BATTERY RESEARCH

LITHIUM-ION BATTERY TESTING, FAILURE ANALYSIS, AND ESTIMATION OF STATE OF CHARGE, STATE OF HEALTH, AND REMAINING USEFUL PERFORMANCE

MARCH 2014

The Center for Advanced Life Cycle Engineering (CALCE) is a world leader in systems reliability, accelerated testing, electronic parts selection, and supply-chain management. CALCE has over 120 faculty, staff, and students who collectively have authored over 35 books and well over 2000 research publications relevant to electronics reliability. Today, CALCE is funded by over 150 of the world’s leading companies at over $6M/year.

The Battery Group at CALCE performs fundamental and applied research on a variety of lithium-ion battery materials and form factors. This includes fundamental failure mechanisms that result in both long-term performance degradation (capacity fade / power fade) as well as catastrophic failures (cell venting / thermal runaway). Additionally, the team is developing state of charge (SOC) prediction methods to control a battery during use.

Using both data-driven and physics-of-failure approaches, the CALCE Battery Group is developing models to predict performance degradation failure with consideration of the device’s life cycle operating conditions. Life prediction models are used to assess the reliability of lithium-ion batteries as they are implemented into more demanding applications, such as the aerospace or automotive industries.

For questions related to CALCE’s battery research, please contact Michael Pecht, Director of CALCE, at pecht@calce.umd.edu.

THE HIGH COST OF BATTERY FAILURE

High profile lithium-ion battery failures in 2013 included the Boeing 787 Dreamliner and the Tesla Model S electric car. These failures illustrated the need for better battery management and failure mitigation strategies.

The cost of lithium-ion battery failure is high. Any incident involving lithium-ion batteries will receive scrutiny and could result in loss of market share and public trust. However, lithium-ion batteries still remain a good choice for energy and power dense storage. Proper battery management can be achieved, and will allow lithium-ion batteries to continue dominating the market for energy storage devices.

CALCE is committed to developing strategies for improved failure prediction and detection. In the CALCE paper Lessons Learned from the 787 Dreamliner Issue on Lithium-Ion Battery Reliability, published in the journal Energies, areas for improved battery management, qualification, and supply chain management was highlighted.

www.calce.umd.edu/batteries
CALCE’s battery team was awarded a $240,000 grant through the National Science Foundation (Award No. 1234451), to develop prognostic methods for improving the safety and availability of battery-powered systems, including electric vehicles. The CALCE team saw an opportunity to improve the state-of-art for battery management in applications with dynamic use conditions. CALCE is also adopting methods from traditional electro-chemical battery modeling and incorporating machine learning techniques to improve estimates of a battery’s remaining charge. This will help to ease the range anxiety in electric vehicles that users experience when they are unsure if they will be able to reach their destination.

Improvements to state of charge (SOC) and end of discharge (EOD) prediction will help alleviate range anxiety. In this project, EOD prediction will utilize several models to relate externally measurable parameters to the battery’s state of charge and remaining time until end of discharge. Uncertainty in the future loading conditions will be accounted for through stochastic modeling of the current and temperature profiles. Using these predicted loading conditions as inputs to each of the battery models, a fusion approach will be used to combine estimates from the different battery models into an optimal voltage estimation. Once the voltage at a future time is known, predictions can be made about the EOD.

However, EOD prediction is further complicated by the age of the battery and the stresses that it has experienced over its life cycle. Battery degradation is inevitable, and thus predictions about the future health of the battery are required to update EOD strategies and identify when the battery can no longer meet usage requirements. Batteries degrade due to internal chemical reactions that consume the active materials necessary for charge storage. As a result, the maximum amount of energy and power that a battery can supply decreases as a function of time and use conditions. The battery’s state of health (SOH) is usually calculated as a percentage reduction in deliverable capacity or an increase in internal resistance. Due to the long lifetime expected of electric vehicles, it is necessary to understand how the batteries are degrading under a wide variety of operating conditions. Modern electric vehicle battery packs are overdesigned to handle uncertainty in battery degradation, increasing the overall cost of the electric vehicle. Accurate SOH estimation and a prediction of the remaining useful performance (RUP) of a battery pack are important when confronted with the issues of battery life requirements, repair, replacement, and repurposing. The CALCE Battery Team is developing degradation models based on the physics-of-failure approach to capture the relationship between the product’s life cycle and the failure mechanisms experienced. Statistical techniques, such as particle filtering, are used to account for uncertainty in model predictions so that the battery health can be extrapolated into the future and used to plan control and replacement strategies.

Developing models that capture the battery behavior under a wide variety of operating conditions requires extensive testing for validation and verification. The Battery Team is performing long-term cycle life testing of lithium-ion batteries to validate the models using dynamic simulated driving profiles. This work will provide further insight into battery aging under actual use conditions, and will advance the state-of-art in battery management systems.
Lithium-ion batteries are used in naval aviation systems to help start the auxiliary power unit and to serve as a backup for electronic flight systems. For such systems, the battery must be reliable.

CALCE received an $80,000 grant from the Naval Air Warfare Center – Aircraft Division (NAWC-AD) to develop advanced prognostics technologies for lithium-ion batteries to assure high reliability and performance with minimum maintenance.

Under some usage conditions, lithium-ion batteries can fail catastrophically, resulting in fire and/or an explosion. This type of failure can jeopardize the safety of the pilot in addition to interfering with mission-critical activities. Assessing the overall safety and health of the battery pack within a single aircraft and across the fleet enables optimal maintenance and repair strategies. Condition-based maintenance is employed to proactively prevent failure through advanced prognostics methods. Operational readiness is ensured and missions can be confidently undertaken.

Prediction of battery failure requires knowledge of the life cycle conditions that the battery is expected to experience and how environmental stresses cause the battery to fail. Data collected from the batteries during operation will provide researchers at CALCE with the data necessary to develop algorithms to sense anomalous behavior prior to the evolution of a fault into a more catastrophic failure. Adequate warning of failure is necessary to minimize the damage that a battery failure event can cause. Methods for measuring precursors to failure with advance warning capabilities are being researched.

The progression of health indicators from healthy to unhealthy can be modeled based on a variety of techniques. CALCE is taking a two-fold approach to modeling the drift of the health indicators. Machine learning (ML) and equivalent circuit models are being developed to make separate health predictions about the battery. Uncertainties are being handled through non-linear filtering, and the models are being evaluated on test batteries to assess their accuracy. Model adaption schemes are being developed to handle unit-to-unit differences and unknown future loading conditions and stresses. The results from the different models can be combined in a fusion approach that incorporates the beneficial aspects of each model into the overall health prediction.

CALCE’s battery team is producing battery management models that can make condition-based maintenance of lithium-ion batteries a reality. Battery health and safety prediction is a function of the previous stresses that the battery has experienced during its life cycle and the expected future demands. In addition to demonstrating prognostic methods for battery health assessment, CALCE will make recommendations for improvements to battery monitoring hardware and sensors that can be implemented in aircraft that utilize lithium-ion batteries.
CALCE Researcher Co-ops

Three CALCE students spent the summer of 2013 conducting battery research as co-ops. This provided them with a great opportunity to work with experts from around the world.

Wei He – Bosch

In 2013, Wei He, a Ph.D. candidate advised by Prof. Pecht, worked with the Energy Modeling, Control and Computation Team at the Bosch Research and Technology Center in California for 6 months. Wei’s role was focused on the development and design of battery management software functions and advanced battery models. In particular, he developed an efficient numerical solution for a system of algebraically coupled partial differential equations in an electrochemical model of a Li-ion battery for use in a real-time battery management system. He also developed a cumulative numerical integration scheme needed in the software. He selected the Clenshaw-Curtis integration scheme based on its ease of computation and generalized the method to perform cumulative integration to each of its nodes. He also implemented a reduced-order electrochemical battery model in Matlab/Simulink, and ran the models in dSPACE for use in the hardware in the loop validation of battery management systems.

Christopher Hendricks – Idaho National Laboratory (INL)

Christopher Hendricks is a Ph.D. candidate, also advised by Prof. Pecht, in CALCE’s Battery Group. During Chris’s co-op, he worked at Idaho National Laboratory (INL) on lithium-ion battery prognostics and diagnostics development. INL performs fundamental and applied energy storage research, including battery testing for electric vehicles in conjunction with the United States Advanced Battery Consortium (USABC). Christopher worked under the direction of Dr. Jon P. Christophersen, a principle investigator for INL’s Energy Storage and Transportation Systems Department. CALCE’s extensive experience in lithium-ion battery testing and prognostics matched the Energy Storage and Transportation Systems Departments’ mission. While at INL, Chris worked closely with Dr. Christophersen and his colleagues to develop prognostic techniques for electric vehicle battery management systems. The work focused on analyzing impedance spectra obtained using specialized equipment developed at INL. Chris helped design a series of experiments to further characterize the impedance response of lithium-ion batteries at various stages of degradation in a battery pack. CALCE will continue to work with INL to implement impedance measurement technology in diagnostic and prognostic applications.

Nicholas Williard – Korean Institute of Machinery and Materials (KIMM)

Nicholas Williard, a Ph.D. candidate advised by Prof Pecht, is also in CALCE’s Battery Group. He co-oped with the Korean Institute of Machinery and Materials (KIMM). This is a government research institute in Daejeon, Korea, focused on developing machine technologies for industrial use and providing reliability and assessment tests for these technologies. During an earlier visit to KIMM, Prof. Michael Pecht saw an avenue for collaboration as KIMM was beginning work on super capacitor reliability. Because of CALCE’s experience in electronics and energy storage device reliability, this was an opportunity for CALCE to share its knowledge and form a relationship with another respected world-class reliability group. During Nicholas’s time at KIMM he helped to design and perform accelerated testing on super capacitors under a variety of voltage and temperature conditions. With the accelerated life data, he improved upon an existing life model that helps to better describe the operational life of a capacitor under high voltage and temperature conditions. CALCE and KIMM are currently in the process of co-publishing a paper on their results from this work.
CALCE COLLABORATES WITH IDAHO NATIONAL LAB (INL)

CALCE and Idaho National Laboratory (INL) are working together to improve lithium-ion battery diagnostics and prognostics. INL, located in Idaho Falls, ID, performs extensive testing for the United States Advanced Battery Consortium (USABC) to enable the development of next generation electric vehicles. Improving battery prognostics and diagnostics was a main motivation for the development of a collaborative relationship between CALCE and INL. CALCE will work with INL to identify battery monitoring strategies that incorporate real-time impedance measurements to address battery degradation and safety issues.

As part of the collaboration, CALCE will receive an INL Impedance Measurement Box (IMB) for rapid measurement of the impedance spectrum of electrochemical devices. Electrochemical Impedance Spectroscopy (EIS) can be used to determine the health of a battery and offers data for prognostic and diagnostic purposes. While typical EIS measurement devices require long measurement periods, the IMB captures relevant information in a fraction of the time required by traditional techniques, allowing it to be effectively used in applications requiring real-time health assessment. The IMB was developed by Dr. Jon P. Christophersen and his collaborators, and it won an R&D 100 Award from R&D Magazine in 2011.

CALCE’S NEW BATTERY TESTING EQUIPMENT

CALCE has teamed up with Neware to expand electrochemical device testing capabilities. Neware is the leading battery test system manufacturer in China. The Neware test channels allow for the testing of high voltage and high current battery packs and modules in addition to individual cells. CALCE already has extensive testing experience with single cells and small battery packs, and the addition of this equipment will allow us to develop and validate new monitoring and control strategies for large battery modules. Managing the cell-to-cell interactions present in battery packs is extremely important for the development of improved electric vehicles. Electric vehicle battery packs are oversized to compensate for the uncertainty in battery degradation under the harsh driving environments expected in the automobile industry.

CALCE BATTERY DEGRADATION AND FAILURE ANALYSIS

CALCE has advanced laboratory equipment for non-destructive inspection and destructive failure analysis of lithium-ion batteries. The CALCE Test Services and Failure Analysis Laboratory has developed disassembly and inspection procedures that have helped several industrial clients in identifying root causes of battery failure. Determining the root cause of failure is a critical part of the failure analysis process, and its success depends on employing proper disassembly and inspection methodologies.

Non-destructive inspection is performed using a GE Nanomex X-ray System that is capable of 2D and computed tomography (CT, 3D) inspection of cells. This enables the identification of gas generation, electrode buckling, and other mechanical damage that is not visible externally. Ultrasonic transducers have been employed along with X-ray imaging as a means of inspecting the battery interfaces for delamination, air pockets, and electrode buckling.

Battery disassembly takes place inside a glove box using the appropriate safety precautions. Disassembly allows inspection and materials characterization of the electrodes, current collectors, and separator. Any evidence of internal short circuits or delamination can be uncovered at this point in the process. The electrode samples are then mounted and taken through a series of grinding and polishing steps before being inspected using an optical microscope and an environmental scanning electron microscope (ESEM). Energy dispersive spectroscopy allows for elemental composition analysis and dot mapping. The ESEM is capable of resolution on the order of nanometers, allowing for the inspection of the surface of the electrodes to examine particle fracture.
CALCE DEVELOPS PROCEDURES FOR BATTERY DISASSEMBLY

CALCE has performed failure analysis and investigated degradation phenomena in numerous lithium-ion batteries. This work requires direct access to the internal materials of batteries in order to perform microanalysis and materials characterization. One of the most critical steps in analyzing internal battery materials is performing the disassembly. There are several safety precautions that must be taken during disassembly in order to prevent burns and exposure to corrosive materials. At the same time, disassembly must be performed in a manner that preserves the internal state of the battery so analysis results reflect the battery materials without introducing artifacts from the disassembly procedure. These issues were addressed in a 2011 CALCE paper titled “Disassembly methodology for conducting failure analysis on lithium–ion batteries,” published in the Journal of Materials Science: Materials in Electronics. Since the publication of this paper, CALCE has continued to update the battery disassembly process.

ELECTROCHEMICAL MODELING OF LITHIUM-ION BATTERIES

A battery’s performance and degradation depends on the electrochemical processes inside the battery. Electrochemical models are needed to understand the relationship between the electrochemical processes and battery current and voltage measurements. CALCE has been developing detailed electrochemical models that include all the key physics of Li-ion batteries, including mass transportation, kinetics, and diffusion. These models are governed by coupled partial differential equations (PDEs). In order to implement these models in real-time battery management systems, model order reduction of the PDEs is needed. Efficient Galerkin-type solutions have been developed to solve the PDEs in the electrochemical model. Based on the electrochemical model, seeded fault simulation, such as loss of active materials, growth of the solid/electrolyte interface, and decomposition of electrolyte, can be conducted by changing the model parameters, such as volume fractions, film resistances, and diffusion coefficients. By the seeded fault simulation, the state of health indicator of Li-ion batteries can be identified.

Overpotential is the driving force of side reactions inside Li-ion batteries. For example, lithium plating will occur if the surface overpotential at the negative electrode is below zero. It is hard for conventional battery control algorithms based on fixed voltage limits to prevent side reactions. Future work will involve developing a method to estimate overpotential based on CALCE’s electrochemical models. Then new control algorithms can be developed to avoid side reactions that could result in lithium plating, dendrite growth, and catastrophic failure.
A battery’s capacity to store energy can decrease for any number of reasons. One cause of capacity loss is progressive degradation of the battery. As lithium ions intercalate into the electrodes, the solid particles expand in volume. This expansion can cause the particles to fracture, which opens up fresh reaction sites for the consumption of the lithium. Additionally, localized stress concentrations can lead to electrode buckling or ruffling, which can also expose new reaction sites.

To non-destructively probe the battery for internal structural changes, ultrasonic transducers acoustically detect electrode separation and delamination within the battery without the need to disassemble. Two transducers act in a through transmission mode whereby an ultrasonic signal is injected into one side of the battery, and a second transducer measures the acoustic impedance. By comparing a degraded battery to a brand-new battery, changes in the acoustic signal are detectable by this measurement technique.

Ultrasonic inspection collected over the lifetime of a battery can be used to predict the state of health (SOH) and the remaining useful performance (RUP) to enable better decision making. Implementing ultrasonic transducers into a battery management system will provide additional information about the battery that cannot be determined by voltage, current, and temperature measurements alone. Additionally, detection of gas generation can provide warning for potentially hazardous operating conditions and the possibility of catastrophic failure.
DATA-DRIVEN METHODS FOR BATTERY STATE ESTIMATION

State of charge (SOC) estimation is critical for battery-powered systems, because it indicates when a battery needs to be recharged and provides information to battery management systems to prevent the over-charge and over-discharge of batteries. However, SOC estimation becomes challenging when batteries are subjected to dynamic discharge profiles or sensor error accumulation results in inaccurate results. Additionally, the change in SOC is drastically influenced by operating conditions and ambient environments. SOC estimation needs to account for the variation in factors such as battery temperature, discharge rate, battery aging, and self-discharge phenomena. In addition, different battery materials possess different charge/discharge characteristics that influence the SOC.

CALCE has developed a data-driven SOC estimation model based on a two-layer feed-forward neural network model. The inputs of the neural network are the current, voltage, and temperature, and the output is the SOC. The neural network model can be used to fit to any battery chemistry after collecting initial training data. Neural networks are able to determine their structure automatically based on the training data collected from battery discharge tests. Once the neural network has been built and optimized, it is possible to estimate the SOC from incoming current and voltage measurements. Due to inherent variability in sensor measurements and unit-to-unit battery differences, a statistical algorithm can be used to filter the SOC estimates and minimize the noise in the predictions. An unscented Kalman filter was designed to filter out the errors in the SOC output of the neural network and improve the overall accuracy of the SOC estimates. The combined SOC estimation approach based on a neural network and an unscented Kalman filter was validated using the data collected from automotive lithium-ion batteries under simulated electric vehicle driving conditions.

State of health (SOH) estimation is needed to determine the loss in deliverable capacity and power as a function of time. CALCE is determining new features that can be related to the overall health of the battery. Typically, battery health is determined by completely discharging a battery to determine how much capacity the battery can deliver. This is compared to the starting capacity to determine exactly how much loss in usability has occurred. Alternately, the internal resistance of the battery or the pulse power capabilities of the battery can be measured and related to health. New features that correlate well with battery state of health focus on the charging behavior of the battery instead of the discharge behavior. Typically, the charge stage of the battery is well controlled and does not feature dynamic current fluctuations. By measuring the time that the battery takes to reach voltage or current thresholds, the health of the battery can be assessed and related to the available capacity that the battery can deliver.

Data-driven methods rely heavily on the amount and type of data that is collected. This makes sensors a very important part of PHM, and this is certainly true of batteries. The battery team is testing different sensors that can provide further information about the internal electrochemical processes. It has been well established in the literature that lithium-ion batteries increase in thickness due to lithium-ion intercalation, electrode swelling, structural damage to the electrode, and gas generation. CALCE is developing sensor systems that relate these structural changes to both SOC and SOH estimation.
RECENT CALCE BATTERY PUBLICATIONS

The following are selected CALCE publications on lithium-ion batteries. For more information please see CALCE battery website: http://www.calce.umd.edu/batteries/articles.htm.


• Nick Williard, Wei He, Christopher Hendricks, Michael Pecht, “Lessons Learned From the 787 Dreamliner on Lithium-Ion Battery Reliability,” Energies, 6(9), pp. 4682–4696, 2013.


FALL 2014 COURSE ON PHM @ UMD

Prof. Michael Pecht will be teaching a semester-long course on prognostics and health management (PHM) during the Fall 2014 semester at the University of Maryland. This is an interdisciplinary course and students in many areas including mechanical, electrical, civil, and aerospace engineering, public policy, and engineering management are welcome. Students will get the opportunity to learn the basic scientific foundations that enable prognostics and health management and work on its implementation in real-life applications through projects. Guest lectures in this course will be taught by experts from industry, government, and academia. Some of the topics covered in this course include:

- Health monitoring (structures, electronics, mechanical components)
- Methods for in-situ monitoring
- Sensors for prognostics
- Data collection, pre-processing, reduction, and feature extraction
- Methods for identifying and analyzing precursors based on failure mechanisms
- Prognostic approaches (physics-of-failure-based techniques, data-driven techniques, fusion prognostics, statistical methods)
- Damage assessment
- Anomaly detection
- Machine learning and intelligent systems
- Diagnostics
- Risk and uncertainty analysis
- Software tools for diagnostics and prognostics
- Life cycle cost and Return on Investment for prognostics
- Condition-based maintenance and prognostics-based mission planning
- Case studies

For more information, contact Prof. Michael Pecht (pecht@calce.umd.edu).

JOIN THE CALCE PHM CONSORTIUM

To become a member and support the CALCE battery and PHM team, please email Prof. Michael Pecht (pecht@calce.umd.edu), and we will provide you with the membership agreement.