Optimal Operation and Management of Energy Storage Systems Based on Real time Predictive Modeling and Adaptive Battery Management Techniques

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Performance Targets and Validation Plan

- **Integration of microcontroller with physics-based control models onto a large format cell and to demonstrate**
  - **i) a 20% reduction in the weight of the cell**
  - **ii) a 50% reduction in the charging time for the cell without compromising the number of cycles**
- **3 cells will be subject to cycling with no heat control in a chamber held at -17, 0 and 30°C for 3 test plans. Life of cells tested in case (B) will be better than (A), and ideally closer to base conditions (Test-0)**
  - **Test 0: 30% to 85% SOC window**
  - **Test A: 0% to 100% SOC window**
  - **Test B: 0% to 100% SOC window with MPC based charging control**

Cost / Benefit – Battery downsizing

- **Assumptions**
  - 10 kWh useable system
  - **Costs escalate at 2% per year**
  - Discount rate of 5% per year is applied
  - **10,000 vehicles produced per year**
- **Outcome**
  - Present value of potential savings is **$47M** for each vehicle model

Useable Capacity	Today's Total Capacity	Total Capacity w/ AMPED model	Per vehicle battery cost savings	Per vehicle Additional BMS HW cost	Per vehicle development cost savings
1 kWh	1.7 kWh	1.11 kWh	$111	$35	-$1.67
4 kWh	6.7 kWh	4.44 kWh	$458	$35	-$1.67
6 kWh	10.0 kWh	6.67 kWh	$690	$35	-$1.67
10 kWh	**16.7 kWh**	**11.1 kWh**	**$1,152**	**$35**	**-$1.67**
20 kWh	33.3 kWh	22.2 kWh	$2,310	$35	-$1.67

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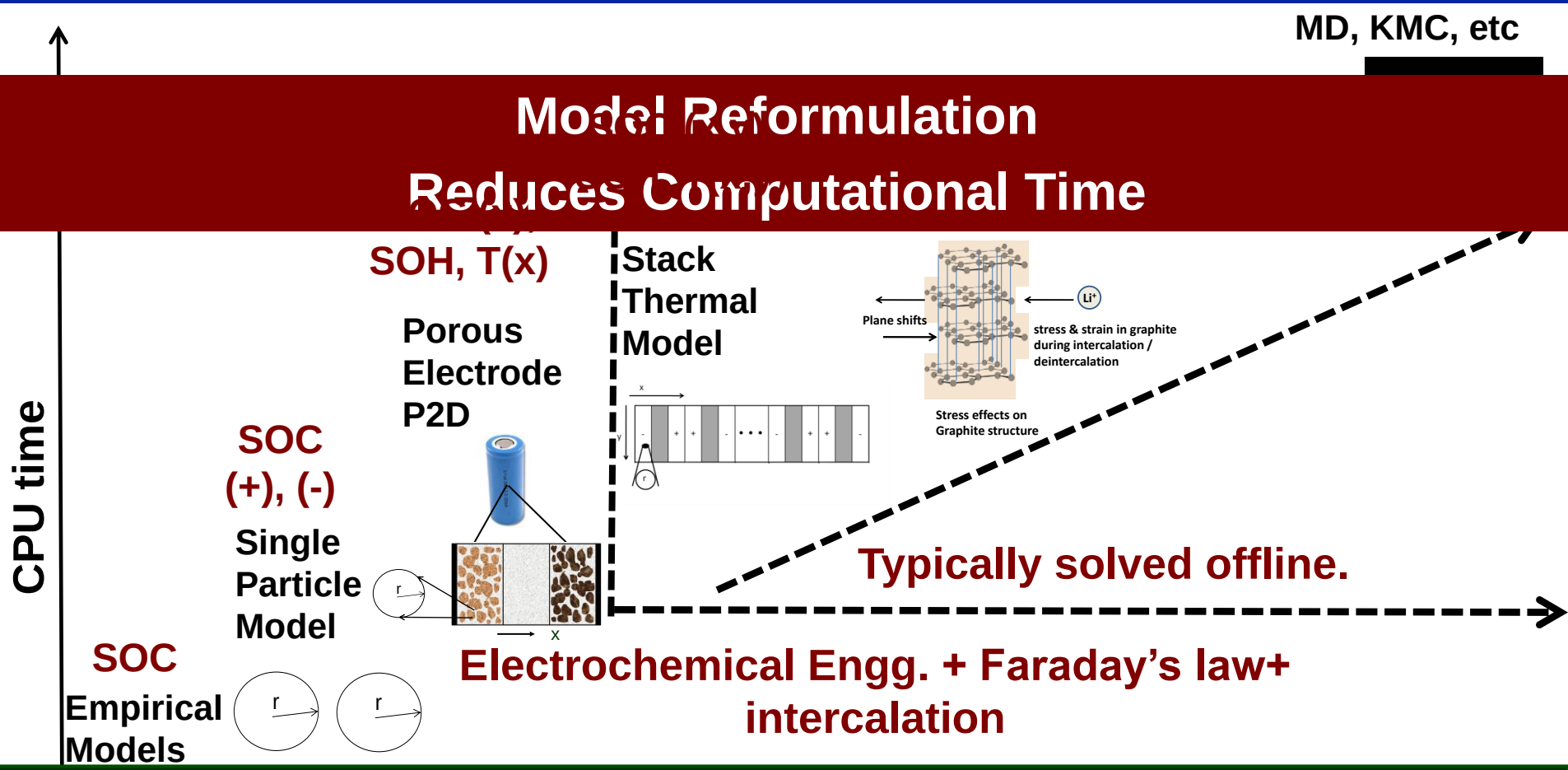
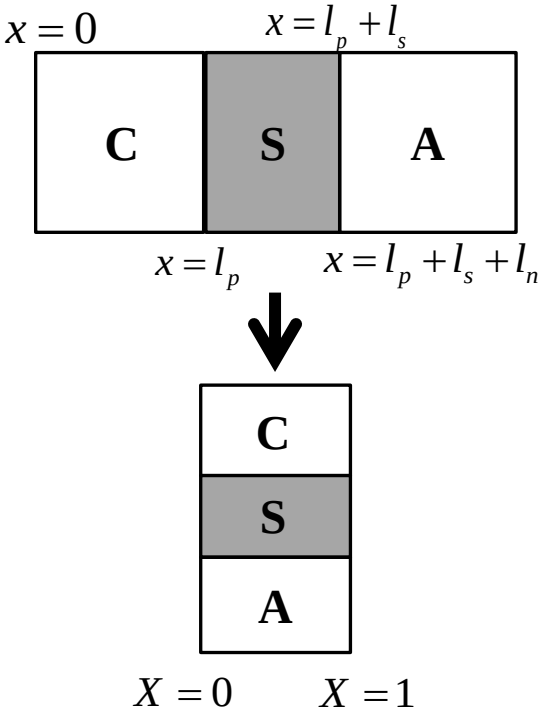
Models for batteries



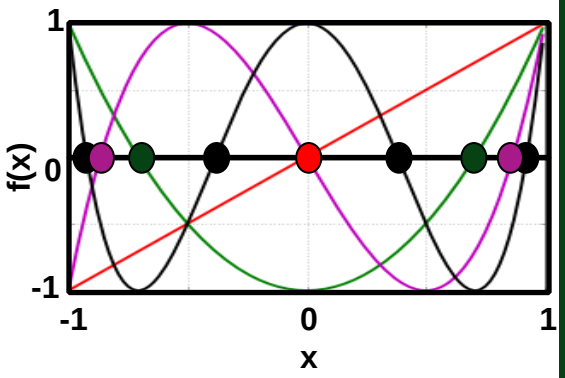
- Adding more physics provides more *fidelity* and *functionality* for the model and the BMS
- Comes at increased computational cost

Mathematical Reformulation

Coordinate Transformation



Orthogonal Collocation



Analytical Solutions

Original System
3000-10000 DAEs

Reduces into

Final System
30-50 DAEs

(P.W.C. Northrop+, JES, 2011)

(Patent US20140136169)

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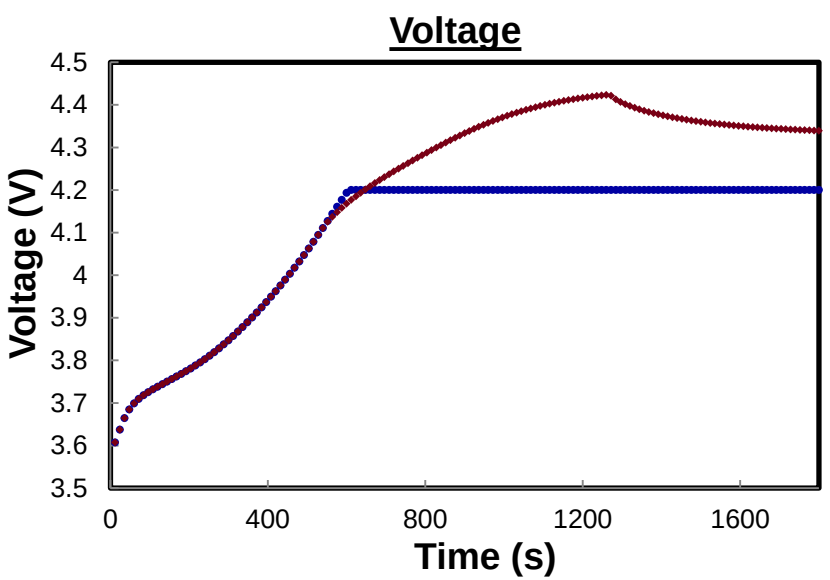
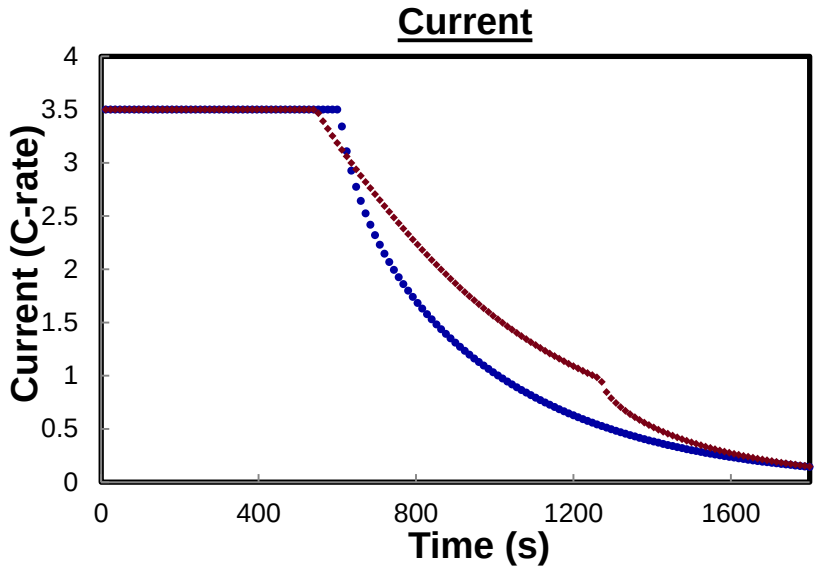
Which charging protocol is better?





- **Protocol 1 reaches 4.2 V first and stays there**
- **Protocol 2 reaches 4.2 V at a later time but goes well above 4.2 V**

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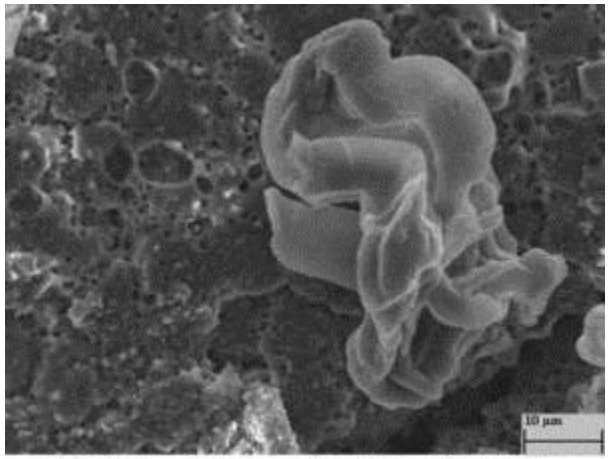
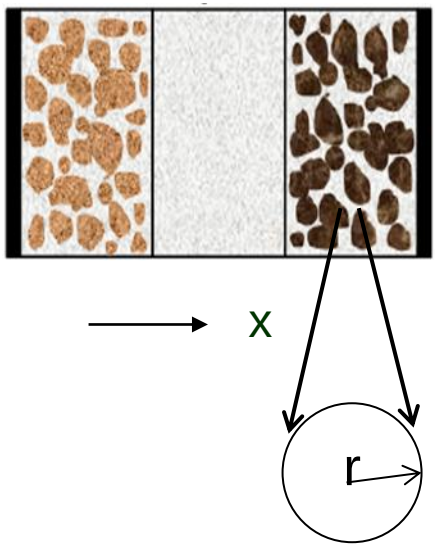
Lithium plating

- **Negative potential at the anode causes lithium to plate**
  - **Anode overpotential < 0**



Lithium deposited on the surface of a graphite electrode



(www.ifw-dresden.de/de)

Optimal control for charging – avoid plating

- **Problem formulation**

$$\max_{i_{app}(t)} \; Q = \int_0^{t_f} i_{app}(t)\,dt$$

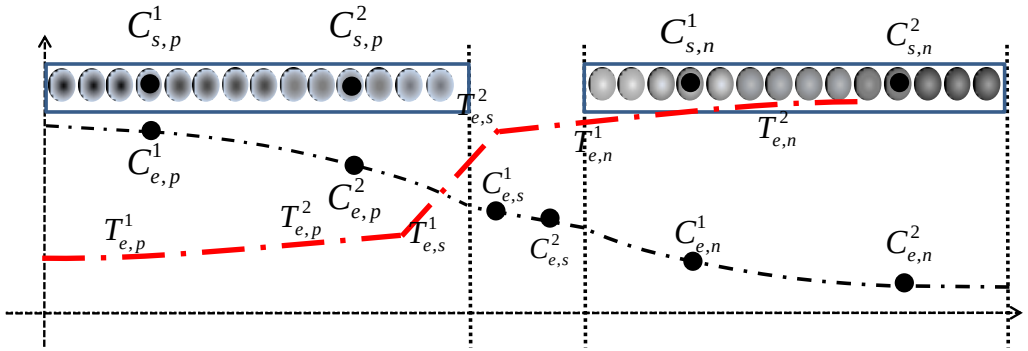
Maximize charge stored

such that

$$0 \le i_{applied} \le i_{max}\left(=3.5C\right);$$

$$\eta_{plating} > 0$$

- **Model description**
  - **Reformulated model**



(Patent US20140136169, "Systems and methods for improving battery performance;" P.W. C. Northrop+, JES, 2014)

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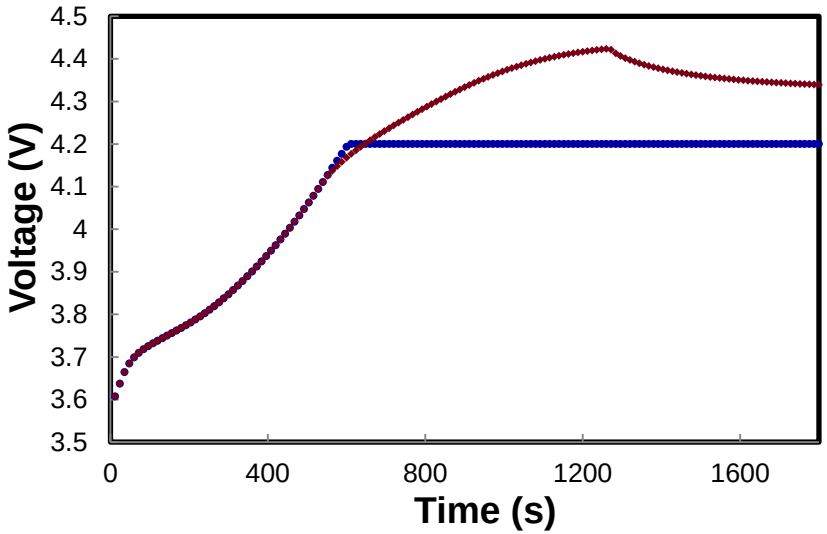
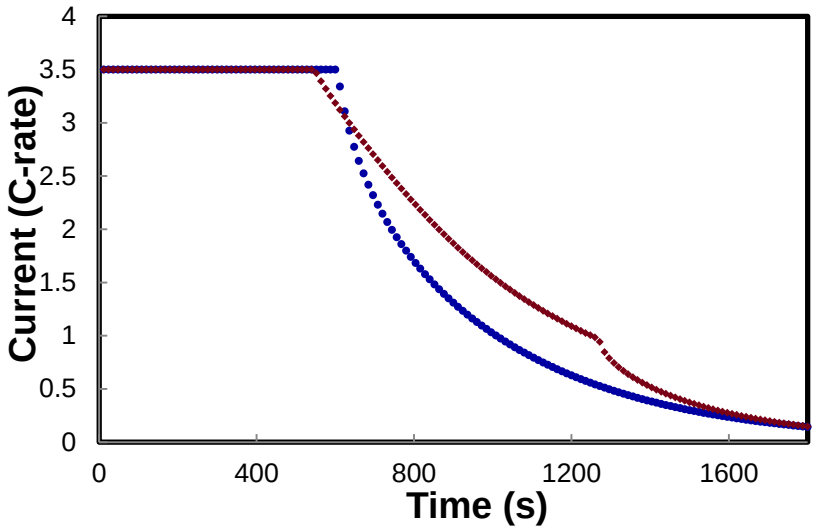
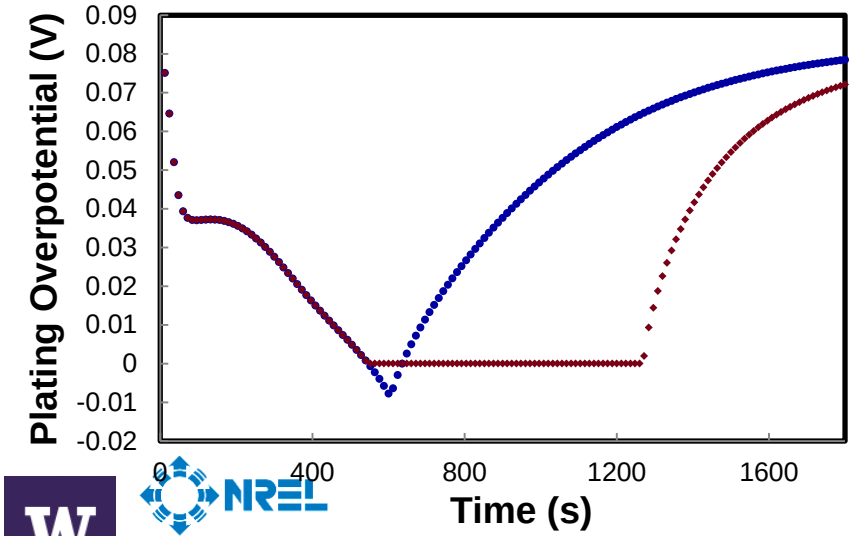
Which charging protocol is better?







- **Protocol 1 reaches 4.2 V first and stays there**
- **Protocol 2 reaches 4.2 V at a later time but goes well above 4.2 V**
- **Protocol 2 avoids lithium plating (optimal control)**

P.W-C. Northrop +, JES (2014).

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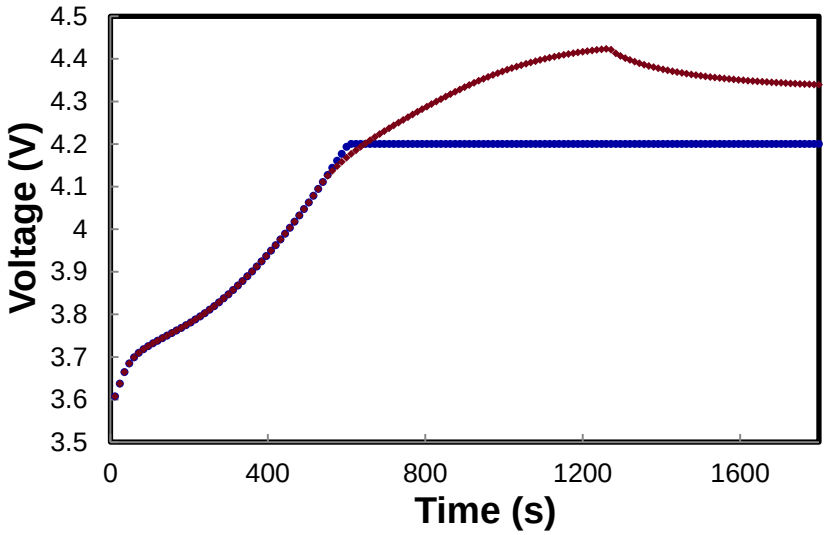
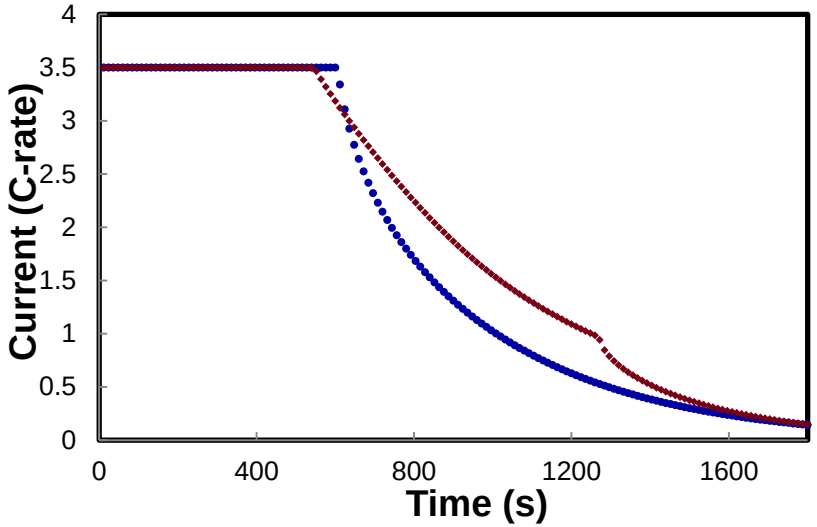
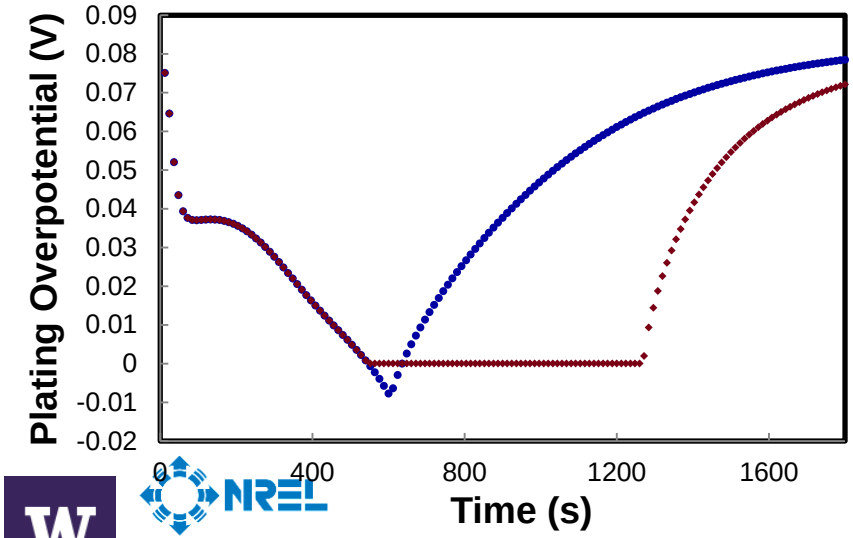
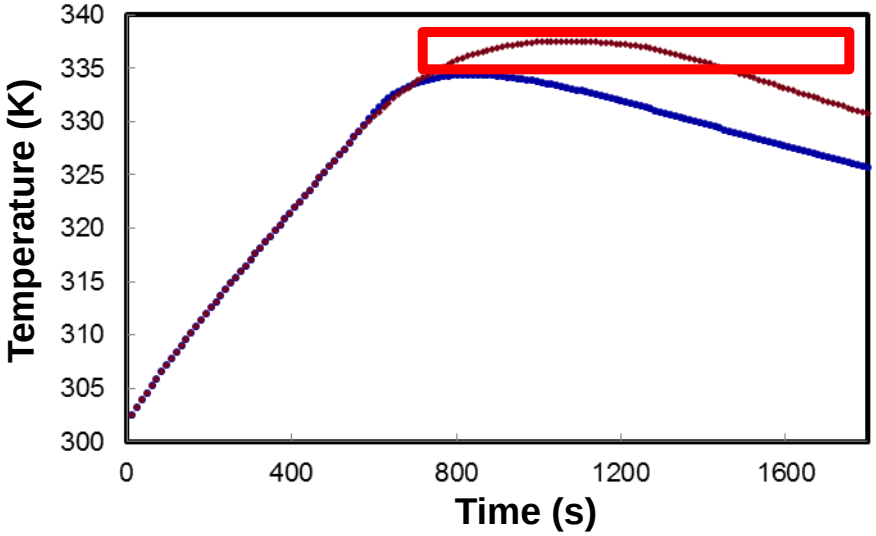
Is avoiding plating enough?









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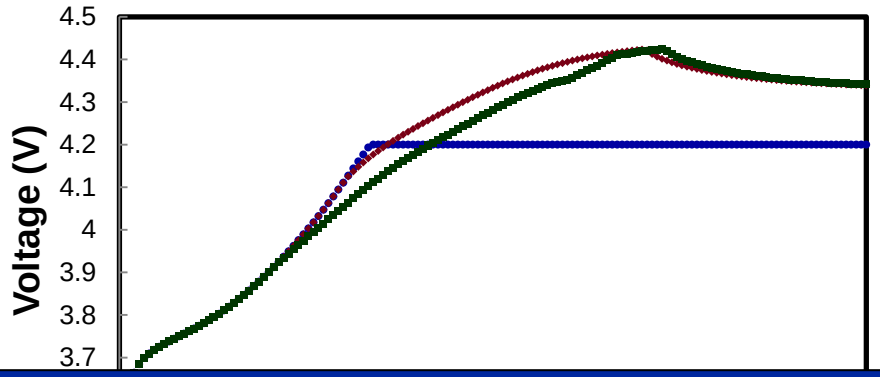
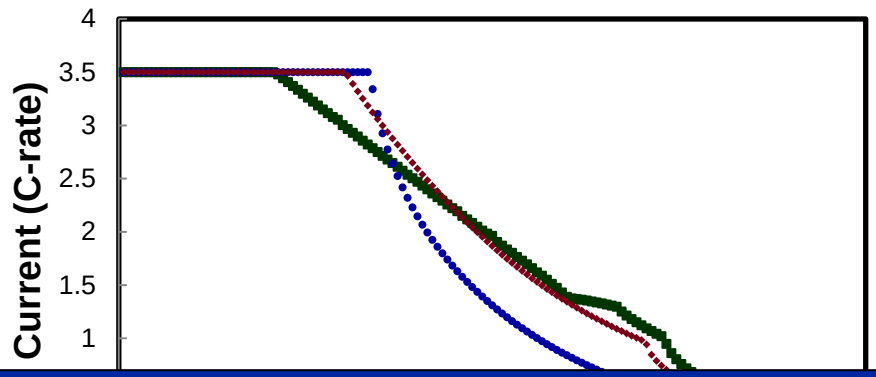
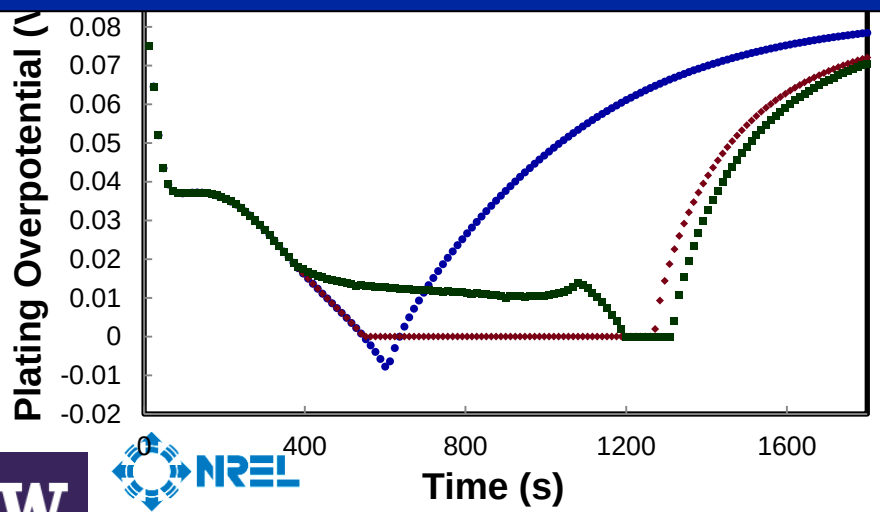
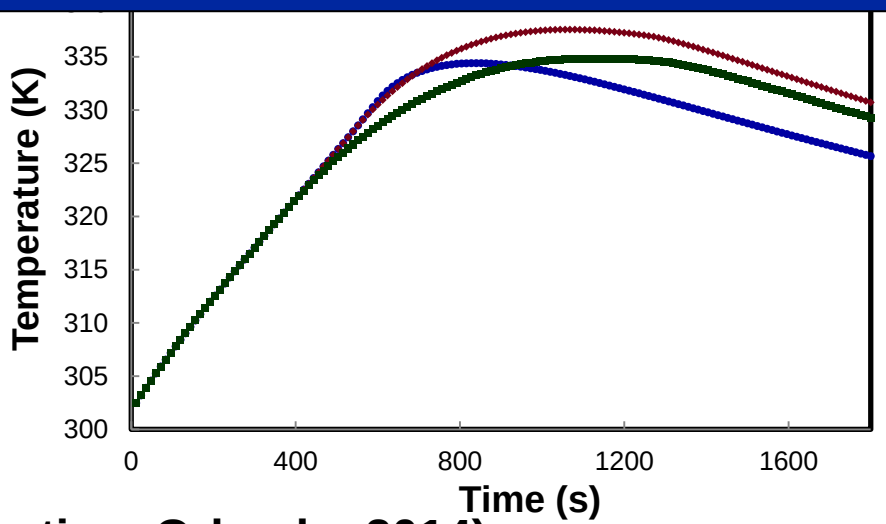
Determining optimal charge profile





Optimal fast charge yields 10.5% increase in SOC with no lithium plating or effects from temperature rise





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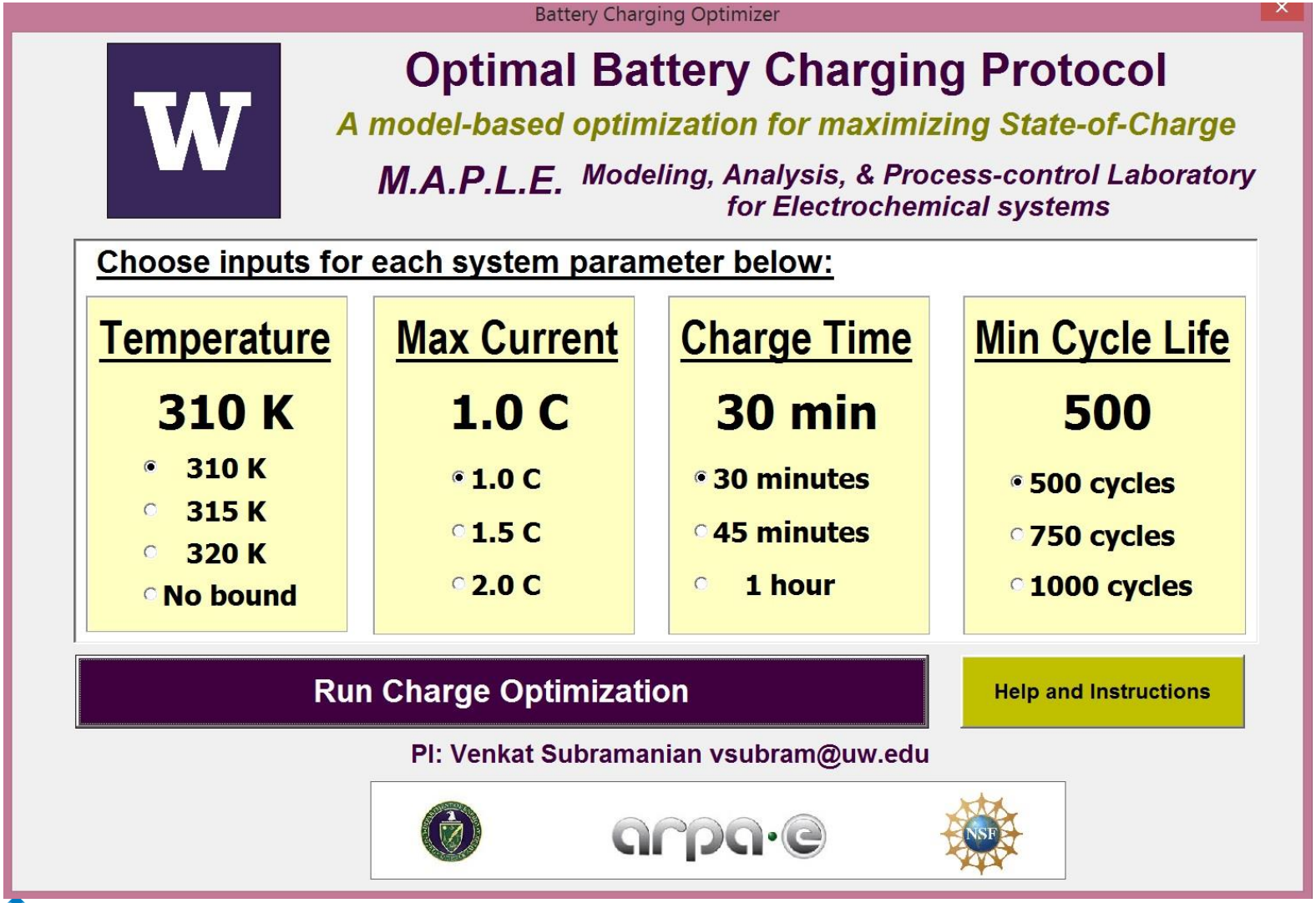
(B. Suthar+, ECS meeting, Orlando, 2014)

User Interface



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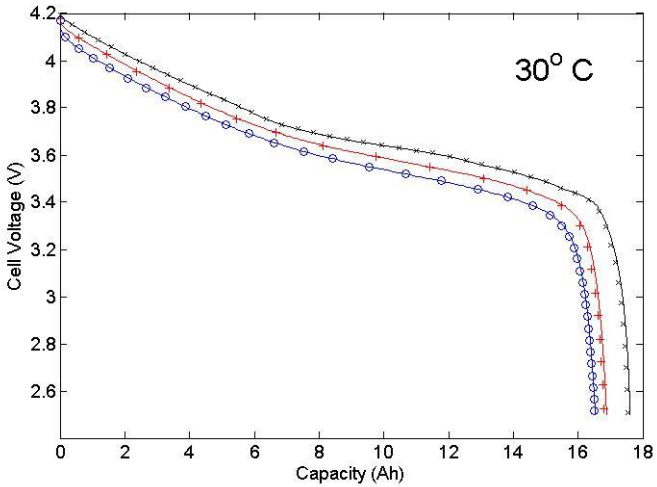
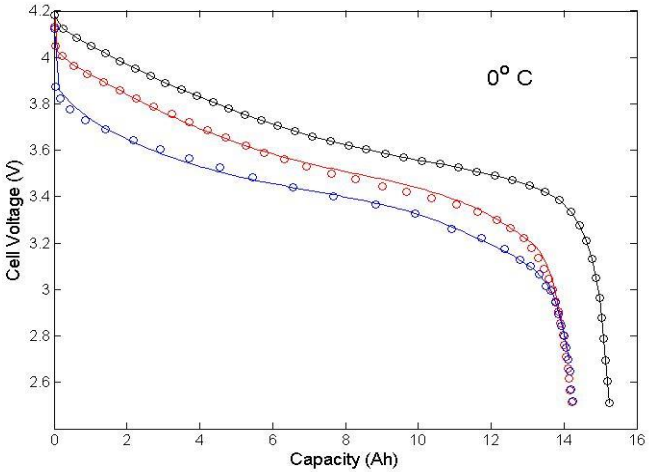
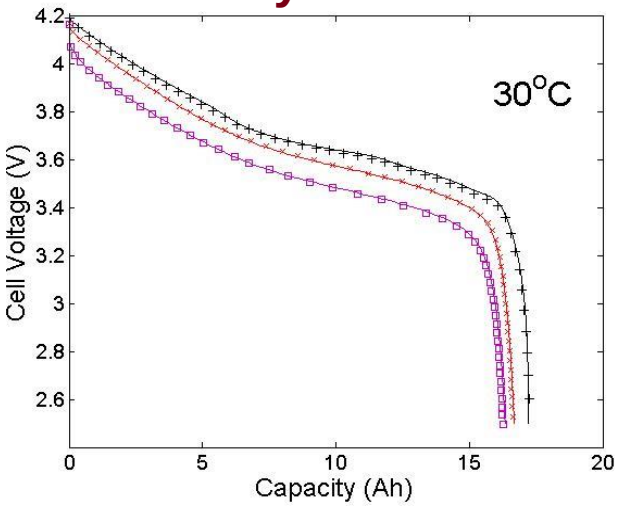
Model Vs Data (Case 0)

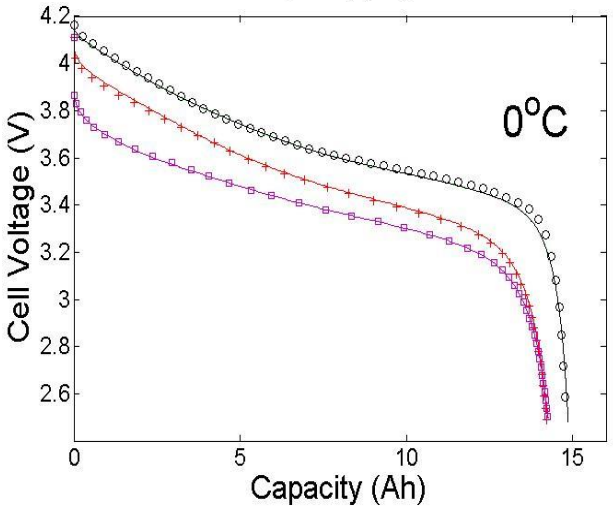
Fresh Cells





Cycled Cells





- Capacity check between 4.2 and 2.5 V
- 0.1C to 3C rate discharge

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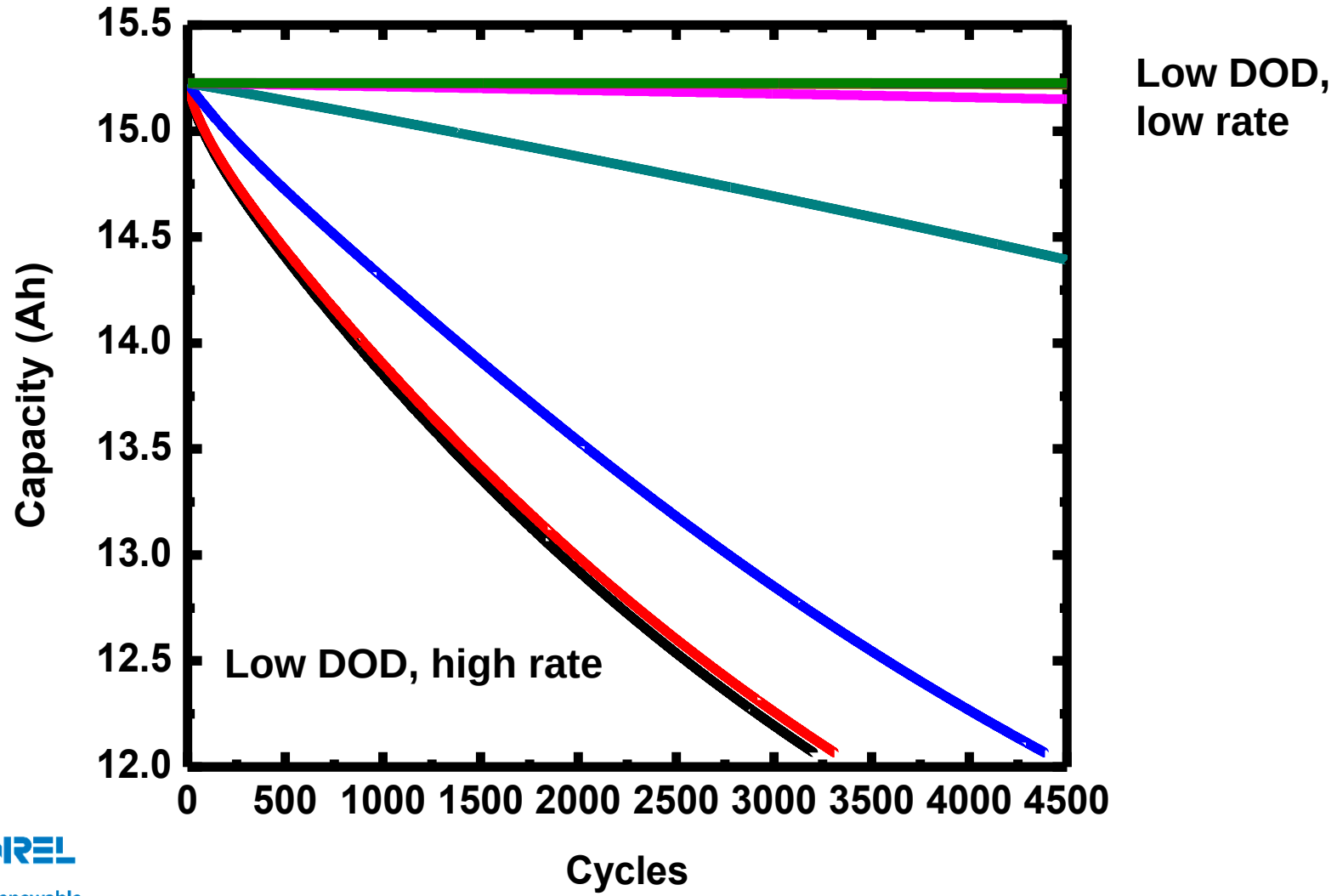
Life prediction (Best case, room temp)



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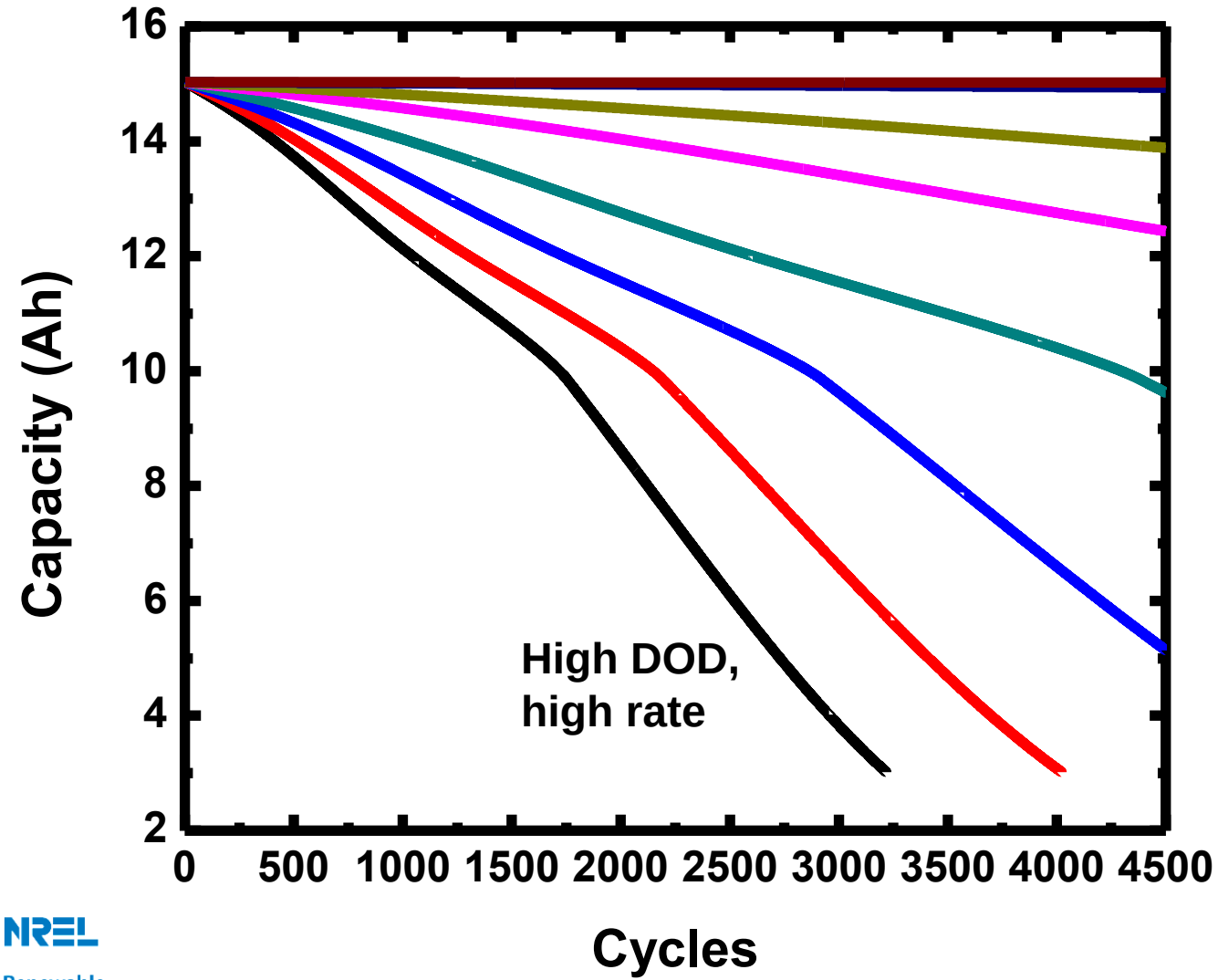
Life prediction (all scenarios)



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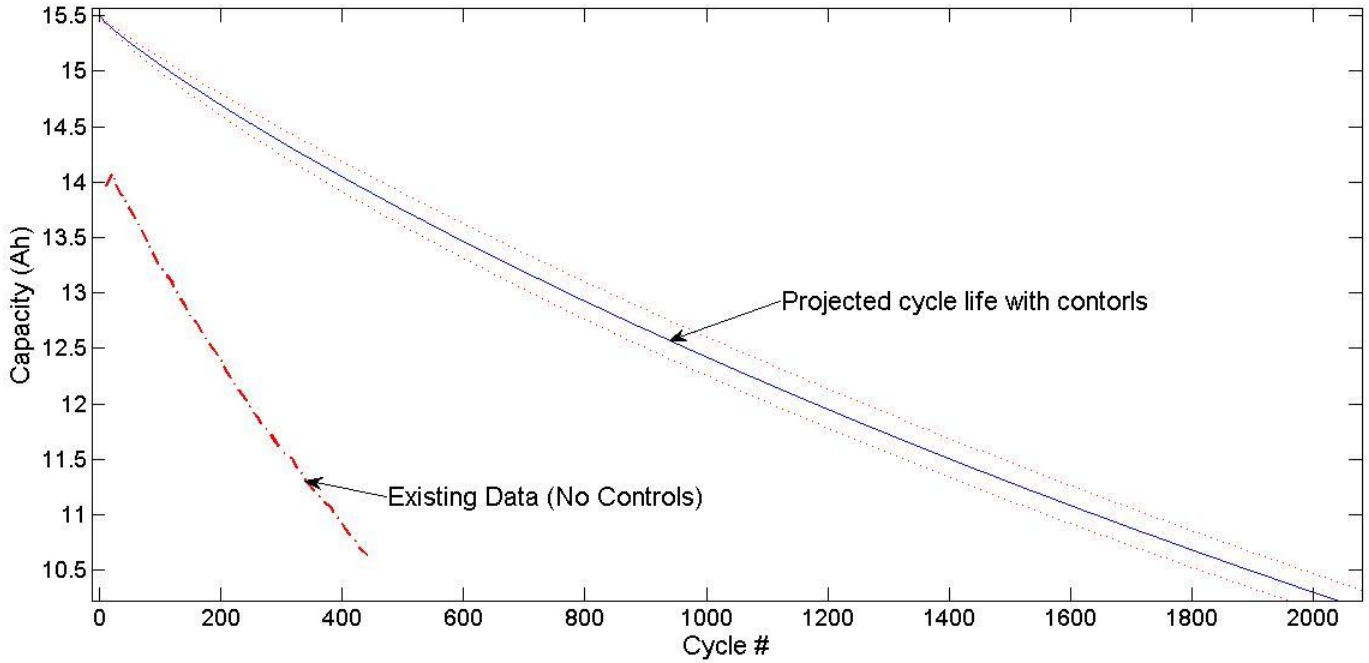
Extending Operational Window



- **During 2C charge/5C discharge at 0 deg. C, the cell capacity drops to less than target usable capacity within 500 cycles.**
- **MPC will enable longer cycle life.**

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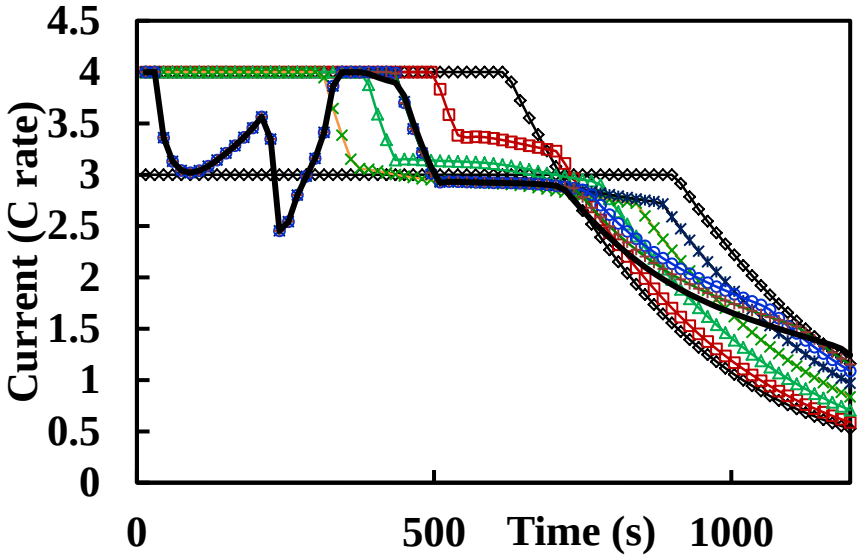
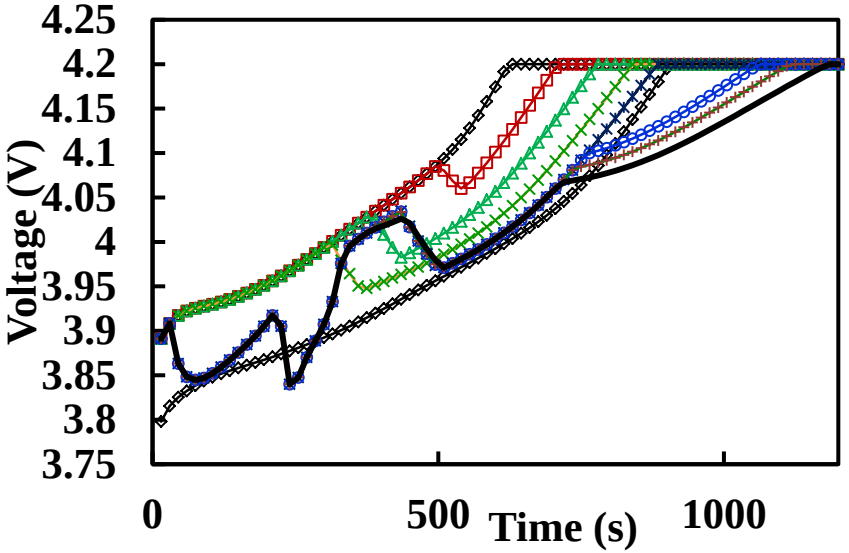
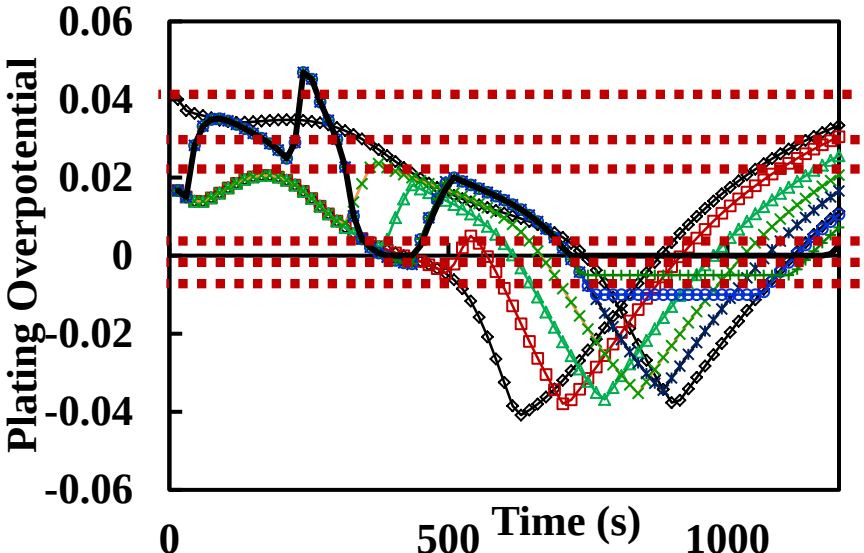
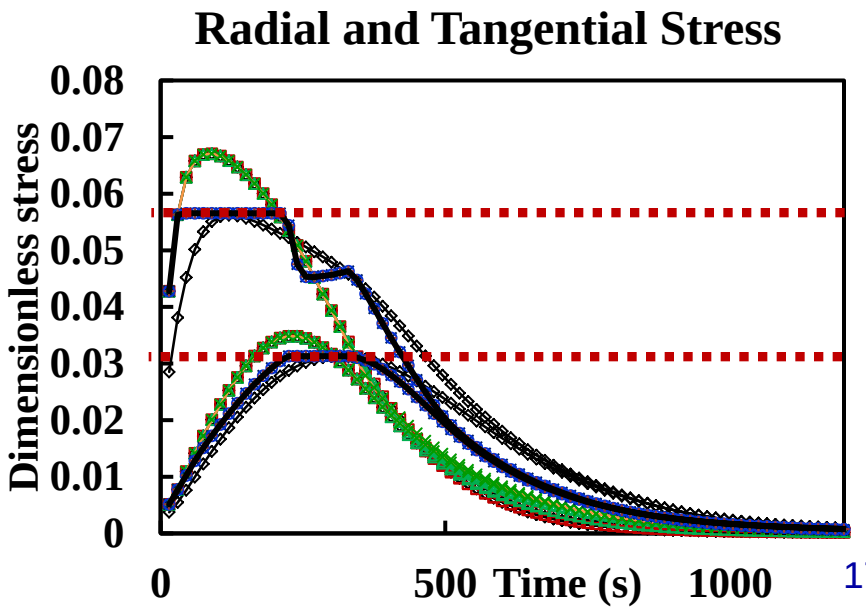
Optimal charging profiles – for newer materials









Publications and Codes

- Lawder, M., et al. "Model-Based SEI Layer Growth and Capacity Fade Analysis for EV and PHEV Batteries and Drive Cycles" *J. Electrochem. Soc.*, 161(14), A2099-A2108 (2014)

- Northrop, P.W.C., et al. "Efficient Simulation and Reformulation of Lithium-Ion Battery Models for enabling Electric Transportation" *J. Electrochem. Soc.*, 161(8), E3149-E3157 (2013)

- Suthar, B., et al. "Optimal Charging Profiles with Minimal Intercalation-Induced Stresses for Lithium-Ion Batteries Using Reformulated Pseudo 2-Dimensional Models" *J. Electrochem. Soc.*, 161(11), F3144-F3155 (2014)

- Code for *optimally* charging batteries and GUI for battery optimization are available at www.depts.washington.edu/maple