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

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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.

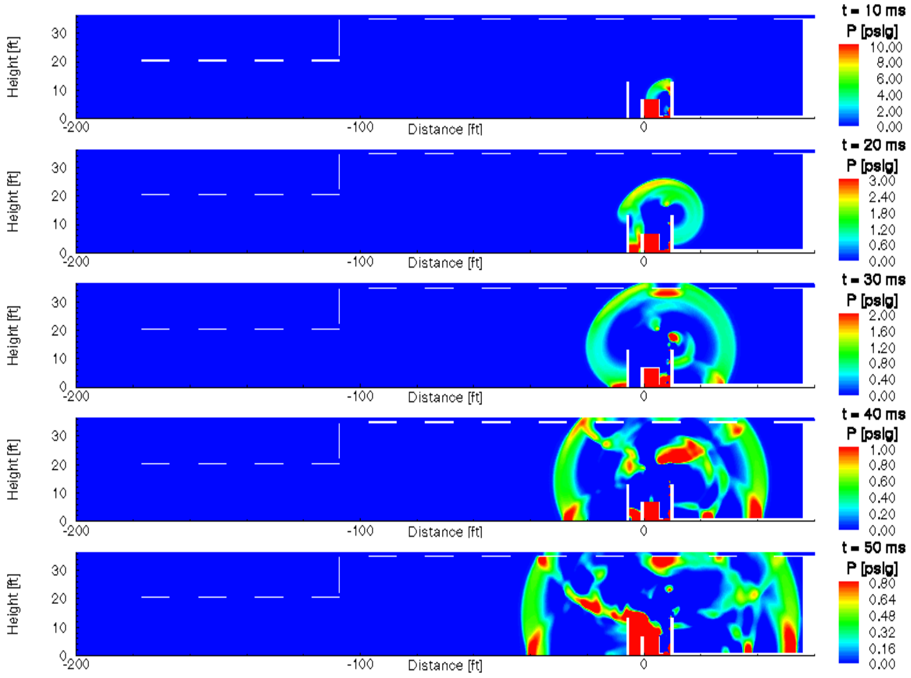

Figure 1. Example of CFD Blast Load Analysis Results

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.

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

[10] ANSYS reference.

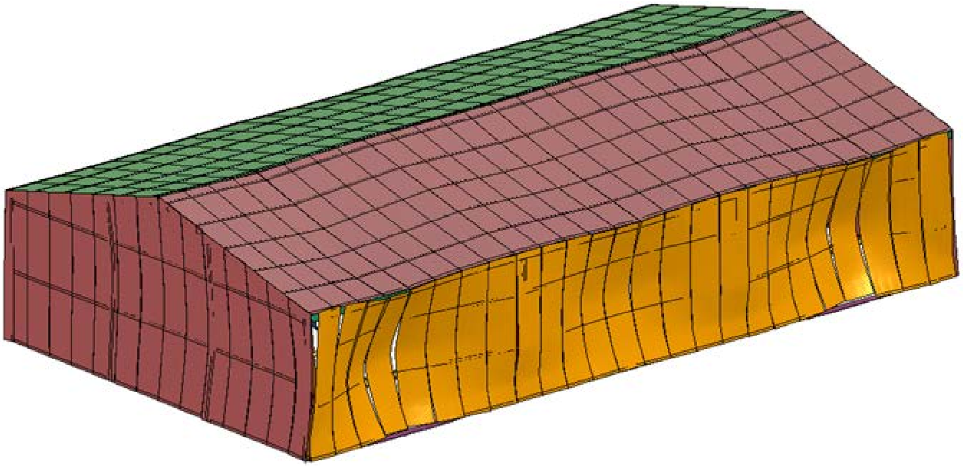

Figure 2. Example of an FEA Model

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

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[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.

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