Li-ion battery fires have occurred in various products including cell phones, hoverboards, laptops, e-cigarettes, Tesla cars and Boeing airplanes. In many instances, the fires and in some cases, explosions, have resulted in critical injuries. For example, a Texas man died on January 29 after the e-cigarette he was using exploded and tore his carotid artery.

To understand how batteries explode, the CALCE battery team has been provided numerous exploded batteries by companies, and we are also conducting our own explosion tests. In addition, CALCE has had visitors from the U.S. Food and Drug Administration (FDA), the U.S. Consumer Protection and Safety Agency (CPSA), and from numerous companies including IBM, Dell, Huawei, HP, and All Nippon Airlines (ANA) Japan, to discuss causes of battery fires and collaboration efforts to identify battery safety causes, prognostics and preventive measures.

We have been subjecting lithium-ion batteries to abusive conditions including overheating and overcharge to induce battery explosion inside our in-house explosion chamber. We are studying the electrical and thermal characteristics of the batteries to understand underlying process of thermal runaway and develop better protection strategies. Areas of concern include the various tab materials, locations, and welding methods, vent designs, and the performance of protection devices such as positive temperature coefficient (PTC) resistor and current interruption device (CID), and their implications on battery safety.

CALCE also uses a variety of techniques to identify root causes in the failed and exploded batteries. Methods to analyze batteries include non-destructive computed tomography (CT) scans, which provide a 3D view of internal structure of the battery and have also helped in identifying various manufacturing defects including burrs on tabs, overlapping tabs, presence of foreign materials, and poor vent design, which resulted into battery fires. We find that there is a lack of standards for battery manufacturing quality control and the current standards such as IEEE 1625, which provides guidance for burr prevention, but is not conservative enough, since tearing over time can occur due to the swelling and thermal deformations within the battery.

The CALCE battery has been using an optical window cell for in-situ monitoring of lithium dendrite growth, one of the mechanisms responsible for battery internal shorts. We are also studying the dendrite morphologies and operating conditions favorable to dendrite growth. CALCE is also developing guidelines for companies for counterfeit battery detection and avoidance. For questions related to CALCE’s battery research, contact Prof. Michael Pecht (pecht@calce.umd.edu).
What Really Caused Apple’s iPhone Slowdown?

On January 23, 2017, Apple released an updated iPhone operating system (iOS 10.2.1) to help avoid premature shutdown problems. However, after this update Apple customers complained that their iPhones began functioning so slowly that their iPhones became essentially useless. On December 28, 2017, Apple announced a program to provide battery replacements at a cost of $29, which was $50 less than the original battery replacement cost, although still quite costly for this battery. Apple emphasized that continued chemical aging contributed to the slow performance. However CALCE analysis suggests a different story. It is our opinion that the “sudden shutdown” fix, based on the revised iOS software, was implemented to reduce high C-rate (electrical current drain rate) of the battery. In fact, a former CALCE Ph.D. student noted that C-rates in Apple iPhone APPs can reach as high as 6C, well beyond normal test conditions (C or C/2) conducted by the battery manufacturers. This high C-rate results in higher battery degradation and the rapid loss of capacity. While reducing high electrical current (C-rates) would result in longer battery use for a given charge, the unintended consequence is slow phone performance.

As of December 2018, Apple has sold more than 150 million iPhones each year since 2013. Throughout this time, there have been many complaints about slow performance and unexpected shutdown in iPhones. Unexpected shutdown problem has been reported across a wide range of iPhones from iPhone 5 to the latest iPhone X. A battery for a cell phone should last for the expected life of the product without the battery reaching its end of life (EOL) or causing unexpected shut downs. Apple notes that “a normal battery is designed to retain up to 80% of its original capacity at 500 complete charge cycles when operating under normal conditions.” However, the complaints about batteries in various iPhones have often started to appear within months after each iPhone was introduced to the market, which suggests that decreased performance and shutdowns cannot be attributed to normal aging. It appears that a combination of defective batteries and high C-rate applications has plagued the batteries of iPhones.

Analysis of the battery issues and subsequent responses from Apple highlight the complexity of the electrical characteristics and aging behavior of Li-ion batteries. CALCE has been conducting design of experiments (DOE) to study the effects of high C-rate on battery capacity and on long-term degradation process. We find that the effects of C-rate are highly non-linear in nature due to various confounding effects including battery temperature changes. For questions related to CALCE’s battery research, contact Prof. Michael Pecht (pecht@calce.umd.edu).

calce.umd.edu/batteries
Novel Acceleration Methods for Li-ion Battery Testing

Life testing of Li-ion batteries is conducted to qualify a battery by assessing its capacity fade and power requirements for its targeted application. However, testing at normal operating conditions can be quite time-consuming. To identify very highly accelerated testing methods, CALCE has been collaborating with a major consumer electronics manufacturer and 6 of the world’s largest battery manufacturers. While the effects of temperature on accelerated degradation of Li-ion battery performance have been studied in the literature, the combined effects of discharge C-rate with other factors still require deeper understanding. Of note is whether discharge C-rate affects battery capacity fade behavior, through ohmic heating and the resulting increase in battery temperature or whether the C-rate as its own unique degradation effects. Other parameters of interest include the effects of rest time after batteries are fully charged on long-term capacity fade and on degradation acceleration. Depth of discharge and charge cut-off current are additional related parameters which can affect the state of charge ranges during cycling and can be used for accelerating the battery degradation.

The interaction of temperature with discharge C-rate and rest period (after charge) is also equally important and is being investigated as part of this study. One of the main challenges is to generalize these findings across different manufacturers and understand why different battery manufacturers with similar cell chemistries perform differently under the same testing conditions.

For more information on accelerated testing of lithium batteries, contact Saurabh Saxena (saxenas@umd.edu) or Prof. Michael Pecht (pecht@calce.umd.edu).

www.calce.umd.edu/batteries
Degradation Trend Characterization

In a study with one of the leading telecommunications companies, CALCE has been conducting capacity fade tests at temperatures ranging from 10 °C to 60 °C and discharge currents from 0.7C to 2C. At the normal temperature of 25 °C, the battery capacity decreases in an approximately linear way, and capacity retention is more than 90% of the initial capacity at the 550th testing cycle. However, at 60 °C, the capacity fade can be quickly precipitated and the 80% end-of-life threshold is reached in 200 cycles. Accelerated degradation models are now being developed to extrapolate testing data to predict the capacity fade trend as well as the occurrence of the knee points at 25 °C.

Increasing the charge/discharge C-rate reduces the time required to conduct a charge-discharge cycle and affects capacity fade over cycles. However, for this particular manufacturer, it is found that the discharge C-rate does not accelerate capacity fade rate with respect to cycles. Batteries have been designed using such small electrode particle sizes that they can sustain this discharge C-rate range without experiencing any particle cracking for temperatures less than 45°C.
Investigating Lithium Dendrite Growth

The Li-ion battery capacity has been limited by the electrode materials for decades without much increase. In order to expand the battery capacity while maintain the size of the battery, new generation of battery electrode material is desired. Among various candidates, the lithium metal is a promising material which has a specific capacity ten times higher than the graphite electrode material. However, the application of the lithium metal is hindered by the lithium dendrite growth issue. A lithium dendrite is a metallic microstructure that forms on the negative electrode during the charging process. Its growth can lead to quick capacity fade or cause an internal short. The lithium dendrite growth can be influenced by multiple parameters including the electrolyte, separator, applied current density, and temperature.

However, the traditional current or voltage measurement alone cannot reveal the lithium dendrite growth process. Meanwhile, the lithium dendrite growth process is not observable if there is a metal outer case. In order to reveal the dendrite growth process and study the mechanism for the various morphologies of lithium dendrite, a homemade fixture with an optical observation window is used.

In order to reveal the external parameters’ influence on the lithium dendrite growth process, symmetrical lithium cells that both the positive and negative electrodes were made of lithium metal was assembled. At this stage, we limited the variable parameters and conducted dendrite growth tests at room temperature in EC: DMC 1M LiPF₆ electrolyte. There is no separator involved in the samples shown here. All samples were charged under the constant current. But the applied current values are different in order to change the initial current density on the sample. Both the real time sample voltage and the lithium dendrite images were collected, which allowed the analysis on average lithium dendrite growth rate and the morphology changes. For more information on this lithium dendrite study, contact Prof. Michael Pecht (pecht@calce.umd.edu).

Dendrite growth under various current densities. The time in each image indicates the time of first internal short.
Battery Internal Structure Investigation and the Material Characterization

Li-ion batteries contain flammable materials including the battery separator and organic electrolyte. These materials limit the battery’s operating temperature to be usually lower than 60 °C. Once the battery is heated up to higher temperature than the operation range, there is an increased possibility of triggering exothermic reactions and thermal runaway, which can in turn lead to battery fire and explosion. Thermal stability depends on the design of the battery’s internal structure and the involved materials.

In order to evaluate the safety risks of a Li-ion battery, it is necessary to investigate the battery’s internal structure and materials. In CALCE, we use multiple methods to achieve this goal. For example, X-ray CT (computed tomography) is used to investigate the internal structure. The X-ray CT is an advanced technique similar to the traditional X-ray imaging, the brightness in the image is related to the materials’ atomic number. Usually, a higher atomic number will lead to a higher brightness. Different from the 2D X-ray imaging, the sample will be rotated for 360 degree during the X-ray CT scanning process. The X-ray intensity changes at every angle will be recorded and a 3D model of the battery will be built based on the data. With the X-ray CT technique, the internal structure of the sample can be analyzed without disassembly. For example, the CT image above shows a cross-section of a coin cell. The “thin” gray layer corresponds to the battery anode, and the “thick” brighter layer corresponds to the battery cathode. The alternative sequence of the two type of layers indicates the battery has a jelly roll structure that is a common choice for the cylindrical Li-ion batteries. The periodical sequence was kept well till wrinkles appear on the right most side layer presented in the above image. The wrinkle may be formed due to the poor quality control during battery manufacturing.

www.calce.umd.edu/batteries
Tab Design and Failures in Cylindrical Li-ion Batteries

Lithium-ion (Li-ion) batteries have powered today’s portable and rechargeable products, and the cylindrical format is widely used in applications ranging from e-cigarettes to electric vehicles. The tabs in these batteries connect the electrodes (current collectors) to the external circuits. Li-ion battery failures such as fires and explosions can be caused by defects during the manufacturing process, especially associated with tab defects such as welding burrs and improper tab locations. The electrode tabs are the metallic strips that are welded onto the current collectors without active materials. When the battery is charged or discharged, the temperature around the electrode tabs is higher than other places inside the cell due to the high current density. CALCE is studying the effect of tab design and placement on battery reliability and safety.

The red arc in the tab location figure represents the positive electrode tab, and the two blue arcs represent the negative tabs. The two tabs placed on different sides of the battery can prevent short circuit. This opposite position of the tabs also generates a more uniform current distribution. However, for high-power batteries, companies often place the tabs on the same side to reduce the ohmic resistance. Overlapped tabs can cause localized high temperature in a cell, which in turn can lead to internal short circuits. For more information on tab design study, contact Prof. Michael Pecht (pecht@calce.umd.edu).

calce.umd.edu/batteries
All Nippon Airways Japan visits CALCE

A team from All Nippon Airways (ANA) Japan visited CALCE on February 7, 2019 to discuss possible areas of collaboration to improve reliability and maintainability of their aircrafts. ANA is the largest airline in Japan on the basis of fleet size. Its headquarters are located in the Shiodome area of Minato, Tokyo, Japan. Safety and reliability of Li-ion batteries have been a concern for every airline especially after the battery fires in Boeing Dreamliners. Manufacturing defects are a major problem for the safety of these batteries and are difficult to detect. Part of the discussion concerned the need for methods to detect internal shorts using conventional battery sensors such as voltage, current and temperature. CALCE researchers presented their research focused on battery modeling, accelerated testing, and battery safety.

Doosan Fuel Cell America Inc. visits CALCE

Sridhar Kanuri, Vice President, Global Research & Engineering, and Brian Chakulski, System Engineering Manager at Doosan Fuel Cell America Inc. visited CALCE to discuss areas of collaboration to improve the reliability of electronic and energy storage systems. Doosan Fuel Cell America, Inc. is the newest addition to 121-year-old Doosan’s global industrial and energy-related companies. The fuel cell division is instrumental in offering clean energy solutions in the form of fuel cell based power plants which are being setup in different parts of the world including South Korea, UK, and USA. Battery systems forms an integral part of any clean (renewable) energy sources based power plants and their grid interconnection. While Li-ion batteries are ideal for these applications due to their high energy density and maintenance-free operation, they also pose safety risks and exhibit performance degradation over time. Control and management of these batteries is a critical research area for CALCE. CALCE researcher presented the overview of different battery projects being pursued by the CALCE battery group, including accelerated reliability testing of battery, battery thermal runaway testing, vibration testing, and investigation of lithium dendrite formation.

Visiting Scholar

Bin Xu is a research scholar at CALCE and a candidate for a doctoral degree at Xi’an Jiaotong University (XJTU), China. He received his master’s degree (2014) from the School of Mechanical Engineering at XJTU. He plans to study the effects of discharge current on Li-ion battery reliability modeling and will be working with the CALCE Battery Group for the next two years.
Open Access to CALCE Battery Data

CALCE is conducting a study in collaboration with six different battery manufacturers and two consumer electronics manufacturers to develop accelerated qualification test plans to reduce overall testing time. Multiple stress factors including temperature, discharge C-rate, and rest time during cycling have been examined in this study to characterize battery degradation behavior and find novel test methods to accelerate the testing. The data from this study is being made available on the CALCE Battery Database website free of charge.

The CALCE Battery Database contains data from previous studies and experiments as well. The data from these tests can be used for battery state estimation, remaining useful life prediction, accelerated battery degradation modeling, and reliability analysis. CALCE has published many articles using this data. Researchers such as Prof. Daniel T. Schwartz from the Department of Chemical Engineering at the University of Washington, Seattle; Prof. Malcolm D. McCulloch from the Department of Engineering Sciences at the University of Oxford; Dr. David Flynn from Heriott-Watt University; and Dr. Datong Liu from the Department of Automatic Test and Control at Harbin Institute of Technology have used CALCE battery data for their research. The cycling data has been generated using Arbin, Cadex, and Neware battery testers. Impedance data has been collected using Idaho National Laboratory’s Impedance Measurement Box (IMB). For questions on the CALCE Battery Database, contact Saurabh Saxena (saxenas@umd.edu).

Recent CALCE Battery Publications

The following are recent CALCE publications on Li-ion batteries. For more information, visit the CALCE battery website: http://web.calce.umd.edu/batteries/articles.htm.

- Y Zhang, R. Xiong, R., H. He, M. Pecht, “Validation and verification of a hybrid method for remaining useful life prediction of lithium-ion batteries,” Journal of Cleaner Production, 212, 240-249, 2019.

calce.umd.edu/batteries
Recent CALCE Battery Publications (continued)

- Saxena, S., Kang, M., Xing, Y., & Pecht, M. Anomaly Detection During Lithium-ion Battery Qualification Testing. In 2018 IEEE International Conference on Prognostics and Health Management (ICPHM) (pp. 1-6), 2018.