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Energy Storage Monitoring System and In-Situ Impedance Measurement Modeling

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Idaho National Laboratory

Overview

Timeline

- Ongoing Project
- Start – October 2007

Budget

- Total project funding:
  - DOE – 660k (through FY11)
- Funding received in FY11:
  - $450k
- Funding for FY12:
  - $400k

Barriers

- Cost
- Performance
- Abuse Tolerance and Reliability
- Life Estimation

Partners

- Montana Tech of the University of Montana
- Qualtech Systems, Inc.

Relevance

- **Objective:**
  - Develop advanced in-situ diagnostic and prognostic tools for more accurate prediction of the state-of-health and remaining useful life of energy storage devices.

- **Benefits:**
  - Safety and reliability: Rapid identification of failure thresholds
  - Cost: Smarter replacement schedules
  - Life Estimation: Improved sensor technology for state estimation
  - Performance: Improved management systems based on battery condition using both energy and power.

- **Applications:**
  - Automotive (EV, HEV, PHEV)
  - Military (field radio operations, warehouses, vehicles, etc.)
  - Other applications include NASA, electric utilities, telecommunications, aeronautics, consumer electronics, etc.

Relevance (cont.)

- **Mission Areas:**
  - Rapid, in-situ impedance spectrum measurement techniques using hardware and control software – Impedance Measurement Box
  - Modeling and prognostic tools that smartly combine impedance measurements with other observations to determine a more accurate definition of battery health.
  - Hardware and software that directly interfaces with onboard battery technologies to smartly monitor and report health – Energy Storage Monitoring System.

- **FY-12 Objectives:**
  - Design and build a 50-V rapid impedance measurement system.
  - Improve calibration system of rapid impedance measurement.
  - Continue validation studies of rapid impedance measurement techniques using commercially available lithium-ion cells.
  - Initiate incorporation of rapid impedance measurements into new and existing modeling and prognostic tools.

Approach

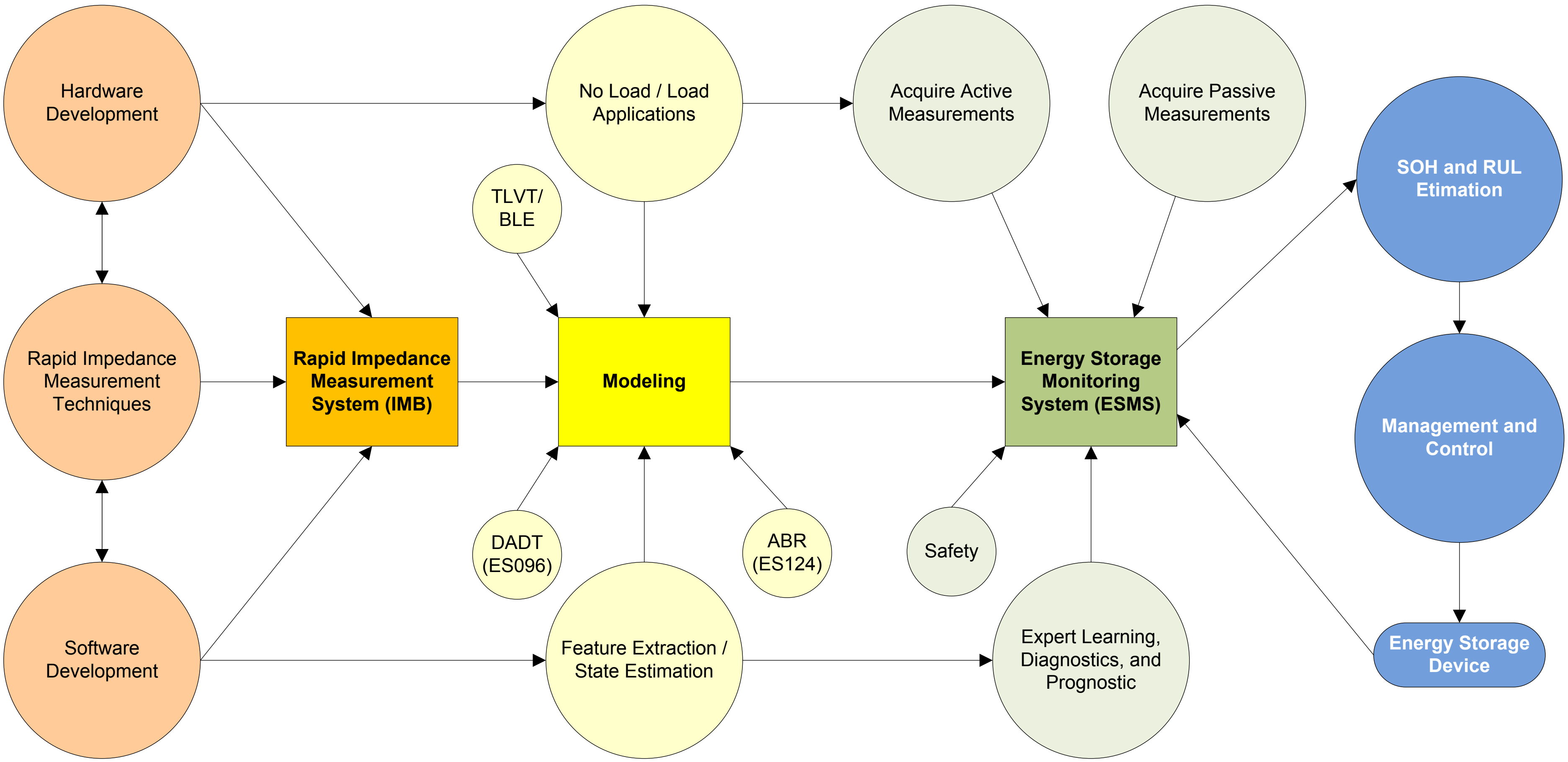
- **Impedance Measurement Box:**
  - Develop rapid impedance spectra measurement techniques
  - Design low-cost hardware and control software
  - Implement measurements under no-load and load conditions

- **Modeling:**
  - Equivalent circuit modeling of rapid impedance measurements
  - Feature extraction (e.g., effective charge transfer resistance, etc.)
  - Estimate pulse resistance and power capability from impedance measurements
  - Implement existing modeling capabilities (ES124) to develop prognostic tools for arbitrary aging conditions

- **Energy Storage Monitoring System:**
  - Passive measurements (voltage, current, temperature)
  - Active measurements (rapid impedance spectra)
  - Incorporate models to estimate overall state-of-health (SOH) and remaining useful life (RUL)

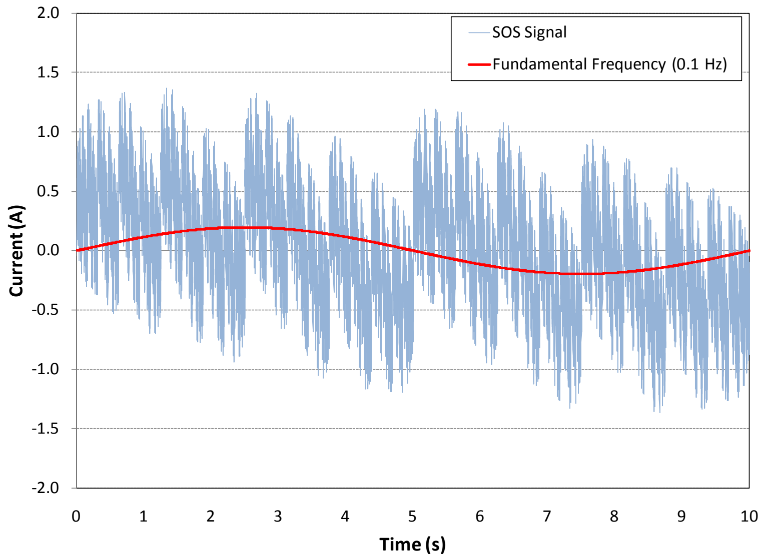
Approach (cont.)

- **Flow diagram of the overall ESMS concept:**



Technical Accomplishments and Progress

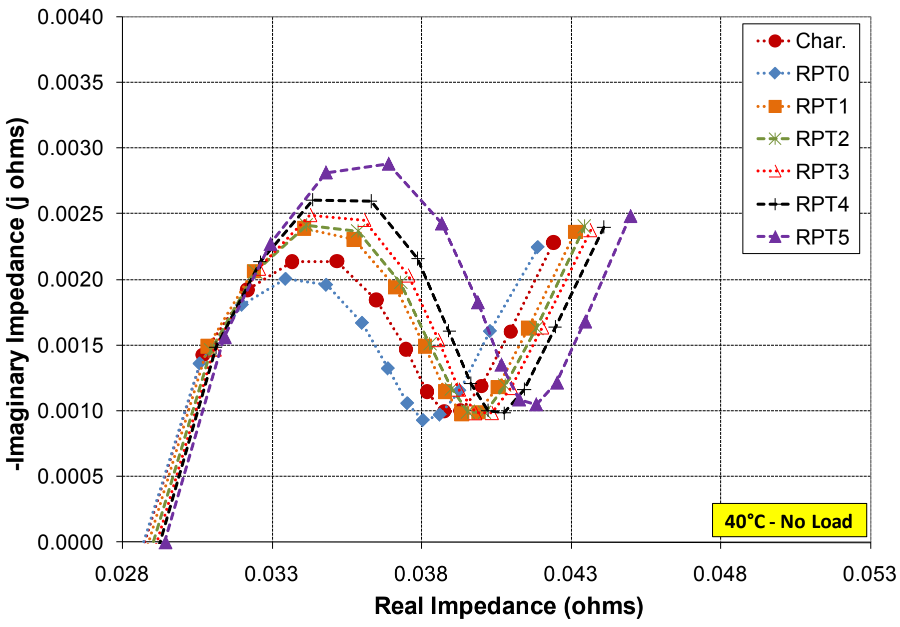
- **Novel techniques have been developed to acquire wideband impedance within seconds.**
  - Harmonic Compensated Synchronous Detection (HCSD)
    - Low resolution, computationally intensive, short test duration
- **Input signal is an octave harmonic sum-of-sines excitation current.**
  - The excitation signal has a duration of one period of the lowest frequency.
- **Synchronously detect the magnitude and phase of the captured voltage response time record.**

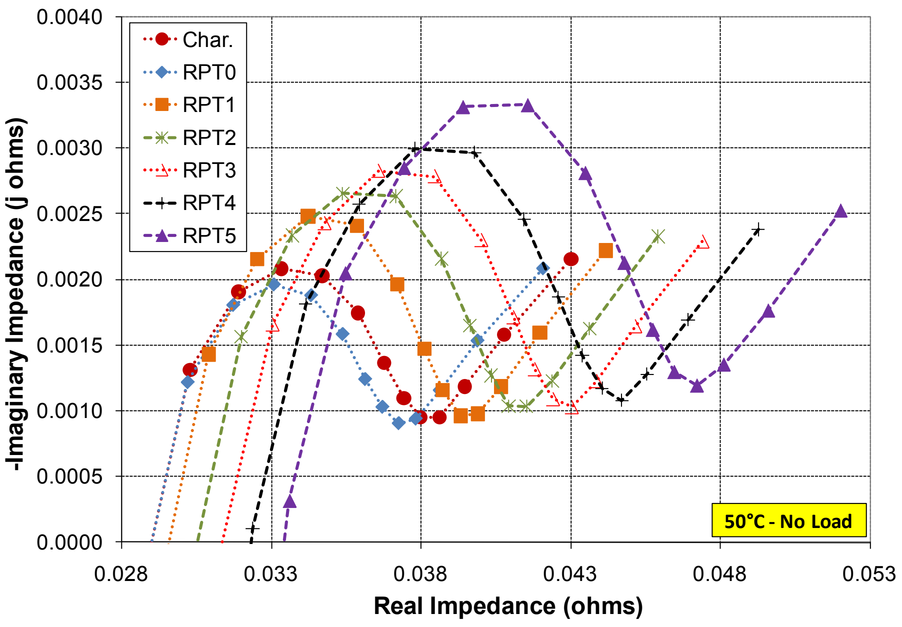


- **Long term validation testing was completed using Sanyo SA cells.**
  - Cells aged at 40 and 50°C with periodic HCSD measurements under both no-load and load conditions.

Accomplishments and Progress (cont.)

- **HCSDs under no-load conditions:**
  - HCSD impedance spectra grow in both ohmic and effective charge transfer resistance.
  - The rate of impedance growth is higher at 50°C, as expected.

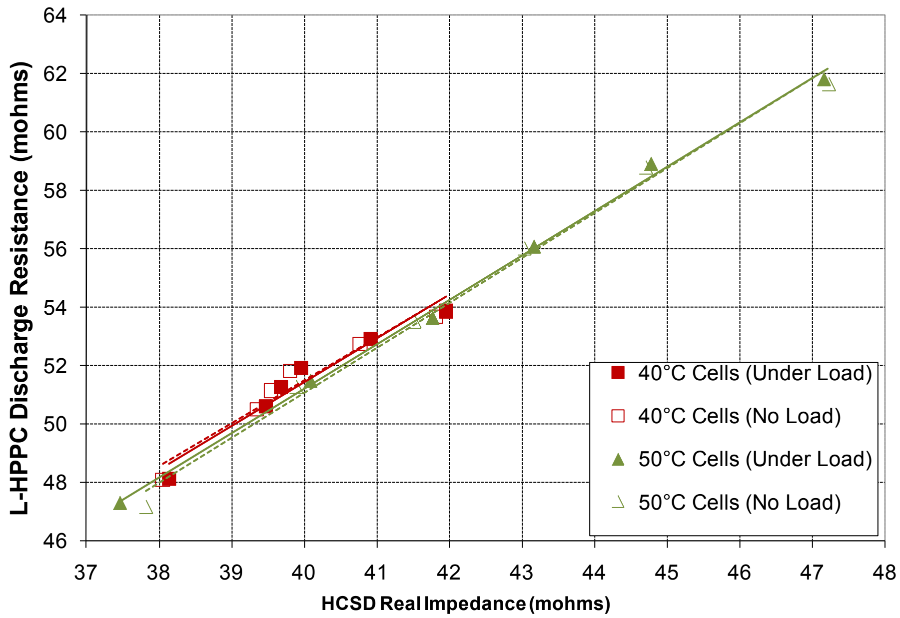


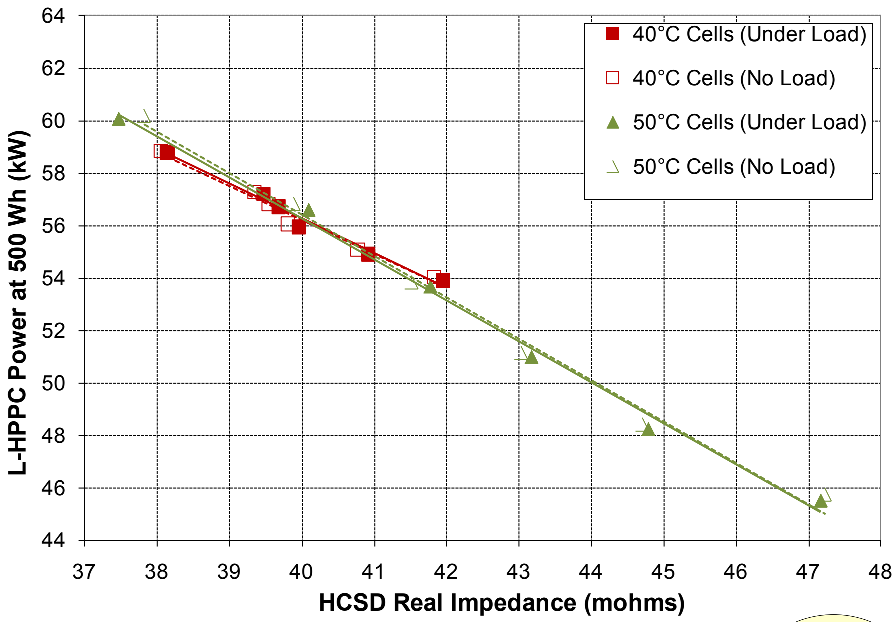


No Load / Load Applications

Accomplishments and Progress (cont.)

- **HCSDs under no-load conditions (cont.):**
  - The HCSD real impedance at the semicircle trough is highly correlated with both HPPC discharge resistance and available power.
  - $r^2 \geq 0.950$ in all cases, most fits are $r^2 \geq 0.980$.

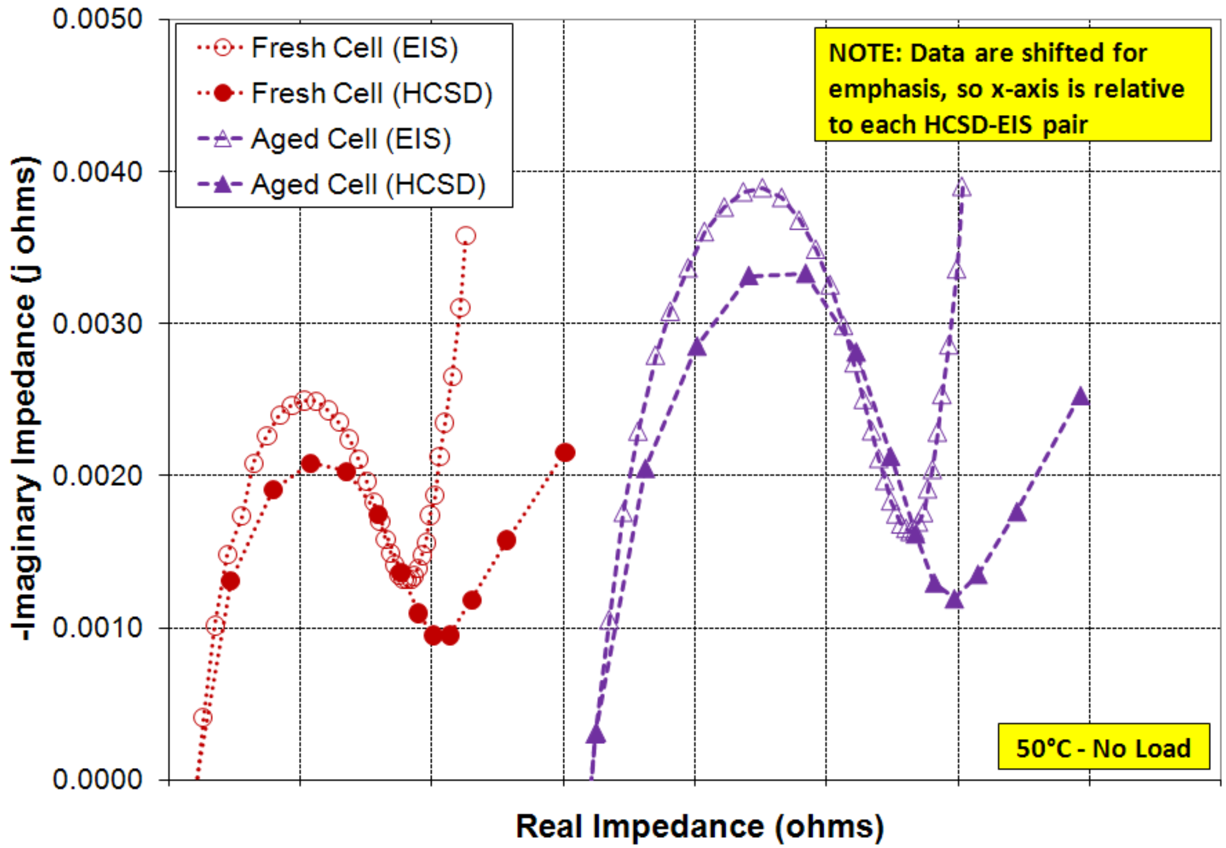




No Load / Load Applications

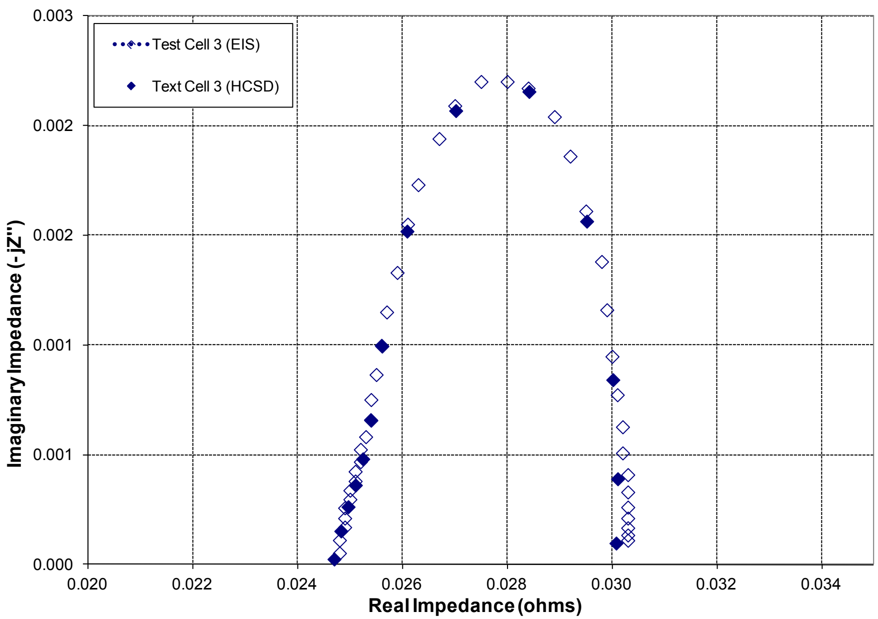
Accomplishments and Progress (cont.)

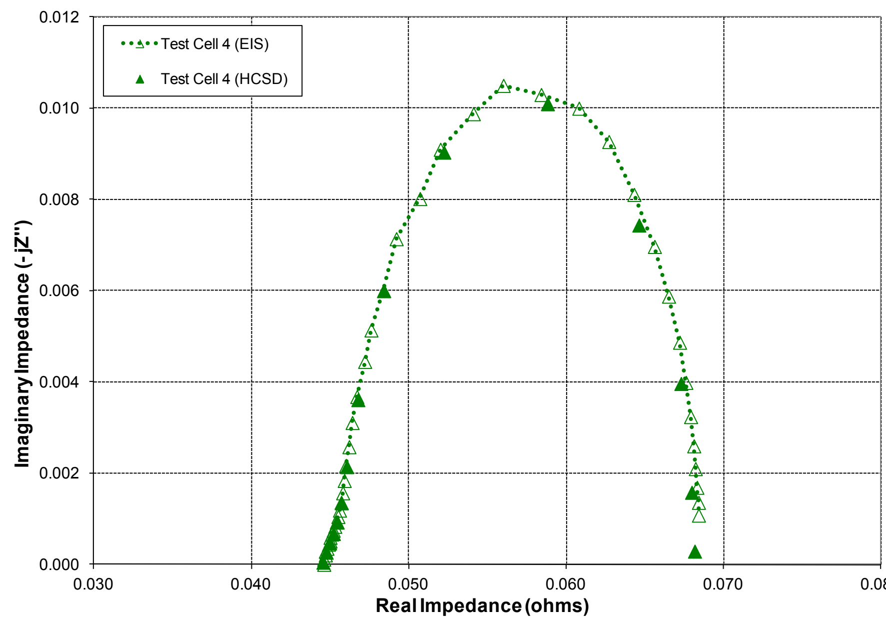
- **HCSDs under no-load conditions (cont.):**
  - HCSD results generally match standard EIS measurements in the key mid-frequency range.

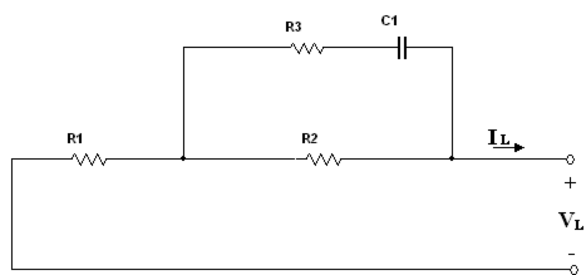


Accomplishments and Progress (cont.)

- **HCSDs under no-load conditions (cont.):**
  - The calibration issue has been resolved and the EIS and HCSD measurements now match very well using test cell circuits.

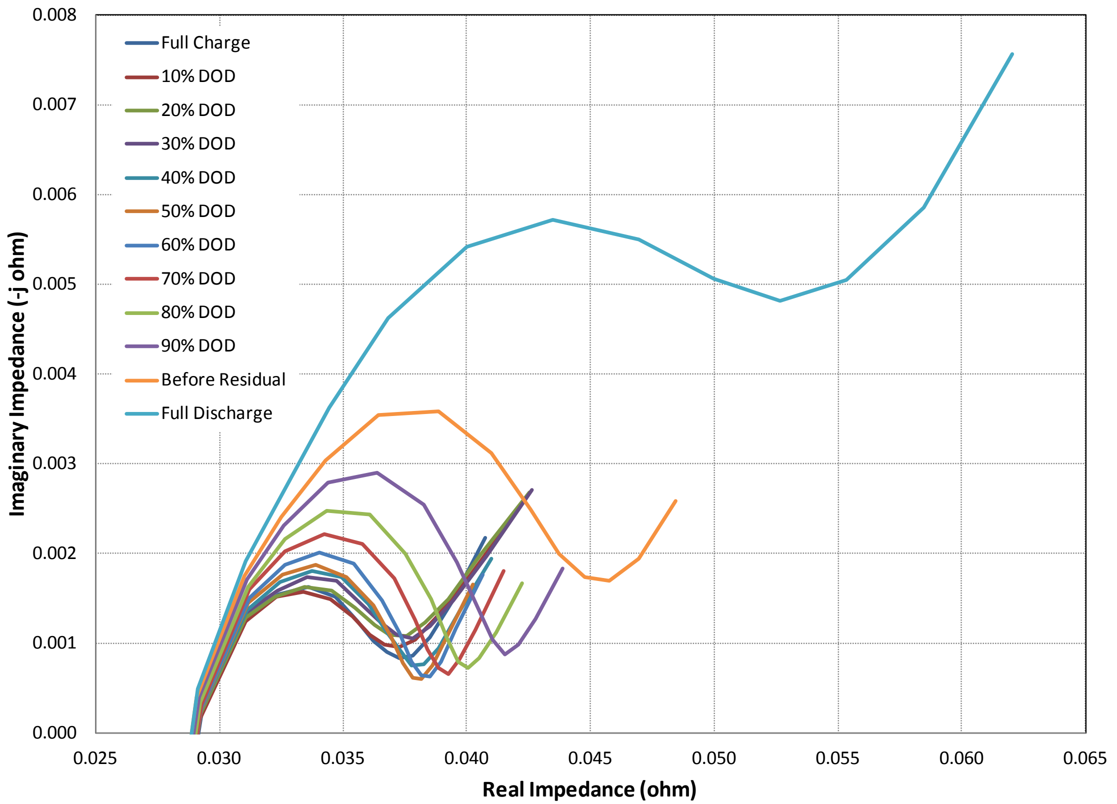






Accomplishments and Progress (cont.)

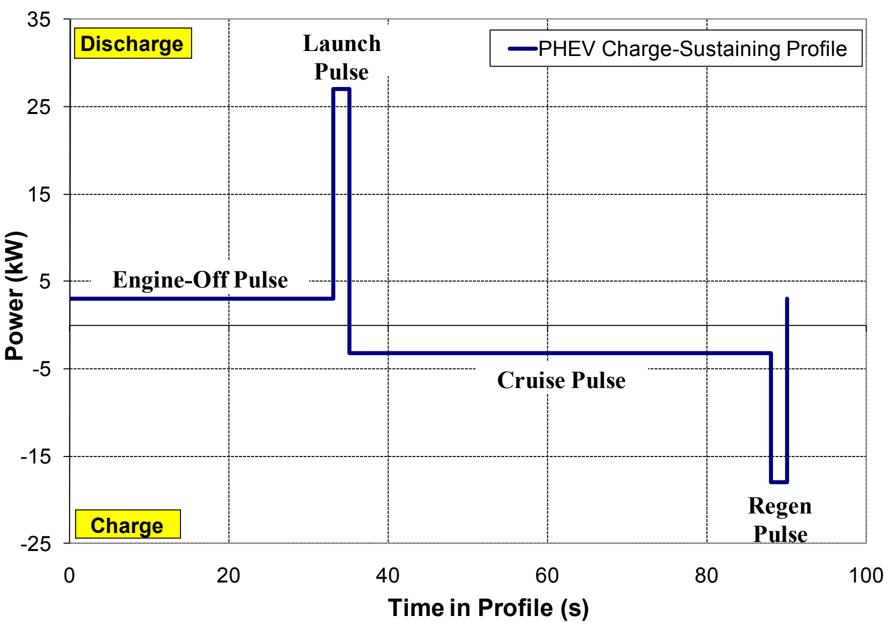
- **HCSDs under no-load conditions (cont.):**
  - A new validation study is now underway with Sanyo SA cells to measure HCSD at multiple DODs.
  - At RPT0, the mid-frequency semicircle generally increases in both height and width with increasing DOD.

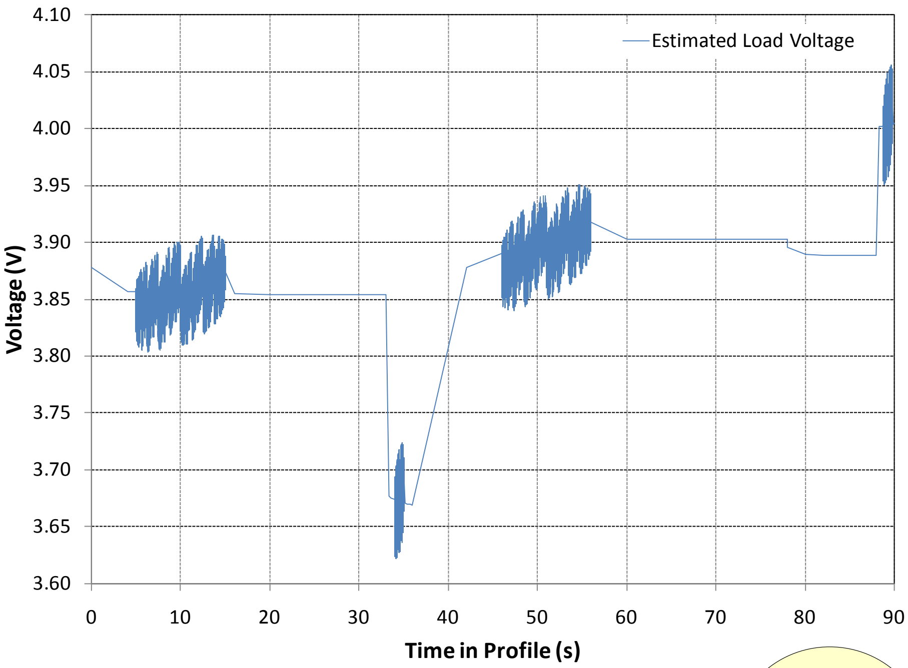


No Load / Load Applications

Accomplishments and Progress (cont.)

- **HCSDs under load conditions :**
  - Cells were cycled at elevated temperatures with HCSD measurements triggered every 50 cycles.
  - Under-load measurements were affected by a non-constant DC bias voltage.

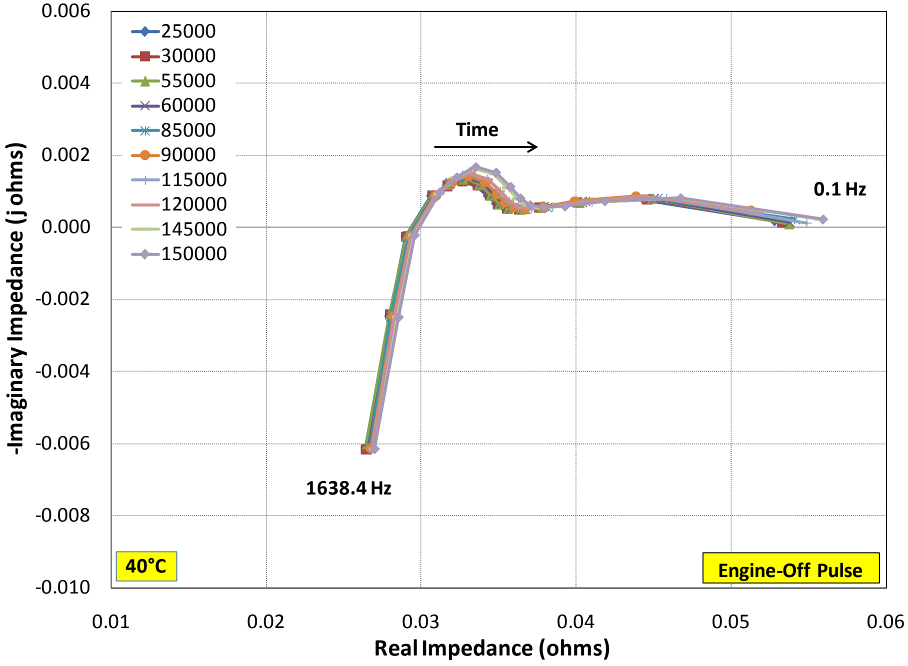


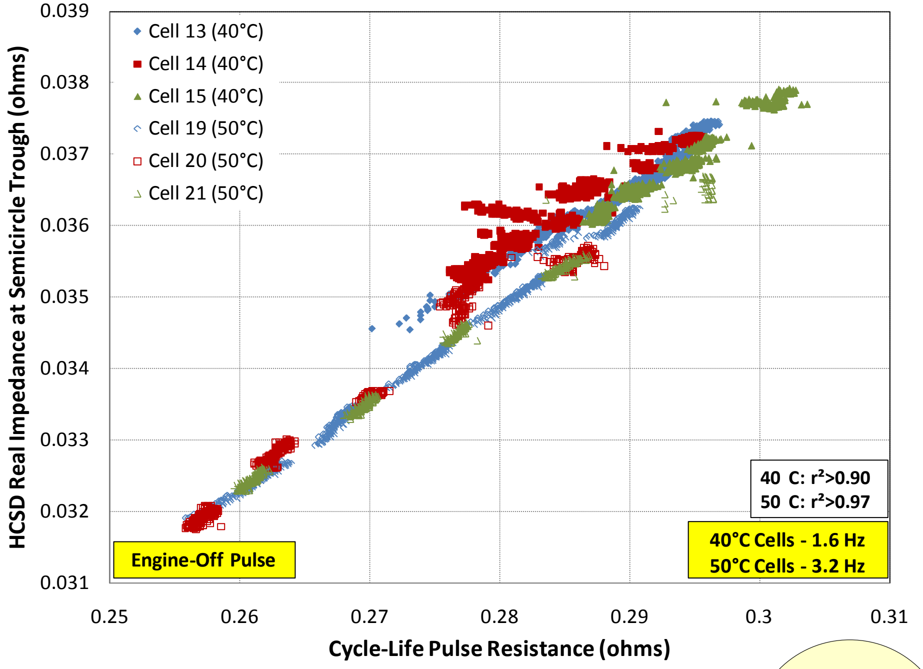


No Load / Load Applications

Accomplishments and Progress (cont.)

- **HCSDs under load conditions :**
  - The Engine-Off impedance measurement under load still shows a mid-frequency arc, but the Warburg tail has flattened out.
  - The growth in effective charge transfer resistance is linearly correlated to the corresponding cycle-life pulse resistance.

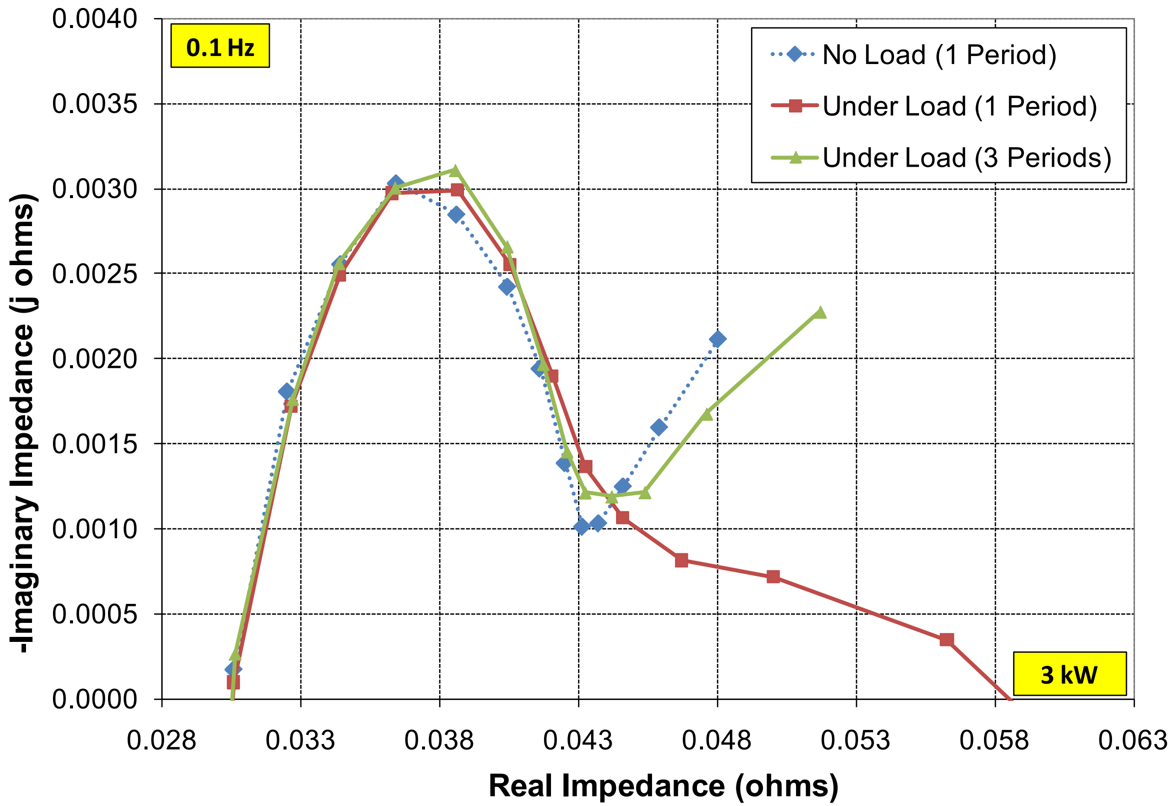




No Load / Load Applications

Accomplishments and Progress (cont.)

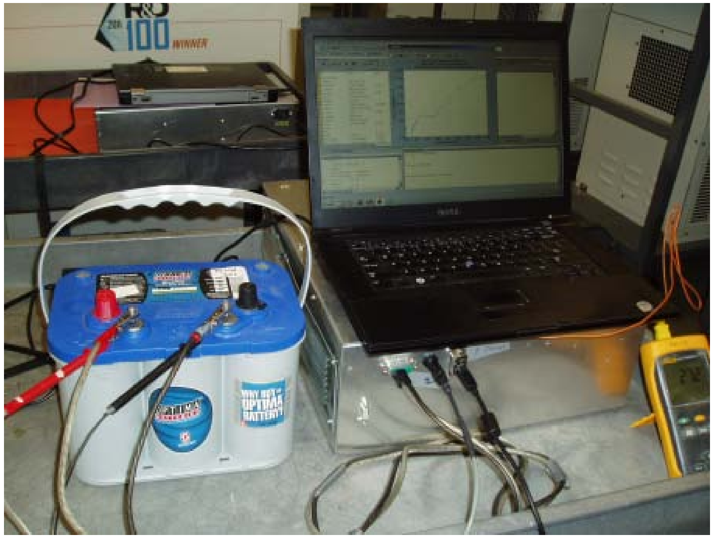
- **HCSDs under load conditions :**
  - Despite the low-frequency effects, the height and width of the effective charge transfer resistance semicircle is similar under both no load and load conditions.



No Load / Load Applications

Accomplishments and Progress (cont.)

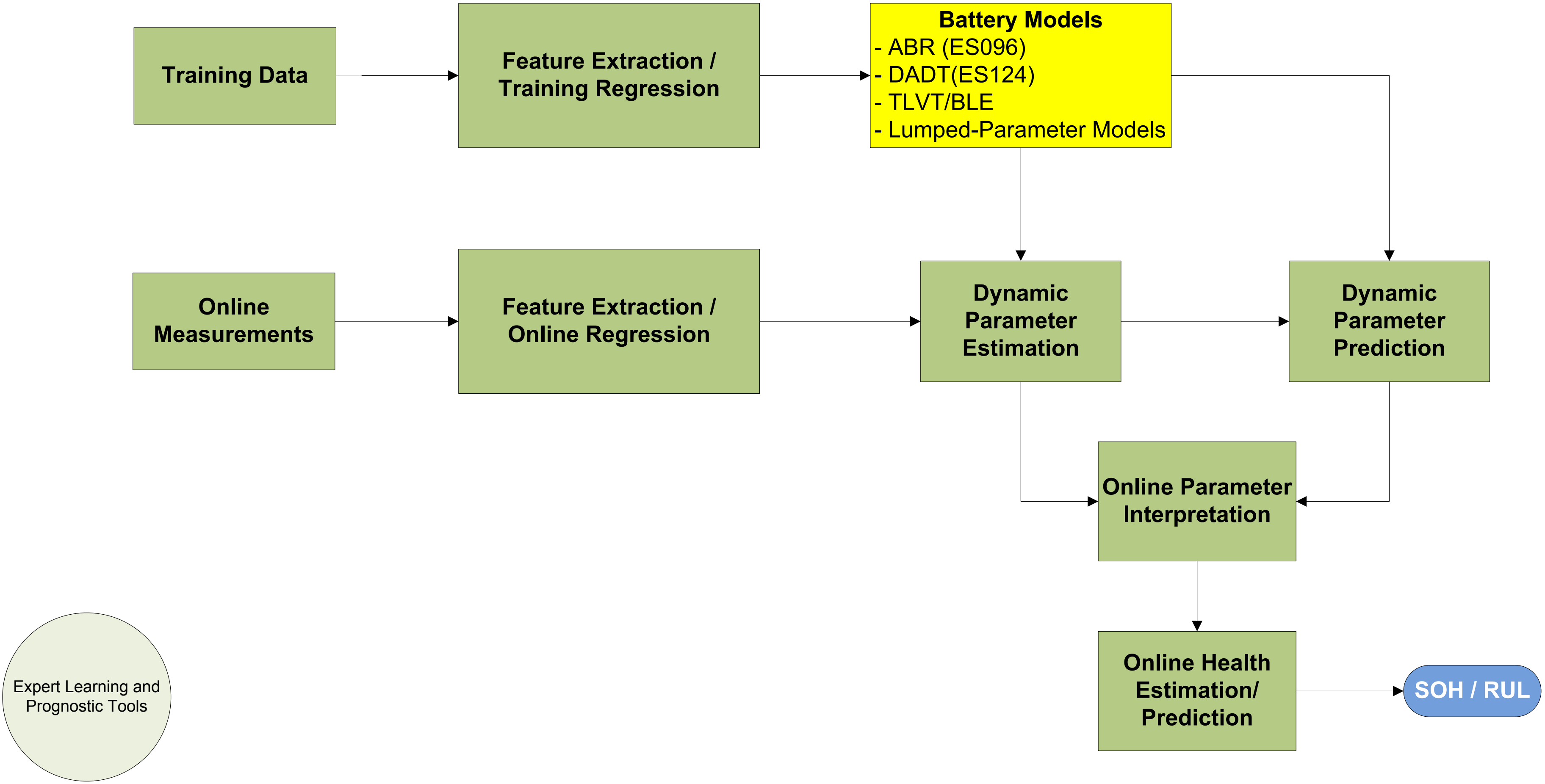
- **Hardware Development:**
  - The 50-V Impedance Measurement Box, including prototype hardware and upgraded control software, has now been completed.
  - Upgraded features for this hardware system include:
    - Applied dynamic voltage range between 0 and 50 V (i.e., system can test 5-V cells and 50-V modules)
    - Significantly reduced noise crosstalk in voltage feedback loop when removing the DC bias (up to 50 V)
    - Modular design for easier debugging and future upgrades
    - Voltage and current probe protection
    - Improved calibration technique



Hardware Development

Accomplishments and Progress (cont.)

- **Modeling and State-of-Health Estimation:**
  - Preliminary SOH assessment tool under development using results from the HCSD validation studies.



Collaborations

- **Montana Tech of the University of Montana:**
  - Expertise in signal processing, hardware design
  - A professor and several graduate students have been involved in this effort.
- **Qualtech Systems, Inc.:**
  - Expertise in software development
- **Other (future) collaborators:**
  - Agreement for a developmental collaboration between INL and the Army (CERDEC) is being drafted.
  - Various discussions with private industry about IMB/ESMS applications are also underway.

Proposed Future Work

- **Impedance Measurement Box:**
  - Investigate possibility of lower frequency measurements while still retaining fast measurement speeds.
  - Mitigate observed transient effects and bias voltage error for under-load measurements.

- **Modeling:**
  - Develop dynamic parameter estimation and prediction tools for online prognostics at arbitrary aging conditions.
    - Feature extraction from impedance spectra
    - New and existing modeling tools (e.g., ES124)
  - Continue validation testing for enhanced modeling capability.

- **Energy Storage Monitoring System:**
  - Explore low-cost hardware solutions for embedded system applications.
  - Seek collaborative opportunities with other groups involved in battery prognostics and control.

Summary

- **The Impedance Measurement Box (IMB) enables low-cost, rapid, in-situ impedance spectra measurements.**
  - The IMB addresses cost, safety, performance, and life estimation barriers for energy storage devices.

- **Significant IMB accomplishments:**
  - The 50-V Gen 3 IMB hardware design has been completed.
  - Improved calibration techniques have been implemented for more accurate impedance measurements.
  - Initial validation study is complete and a new study is underway with rapid impedance measurements at multiple DODs.

- **A preliminary state-of-health assessment architecture design has been developed.**
  - Dynamic parameter estimation and prediction rely extensively on battery modeling capability and training regression tools

TECHNICAL BACK-UP SLIDES

Impedance Measurement Box

- **Novel techniques have been developed to acquire wideband impedance within seconds:**
  - Impedance Noise Identification (INI)
    - Very high resolution, computationally very intensive, very long test duration
  - Compensated Synchronous Detection (CSD)
    - Lower resolution, computationally intensive, long test duration
  - **Harmonic Compensated Synchronous Detection (HCSD)**
    - Low resolution, computationally intensive, short test duration
  - Fast Summation Transformation (FST)
    - Low resolution, computationally simple, short test duration
  - Cross-Talk Compensation (CTC)
    - High resolution, computationally intensive, short test duration

- **INL, Montana Tech, and Qualtech Systems Inc. collaborated on the development of these techniques .**

HCSD Validation Testing

- **Purpose of the initial HCSD validation tests:**
  - Demonstrate the effectiveness of the rapid impedance spectra measurement technique under both no-load and load conditions using Sanyo SA cells.
- **Cells aged at 40 and 50°C for 150,000 cycles with periodic reference performance tests (RPTs) to gauge degradation.**
- **HCSD measurements under no-load conditions conducted on all cells at each RPT.**
- **HCSD measurements under load conditions conducted on some cells during cycling.**
  - Designated cells were subjected to a total of 10,000 HCSD measurements under load with no obvious signs of additional degradation.

Sanyo SA Cells

- **Chemistry:**
  - Li(Mn, Co, Ni)O_2 + Li-Mn-O spinel / Graphite
- **Rated Capacity:**
  - 1.2 Ah (C/1 Rate)
- **Battery Size Factor:**
  - 1400
- **HPPC Voltage Range:**
  - Vmax = 4.1 V
  - Vmin = 3.0 V
- **USABC Application:**
  - Minimum PHEV

Voltage Bias (Under Load)

- The voltage bias profile for HCSD measurements under load can be observed with simulations.
- A bias voltage remains once the DC term is removed and it affects the measured spectra, especially at low frequencies.