Control Enabling Solutions with Ultrathin Strain and Temperature Sensor System for Reduced Battery Life Cycle Cost

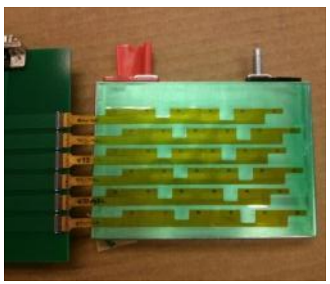
2015 Annual Meeting – Open Session

April 1, 2015

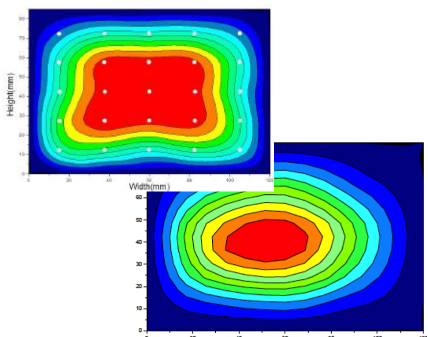
Imagination at work.

Program Overview

Develop Sensors → Characterize Cells → Multi-Physics Models → Data & Model Fusion → Pack Integration & Validation

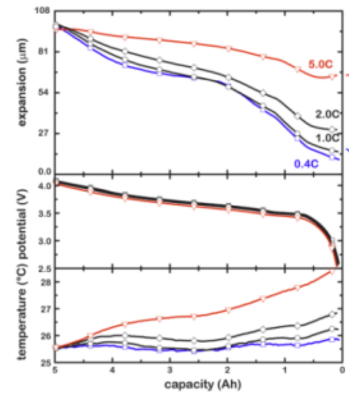


Ultra-thin Temp & Expansion Sensor Development

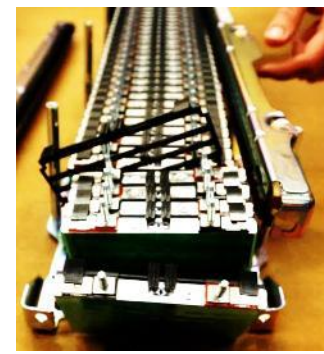


Swelling due Li-Intercalation (top) & Thermal Expansion (bottom)

Thermal
Electrochemical
Mechanical



Observability Integration & Controls Development



Estimation / Limits

- State of Power
- State of Charge
- State of Health

Multi-parameter in-situ cell monitoring to increase operating window and improve SOH

Team

Aaron Knobloch - Principal Investigator
Jason Karp
Chris Kapusta
Yuri Plotnikov
David Lin

Brian Engle – Automotive Vertical Ldr
Rob Twiney – GM Advanced Sensors
Dave Geer – Principal Engineer
Dave Villella – Test Engineer
Ron Martonik – Product Manager

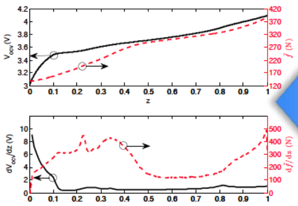
Amphenol

Anna Stefanopoulou – Michigan Lead
Jason Siegel
Bogdan Epureanu
Charles Monroe
Krishna Garikipati
Nassim Samad
Ki Yong Oh
Howie Chu
Zhenlin Wang

Dyche Anderson – Ford Lead
Arnold Mensah-Brown
Ramzi Chraim
Tommy Coupar
Xinfan Lin
Bruce Blakemore

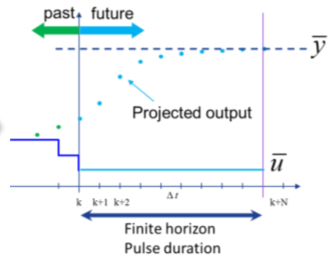
Program Summary & value Proposition

Expected System Benefit

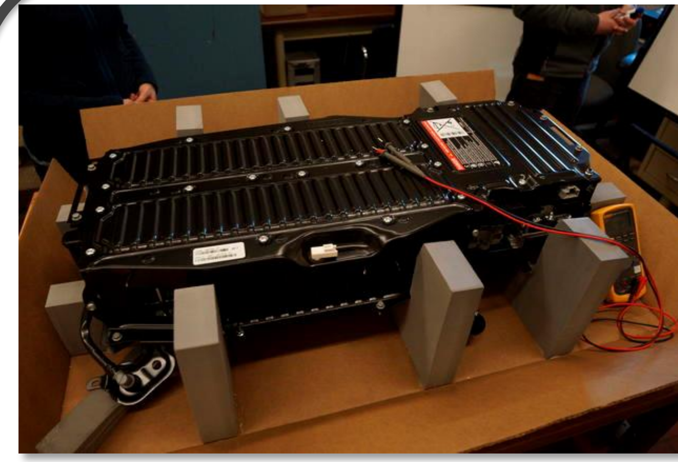


Estimation

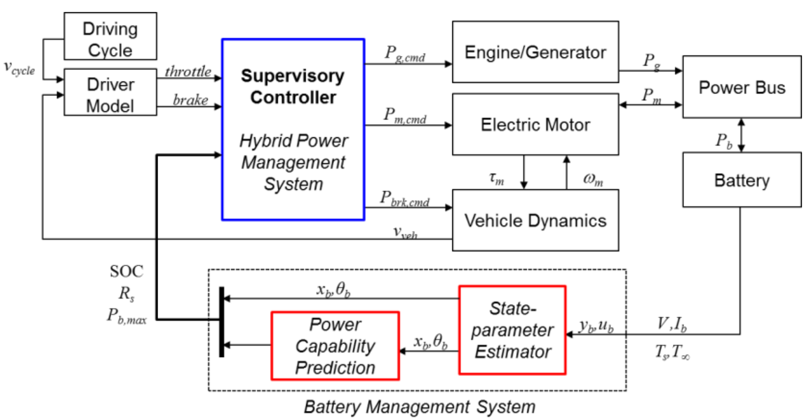
Temp & Expansion Sensor



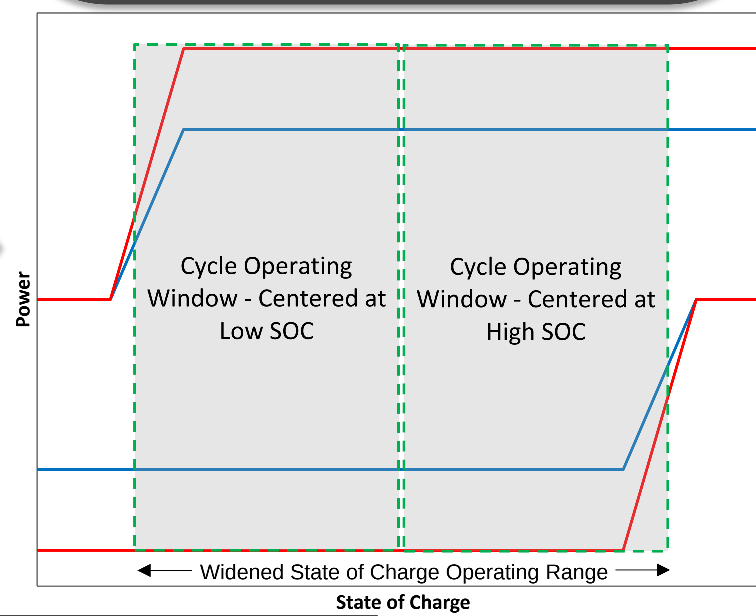
Prediction



20% Reduction in pack size while maintaining life at higher throughput



Real-time Dynamic Model-based Power Limits



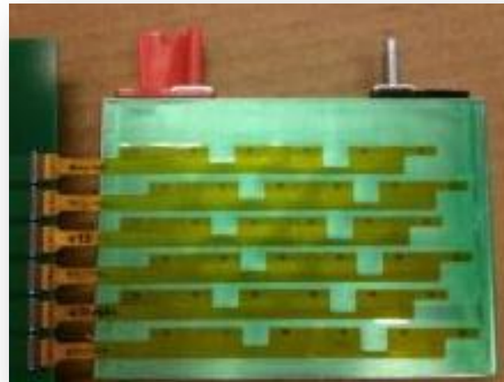
Test Case – 5 Amp-hr Panasonic Cell for HEV Applications

Enabling Sensor Technologies

Benefits

Temperature

Thin film RTD
- Thin (<100μm) – locate anywhere on surface
- Develop arrays
- Accuracy
- Time response
- Enables lower cost battery packaging

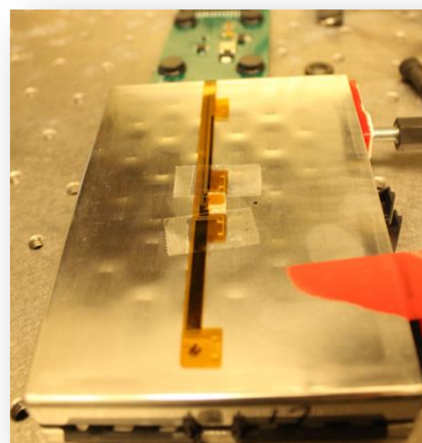


36 point Temperature Array

Leverages high volume, low cost Flex manufacturing

Expansion

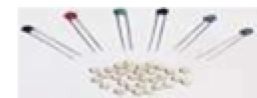
Eddy Current
- Not able to measure expansion today
- Small / cost effective
- Can measure between cells
- Potential correlation to battery health, SOC, …



Integrated Expansion & Temperature Sensor

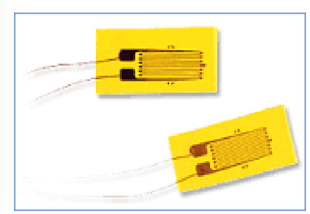
Competitive Technologies

Thermistors
- Thick (>1mm)
- Limited locations
- Slower
- Lower accuracy
- Higher installation costs



Strain Gages:
- Drift, low signal level
- Temp effects

Load Cells:
- Thick (>1/4")
- Not cell specific

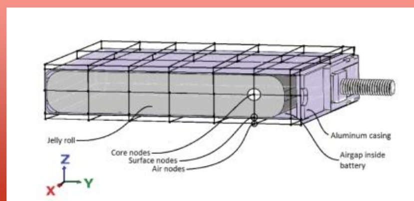


Fusion of Sensor Data and Models

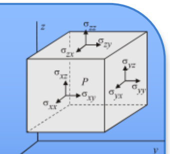
T

T ε, ϵ

Thermal

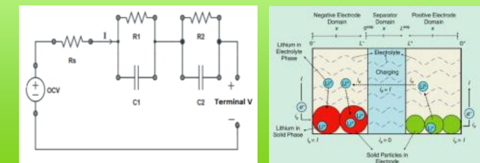


Mechanical

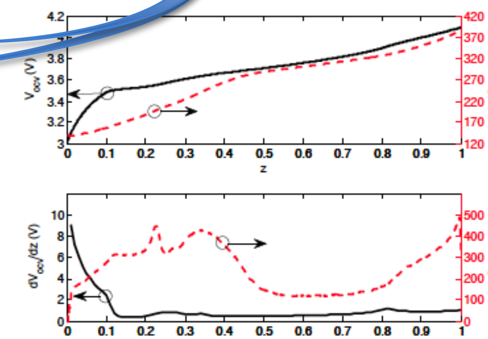


-Thermal and Intercalation swelling, sensor response, and porosity change.

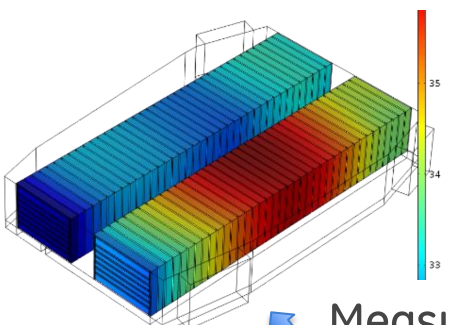
Electrochemical (ECM or DFN)



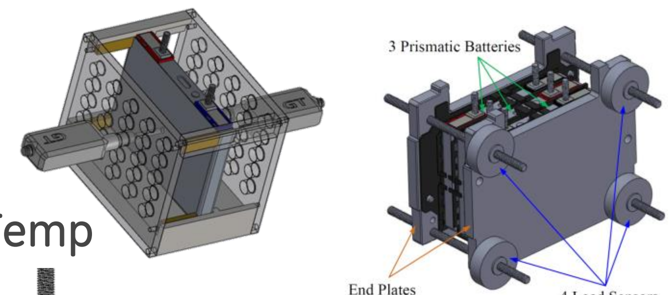
SOC



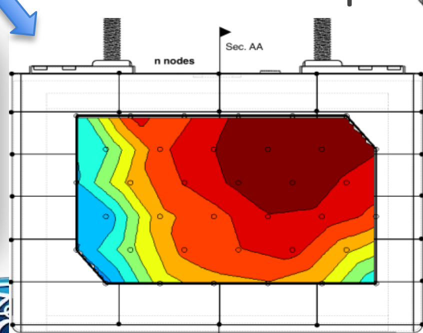
Modeled Pack Temp

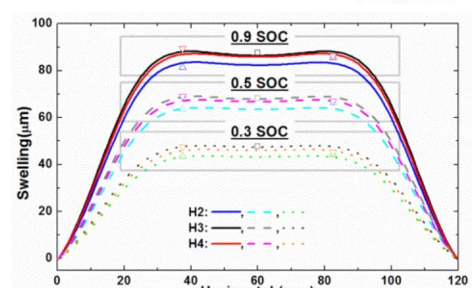


Free and Constrained Swelling

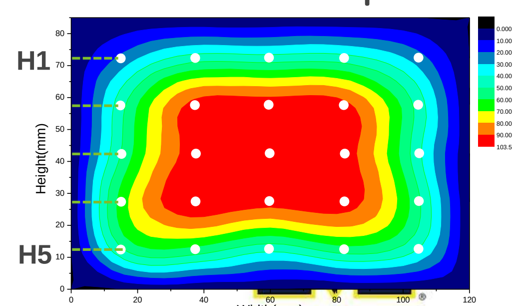


Measured Temp





Enhanced SOC Estimation with Measured Expansion



Model Based Power Limit

Prediction

Linear Discrete Time Model

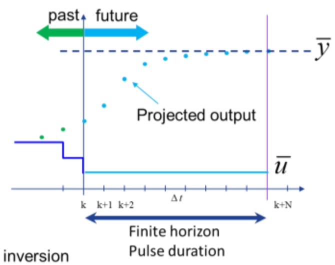
$$x_{k+1} = Ax_k + Bu_k + E$$
$$y_k = Cx_k + Du_k + F$$

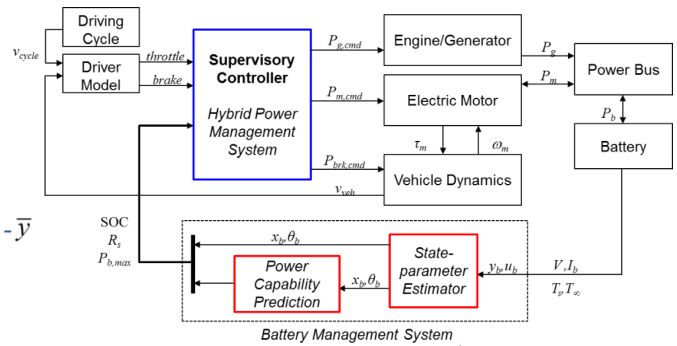
For a constant input $\bar{u}$,

$$x_{k+N} = A^N x_k + \sum_{i=0}^{N-1} A^i B\bar{u} + \sum_{i=0}^{N-1} A^i E$$
$$y_{k+N} = Cx_{k+N} + D\bar{u} + F$$

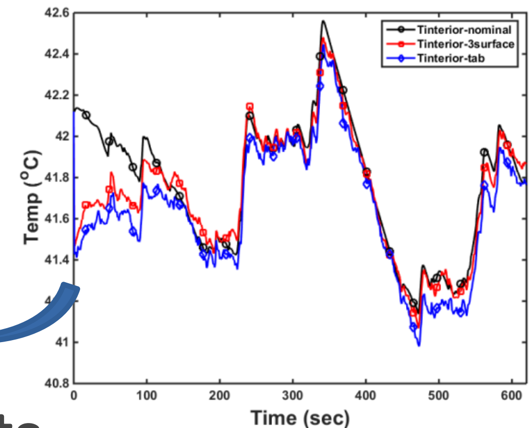
Maximum permissible input via model inversion

$$\bar{u} = \left(\sum_{i=0}^{N-1} CA^i B + D\right)^{-1} \left(\bar{y} - CA^N x_k - \sum_{i=0}^{N-1} CA^i E - F\right)$$

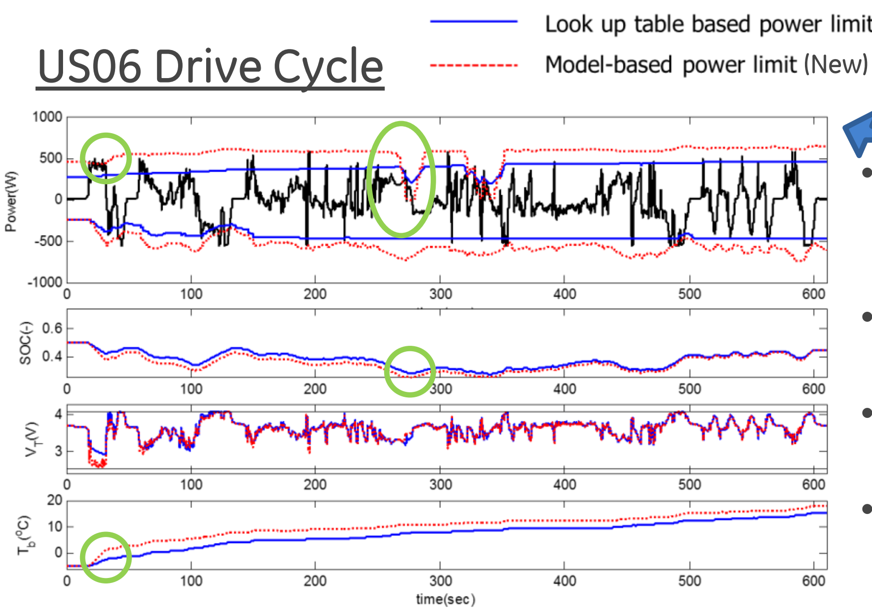




Estimation



US06 Drive Cycle

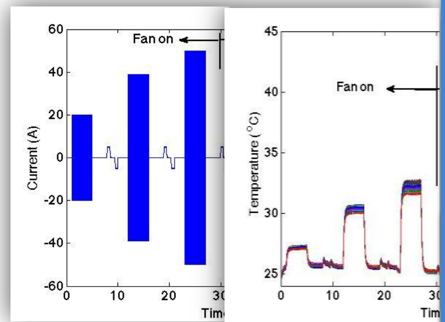


Benefits

- Improved battery core temperature estimation using thin film temperature sensor -> 2 minute faster convergence rate.
- Model based power limiting strategy enables faster warmup to full power, and wider SOC operation.
- Dynamic power limits can be more conservative when necessary for health and safety.
- At low temperatures (-5°C), battery utilization (Whr throughput per cell) can be increased up to 26%.

Key Learnings & Results

Electro-Thermal Model Validation



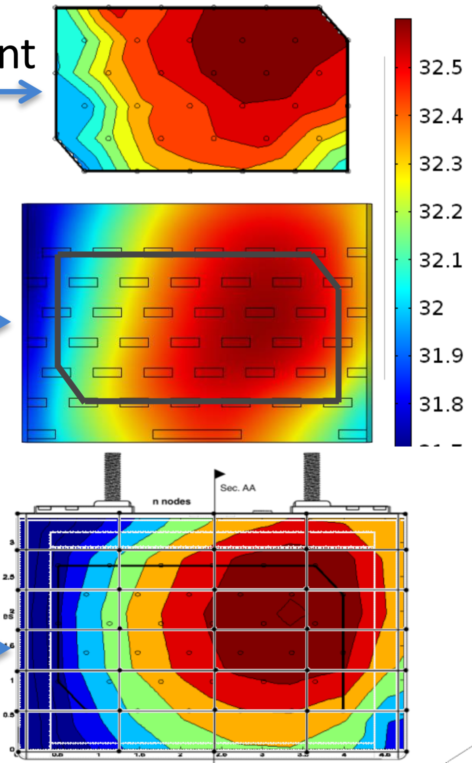
Charge sustaining pulses

- **20, 39, 50A**
- **Fan on, fan off**

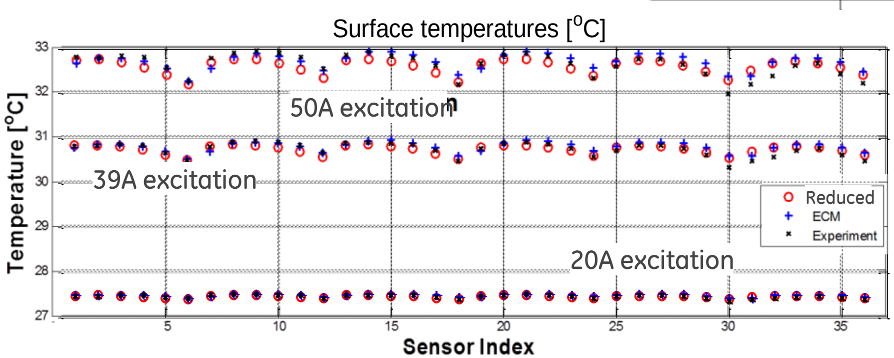
Experiment

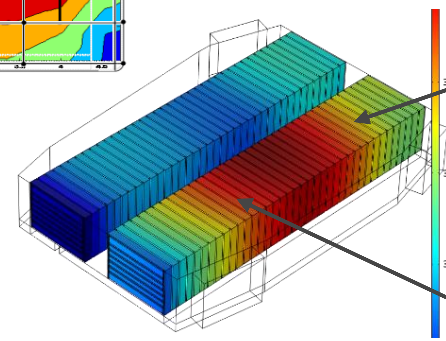
Comsol

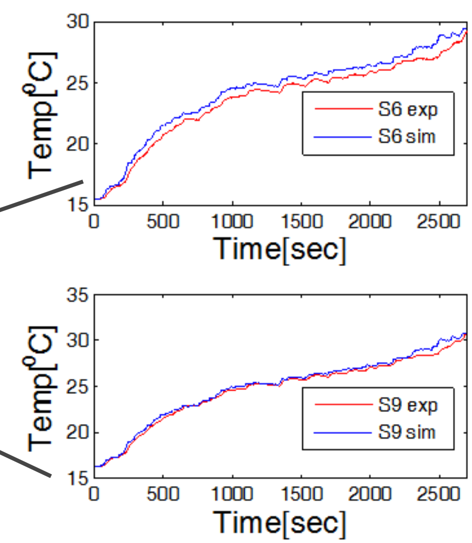
Reduced TEM



- Performed observability analysis for optimal sensor placement.
- Thin film sensor enables faster core temp estimation over existing measurement location (side vs top of cell)
- Less than 2°C modeling error in pack cell temperature predictions over a 35°C operating range





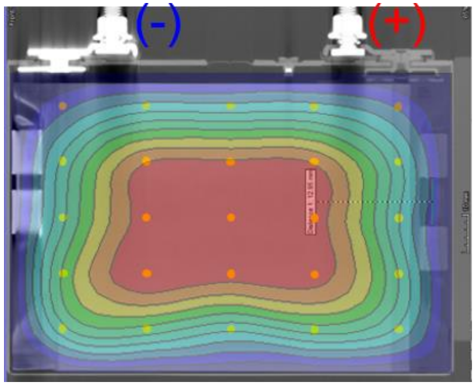


Finite element and reduced order pack models validated against vehicle drive cycle data.

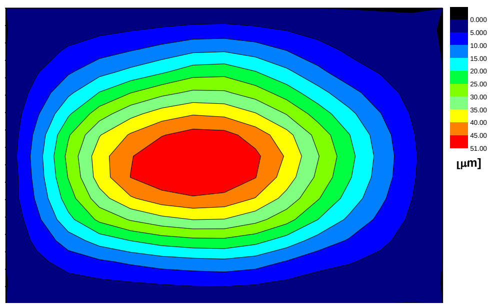
Samad, N., e.t. al. DSCC 2014-6321, 2014.

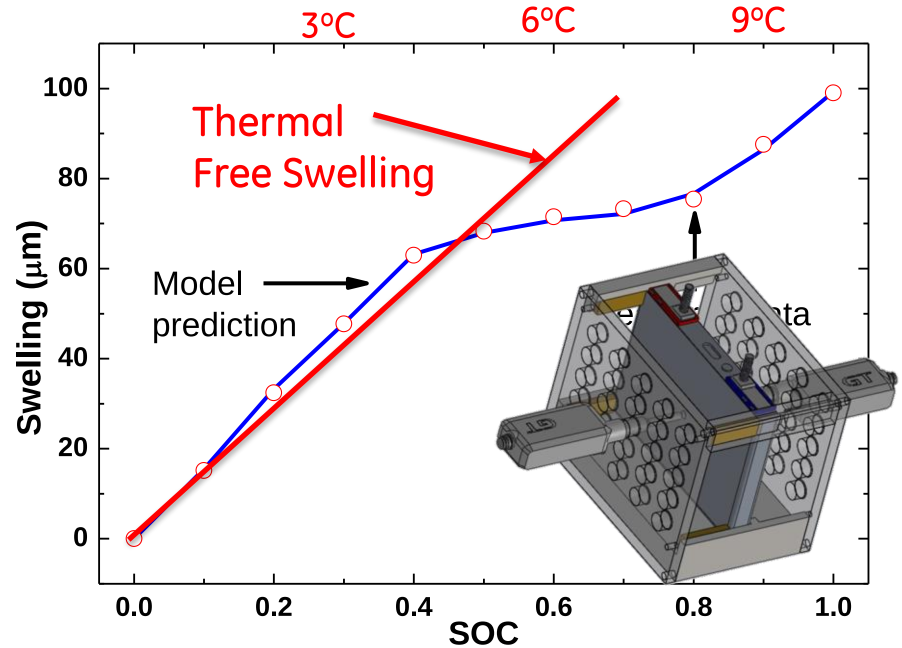
Swelling (Free)

Li Intercalation Swelling

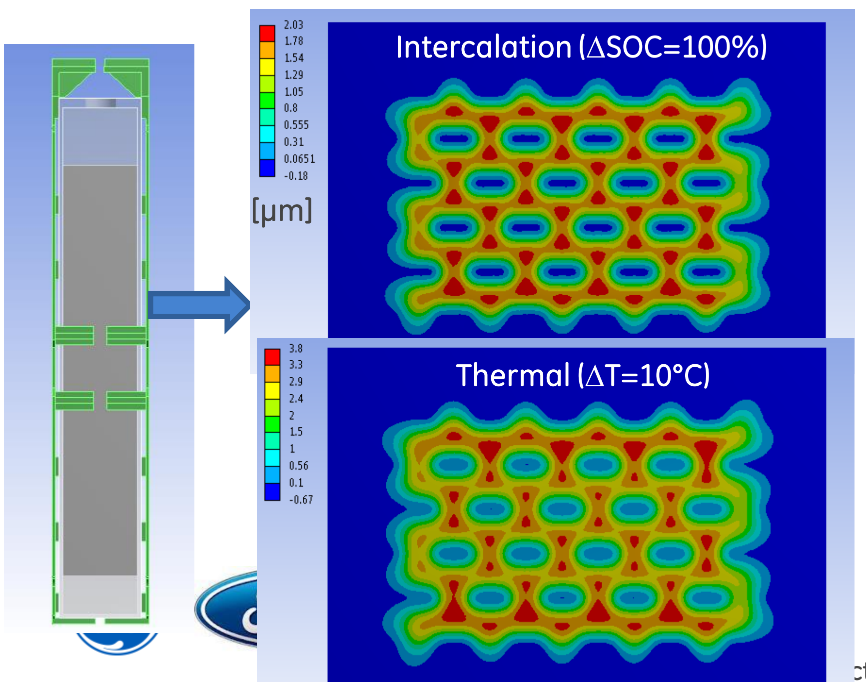


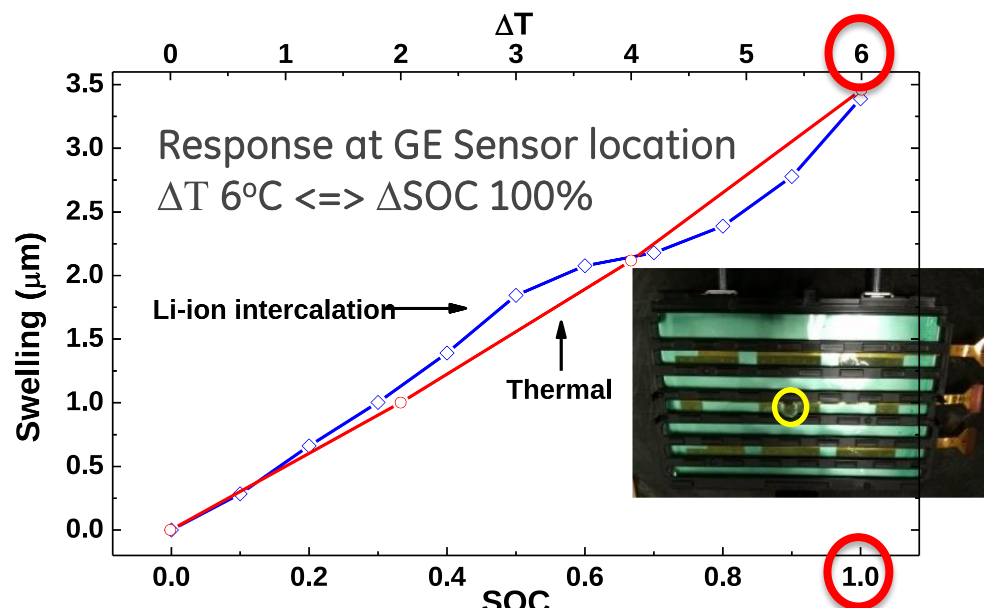
Thermal Swelling





Swelling (Constrained)



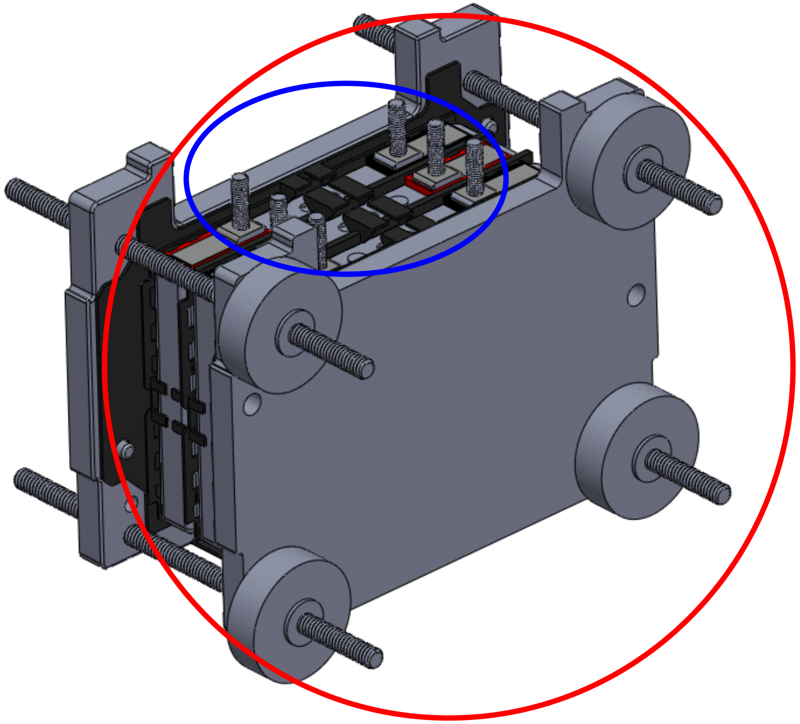


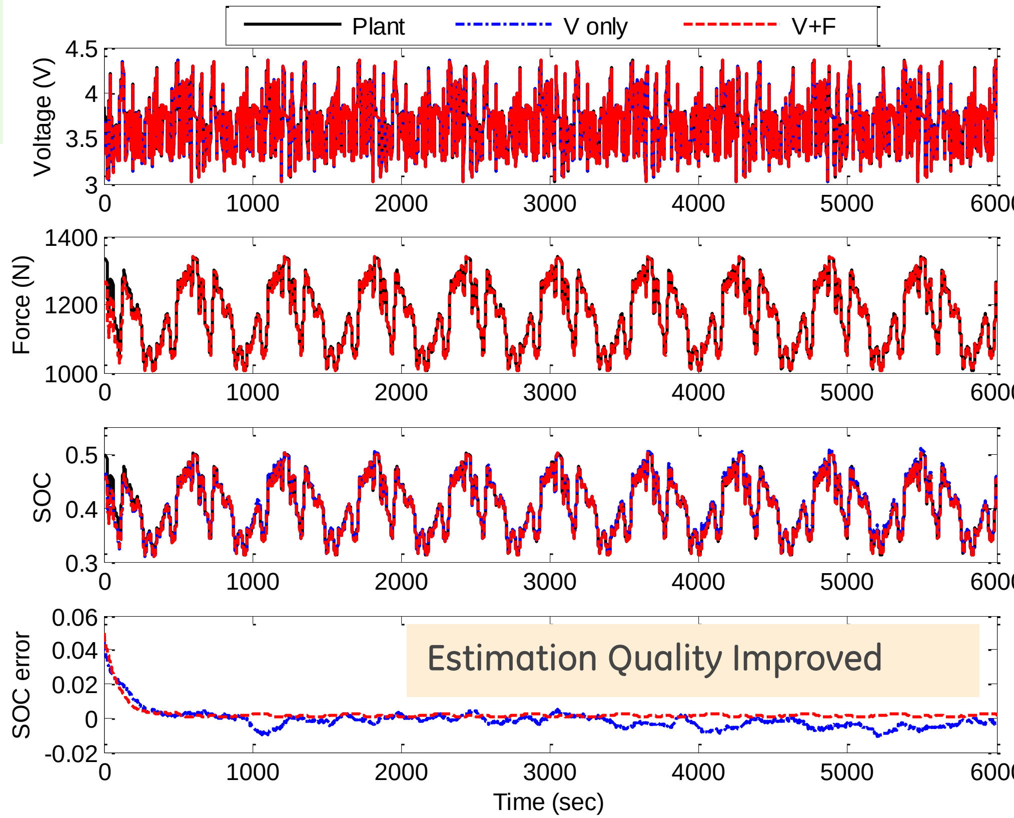
MICHIGAN

Oh, e.t. al. *J. Power Sources*, 267(0):197 - 202, 2014.

SOC Estimation

The relation among temperature, SOC, current and force enables the use of measured for in SOC estimation.



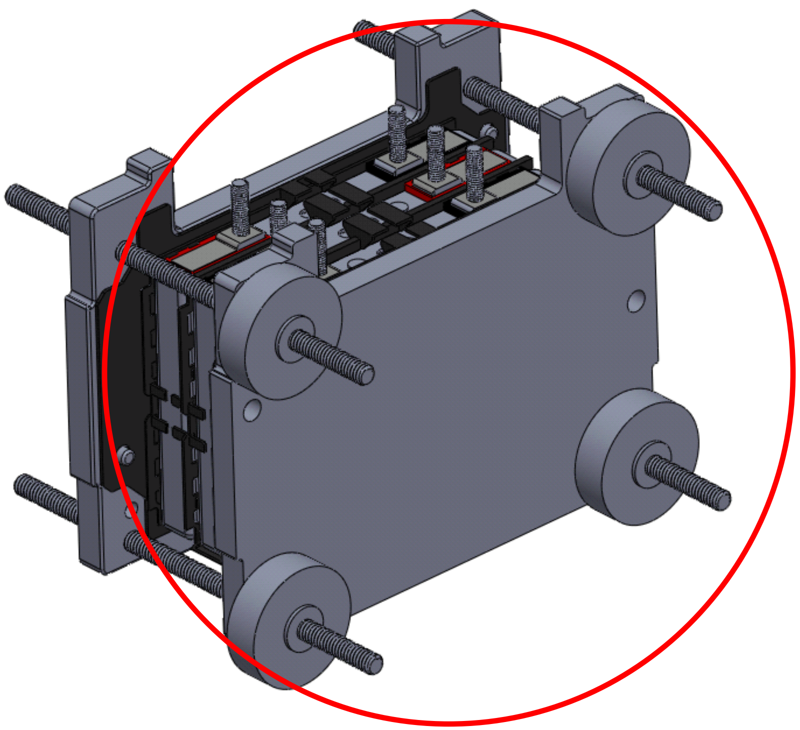


Mohan S., e.t. al. *DSCC 2015*, in preparation

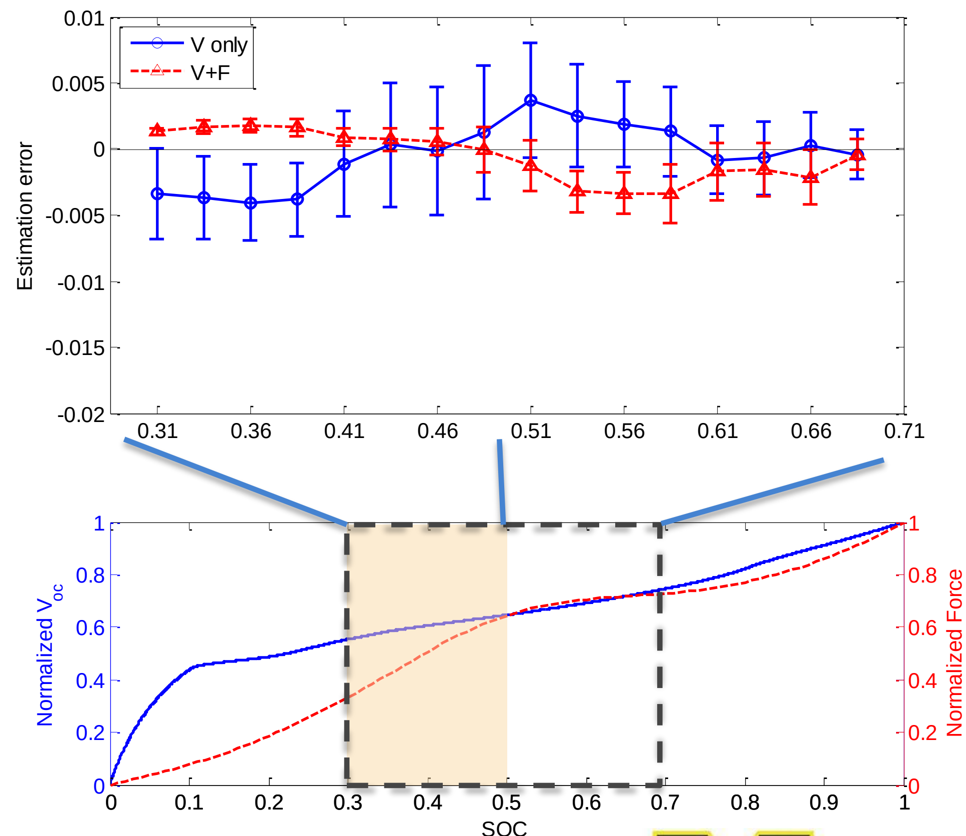
U.S. Utility Patent Application No. 62/043,519

SOC Estimation

The relation among temperature, SOC, current and force enables the use of measured for in SOC estimation.



Estimation quality improved by a adding force measurement - more prominent in SOC range between 30~50%



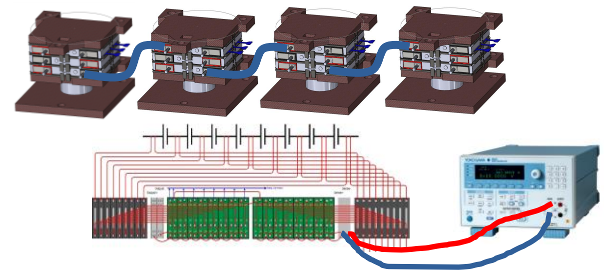
Mohan S., e.t. al. *DSCC 2015*, in preparation

U.S. Utility Patent Application No. 62/043,519

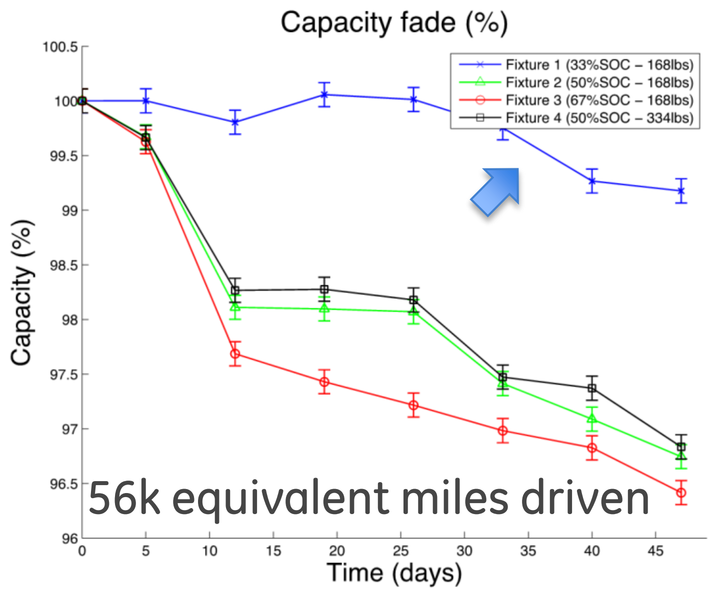
3-Cell Degradation Testing

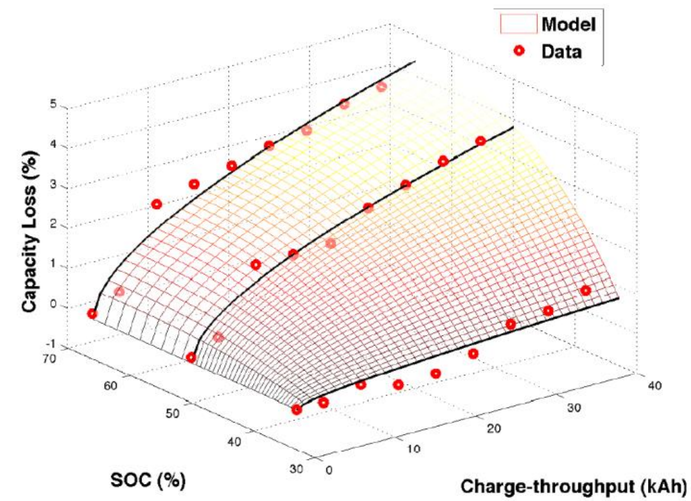
- Established baseline degradation
  - 25°C cell temperature (-10°C ambient air)
- Open loop US06 power profile, no controls (yet).

33% 50% 66% 50% SOC high preload



<u>Using 3-fixtures to assess capacity loss</u>





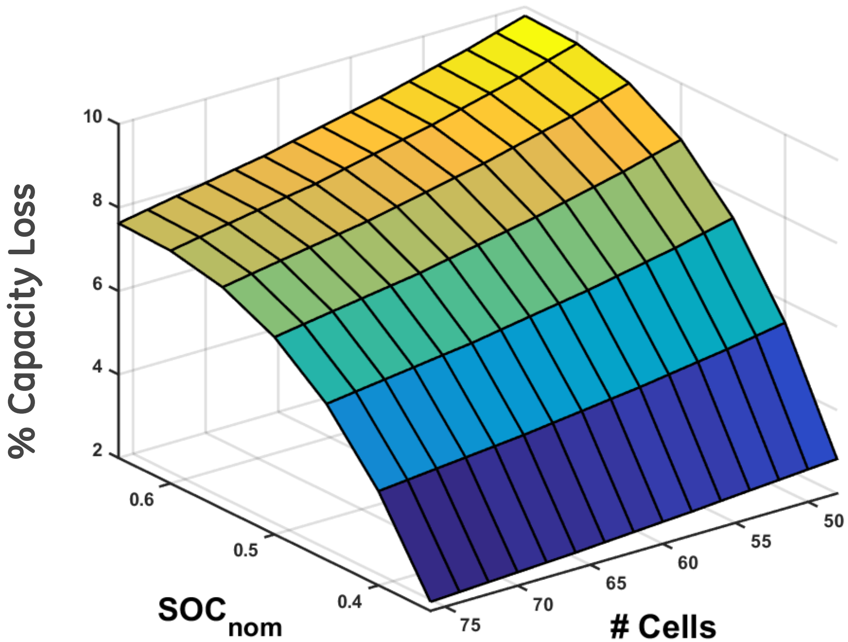
$$S_{loss}(Ah) = \alpha_c + \gamma_c(0.66 - SOC_0)^c \cdot Ah^z$$

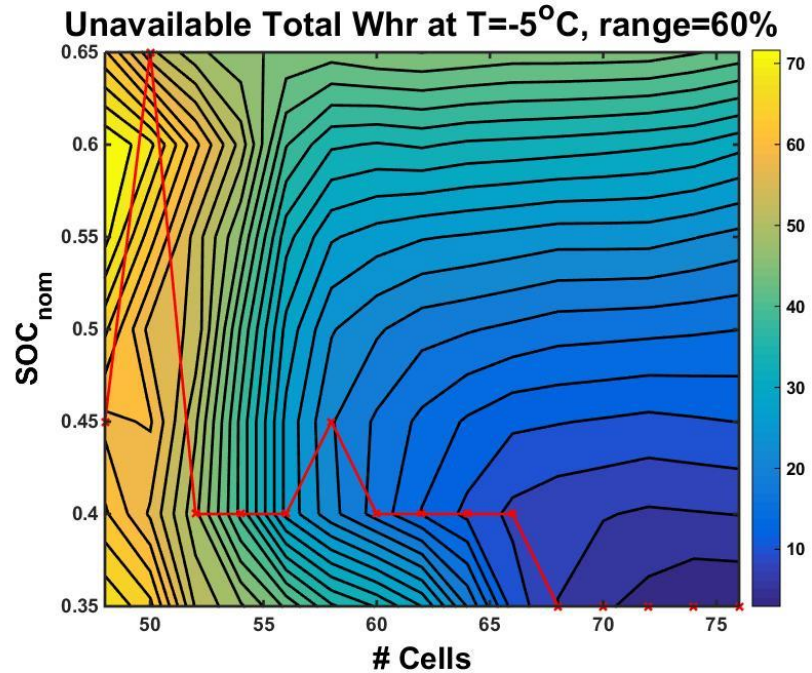
- Conclusion: Lower capacity loss at lower SOC.
- Next steps: compare degradation effects for closed loop power limiting and wider SOC window on downsized pack.

Power Limits, Downsizing, and Degradation

- Shift to lower SOC operation for reduced degradation and more charge acceptance (regen braking) at -5°C.

Projected capacity fade at 150k miles using model based power limit



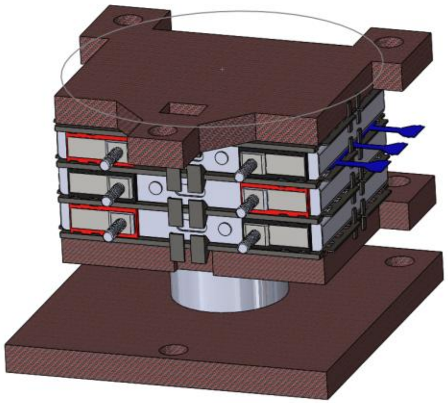


$$S_{loss}(Ah) = \alpha_c + \gamma_c(0.66 - SOC_0)^c \cdot Ah^z$$

# of times algorithm would limit power deliver/acceptance, i.e. Energy left on the table <==> FE.

Validation Plan & Performance Targets

Status of Proof of Concept – Demonstration Pack



Baseline U-M 3 Cell Rig
56k miles
Complete Q1 2015

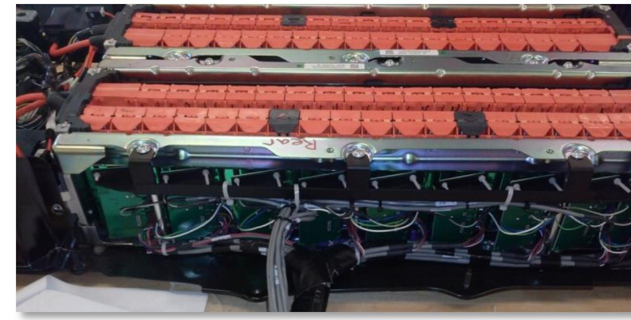
Verify model & control

- Hardware in the loop simulation
- Impact on degradation on validation conditions

Sensor-Pack Integration
Gen 1 Open Loop UM Model
Complete Q1 2015

Confirm functionality

- Verify sensor fit
- Test software / find bugs
- Confirm accuracy of model estimates

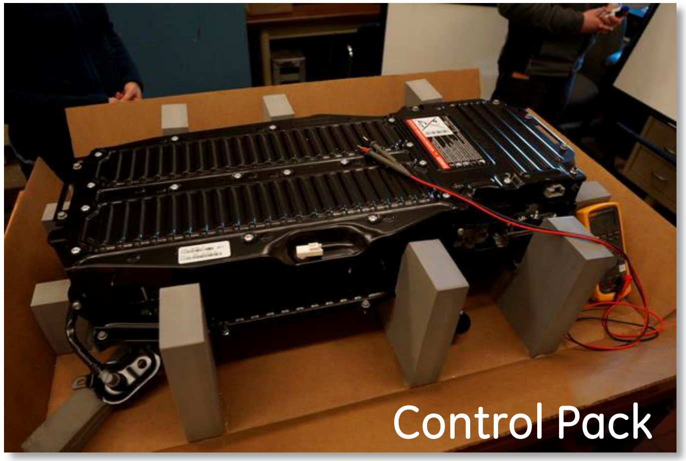


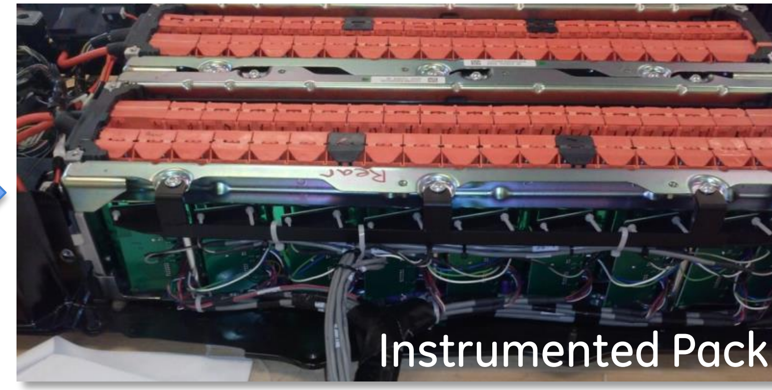
Developmental Pack Operation
Validate UM Testing & Simulation
Start Q2 2015

Operation

- Integration
- Examine target SOC window
- Sensor accuracy & perf
- Confirm accuracy of model estimates

Benefit Demonstration & Validation

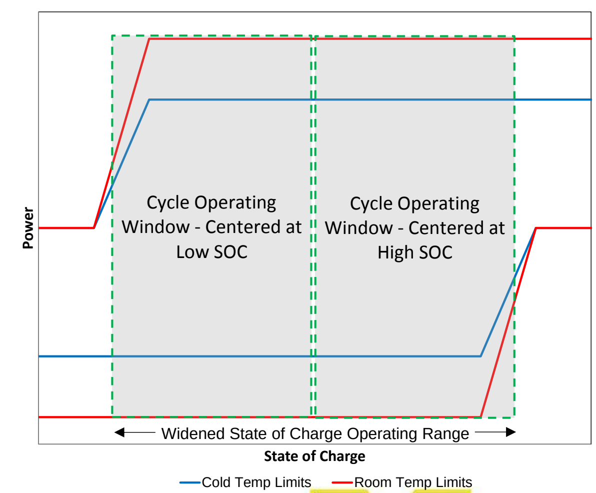




Ford Controls
Wider Operating Window

GE Sensors & UM Controls
Wider Operating Window

- Use existing test profiles, adjusting SOC ranges
  - Two cycles “high”, two cycles “low”
  - Adjust between cycles if significant drift in center point
- Run for c. 30,000 mi equivalent minimum
- Capacity & power tests every month – examine degradation

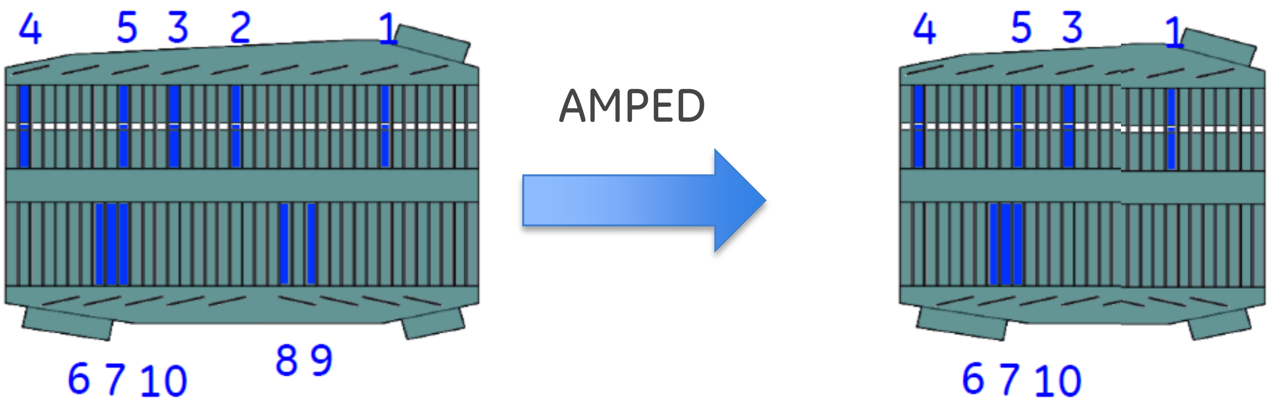


Expected Performance Benefits

- Improved state of charge and power capability estimation
- Improved power availability at low temperatures
- Pack may be downsized (fewer cells or smaller cells)

Full Pack (76 cells) – 2014MY

Reduced Pack (60 cells) same total power



Increased Utilization (Wh throughput per cell)

Cell Count Reduction	Cold (-5C)	+25C	Faster Warmup
-21%	+23%	+27%	105s *

*Results for scaled US06 battery power profile at 25°C.

Summary

Summary

- Proven
  - Temperature sensor + physics based model enables more accurate and faster (2x) prediction of core temperature
  - Developed SOC estimation based on force / expansion – more sensitive (in 30-50% SOC range) than typical voltage based measurements
  - Demonstrated integration of sensors & open loop control with Ford pack
  - Simulated validation performance based on improved state estimation
- Ongoing
  - Verify validation windows on 3 cell rig and developmental pack
  - Development of closed loop control with expansion/force input
  - Instrument and run validation pack to demonstrate benefit
- Challenges Addressed
  - Cell SOC estimation
  - SOH measurements / battery lifetime
  - Model to extract maximum power capability and throughput with long life

Program Next Steps

- Examining sensor performance on other cell types (soft pouch, larger size)
- Commercialization of sensors & model-based algorithms