Fire Risks from Lithium-ion Batteries: Navigating Evolving Regulations

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Introduction

For any Lithium-ion battery system, fire hazards exist during transportation of the cells or battery, installation of the battery, and during use of the battery. In most industries, fire safety is addressed by following guidelines set forth by nationally recognized standards, such as standards issued by the National Fire Protection Association. However, in the Lithium-ion battery industry, the vast majority of existing standards and safety certifications are only intended to address the cell and pack level. Because Lithium-ion batteries are widely used among many end products, cell level safety standards are inadequate to assess system safety.

Due to the fire hazards, several regulatory agencies including the Department of Transportation (DOT), Federal Aviation Administration (FAA), and local fire departments, have expressed concern with fire hazards from Lithium-ion batteries. For example, the DOT recently proposed regulations to limit the state-of-charge of the cells to 30%. However, the DOT will allow for exemptions if several fire safety criteria are met. Local fire departments or building authorities are also facing challenges in approving battery installations due to the lack of battery-specific prescriptive requirements in building codes and other fire safety standards. Many local authorities have placed the onus of safety on the end user of the battery system. In response to recent fire events involving self-balancing scooters (hoverboards), the Consumer Product Safety Commission (CPSC) has issued statements warning that although the battery and chargers used in the scooter may have proper certifications, the scooter itself does not have a scooter specific certification.

For stationary battery manufacturers and end users, addressing fire safety of the battery system may be challenging due to the lack of specific industry battery standards. To properly address fire safety, conducting hazard assessments is an attractive option. Several national fire and building codes allow for hazard assessments to be conducted provided that the local authority approves of the assessment. Several methodologies, such as fault trees, HAZOPS, What If analysis, can be used as a framework for a hazard assessment. These methods rely on engineering and scientific tools such as testing, analysis or computational simulations to evaluate specific fire or failure scenarios. This paper will present a brief overview of the current state of regulations and standards for industries that use Lithium-ion batteries. Common methodologies used for hazards assessments will also be discussed.

Battery Regulations and Testing Standards

A number of regulations and safety standards have been developed and are currently used in battery manufacturing. These regulations and standards have been developed by a variety of agencies and associations including Underwriters Laboratories (UL), Institute of Electrical and Electronics Engineers (IEEE), International Electrotechnical Commission (IEC), United Nations (UN) and Department of Transportation (DOT), and are typically applicable to individual cells or battery packs for specific applications ranging from consumer products to electric vehicles. Table 1 summarizes several of these safety standards[1].

Table 1: Summary of Battery Testing Standards[1]

	Standard	UL1642	UL2054	UL Subject 2271	UL Subject 2580	UL 2575	UL 1973
	Application	Consumer Products	Consumer Products	Light Electric Vehicles (LEV)	Electric Vehicles	Electric Power Tools, Motors, Heating and Lighting	Light Electric Rail and Stationary Applications
Electrical Tests	External Short Circuit	X	X	X	X	X	X
	Abnormal Charge	X	X	X	X	X	X
	Forced Discharge	X	X	X	X	X	X
Mechanical Tests	Crush	X	X	X	X	X	X
	Impact	X	X	X	X		X
	Shock	X	X	X	X	X	X
	Vibration	X	X	X	X	X	X
	Drop			X	X		X
	Penetration			X	X		
Environmental Tests	Heating	X	X	X	X	X	X
	Temperature Cycling	X	X	X	X	X	X
	Low Pressure	X		X	X	X	

	Standard	IEC 62281	IEEE 1625	IEEE 1725	UN Pt.III,S 38.3	SAE J2464
	Application	Transportation	Laptops and Other Mobile Devices	Cell Phones	Transportation	Electric and Hybrid Vehicles
Electrical Tests	External Short Circuit	X	X	X	X	X
	Abnormal Charge	X	X	X	X	X
	Forced Discharge	X	X	X	X	X
Mechanical Tests	Crush		X	X		X
	Impact	X	X	X	X	
	Shock	X	X	X	X	X
	Vibration	X	X	X	X	X
	Drop	X				
	Penetration					X
Environmental Tests	Heating		X	X		X
	Temperature Cycling	X	X	X	X	X
	Low Pressure	X	X	X	X	

In general, these standards address cell manufacturing and cell transportation and require cells to adhere to specific manufacturing criteria and pass several types of safety testing. The safety testing requires cells to be subjected to potentially hazardous electrical, mechanical and environmental conditions without resulting in an uncontrolled fire or explosion. The purpose of the electrical tests is to address failure scenarios such as external short circuits and abnormal charging. Mechanical tests often include crush tests, impact tests and vibration tests to ensure that a cell exposed to physical damage does not fail catastrophically. Environmental tests are conducted to demonstrate cell safety when exposed to external heating, extreme temperature cycles (hot and cold) and low pressure scenarios.

Despite the number of cell safety standards that have been developed and are being used as industry guidance for cell safety, most cell safety standards do not include testing of internal short circuits. Internal short circuits due to such causes as manufacturing defects, dendrite growth, or lithium plating lead to internal heating of the cell and potential thermal runaway can occur and result in a fire or explosion. Although several cell-level safety devices exist, such as Positive Temperature Coefficient (PTC) devices, Circuit Interrupt Devices (CIDs), or thermal fuses, these integrated safety devices do not always prevent a cell from undergoing thermal runaway.

Additional safety challenges arise because Lithium-ion batteries are typically sold to original equipment manufacturers (OEMs) who integrate the batteries into end-use products such as laptops, backup power supplies, or vehicles. In most end-use products, the OEM integrates the battery into a larger system design which is often controlled by proprietary software or hardware. In these cases, safety issues related to thermal management or battery management may not be adequately addressed by battery safety standards. For example, UL 1642, a common battery safety certification standard, states in the scope[2]:

> *1.3 These requirements are intended to reduce the risk of fire or explosion when lithium batteries are used in a product. The final acceptability of these batteries is dependent on their use in a complete product that complies with the requirements applicable to such product.*

An example of safety issues related to battery integrated systems recently came into the public eye due to fire incidents of self-balancing scooters. In the midst of several reports of self-balancing scooters catching on fire, the Consumer Product Safety Commission issued statements “that while components of hoverboards, such as battery packs and power supplies, might be UL certified, there currently is no UL certification for hoverboards themselves” and that “the presence of a UL mark on hoverboards or their packaging should not be an indication to consumers of the product’s safety”[3]. In response, UL issued a document addressing self-balancing scooters several months after the initial reported fire[4].

Hazard Assessments

In the energy storage and stationary battery industry, an industry-specific battery standard is in development, but does not currently exist. The Department of Energy is organizing energy storage safety workshops, whose goal is to address technical gaps in order to develop an energy storage safety standard. Participants in these workshops include industry representatives as well as government research organizations. Although, many cells are manufactured in conformance with battery standards, use of certified batteries do not eliminate the risk of fires and explosions from the end-use product. In many industries such as building construction and industrial refineries, industry fire safety guidelines specified by local and national fire codes and standards, such as those issued by the National Fire Protection Association (NFPA), allow for the use of hazard assessments as an alternative to prescriptive requirements detailed in applicable standards. Hazard assessments can also be used to address safety of newer technologies. For example, installation of batteries for grid stabilization or peak shaving applications in buildings often requires approval by local building authorities or local fire departments. Because current building codes may not address installation of large Lithium-ion battery packs, a hazard assessment may be a valuable tool in addressing fire safety concerns and insuring that the system meets an equivalent fire safety standard.

Hazard Assessment Strategy

Before starting the hazard assessment, one must first define which hazards and risks are to be managed. Broadly speaking, a battery failure could lead to a fire, explosion, or toxic gas release. The severity of the hazard, called the consequence, depends on the mass and energy release rates triggered by the failure. The risk, however, depends on the physical setting where the battery is used and the potential occupancy of the user space. Even though this process is called a hazard assessment, both hazards and risks must be considered. Once these basic hazards and risks have been identified, one must then decide whether each of these is an acceptable risk or if some type of risk mitigation or control must be implemented.

Risk management objectives are difficult to articulate without some basic reasoning towards their development. For example, as a first iteration, one may choose a risk management objective that is essentially equivalent to the physician's credo, "Do no harm." The second iteration becomes more specific by considering specific consequences that can occur from a battery failure. Typical risk management objectives might be the prevention of the following different kinds of losses: human injury, property damage, environmental damage, business interruption, or business reputation. The consequence of a battery failure may have little effect on one of these objectives but may have a strong effect on another. Different risk management objectives may be better addressed by different safeguards. Thus, this is not an exercise in finding a "one size fits all" solution. This task can be rendered into an organized, systematic, objective process by employing a recognized hazard assessment technique.

There are many different ways to conduct a hazard assessment. The key to success is not necessarily dependent on which methodology is chosen. Instead, success depends on identifying, evaluating, and controlling the right hazards. There are some excellent risk assessment/risk management guidance documents available to assist in this process[5-9].

There are four steps to an effective hazard assessment:

1. Identify the hazard scenarios to be analyzed.
    a. What hazards are to be considered (fire, explosion, gas release)?
    b. Is this hazard analysis restricted to the battery only or should it be expanded to consider a larger system/product?
    c. Define the physical setting where the battery or product will be used.
    d. Determine the user population and specify situations where a user or member of the public might be exposed to a battery failure.
2. Define your risk management objectives and metrics.
    a. What are your risk management objectives?
    b. Metrics: Risk is defined as the product of consequence severity and likelihood. How will risk be measured?
    c. What is an acceptable level of risk?
    d. Many organizations use a risk matrix to facilitate the risk evaluation process. Select a risk matrix that includes a specification of consequences and likelihoods to an appropriate level of detail. Ensure that the risk matrix truly represents upper management's risk attitudes.
3. Perform the hazard assessment.
    a. Evaluate the hazard scenarios and existing safeguards, and determine the risk.
    b. Do the existing safeguards reduce risk to an acceptable level?
    c. Implement additional safeguards to reduce the risk to an acceptable level.
4. Document the hazard assessment and risk evaluation.
    a. Document the thought processes involved in performing the hazard assessment.
    b. Get management review, critique, and approval on the final document. Many organizations consider it to be essential to get either in-house or outside counsel to supervise or review this process.

Once this process is completed, there is great benefit to monitoring the deployment of the product into the user environment. The hazard assessment is not a one-time activity that remains frozen in time. It should be a living document that gets updated periodically as new information becomes available. It is especially important to investigate battery failures that occur in the field as the information thus obtained can lead to important learnings that can prevent future recurrences. These failure data can then be incorporated into the hazard assessment and become part of the organization's body of knowledge on battery technology.

In the event that a new battery design is to be launched, there may be little or no failure data available to assist in the hazard assessment. In that case, specific dedicated testing or engineering analysis may need to be performed to gather the data necessary to bridge the technical knowledge gaps and to better understand the hazards.

Addressing Technical Knowledge Gaps

The challenge for a new and emerging industry is addressing fire safety without having a prior knowledge and experience basis or proven track record of safety. As discussed above, hazard assessment methods can be useful in providing an organized framework to assess fire risks of batteries in energy storage and stationary battery applications. One challenge in conducting an effective risk assessment is conducting a thorough hazard assessment. Often, technical knowledge gaps are identified when one begins to evaluate the hazard scenarios and existing safeguards. To address these knowledge gaps, in-depth technical analysis, which includes experimental, analytical, and modelling methods, is often required.

One example of a technical issue that may be identified when performing a hazard assessment is whether the current sprinkler system in a building is capable of extinguishing a fire originating from or externally attacking a battery storage system in a data storage room. Typically, to evaluate sprinkler systems, guidance from industry standards such as NFPA 13: Standard for the Installation of Sprinkler Systems is followed. Such an evaluation requires the determination or measurement of the heat release rate of the potentially flammable material. For traditional materials in buildings, such as woods and plastics, the heat release rate is typically known *a priori* or can be measured using a measurement technique called oxygen consumption calorimetry (OCC). For these materials, the OCC method is robust and very well established. However, for Lithium-ion batteries, modifications to the standard OCC technique are required[10]. Figure 1 shows the heat release from of a 2.1 Ah Lithium-ion pouch cell as measured by the OCC technique modified for Lithium-ion cells. Using this method to determine the heat release rate of and guidance from industry standards, the adequacy of an existing sprinkler system can be evaluated and additional safeguards, if required, can be implemented.

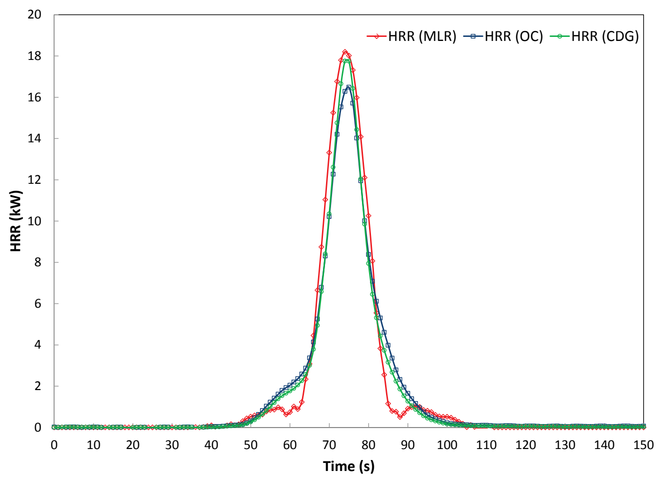

Figure 1. Heat release rate (HRR) during the combustion of a 7.7 Wh lithium-ion cell at 50% SOC. The three different curves correspond to three different HRR estimates based on the same cone calorimeter test[10].

A second example is that thermal failure of a cell in a pack can propagate from one cell in to another resulting in an increased fire and explosion risk. To safeguard and reduce the hazard from cell failure propagation in a battery pack, the thermal management of the pack design is crucial. Several possible safeguards, including active and passive cooling, cell separation and active suppression systems, may be viable. To evaluate such designs, thermal modelling can be used as a tool to design effective safeguards. To properly model the thermal propagation of a battery pack, several thermal and material inputs are required—the heat generated from a thermal failure of a cell, and the heat capacity and thermal conductivity of the cell and other materials in the pack. For pack materials such as circuit boards, plastics and metals, these inputs are well defined. However, for a Lithium-ion cell which is made up of different materials ranging from copper or aluminum electrodes to liquid electrolyte, theses inputs may not be known and testing may be required to quantify the inputs. Figure 2 shows the effectiveness of heat fins on a battery pack[11]. Additional thermal management methods, such as active cooling, can also be evaluated using thermal modeling.

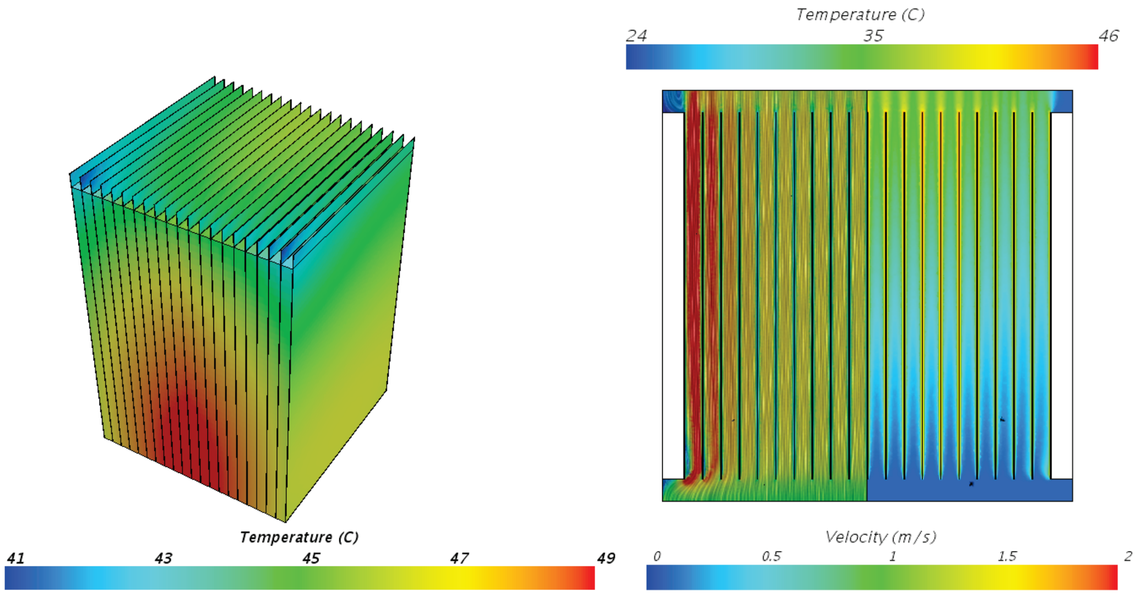

Figure 2. Typical results of a numerical analysis of a thermal management system. Temperature of cells and fins (left) and associated air flow characteristics (right)[11].

Conclusions

In energy storage and stationary battery applications, fire and explosion hazards are an important safety issue. Current regulations in consumer product and transportation industries are currently evolving and changing. Due to the uncertainty and lack of industry-specific battery safety standards for energy storage or stationary battery applications, safety cannot be addressed by following a prescriptive guideline or standard. Rather, safety is more effectively addressed by performing a risk or hazard assessment. The effectiveness of a hazard assessment depends on how successful one is in identifying, evaluating, and controlling the right hazards. In particular, effective evaluation and hazard control is directly tied to the performance step of the hazard assessment process. Often, technical gaps in knowledge are encountered when evaluating hazard scenarios or mitigation strategies for new technologies. Applying technical tools such as engineering analysis, testing and modeling can provide valuable information to help fill these knowledge gaps.

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