INL/LTD-20-57812-Revision-0

INL Energy Storage Overview

February 2020

Changing the World's Energy Future

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Idaho National Laboratory

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INL Energy Storage Overview

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2/25/20

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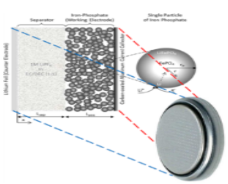
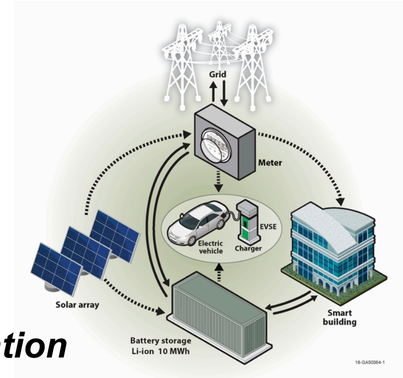
INL Advanced Transportation

Understanding material limitations



Advanced Battery Characterization

Secure, intelligent, connected infrastructure



U.S. DEPARTMENT OF ENERGY SMARTMOBILITY
Systems and Modeling for Accelerated Research in Transportation

Quantification, verification and validation across temporal and spatial domains

Encompassing materials to advanced mobility

Vehicles, Energy Storage & Infrastructure

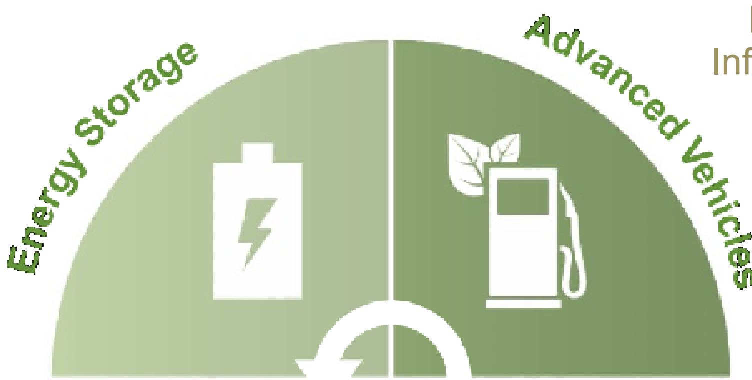
Using known operational conditions to understand limitations and provide solutions

- Benchmark, advanced aging and activities with USABC (Ford, GM and FCA)
- 30+ years experience in energy storage
- Advancing fundamentals of durability, reliability and safety – *high power and energy*
- Evaluation from cell level to full vehicle packs
- Standard and aggressive operating conditions

Battery Test Center (BTC)

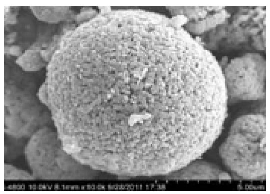
Non-destructive Battery Evaluation Lab (NOBEL)

Electric Vehicle Infrastructure Lab (EVIL)



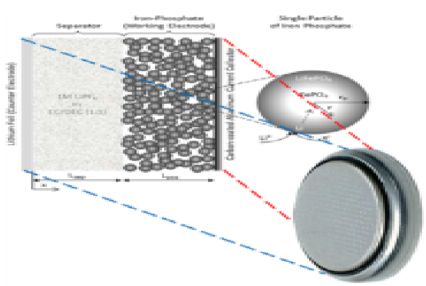
INL Approach

Safety, Reliability, Durability



Materials

- Classical materials development



Structure, Integration And Combination

- Optimization for cross talk, minimize impact to components/integrated system

Quantitative Analysis

Full Cell

- Increased depth and length

Technology Goals

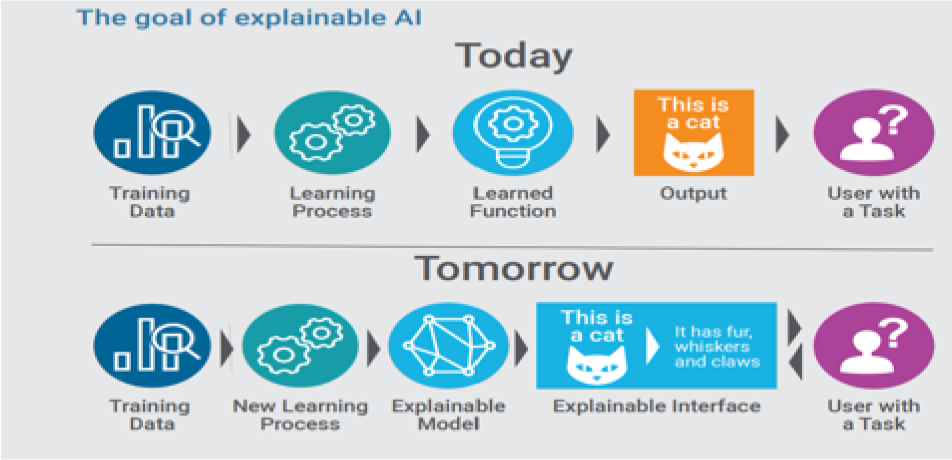
Table II-5. U.S. Advanced Battery Consortium Goals for Electric Vehicle Batteries

Primary Criterion	Long-term goals[6] (2005-2008)
Power Density, W/L	460
Specific Power, W/kg (80% DOD/30 sec)	300
Energy Density, Wh/L (C/3 discharge rate)	230
Specific Energy, Wh/kg (C/3 discharge rate)	150
Life, years	10
Cycle life (cycles)	1000 (80% DOD) 1,600 (50% DOD) 2670 (30% DOD)
Power and capacity degradation[7] (% of rated spec)	20%
Ultimate price[8], $/kWh (10,000 units @ 40 kWh)	<$150 (desired to 75)
Operating environment	-30C to 65 C
Recharge time	< 6 hours
Continuous discharge in 1 hour (no failure)	75% (of rated energy capacity)
Secondary Criteria	**Long-term goals (2005-2008)**
Efficiency (C/3 discharge and C/6 charge[9])	80%
Self-discharge	<20% in 12 days
Maintenance	No maintenance. Service by qualified personnel only.
Thermal loss	Covered by self-discharge
Abuse resistance	Tolerant. Minimized by on-board controls.
Specified by contractor: Packaging constraints, Environmental impact, Safety, Recyclability, Reliability, Overcharge/over-discharge tolerance	

Sources: various literature documents

Status and Opportunity

- Demonstrated ability to predict performance with high fidelity
  - Clustering of data
  - Bootstrap to quantify uncertainty
- Opportunity in emerging R&D, validation and demonstration
  - Flexibility and ability to rapidly adapt to emerging industry needs
  - Multi-lab coordination and use case knowledge expansion
- Support across designs
  - High energy, high power, aggressive use, etc.



Desired ability to understand and define life by chemistry/design

Current Status and Tasks

Correlated and aligned analysis

Mechanism validation

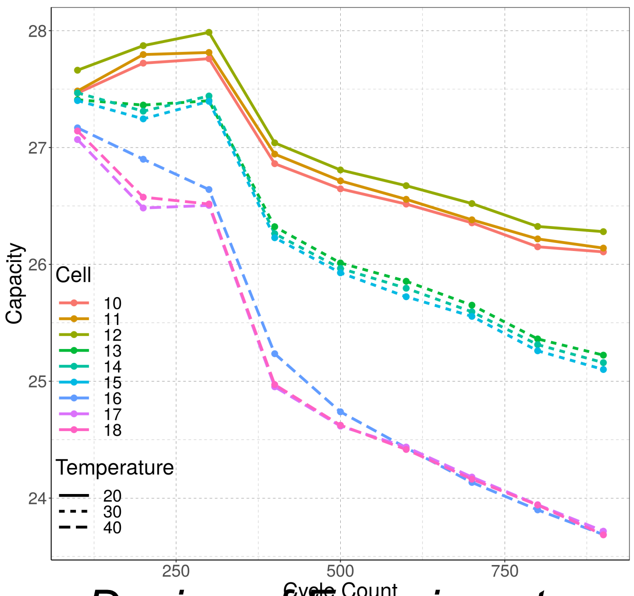
Physics-based feature extraction

Life validation

Leaf Battery Analysis via Machine Learning

- **Goal:** Predict Reference Performance Test Capacity (RPT) from Dynamic Stress Test (DST)
- Target net discharge energy is 74.35Wh.
- 100% Discharge Power = 250 W.
- Rest for approximately 5 minutes rest
- Charge cells at 260.4 W constant power to VmaxOP and taper until C/20 current is reached or 60 minutes of charging have occurred (CP+CV).
- 3 discharge cycles per day.
- DCFC = 50kw
- ACL2 = 3.3kw

DCFC Capacity



Design of Experiment

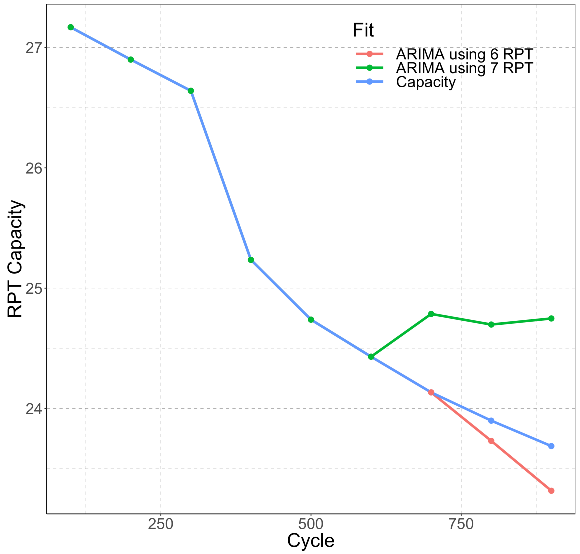
Charging Protocol	V_{max}/V_{min} (V)	Temperature (°C)	Number of Packs/Cells	Capacity at Beginning of Life (Ah)
Pack				
AC Level 2	395/285	30	1	57.10
DCFC		30	1	56.34
Cell				
AC Level 2	4.11/2.5	20	3	28.28±0.02
AC Level 2		30	3	28.33±0.04
AC Level 2		40	3	28.20±0.04
DCFC		20	3	28.30±0.05
DCFC		30	3	28.24±0.05
DCFC		40	3	28.28±0.08
Delayed DCFC		30	3	28.31±0.08

Tanim, Tanvir R., et al. "Fast charge implications: Pack and cell analysis and comparison." *Journal of Power Sources* 381 (2018): 56-65.

Forecasting for a Given Cell

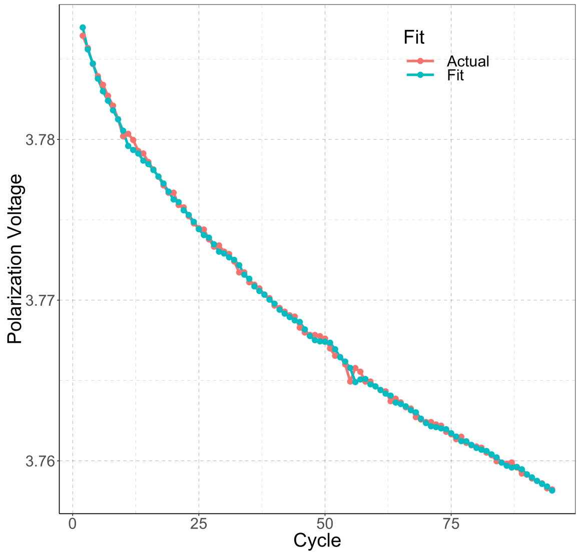
- Time / cycle dependence cannot be ignored
- Use of summary data does not fully capture behavior
- Need physical interpretation of mechanisms
- ARIMA as dimension reduction

Prediction of RPT Capacity with ARIMA



Need physics!

Prediction of Polarization with ARIMA

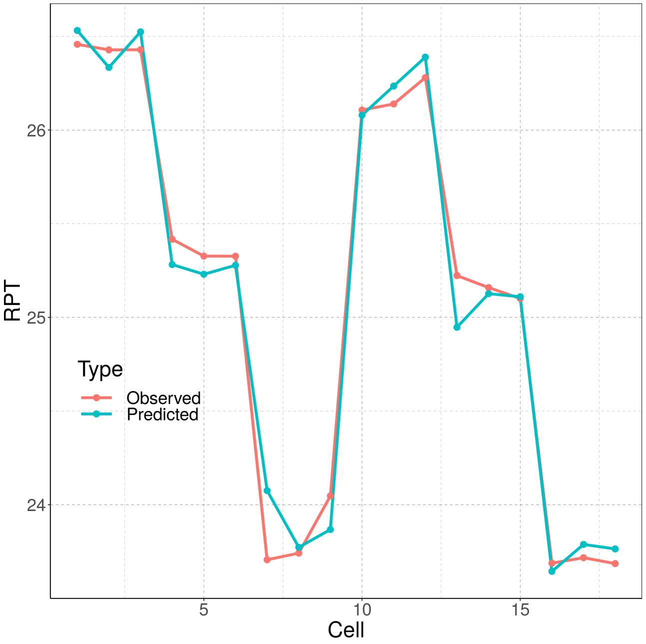


Representation of a time series with only 3 coefficients

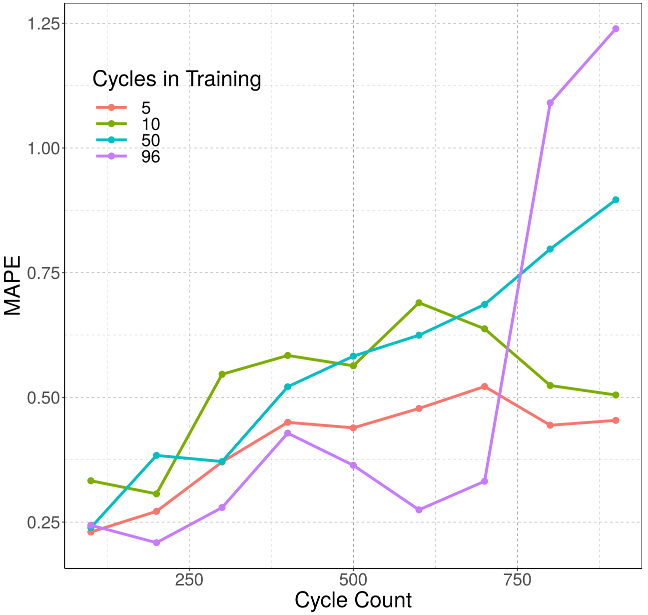
Results

- Able to predict the capacity of the cells at 900 cycles within 1.5% mean absolute percent error
- Dramatically reduce required number of cycles in future prediction
- Able to integrate physics such as Life Model / Cell Sage

Prediction of Capacity at 900 Cycles



Prediction of Capacity using Minimal Cycles



Battery500 Consortium Thrusts

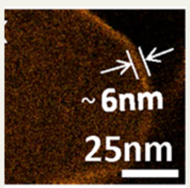
Extract Maximum Capacity from Promising Battery Chemistries

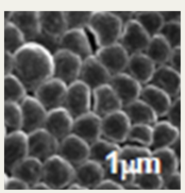
High Ni NMC-Li: achieving >50% of theoretical capacity at cell level

Solid State Li-S: solving polysulfide dissolution and Li degradation problems

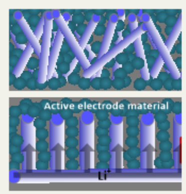
Diagnosis & prognosis, assessment and validation

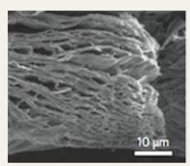
1. Materials/Interfaces:
Mixed conductive coating
Controlled surface reaction



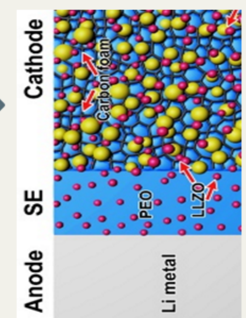


2. Electrode Architecture
Thick, conductive cathode
3D Li composite structure





3. Cell Design/Integration
Cell modeling
1D or 2D Li conductor
De-coupled SEI reactions



Technology off ramp to current improve Li ion batteries

500 Wh/kg Li battery
1000 cycles

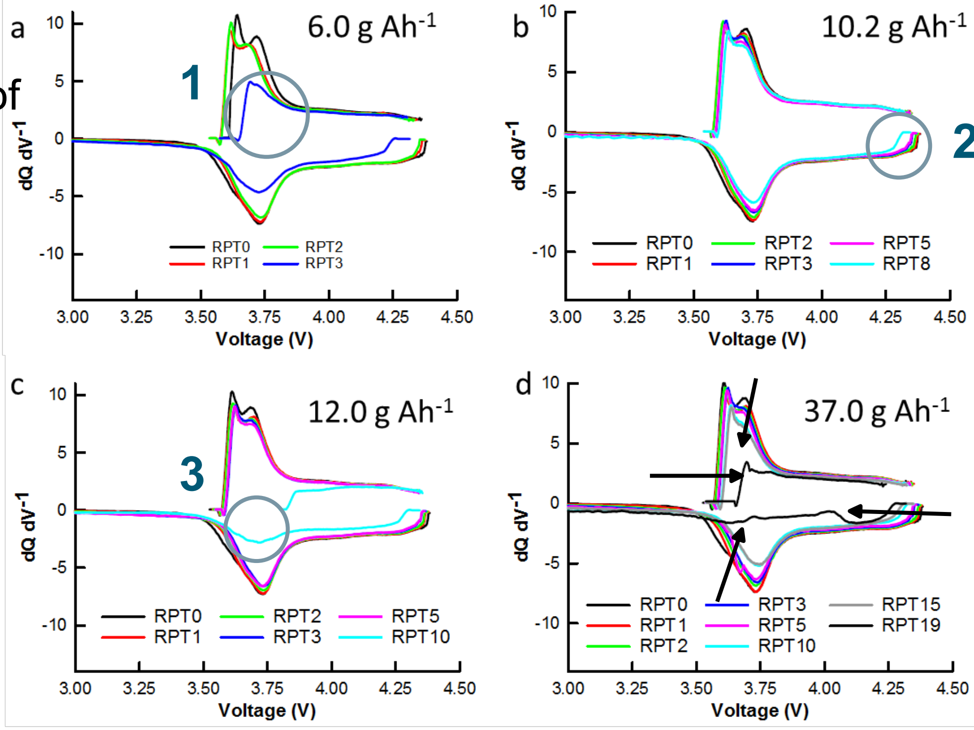
New test bed or spin-off to scale up technologies in US

Seedling projects: emerging concepts, alternative cathodes, 3D printed architectures, lay-by-layer fabrication of solid electrolytes, etc.

Closing the gap experimental gap to cell design

- Refined understanding of cell failure
- At low electrolyte quantities "dry out"/Li transport from electrolyte predominates
- At high loading levels mass transport due to Li metal becomes limiting
- Lessons apply to early identification of cell variability and failure

1. During charging – Only the solid solution region available to accept charge
2. Initial discharge – The initial capacity loss indicates loss of available Li inventory (during charging)
3. During discharge – The cell increasingly suffers from delivering capacity due to passivation on the Li anode



Refined analysis provides early, direct, mechanistic path to comparison

S. Nagpure et. al, submitted to J. Power Sources

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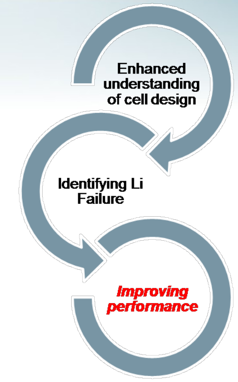
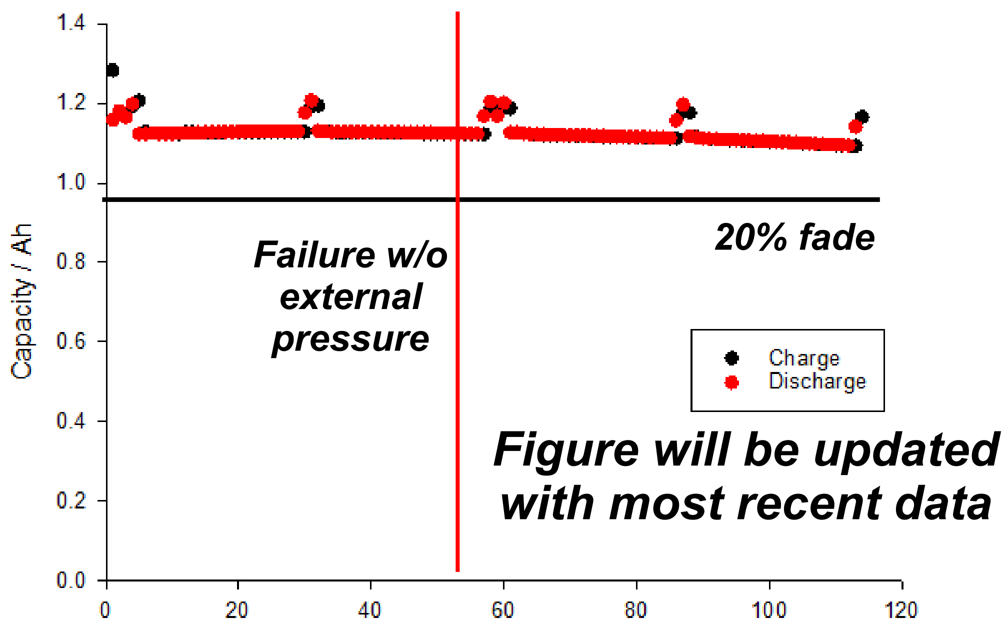
Improving performance with pressure control



- Over 2x life improvement with slight pressure application (0.8 N/cm^2, 1.2 PSI) – *Cell still cycling*
- Discharge specific energy 309 Wh/kg at BOL (C/3)
- *Further optimizing pressure regulation using both Swagelok and pouch cell studies*

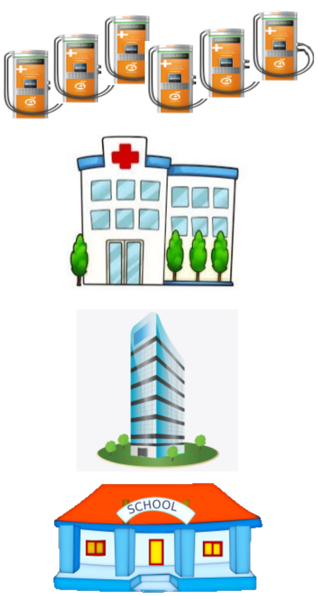


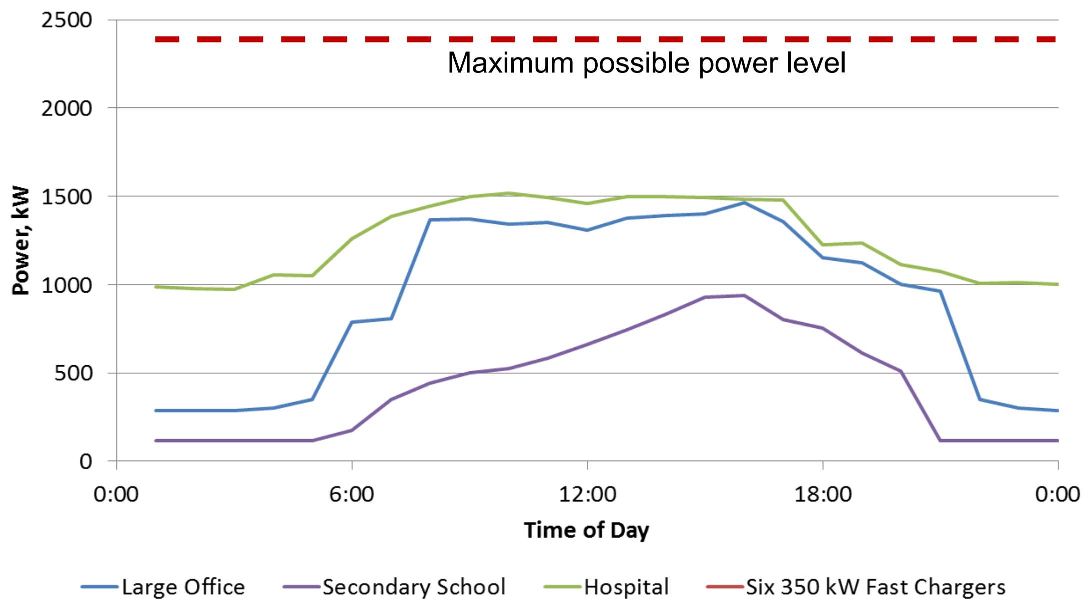
Rigid pressure control significantly improves life

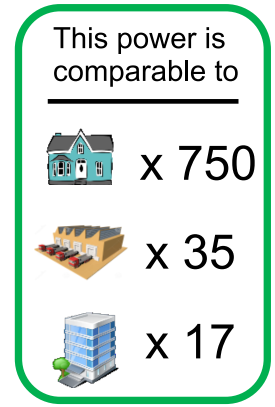
Cell from PNNL, J. Xiao, electrolyte J. Zhang

Extreme Fast Charging

- Charging in 15 minutes or less
  - Key issues with infrastructure, batteries and vehicles







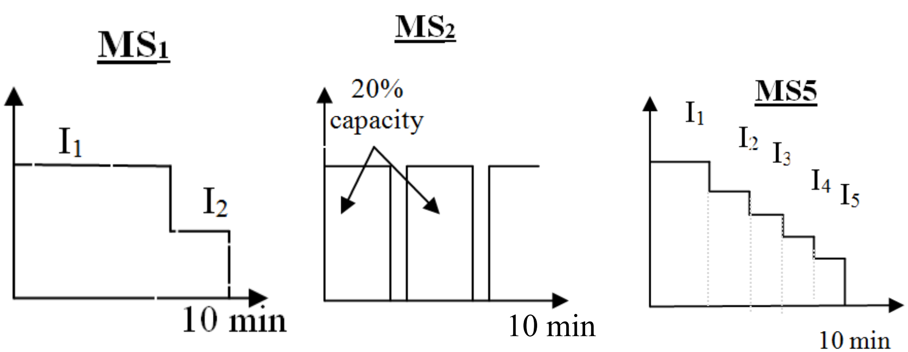
DER may help utilities cope with unpredictable/intermittent XFC power demands

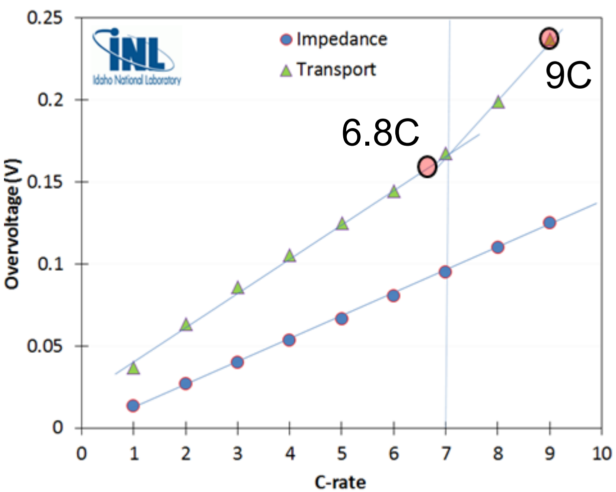
NREL-developed load profile data for DOE commercial reference buildings in Baltimore area. From OpenEI.org.

Charging Protocols

Gr/ NMC523
V_{max}/V_{min}= 4.1V/3V

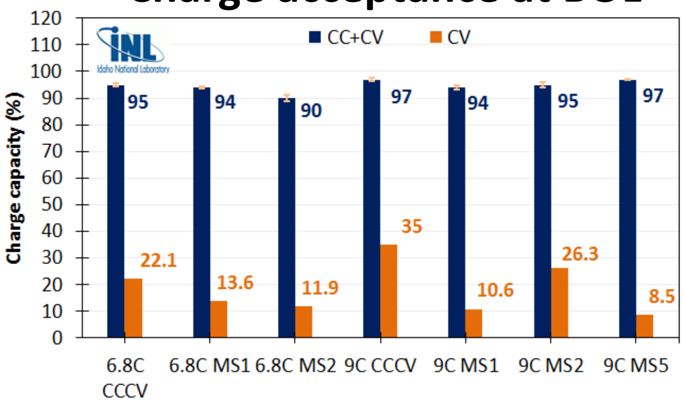
- **Protocols established based on overvoltage characterization and analysis**
  - **Overvoltage from rate characterization**
- **Strong correlation between overvoltage, charge accepted and capacity fade**
- **Protocols defined to look at different transport regimes, not at optimization**





Gr.	10 min charging protocol
B	6.8C CCCV
C	6.8C MS1 (2 step current)
D	6.8C MS2 (pulsed current)
E	9C CCCV
F	9C MS1 (2 step current)
G	9C MS2 (pulsed current)
H	9C MS5 (5 step current)

Charge acceptance at BOL

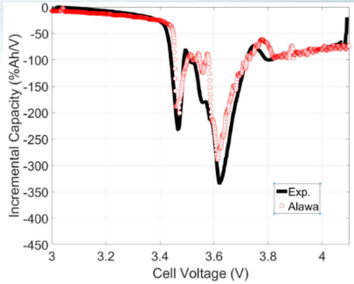


Recharge capacity is normalized by individual cells discharge capacity@C/1 at BOL and then averaged out

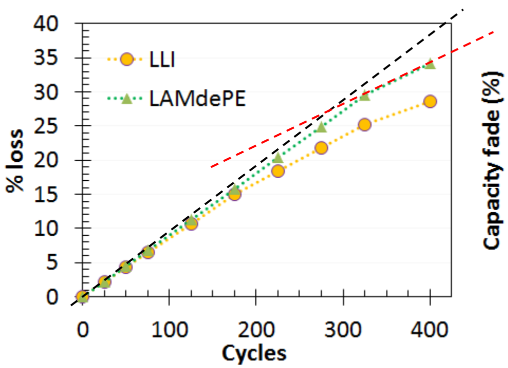
Understanding Failure

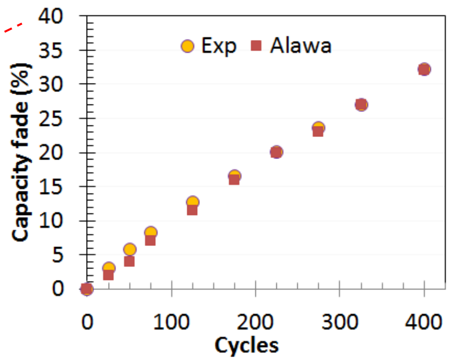
Multiple degradation modes

- Experimental dQ/dV compared to simulated fade using Alawa
- Best fit aligned combined loss of Li inventory (LLI) and loss of cathode material (LAM_{dePE}) - for highest fade some change in rate near end of testing
- Rates of fade vary as does ratio of LLI:LAM_{dePE}

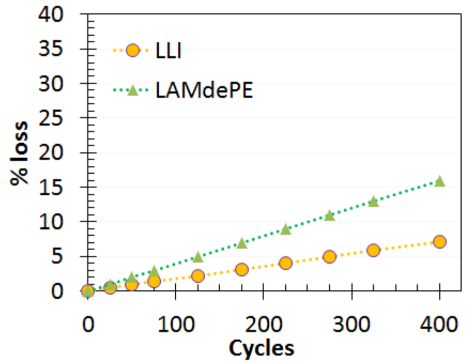


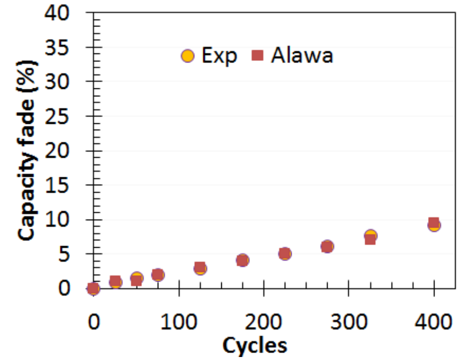
33% fade





8% fade

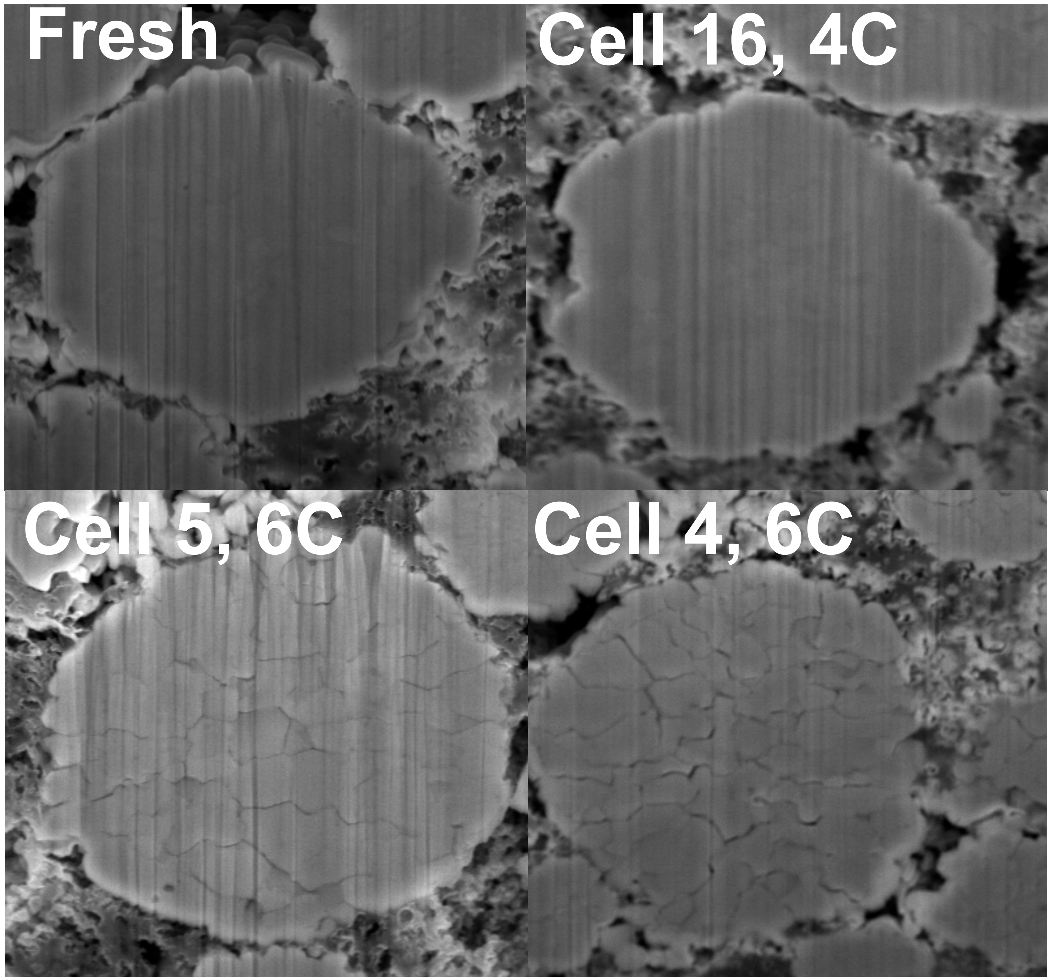


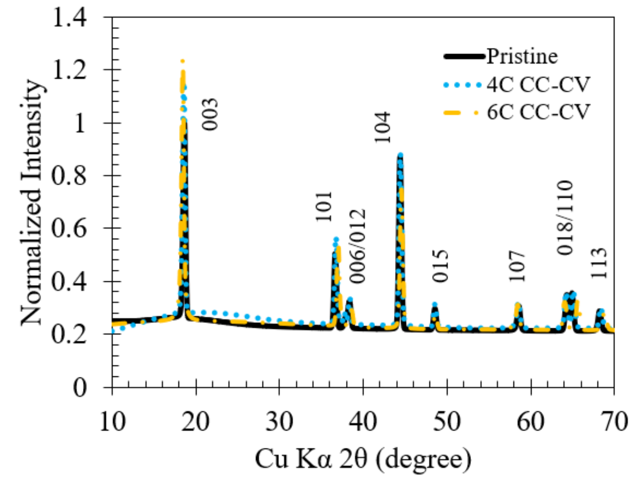


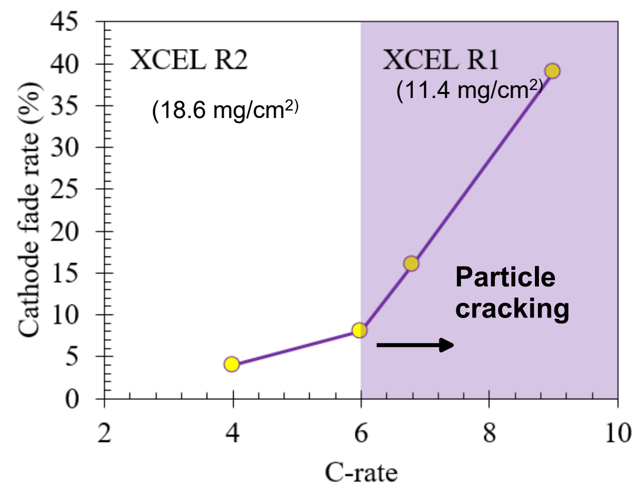
M. Dubarry, C. Truchot, B. Y. Liaw, J. Power Sources, 219, 204 (2012). 595
Alawa toolbox, available at: https://www.soest.hawaii.edu/HNEI/alawa/

Additional Cathode Fade

Cathode cracking at high rates, but no apparent bulk cation mixing



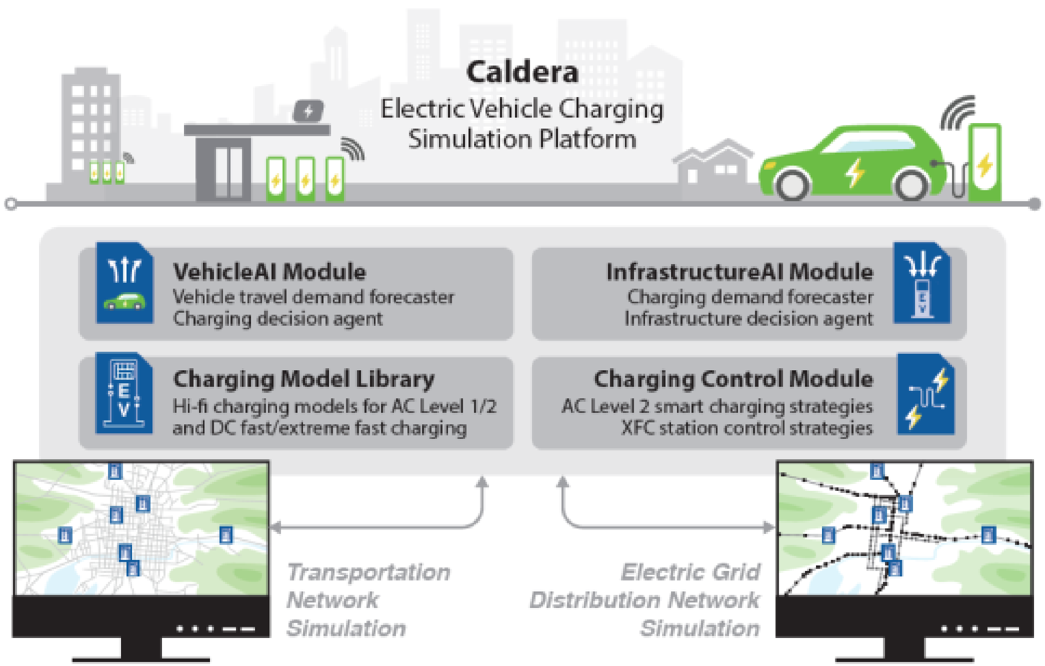




Program Highlights

Caldera

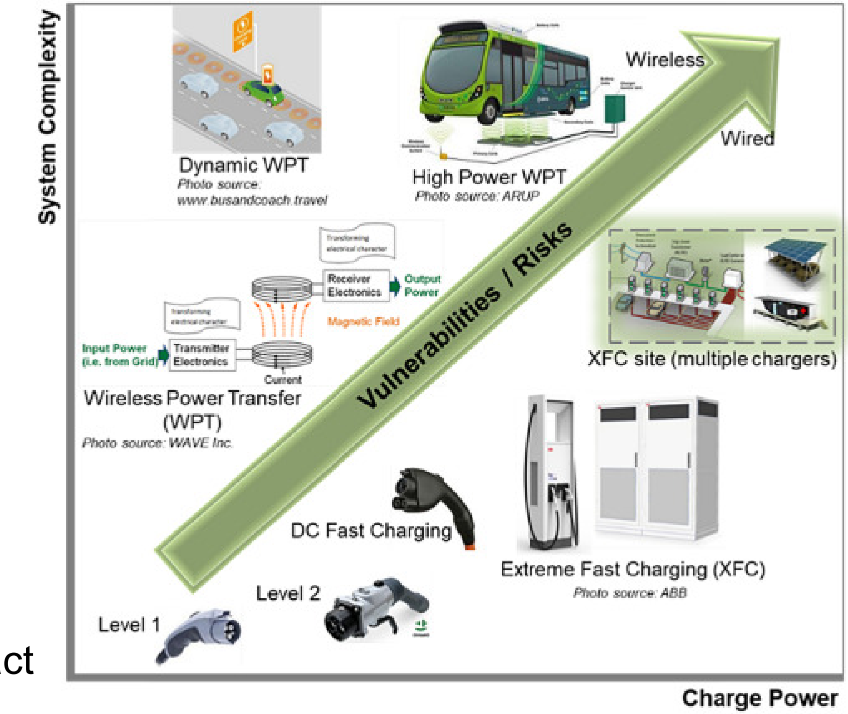
- INL is developing integrated tools that will inform on vehicle use, infrastructure needs and how the future of transportation will impact the grid while satisfying consumer needs

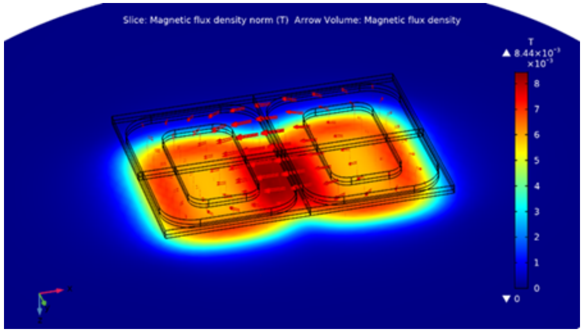


Program Highlights

Charging infrastructure risk and performance

- *INL researchers have expanded knowledge on wireless power transfer and cybersecurity risks*
- Hardware development, evaluation and risk assessment
    - Identified risks and vulnerabilities
    - Shielding to enable high power/dynamic wireless charging
    - Understanding how high power charging will impact the grid and present new challenges





B. Zhang et. al "Challenges of future high power wireless power transfer for light-duty electric vehicles – technology and risk assessment" *eTransportation*, **2019**, 2, 100012

Questions?