Physics-based Degradation Analysis of Lithium-ion Batteries for Health Monitoring

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INTRODUCTION

- Increasing trend on electrification rate of modern machinery and appliances caused a shift in focus on battery power
- Lithium-ion batteries are used as a source for sustainable power
- High energy density and lightweight
- Consist of several layers of anode, cathode, separator, current collectors, and electrolyte
- Due to certain instances of failure, physics-based models were used to understand the degradation process of batteries in actual operations over time
- With the above information, we can construct a health-monitoring-based prognostic analysis of battery management systems

FAILURE MECHANISMS

1. **Swelling**: deep discharge, overcharge
2. **Ruptured or Leaking**: overcharge, thermal runaway
3. **Smoking or Fire**: short circuit → thermal runaway

Thermal Runaway- process accelerated by spike in temperature, which releases energy to further increase temperature

Short Circuiting- damage to separator causes two electrode materials to touch, creating smoke, overheating, etc.

4. **Deformation or Crushed**: catastrophic failure

METHODS AND APPROACHES

Lithium-ion batteries are sensitive to:

- High power (fast) charging
- Too high/low operation temperatures
- Mechanical abuse →capacity fade, short-circuiting, hazard of thermal runaway

Common testing methods listed below create environments for the batteries that initiate the above failure mechanisms:

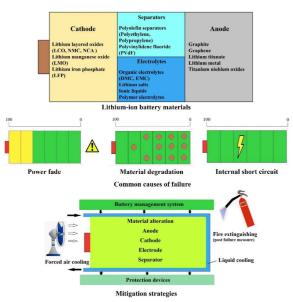

Figure 1. Battery Overview

- Temperature Acceleration: creates an environment at temperatures above/below recommended working condition temperatures

Best operating temperatures are 10-40 degrees Celsius (50-100 degrees F)

- Nail and Crush Test: puncture battery to judge safety performance and short circuit tolerance
- Charge/Discharge: put battery through cycles of charging/discharging to determine its aging characteristics and degradation process (capacity fade)

ANALYSIS

Oven Test: Temperature Acceleration

- Simulates overheating of battery cells, excess temperature and capacity degradation
- Li-ion batteries deteriorate tremendously around/above temperatures of 70 degrees C
- Batteries are charged and discharged before put into oven
- After X time in oven, capacity drops significantly, until its approximately zero
- Executed thermal runaway → as oven temperatures increased, onset of thermal runaway happened faster → severity of thermal runaway increased with higher peak temperatures

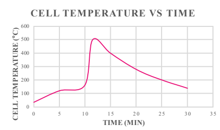

Figure 2. Cell Temperature vs. Time

Nail and Crush Test: Predicted Thermal Runaway

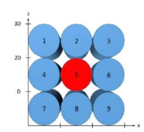

Figure 3. Nine cylindrical Li-ion battery

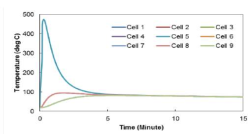

Figure 4. Temperature vs. Time

- Used short-circuit induced by physical impact for study of thermal runaway
- Less thermal runaway when failure is initiated in center cell of battery because the heat is distributed more evenly versus higher and earlier peak rate of heat release when failure occurs in corner, outside cell
- Concluded thermal runaway does *not* propagate spread due to its small contact surface geometry which deters heat transfer to surrounding cells.

Charge/Discharge:

- Charge batteries to a certain voltage, at a specific current
- Once battery reaches said voltage, batteries are discharged using a sequence of discharging currents
- Random-Walk Mode of battery cycling; the discharging currents are randomized between 0.5-5 Amperes.
- As the battery ages, it's charge storage capacity decreases, and its internal resistance increases.

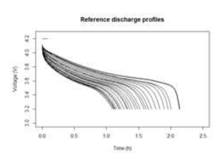

Figure 5. Voltage vs. Time

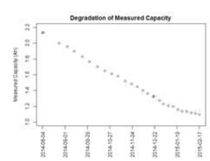

Figure 6. Capacity vs. Time

CONCLUSION

In summation:

- Operating time after a full charge becomes shorter over time due to the charging and discharging process
  - Capacity fades with cyclic charge and discharge → This is shown in the Capacity vs. Time graph

Degradation Overtime:

- Loss of Li-ions in the battery
- Often lost through side reactions that occur with the electrolyte → free lithium becomes stuck, forming compounds → reduces Li-ions that move between the electrodes
- Loss of active ions reduces the maximum achievable battery capacity
- Trickle charging refers to the process by which the battery is continually topped up to 100% every time any charge is lost → Bouncing back between 100% and just under 100% charge can elevate internal temperature, which diminishes battery capacity and lifetime

Future Focuses to Prevent Failures and Delay Capacity Degradation

- Expand normal operating temperatures
- Minimize loss of active Li-ions over time
- Advance the venting system or develop method to decrease effects of thermal runaway from short circuiting or a spiked temperature

Looking forward to the future, we see a lot of potential in our work. These plans consist of:

- Investigating more complex mathematical prediction models, possibly related to Remaining Useful Life (RUL) prediction
- Battery pack testing versus single cell testing
- Conducting personal experiments within the campus lab using equipment funded by SRU's research grant

ACKNOWLEDGEMENTS

This work is funded by the Faculty/Student Research Grant of Slippery Rock University, 2021-2022.

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