calce™ BATTERY RESEARCH

IMPROVING PERFORMANCE, RELIABILITY, AND SAFETY OF BATTERY-POWERED SYSTEMS

JULY 2019

More Li-ion Battery Fires Reported: This Time in Apple Products

A battery recall and replacement program was recently launched by Apple for the 15-inch Macbook Pro (Retina). This recall involves about 432,000 15-inch MacBook Pro units in the U.S. and 26,000 in Canada that were sold primarily between September 2015 and February 2017. Consumers are being urged to immediately stop using the recalled laptops and follow the instructions to have their battery replaced. Consumers can determine if their laptop is included in this recall by checking the laptop's serial number on the recall website. Apple has noted that each MacBook Pro will be examined prior to any service to verify that it is eligible for this program.

Macbook Pro (Image only for illustration purpose - pixabay.com)

Apple has received 26 reports of the laptop's battery overheating, causing consumers to suffer from burns and smoke inhalation, as well as damage to personal property. While the recall and replacement program is a good step to prevent any safety hazards, Apple has still not disclosed the root cause of the overheating/fire issue in these batteries. However, CALCE has previously reported on problems with Apple's batteries.

CALCE has been conducting various analyses of performance and safety issues in the batteries of electronic products. Manufacturing defects are one of the major causes of battery fires, and CALCE has been actively using technologies such as computed tomography (CT) scan to detect these defects and identify the mechanisms that can lead to battery fires. CALCE is also developing efficient testing methods to quickly assess battery reliability, using a variety of physics-of-failure, empirical, and machine learning models.

The CALCE battery team possesses expert knowledge from both fundamental research and field experience of batteries and offers battery testing and failure analysis services to actively engage with the industry.

For questions related to CALCE's battery research, contact Prof. Michael Pecht (pecht@calce.umd.edu).

INSIDE THIS ISSUE:

Safety Protection Devices in 18650 Lithium-ion Batteries

On June 19, a 17-year-old Nevada teen was vaping when the device exploded, shattering his jaw. This incident was not new—products that use Li-ion batteries have been exploding since the first batteries were developed. For example, there were over 17 fires and explosions of Li-ion batteries in airplanes in 2017. The trend to pursue high energy density, such as by using thinner separators and fewer safety-related accessories, compromises the safety performance of Li-ion cells. While manufacturers have provided some built-in protection components, including positive temperature coefficient (PTC) thermistor, cell vents, and current interrupt devices (CIDs), these components have often been improperly designed and have thus failed to prevent the occurrence of thermal runaway or explosion.

CALCE has been evaluating the designs of the various safety mechanisms and methods that are implemented in today's batteries. Some of our findings are summarized in the article "Li-ion battery fire hazards and safety strategies". A PTC thermistor is a fuse-type device. When the temperature is above a critical level, PTC resistance increases dramatically to reduce the current flow. During normal operation, the current flows from the current collector attached to the cathode through the tab to the metallic foil, bottom disk, top disk, PTC and terminal contact, and finally to the external load. The first and second plastic inserts insulate the current path from the metal outer jacket connected to the negative terminal. The trigger of the PTC is reversible, which means that it will return to a highly conductive state when the temperature drops back to a normal level.

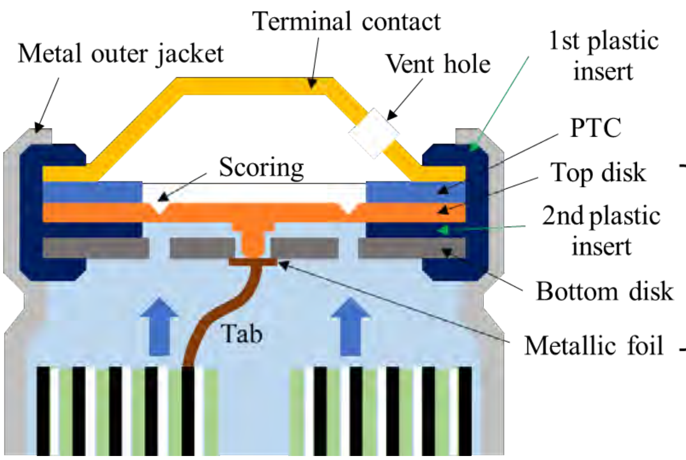
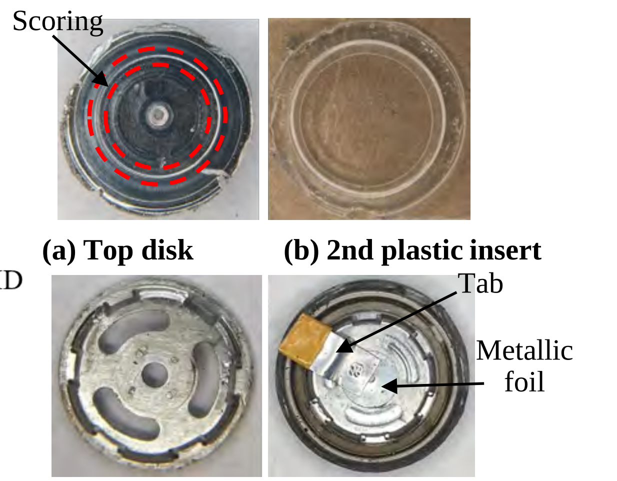


Fig. 1 Typical Structure of the 18650 Battery Cap



(a) Top disk (b) 2nd plastic insert

(c) Bottom disk (d) Disks before disassembly

Fig. 2 MXJO Battery Cap Disassembly

A CID is also a fuse-type device that cuts off the electrical path. However, the change is irreversible and the CID can be triggered by excessively high pressure, high temperature, or high voltage, depending upon the specific design. One example of a pressure-responsive CID is shown in Fig. 1. When the internal pressure increases to a defined level, the pressure will force the top disk, a conductive flexible disk, to move upwards to break the connection between the top disk and the metallic foil, by which the current path to the load is cut off.

The last fail-safe device is the safety vent, which allows a controlled release of gas in the event of a rapid increase in cell internal pressure. When the internal pressure further increases to a predetermined level, the scoring on the top disk, which is the weak point of the top disk, ruptures to vent gas through the vent holes to prevent explosion. The trigger pressure of the vent is often higher than that of the CID, for example, the weak points of the top disk in some kinds of 18650 cells will break at a pressure around 1,800 kPa, whereas the CID is activated at around 1,000 kPa. Not every cell includes all these safety features because the current trend in battery safety device design is toward compact and effective.

Predicting Two-stage Degradation Behavior and Identifying the Knee Point on Capacity Fade Curves

Lithium-ion batteries typically exhibit a transition to a more rapid capacity fade trend when subjected to extended charge–discharge cycles and storage conditions. The occurrence of this transition in the targeted applications is important for device companies to notice because Li-ion cells are no longer efficient to supply the required power and energy. The identification of the knee point can be valuable to identify more severe degradation trends and to provide guidance when scheduling battery replacements and planning secondary uses of the battery.

To predict the two-stage degradation behavior at normal operating conditions, an accelerated degradation model was developed that can describe the capacity fade trend with a knee point:

$$NDC = f(N,T) = 1 - \exp(A*T+B) * N^{G} - \exp(C*T+D) * N^{E*T+F}$$

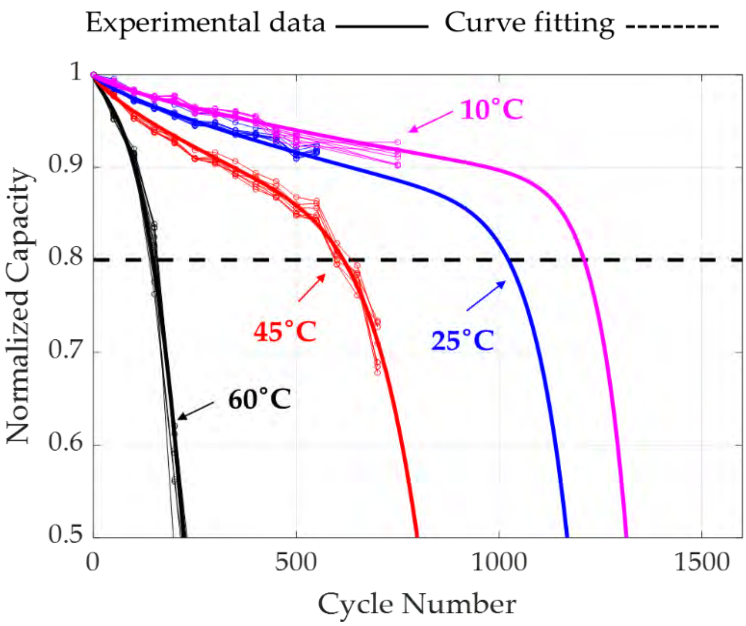
where NDC is the normalized discharge capacity, N is the number of cycles, T is the ambient temperature, $A\sim G$ are the model coefficients to be calibrated.

While a knee point can often be approximately identified visually once data is plotted, the difference between observers can be as much as 100 cycles, and there is no standard approach or algorithm that can always identify the location.

To address the challenge of identifying the knee point on capacity fade curves in a concise, repeatable, and automated manner, we define the knee point in a new way—as the cycle number of the intersection of two tangent lines on the capacity fade curve.

This definition is implemented by assessing the slope-changing ratio of the curve:

$$s(N) = \frac{l'(N+1)-l'(N)}{l'(N)} = \frac{l'(N+1)-l'(N)}{(N+1-N)\times l'(N)} \approx \frac{f''(N)}{f'(N)}$$



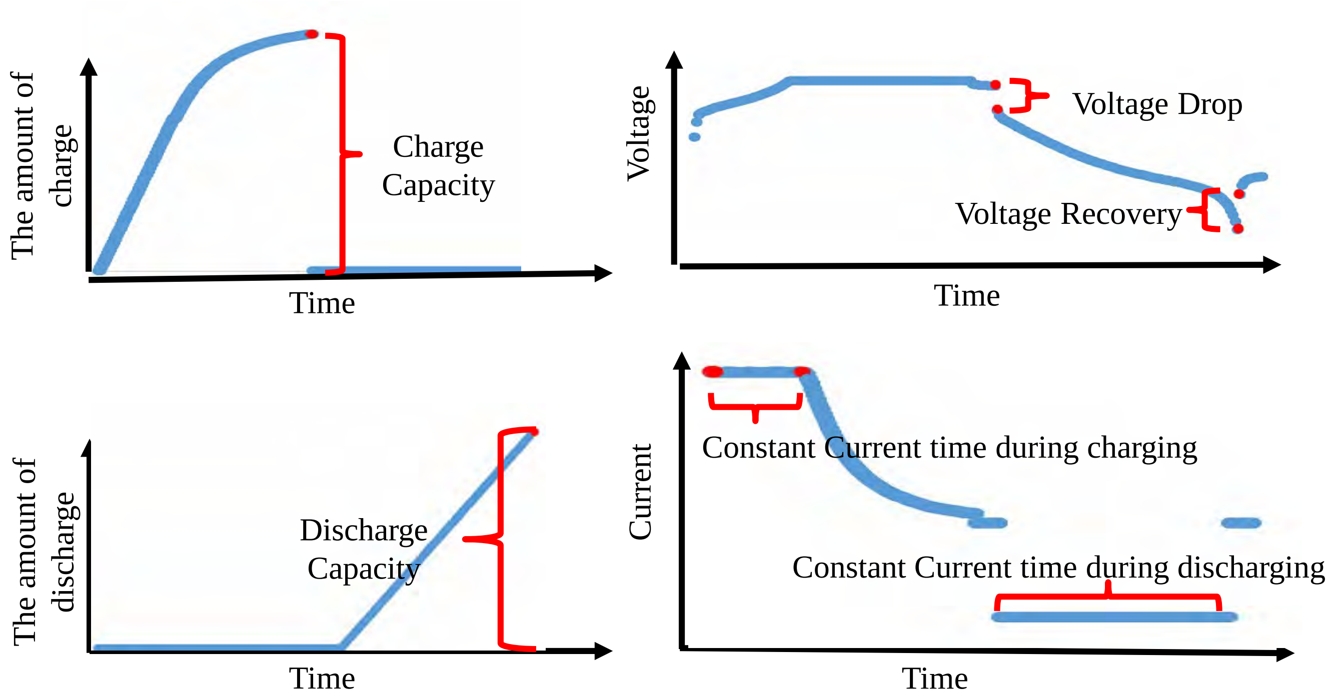
where $l'(N)$ is the curve slope at the cycle interval [N – 1, N]; $l'(N+1)$ is the curve slope at the adjacent cycle interval [N, N + 1], $f''(N)$ and $f'(N)$ are the second and first derivatives of functions. The tangent lines are then obtained from the minimum and maximum $|s(N)|$.

This approach gives more acceptable and repeatable results than the other methods (e.g., inflection point method, maximum curvature method).

To obtain more information on CALCE's approach, please see "Accelerated Cycle Life Testing and Capacity Degradation Modeling of $LiCoO_2$-graphite Cells", Journal of Power Sources.

Prediction of Remaining Useful Life of Lithium-ion Batteries Using a Multivariate Historical Data Set

CALCE has developed a large data set comprising 22 tests, each having a sample size of 3, under varying conditions for 6 pouch lithium-ion battery vendors. The batteries were tested at different temperatures, charged/discharged at different C-rates, and had open/float voltage and different rest times at a fully charged condition. All batteries were periodically cycled at a common baseline condition to collect the comparable data. During the tests, a variety of features such as the cycle number, calendar time, relative time, surface temperature, ambient temperature, current, voltage, the amount of charge and energy transferred during charging/discharging, impedance, and the thickness of the batteries were recorded. Additional features including charge/discharge capacity, voltage drop, voltage recovery, and the constant current time during charging/discharging, as shown in the figure below, were extracted from the data.



Pre-processing techniques were applied on the data collected by the vendors and the features extracted from the data to 1) remove redundant and irrelevant features to the degradation of lithium-ion batteries and 2) rank the importance of the remaining features. The remaining features were then used to predict the remaining useful life (RUL) of the lithium-ion batteries using a deep neural network (DNN).

In order to reduce the complexity of the DNN and achieve an accurate and time-efficient DNN, a stepwise increment of the number of ranked features fed into the DNN was conducted , along with tuning the DNN parameters such as the number of layers, activation function, and learning rate. The DNNs with a different number of features were ranked based on their accuracy and computation time. The top ranked DNN was used to predict the RUL of lithium-ion batteries.

Agency for Defense Development of South Korea Visits CALCE

On May 23, CALCE welcomed two visitors from the Agency for Defense Development of South Korea, Dr. Joon Ki Min, Team Leader and Principal Investigator, and Mr. Tae Yeob Kang, Senior Researcher. The visitors attended CALCE's daily morning research meeting, during which Varun Khemani described CALCE's successful efforts to develop prognostic algorithms for key failure modes on a legacy helicopter.

The visitors met with members of CALCE's PHM team, including Prof. Pecht, Dr. Michael H. Azarian, Varun Khemani, and Nam Kyoung Lee, and Mr. Kang overviewed the Agency for Defense Development, which is the principal national laboratory in South Korea that is dedicated to national defense. The two groups then discussed opportunities for collaboration on PHM research.

Dr. Cher Ming Tan Presents Reliability Lecture of Electronics to CALCE

Professor Cher Ming Tan, Ph.D., Chang-Gung University, Taiwan, visited CALCE to discuss physics of failure (PoF) based reliability analysis of electronics including lithium-ion batteries, with a focus on using finite element methods to extract key insights on failure mechanisms.

The CALCE Battery Group, including Saurabh Saxena, Lingxi Kong, Weiping Diao, and Neda Shafiei, presented their research on accelerated battery life testing, anomaly detection in an ongoing reliability test, lithium dendrite growth mechanism, and battery safety.

Prof. Tan presented his ideas on battery degradation mechanisms classification using nondestructive statistical analysis methods, and collaboration on test methods for the effects of current density on lithium dendrite growth were discussed. Prof. Tan will also be involved with the new working groups for IEEE 1413.1 and IEEE 1624 review.

Open Access to CALCE Battery Data

CALCE is conducting a study in collaboration with six 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 used in this study to characterize battery degradation behavior and find novel test methods to accelerate the testing. The data from this study is 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. The following researchers are among those who have used CALCE battery data for their research: 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. 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: https://calce.umd.edu/battery-publications

- Diao, W., Saxena, S., & Pecht, M. (2019). Accelerated cycle life testing and capacity degradation modeling of $LiCoO_2$-graphite cells. Journal of Power Sources, 435, 226830.
- Wu, Y., Wang, Y., Yung, W. K., & Pecht, M. (2019). Ultrasonic health monitoring of lithium-ion batteries. Electronics, 8(7), 751.
- Diao, W., Pecht, M., & Liu, T. (2019). Management of imbalances in parallel-connected lithium-ion battery packs. Journal of Energy Storage, 24, 100781.
- Saxena, S., Xing, Y., Kwon, D., & Pecht, M. (2019). Accelerated degradation model for C-rate loading of lithium-ion batteries. International Journal of Electrical Power & Energy Systems, 107, 438-445.
- Yao, X. Y., & Pecht, M. (2019). Tab design and failures in cylindrical Li-ion batteries. IEEE Access, 7, 45978-45982.
- Sun, Y., Kong, L., Khan, H. A., & Pecht, M. (2019). Li-ion battery reliability–A case study of the Apple iPhone. IEEE Access, 7, 71131-71141.
- Yao, X. Y., Saxena, S., Su, L., & Pecht, M. G. (2019). The explosive nature of tab burrs in Li-ion batteries. IEEE Access, 7, 45978-45982.
- Yu, Q., Xiong, R., Li, C., & Pecht, M. G. (2019). Water-resistant smartphone technologies, IEEE Access, 7, 42757-42773.
- Zhang, Y., Xiong, R., He, H., & Pecht, M. (2019). Validation and verification of a hybrid method for remaining useful life prediction of lithium-ion batteries. Journal of Cleaner Production, 212, 240-249.
- Zhang, Y., Xiong, R., He, H., & Pecht, M. G. (2019). Lithium-ion battery remaining useful life prediction with Box–Cox transformation and Monte Carlo simulation. IEEE Transactions on Industrial Electronics, 66(2), 1585-1597.

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- Lee, J., Kwon, D., & Pecht, M. (2019). Reduction of Li-ion battery qualification time based on prognostics and health management. IEEE Transactions on Industrial Electronics, 66, 7310–7315.
- Xiong, R., Zhang, Y., Wang, J., He, H., Peng, S., & Pecht, M. (2019). Lithium-ion battery health prognosis based on a real battery management system used in electric vehicles. IEEE Transactions on Vehicular Technology, 68, 4110–4121.
- Diao, W., Xing, Y., Saxena, S., & Pecht, M. (2018). Evaluation of present accelerated temperature testing and modeling of batteries. Applied Sciences, 8(10), 1786.
- Kong, L., Li, C., Jiang, J., & Pecht, M. (2018). Li-ion battery fire hazards and safety strategies. Energies, 11(9), 2191.
- He, W., Pecht, M., Flynn, D., & Dinmohammadi, F. (2018). A physics-based electrochemical model for lithium-ion battery state-of-charge estimation solved by an optimised projection-based method and moving-window filtering. Energies, 11(8), 2120.
- Peng, S., Zhu, X., Xing, Y., Shi, H., Cai, X., & Pecht, M. (2018). An adaptive state of charge estimation approach for lithium-ion series-connected battery system. Journal of Power Sources, 392, 48-59.
- Zhang, Y., Xiong, R., He, H., & Pecht, M. G. (2018). Long short-term memory recurrent neural network for remaining useful life prediction of lithium-ion batteries. IEEE Transactions on Vehicular Technology, 67(7), 5695-5705.
- Patel, N., Bishop, S., Utter, R., Das, D., & Pecht, M. (2018). Failure modes, mechanisms, effects, and criticality analysis of ceramic anodes of solid oxide fuel cells. Electronics, 7(11), 323.
- Sun, Y., Hao, X., Pecht, M., & Zhou, Y. (2018). Remaining useful life prediction for lithium-ion batteries based on an integrated health indicator. Microelectronics Reliability, 88, 1189-1194.
- Zou, C., Zhang, L., Hu, X., Wang, Z., Wik, T., & Pecht, M. (2018). A review of fractional-order techniques applied to lithium-ion batteries, lead-acid batteries, and supercapacitors. Journal of Power Sources, 390, 286-296.
- Zhou, Y., Huang, M., & Pecht, M. (2018). An online state of health estimation method for lithium-ion batteries based on integrated voltage. In 2018 IEEE International Conference on Prognostics and Health Management (ICPHM) (pp. 1-5). IEEE.
- Saxena, S., Kang, M., Xing, Y., & Pecht, M. (2018). Anomaly detection during lithium-ion battery qualification testing. In 2018 IEEE International Conference on Prognostics and Health Management (ICPHM) (pp. 1-6). IEEE.
- Li, J., Wang, L., Lyu, C., Liu, E., Xing, Y., & Pecht, M. (2018). A parameter estimation method for a simplified electrochemical model for Li-ion batteries. Electrochimica Acta, 275, 50-58.
- Wu, Y., Saxena, S., Xing, Y., Wang, Y., Li, C., Yung, W., & Pecht, M. (2018). Analysis of manufacturing-induced defects and structural deformations in lithium-ion batteries using computed tomography. Energies, 11(4), 925.
- Saxena, S., Xing, Y., & Pecht, M. (2018). A unique failure mechanism in the Nexus 6P lithium-ion battery. Energies, 11(4), 841.