Understanding the factors impacting battery failure propagation and its mitigation

**Presented by**

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Outline

- Introduction
  - Battery Abuse Testing Laboratory (BATLab) Capabilities
  - Motivation
  - Objective

- Methodology

- Results & Discussion
  - Baseline Failure Propagation
  - Passive Thermal Management
  - Predicting Thermal Runaway

- Summary

- Acknowledgements
Capabilities and Infrastructure: Battery Abuse Testing Laboratory (BATLab)

Comprehensive abuse testing platforms for safety and reliability of cells, batteries and systems from mWh to kWh.

<table>
<thead>
<tr>
<th>Mechanical abuse</th>
<th>Thermal abuse</th>
<th>Electrical abuse</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Penetration</strong></td>
<td>Over temperature</td>
<td>Overcharge</td>
</tr>
<tr>
<td>(max. force 25 klbs, max</td>
<td>(250 °C, 5 °C/min)</td>
<td>(max. current 300 A)</td>
</tr>
<tr>
<td>speed 10 mm/s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Crush</strong></td>
<td>Flammability measurements</td>
<td>Overdischarge</td>
</tr>
<tr>
<td>(max. force 100 klbs, max</td>
<td>(250 °C, 5 °C/min)</td>
<td>(max. current 300 A)</td>
</tr>
<tr>
<td>speed 2 mm/s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Impact</strong></td>
<td>Calorimetry</td>
<td>Short Circuit</td>
</tr>
<tr>
<td>(max. height 8”8’, max.</td>
<td>(405 °C, 5 °C/min)</td>
<td>(max. current 2500 A)</td>
</tr>
<tr>
<td>drop weight 700 lbs)</td>
<td></td>
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<tr>
<td><strong>Immersion</strong></td>
<td></td>
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</tbody>
</table>
Materials R&D
- Non-flammable electrolytes
- Electrolyte salts
- Coated active materials
- Thermally stable materials
- Battery failure post mortem materials analysis

Testing
- Diagnostics during battery failure (pictured right)
- Gas analysis
- Battery calorimetry
- Electrical, thermal, mechanical abuse testing
- Failure propagation testing on batteries/systems
- Large scale thermal and fire testing (TTC)

Simulations and Modeling
- Multi-scale models for understanding thermal runaway
- Validating failure propagation models
- Fire Simulations to predict the size, scope, and consequences of battery fires

Procedure Development and Stakeholder Interface
- USABC Abuse Testing Manual (SAND 2005 3123)
- OE Energy Storage Safety Roadmap
- R&D programs to inform best practices, and policies.
- Hosted International Battery Safety Workshops and Energy Storage Safety Workshop

- Sandia is uniquely positioned to study the entire life cycle of a technology.
- Diagnostic tests can be performed under extreme failure conditions to understand the how and why of battery failure.
Team Members

Sandia Battery Test Facilities
- Summer Ferreira
- Yuliya Preger
- Armando Fresquez

Sandia Battery Abuse Lab
- Loraine Torres-Castro
- Joshua Lamb
- June Stanley
- Jill Langendorf

Sandia Fire Sciences
- John Hewson
- Randy Shurtz
- Andrew Kurzawski

Center for Integrated Nanotechnologies
- Sergei Ivanov

Baseline electrochemical performance analysis
Materials characterization and thermal stability testing
Whole-cell abuse response analysis
Modeling of thermal propagation
Design of new power electronics for battery safety
Motivation for Propagation Testing

How do these behaviors impact a larger, more complex system?

Objective
Understand the extent of propagation with inclusion of passive thermal management in the form of spacers (aluminum and copper) between (i) pouch cells in a 5 cells pack, and (ii) between modules of a 3s3p configuration battery pack.
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Methodology and Approach

Part I: Baseline failure propagation
- COTS LCO 3 Ah pouch cells
- 5 cells closely pack together
- Failure initiated by a mechanical nail penetration along longitudinal axis of outer cell (cell 1)

Part II: Passive thermal management between cells
- COTS NMC 3 Ah pouch cells
- 5 cells closely pack together
- Aluminum or copper spacers between cells (1/8 in, 1/16 in, 1/32 in)
- Failure initiated by a mechanical nail penetration along longitudinal axis of outer cell (cell 1)

Part III: Predicting thermal runaway
- Develop validated predictive models of cell-to-cell then module-to-module propagation
- Identify boundaries of propagation versus mitigation
- Develop capabilities to evaluate design tradeoffs.
- Promote a broader acceptance of quality approaches to energy storage safety.
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Baseline Failure Propagation

Failure initiated by mechanical insult to edge cell of a COTS LCO pack at 100% SOC (3Ah cells)

Observed complete propagation when cells are close packed with no thermal management

- Successful initiation at Cell #1
- Propagation to adjacent cells
- Cascading failure to entire battery over 82 s

Observed complete propagation when cells are close packed with no thermal management
Failure Propagation and Cell Failure at Reduced States of Charge

Failure initiated by mechanical insult to edge cell of COTS LCO packs (3Ah cells)

- **50% SOC**
  - No cell to cell propagation.
  - Thermal runaway of initial cell failure was minimal.

- **75% SOC**
  - Limited propagation.
  - Damage was observed for Cell 2 but no high thermal runaway events seen for cell 3 to 5.

- **80% SOC**
  - Full failure propagation.
  - Compared to baseline test, peak temperatures were marginally lower (550 °C vs 620 °C)
  - Cascading failure to entire battery over ~240 s.
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The focus of this section is to understand the extent of propagation with the inclusion of thermal management in the form of heat sinks between pouch cells.
Thermal Management: 1/8 inch barrier

Failure initiated by mechanical insult to edge cell of COTS LCO packs

- Successful initiation of Cell #1 for all the different tests.
- Failure of cell 1 in both cases were consistent and peak temperatures reached ~400 °C.
- No propagation was realized while using 1/8 inch aluminum or copper spacer.
- Energetic thermal runaway was not observed beyond the initial failed cell in either case.
Thermal Management: 1/16 inch barrier

Failure initiated by mechanical insult to edge cell of COTS LCO packs

- Successful initiation of Cell #1 for all the different tests.
  - Limited propagation (from cell 1 to 2).
- For both cases, cell 2 reached ~300 °C and eventually lost voltage.
Thermal Management: 1/32 inch barrier

Failure initiated by mechanical insult to edge cell of COTS LCO packs

- Successful initiation of Cell #1 for all the different tests.
- Pulsing propagation behavior observed over the next several minutes.
- Entire pack consumed ~4 minutes after initial failure.
Global rates allow estimates of possible active cooling requirements.

Adding spacers increases gap crossing time, but decreases cell crossing time. Increasing state of charge (SOC) decreases both space and cell crossing time.
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Large-scale testing is costly and simulations allow exploration of the design space if well grounded in reality.

- Measurements are reality but simulations allows us to better understand the behavior changes
- Explore boundaries between mitigation and cascading failure

Temperature-time propagation measurements and predictions

100% SOC, no spacers

- Add heat capacity.
- Increase time delay for cell runaway.
- Prevent propagation for 30% increase in net heat capacity.
- Reduced SOC results suggest homogeneous heat capacity changes of 25% sufficient.

1/32” copper spacers

1/32” aluminum spacers
Energy per heat capacity, cooling and inter-cell resistance defines propagation limits. Model maps delay in propagation: yellow region is infinite delay—*failure to propagate*.

Convection cooling and conduction through stack results in failure to propagate for some scenarios.

Consider cost/design tradeoff: cooling versus thermal resistance.
Summary

• A cell may exhibit dramatically different failure response when in a string, module or pack than during single cell abuse testing.

• Limiting the SOC can have a meaningful impact in propagating failure, however this comes at a significant cost to total energy storage.

• Propagation can be mitigated through system engineering, however the results can be unpredictable. Further, electrical design will play a role in susceptibility to failure testing.

• Failure testing of large, complex systems is fairly resource intensive. Model based design presents a potential remedy to this, allowing us to infer a large amount of information from a relatively small number of tests.
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