Scale-Up of PPR Battery Design for 21700 Format Cells

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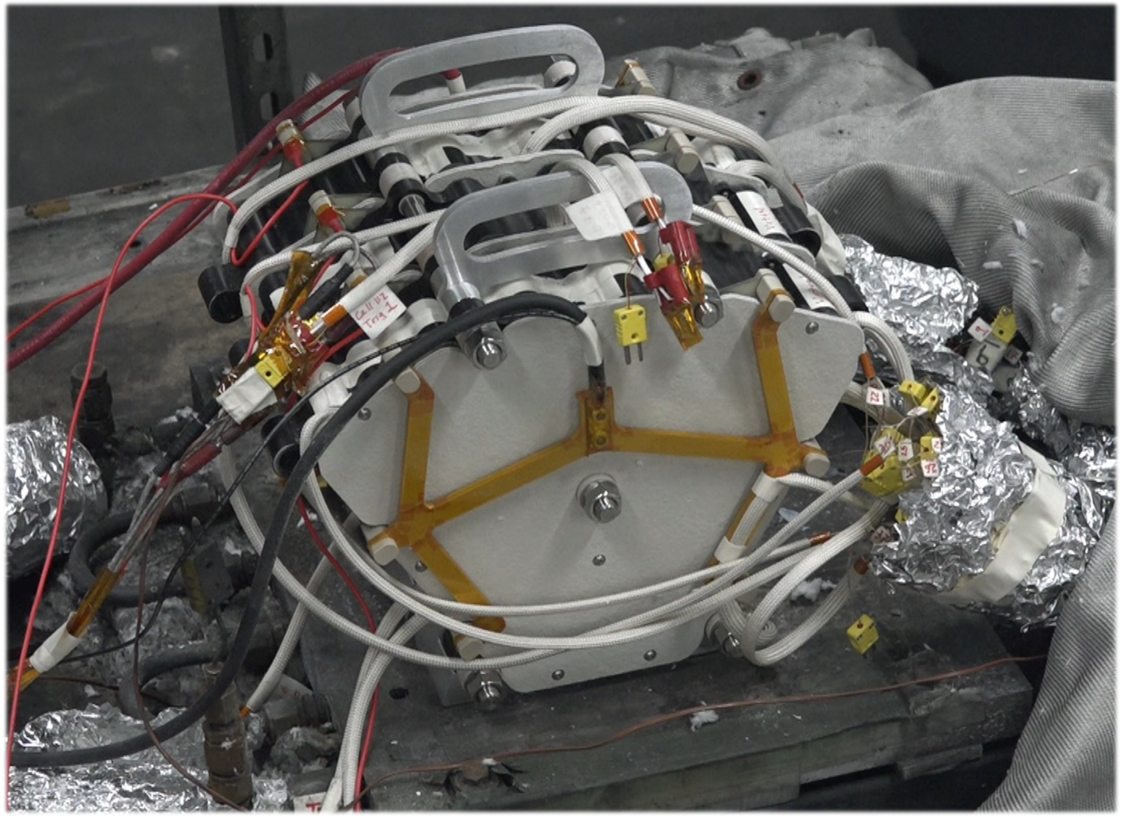
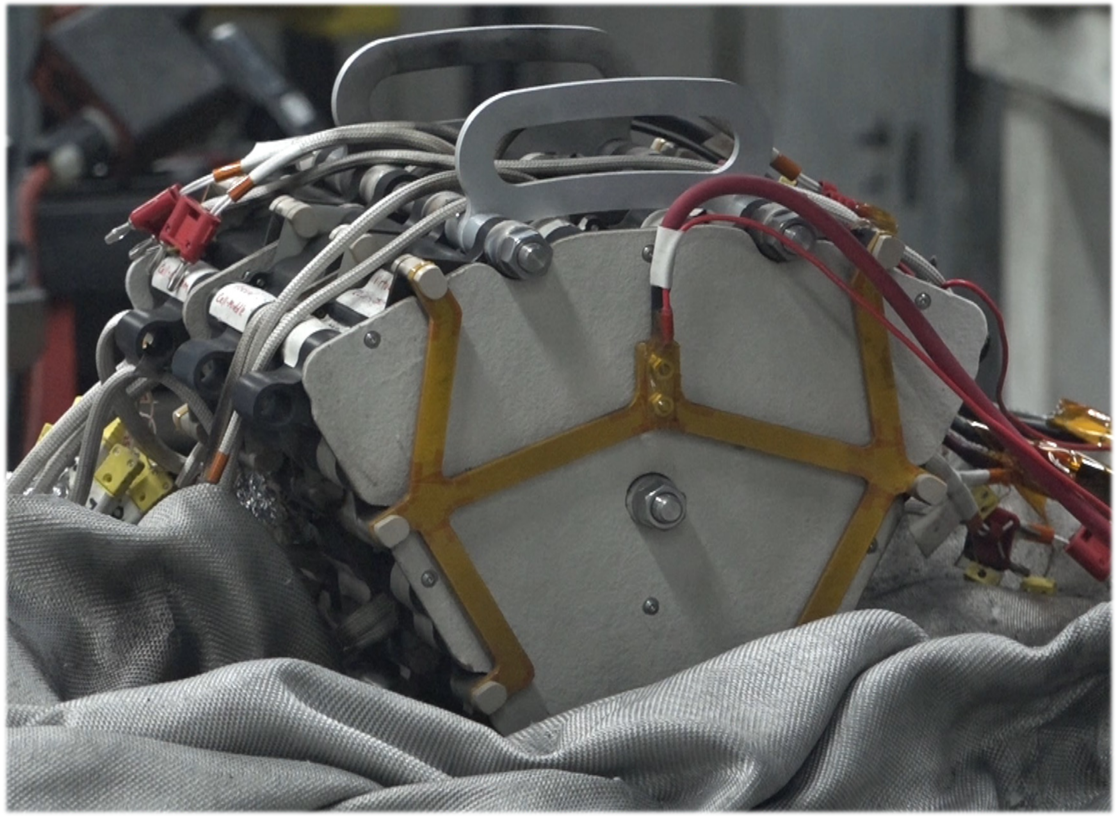
Presentation Outline

- Motivation and Background
  - Leveraging insights and lessons learned from ***M3*** PPR battery design
  - Criteria for Thermal Runaway (TR) Passively Propagation Resistant (PPR) design guidelines
- Scaling PPR Batteries from 18650 to 21700 Cells
  - Potential cell candidates and Fractional Thermal Runaway Calorimetry (***FTRC)*** data
  - Modeling predictions on varying interstitial webbing thicknesses
- Blast Plate Evaluation Platform and Test Results
  - Platform design and coupon construction
  - Sample test videos and thermal results
- ***M3*** (18650) and ***M5*** (21700) Subscale Design and Test Results
  - Design features observing PPR guidelines
  - PPR test results and insights on scaling up PPR batteries

Thermal Runaway Tests - ***M3*** PPR Battery

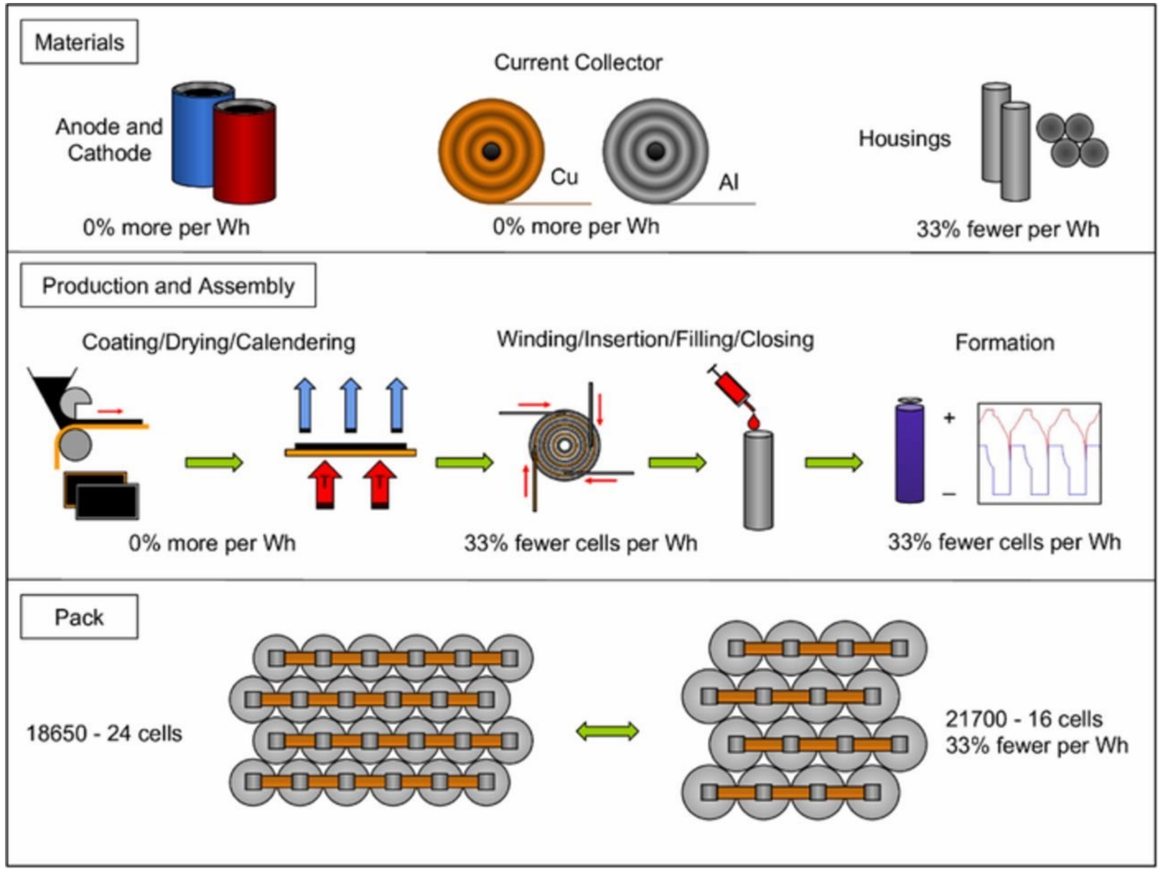


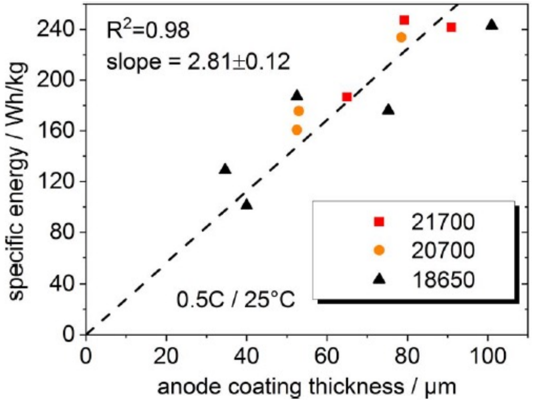
Video: First M3 thermal runaway video (middle virtual cell, trigger cell located in the center).

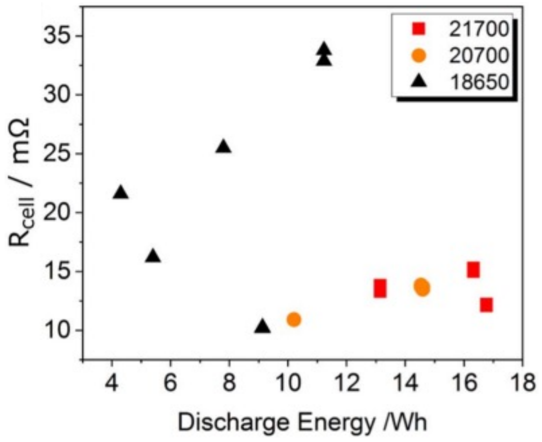


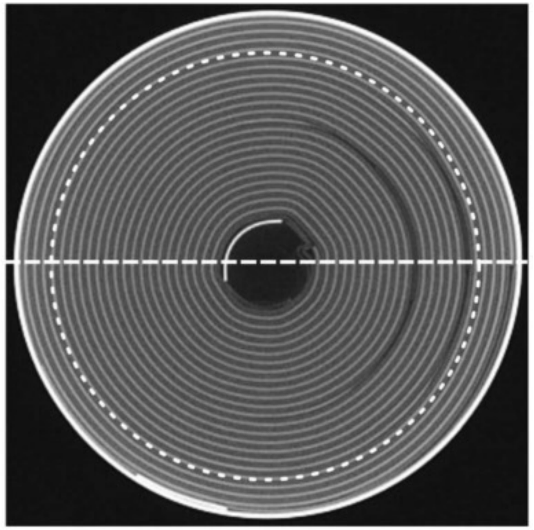
Video: Last M3 thermal runaway video (virtual cell in "top/front" virtual cell, trigger cell in the upper middle).

Cell Comparison: 18650 versus 21700



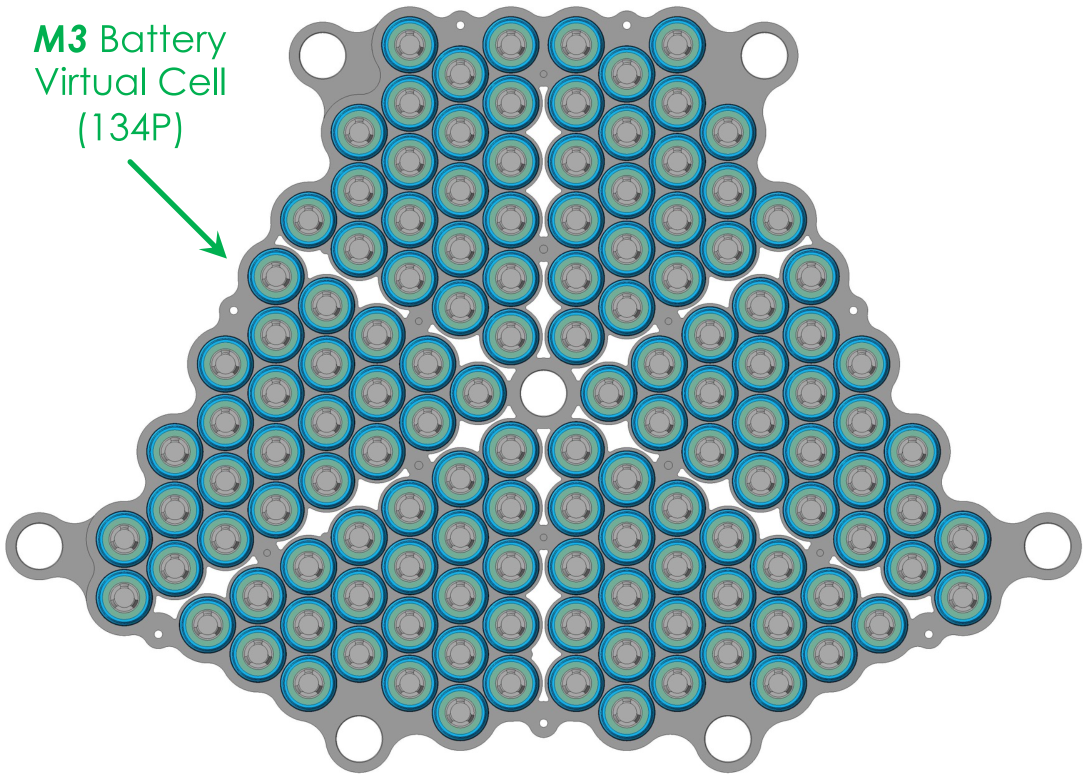


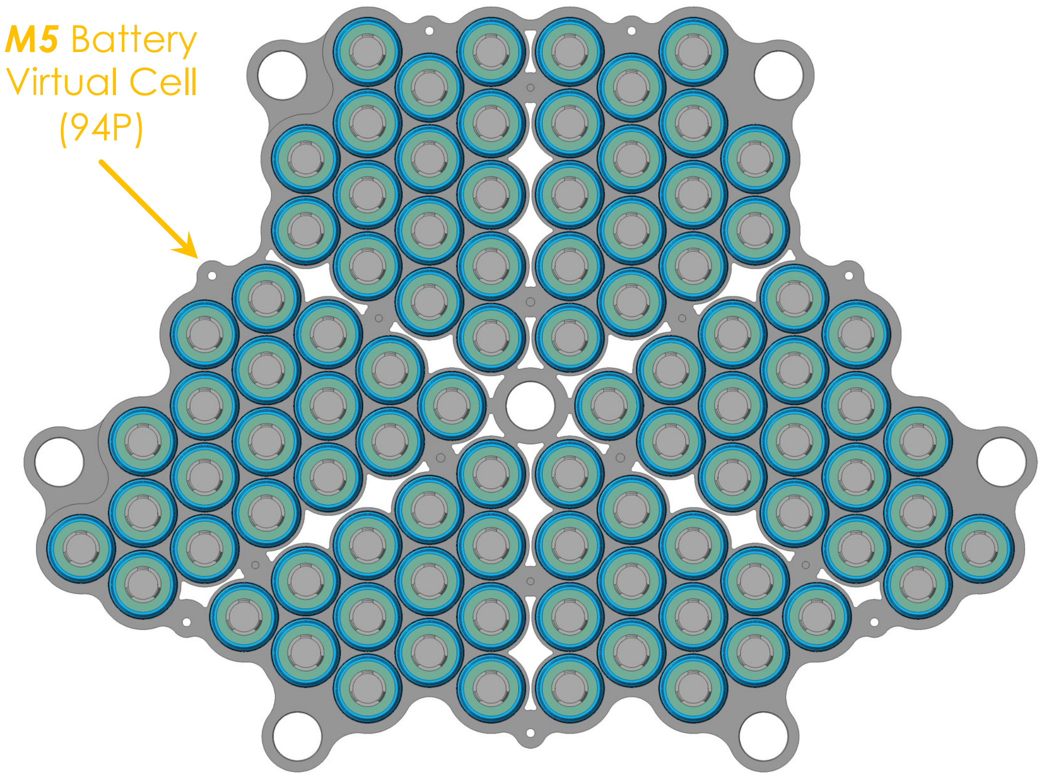




Reference: Jason B. Quinn, Thomas Waldmann, Karsten Richter, Michael Kasper and Margret Wohlfahrt-Mehrens, "Energy Density of Cylindrical Li-Ion Cells: A Comparison of Commercial 18650 to the 21700 Cells" Journal of The Electrochemical Society, Volume 165, Number 14

Towards the Development of 21700-Format PPR Battery





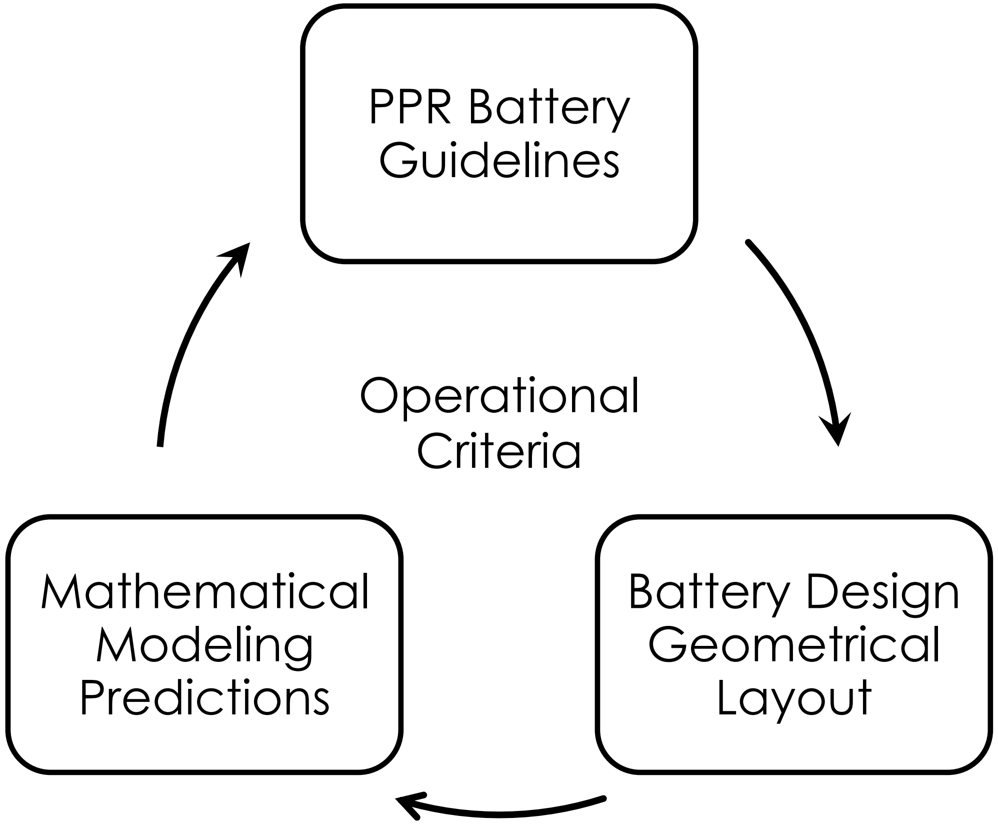
- Achieve PPR battery pack using 21700 cells leveraging lessons learned from 18650 PPR battery designs
- Provide direct comparison of 18650 M3 battery to 21700 M5 battery with modeling and test results to determine benefits and drawbacks of using 21700 cells in PPR packs compared to 18650 cells

Criteria for TR Propagation Resistant Batteries

Guidelines for PPR Batteries:

1. Reduce the risk of cell can side wall breaches (sidewall rupture)
2. Provide adequate cell spacing and heat rejection
3. Individually fuse parallel cells
4. Protect the adjacent cells from the hot TR ejecta
5. Prevent flames and sparks from exiting the battery**

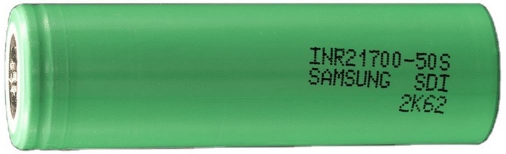
**Vehicle housing prevents flames and sparks from escaping in this application



Reference: Darcy, E. C., Jacob, D., Walker, W., Finegan, D. P. & Shearing, P. Driving Design Factors for Safe, High-Power Batteries for Space Applications. in Advanced Automotive Battery Conference (2018).

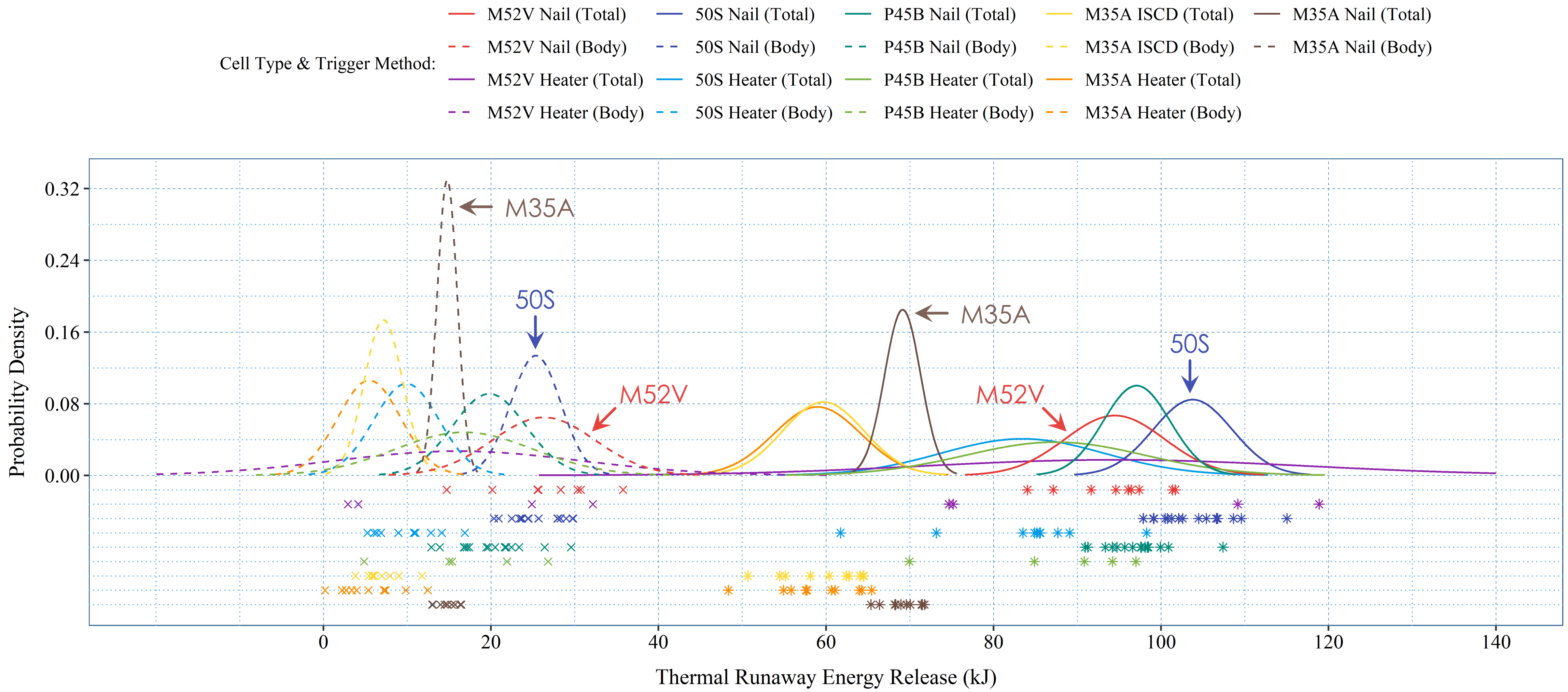
SCALING PPR BATTERY FROM 18650 TO 21700 CELLS

Selected Specification of Candidate Cells



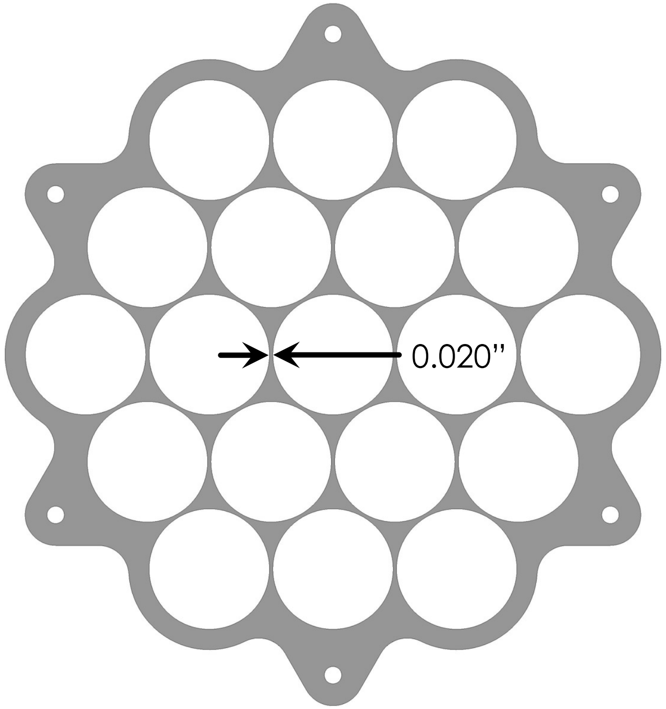
Cell Type:	Molicel M35A	Samsung 50S	LG M52V
Form Factor:	**18650**	**21700**	**21700**
Nominal Capacity:	3,500 mAh	5,000 mAh	5,096 mAh
Nominal Voltage:	3.6 V	3.6 V	3.69 V
Measured Capacity (C/5):	3,412 mAh	4,990 mAh	5,081 mAh
Measured Energy (C/5):	12.163 Wh	17.952 Wh	18.542 Wh
Measured Average Mass:	45.36 g	70.04 g	67.32 g
Measured Height:	64.90 mm	70.46 mm	70.46 mm
Measured Diameter [Max]:	18.17 mm	21.06 mm	21.11 mm
Gravimetric Energy Density:	**268.1 Wh/kg**	**256.3 Wh/kg**	**275.4 Wh/kg**
Volumetric Energy Density:	722.8 Wh/L	731.4 Wh/L	751.9 Wh/L

Cell Energy Distributions (Data from FTRC)



Subscale Battery Heat Sink Design

Shown to Scale



Shown to Scale

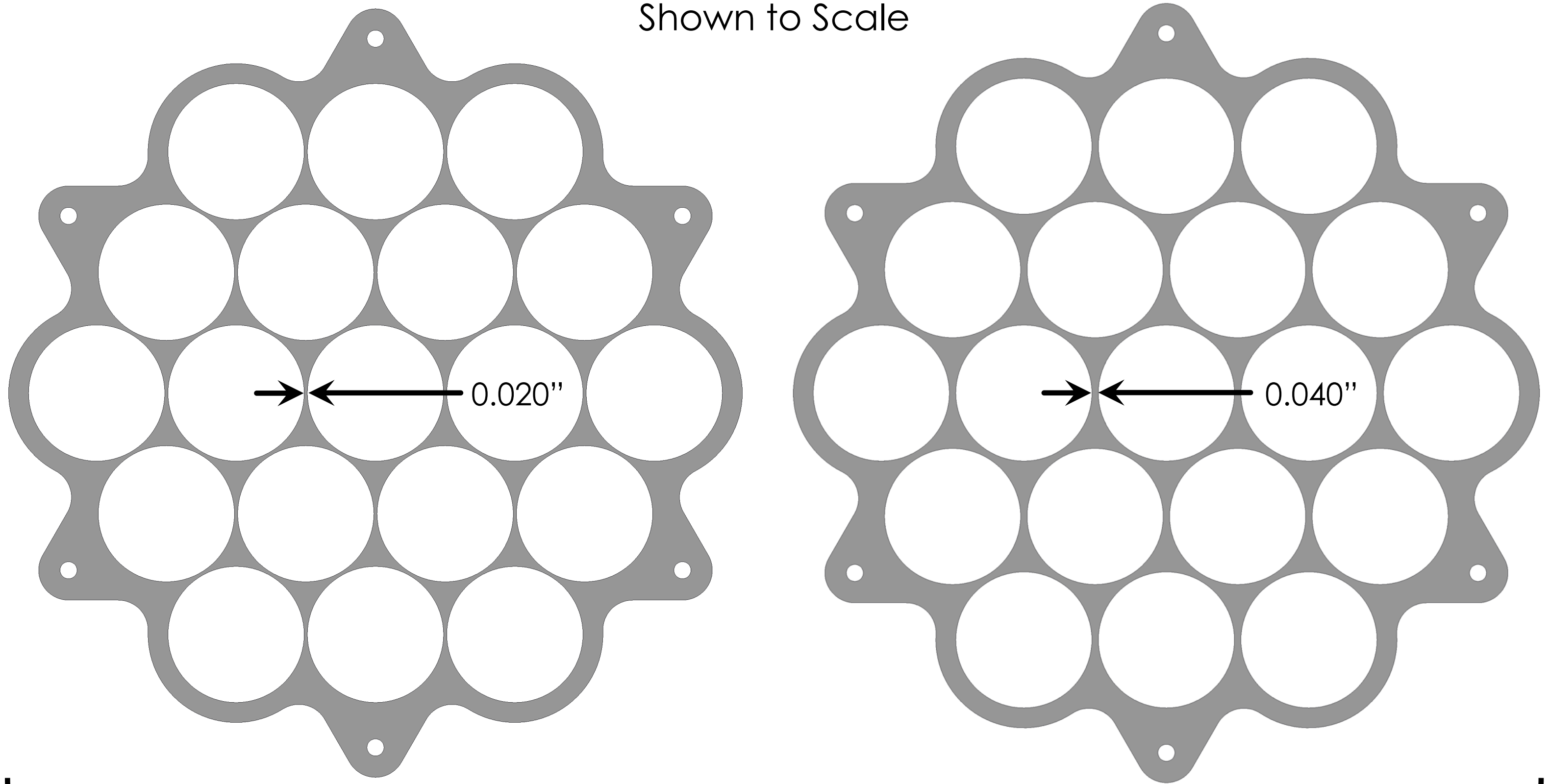
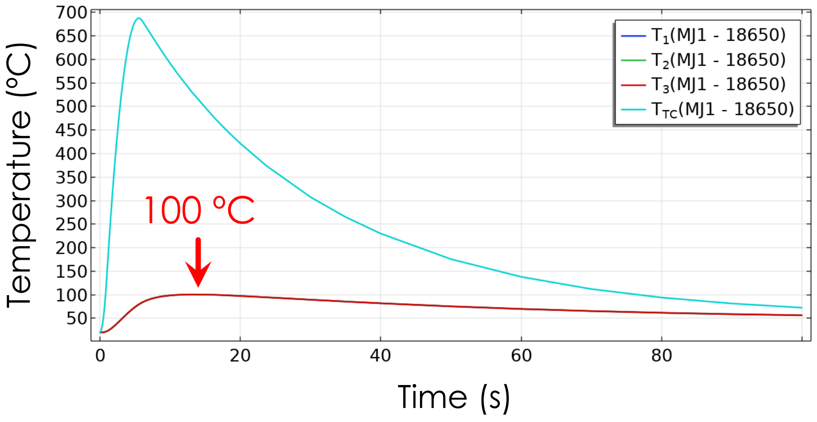


Figure: heritage PPR heat sink design for **18650 cells** with 0.020" min. web thickness.

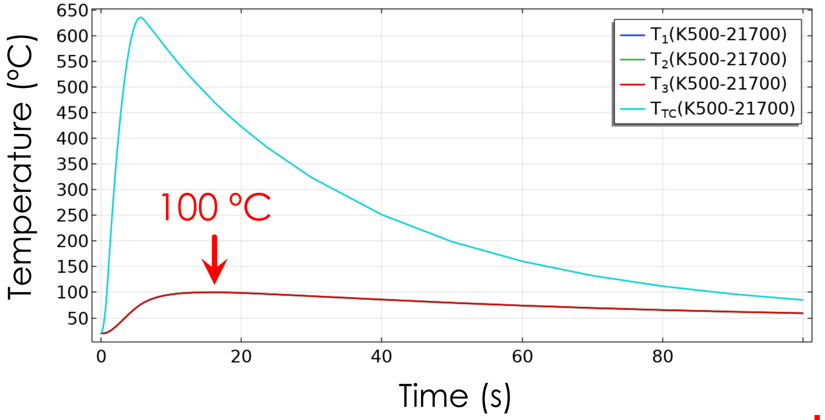
Figure: proposed PPR heat sink designs for upscaling to **21700 cells**. Two webbing thicknesses will be evaluated (0.020" left, 0.040" right) and compared to the 18650-equivalent subscale test article to calibrate thermal modeling predictions.

Modeling Predictions vs. Web Thickness

LG MJ1 (18650, 32.6 kJ, **0.020"**)



KULR K500 (21700, 41.8 kJ, **0.020"**)



Results with 0.020" webbing thickness

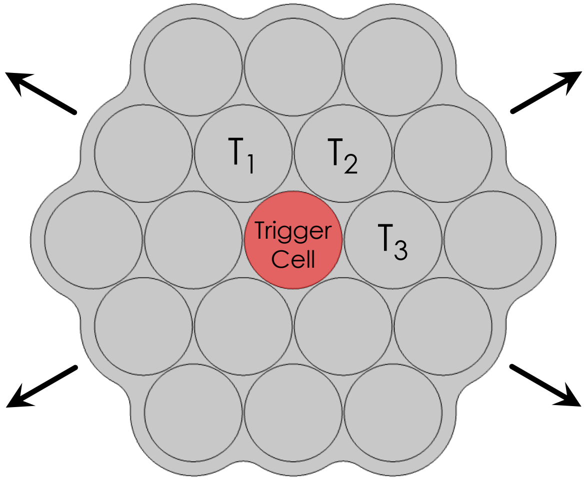
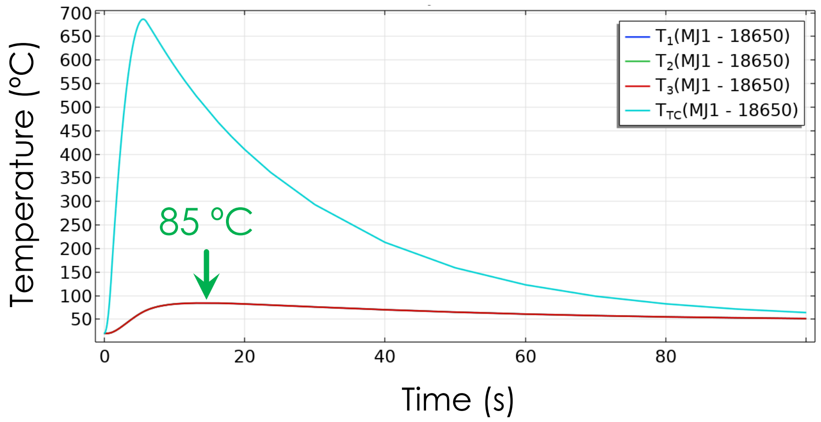
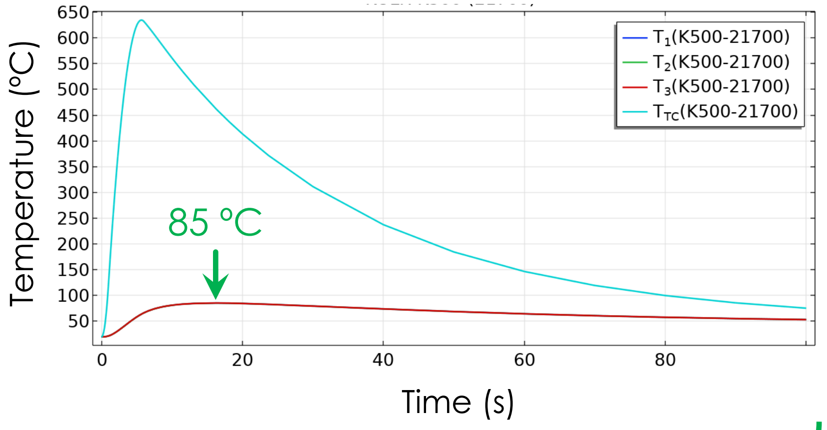


Figure: heat sink with select neighboring cells correlating to plots with thermal modeling predictions.

LG MJ1 (18650, 32.6 kJ, **0.040"**)



KULR K500 (21700, 41.8 kJ, **0.040"**)



Results with 0.040" webbing thickness

BLAST PLATE EVALUATION PLATFORM AND TEST RESULTS

Blast Plate Test Bed (Nail Penetration)

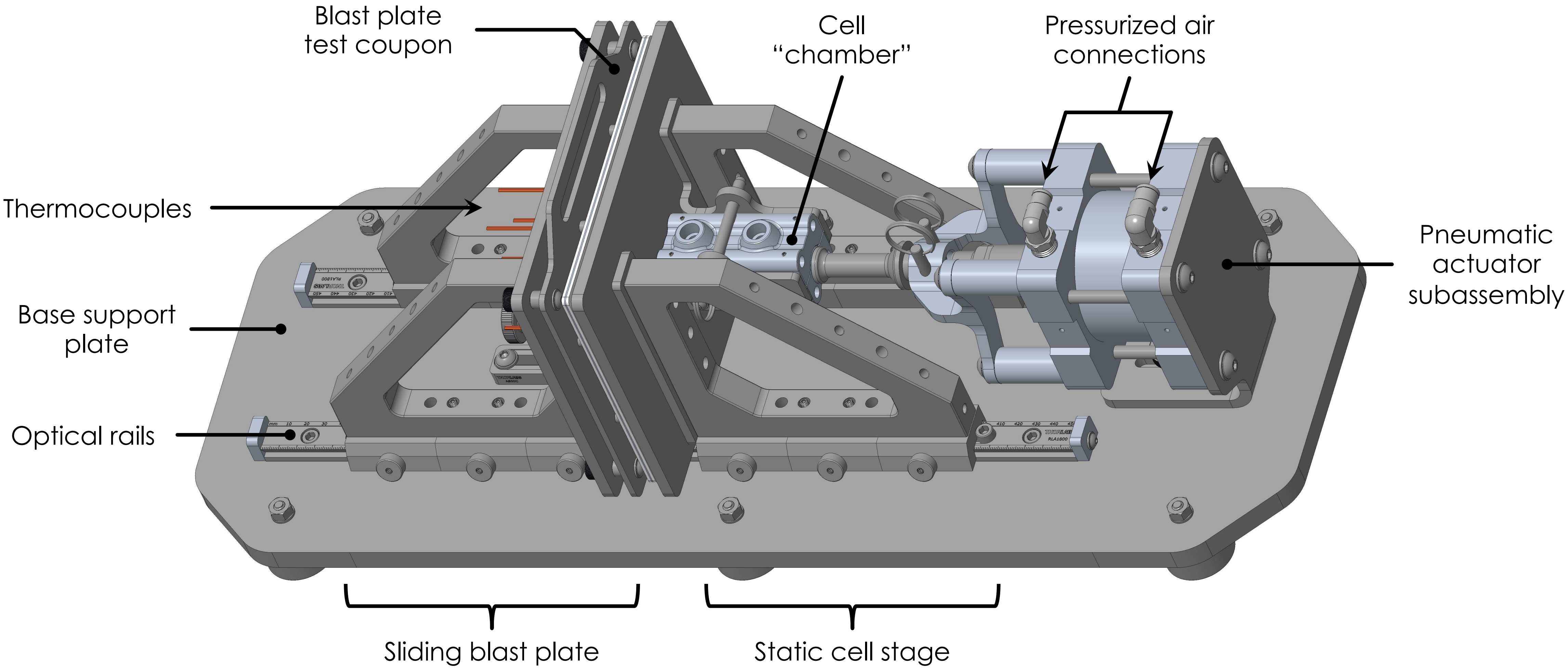


Figure: components of the Blast Plate Test Stand featuring two trigger mechanisms (nail and heat) for driving cell into TR.

Blast Plate Test Coupon Construction

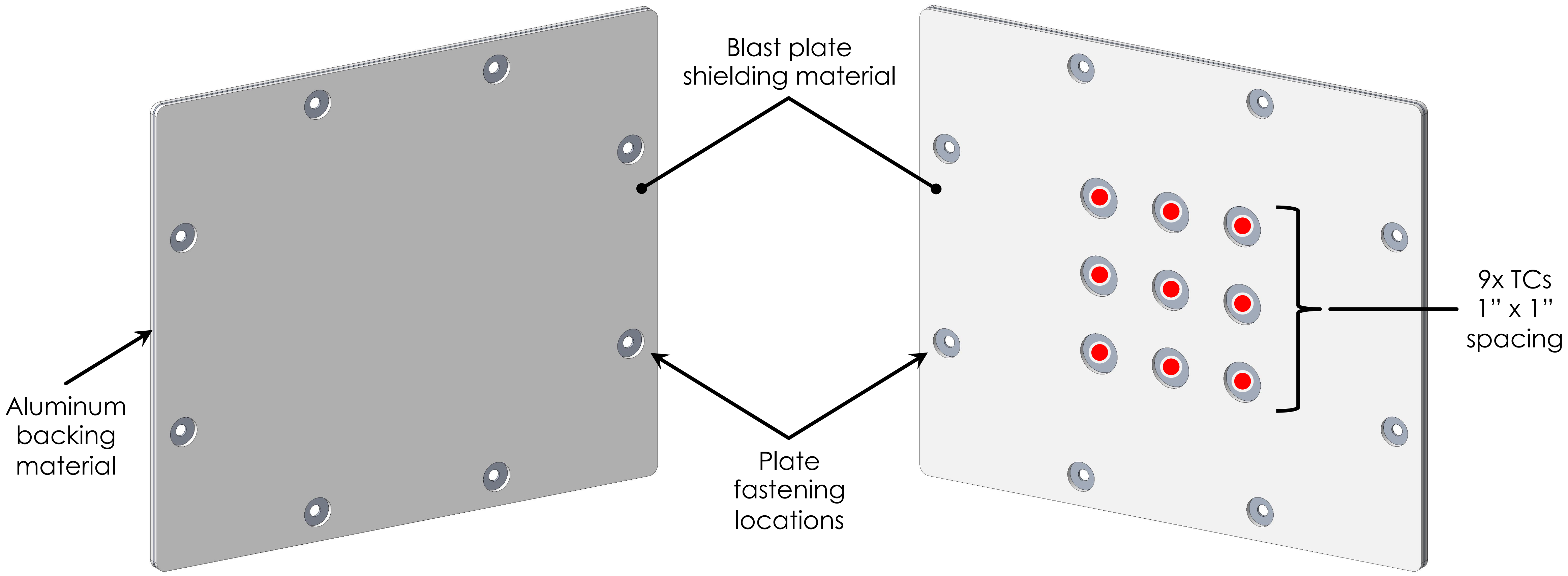


Figure (front view): blast plate shielding material bonded to both sides of 6061 aluminum plate (7" x 6") to produce a test coupon.

Figure (rear view): nine (9) thermocouples, oriented in 1" array, are bonded to aluminum substrate on the rear of the test coupon.

Blast Plate Design of Experiment Factors

Candidate Cells:

- Samsung INR21700 50S
- LG INR21700 M52V
- Coulometrics 5.15Ah Control and ISCD Cells

Standoff Distance:

- 5mm (heritage **M3**)
- 7.5mm (capacity scaled)
- 10mm (oversized gap)

Shielding Materials:

- RS 200 (0.050" Thk.)
- Kaowool 1401 (0.062" Thk.)
- HS900 (0.048" Thk.)
- HS910 (0.070" Thk.)

Test Conditions:

- Perform six (6) test at each configuration to demonstrate repeatability
- Cells triggered via nail (axial insertion) or via heat (~1000W)
- Monitoring temperature of cell can and nine (9) discreet locations on blast plate substrate material

Morgan Advanced Materials

(Kaowool 1401)

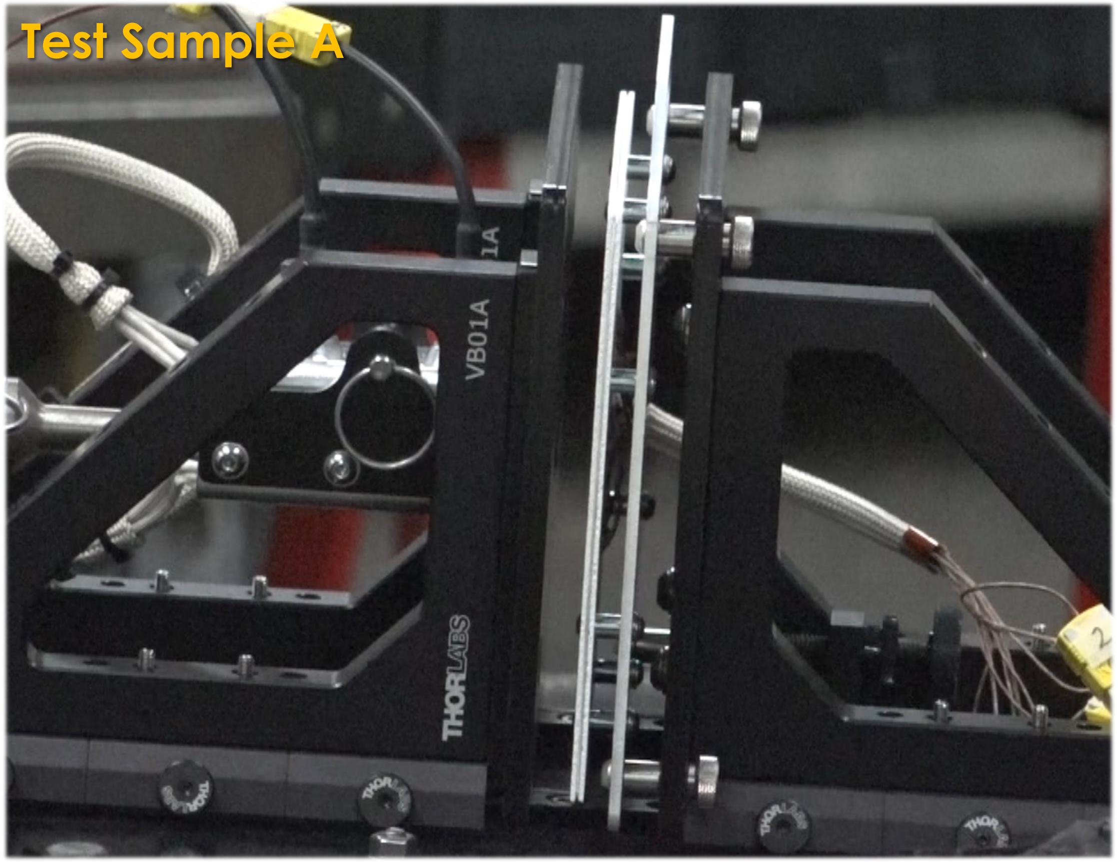
oerlikon

(HS900 and HS910)

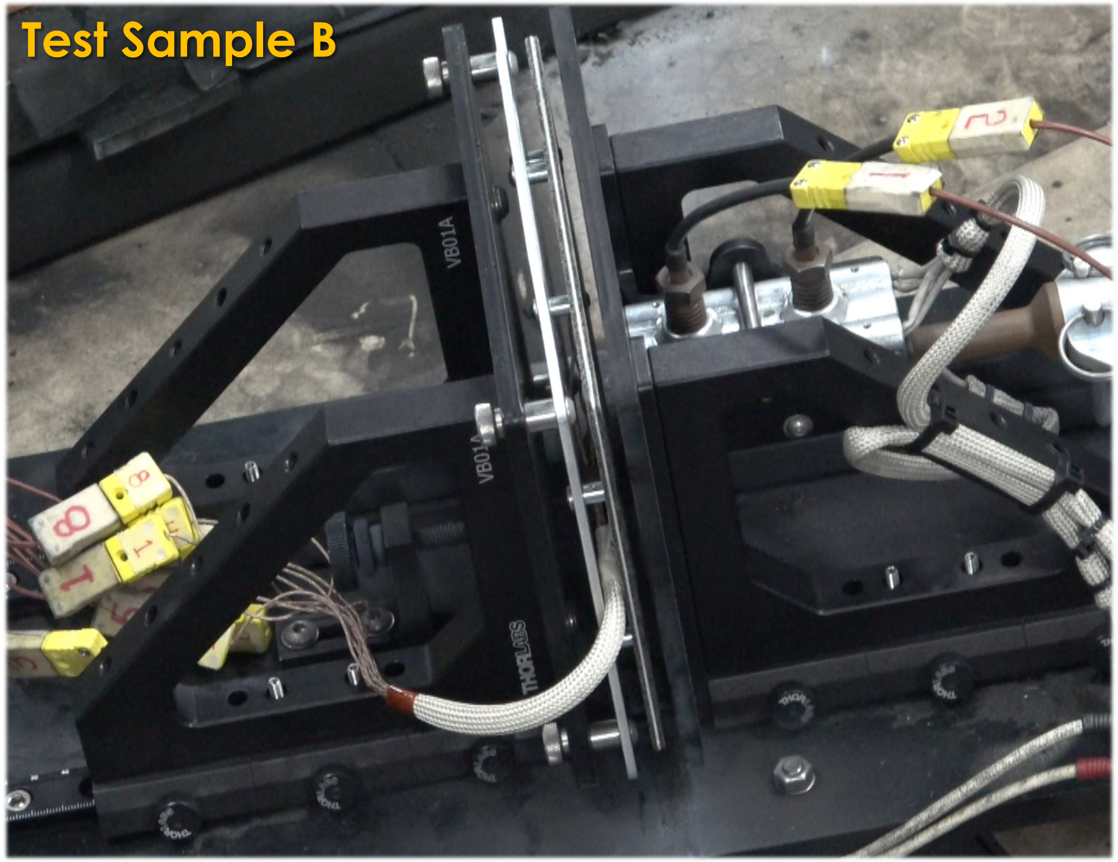
ZRCI REFRACTORY COMPOSITES

(Zircar RS 200)

Blast Plate Testing to Evaluate Shielding Materials



Video: Blast plate test conducted at a fixed distance with a Samsung 50S cell triggered via axial nail penetration.



Video: Blast plate test conducted at a fixed distance with a Samsung 50S cell triggered via axial nail penetration.

Blast Plate Coupon Post-Test – Test Sample A

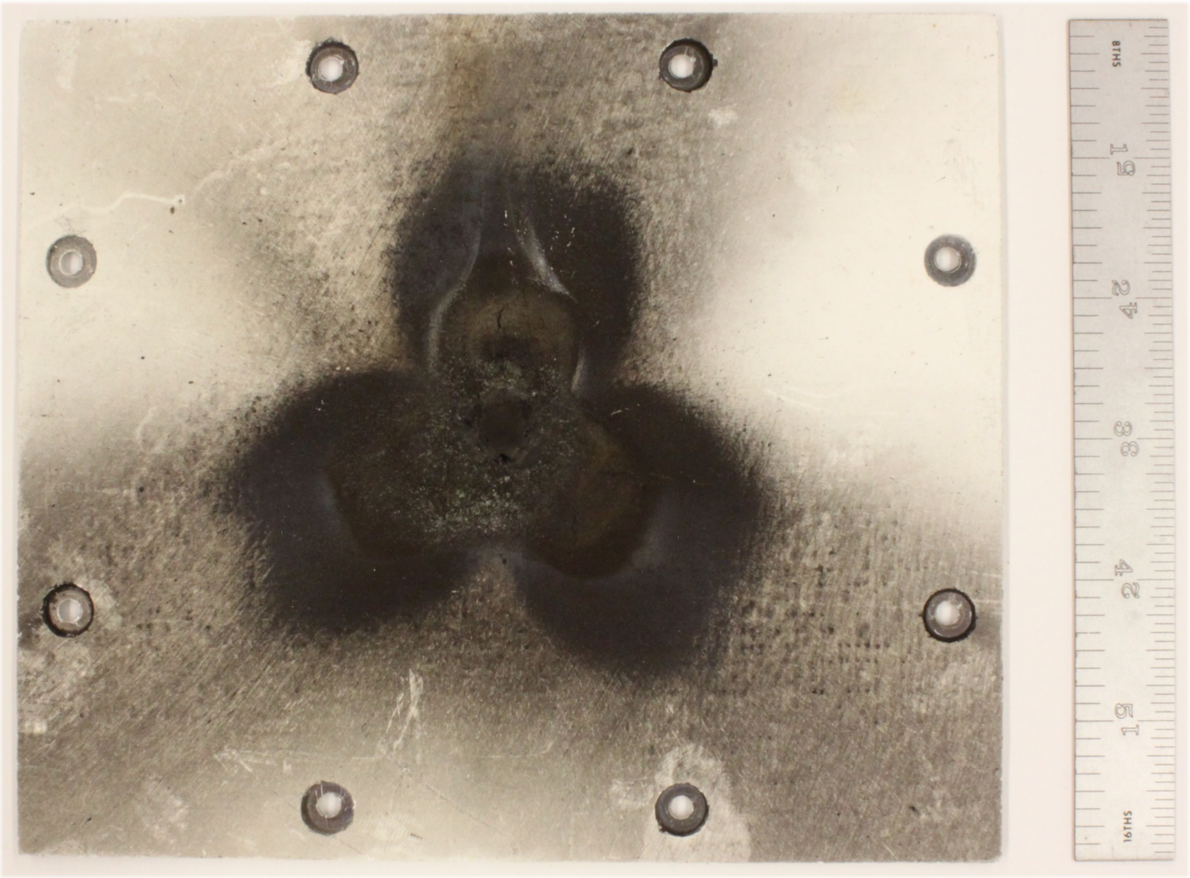
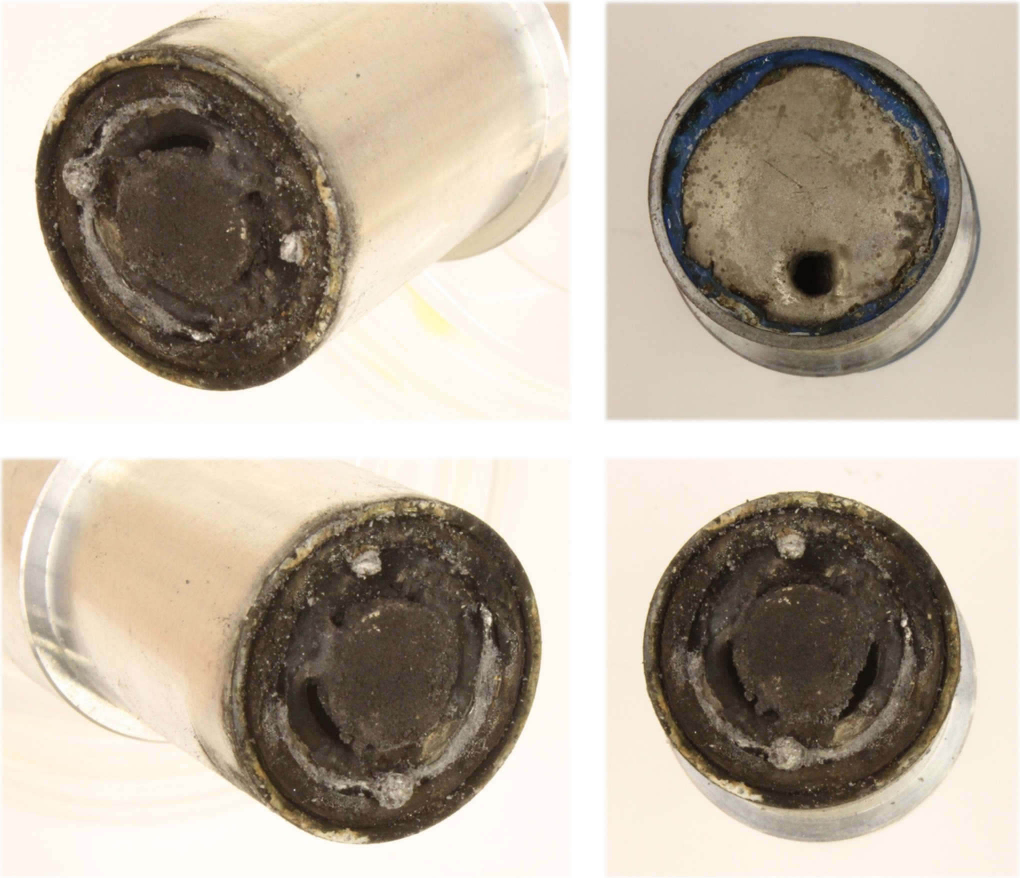


Figure: Front view of test coupon following thermal runaway test with a Samsung 50S cell.



Figures: various views of “spent” Samsung 50S cell following blast plate test at pre-set distance.

Blast Plate Coupon Post-Test – Test Sample B

Figure: Front view of test coupon following thermal runaway test with a Samsung 50S cell.

Figures: various views of "spent" Samsung 50S cell following blast plate test at pre-set distance.

Blast Plate Substrate Material Thermal Profiles

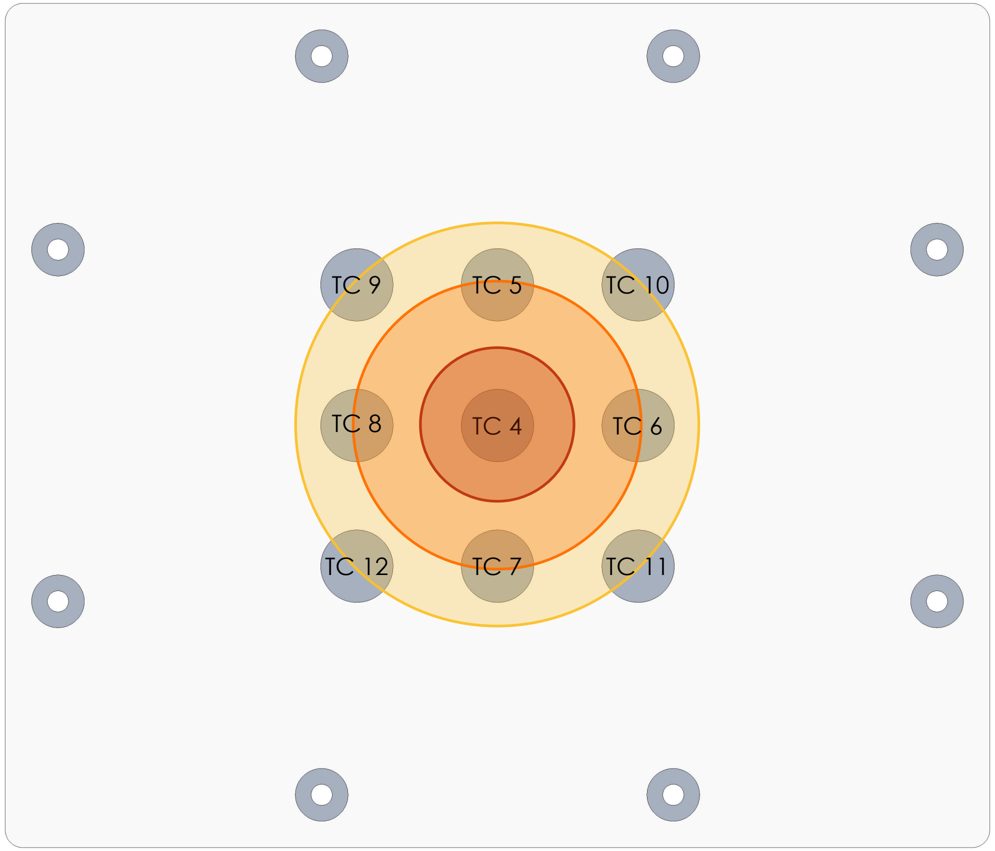


Figure: Shaded circles representing relative "isotherms" measured in the blast plate substrate.

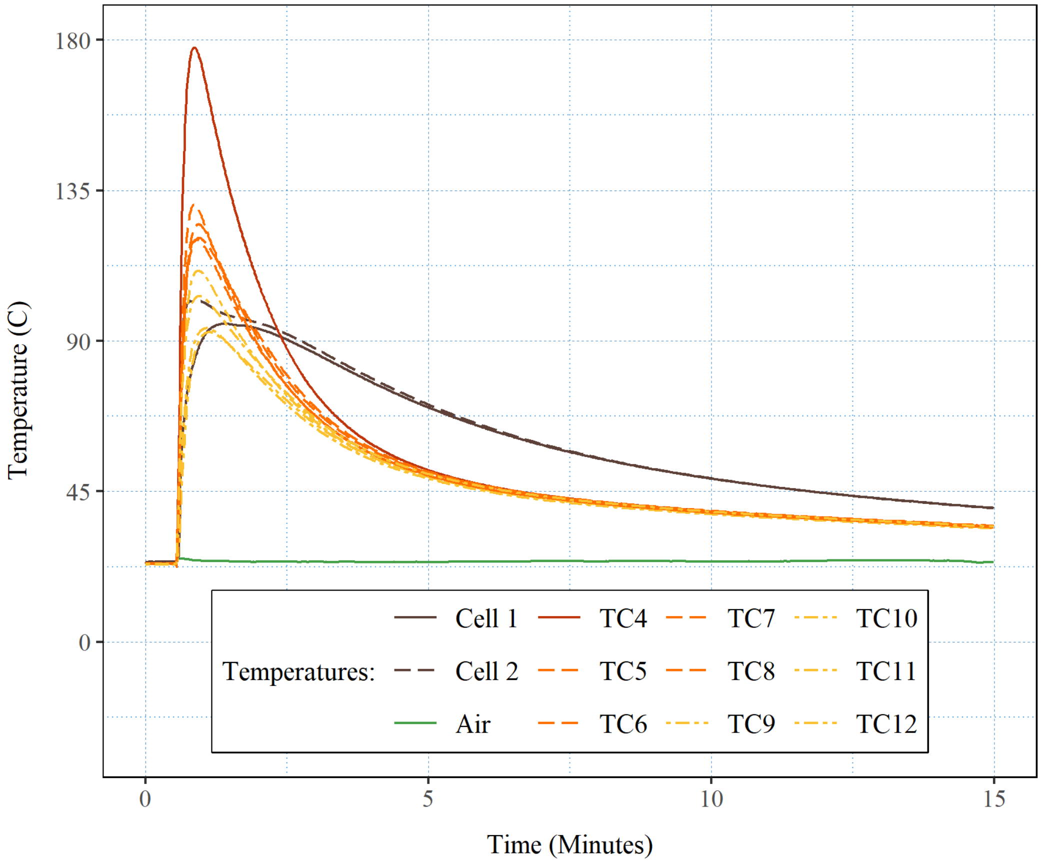


Figure: Thermal test data measured at discrete points (TC 4-11, left) on blast plate substrate material.

M3 AND ***M5*** SUBSCALE MODULE DESIGN AND TEST RESULTS

Objectives for Subscale Battery Testing

- Design a representative battery module for testing candidate cells to evaluate PPR safety features successfully implemented in18650 batteries
- Three (3) heat sink designs were considered:
  - 18650 with 0.020" webbing (baseline for comparison)
  - 21700 with 0.020" webbing (optimal design)
  - 21700 with 0.040" webbing (alternate design)
- Two (2) candidate cells would be evaluated in each of the 21700-heat sink designs: Samsung 50S, LG M52V
- Implement lessons learned from blast plate testing toward the design of the subscale battery modules
- Conduct three (3) separate thermal runaway events, recording electrical and thermal data for model calibration and analysis
- Provide relevant comparisons (energy density, etc.) to guide future full-scale battery designs

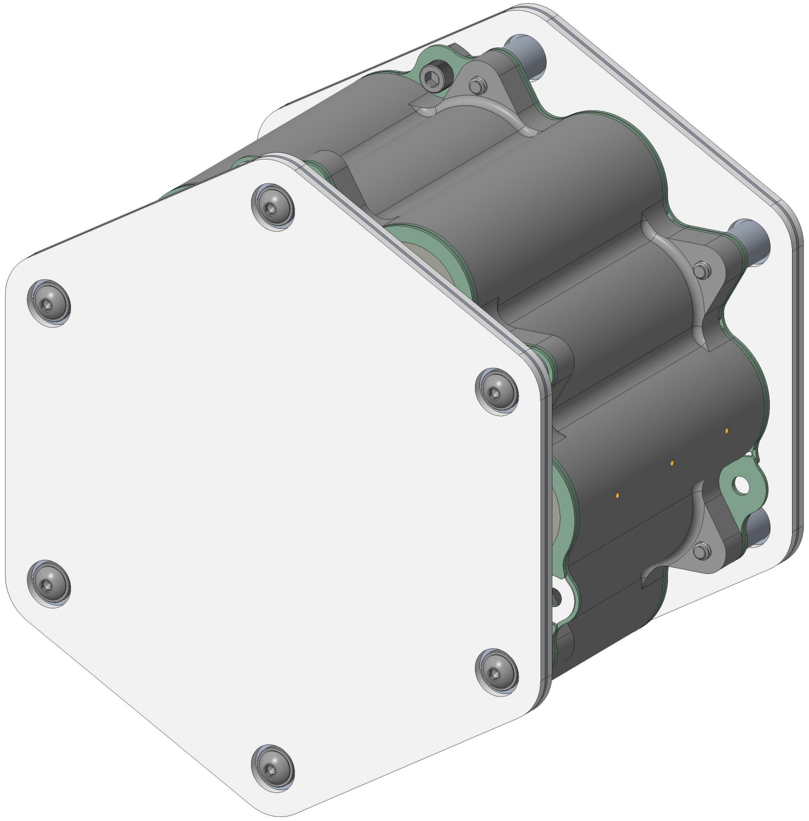
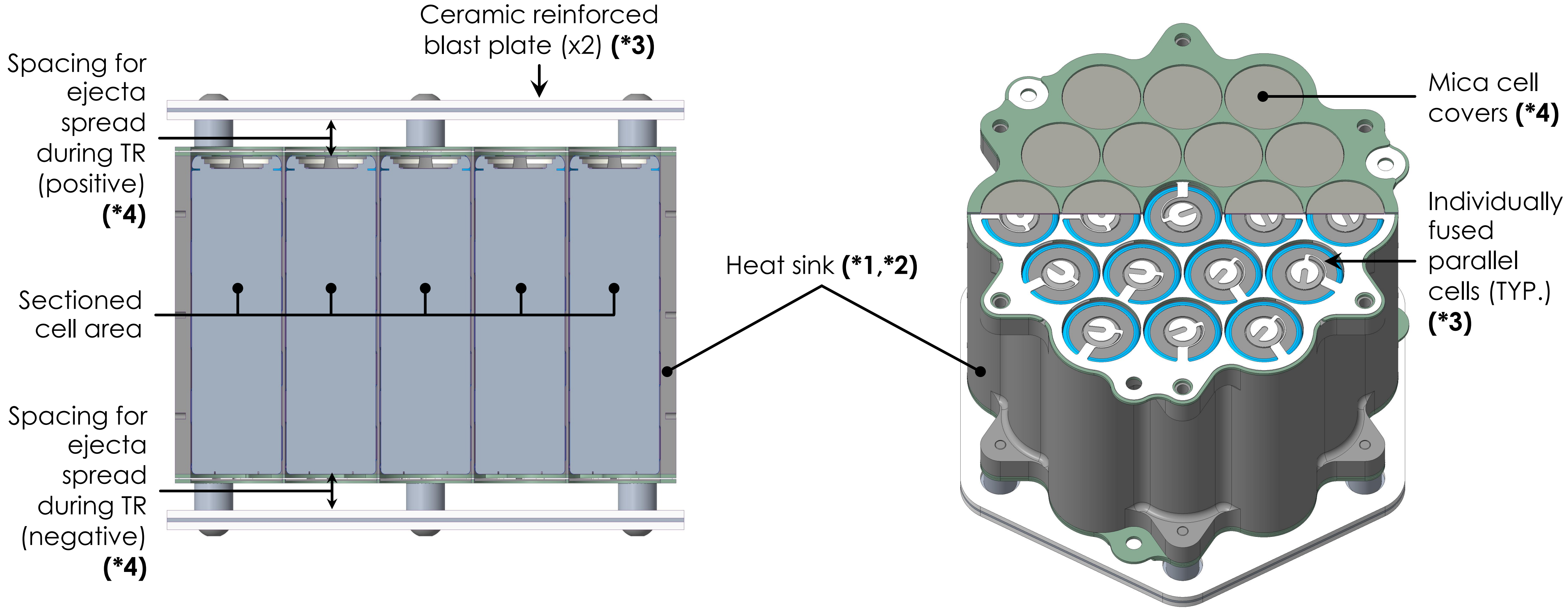


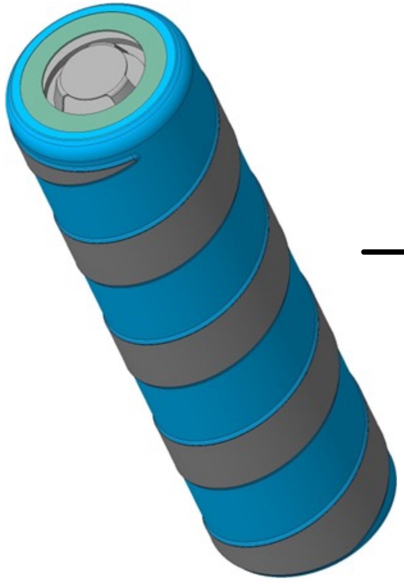
Figure: CAD rending or subscale 19-cell module designed for testing and comparing PPR features and thermal performance.

Subscale Battery PPR Design Features

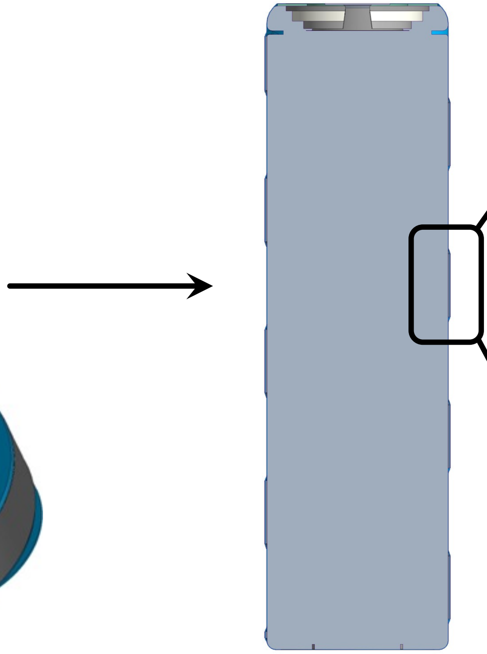


Note: An asterisk followed by a number (e.g., ***1**) indicates the PPR Battery Guideline the feature correlates to. Guideline 5 (battery enclosure) guideline was not represented in this battery design due to application requirements.

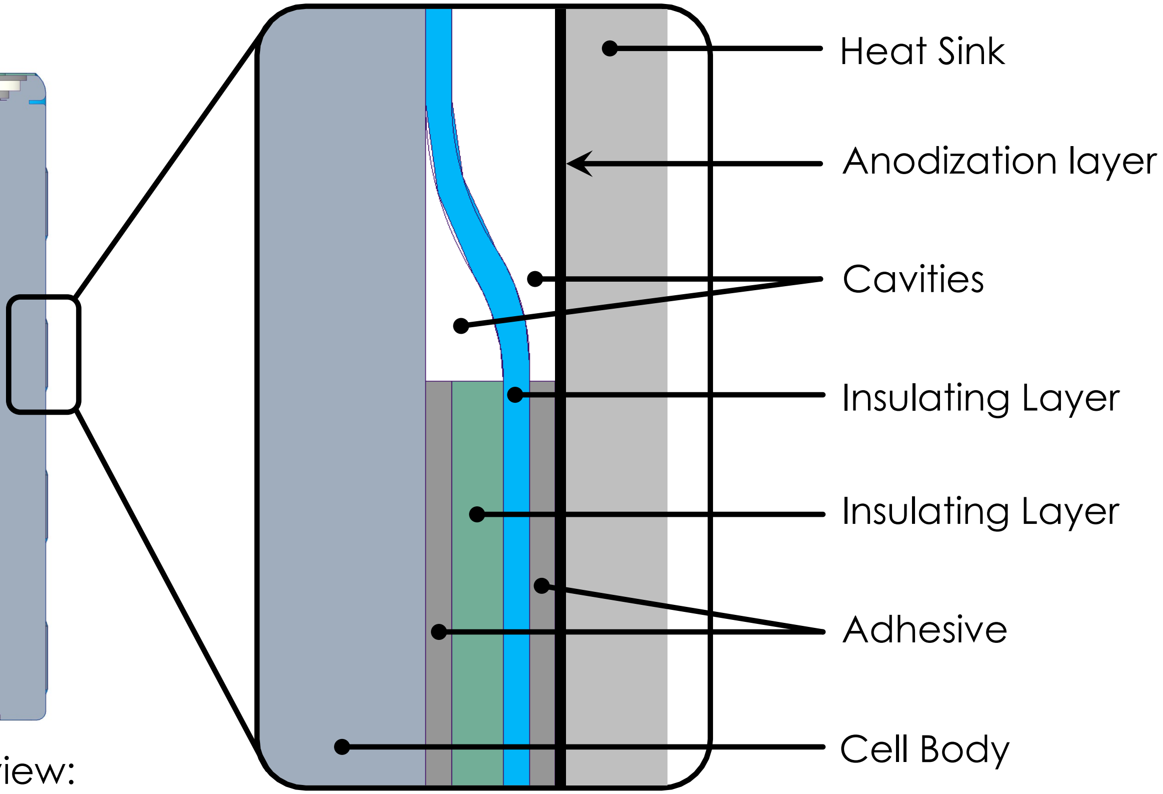
Cells Prepared with Layered Ribbon Insulation



Isometric view: wrapped cell



Section view: wrapped cell



Reference: Junghoon Lee, Yonghwan Kim, Uoochang Jung, Wonsub Chung - Thermal conductivity of anodized aluminum oxide layer: The effect of electrolyte and temperature, Materials Chemistry and Physics, 141 (2013) 680-685.

Thermal Effects of Layered Ribbon Insulation

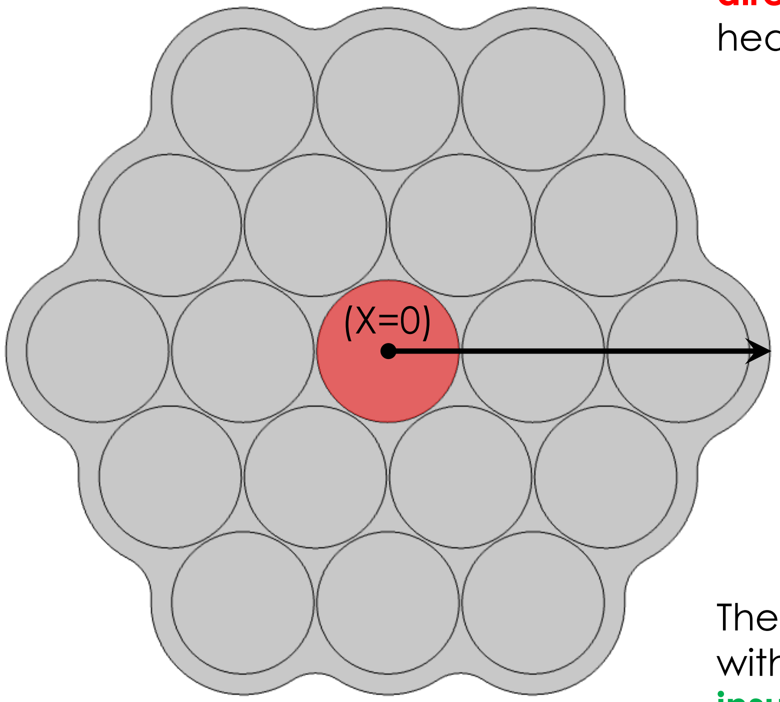
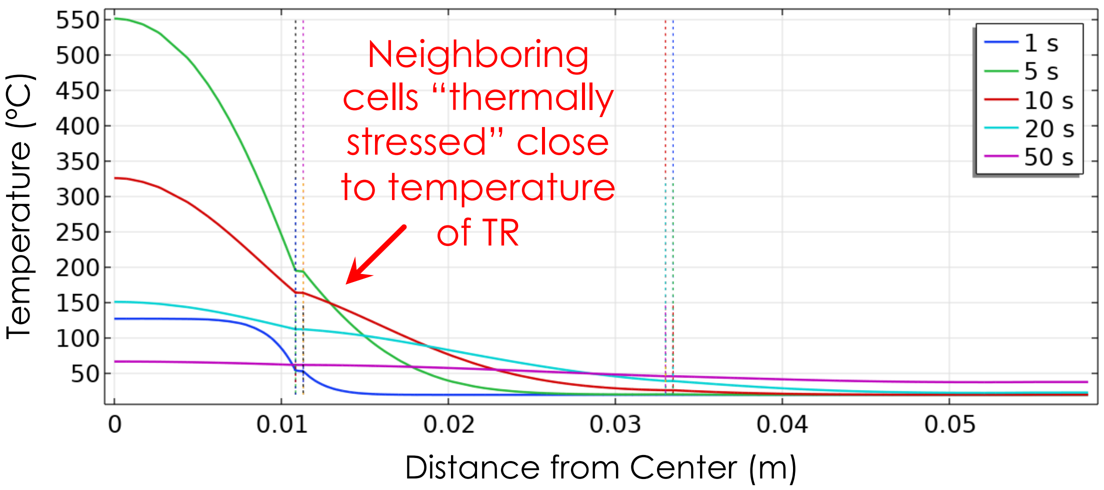
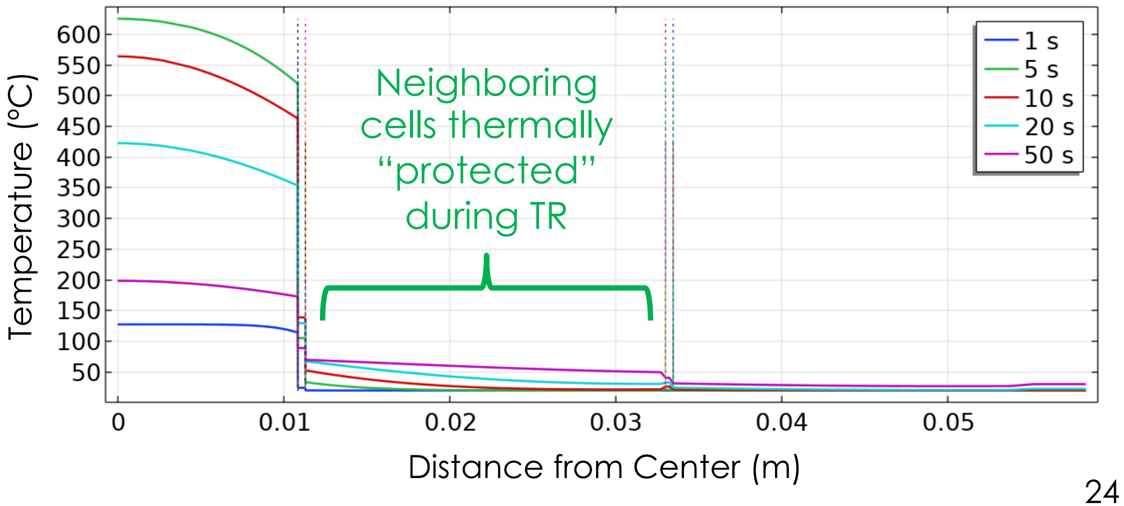


Figure: Heat sink with 21700 cells spaced with 0.020" interstitial webbing.

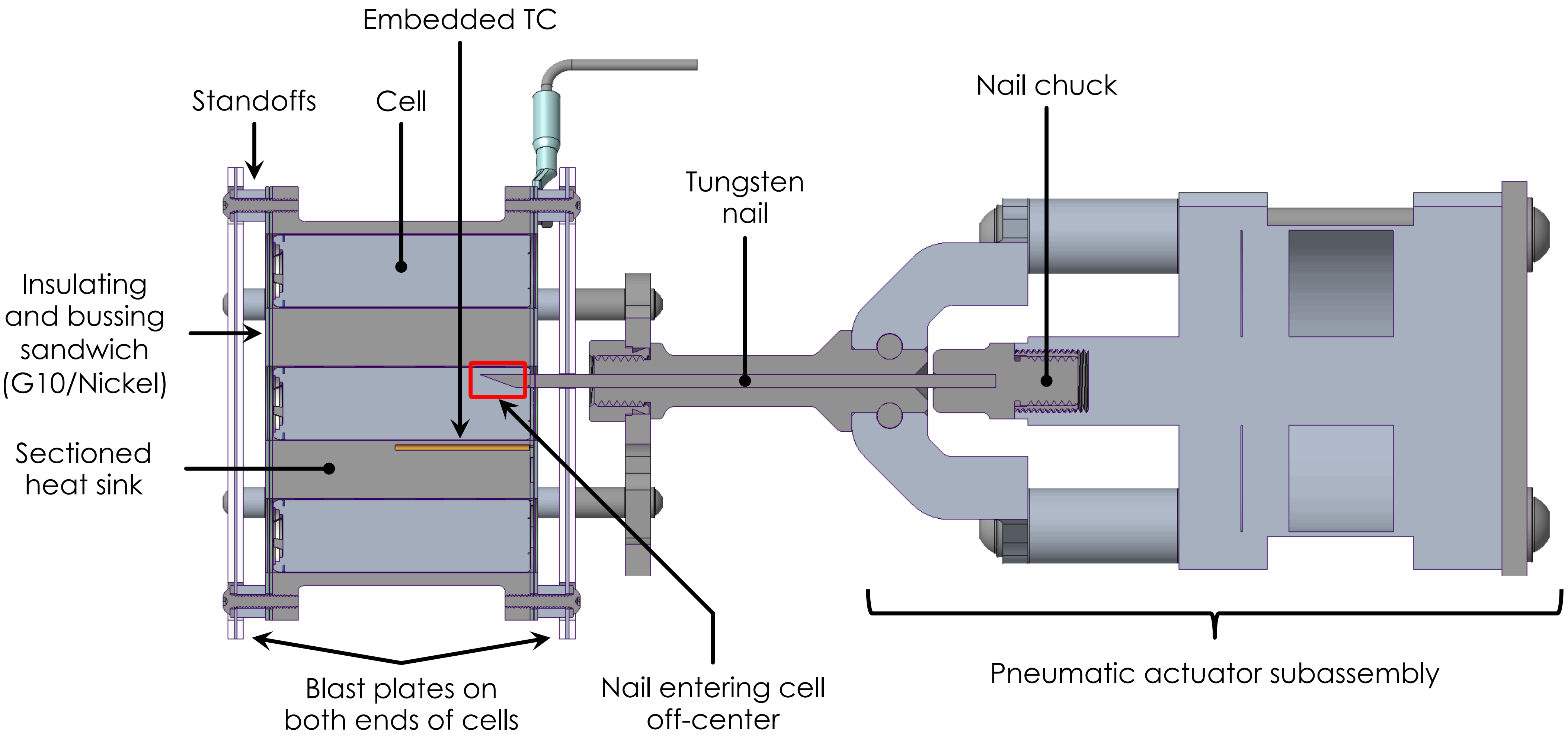
Thermal predictions with cells bonded **directly** to aluminum heat sink



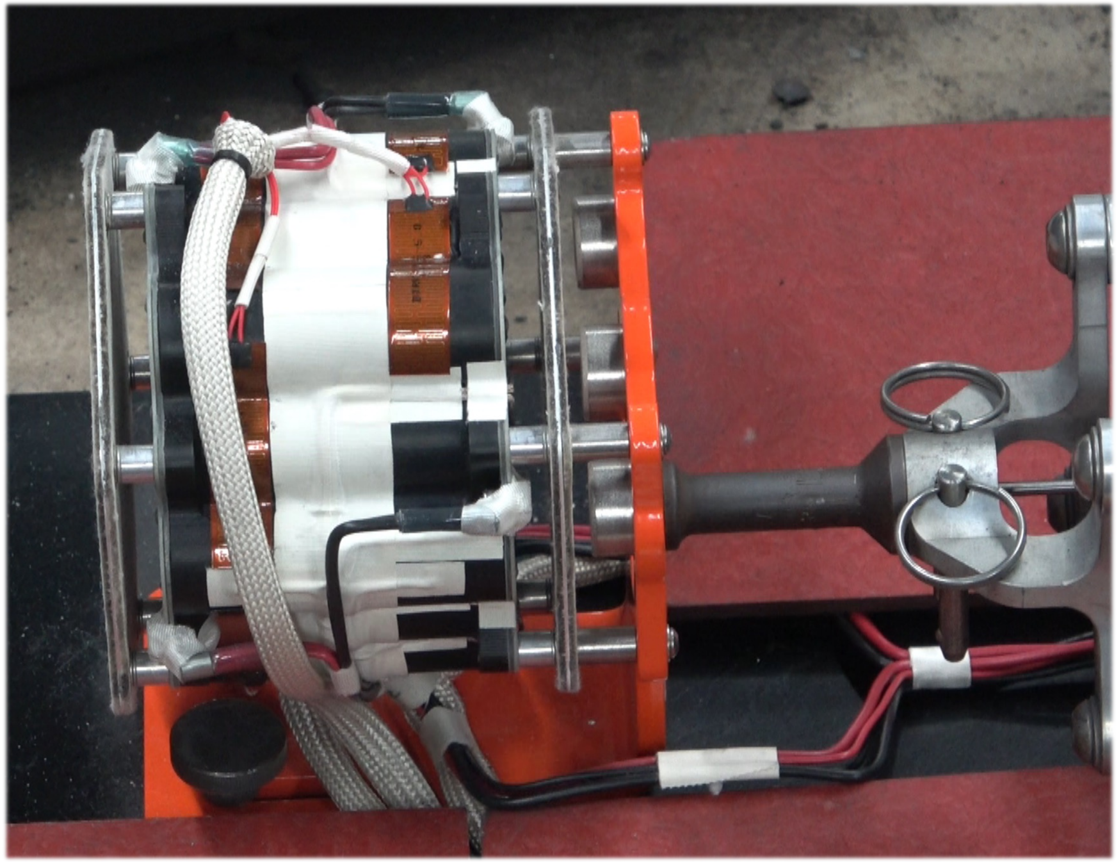
Thermal predictions with **layered ribbon insulation** applied to cells for thermal and electrical isolation



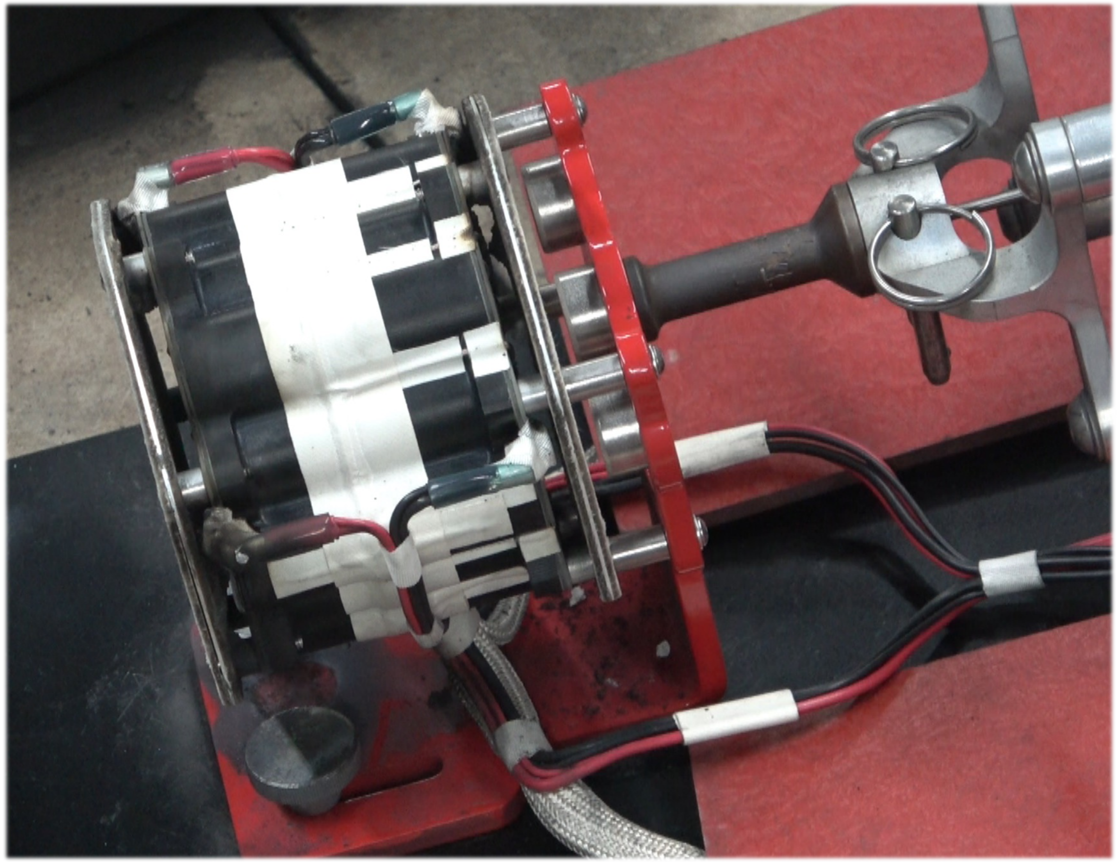
Subscale Battery Test Platform (Section View)



M5 and ***M3*** Subscale PPR Battery TR Tests



Video: Elevated temperature test; thermal runaway of LG M52V edge cell (Cell 8) with a positive end failure.



Video: Thermal of Molicel M35A internal cell (Cell 10) with failure observed from both the positive and negative ends.

Comparison of Modeling Predictions to Test Data

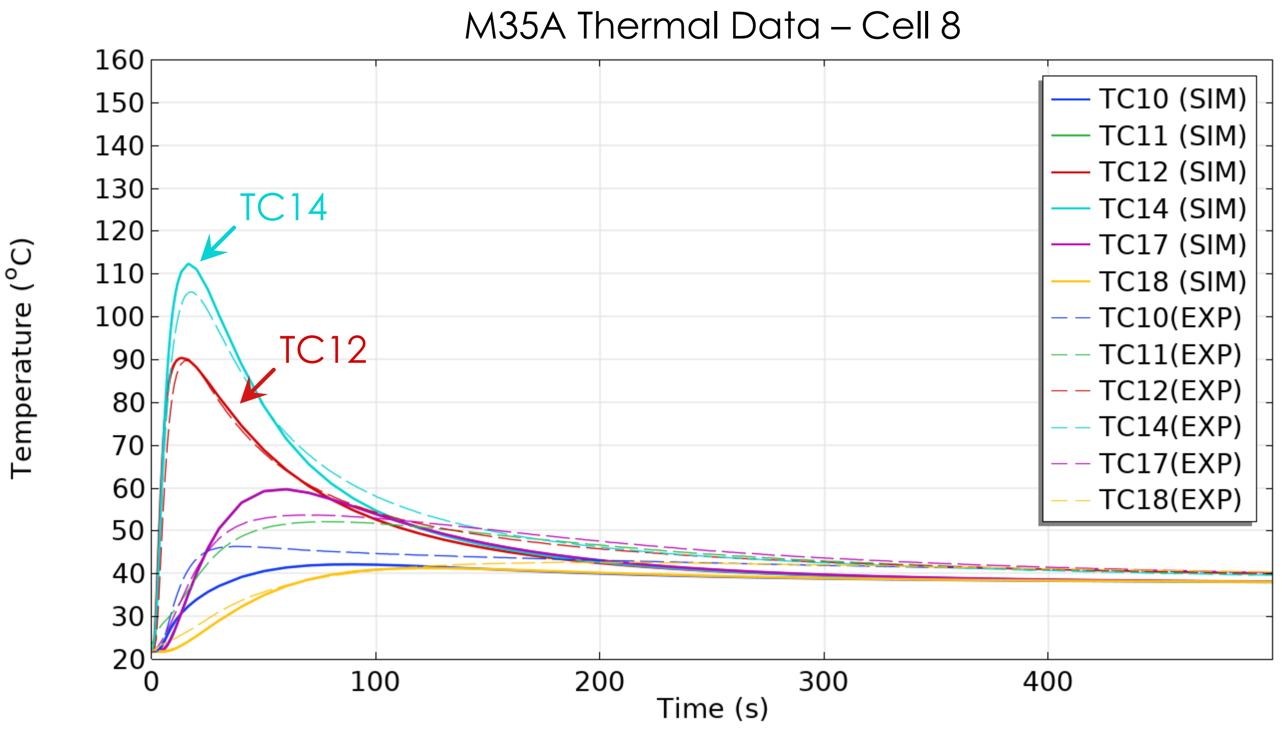


Figure: Experimental data plotted together with modeling data for selected thermocouple locations. The experimental results (EXP) of the heat sink (TC 12, 14) have good agreement with the model predictions surrounding the trigger cell (Cell 8).

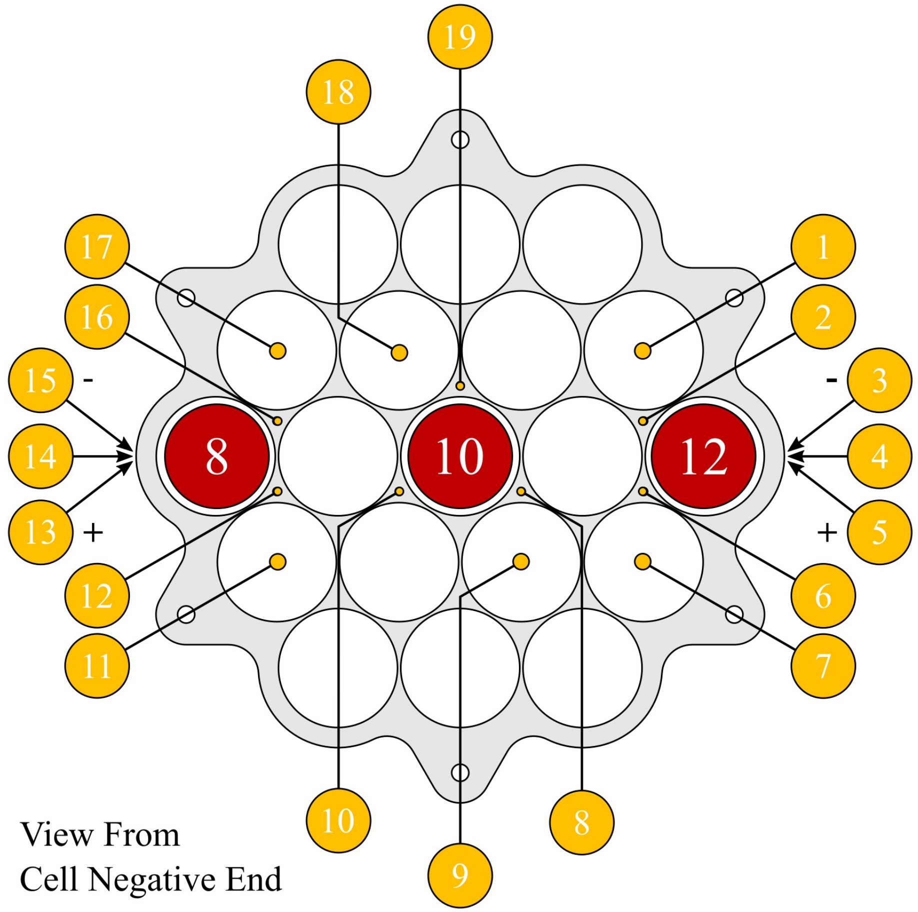
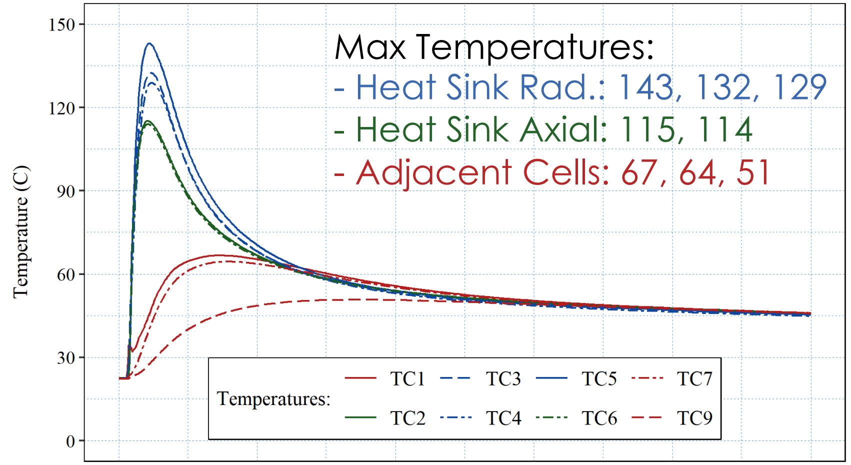


Figure: Location of trigger cells (**red**, run order: Cell 1, Cell 12, Cell 10) and thermocouples (**yellow**).

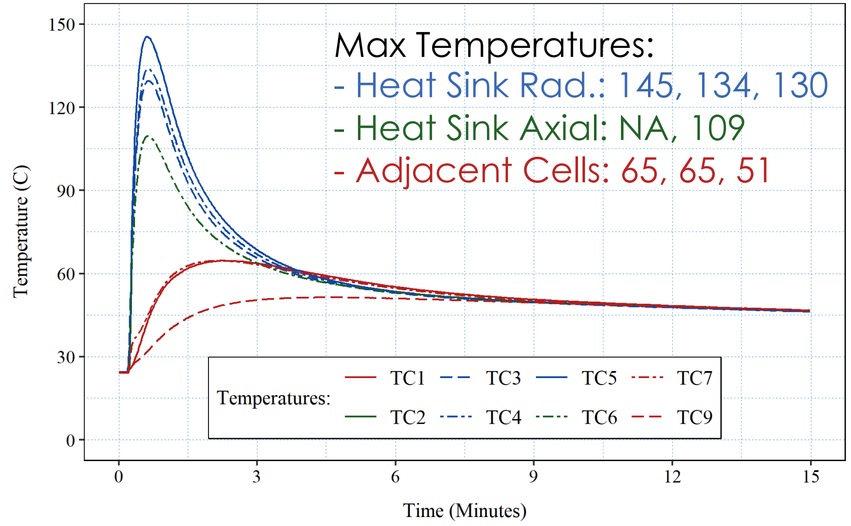
Thermal Impact of Webbing Thickness (Cell 12)



M5 | 0.020" 50S

Max ΔT = 7°C

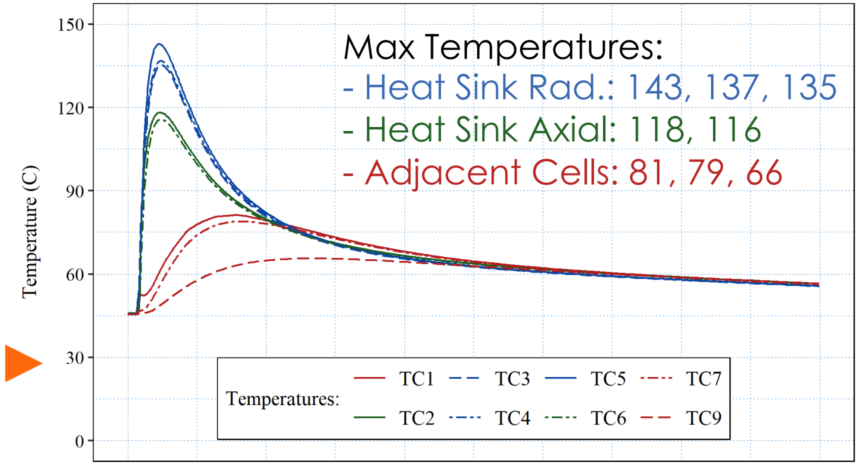
M5 | 0.040" 50S

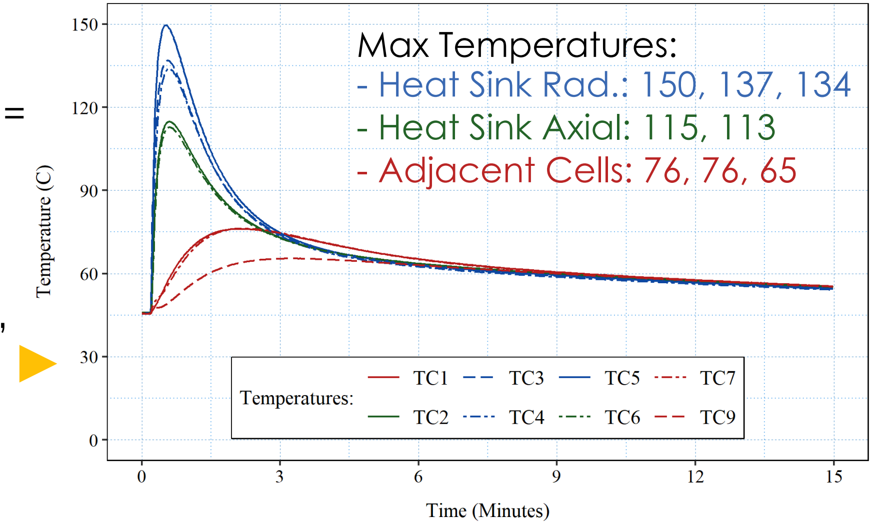


M5 | 0.020" M52V

Max ΔT = 7°C

M5 | 0.040" M52V





Sample Post Test Battery DPA Results

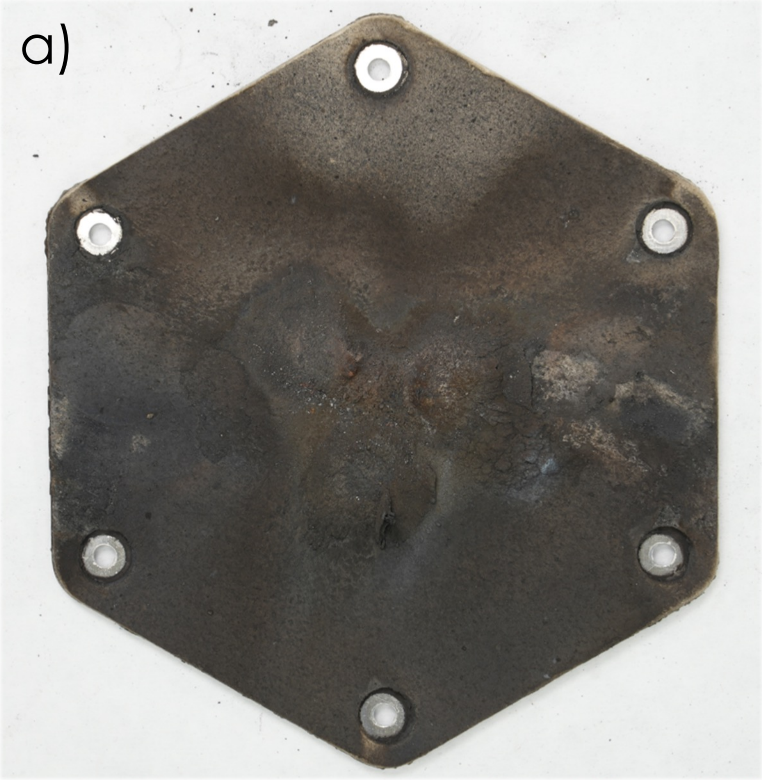


Figure: Positive end blast plate removed post-test. Buildup of cell ejecta "domes" aligned with trigger cell locations.

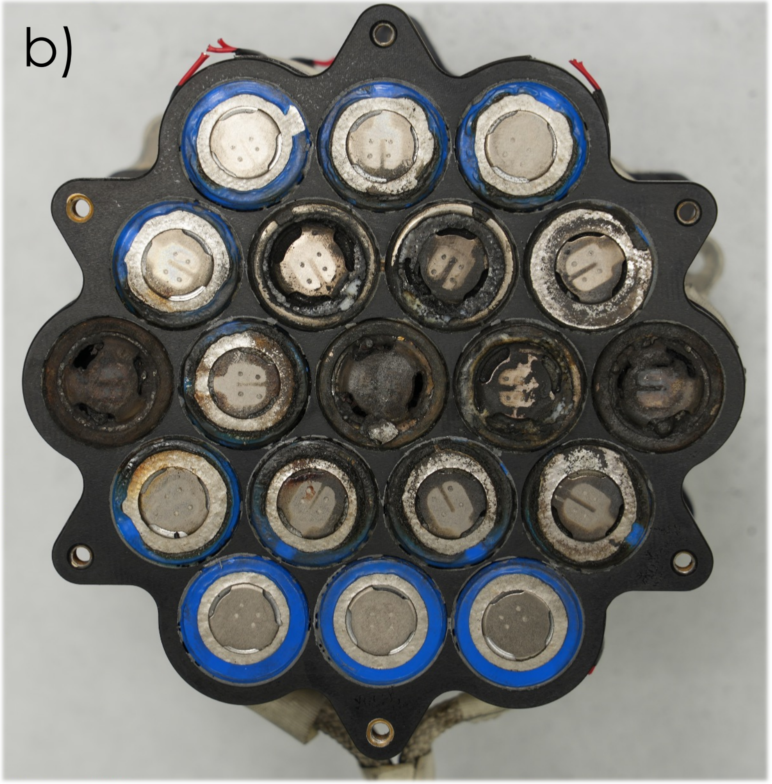


Figure: Bussing removed for inspection of interstitial webbing between cells due to off-nominal failures such as SWR/SGR.

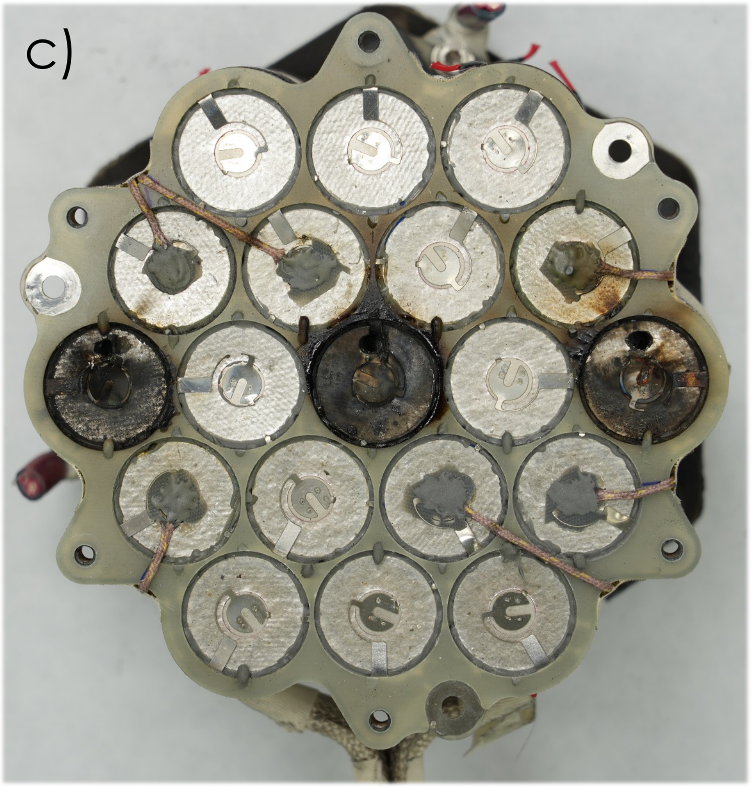


Figure: Mica cell covers removed for the inspection of the fuses post-test. Fuses on Cells 5 and 9 were blown.

M3 *and* ***M5*** Subscale Battery Characteristics

	M3 0.020" M35A	M5 0.020" 50S	M5 0.040" 50S	M5 0.020" M52V	M5 0.040" M52V
Form Factor:	18650	21700	21700	21700	21700
Cell Type:	Molicel M35A	Samsung 50S	Samsung 50S	LG M52V	LG M52V
Battery Capacity:	231.1 Wh	340.3 Wh	341.1 Wh	351.5 Wh	352.3 Wh
Total Battery Mass:	1.311 kg	1.915 kg	1.974 kg	1.863 kg	1.922 kg
Gravimetric Energy Density:	**173.6 Wh/kg**	**177.7 Wh/kg**	**172.8 Wh/kg**	**188.7 Wh/kg**	**183.3 Wh/kg**
Parasitic Mass Factor:	**1.544**	**1.439**	**1.484**	**1.457**	**1.503**
Total Cell Mass Percentage:	64.7%	69.5%	67.4%	68.6%	66.5%
Heat Sink Mass Percentage:	24.3%	21.3%	23.5%	21.9%	24.1%
Blast Plate Mass Percentage:	3.9%	3.2%	3.2%	3.3%	3.3%

Insights on Upscaling – 18650 to 21700

- Passing criteria for blast plate tests:
  - No perforations in the blast plate coupon (shielding and substrate materials)
  - Adequate standoff distance between the cell and blast plate for sufficient ejecta spread
- Fifteen (15) individual thermal runaway trigger events **demonstrate high level of robustness** of interstitial aluminum heat sink design in protecting against TR propagation
  - 10 edge triggers (3 neighboring cells)
  - 5 center triggers(6 neighboring cells, all **double insult tests**)
- Doubling thickness of aluminum webbing between cells has marginal benefit on thermal response (**less than ~10°C delta**)
- Energy density benefit largely dependent on candidate cell, **~8.6% specific energy benefit** comparing Molicel M35A vs. LG M52V with 0.020" webbing

Figure: video frame capture moments after initiating thermal runaway of Cell 8 via axial nail penetration.

Acknowledgement of Partnership

NAVSEA Warfare Centers	NASA	UofSC
Joe H. Fontaine (NSWC Crane, IN)	Eric C. Darcy (JSC)	Ralph E. White
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THANK YOU!

BACKUP SLIDES

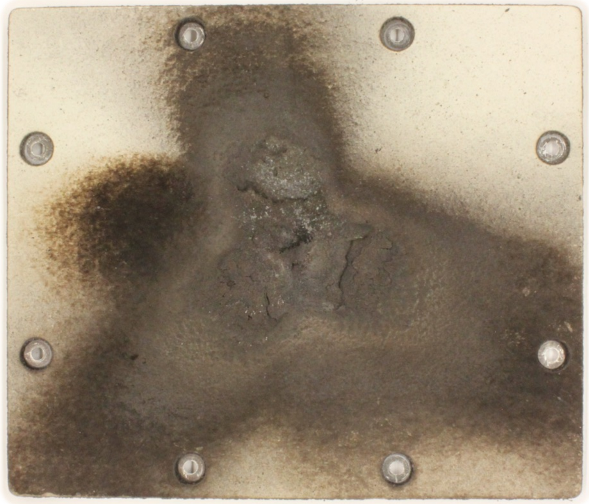
Studies that Guide PPR Battery Design

Side Wall Rupture (SWR) Testing

- Evaluating the propensity of cells to fail "off-nominally" when subject to constraints of PPR battery pack
- Provides a statistical representation of the chance of the failure occurring in the full population of cells

Blast Plate Testing (BPT)

- Evaluating blast plates constructed with a refractory material bonded to substrate to tolerate TR events
- Evaluating the offset distance between the cell and blast plate necessary to provide sufficient space for cell ejecta to occupy



Fractional Thermal Runaway Calorimetry (FTRC)

- Evaluating thermal response from cells undergoing thermal runaway

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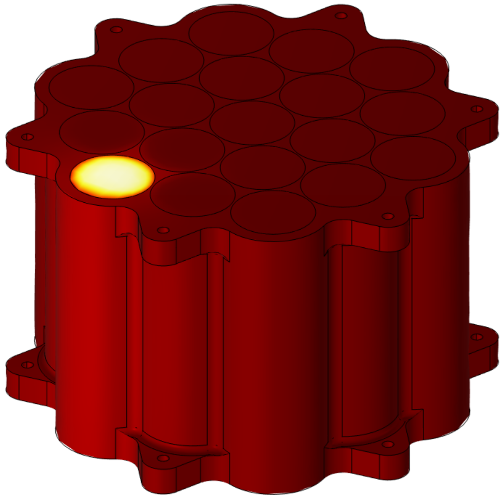


Blast Plate Test Bed (Nail Penetration)

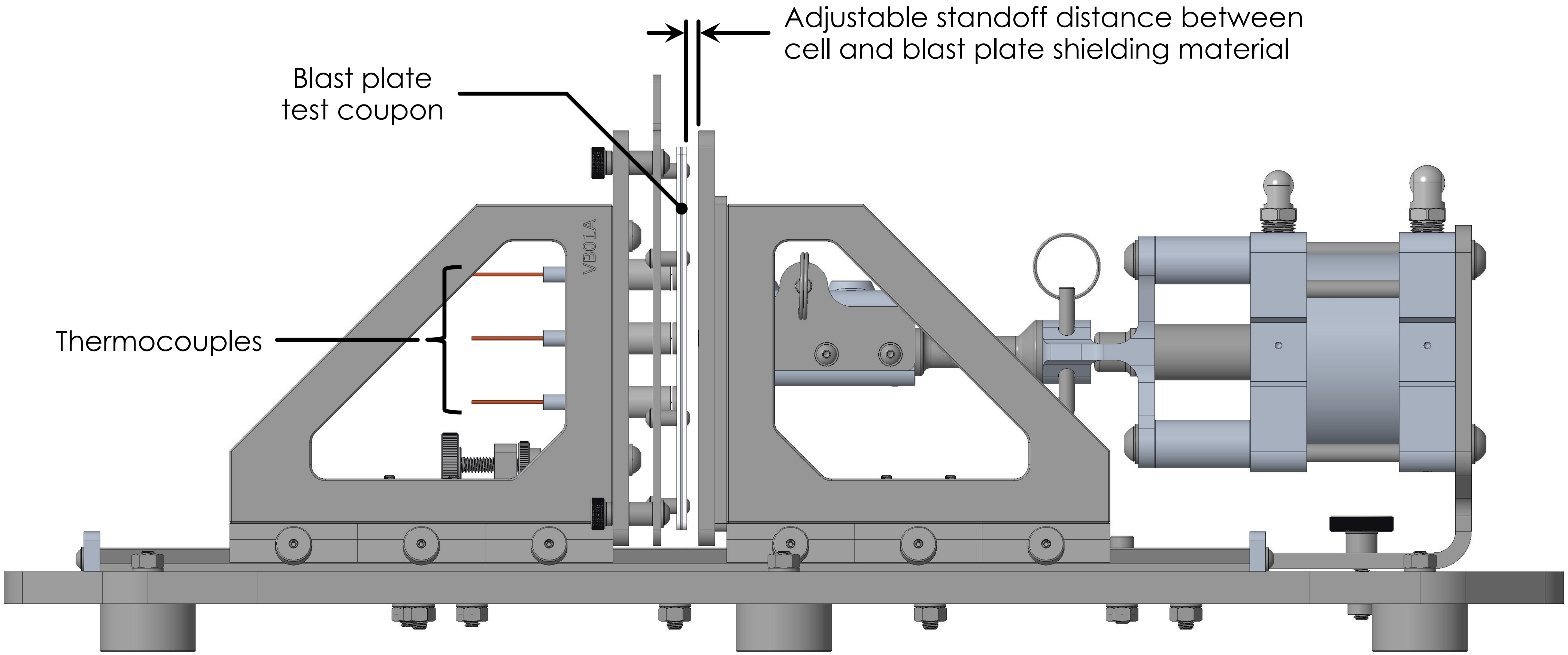
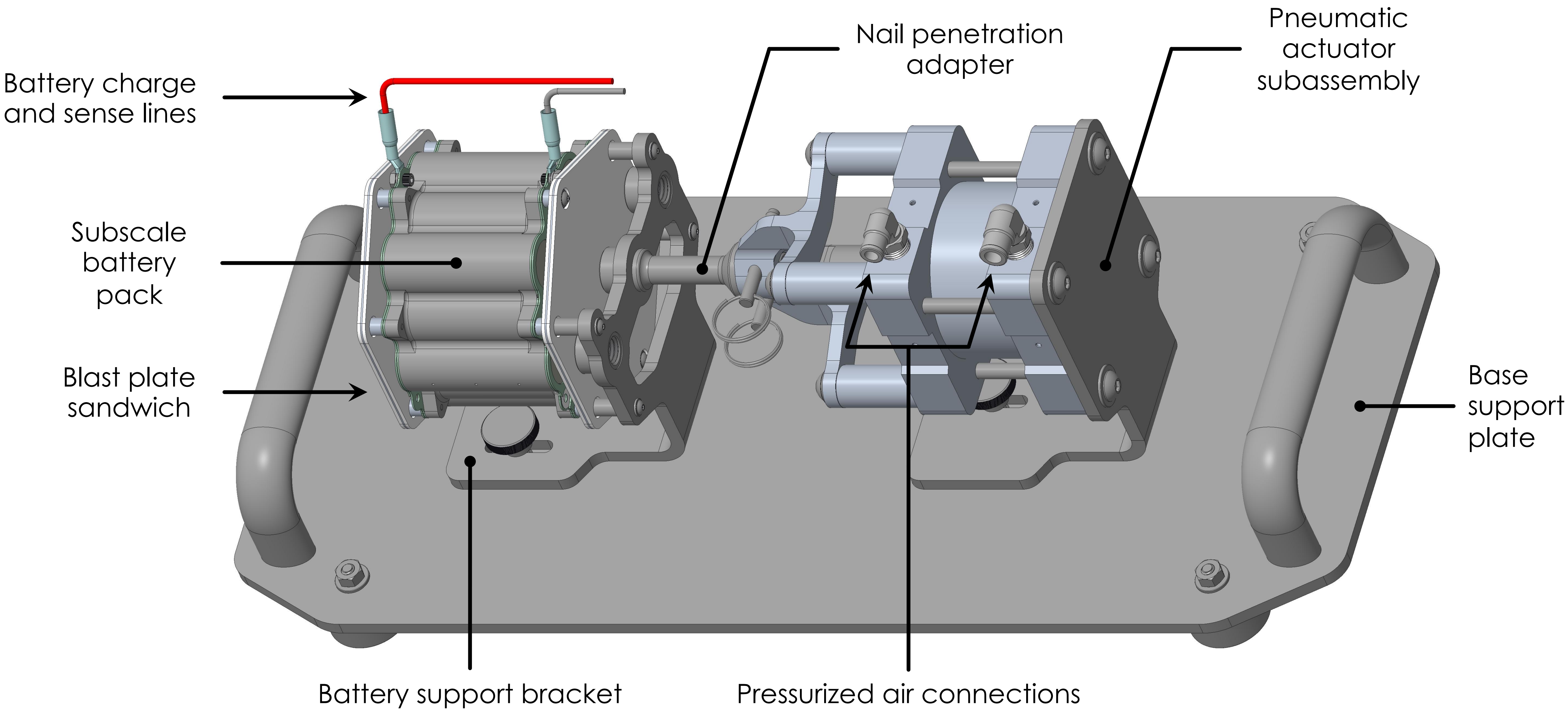
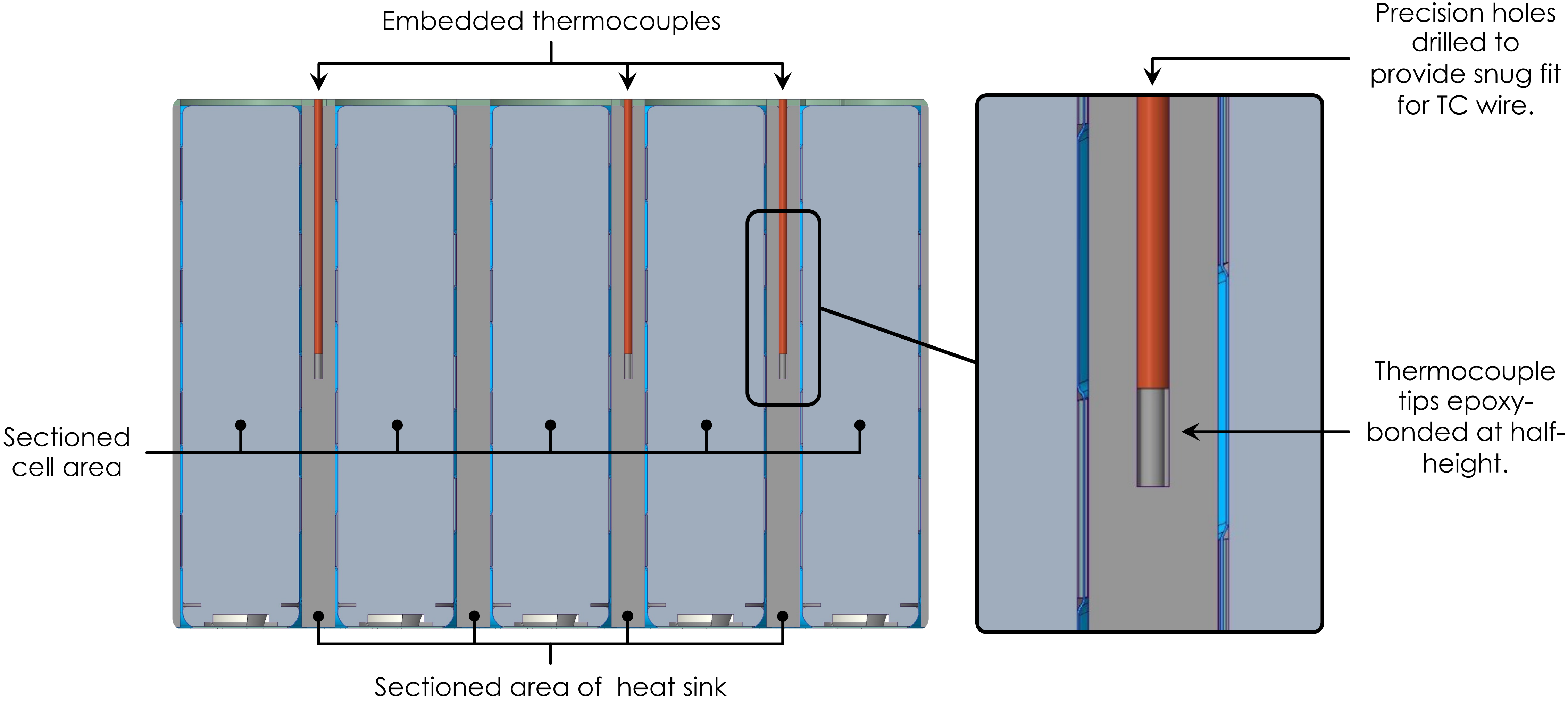


Figure: an adjustable sliding stage allows adjustment of the standoff distance between the blast plate and cell.

Subscale Battery Test Platform (Nail Penetration)



Thermocouple Installation



Cell and Battery Instrumentation Details

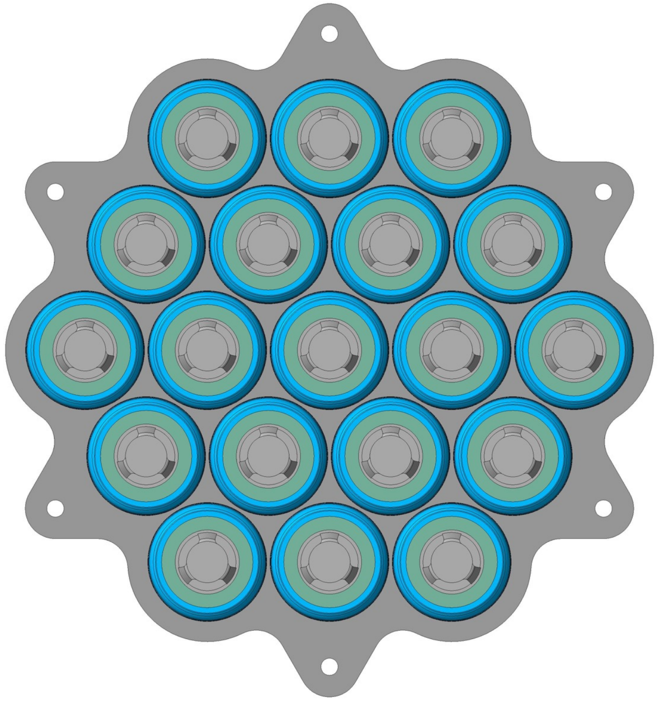


Figure: battery modules with a 19-P topology were designed for testing candidate 21700-cells (top view).

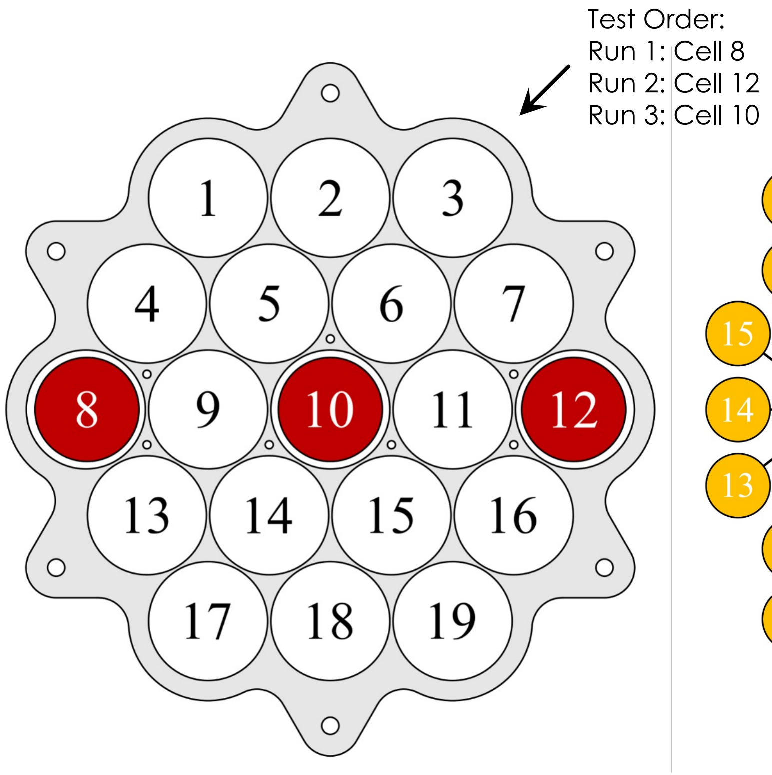


Figure: cell positions with trigger cells highlighted in red circles triggered in separate TR events.

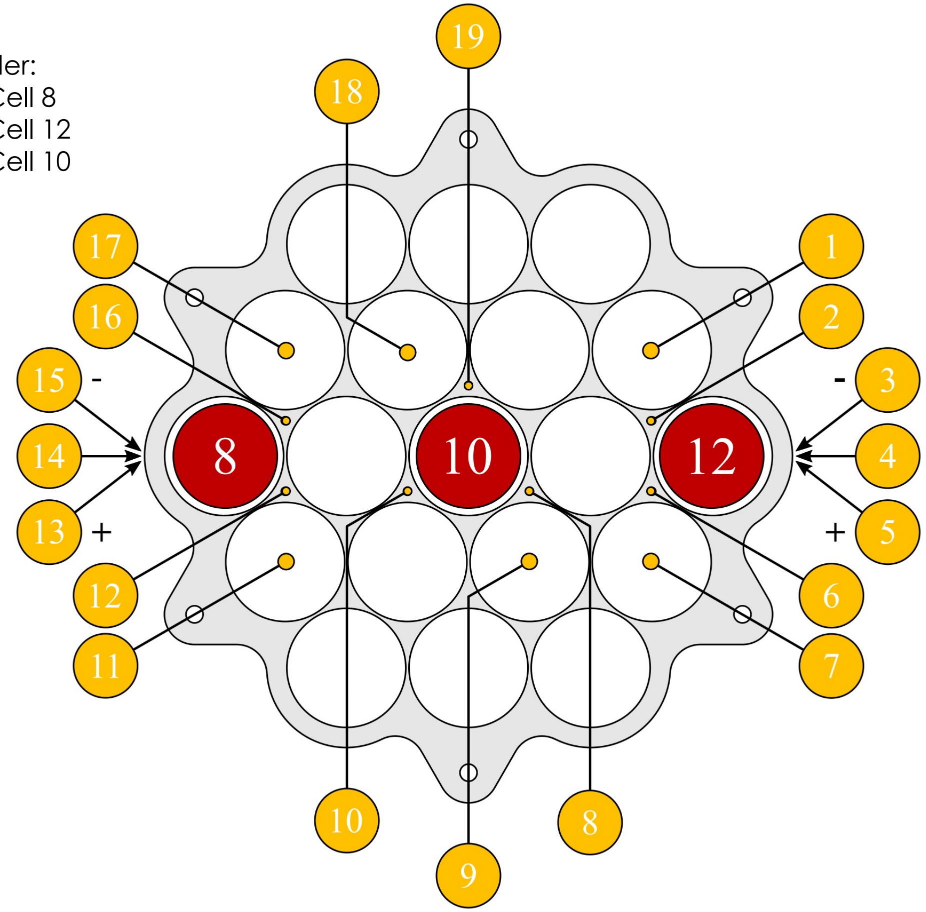


Figure: each battery was instrumented with 19 thermocouples for capturing thermal data.

Elevated Temperature Test Preparation

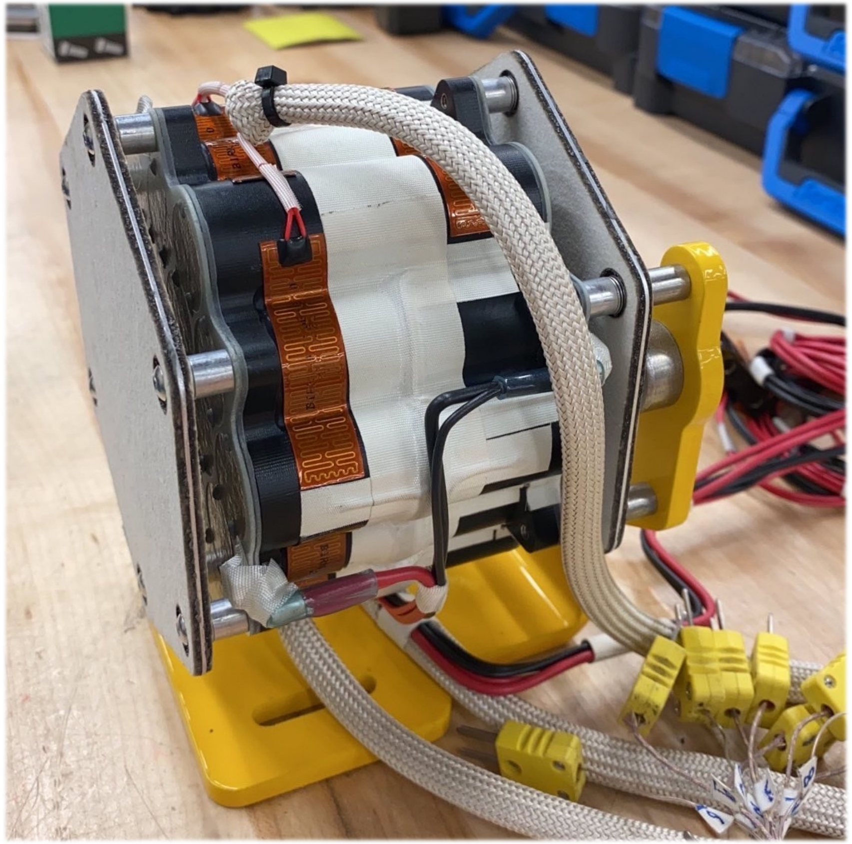


Figure: COTS heaters attached to heat sink for pre-test battery thermal conditioning.

Figure: For elevated temperature runs, batteries were insulated and thermally conditioned. Insulation was removed immediately prior to TR.

Sample Post Test Battery DPA Results

Figure: blast plate removed from positive end of battery – note buildup of cell ejecta aligned with trigger cells.

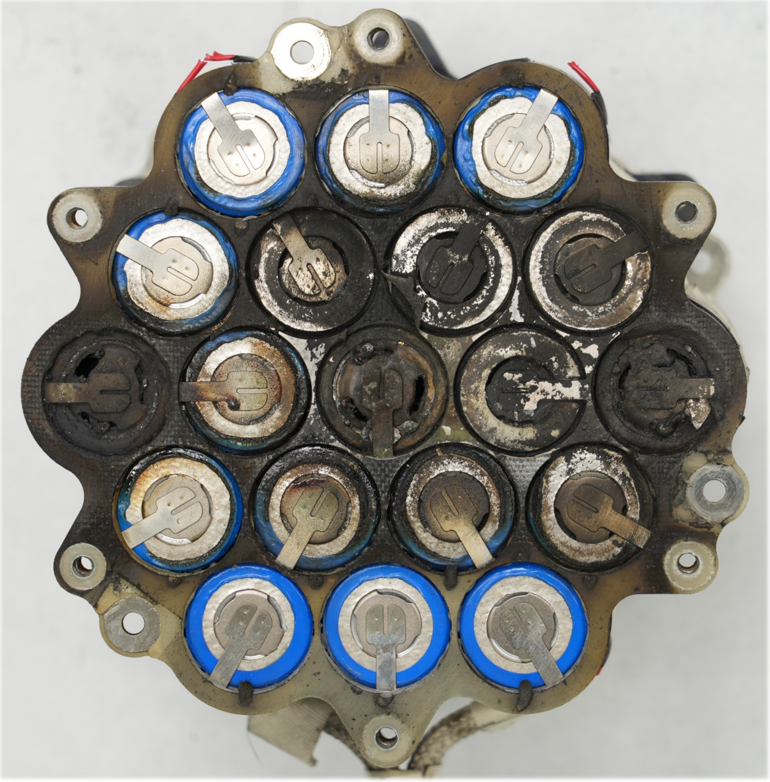


Figure: following the removal of cell covers from positive end of cells for inspection of cells.

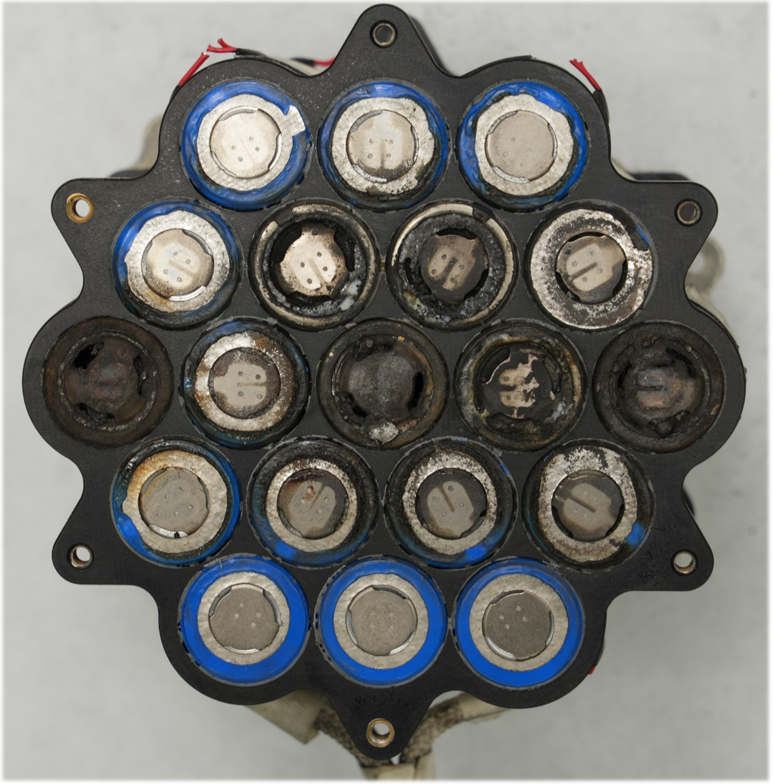


Figure: following the removal of bussing material for inspection of heat sink between cells.

Sample Post Test Battery DPA Results

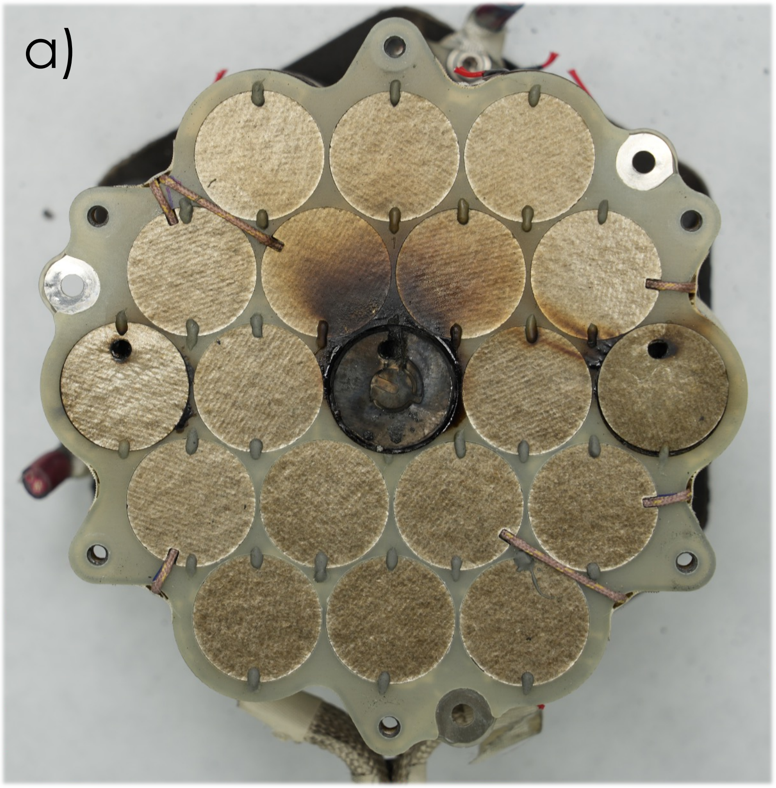


Figure: post-test disassembly (from negative end) following removal blast plate from negative end.

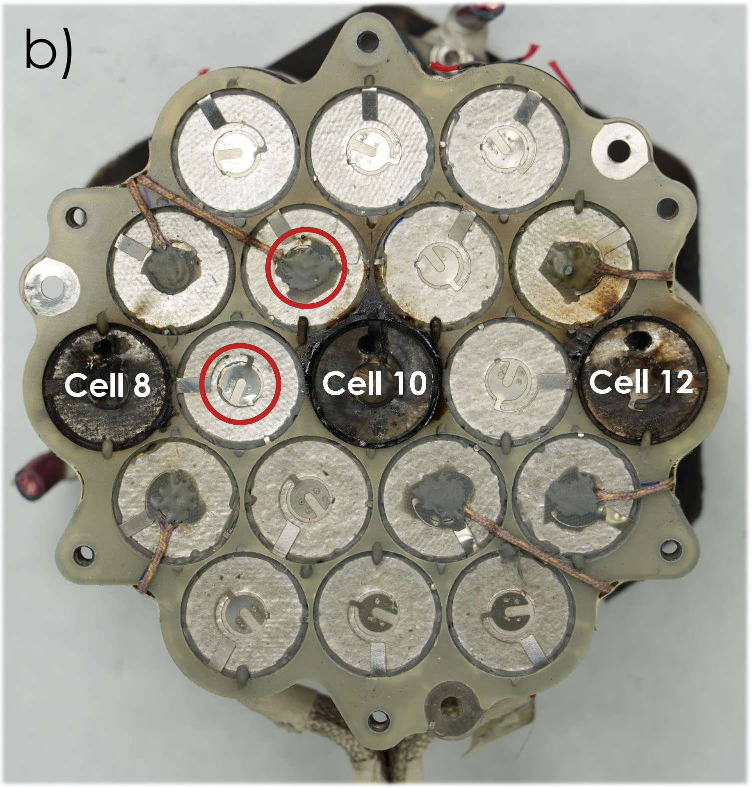


Figure: following the removal of cell covers from negative end of cells for inspection of cell and fuse damage.

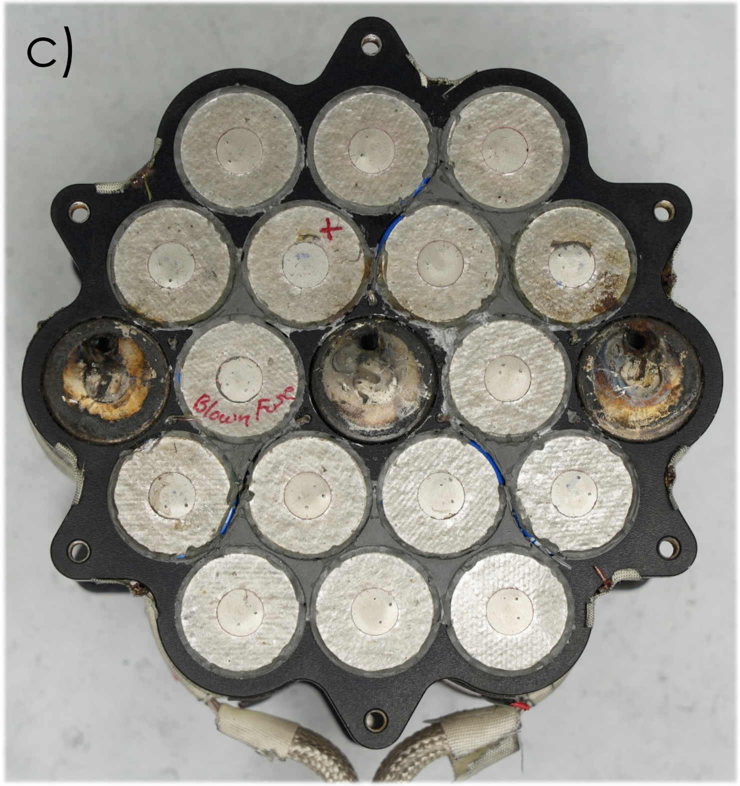


Figure: following the removal of bussing material for inspection of heat sink between cells.

Blast Plate Testing - Lessons Learned

- Passing criteria for blast plate tests:
  - No perforations in the blast plate coupon (shielding and substrate materials)
  - Adequate standoff distance between the cell and blast plate for sufficient ejecta spread
- Important to perform repeat test runs of the same test configuration (cell, standoff gap, shielding material) to map stochastic nature of thermal runaway failures
- Imperative to test various trigger mechanisms as results may vary
  - Introducing energy via cartridge heater results in very kinetic response
- 120 individual test runs completed to date

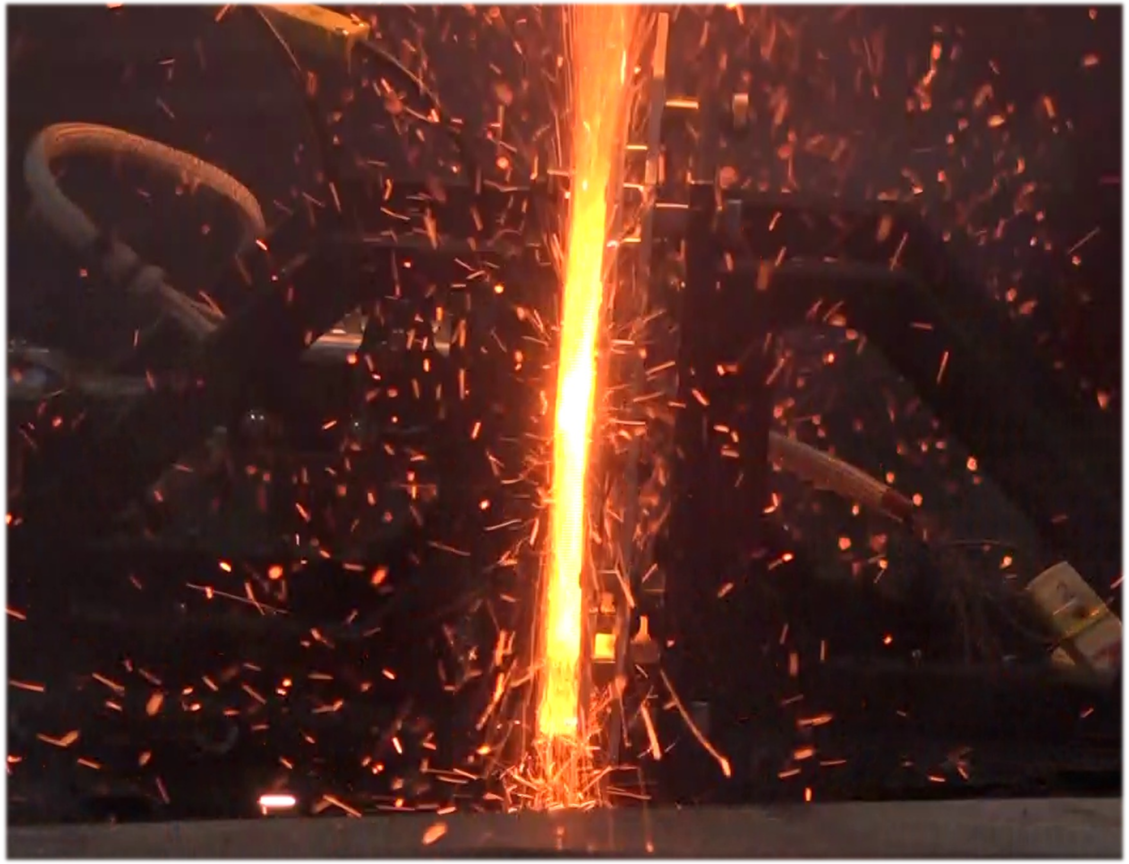


Figure: video frame capture moments after initiation of thermal runaway via axial nail penetration.