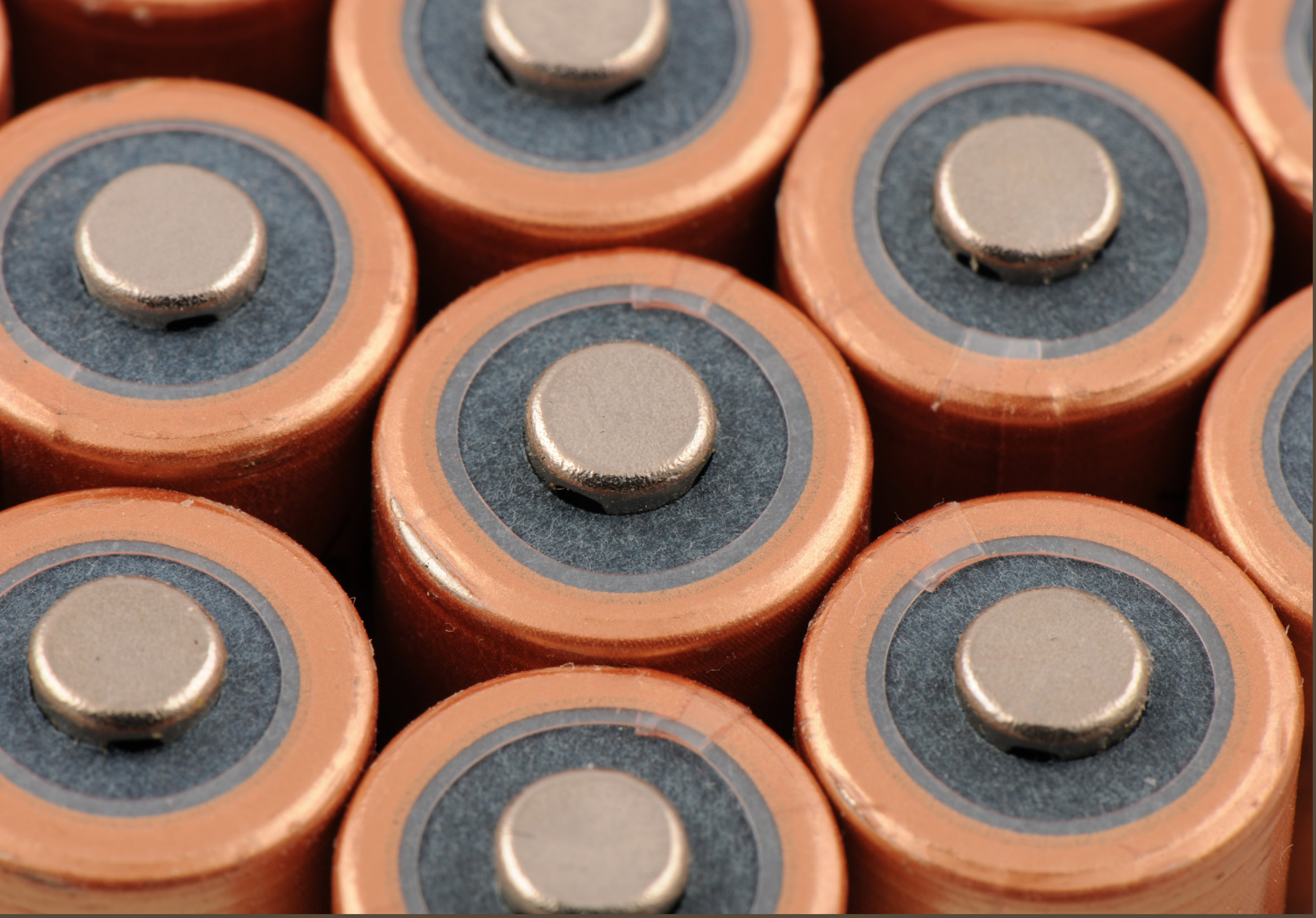

Safety Issues for Lithium-Ion Batteries

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Lithium-ion batteries are widely used as a power source in portable electrical and electronic products. While the rate of failures associated with their use is small, several well-publicized incidents related to lithium-ion batteries in actual use have raised concerns about their overall safety. Test standards are in place that mandate a number of individual tests designed to assess specific safety risks associated with the use of lithium-ion batteries. However, UL and other standards development organizations are continuing to revise and update existing lithium battery standards to reflect new knowledge regarding lithium-ion battery failures in the field. UL and other research organizations are contributing to battery safety research with a focus on internal short circuit failures in lithium-ion batteries. The research is directed toward improving safety standards for lithium-ion batteries.

Overview

Over the past 20 years, rechargeable (also known as secondary) lithium-ion battery technologies have evolved, providing increasingly greater energy density, greater energy per volume, longer cycle life and improved reliability. Commercial lithium-ion batteries now power a wide range of electrical and electronic devices, including the following categories:

- **Consumer electrical and electronic devices** — Lithium-ion batteries power consumer electrical and electronic devices from mobile phones and digital cameras, to laptop computers.
- **Medical devices** — Lithium-ion batteries are also used in medical diagnostic equipment, including patient monitors, handheld surgical tools, and portable diagnostic equipment.
- **Industrial equipment** — Industrial equipment offers a wide range of applications for lithium-ion batteries, including cordless power tools, telecommunications systems, wireless security systems, and outdoor portable electronic equipment.
- **Automotive applications** — A new generation of electric vehicles is being powered by large format lithium-ion battery packs, including battery-electric vehicles, hybrid-electric vehicles, plug-in hybrid-electric vehicles and light-electric vehicles.

The worldwide market for lithium batteries is projected to reach nearly $10 billion (USD) in annual sales by 2014, with the market for lithium-ion batteries representing almost 86% of those sales ($8.6 billion).[1] However, as the use of lithium-ion batteries is growing globally, and with the large number of batteries powering a wide range of products in a variety of usage environments, there have been several reported incidents raising safety concerns. While the overall rate of failures associated with the use of lithium-ion batteries is very low when compared with the total number of batteries in use worldwide, several publicized examples involving consumer electronics like laptop computers and electronic toys have led to a number of product safety recalls by manufacturers, the U.S. Consumer Product Safety Commission and others. Some of these cases have been linked to overheating of lithium-ion batteries, leading to possible fire or explosion. In addition, the concern of regulators with the safe transport of lithium-ion batteries following the crash of two cargo planes that were carrying large quantities of lithium-ion batteries has resulted in revised lithium battery transport regulations.

Though global independent standards organizations, such as the International Electrotechnical Commission and UL, have developed a number of standards for electrical and safety testing intended to address a range of possible abuses of lithium-ion batteries, knowledge about potential failure modes is still growing as this complex technology continues to evolve to meet marketplace demands.

Translating this knowledge into effective safety standards is a key focus of UL battery research activities, and is intended to support the continual safe use and handling of lithium-ion batteries.

Lithium-Ion Battery Design and Selection Considerations

A lithium-ion battery is an energy storage device in which lithium ions move through an electrolyte from the negative electrode (the “anode”) to the positive electrode (the “cathode”) during battery discharge, and from the positive electrode to the negative electrode during charging. The electrochemically active materials in lithium-ion batteries are typically a lithium metal oxide for the cathode, and a lithiated carbon for the anode. The electrolytes are typically a nonacqueous liquid, but can also be gel or polymer. A thin (on the order of microns) micro-porous film separator provides electrical isolation between the cathode and anode, while still allowing for ionic conductivity. Variations on the basic lithium chemistry also exist to address various performance and safety issues.

The widespread commercial use of lithium-ion batteries began in the 1990s. Since then, an assortment of lithium-ion designs has been developed to meet the wide array of product demands. The choice of battery in an application is usually driven by a number of considerations, including the application requirements for power and energy, the anticipated environment in which the product powered by the battery will be used, and battery cost. Other considerations in choosing a suitable battery may include:

UL is involved in standards development worldwide and has technical staff participating in leadership and expert roles on several national committees and maintenance teams associated with battery and fuel cell technologies.

Ms. Laurie Florence is the convener (chair) of IEC SC21A—Working Group 5. She is a member of the SC21A US TAG and SC21A WGs 2, 3, 4 and 5. Florence is also a member of the IEC TC35 USTAG, TC35 MT15, IEC TC31 HWG37, and the ANSI NEMA C18 committees. She participated in the IEEE 1625 and IEEE 1725 revisions, as well as the CTIA battery ad hoc committee. Florence is also on the informal group working on revising UN Electric Vehicle Safety – Global Technical Regulation (EVS-GTR).

Florence is also a member of ISO TC 22/SC21 US TAG and a member of the WG 3 committee for electric vehicle batteries, as well as the SAE TEVVBC1 battery safety committee (developing SAE J2929 safety standard for lithium ion EV batteries) and TEVHYB4 (SAE J2464 RESS abuse manual). Florence participates on the ANSI EVSP committee, which has developed an electric vehicle standardization road map.

Mr. Harry P. Jones is the convener (chair) of IEC TC105—Working Group 8.

Florence and **Mr. Alex Liang** (UL Taiwan) are on ETF 13 for batteries.

UL Taiwan was the first CBTL for IEC 62133, followed by UL Suzhou, UL Japan at ISE and UL Northbrook offices.

UL Japan is approved to provide the PSE mark in Japan for lithium-ion batteries as part of the DENAN program.

UL is a CTIA CATL for the battery certification program.

- Anticipated work cycle of a product (continual or intermittent)
- Battery life required by the application
- Battery's physical characteristics (i.e., size, shape, weight, etc.)
- Maintenance and end-of-life considerations

Lithium-ion batteries are generally more expensive than alternative battery chemistries, but they offer significant advantages, such as high energy/density levels and low weight-to-volume ratios.

Causes of Safety Risk Associated with Lithium-Ion Batteries

Battery manufacturers and manufacturers of battery-powered products design their products to deliver specified performance characteristics in a safe manner under anticipated usage conditions. As such, performance or safety failures can be caused by poor execution of a design, or an unanticipated use or abuse of the product.

Passive safeguards for single-cell batteries and active safeguards for multi-cell batteries such as those used in electric vehicles have been designed to mitigate or prevent some failures. However, major challenges in performance and safety still exist, including the thermal stability of active materials within the battery at high temperatures, and the occurrence of internal short circuits that may lead to thermal runaway.

As part of the product development process, manufacturers should conduct a risk assessment that might involve tools such as failure modes and effects analysis and fault tree analysis. UL employs these tools to generate root cause analyses that lead to the definition of safety tests for product safety standards.[2]

Applicable Product Safety Standards and Testing Protocols

To address some of the safety risks associated with the use of lithium-ion batteries, a number of standards and testing protocols have been developed to provide manufacturers with guidance on how to more safety construct and use lithium-ion batteries.

Product safety standards are typically developed through a consensus process, which relies on participation by representatives from regulatory bodies, manufacturers and industry groups, consumer advocacy organizations, insurance companies and other key safety stakeholders. The technical committees developing requirements for product safety standards rely less on prescriptive requirements and more on performance tests that simulate reasonable situations that may cause a defective product to react negatively.

The following standards and testing protocols are currently used to assess the safety of primary and secondary lithium batteries:

Underwriters Laboratories

- UL 1642: Lithium Batteries
- UL 1973: Batteries for Use in Light Electric Rail (LER) Applications and Stationary Applications
- UL 2054: Household and Commercial Batteries
- UL 2271: Batteries for Use in Light Electric Vehicle Applications
- UL 2595: General Requirements for Battery Powered Appliances
- UL 2580: Batteries for Use in Electric Vehicles

Institute of Electrical and Electronics Engineers

- IEEE 1625: Rechargeable Batteries for Multi-Cell Mobile Computing Devices
- IEEE 1725: Rechargeable Batteries for Cellular Telephones

National Electrical Manufacturers Association

- C18.2M: Part 2, Portable Rechargeable Cells and Batteries—Safety Standard

Society of Automotive Engineers

- J2464: Electric and Hybrid Electric Vehicle Rechargeable Energy Storage Systems (RESS), Safety and Abuse Testing
- J2929: Electric and Hybrid Vehicle Propulsion Battery System Safety Standard—Lithium-based Rechargeable Cells

International Electrotechnical Commission

- IEC 62133: Secondary Cells and Batteries Containing Alkaline or Other Non-Acid Electrolytes – Safety Requirements for Portable Sealed Secondary Cells, and for Batteries Made from Them, for Use in Portable Applications
- IEC 62281: Safety of Primary and Secondary Lithium Cells and Batteries During Transportation

- IEC 62619: (Proposed) Secondary Cells and Batteries Containing Alkaline or Other Non-Acid Electrolytes – Safety Requirements for Secondary Lithium Cells and Batteries for Use in Industrial Applications

International Organization for Standardization

- ISO 12405-3: (Proposed) Electrically Propelled Road Vehicles – Test Specification for Lithium-Ion Battery Packs and Systems – Part 3: Safety Performance Requirements

United Nations (UN)

- Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria, Part III, Section 38.3

Japanese Standards Association

- JIS C8714: Safety Tests for Portable Lithium-Ion Secondary Cells and Batteries for Use In Portable Electronic Applications

Common Product Safety Tests for Lithium-Ion Batteries

The above standards and testing protocols incorporate a number of product safety tests designed to assess a battery's ability to withstand certain types of abuse. Table1 provides an overview of the various abuse tests, and illustrates the extent to which safety standards and testing protocols for lithium-ion batteries have been harmonized.

It is important to note that similarly named test procedures in various documents might not be executed in a strictly identical manner. For example, there may be variations between documents regarding the number of samples required for a specific test, or the state of sample charge prior to testing.

The most common product safety tests for lithium-ion batteries are typically intended to assess specific risk from electrical, mechanical and environmental conditions. With minor exceptions, all of the above mentioned standards and testing protocols incorporate these common abuse tests. The following sections describe individual common tests in greater detail.

	UL						IEC		ISO
Test Criteria/Standard	**UL 1642**	**UL 1973****	**UL 2054***	**UL 2271****	**UL 2580****	**UL 2595**	**IEC 62133**	**CDV 62C19**	**ISO 12405-3**
External short circuit	●	●	●	●	●	●	●	●	●
Abnormal charge / Overcharge	●	●	●	●	●	●	●	●	●
Forced discharge / Overdischarge	●	●	●	●	●	●	●	●	●
Crush	●	●		●	●	●	●		●
Impact (cell)	●		●	●	●			●	
Shock	●	●	●	●	●	●	●		●
Vibration	●	●	●	●	●	●	●		●
Heating (cell)	●		●	●	●	●	●	●	
Temperature cycling	●	●	●	●	●	●	●		●
Low pressure (altitude) (cell)	●			●	●	●	●		
Projectile / External fire	●	●	●	●	●				●
Drop		●		●	●		●	●	
Continuous low rate charging							●		
Molded casing heating test		●	●	●	●		●		
Insulation or isolation resistance				●	●		●		●
Internal short circuit test or propagation test		●			●		●	●	

* Cells required to comply with UL 1642 tests
** Cells required to comply with either UL 1642 test program or application specific program outlined in standard

Table 1: Summary of abuse tests found in international safety standards and testing protocols for lithium-ion batteries[3]

	ANSI	SAE	UN	IEEE		JIS	
Test Criteria/Standard	**C18.2M, Pt2**	**J 2929**	**IEC 62281**	**IEEE 1625*** **	**IEEE 1725*** **	**JIS C8714**	**JIS C8715**
External short circuit	●	●	●	●	●	●	●
Abnormal charge / Overcharge	●	●	●	●	●	●	●
Forced discharge / Overdischarge	●	●	●				●
Crush	●	●	●			●	
Impact (cell)	●		●				●
Shock	●	●	●				
Vibration	●	●	●				
Heating (cell)	●			●	●	●	
Temperature cycling	●	●	●				
Low pressure (altitude)	●		●				
Projectile / External fire		●		●	●		
Drop	●	●		●	●	●	●
Molded casing heating test	●						
Insulation or isolation resistance		●					
Internal short circuit test or propagation test						●	●

*** Cells required to comply with UL 1642 tests and packs required to meet UN38.3 transport test criteria for lithium ion batteries

Table 1: Summary of abuse tests found in international safety standards and testing protocols for lithium-ion batteries[3]

Electrical Tests

- **External Short Circuit Test —** The external short circuit test creates a direct connection between the anode and cathode terminals of a cell to determine its ability to withstand a maximum current flow condition without causing an explosion or fire
- **Abnormal Charging or Overcharging Test —** The abnormal charging test applies an over-charging current rate and charging time to determine whether a sample can withstand the condition without causing an explosion or fire. The overcharge test attempts to charge a battery to greater than 100% state of charge through various methods
- **Forced Discharge or Overdischarge Test —** The forced discharge test determines a battery's behavior when a discharged cell is connected in series with a specified number of charged cells of the same type. The goal is to create an imbalanced series connected pack, which is then short-circuited. To pass this test, no sample cell may explode or catch fire. The overdischarge attempts to continue discharging beyond the specified of the discharge limit

Mechanical Tests

- **Crush Test —** The crush test determines a cell's ability to withstand a specified crushing force (typically 13 kN) applied by two flat plates (typically although some crush methods such as SAE J2929 include a steel rod crush for cells and ribbed platen for batteries). To pass this test, a sample may not explode or ignite. There are additional criteria for high voltage or large batteries such as those used in electric vehicle applications
- **Impact Test (cell) —** The impact test determines a cell's ability to withstand a specified impact applied to a cylindrical steel rod placed across the cell under test. To pass this test, a sample may not explode or ignite
- **Shock Test —** The shock test is conducting by securing a cell or battery under test to a testing machine that has been calibrated to apply a specified average and peak acceleration for the specified duration of the test. To pass this test, a sample may not explode, ignite, leak or vent
- **Vibration Test —** The vibration test applies a simple harmonic motion at a specified amplitude, with variable frequency and time to each sample. To pass this test, a sample may not explode, ignite, leak or vent
- **Drop Test —** The drop test subjects each cell and/or battery sample to a specified number of free falls to a hard surface. The sample is examined after a time following each drop. To pass this test, a sample may not explode or ignite. There are additional criteria for high voltage or large batteries such as those used in electric vehicle applications

Environmental Tests

- **Heating Test —** The heating test evaluates a cell's ability to withstand a specified application of an elevated temperature for a period of time. To pass this test, a sample may not explode or ignite
- **Temperature Cycling Test —** The temperature cycling test subjects each sample to specified temperature excursions above and below room temperature for a specified number of cycles. To pass this test, a sample may not explode, ignite, vent or leak. There are additional criteria for high voltage or large batteries such as those used in electric vehicle applications
- **Low Pressure (altitude) Test —** The low-pressure test evaluates a sample for its ability to withstand exposure to less than standard atmospheric pressure (such as might be experienced in an aircraft cabin that experiences sudden loss of pressure). To pass this test, a sample may not explode, ignite, vent or leak

Additional Specialized Tests

In addition to the common abuse tests discussed above, certain product safety standards and testing protocols for lithium-ion batteries require additional specialized testing. These specialized tests address exposure to an external or internal fire and material/insulation integrity evaluations.

- **Projectile (fire) or Internal Fire Test —** The projectile test subjects a cell sample to a flame from a test burner, while positioned within a specified enclosure composed of wire mesh and structural support. If the application of the flame results in the explosion or ignition of the cell, no part of the cell sample can penetrate or protrude through the wire mesh test cage. The internal fire test attempts to create a cell thermal runaway condition with internal fire in a single cell within the pack to determine if it is contained within the pack

- **Mold Stress Test —** The molded casing-heating test exposes plastic-encased batteries to a specified elevated temperature and for a specified time. The battery is then examined once it has cooled to room temperature. To pass this test, the internal cells may not show any evidence of mechanical damage
- **Insulation Resistance Test —** The insulation resistance test subjects a sample to a resistance measurement between each battery terminal and the accessible metal parts of the battery pack. To pass this test, the measured resistance must exceed the specified minimum value
- **Reverse Charge Test —** The reverse charge test is required under IEC 62133, UL Subject 2271 and UL Subject 2580. This test determines a discharged cell sample's response to a specified charging current applied in a reverse polarity condition for a defined period of time. To pass this test, the cell may not explode or ignite
- **Penetration Test —** The penetration test is required under UL Subject 2271, UL Subject 2580 and SAE J2464. The test uses a pointed metal rod to penetrate a cell and simultaneously measures rod acceleration, cell deformation, cell temperature, cell terminal voltage and resistance

Internal Short Circuits: Potential Causes And Testing Issues

A review of the research in the area of lithium-ion battery safety shows a strong focus on internal short circuits. Some field failures resulting in fires or explosions and leading to product damage or personnel injury have been linked to an internal short circuit within the lithium-ion battery.

However, as shown in Table 1, most lithium-ion battery safety standards and testing protocols do not specifically include testing for internal short circuits. In recent years, UL has partnered with key battery research facilities such as Oak Ridge National Laboratory and the National Aeronautic and Space Administration to better understand the root causes of internal short circuits. The focus of this research has been on defining and developing safety tests that assess the propensity of a battery to experience a short circuit under certain abuse conditions.

Potential Causes of Internal Short Circuits

Although an internal short circuit may have many causes, it is basically a pathway between the cathode and anode that allows for efficient but unintended charge flow. This highly localized charge flow results in joule heating due to internal resistance, with subsequent heating of the active materials within the lithium-ion battery. The increased heat may destabilize the active materials, in turn starting a self-sustaining exothermic reaction. The subsequent heat and pressure build-up within the cell may lead to the catastrophic structural failure of the battery casing, and the risk of additional combustion as a result of exposure to outside air.

Lithium-ion batteries are designed with integrated safety devices that open the external electrical load in the event of an over-current condition, or relieve excessive pressure build-up in the cell. However, these safety devices are unable to mitigate all internal cell fault situations, such as an internal short circuit. For products like electric vehicles, the presence of hundreds of these batteries requires more sophisticated safeguards such as battery management systems. Clearly, the desired goal is a test portfolio that simulates a wide variety of abuse conditions, and that can assess the likelihood of a battery to manifest a short circuit.

However, in designing a test for a specific failure, the root causes and failure pathways must be known. These causes may include a large internal defect or a severe external force that deforms the inner layers of the battery sufficiently to compromise the separator. In many failure incidents, only partial root-cause and failure information is available. Lithium-ion battery designers and researchers are working to create new battery designs that mitigate the impact of these causes.

Internal Short Circuit Tests

The variety of root causes for internal short circuits makes it difficult to design a single safety test that can assess the robustness of a lithium-ion battery. To date, only JIS C8714, SBA S1101 and IEC 62133 second edition (to be published in 2013) specify an internal short circuit test, known as the forced internal short circuit (FISC) test. (Note that IEEE 1625, Annex D, references the FISC test found in JIS C8714, etc.) This test creates an internal short circuit by disassembling a charged cell sample casing and placing a specified nickel particle under the cell winding construction. (This is a complex sample preparation process and can potentially be an inherently dangerous process for the test operator if care is not taken during sample preparation and handling.) The cell sample, minus the casing, is then subjected to a specified crushing action at an elevated temperature. However, best practice in safety test design precludes disassembly of a product. All tests should be designed for execution with minimum risks to laboratory personnel.[4]

To that end, UL researchers are developing a test method[5] that induces internal short circuits by subjecting lithium-ion battery cells to a localized indentation. During this test, the open circuit voltage, the cell surface temperature, and the force and position of the indenter probe are measured in real time. The test is currently under development for possible inclusion in UL 1642 and other UL Standards for lithium-ion batteries.

Moving from Battery to System Safety

Lithium-ion batteries are typically marketed and sold directly to original equipment manufacturers (OEMs) as components to be integrated into end-use products. Because the OEM's product actually controls these functions, product safety issues involving cell charging rates, discharging rates, and reverse charging may not be adequately addressed at the battery testing alone.

In such cases, international standards organizations are working to improve OEM product compatibility with integrated lithium-ion batteries by including appropriate performance testing in applicable standards. An example of such an approach to performance testing can be found in IEC 60950-1 (UL 60950-1), Information Technology Equipment – Safety – Part 1.

Looking Ahead

As the development of lithium-ion batteries is an active area in fundamental research and product development, knowledge regarding the use and abuse of these products and their possible failure modes is still growing. Therefore, it is important that safety standards continue to evolve to help drive toward the safe commercial use of these energy storage devices as they power more and more products. UL will continue dedicating significant resources to translating battery safety research into safety standards. This focus will cover the wide range of chemistries and battery designs. This work includes the multi-scale continuum, from material and component-level characterization to battery systems and beyond.

For further information about the safety of lithium-ion batteries, contact Laurie Florence, Principal Engineer - Large Batteries, Fuel Cells and Capacitors at Laurie.B.Florence @ul.com or Mr. Alex Liang, Principal Engineer - Small Batteries at Alex.Liang@ul.com

[1] "Lithium Batteries: Markets and Materials," Report FCB028E, October 2009, www.bccresearch.com.

[2] "FTA/FMEA Safety Analysis Model for Lithium-Ion Batteries," UL presentation at 2009 NASA Aerospace Battery Workshop.

[3] Jones, H., et al., "Critical Review of Commercial Secondary Lithium-Ion Battery Safety Standards," UL presentation at 4th IAASS Conference, Making Safety Matter, May 2010.

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