Quantifying and Mitigating Lithium-ion Battery Hazards

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Abstract

Lithium-ion (Li-ion) batteries have the potential for hazards such as fire, explosions, and the release of toxic gasses. Battery Energy Storage System (BESS) is a collection of Li-ion batteries that are assembled into racks of modules. Depending on the arrangement of the racks and modules, the hazards have the potential to propagate between batteries, modules, or even the racks. The consequences of the hazards are dependent upon many factors including the chemistry of the battery, the arrangement of modules and racks, and the overall geometry of the BESS equipment group or enclosure. This paper aims to describe how thermal runaways can occur in BESS and studies the blast impacts and structural response due to release of flammable gas mixtures from batteries.

Most current Li-ion battery cells contain flammable electrolyte that can become a hazard if a cell is breached. In addition, Li-ion batteries have the potential to eject flammable decomposition gases once they enter in thermal runaway. The UL 9540A test standard typically provides information regarding the composition of the battery gas produced by the Li-ion batteries. The combustion properties of the flammable gas mixture can be used to predict blast loads using an internal deflagration scenario (explosion confined in an enclosure) or as an open field vapor cloud explosion scenario (explosion outside an enclosure). The blast load prediction can be used to develop compound blast contours for the BESS facility site.

These contours can be compared with human injury limits for human targets located in the open areas within and surrounding the BESS facility sites. These loads can also be compared to threshold limits for associated equipment (BESS is commonly used at solar or wind farms). Finally, the structural response of buildings in the vicinity of a BESS site can be assessed against the predicted blast using screening methodologies (for offsite, or far-field buildings) and dynamic structural analysis methods such as Single Degree of Freedom (SDOF) analysis methodologies (for on-site or nearfield buildings). The BESS enclosures can themselves be analyzed using SDOF and the potential for debris hazards can be predicted.

1 Introduction

Lithium-ion batteries (LIBs) are used in a variety of applications to provide energy on demand, collectively known as Battery Energy Storage System (BESS) when they are assembled into racks of modules. Unfortunately, due to the combustible materials contained within them, LIBs also have the potential for hazards such as fire, explosions, and the release of toxic gasses, which can amplify those hazards when they are components of a BESS. Depending on the arrangement of the racks and modules, the hazards can propagate between batteries, modules, or even rack-to-rack. The consequences of the hazards are dependent upon many factors including the chemistry of the battery, the arrangement of modules and racks, and the overall geometry of the BESS equipment group or enclosure.

2 Quantifying Hazards

There are several failure modes that can result in thermal runaway (TR). Heat is generated inside a battery due to the reversible reactions that facilitate the cycling of energy. Thermal management is key to the battery health, as high temperature enables irreversible degrading reactions that release even more heat, permanently affecting the battery performance. Improper dissipation of generated heat, or an external heat source are just two of the several modes of failures that can generate temperature build-up in a battery cell. Once the temperature rises above the thermal runaway critical point, more heat is generated spontaneously through the chemical reactions at a quicker rate than can be dissipated until destruction of the battery occurs, possibly rupturing of the battery casing. Since TR is exothermic, it can also heat up adjacent battery cells, propagating from the initial cell to an adjacent cell. This phenomenon can also cause propagation from module to module, or from rack to rack.

TR can cause off-gassing of a mixture of gasses that have the potential to result in fire, explosion, or toxic exposure consequences. Once the integrity of the battery cell casing is lost, flammable materials, such as the electrolyte solvent and gaseous decomposition products formed during the thermal runaway may escape into the surrounding air. 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 has been observed in a severe incident where a clean fire suppressant agent prevented open flames from forming.[1,2]

Understanding the consequences of LIB thermal runaway can provide a design basis by which to assess BESS safety. Industry accepted methods can be used to quantify the hazards associated with LIBs.

A key parameter to understanding the potential hazards of LIBs is to know the battery chemistry. Much information regarding battery chemistry can be found in a UL 9540A report[3] published by Underwriter's Laboratories (UL). This report describes a test of the propagation of a single battery cell that is forced into a TR situation toward the adjacent cells, adjacent battery modules, or adjacent racks. The report provides the chemical breakdown of the off gassing as a percentage by volume. UL 9540A reports can also include additional information regarding the rate of off-gassing, the total amount of gas produced, and the heat release rate of a fire.

The battery chemistry can be used to calculate the flammability parameters of the gas mixture. This can be done using readily available data and software methods.[4,5]

These flammability parameters are used to calculate the blast loads and the fire hazards. This can be done using NFPA 68[6] for explosions where the gas is released into an enclosure such as a BESS. NFPA 68 provides guidance on estimating the residual blast loads on the interior of an enclosed space, accounting for the mitigation from vent panels that are designed to release at a lower pressure. If the gas is released and escapes the enclosure, those blast loads can be determined using methods for vapor cloud explosions (VCEs) in air, such as BST.[7] Note that computational fluid dynamics (CFD) modeling requires a higher level of expertise and takes longer to develop but is typically more accurate than empirical models.

Most of these models assume that the gas clouds are of a uniform concentration, which also assumes that the enclosure contents are well mixed. This approach can be considered as conservative because it assumes that all of the potential chemical energy in a gas cloud is used in the ensuing explosion or fire scenario. Using high fidelity analytical methods such as CFD for determining the concentration gradients of the gas mixture can help in calculating a more accurate quantity of gas mixture in the stoichiometric range. **Error! Reference source not found.** shows a series of images of pressure contours through a postulated release scenario.

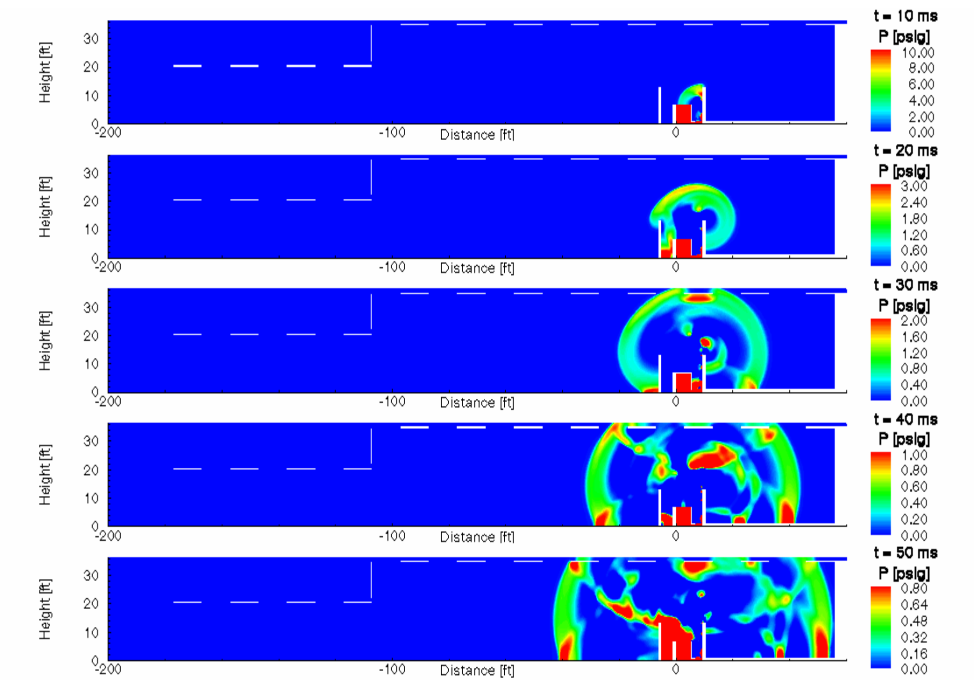

Figure 1. Example of CFD Blast Load Analysis Results

Once the blast analysis has been completed, the results can be reported as blast contours, or as pressure/impulse standoff distances. Figure 2 shows the pressure contours for a BESS scenario.

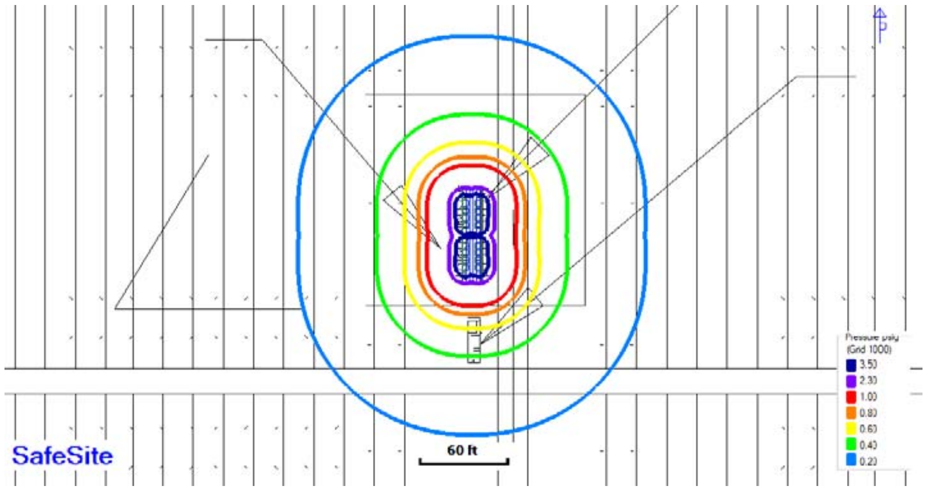

Figure 2. Pressure Contours for a BESS.

3 Mitigation of Hazardous

Once the hazards associated with LIBs have been quantified, various approaches can be used to mitigate them. These pressure and impulse loads, as well as thermal loads, can be used to evaluate or design structures to contain or resist such loads.

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.

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 the building occupants.

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.

Most conventional structural analysis employs static analysis methods, using loads that have been developed in a way that are communicated as "static load equivalents," which even applies to loading phenomena with dynamic properties, such as wind. Because blast loads are typically high in pressure but short in duration, a dynamic analysis methodology is more appropriate than using a static design method. Using a static methodology for 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 3 shows an example of an FEA model of a pre-engineered metal building responding to a blast load.

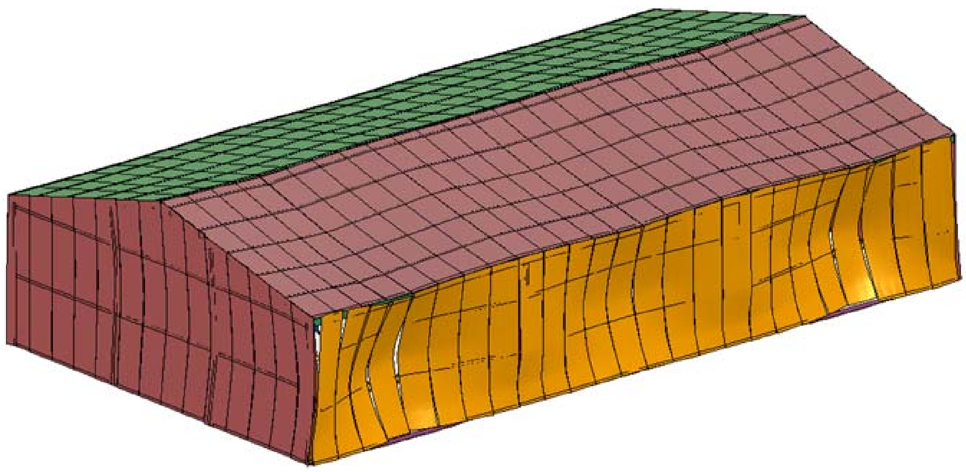

Figure 3. Example of an FEA Model

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 in response to blast loading. 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 resulting response can then be compared to structural response criteria to determine if the components will 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 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 (due to 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 the 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]

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 and personnel to thermal loads is similar to those of blast loads 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 lowest 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 through literature review, calculation, or depending on manufacturer claims. Regardless of the method chosen, 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, but 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**Error! Bookmark not defined.** 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).

4 Conclusion

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.

5 References

[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.

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

[4] Goodwin, D.G., 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

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

[6] NFPA 68, "Standard on Explosion Protection by Deflagration Venting," National Fire Protection Association 2018

[7] Q.A. Baker, M.J. Tang, E.A. Scheier, and G.J. Silva, "*Vapor cloud explosion analysis*", Proc 28th AIChE.

[8] National Institute of Standards and Technology (NIST), FDS version 6.3.1

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

[10] Khonke, Peter, PhD., ANSYS Theory Reference, Release 5.6 (Eleventh Edition), Ansys, Inc., 1997

[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.

[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

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