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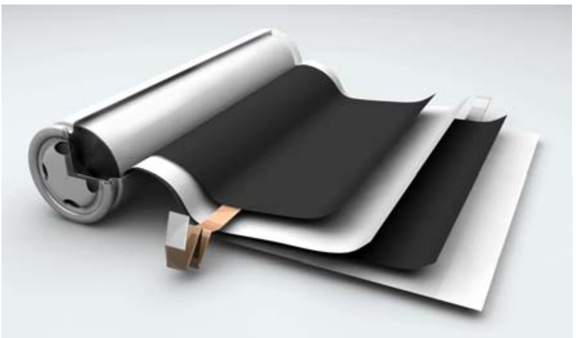
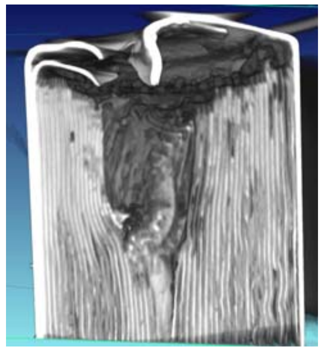

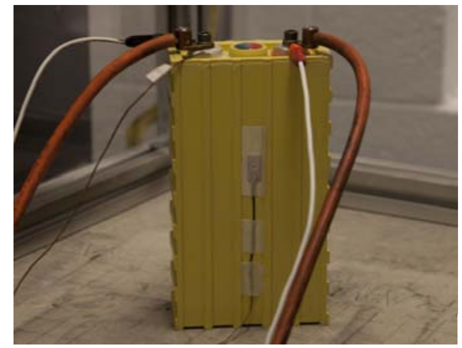

# Battery Safety Testing


Christopher J. Orendorff, Josh Lamb, Leigh Anna M. Steele, Scott W. Spangler, and Jill L. Langendorf

Sandia National Laboratories


**ES203**

2015 Energy Storage Annual Merit Review

Washington, D. C. June 2015

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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

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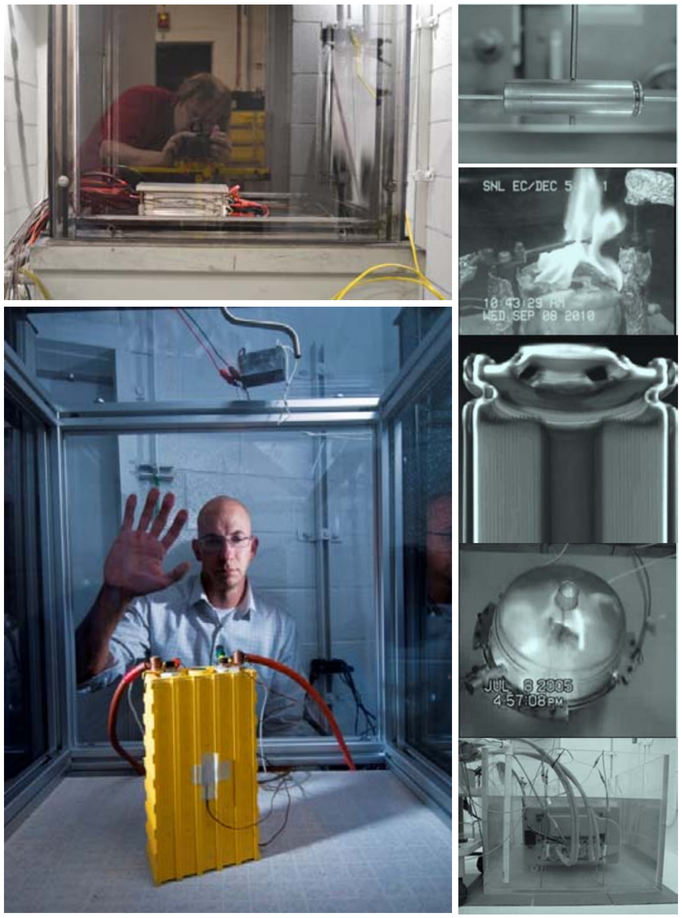
## Demonstrate improved abuse tolerant cells and report to DOE and the battery community

| Milestone | Status |
|---|---|
| Draft revision of the USABC Abuse Testing Manual provide to USABC (Q1) | Milestone Complete |
| Complete USCAR fully constrained side/end crush testing | Milestone Complete |
| Complete Q1 USABC deliverables (JCI cells) | Milestone Complete |
| Complete Q2 USABC deliverables (Aged SKI cells) | Milestone Complete |
| Provide propagation testing data to NREL to begin model development | Milestone Complete |
| Complete propagation testing of 1S10P LFP cells | Milestone Complete |
| Complete analysis of aged Sanyo SA cells to 50% fade | Milestone Complete |
| 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

**Cell and Module Testing**
**Battery Abuse Testing Laboratory (BATLab)**




**Battery Pack/System Testing**
**Thermal Test Complex (TTC)**

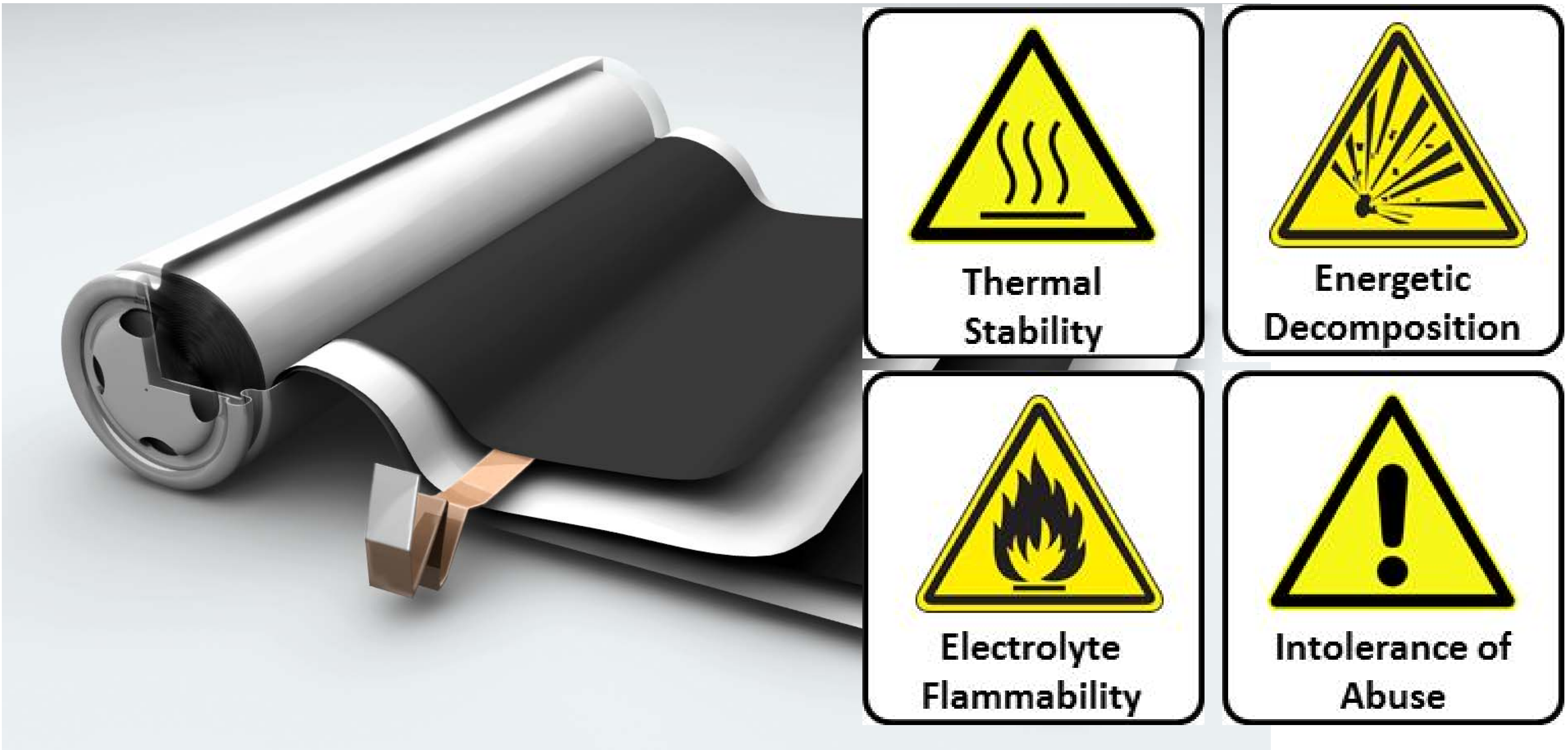
**Battery Calorimetry**

# 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



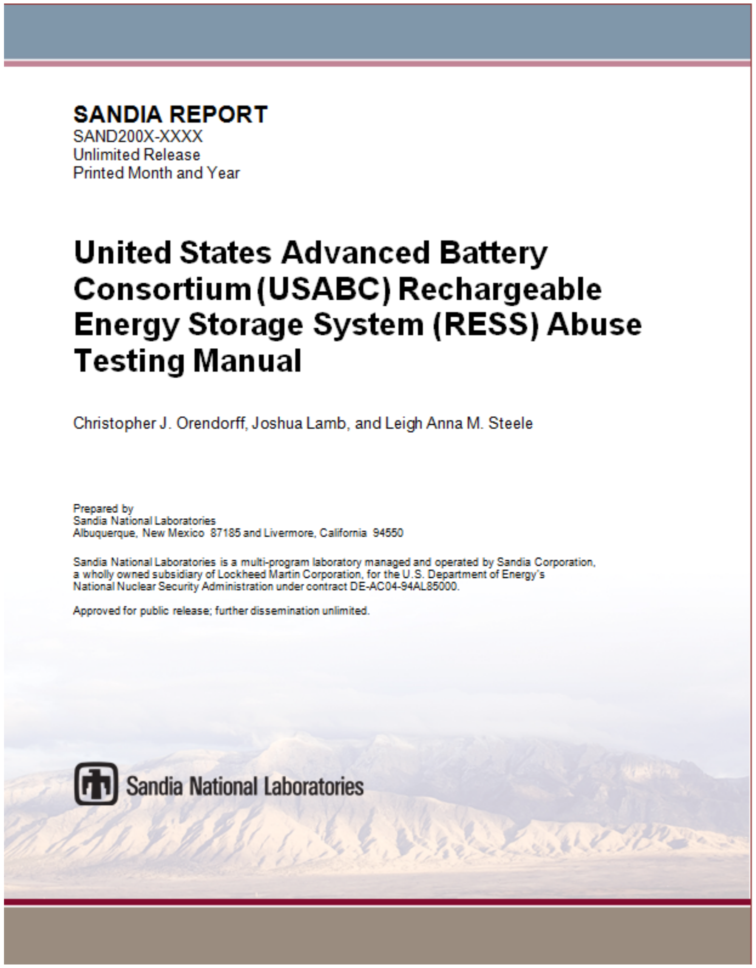

***Testing program aimed at understanding and improving abuse tolerance of energy storage systems***

# 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


SANDIA REPORT
SAND200X-XXXX
Unlimited Release
Printed Month and Year

**United States Advanced Battery Consortium (USABC) Rechargeable Energy Storage System (RESS) Abuse Testing Manual**

Christopher J. Orendorff, Joshua Lamb, and Leigh Anna M. Steele

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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**Notable changes:**

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

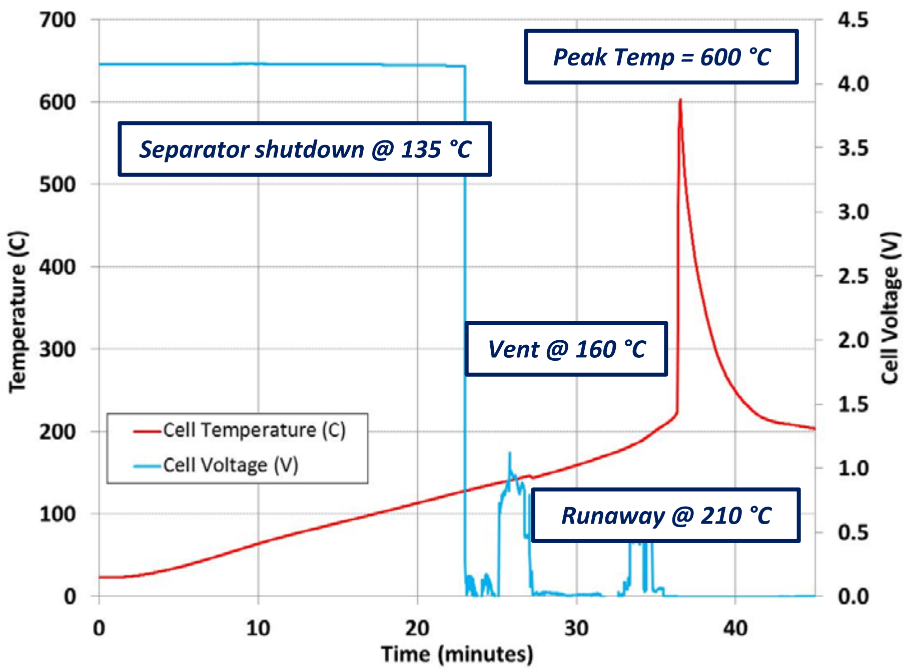
***Revision to the USABC Abuse Manual delivered to USABC in Q1***

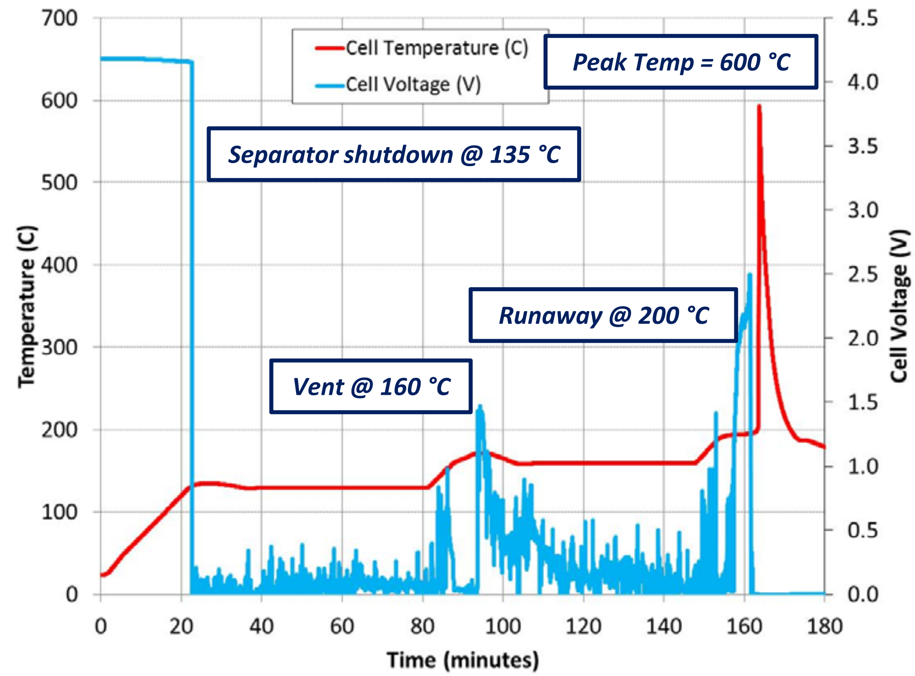
# Abuse Testing

***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

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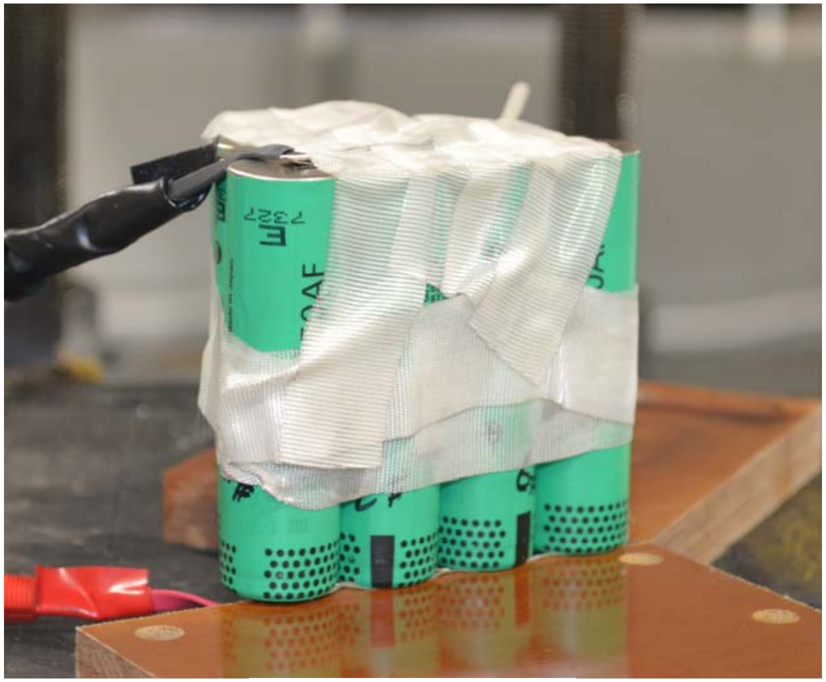
**Methodology:**

- 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 $LiCoO_2$ 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*



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

# Failure Propagation

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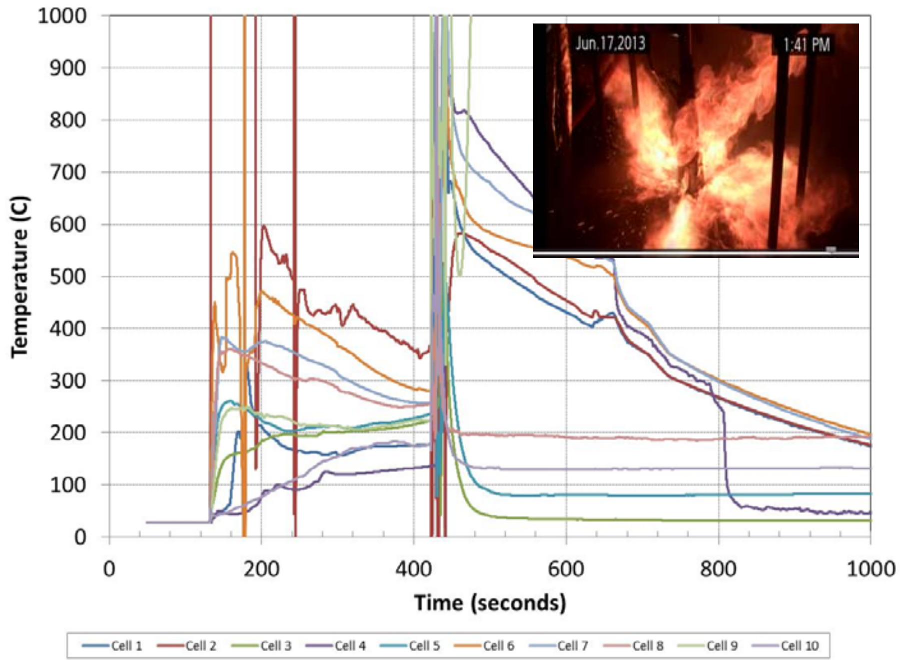
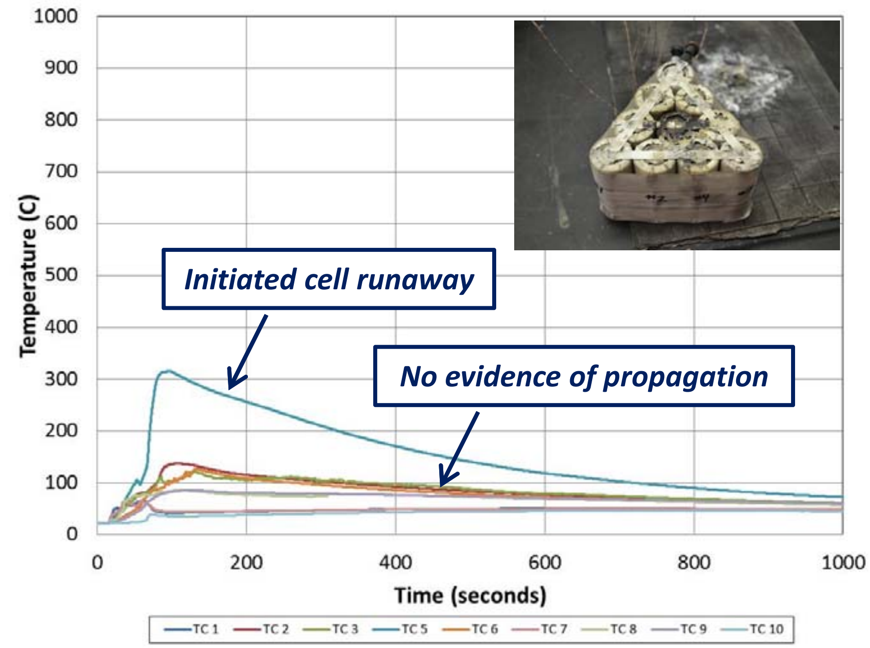
***Failures initiated by mechanical insult to the center cell (#6)***

## ***$LiCoO_2$ - 1S10P***




## ***LFP - 1S10P***

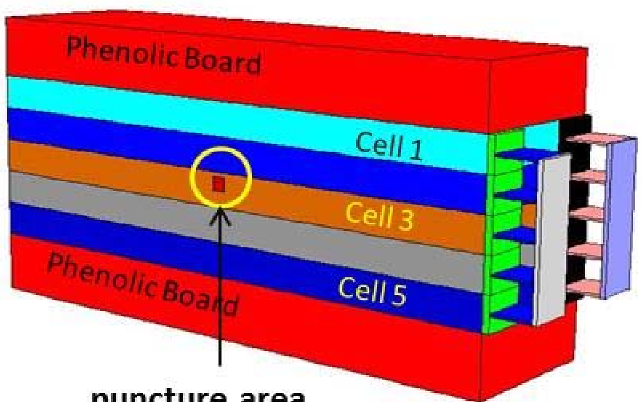


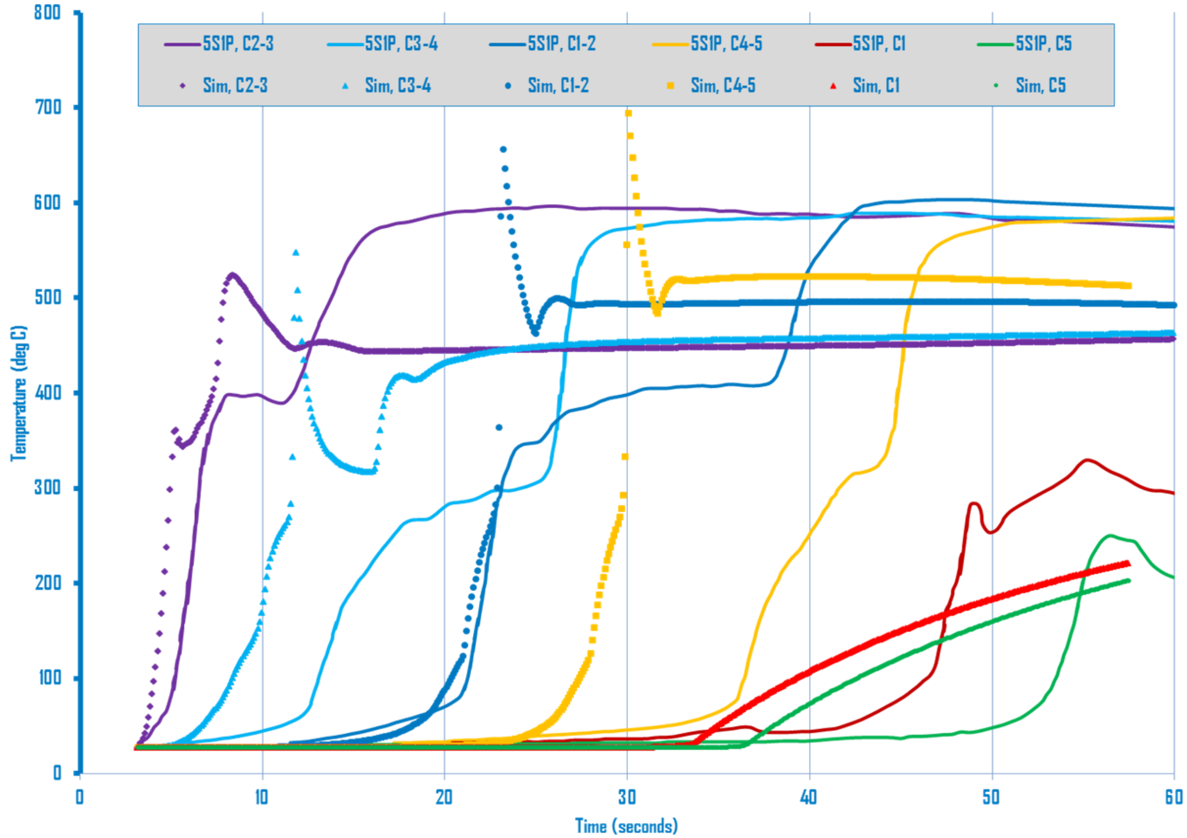

***Complete propagation of a single point failure in the $LiCoO_2$ 1S10P pack***
***No evidence of failure propagation in the LFP 1S10P pack***

# Failure Propagation Model (NREL)

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

***$LiCoO_2$ Pouch Cell - 1S5P***

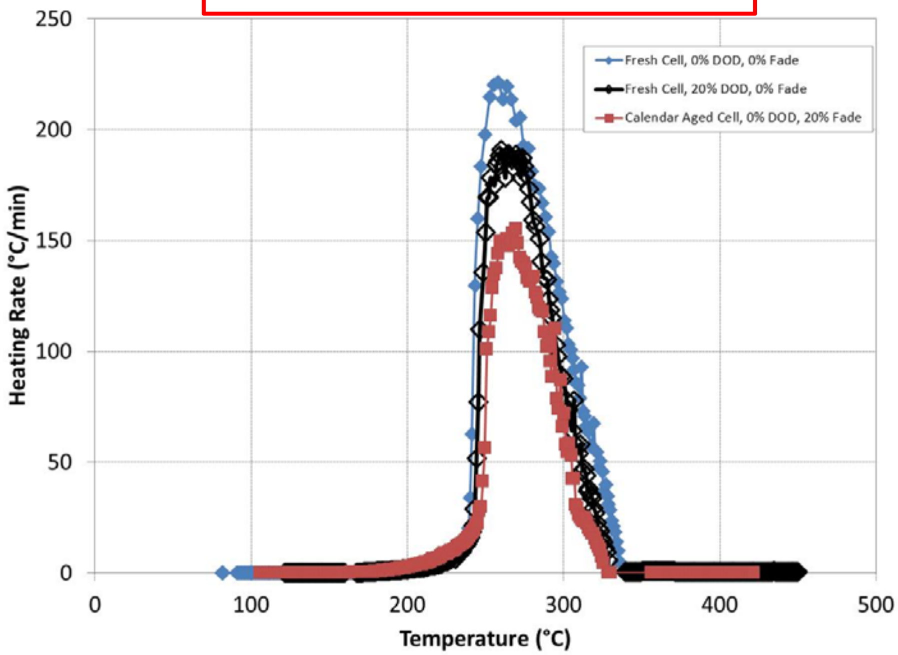


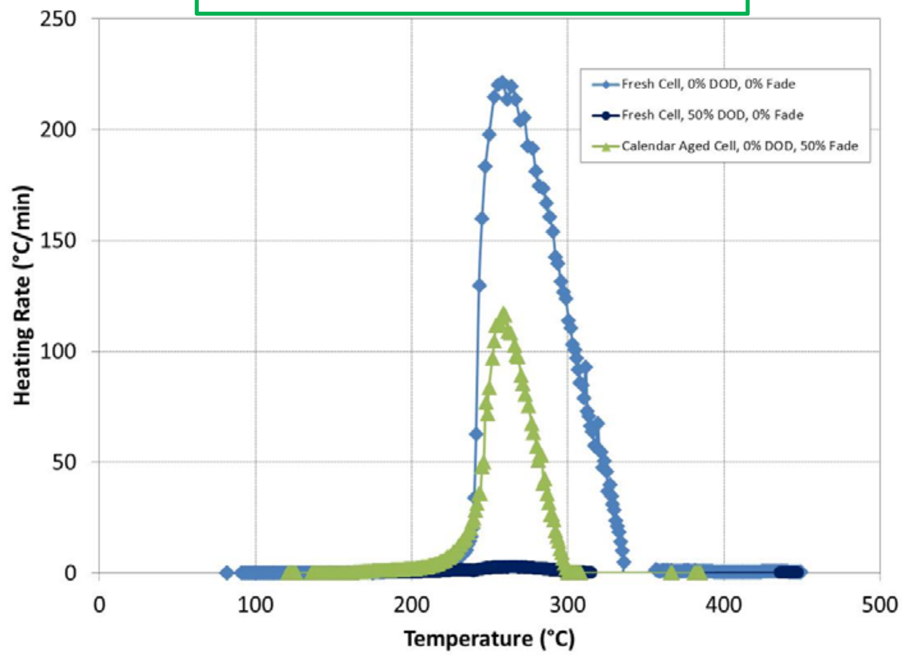

***Good agreement in the initial simulations with experiments with some deviation in the long duration events likely due to electrical or connectivity changes within battery over time during the failure event***

# Abuse Response of Aged Cells

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

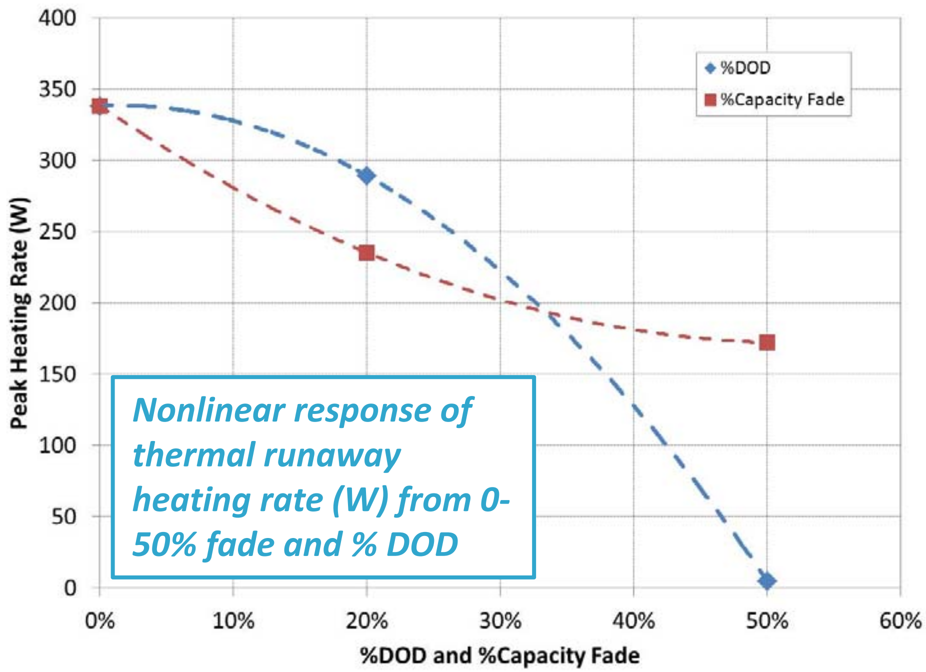


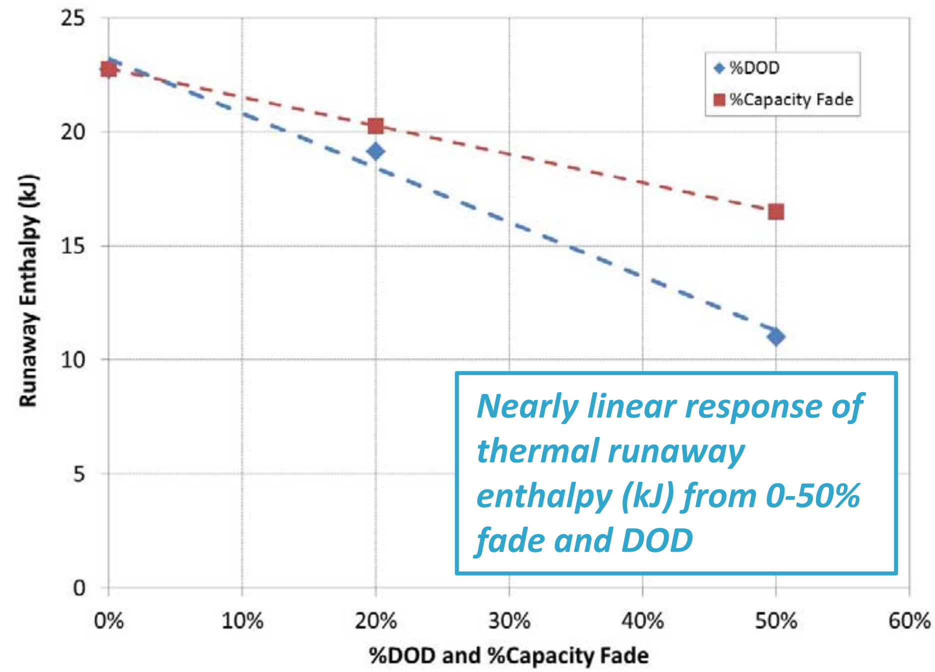

***50% Capacity Fade & 50% DOD***




- ***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

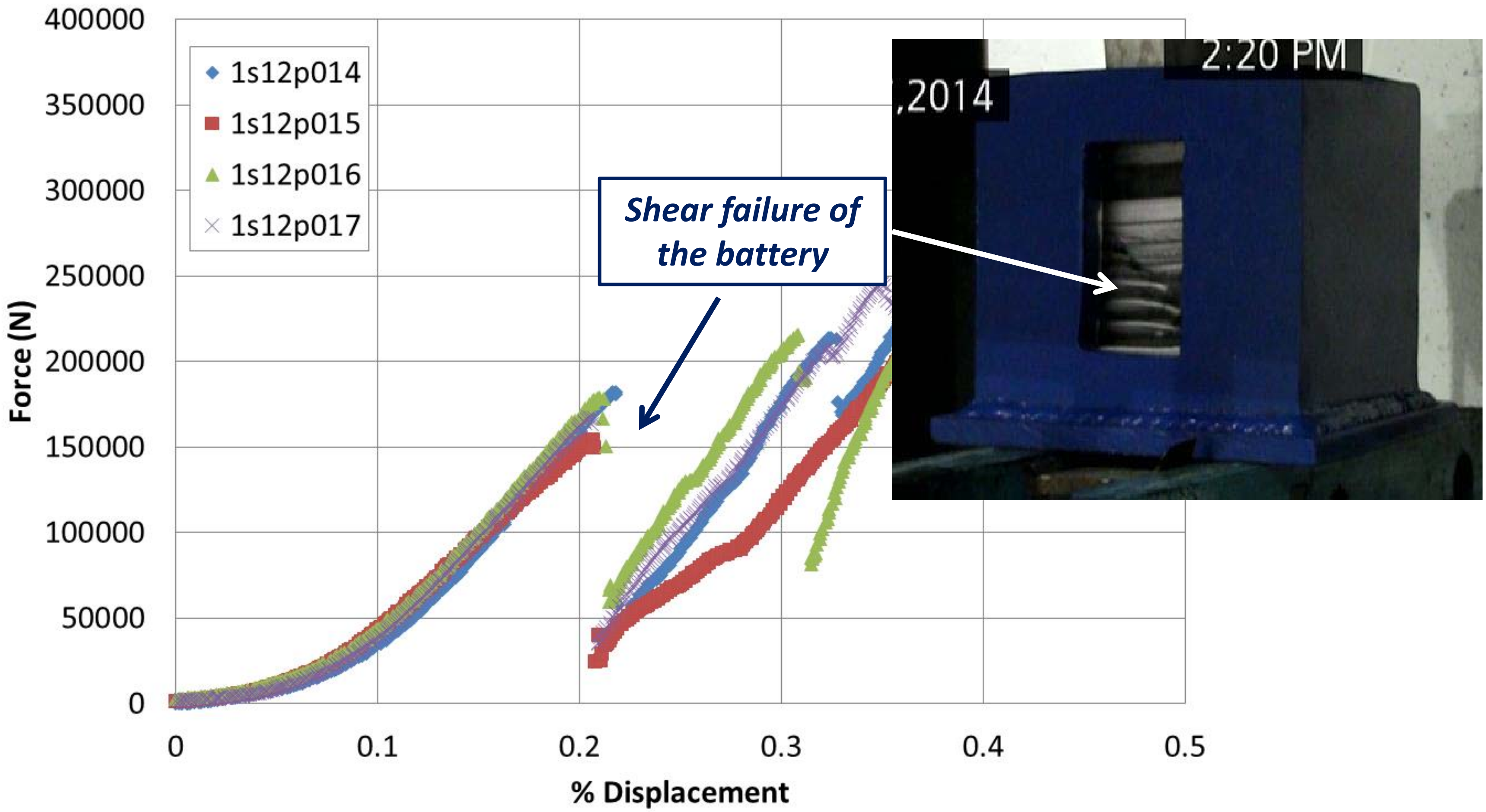



***Thermal runaway response heat release (W and kJ) correlation between % capacity fade and % DOD diverge significantly from 20 to 50%***

# USCAR – Battery Crash Worthiness

***Mechanical testing support of battery mechanical model development***

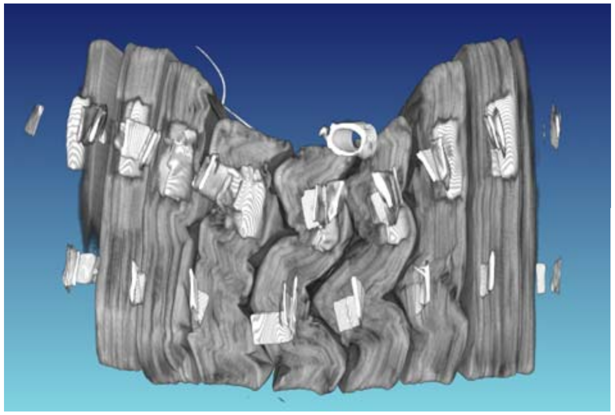



***Completely mechanically constrained geometry provides reproducible test results to generate mechanical model input parameters***

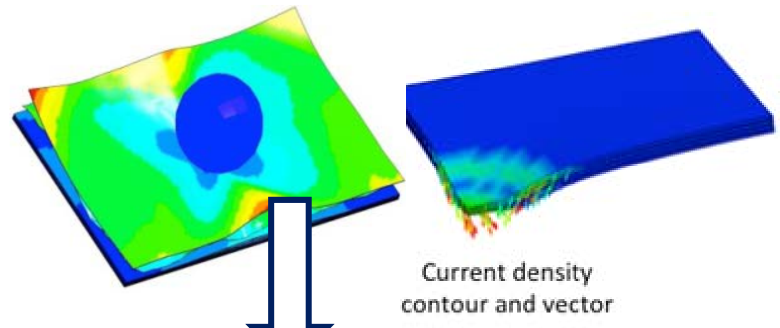
# Supporting CAEBAT Crash Worthiness

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

***Battery Crush Experiment (SNL, USCAR)***

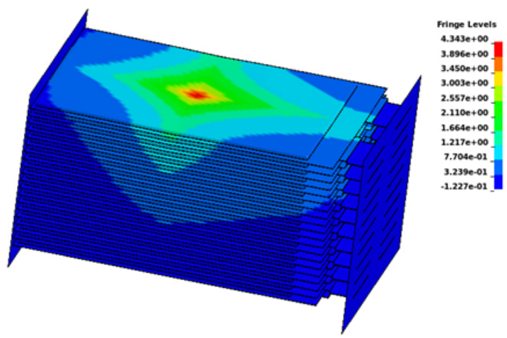


***Cell-level Mechanical Model (MIT/NREL)***

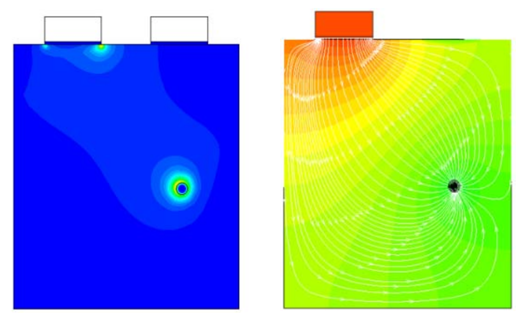



***Integrated Thermoelectrochemical & Mechanical Model (NREL)***

**Thermal Cell-to-Cell Propagation Model**




**Thermoelectrochemical 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 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


- Dave Howell (DOE)
- Brian Cunningham (OVT)
- Jim Barnes (OVT)
- Jack Deppe (OVT)
- Ahmad Pesaran (NREL)
- Gi-Heon Kim (NREL)
- Shriram Santhanagopalan (NREL)
- Jon Christophersen (INL)
- USCAR CSWG members
- Tom Wunsch
- Kyle Fenton
- Bill Averill
- Lorie Davis
- Jill Langendorf
- Mani Nagasubramanian

# REVIEWER ONLY SLIDES

# Response to Previous Year Reviewer's Comments

- "One difficulty the reviewer had with the safety testing in general is that the safety events in field use are always different from the simulated abuse tests and the response is often difficult to predict"
  - **We agree that it is a challenge to test every potential failure mode and predict the response with 100% accuracy. But, there are several cases of abuse failures in the field where batteries in EVs experience a mechanical abuse insult in the field. We believe our role is one where we can test storage systems to understand some of the risks and safety boundary conditions of a particular design, chemistry, or product.**
- "The reviewer noted that one area that SNL should improve its expertise was in the analysis of gases during and after abuse-testing. This was especially true for quantitative analysis of large format cells."
  - **Historically, we have done an extensive amount of gas analysis during abuse testing and cell failure events, but agree that is has not been reported as broadly as it should. A Journal of Power Sources article on the effect of electrolyte composition on gas generation from our group was submitted in April 2015. Additional work on gas analysis will be a continued focus of our group and we will work to report these results more consistently.**

# Publications and Presentations

Sandia National Laboratories

- C. J. Orendorff et al. "Failure Propagation in Multi-Cell Batteries" SAND2014-17053, October 2014.
- C. J. Orendorff et al. "Abuse Testing Update" USABC TAC, Southfield, MI, November 2014
- C. J. Orendorff et al., "Quantifying Thermal Runaway by Battery Calorimetry and Opportunities for Improvement" IAPG Safety Panel, San Diego, CA, February 2015
- J. Lamb et al. "Failure Propagation in Multi-Cell Lithium Ion Batteries" J. Power Sources 283 (2015), 517-523.
- C. J. Orendorff et al. "Abuse Testing Update" USABC TAC, Southfield, MI, February 2015
- C. J. Orendorff et al., "Advancing Battery Safety through Materials Development and Testing" Next Generation Batteries 2015, San Diego, CA, April 2015
- J. Lamb et al. "Safety Testing Challenges for Grid-Scale Energy Storage Systems" Next Generation Batteries 2015, San Diego, CA, April 2015.
- C. J. Orendorff et al. "Abuse Testing Update" USABC TAC, Southfield, MI, May 2015