Battery Failure Analysis and Characterization of Failure Types

By Sean Berg

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

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

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.

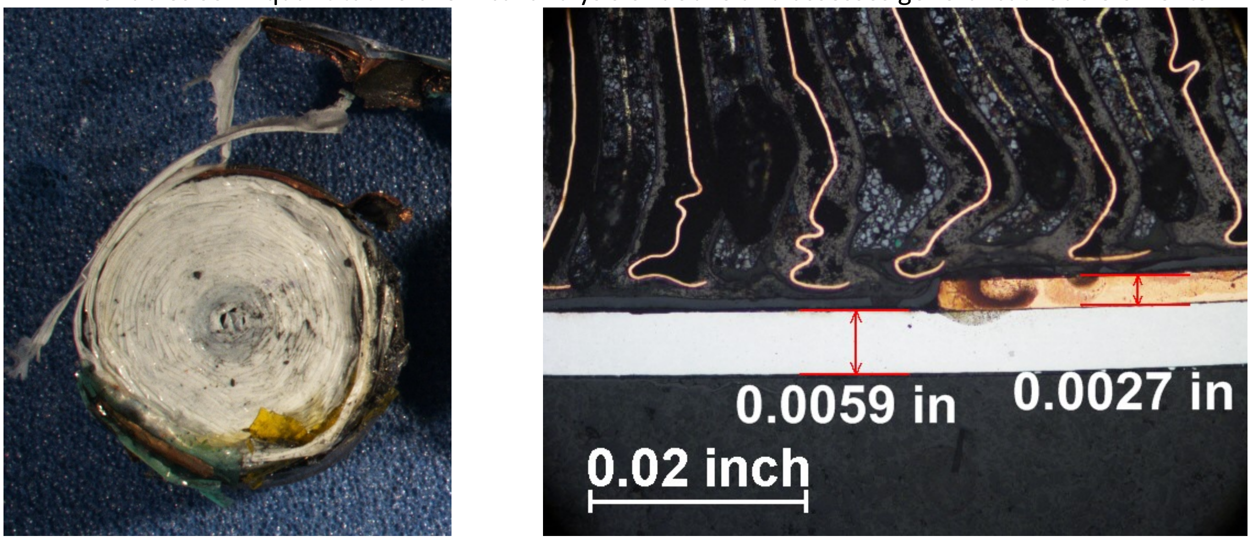

Figure 2: Example of a cell opening (left) of a button cell Li-ion battery, and metallographic cross-section (right) of battery

- 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.

Figure 3: Sample data from cell testing of a LFP battery showing charge/discharge cycling

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.

BESS Frequency of Failure Research Topic

By Wun Wong

October 8, 2021

This article is an introduction to the current state of failure frequency research for Battery Energy Storage Systems (BESS). This is the second article in a six-part series. To read other articles in this series, click here.

BESS is a subset of Energy Storage Systems (ESS), which is a system of devices intended to store energy and then release for use. BESS is specifically the type of ESS that uses a rechargeable battery for energy storage, a component to convert/release the electrical energy into motive force or to feed an electric grid/device(s), often with a Battery Management System (BMS) to control its performance and ensure safety. BESS is utilized in a multitude of applications, but the most attention is paid to the growing field of vehicular batteries for hybrid or fully electric vehicles, and stationary battery systems for electrical grids or facilities. In article one of this series, battery failures and the mechanisms of how they occur, and techniques used to evaluate them were discussed. This article discusses the frequency of such failures, which can in turn be helpful in determining the risk from such systems. Failure rate predictions of BESS are conducted with a variety of methods and with differing amounts of success. Review of literature on this topic shows that there are numerous factors that limit the accuracy and usefulness of these prediction methodologies. The primary factors are:

- **BESS has many failure modes, and they are not uniformly defined.** There are many different failure modes for different batteries, or under different configurations. Even among the Lithium-ion batteries (by far the most used in the market), each type has widely different characteristics with regards to fire resistance, fire and explosion propagation, and resilience to ambient conditions. This is not including factors such as manufacturing flaws, the wide range of operating conditions that BESS are subjected to, and effectiveness of the BMS. There are also non-Lithium-ion batteries with different chemical characteristics or mode of operations, such as flow batteries, which have different failure modes and risks.
- **BESS reliability data is scarce**. The publicly available data is limited and non-uniform. Additionally, data recorded is often in the range of fixed temperatures and with fixed cycling conditions. These conditions do not reflect the variability of real-world use.
- **BESS design changes are ‘fast paced’**. The drive to develop BESS with more energy density, efficiency, and higher integrity results in changes in BESS design at a high pace. This changes the potential failure modes and frequencies of BESS being modeled, and gathering potentially obsolete failure rate data from older designs.

Standard “simple” equations of component failures

A BESS consists of not only the battery cell but multiple components that can fail and cause the chain of events that result in hazards. Failure rates for BESS can be roughly estimated by conducting failure mode analysis (fault tree, FMEA, etc.) and evaluating the failure rates of each component in its system to determine the overall failure rate. Because failure rates for electronic instrumentation and components are extensively studied, there are simplified equations to estimate failure rates that are commonly used for electronic systems. The IEC TR62308-2004[1] provided calculation equations that were used in a large body of work assessing BESS failures of electric vehicles. The usefulness of these equations is uncertain as the failure rates were not specified for types of failure, and the failure of the battery module is too generic to account for the wide (widening) range of battery systems in the market today. It follows that IEC TR62308-2004 was withdrawn by IEC, and in its place a new IEC TR62308-2006 was re-issued for reliability testing methodology. While there is ongoing research and studies of electric vehicles that use those equations from IEC TR62308-2004, an accurate estimation of battery failure rates will require a new approach, as described below.

Physics based model of prediction

Physics of Failure (PoF) methodology was developed to determine the reliability of early generation electronic parts and systems. It is the use of degradation algorithms that describe how physical, chemical, mechanical, thermal, or electrical mechanisms evolve over time and eventually induce failure. This approach takes the understanding of battery chemistry, material of construction, component failure modes, degradation mechanisms, test experience, etc. to develop first-order equations that allow the design or reliability engineer to predict the time to failure behavior based on information on the design architecture, materials, and environment.

This methodology is already utilized in virtual simulations in industries like aircraft design. However, significant testing is necessary to develop the understanding of battery failure for each type of battery, and proper assumptions are needed to ensure the models developed are accurate. Ultimately, PoF development requires highly knowledgeable experts to perform the analysis, and in developing technologies like BESS, such expertise is not widely available. PoF is not the only type of physics-based approach to model battery failure modes, performance, and degradation process. Other physics-based models have similar issues in development as PoF, and as such they work best with support of empirical data to verify assumptions and tune the results.

Empirical model of prediction

Assessment of instrumentation failures are often performed using failure distribution models to combine time failure data and simplified equations to estimate failure. For example, distribute major types of failures for electronic components such as early failures, random failures, and wear out failures into a 'bathtub' curve. Figure 1 shows an example of how failures are combined to generate a 'bathtub' curve.

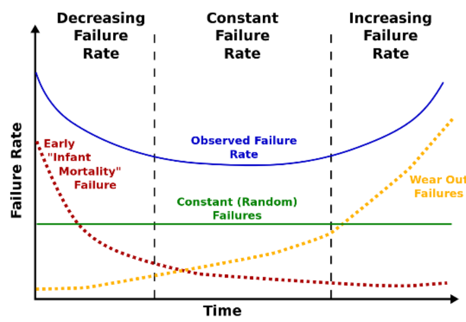

Figure 1. Generic Examples of Bathtub Curves[2]

[1] IEC TR62308-2004, Reliability data handbook - Universal model for reliability prediction of electronics components, PCBs and equipment, International Electro technical Commission, Geneva, 2004

[2] Wyrwas, Edward & Condra, Lloyd & Hava, Avshalom. (2011). Accurate Quantitative Physics-of-Failure Approach to Integrated Circuit Reliability. IPC APEX EXPO Technical Conference 2011.

Standard “simplified equations” used for instrumentation systems generally use the ‘constant’ failure rate value in the ‘useful life’ section of the curve. This is due to the tendency of the random failures being representative of the majority of the instrument’s life-cycle of use. While this approach is widely used for electronic components, it is not appropriate for hazardous evaluation of battery cell failure where significant failure modes of interest tend to be caused by flawed construction (early failures) or degradation (wear out).

BESS will require different distribution models and significant data sets for each type of BESS and configuration. Currently, the most popular type of batteries (Lithium-ion) is receiving the largest share of attention from researchers; however, testing is performed only for a small number of battery cells. For example, investigation of cycling data from the beginning to the end of a battery’s life requires a significant investment of time and resources spanning many months or years. Several organizations have made their testing data for battery cycling public, as listed in Table 1:

Table *1*. Publicly Available Battery Overcycle Data Sets[3]

Source	URL
National Aeronautic and Space Administration (NASA)	https://ti.arc.nasa.gov/tech/dash/groups/pcoe/prognostic-data-repository/
Centre for Advanced Life Cycle Engineering (CALCE)	https://web.calce.umd.edu/batteries/data.htm
Toyota research institute (TRI)	https://data.matr.io/1/
Sandia National Laboratory	https://www.batteryarchive.org/snl_study.html
Battery intelligence lab at Oxford	https://howey.eng.ox.ac.uk/data-and-code/
Hawaii Natural Energy Institute (HNEI)	https://www.batteryarchive.org/study_summaries.html
EVERLASTING Project funded by European Commission	https://data.4tu.nl/articles/dataset/ Lifecycle_ageing_tests_on_commercial_18650_Li_ion _cell_10_C_and_0_C/1437729
Karlsruhe Institute of Technology (KIT)	https://rdr.ucl.ac.uk/articles/dataset/Lithium-ion_Battery_INR18650_MJ1_Data_400_Electrochemical_Cycles_EIL-015_/12159462/1
University College London (UCL)	https://publikationen.bibliothek.kit.edu/1000094469
UC Berkeley	https://data.mendeley.com/datasets/c5dxwn6w92/1
Xi’an Jiaotong University	https://datadryad.org/stash/dataset/doi:10.6078/D1MS3X
Diao et al. (paper)	https://data.mendeley.com/datasets/c35zbmn7j8/1
Poznan University of Technology	https://data.mendeley.com/datasets/k6v83s2xdm/1

However, most have less than 50 battery cells tested, and none have more than 240 cells tested. Fortunately, research is proceeding at a significant pace, and public data storage platforms are providing common and easily navigable locations to find and (possibly) share data. They also promote standardization in data format and descriptions. Some well-known platforms are listed in Table 2:

[3] Dos Reis, Gonçalo & Strange, Calum & Yadav, Mohit & Li, Shawn. (2021). Lithium-ion battery data and where to find it. Energy and AI. 5. 100081. 10.1016/j.egyai.2021.100081.

Table 2. Platforms with Freely Accessible Battery Data Sets

Source	URL
Battery archive, developed at the City University of New York Energy Institute	https://www.batteryarchive.org/
U.S. Department of Energy's Office of Electricity (DOE OE)	https://www.sandia.gov/energystoragesafety-ssl/research-development/research-data-repository/
National Renewable Energy Laboratory (NREL)	https://www.nrel.gov/research/data-tools.html

Additionally, some battery testing data have been deposited at publicly accessible data repositories (see Table 3). These repositories provide users with a storage medium for their open-source data, i.e., generate a Digital Object Identifier (DOI), to make them citable and trackable, and in some cases provide data review and quality assurance.

Table *3*. Curated Public Data Repositories with Battery Data Sets3

Source	URL
Dryad	https://datadryad.org/stash
Zenodo	https://zenodo.org/
European federation of data driven innovation hubs	https://euhubs4data.eu/datasets/
Mendeley data center	https://data.mendeley.com/
4TU.ResearchData	https://data.4tu.nl/

Summary of the state of Failure Rate Research

Currently, the communication of data between end-users, manufacturers, distributors, and providers is poor. There are not many instances of 1) field data shared publicly for battery failures, 2) second-life battery failure data, 3) abuse testing data, and 4) data containing mechanical measurements. Furthermore, there is a general lack of consensus on the way to present data, making efforts difficult to combine or evaluate dataset together. There is considerable room for further research, particularly testing and collection of field observations to generate failure rate models that are accurate and applicable to a greater number of BESS.

BakerRisk is currently working on performing statistical analysis on the failure rate data available, as well as setting up tests to simulate failure; and invites participants in this effort. Once the failure modes and frequency are established, it is important to understand what the consequences of failure may be expected. This is the topic of the third article in this six-part series.

A Review of Fire Mitigation Methods for Li-ion BESS

By Roshan Sebastian
November 12, 2021

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

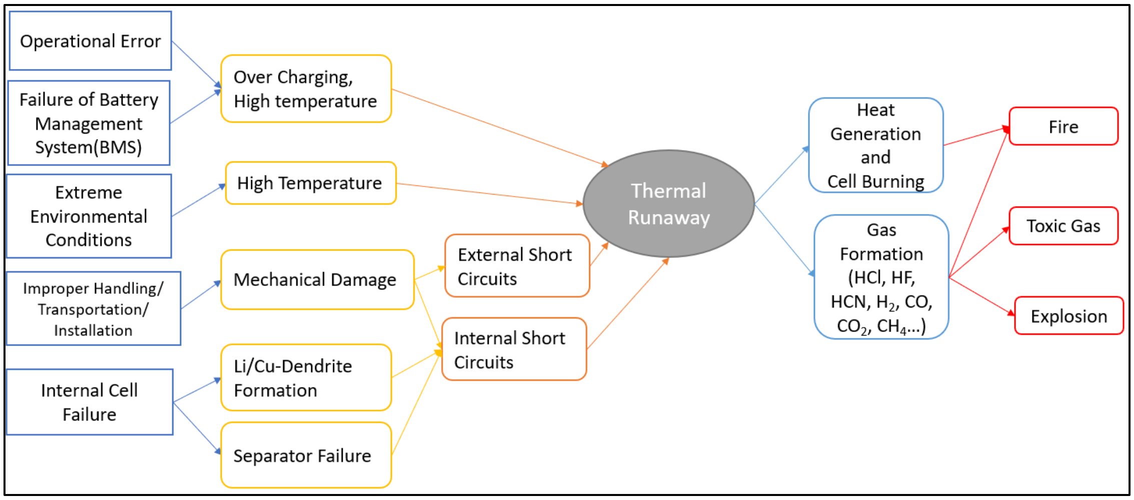

Figure 1. Li-ion Battery Thermal Runaway Schematic

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.

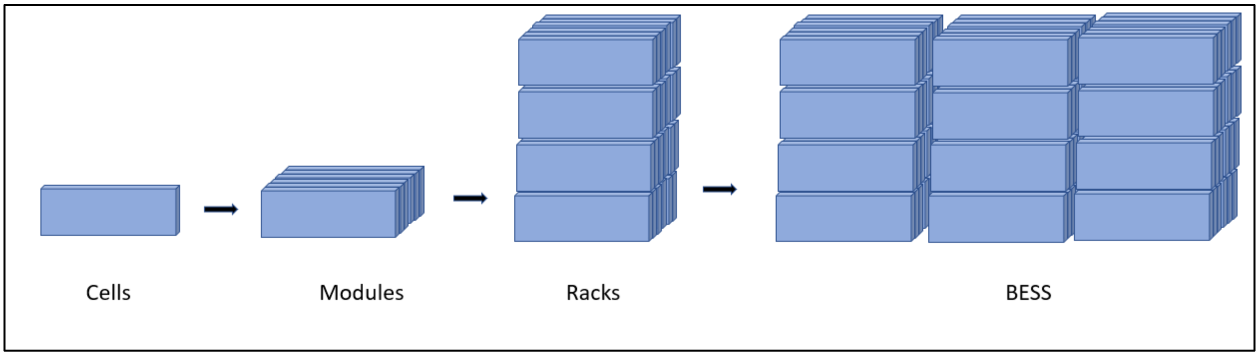

Figure 3. General BESS Arrangement

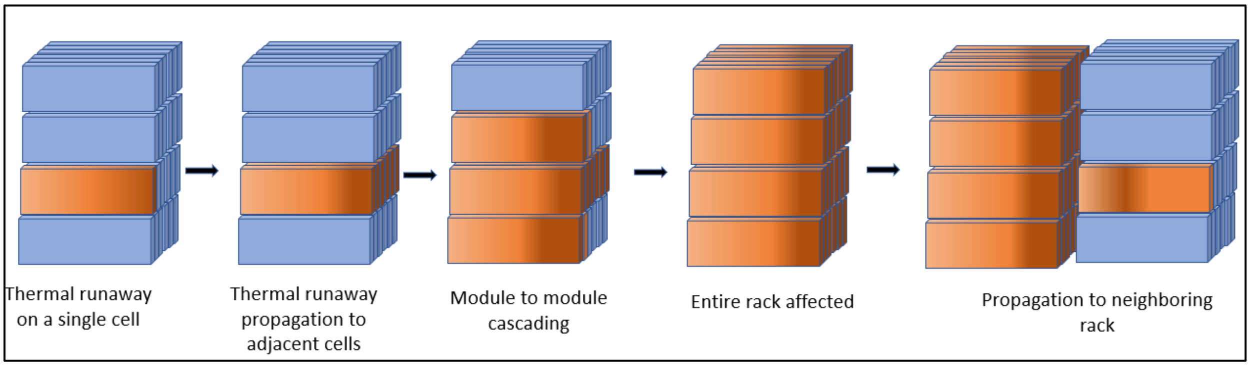

Figure 4. Thermal Runaway Propagation Phenomenon in a BESS

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.

BESS Part 4: Flammable Hazards of BESS Failures

By Aníbal Morones, PhD
December 3, 2021

This article is the fourth in BakerRisk's six-part series on Battery Energy Storage System (BESS) hazards (previous articles can be found here). The first article described ways in which lithium ion (Li-ion) batteries can fail, followed by a discussion of challenges assessing the reliability of such a rapidly-evolving technology. The third article discussed potential mitigation strategies for BESS facilities. This article discusses the consequences of catastrophic failure in a BESS.

The combustible materials used to build battery cells are contained in a casing that prevents exposure to air. Nevertheless, under certain conditions, batteries can produce flammable and/or explosive atmospheres and pose related risks. This article describes basic concepts of combustion that aid in the analysis of consequences of fires and explosions associated with BEES failures.

During normal operation, useful energy is cycled in and out of a battery cell when powering a load or recharging the battery. Some heat is generated inside battery as a byproduct of the reversible reactions that facilitate such cycling of energy. Thermal management is key to the battery health, as high temperature enables irreversible degrading reactions that release more heat and permanently affect the performance. Improper dissipation of generated heat, or an external heat source are just two of the several modes of failures (for more information click here) that can generate a build-up of temperature in a battery cell. Once the temperature rises above the thermal runaway critical point, the heat is generated spontaneously through the aforementioned irreversible reactions at a quicker rate that it can be dissipated until destruction of the battery occurs and possibly the rupture of the casing. The strength of the casing and the internal gas volume within are factors in burst intensity. The weakest of the structural components and connections in the casing will control the pressure at which the casing fails. As battery casings are not typically designed as pressure vessels and the interior volume is mostly occupied by solids, the bursting of casing itself is unlikely to be of major consequence.

With the battery casing integrity lost, air may come in contact with flammable materials, such as the electrolyte solvent and gaseous decomposition products formed during the thermal runaway. The released gas is composed of a mixture of hydrogen, carbon dioxide, and carbon monoxide with traces of light hydrocarbons. Exposing these flammable materials into air means that all the elements (fuel, oxidizer, and a competent ignition source) required for a fire are present. Fire increases the chances of cascading runaway, but it is not it a necessary condition. Cascading runaway was observed in a severe incident where a clean fire suppressant agent prevented open flames to exist.[1,2]

Figure 1 examines different paths in which the materials expelled from a Li-ion cell may be transformed into one or more damaging effects through different modes of combustion. Strictly speaking, all flames happen in the gas phase, even if the fuel is originally in a different state. If the fuel is already in gas phase and thoroughly mixed with air, the combustion regime is referred to as a pre-mixed flame. When fuel and air are physically separate, the flame establishes near the contact surface of the reactants. This mode of combustion is called a diffusion flame. A diffusion flame may supply the heat necessary to gasify and/or melt the fuel entering the reaction zone if the fuel is not in the gas phase already. Pool fires, jet fires, and candle flames are examples of diffusion flames. See Figure 2 for examples of diffusion and premixed flames in the context of battery failures.

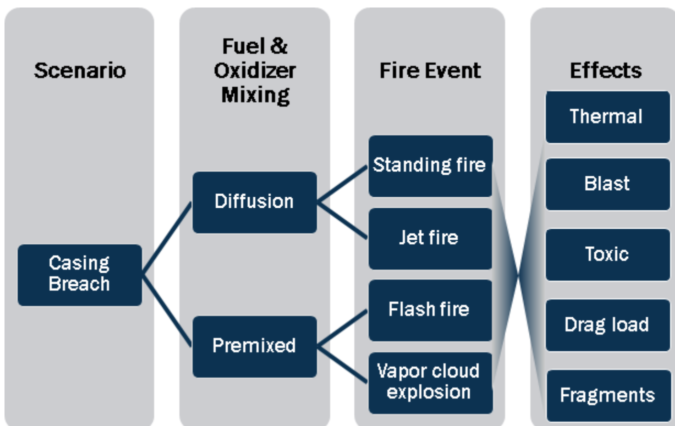

Figure 1. Failure hazards of Li-ion batteries

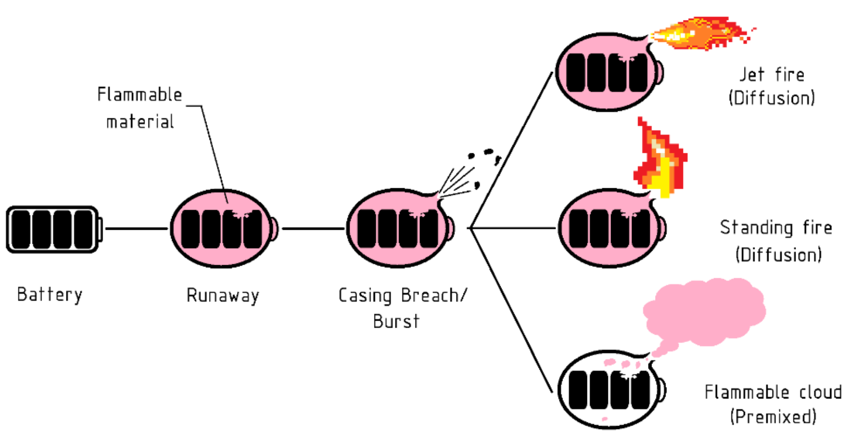

Figure 2. A possible line chain of events during runaway

1 DNV GL Energy Insights USA, McMicken Battery Energy Storage System Event Technical Analysis and Recommendations, in Technical Support for APS Related to McMicken Thermal Runaway and Explosion. 2020.

2 McKinnon, M.B., S. DeCrane, and S.I. Kerber, *Four Firefighters Injured In Lithium-Ion Battery Energy Storage System Explosion - Arizona*. 2020, UL Firefighter Safety Research Institute.

Pre-mixed flames can also be formed during battery failures. If a battery cell off-gases decomposition products that are allowed to mix with ambient air prior to finding an ignition source, then a flammable premixed cloud may be created. In pre-mixed flames, the reactants are already in contact and therefore the flame advances unhindered by the intermediate steps such as mixing, and/or evaporation sometimes present in diffusion flames. In addition, the flame front of pre-mixed flames is not bound to the contact surface of fuel and oxidizer, so it can grow to encompass the extent of the reactant field. This readiness for reaction means that pre-mixed flammable clouds have the potential to convert the chemical energy into thermal energy very quickly resulting in a flash fire or a deflagration explosion[3]. Deflagrations are pre-mixed flames that stay subsonic, such as flash fires and vapor cloud explosions. Thermal run-away in Li-ion batteries has the potential to produce deflagrations.

Flash fires are typical of clouds consumed in open, uncongested spaces. No overpressure or blast is expected from a flash fire. Flashfires have been observed in prior catastrophic battery failures (e.g. *Electric bus bursts into flames, sets nearby vehicles on fire in China* | South China Morning Post (scmp.com)).[4]

Under certain conditions that can create sufficient turbulence, the combustion of premixed flammable clouds can occur so rapidly that a vapor cloud explosion occurs producing a perceptible blast wave. Reactivity, concentration, and turbulence strongly influence the rate at which a deflagration consumes the available fuel and oxidizer (usually air). The energy associated with unintended deflagrations scales the size of the flammable cloud. If the cloud is large enough to engulf nearby structures and equipment, the interaction with these objects could intensify the reaction rate. In general, any obstruction or body immersed in the cloud stirs turbulence as the deflagration front wraps around it. These objects are collectively called "congestion" in the context of unintended flammable releases. The more congestion, the more turbulence is created resulting in quicker energy release resulting higher overpressures.

A vented deflagration is a special type of vapor cloud explosion that occurs within an enclosed structure, which ultimately fails (hopefully in a designed fashion) and allows the flammable cloud/combustion event to vent to the outside environment. This venting relieves the pressure applied to the inside of the structure. To describe vented deflagrations, it is useful to describe the effect of heat addition to a rigid closed volume (isochoric). A finite quantity of gas molecules held captive at constant volume have density ρ and will maintain that density as long as none of the molecules are allowed to enter or leave the space. Temperature, T, and pressure, p, of the gas are linked in this type of constant-volume system. For ideal gases, pressure is proportional to temperature with the factor ρR, where R is the ideal gas constant. This relationship is depicted in Figure 3. If heat is added to an isochoric system, both pressure and temperature increase. Combustion could be the source of the heat that increases temperature of gas trapped inside of a closed volume.[5]

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[3] "Explosion" is used in this text in colloquial sense of the word and is synonymous with blast.

[4] https://www.scmp.com/video/china/3136069/electric-bus-bursts-flames-sets-nearby-vehicles-fire-china

[5] The molecule count in combustion is not necessarily conserved as atoms in reactants may arrange in products in such way thar results in net change of molecule quantity. For the sake of simplicity, this discussion assumes the molecule count stays relatively constant, which is fair for many cases of combustion in air, since inert nitrogen molecules make up most of the molecules.

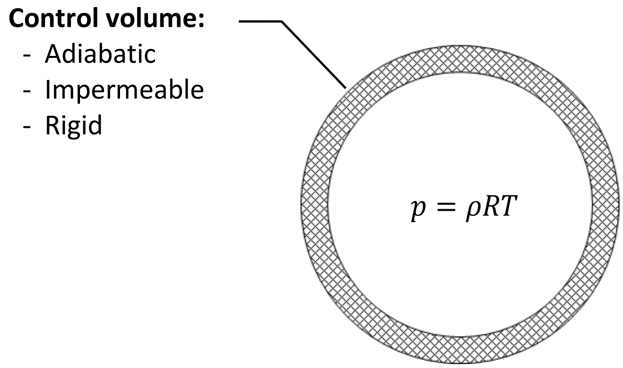

Figure 3. Illustration of Isochoric System
Pressure scales with temperature with ratio ρR

Figure 4 presents a pressure trace of a confined combustion test in a laboratory. The vessel was filled with gaseous fuel and oxidizer at 1 atmosphere before sealing it. The mixture was then ignited, and the instruments recorded peak pressure of about 8 atmospheres before thermal losses to the walls of the test vessel cooled the vapor space and forced the gas pressure to gradually decay (solid line in Figure 4). While a pressure vessel in a laboratory can be made to handle the maximum pressure developed by confined combustion, buildings and structures are seldom built to withstand such loads.[6]

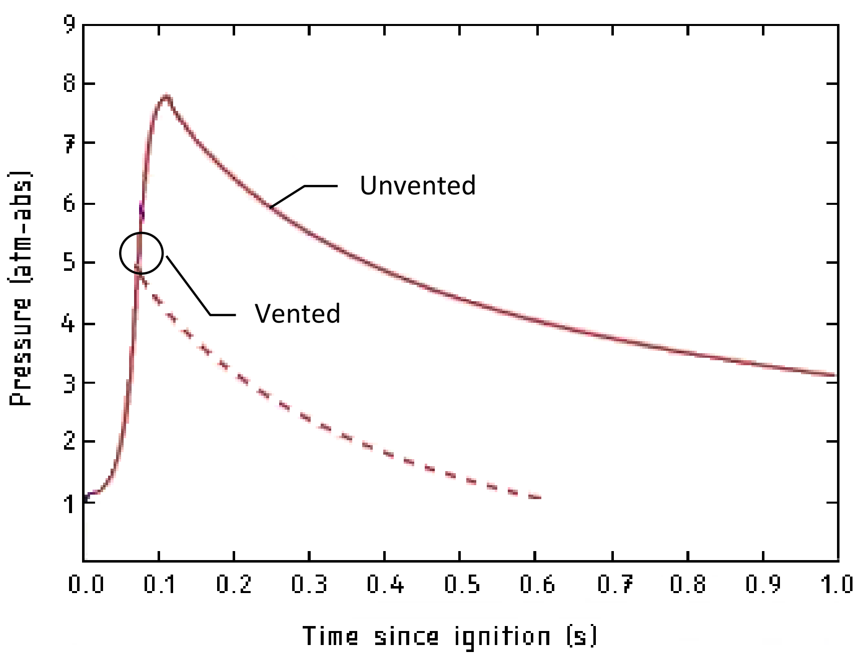

Figure 4. Pressure traces of confined combustion

[6] https://www.click2houston.com/news/2017/04/24/lithium-batteries-causes-train-car-explosion-in-ne-houston/

Typically, a space that initially contains an internal combustion event will fail due to the increase in internal pressure and breach to allow gases to escape and reduce further pressure escalation (dotted line in Figure 4). The failure of the structure creates blast wave, fireball ejection, and possibly debris throw. The gases leaving the confided volume do so at high speed and can exert significant drag loads on nearby objects. Internal deflagrations and venting have been reported in catastrophic incidents involving battery energy storage systems, sometimes with fatal consequences.[7]

Batteries have been observed to fail catastrophically for a variety of reasons.[8] While there is a fair degree of uncertainty on how and when a battery system may fail, the effects described above can be reasonably bounded and modeled. Once the effects have been assessed, the consequences to structures, equipment, and/or personnel are estimated to determine risk. Part 5 in this series will cover the assessment of damage caused by catastrophic hazards and address considerations for mitigation design.

[7] Accident analysis of the Beijing lithium battery explosion which killed two firefighters | CTIF - International Association of Fire Services (https://www.ctif.org/news/accident-analysis-beijing-lithium-battery-explosion-which-killed-two-firefighters)

[8] https://storagewiki.epri.com/index.php/BESS_Failure_Event_Database

BESS Part 5: Evaluation and Design of Structures to Contain Lithium-ion Battery Hazards

By: Gabriel A. Shelton, P.E.
Senior Structural Engineer – BakerRisk Protective Structures Section

January 19, 2022

This article is a continuation of BakerRisk's six-part series on Battery Energy Storage System (BESS) hazards, with the previous articles located here**.** To date, the series has introduced failure types, failure frequencies, fire mitigation methods, and quantifying explosion and fire hazard consequences related to BESS hazards.

Lithium-ion (Li-ion) batteries have the potential for serious explosion and fire hazards due to the ability of Li-ion batteries to experience thermal runaway reactions that can continue without supplemental oxygen. These hazards can have serious consequences to human life, equipment, and building integrity. Li-ion batteries have many uses from cell phones to electric vehicles and are also located in various facilities such as BESS or battery test labs. This BESS hazards series Part 5 provides a review of available analytical approaches to evaluate existing structures and design new structures for protection from Li-ion battery hazards.

To evaluate or design a structure with regard to Li-ion battery hazards, those hazards must first be quantified in terms of loads. Li-ion batteries will off-gas when undergoing thermal runaway. This off-gas product is typically a mixture of hot gasses that are made up of the battery solvents and other chemicals, and consist of varying amounts of hydrogen gas, carbon monoxide, carbon dioxide, and hydrocarbons.

The volume basis breakdown of the molecular components of a gas cloud produced by off gassing Li-ion batteries is provided by battery manufacturers in the form of a report[1] published by Underwriter's Laboratories (UL). The UL report also evaluates the propagation of thermal run-away fires from battery to battery, module-to-module, or rack-to-rack. This gas mixture breakdown can be used to determine the combustion properties of the gas mixture using publicly available software.[2,3] The fourth paper in this series discusses the potential the potential for fires and explosions outcomes depending upon the specific conditions of the installation.

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1 UL 9540A (Ed. 2018), Underwriter's Laboratories. Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems.

2 D.G. Goodwin, H.K. Moffat, and R.L. Speth, Cantera: An object-oriented software toolkit for chemical kinetics, thermodynamics, and transport processes; 2017. http://www.cantera.org

3 J.C. Prince, C. Treviño, and F.A. Williams, *A reduced reaction mechanism for the combustion of n-butane.* Combustion and Flame, 2017. **175**: p. 27-33.

NFPA 68[4] provides guidance on estimating the residual blast loads on the interior of an enclosed space taking into account the mitigation from vent panels designed to release at a lower pressure. Blast loads for scenarios such as enclosed spaces without vent panels or flammable gas clouds in open-air can also be evaluated using various approaches such as computational fluid dynamics (CFD) codes[5,6] or other load prediction models.[7] CFD modeling requires a higher level of expertise and takes longer to develop but is typically more accurate than empirical models. Figure 1 shows a series of images of pressure contours through a postulated release scenario.

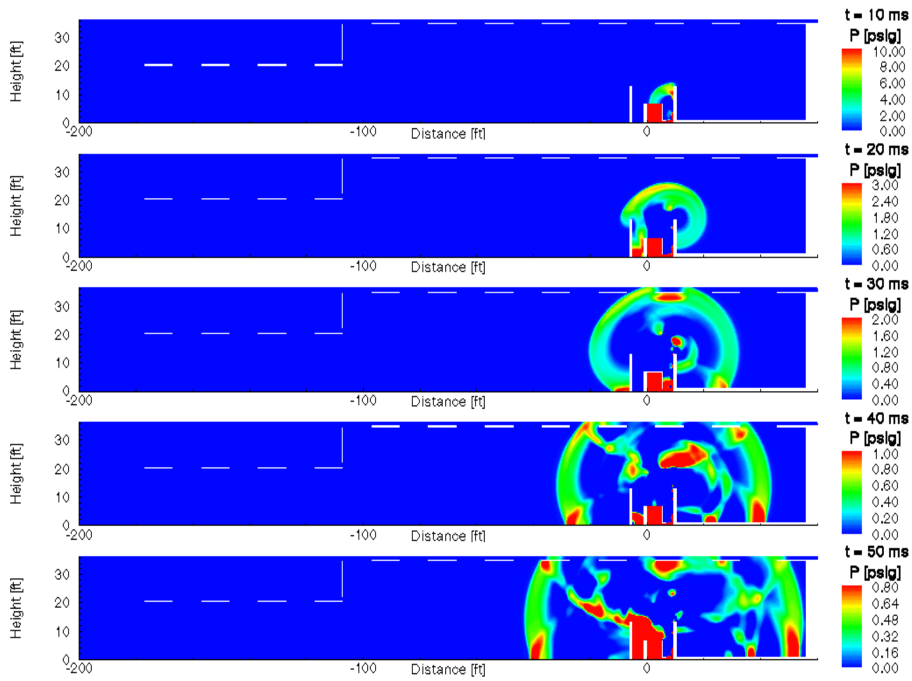

Figure 1. Example of CFD Blast Load Analysis Results

Thermal loads from fires can be also predicted using NFPA 68 or using specialized CFD codes.[8] Once the appropriate blast and thermal loads have been determined, they can be used to evaluate existing structures or design new structures.

Conducting an effective evaluation of the hazards presented by Li-ion batteries depends on the target in question. If the targets of interest are personnel, then the purpose of the evaluation is to minimize injury and loss of life.

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4 NFPA 68, Standard on Explosion Protection by Deflagration Venting; National Fire Protection Association, 2018.

5 Geng, J., Thomas, K., Simulation and Application of Blast Wave Target Interactions, BWTI™, BakerRisk, AICHE Conference 2007.

6 FLACS-CFD 21.2 User Manual, 2021, Gexcon AS.

7 Q.A. Baker, M.J. Tang, E.A. Scheier, and G.J. Silva, “Vapor cloud explosion analysis”, Proc 28th AIChE.

8 Fire Dynamics Simulator reference.

If the target of interest is the building that houses the batteries, then the purpose of the evaluation is to minimize the damage to the building to the extent practical. This can mean that some damage is acceptable or that significant damage is acceptable; but building collapse (or failure) is not acceptable. Consequences for buildings may also be couched in the context of building occupant vulnerability; i.e., the likelihood of fatality or serious injury of building occupants.

If the target of interest is equipment, the purpose of the evaluation is to minimize loss or damage of the infrastructure/equipment. Equipment loss is complex and highly dependent on the type of equipment and so, for the purposes of this paper, will be neglected.

For evaluation of thermal (fire) hazards, the purpose of the evaluation is similar: for structures it is to minimize damage to the buildings, for personnel it is to minimize injury and loss of life, and for equipment it is to minimize the loss or damage of equipment.

Most conventional structural analysis employs static analysis methods, using loads that have been developed in a way that are communicated as "static load equivalents," even for loading phenomena that may have dynamic properties, such as wind. Because blast loads are typically high in pressure, but very short in duration, a dynamic analysis methodology is more appropriate as opposed to a static design method. Using a static methodology with dynamic loads can often result in overdesigned structures and thus a more expensive building. Conversely, existing structures evaluated using static methodology can result in underestimating the structural capacity of the building.

Single Degree of Freedom (SDOF) or Multi-Degree of Freedom (MDOF) methods are well-established analytical design/analysis methods that can be used to evaluate or design structural components or systems by modeling them as a spring mass system. SDOF and MDOF software is available publicly. High fidelity Finite Element Analysis (FEA) codes[9,10] can also be used to design or analyze structures subjected to blast loading. Like CFD analysis, FEA requires a higher level of expertise and requires more time to develop, but the results are often more accurate and less conservative. Figure 2 shows an example of an FEA model of a pre-engineered metal building responding to a blast load.

[9] LS-DYNA User's Manual, "Nonlinear Dynamic Analysis of Structures," Version 971, Livermore Software Technology Corporation, Livermore, California, September 2006.

[10] ANSYS reference.

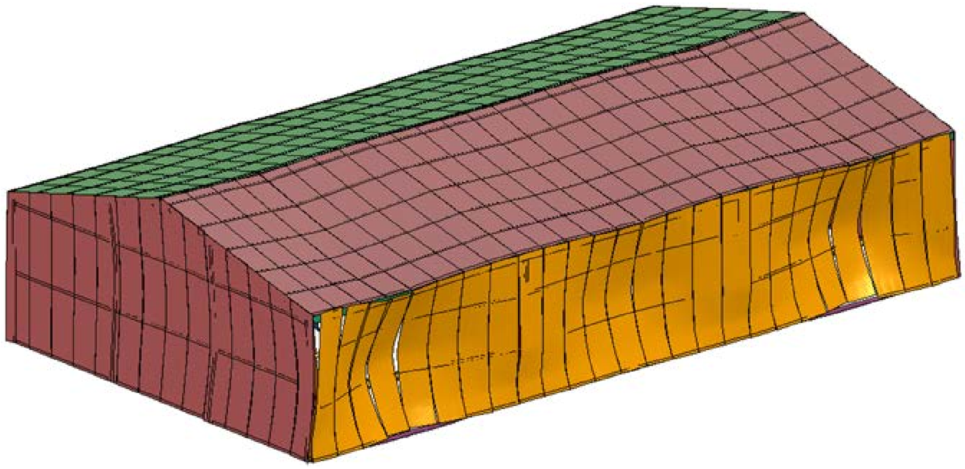

Figure 2. Example of an FEA Model

Structural response criteria for structural components are typically defined as deformation limits and/or deflection limits. Deformation is the stress level of a material compared to the maximum yield strength of the material and is also often referred to as ductility. Deflection, usually communicated in a value of degrees of support rotation, is the amount that a structural component has bent out of its original position. Several references are available for determining response criteria for various structural component types.[11,12]

Component response definitions taken from ASCE[11] are provided in Table 1. Structural components can be evaluated to determine the structural response to dynamic loads, and the response can then be compared to structural response criteria to determine if the components meet the requirements of the project.

Table 1. Component Response Descriptions[11]

Low	Component has none to slight visible permanent damage.
Medium	Component has some permanent deflection. It is generally repairable, if necessary, although replacement may be more economical and aesthetic
High	Component has not failed, but it has significant permanent deflections causing it to be unrepairable.
Failure	Component has failed or collapsed.

Humans are vulnerable to open-air blast loads although the extent of predicted vulnerability differs by reference source. However, a review of the data suggests that humans may experience approximately

[11] Design of Blast-Resistant Buildings in Petrochemical Facilities, Second Edition, prepared by the Task Committee on Blast Resistant Design of the Petrochemical Committee of the Energy Division of the American Society of Civil Engineers, 2010.

[12] Single Degree of Freedom Structural Response Limits for Antiterrorism Design, USCOE PDC TR 06-08, Jan. 2008.

the following consequences which occur at the respective blast pressures:[12,13]

- 50% Chance of Ear Drum Rupture: 15.0 psig
- Knock-down, Lung Damage: 8.0 psig
- 10% Chance of Ear Drum Rupture: 3.5 psig
- Temporary Hearing Loss: 2.3 psig

Building occupants exposed to blast loads are vulnerable to debris hazards and potentially fatal injuries (roof or wall collapse). There are methods[14] available to determine building occupant vulnerability estimates from structural response results.

Personnel located near explosion sources are vulnerable to potential projectiles that could be thrown as fragments from the explosion. Projectiles launched from explosions are typically thrown at very high velocity, causing more serious injuries to nearby people.[15] Because of this, projectiles require full containment.

Humans are also vulnerable to toxic hazards produced by battery off-gassing. Modeling the exposure of personnel to toxic concentrations can be done using analytical models of varying complexity. The criteria for human injury from toxics can be defined using simplified threshold limits such as OSHA permissible exposure limits (PELs)[16] or by more complex techniques such as toxic probit functions.[17]

Equipment response limits are wide ranging and dependent on the type of equipment. The criteria for equipment response is dependent on how important the equipment is to the overall process or to site safety. Evaluating equipment response to structural damage from blast loads or thermal loads requires input from the equipment owners and is beyond the scope of this paper.

The design of buildings for thermal loads is a complex topic. Material properties for the various structural components such as thermal conductivity, heat capacity, and emissivity come into play. Other factors like ventilation, passive fire protection, and active fire protection should be considered. Covering all characteristics of these aspects is beyond the scope of this paper, but in general the predicted loads are compared to the criteria or limits that have been established. If the loads are higher than the limits, then the design does not meet the criteria and will require redesign.

The evaluation of structures, equipment, and personnel to thermal loads is similar to those of blast loads

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[13] U.S. Dept. of Energy, A Manual for the Prediction of Blast and Fragment Loadings on Structures, DOE/TIC-11268, USDOE – Albuquerque Operations Office, July 1992

[14] Oswald, Charles J., and Baker, Quentin A., "Vulnerability Model for Occupants of Blast Damaged Buildings," presented at the 34th Annual Loss Prevention Symposium, March 6-8, 2000.

[15] Department of Defense, DoD Ammunition and Explosives Safety Standards: General Explosives Safety Information and Requirements, 6055.09 M, February 29,2008

[16] 29 CFR 1910.1000, OSHA, Permissible Exposure Limits, Table Z-1,

[17] TNO, Guidelines for Quantitative Risk Assessment (Purple Book), The Hauge, Advisory Council of Dangerous Substances (Adviesraad Gevaarlijke Stoffen – AGS), 2008

to some degree: e.g., once loads have been developed, a comparison of the loads on the targets of interest must be compared to some criteria to determine acceptability. For buildings, the loosest criteria may be if the temperature of the critical (primary) steel components does not exceed some predefined temperature threshold. This threshold may be 600°F which is the temperature that steel begins to soften (and weaken), or some fraction of that temperature for a margin of safety.

Some building criteria may employ the use of the ASTM E-119 time-temperature curve[18] which is the temperature increase that corresponds to an idealized cellulosic (wood/paper) fire. This time-temperature curve is used to establish fire ratings for building components using a testing method that subjects building components to the time-temperature curve and records the amount of time that the component either fails to maintain its structural integrity or allows enough heat to transfer though a barrier component to allow the air on the protected side to reach temperatures that will ignite cellulosic materials. Fire ratings for components of concern can be determined by literature review, by calculation, or depending on manufacturer claims. If the thermal loads are lower than a component's fire rating then the criteria is met; if the predicted thermal loads are higher than the fire rating, then the criteria is not met.

Other criteria may involve the susceptibility of temperature sensitive equipment such as battery-related equipment, adjacent batteries, computer server equipment, or process control equipment to high temperatures. Such equipment criteria are likely to be in the form of temperature thresholds and are equipment specific.

Humans can sustain low levels of thermal loading without permanent injury or fatality. Personnel who are engulfed in a fireball may be considered as a fatality for the purposes of modeling; however, personnel who are even short distances from the boundary of a fireball and are exposed to thermal radiation for the duration of the event may suffer less serious injury. Several equations[17] have been developed as thermal probit equations or thermal vulnerability models that consider not only temperature, but thermal dose (thermal intensity in terms of radiant flux (kW/m^2) and duration).

Battery hazards can have serious consequences in the form of explosions or fires which can be quantified in terms of blast and thermal loads, respectively. These consequences have the potential to threaten buildings, equipment, and most importantly people. There are existing industry-accepted methods that can be used to evaluate existing structures or design new structures to withstand these loads. In addition, various criteria can be used to determine what level of protection is acceptable. These collective approaches can be used together to protect targets of concern when battery hazards cannot otherwise be mitigated.

[18] American Society for Testing and Materials-International, Standard Test Methods for Fire Tests of Building Construction and Materials, ASTM E-119, 2018.

BESS Part 6:
Overview of Li-ion BESS Failures and Risk Management Considerations

By Roger Stokes

February 4, 2022

This is the final article in a six-part series on Battery Energy Storage Systems (BESS), available for download here, which have examined:

1. Battery Failure Analysis and Characterization of Failure Types
2. BESS Frequency of Failure Research
3. Review of Fire Mitigation Methods for Li-ion BESS
4. Consequences of BESS Catastrophic Failure
5. Evaluation and Design of Structures to Contain Lithium-ion Battery Hazards

These articles explain the background of Lithium-ion battery systems, key issues concerning the types of failure, and some guidance on how to identify the cause(s) of the failures. Failure can occur for a number of external reasons including physical damage and exposure to external heat, which can lead to thermal runaway. Thermal runaway can also be triggered by numerous functional causes including overcharging, overloading, ageing, or design issues including internal component failures or short circuits.

We have also learned that the cause, likelihood and consequences of failure are dependent upon the many different designs and configurations of Lithium-ion batteries and associated systems. Forensic examination of a failed battery can determine cause and origin, although this can be difficult when there has been damage due to a major fire or explosion. However, other evidence, such as electronic data and video footage, can help piece together likely cause(s).

Lithium-ion battery technology is moving fast. At present, there is little data available on the reliability of BESS and as designs evolve to achieve higher charging rates, higher energy density, longer life, lower cost and improved reliability, any current data is likely to quickly become out of date. Nevertheless, data is being collected by various organizations and BakerRisk is working on developing statistical models to help our understanding of the likelihood of BESS failures.

Mitigation of fires involving Lithium-ion BESS was discussed in our third paper, which explained how the thermal runaway leads to the release of hot, flammable/toxic components. The high energy density of a typical BESS and the potential propagation/escalation of a runaway reaction incident presents a significant challenge in terms of specifying a suitable fire protection system. A water-based sprinkler system may not be effective in many situations and could make matters worse by causing electrical short-circuits. Water mist systems can be used, some of which use additives such as surfactants or gelling agents, but have limitations that need to be considered. While gaseous clean-agent systems can help extinguish or reduce the extent of the fire, they do not have sufficient cooling properties to prevent the escalation of a thermal runaway from a single cell or module/ rack, plus have the potential disadvantage of adding more toxic materials to the fire. The best strategy is to consider a layered approach that combines design features, early detection, and suppression methods.

The consequences of a thermal runaway can range from minor, localized damage or may escalate to a major event where an entire rack of batteries, or a whole BESS unit, go into thermal runaway with associated release of toxic and flammable/explosive vapors. If ignited, the released vapors can exhibit jet fire characteristics and in some cases, inner materials are ejected forcefully and ignite when they leave the batteries. Where there is a delayed ignition of flammable vapors, there could be a flash fire in an open area or possibly a vapor cloud explosion in an area of congestion similar to the incident where two firefighters were killed following an explosion while fighting a BESS fire in Beijing in April 2021.[1]

Thermal and blast loads that cause injuries and building damage can be evaluated on the basis of the rate and constituents of the gases released. The effect on the surrounding structures can be evaluated using a range of tools and techniques. Mitigation measures against the effect of blast loads include the provision of explosion relief panels.

Large Lithium-ion based BESS should have multiple layers of protection to minimize the likelihood of a thermal runaway occurring and cascading from a single cell or module as well as mitigating the resulting consequences associated with the potential fire, toxic release, or explosion. Mitigation measures start with the design and there is currently a lot of ongoing work to improve the reliability of the individual components. A well-designed Battery Management System (BMS) should monitor down to the module level and ideally isolate individual cells or modules that are displaying unusual behaviour well in advance of the onset of a thermal runaway.

Lithium-ion cells start to release gases in the early stages of a potential runaway event and gas detection can also be used as a signal to the BMS. There are several actions that can be taken to minimize the potential for runaway and escalation including:

- Electrically isolate adjoining modules, the rack, or an entire BESS unit.
- Activate fixed firefighting systems within the module or rack
- Pressure relief panels, either in buildings or the walls/roof of containerized BESS units can prevent damage to structures in the event of an explosion.
- Emergency Response Plans (ERPs) and procedures should ensure that any responding agencies are aware of the unusual properties of a Lithium-ion fire and do not allow air to mix with gaseous emissions (by not opening the doors of a containerized BESS unit[2]).

A simplified Bow-Tie diagram for Lithium-ion battery thermal runaway with various protection layer (barrier) concepts is shown in Figure 1. Many additional barriers could be added to both sides of the diagram.

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[1] Two firefighters killed after Beijing battery blaze – pv magazine International (pv-magazine.com)

[2] New reports look at 2019 Arizona battery explosion – pv magazine International (pv-magazine.com)

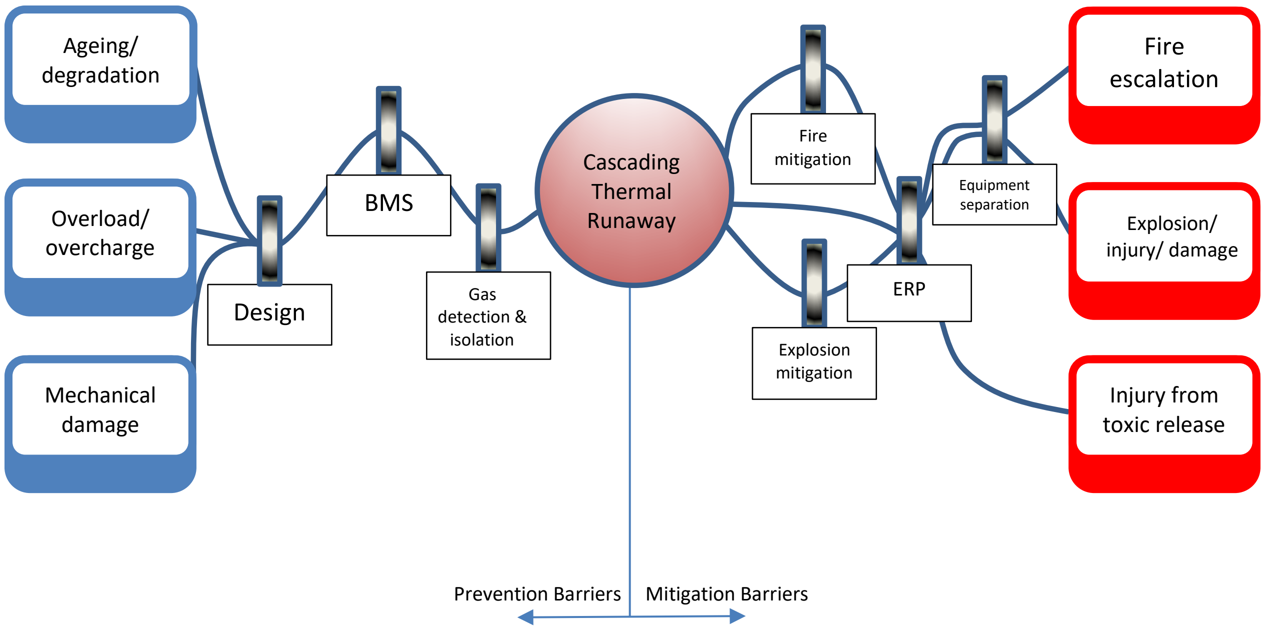

Figure 1: Simplified Bow Tie diagram for Thermal Runaway of Lithium-Ion Batteries

It has been demonstrated through multiple incidents that these protection layers (barriers) do fail occasionally as discussed earlier in this series. Incidents have resulted in injuries from explosions in containerised BESS that have undergone runaway and subsequently been exposed to air when the container doors were opened. Currently it appears that the best course of action is to design the BESS container system for the worst-case basis that a runaway will occur and assume that all of the cells/ modules/racks within the container will be involved.

The objective should be to prevent injury to personnel, escalation of the event to adjacent containers, and to provide suitable means for emergency response teams (ERT)/ fire brigade personnel to provide cooling for adjacent containers and other equipment.

BESS containers should be designed with explosion relief panels in the walls/roof that are sized to release at pressures well below those that might cause any structural damage to the container.

To prevent escalation, consider proper spacing, and, when space is constrained, consider using thermally resistive barriers to allow time for the ERT/fire brigade to set up cooling. The recommended container separation distances are likely to be reviewed/reconsidered as there is continued learning from BESS incidents; some incidents were able to contain damage to one container, but others have not. The layout of the BESS containers should provide ease of access for ERTs /fire brigades between containers and there should be an adequate supply of water available. ERTs also need to be aware of the hazard of ventilating a BESS container that is undergoing thermal runaway.

From the insurance and risk tolerance viewpoint, the total loss of an entire BESS container and its contents should be assumed to be a credible event provided that sufficient separation distance exists between BESS containers. Even if fire suppression/firefighting has prevented 100% involvement of the equipment within a container, it is unlikely that there would be any value in the salvage. If separation distances are inadequate, there is the potential for further damage and the involvement of any adjacent BESS units.

Environmental damage and clean-up costs could be significant where firewater and lithium-ion cell electrolytes contaminate the ground/water courses and secondary containment should be considered.

Throughout this series, it has been our intention to educate and inform the reader about the hazards and risks of Lithium-ion battery energy storage schemes based on current knowledge. Other battery types are also being developed, such as Lithium-air and flow batteries, and, as experience with BESS increases, it is important to keep up to date with this rapidly evolving technology. BakerRisk continues to monitor developments and will provide further updates as more information and knowledge becomes available.

BESS Incidents - Recent failures and risk management considerations

By Roger Stokes
September 11, 2023

This is a follow-up to an article published in February 2022 on Battery Energy Storage Systems (BESS), which was the sixth in a series as follows:

1. Battery Failure Analysis and Characterization of Failure Types
2. BESS Frequency of Failure Research
3. Review of Fire Mitigation Methods for Li-ion BESS
4. Consequences of BESS Catastrophic Failure
5. Evaluation and Design of Structures to Contain Lithium-ion Battery Hazards

Incident Review

Since this series was first issued, there have been at least sixteen further incidents of BESS failures[1] around the world that have resulted in fires and damage to property, although there are no reports of significant injuries. As shown in Figure 1, some 10-15 incidents are reported each year against an increasing number and size of BESS projects that are being installed around the world.

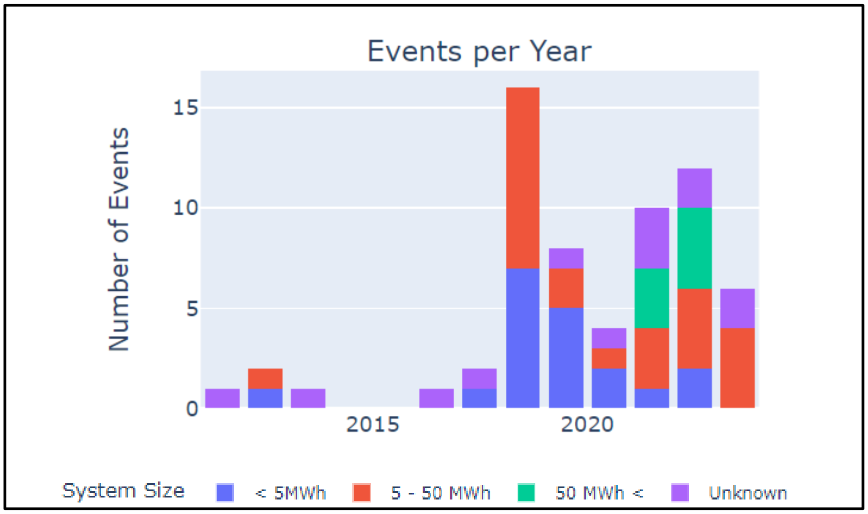

Figure 1: Annual BESS incidents since 2011 (source EPRI [1])

[1] EPRI database; https://storagewiki.epri.com/index.php/BESS_Failure_Event_Database

The only reported explosion involved a lead-acid BESS (Figure 2), which appears to have been a result of a hydrogen explosion, not a thermal runaway of a Lithium system.

Figure 2: Lead acid battery explosion (likely due to hydrogen)[2]

The most recent event occurred near Lake Ontario in New York state and took some four days to extinguish.[3] Firefighters appear to have taken a sensible approach and kept a reasonable distance away from the burning container, as shown below in Figure 3.

Figure 3: Firefighters at Chaumont, New York State, July 2023

2 https://krcrtv.com/north-coast-news/eureka-local-news/battery-storage-container-explodes-rocking-rio-dell-rv-park

3 CTIF; photo credit Three Mill Bay Fire Company Inc. https://ctif.org/news/solar-farm-lithium-ion-battery-fire-took-four-days-extinguish

In contrast, at an earlier incident in South Korea in January 2022, unaware of the potential risk of an explosion during a BESS fire, the responding fire brigade entered the building. Fortunately, no explosion occurred, although the situation caused great controversy in the region.[4]

Figure 4: Firefighters at Gunwi-gun, North Gyeongsang Province, S Korea, January 2022

A fire in April 2022 involving one containerized unit at Chandler, Arizona, burnt for over ten days. To keep the temperature down, an automatic sprinkler system was left running the entire time. A robot was eventually used to open the doors of the container, which kept the responders at a safe distance in case of an explosion.

At least three of the fire incidents over the last 12 months have involved Lithium Iron Phosphate (LFP) batteries—a type that some references had previously stated were inherently safe (or at least safer) from cascading thermal runaways. While they might be safer, LFP batteries are still subject to these runaway conditions and, like lithium ion batteries, they typically contain ethylene carbonate electrolyte, which can generate flammable gases if the battery undergoes thermal runaway. An example of an incident involving an LFP BESS is shown in Figure 5.

[4] (http://www.e2news.com)

Figure 5: Reported LFP Battery fire at in Longjing District, Taichung City, Taiwan, July 2023[5]

Two incidents occurred on consecutive days in June 2023, in two separate locations at Warwick in New York State, both involving the same company and same model of batteries. The resulting fires were reported to be smouldering for more than a week and although no official report is yet available, there were reports that the initiating event may have been weather-related.

There were three further incidents in S Korea, two of which appear to have involved BESS units in larger buildings, in which the entire buildings were destroyed by fire. The third incident destroyed “at least one of 24 BESS buildings”.

Discussion

It is clear that the risks associated with BESS are here to stay and with the ever-increasing number of installations, there will be more incidents. The learnings from events are trickling through the industry, although there is no one solution or design that is inherently safe, i.e., that cannot go into a cascading thermal runaway with the potential to spread to other units if they are too close together. Where BESS units are inside large buildings, this does appear to present the greater risk, as the total loss of the building is a credible outcome.

The industry continues to learn and has identified, for example, certain battery designs that should be avoided. Various recalls of BESS that used a certain LG Energy Solutions design manufactured in 2017 and 2018 have been made,[6] including those installed in some vehicles or domestic systems.

NFPA 855 specifies a minimum clearance from buildings, rights of way, combustible/hazardous materials etc. of 10 ft (3 m), reducing to 3 ft (0.9m) based on fire and explosion testing to UL9540A or equivalent.

[5] https://udn.com/news/story/7320/7279049

[6] https://www.prnewswire.com/news-releases/lg-energy-solution-announces-plan-for-replacement-of-certain-energy-storage-system-ess-batteries-to-strengthen-confidence-in-the-ess-industry-and-further-enhance-safety-301298584.html

Furthermore, BESS units that contain modules that are larger than 50 kWh and/or with separation distances between modules of less than 3 ft (0.9m), must undergo UL9540A testing, to determine whether a runaway would be contained, or propagate to other modules or units. Although this provides great opportunities for design refinements, such as internal separation distances, fire barriers, and other mitigation systems, it does not guarantee that a runaway would be contained in all circumstances.

There is still plenty of debate over the benefits and disadvantages of suppression systems (that could lead to a subsequent explosion) and water sprinklers (that may help to prevent an escalation). The insurer, Allianz, recommends installing sprinkler protection within BESS rooms and ideally within BESS containers.[7] Allianz also notes that other agents, such as aerosol or gaseous extinguishing systems, will extinguish the fire, but they do not provide cooling. This allows the heat to rapidly spread back through the battery, providing an opportunity to reignite any remaining active sections.

The industry is demanding ever increasing power densities, which goes against the concept of providing space between units, which can help to reduce the potential for thermal runaway.

The responding agencies are continuing to learn the best and safest ways to tackle such incidents and to keep their distance, so hopefully, there will be no other loss of life due to people being too close to any potential deflagrations in the future.

In the meantime, the familiar simplified Bow-Tie diagram for Lithium-ion battery thermal runaway with various protection layer (barrier) concepts is shown in Figure 6. Although only a few barriers are included in the figure, many additional barriers could be added to both sides of the diagram.

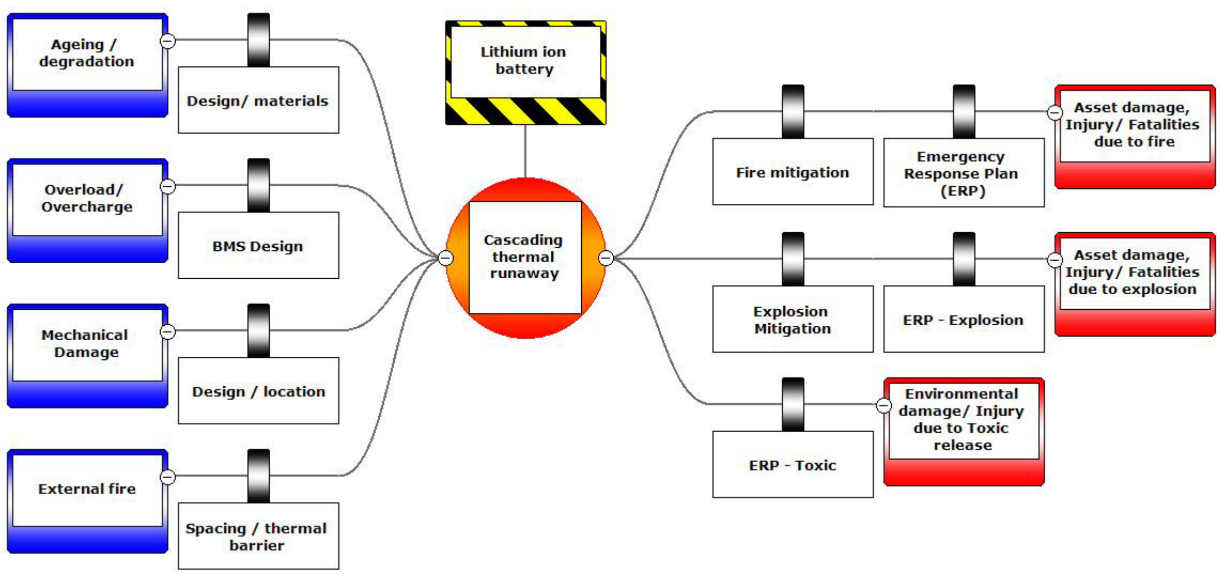

Figure 6: Simplified Bow Tie diagram for Thermal Runaway of Lithium-Ion Batteries

[7] Allianz Global, Battery Energy Storage Systems (BESS) using Li-Ion Batteries, Tech Talk Volume 26, available from: https://commercial.allianz.com/news-and-insights/risk-advisory/tech-talk-volume-26-bess-english.html

Recommendations

It appears that the best course of action is still to design the BESS container system assuming that the worst-case runaway will occur and that all of the cells/modules/racks within the container will be involved.

The objective should be to first and foremost prevent injury to personnel, then prevent escalation of the event to adjacent containers, while providing suitable means for emergency response teams (ERT)/fire brigade personnel to provide cooling for adjacent containers and other equipment from a decent standoff distance. The responding agencies must be informed of the potential risks of deflagration and any water sprinklers (dry or wet) should be confirmed to be in working order and have valves/connection points that are a safe distance from the container.

It may be appropriate to design BESS containers with tethered wall and/or roof explosion relief panels that are sized to release to the outside at pressures well below those that might cause any structural damage to the container.

We have noted a variety of separation distances between BESS containers located outside, ranging from less than 0.3m (1ft) to more than 3 metres. There has been some discussion in the insurance industry about spacing BESS containers up to 25ft apart. [8]

From the insurance and risk tolerance viewpoint, the total loss of an entire BESS container and its contents should be assumed to be a credible event provided that sufficient separation distance exists between BESS containers. Even if fire suppression/firefighting has prevented 100% involvement of the equipment, it is unlikely that there would be any value in the salvage. If separation distances are inadequate, there is the potential for further damage and the involvement of any adjacent BESS units. Installations within a large building also carry a risk of an incident escalating to include the entire building. Environmental damage and clean-up costs could be significant where firewater and lithium-ion cell electrolytes contaminate the ground/water courses, such that secondary containment should be considered.

Throughout this series, it has been our intention to educate and inform the reader about the hazards and risks of Lithium-ion battery energy storage schemes based on current knowledge. Other battery types are also being developed, such as Lithium-air, solid state and flow batteries, and as experience with BESS increases, it is important to keep up to date with this rapidly evolving technology. BakerRisk continues to monitor developments and will provide further updates as more information and knowledge becomes available.

[8] Mylenbusch IS, Claffey K, Chu BN. Hazards of lithium-ion battery energy storage systems (BESS), mitigation strategies, minimum requirements, and best practices. *Process Saf Prog*. 2023;1-10. doi:10.1002/prs.12491