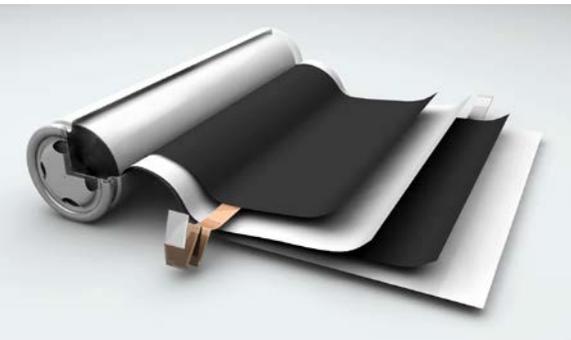


Exceptional service in the national interest



Battery Safety Testing

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Sandia National Laboratories

ES203

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Overview

Timeline

- **Start Date: Oct. 2014**
- **End date: Oct. 2015**
- **Percent complete: >75%**

Budget

- **FY15 Funding: \$1.3M**
- **FY14 Funding: \$1.4M**
- **FY13 Funding: \$1.4M**

Barriers

- **Barriers addressed**
 - Safety continues to be a barrier to widespread adoption
 - Understanding abuse response for a variety of cell types, battery chemistries, and designs
 - Failure propagation in battery systems limits inherent safety
 - Issues related to cell safety are represent significant challenges to scaling up lithium-ion for transportation applications

Partners

- **NREL, INL, ANL, ORNL, University of Hawaii**
- **USABC Contractors, USCAR**

Relevance and Objectives

Abuse tolerance evaluation of cells, batteries, and systems

- Provide independent abuse testing support for DOE and USABC
- Abuse testing of all deliverables in accordance with the USABC testing procedures
- Evaluate single point failure propagation in batteries
- Study the effects of cell age on abuse response
- Provide experimental support for mechanical modeling battery crash worthiness for USCAR

Milestones

Demonstrate improved abuse tolerant cells and report to DOE and the battery community

Milestone	Status
Draft revision of the USABC Abuse Testing Manual provide to USABC (Q1)	
Complete USCAR fully constrained side/end crush testing	
Complete Q1 USABC deliverables (JCI cells)	
Complete Q2 USABC deliverables (Aged SKI cells)	
Provide propagation testing data to NREL to begin model development	
Complete propagation testing of 1S10P LFP cells	
Complete analysis of aged Sanyo SA cells to 50% fade	
Complete Q3 USABC deliverables (Aged Envia cells)	Q3
Validation testing of preliminary USCAR/NREL battery mechanical model	Q4
Joint publication on propagation failure with NREL	Q4
Publication on the effect of cell age on abuse response	Q4
Complete Q4 USABC deliverables (LG Chem modules, SEEO modules)	Q4

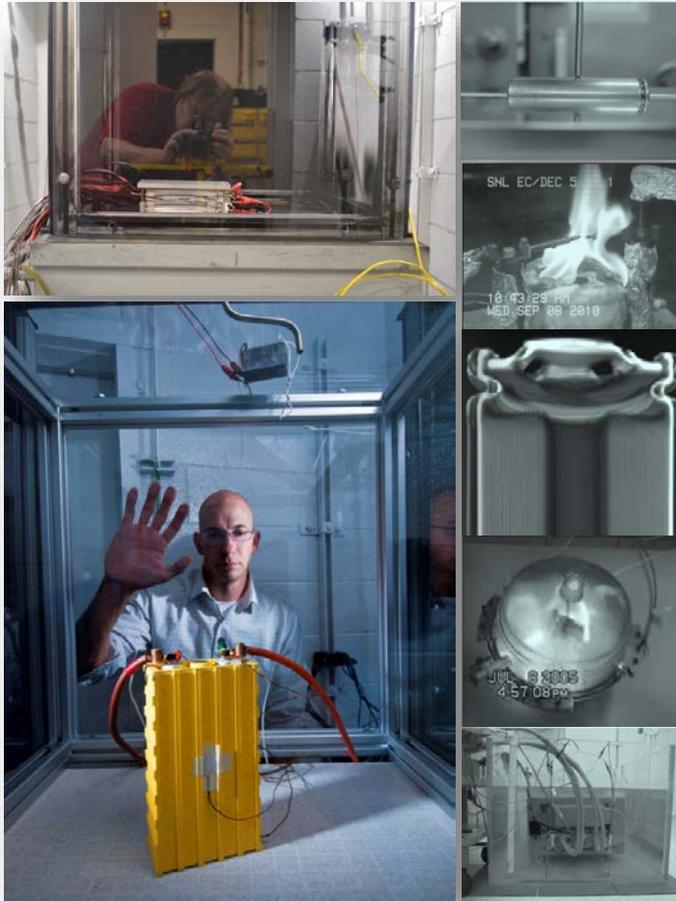
 Milestone Complete

Approach and Capabilities

Battery Pack/System Testing Thermal Test Complex (TTC)



Cell and Module Testing Battery Abuse Testing Laboratory (BATLab)



Battery Calorimetry

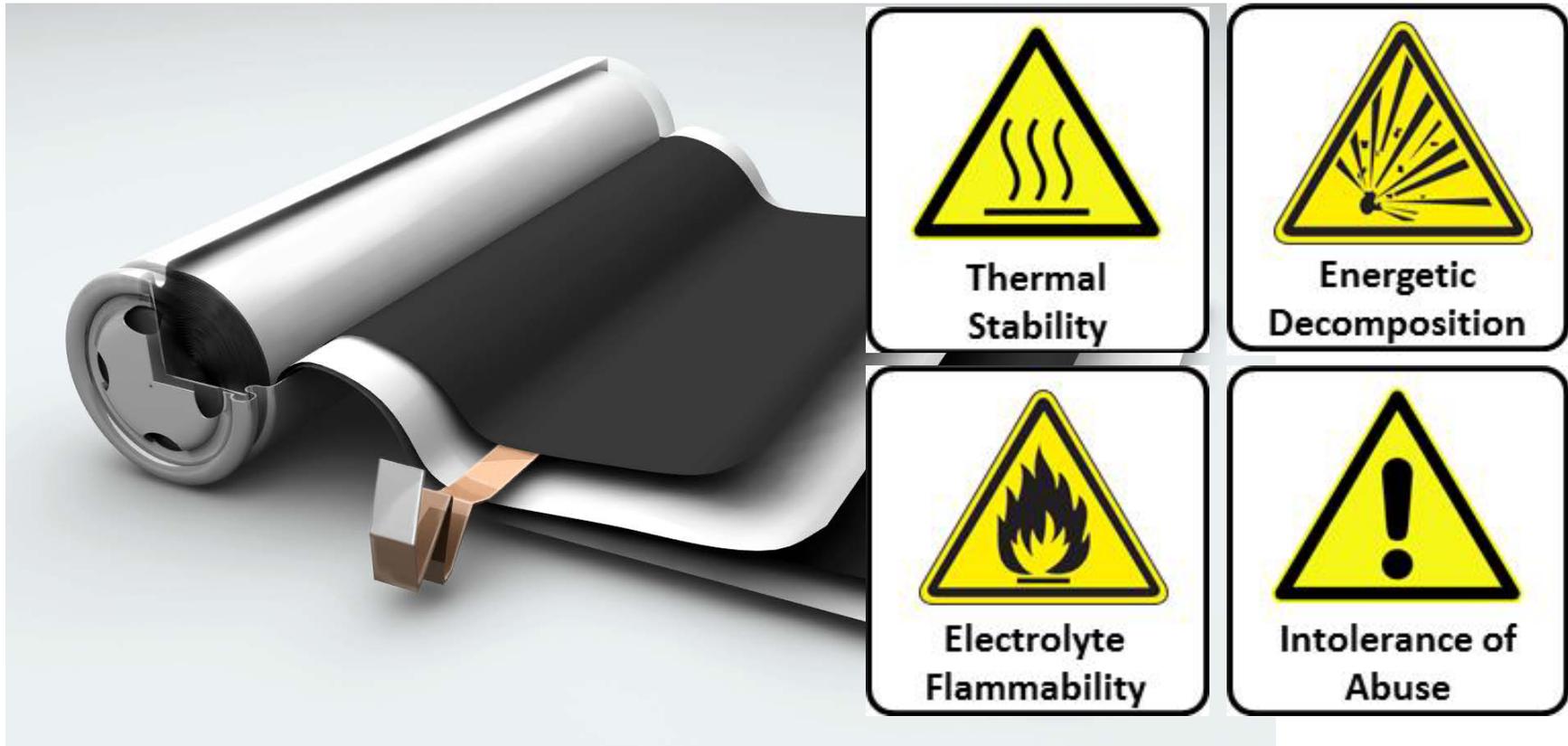


Technical Accomplishments/ Progress/Results

Abuse Testing and Characterization:

- Completed testing of all USABC deliverables and reported results to the USABC TAC
- Drafted a revision USABC Abuse Testing Manual (revision to SAND2005-3123)
- Evaluated the abuse and thermal runaway response of cells aged to 20% and 50% capacity fade and cells at 20% and 50% DOD
- Thermal runaway response diverges significantly with %fade and %DOD
- Studied the effect of cell chemistry on failure propagation. Results show complete propagation with higher energy chemistry cells (LiCoO_2) in 1S10P batteries and no evidence of failure propagation for more benign cell chemistries (LiFePO_4)
- Completed fully constrained battery mechanical testing to provide provides the USCAR Crash Safety Working Group (CSWG) information to build and validate a battery crash worthiness model. Fully constrained tests provide a consistent test geometry and parameters will be used to support the development of a CAEBAT mechanical model

Lithium-ion Safety Issues



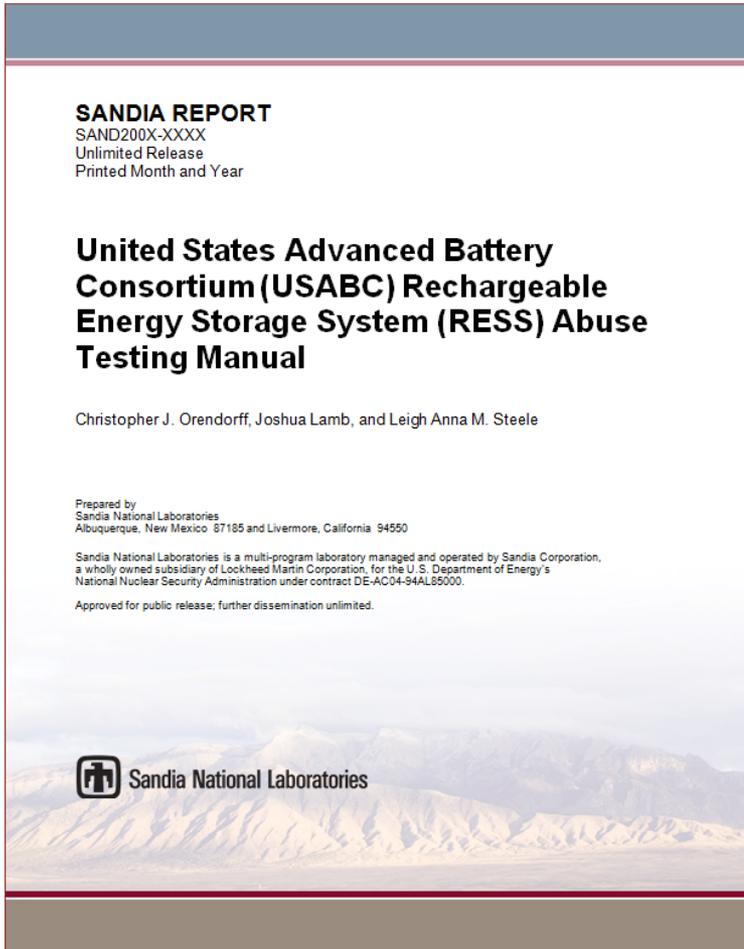
Testing program aimed at understanding and improving abuse tolerance of energy storage systems

USABC Program Deliverables to SNL

Program	Deliverable
SKI EV	Aged cells (ANL):
JCI PHEV	Cells (11)
Envia	Aged cells (INL):
LGChem PHEV	Modules (3)
SEEO TAP	Modules (3)

Testing results for USABC are protected information

USABC Abuse Testing Manual



Notable changes:

- Enhanced safety basis
- Empirical data to support test conditions
- Failure propagation test
- Cell vent flammability test

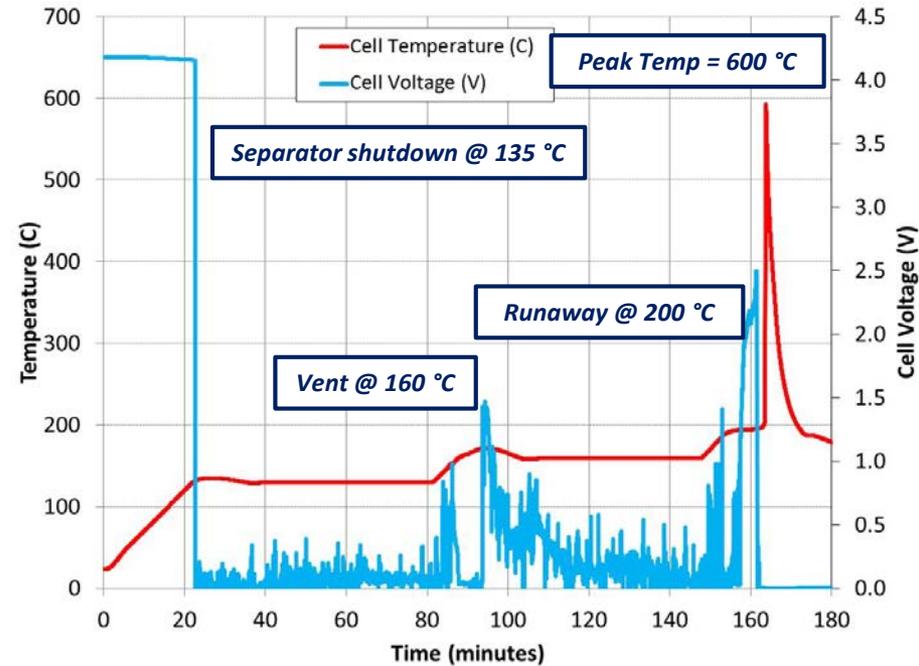
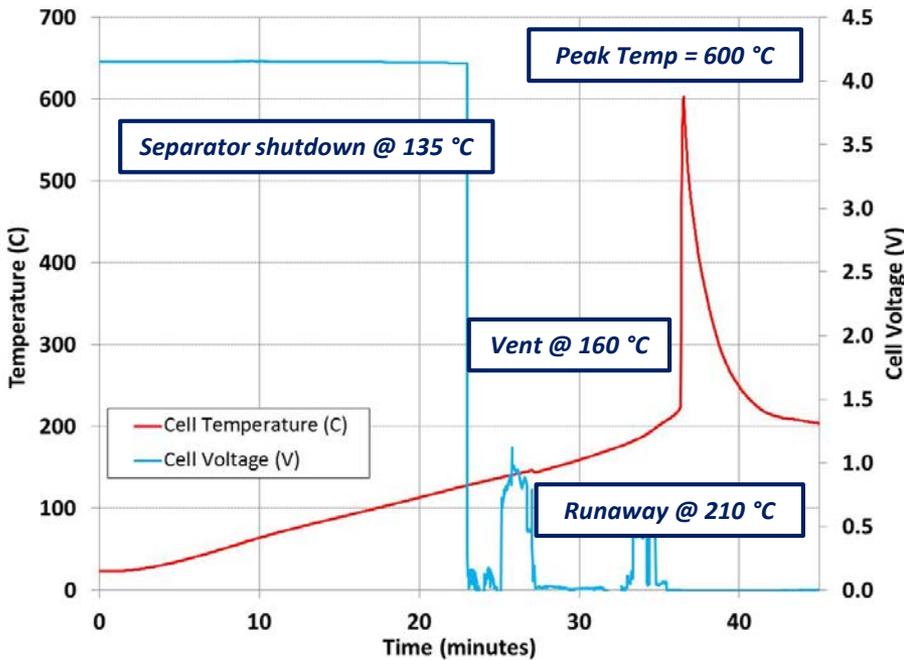
Revision to the USABC Abuse Manual delivered to USABC in Q1

Abuse Testing

Representative thermal abuse test of a COTS lithium-ion cell (non-USABC)

USABC Thermal Ramp vs. Modified Hotbox Tests

- Perception by some the modified hotbox is a “better” test
- The intent of a thermal test should be to determine the magnitude and hazard severity of a thermal runaway
- Pragmatic testing should balance test duration and utility of test results



USABC Thermal Ramp test results provide data as complete as a hotbox test in < 1 hr

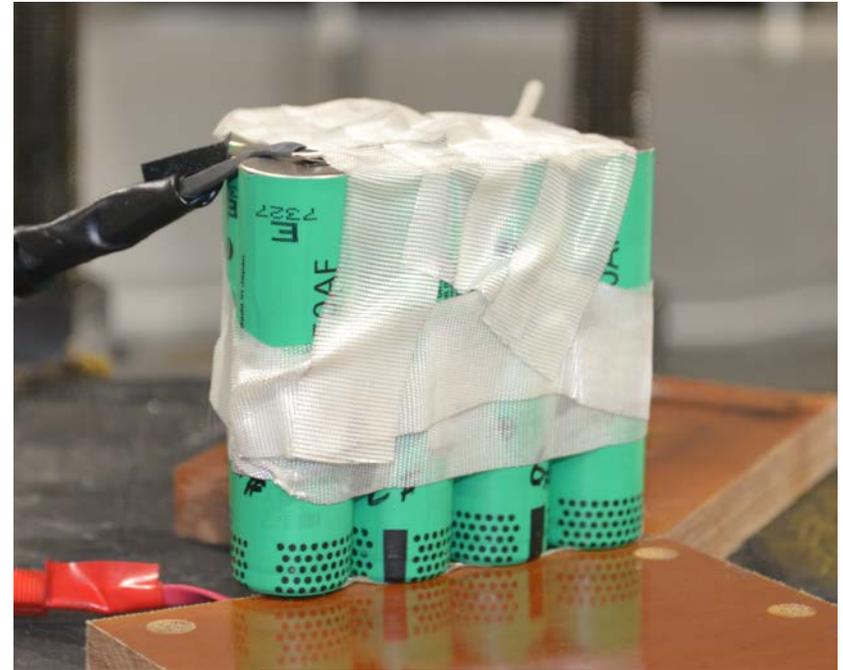
Failure Propagation Testing

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 LiCoO₂ and LFP 18650/26650 cells
- 1S10P configurations
- Failure initiated by a mechanical nail penetration along longitudinal axis
- **The current effort is focused on understanding the effect of cell chemistry on single cell failure propagation and to develop a propagation model (NREL)**

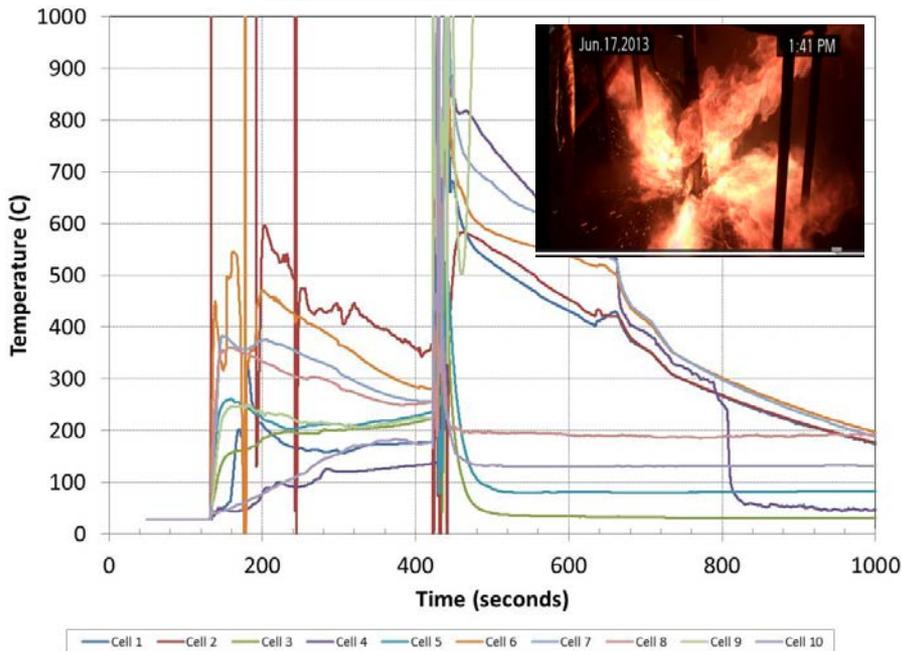


1S10P Battery

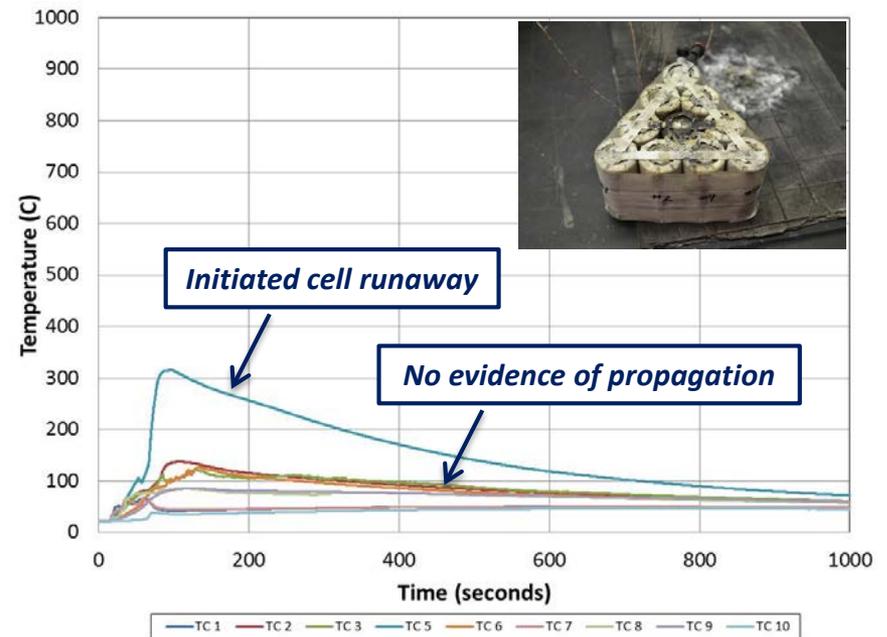
Failure Propagation

Failures initiated by mechanical insult to the center cell (#6)

LiCoO₂ - 1S10P



LFP - 1S10P

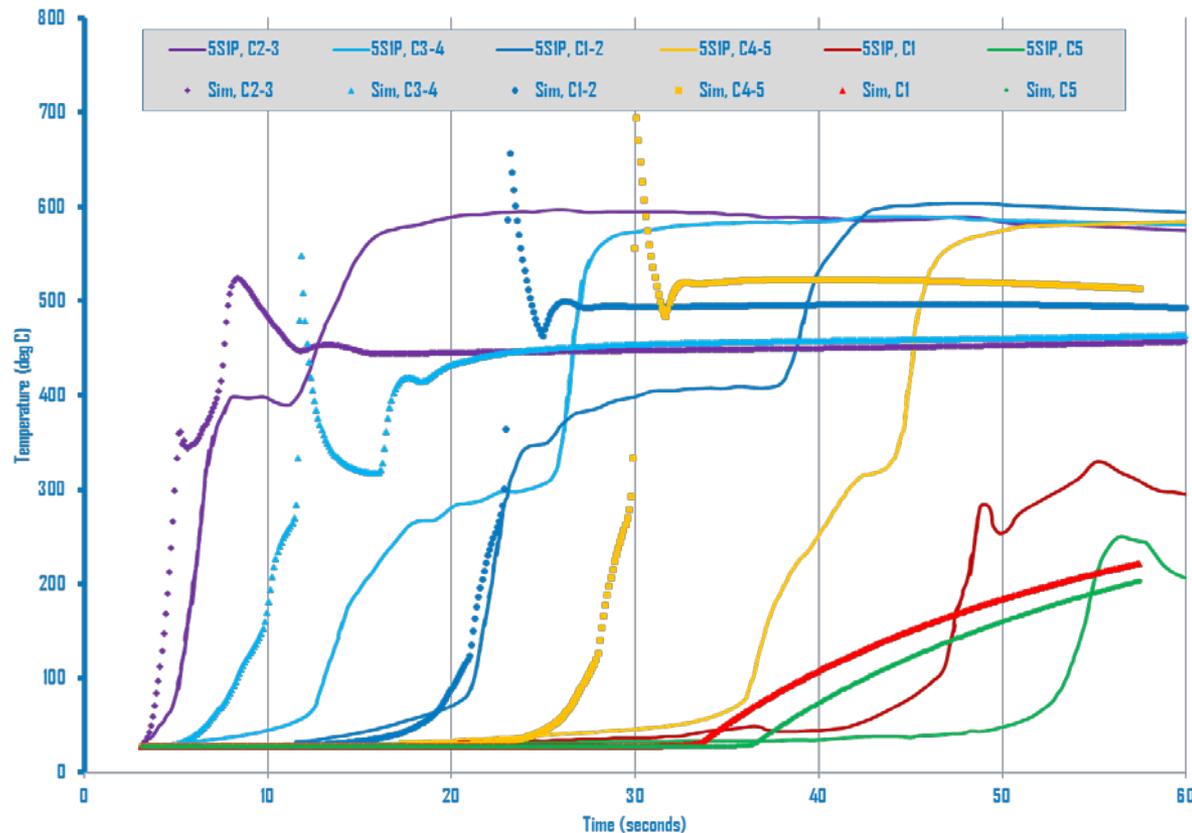
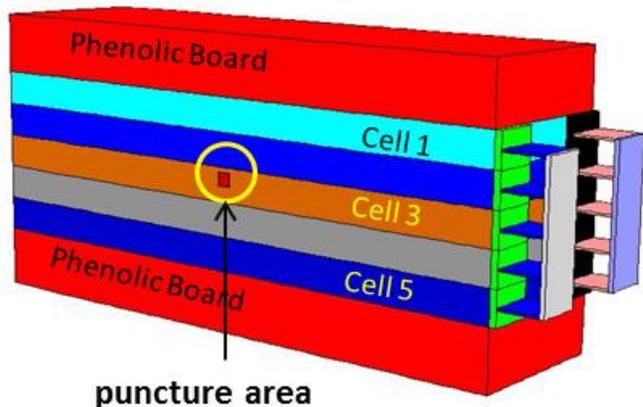


***Complete propagation of a single point failure in the LiCoO₂ 1S10P pack
No evidence of failure propagation in the LFP 1S10P pack***

Failure Propagation Model (NREL)

NREL electro-thermal and abuse model using lumped cell materials properties

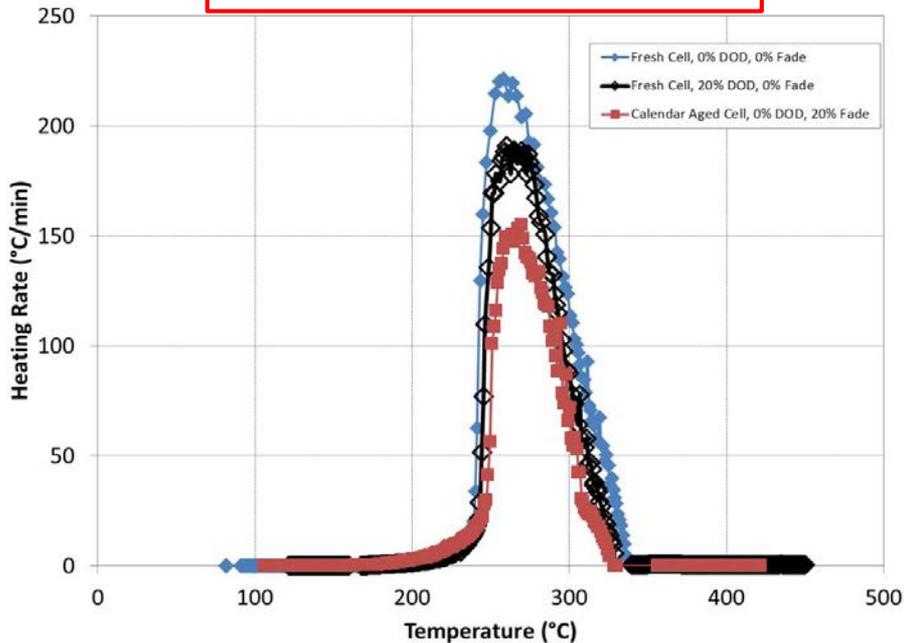
LiCoO₂ Pouch Cell - 1S5P



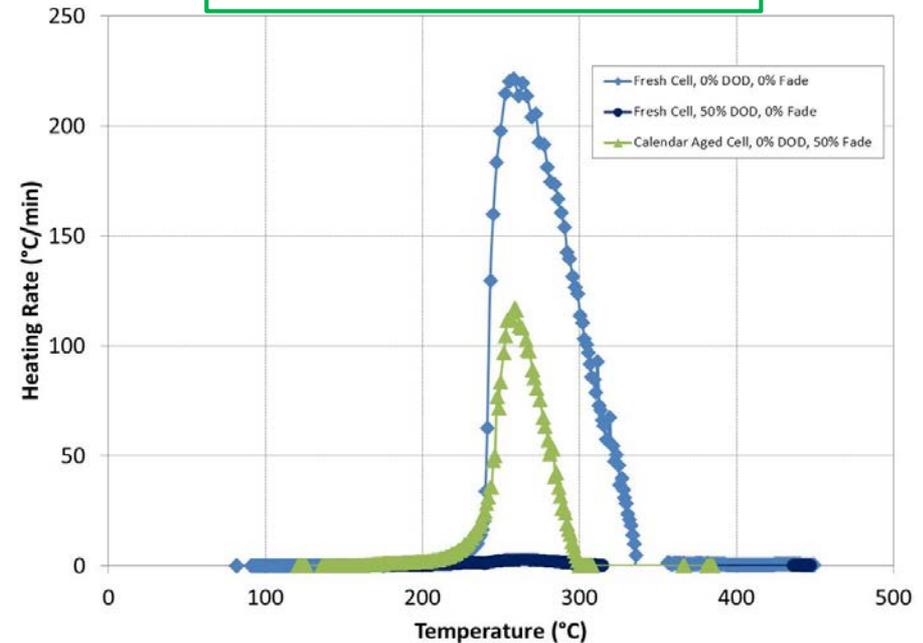
Good agreement in the initial simulations with experiments with some deviation in the long duration events likely due to electrical or connectivity changes within battery over time during the failure event

Abuse Response of Aged Cells

**20% Capacity Fade
& 20% DOD**

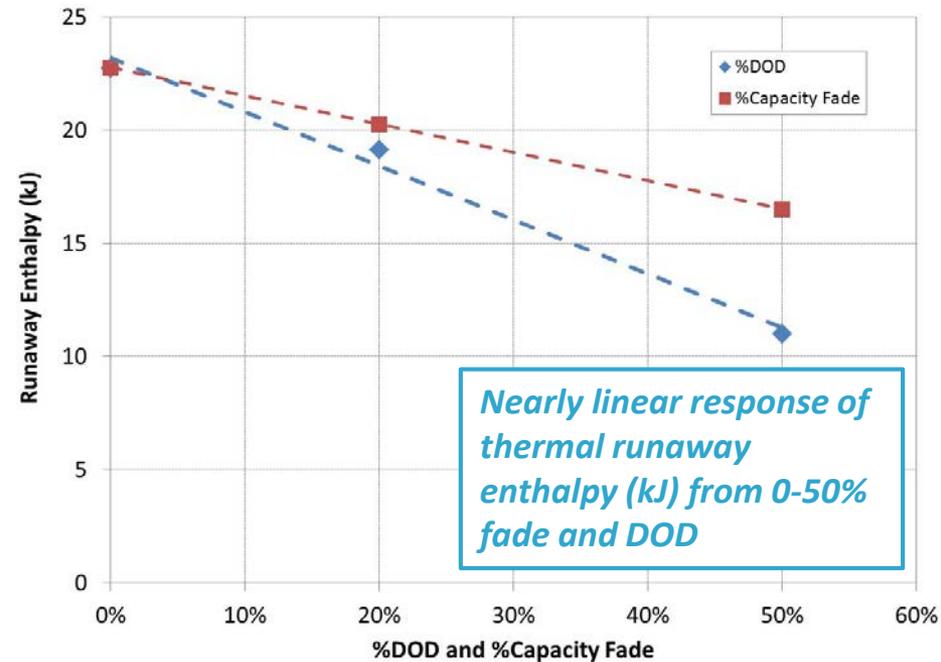
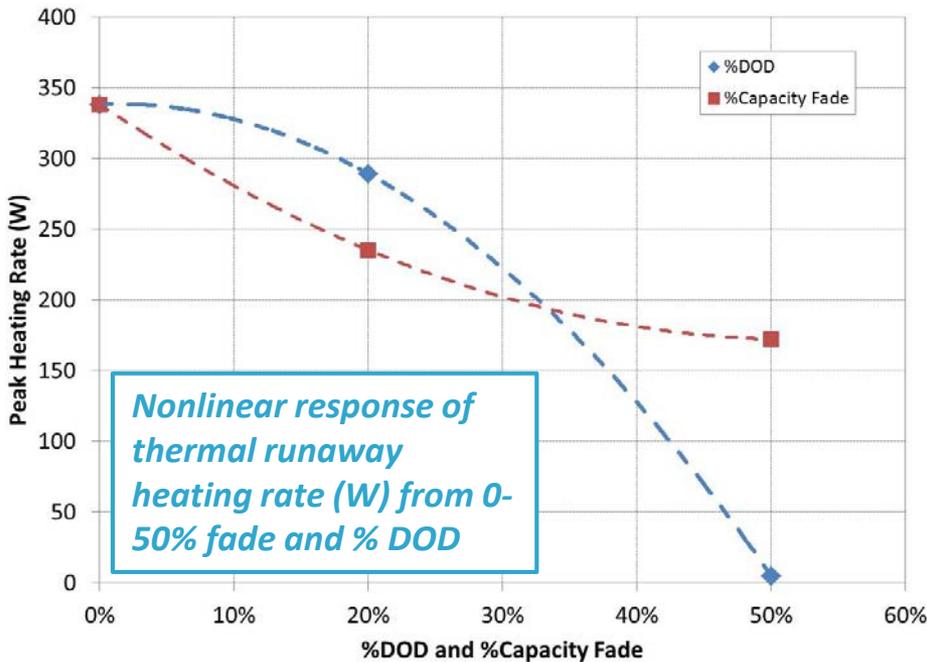


**50% Capacity Fade
& 50% DOD**



- *Aged cells to 20% capacity fade show minimal difference in peak heating rate and runaway enthalpy*
- *Differences are more pronounced in the cells aged to 50% capacity fade*
- *Fresh cells at 50% DOD exhibit very different thermal runaway response than 50% capacity faded cells*

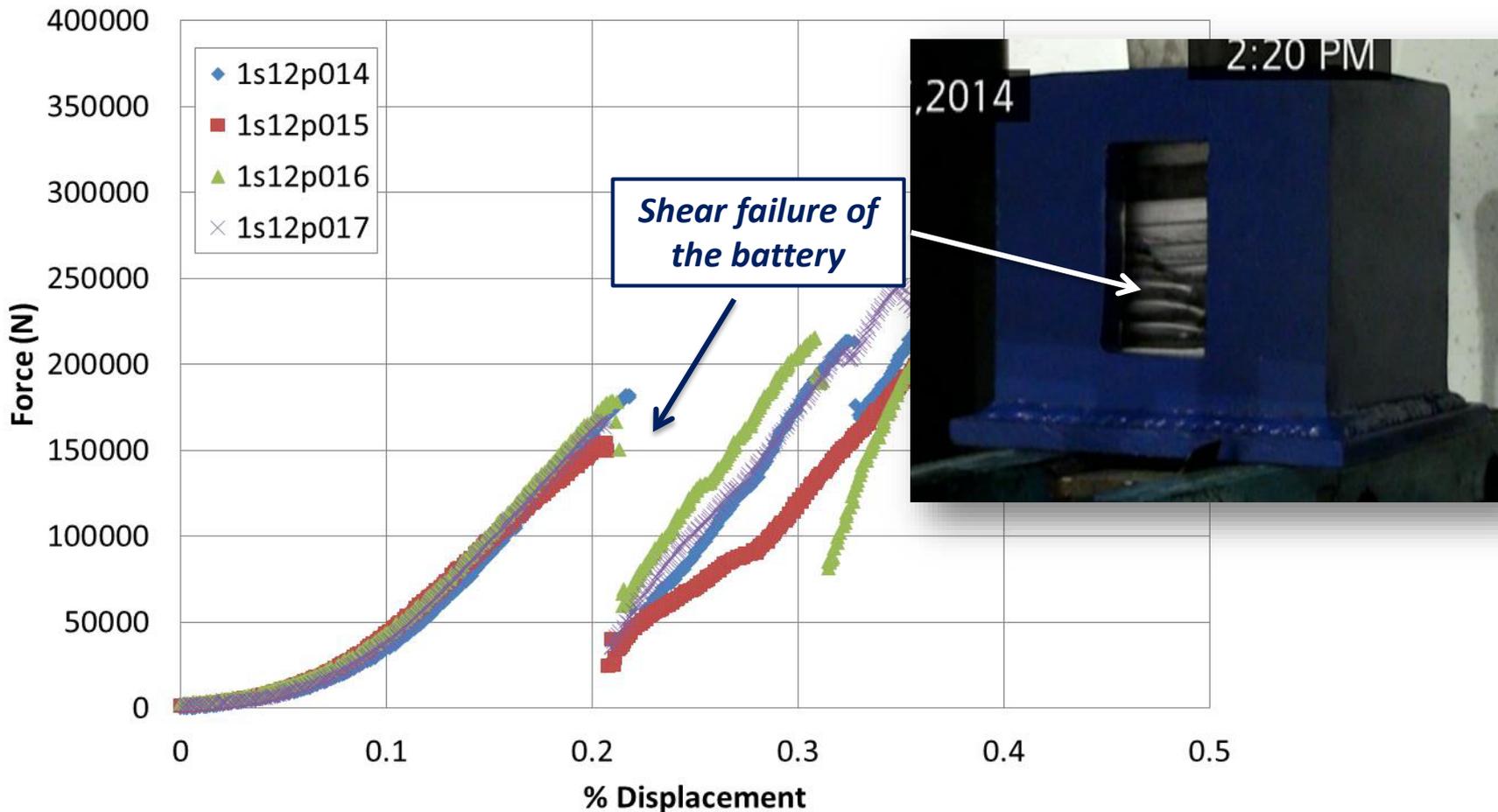
Abuse Response of Aged Cells



Thermal runaway response heat release (W and kJ) correlation between % capacity fade and % DOD diverge significantly from 20 to 50%

USCAR – Battery Crash Worthiness

Mechanical testing support of battery mechanical model development

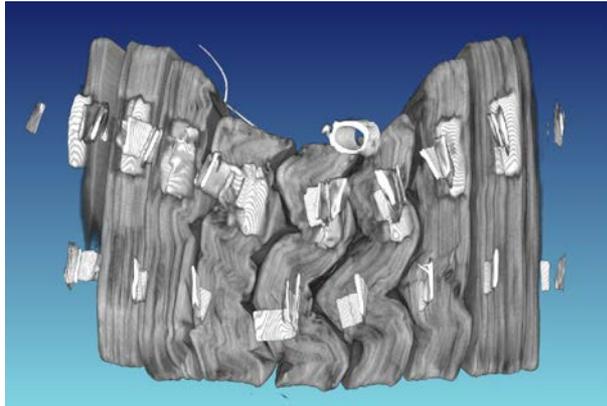


Completely mechanically constrained geometry provides reproducible test results to generate mechanical model input parameters

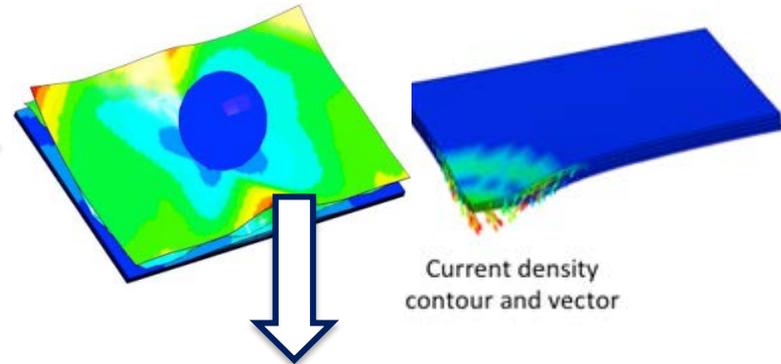
Supporting CAEBAT Crash Worthiness

NREL/MIT Computer Aided Engineering for Batteries (CAEBAT) Program

Battery Crush Experiment (SNL, USCAR)

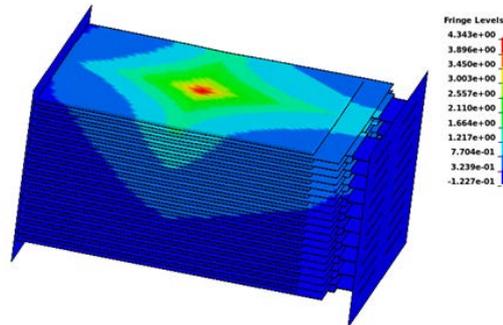


Cell-level Mechanical Model (MIT/NREL)

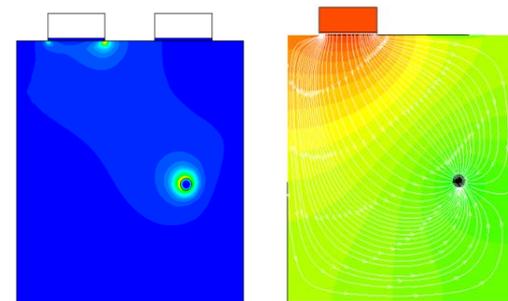


Integrated Thermochemical & Mechanical Model (NREL)

Thermal Cell-to-Cell Propagation Model



Thermochemical Model



Use battery crush data to validate the integrated model

Develop a predictive capability for battery thermal runaway response to mechanical insult

Collaboration and Coordination with Sandia National Laboratories Other Institutions

- NREL (Propagation and mechanical modeling)
- INL (Aged cell evaluation)
- University of Hawaii (Aged cell evaluation)
- INL, NREL, ANL, ORNL (USABC)
- USABC Technical Advisory Committee (TAC)
- USABC Contractors
- USCAR Crash Safety Working Group (CSWG)

Proposed Future Work

- Abuse testing cells and batteries for upcoming USABC deliverables and new contracts
- Working with NREL on developing a predictive failure propagation model
- Propagation testing of batteries with increasing levels of designed passive and active thermal management to demonstrate the effectiveness of engineering controls to mitigate propagation in batteries
- Detailed analysis of the thermal runaway of aged cells and cell-to-cell variability of the response with age (Univ. Hawaii)
- Dynamic mechanical testing of batteries and model validation to demonstrate battery crashworthiness (USCAR, NREL, CAEBAT)

Summary

- **Fielding the most inherently safe chemistries and designs can help address the challenges in scaling up lithium-ion**
- **Materials choices can be made to improve the inherent safety of lithium-ion cells**
- **Completed abuse testing support for all USABC deliverables to date and on track to complete all work by the end of FY15**
- **Cell chemistry and thermal runaway response has a significant impact on the propagation of single cell failure events in parallel configurations.**
- **Analysis of aged cells suggests that stored energy or useable capacity is not the only factor that impacts thermal runaway (when compared to cells at matching %DOD)**
- **Results for the mechanical testing of batteries will be used as input parameters for a crash worthiness model developed by NREL/MIT supported by CAEBAT. SNL will also provide validation test support when the model is complete.**

Acknowledgements

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