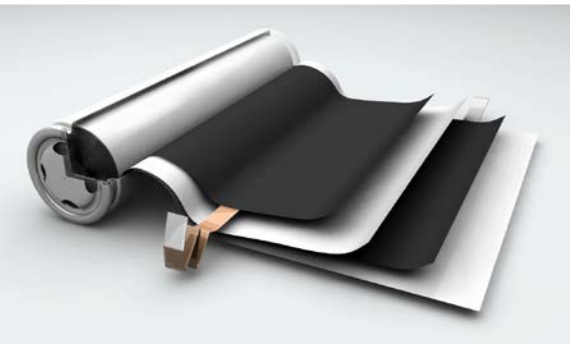
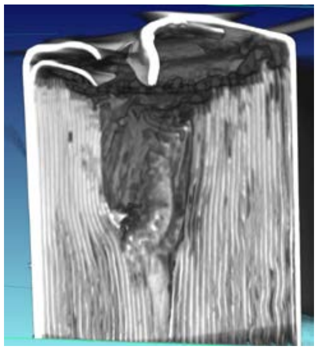




Battery Safety Testing

Leigh Anna M. Steele*, Josh Lamb, Christopher Orendorff, Scott W. Spangler, Chris Grosso, and Jill Langendorf

Sandia National Laboratories

ES203

2016 Energy Storage Annual Merit Review

Washington, D. C. June 2016

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview

Timeline

- **Start Date: Oct. 2015**
- **End date: Oct. 2016**
- **Percent complete: >75%**

Budget

- **FY16 Funding: $1.3M**
- **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 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
- Evaluate short circuit current during failure propagation of battery strings
- Provide testing data to support failure propagation model developed by NREL
- Study thermal runaway of cells at various states of charge
- Provide experimental support for mechanical modeling battery crash worthiness including dynamic testing development for CAEBAT

Milestones

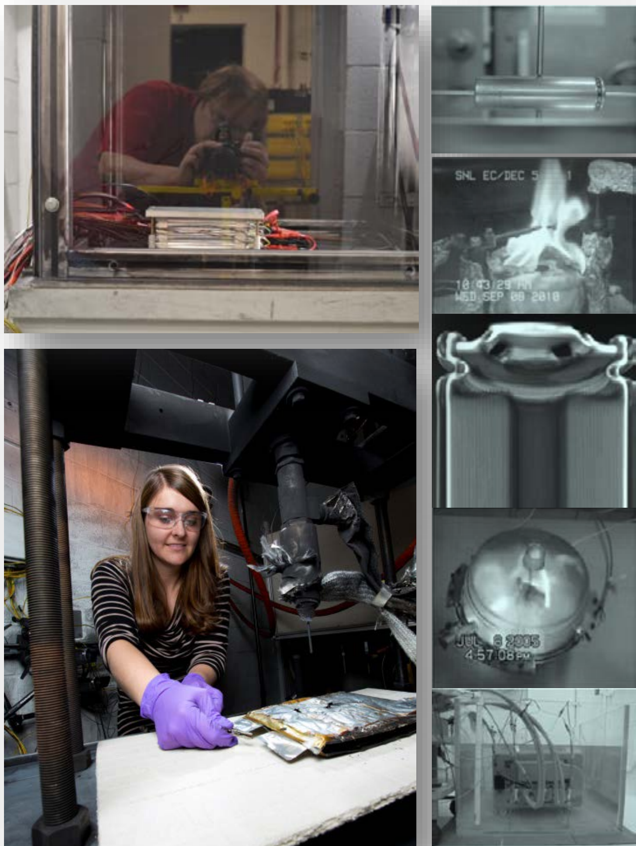
Demonstrate improved abuse tolerant cells and report to DOE and the battery community

Milestone	Status
Complete Q1 USABC deliverables (SEEO and Maxwell module testing)	
Report update on USABC Abuse Testing Manual Revision progress to DOE	
Complete Q2 USABC deliverables (Amprius-EV and Envia aged cells)	
Evaluation of shutdown separator materials (Miltech-DOE-VTO program) using Sandia's Separator Evaluation Platform	
Complete evaluation of thermal runaway for cell at various states of charge (%DOD)	
Propagation testing with alternative cell designs : interior vs exterior cell failure	
Propagation testing with alternative cell chemistries : LFP vs $LiCoO_2$	
Analysis of short circuit current during failure propagation: resistance measurements on constantan bridges between cells during propagation	Q3/Q4
Complete Q3 USABC deliverables (Envia-EV and LG-CPI 12VSS)	Q3
Development of dynamic testing for USCAR-CSWG/CAEBAT	Q4
Report on Abuse Manual Revision update to DOE	Q4
Complete Q4 USABC deliverables (NOHMS-electrolyte and Maxwell ultracap pouch cells- 12VSS)	Q4

Milestone Complete

Approach and Capabilities

Cell and Module Testing
Battery Abuse Testing Laboratory (BATLab)



Battery Pack/System Testing
Thermal Test Complex (TTC) and Burnsite

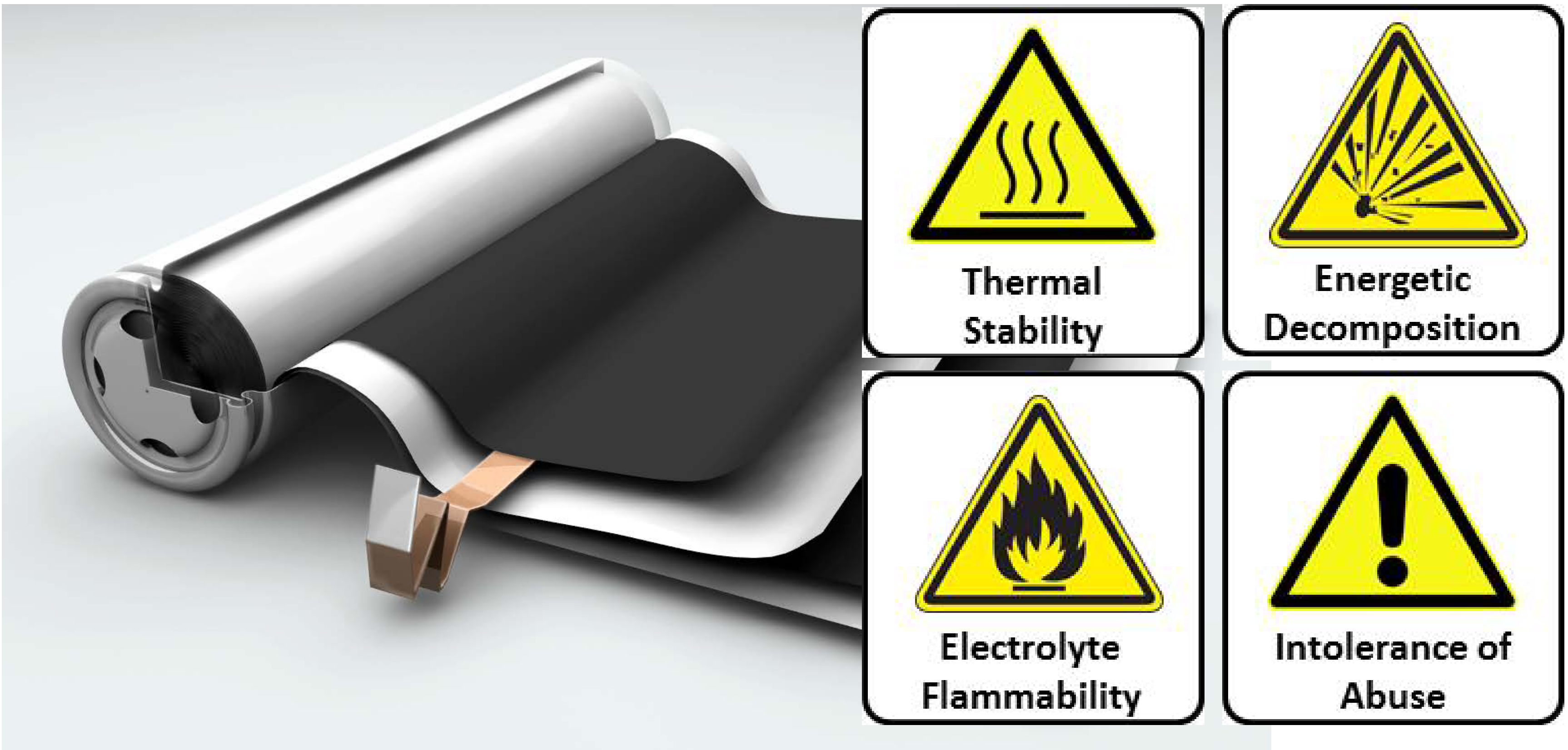
Battery Calorimetry

Technical Accomplishments/Progress/Results

Abuse Testing and Characterization:

- Completed testing of all USABC deliverables and reported results to the USABC TAC
- Stood up permanent large scale battery testing capability at Sandia's Burnsite and successfully completed testing of several USABC modules
- Supported DOE-VTO program with shutdown separator analysis
- Revision of Abuse Testing Manual (revision to SAND2005-3123) provided to USABC with review and revisions underway by the TAC
- Completed thermal testing of fresh cells at various states of charge (%DOD)
- Investigated propagation effects with alternative cell designs
  - Interior and exterior cell failures of both parallel and series packs
  - Pack design
- Developed testing method to analyze short circuit current between cells during failure propagation. Current during failure peaked at 37A for 18650 $LiCoO_2$ string and 30A for 18650 LFP string. Future work is to apply concept to larger strings/packs as well as alterative battery chemistries and designs (pouch vs cylindrical) and report results
- Comparison of constrained single cell and pack end crush test for USCAR-CSWG show similar slopes on force vs displacement curve once the initial crush is initiated.
- Supporting testing of cell to varied levels of overcharge for post test analysis to be done by ANL supporting the ABR program

Lithium-ion Safety Issues



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

USABC Program Deliverables to SNL

Program	Deliverable
SEEO TAP	Modules (3) Q1
Maxwell	Modules (4) Q1
Envia	Aged cells (4-INL) Q2
Amprius EV	cells (10) Q2
Envia EV	Cells (11) Q3
LG-CPI 12VSS	Cells (10) Q3
NOHMS (electrolyte)	Cells (24) Q4
Maxwell 12VSS	Ultracap pouch cells (4) Q4

Testing results for USABC are protected information

USABC Abuse Testing Manual

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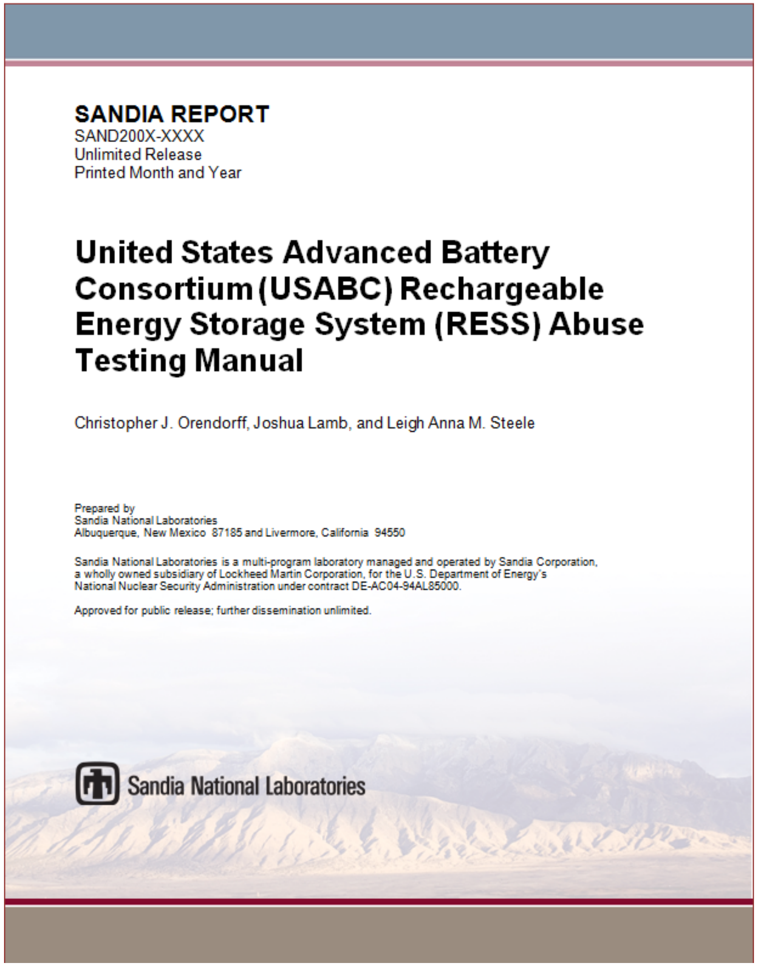
SANDIA REPORT
SAND200X-XXXX
Unlimited Release
Printed Month and Year

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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Approved for public release; further dissemination unlimited.

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Notable changes:

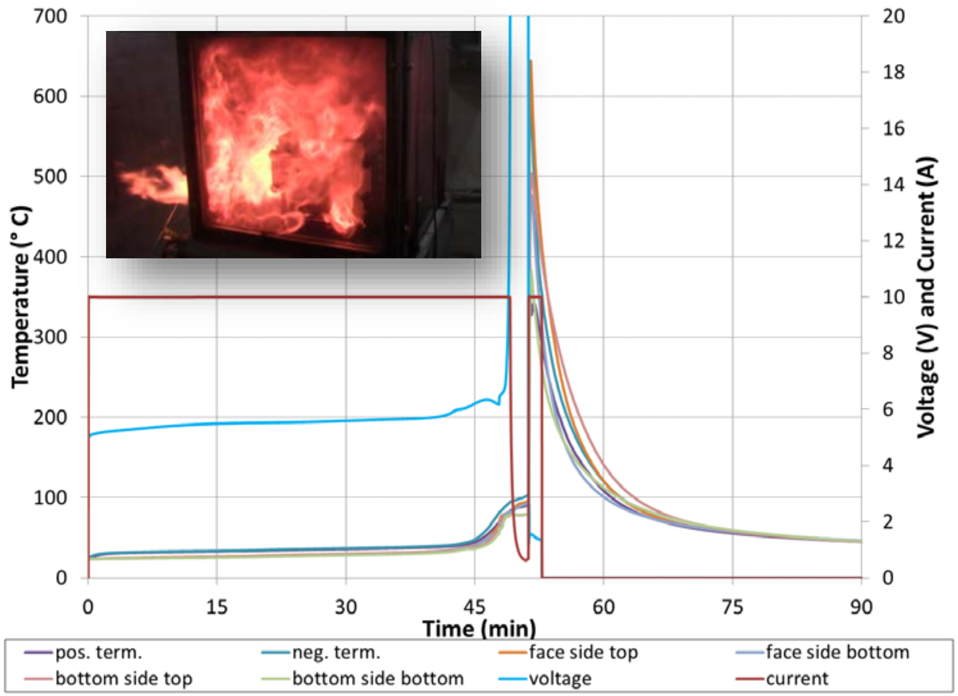
- Enhanced safety basis
- Empirical data to support test conditions
- Failure propagation test
- Cell vent flammability test

- ***Revision to the USABC Abuse Manual delivered to USABC in Q1***
- ***Expect USABC TMD approval in Q3***

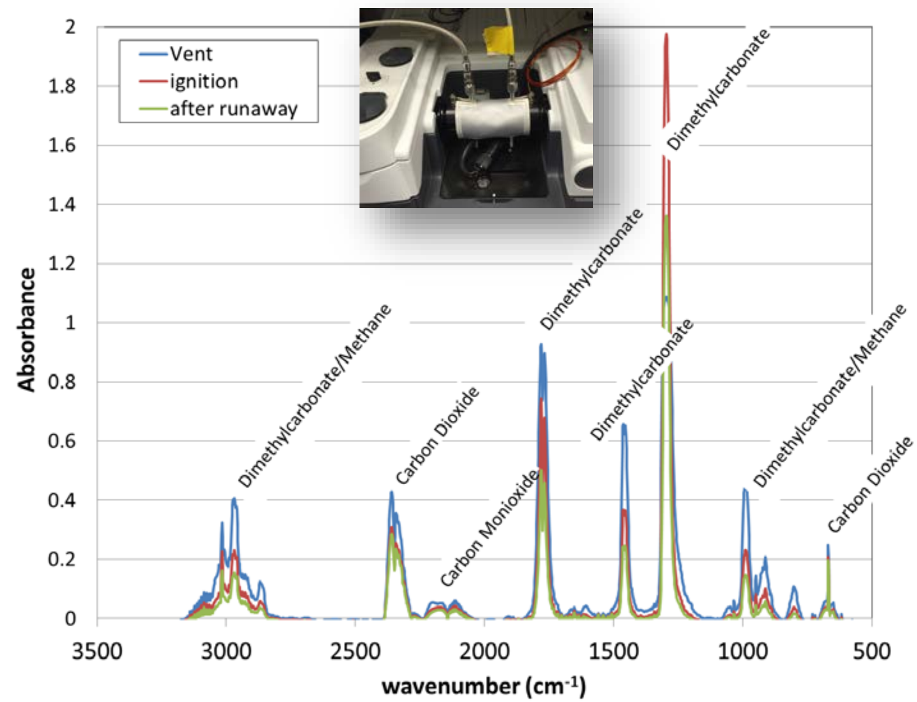
Abuse Testing

Representative overcharge abuse test of a COTS lithium-ion cell (non-USABC) with gas analysis data

1C (10A) OC-$LiCoO_2$ pouch cell



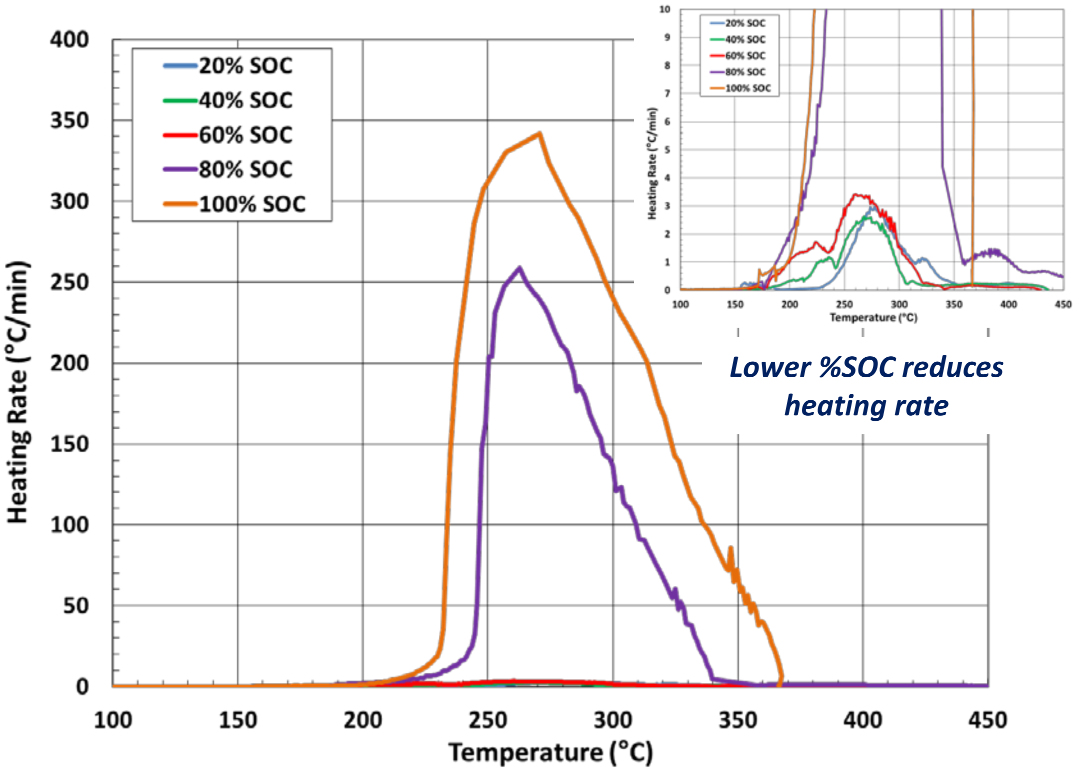
FTIR gas data during cell runaway



- ***Testing performed according with the USABC Abuse Test Manual***
- ***Ancillary measurement capabilities includes gas analysis (gas data shows DMC and combustion products)***

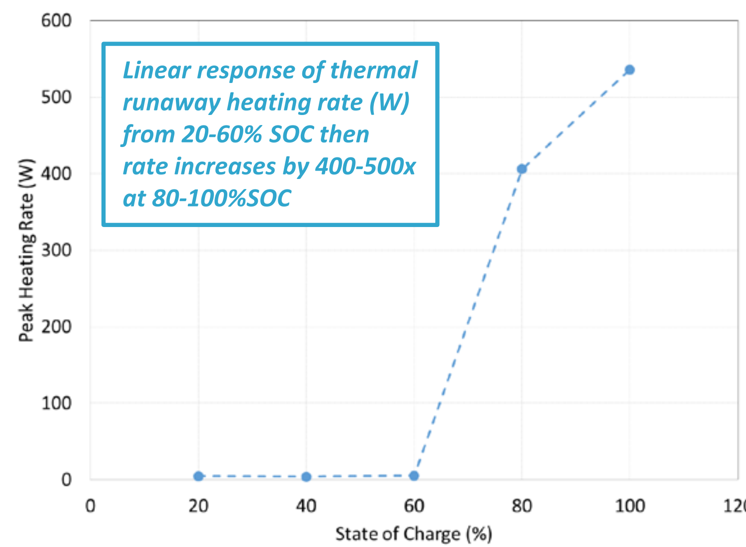
Impact of SOC on Abuse Response

Fresh cells 20-80% SOC (80-20%DOD):Sanyo



Energies as a function of %SOC

%SOC	KJ	KJ/Ah	W	W/Ah
20	19.5	78.0	4.64	18.6
40	23.9	47.8	4.14	8.27
60	25.7	34.3	5.37	7.17
80	31.0	31.0	406	406
100	25.5	20.4	536	429



- ***Peak heating rate profiles are similar for lower states of charge (20-60%) then drastically increase at 80% and 100% SOC as shown by the total energy output (W)***
- ***The onset of thermal runaway increases as the %SOC decreases***

Failure Propagation Testing: Alternative Designs

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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 $LiCoO_2$ 18650 and LFP 18650/26650 cells
- 1S10P and 10S1P electrical configurations
- Failure initiated by a mechanical nail penetration along longitudinal axis
- **The current effort is focused on understanding the effect on propagation from single cell failure at different locations within 1S10P and 10S1P packs as well as the evaluation of pack design (nickel tabbing, copper bus architecture, and air gaps between cells)**

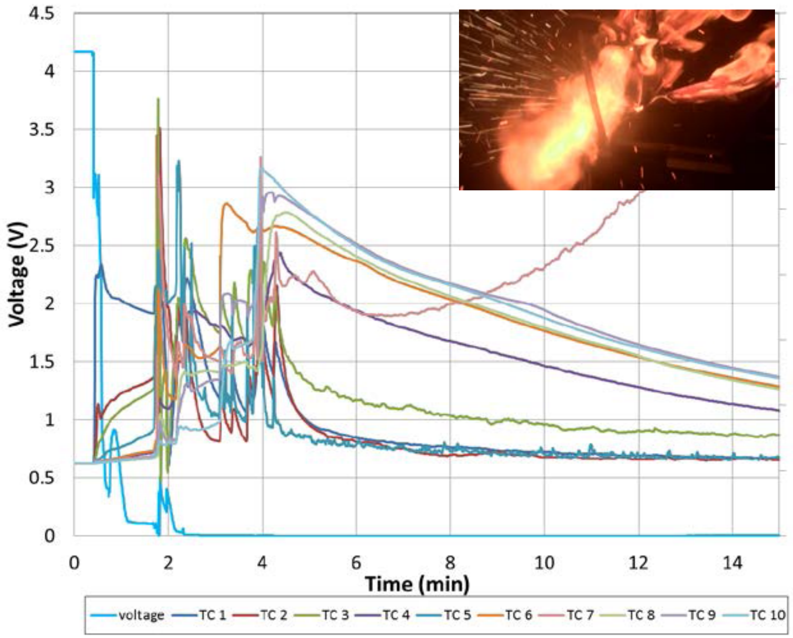
1S10P Battery: Failure point on edge cell

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

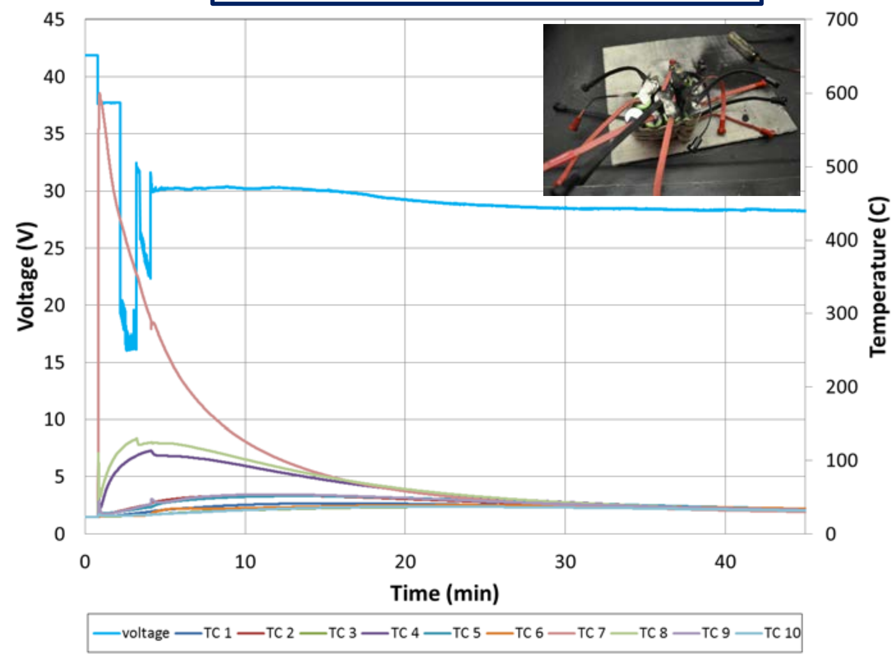
Failure Propagation: Edge Cell Failure

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

$LiCoO_2$ - 1S10P(parallel)



$LiCoO_2$ - 10S1P (series)



- *Previous testing with center cell failure point in $LiCoO_2$ packs: limited propagation in 10S1P and complete propagation in 1S10P pack*
- ***Edge cell failure: complete propagation for 1S10P and a range of responses for 10S1P: limited (cells next to failure point engaged) to complete propagation***
- ***Parallel packs, regardless of initiation point, have full propagation while there is variation within series packs (limited to full propagation)***

Failure Propagation: Design Effects (Connections)

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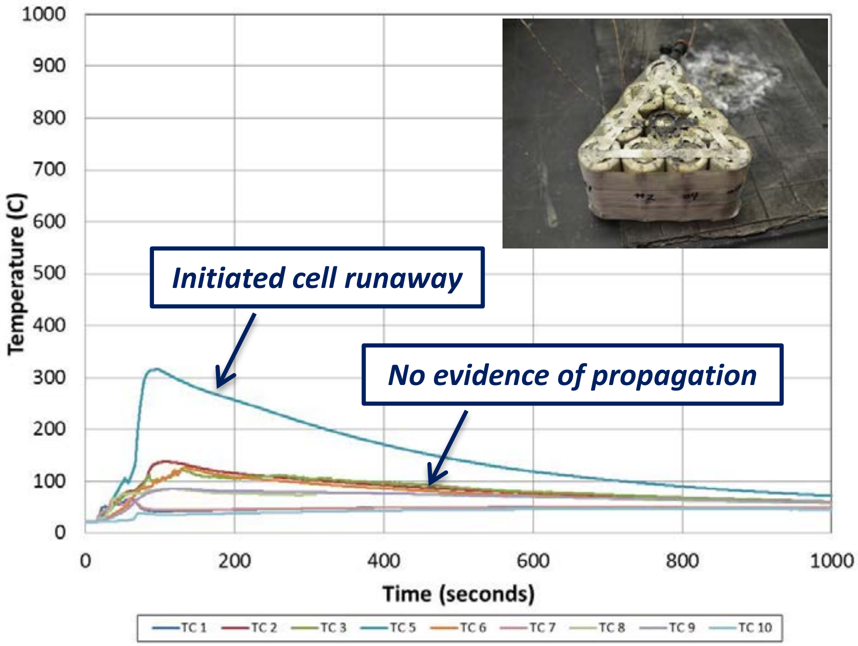
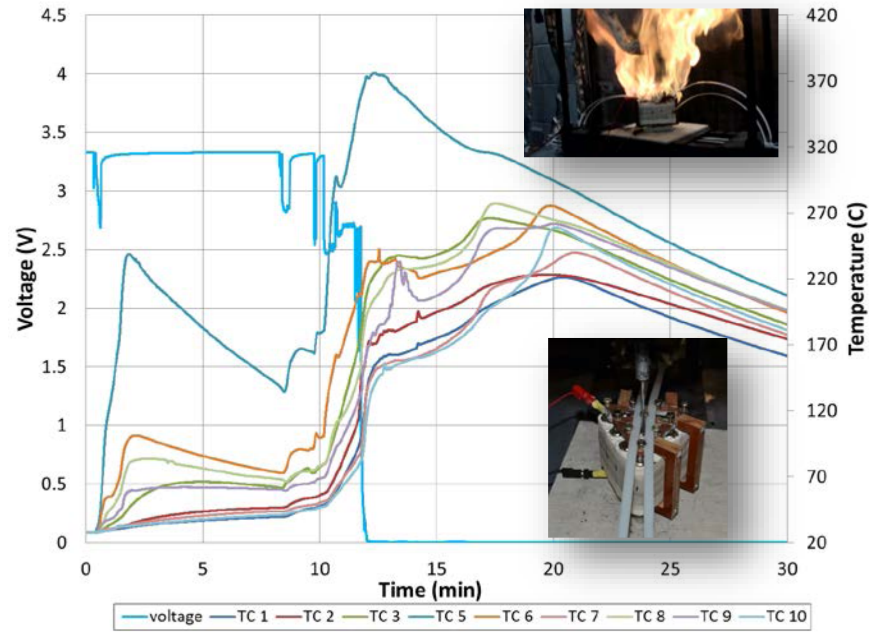
Failures initiated by mechanical insult to center cell of LFP COTS packs

LFP - 1S10P connected using nickel tabs



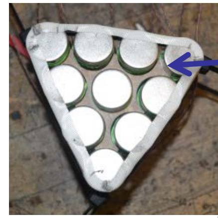
LFP - 1S10P connected using copper bus



- ***Packs with alternative designs were assembled using 26650 LFP COTS cells in 1S10P configurations The pack connected with nickel tabbing show no evidence of propagation***
- ***Complete propagation failure occurred once a copper bus was installed***
- ***Pack design impacts the ability for failures to propagation***

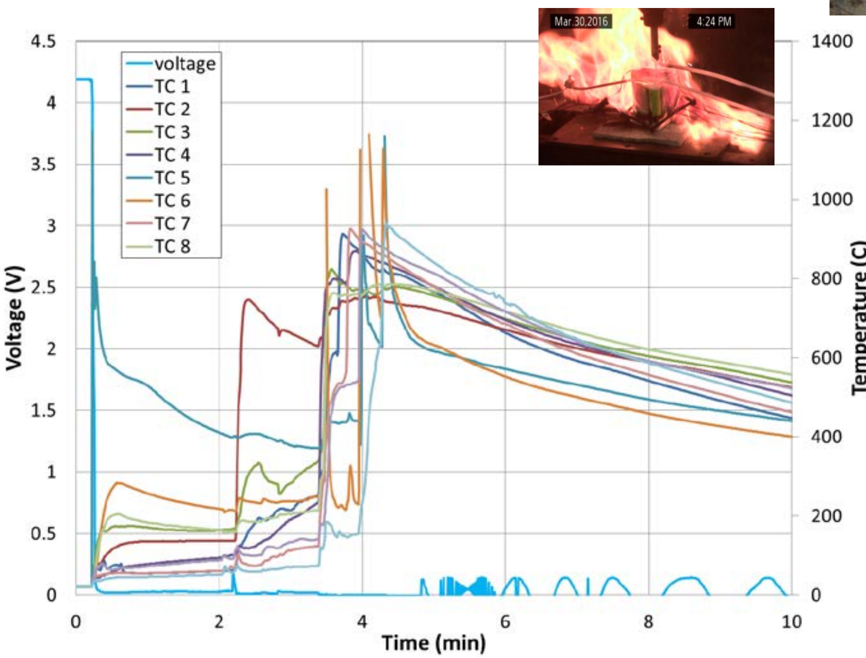
Failure Propagation: Design Effects (Air Gap)

Failures initiated by mechanical insult to the center cell: 2mm air gap between cells

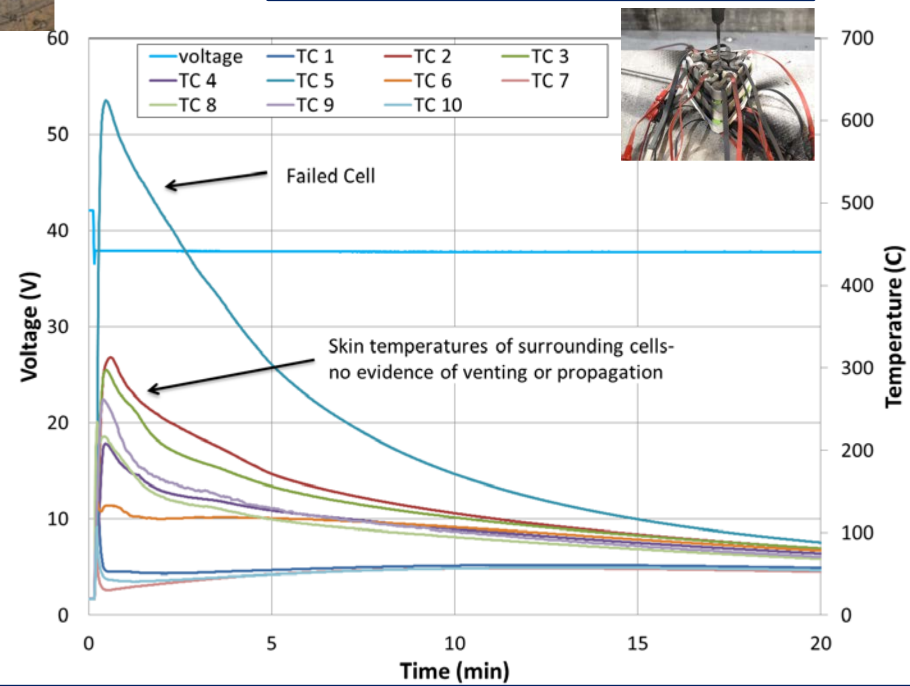


2mm spacer

18650 $LiCoO_2$ - 1S10P



18650 $LiCoO_2$ - 10S1P

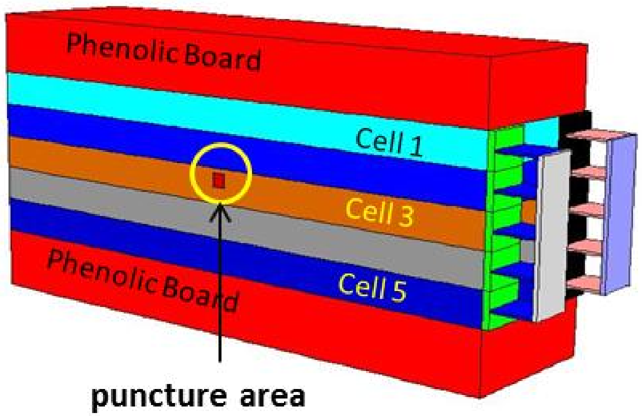


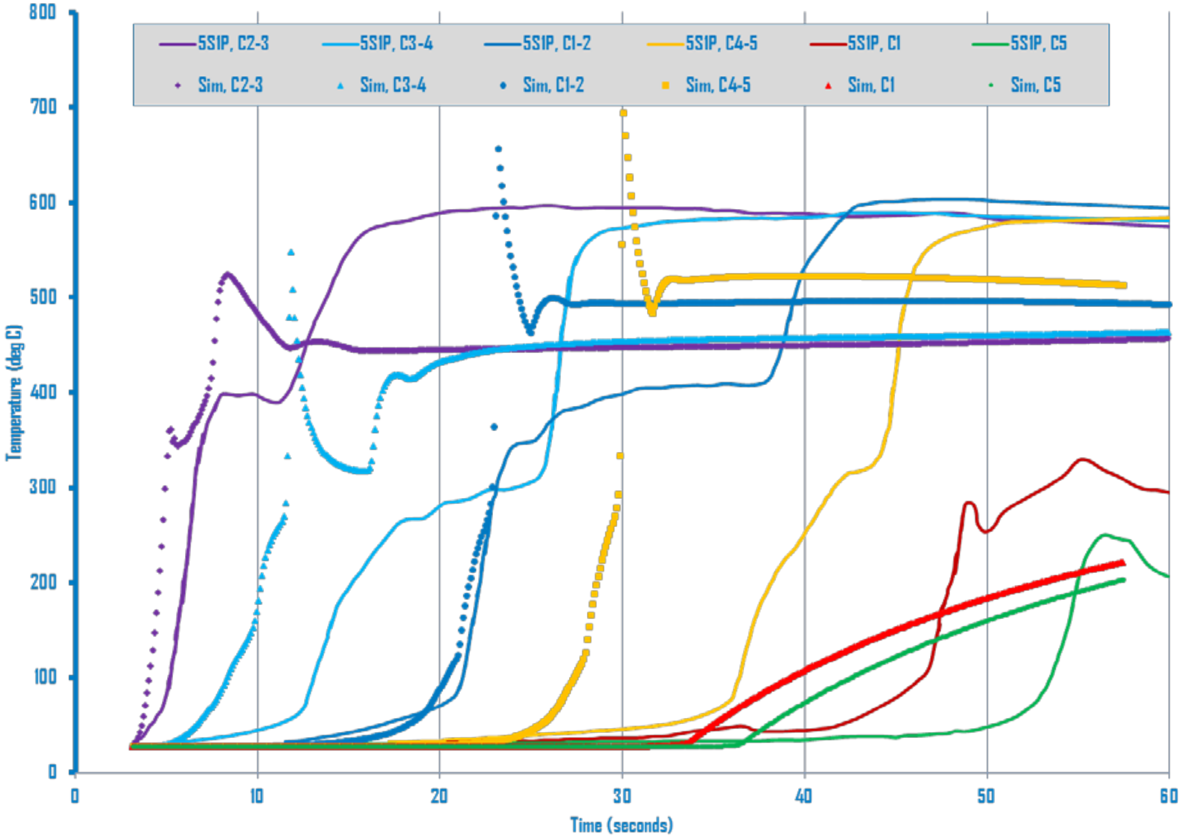
- ***Complete propagation in parallel pack regardless of air gap***
- ***No propagation in series pack with 2mm air gap between cells***
  - ***Center cell went into thermal runaway and reaches 600°C***
  - ***Neighboring cells skin temperatures see 150-300°C during failure of center cell but do not go into runaway***
- ***Air gap allowed for heat to dissipate quickly in the series pack to eliminate propagation***
- ***The electrical configuration of the parallel pack allows for propagation to occur regardless of the air gap between cells***

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

Short Circuit Current During Failure Propagation

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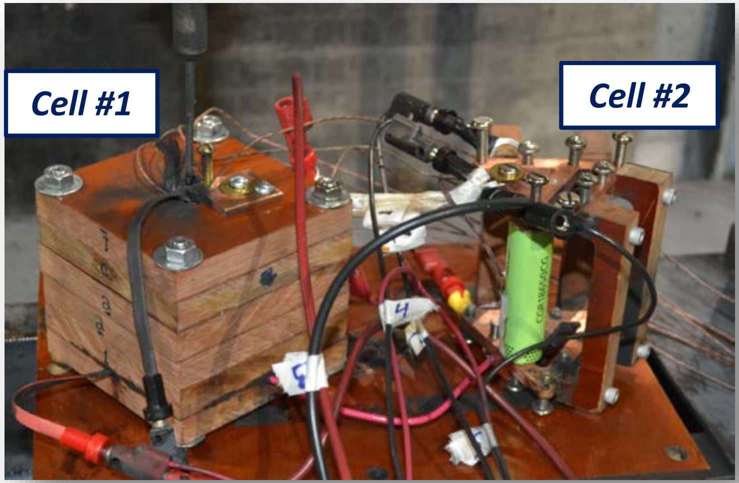
Methodology:

- Use mechanical nail penetration along longitudinal axis to initiate thermal runaway in cell #1
- Develop fixturing to enable short circuit evaluation
- Evaluate the short circuit current between initiation point and cells in parallel

Experiment

- COTS $LiCoO_2$ 18650 and LFP 18650 and 26650 cells in 1S2P configurations
- Cells electrically connected by constantan wire of know resistance
- **The current effort is focused on evaluation of the short circuit current when cell #1 undergoes a runaway event**
- **Method will be applied to larger cell strings and with complex electrical connections**

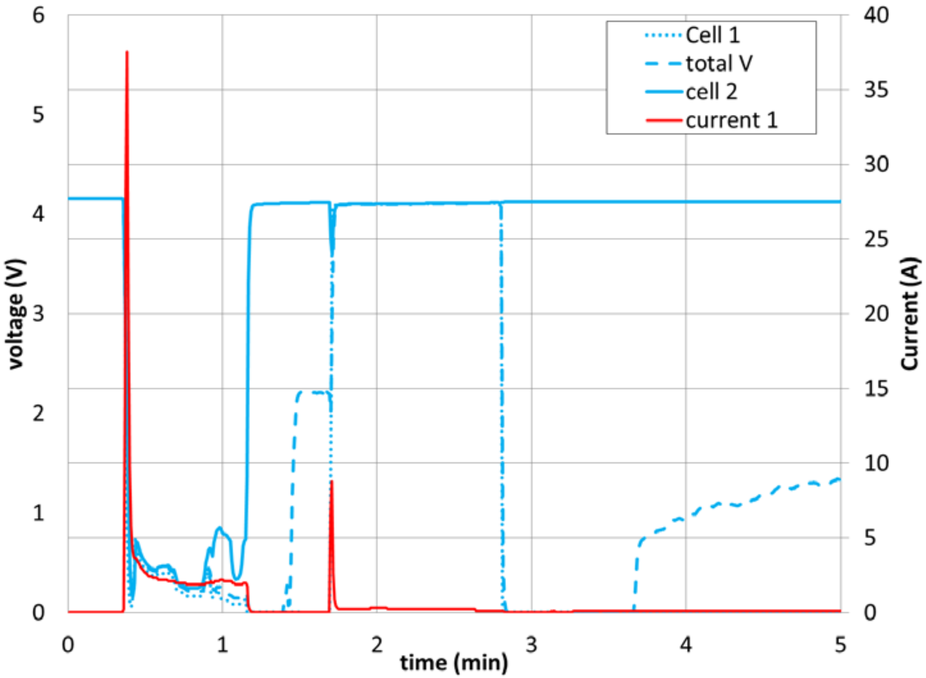


1S2P Battery: Constantan bridge wire connecting cells. Failure initiation point at Cell #1

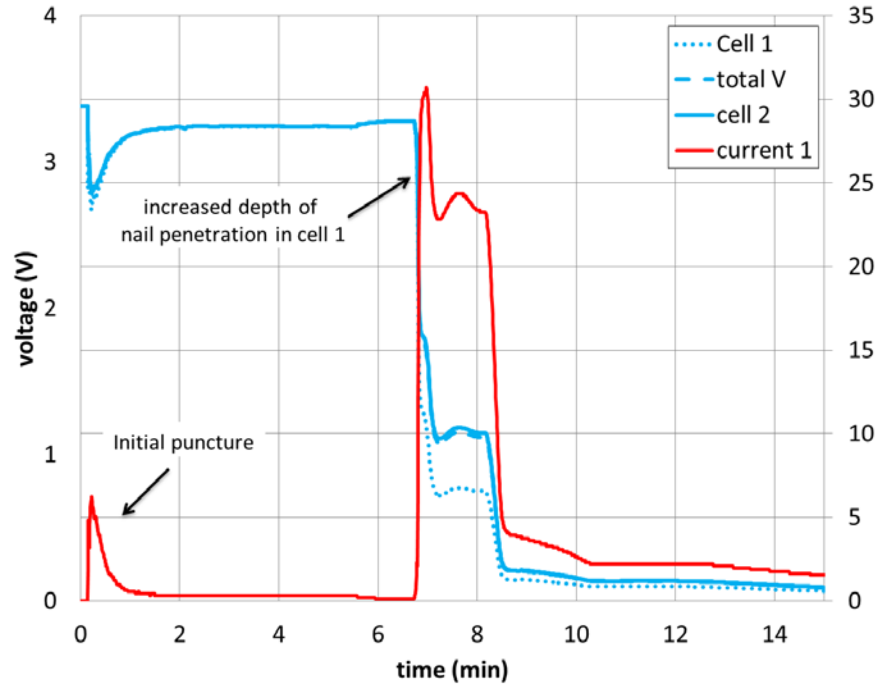
Short Circuit Current During Failure Propagation

Failures initiated by mechanical insult to cell 1 which is connected to cell 2 through constantan bridge wire

18650 $LiCoO_2$ cells – 1s2p



18650 LFP cells – 1s2p

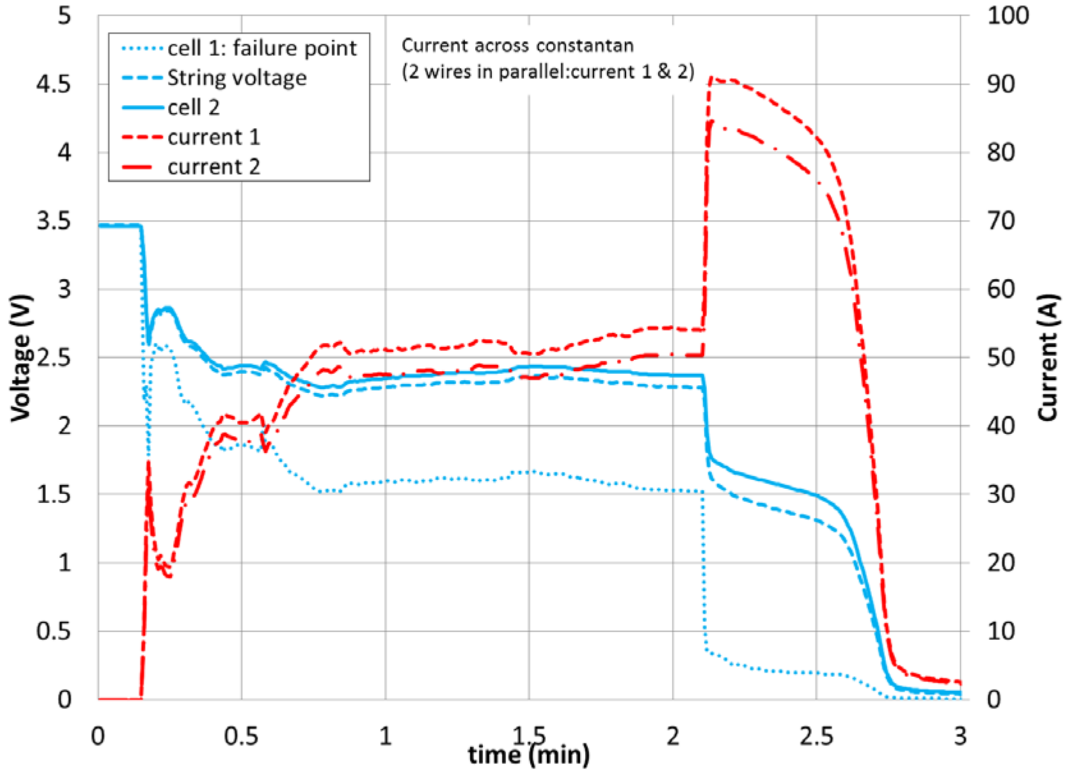


- ***Peak currents across constantan bridge during failure propagation of 18650 $LiCoO_2$ and LFP string reached 37A and 30A respectively***
- ***Energy output during discharge for duration of 1 hour was 0.49 Wh for LiCoO2 and 1.04 Wh for LFP***

Short Circuit Current During Failure Propagation

Failures initiated by mechanical insult to cell 1 which is connected to cell 2 through constantan bridge wire

LFP-26650 cells – 1s2p

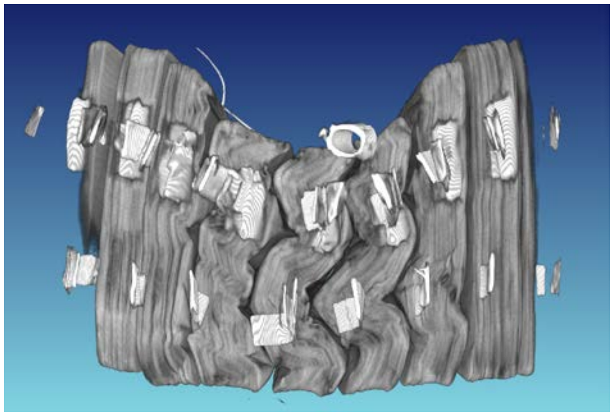


- ***Peak currents across constantan bridge during failure propagation of LFP 26650 string reached 90A***
- ***Energy output during discharge for a duration of 1 hour was 4.77Wh***

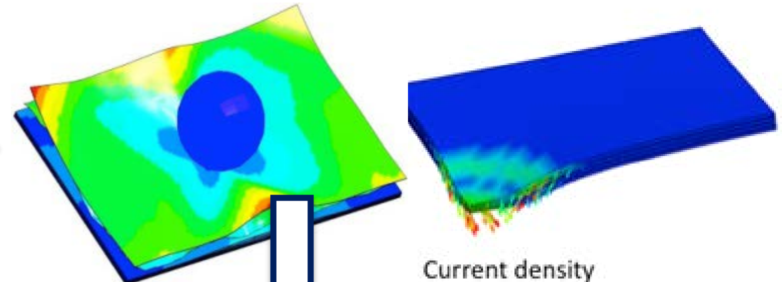
Supporting CAEBAT Crash Worthiness

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

Battery Crush Experiment (SNL, USCAR)

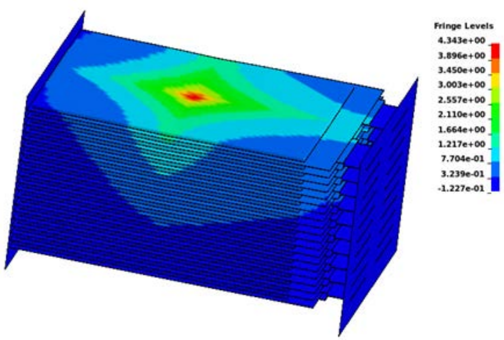


Cell-level Mechanical Model (MIT/NREL)

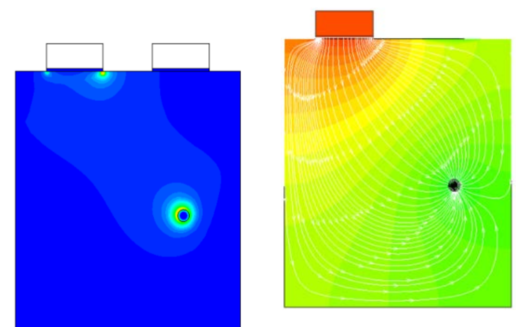


Integrated Thermoelectrochemical & Mechanical Model (NREL)

Thermal Cell-to-Cell Propagation Model



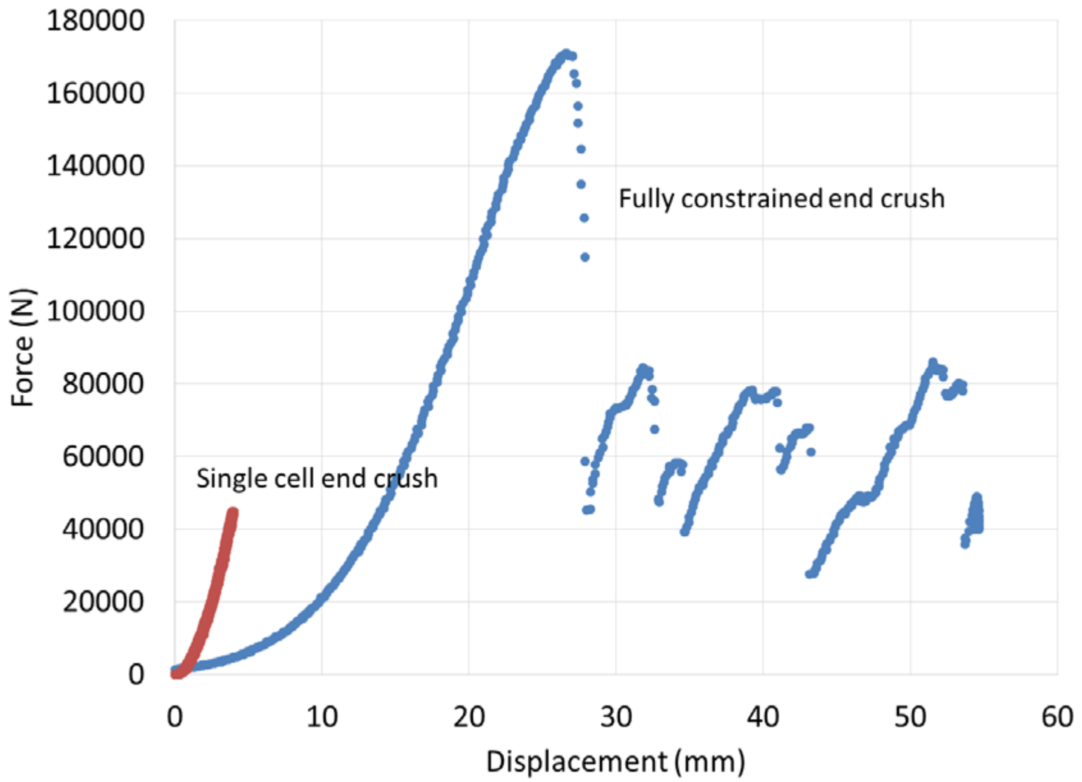
Thermoelectrochemical Model



Use battery crush data to validate the integrated model
Develop a predictive capability for battery thermal runaway response to mechanical insult

USCAR – Battery Crash Worthiness

Mechanical testing support of battery mechanical model development



- ***Single cells somewhat more resistant to crush initially, but slope becomes similar.***
- ***Free volume/liquid volume can account for the allowable compressible space in 1 cell vs 12 and could attribute to the initial slope differences***

Collaboration and Coordination with Other Institutions

- **Propagation and mechanical modeling through CAEBAT:NREL**
- **Post test analysis supporting ABR: ORNL and ANL**
- **USABC: INL, NREL, ANL, ORNL**
- **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
- Propagation testing of batteries with increasing levels of designed passive and active thermal management (leverage industry partnerships) to demonstrate the effectiveness of engineering controls to mitigate propagation in batteries
  - Investigate laser induced short circuit failure mechanism
- Working with NREL on developing a predictive failure propagation model
- Dynamic mechanical testing of batteries and model validation to demonstrate battery crashworthiness (USCAR, NREL, CAEBAT)
- External analysis of battery during thermal runaway (gas analysis, heat flux, and pressure release)
- Support testing for post test analysis of cells to determine degradation mechanisms from cell overcharging: ORNL and ANL as part of ABR

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 FY16
- Failure point, electrical configuration, and design architecture all effect the extent of propagation.
- A method for measuring short circuit current during propagation was developed for 2 cell strings and will be applied to larger packs in various electrical configurations
- 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.
- Testing support for post mortem materials analysis started in collaboration with ORNL and ANL

Acknowledgements

- Dave Howell (DOE)
- Brian Cunningham (OVT)
- Jim Barnes (OVT)
- Jack Deppe (OVT)
- Ahmad Pesaran (NREL)
- Gi-Heon Kim (NREL)
- Shriram Santhanagopalan (NREL)
- Eric Dufek (INL)
- Ira Bloom (ANL)
- USCAR CSWG members
- Tom Wunsch
- Kyle Fenton
- Eric Allcorn
- Lorie Davis
- Mani Nagasubramanian

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