calce™ BATTERY RESEARCH

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

MAY 2019

CALCE Offers a Wide Range of Battery Services

Batteries are still failing. For example, on April 21, 2019, a Tesla Model S burst into flames in a parking lot in Shanghai, China, even though the car battery was not being charged. Numerous Li-ion battery fires have also been reported recently that have caused severe injuries, resulting in substantial safety concerns for Li-ion powered devices. In addition, there have been numerous operational problems in batteries developed by some of the best battery manufacturers in the world, showing rapid end-of life and poor high C-rate performance. The question is how can we assess the reliability of batteries today?

The CALCE Battery Research Group is dedicated to solving various reliability and safety issues that the battery industry commonly experiences and that arise throughout the process from battery design, manufacture, and testing, to storage, transportation, and operation of single- and multi-cell systems.

Various design and manufacturing defects as well as mechanical, electrical, and thermal abuse conditions are often the root cause of rapid performance degradation and catastrophic battery failures. CALCE conducts failure analysis that explores battery issues such as swelling, leakage, and thermal runaway (e.g., fire, explosion).

CALCE is developing efficient testing methods to quickly assess battery reliability, using a variety of physics-of-failure, empirical, and machine learning models. Software has been developed to detect anomalous cells in the ongoing reliability tests.

CALCE has equipment that facilitates a multitude of analysis techniques, including non-destructive techniques such as electrical tests, X-ray CT, and X-ray fluorescence spectroscopy (XRF), and destructive analysis techniques such as scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS). CALCE has access to X-ray photoelectron spectroscopy (XPS) and nuclear magnetic resonance (NMR).

To provide the most accurate battery information and assure safe usage, CALCE has been developing advanced battery management algorithms using equivalent circuit models and electrochemical models, and investigating applications of sensor technologies for lithium-ion batteries, such as strain gauge, acoustics, and heat-flux.

The CALCE battery team possesses expert knowledge from both fundamental research and field experience of batteries. We offer comprehensive battery services to solve your problems. For questions related to CALCE's battery research, contact Prof. Michael Pecht (pecht@calce.umd.edu).

Water-Resistant Smartphone Technologies

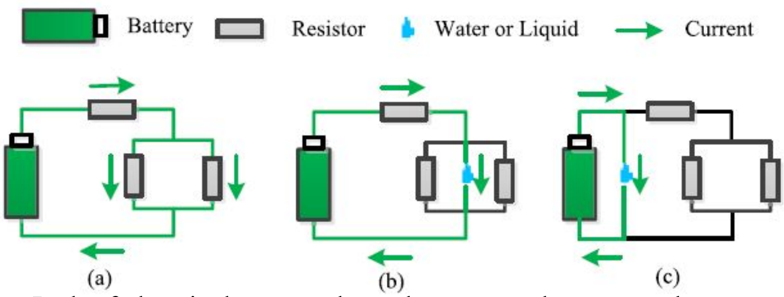
Statistical data show that 61% of smartphone consumers have used their phone in the washroom (bathroom/toilet) and 9% have dropped a phone in a toilet. According to the International Data Corporation (IDC), in 2016, contact with water was the second-largest cause of damaged smartphones, topped only by shattered screens from mechanical impacts (e.g., dropping the phone).

Advertisements from companies such as Apple, Samsung, and Huawei suggest that their smartphones are waterproof. A product is water-resistant if it can resist the penetration of water to some degree. However, the term “waterproof” indicates that the enclosure of the device is completely impermeable to water. “Waterproof” was replaced by “water-resistant” in the International Organization for Standardization (ISO) 2281:1990 standard in 1990. Since then, only the term “water-resistant” has been used to describe electrical devices and the water-resistance test standards set forth by the ISO and IEC (International Electrotechnical Commission).

Disassembly of three smartphones.

There is clearly a contradiction in what a company advertises and what it warrants. The CALCE battery team has conducted a water-resistance study, where the concepts, design practices, tests, and limitations of water-resistant smartphones were presented, along with a discussion on the standards and ratings for water resistance. We disassembled three popular smartphones (iPhone 7 Plus, Samsung S7 Edge, and Huawei P9 Lite) to assess the use of gaskets, glues and other adhesives, and emerging high-end technologies including water-resistant coatings and breathable fabric membranes.

Unfortunately, test methods used to assess the water resistance of smartphones are generally inconsistent with actual consumer usage conditions. The CALCE battery team has identified the water-induced failure causes, and found that design defects, material defects, poor test methods, and aging can allow water damage to occur. We thus proposed recommendations to manufacturers to avoid misleading smartphone consumers regarding water resistance.



Path of electrical current through a powered-on smartphone: (a) normal state, (b) and (c) short circuit state.

“Water-Resistant Smartphone Technologies” has been published in *IEEE Access*. Paper download link: https://ieeexplore.ieee.org/document/8671469.

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

Investigating the Vent Efficiency of 20700 Cylindrical Batteries

Li-ion batteries have various shapes and geometries for different types of applications. Over the last 30 years, amid all the types of rechargeable Li-ion batteries, the cylindrical battery has been the most popular product due to its standardized shapes. Because of the desire for higher capacity and energy density, there is a tendency to transition from the 18650 (18 x 65 mm) battery to the 20700 (20 x 70 mm) battery. However, it is unclear whether the vent design inherent from the 18650 battery is able to deal with thermal runaway in the 20700 battery since the battery capacity is also increased. In order to evaluate the venting efficiency of the 20700 battery, CALCE conducted X-ray computed tomography (CT) scan of both unexploded and exploded 20700 batteries.

Figure 1 shows the CT images from the unexploded sample (Fig. 1a) and the exploded sample (Fig. 1b). The battery has a designed venting area located in the battery cap area near the positive terminal and a vent disk that will break from the notch when the battery internal pressure increases to the predetermined value (usually around 1900 kPa). When the battery went through the thermal runaway process, although the vent was opened in the exploded sample (Fig. 1b), some generated gas was trapped inside the battery and could not be expelled from the designed venting area, thus leading to the battery exterior case rupture and a hole (A) on the battery side-wall. The yellow dashed lines indicate the location of the electrode structure after the thermal runaway. Compared with the unexploded sample, the electrode structure was pushed into the cap area and blocked the venting area. The pathway in the middle of the battery was also blocked due to the compression effect.

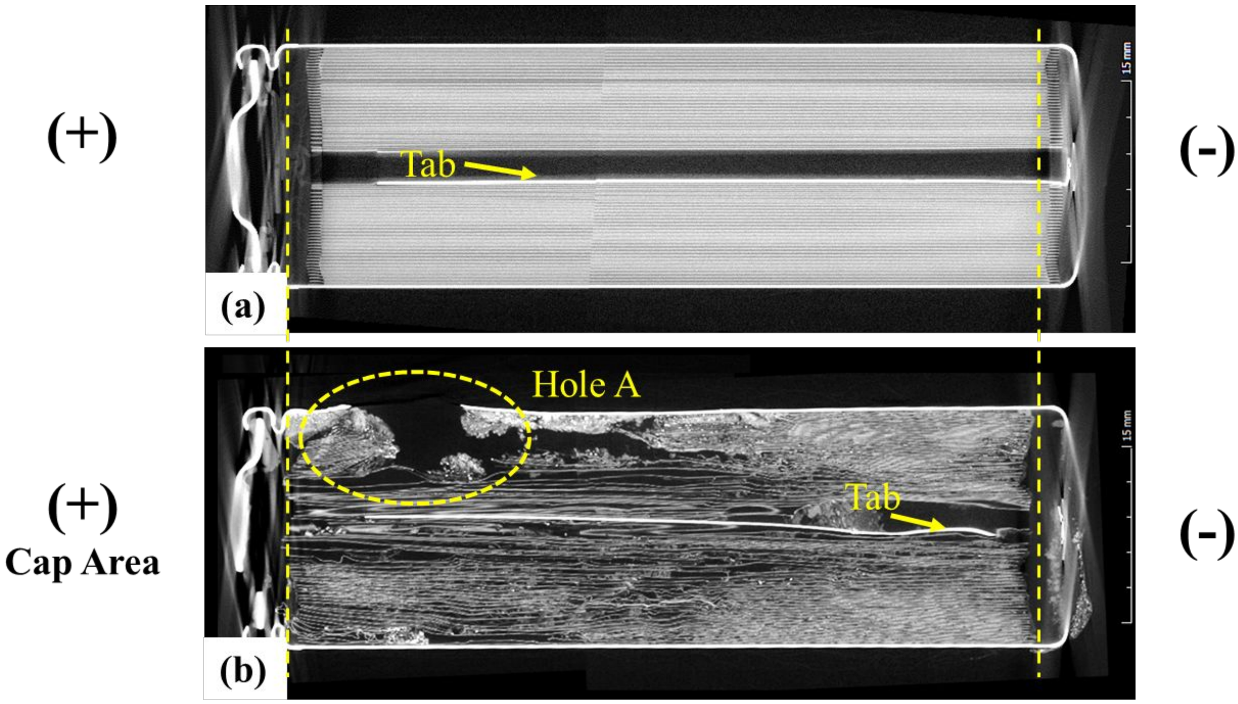


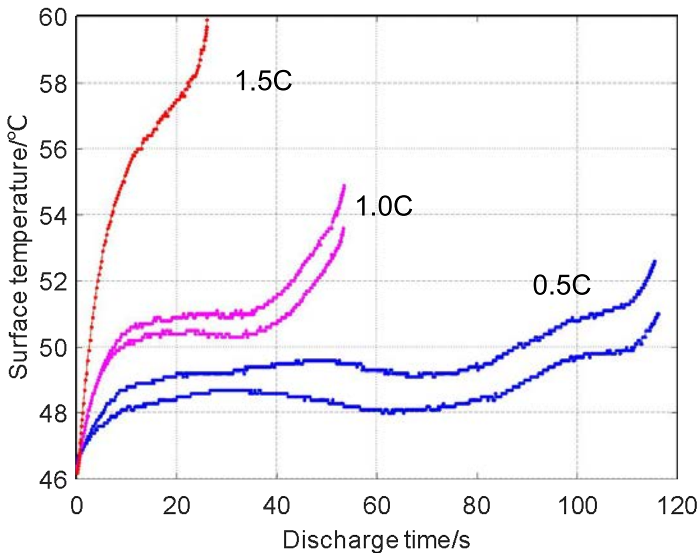
Fig. 1 X-ray CT image of the sample cross-sections along the height directions: (a) unexploded sample, (b) exploded sample.

CALCE Ph.D. student Lingxi Kong will present this topic at the First International Symposium on Lithium Battery Fire Safety, to be held 18–20 July, 2019, in Hefei, China. For more information on this venting study, contact Prof. Michael Pecht (pecht@calce.umd.edu).

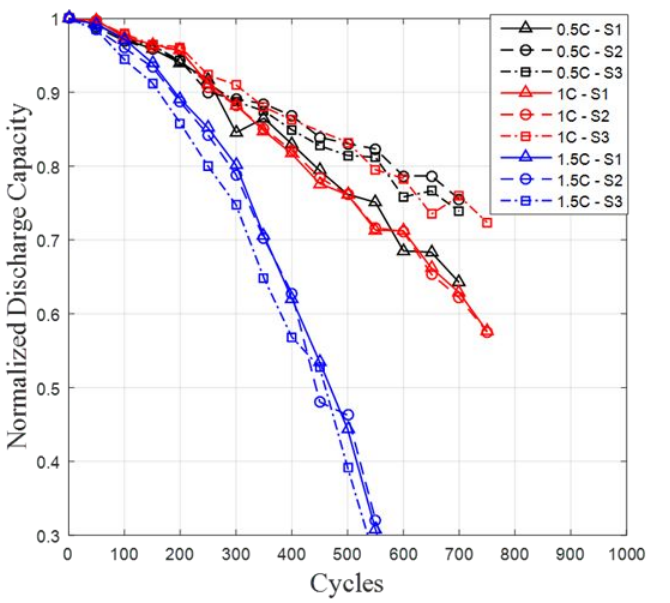
Deconvoluting the Effects of Temperature and Discharge C-rate on Li-ion Battery Degradation

CALCE has been collaborating with a major consumer electronics manufacturer and six of the world's largest battery manufacturers to develop accelerated test plans and degradation models for Li-ion batteries. As part of this project, the effects of various individual stress factors including ambient temperature, discharge and charge C-rate, charge cut-off, and depth of discharge as well as their interactions on battery degradation are being investigated. One of the most interesting studies involves determining whether discharge C-rate affects battery capacity fade behavior through ohmic heating and the resulting increase in battery temperature or whether the C-rate has its own unique mechanical degradation effects.

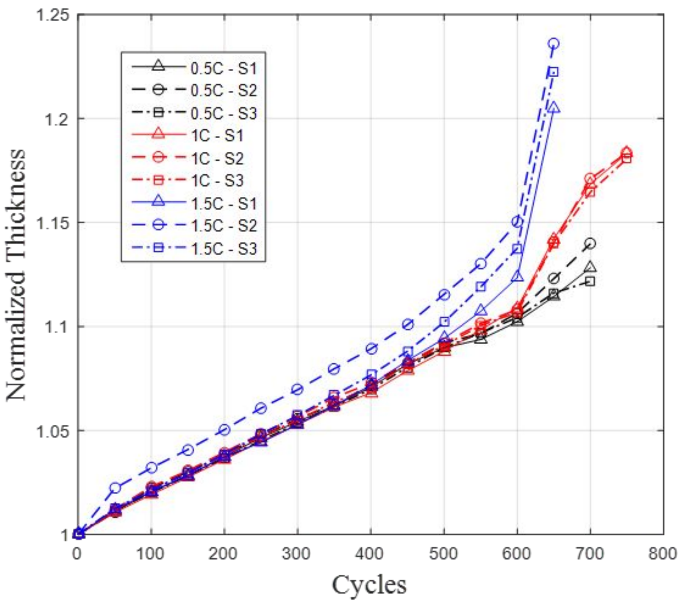
During battery cycling, it is not possible to measure the internal temperature of the battery. CALCE is developing models to estimate battery internal temperature as a function of ambient temperature, battery surface temperature, and C-rate. Battery impedance measurements are also being considered as input to the model. Estimation of internal temperature will be useful in understanding battery degradation trends and associated degradation mechanisms. It can be observed that battery surface temperature changes nonlinearly with the discharge C-rate, and similar behavior is expected for the internal battery temperature as well. However, the battery degradation (capacity fade and swelling) trends indicate that these heating effects of C-rate alone cannot explain the degradation behavior of batteries.



Surface temperature during discharging (300th cycle) at ambient temperature of 45 ℃



Capacity fade at different discharge C-rates with ambient temperature of 45 ℃



Swelling at different discharge C-rates with ambient temperature of 45 ℃

CALCE Software for Anomaly Detection in Lithium-ion Battery Ongoing Reliability Test

Electronic device companies qualify lithium-ion batteries from a manufacturer according to the performance requirements and the life expectation for their targeted application before they make a mass purchase from the manufacturer. To ensure that qualified batteries continue to meet reliability targets, ongoing reliability testing (ORT) is conducted for each subsequent lot.

CALCE has been developing software to determine whether batteries from a production lot behave similarly to the qualified population from an earlier healthy lot. Five data-driven methods—curve fitting, one-class support vector machine (SVM), local outlier factor, Mahalanobis distance, and sequential probability ratio test—are evaluated in terms of how well they can perform the mission of early anomaly detection. During the ORT when batteries are already assembled into the devices, shipped out, and even sold, this software provides the earliest warning to companies and can facilitate timely decision making and mitigate market loss.

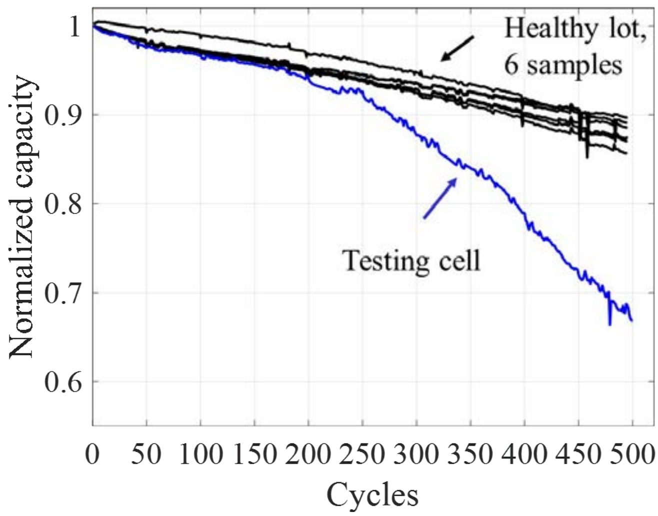


Fig. 1 Normalized capacity of healthy lot samples and a testing cell from a subsequent lot

The curve-fitting method and one-class SVM have been embedded into the software. Fig. 1 shows that the normalized capacity of a testing cell from a subsequent lot deviates from the healthy population. Fig. 2 shows the anomaly detection results using the one-class SVM method. The threshold (blue dashed line) is determined based on the anomaly score of training data using mean + 3sigma rule. At about 60 cycles when the anomaly score of the testing cell exceeds the threshold, a warning sign is given.

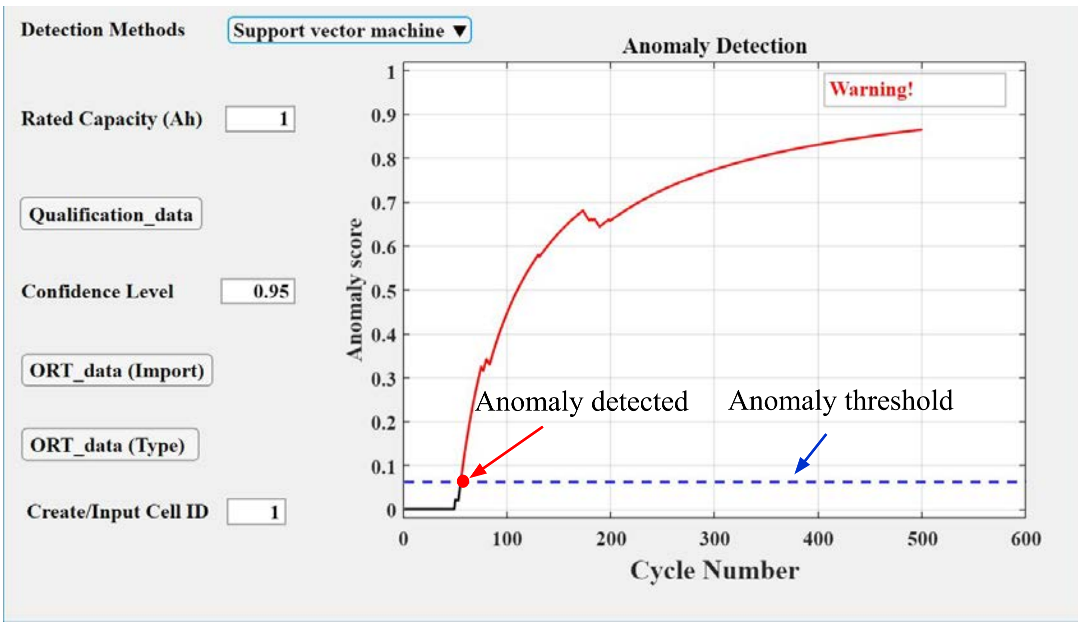


Fig. 2 Graphical user interface – anomaly detection result using SVM method

U.S. Consumer Protection and Safety Commission Visits CALCE

A team from the U.S. Consumer Protection and Safety Commission (CPSC) visited CALCE on March 15, 2019, to discuss possible areas of collaboration in Li-ion battery safety, such as understanding causes of battery fires and developing mitigation strategies. CPSC works to reduce the risk of injuries and deaths from consumer products by developing standards and bans. Li-ion battery safety has been a concern for every company, with batteries catching fire in cell phones, hoverboards, laptops, e-cigarettes, and electric vehicles. These incidents have also raised the stakes for regulators such as the CPSC who need to ensure the safety of consumers from the exploding batteries and prevent the distribution of products with unsafe batteries. Manufacturing defects are a major problem inducing safety incidents and are difficult to detect. Part of the discussion concerned the need for methods to detect manufacturing defects and internal shorts. Mr. Douglas Lee, Battery Project Manager/Electrical Program Area Risk Manager, initiated the meeting with a brief introduction of CPSC and their battery failure analysis work. CALCE researchers presented their research focused on battery modeling, accelerated testing, and battery safety.

CALCE Installs New Battery Impedance Tester and Analyzer

The VersaSTAT 3 is an option-based platform that provides both standard core functionality and the ability to expand the range of measurements. The VersaStudio software is comprised of four main modules, each containing techniques and analysis tools unique to that module. The modules available are Voltammetry (research electrochemistry techniques), Corrosion (DC corrosion techniques), Energy (battery and energy storage device related techniques), and Impedance (electrochemical impedance spectroscopy techniques).

Visiting Scholar

Dr. Haining Liu is a visiting research scholar from University of Jinan (UJN), China. He received his PhD from the School of Mechanical Engineering at Shanghai Jiao Tong University (SJTU). His research with CALCE focuses on accelerated testing of Li-ion batteries and advanced algorithms for state of health estimation and remaining useful life prediction.

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 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. 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).

Reduction of Li-ion Battery Qualification Time Based on Prognostics and Health Management (Recently published in IEEE Transactions on Industrial Electronics)

During repetitive charging and discharging, a battery's capacity fades due to electrochemical reactions such as solid electrolyte interphase growth. Li-ion batteries reach an end-of-life (EOL) point, after which using them is not recommended. However, some unhealthy batteries reach their EOL sooner than expected. A qualification test is usually conducted to evaluate the reliability of Li-ion batteries and classify unhealthy batteries, but this test requires several months. This paper develops a data-driven method to reduce the qualification time by detecting anomalies before EOL. This method detects an anomaly in the capacity fade curve of unhealthy batteries based on their capacity fade trend. Since the developed method detects anomalies of unhealthy batteries before EOL, the method is effective in reducing the time for the qualification test of Li-ion batteries.

Paper download link: https://ieeexplore.ieee.org/abstract/document/8536863.

Recent CALCE Battery Publications

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

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- 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.

Recent CALCE Battery Publications

- 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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- Zhou, Y., Huang, M., & Pecht, M. (2018, June). 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, June). 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.
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- Saxena, S., Xing, Y., & Pecht, M. (2018). A Unique Failure Mechanism in the Nexus 6P Lithium-Ion Battery. Energies, 11(4), 841.