Electrochemical Performance Testing

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Project ID: ES201

Overview

Timeline

- Facility established: 1976
- End: Open – this is an on-going activity to test/validate/document battery technology as technologies change and mature

Budget

- DOE Funding FY14: $2.0 M
- FY13: $2.3 M
- FY12: $2.3 M

Barriers

- Performance (power and energy densities)
- Cycle life (1,000-300,000 depending on application)
- Calendar life (15 y)
- Low-temperature performance

Collaborations

- US battery developers
- Idaho National Laboratory, Sandia National Laboratories
- CATARC (China)

Relevance

Objective

- To provide DOE and the USABC an independent assessment of contract deliverables and to benchmark battery technology not developed under DOE/USABC funding
- To provide DOE and the USABC a validation of test methods/protocols
- To utilize test data to project battery life

Approach

- Apply standard, USABC testing methods in a systematic way to characterize battery-development contract and benchmarking deliverables
- Characterize cells, modules and packs in terms of:
  - Initial performance
  - Low temperature performance/Cold cranking
  - Cycle life
  - Calendar life
- Compare test results to DOE/USABC goals
- Adapt the test facility hardware and software
  - to accommodate programmatic need
  - to accommodate the unique needs of a given technology and/or deliverable

Program Milestones

- All deliverables below were characterized in terms of initial performance, calendar and cycle

Milestone	Due date	Status
Complete testing of JCI/USABC cells	12/31/2013	Delayed. The USABC decided to keep these on test.
Complete testing of ActaCell/USABC cells	3/31/2014	Complete
Complete testing of SKI/USABC cells	6/30/2014	Delayed. The facility moved to a new location
Start testing Leyden Energy cells	9/30/2014	On track

Technical Accomplishments: Progress and Results - Testing Contract Deliverables

- Test deliverables are mostly cell-oriented and include developments in
  - Lithium-ion battery chemistry (graphite anodes)
  - Silicon anodes
  - Lithium metal anodes
  - Separators
  - Advanced cell chemistries (beyond Li-ion)
- Deliverables are characterized in terms of initial capacity, resistance, energy and power. They are then evaluated in terms of cycle and calendar life for the given application
- Results are used to show progress toward meeting DOE/USABC initial commercialization goals

Progress and Results – Testing Contract Deliverables

- Test deliverables come from many developers

Developer	Sponsor	Level	Quantity	Capacity (Ah)	Application	Status
JCI	USABC	Cell	6	27	PHEV 20	on-going
	DOE FOA	Cell	18	15	PHEV 20	complete
	DOE ARRA	Cell	6	41, 6	PHEV 20, HEV	on-going
	USABC	Cell	18	36	PHEV 20	on-going
	DOE FOA	Cell	18	3	PHEV 20	on-going
SKI	USABC	Cell	18	40	EV	on-going
Actacell	USABC	Cell	9	4	LEESS	complete
Cobasys	USABC	Cell	15	36.5	EV	on-going
Dow Kokam	DOE FOA	Cell	15	2.1	EV	on-going
OptoDot	DOE FOA	Cell	9	2.1	EV	on-going
Sakti3	USABC	Cell	18	0.0024	EV	complete
3M	DOE FOA	Cell	18, 6	1.7, 2.7	EV	on-going
Seeo	DOE FOA	Cell	6	0.00897	EV	complete
Tiax	DOE FOA (ABR-IC^{3}P)	Cell	14	2	based on EV+PHEV	on-going
3M	DOE FOA (ABR-IC^{3}P)	Cell	14	0.5	based on EV+PHEV	on-going
Leyden Energy	USABC	Cell	15	2.2	12 V Start/Stop (LMO/LTO)	on-going
Navitas	DOE FOA	Cell	13	5 x 4; 8 x 2	EV	on-going

Progress and Results – Collaborative US/China Protocol Comparison

- Battery testing is a time-consuming and costly process
- There are parallel testing efforts, such as those in the US and China
- These efforts may be better leveraged through international collaboration
- The collaboration may establish standardized, accelerated testing procedures and will allow battery testing organizations to cooperate in the analysis of the resulting data
- In turn, the collaboration may accelerate electric vehicle development and deployment
- There are three steps in the collaborative effort

Step	Status
Collect and discuss battery test protocols from various organizations/countries	Complete
Conduct side-by-side tests using all protocols for a given application, such as an EV	Complete in US
Compare the results, noting similarities and differences between protocols and test sites	In progress

Conduct Side-by-Side Experiments

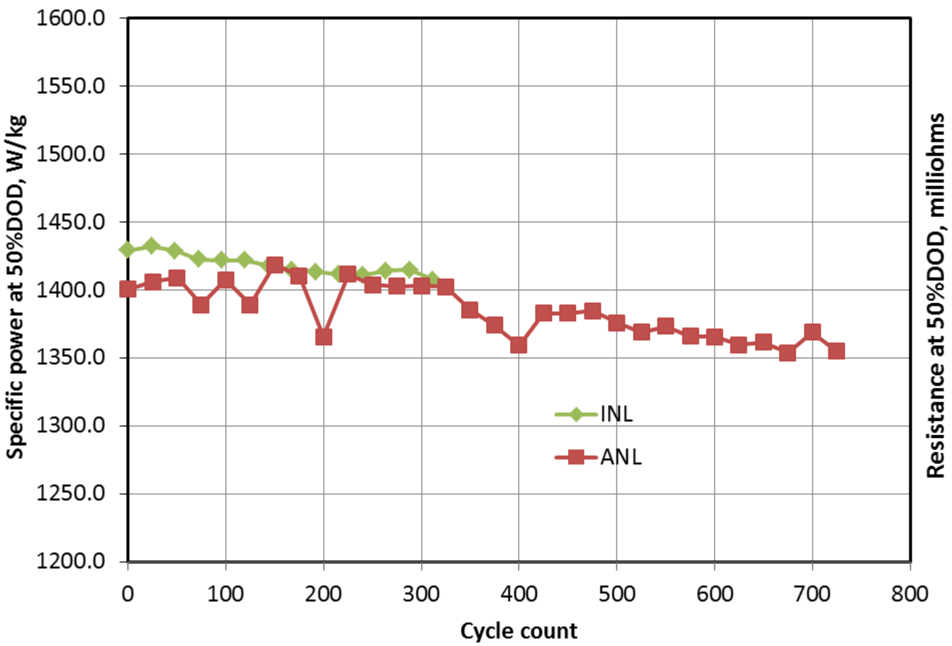
- A test plan based on an EV application was written and agreed to
- Commercially-available batteries based on $LiFePO_4$ and carbon were procured. The batteries were distributed to ANL, INL* and CATARC (China)
- Initial similarities and differences
  - The US cycle-life aging protocol consists of a dynamic, constant-power profile and constant-current charging
  - The Chinese cycle-life aging protocol consists of constant-current discharges and charges
  - USABC Reference Performance Test consists of 2 capacity cycles, peak power pulse test at 10% DOD increments and full DST cycle. The cells are characterized using these performance tests every 50 cycles
  - China Reference Performance Test consists of 1 capacity cycle and 10 second discharge pulse at 50% DOD. The performance of the cells were characterized using these performance tests every 25 cycles
  - Both cycle-life protocols terminate discharge at 80% DOD

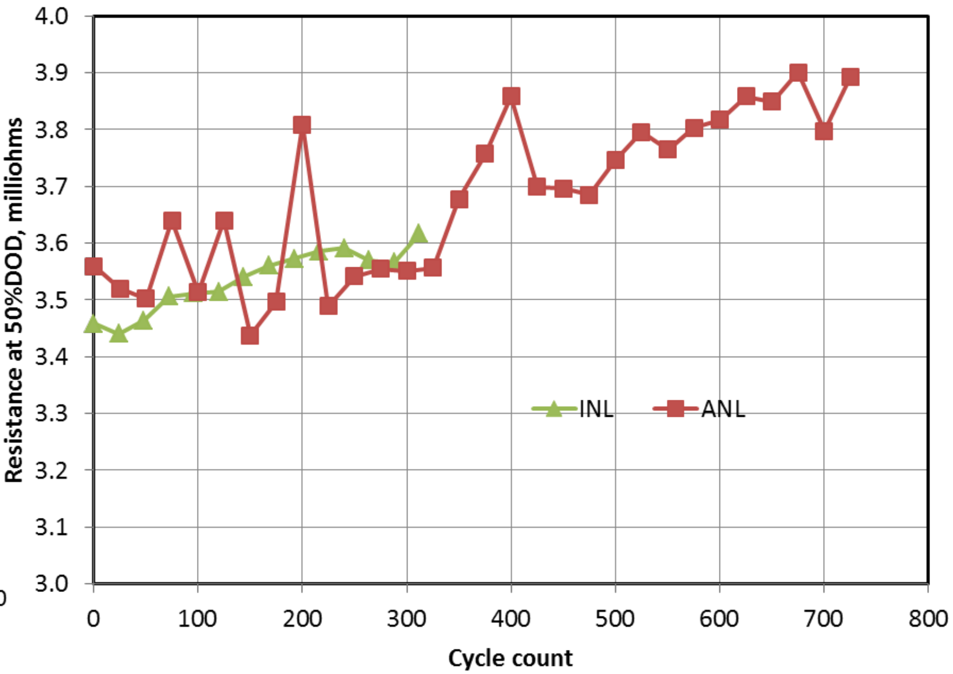
*Jon Christophersen, Taylor Bennet

Comparing the Protocols Shows…

	USABC	China
DOD (Energy) Window	0-80% DOD	0-80% DOD
Temperature	25 °C	25 °C
Capacity measurement rate	C/3	C/3
End of Test criteria	80% degradation	80% degradation
Cycle Type	Dynamic, Power based	Constant-current
Power Capability Measurement	Peak Power Pulse Estimation at 80% DOD	Pulse Power Density at 50% DOD
Pulse duration	30 seconds	10 seconds
Pulse Current	75A	225A
RPT Frequency	50 cycles (10.5 days)	24 cycles (6 days)
RMS power of cycle	50-51 W	12-13 W
RMS current of cycle	15-16 A	3.5-4 A
Average Voltage of cycle	3.17V fading over time	3.27V without fading
Energy throughput of cycle	27 Wh	19.5 Wh

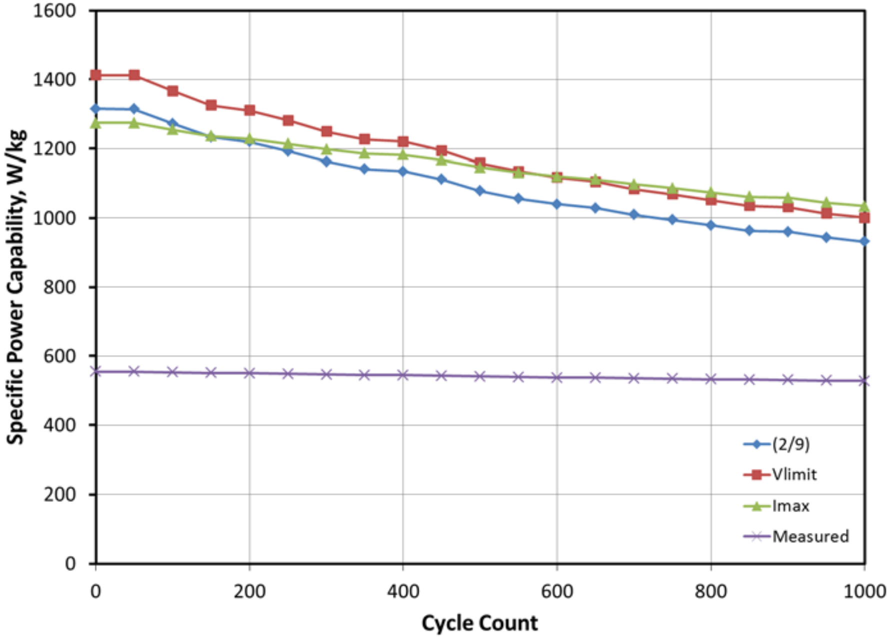
Chinese Protocol Results – Effects of Cycling on Resistance and Power

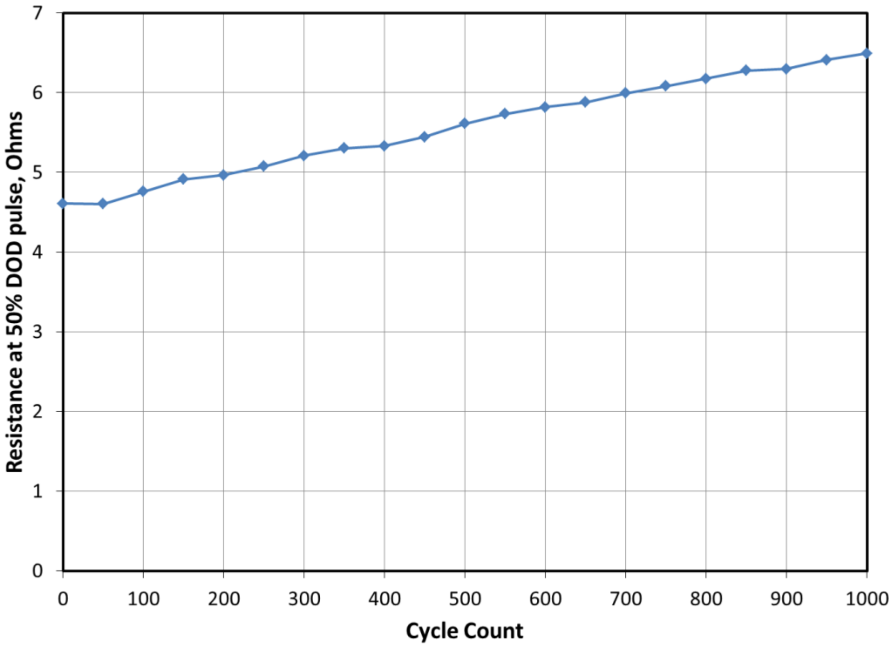




- Power density at 50% DOD decreased ~3.3% over the course of 725 cycles
- Resistance at 50% DOD increased ~9.3%
- Data from INL and ANL are consistent

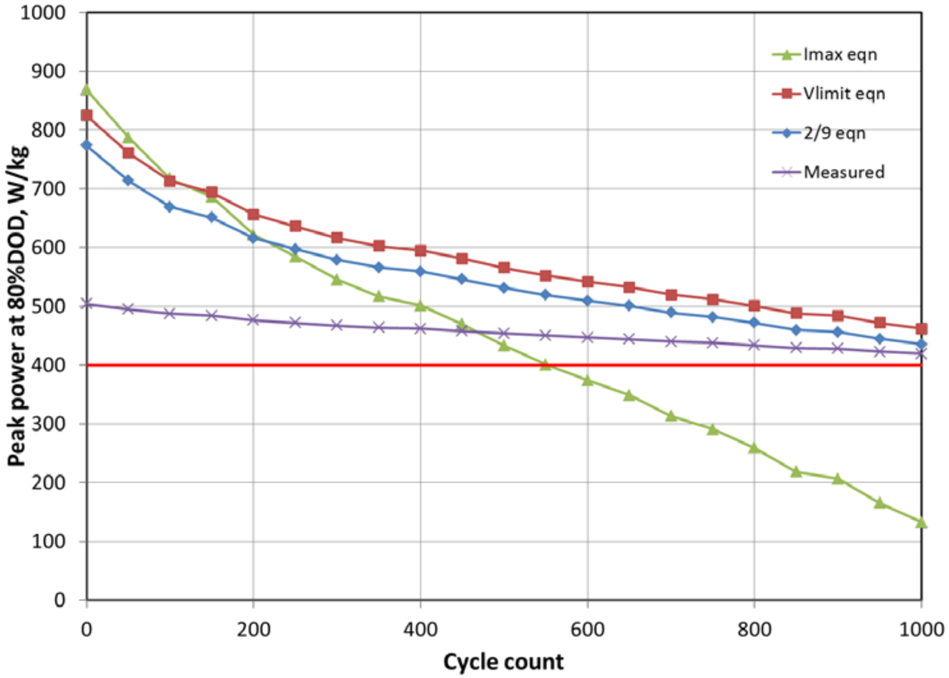
USABC protocol results – Effects of Cycling on Resistance and Power at 50% DOD

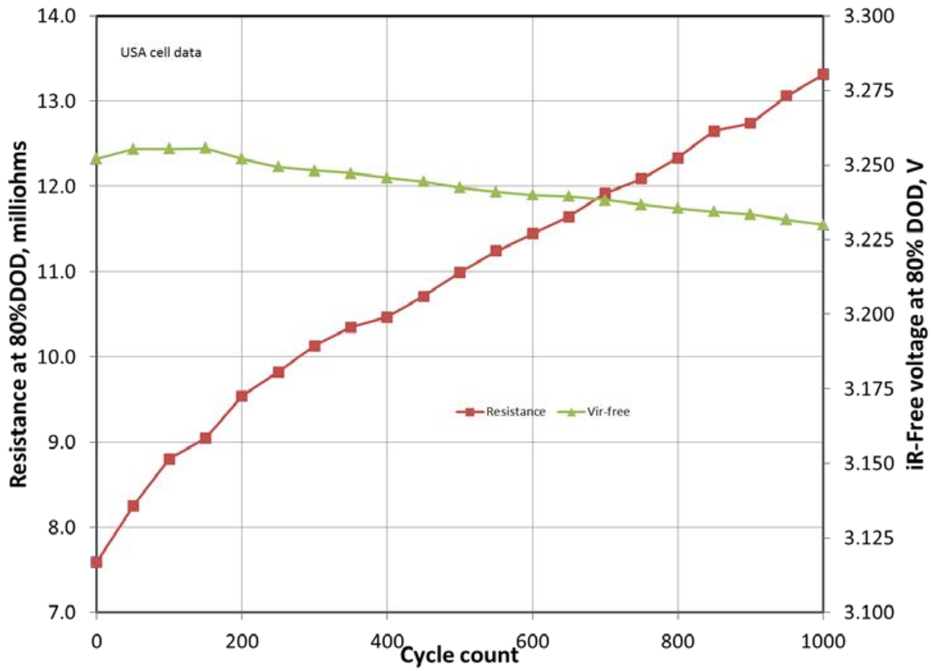




-The effect of USABC DST cycles shows a clear degradation and aging trend in resistance and power capability.
-Comparing the 50% DOD pulse show similar beginning of life capabilities for both test methods.

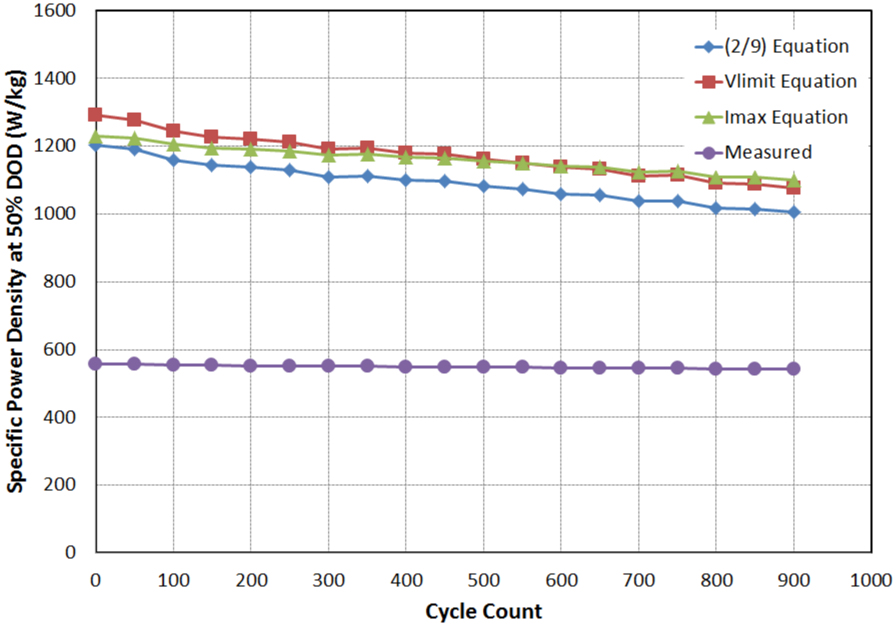
USABC protocol results – Effects of Cycling on Resistance and Power at 80% DOD





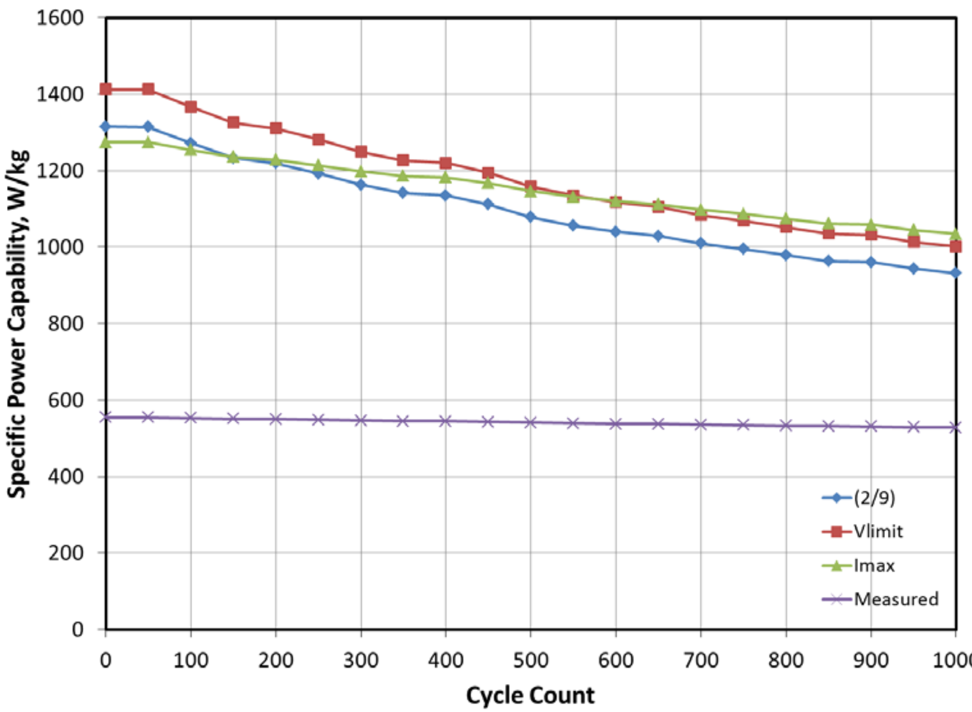
- USABC test method focuses on 80% DOD capability
- 80% DOD is considered worst condition of EV operating range
- Increase in resistance and decrease in power capability are more pronounced at this depth of discharge
- According to USABC protocols, this cell failed at 550 cycles

Comparing USABC Results at 50% DOD from INL and ANL Shows They Are Similar



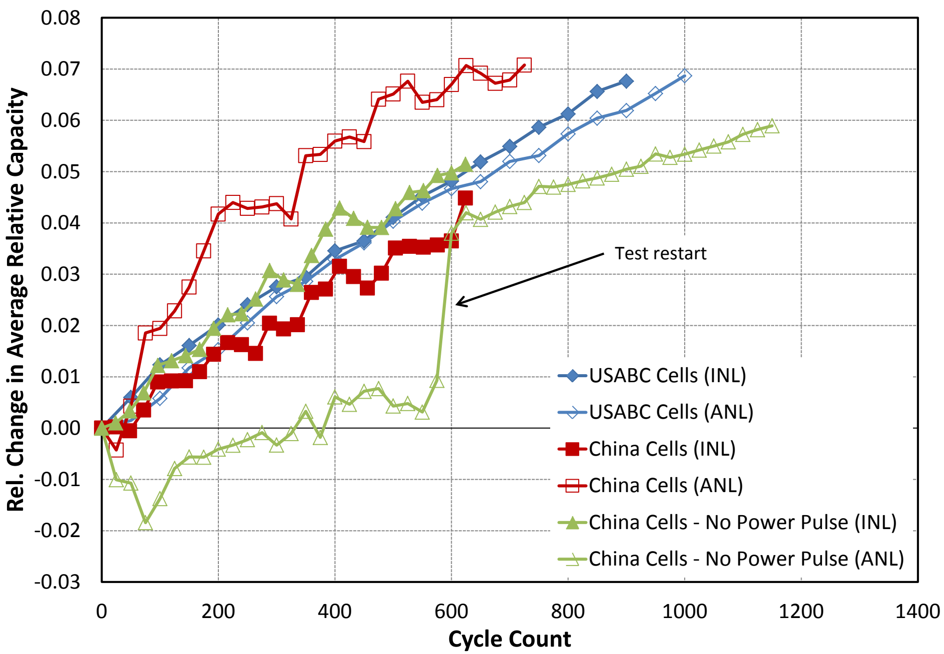
INL

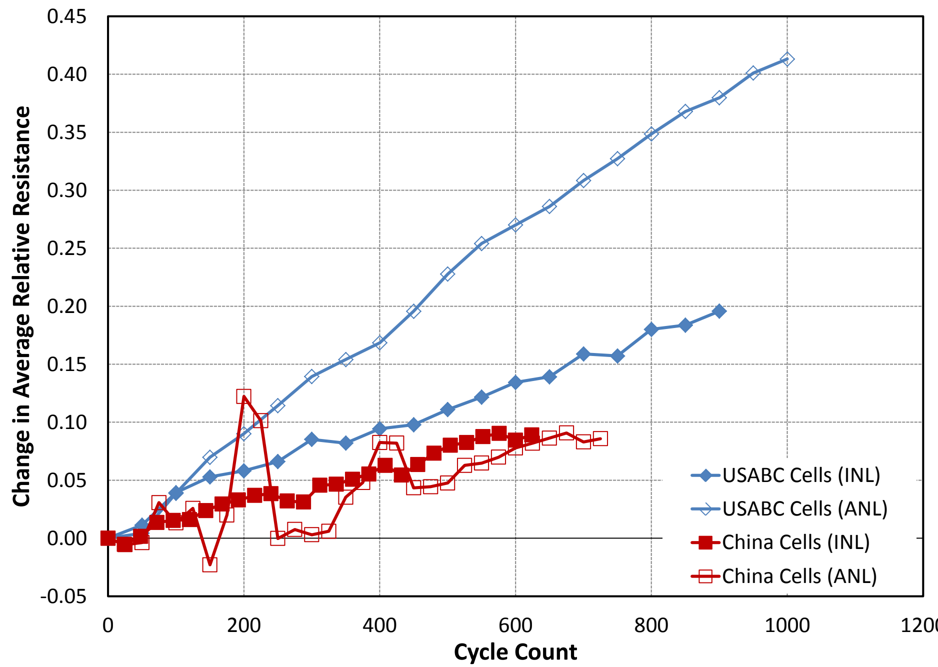
ANL



- Data are similar
- Differences may be due to cell-to-cell variation

Normalized Capacity and Resistance trends





- Capacity degradation observed in all test methods at both sites. There appears to be little dependence on test method
- After restarting the test after about 8 weeks, a significant capacity loss was seen, but the aging data follow the earlier trend
- Resistance increase was more significant using the USABC protocol at ANL than those seen at INL or using the Chinese protocol at ANL. It is not known why there were differences between the sites. Cell-to-cell variability is a possible source
- **Temperature had a strong effect on the resistance data!!!**

Comparing the Results Shows…

- There are similarities and differences in the test protocols
- Results indicate that:
  - For capacity, the Chinese test protocol produced slightly more fading that the USABC at both ANL and INL
  - For resistance, the USABC test protocol caused a greater increase in cell resistance at both test sites
- We still need to compare these results with those from CATARC

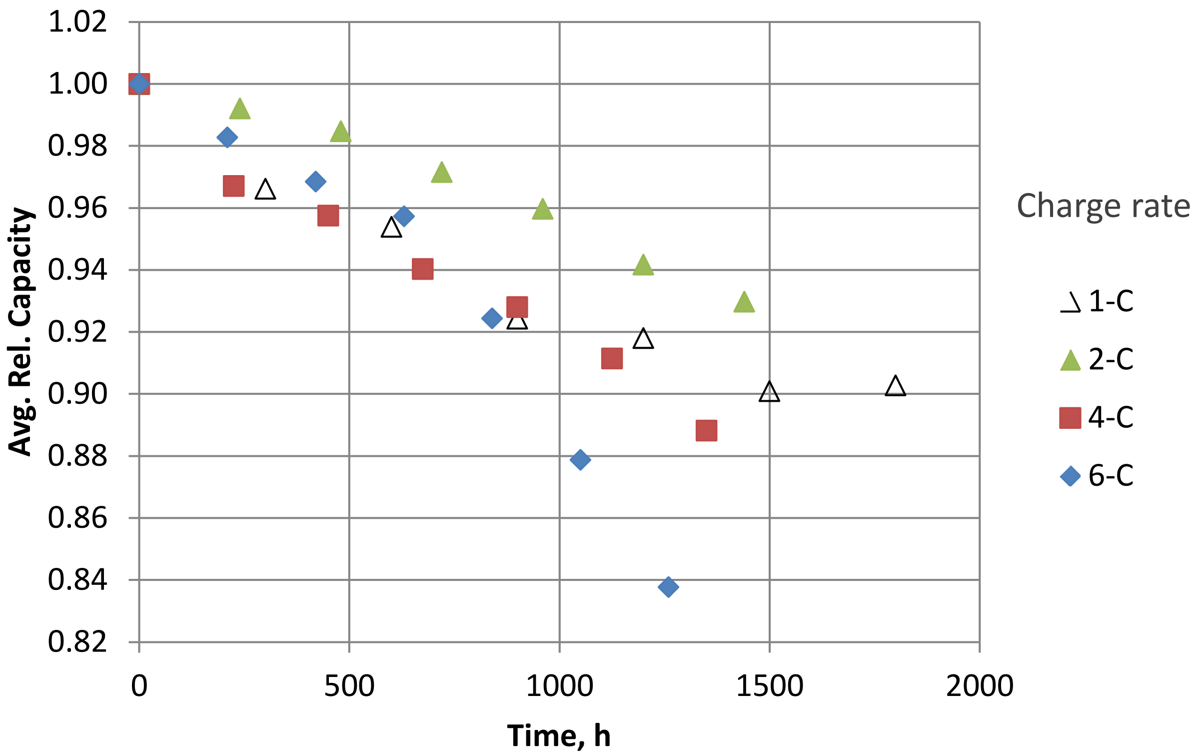
Progress -- Protocol Validation/Effect of Fast Charge

- With further vehicle electrification, customers would desire battery charging to take the same amount of time as refueling an ICE does at a service station. This does not have to be a full charge
- The Fast Charge Test in the USABC EV Manual[2] determines the impact of charging a battery from 40 to 80% SOC at successively faster rates, starting from about twice the overnight rate. Since the manual was written for Ni/MH technology, the ideas were adapted for the higher-performing, lithium-ion cells
- Two commercial, lithium-ion cell chemistries, A and B, were chosen based on NMC materials in the form of 18650 cells
- Two tests were planned for each chemistry:
  - 0 to 100% SOC charging at the manufacturer's rate (~C-rate), 2C-, 4C- and 6C-rate
  - Limited charging, between 40 and 80% SOC, at the above rates
  - RPTs (C/1 capacity and EV Peak Power Test) every 100 cycles

[2]Electric Vehicles Battery Test Procedures Manual, Rev. 2, January 1996.

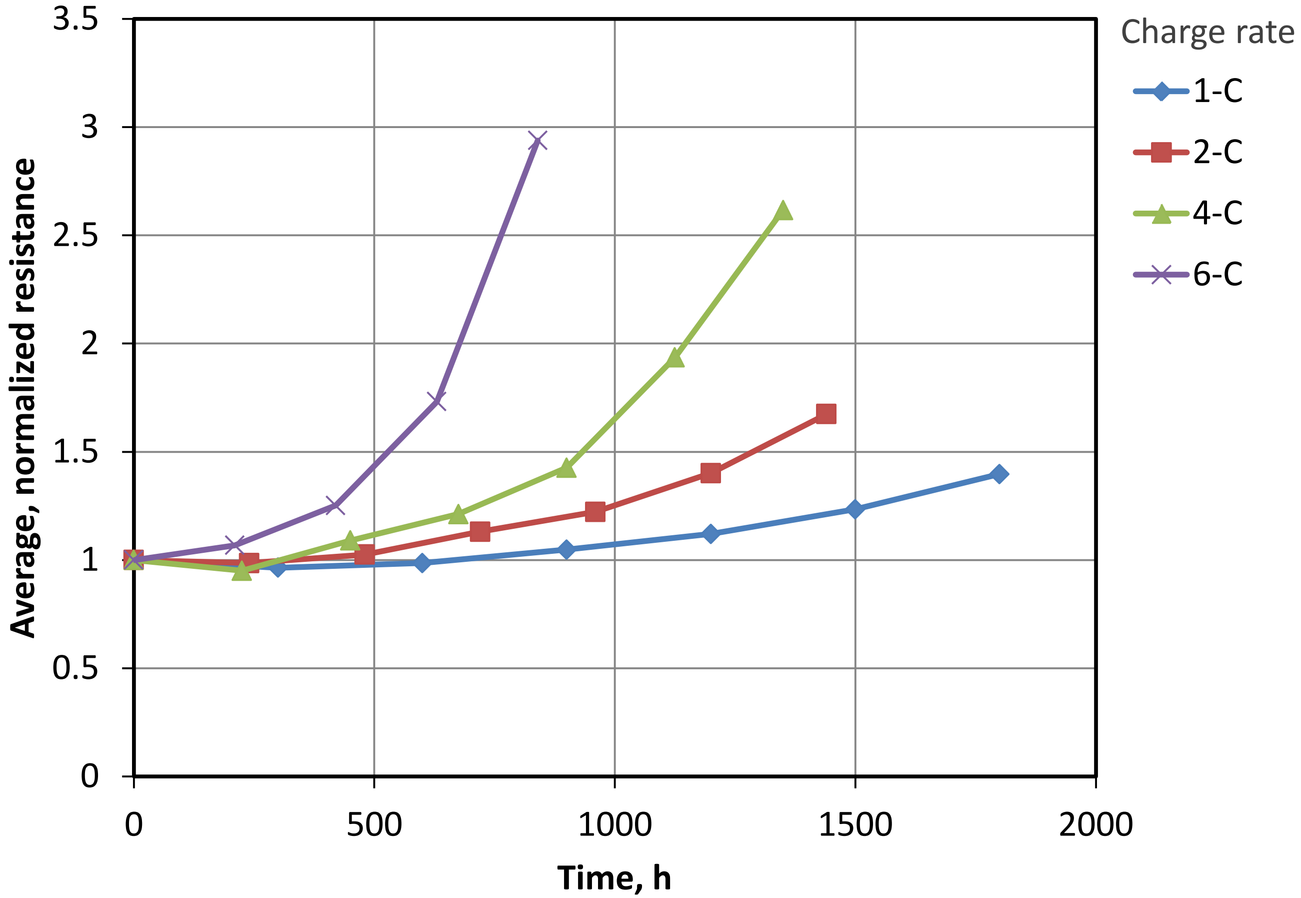
Effect of Fast Charge on Cell Performance - Capacity

- Chemistry A
- 0-100% SOC charge
- Rate of capacity fade depends on charge rate, but there is not a simple, linear relationship

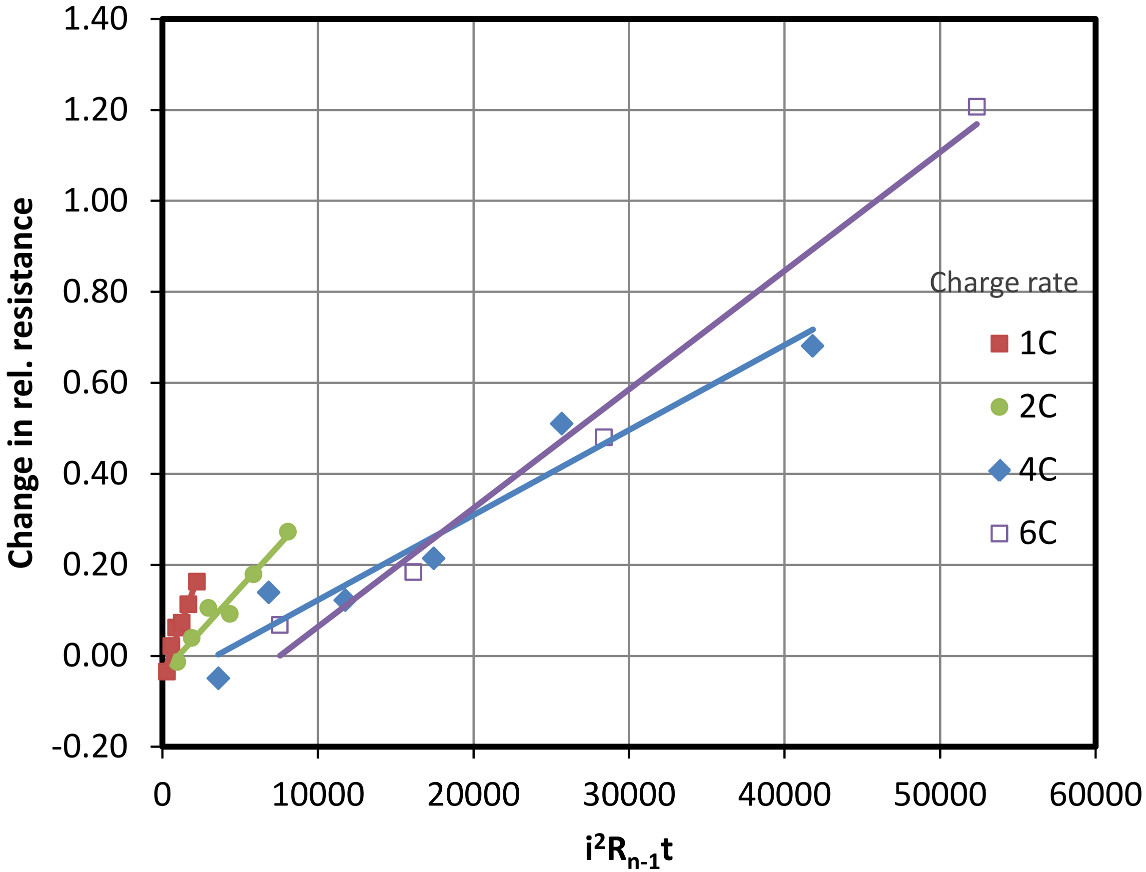


Effect of Fast Charge on Cell Performance - Cell Resistance

- Rate of resistance increase depends on charge rate
- Rate of resistance increase accelerates with time



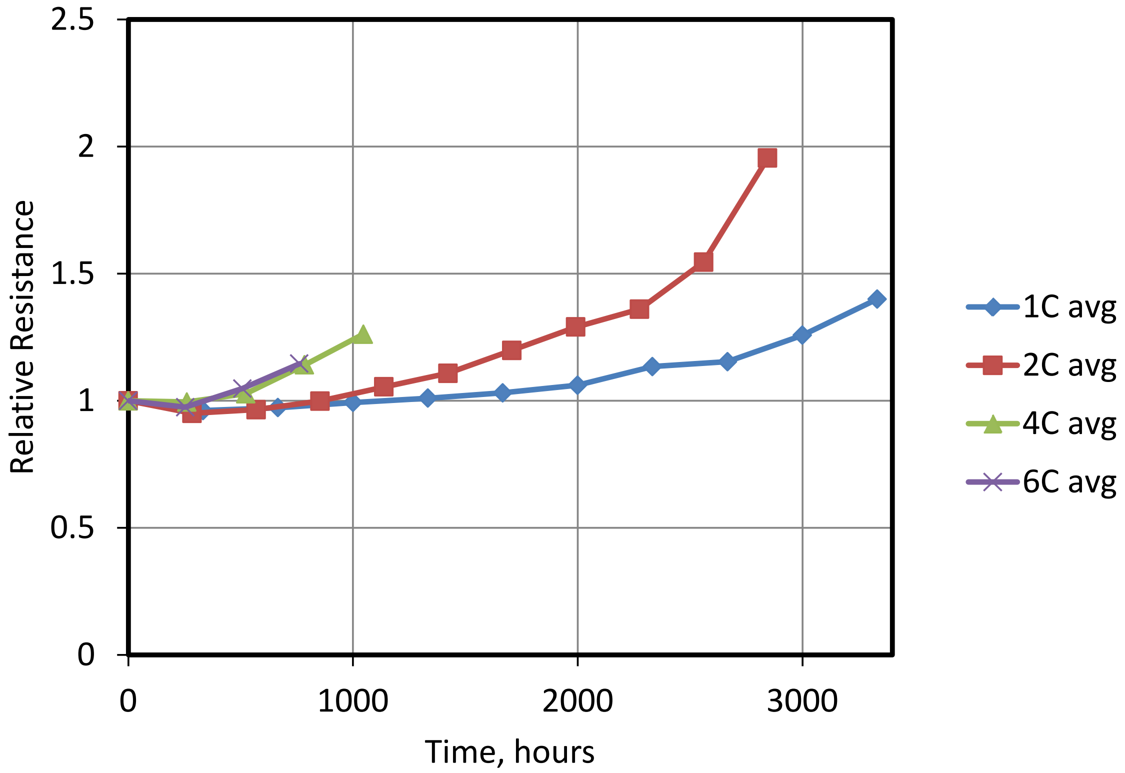
Change in Cell Resistance Depends on Charging Current



- Increases in cell resistance and the rate of increase depend on prior values of cell resistance and energy loss
- Indicates internal, i^2R heating and the time of being heated are important
- Practical implications are that active cooling provided during fast charging could mitigate degradation

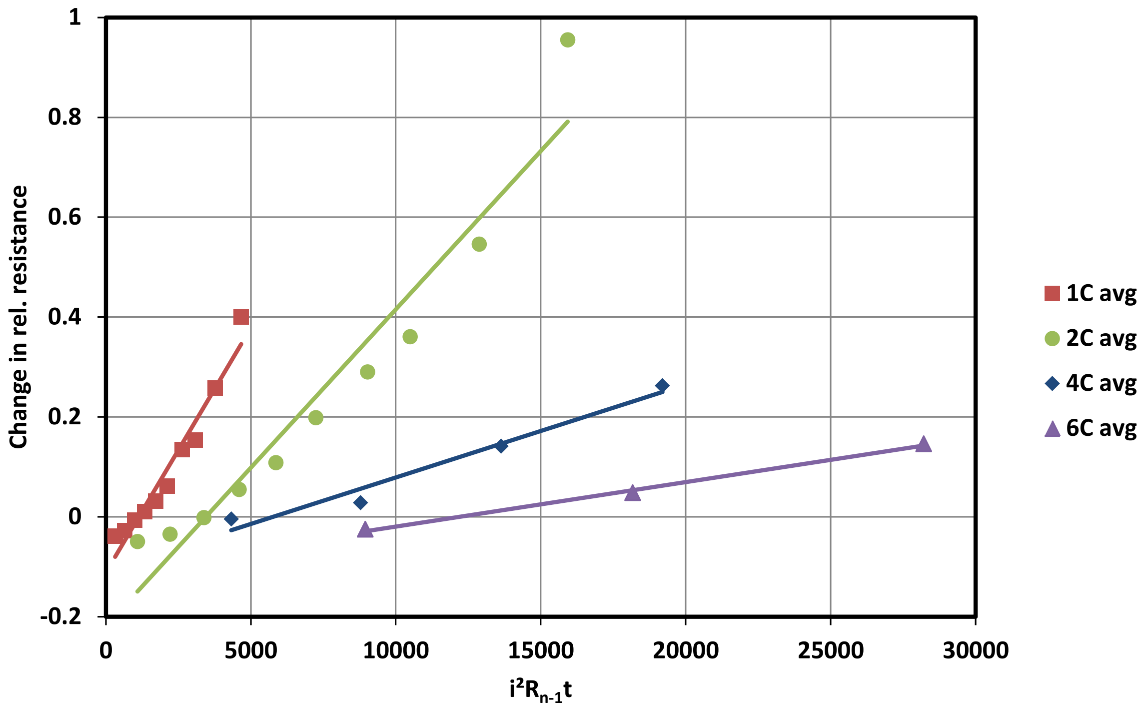
Effect of Cell Chemistry on Resistance Increase (1)

- Chemistry B
- 0-100% SOC charge
- Response of relative resistance looks similar to that from Chemistry A



Effect of Cell Chemistry on Resistance Increase (2)

- Plotting the response versus $i^2R_{n-1}t$, energy loss due to iR heating, shows that there may be difference, especially at low rates
- More data at the higher rates are needed to confirm trend



Summary and Future Work

- Summary
  - Hardware deliverables from many sources have been tested at Argonne and continue to be evaluated for a variety of vehicle applications
  - This testing directly supports DOE and USABC battery development efforts
  - The US/China Protocol Comparison has shown
    - There are similarities and differences in the test protocols
    - For capacity, the Chinese test protocol produced slightly more fading that the USABC at both ANL and INL
    - For resistance, the USABC test protocol caused a greater increase in cell resistance at both test sites
  - The results of the fast charge test have shown that cell heating at high charge rates is the main cause of resistance increase. This result may have practical implications
- Future Work
  - Continue to support the DOE and USABC battery development efforts by performing unbiased evaluations of contract deliverables, using standardized test protocols
  - Complete the protocol comparison effort as soon as data are available from China. Discuss implications of the results with the participants and report them
  - Complete the fast charge experiment. Continue to support protocol evaluation efforts, as needed

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