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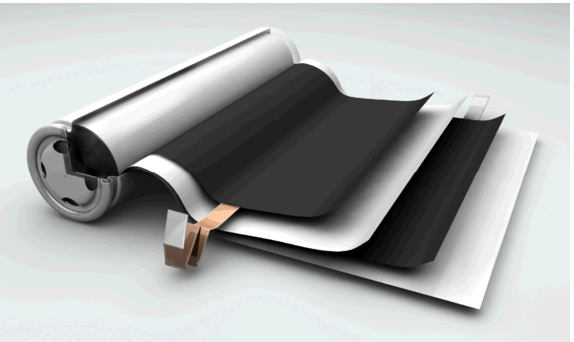

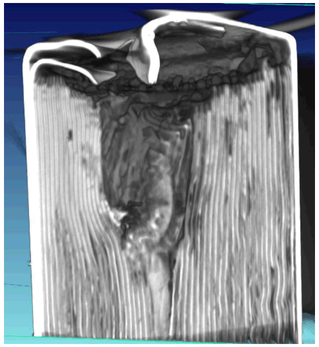

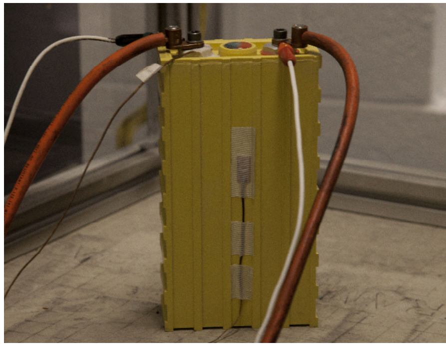

Advanced Diagnostic Tool Development

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Sandia National Laboratories

April 14, 2016

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Motivation

- ***Conventional battery management:***
  - *Measures battery **symptoms***
  - *May be **inadequate** to initiate the best response*
  - *Need for understanding **root causes** of performance or safety issues*
- ***Post-incidents scenarios***
  - ***Loss of communication** from physical damage*
  - *Hazards associated with **stranded stored energy***
  - ***Latency** of a defect or fault*
  - ***Cost and practicality** of analytical techniques*

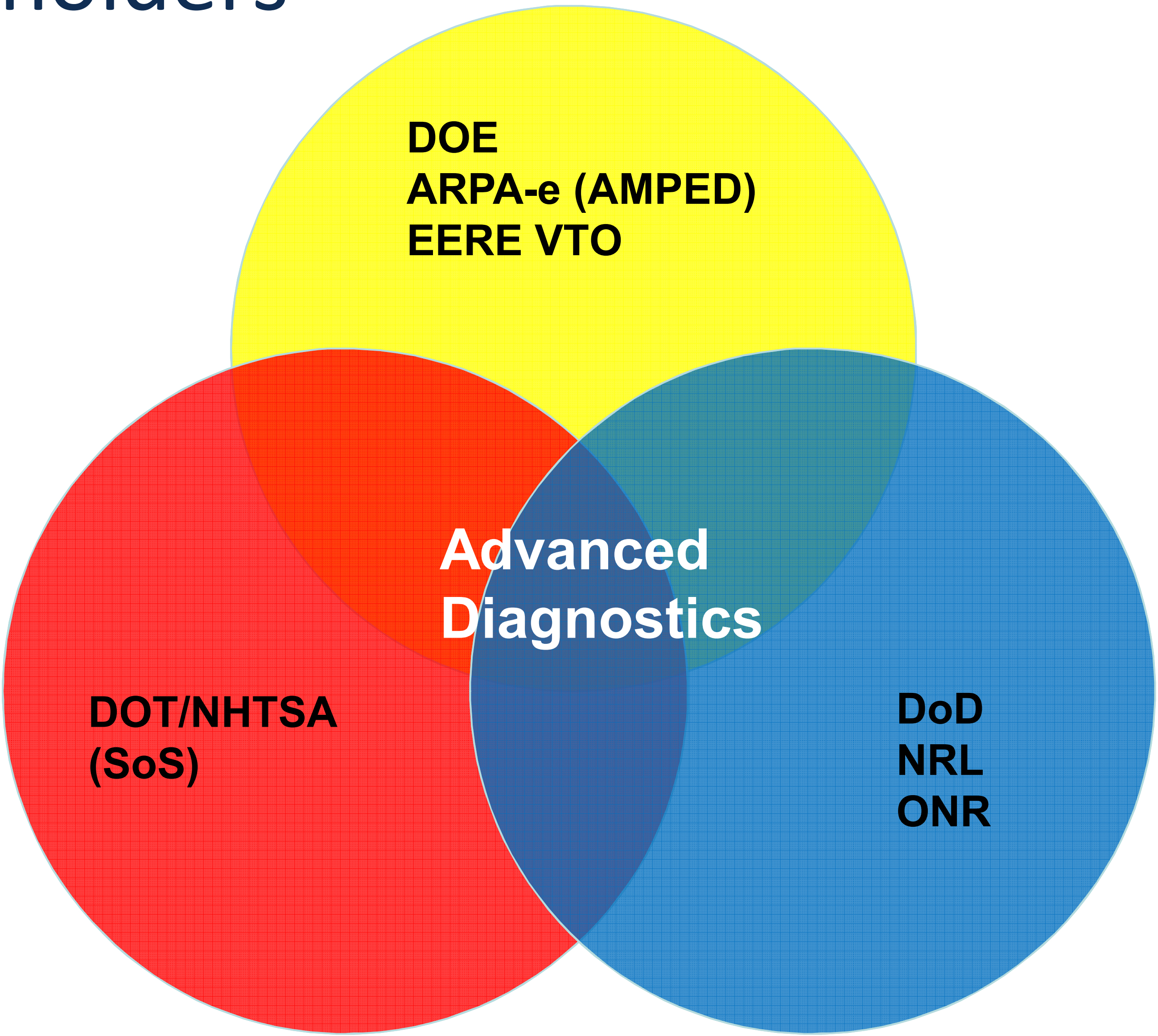
Objective Statement

Development and demonstration of on-board diagnostics to determine battery state of stability and trigger a battery control system response to eliminate a impending safety related failure issues

Drivers for Advanced Diagnostics

- DOT and DoD
  - Early detection of battery safety issues in electric vehicles, ship-board systems, and aircraft/aerospace buys down risk associated with high energy dense energy storage solutions
- DOE
  - Fundamental understanding of degradation mechanisms that lead to safety issues
  - Widespread adoption of safe, responsible energy storage solutions for electric vehicles
  - Disruptive technologies represent a new paradigm from traditional battery management to battery control systems

Stakeholders



Scope

- Technique Development
  - Sensitivity of the methods to cell abuse and performance fade
  - Data analysis to determine appropriate data indicators
  - Feasibility at the cell string level
  - Validating method to standard measurement performance
- Technology Demonstration Platform
  - Hardware/battery control architecture integration
  - Demonstration of performance
  - Modification to improve performance

Phase I Year 2 Milestones

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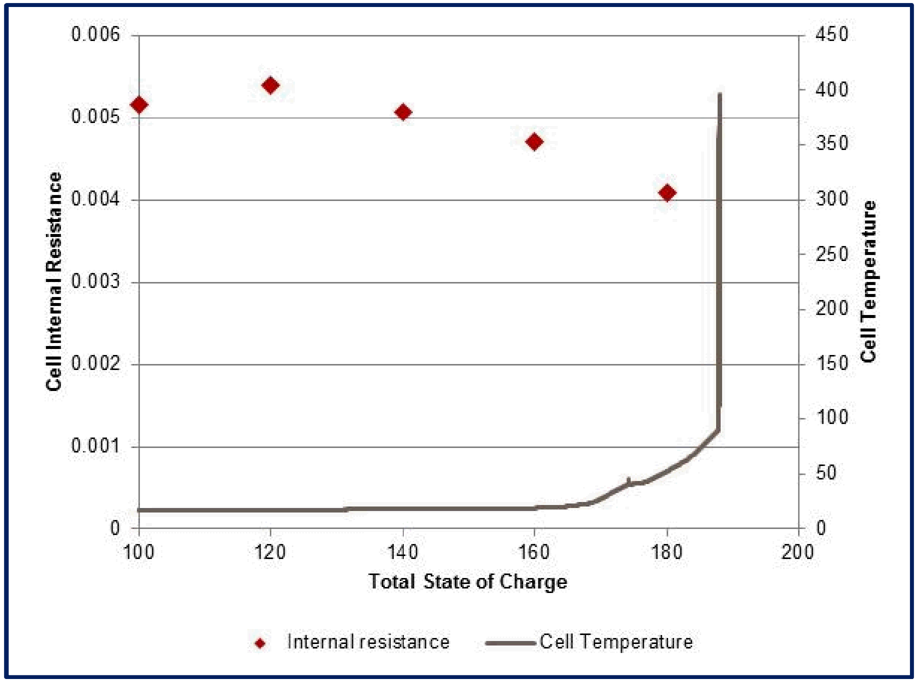
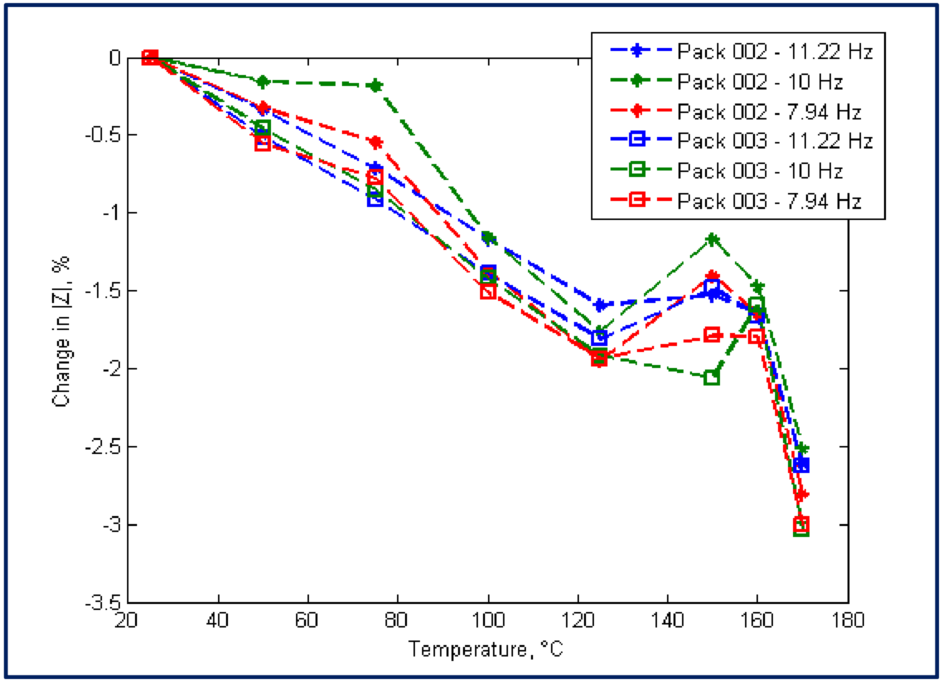
Objective	Milestone	Target	Adjusted	Completed
With the developed BMS from Year 1, initiate performance testing of module-level systems and, where feasible, incorporate under-load impedance measurements	Demonstration of module/BMS/rapid impedance performance on a battery platform (size TBD)	2/29/2015	4/30/2015‡	-On target for completion
Initiate under load measurements for overcharge abuse and comparison to earlier work under open circuit conditions. Optimization of "under load" impedance measurements based on experimental results.	Demonstration of electrical abuse testing batteries using the under-load rapid impedance hardware (without BMS). Interim progress reported at month 18.	3/30/2016	9/30/2016‡	
Develop a preliminary of stability model based on performance and abuse testing results using the rapid impedance measurement sensor and other relevant test data		9/30/2016		
Initial evaluation of other test methods most promising for follow on work	Provide written recommendations for other state of stability diagnostics that should be integrated into this tool set	9/30/2016		-Development of precision cuolometry underway
Go/no-go decision: down select candidate techniques to move forward within this program				
Integrate abuse testing and rapid impedance measurements on multi cell batteries with BMS	Initiate module testing and provide a progress report	9/30/2016		
Complete Phase I activities	Final report to NHTSA on Phase I activities	9/30/2016		

TECHNICAL ACCOMPLISHMENTS

Previous Work

Rapid impedance diagnostic tool development



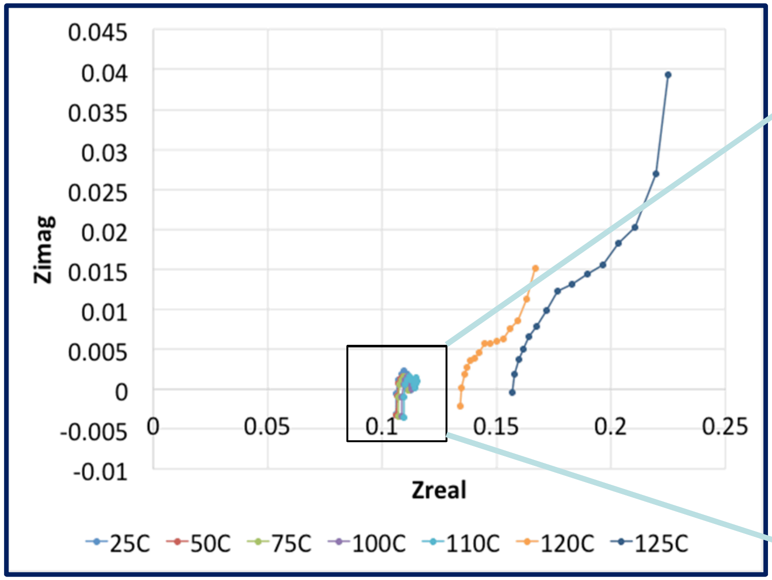


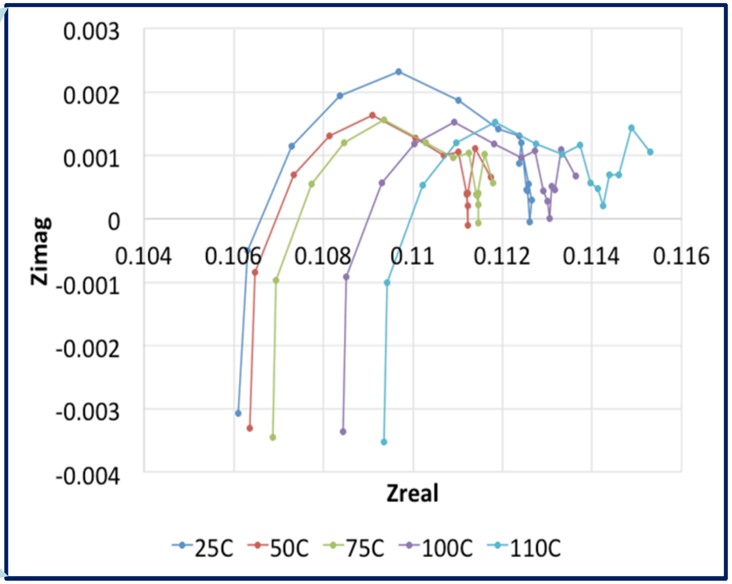
Measureable changes in impedance in regions where cell temperature unchanged during overcharge abuse, which highlights the added fidelity of the technique

Measureable changes in single frequency markers during thermal abuse of multicell strings highlights viability at the next level of assembly

Impedance measurements

Commissioning of the 50V impedance module allows for the measurement of higher voltage series configurations. 50V IMB measurements of 3S1P packs are shown here. (12.6 V, 10 Ah)



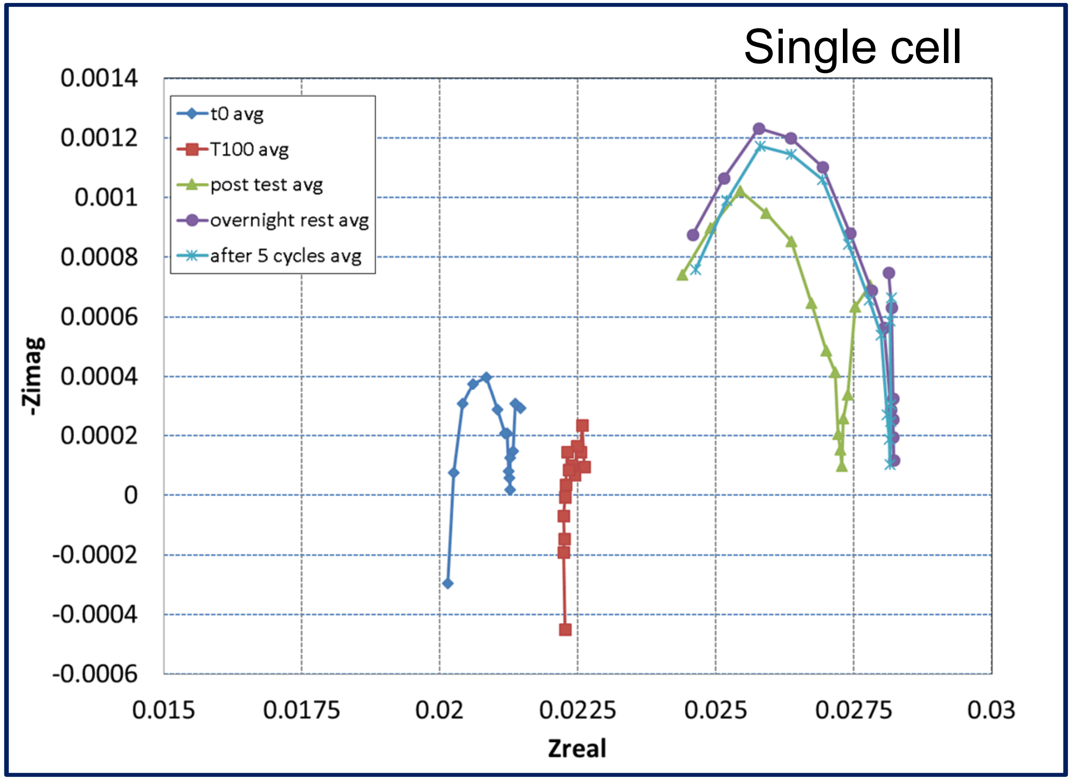


Evaluating for permanent damage

An important aspect of a tool will be the ability to evaluate cells for potential damage

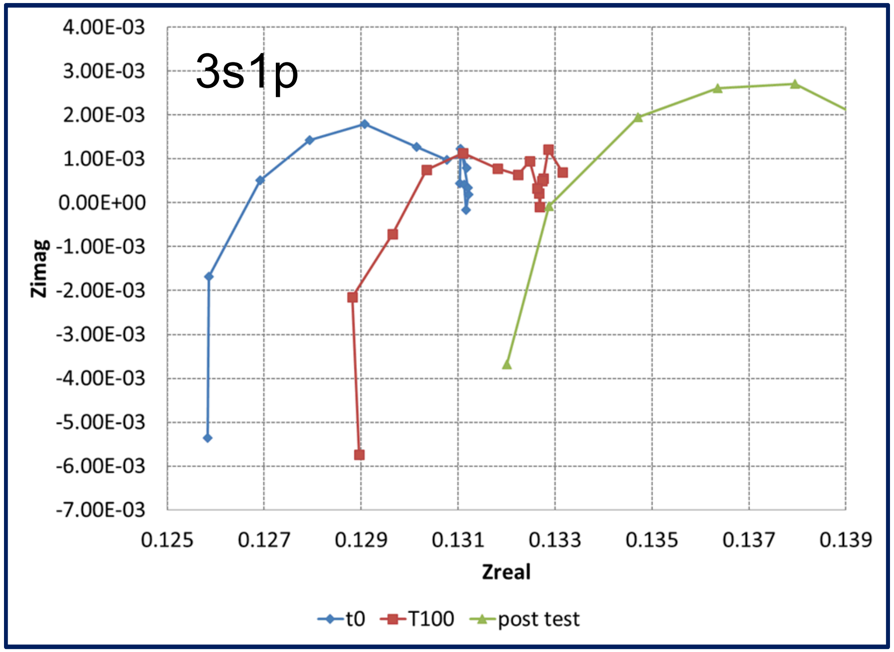
Single cells evaluated by soaking cells at target temperature (80 °C, 100 °C, 120 °C)

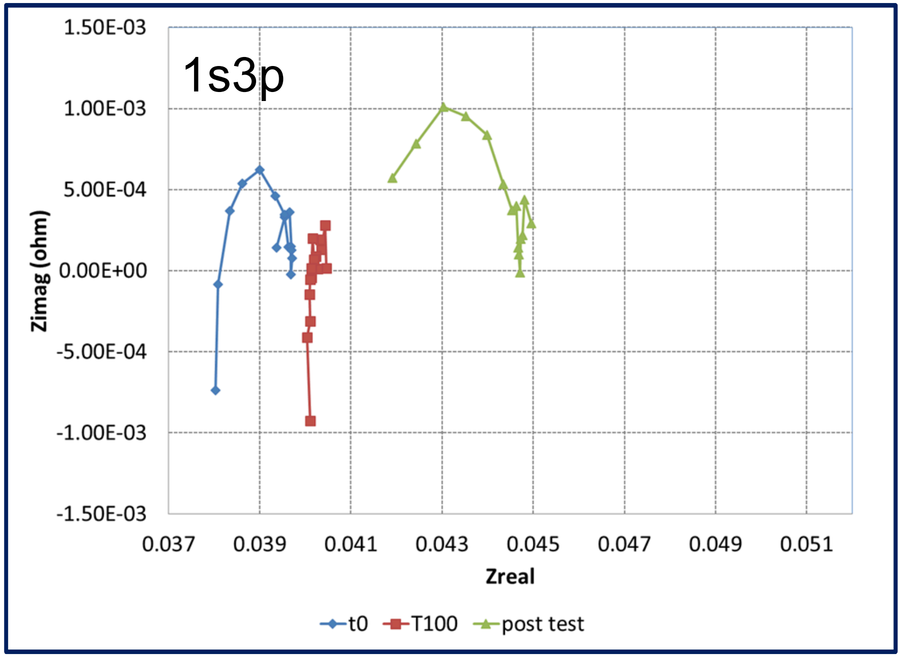
- Impedance measured before, during and after soak
- Single cell allowed to rest overnight, and measured after 5 C-D cycles



Scanning for damaged cells within pack

Full pack measurements of packs containing a single damaged cell





Technical Achievements

- 50V impedance module fully commissioned at Sandia
  - Real time impedance measurement of series packs
- Measurement of permanent damage due to over temperature conditions
  - Data shows the potential to evaluate packs that are in an unknown state for potential damage to cells within the pack even after being at ambient conditions for some time
- BMS hardware acquired and received at both INL and Sandia
  - Final stage of current phase will involve measurements of cells controlled by BMS hardware

Acknowledgements

- Thomas Wunsch
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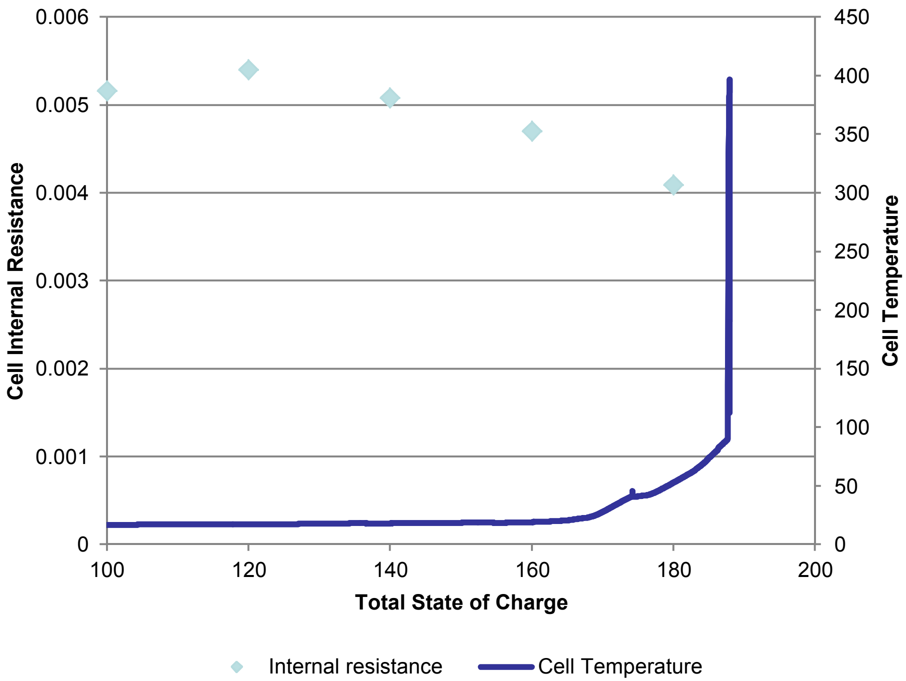
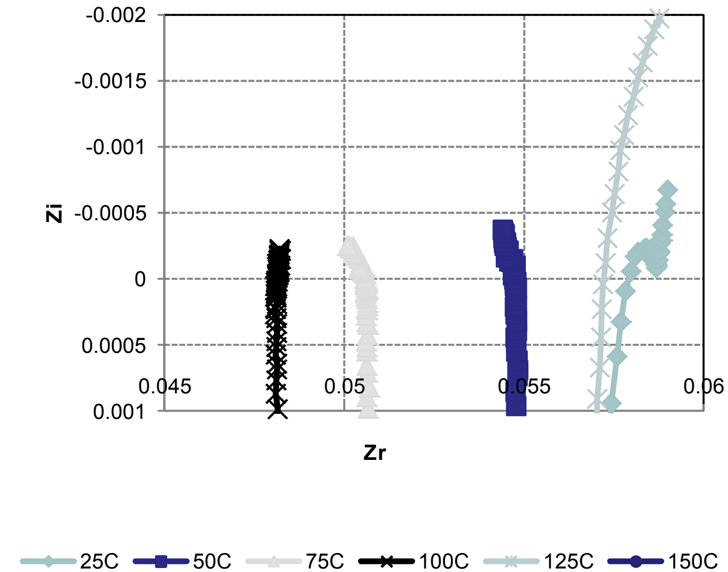
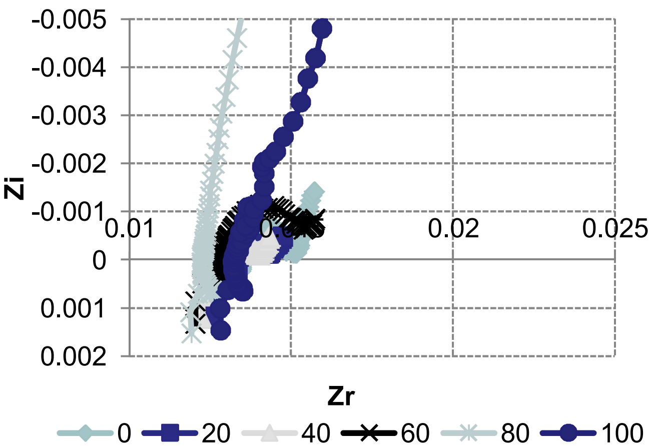
  - Phil Gorney
  - Steve Summers

EXTRA SLIDES AND DETAILED TECHNICAL INFORMATION

Single cell testing





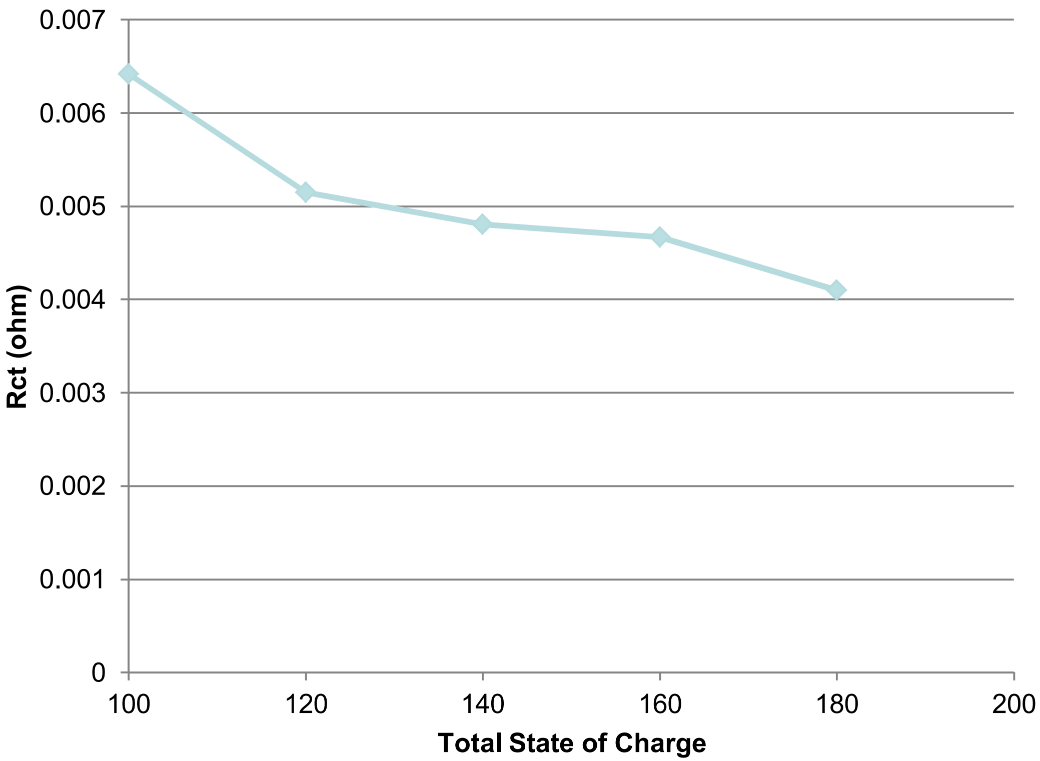


Temperature and internal resistance during overcharge testing- Temperature remains close to ambient up to 60% Overcharge, beginning to increase rapidly above 70% overcharge

Impedance data collected after thermal ramp of a single cell at 25C intervals

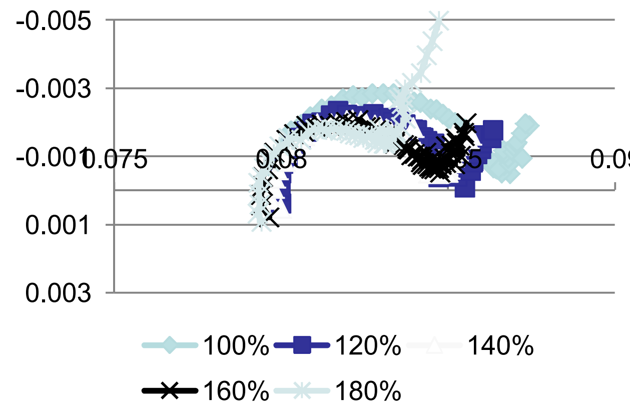
Decreases in internal resistance observed with initial temperature increase, with sharp increases to the resistance above 100C.

3 Cell string data – overcharge

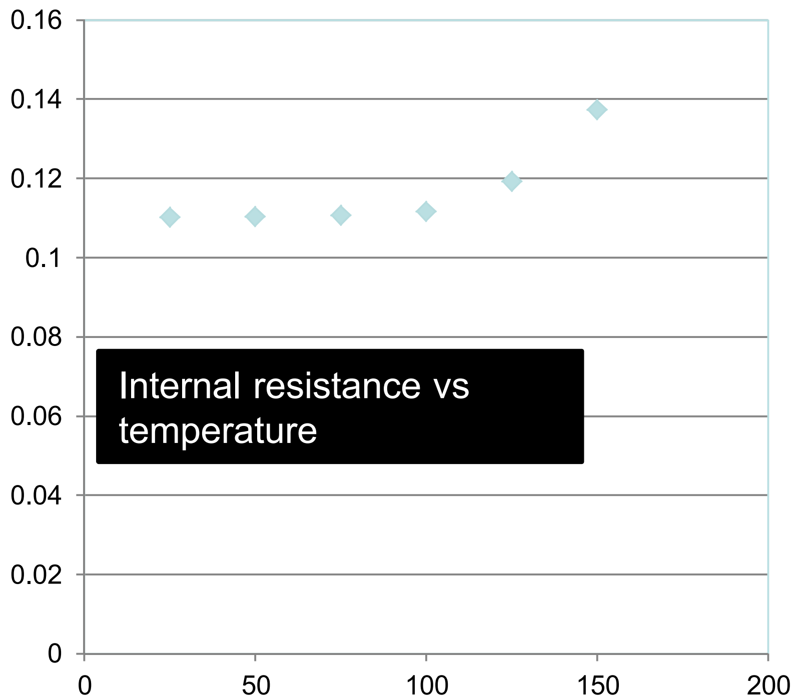


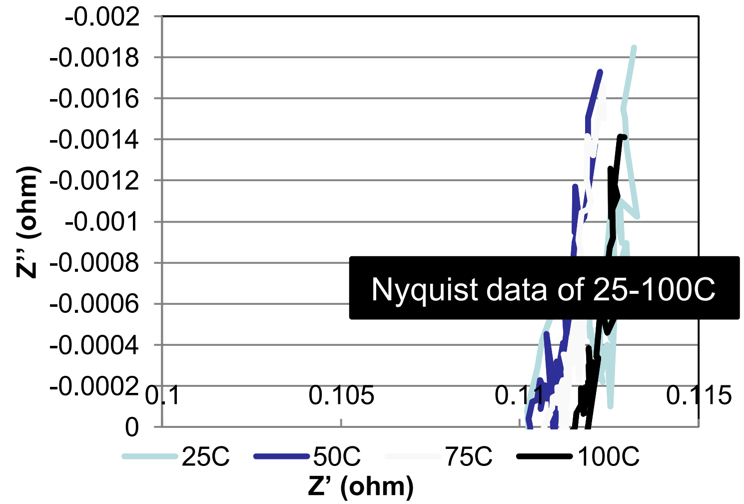
Runaway occurred during charging after 180% total charge
Results less dramatic than those seen for single cells.
Reduction in charge transfer resistance as overcharge increases
Large Warburg or resistive element present at 180% SOC

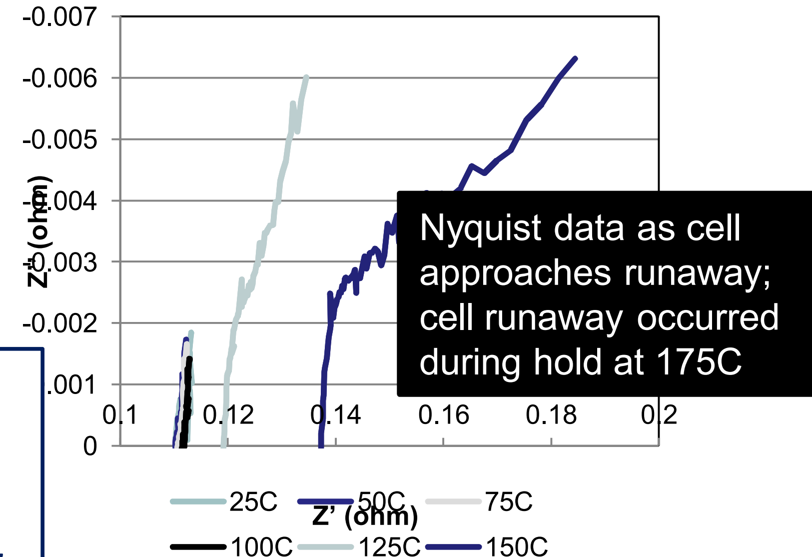
Charge transfer resistance vs SOC; determined using Randle circuit approximation



3 cell string data – thermal ramp



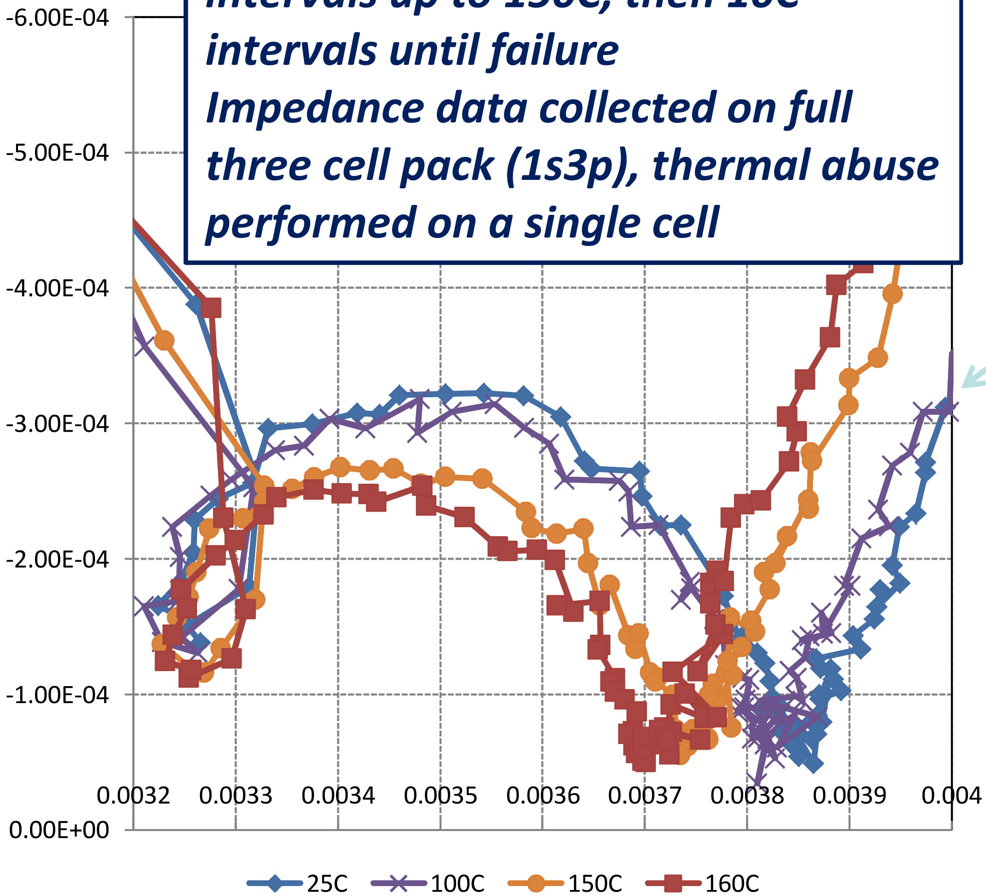


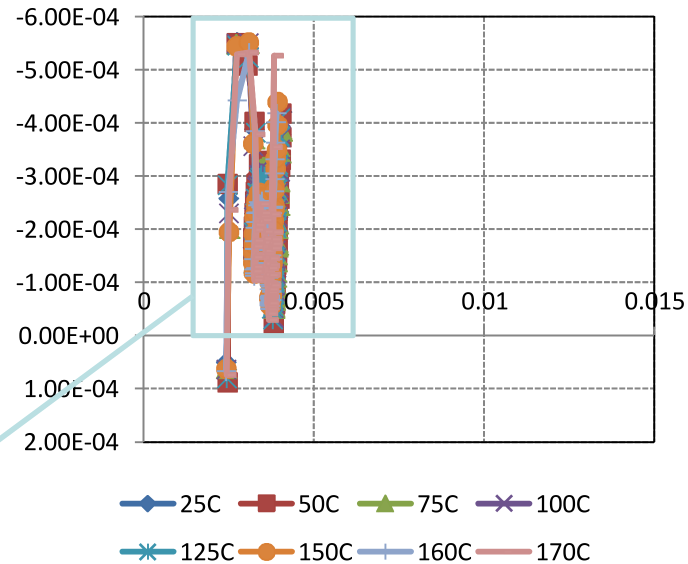


Little change is observed from 25-100C
Large increases to resistance observed with increasing temperature above 100C
Significant inductive interference is currently present in thermal ramp data

Parallel Pack Testing

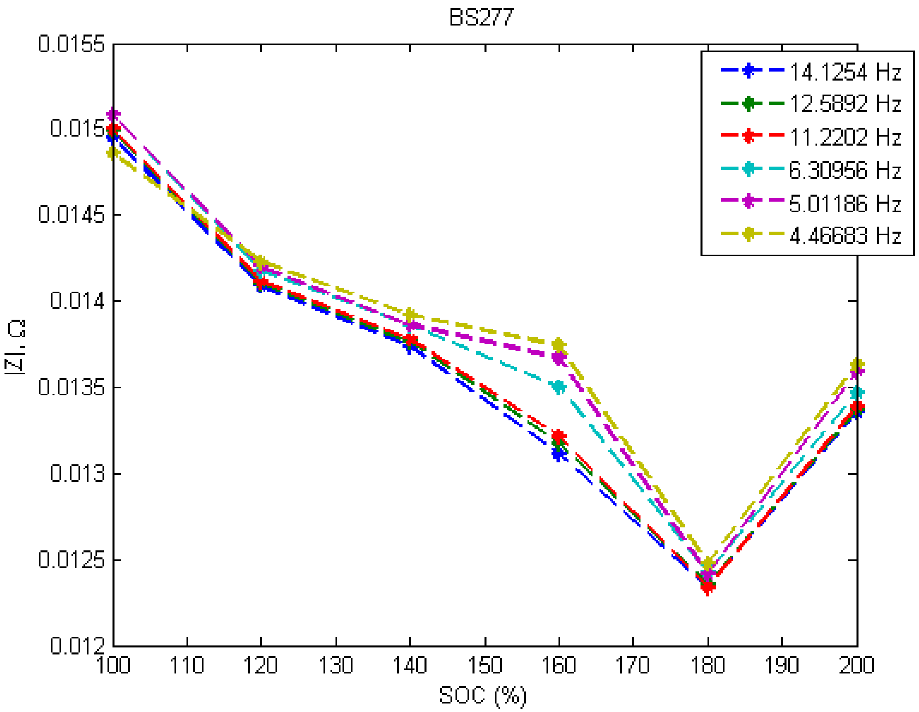
Impedance data collected at 25 C intervals up to 150C, then 10C intervals until failure
Impedance data collected on full three cell pack (1s3p), thermal abuse performed on a single cell

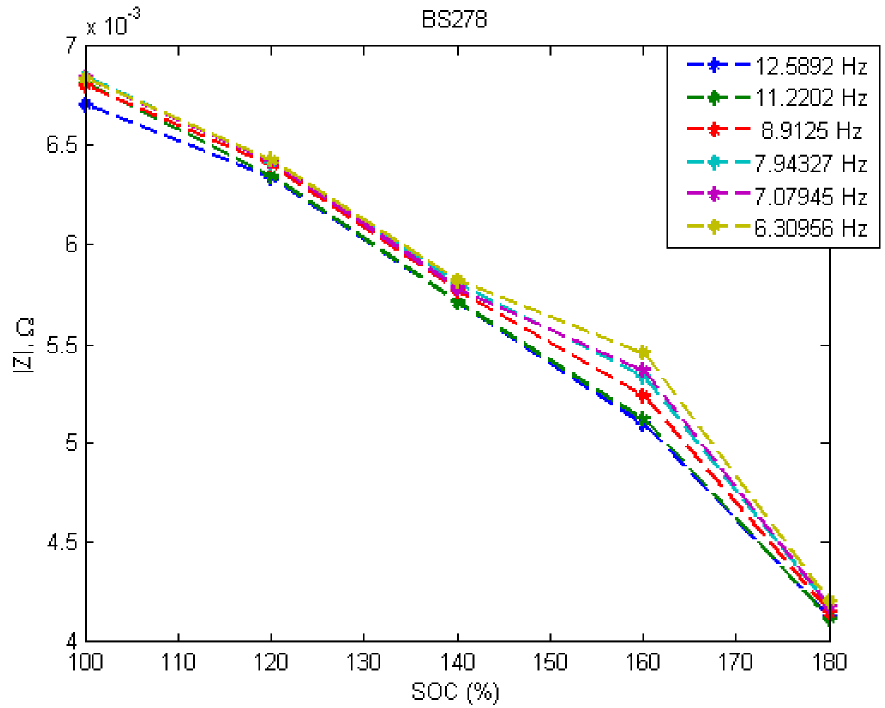




Little change observed up to 100C. Shifts in RCT observed as temperature increases above 100C. Thermal runway observed during data collection at 170C

Single cell analysis

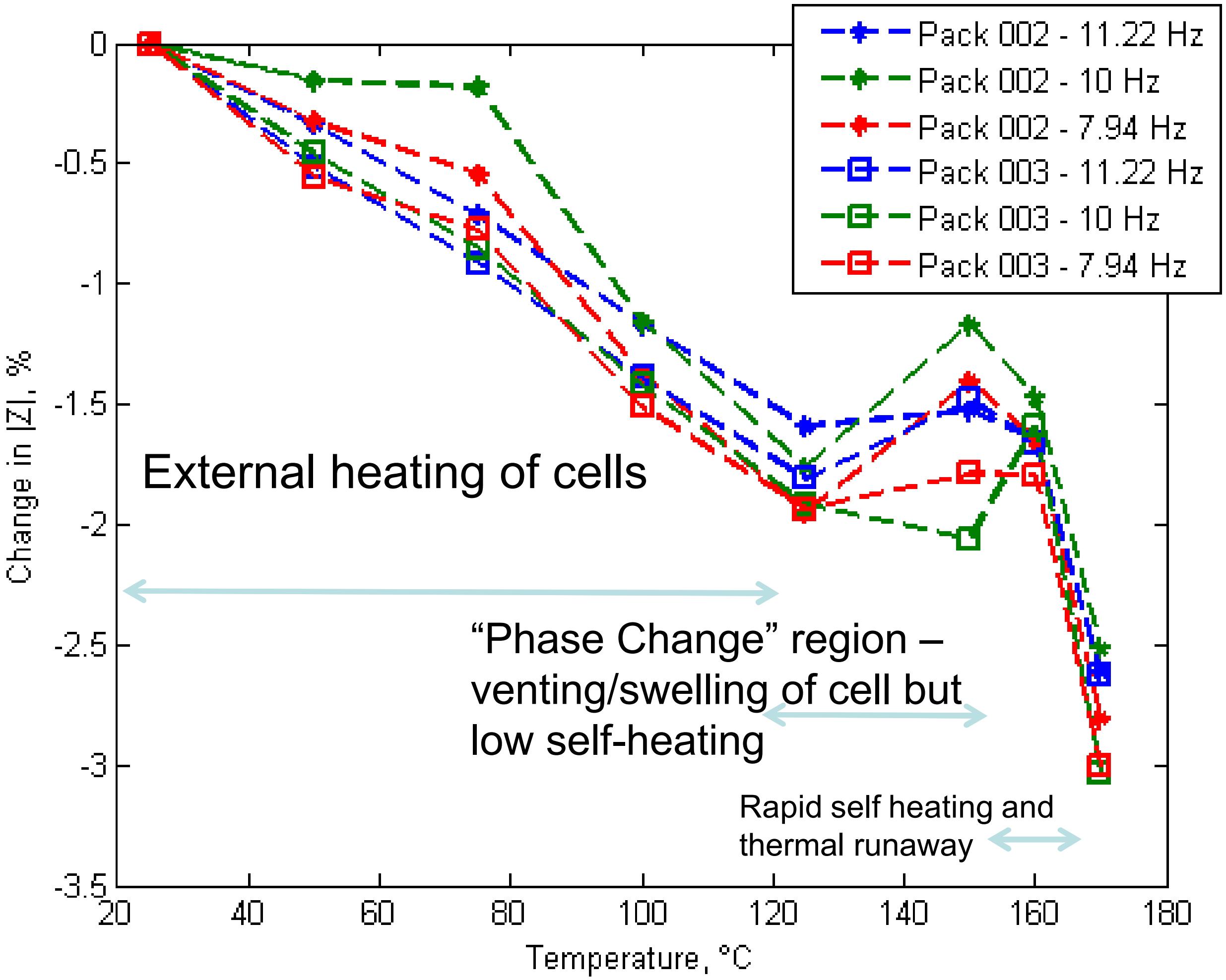




$$|z| = \sqrt{ReZ^2 + ImZ^2}$$

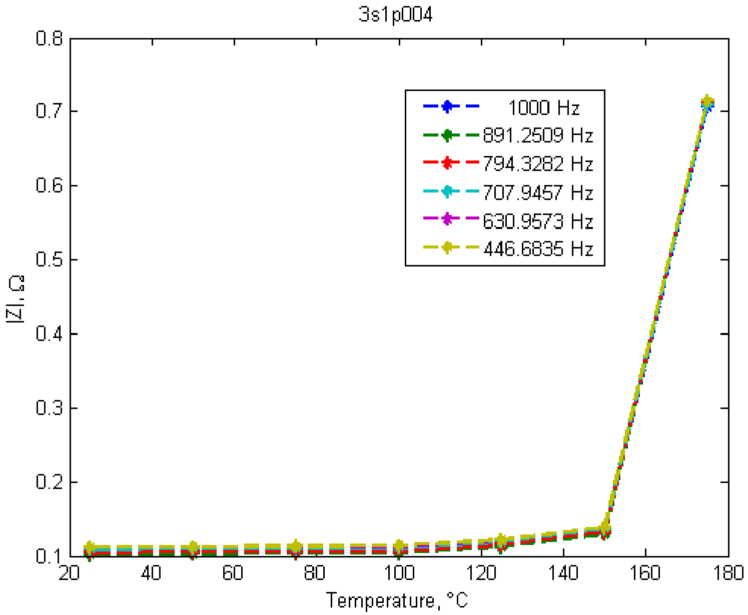
Analysis of impedance data collected at varying levels of single cell overcharge

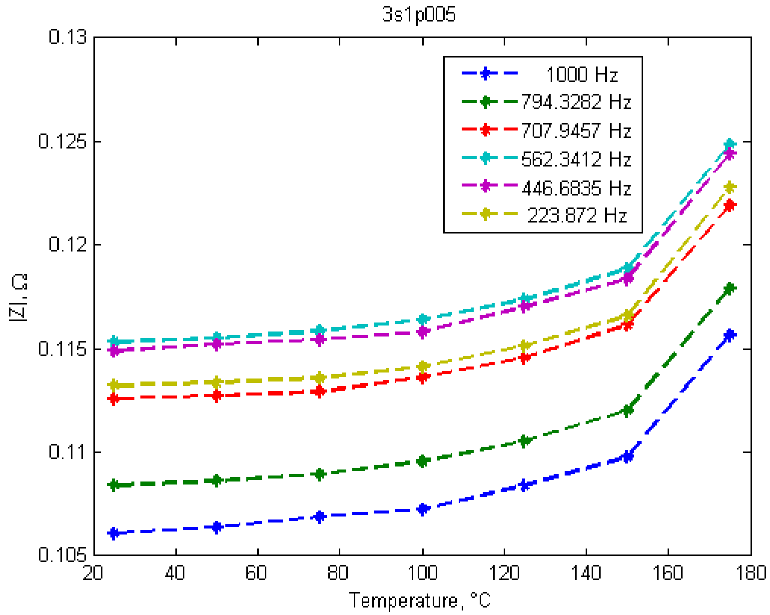
Three cell parallel testing



Impedance measurement of entire pack, thermal abuse applied to a single cell within the pack until runaway

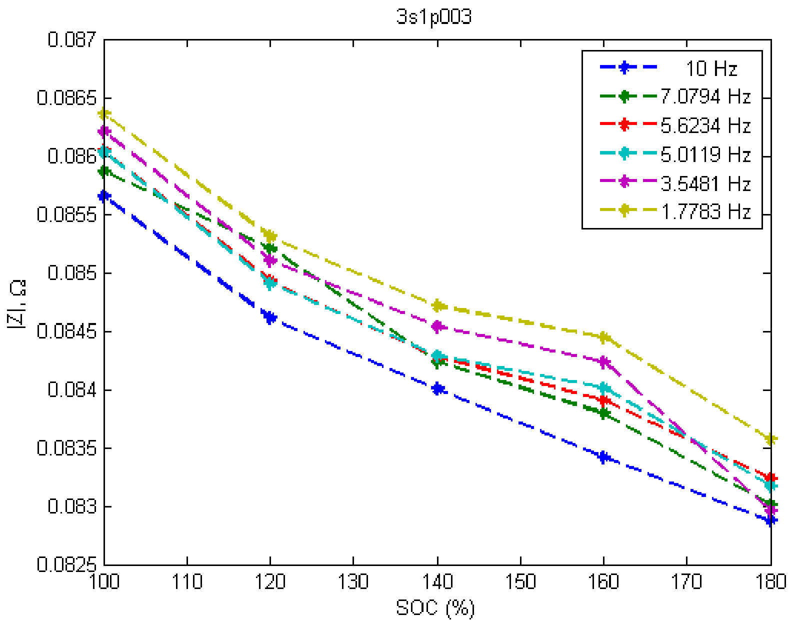
Three cell series analysis -TR

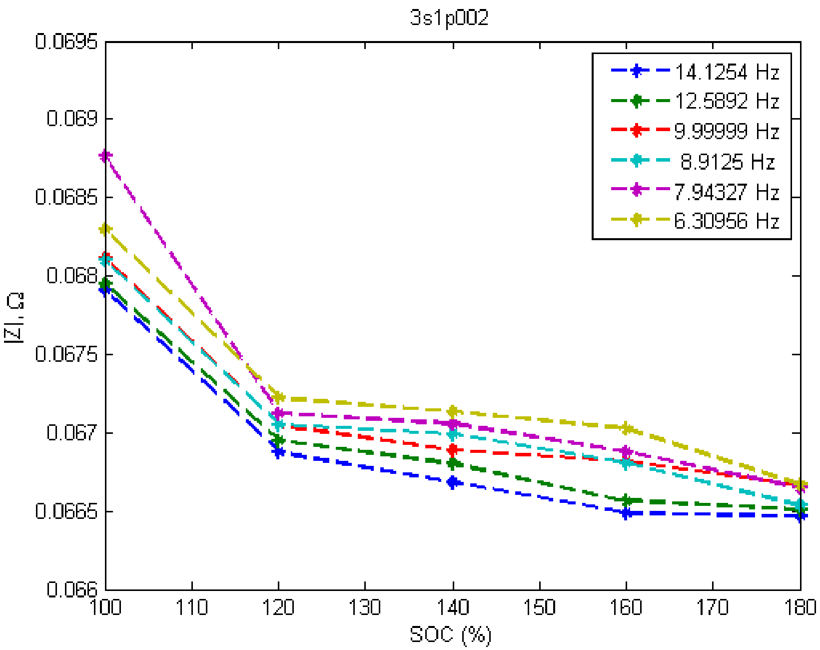




Thermal ramp tests on series modules show increasing trends at middle-high frequencies

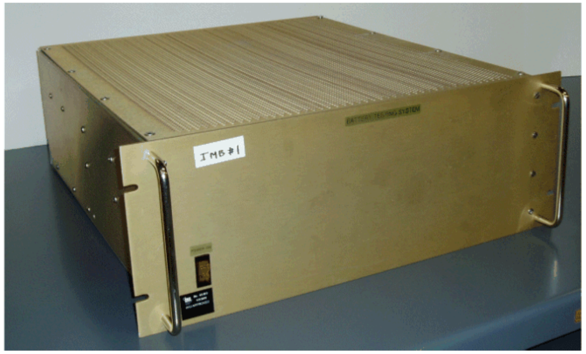
Three cell series analysis - OC



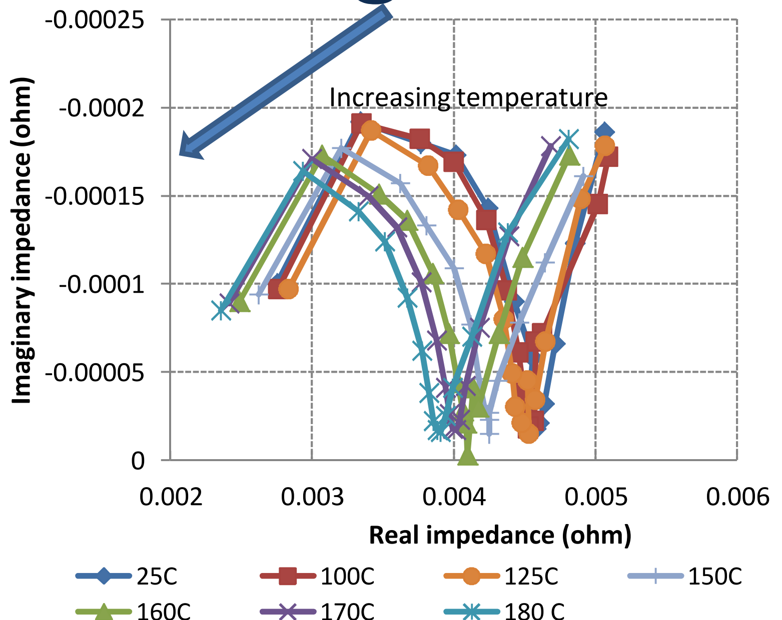


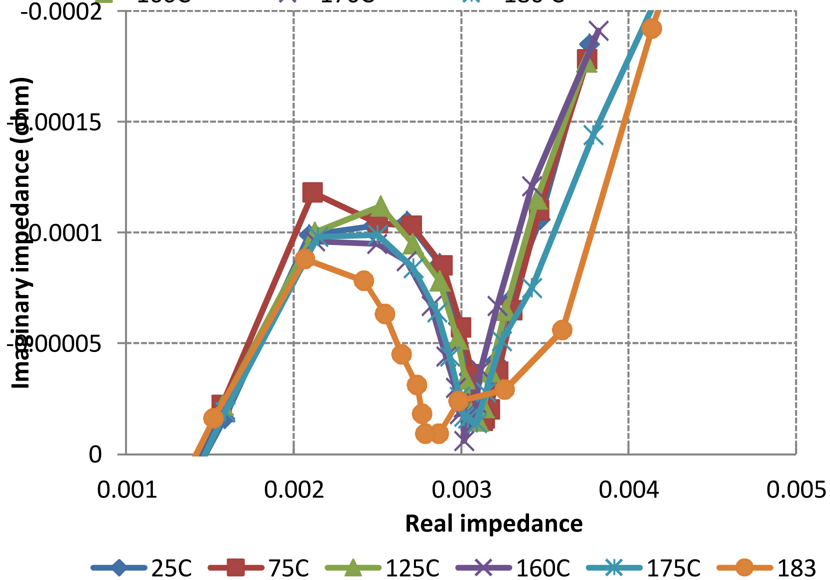
Thermal ramp tests on series modules show increasing trends at middle-high frequencies

Fast impedance monitoring



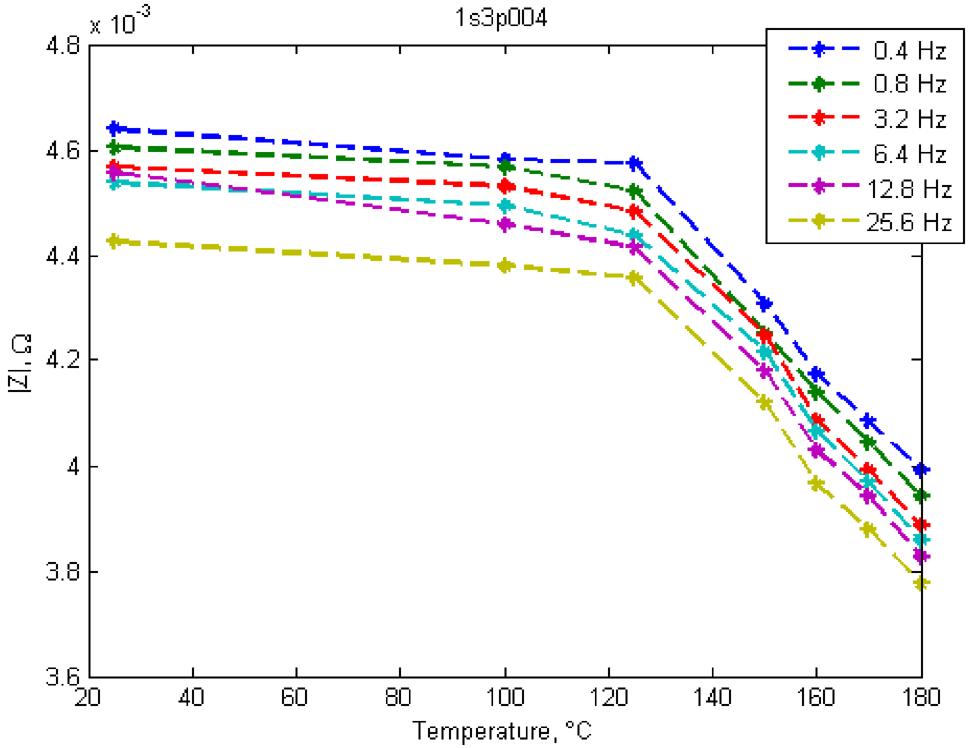
Impedance measurement box developed by INL





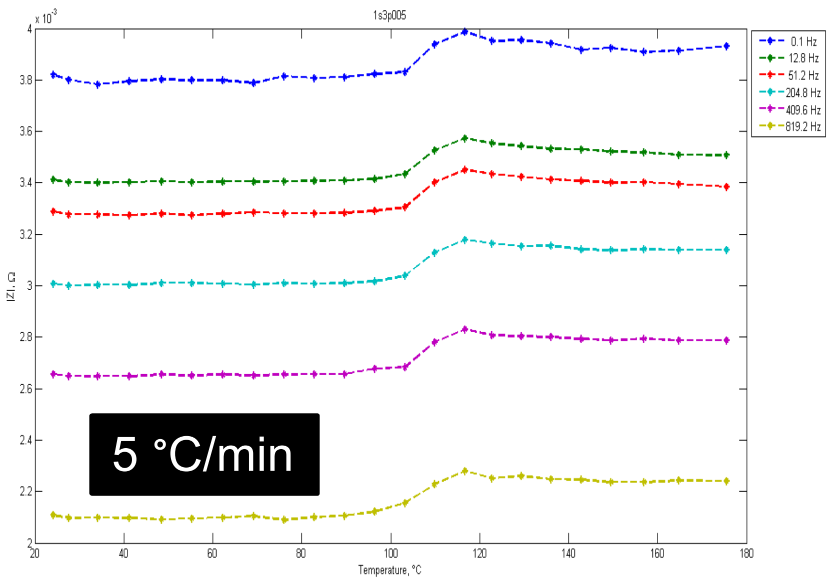
Impedance data collected after temperature is allowed to equilibriate vs. scans taken every 20 seconds during a 3 °C/min thermal ramp test

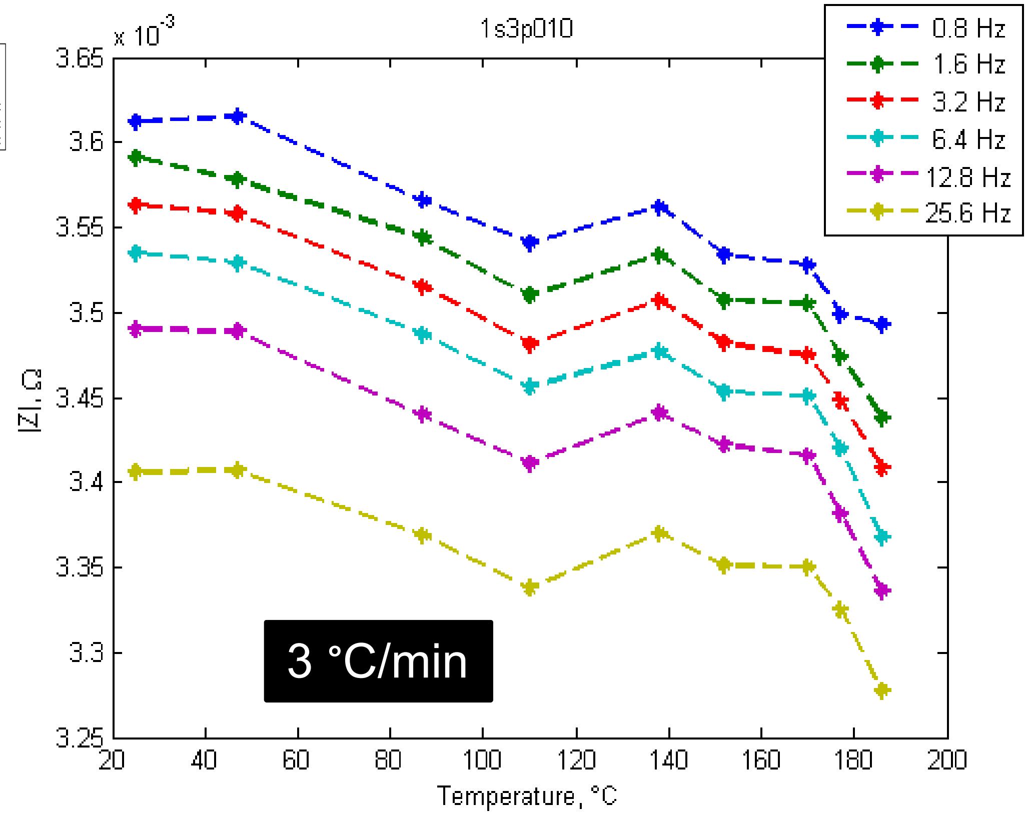
Fast impedance monitoring – step by step thermal abuse



Impedance measurements of entire 1s3p module made at 25 °C increments up to 150 °C, followed by 10 °C increments . Decreasing trend observed at temperatures above 120 °C.

Three cell parallel continuous monitoring





Impedance measurement of entire pack, thermal abuse applied to a single cell within the pack until runaway at a constant rate of 5 °C/min shows little change at any frequency (example left) Test at a constant heating rate of 3 °C/min show similar behavior to that observed during step-by-step measurements.

Summary

- Single cell data, as well as that for 3 cell series modules, show strong shifts as cell approaches failure.
- Parallel data shows more subtle changes as cell approaches failure, with the most noticeable changes coming in the charge transfer resistance and capacitance of the module.
- Use of the fast impedance measurement hardware on single cells gives data similar to that for traditional measurements, supporting its use in obtaining continuous impedance measurements from a cell
- Future work in the near term will include use of the INL impedance measurement hardware on 3 cell series modules using new 50V equipment.
- Further work will involve the development of impedance tests under active load for analysis of behavior under electrical abuse.