A Viable Pathway from Durability to Reliability and Safety

Boryann (Bor Yann) Liaw, Ph.D. FECS

Energy Storage and Advanced Vehicles Department
Idaho National Laboratory
Idaho Falls, ID 83415

February 22-23, 2017
Meeting the Challenge: 2017 ESS Safety Forum
Santa Fe, NM
Vehicles, Energy Storage & Infrastructure

Development of Next-Generation Low Cost / Reliable Batteries:
- Leverage unique INL capabilities to lead Performance Science
- Foundation: Battery Testing Center & Advanced Vehicle Testing
- Growth via strong partnerships with:
  - DOE-EERE (USABC)
  - Automotive OEMs
  - Battery Developers
- Impact: Enabling / accelerating next gen low cost, safe and reliable batteries
Performance, durability, reliability and safety in a proper perspective – Risk assessment & management

System
Device
Durability

Manuals
• Installation
• Operation

Policies & regulations
• Protocols & procedures
• Control, management & auditing

Education, training & enforcement

Environmental Factors:
• Mechanical
• Electrical
• Thermal
• Chemical

Human Factors:
• Duty cycle & schedule
• Frequency
• Habit
• Preference

Safety

Catastrophic Events

Abuse Tolerance
Safety relies on proper cell design and deep understanding of cell performance

- Materials selection & processing
  - Electrode architecture
- Cell balance
  - Manufacturing quality
- System control and management
  - Preventive measures
Design-Build-Test Paradigm

- Forward-looking design principles – Insufficient to enable failure mode and effect analysis (FMEA)

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

<table>
<thead>
<tr>
<th>Primary Criterion</th>
<th>Long-term goals* (2005-2008)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Density, Wh/kg</td>
<td>460</td>
</tr>
<tr>
<td>Specific Power, W/kg (80% DOD, 10 sec)</td>
<td>300</td>
</tr>
<tr>
<td>Energy Density, Wh/L (C/2 discharge rate)</td>
<td>220</td>
</tr>
<tr>
<td>Specific Energy, Wh/kg (C/3 discharge rate)</td>
<td>150</td>
</tr>
<tr>
<td>Life, years</td>
<td>10</td>
</tr>
<tr>
<td>Cycle life (cycles)</td>
<td>1000 (80% DOD), 1,650 (50% DOD), 2,670 (30% DOD)</td>
</tr>
<tr>
<td>Power and capacity degradation (% of rated spec)</td>
<td>20%</td>
</tr>
<tr>
<td>Ultimate price, $/kWh (10,000 units, 40 kWh)</td>
<td>&lt;$120 (desired to 75)</td>
</tr>
<tr>
<td>Operating environment</td>
<td>-10°C to 65°C</td>
</tr>
<tr>
<td>Recharge time</td>
<td>6 hours</td>
</tr>
<tr>
<td>Continuous discharge in 1 hour (no failure)</td>
<td>75% of rated energy capacity</td>
</tr>
<tr>
<td>Efficiency (C/3 discharge and C/6 charge)</td>
<td>85%</td>
</tr>
<tr>
<td>Self-discharge</td>
<td>&lt;5% in 12 days</td>
</tr>
<tr>
<td>Maintenance</td>
<td>No maintenance. Service by qualified personnel only.</td>
</tr>
<tr>
<td>Thermal loss</td>
<td>Covered by self-discharge</td>
</tr>
<tr>
<td>Abuse resistance</td>
<td>Tolerant. Minimized by on-board controls</td>
</tr>
</tbody>
</table>

Sources: various literature documents
Engineering approach

Durability
Reliability
Safety

FMEA

Quantitative Analysis

Diagnostics
Prognostics
Cell Variability – Origins

Chemistry: Redox Couple

Crystal Structure

Voltage

Theoretical Capacity

Intrinsic

Rate capability
Cycle life

Electrode Processing

Δ Rate Capability

Δ Resistance

Δ Weight

Packaging

Δ Capacity

Cell Balance

Cell specific capacity

Nominal capacity

Polarization resistance

Cell Manufacturing

Δ PERFORMANCE

INL Idaho National Laboratory
Origins and accommodation of cell variations in Li-ion battery pack modeling

Matthieu Dubarry, Nicolas Vuillaume and Bor Yann Liaw*

Hawaii Natural Energy Institute, SOEST, University of Hawaii at Manoa, 1680 East-West Road, POST 109, Honolulu, HI 96822, U.S.A.

SUMMARY

Rechargeable battery industry will see significant growth in the use of battery systems for portable devices and power electronics, renewable energy storage, power systems for transportation, and telecom backup power applications. Despite such promising market sentiment, the battery system management remains as a challenging issue to be resolved in order to provide a safe and reliable power and energy storage system. Here we report advancement in the battery management approach by providing a solution to analyze battery performance variations in a lot of batteries produced from the same manufacturing process. A lot of 100 Li-ion cells were analyzed in order to quantify the inherent cell variations associated with cell manufacturing process and test protocol. Both statistical and electrochemical analyses were used to characterize and quantify the capacity variations among the cells along with other parameters that can be readily derived from the test results. Information extracted from a minimal testing of the cells in the lot and more intensive characterizations on a few cells including one as the nominal sample cell allows the establishment of a single cell model (SCM), based on a generic equivalent circuit, with high accuracy in predicting cell performance. The analyses also permit a carefully crafted logic development of how to separate the origins that cause the cell variations in performance. Such separation of the attributes enable a proper tuning of the cell parameters in the model, which allows the accommodation of cell variations in a battery pack model to handle most of the imbalance issues. A careful validation of the SCM to predict performance of any arbitrary cell in the lot with high accuracy was demonstrated. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS: intrinsic cell imbalance; battery pack management; equivalent circuit model; statistical analysis; battery pack
Experimental

- 100 commercial AAA size 300 mAh Gr/LiCoO\textsubscript{2} cells.
- Charging regime: CC @C/2 + CV @4.2V and 0.5 hrs cutoff
- Discharge regime: C/5, C/2 (RPT: C/25, C/3, 1C and 2C)
  - High rate: Solartron 1470
  - Low rate: Bio-logic VMP3
- Rest: 3 hrs → relaxed cell voltage (RCV)
- SOC = Q/Q\textsubscript{25} → pseudo-OCV vs. SOC curve
- SOC determination by RCV
Speciation in cell metrics to performance variations

W = 8.89±0.15 g (±1.69%)

RCV = 3.880±0.018V (±0.45%)

Q2 = 295.5±5.5 mAh (±1.9%)

Q5 = 298.6±4.7 mAh (±1.6%)

Int. J. Energy Res. 2010; 34:216–231
EOC to BOD

(a) RCV @ EOC (V)

(b) EOC termination current (A)

(c) Polarization resistance (Ω·Ah)

Int. J. Energy Res. 2010; 34:216–231
BOD to EOD

Int. J. Energy Res. 2010; 34:216–231
EOD to Capacity

Int. J. Energy Res. 2010; 34:216–231
Capacity normalization to SOC

Int. J. Energy Res. 2010; 34:216–231
Cell variability in SOC during testing

Int. J. Energy Res. 2010; 34:216–231
Capacity ration (mAh/%SOC)
Impacts from DCR on SOC

Int. J. Energy Res. 2010; 34:216–231
Impacts from DCR on capacity
High fidelity of cell model and simulation

Int. J. Energy Res. 2010; 34:216–231
Every cell in the pack can be modeled precisely

Int. J. Energy Res. 2010; 34:216–231
Cell variability in aging & capacity fading

- Even with the best state-of-the-art cell design and manufacturing, variability in endurance remains as an issue that impacts durability, reliability and safety

![Graph showing cell variability](image)

- 2863.09 ± 11.35 mAh
  - (+ 0.40%)
- 66.30 ± 2.45 mΩ
  - (+ 3.7%)

- Commercial 2.8 Ah G || LCO + NMC
- 18650 cells
- 6% spread

![Graph showing normalized capacity over cycle number](image)
Quantify Cell Variability over Aging

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

