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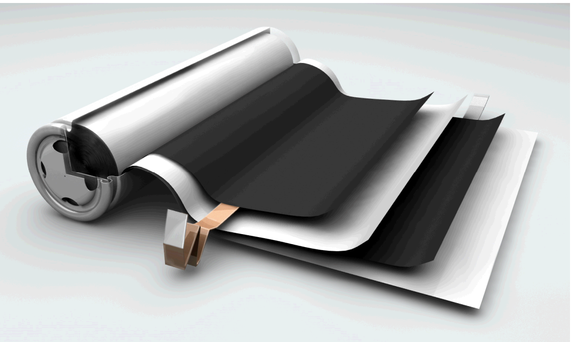
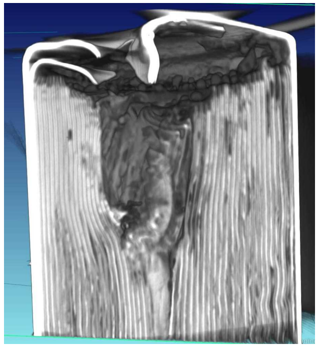

Battery Safety Testing

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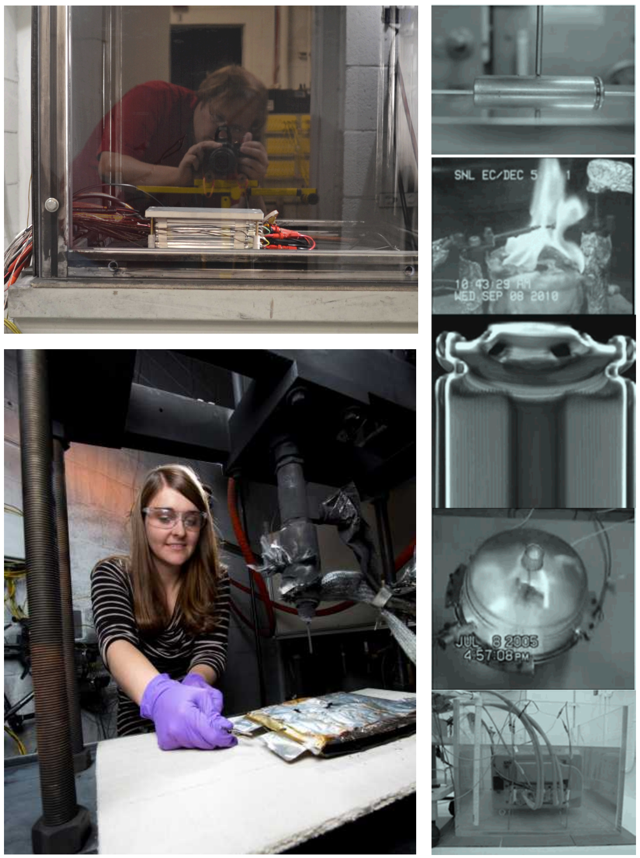
Sandia National Laboratories

Energy Storage Safety Workshop

Santa Fe, NM, February 2017

Approach and Capabilities

Cell and Module Testing
Battery Abuse Testing Laboratory (BATLab)



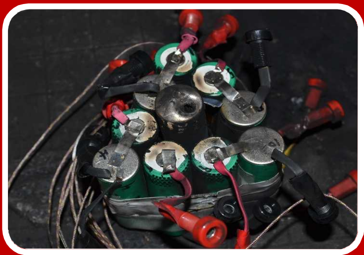
Battery Pack/System Testing
Thermal Test Complex (TTC) and Burnsite

Battery Calorimetry

Understanding Battery Safety

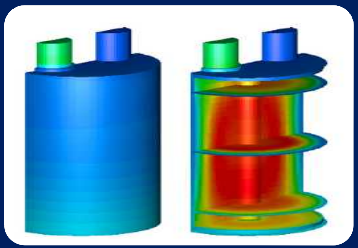
Materials R&D

- Non-flammable electrolytes
- Electrolyte salts
- Coated active materials
- Thermally stable materials



Testing

- Electrical, thermal, mechanical abuse testing
- Large scale thermal and fire testing (TTC)
- Failure propagation testing on batteries/systems
- Diagnostic techniques for battery state of stability
- Development for DOE Vehicle Technologies and USABC



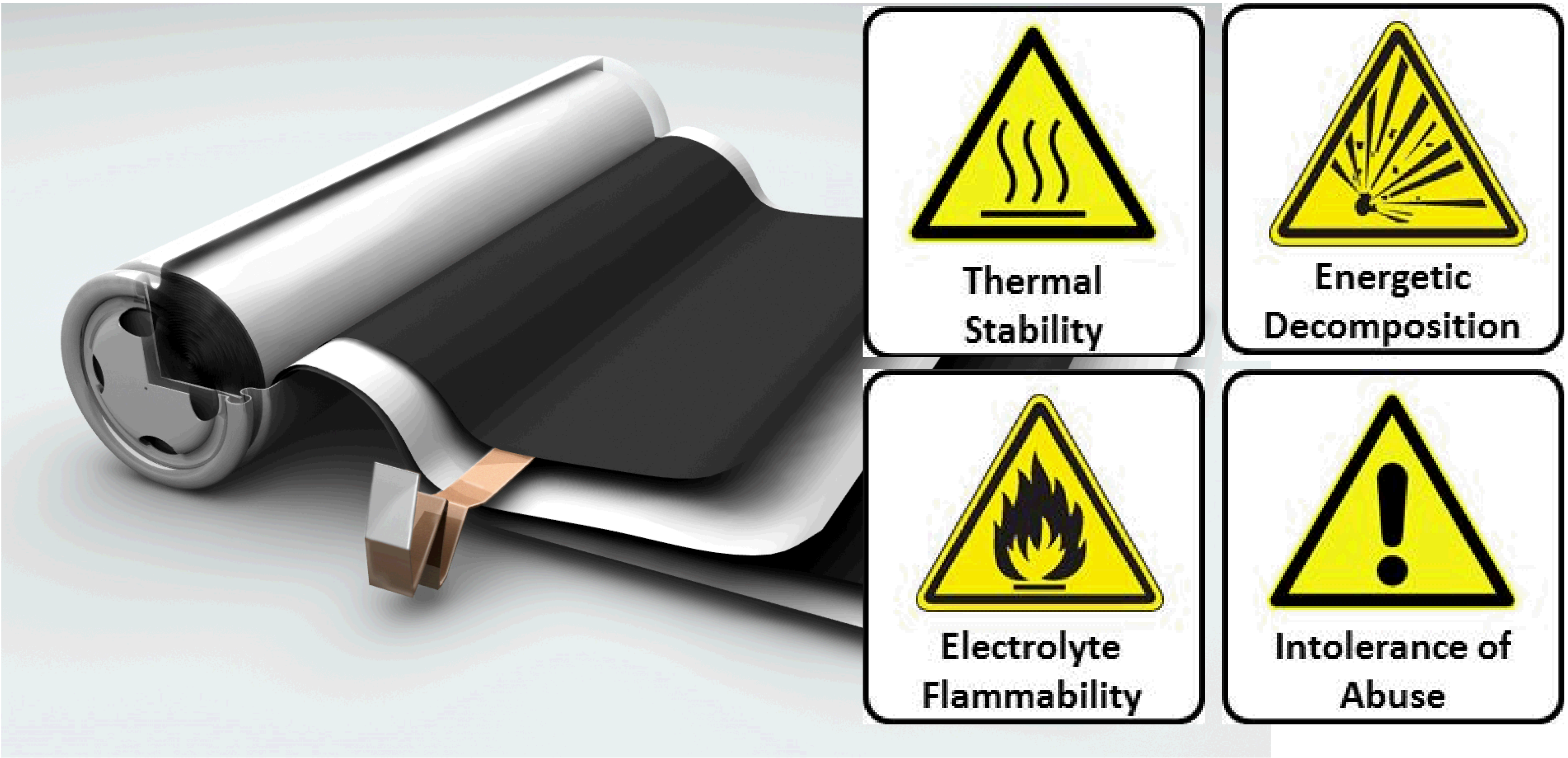
Simulations and Modeling

- Multi-scale models for understanding thermal runaway
- Validating vehicle crash and failure propagation models
- Fire Simulations to predict the size, scope, and consequences of battery fires

Procedures, Policy, and Regulation

- USABC Abuse Testing Manual (SAND 2005-3123)
- SAE J2464/UL 1642 procedures and standards
- R&D programs with NHTSA/DOT to inform best practices, policies, and requirements

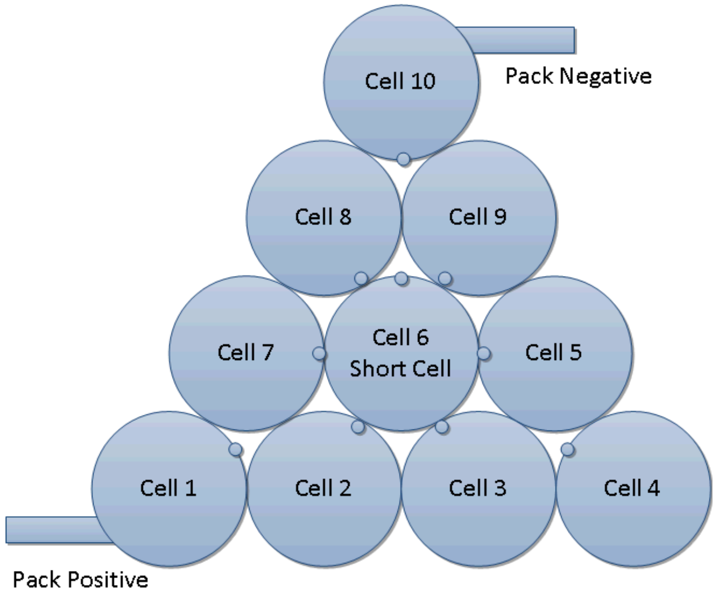
Lithium-ion Safety Issues



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

Battery Failure Propagation

- Simply, the propensity of the energetic failure of a single cell to cause widespread thermal runaway within a battery
- Most large battery systems are designed to withstand the loss of several cells from a performance standpoint
- A point failure becomes more serious if it can send nearby cells into thermal runaway
- Recent events have had battery runaway events that engulfed the entire pack



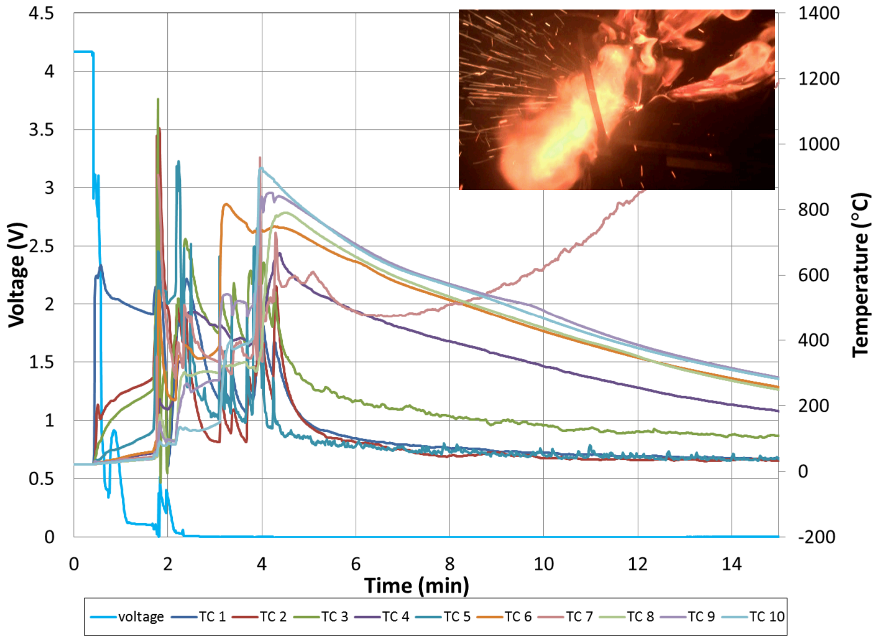
- *Diagram showing cell and thermocouple locations*
- *Series and parallel constructions used, series pack wired in order from Cell 1 to cell 10*

Cells:
Panasonic
Model CGR18650CG
2250 mAh nominal capacity
Avg wt. 44g

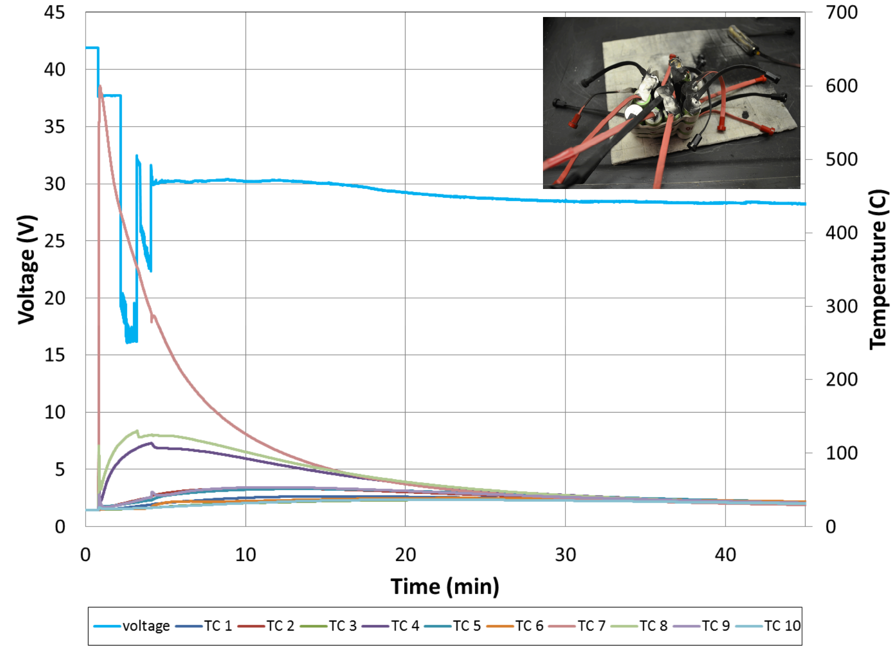
Failure Propagation: Edge Cell Failure

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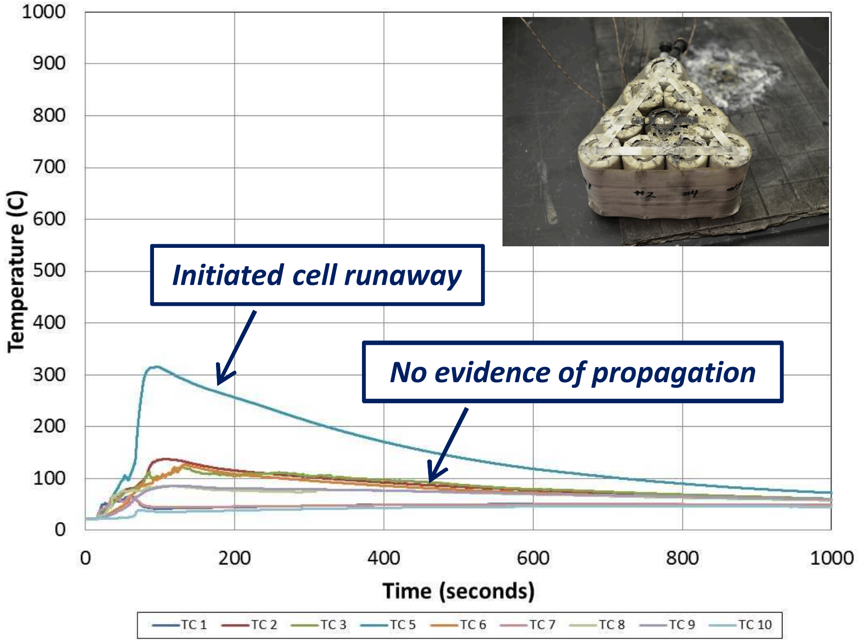
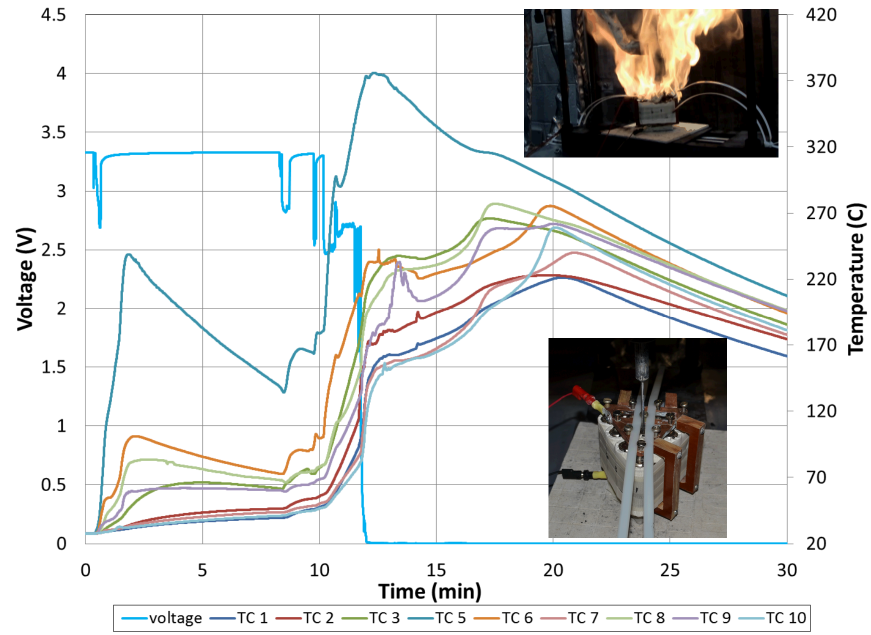
Failures initiated by mechanical insult to center cell of LFP COTS packs

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)

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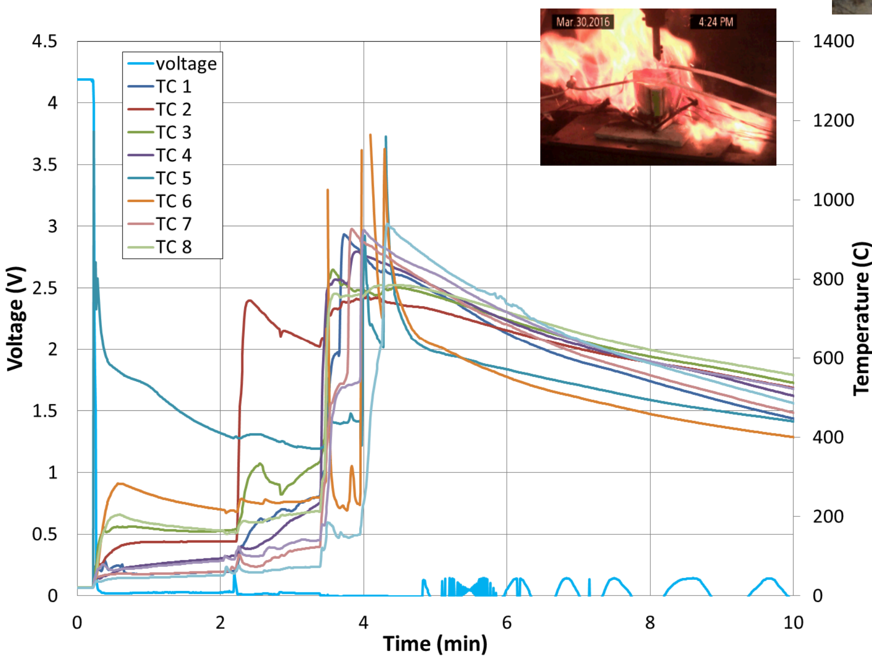
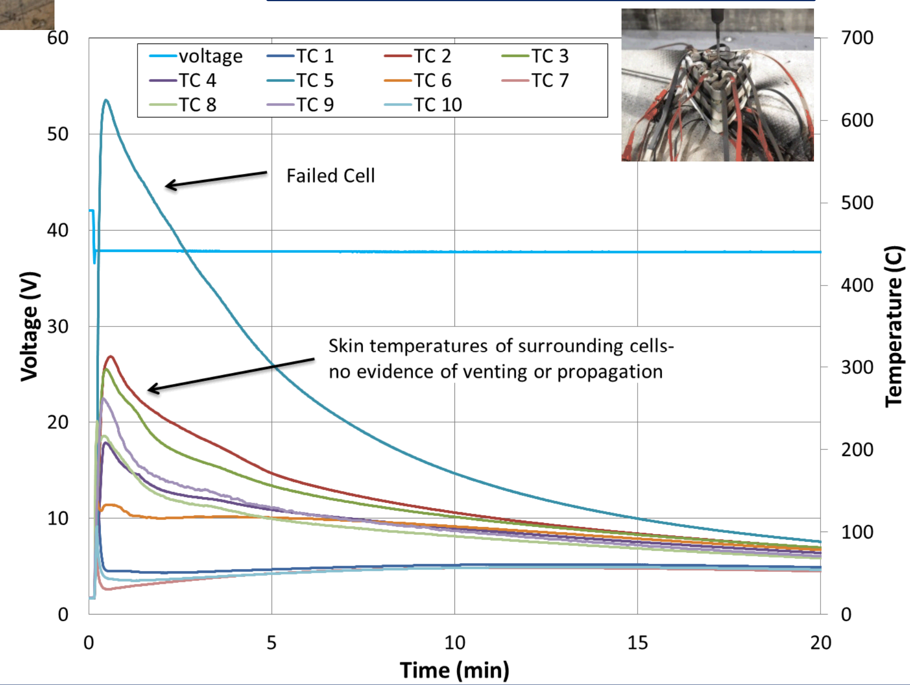
Failures initiated by mechanical insult to the center cell: 2mm air gap between cells

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***

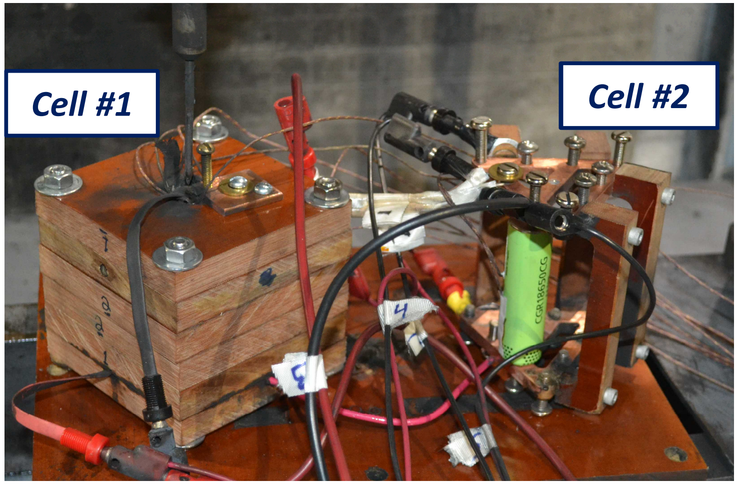
Short Circuit Current During Failure Propagation

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

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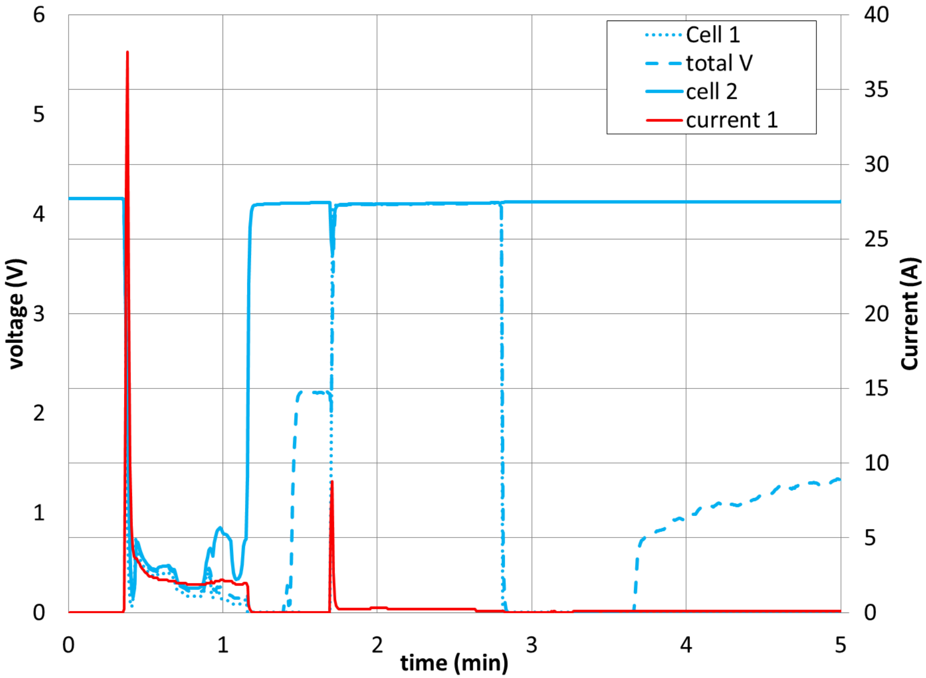
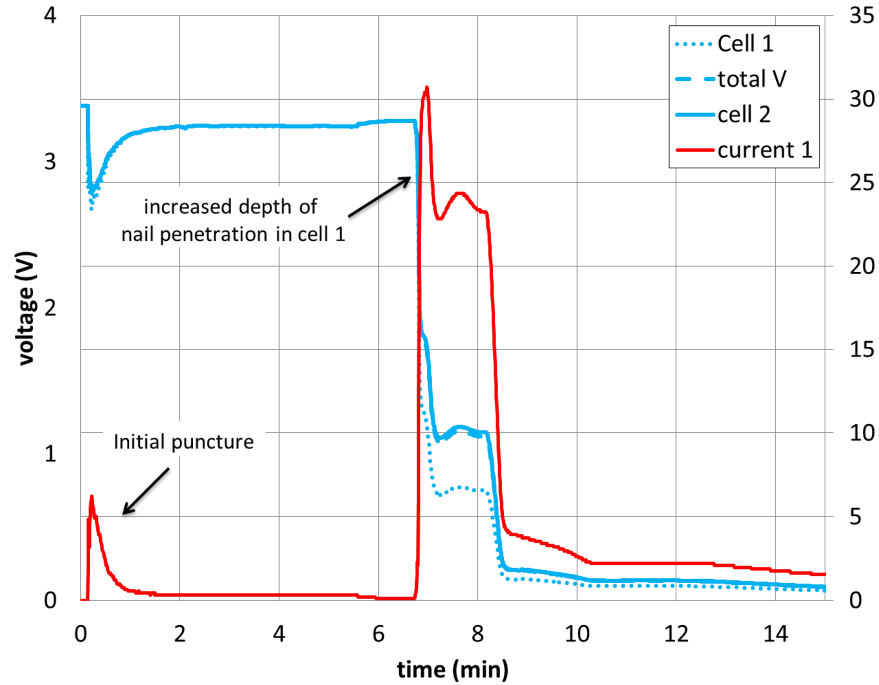
Failures initiated by mechanical insult to cell 1 which is connected to cell 2 through constantan bridge wire

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

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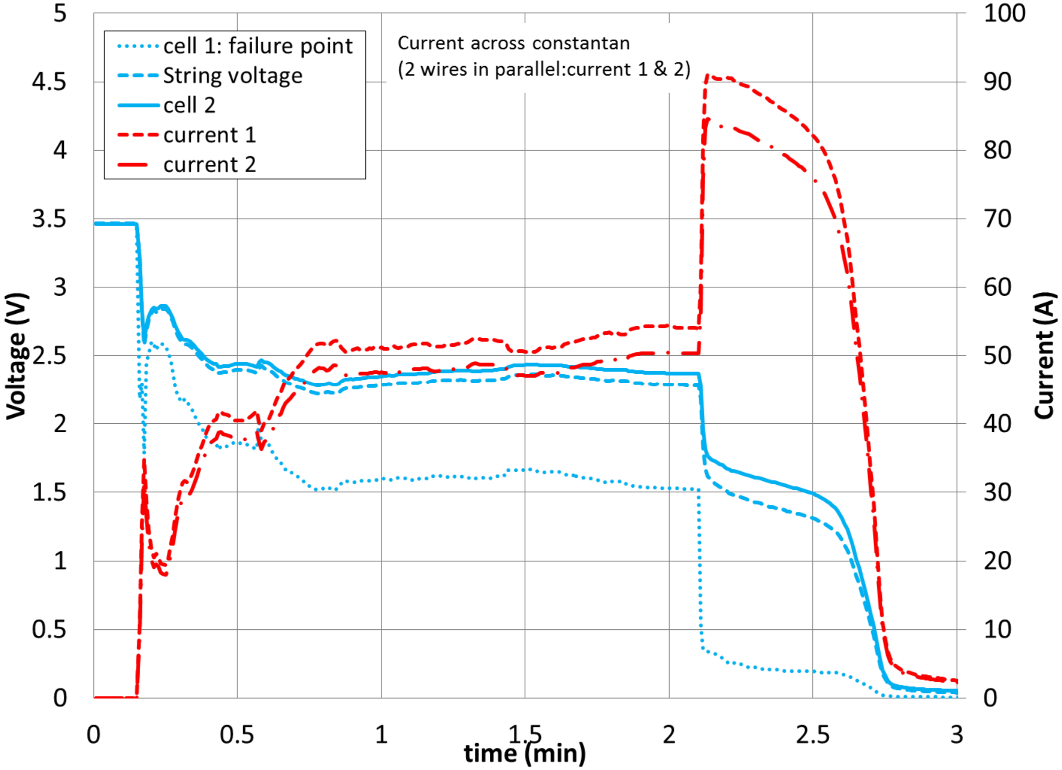
Failures initiated by mechanical insult to cell 1 which is connected to cell 2 through constantan bridge wire

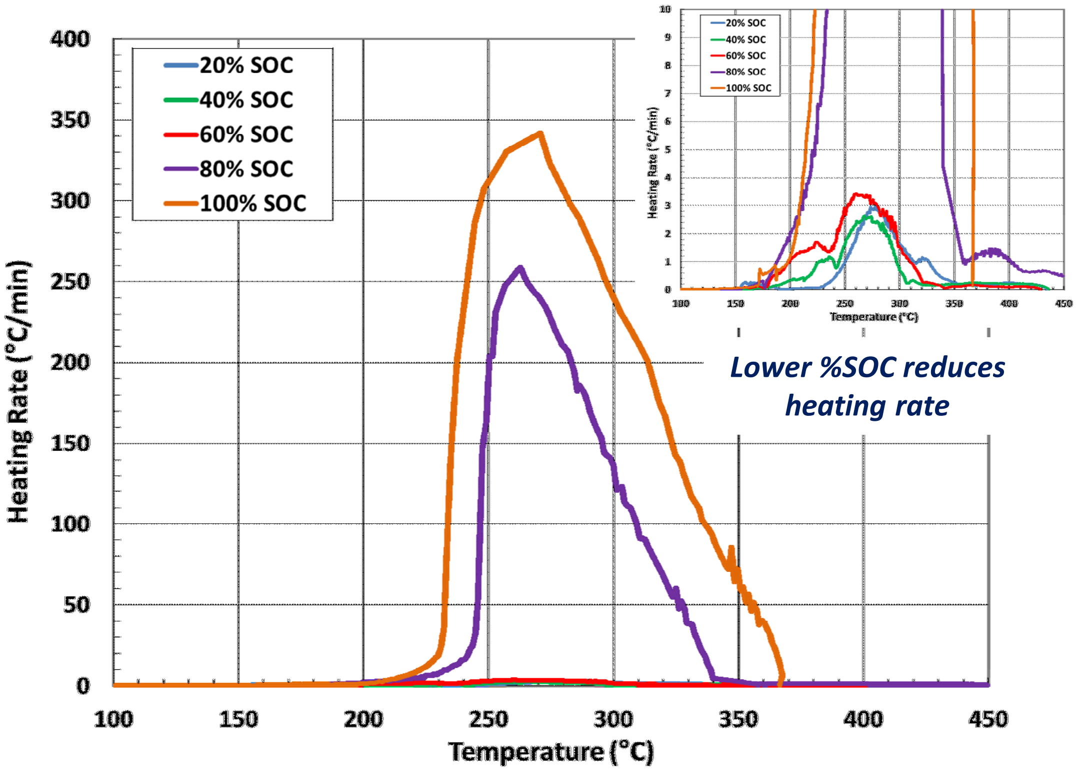
LFP-26650 cells – 1s2p



- ***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***

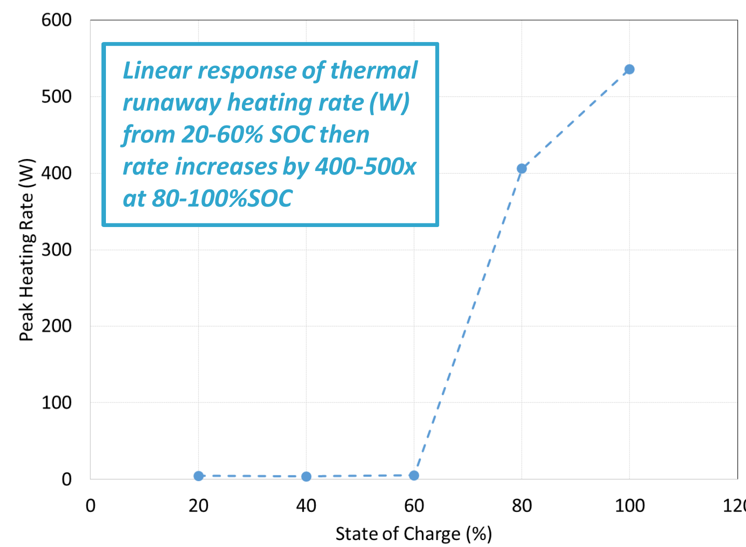
Impact of SOC on Abuse And Propagation

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



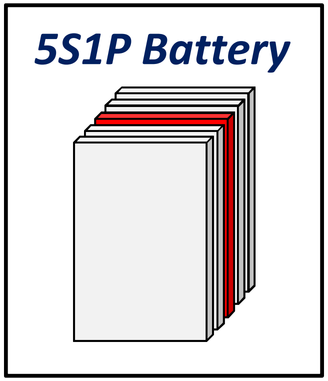
Energies as a function of %SOC

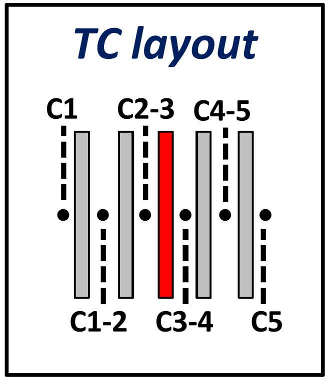
%SOC	KJ	KJ/Ah	W	W/Ah
20	19.5	78.0	4.64	18.6
40	23.9	47.8	4.14	8.27
60	25.7	34.3	5.37	7.17
80	31.0	31.0	406	406
100	25.5	20.4	536	429



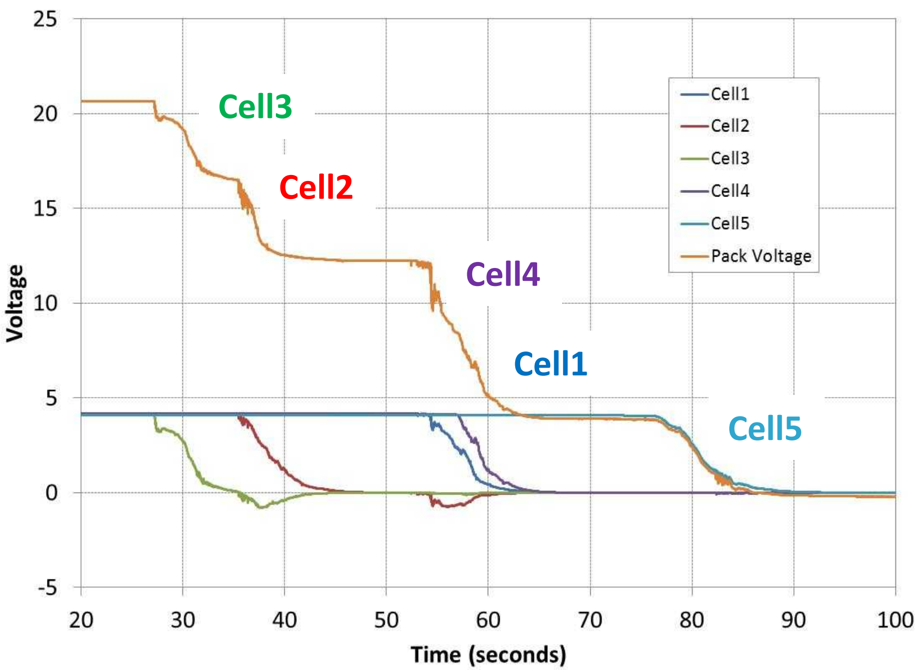
- ***Peak heating rate profiles are similar for lower states of charge (20-60%) then drastically increase at 80% and 100% SOC as shown by the total energy output (W)***
- ***The onset of thermal runaway increases as the %SOC decreases***

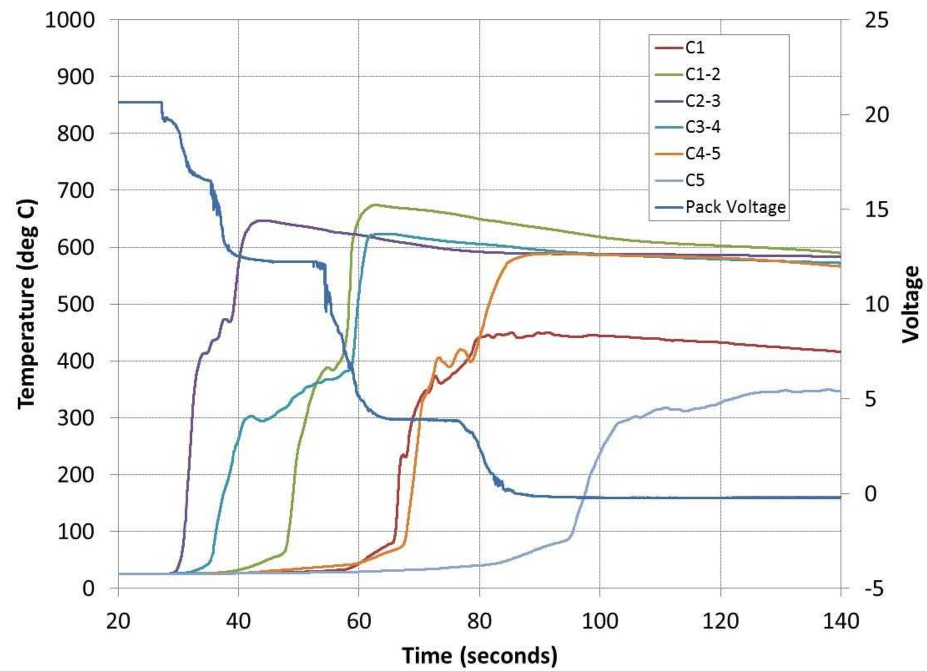
Propagation Testing (5S1P) – 100%



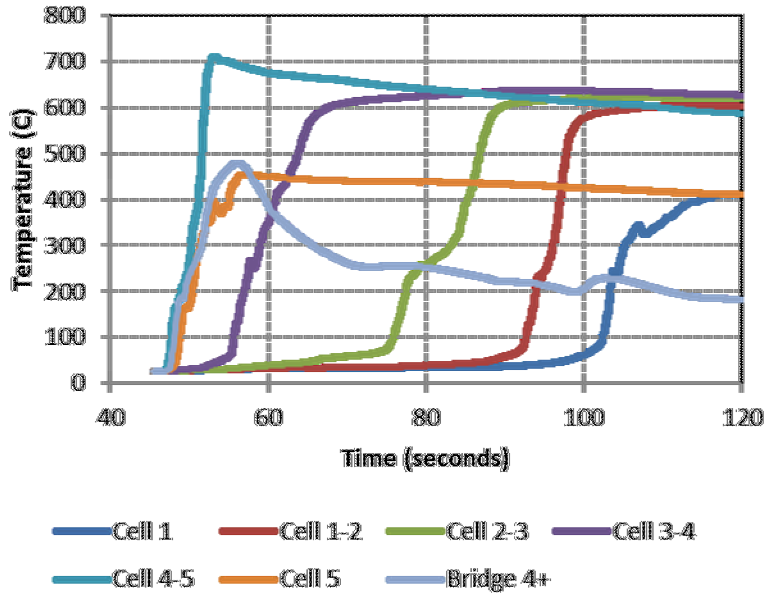


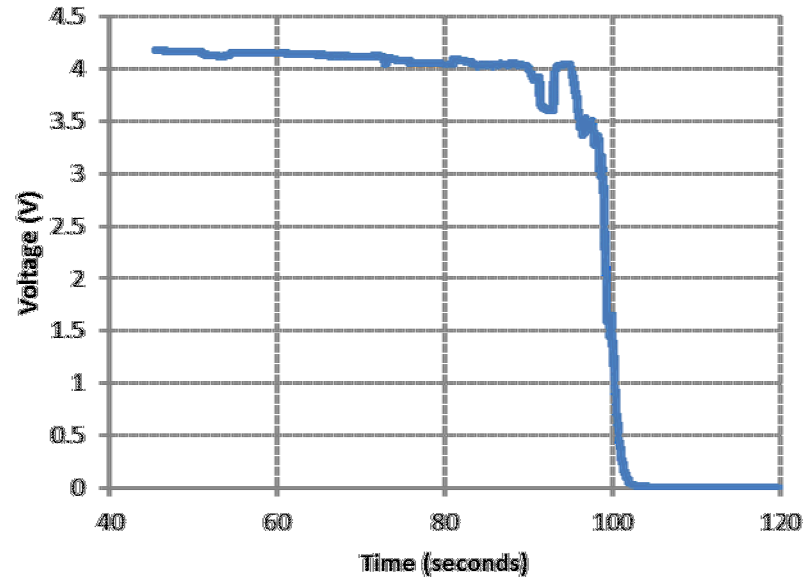
- Successful initiation at Cell #3
- Propagation to adjacent cells
- Cascading failure to entire battery over 60 s

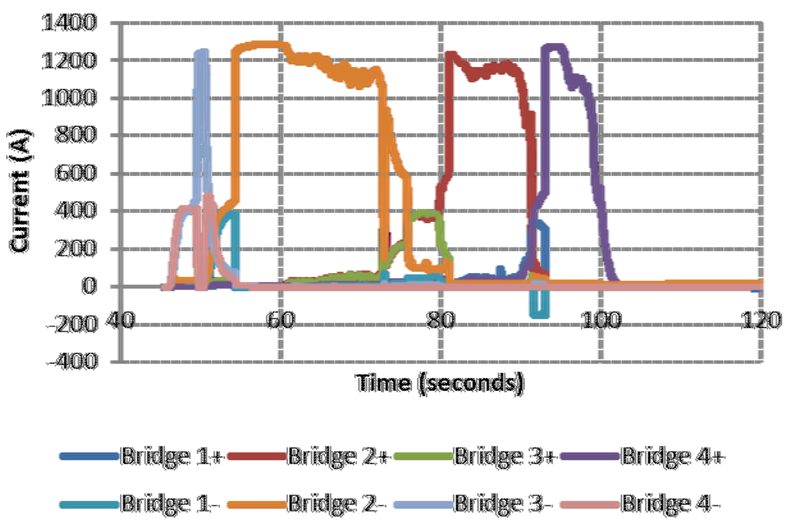




Propagation Testing (1S5P)

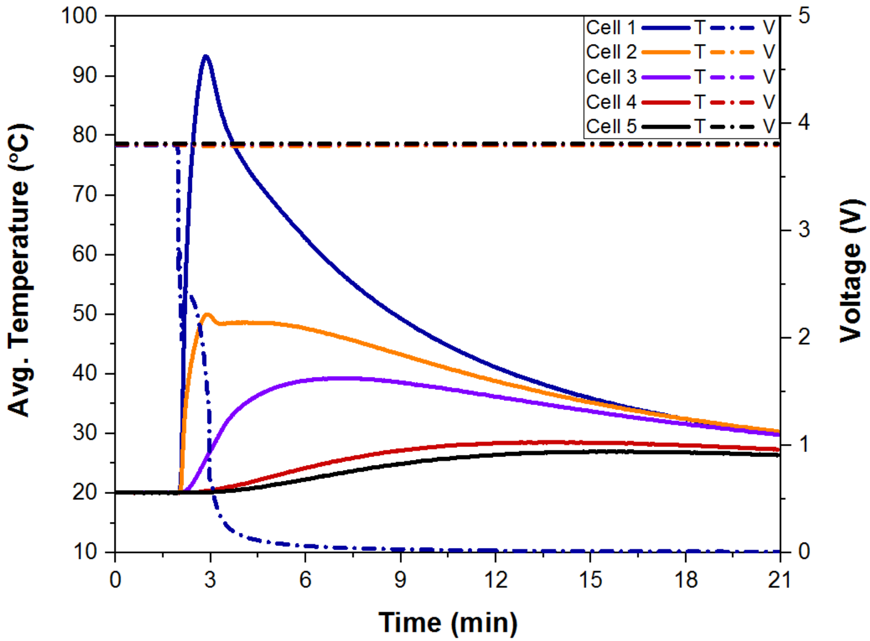


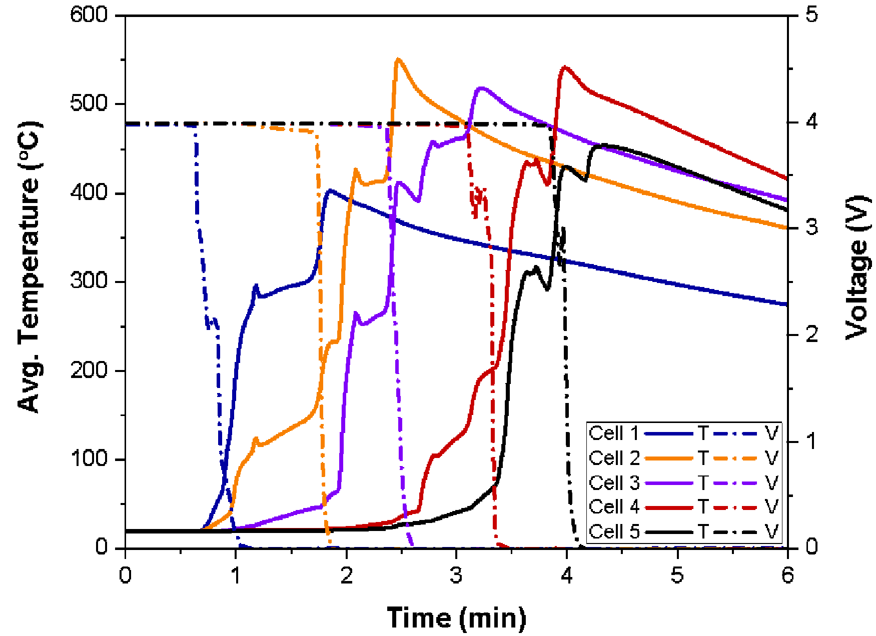




- Failure and runaway initiated at Cell #5
- Current measurements taken on nickel connections

50% vs 80% Pouch cell propagation





- ***50% SOC no cell to cell propagation observed***
- ***"Pulsating" propagation observed during failure of 80% pouch pack***
- ***Total pack propagation observed after ~4 minutes***

Summary

- Failure propagation behavior observed in both cylindrical cell strings and pouch cell strings
- Electrical and cell configuration observed to play a significant role in how cylindrical cells propagate
- Electrical configuration shows a smaller impact in pouch cells, owing to the large area of thermal contact
- Propagating failure is possible at reduced SOC; current work is ongoing to determine how cell configuration might impact the severity of failure at reduced SOC

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