

Development of a propagating battery failure test

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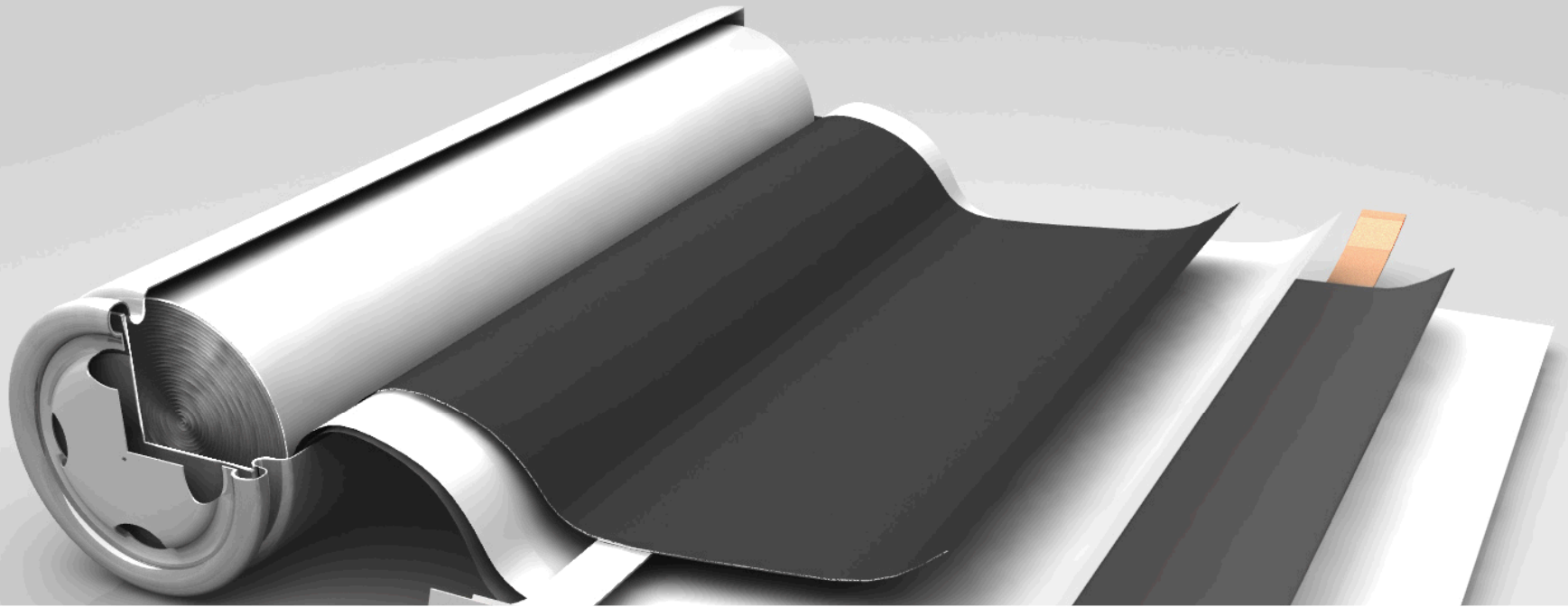
Sandia National Laboratories

The Battery Show

Novi, MI

September 11-14, 2017

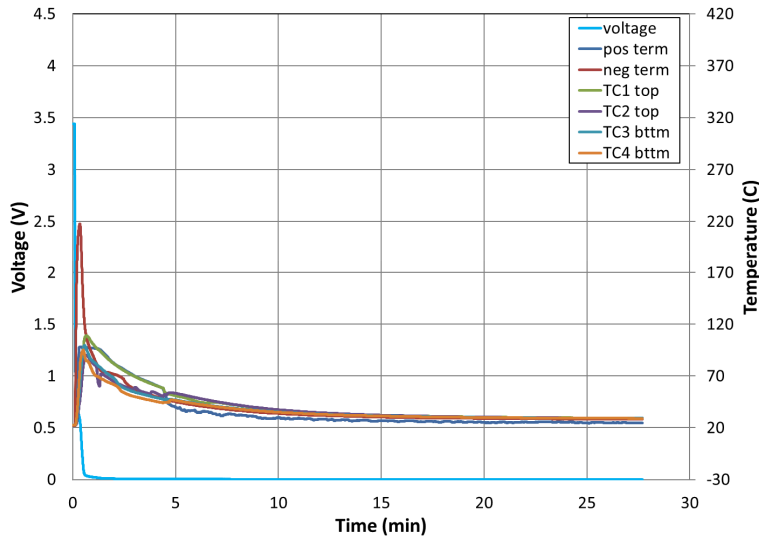
Single vs multi cell testing



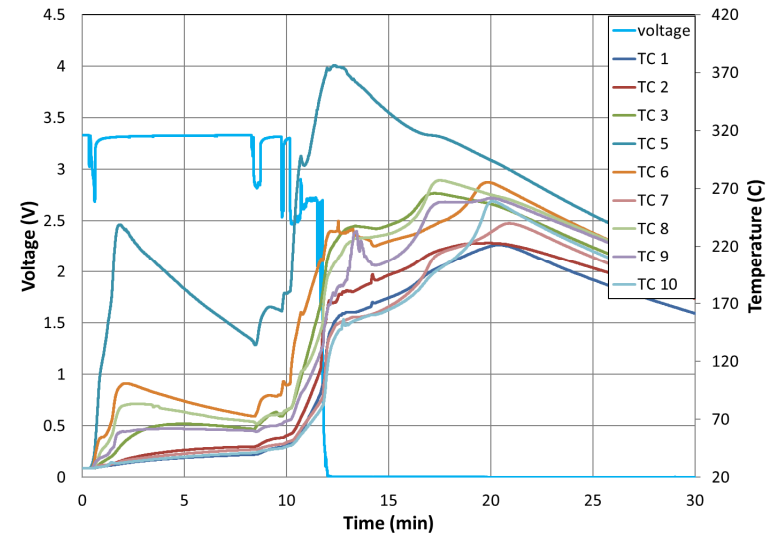
- **Battery safety testing has historically focused on single cell tests**
- **Until the last decade, lithium ion battery use was confined to small consumer electronics items**
- **Impact would be limited to the device and a very small area around it**

Motivation for propagation testing

Single cell



1S10P string

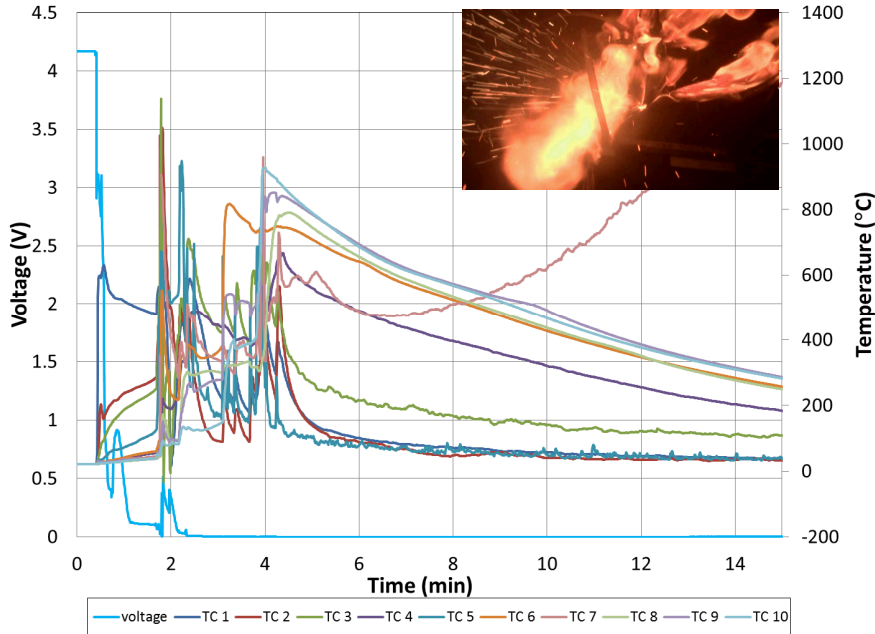


- *Results of single cell nail penetration and 1S10P propagation test*
- *26650 LFP cell*
- *Significant increase in intensity and duration of failure event in string*
- *The most basic principle of propagating failure tests is that single cells performance is not necessarily indicative of multi-cell performance*

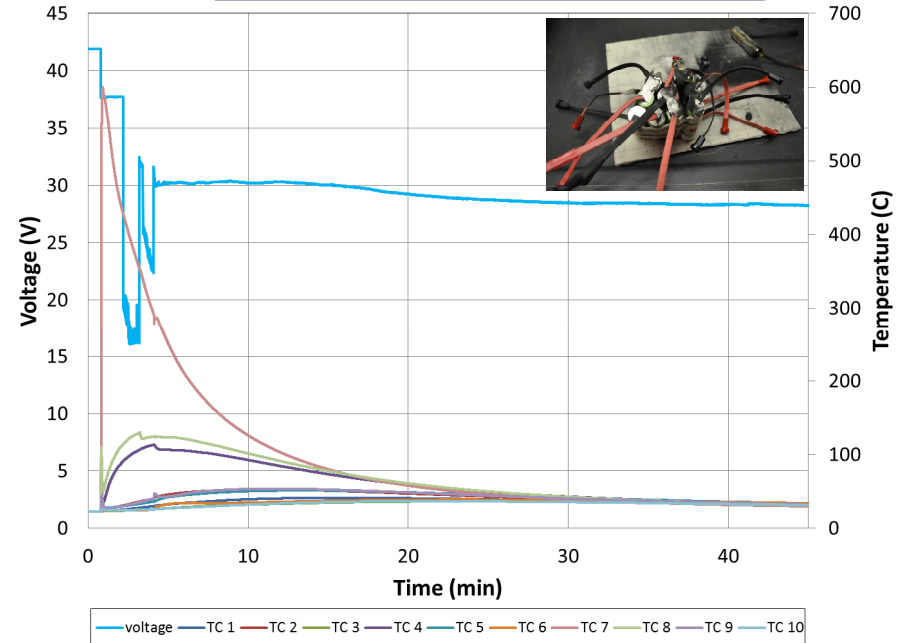
Electrical configuration impact – cylindrical cells

Failures initiated by mechanical insult to edge cell of parallel and series COTS LiCoO₂ packs

LiCoO₂ - 1S10P(parallel)

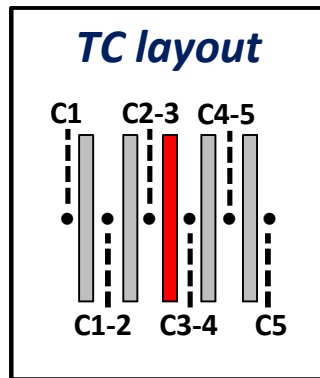
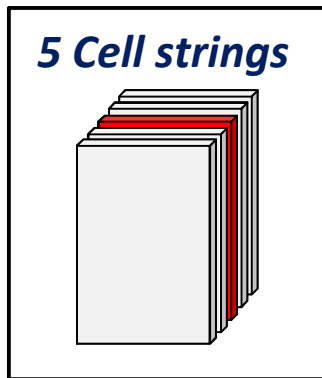


LiCoO₂ - 10S1P (series)

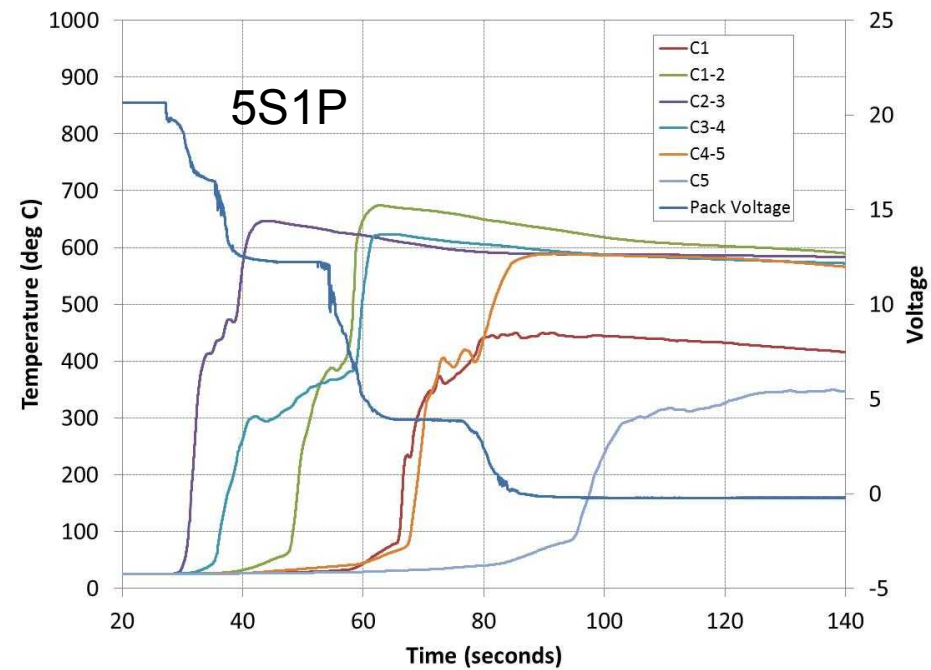
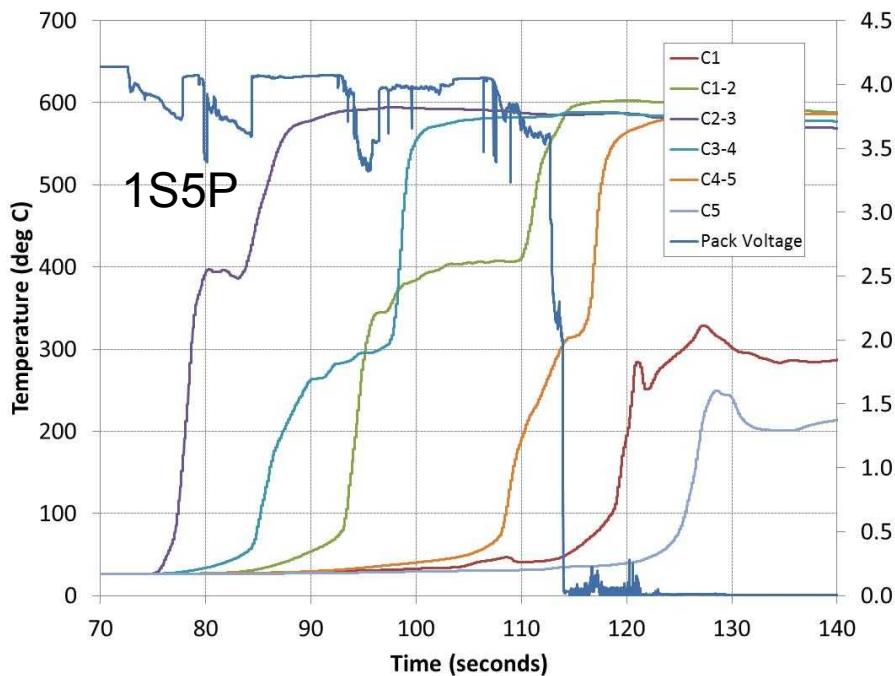


- *Previous testing with center cell failure point in LiCoO₂ packs: limited propagation in 10S1P and complete propagation in 1S10P pack*
- *Edge cell failure: complete propagation for 1S10P and a range of responses for 10S1P: limited (cells next to failure point engaged) to complete propagation*
- *Variation also seen depending on location of cell failure*

Electrical configuration impact – pouch cells



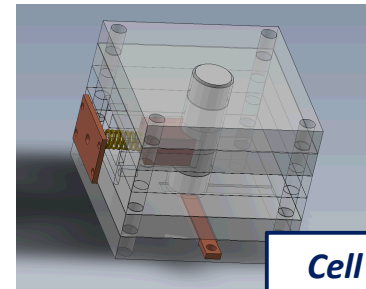
- *5 cell LCO strings*
- *Similar failure time and intensity observed in both configurations*
- *Strong thermal contact between cells controls impact*



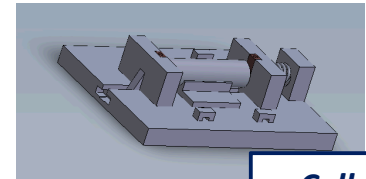
Measuring the impact of electrical connections

- 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

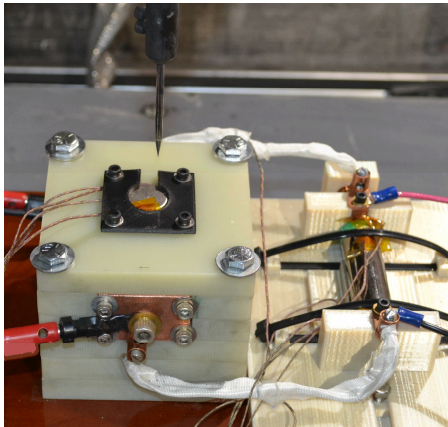


Cell #1 holder

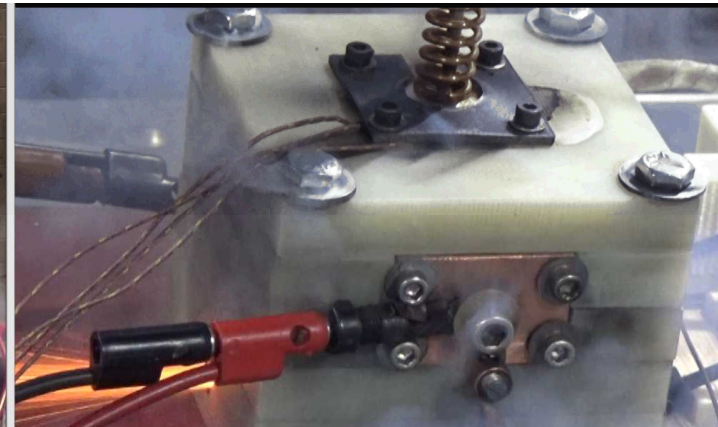
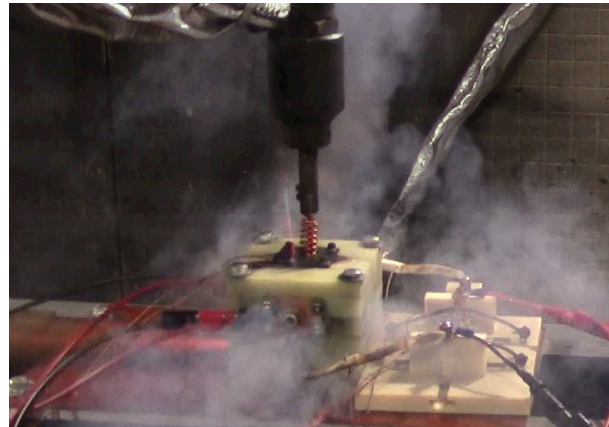


Cell #2 holder

Standard Setup



Improved Mechanical Contact



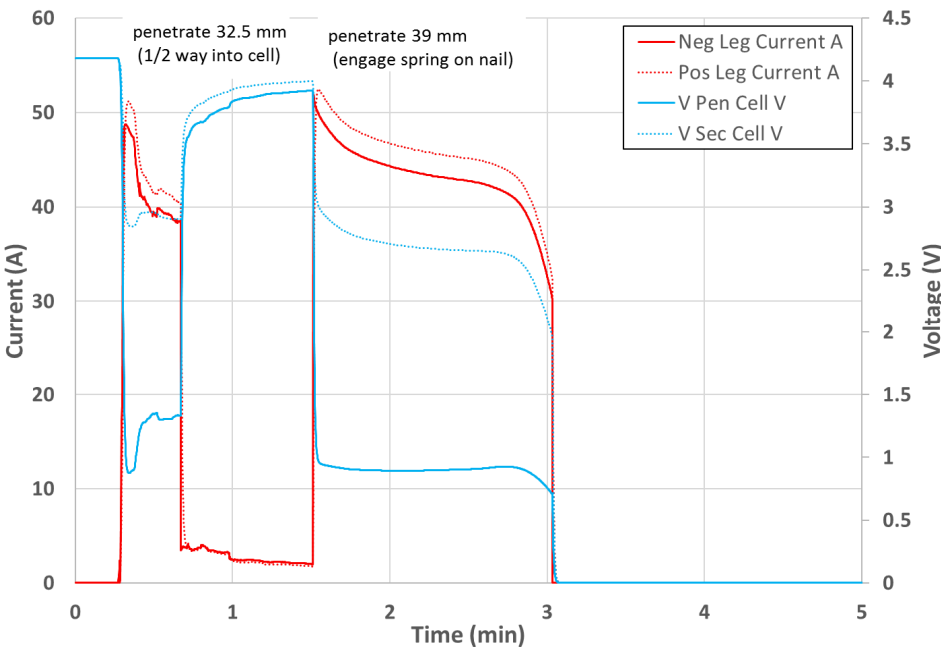
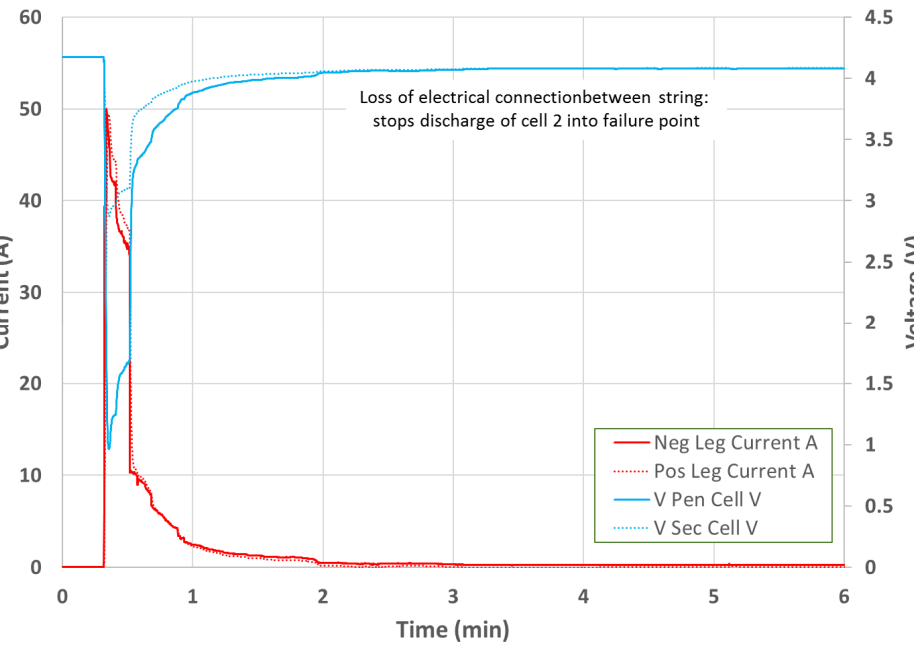
Short Circuit Current During Failure Propagation:NMC



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

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) <small>*Internal safety device might be preventing an external short current</small>

*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**

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 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)**

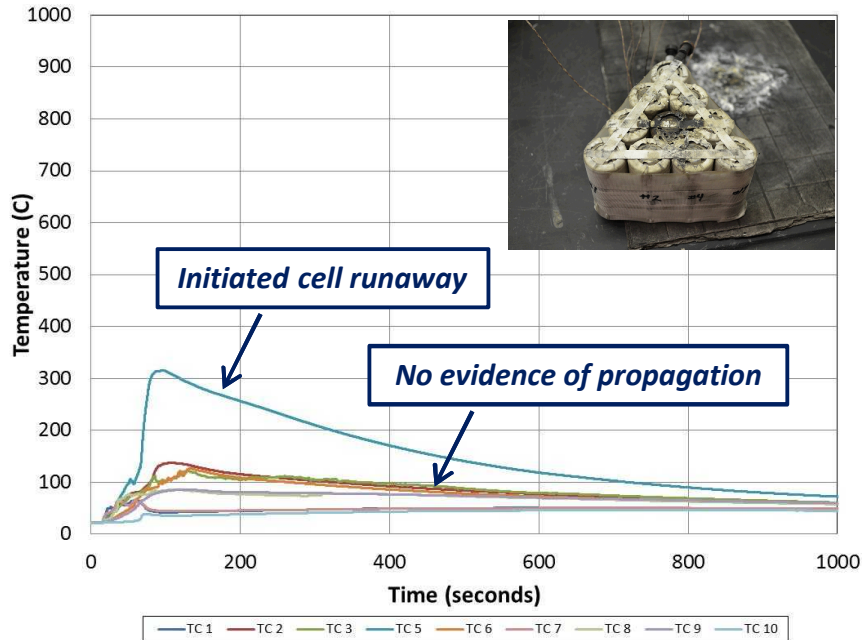


1S10P Battery: Failure point on edge cell

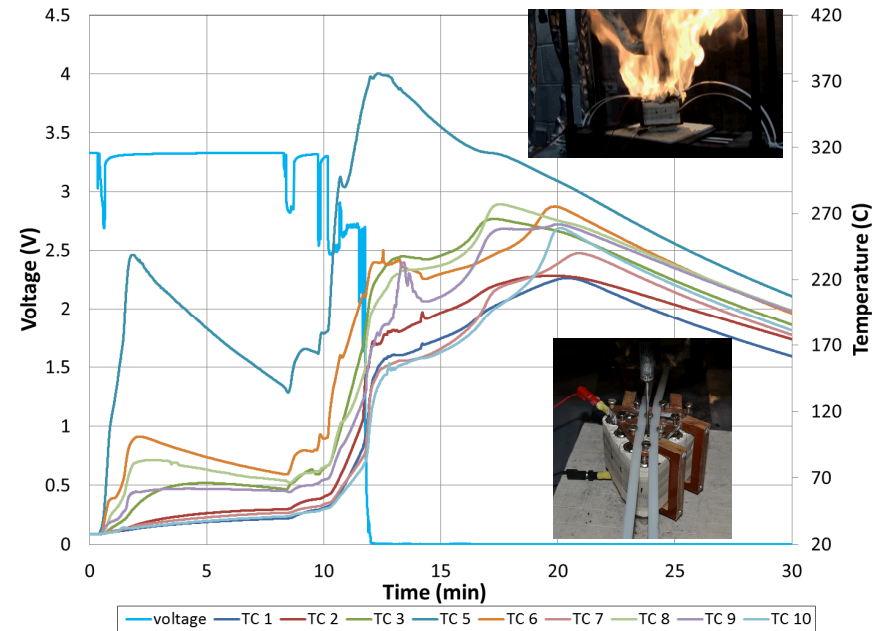
Failure Propagation: Design Effects (Connections)

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

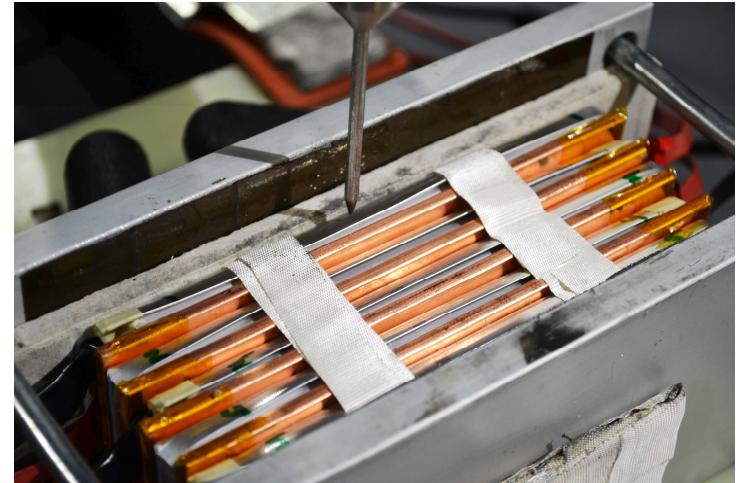
Failure Propagation Testing: Inclusion of Thermal Management

Methodology:

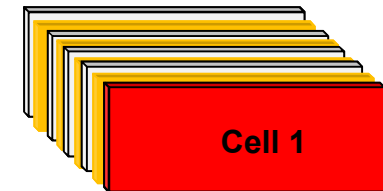
- Experimentally determine a reproducible thermal runaway initiator for each cell type
- Use this initiator to trigger a single cell thermal runaway failure in a battery
- Evaluate the propagation of that failure event

Experiment

- COTS LiCoO₂ 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)**

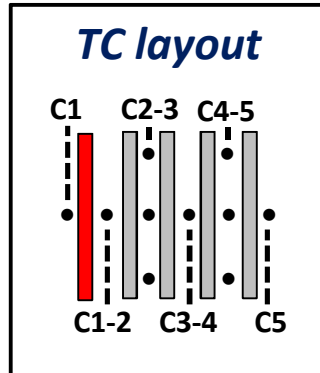
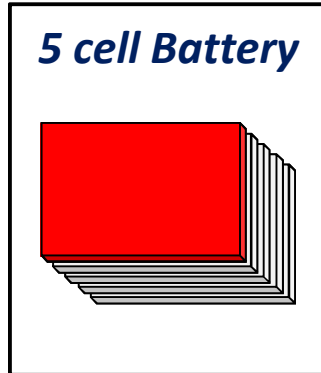


5 cell pack with aluminum or copper spacers between cells

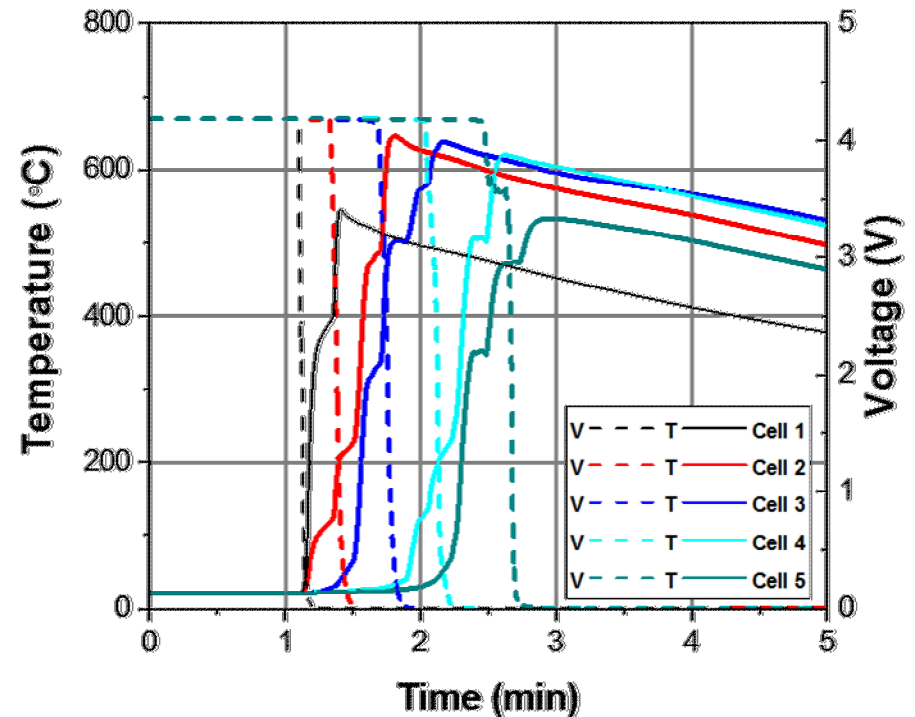
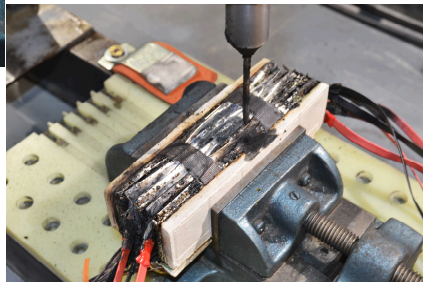
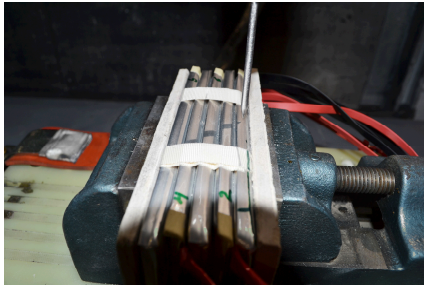


Failure Propagation: No Thermal Management

Failures initiated by mechanical insult to edge cell of COTS LiCoO₂ packs (3Ah cells)



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

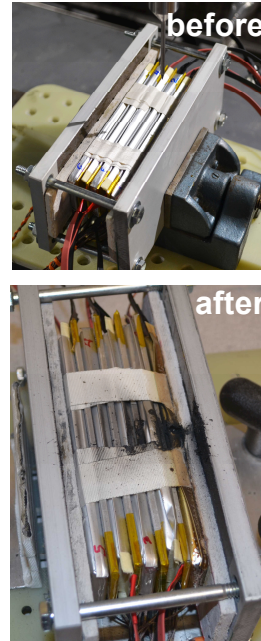
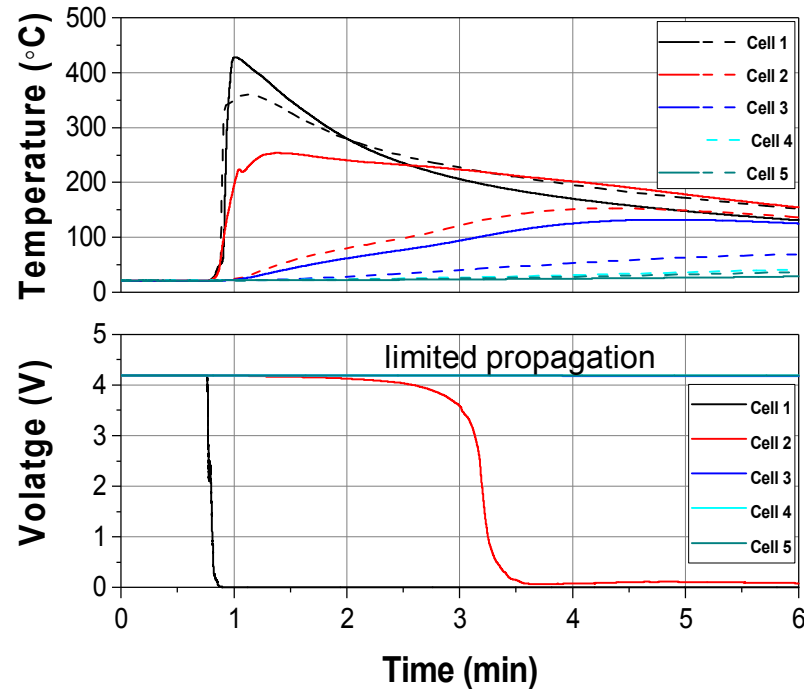


- **Observed complete propagation when cell are close packed with no thermal management**

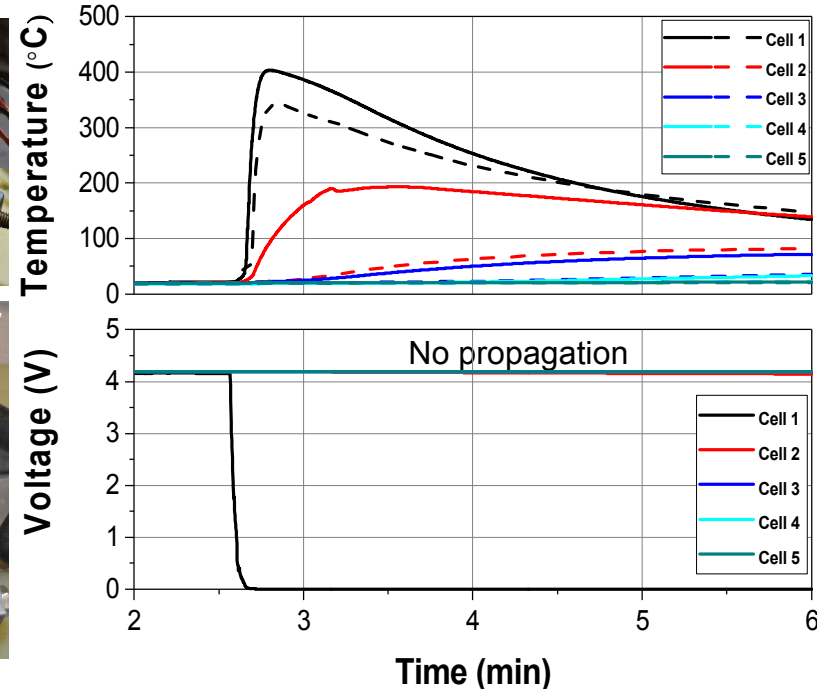
Failure Propagation: Aluminum spacer

Failures initiated by mechanical insult to edge cell of COTS LiCoO₂ packs

LiCoO₂ – 1/16" thick spacers



LiCoO₂ – 1/8" thick spacers

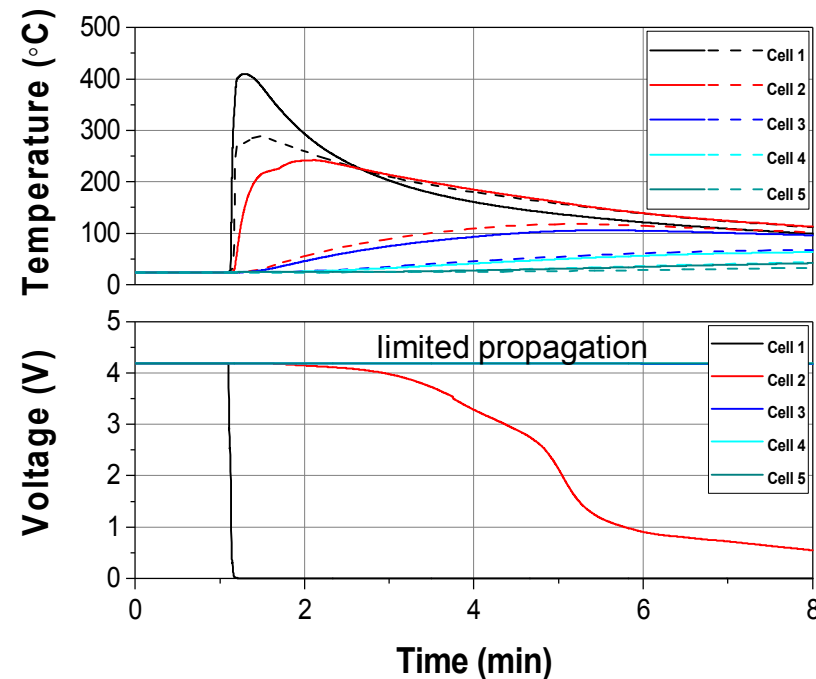


- *Addition of aluminum spacers cut to the size of 3 Ah COTS cells was achieved*
- *Failure of cell 1 in both cases were consistent and peak temperatures reached ~400 °C*
- *Limited propagation (from cell 1 to 2) occurred with the thinner material (1/16")*
- *No propagation was realized when space thickness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

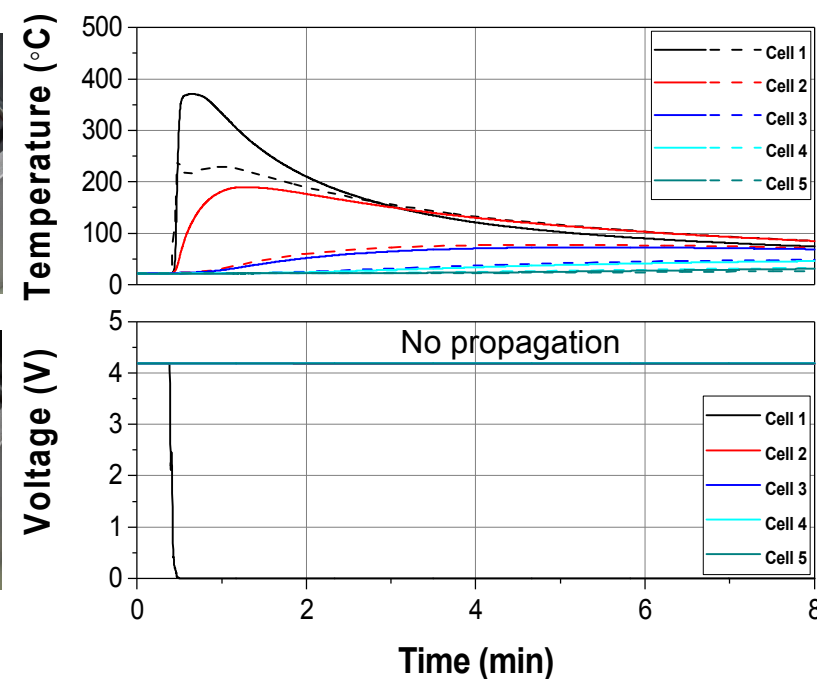
Failure Propagation: Copper spacer

Failures initiated by mechanical insult to edge cell of COTS LiCoO₂ packs

LiCoO₂ – 1/16" thick spacers



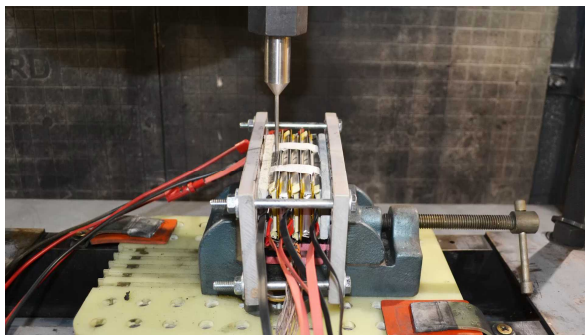
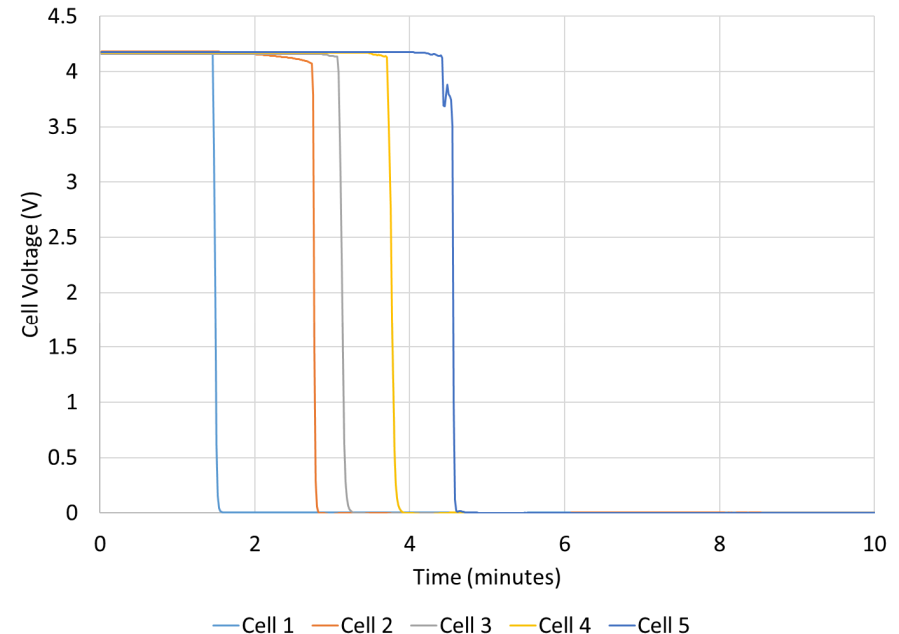
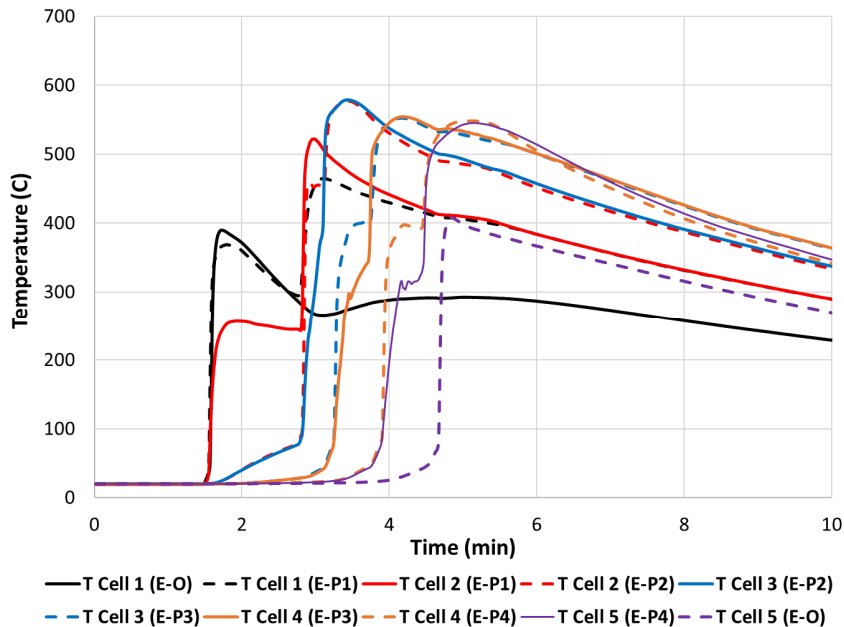
LiCoO₂ – 1/8" thick spacers



- *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 – copper spacer

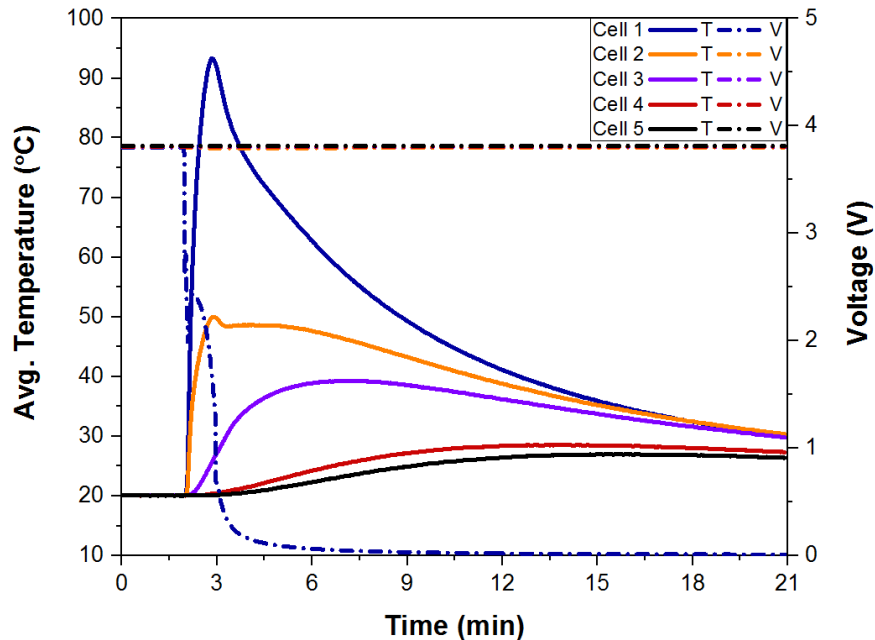
LiCoO₂ – 1/32" thick spacers



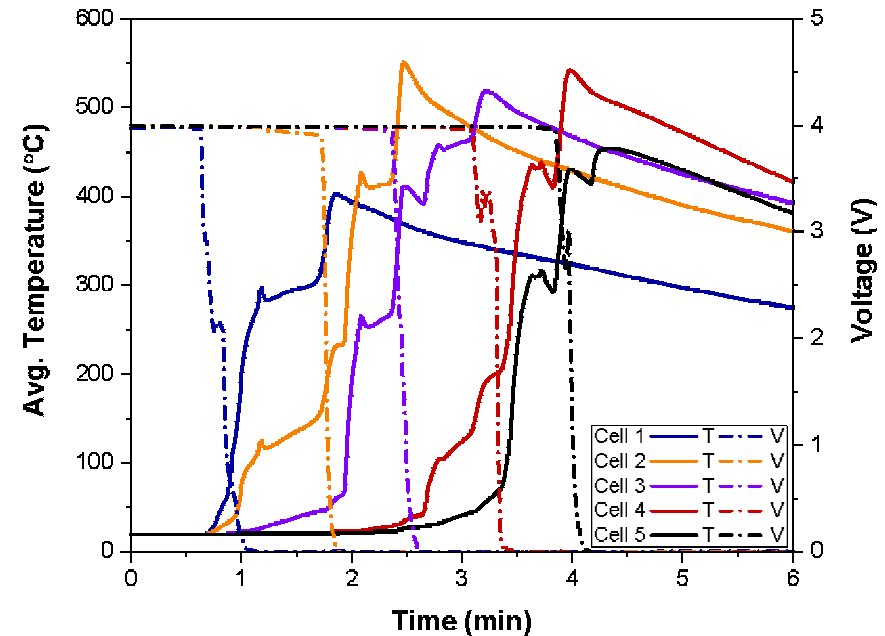
- *Aluminum spacers 1/32" thick*
- *Failure of Cell 1 observed initially*
- *Pulsing propagating failure behavior observed over the next several minutes*
- *Entire pack consumed ~4 minutes after initial cell failure*

50% vs 80% Pouch cell propagation

Cells at 50% SOC



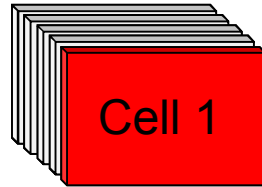
Cells at 80% SOC



- **50% SOC no cell to cell propagation observed**
- **“Pulsing” propagation again observed during failure of 80% pouch pack**
- **Total pack propagation observed after ~4 minutes**
- **80% SOC shows runaway temperatures similar to fully charged single cells**

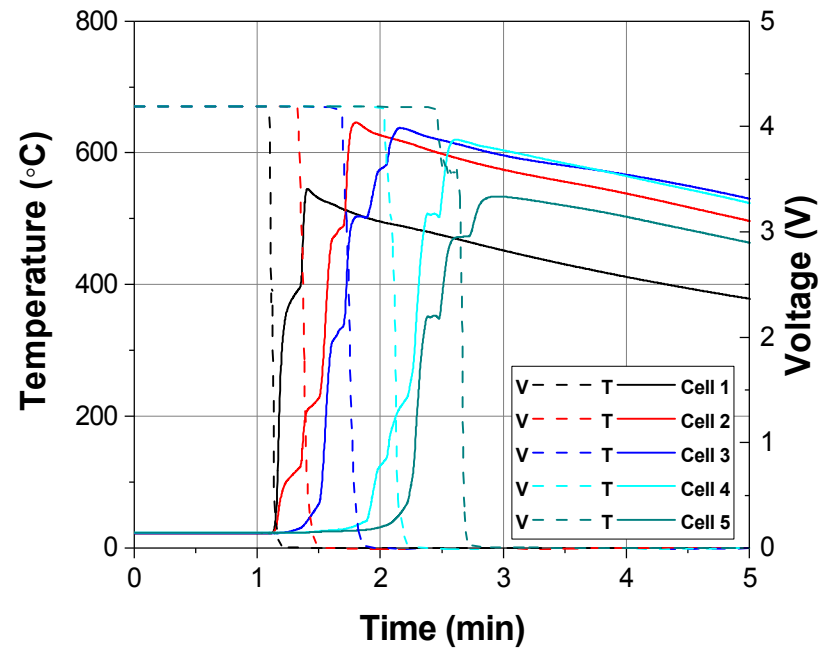
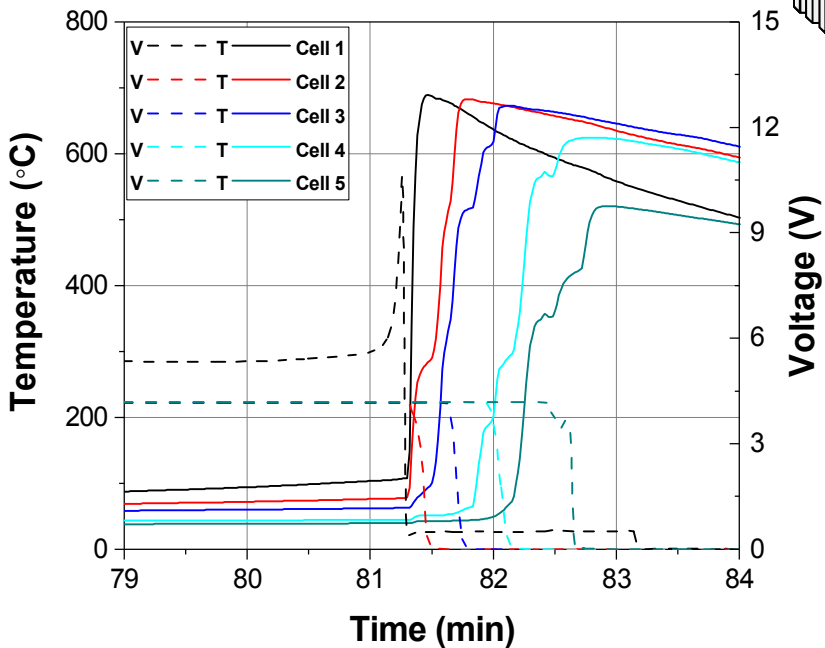
Impact of initiation method

A major outstanding issue with propagation testing is how to initiate runaway of a single cell. Early work compares the initiation of a 5 cell pack with single cell overcharge and nail penetration data; DOT-NHTSA has funded a study to explore this in greater detail (currently underway)



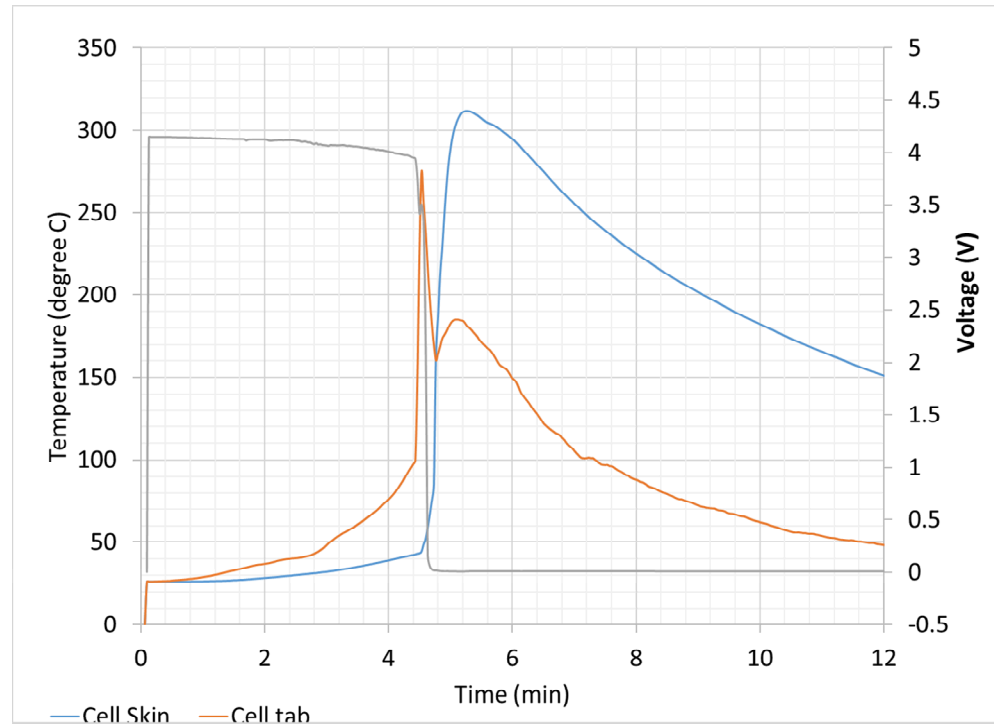
1C overcharge data

Nail penetration data



- *The overcharged cell failure more energetic than in nail penetration (faster heating rate) but did not impact the overall rate of propagation through the pack (in line with nail penetration)*
 - *peak battery temperatures are comparable for both testing methods*
 - *Complete propagation of all 5 cells was realized in both cases*
 - *Total time for propagation was ~1 min for overcharge and 1 min 20 sec for nail penetration*

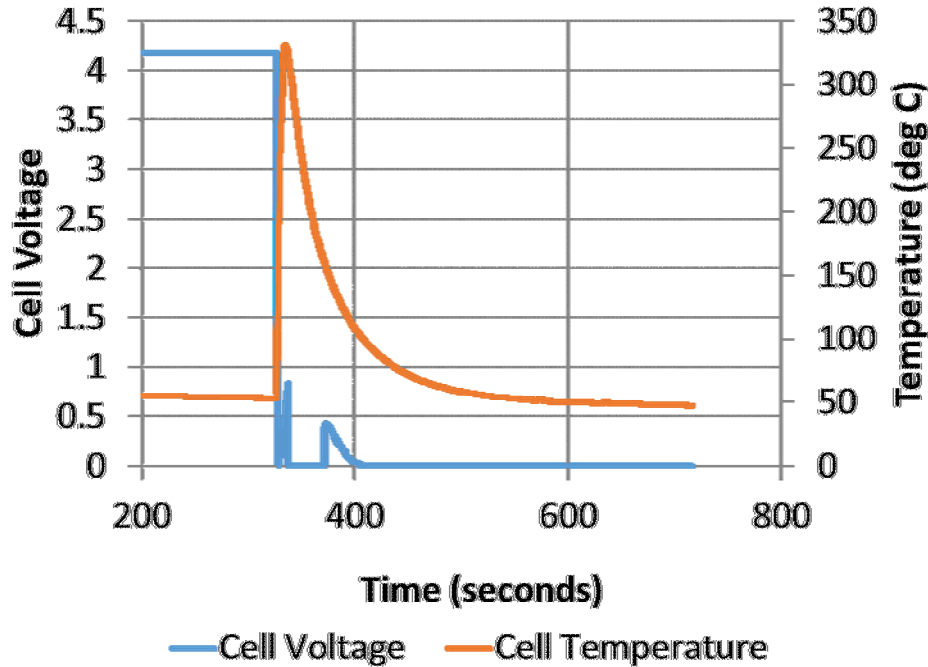
Novel initiation methods- Laser Battery Failure Initiation



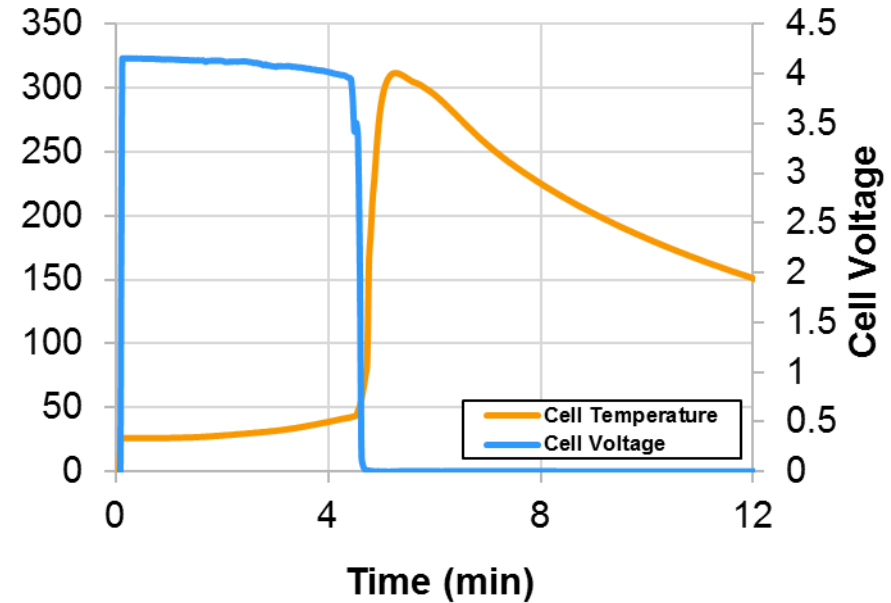
Single cell failure initiated using 40W
pulse laser
~38 J total energy needed for failure
(20 1.9J pulses)

Comparison to Mechanical Data

Nail Penetration Failure



Low Impedance Laser Induced Failure



- Comparison of failure to nail penetration of same model of cell
- Peak temperatures observed are similar, however the nail penetration shows much higher rate of failure after onset

Energy Injection Comparison

Test	Energy Source	Conditions	Estimated Energy
Nail Penetration	Mechanical	20 mm penetration ~200 lb peak load	1.8 J
20 Pulse laser	IR Laser	20 1.9 J pulses	38 J
Undirected light	Quartz lamp	Exposure to light source through aperture	6000 J*
Thermal Ramp	Thermal	Heat to 200 °C	6300 J**
Overcharge	Electrical	1C to 200% SOC	43200 J***

* Based on radiometer measured flux through aperture

** Calculated for hypothetical 40g cell – larger cells will require more energy

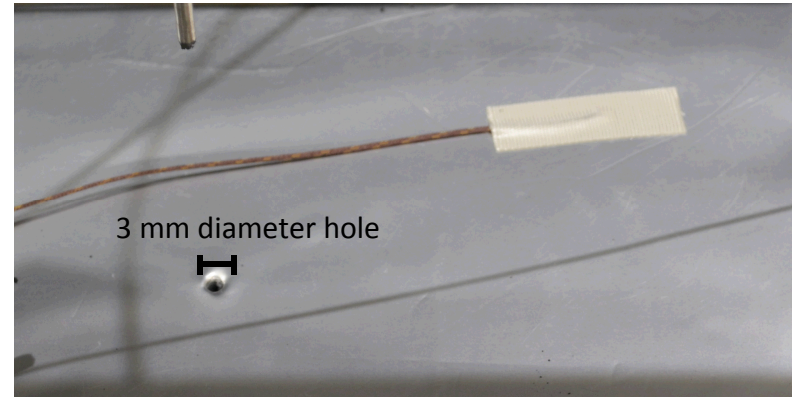
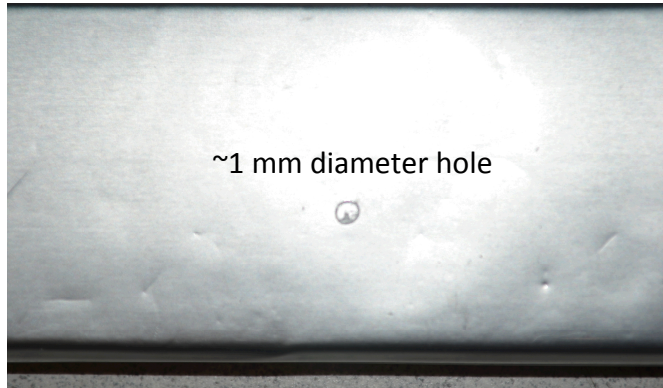
*** Calculated for a hypothetical overcharge at 3 A and 4 V at a 1C rate

Damage comparison: Laser vs. Nail

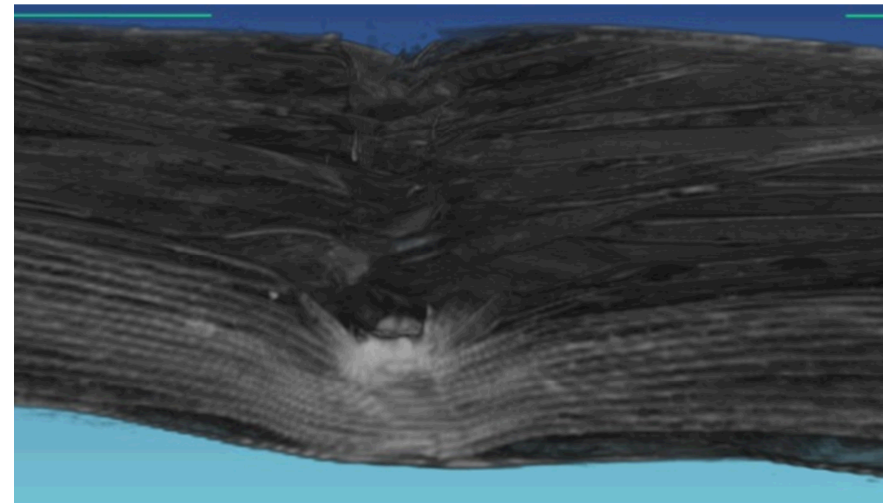
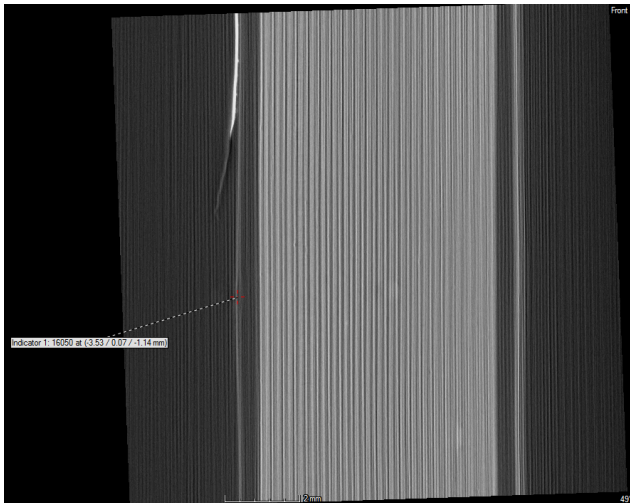
20 Pulse Laser

Blunt Rod

External



Internal



- Nail penetration shows significantly more internal damage.
- Internal damage done by laser initiation is very limited to surface layers.

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.
- A major outstanding issue is how to perform propagation testing on real systems – what is the proper initiation method and what is the desired result of the test?

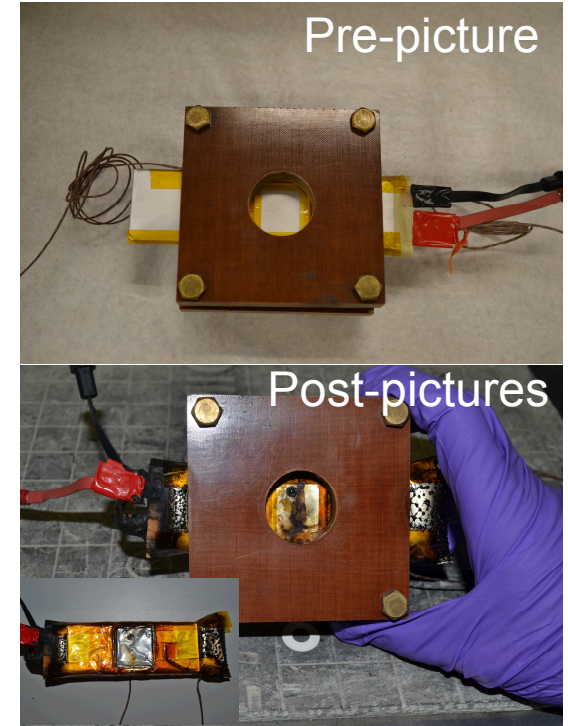
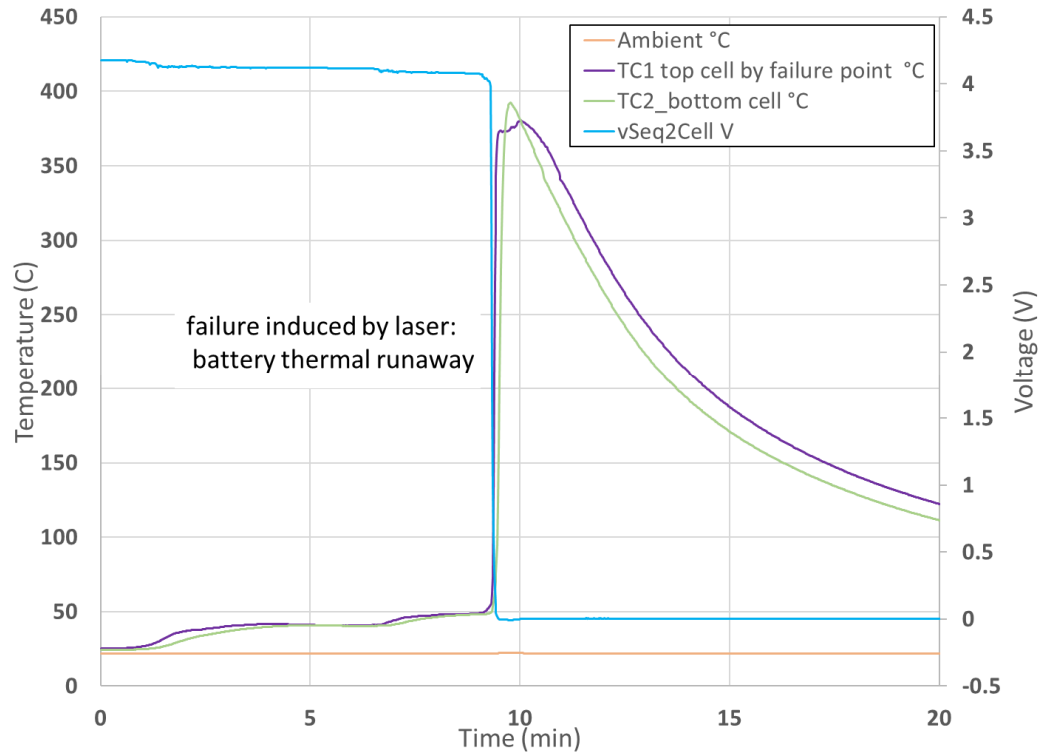
Acknowledgements

- **Phil Gorney (DOT – NHTSA)**
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- **Christopher Orendorff**
- **Mohan Karulkar**
- **Summer Ferreira**
- **John Hewson**
- **Kyle Fenton**
- **Eric Allcorn**
- **Lorie Davis**
- **Mani Nagasubramanian**
- **Jill Langendorf**

Extra slides

Laser initiated failure through fused silica slide (2mm)

In hopes to reduce the oxygen exposure to hole being produced from laser, an IR transparent slide was used as barrier during testing



- Able to induce failure using laser through silica slide
- Final power setting of 350V, 20ms, 1Hz to induce thermal runaway
 - More energy needed to induce runaway through silica slide
- Maintained seal between silica and pouch cell until full runaway



Slide 25

SJ4

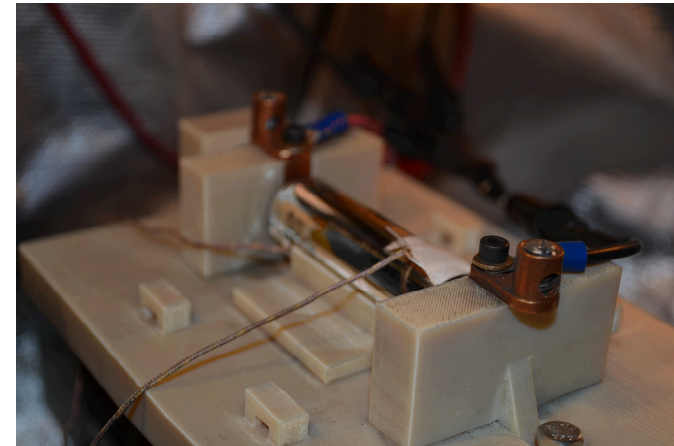
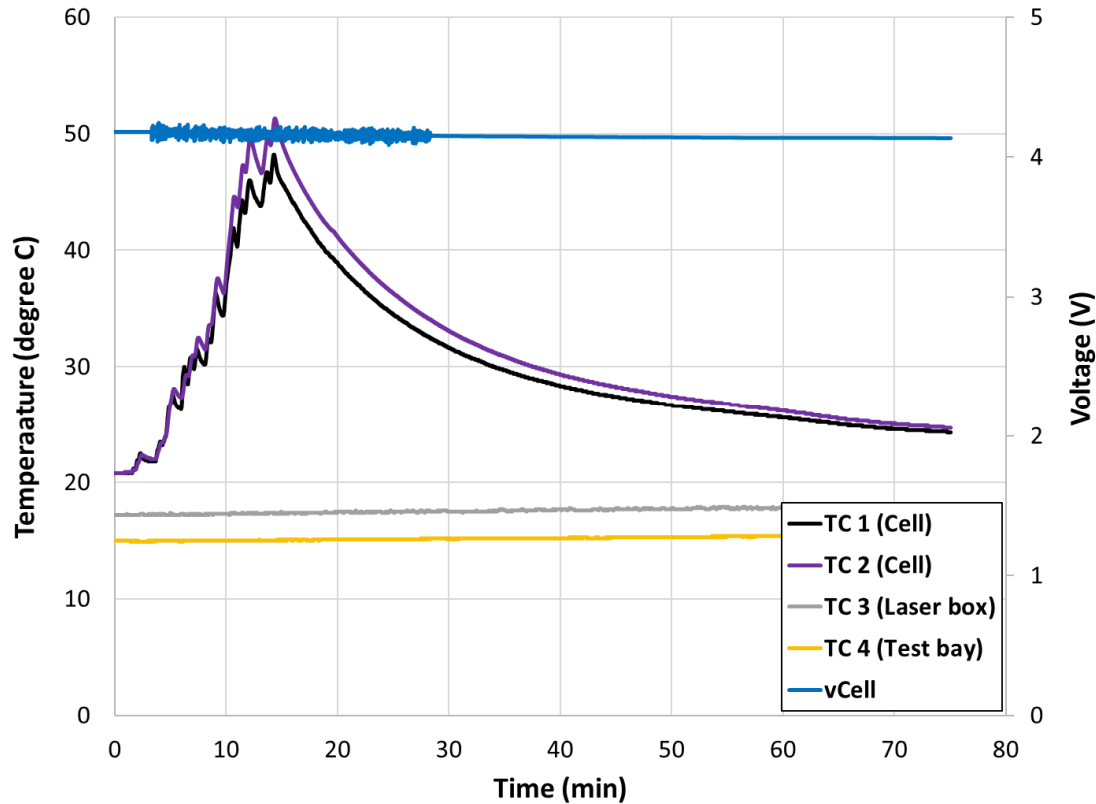
Legend: replace vSeq2Cell V to 'Cell Voltage'

Stanley, June, 5/26/2017

Post test –detail

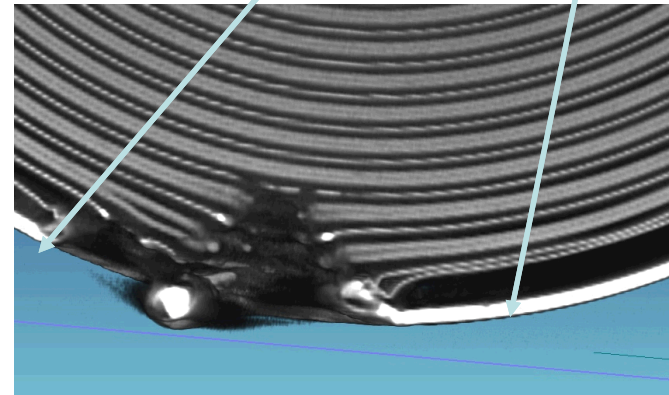
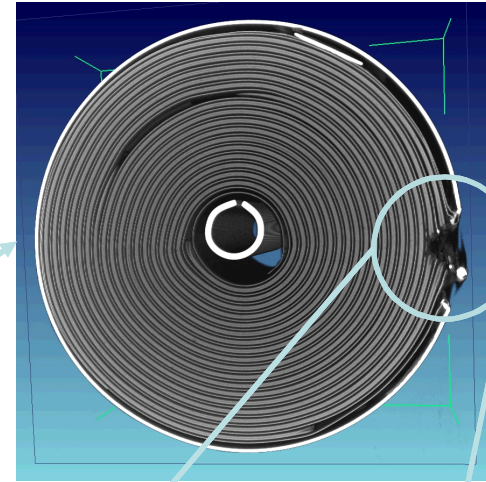
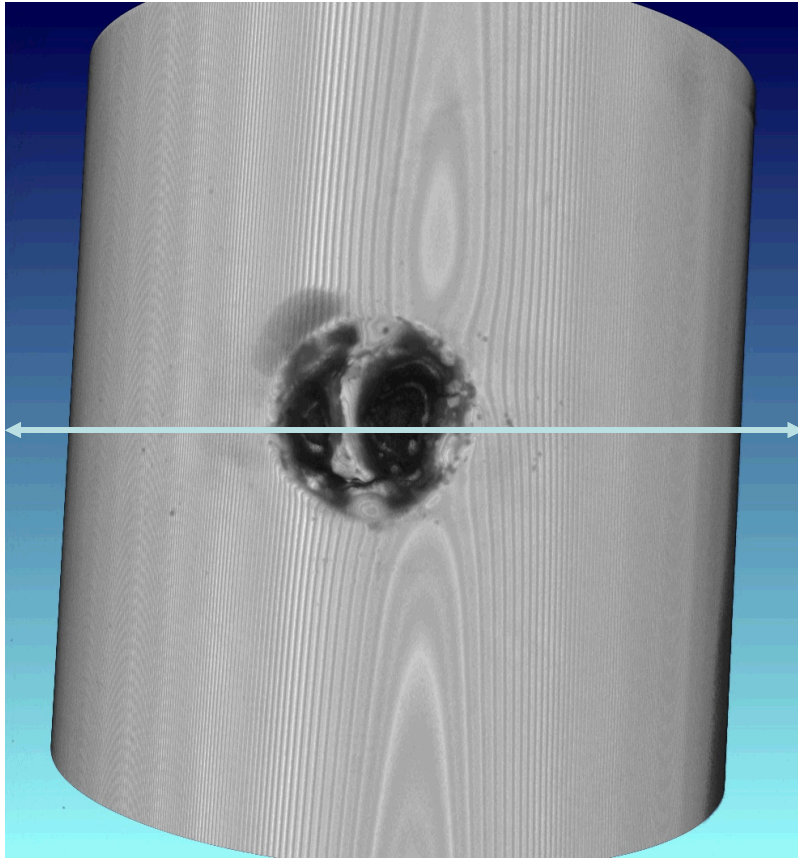


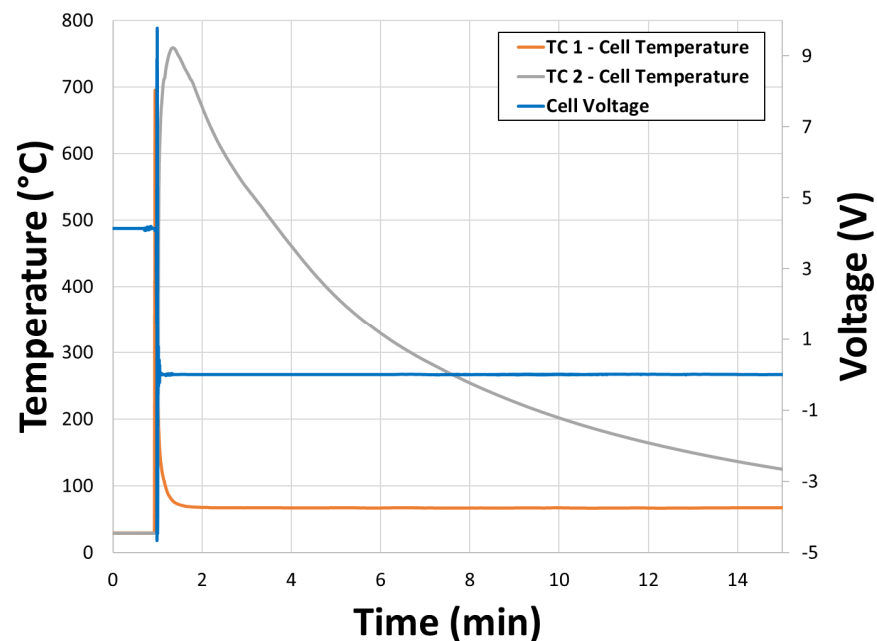
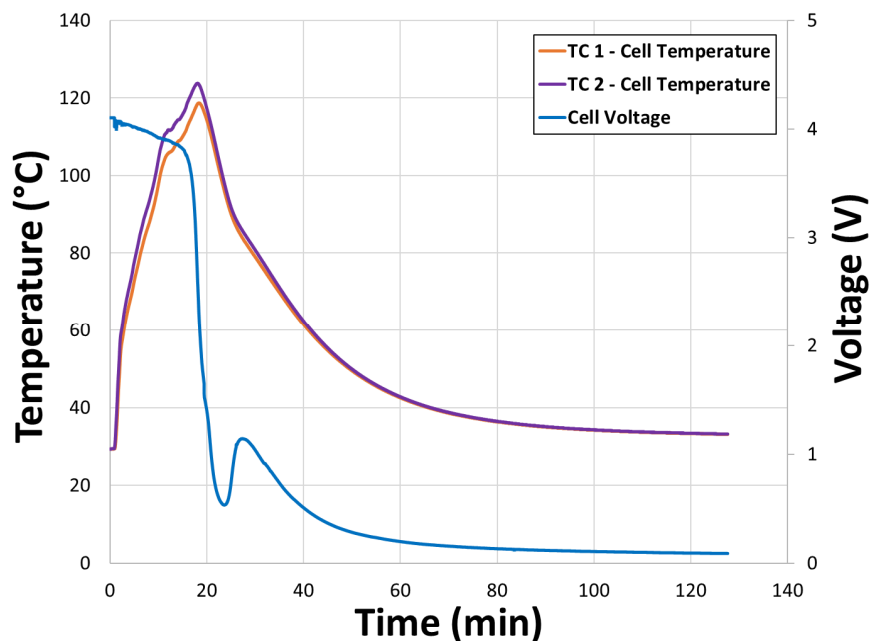
Cylindrical cell tests



- Some cell heating and voltage drop observed
- No thermal runaway initiated
- Visible damage caused to can surface and evaluated with CT

CT of 18650 damage





- Some variance observed testing NCA 18650s, but in both cases failure lower impedance than that observed for LCO cells

NCA rapid runaway failure

