Knee-Point Based Degradation Modeling and Lifetime Prognostics of Li-Ion Cells Under Sustained Thermal Stress

Aditya Amatya, Pradeep Lall

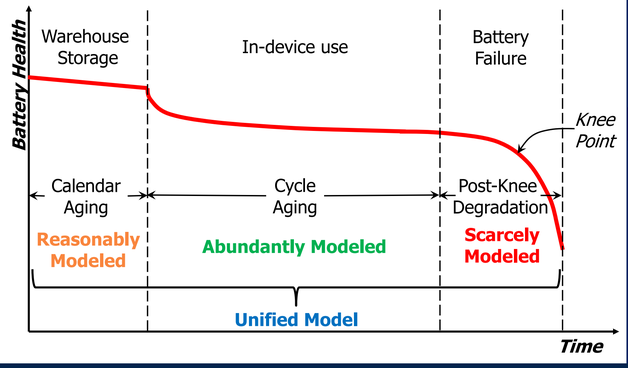
Auburn University, Department of Mechanical Engineering,
Electronics Packaging Research Institute, Auburn, AL 36849
Tele: (334) 844-3424; Email: lall@auburn.edu

InterPACK: 174751

Introduction

State of Health (SOH) Estimation: Process of estimating the current battery health from internal parameters: Battery voltage, current, etc.

$$SOH(\%) = \frac{Battery\ Capacity}{Rated\ Capacity}$$



Objectives

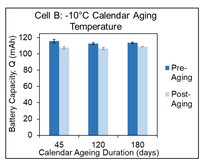
- **Objective 1:** Develop SOH estimation models for li-ion cells considering at higher temperature considering Calendar aging and post-Knee degradation
- **Objective 2:** Test batteries to gather data at higher temperature
- **Objective 3:** Investigate battery knee-point failures and propose leading indicators for the same

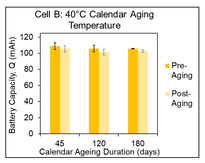
Battery Test Vehicle Specifications

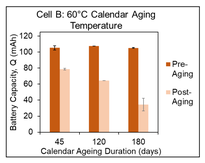
Parameters	Value
Battery Chemistry	Li-Ion NMC-Graphite
Nominal Capacity	120 mAh
Nominal Voltage	3.7 V
End of Charge Voltage	4.2V
End of Charge Current	4 mA
Charge Current Range	1.5C
End of Discharge Voltage	3 V

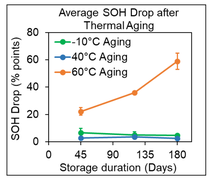
Calendar Aging

Test Matrix	
Storage Temperature	Storage duration
-10°C, 40°C, 60°C	45, 120, 180 days







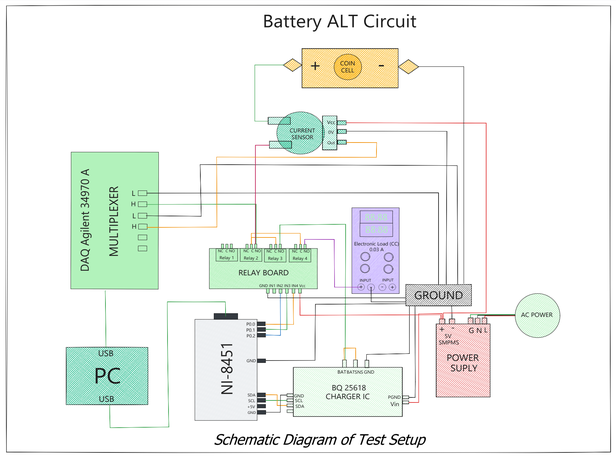


$$\Delta SOH_{calendar} = 0.76 T_{ratio}^{39.54} D_{ratio}^{0.48} \quad \text{(I)}$$

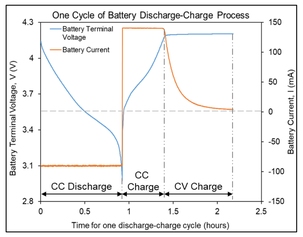
$$T_{ratio} = \frac{T_{Kelvin}}{298K}, \qquad D_{ratio} = \frac{D_{days}}{365\ days}$$

R^2= 88.6 %

Cycle Aging – Test Setup

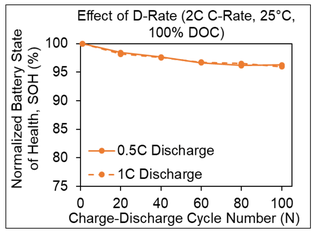


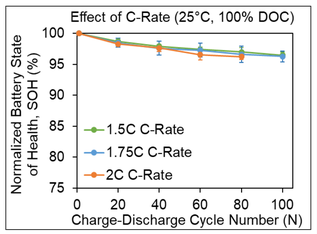
Schematic Diagram of Test Setup



Cycle Aging Study	
Test parameter	Levels
Discharge current	0.5C, 1C
Charge Current	1.5C, 1.75C, 2C
Depth of charge	50%, 75%
Depth of discharge	50%, 75%
Depth of cycling	100%
Operating temperature	25°C, 40°C

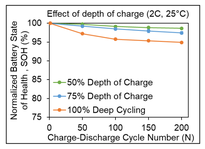
CC Discharge & CCCV Charge Profile

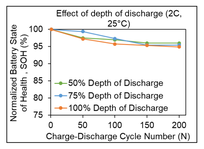


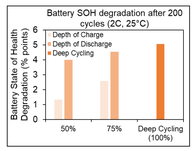


C-Rate has more effect on SOH degradation than D-Rate

Effect of Partial Cycling







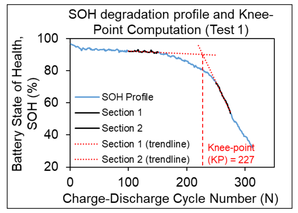
Higher operating voltages degrade the SOH more

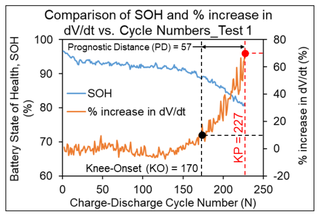
$$\Delta SOH_{cycle} = 0.3 N^{0.5} C^{0.43} V_{ratio}^{0.11} I_{ratio}^{0.25} \quad \text{(II)}$$

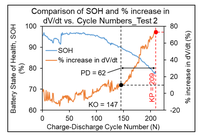
$$V_{ratio} = \frac{V_{end-of-charge} - 3}{4.2 - 3}, \qquad I_{ratio} = \frac{I_{end-of-charge}}{I_{cc}}$$

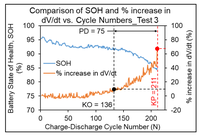
R^2= 97.3 %

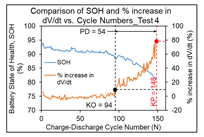
Knee-Point Prognostication











$$\Delta SOH_{post-knee} = c_1 N^{c_2} \left(\frac{dV}{dt}_{,\%inc} \right)^{c_3} \quad \text{(III)} \qquad \frac{dV}{dt}\Big|_{\%inc} = \frac{\frac{dV}{dt}\Big|_N - \frac{\sum_{N=1}^{10} \frac{dV}{dt}\Big|_N}{10}}{\frac{\sum_{N=1}^{10} \frac{dV}{dt}\Big|_N}{10}}$$

R^2= 97.8 %

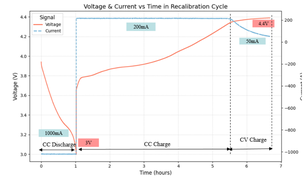
Unified SOH Estimation Model

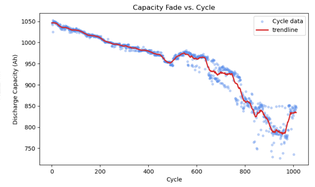
$$SOH = SOH_0 - \text{I} - \text{II} - \text{III}$$

$$SOH = SOH_0 - 0.76 T_{ratio}^{39.54} D_{ratio}^{0.48} - 17.45 N^{0.22} C^{0.08} T^{0.18} V_{ratio}^{-0.06} I_{ratio}^{0.02} + 18.15 N^{0.21} \left(\frac{dV}{dt}_{,\%inc} \right)^{0.81}$$

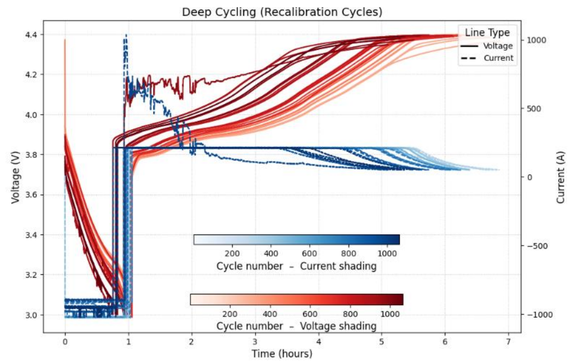
Pouch Cell Modelling

Parameters	Value
Nominal Capacity	1080 mAh
Nominal Voltage	3.81 V
End of Charge Voltage	4.4V
End of Charge Current	4 mA
Charge Current	1.5C
Discharge Current	1C
End of Discharge Voltage	3.3V
Test Temperature	40 °C

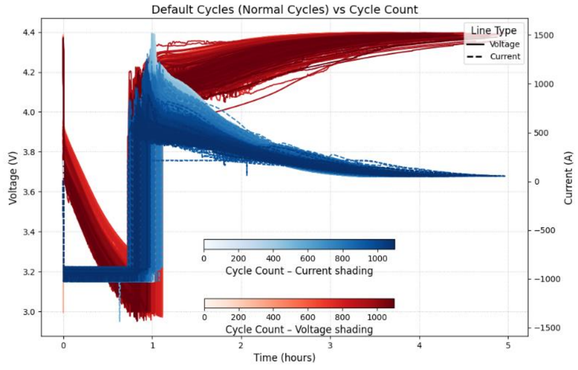




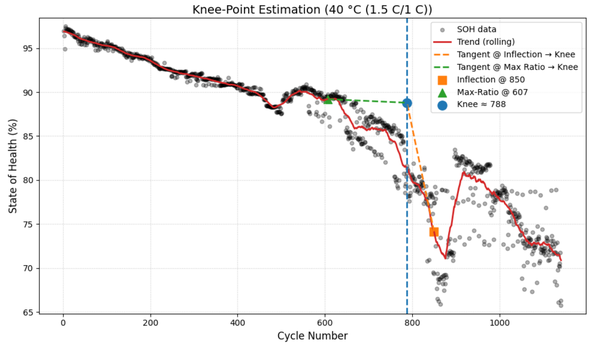
Pouch Cell Aging – Results



Voltage and Current Evolution Profile for Recalibration Cycle



Voltage and Current Evolution Profile for Default Cycle



Knee-Point Estimation for Pouch cells

Summary & Conclusions

- **Unified model can estimate battery SOH encompassing all 3 phases**
- **10% increase in dV/dt indicates a prognostic distance of ~60 cycles from knee-point**
- **Pouch Cells Cycle aging and Knee-Point Estimation at High Temperature**
- **Ongoing – Cross-form-factor Modelling and In-situ swelling correlation with battery health**

Acknowledgements

- The research results presented in this paper have been supported by members of Auburn University Electronics Packaging Research Institute