SILICON VALLEY
AMES RESEARCH CENTER

Predicting Thermal Response in a Li-ion Cell on a UAV Fight Profile

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Overview

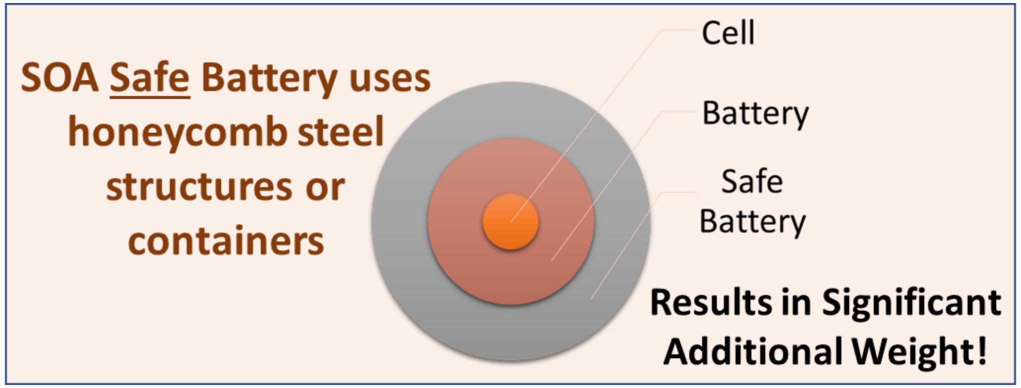
- Introduction
- Prognostics
- Reduced Order Model
- Preliminary Results

Improving Stack Specific Energy for a Safe Electric Aircraft Battery

Electric Aircraft need Better and Safer Batteries

- **Consequence of Unmitigated Cell Thermal Runaway Events**
  - Fire
  - Explosion
  - Debris

- **Current Solution Results in Low Specific Energy and Specific Power for a Current Li-ion Battery**



- **Non-Battery Chemistry Mass can be reduced by the development of:**
  - Better Internal Battery Monitoring Tools
  - Developing internal fault detection & mitigation strategies

Problem Formulation

Current focus

High C-rate

Temperature

Dendrite/ Short

Degradation

Side Reactions

Abuse

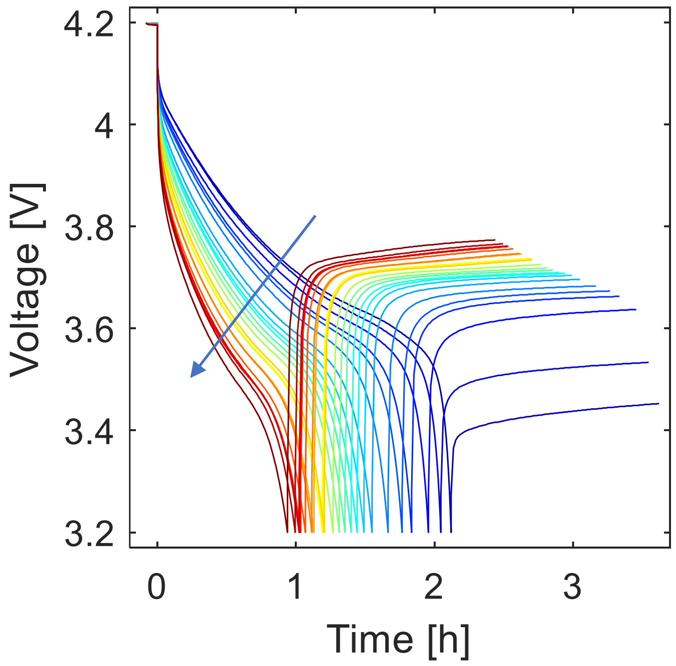
Fast and Slow Prognostics Blocks

***Abuse is assumed to mean extreme degradation**

Predict the number of cycles to the thermal runaway cycle

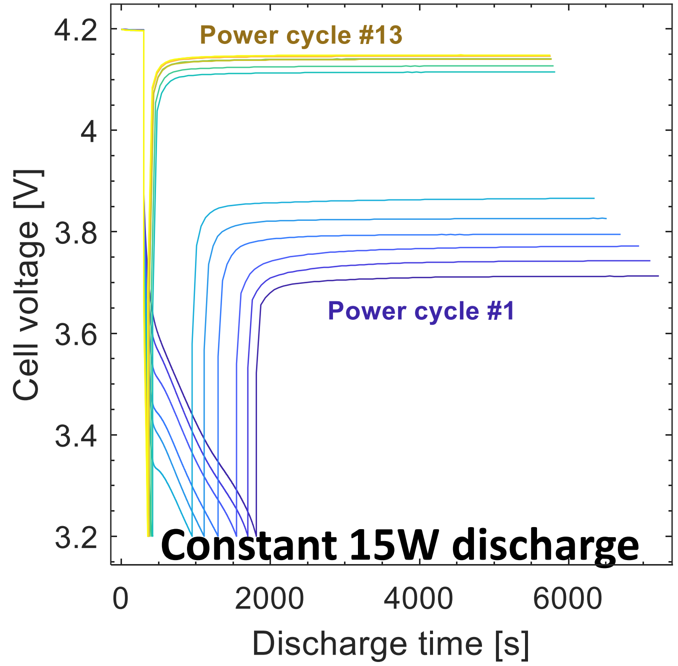
Dataset Used (Battery: LG ICR18650S3)

Reference Discharge Cycle



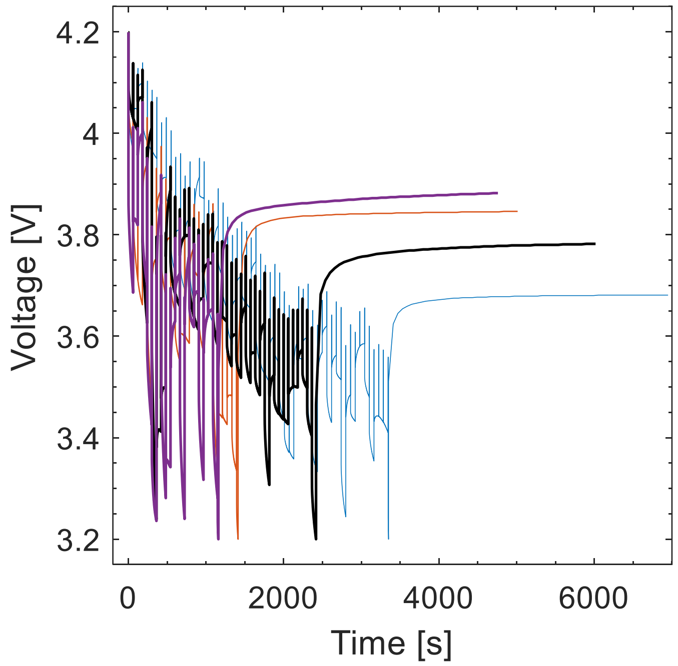
10 Ref. cycles with decreasing SOH

Power Discharge Cycle



A Power cycle is measured after each Ref. cycle

Random Discharge Cycle



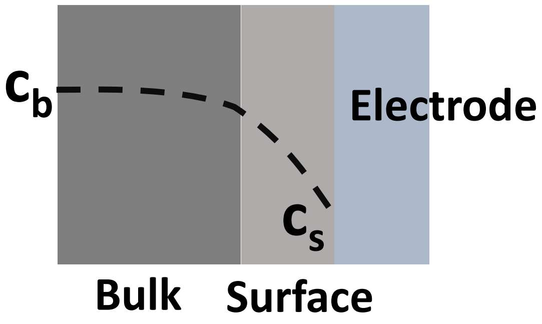
50 Random cycles between two Ref. cycles

B. Bole, C. Kulkarni, and M. Daigle "Randomized Battery Usage Data Set", NASA Ames Prognostics Data Repository (http://ti.arc.nasa.gov/project/prognostic-data-repository), NASA Ames Research Center, Moffett Field, CA

Model Used for Prognostics

Hybrid Echem Model (SPM + ECM):

concentration distribution assumption



Cell Voltage:

$$\boxed{\boldsymbol{V = E_p^0 - E_n^0 - \dot{V}_o - \dot{\eta}_p - \dot{\eta}_n}}$$

$\boldsymbol{V_o}$ Voltage across ohmic resistance

$\boldsymbol{\eta}$ Butler-Volmer Kinetics

$$\boldsymbol{\dot{c} = \frac{c_b - c_s}{\tau_{diff}}}$$ Li^+ concentration in a electrode

$$\{\dot{\cdot}\}^t = \frac{\{\cdot\}^{t+1} - \{\cdot\}^t}{\tau_{\cdot}}$$ State Evolution

Lumped Thermal Model:

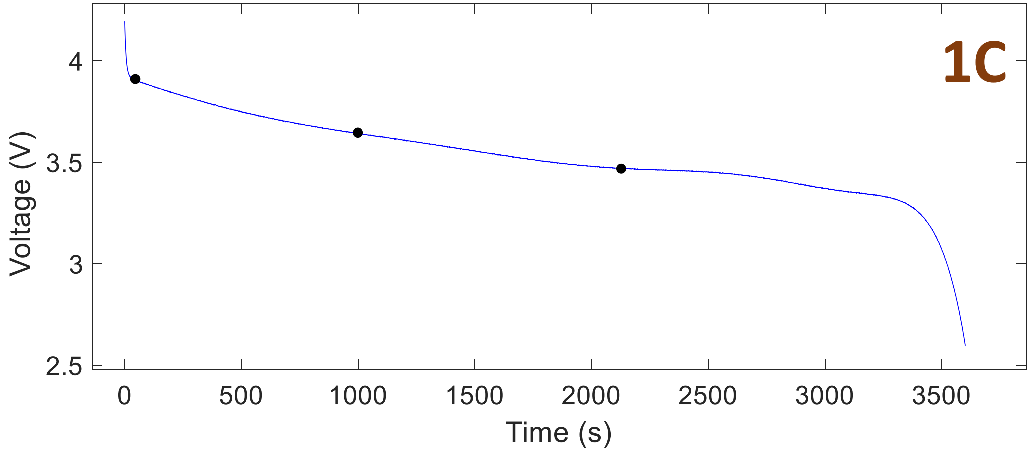
$$\frac{\partial \mathrm{T}}{\partial \mathrm{t}} = \underbrace{\boxed{\frac{Q}{m_{\mathrm{cell}}\mathrm{C_p}}}}_{\text{Heat generated}} - \underbrace{\boxed{\epsilon_{conv}(T - T_{amb})}}_{\text{Heat loss}}$$

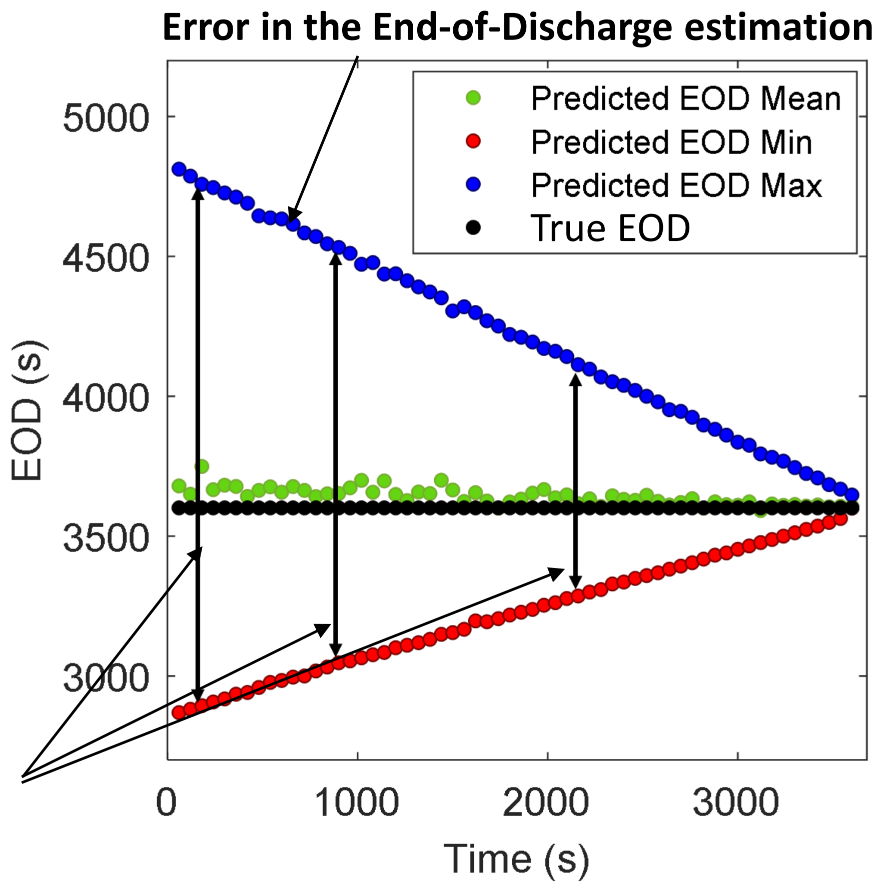
$$Q = \mathrm{I}\left(U_c - \alpha U_a - V - T\frac{dU}{\mathrm{dT}}\right)$$

$$\epsilon_{\mathrm{conv}} = \frac{\mathrm{A_{surf}}}{\mathrm{C}_p m_{\mathrm{cell}}} h_{\mathrm{conv}}$$

M. Daigle, C.S. Kulkarni, Electrochemistry-based Battery Modeling for Prognostics, in: Annual Conference of the Prognostics and Health Management Society, 2013: p. 13.

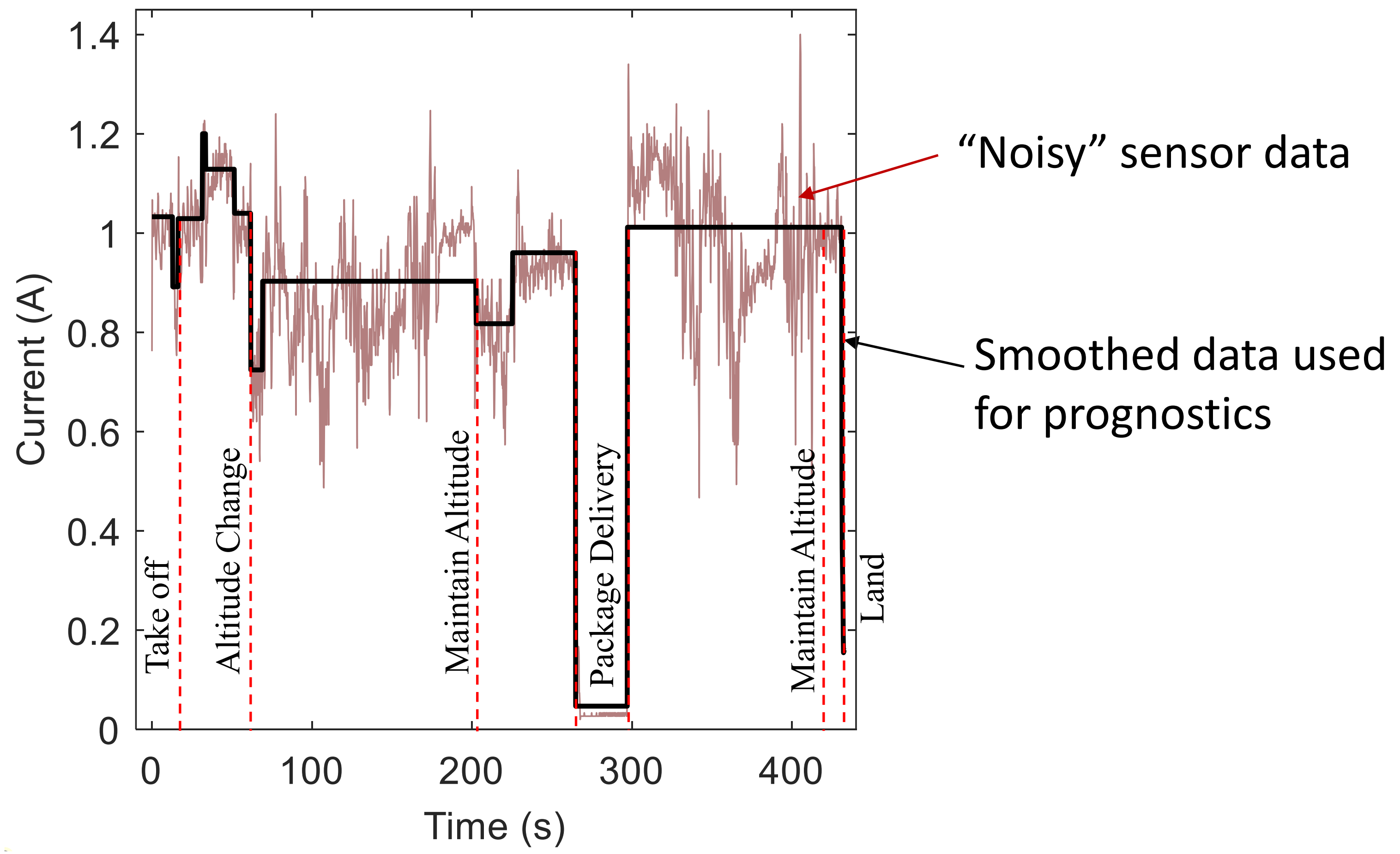
Predicting EOD using Prognostics Algorithm with the Hybrid Model





The estimation error reduces as the discharge time increases

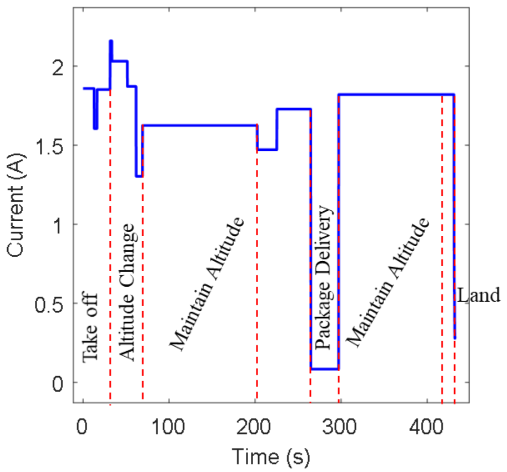
Data from a Short Test Flight

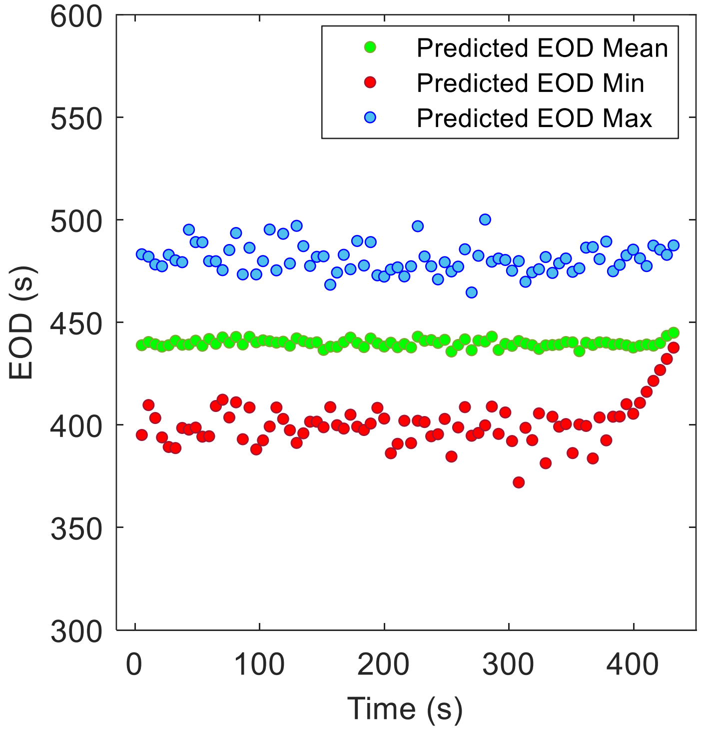


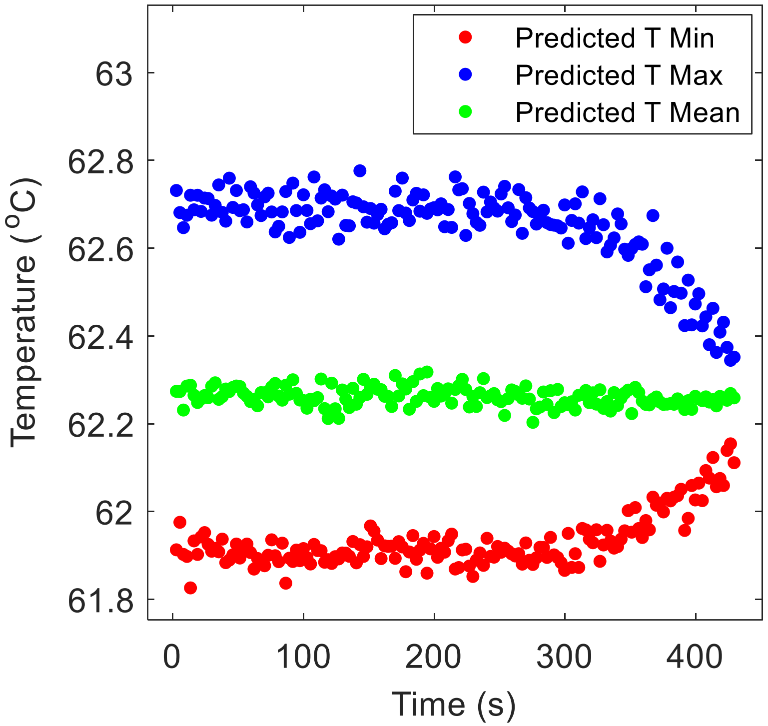
Data pre-processing is needed for accurate estimation

Preliminary Results for EOD Estimation

Applying Prognostics Algorithm on a Short Test Flight Profile



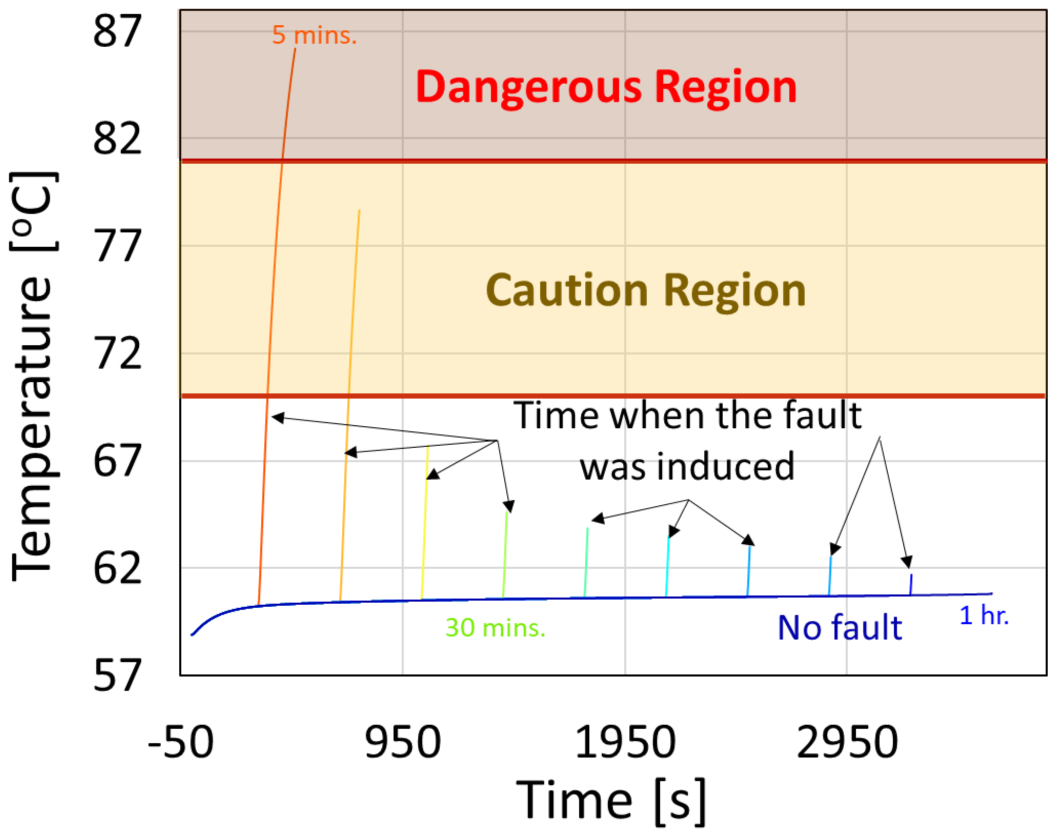


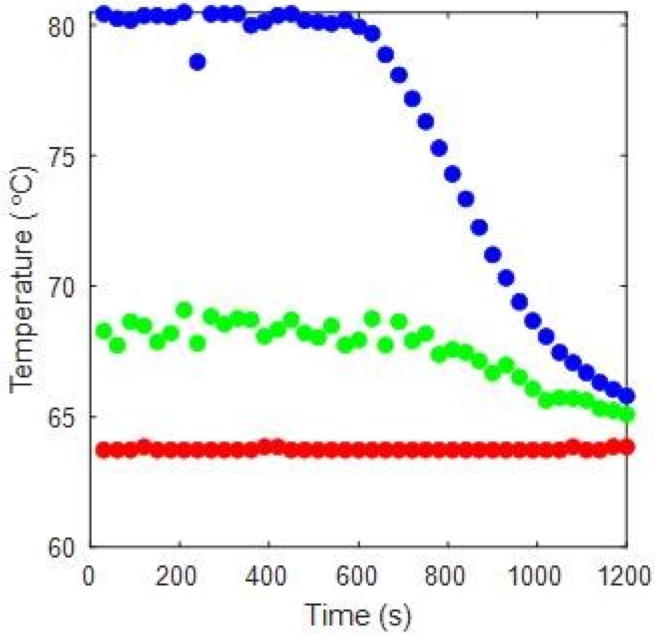


The Distribution of the End-of-Discharge Estimation shows that the Algorithm is working correctly.

Simulating Short Circuit

A simple parallel resistor to simulate short circuit upto 1V

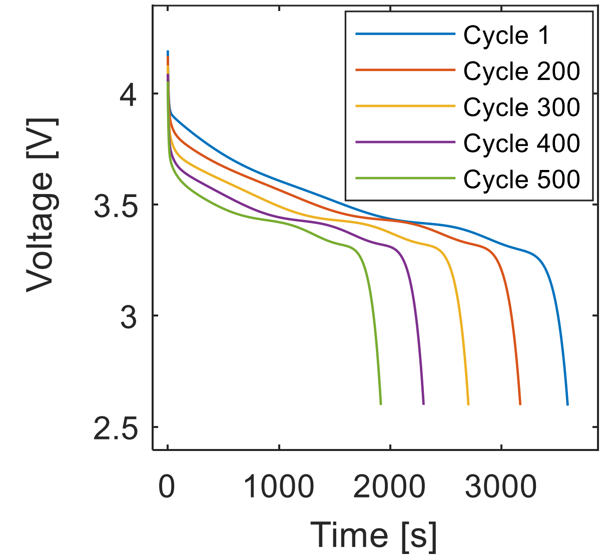


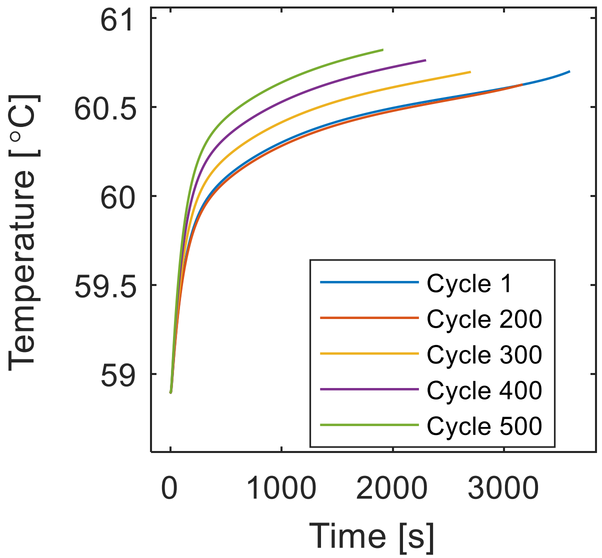


Battery management limits max current to 15A

Short Circuit at High SOC are dangerous if no external preventive current breakers are in place

Simulation Results with Aging for 1C

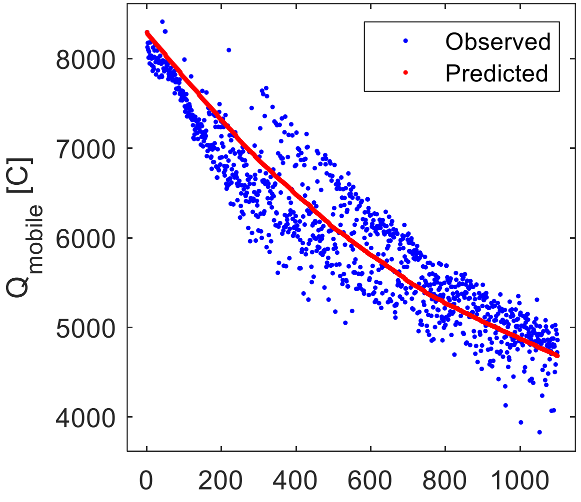




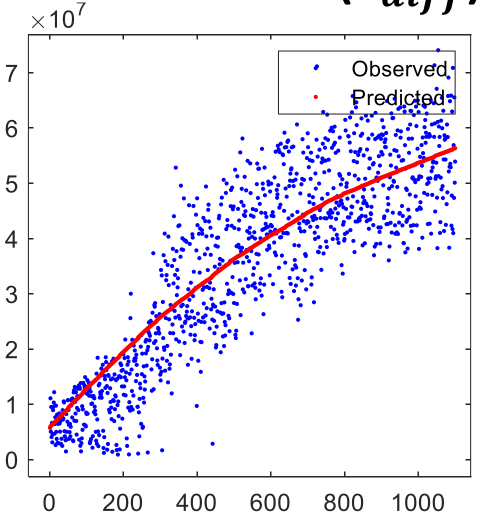
Empirical Aging Model

- Parameters are estimated using random walk cycles
- C-rate ranges from 0.2-2.2C
- Each Random Walk Test is stopped after V_{min} is reached

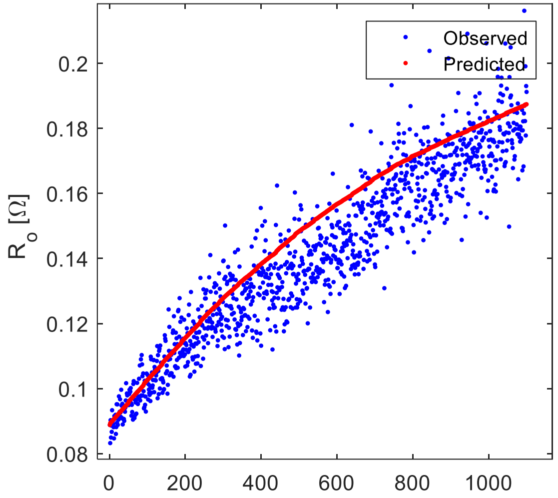
Usable Li-ion (Q_{mobile})



Diffusion time (τ_{diff})

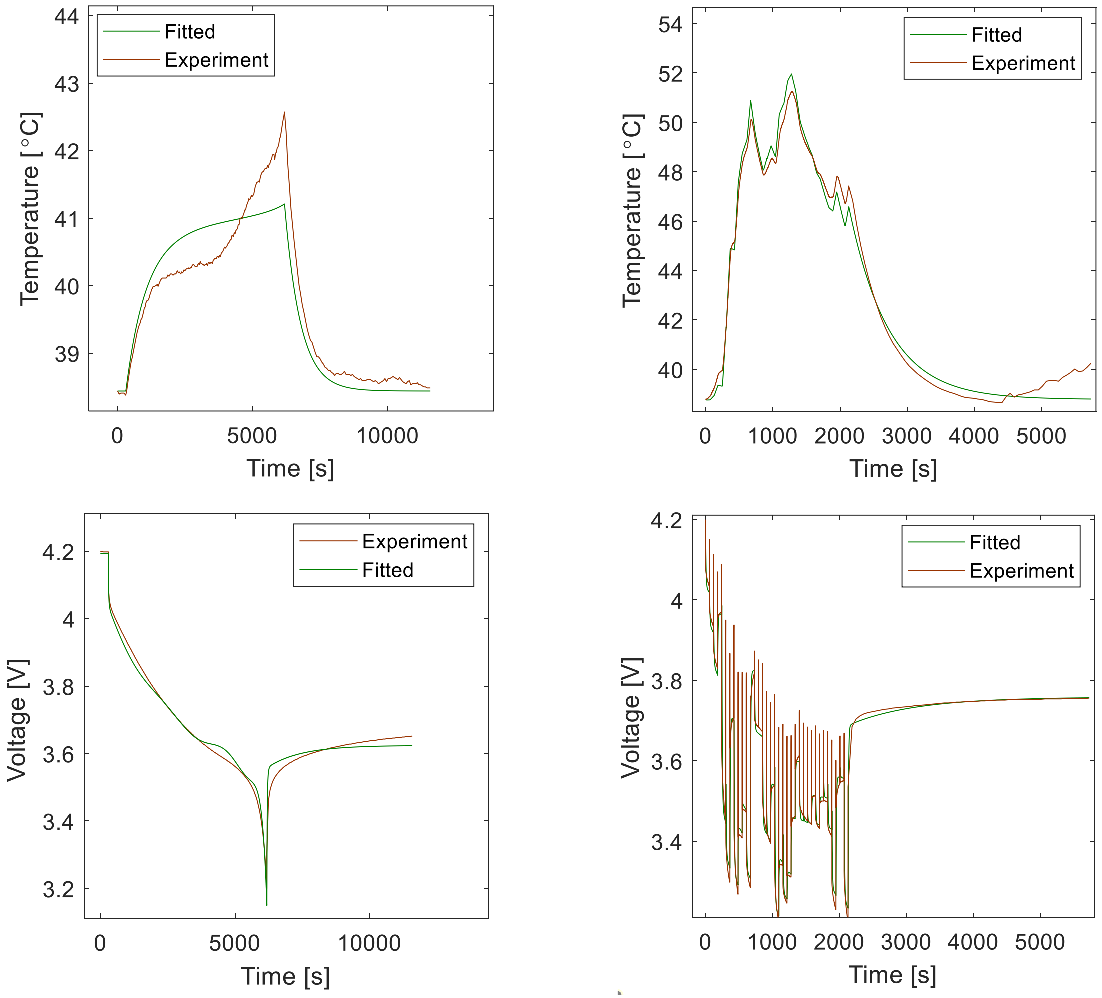


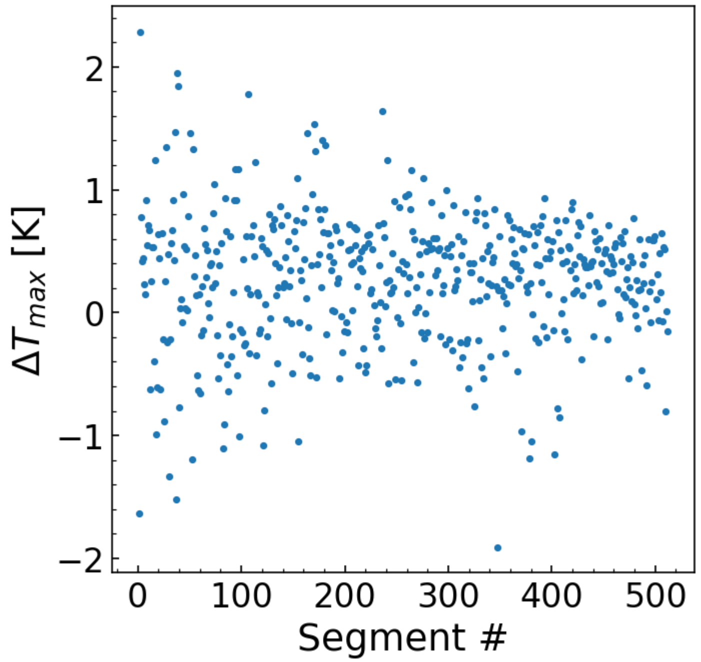
Ohmic Resistance (R_o)



Temperature increases qualitatively on voltage parameterized data

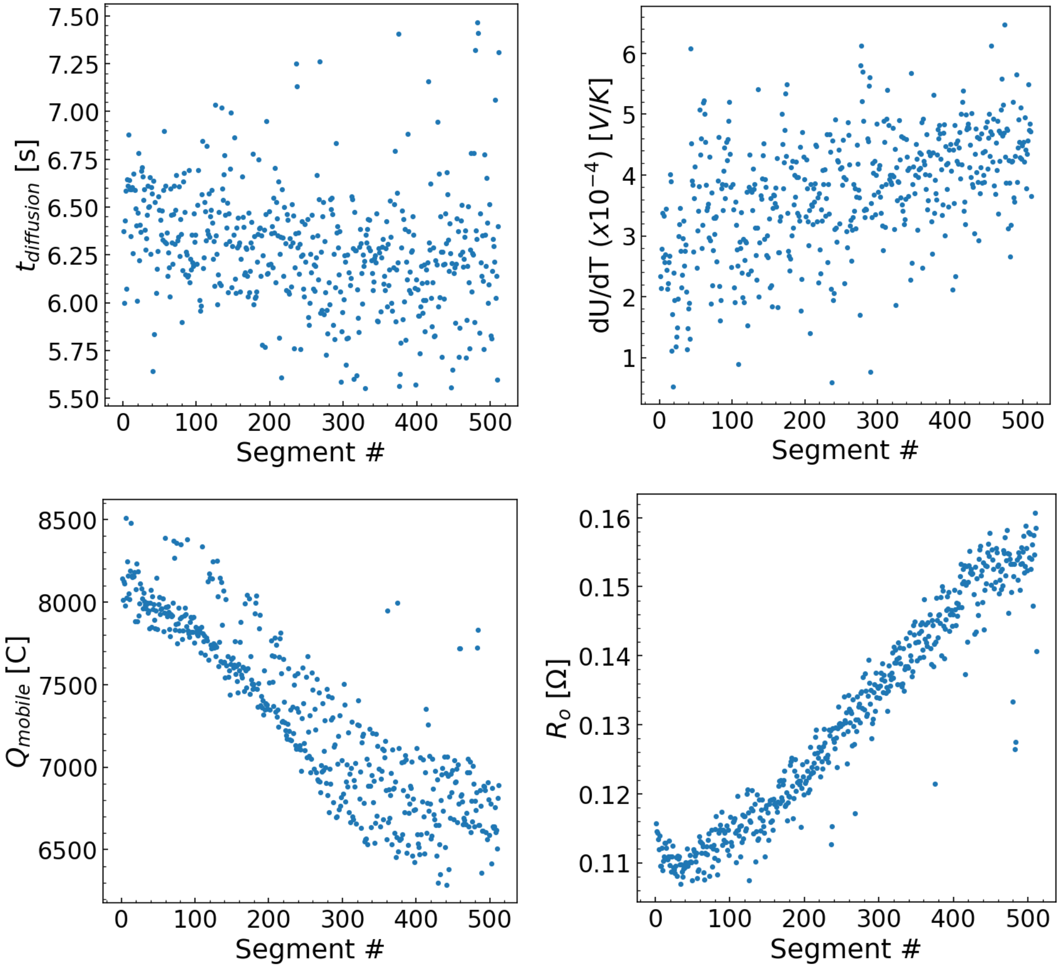
Parameterization of Experimental Data

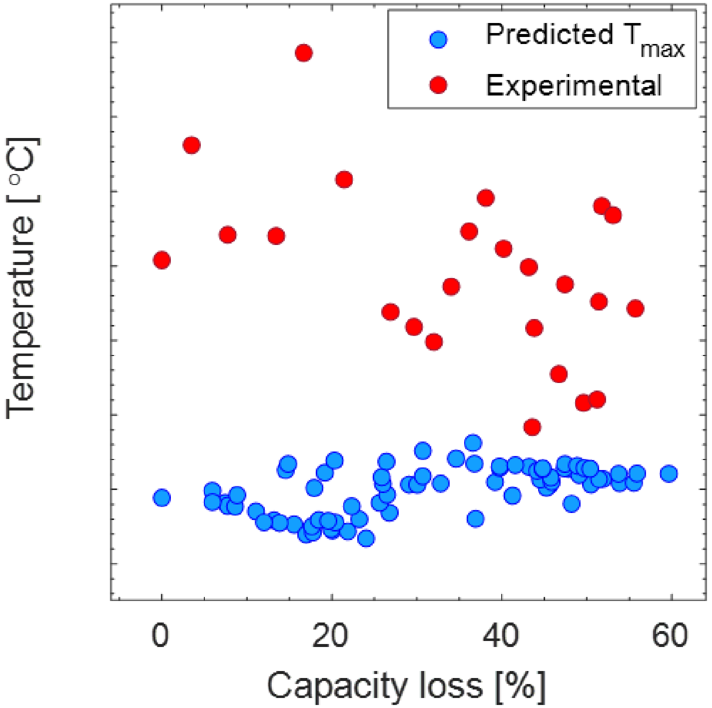




Estimating entropic term (dU/dT) in addition to Q_{mobile}, R_o, τ_{diff} improves temperature prediction for RW but not Reference discharges

Distribution of Estimated Parameters





Non-unique trends in τ_{diff} and dU/dT leads to underestimation of maximum temperature throughout battery life

Conclusions

- Lumped thermal model was implemented and show qualitative agreement with aging using voltage parameterized parameters (lithium diffusivity, ohmic resistance, and usable lithium)
- Maximum temperature and end-of-discharge can be predicted at a particular SOH
- A simple lumped model with a constant thermodynamic term cannot predict the rise in temperature near the end-of-discharge accurately
- The estimated parameters for dU/dT using the experimental data is non-unique, which causes the prediction of maximum temperature over operating life to be under predicted by 7-8^{o}C

Backup for slide 12