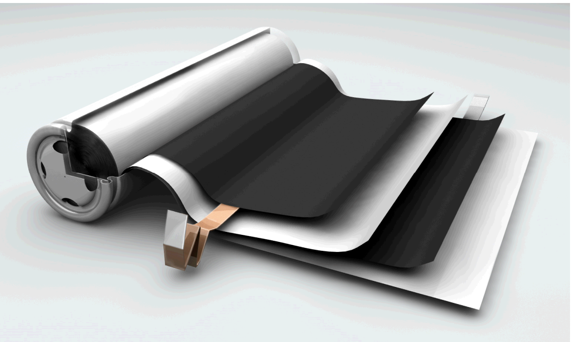
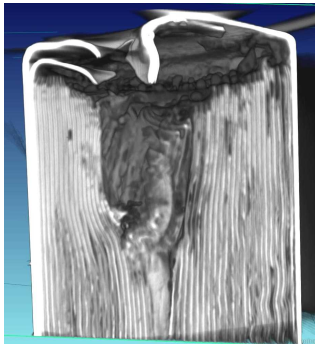
SAND2017-9196PE





Understanding Battery Safety through Abuse Testing

Joshua Lamb, Leigh Anna M. Steele, Chris Grosso, Jerry Quintana, Loraine Torres-Castro, June Stanley

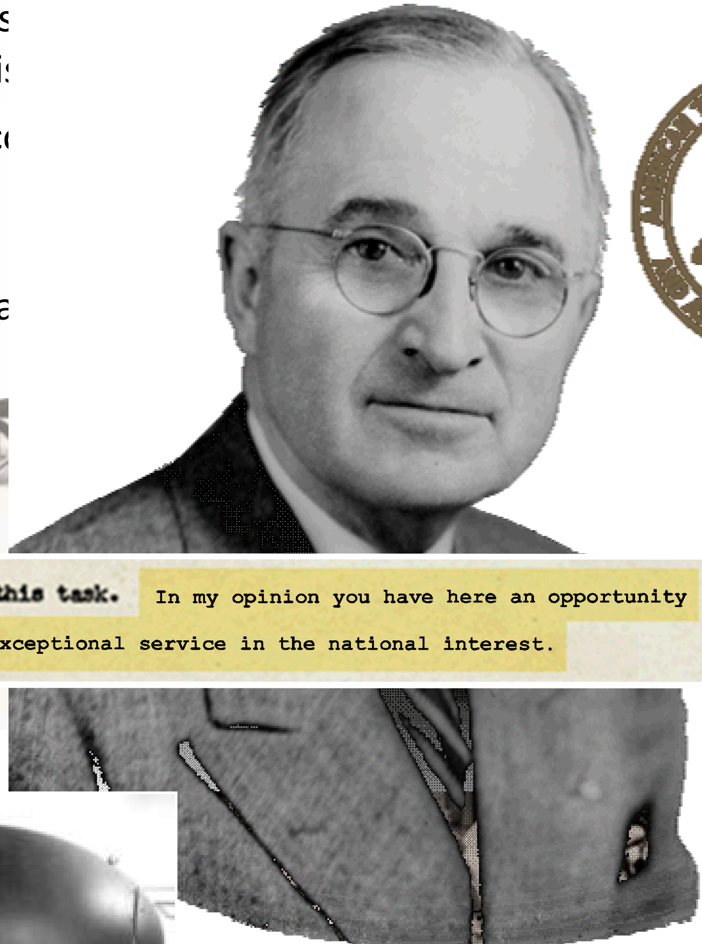
Sandia National Laboratories

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525..

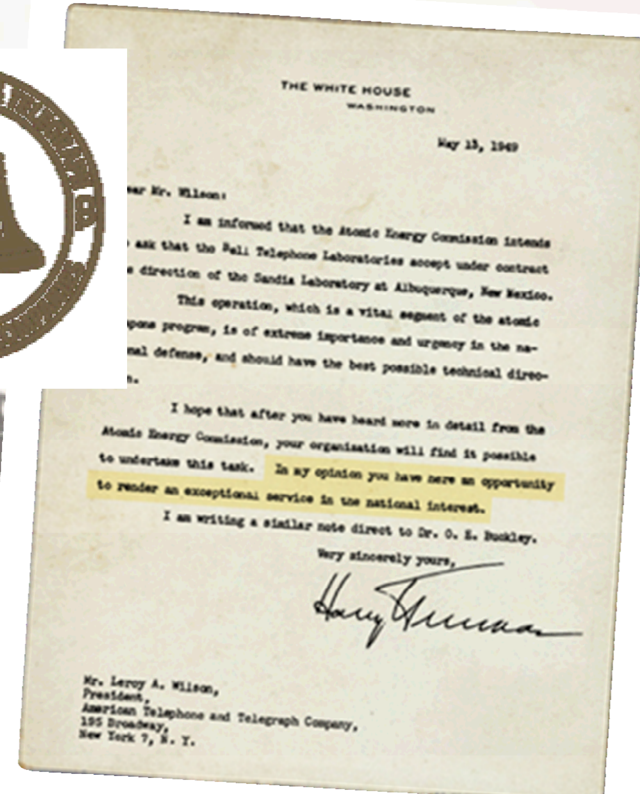
Sandia's History

Exceptional service in the national interest

- July 1945: Los
  creates Z Divi
- Nonnuclear c
  engineering
- November 1,
  Sandia Labora
  established



to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.



THE WHITE HOUSE
WASHINGTON

May 13, 1949

ear Mr. Wilson:

I am informed that the Atomic Energy Commission intends ask that the Bell Telephone Laboratories accept under contract e direction of the Sandia Laboratory at Albuquerque, New Mexico.

This operation, which is a vital segment of the atomic pons program, is of extreme importance and urgency in the nanal defense, and should have the best possible technical direc-n.

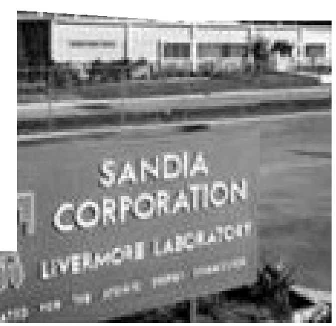
I hope that after you have heard more in detail from the Atomic Energy Commission, your organization will find it possible to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

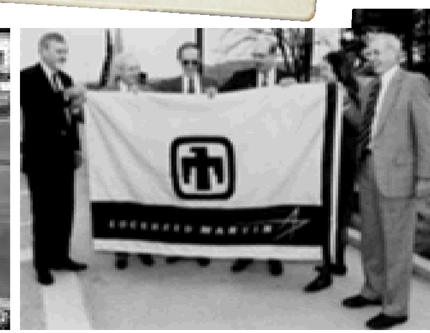
I am writing a similar note direct to Dr. O. E. Buckley.

Very sincerely yours,

Harry Truman

Mr. Leroy A. Wilson,
President,
American Telephone and Telegraph Company,
195 Broadway,
New York 7, N. Y.





Governance of Sandia Laboratories

Sandia Corporation

- AT&T: 1949–1993
- Martin Marietta: 1993–1995
- Lockheed Martin: 1995–2017
- National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc.: 2017-present
- Government owned, contractor operated

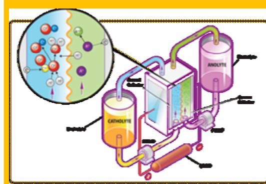
Federally funded research and development center

Power Sources Technology Group

Power Sources Technology Group (PSTG)

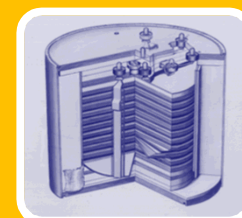
Enterprise Integration

SNL External Production

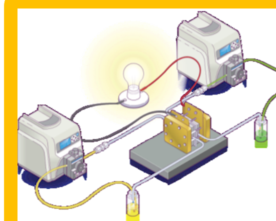


Power Source Production

Design & Development



Component Development



Research & Development

NW | **Grid Storage** | **Transportation** | **Fundamental Science**

- Thermal batteries
- Reserve batteries
- Lithium primary batteries

- Thermoelectrics
- Radioisotope power sources
- Lithium-ion batteries

- Sodium batteries
- Flow batteries
- Battery safety and reliability

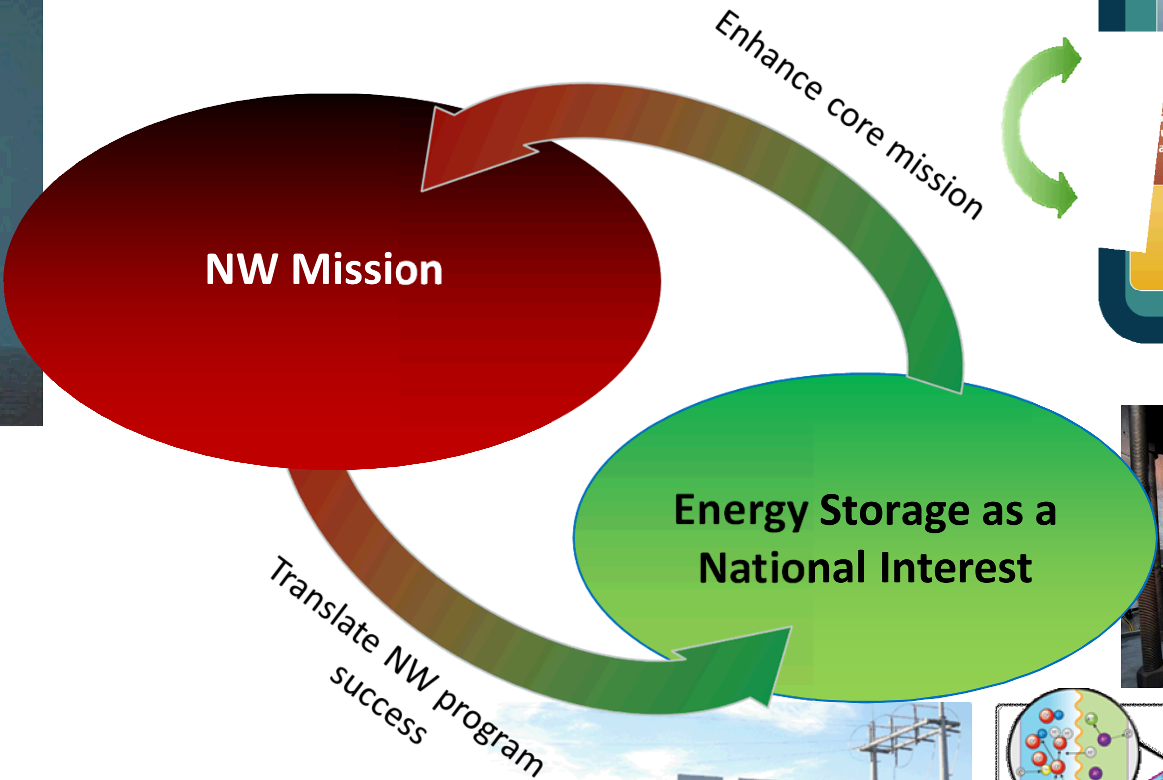
- Electrolyte development
- Solid-state electrolytes
- Beyond lithium chemistries

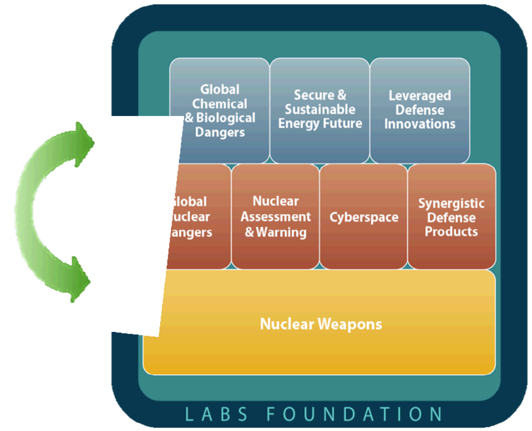
- DOE National Nuclear Security Administration
- Other Government Agencies
- Department of Defense
- Strategic Partnership Programs

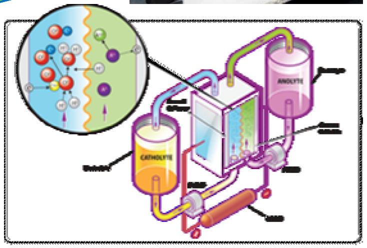
- DOE Office of Electricity
- DOE Vehicle Technologies Office
- DOE Basic Energy Sciences
- Department of Transportation

Power Sources R&D Department

Impact the nation's growing need for energy security, resilience, and assurance while enhancing Sandia's NW mission capability







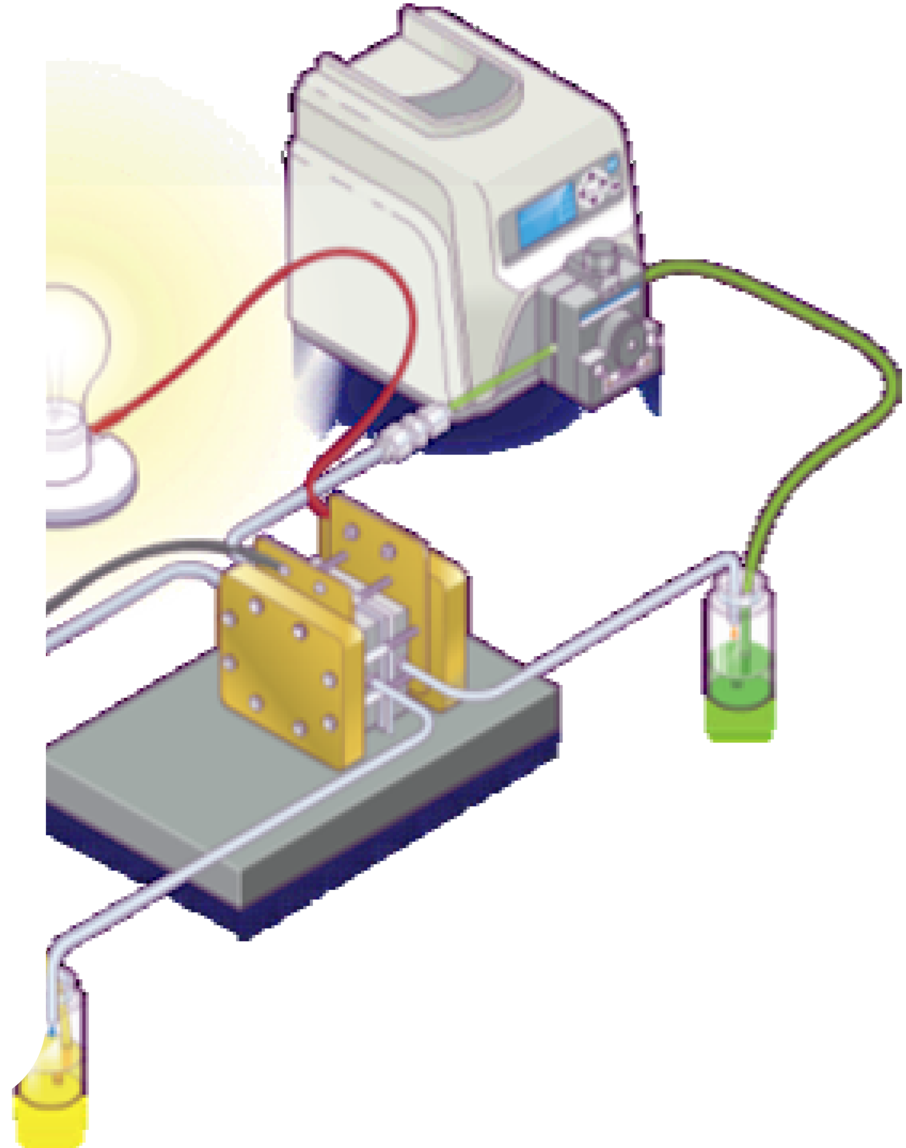
Capabilities

- 10,000 sq. ft. dry room space
- Prototyping for thermal batteries, Li primary, and Li-ion cells and batteries
- Battery design & development
- Performance and abuse testing
- Synthesis of battery materials
- Forensics and analysis
- Fundamental electrochemistry
- Modeling and simulation*
- Environmental testing*
- High hazard test facilities (Burn Site)*

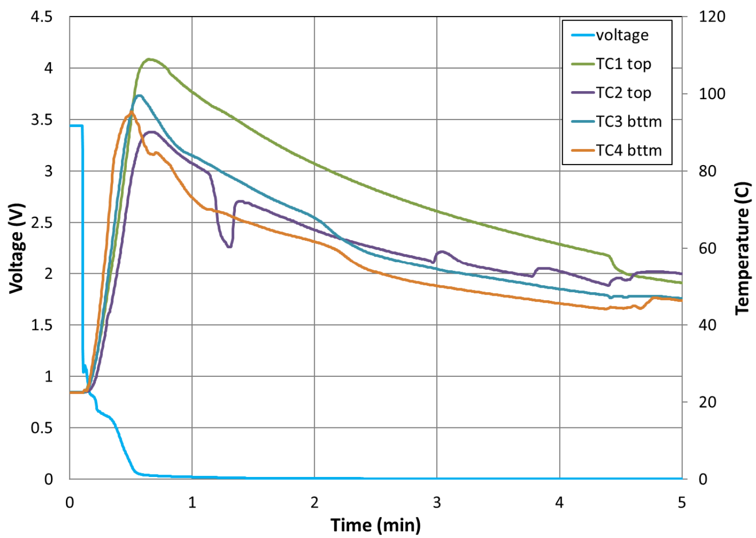
*Facilities leveraged from our Partners in SNL Experimental Sciences Center

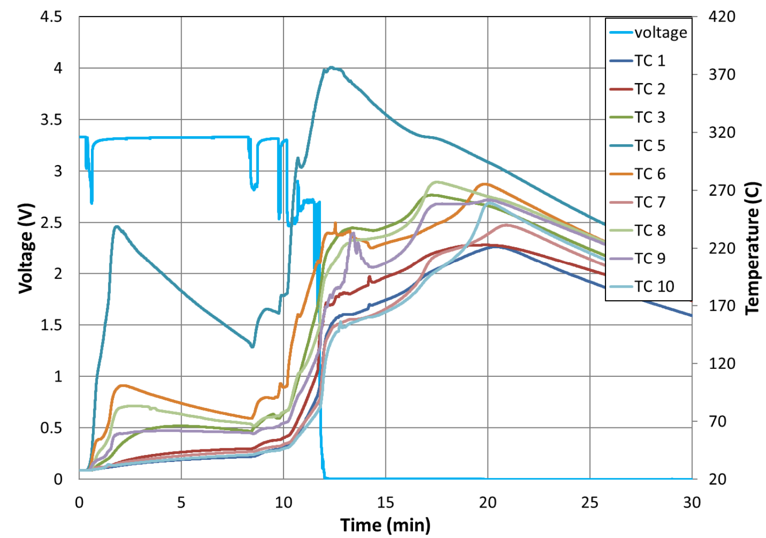
Research and Technology Interests

- Thermal batteries (materials, design, testing, etc.)
- Validated predictive modeling and simulation tools
- Aging phenomenon
- Materials at risk
- Storage, conversion, and harvesting
- Advanced diagnostics for predicting performance and safety
- Battery safety & reliability
- Compact power
- High energy materials
- Solid electrolytes
- Flow batteries
- Sodium batteries



Motivation for propagation testing



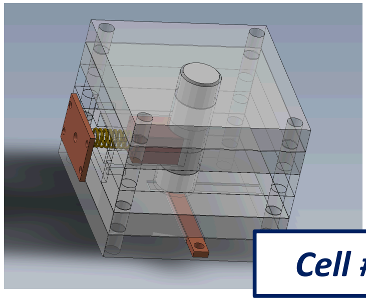


- ***Results of single cell nail penetration and 1S10P propagation test***
- ***26650 LFP cell***
- ***Single cell has relatively minor failure***
- ***Significant increase in intensity with a 10 cell pack***

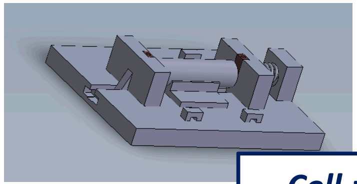
Measuring the impact of electrical connections

- **Failures initiated by mechanical insult to cell 1 which is connected to cell 2 through constantan bridge wire**
- **Development of new testing fixture to increase reproducibility in FY16 (right)**
- **Additional effort to maintain electrical connection with cell 1 after runaway event**
  - **Use of spring on nail to apply opposing force keeping cell from ejecting after runaway (images below)**

Testing Apparatus

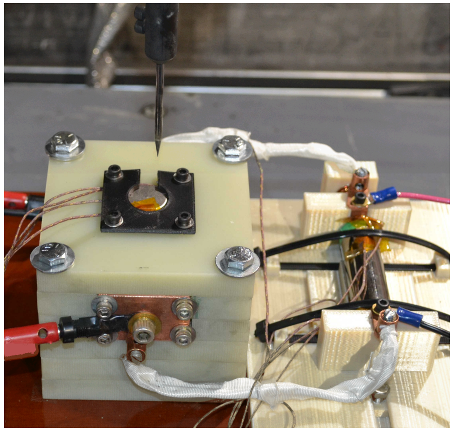


Cell #1 holder

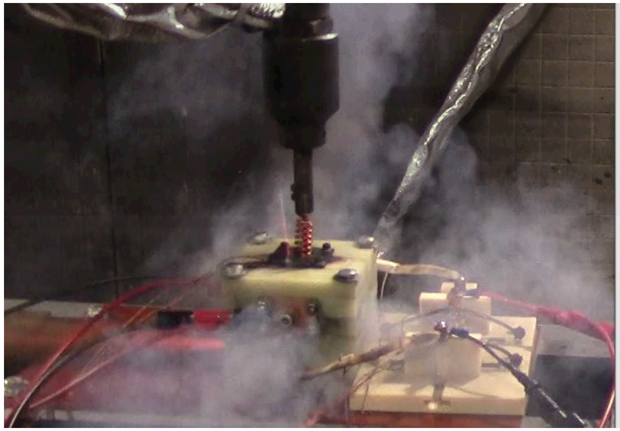


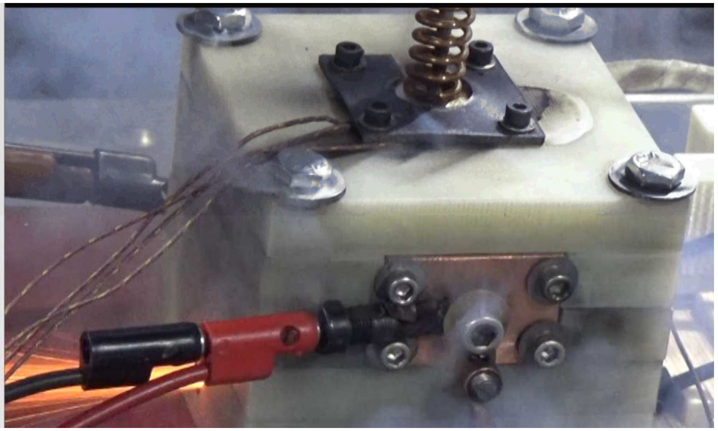
Cell #2 holder

Standard Setup



Improved Mechanical Contact



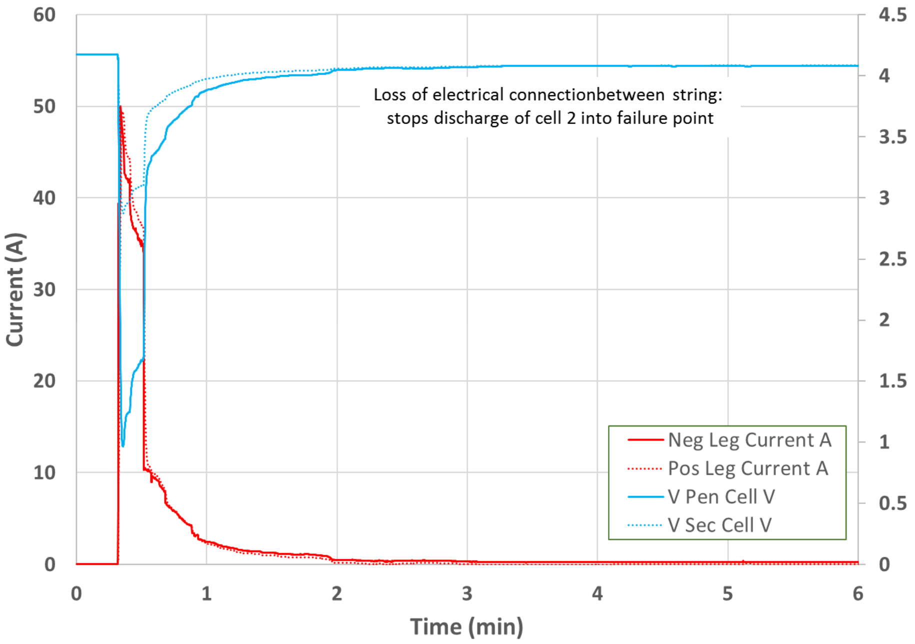


Short Circuit Current During Failure Propagation:NMC

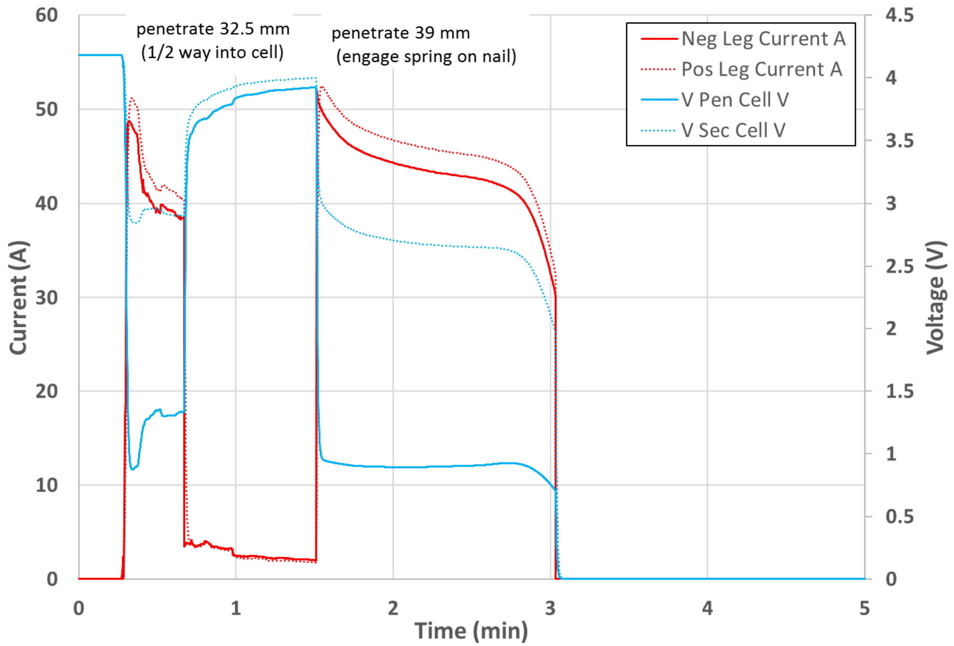
Sandia National Laboratories

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

18650 NMC 3Ah cells – 1s2p



18650 NMC 3Ah cells – 1s2p Improved mechanical contact

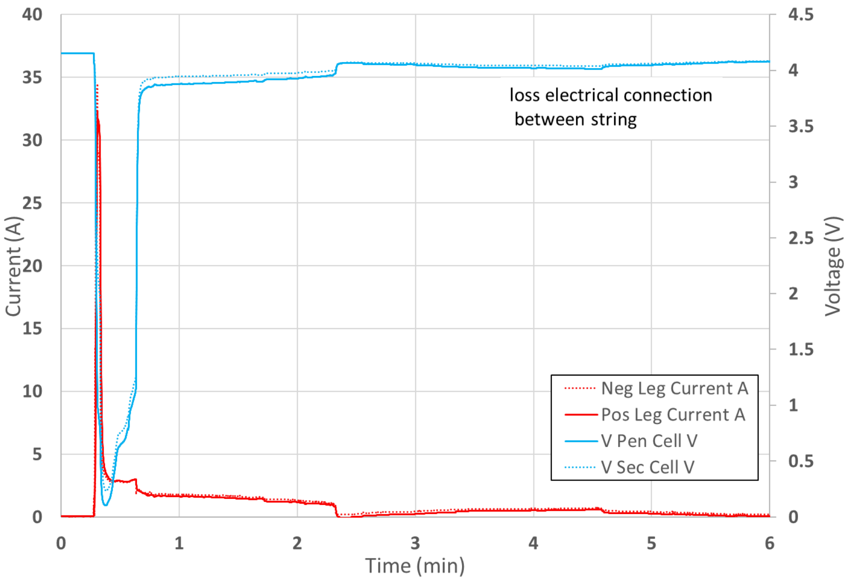


- ***Peak currents across constantan bridge during failure propagation consistent between setups: ~50A***
- ***Total energy discharged into cell 1 varies based on robustness on electrical connection allowing cell 2 to discharge into failure point longer: without spring 0.027 kJ (lost battery connection) and with spring 5.3 kJ***

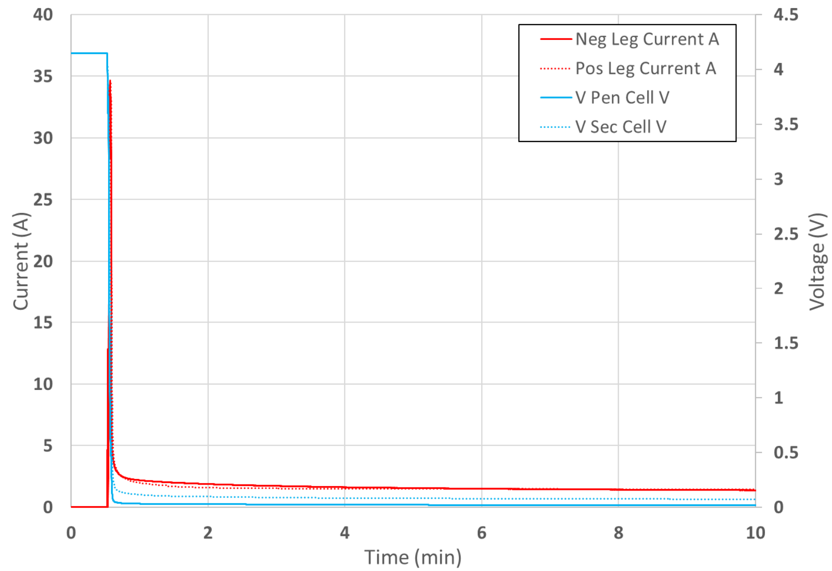
Short Circuit Current During Failure Propagation: NCA

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

18650 NCA 3.1 Ah cells – 1s2p



18650 NCA 3.1 Ah cells – 1s2p improved mechanical contact



- ***Peak currents across constantan bridge during failure propagation consistent between setups: ~35A***
- ***Energy output during discharge varies for two setups: without spring ~0.75kJ and with spring ~0.29 kJ (slow discharge of 1.5 A over 2 hours)***
- ***Cell might contain a safety device making system become resistive during failure***
- ***NCA cell not rated for high discharge currents (max DC is 2C)***

Short Circuit Current During Failure Propagation

Chemistry comparison

Chemistry	Nominal Capacity (Ah)	Max rated discharge current for cell	Peak current during short circuit (A)	Total Energy discharged into Cell 1 (KJ)
LFP (18650)*	1.5	5.6A (3.7C)	37	14.9
LFP (26650)*	2.6	42A (16C)	30	15.0 (av)
$LiCoO_2$ (18650)*	2.2	6.2A (2.8C)	90	2.94 (av)
NMC (18650)	3	20A (6.7C)	80	5.3 (spring), 0.027 (no spring)- lost battery connection
NCA (18650)	3.1	6.2A (2C)	35	0.29 (spring), 0.75 (no spring) *Internal safety device might be preventing an external short current

*testing presented at AMR FY16

- ***Although LFP is a more benign chemistry it is able to sustain a discharge much longer giving a higher total E out during discharge (KJ)***
- ***LFP able to sustain higher currents***
- ***Robustness of connection impacts ability to allow cell 2 to fully discharge into failure point***
- ***NCA has a 2C max discharge current while other cells tested are rated >3C***

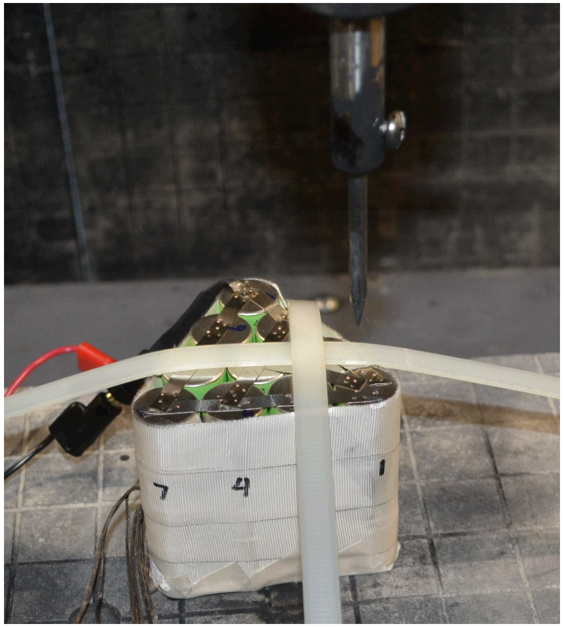
Failure Propagation Testing: Alternative Designs

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)**



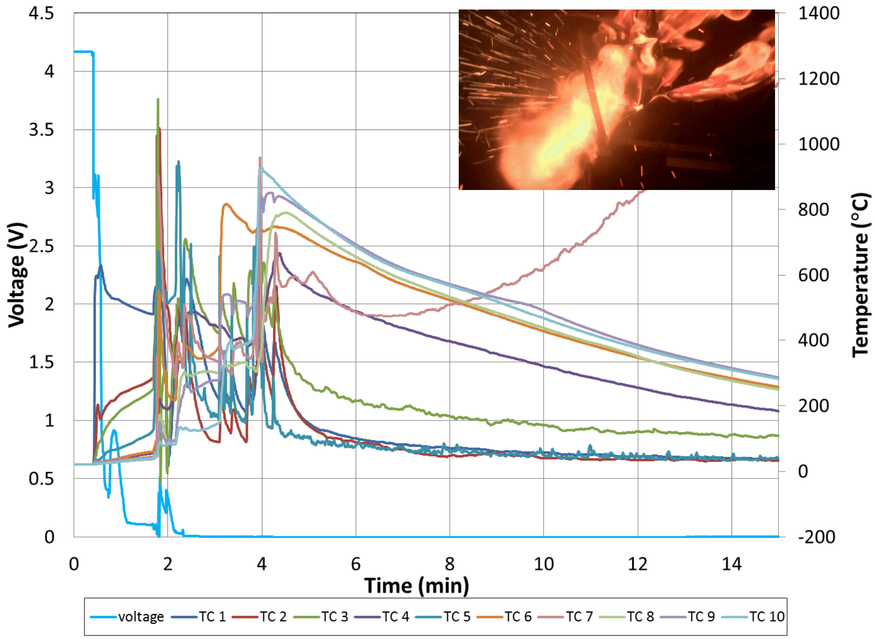
1S10P Battery: Failure point on edge cell

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

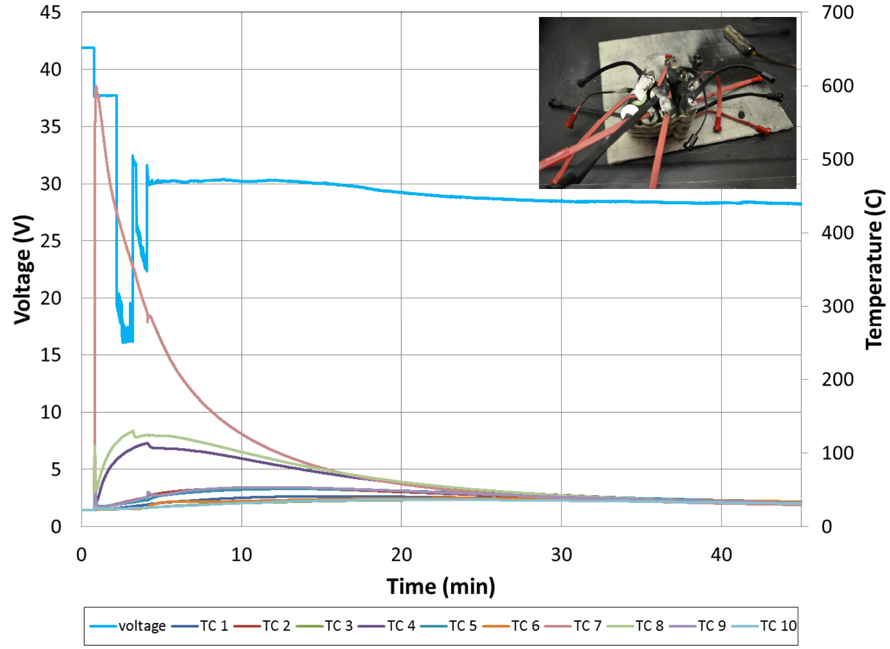
Failure Propagation: Edge Cell Failure

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

$LiCoO_2$ - 1S10P(parallel)



$LiCoO_2$ - 10S1P (series)



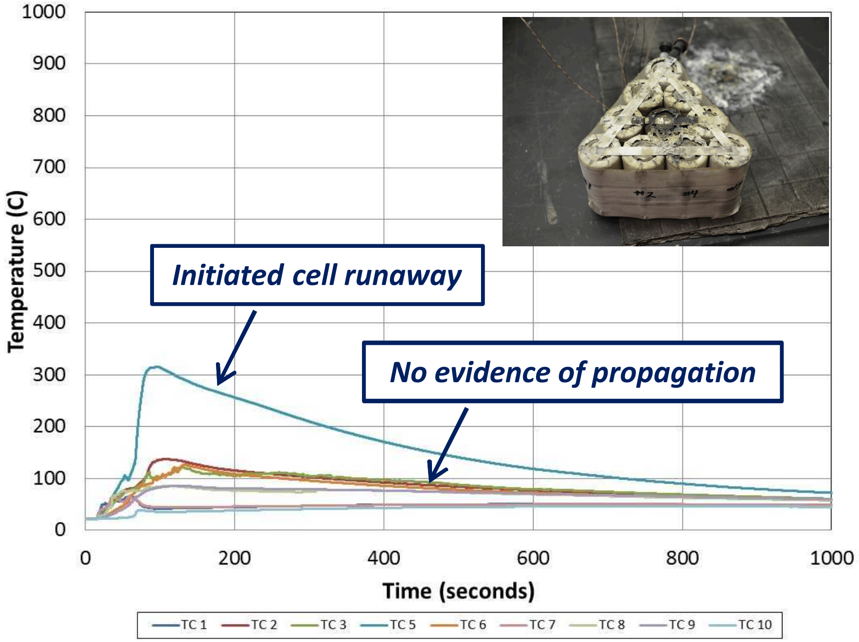
- *Previous testing with center cell failure point in $LiCoO_2$ packs: limited propagation in 10S1P and complete propagation in 1S10P pack*
- ***Edge cell failure: complete propagation for 1S10P and a range of responses for 10S1P: limited (cells next to failure point engaged) to complete propagation***
- ***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)

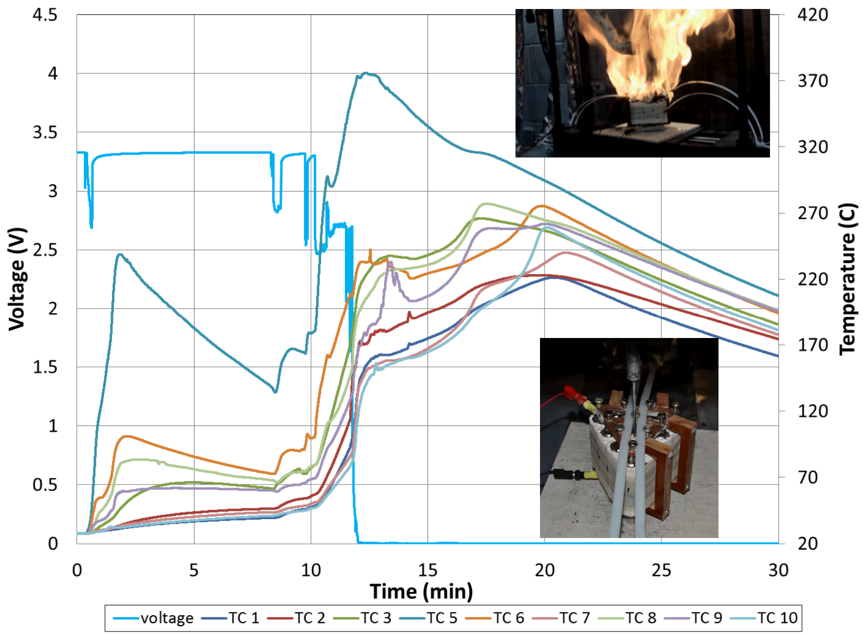
Sandia National Laboratories

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***

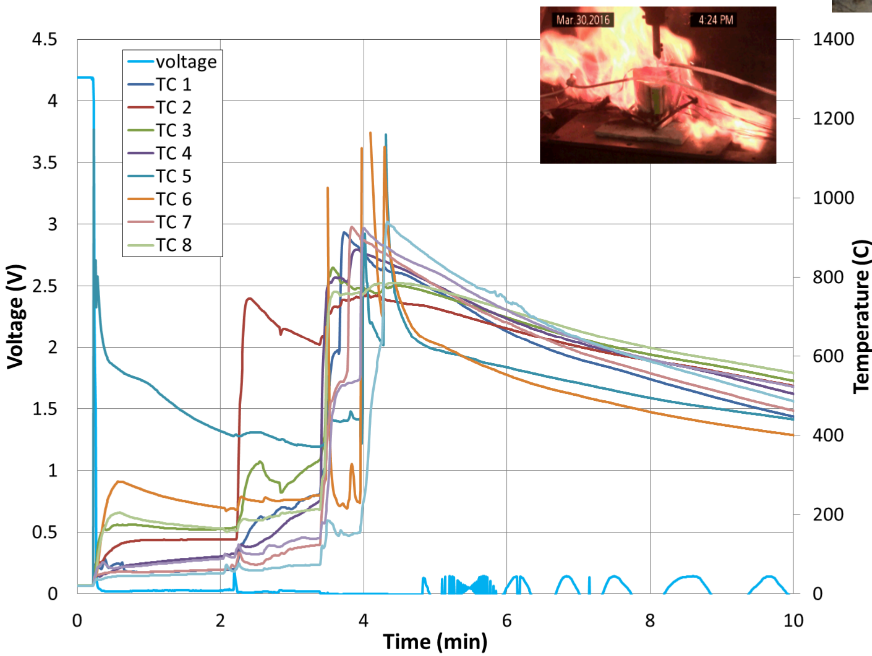
Failure Propagation: Design Effects (Air Gap)

Sandia National Laboratories

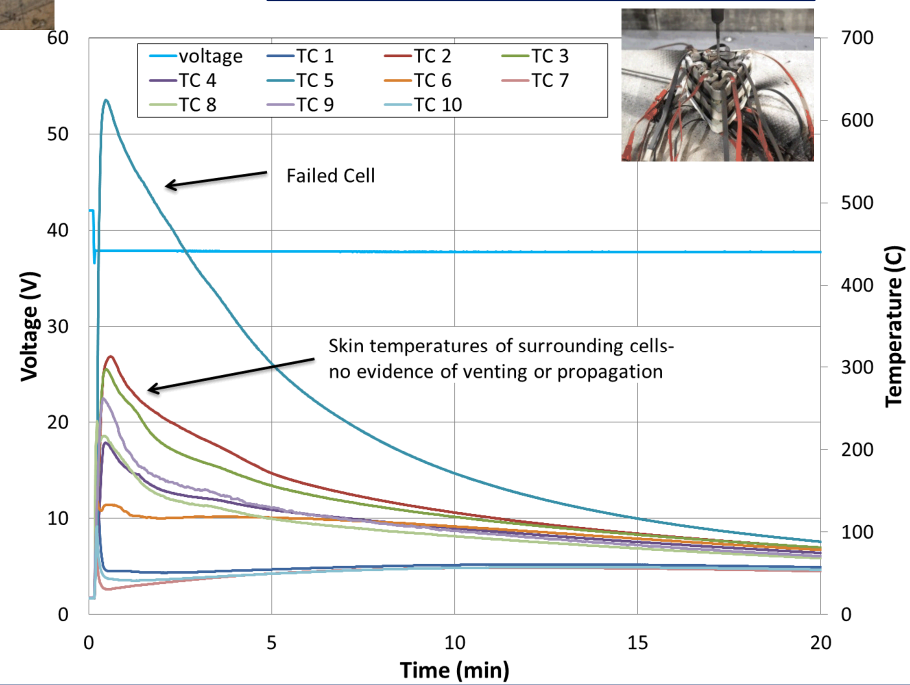
Failures initiated by mechanical insult to the center cell: 2mm air gap between cells

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***

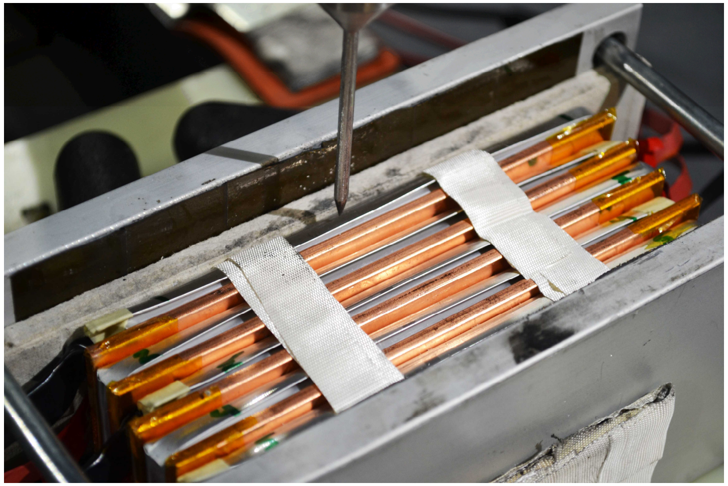
Failure Propagation Testing: Inclusion of Thermal Management

Methodology:

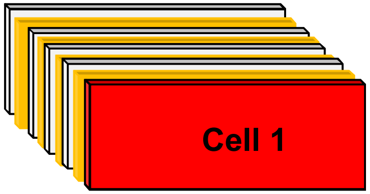
- Experimentally determine a reproducible thermal runaway initiator for each cell type
- Use this initiator to trigger a single cell thermal runaway failure in a battery
- Evaluate the propagation of that failure event

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

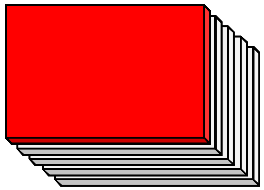


J. Lamb et al. J. Power Sources 283 (2015), 517-523 and C. J. Orendorff et al. SAND2014-17053

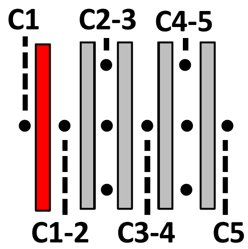
Failure Propagation: No Thermal Management

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

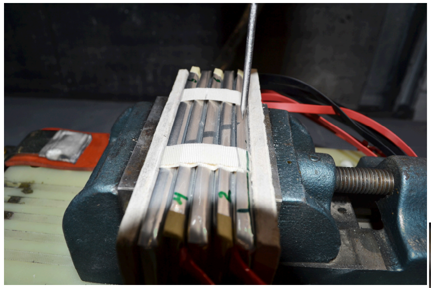
5 cell Battery

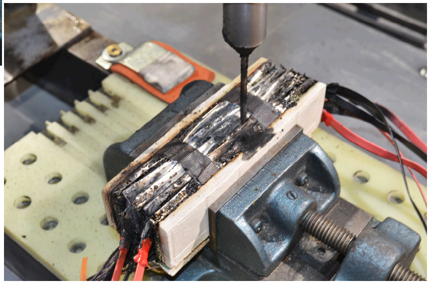


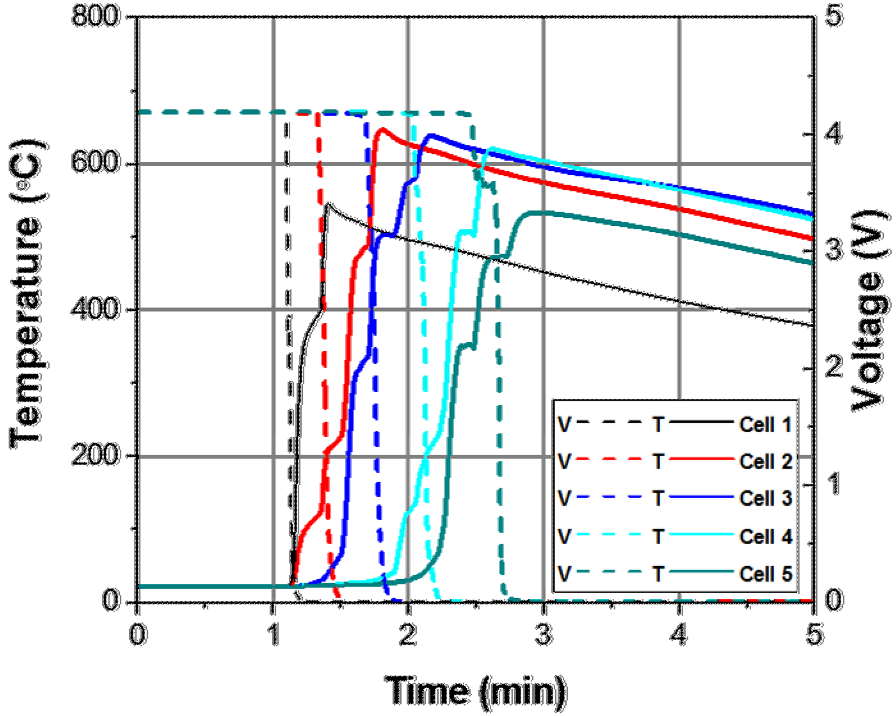
TC layout



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





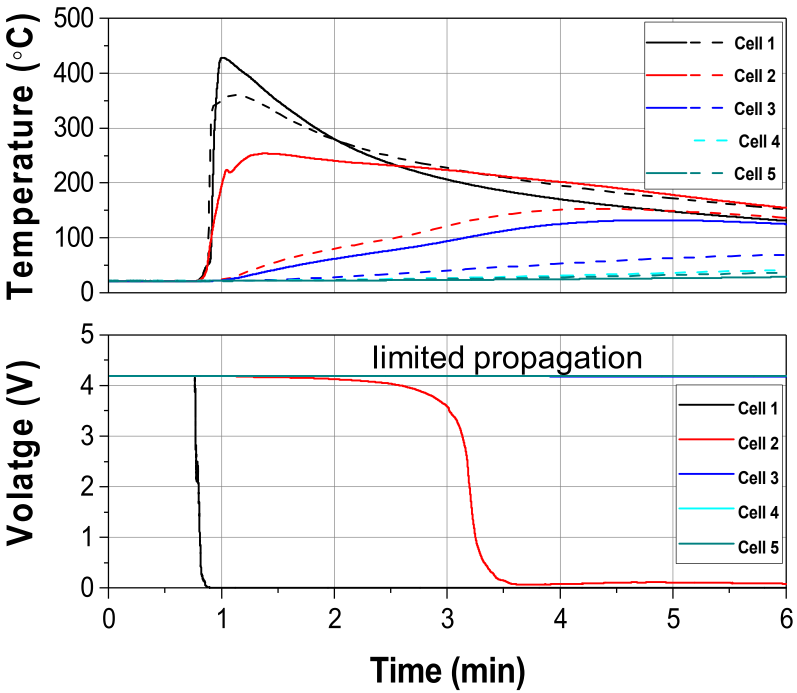


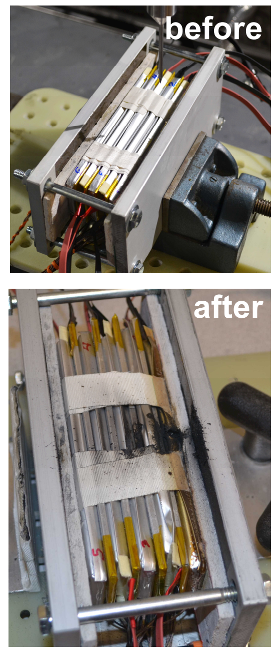
- ***Observed complete propagation when cell are close packed with no thermal management***

Failure Propagation: Aluminum spacer

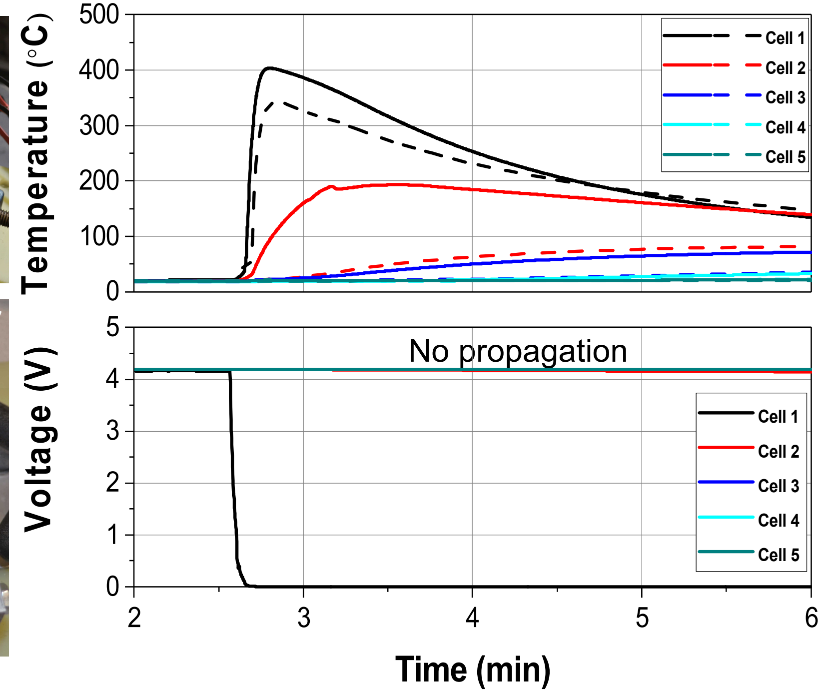
Failures initiated by mechanical insult to edge cell of COTS $LiCoO_2$ packs

$LiCoO_2$ – 1/16" thick spacers





$LiCoO_2$ – 1/8" thick spacers

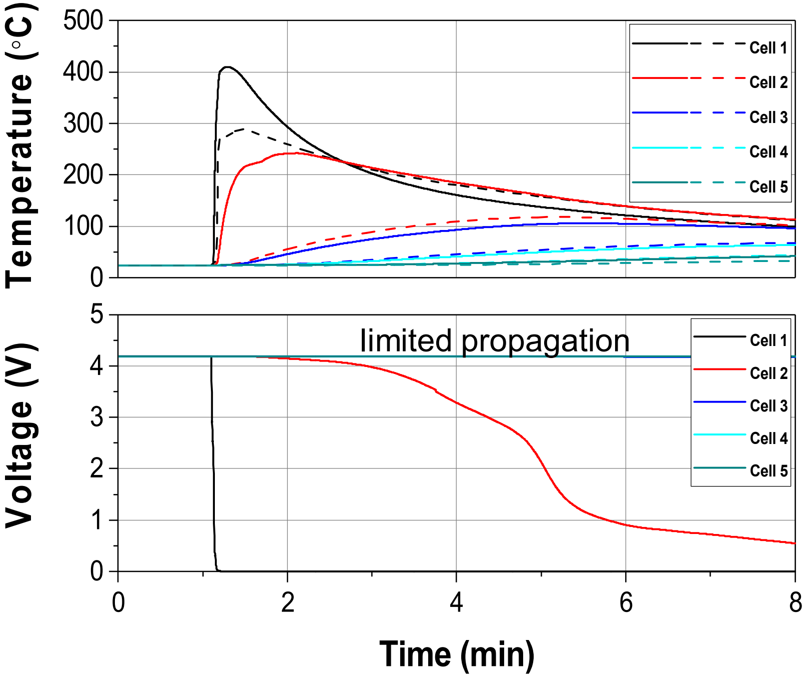


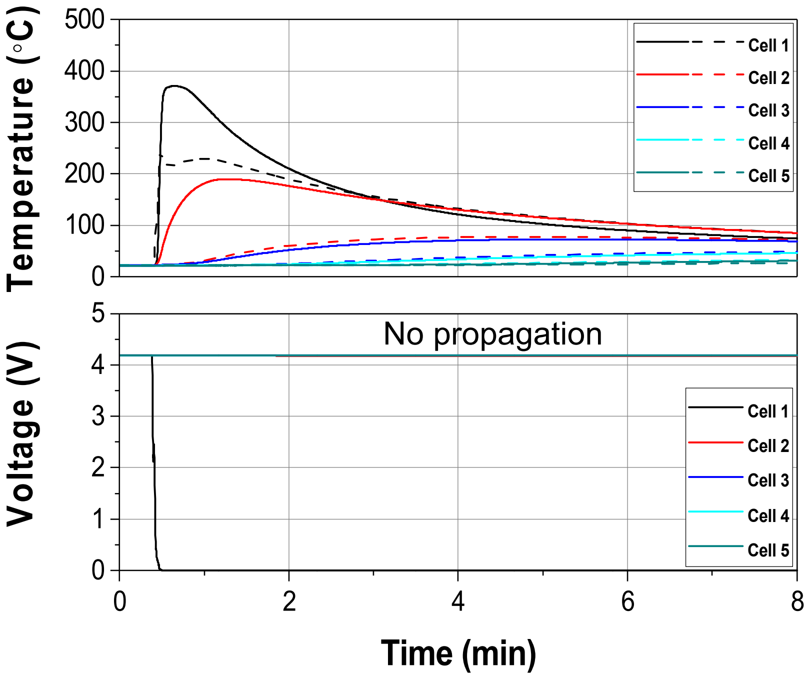
- ***Addition of aluminum spacers cut to the size of 3 Ah COTS cells was achieved***
- ***Failure of cell 1 in both cases were consistent and peak temperatures reached ~400 °C***
- ***Limited propagation (from cell 1 to 2) occurred with the thinner material (1/16")***
- ***No propagation was realized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

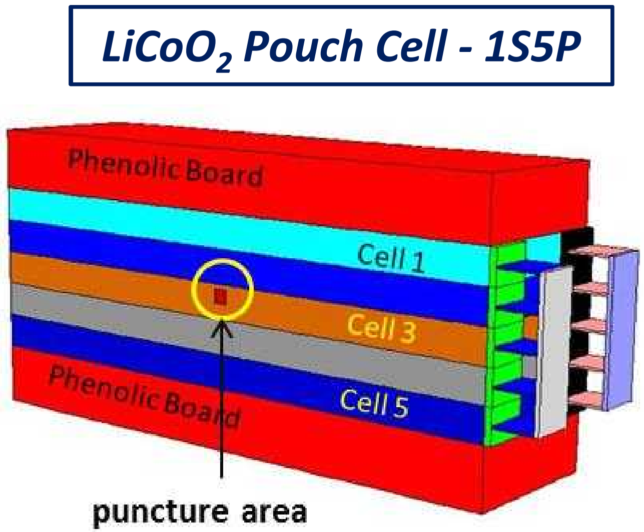


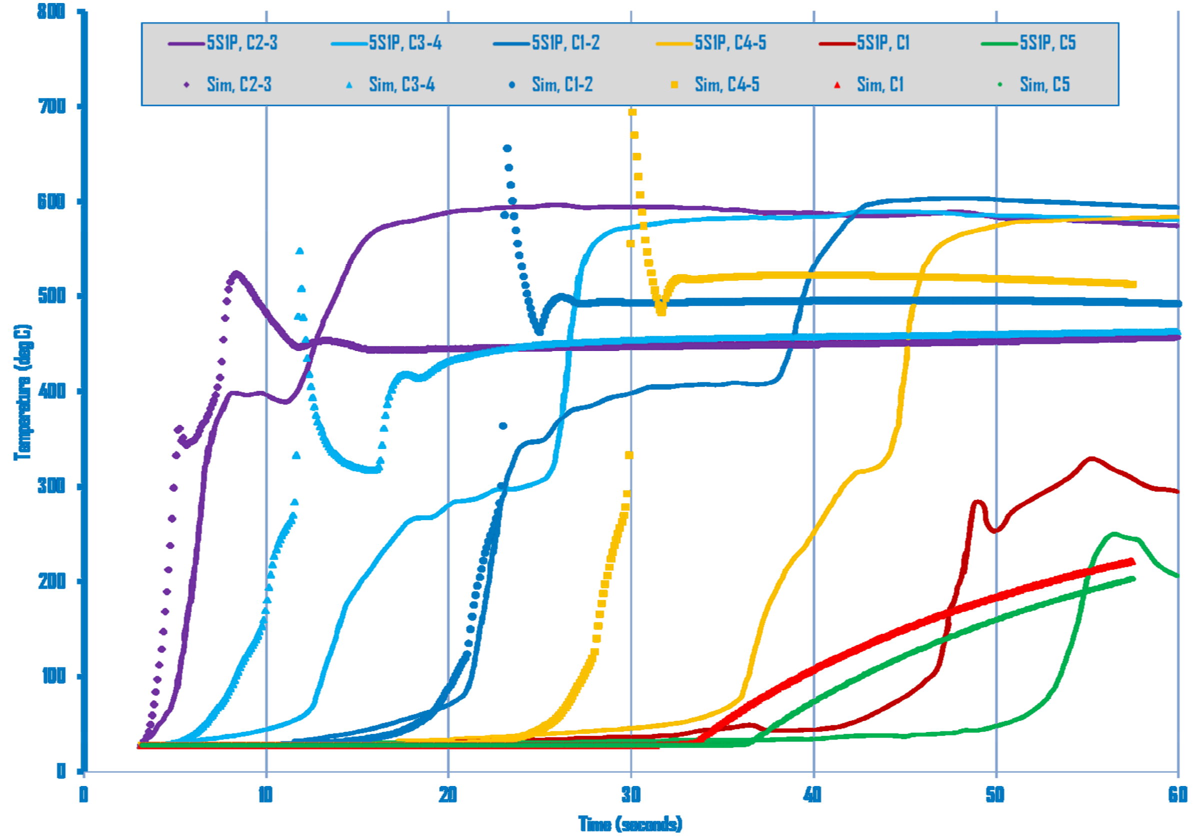


- ***Addition of copper spacers cut to the size of 3 Ah COTS cells was achieved for comparisons of spacer size and material (Al vs Cu)***
- ***Failure of cell 1 in all cases were consistent and peak temperatures reached ~400 °C***
- ***Limited propagation (from cell 1 to 2) occurred with the thinner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

Failure Propagation Model (NREL)

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

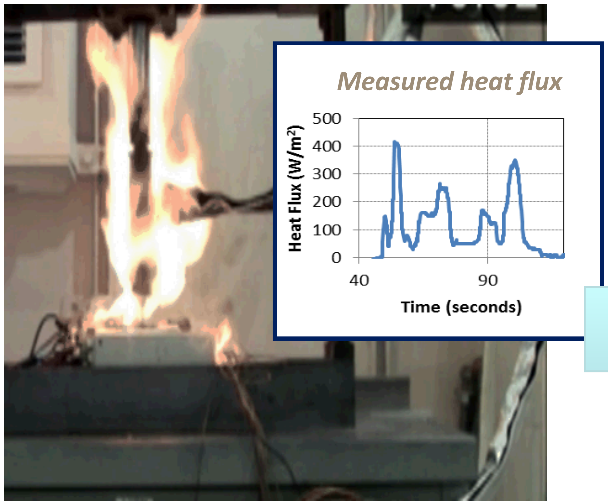




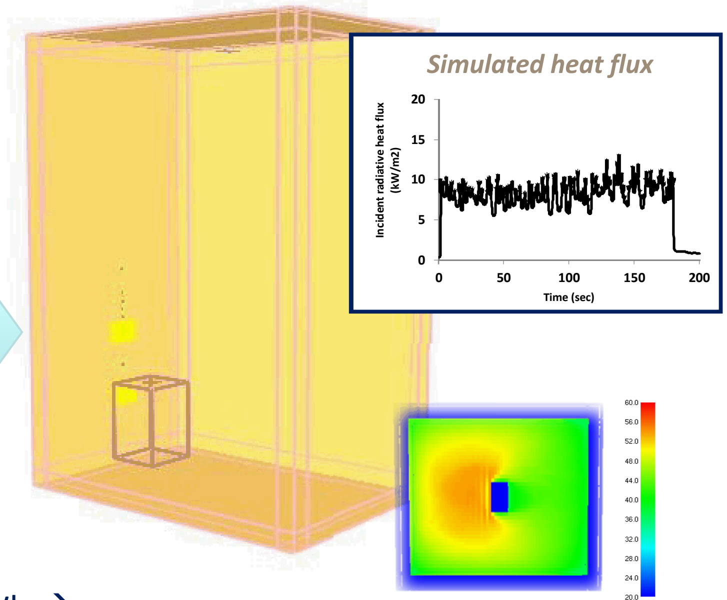
Good agreement in the initial simulations with experiments with some deviation in the long duration events likely due to electrical or connectivity changes within battery over time during the failure event

Quantifying Battery Fires

Experimental Data from Battery Fires



Fire Dynamic Simulations (FDS) of Battery Fires



Test bay ceiling temperature

- Scale up experiments to **validate FDS models** (Wh → kWh → MWh)
- Feedback to **design** storage systems
- Inform **fire suppression** system design
- Provide to regulatory agencies (NFPA, IEEE, UL etc.), utility companies, etc.

Discussion

- A cell may exhibit dramatically different failure response when in a string, module or pack than during single cell abuse testing
- 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

- Phil Gorney (DOT – NHTSA)
- Steve Summers (DOT – NHTSA)
- Dave Howell (DOE)
- Brian Cunningham (VTO)
- Samm Gillard (VTO)
- Jack Deppe (DOE)
- Ahmad Pesaran (NREL)
- Shriram Santhanagopalan (NREL)
- Christopher Orendorff
- Summer Ferreira
- John Hewson
- Kyle Fenton
- Eric Allcorn
- Lorie Davis
- Mani Nagasubramanian
- Jill Langendorf