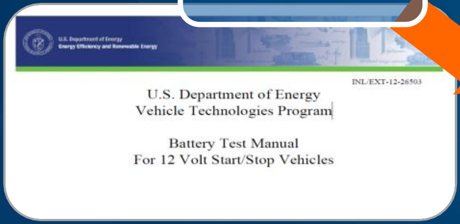
Energy Storage Performance Science at Idaho National Laboratory

Technology Assessment

Protocols & Procedures

Quality Results


INL/EXT-12-26503

U.S. Department of Energy
Vehicle Technologies Program

Battery Test Manual
For 12 Volt Start/Stop Vehicles

INL
Core Capabilities

Eric Dufek
Group Lead Battery Test Center

Joint Service Power Expo *Aug. 25, 2015*

www.inl.gov

Idaho National Laboratory

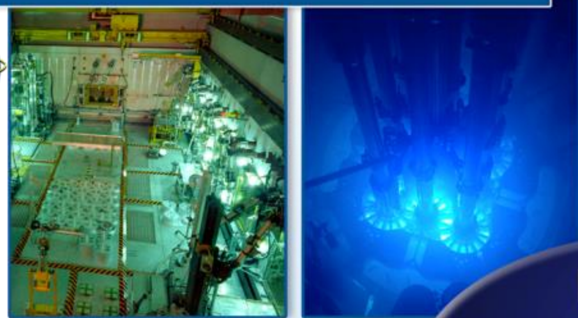
INL – The Place

- 890 square miles
- 111 miles of electrical transmission and distribution lines
- 579 buildings
- 177 miles of paved roads
- 14 miles of railroad lines
- 3 reactors
- Mass transit system
- Security
- Museum
- 300 metric tons of used fuel
- Educational and research partnerships – CAES

Our Identity

Develop world-class Nuclear Energy capabilities

ATR National Scientific User Facility



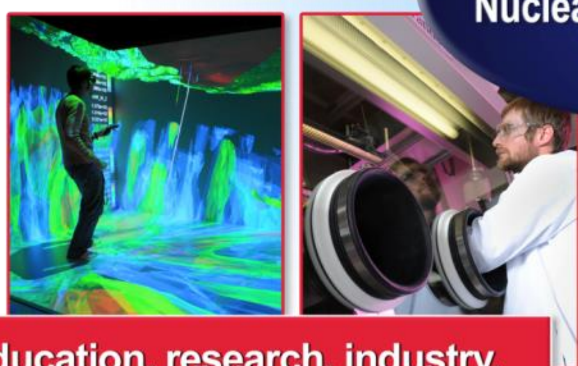
Major center for National and Homeland Security technology RDD&D

INL Wireless TEST BED

Preeminent Internationally-Recognized Nuclear Energy RDD&D Laboratory

i-STEM Education
idaho Science Technology Engineering Mathematics

CAES Center for Advanced Energy Studies



Bio-Feedstock Assembly User Facility

Battery Testing Lab

Foster education, research, industry, government and international collaborations

Lead clean energy systems RDD&D laboratory and a regional resource

Research – Development – Demonstration – Deployment

Quality. Creativity. Impact.

Advanced Transportation

Research to develop and deploy diverse fuels and advance energy storage and vehicle efficiency options

Environmental Sustainability

Research to provide transparency and management of environmental consequence

Clean Energy Innovation

Research to develop, integrate and deploy next generation clean energy systems and technologies

Efficient Manufacturing

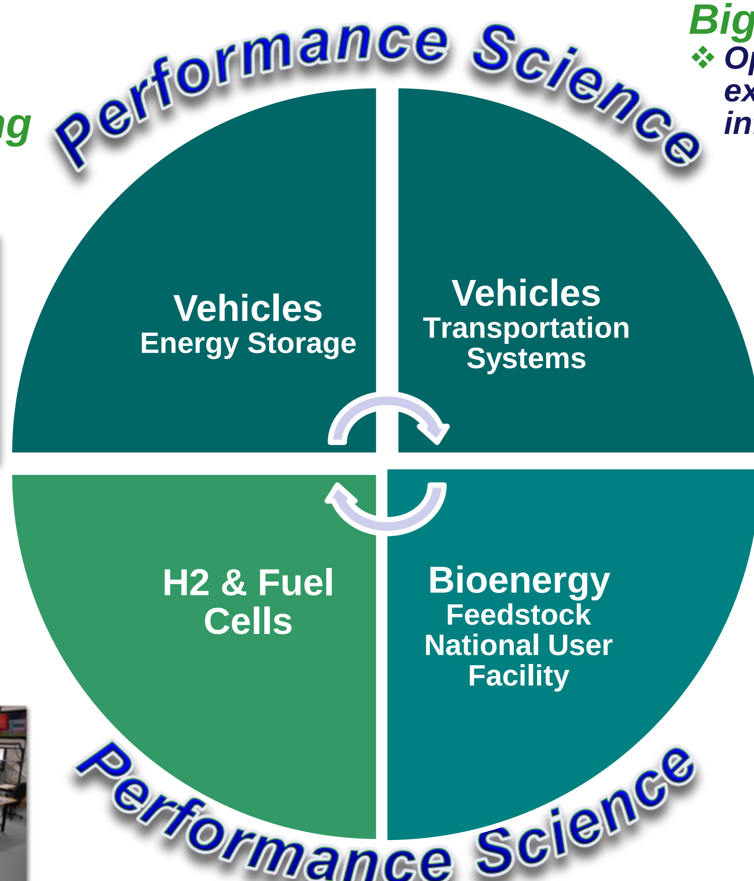
Research that creates efficient, environmentally sustainable, and secure manufacturing solutions

INL's Advanced Transportation Activities

- Attacking the key challenges of cost, consumer acceptance & infrastructure for alt-fuel vehicle adoption:

Big Data
- Optimizing consumer experience w/alt-vehicles & infrastructure

Performance & Life Testing
- Cost reduction
- Safety improvements

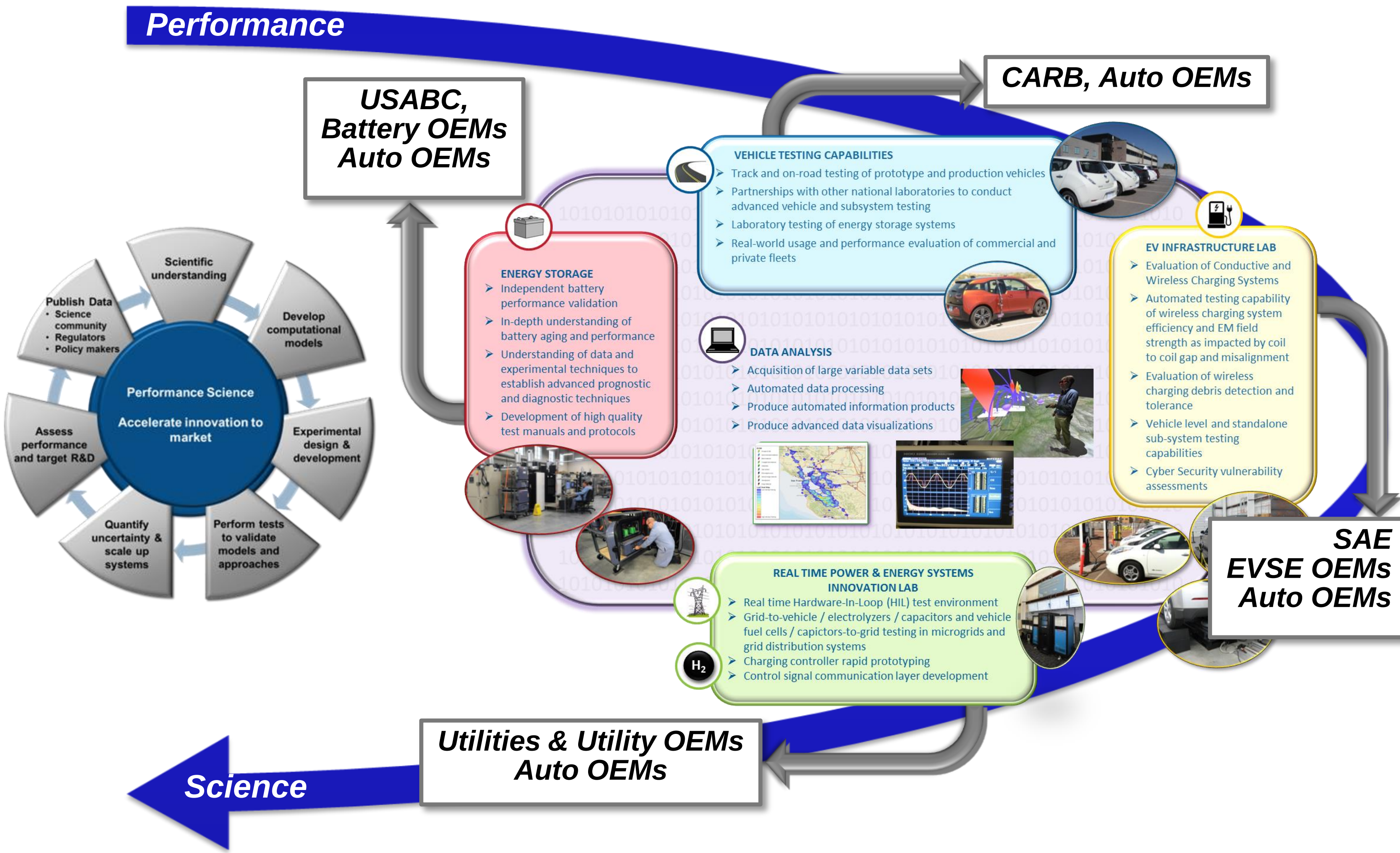


Infrastructure
- Development of global standards

Emulation & Simulation
- Added value hydrogen production

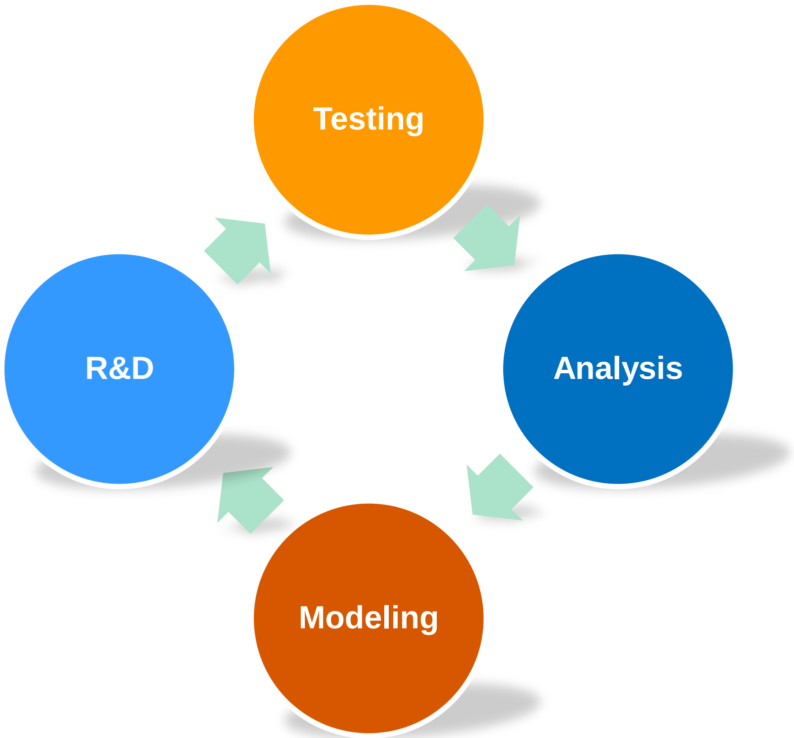
Feedstocks
- Cost reduction
- Quality improvement
- Scale-up and integration

Advanced Transportation at INL
Enabling Disruptive Technologies



Technical Challenge

- Advanced battery chemistries are being introduced at an accelerated rate
  - DOE supported battery research is a major reason for this positive trend
  - Transitioning chemistries from the lab to the consumer often fails due to inadequate testing early in the R&D cycle



Quality testing/validation/analysis is critical for adoption/success in the market

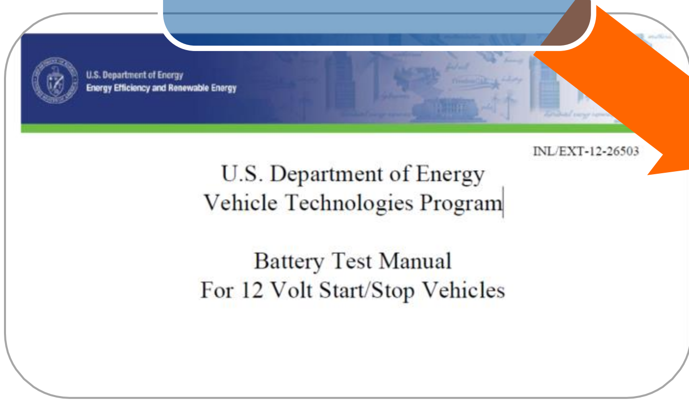
Technology Assessment

Independent, science-based performance assessment of energy storage devices.

Technology Assessment

Protocols & Procedures

Quality Results



U.S. Department of Energy
Energy Efficiency and Renewable Energy

INL/EXT-12-26503

U.S. Department of Energy
Vehicle Technologies Program

Battery Test Manual
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INL

Core Capabilities

INL Battery Test Center Facilities and Equipment

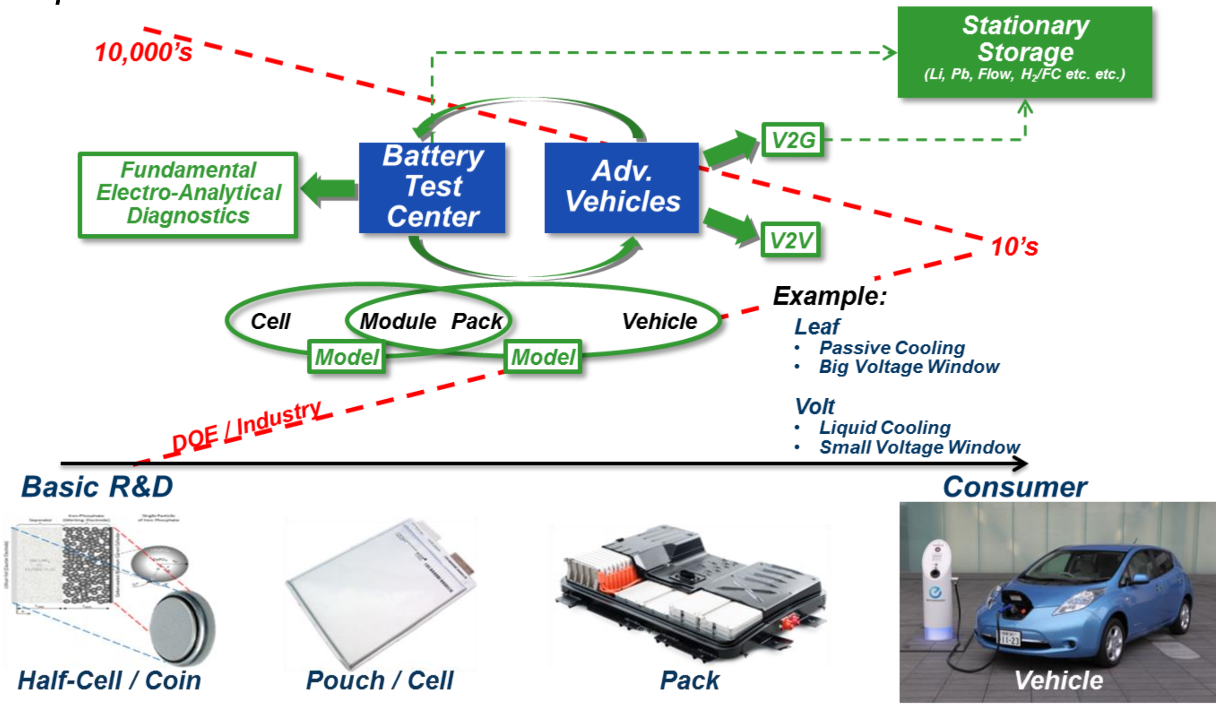
High Energy Testing

http://www.caesonline.org/ESL/Battery%20Lab.html

Vibrational Assessment

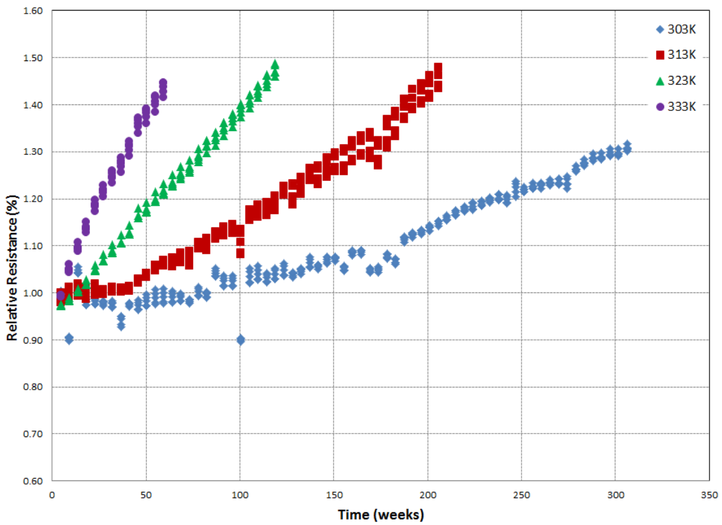
Where does INL fit

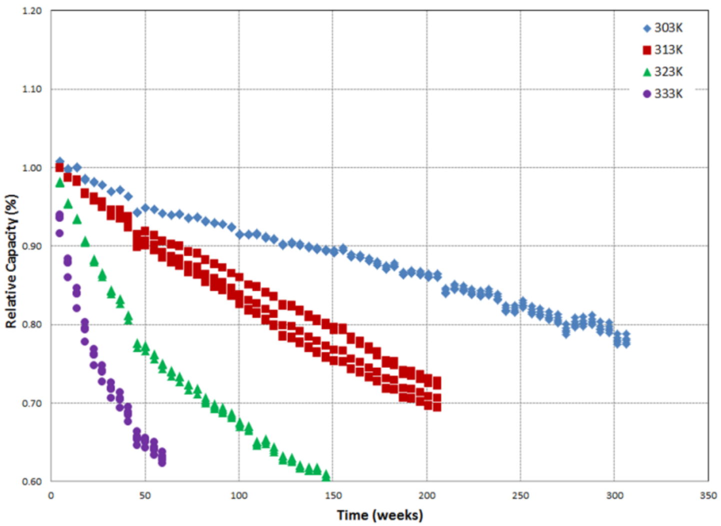
- High fidelity testing to specific application requirements
  - *Performance Science – Understanding how system performance can be impacted chemistry, environment and use*
- Improved understanding of battery health
- Understanding and enhancing battery safety
  - *Electrolyte performance and phosphazene chemistry – Reducing the risk of catastrophic failure*



Accelerated Aging Protocols

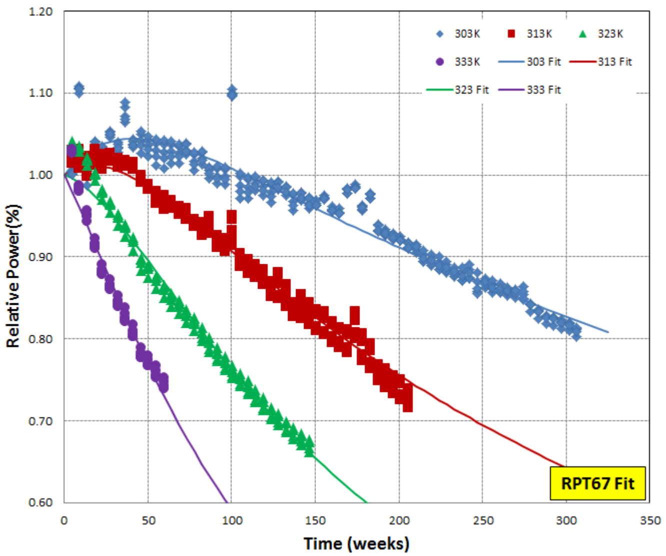
- **Calendar-life capability 15 years at 30°C.**
- **Understanding intended application and stressors which impact performance**
- **Maintaining controlled environment to understand degradation.**
- **Statistically relevant.**
  - At least 3 cells per test condition





Battery Life Models

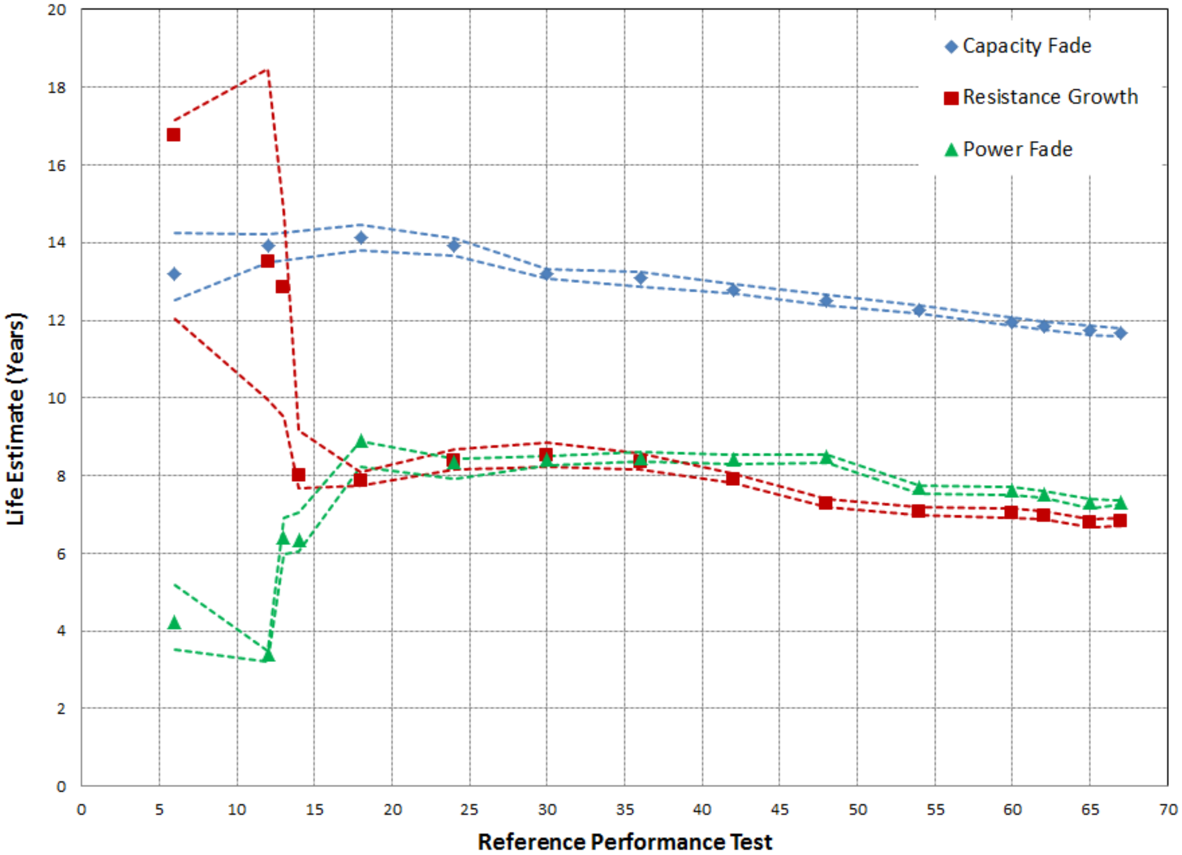
- **Multiple models/mechanisms to evaluate performance**
- **Non-linear model fits were used to estimate battery life:**
  - Capacity:
  - Resistance:
  - Power:
- **Degradation parameter becomes limited by reactive materials.**
- **A 90% statistical confidence window was used to estimate life at 30°C (303K).**



- **Values of fitting parameters**:
  - B0= 14.6
  - B1= -6560.2
  - B2= 1.25
  - B3= 0.12
  - B4= -9.10
  - r^2 = 0.969
- **Life estimate:**
  - 95% LCL: 7.2 yrs
  - 95% UPL: 7.4 yrs
  - **Weighted Avg.: 7.3 yrs**

Battery Life Predictions

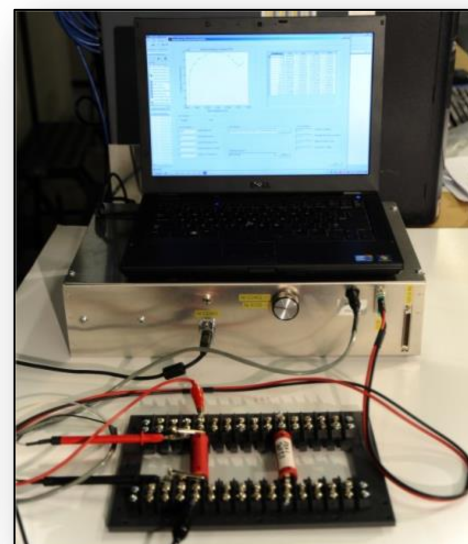
- **The resistance power model prediction appears to converge on 7 to 8 years at ~RPT15**
  - 480 days of calendar life aging.



Advanced Diagnostics

Advanced Diagnostics Sensors

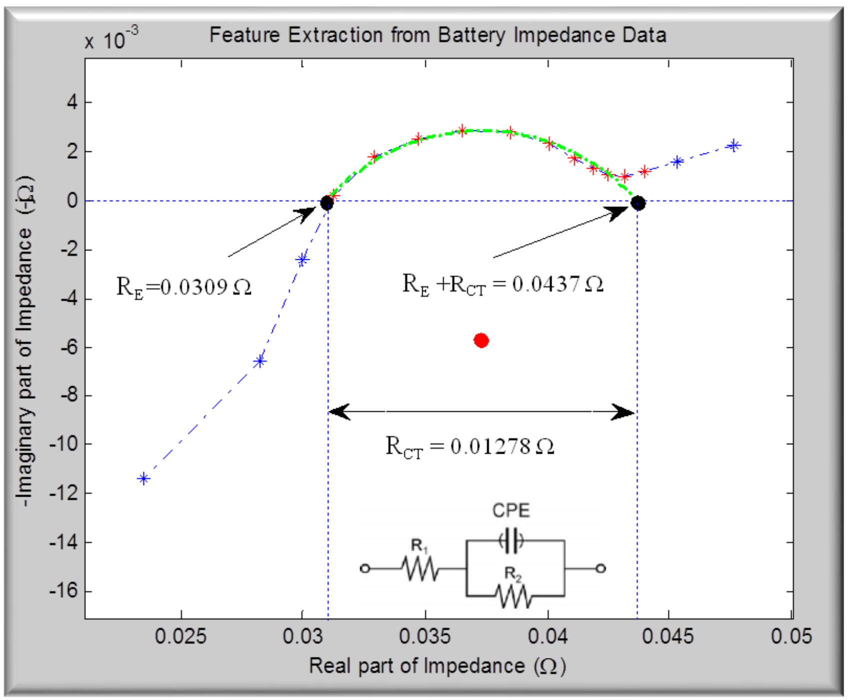
- Advanced, onboard battery management systems still need development.
- Rapid impedance spectrum measurement techniques have been developed for state-of-health and state-of-stability assessment.
- Hardware now capable of measuring modules up to 50V
- Miniaturized / embedded system architecture envisioned.



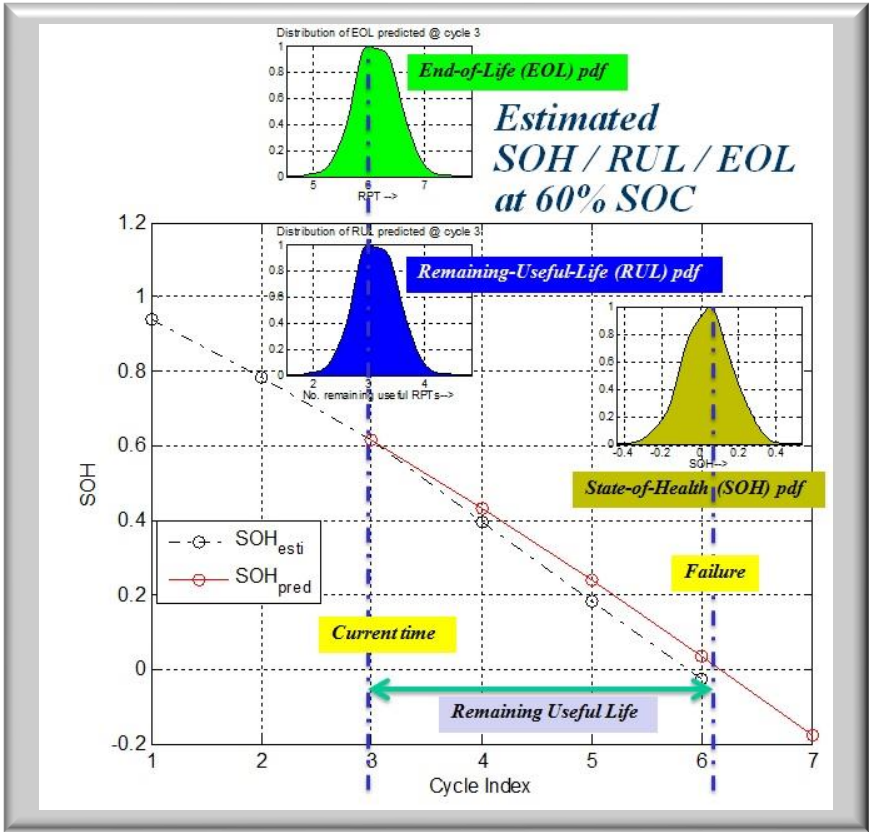
Battery SOH Assessment Architecture

- **To illustrate, predictive estimations of battery SOH and remaining useful life (RUL) have been applied to Li-ion cell data.**
  - With a stochastic framework that combines several SOH metrics, confidence in the life prediction can also be ascertained.

Feature Extraction

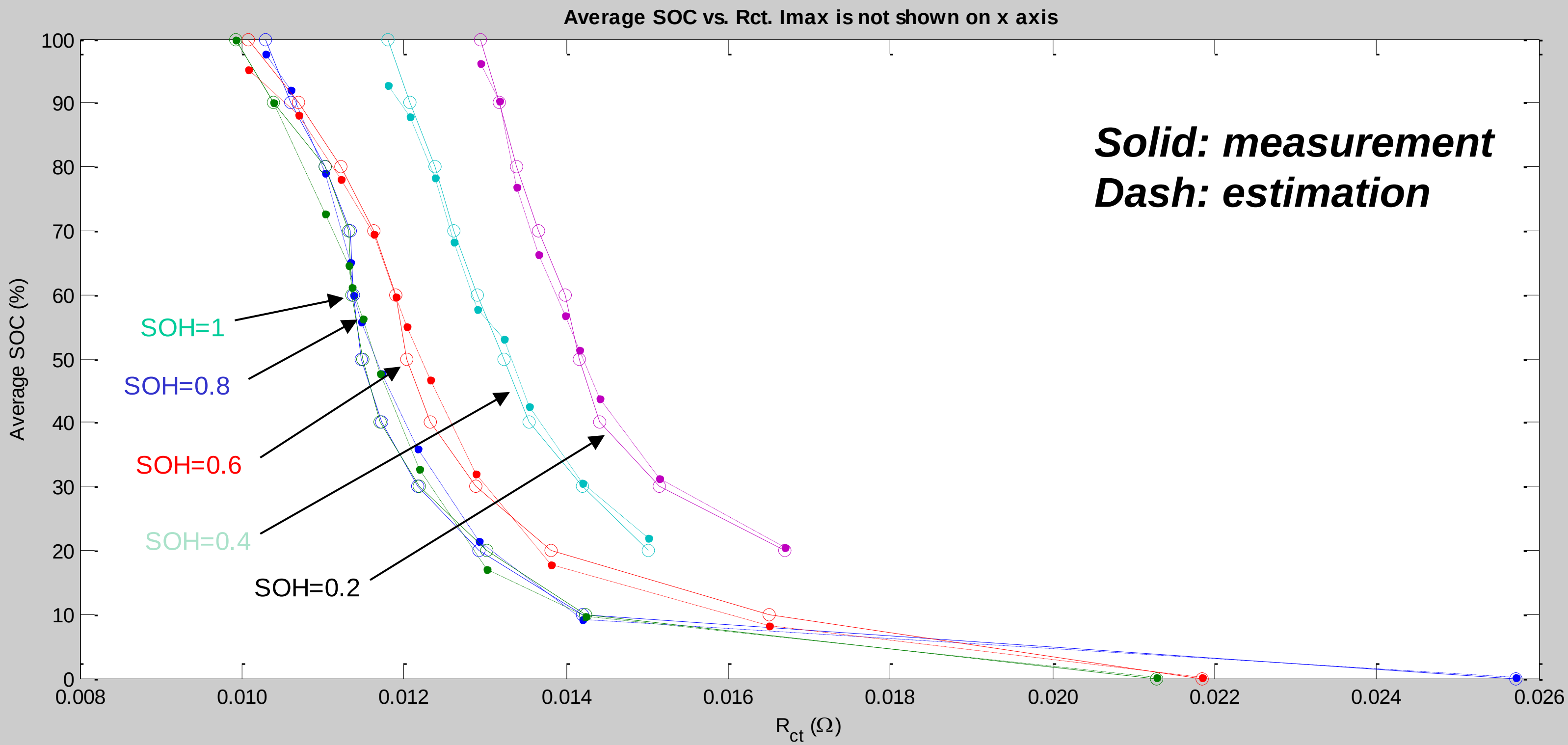


SOH Assessment



Battery SOH Assessment Architecture

- **The estimated SOC compares well with the measured SOC for these lithium-ion cells as a function of SOH.**
  - An extracted parameter is used in this estimate, which is primarily influenced by kinetic reactions at the electrodes.



Extracted Parameter

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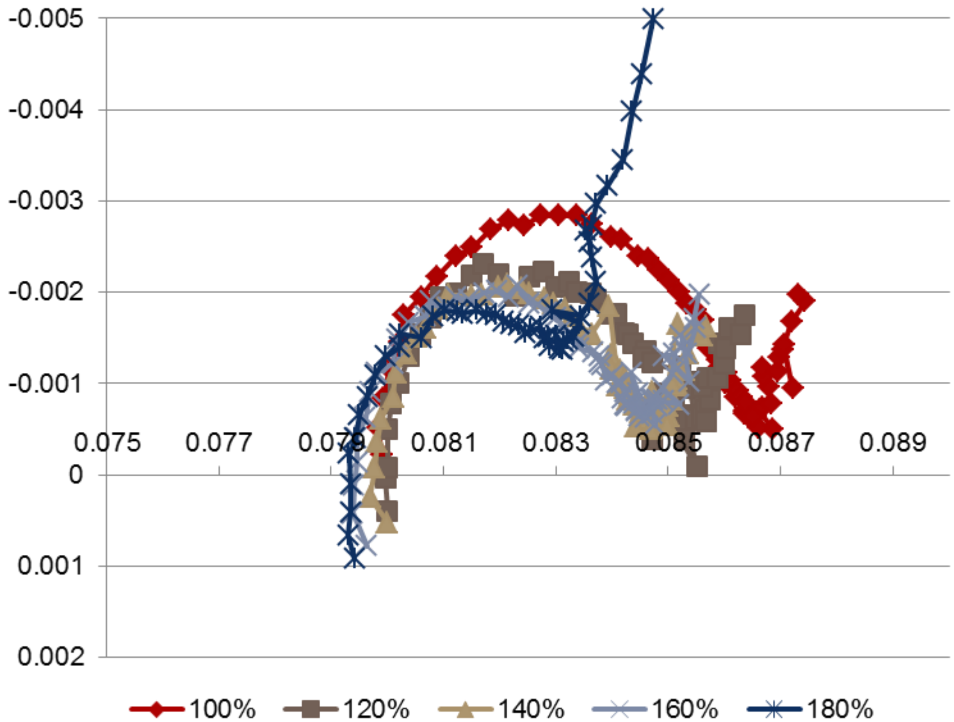
Diagnostics (IMB)

- **Preliminary results show promise in using impedance data as a means of identifying bad strings within a module/pack.***

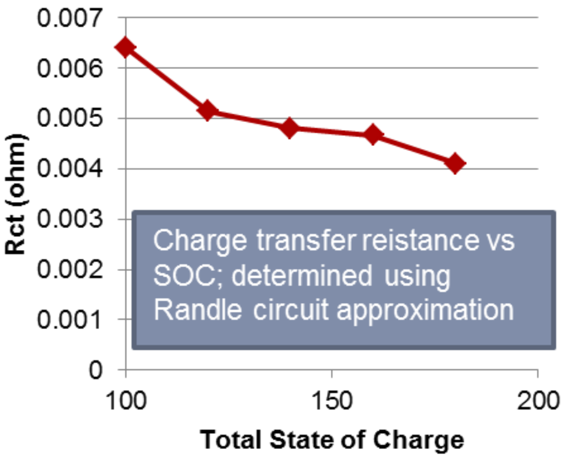


Runaway occurred during charging after 180% total charge

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



****Data acquired at SNL using standard impedance measurement tools.***

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Advanced Electrolyte Materials

Phosphazenes

Benefits:

- ❑ Inherently stable and non-flammable
- ❑ Very low vapor pressure
- ❑ Choice of R groups (pendant arms) has a profound influence on properties
- ❑ Good lithium salt dissolution

Challenges:

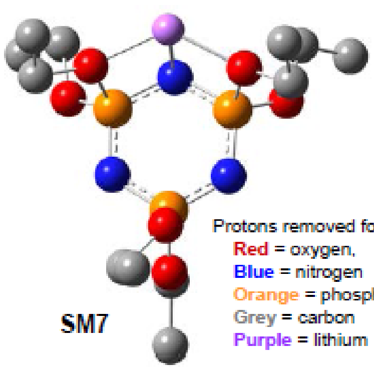
- ➢ High viscosity
- ➢ Need to attenuate N-Li^+ attraction that occurs due to electron doublet transfer

Selected Series of INL Phosphazene Compounds

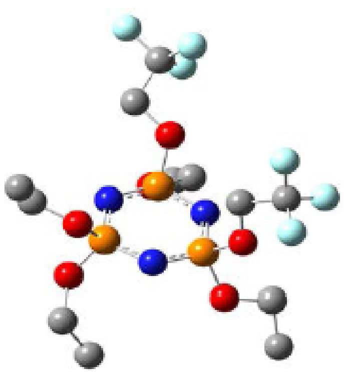
SM: employs ether groups attached to the phosphorus centers

AL: employs unsaturated analogues of the SM series

FM: employs fluorinated analogues of the SM series



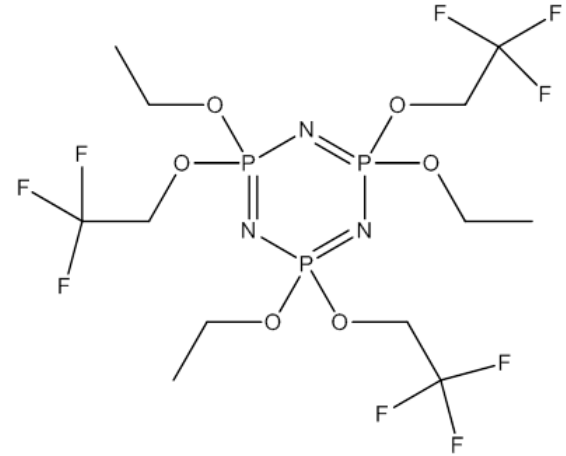
SM7

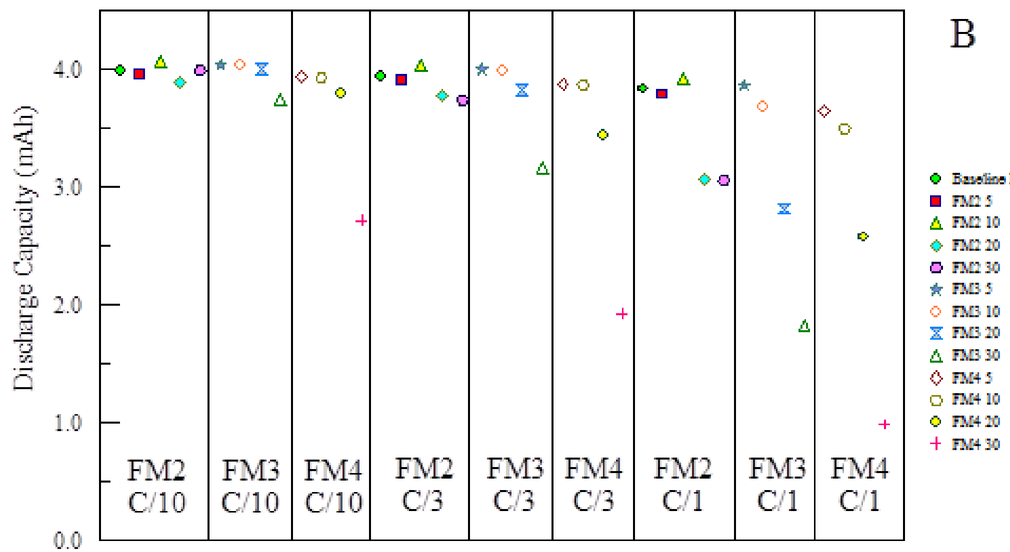


FM3

Cycling performance

- Ability to maintain rate capability up to 10% loading
  - Viscosity becomes a key limiting factor (above 20%)
  - Inhibition of degradation processes through radical scavenging
- Smaller molecules provide opportunity to improve upon early work
- Significant reduction in gas evolution and thermal heating rate during abuse overcharge

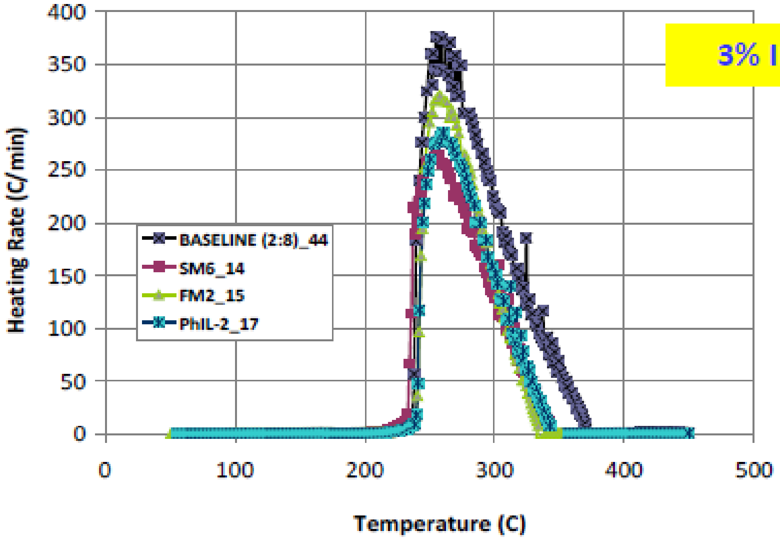




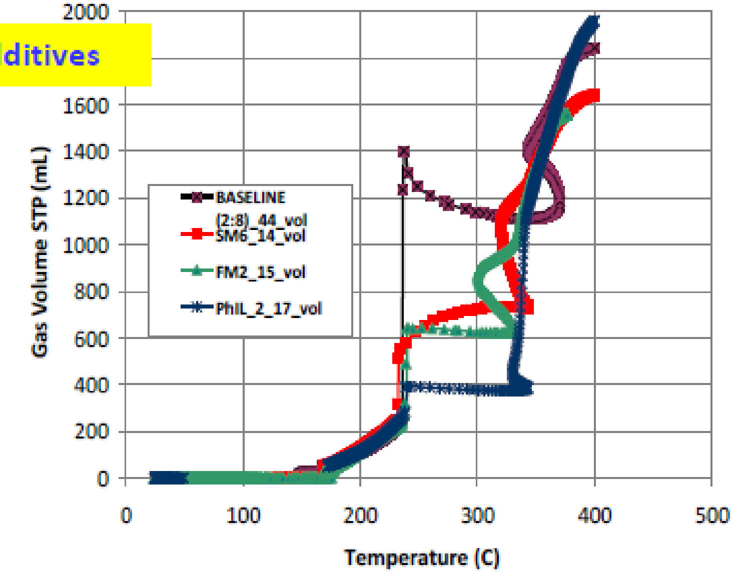
Harry W. Rollins, et. al. , Journal of Power Sources (2014), 263, 66

Tech. Accomplishments

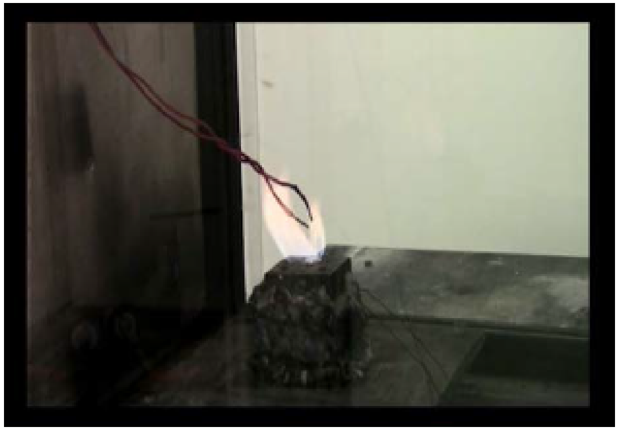
INL additives lower both the heating rate and gas production during thermal runaway.....



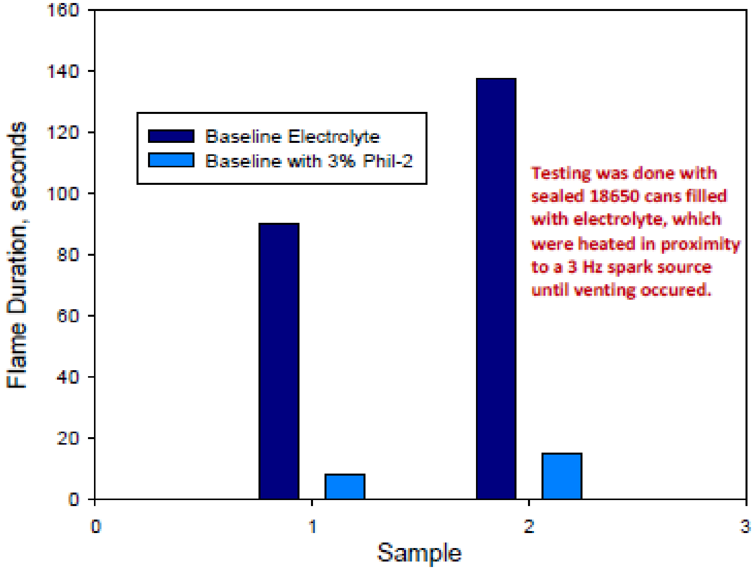
3% INL Additives



...and can significantly reduce flame duration.



Short-lived ignition of electrolyte with PhIL-2 (the vent was very subtle and difficult to observe).



- Testing performed by SNL (Orendorff).
- All Cell Results: NMC/carbon, with **3% additives** in EC-EMC (1:4) + 1.2M $LiPF_6$.

Using Science to Ensure Performance

- INL Battery Test Center is the **DOE Core Capability Laboratory for advanced automotive battery performance testing.**
- **Independent, science-based performance assessment** of energy storage devices.
- **Internationally accepted manuals** for performance assessment of energy storage systems.
- **Flexible state-of-the-art energy storage test facility** capable of supporting current and future development activities.
- **Temperature controlled testing** for reliable and repeatable results.
- **In-depth knowledge of new technology use and limitations**
- **Ability to identify issues prior to failure**
- **Means to reduce safety risk**
- STIMS #INL/CON-15-35387, INL/CON-15-34632, INL/CON-15-35145

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Vibrational Assessment

- **Assessment of vibration on performance**
  - Diminished performance
  - Safety related failure
  - Non-traditional use
  - Multi-axis movement
  - 8 Channel Data Acquisition
  - Ability to test both small and large items
- **Armature (640 mm or 25.2 in diameter)**
  - Sine force peak: 13,000 lbf
  - Random force peak: 12,500 lbf
  - Half sine peak shock force: 26,660 lbf
  - Velocity sine peak: 1.8 m/s (70.9 in/s)
  - Acceleration peak:
  - Sine: 392 m/s^2
  - Random: 392 m/s^2 ($40g_n$)
  - Displacement (continuous) peak to peak:
  - 63.5 mm (2.5 in)

Equipment

Tester Mfr.	Tester Capability	# of Testers	# of Channels
Maccor	0-5V, +/- 5A	1	8
Maccor	0-5V, +/- 5.5A	3	152
Maccor	0-10V, +/- 12.5A	3	72
Maccor	0-5V, +/- 25A	2	48
Maccor	0-5V, +/- 30A	1	96
Maccor	0-5V, +/- 50A	1	24
Maccor	0-5V, +/- 60A	6	144
Maccor	0-7V, +/- 90A	2	48
Maccor	0-5V, +/- 100A	1	8
Maccor	0-5V, +/- 180A	1	8
Maccor	0-5V, +/- 250A	6	47
Maccor	0-7V, +/- 250A	1	8
Maccor	0-7V, +/- 300A	1	8
PEC	0-50V, +/- 80A	1	8
Maccor	0-55V, +/- 220A	2	8
Maccor	0-65V, +/- 250A	1	4
Maccor	0-60V, +/- 275A	1	4
Bitrode	0-100V, +/- 500A	3	3
Bitrode	0-500V, +/- 350A	3	3
Bitrode	0-1000V, +/- 500A	2	2
Energy Systems	0-500V, +/- 500A	2	2
Total # of Testers/Channels		44	705

Equipment

- **Walk-in Environmental Chambers**
  - Temperature control range: -68 to 85°C
  - Humidity control range: 5 to 94% relative
  - Interior volume: 1054 ft^3
  - Programmable humidity and temperature ramping profiles