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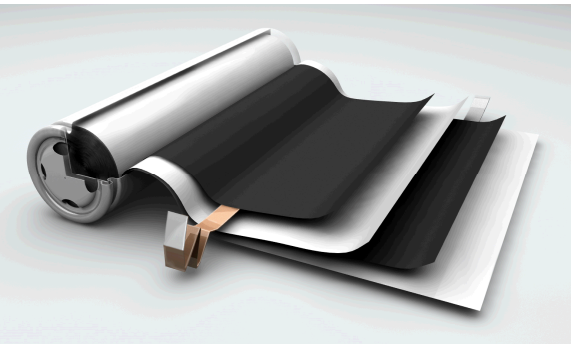
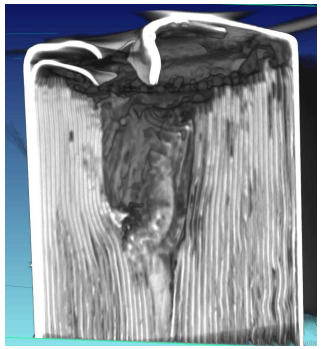

Consequences, mitigation and detection of propagating battery failure

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Sandia National Laboratories

MRS 2017 Fall Meeting

Boston, MA, November 27-Dec1 1, 2017

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Understanding Battery Safety

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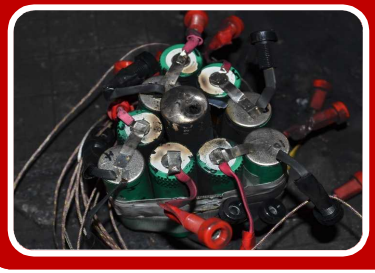
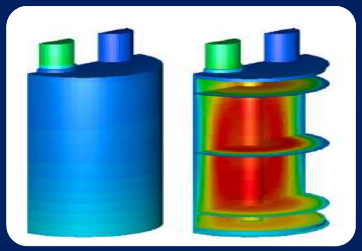
Materials R&D

- Non-flammable electrolytes
- Electrolyte salts
- Coated active materials
- Thermally stable materials



Testing

- Electrical, thermal, mechanical abuse testing
- Large scale thermal and fire testing (TTC)
- Failure propagation testing on batteries/systems
- Diagnostic techniques for battery state of stability
- Development for DOE Vehicle Technologies and USABC



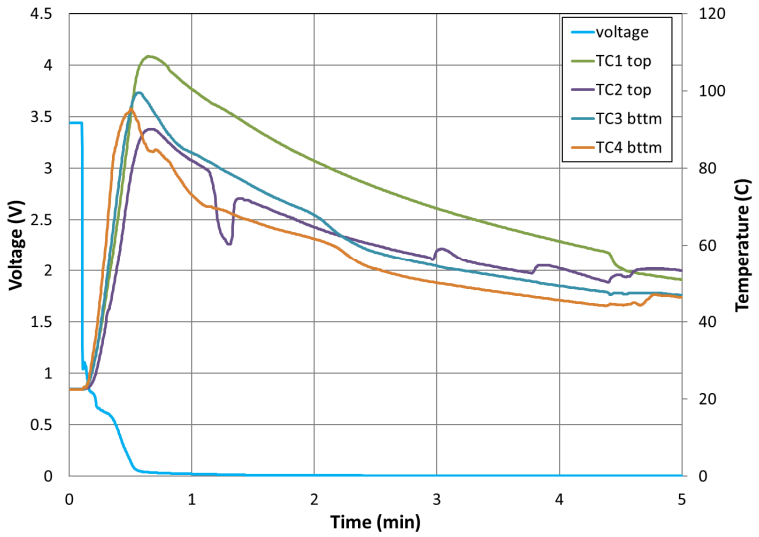
Simulations and Modeling

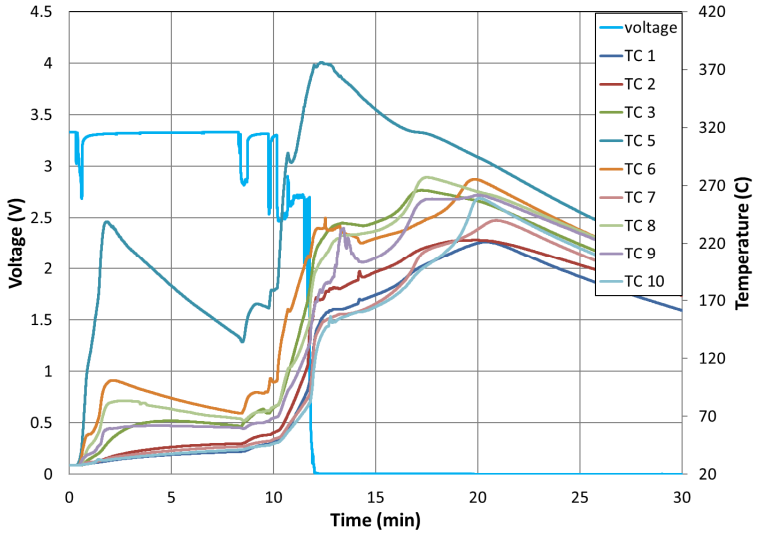
- Multi-scale models for understanding thermal runaway
- Validating vehicle crash and failure propagation models
- Fire Simulations to predict the size, scope, and consequences of battery fires

Procedures, Policy, and Regulation

- USABC Abuse Testing Manual (SAND 2005-3123)
- SAE J2464/UL 1642 procedures and standards
- R&D programs with NHTSA/DOT to inform best practices, policies, and requirements

Motivation for propagation testing

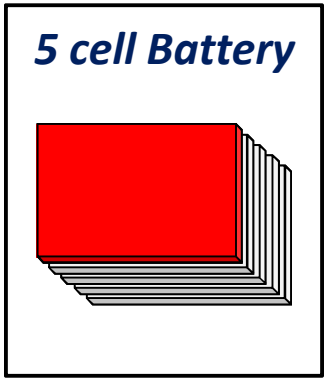


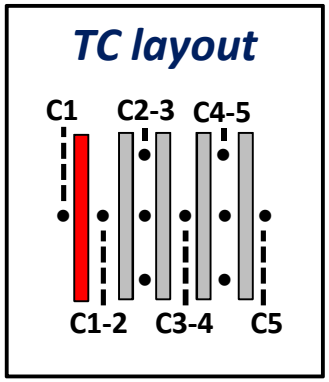


- ***Results of single cell nail penetration and 1S10P propagation test***
- ***26650 LFP cell***
- ***Single cell has relatively minor failure***
- ***Significant increase in intensity with a 10 cell pack***

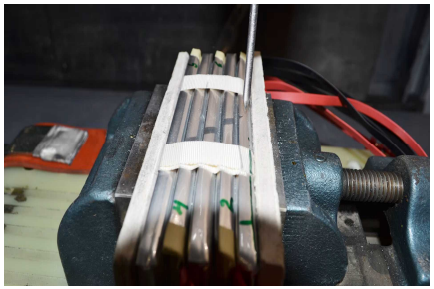
Failure Propagation: No Thermal Management

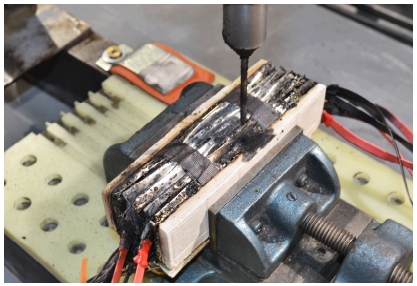
Failures initiated by mechanical insult to edge cell of COTS $LiCoO_2$ packs (3Ah cells)

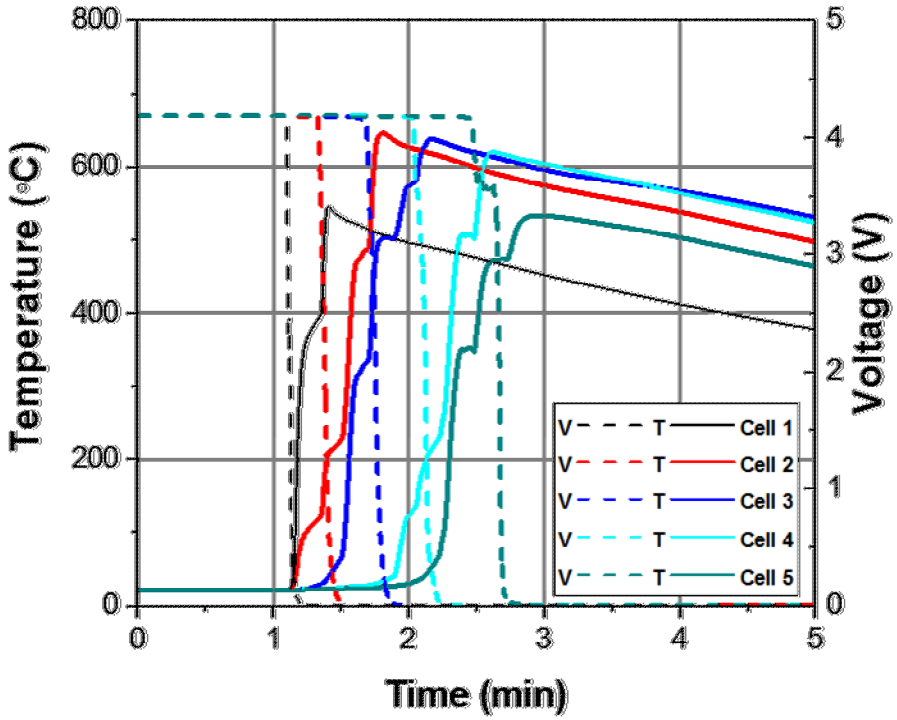




- Successful initiation at Cell #1
- Propagation to adjacent cells
- Cascading failure to entire battery over 60 s

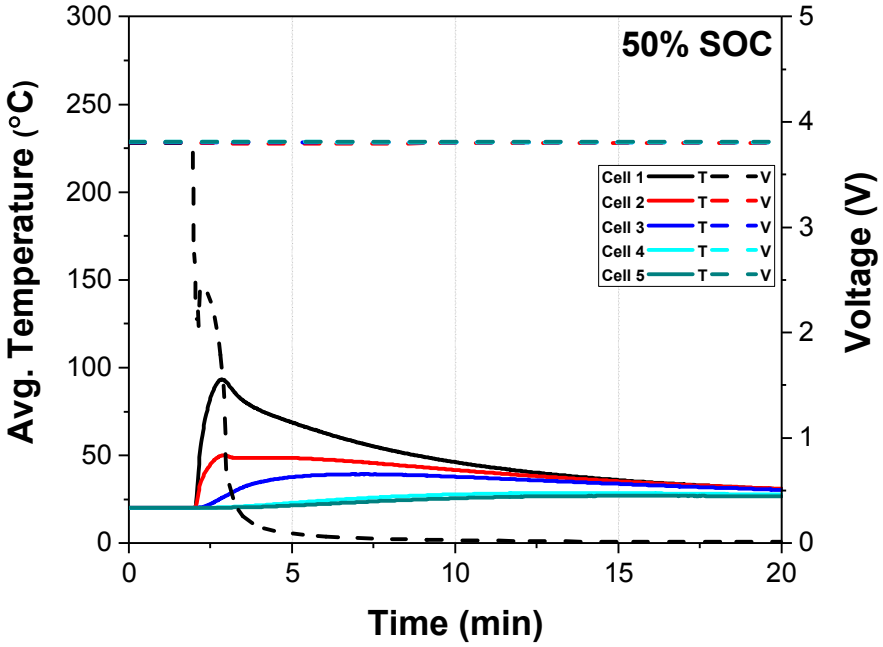


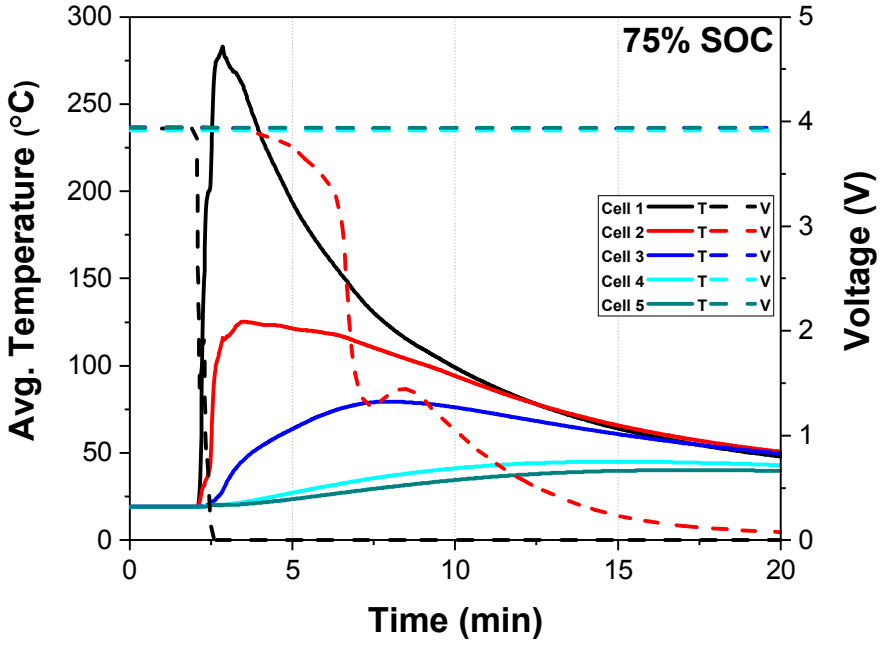




- ***Observed complete propagation when cell are close packed with no thermal management***

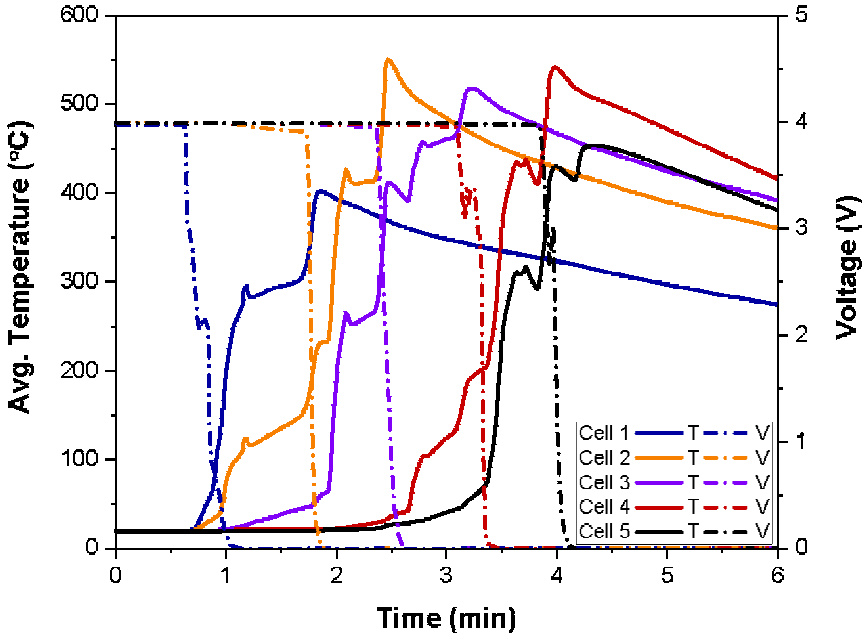
Mitigation through de-rating cells

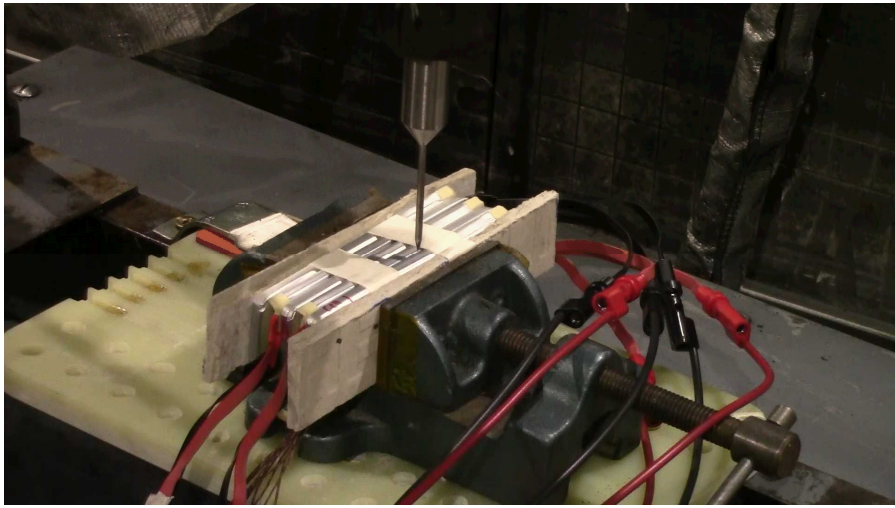




- *50% SOC no cell to cell propagation observed*
  - *Thermal runaway of initial cell failure also fairly minimal*
- *Limited propagation at 75%*
  - *Cell 2 went into thermal runaway following the failure of cell 1*
  - *Some other cell damage was observed but no high rate thermal runaway events seen inn cells 3-5*

Limits to cell de-rating





- ***Full failure of pack observed starting at 80% SOC***
- ***Compared to unmitigated baseline, peak temperatures observed were only marginally lower (550 °C vs 620 °C)***
- ***Total pack propagation observed after ~4 minutes vs ~80 seconds at 100% SOC***

Failure Propagation Testing: Inclusion of Thermal Management

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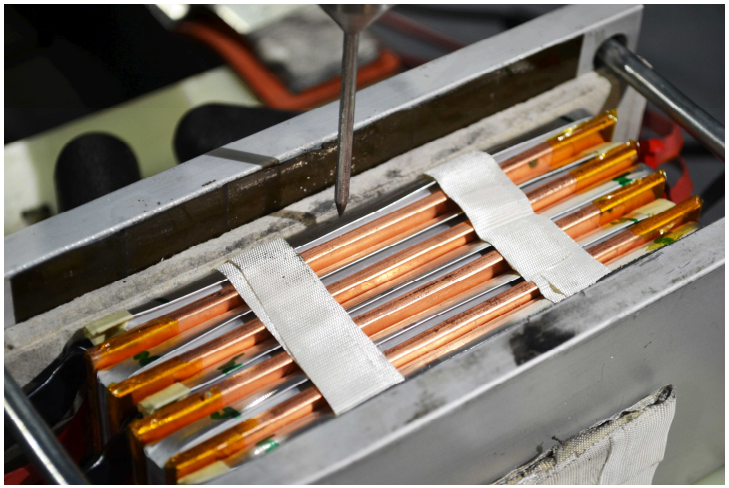
Methodology:

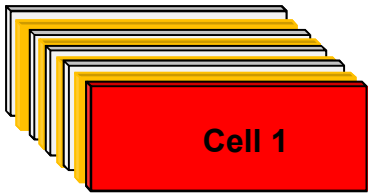
- Experimentally determine a reproducible thermal runaway initiator for each cell type
- Use this initiator to trigger a single cell thermal runaway failure in a battery
- Evaluate the propagation of that failure event

Experiment

- COTS $LiCoO_2$ 3Ah pouch cells
- 5 cells closely packed
- Failure initiated by a mechanical nail penetration along longitudinal axis of edge cell (cell 1)
- **The current effort is focused on understanding extent of propagation with inclusion of passive thermal management in the form of heat sinks between pouch cells (aluminum and copper)**



5 cell pack with aluminum or copper spacers between cells

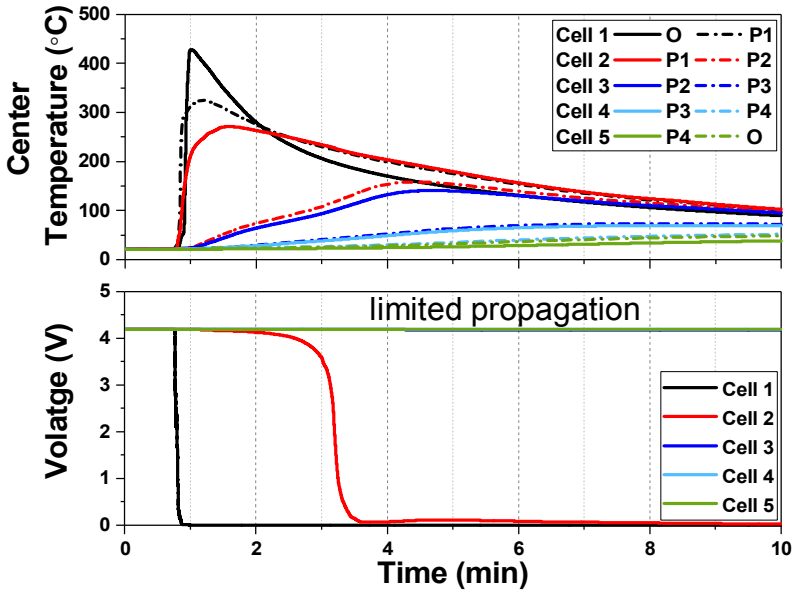


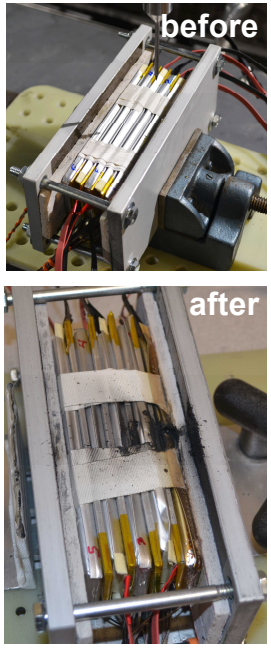
J. Lamb et al. J. Power Sources 283 (2015), 517-523 and C. J. Orendorff et al. SAND2014-17053

Failure Propagation: Aluminum spacer

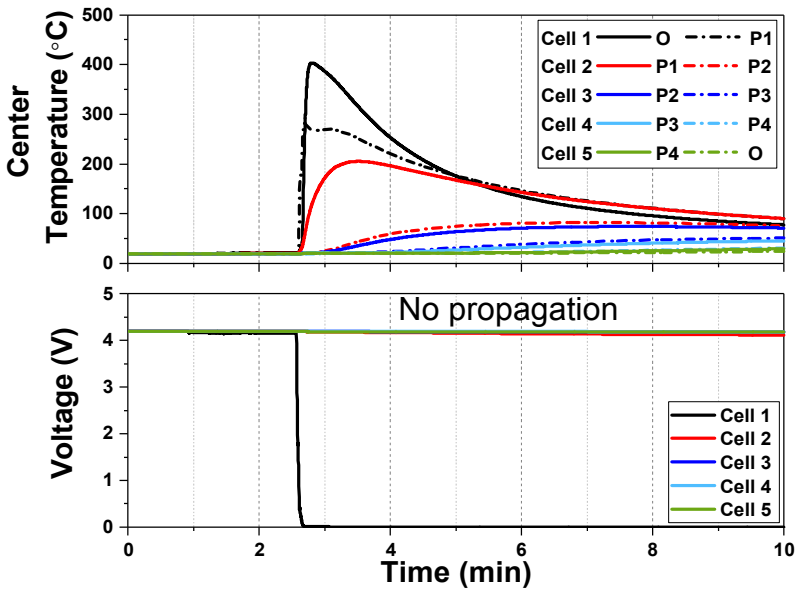
Failures initiated by mechanical insult to edge cell of COTS $LiCoO_2$ packs

$LiCoO_2$ – 1/16" thick spacers





$LiCoO_2$ – 1/8" thick spacers

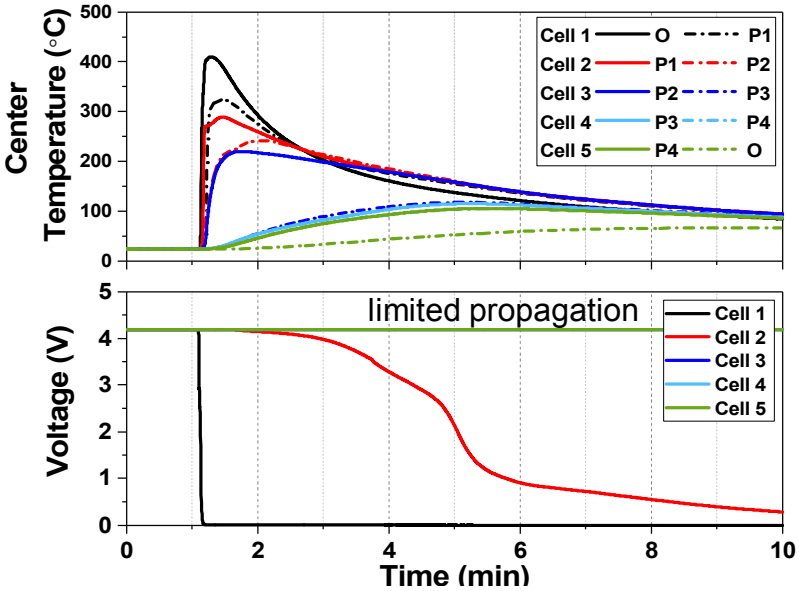


- ***Addition of aluminum spacers cut to the size of 3 Ah COTS cells was achieved***
- ***Failure of cell 1 in both cases were consistent and peak temperatures reached ~400 °C***
- ***Limited propagation (from cell 1 to 2) occurred with the thinner material (1/16")***
- ***No propagation was realized when space thickness was increased to 1/8"***

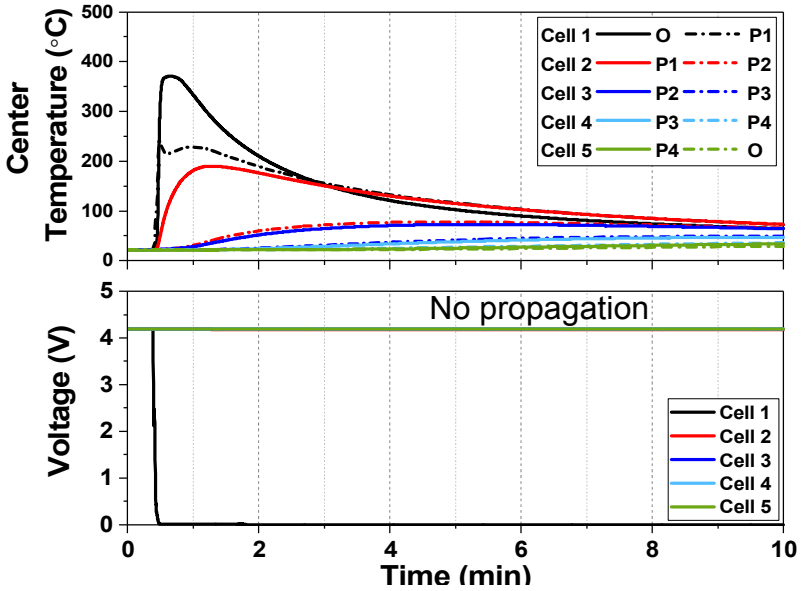
Failure Propagation: Copper spacer

Failures initiated by mechanical insult to edge cell of COTS $LiCoO_2$ packs

$LiCoO_2$ – 1/16" thick spacers



$LiCoO_2$ – 1/8" thick spacers



- ***Addition of copper spacers cut to the size of 3 Ah COTS cells was achieved for comparisons of spacer size and material (Al vs Cu)***
- ***Failure of cell 1 in all cases were consistent and peak temperatures reached ~400 °C***
- ***Limited propagation (from cell 1 to 2) occurred with the thinner material (1/16")***
- ***No propagation was realized when space thickness was increased to 1/8"***

Failure propagation – Aluminum spacer

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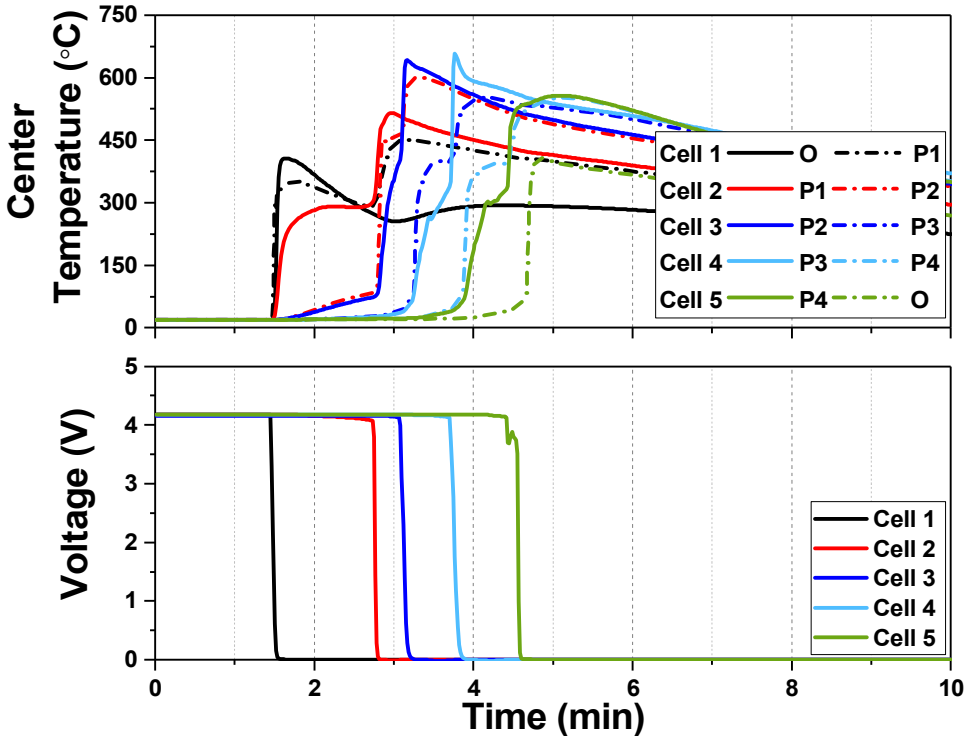
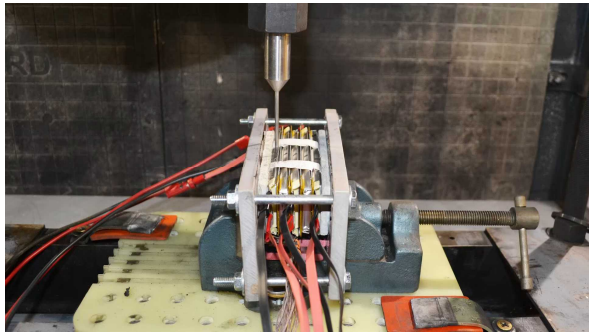
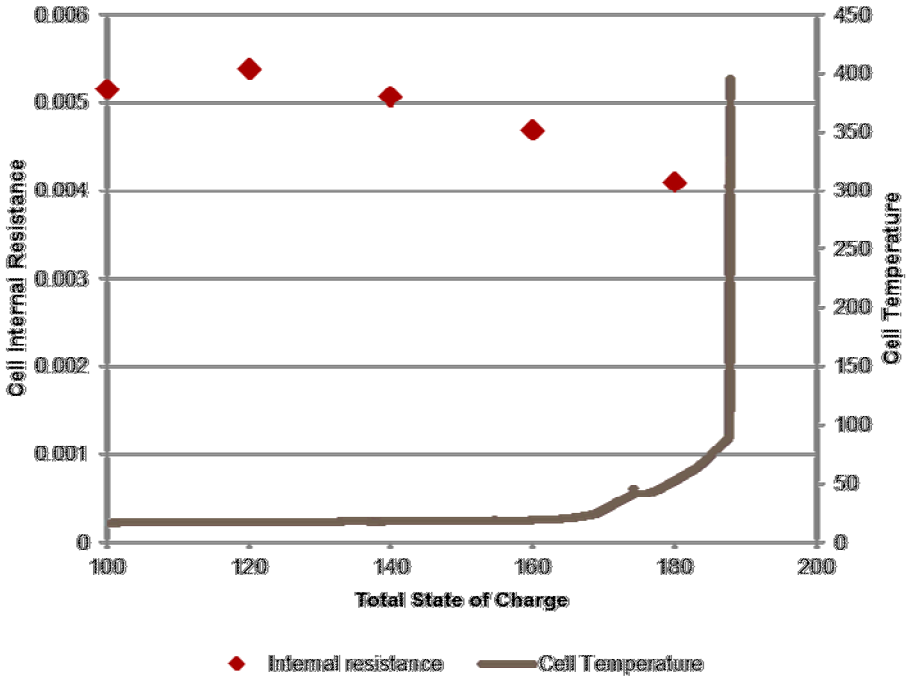
$LiCoO_2$ – 1/32″ thick spacers

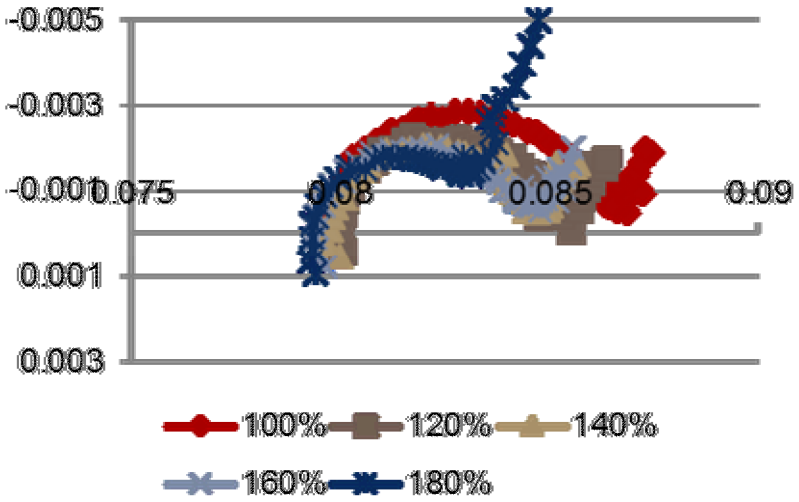




- *Aluminum spacers 1/32” thick*
- *Failure of Cell 1 observed initially*
- *Pulsing propagating failure behavior observed over the next several minutes*
- *Entire pack consumed ~4 minutes after initial cell failure*

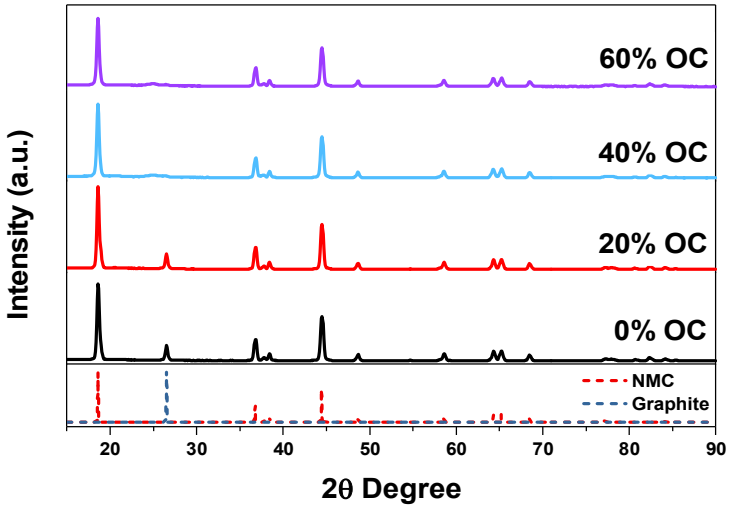
Is early detection an option?

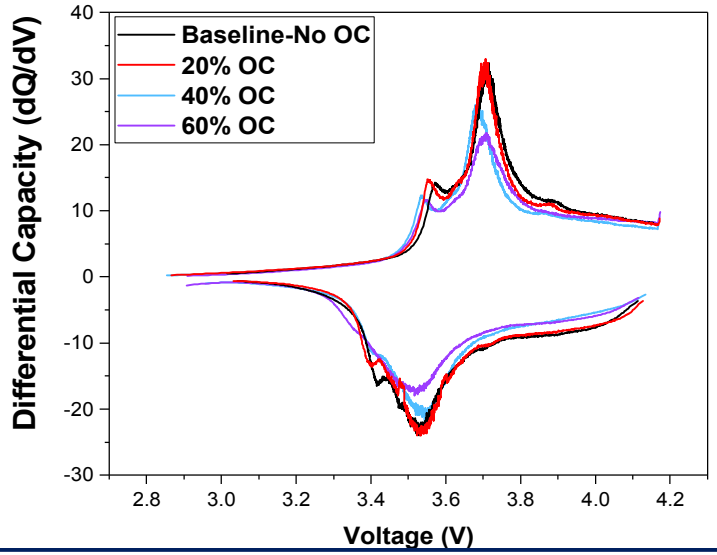


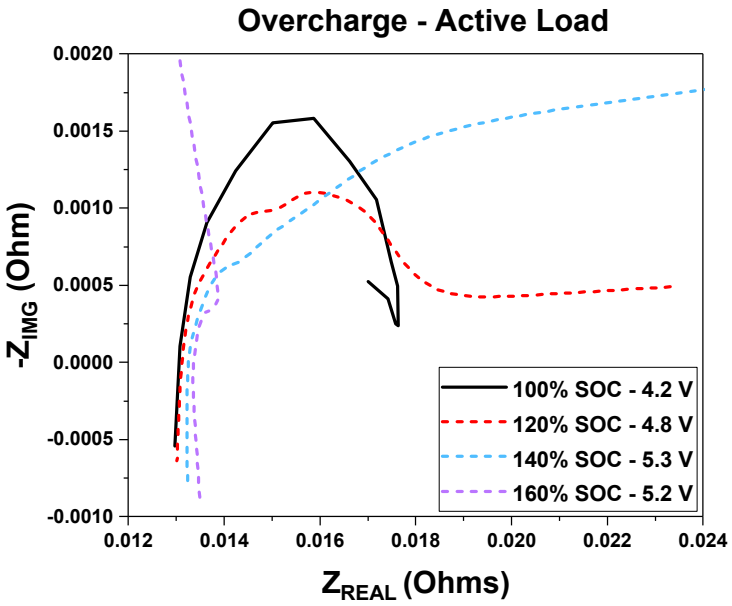


- *Temperature changes often lag severe damage to the cell*
- *Can EIS and other diagnostic techniques be used to detect the failure of a single cell?*
- *Single cell data (left) shows changes in internal resistance of a single cell vs changes in external temperature*
- *3S1P data (right) shows data as single cell within a 3 cell series pack is overcharged*
- *Rather than controlling propagation perhaps the solution is to detect single cell failure and halt operation before catastrophic failure*

Understanding materials consequence of diagnostic markers







- *Overcharge is applied to 10 AH NMC cells*
- *Fast impedance hardware allows for collection of EIS data while cell is under active load*
- *Cycling performed after overcharge test to observe differential capacity behavior*
- *Anode and Cathode materials harvested post test for materials analysis (Harvested at 0% SOC, cathode results shown)*
- *Coupling electrochemical measurement and materials analysis to create a predictive measurement technique*

Discussion

- 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.

Acknowledgements

- DOE Office of Vehicle Technologies
  - Brian Cunningham
  - Samm Gillard
  - Dave Howell
- DOT – NHTSA
  - Phil Gorney
  - Steve Summers
- Imre Gyuk – US Department of Energy Office of Electricity
- Christopher Orendorff
- Babu Chalamala
- Randy Shurtz
- Heather Barkholtz
- Kyle Fenton
- Eric Allcorn
- Lorie Davis
- Mani Nagasubramanian
- Jill Langendorf