INL/CON-16-39009-Revision-0

# Durability, Reliability and Safety of Energy Storage Systems

Boryann Liaw

June 2016

The INL is a U.S. Department of Energy National Laboratory
operated by Battelle Energy Alliance

INL/CON-16-39009-Revision-0

# Durability, Reliability and Safety of Energy Storage Systems

**Boryann Liaw**

**June 2016**

**Idaho National Laboratory**
**Idaho Falls, Idaho 83415**

**http://www.inl.gov**

**Prepared for the**
**U.S. Department of Energy**
**Office of Energy Efficiency and Renewable Energy**
**Under DOE Idaho Operations Office**
**Contract DE-AC07-05ID14517**

# *Durability, Reliability and Safety of Energy Storage Systems*


**Boryann (Bor Yann) Liaw, Ph.D.**
**Manager, Energy Storage and Advanced Vehicles**
**Idaho National Laboratory**
**Idaho Falls, ID 83404**


June 15, 2016

DOE OE Energy Storage Reliability Workshop, June 14-15, 2016, Kennewick, WA

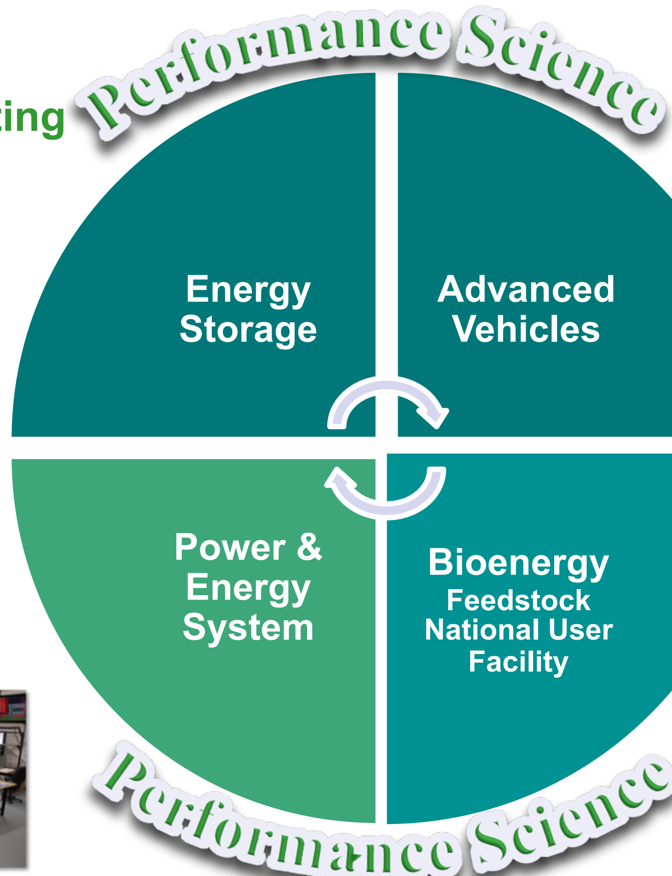
www.inl.gov

Idaho National Laboratory

# *INL's Clean Energy & Transportation Division*

***Attacking the key challenges of durability, reliability, safety, cost, consumer acceptance & infrastructure for alt-fuel vehicle mass-adoption***

- **Talent**
- **Facilities**
- **Partnerships**




## Performance & Life Testing
- ❖ Cost reduction
- ❖ Performance improvements

## Emulation & Simulation
- ❖ Grid integration

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

## Infrastructure
- ❖ Development of global standards

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

INL Idaho National Laboratory

# *INL Battery Test Center Facilities and Equipment*


High Energy Testing

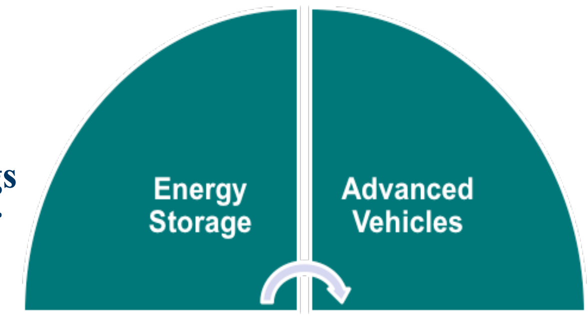
https://at.inl.gov/SitePages/Energy%20Storage.aspx

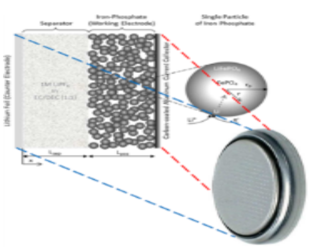
Vibration Assessment

# Vehicles, Energy Storage & Infrastructure

## *Leverage INL capabilities to understand science behind technology performance*

- **Foundation: Battery Testing Center, Advanced Vehicle Testing, Electric Vehicle Infrastructure Laboratory**
- **Multi-scale understanding and evaluation of scientific underpinnings**
- **Impact: Enabling / accelerating next gen low cost energy storage for multiple applications**



**Half-Cell / Coin**

**Pouch / Cell**

**Pack**

**Vehicle**

**Performance Science: Half-Cell to Pack & Vehicle**

# Vehicles, Energy Storage & Infrastructure


## Example of Performance Science:

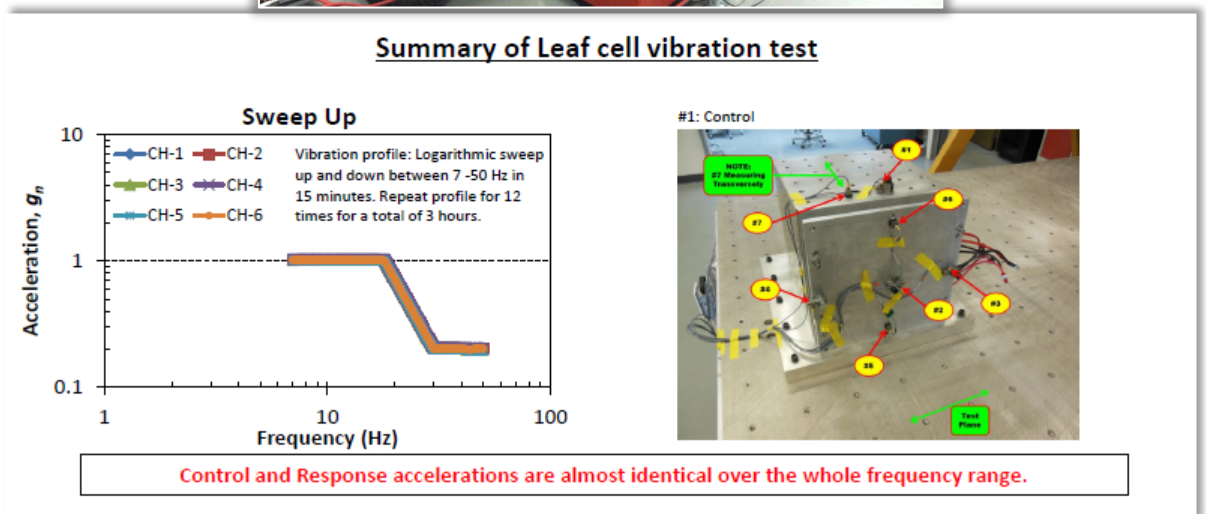
- Battery Degradation of Level II (240V) vs. DCFC (480V)
  - Pre-conceived notions that DCFC would be extremely detrimental for battery durability
- Performance Science Based testing of vehicles on the road and in the lab

# Durability, Reliability and Safety

## *Ensuring application specific performance*

**Understanding performance in aggressive environments**

- **High/low temperature,**
- **Vibration,**
- **Fast charge,**
- **Overcharge**
- **Aggressive power**



Idaho National Laboratory

# Performance Science at INL

***Understanding how performance is impacted by chemistry, use and environmental conditions***

## Testing

**Testing protocol** driven by customer technical targets

**Lead DOE testing lab** for advanced vehicles

**U.S. Advanced Battery Consortium** program deliverables

**Cells, Modules and Full-Size Packs**

## Analysis

**Standards developed** for data acquisition, analysis, quality, management

**Data accuracy and uncertainty analysis**

**Huge amounts of data** generated

**Software analysis tools** developed

## Modeling

**Key modeling tools**:

- Chemical Physics
- Kinetics
- Arrhenius Analysis
- Equivalent Circuit
- Life Prediction
- Life Estimation/ Prognosis
- State-of-Health Assessment

## R&D

Applied research to **explore basic issues** of battery aging and performance

Specialized **diagnostic tests and measurements**

**Novel battery sensor technology**

**Interfacial Regions** (SEI, DL)

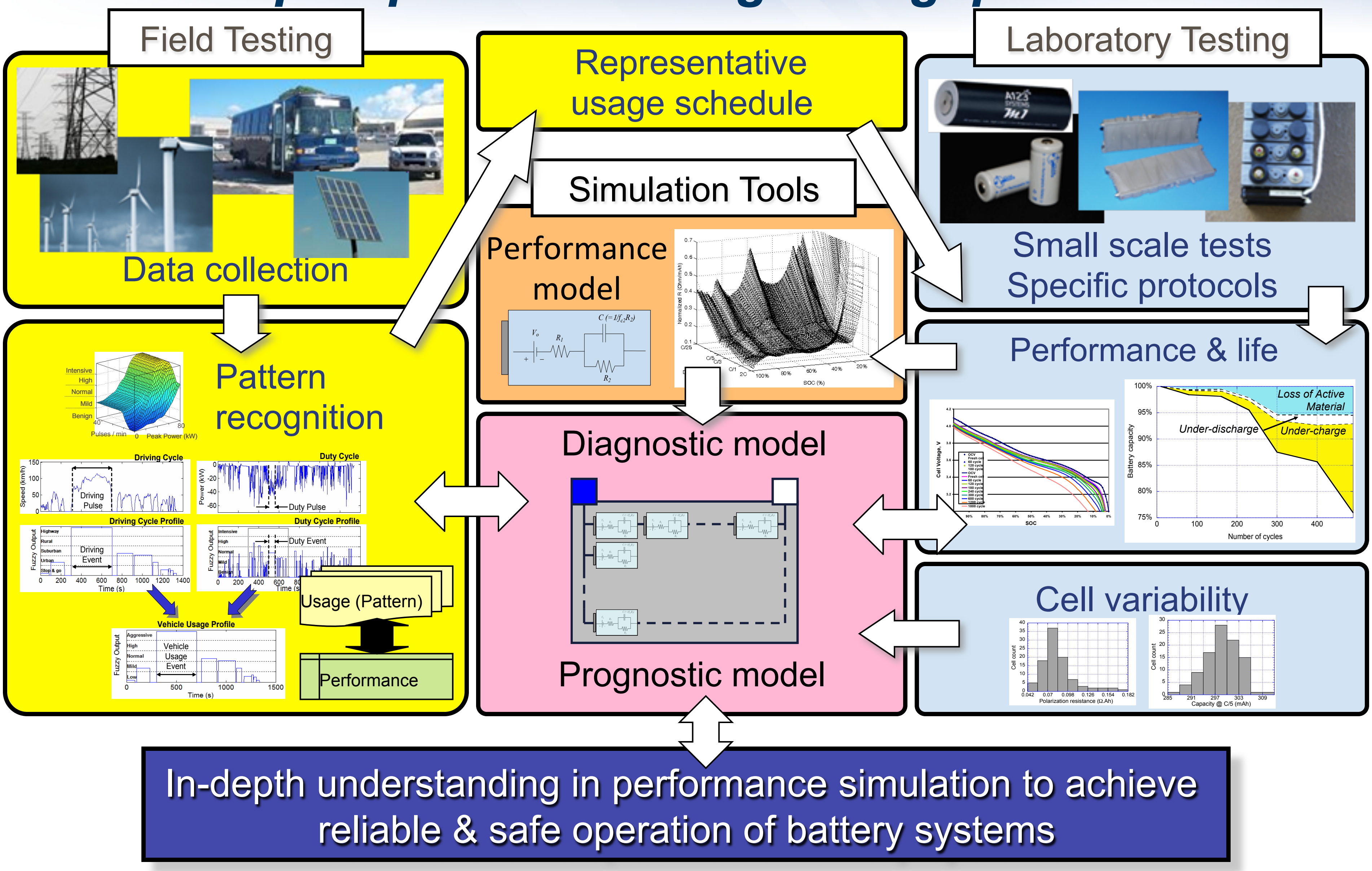
**Coin Cell Testing**

**In-situ reference electrode testing**

- Well-designed and equipped test facilities (batteries, vehicles, & infrastructure)
- Test procedures, codes and standards
- Data collection, database, and clearance house
- Diagnostic and prognostic tools to address durability, reliability and safety issues
- Visualization tools

## *INL CAPABILITIES*

# Roadmap to practice: Bridge the gap



One of the most important issues facing the battery industry is

Durability, Reliability & Safety

Functionality & its durability

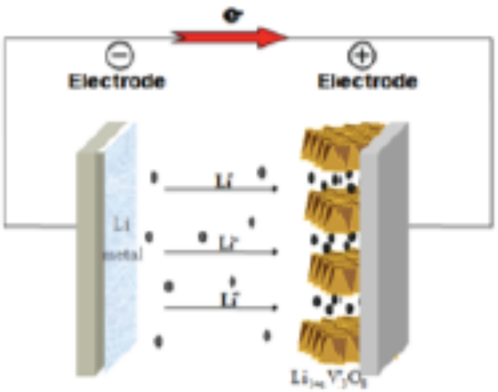
Abuse tolerance

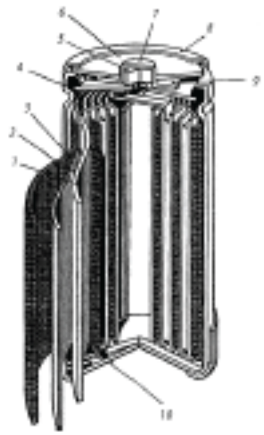
— against malfunctions

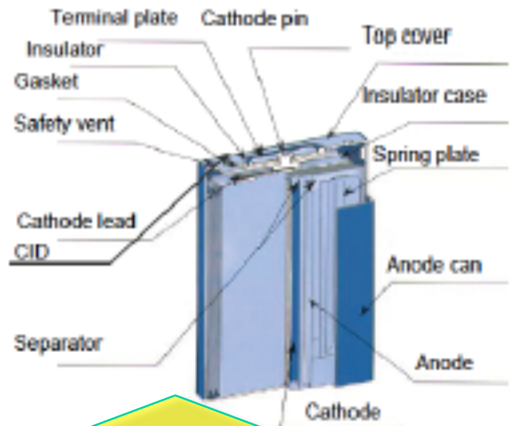
→ Do they trigger safety events?

## *DURABILITY, RELIABILITY AND SAFETY*

# Design-Build-Test Paradigm





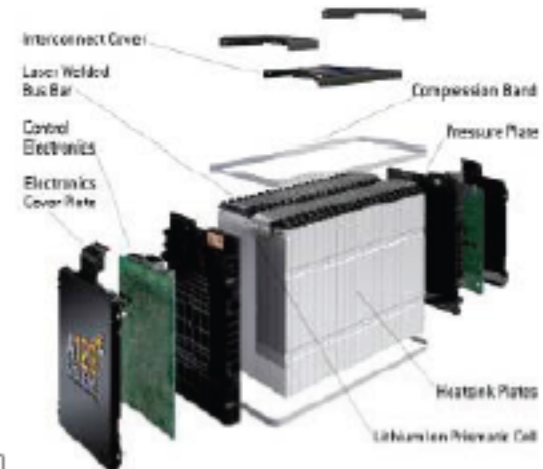
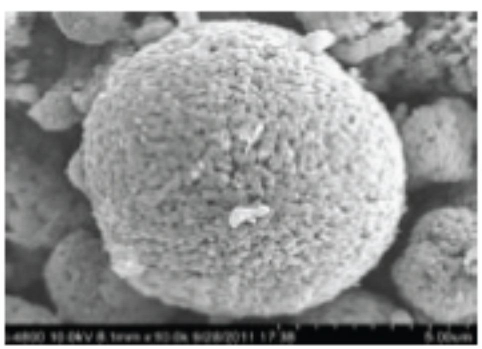
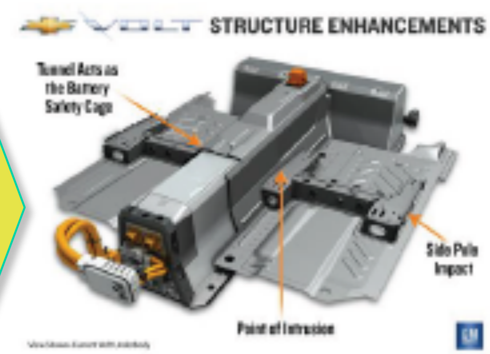




Table II-5. U.S. Advanced Battery Consortium Goals for Electric Vehicle Batteries

| Primary Criterion | Long-term goal (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)<br>1,600 (50% DOD)<br>2670 (30% DOD) |
| Power and capacity degradation (% of rated spec) | 20% |
| Ultimate price, $/kWh (10,000 units @ 40 kWh) | [illegible] |
| Operating environment | -30C to 65 C |
| Recharge time | [illegible] |
| Continuous discharge in 1 hour (no failure) | 75% (of rated energy capacity) |
| **Secondary Criteria** | **Long-term goals (2005-2008)** |
| Efficiency [illegible] | [illegible] |
| Self-discharge | <20% in 12 days |
| Maintenance | [illegible] 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 | |

Sensitive geometric, dimensional dependence governed by processing and fabrication quality






Sources: various literature documents

# *Failure Modes and Effects Analysis (FMEA)*

Idaho National Laboratory

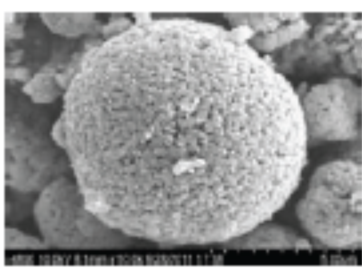
**Battery Management System**

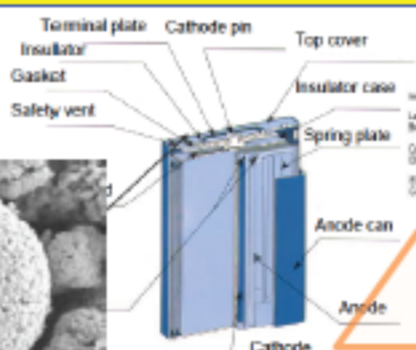
Top Down

**Battery Diagnosis & Prognosis**

✓ Failure Modes and Effects Analysis (FMEA)

**Performance, Durability, Reliability, Safety**





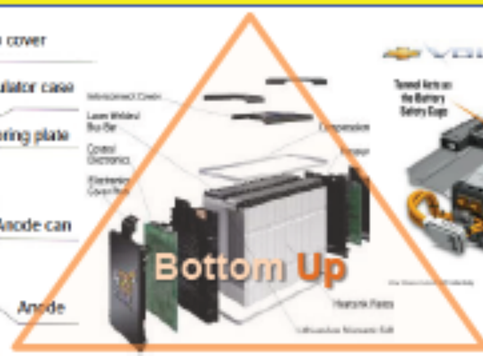





Table II-5. U.S. Advanced Battery Consortium Goals for Electric Vehicle Batteries

| Primary Criterion | Long-term goals (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)<br>1,600 (50% DOD)<br>2670 (30% DOD) |
| Power and capacity degradation (% of rated spec) | 20% |
| Ultimate price, $/kWh (10,000 units @ 40 kWh) | <$150 (desired to 75) |
| Operating environment | -40C to 85 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) | 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 | |

**Design ➔Build ➔Test**

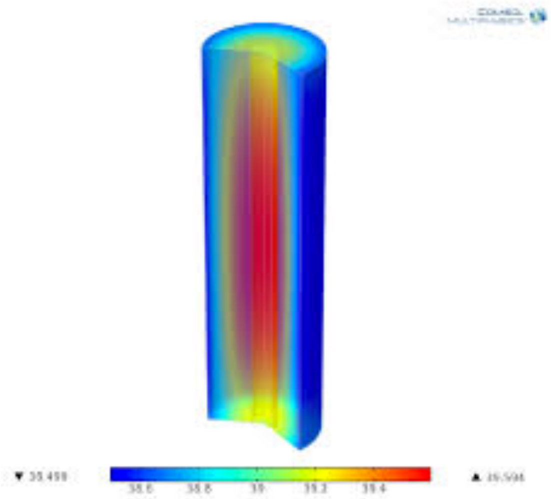
Battery system needs to handle all chemical, electrical, mechanical and thermal energy balance

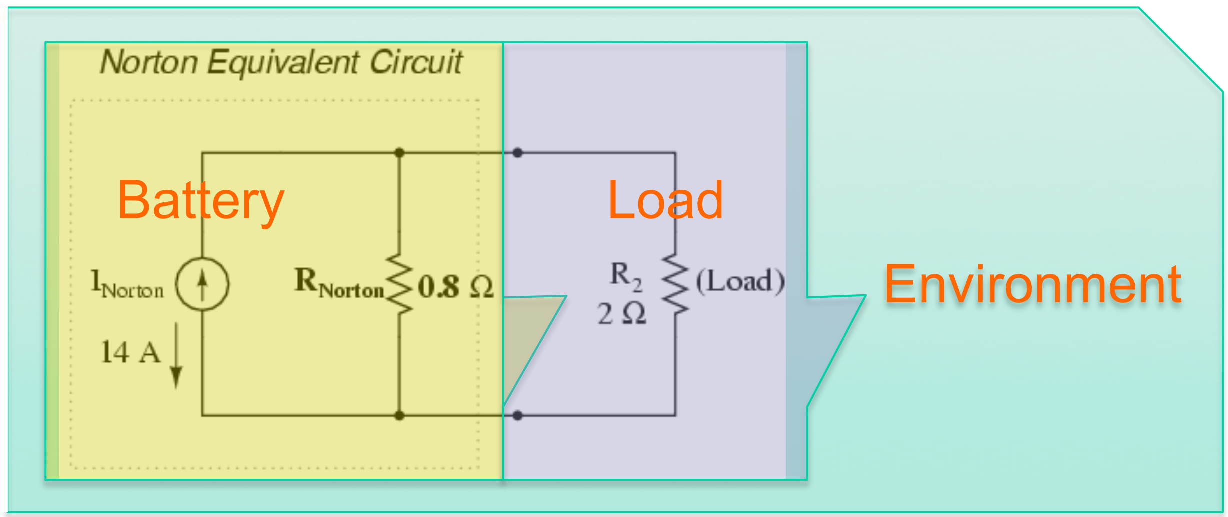
Such balance may pertain over a large range of temporal and spatial scales (i.e. from nano-scale interfacial balance to system control interface and from ms to years)

Quantify such balance with realistic model simulation is a great challenge for reliability assessment

# *MAJOR TECHNICAL BARRIERS*

# *Equivalent Circuit Diagram & Electrochemical + Thermal Coupling*





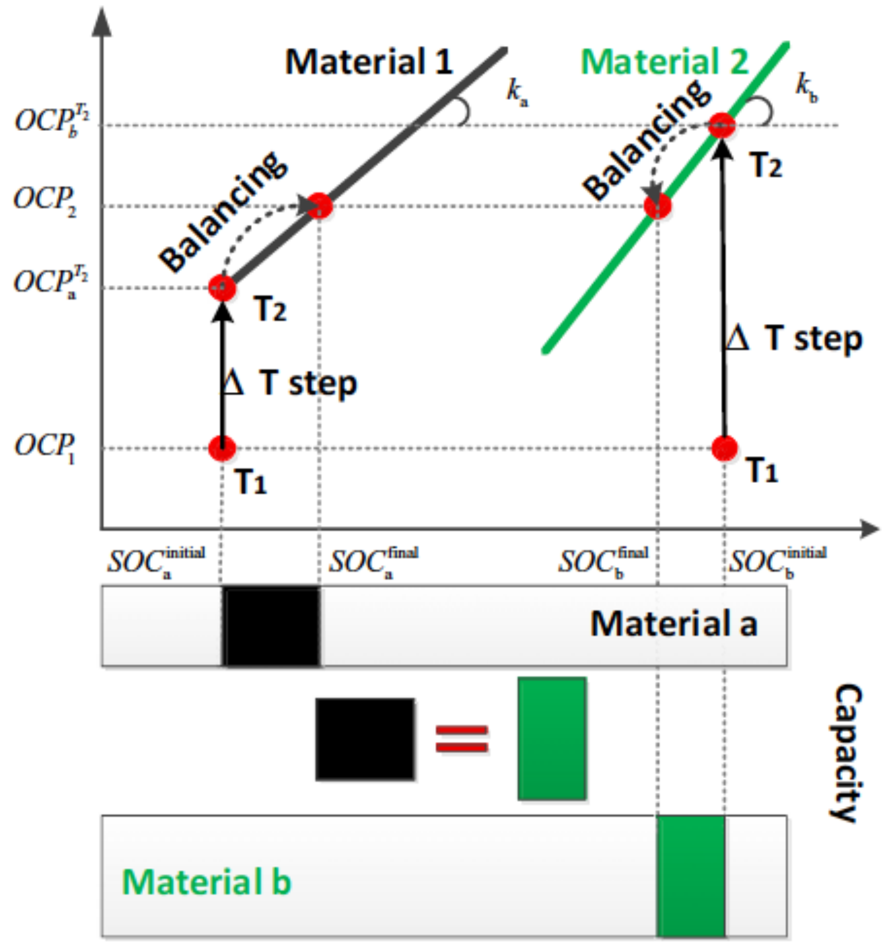

- Electrochemical
  - State functions
    - Temp
    - SOC (composition)
  - Chemical energy --> electrical energy (power conversion)
  - $\Delta H = \Delta G + T\Delta S$
- Thermal
  - Heat generation
    - Joule heating
    - $T\Delta S$
  - Heat retention
    - Heat capacity
  - Heat dissipation
    - Heat conduction
    - Heat exchange

Using a graphite | LMO+NMC cell to illustrate the thermal and electrochemical coupling

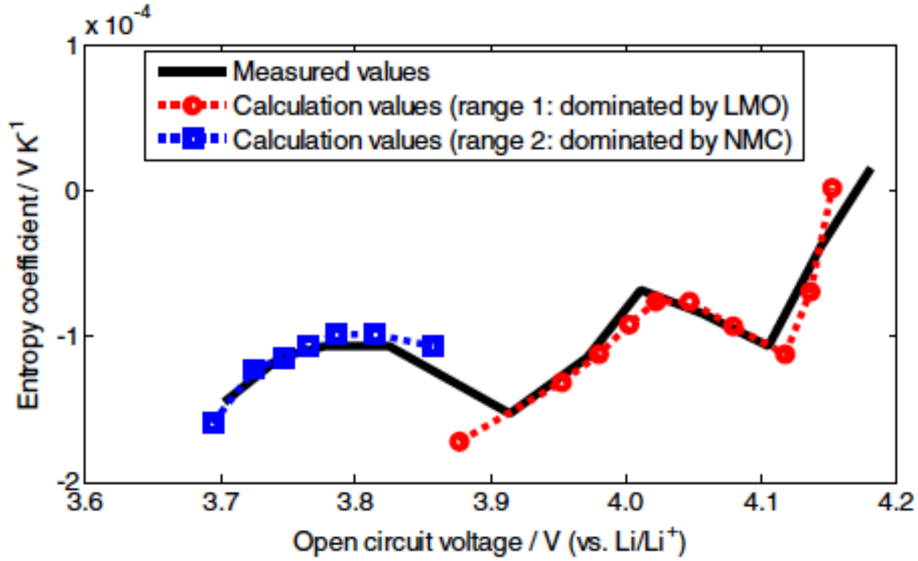
To simplify: isothermal conditions

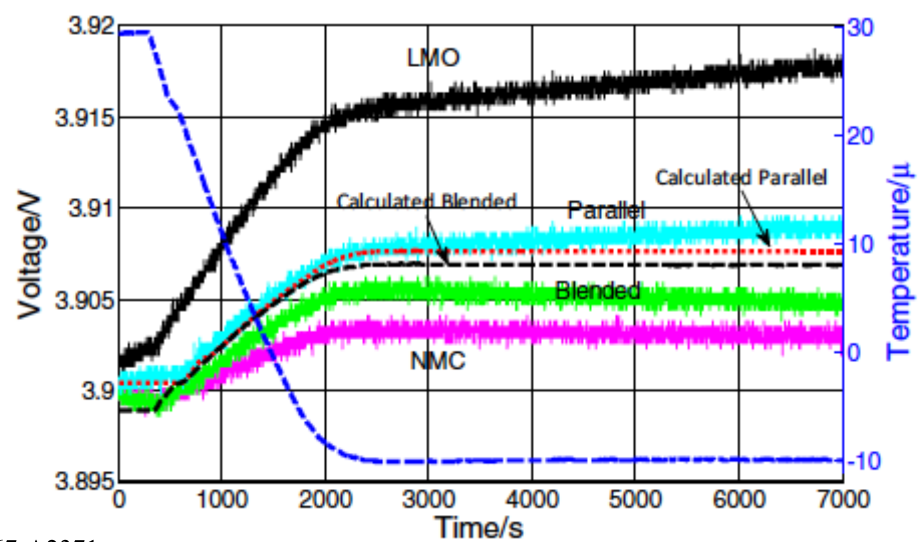
## *CASE STUDY*

# Mixed Entropy Coefficient & Thermal Balance



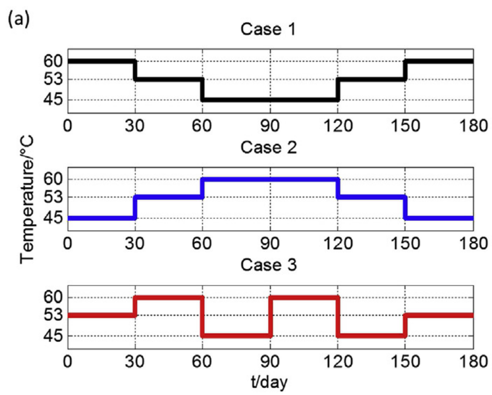

$$\left(\frac{\partial E}{\partial T}\right)_{blended} = \frac{\left(\frac{\partial E}{\partial T}\right)_a k_b C_a + \left(\frac{\partial E}{\partial T}\right)_b k_a C_b}{k_b C_a + k_a C_b}$$



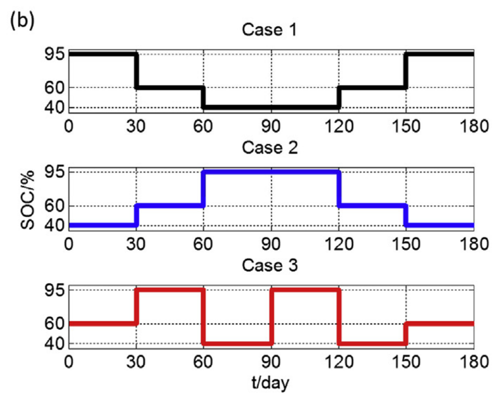




J. Huang et al., *J. Electrochem. Soc*. 162 (2015) A2367-A2371.

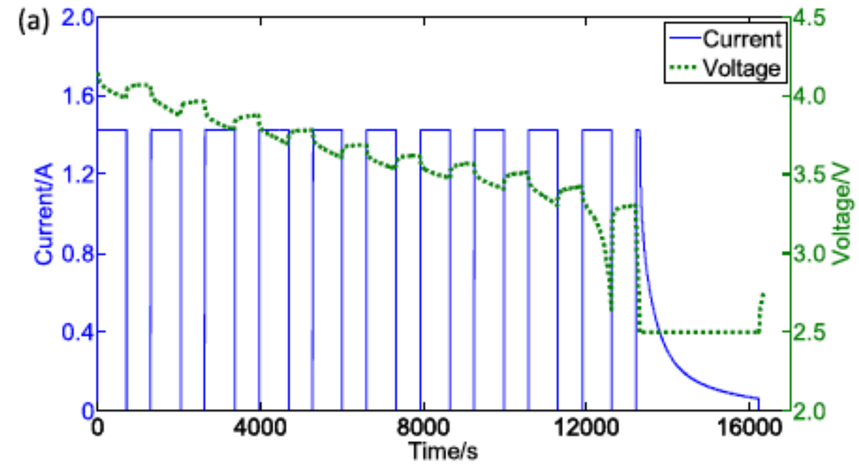
# Path Dependence of Fading Behavior by SOC and thermal conditions

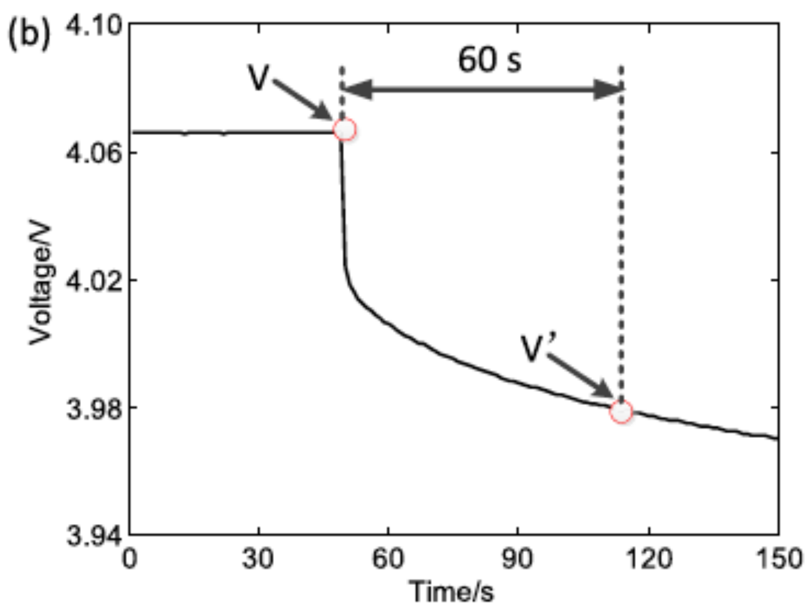


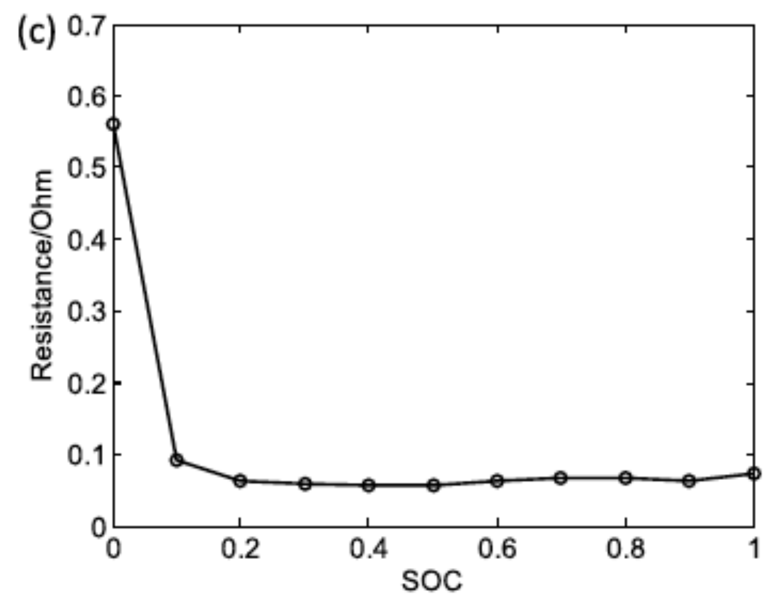

Temperature Dependence




SOC Dependence

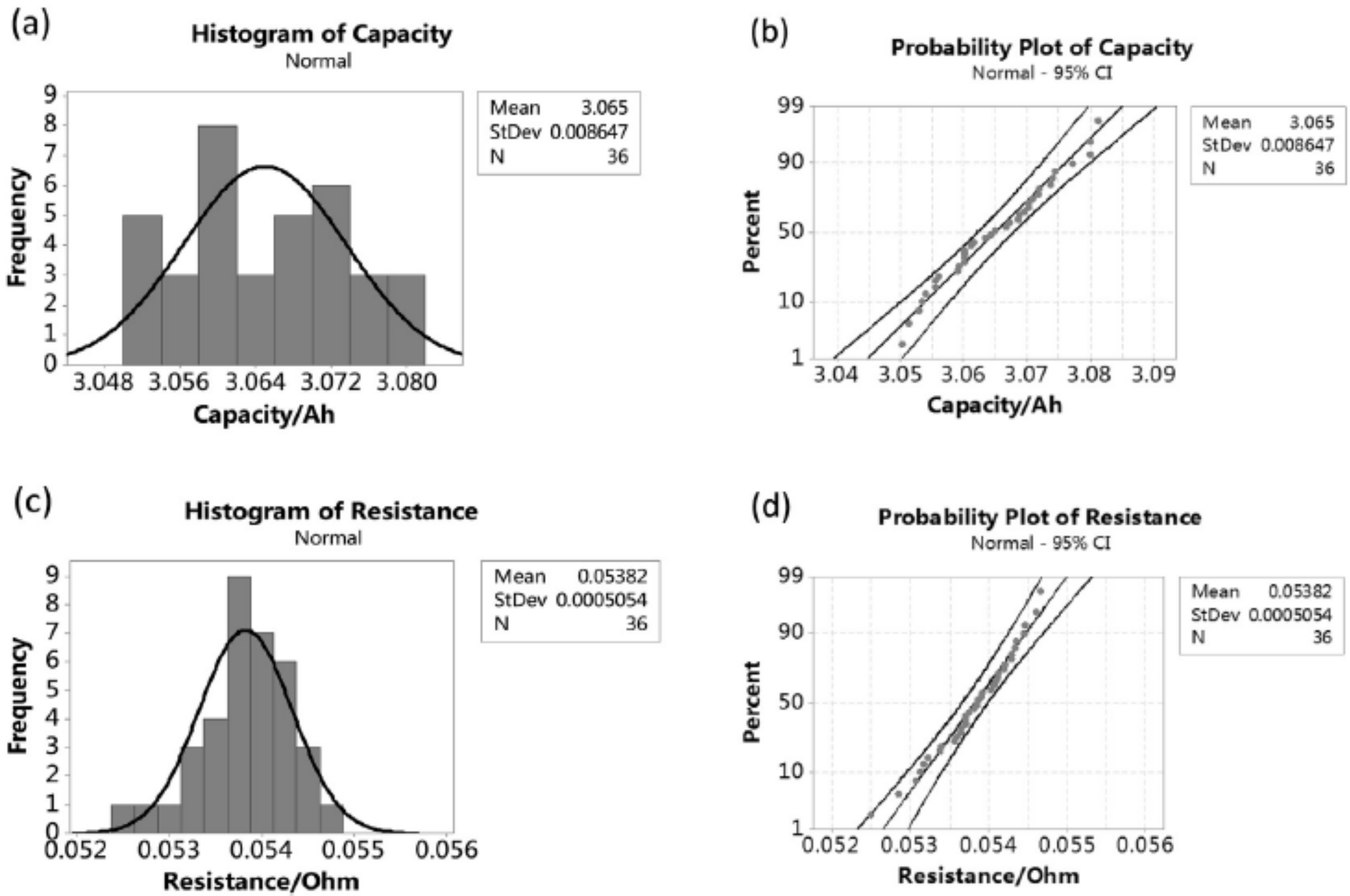


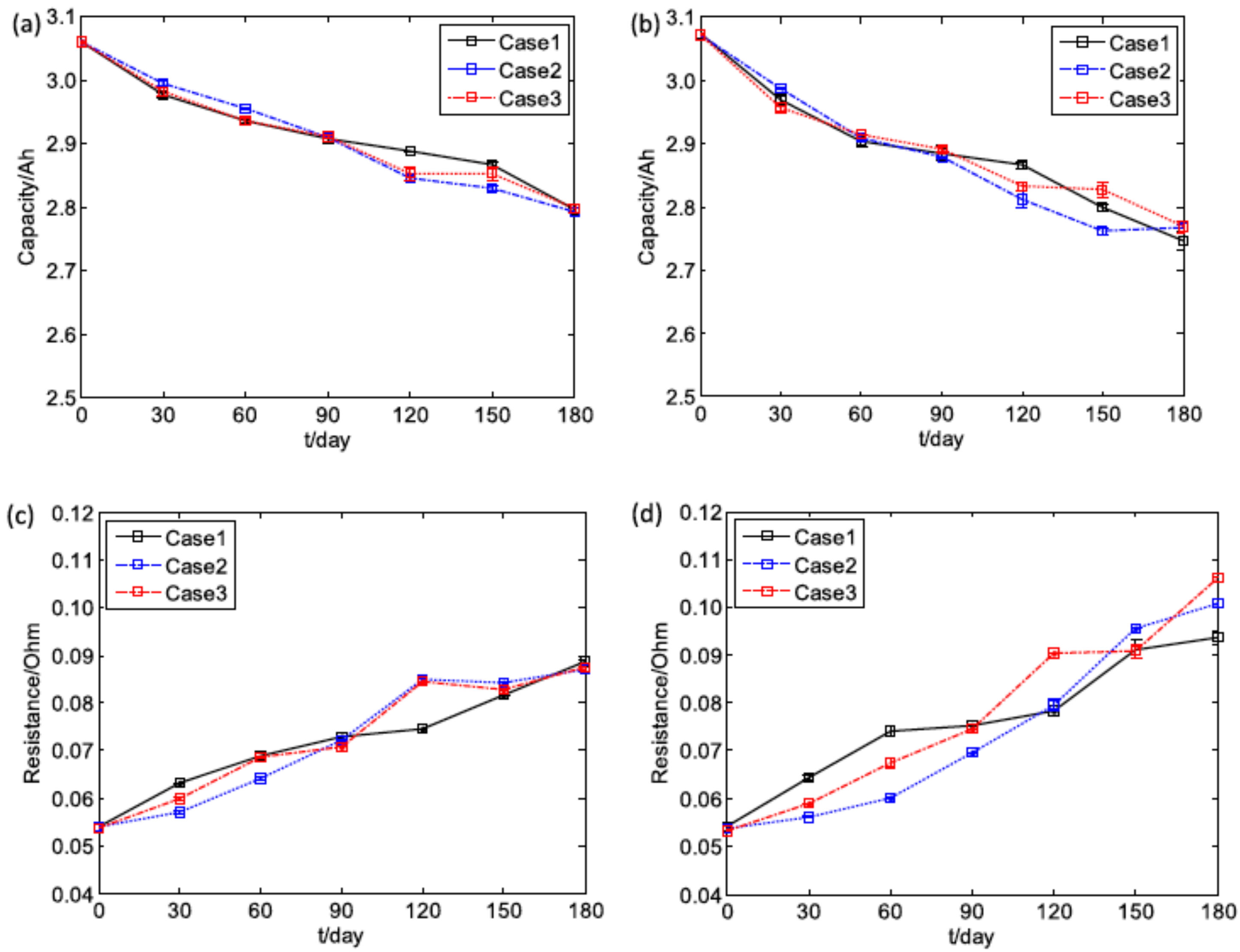




L. Su, et al., *J. Power Sources* 315 (2016) 35–46

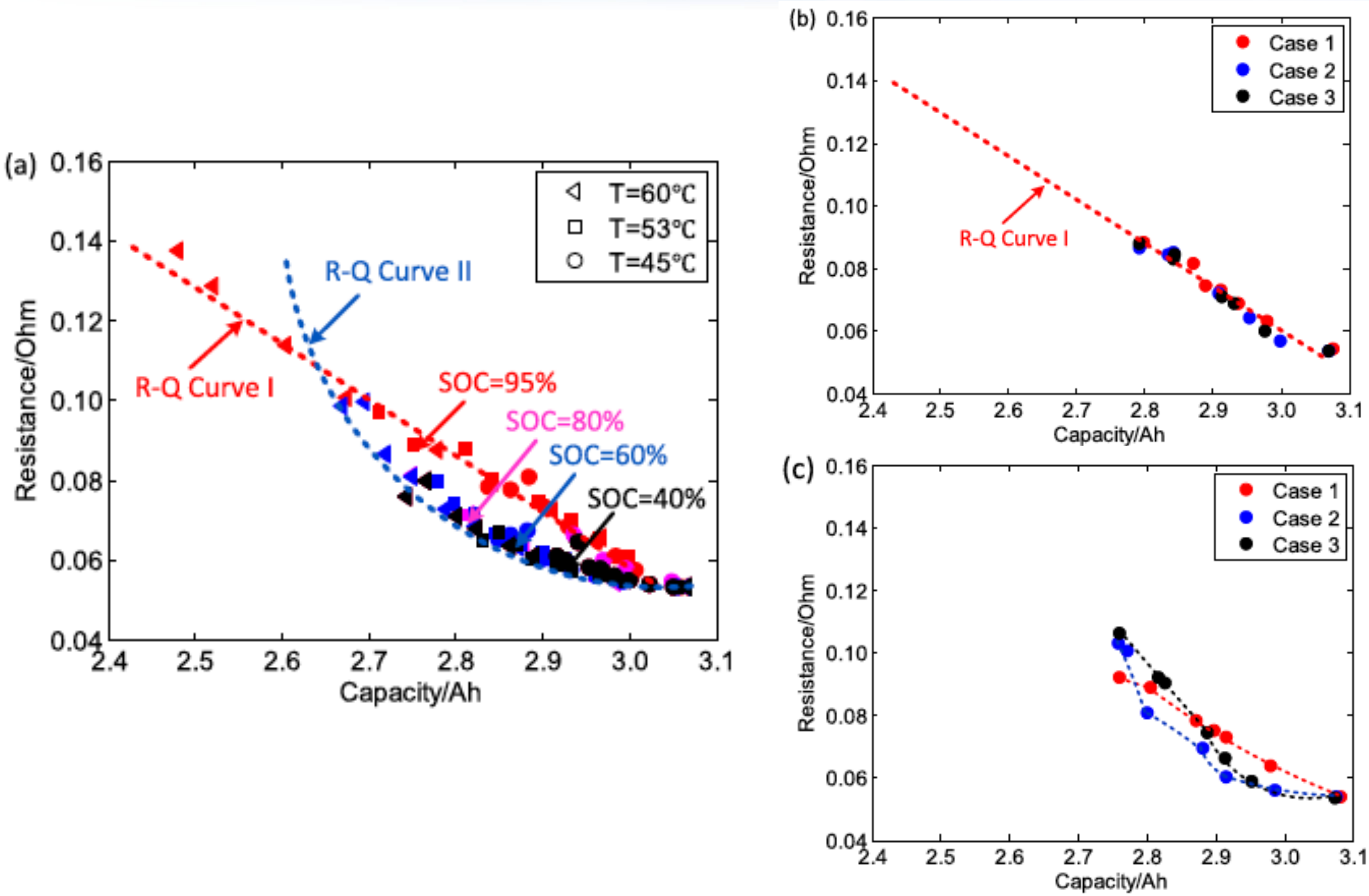
# Cell Variability Considerations



# Path Dependence of the Fading

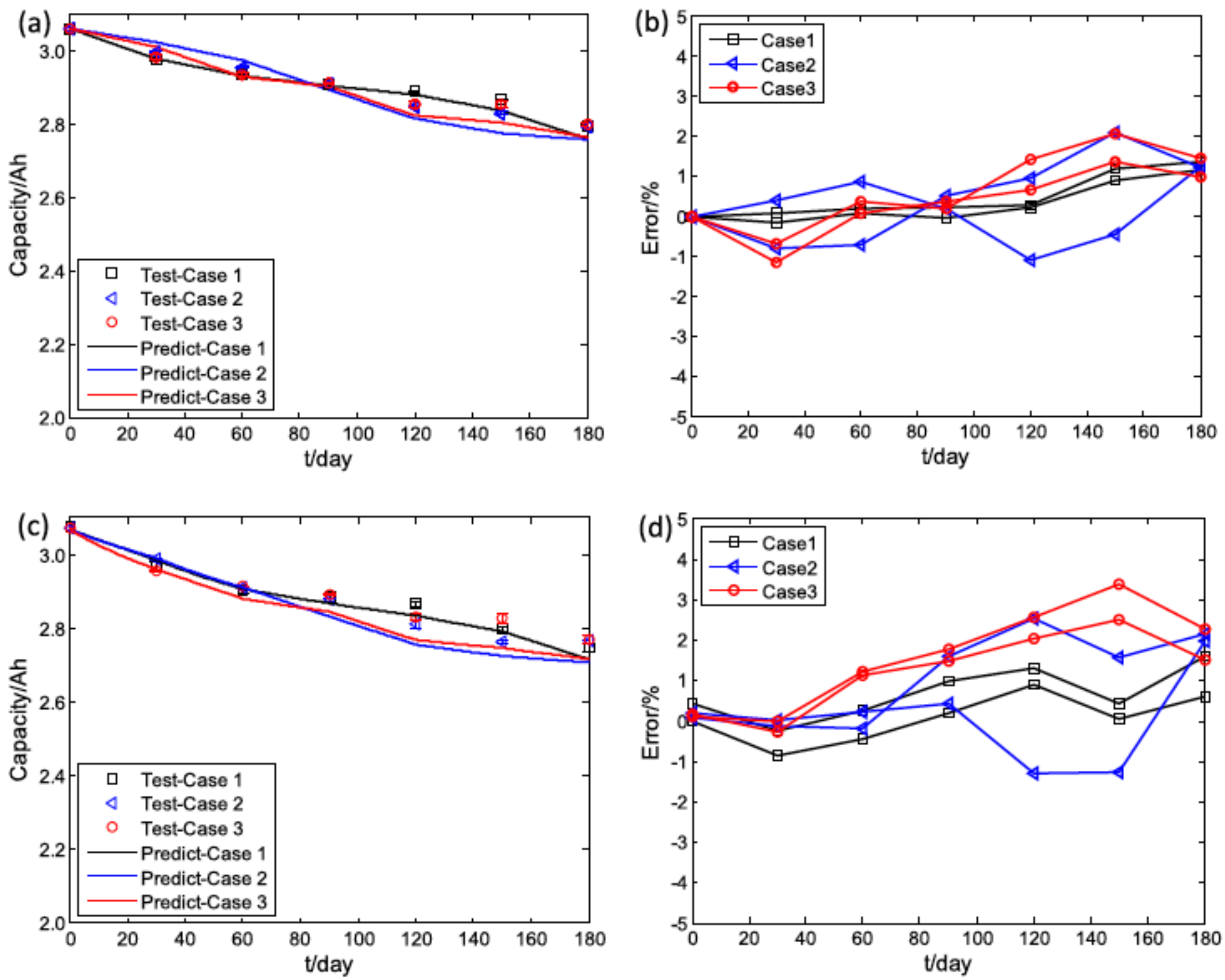


# Correlation Fade with Cell Resistance Changes



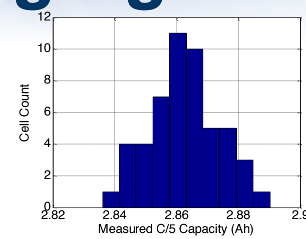
# Prognosis & Life Prediction

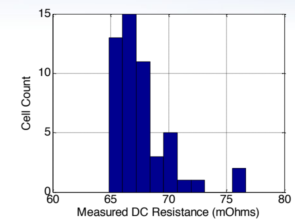
L. Su et al. J. Power Sources 315 (2016) 35–46



# *Quantify cell variability over aging*

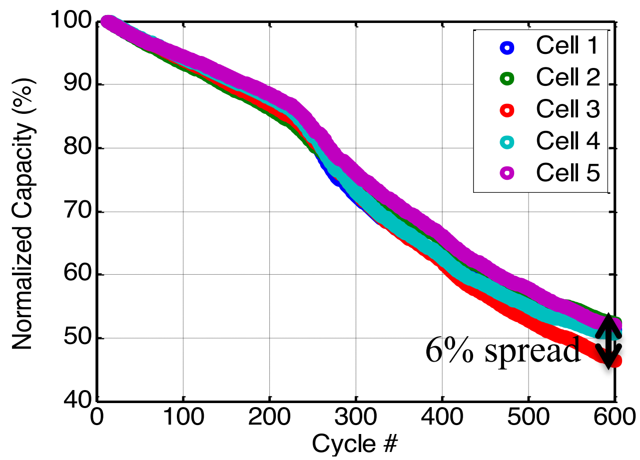
- 51 commercial G||LCO+ NMC 2.8 Ah 18650 cells

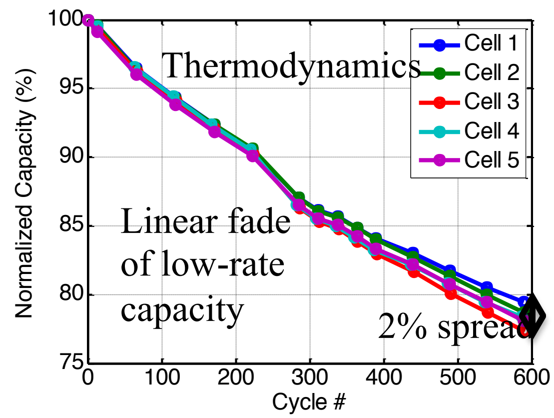


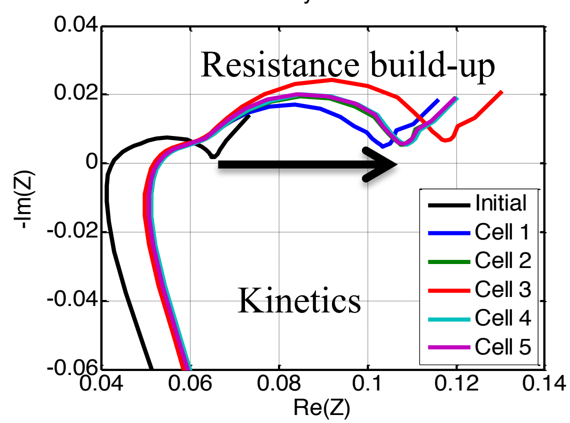



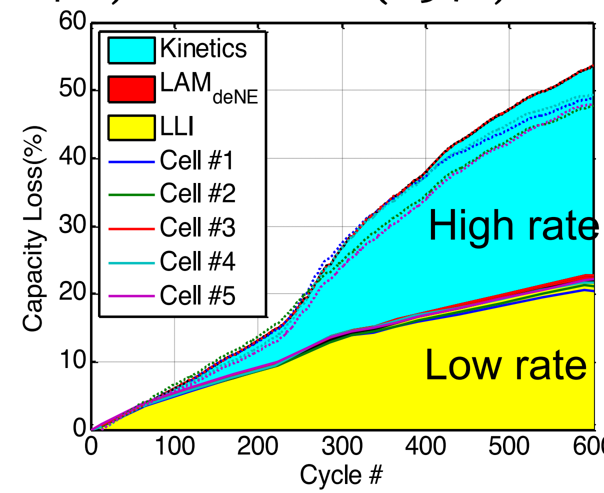

2863.09 ± 11.35 mAh (± 0.40%)

66.30 ± 2.45 mOhms (± 3.7%)




| Performance | LLI (%) | $LAM_{deNE}$ (%) |
|---|---|---|
| Base | 22.5 | 14 |
| Under | 25.5 (↗) | 16 (↗) |
| Over | 20.5 (↘) | 13 (↘) |
| *Batch* | *$22.5^{+3}_{-2}$* | *$14^{+2}_{-1}$* |
| *Avg ratio* | *1.6* | *1* |

$LAM_{deNE}$=f(LLI)

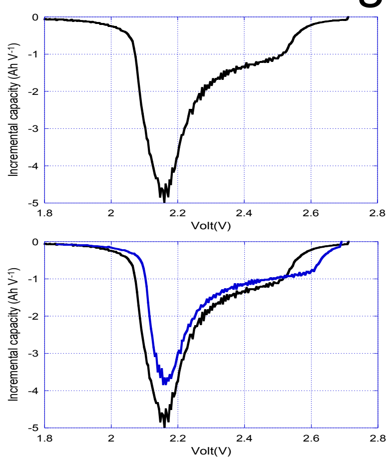
Dubarry and Liaw, "Assessing Cell-To-Cell Variations in Commercial Batteries", 218th ECS, Las Vegas, B2- #326: Battery Safety and Abuse Tolerance, 2010

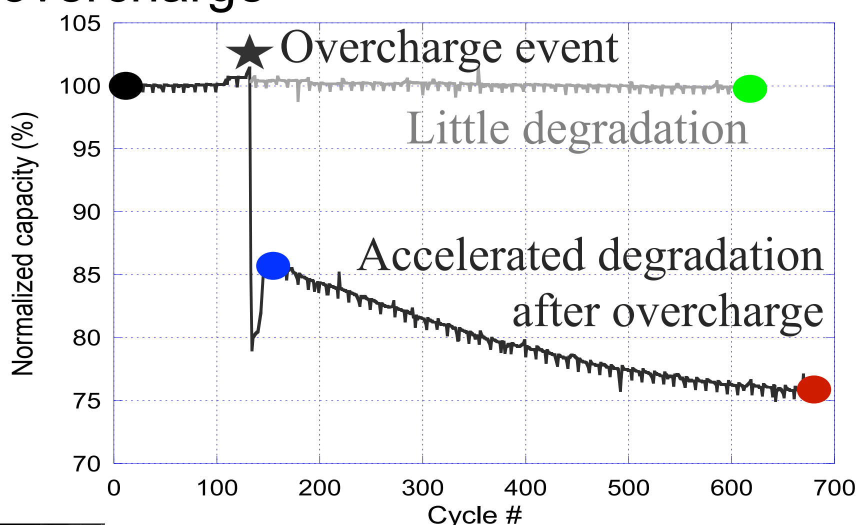
M. Dubarry et al. *Internat. J. Energy Res*. 34 (2010) 216-231

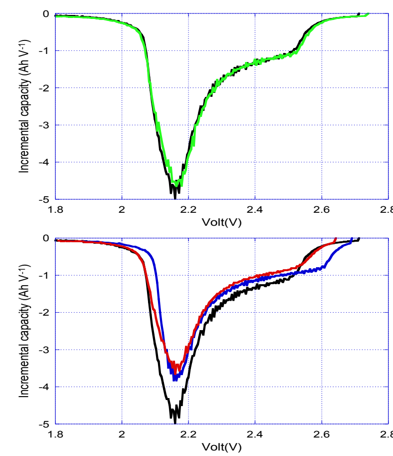
# *Quantify severity of abuse events*

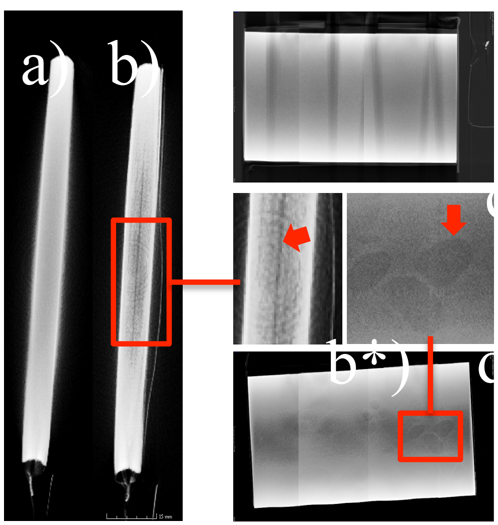
A. Devie et al. *J. Electrochem. Soc.* 162 (2015) A1033

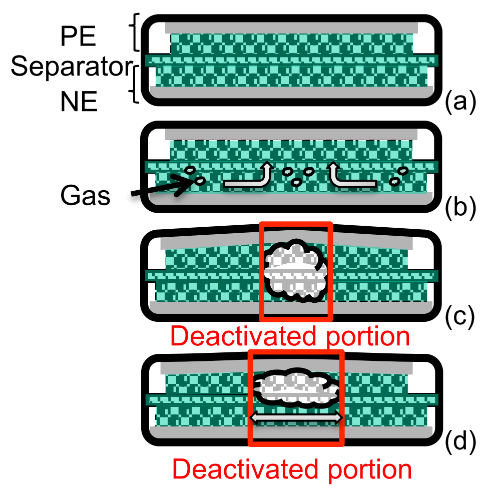
- Over-voltage overcharge

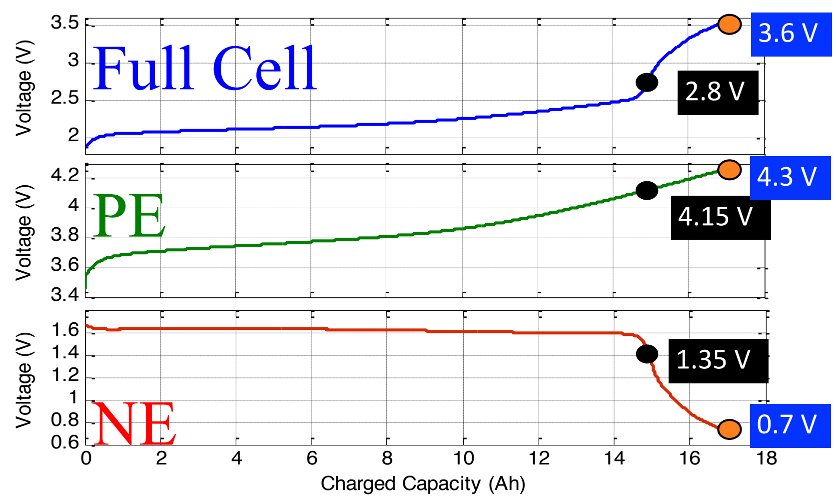


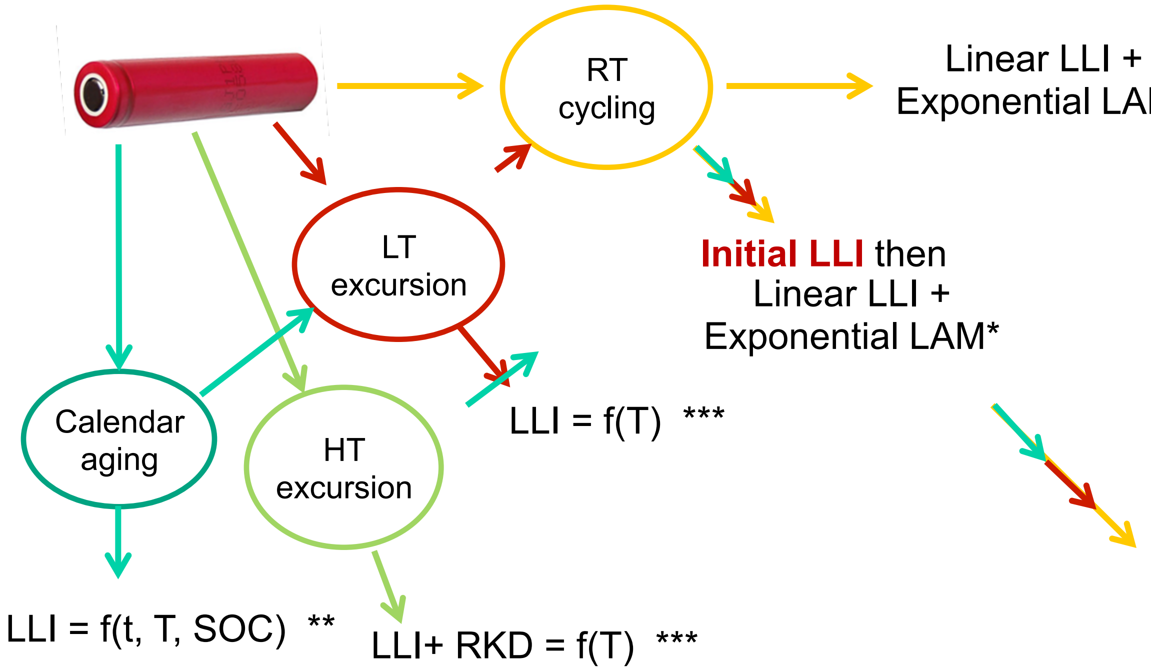



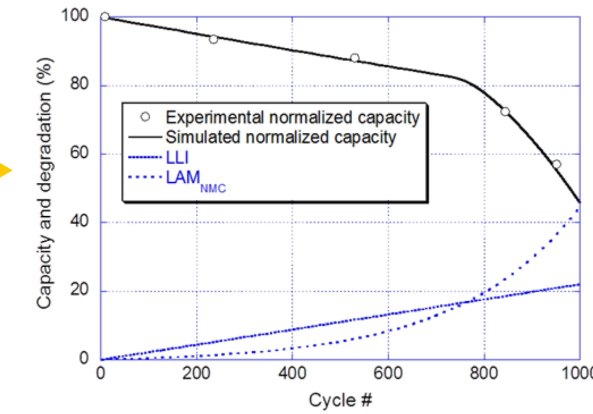



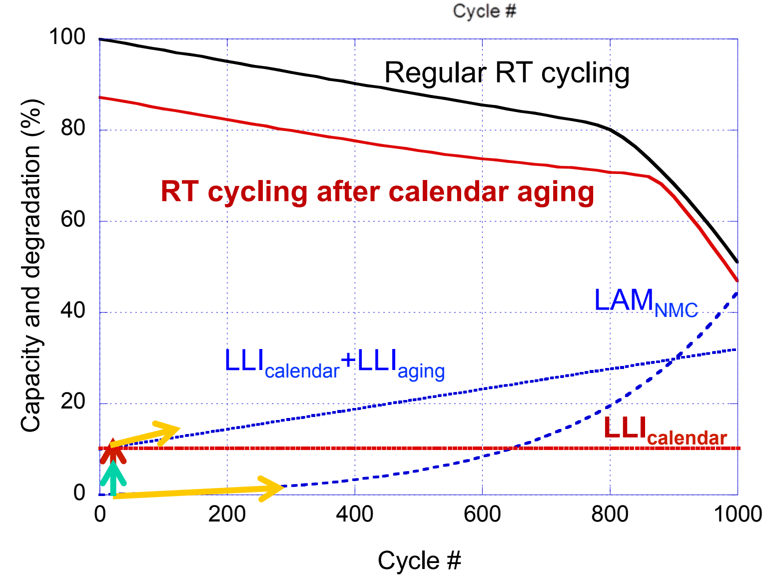



# *Simulation of Aging Path Dependence*

- Dependence on aging pathway can be simulated using results from laboratory testing or hypotheses



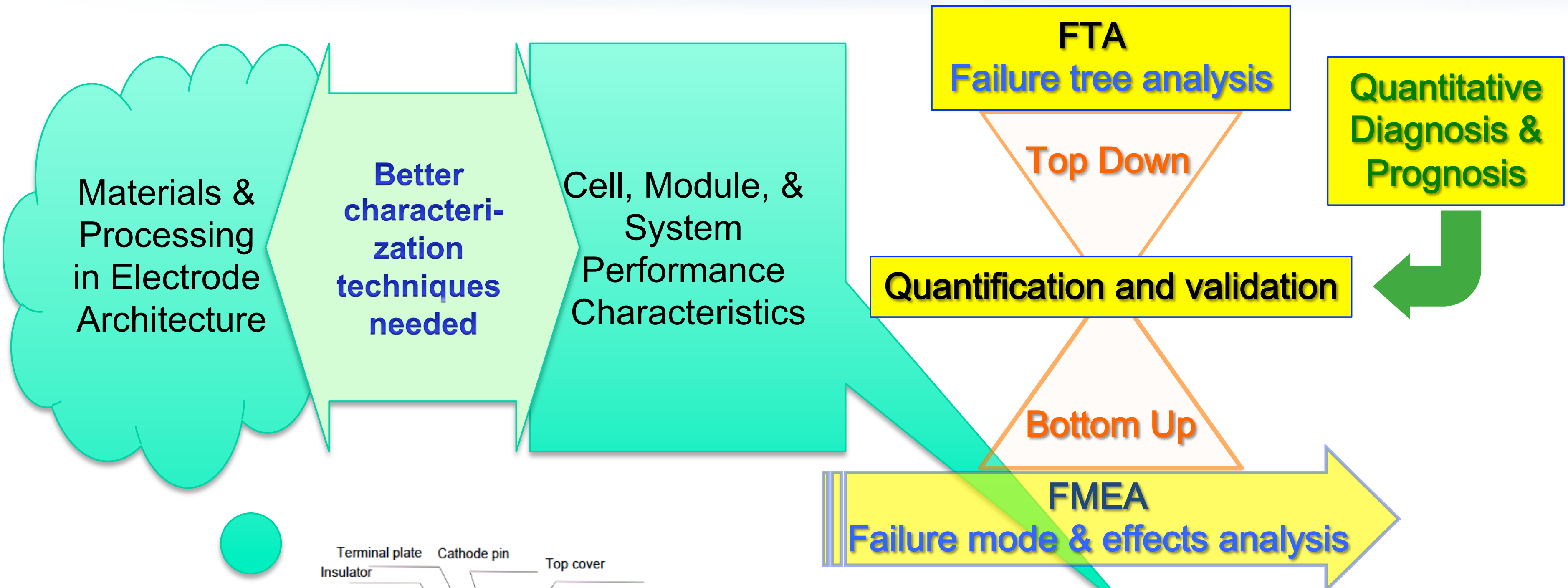


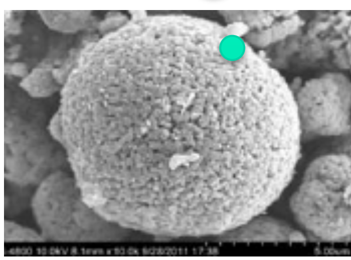
* Dubarry et al. *J. Power Sources* 196 (2011) 10336
** Kassem et al. *J. Power Sources* 208 (2012) 296
*** Dubarry et al. *J. Electrochem. Soc.* 160 (2013) A191 .

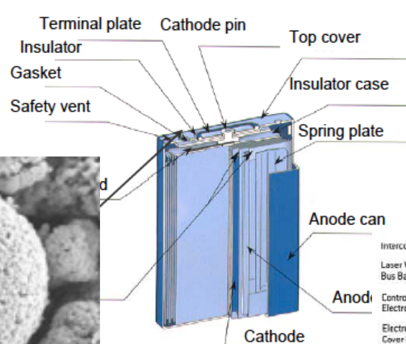

Complement other modeling approaches
Reduce complexity: Provide the link between battery material diagnostics and BMS

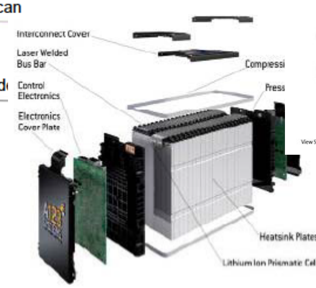
Computation is not intensive.
Easy to parameterize & use.

# *Engineering approach*





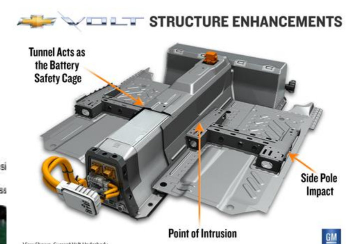




**Table II-5.** U.S. Advanced Battery Consortium Goals for Electric Vehicle Batteries

| 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)<br>1,600 (50% DOD)<br>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 | |

# Materials ←→ Systems Dilemma

Auto Engr

**Market push**

Chem Engr

**Technology pull**

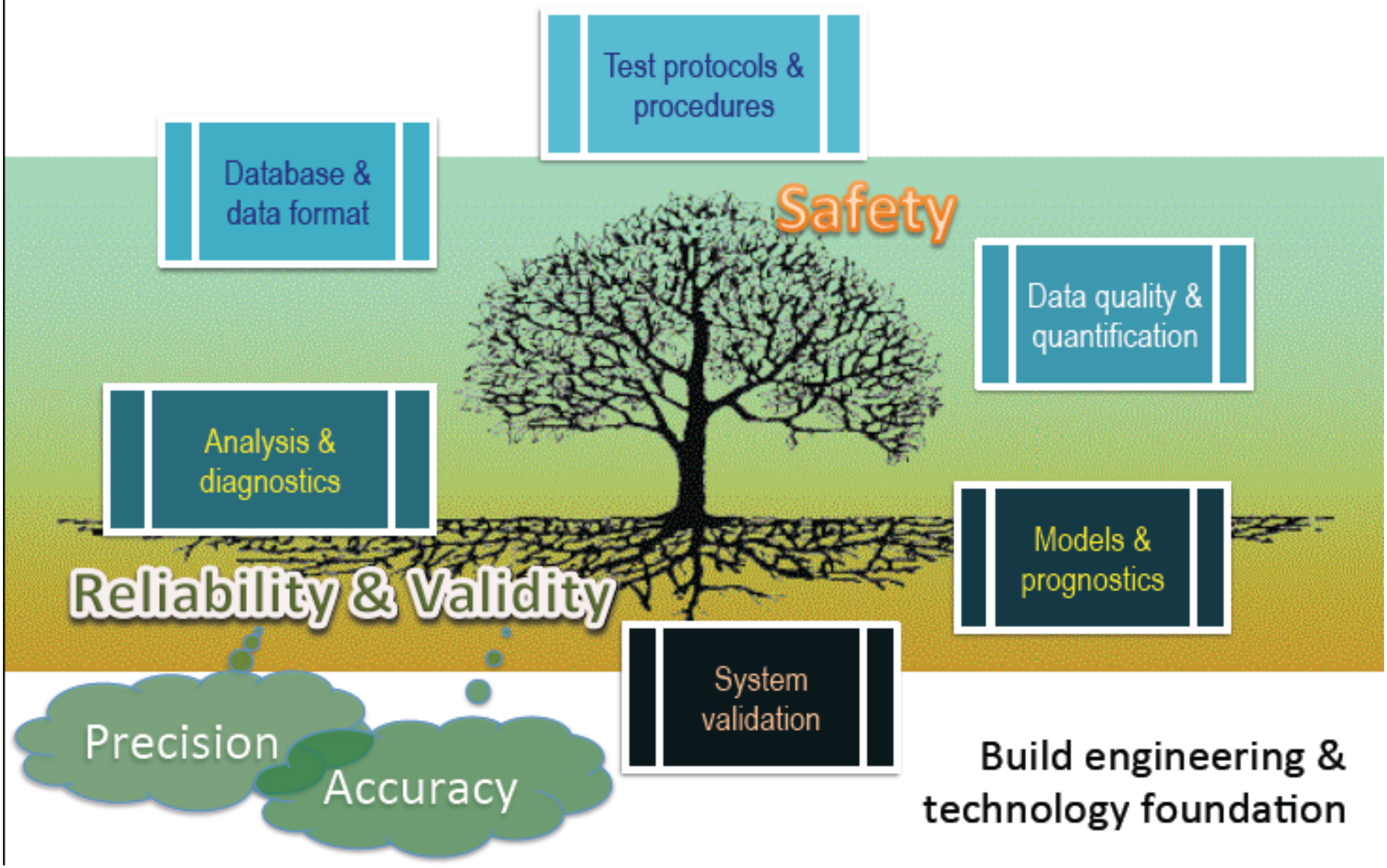
MSE

Cannot wait ...

We need the forest today!

Can we characterize the leaves to predict the growth of the tree?

## *See the Forest before the Tree*




Build engineering & technology foundation