Thermal Analysis to Mitigate Cascading Propagation of Lithium-Ion Cell Stacks

Presented by
John Hewson, Andrew Kurzawski, Randy Shurtz,
Lorraine Torres-Castro, Yuliya Preger, Joshua Lamb

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Validated safety and reliability is one of the critical challenges identified in 2013 Grid Energy Storage Strategic Plan.

Safety incidents are rare but possible, including external causes.

How can we reduce facility investment risk?

- Prevent single point failure from cascading to large-scale system risk.
- Current approach is test to safety.

Large-scale testing is costly and simulations allow exploration of the design space if well grounded in reality.

- We link source terms to material science - morning talk by Randy Shurtz.
OBJECTIVES

Provide robust system scale safety and reliability

Validated safety and reliability is one of the critical challenges identified in 2013 Grid Energy Storage Strategic Plan

Develop methods to mitigate point failures and avoid propagation

1. Develop validated predictive models of cell-to-cell then module-to-module propagation.
   - Concurrent experimental program for validation (Loraine Torres-Castro)
   - Other tasks link predictive heat release to material science (Randy Shurtz)

2. Identify boundaries of propagation versus mitigation
   - Thermal aspects of system design
   - Electrical aspects of system design
   - Battery chemistry and material science
   - Algorithms for active control strategies.

3. Develop capabilities to evaluate design tradeoffs.

4. Promote a broader acceptance of quality approaches to energy storage safety.
OVERVIEW – Reduce facility investment risk: Identify boundaries between mitigation and cascading failure

Short circuit simulated in first cell acts as boundary condition

Baseline cell stack: Thermal runaway propagates

Thermal modifications (Reduced conductivity, increased contact resistance): Propagation mitigated.

RESULTS - Predicting Thermal Runaway

Simulation and measurements: 5 x 3 Ah LCO cells, 100% SOC, no plates
RESULTS - Predicting Thermal Runaway

Challenge: Calorimetry measurements only at lower temperatures.

- Extrapolating thermal runaway models to cascading failure predicts too-fast propagation.
- Lack higher-temperature measurements to predict cascading failure.

- Identified lithium/oxygen diffusion as limiting at cell propagation temperatures.
- Enables prediction over range of propagation/mitigation.

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Successful prediction over a range of reduced SOC and metallic inserts.

Collectively add heat capacity & increase time delay for cell runaway.

Prevent propagation for 30% increase in net heat capacity.

RESULTS - Predicting Thermal Runaway Propagation/Mitigation

Heat capacity/plates and SOC propagation/mitigation summary

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<th>State of Charge</th>
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<th>Simulation</th>
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<td>100% SOC</td>
<td>Propagation</td>
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<tr>
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<td>50/50 Propagation</td>
<td>Propagation</td>
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<tr>
<td>75% SOC</td>
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<tr>
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Quantified: Increased heat capacity per stored energy can inhibit cascading propagation.

Results - Predicting Thermal Runaway Propagation/Mitigation

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Quantified: Increased heat capacity per stored energy can inhibit cascading propagation.

Can we use thin plates to dissipate heat to the rest of the structure/cooling system?

Demonstrated predictive capabilities allow us to ask design questions about previous cases:

• What cell temperature must be avoided to prevent propagation?
  • Next-cell face temperature shows limiting value. *Warm colors propagation; cool colors mitigation*
  • Cleaner separation if we simulate inert cathode.
• Also note time delay with plates versus no plates.
  • Time delays are opportunities to dissipate heat.
  • *But time to conduct heat along plate is long: (20-30 s)*
RESULTS – Opportunities with Predictive Simulations

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Thermal resistance between cells reduces the max heat flux between cells.
- Cell-to-cell contact resistances on the order 0.002 to 0.004 m²*K/W.
- Thermal resistance of a few mm of insulating plastic, ceramic, etc. can increase this by 10x or more.

\[ R'' = 0.004 \text{ m}^2\text{K/W} \]

\[ R'' = 0.010 \text{ m}^2\text{K/W} \]

\[ R'' = 0.020 \text{ m}^2\text{K/W} \]
Insulation and structural materials delay heat transfer to adjacent cells/modules and allow for heat dissipation.

**Heat flux into ‘next cell’**

- Plates & increasing insulation

**Face temp of ‘next cell’**

- Plates & increasing insulation
RESULTS - Predicting and Mitigating Thermal Runaway

Limits of cascading thermal runaway

Model maps delay in propagation: yellow region is infinite delay—failure to propagate.

Result here is for 3 Ah LCO cells.

Other results can be obtained through model parameter sweeps.

Developing LIM1TR: open source code (Lithium-Ion Modeling for 1-D Thermal Runaway)

Provides design tool for system design community.

Look forward to our forthcoming manuscript with analytic expressions for system design criteria
PUBLICATIONS, ETC.

Peer-reviewed publications


Presentations
- R.C. Shurtz and J.C. Hewson “Modeling Thermal Decomposition of Metal Oxide Cathodes in Non-Aqueous Electrolytes for Prediction of Thermal Runaway in Lithium-Ion Batteries” 236th ECS Meeting, Atlanta, GA, October 17, 2019

Tools:
SUMMARY
Predicting and Mitigating Thermal Runaway

- Relate material models to experimental measurements at multi-cell level.

- Address safety modeling associated with thermal modifications. Determine limits of cascading failure.

- Implement new high-temperature chemistry.

- Identified particle diffusion as potential high-temp physics limit.

- Provides comprehensive predictions of propagation and mitigation over range of conditions.

- Mitigate propagation with
  - increased heat capacity per stored energy.
  - thermal resistance between cells.

- Mapped out limits.

- Provide experimental design.

- Quantified relative effectiveness experimentally and through predictions.
Thank you

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