Safe, High Performing Li-ion Battery Designs:
Summary of 2015 Findings

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    - Preventing can side wall ruptures
    - Vaporizing heat sink as interstitial material
    - Metallic interstitial materials
  - Single cell TR trigger methods selected and why
  - Design and performance of "on-demand, implantable internal short circuit device"
  - Demonstrations of safe, >180 Wh/kg battery module designs

Objectives

- Achieve safe, high performing battery designs for manned spacecraft applications
  - No cell-cell thermal runaway (TR) propagation
  - No flames/sparks exiting the battery enclosure
  - >180 Wh/kg, >300 Wh/L at the building block battery module level
- Crewed Space Vehicle Battery Safety Requirements (JSC 20793C)
  - All battery design > 80 Wh must have it's hazard for single cell thermal runaway assessed by test and analyses
  - Implementation impacts of design features that appreciably reduce severity must be identified and assessed

Current and Advanced Battery Applications

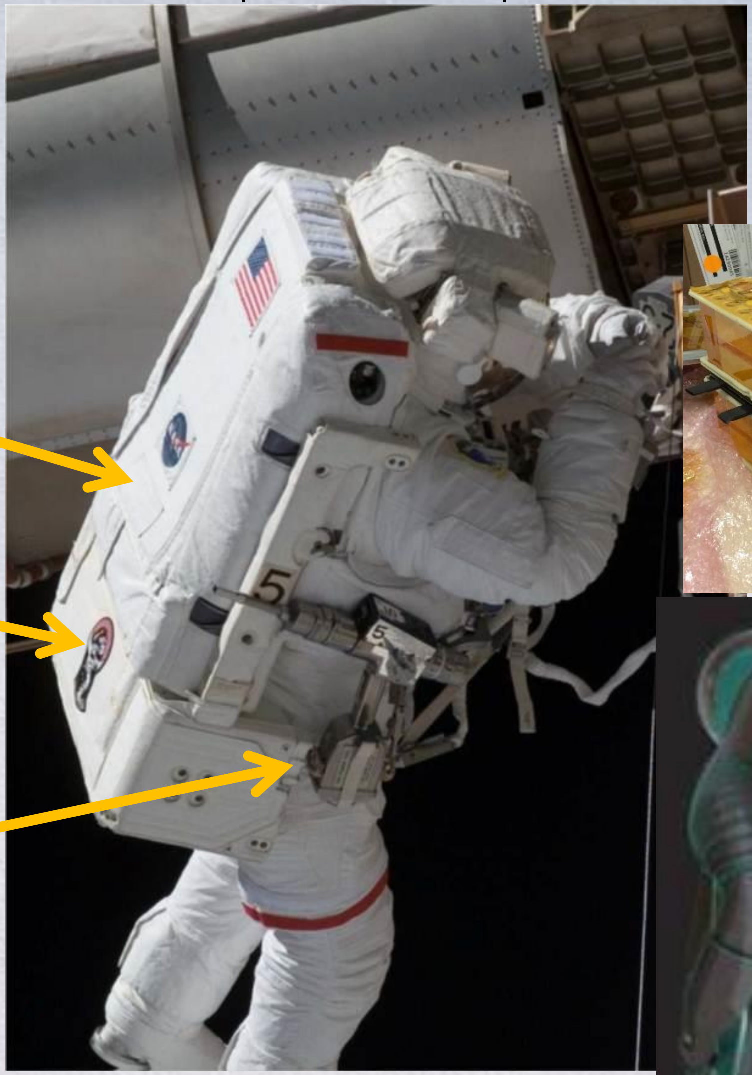
EVA Batteries addressed are:

LLB – 650 Wh
Long-life Battery: primary power for EMU life support, data, comm
80 Cells: 16P-5S config

LREBA – 400 Wh
Li Rechargeable EVA Battery: glove heaters, helmet lights and camera
45 Cells: 9P-5S config

LPGT - 89 Wh
Li Pistol Grip Tool
10 Cells: 10S config in use
2P-5S charging

Current Spacesuit and Backpack



Orion

Robonaut2

Small cell battery brick for Orion

Advanced Spacesuit and Backpack

Figure 3.1-1 – PLSS 2.5 BATT-690 Layout

P/F: No TR propagation and no flames/sparks exiting the enclosure

Last Year's Talk Focused on LREBA

My Take Away

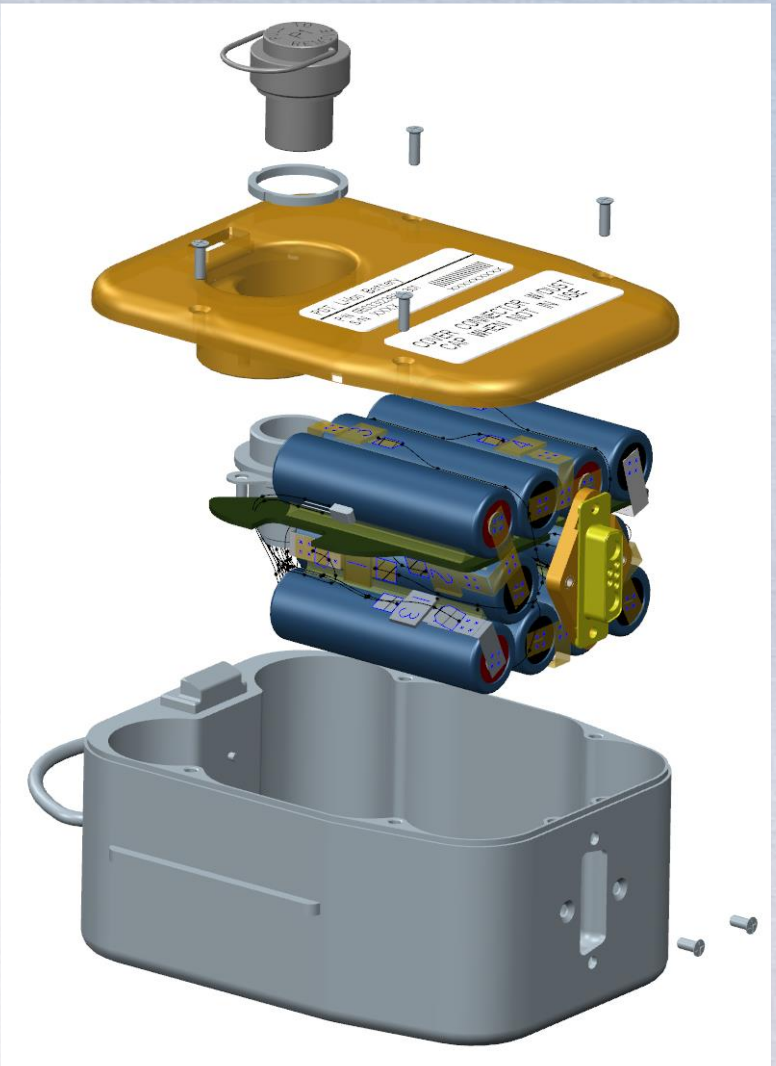
- Preventing cell-cell TR propagation and flames/sparks from exiting battery enclosure is possible with proper design features with minimal mass/volume penalty

Design Rules

- Provide adequate cell spacing
  - Direct contact between cells without alternate heat dissipation paths nearly assures propagation
- Individually fuse parallel cells
  - TR cell becomes an external short to adjacent parallel cells and heats them up
- Protect the adjacent cells from the hot TR cell ejecta (solids, liquids, and gases)
  - TR ejecta is electrically conductive and can cause circulating currents
- Prevent flames and sparks from exiting the battery enclosure
  - Tortuous path for the ejecta before hitting battery vent ports equipped flame arresting screens works well

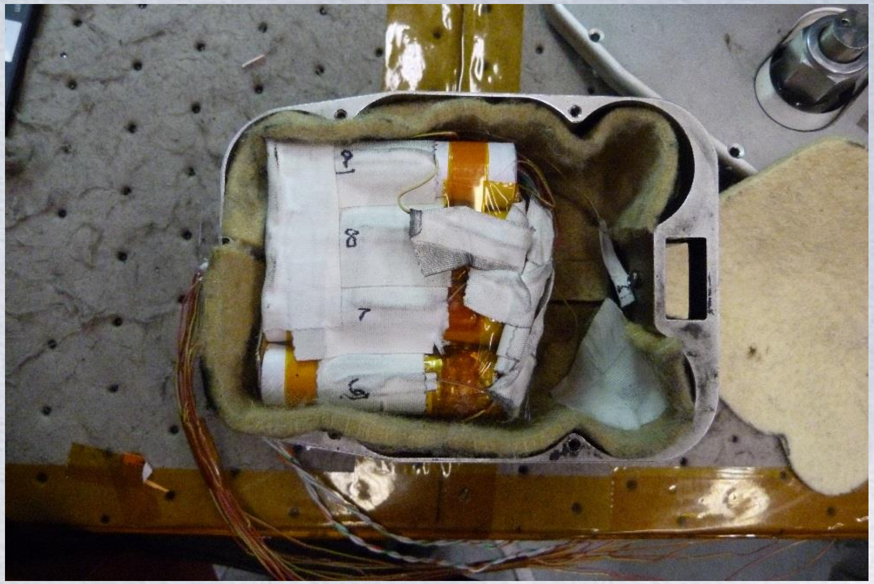
Background – Li-ion Pistol Grip Tool Battery

- 10-cell Li-ion 18650 battery
  - 10S for discharge
  - 2P-5S for charge
- Battery is enclosed in tool holster except for end with the D-latch



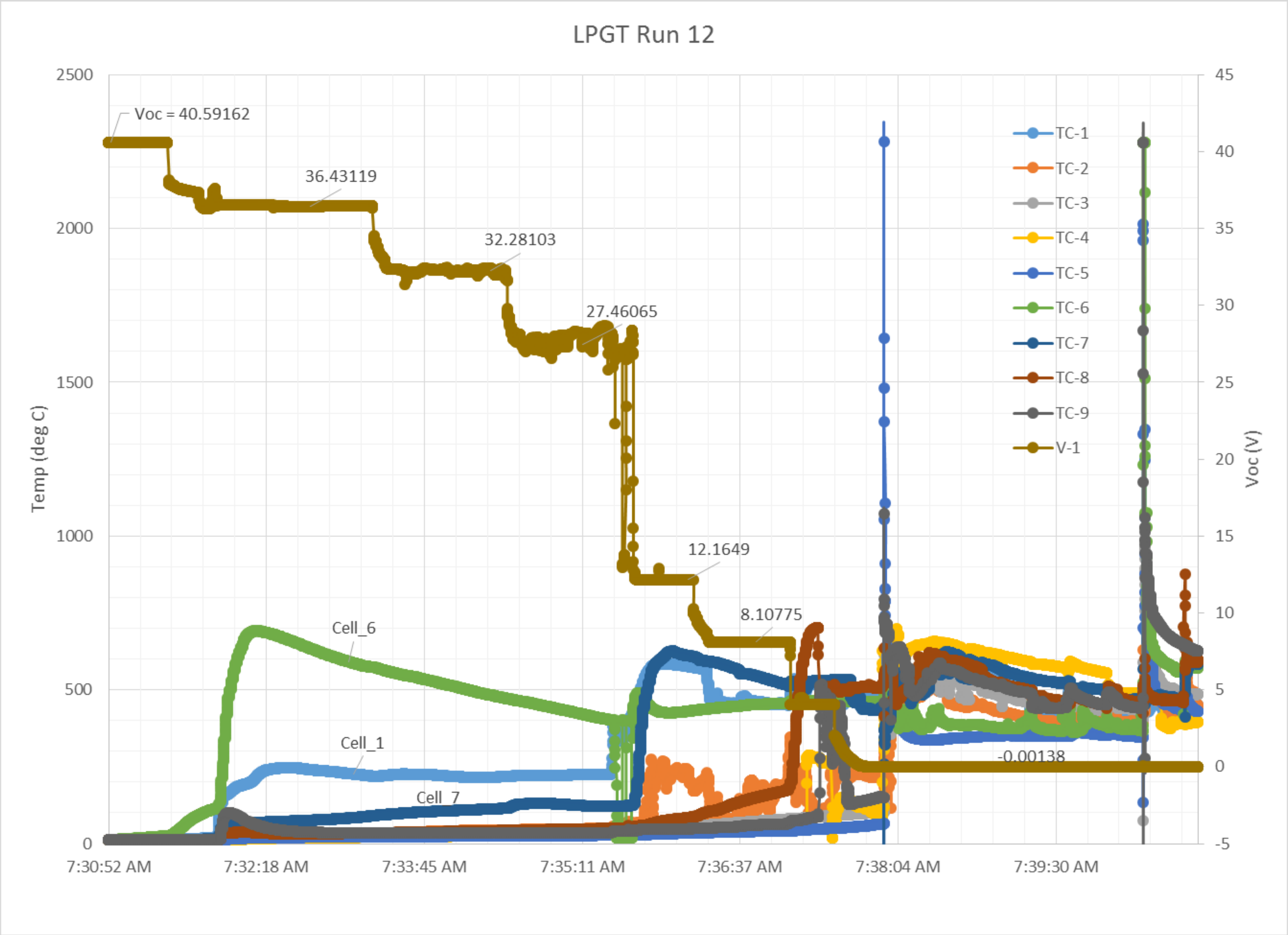
Baseline Design - Pre Test Photos

- Samsung 2.6Ah cell
- Cell in direct contact
- No cell fusing
- Cell brick wrapped in Nomex felt
- No vent ports in enclosure
- No TR vent path protection for the adjacent cells



LPGT Baseline Design - Close-up Plot

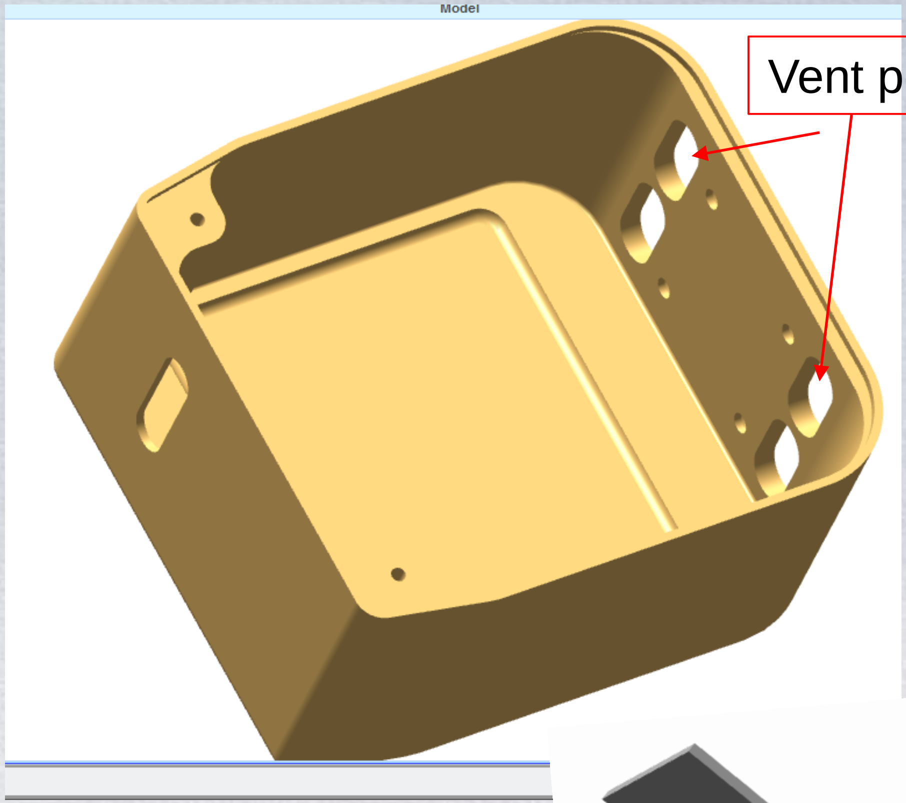
10S configuration



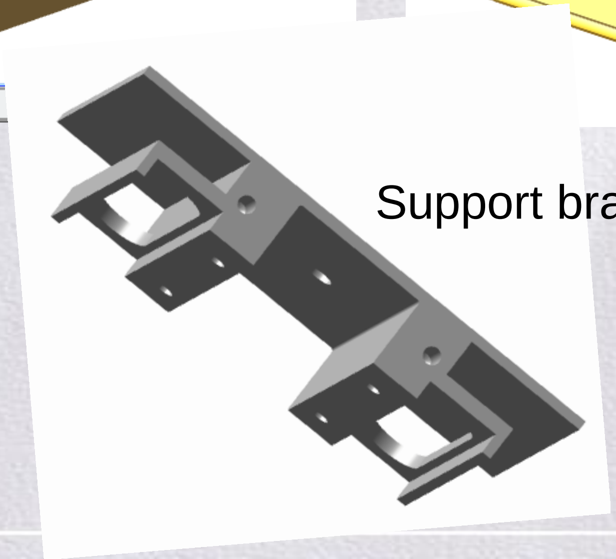
Snapshot – more sparks at 9:56

More sparks occur at 10:20, at 12:37 the supporting tile cracks, and smoldering smoke is intense for another 5 min.

Redesigned LPGT Battery Enclosure



Vent ports added



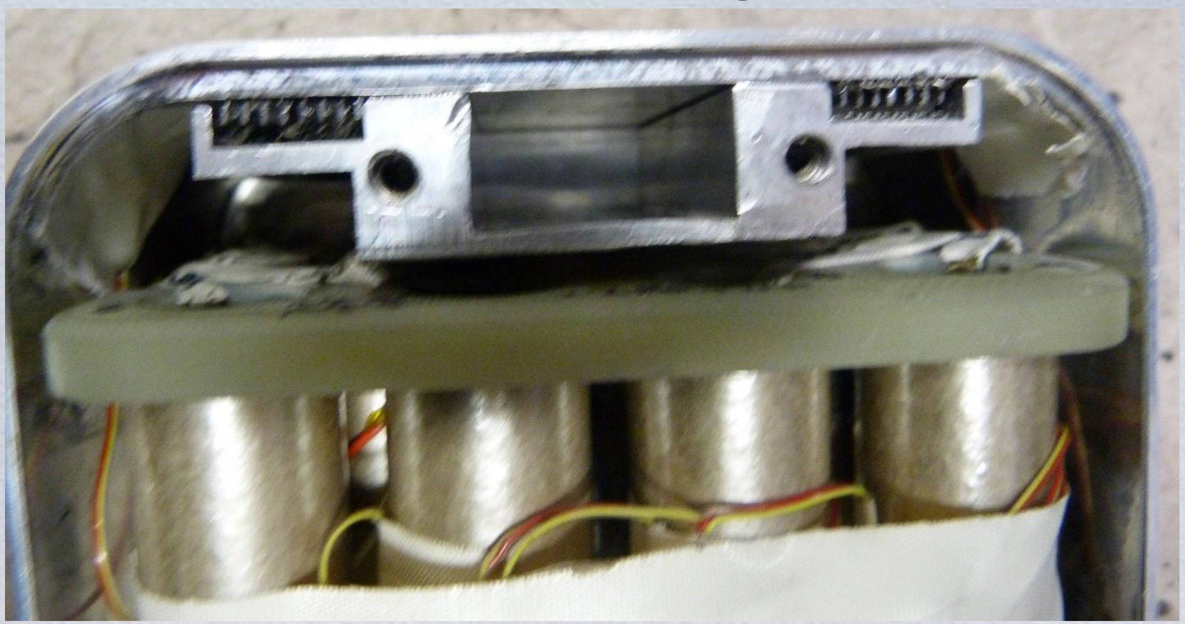
Support bracket for flame arresting screens

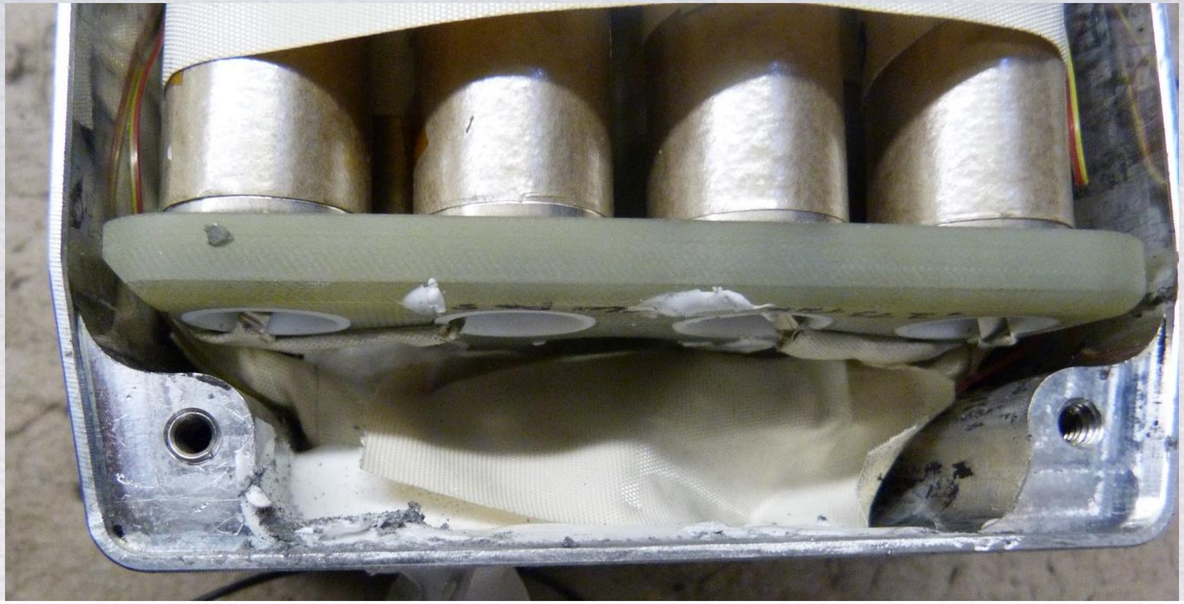
Redesigned LPGT – Pre Test

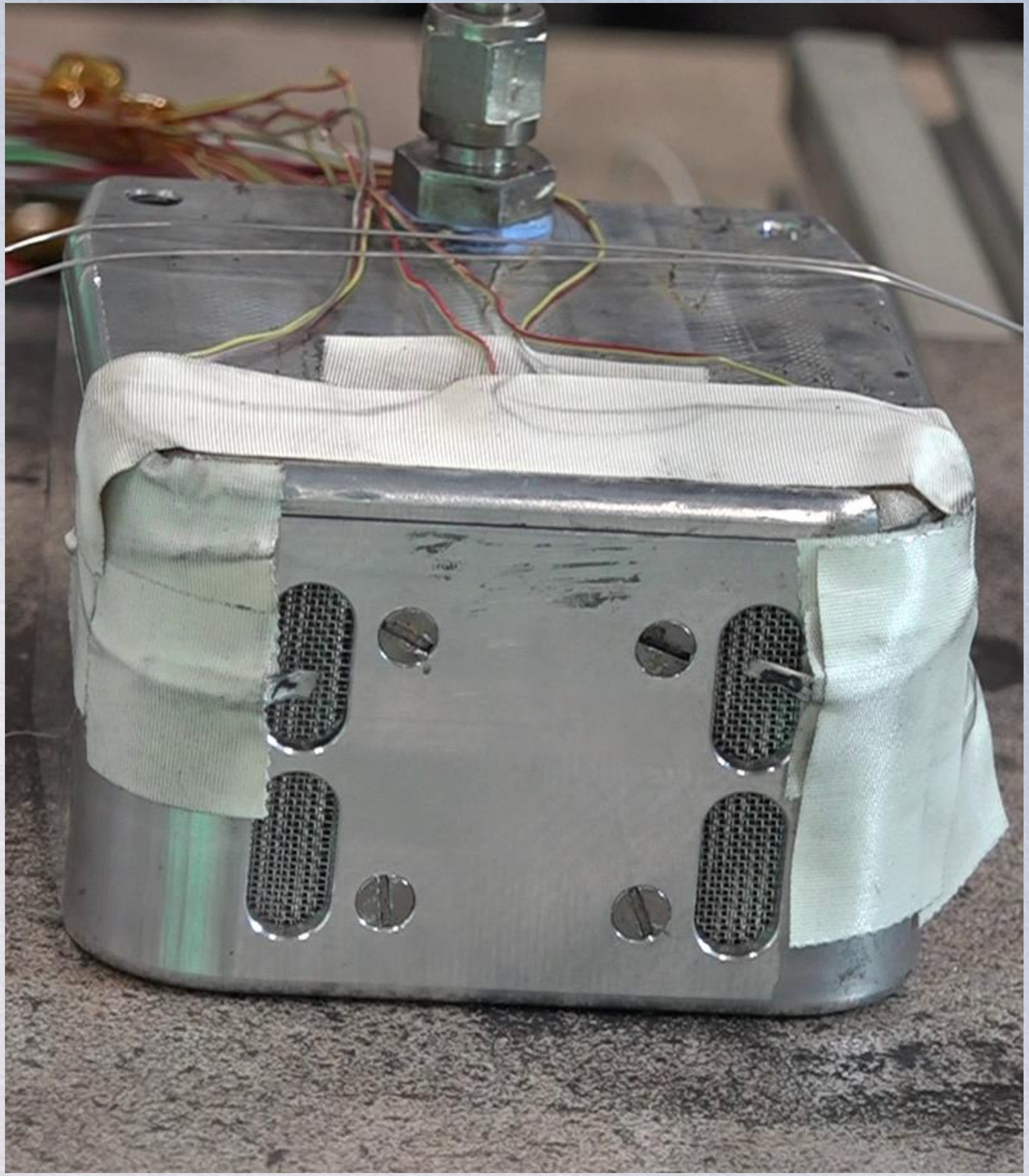
Design Features

- Samsung ICR18650-26F not likely to experience side wall ruptures during TR
- 3mm cell spacing ensured with G10/FR4 capture plates
- 100 micron thick mica paper sleeves on cell cans
- Cell vents directed towards connector wall of enclosure
    - Tortuous path to battery vents
- Battery vent ports screened with carbon fibercore composite

Redesigned LPGT - pre test pics (cont.)

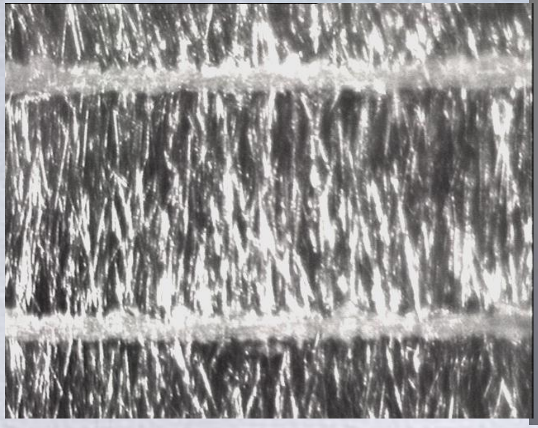


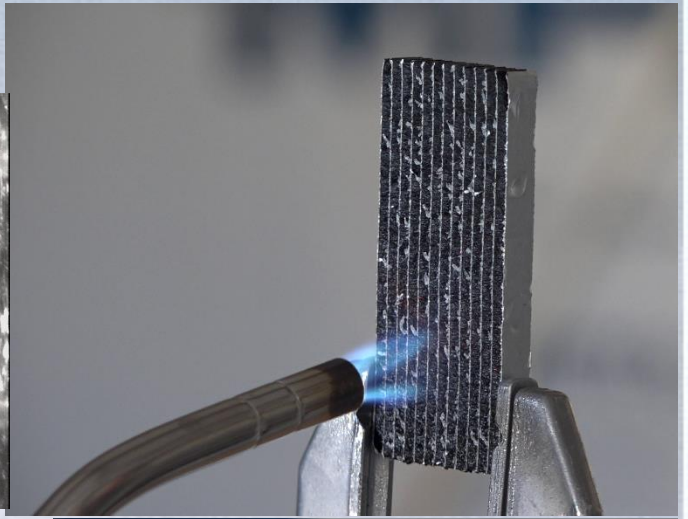


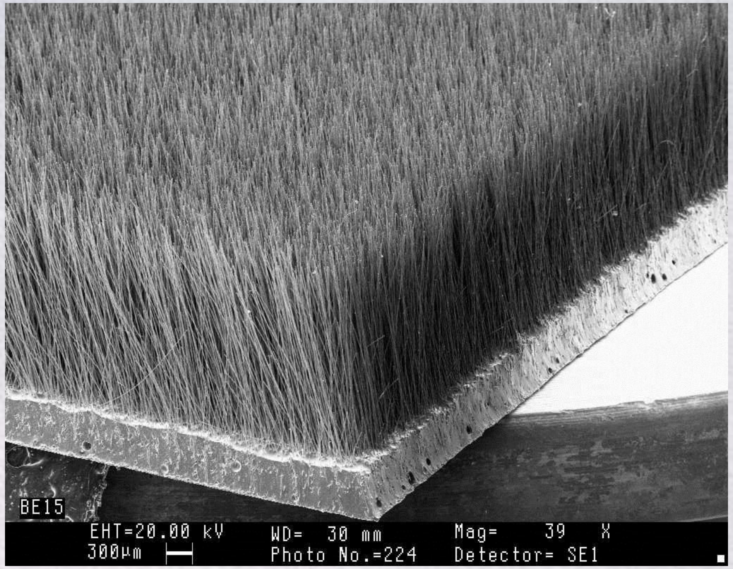


ESLI Carbon Fibercore Torch Test

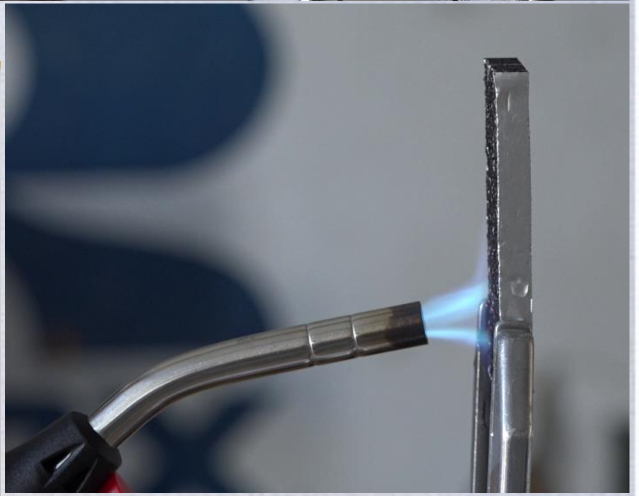
- Lightweight tiny carbon fibers glued to Al foils
  - Very high surface area of very high thermal conductivity material
  - Samples blow torch tested were 1/16, 1/8, and 1/4” thick
- Blow torch flame did not penetrate through sample
  - Even after 10 second application



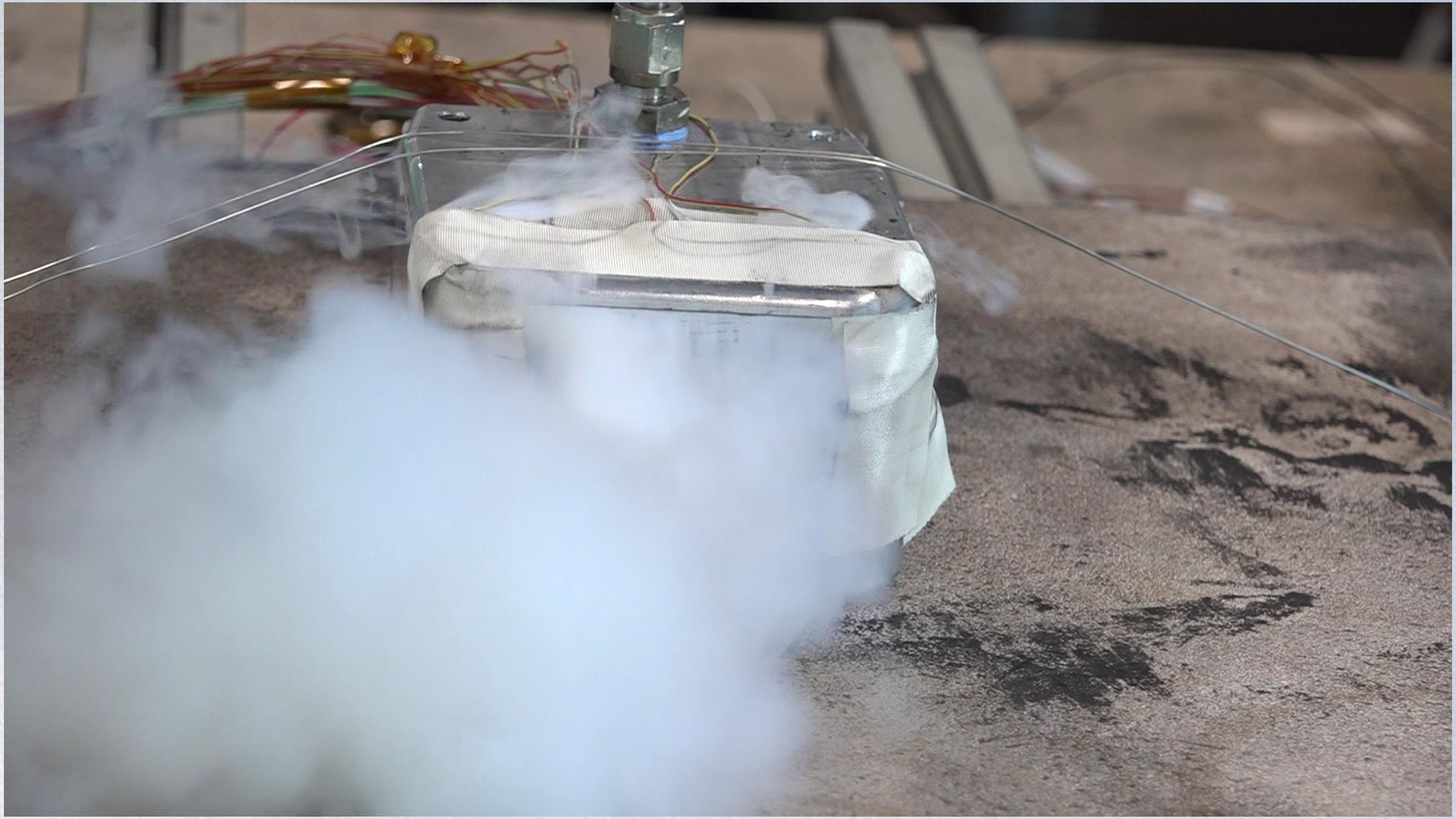




1/16” strips used in LPGT vent ports

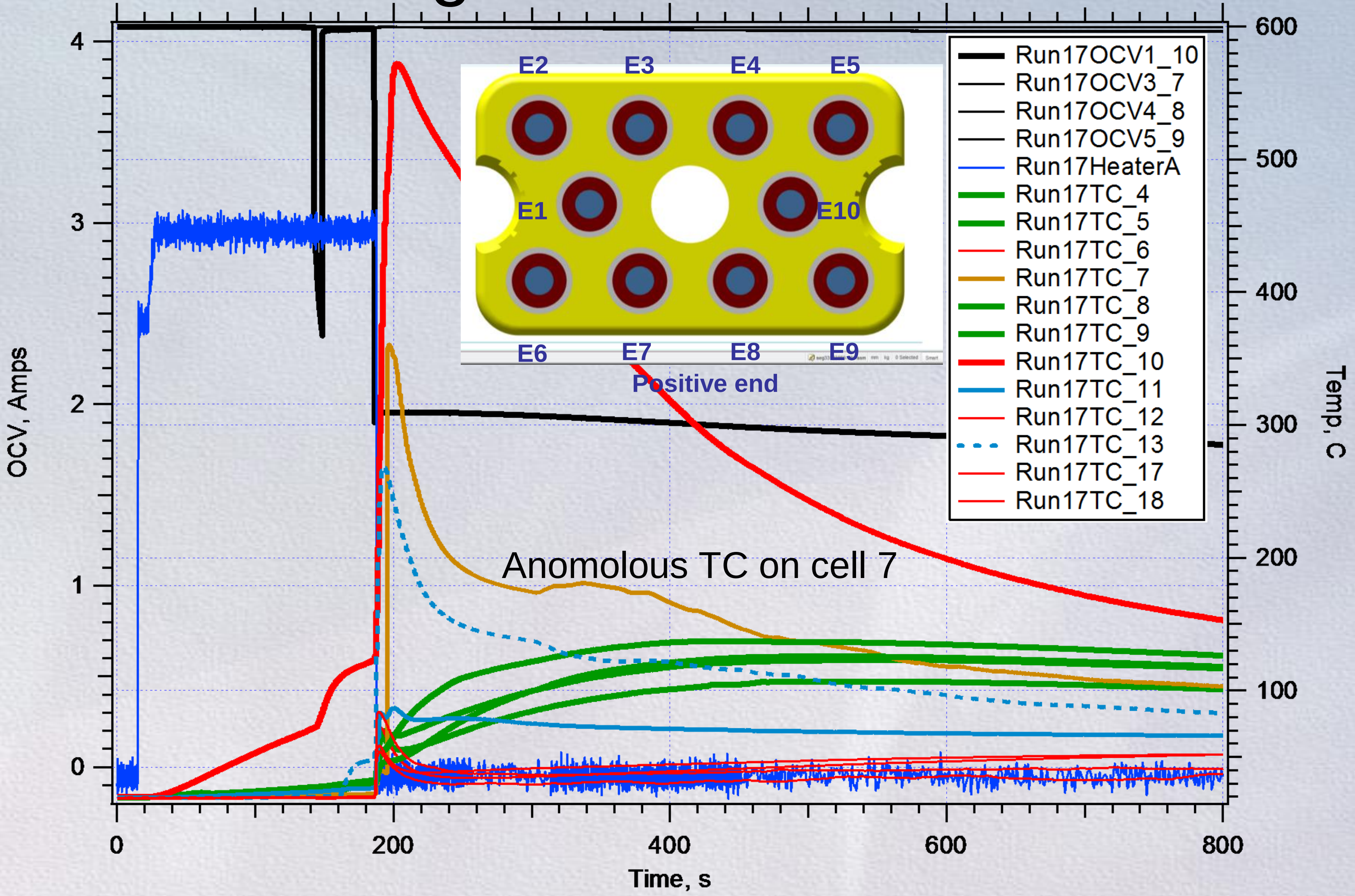


Redesigned LPGT - Snapshot of TR vent



No sparks, no flames exit the battery enclosure

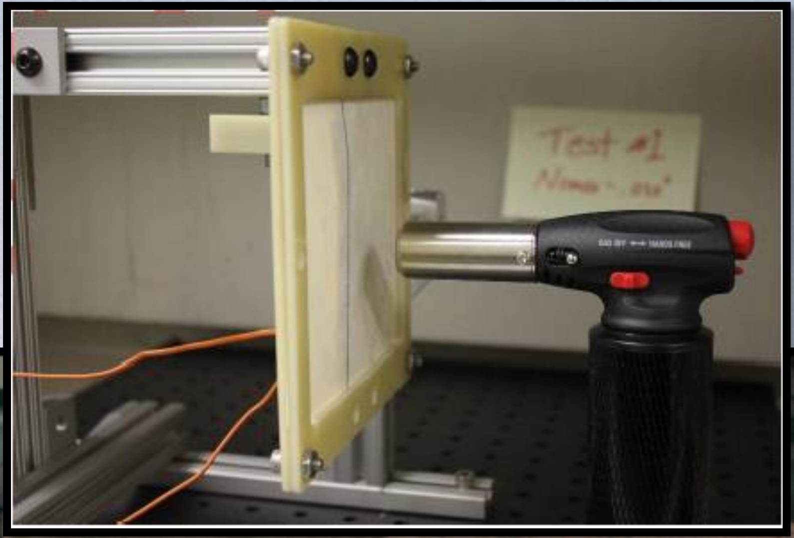
Redesigned LPGT Results

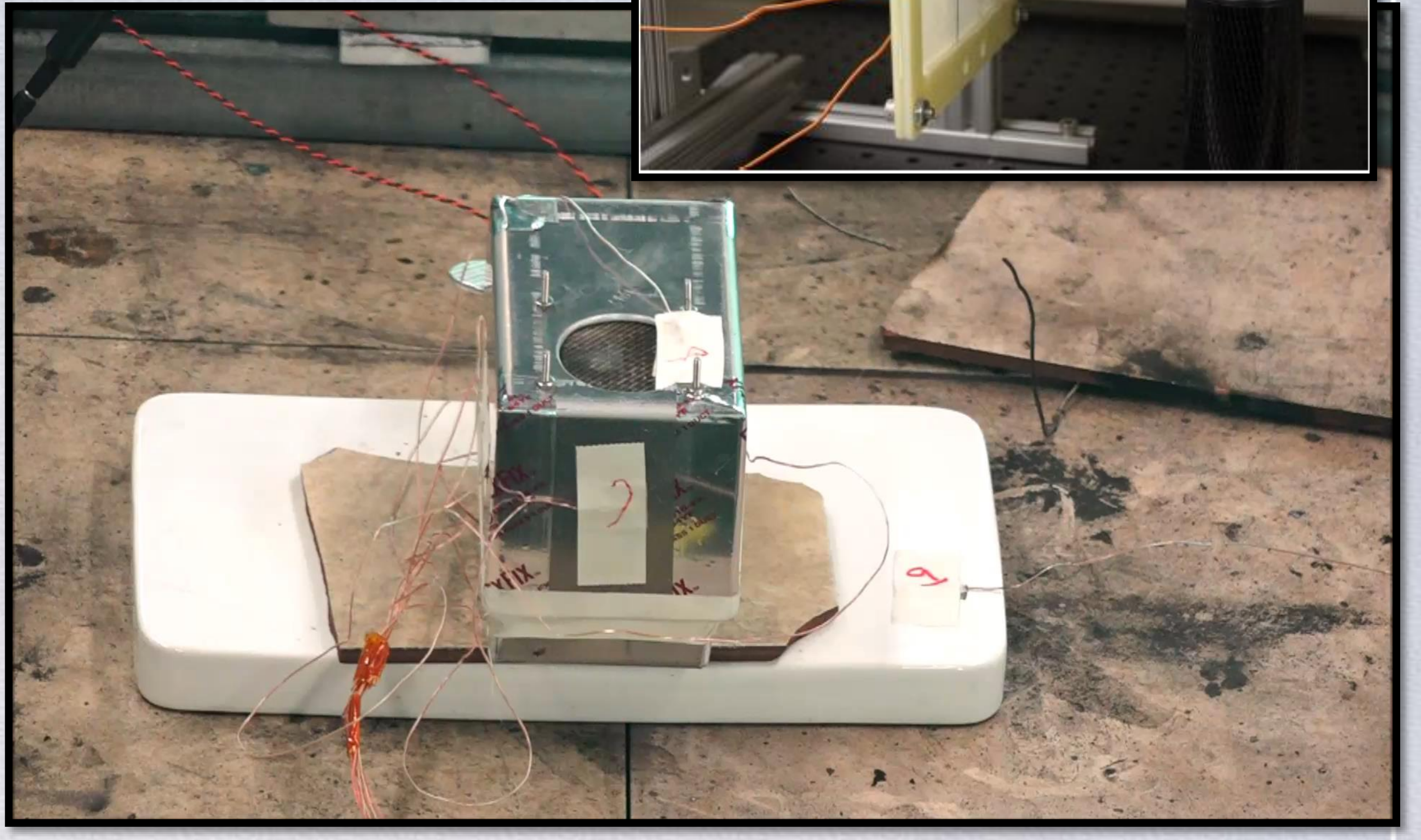


Heater powered at 46W, on for 173s, OCV dip at 130s lasting 6s, onset of trigger cell TR in 171s
Trigger cell max temp = C, adjacent cells 4, 5, 8, & 9 max at 107, 123, 126, & 137C, respectively

Flame Arrestor Characterization Tests

- **Goal:** Identify alternative materials to carbon fibercore (CFC)
- Two stages of testing
  1. Blow Torch Testing
  2. Cell Thermal Runaway Testing
- Materials tested
  1. Carbon Fibercore Material - ESLI
  2. Flotrex – KTex
  3. Nextel AF-10 – 3M
  4. 1/8th Carbon Fiber Braids – Albany Engineered Composites
  5. 1/16th Carbon Fiber Braids – Albany Engineered Composites
  6. Stainless steel screens of 10, 20, 30, & 40 mesh
- Results
  - Combinations of 30, 40 SS mesh found as effective as CFC





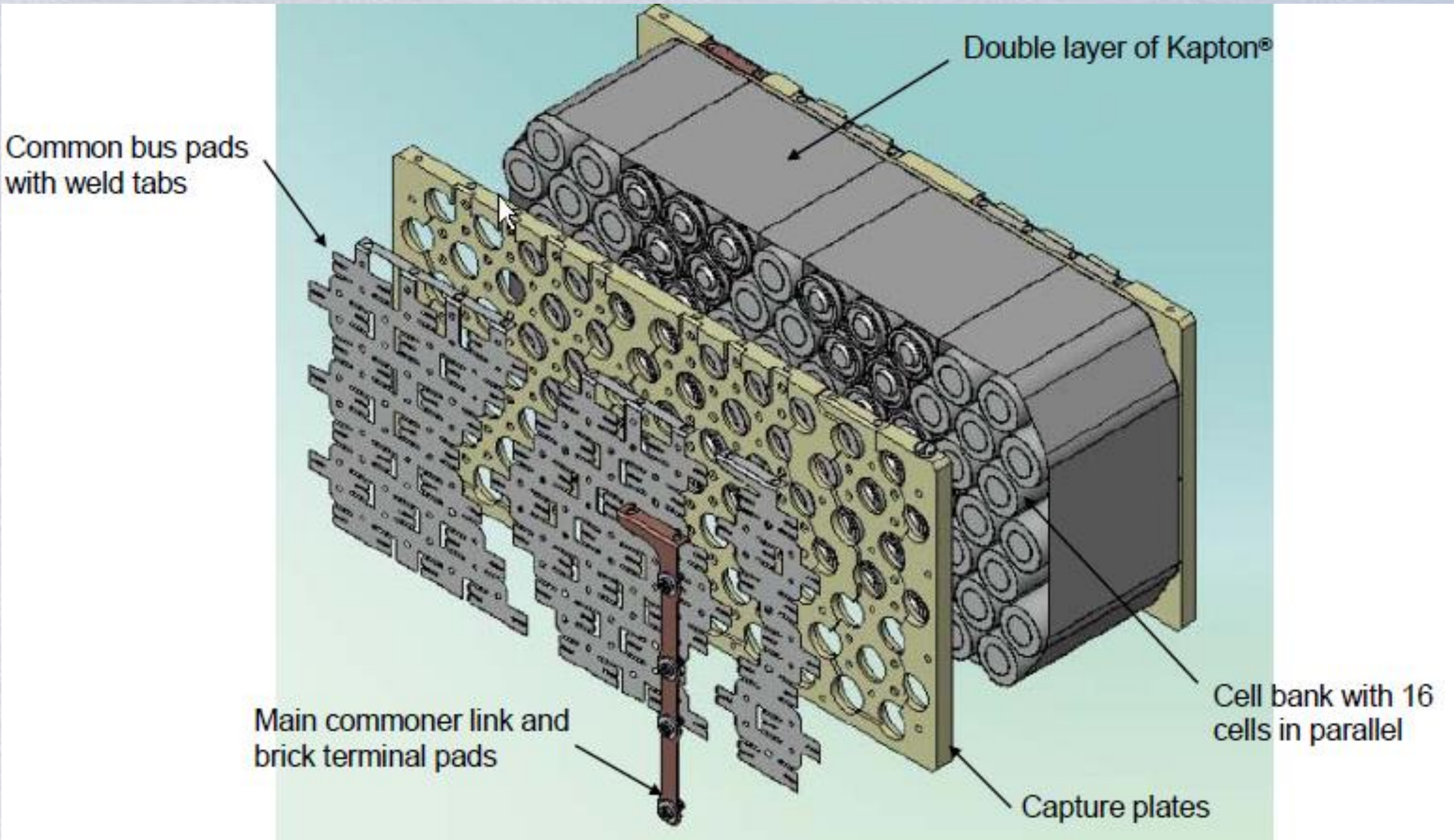
LPGT (Small Battery) Conclusions

- Can only be successful with triggering 2 cells within this 10-cell battery if you replace the flame arresting screen between runs
  - Trapping hot gases with clogged screens resulted in propagation
- Non-propagating design that does not emit flames/sparks was achieved with CFC/SS screen combinations and with SS screens only
  - Adjacent cell maximum cell temperatures < 137°C, but no CID was tripped
  - Effluent maximum temperature detected was 84C
  - Maximum pressure spike of 2 psig detected
- Overall, a very benign hazard compared to what a single cell TR presents

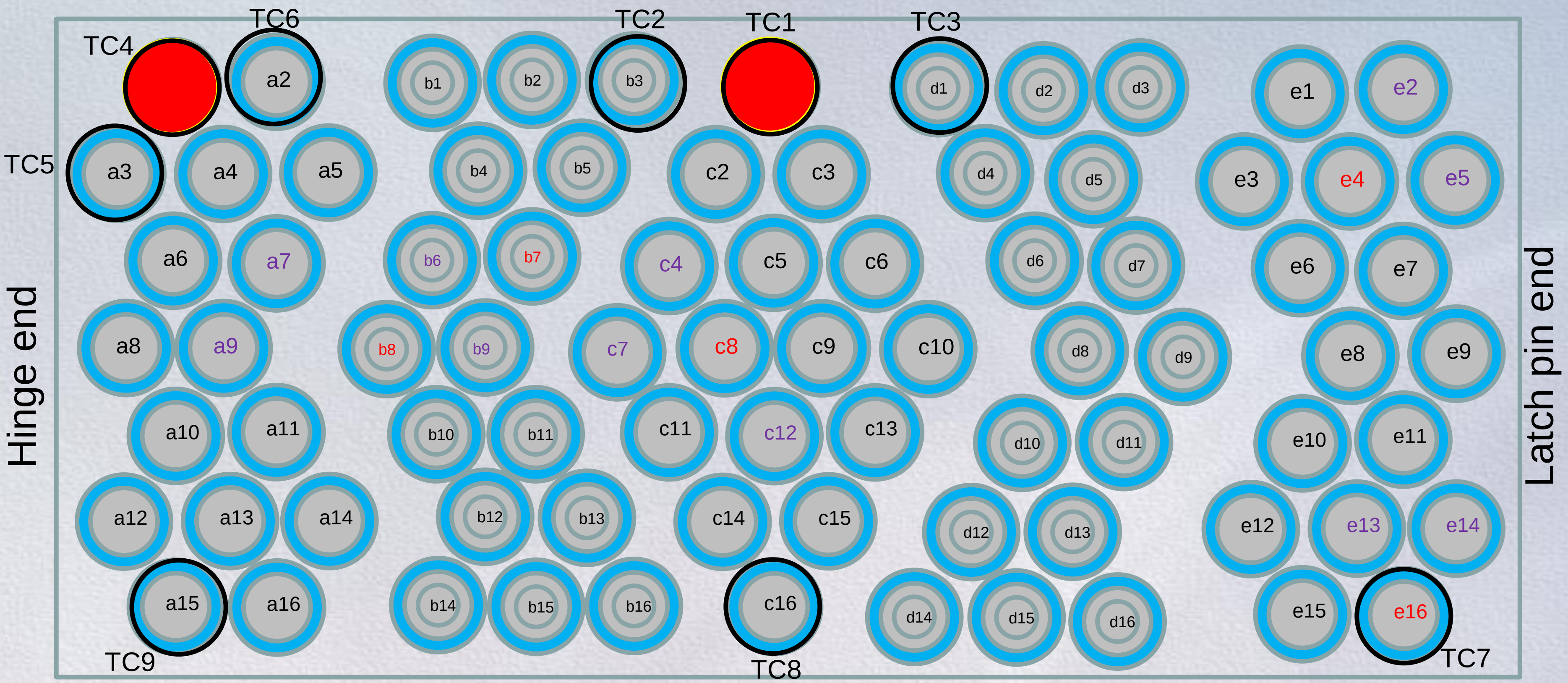
Background – EMU Long Life Battery (LLB)

Design Features

- 80 Li-ion cells (16p-5s)
- ICR-18650J from E-one Moli Energy



Trigger Cell Position Map

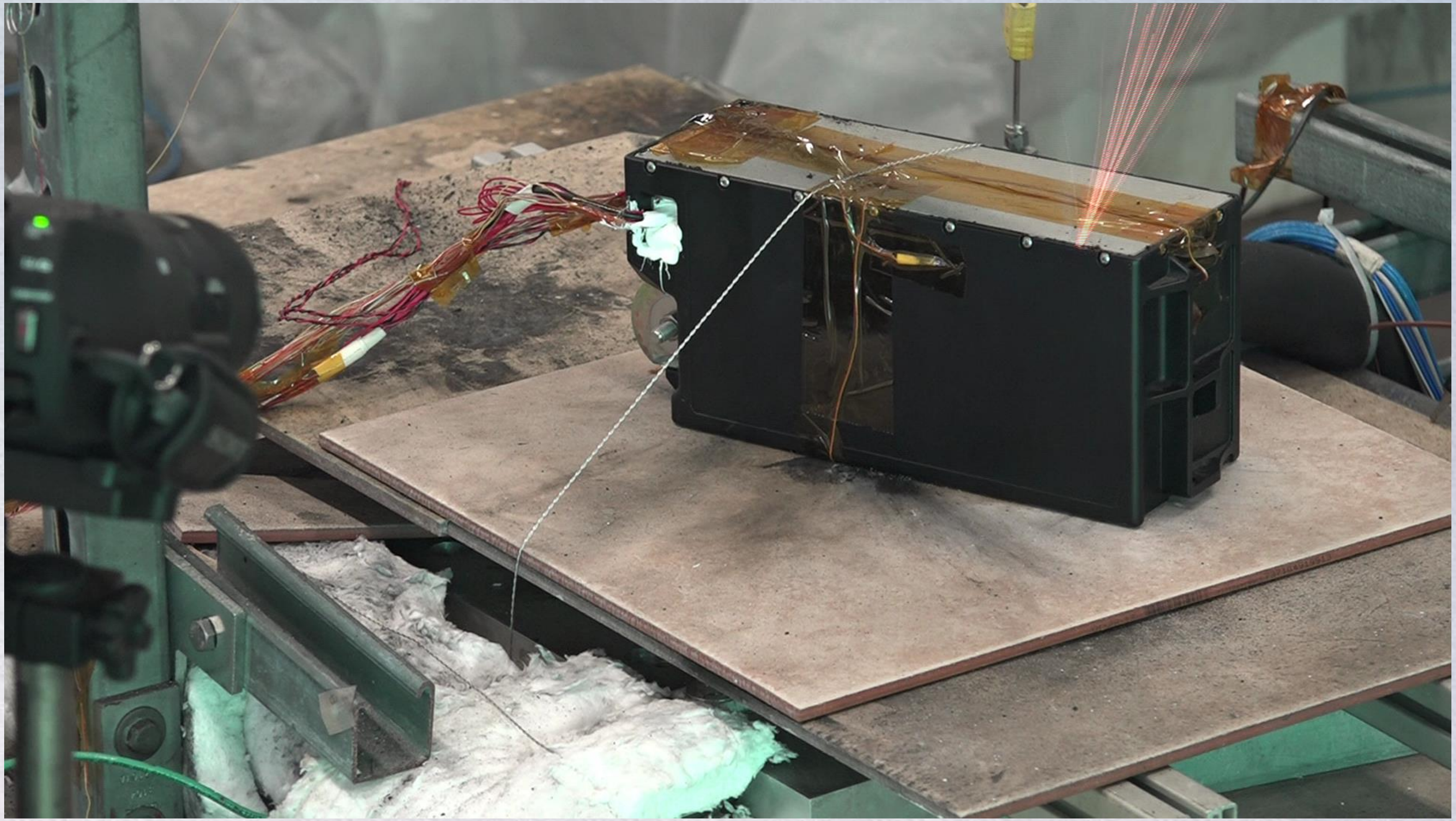


Cell map for current LLB design with 80 cells

Trigger cell location a1, c1,

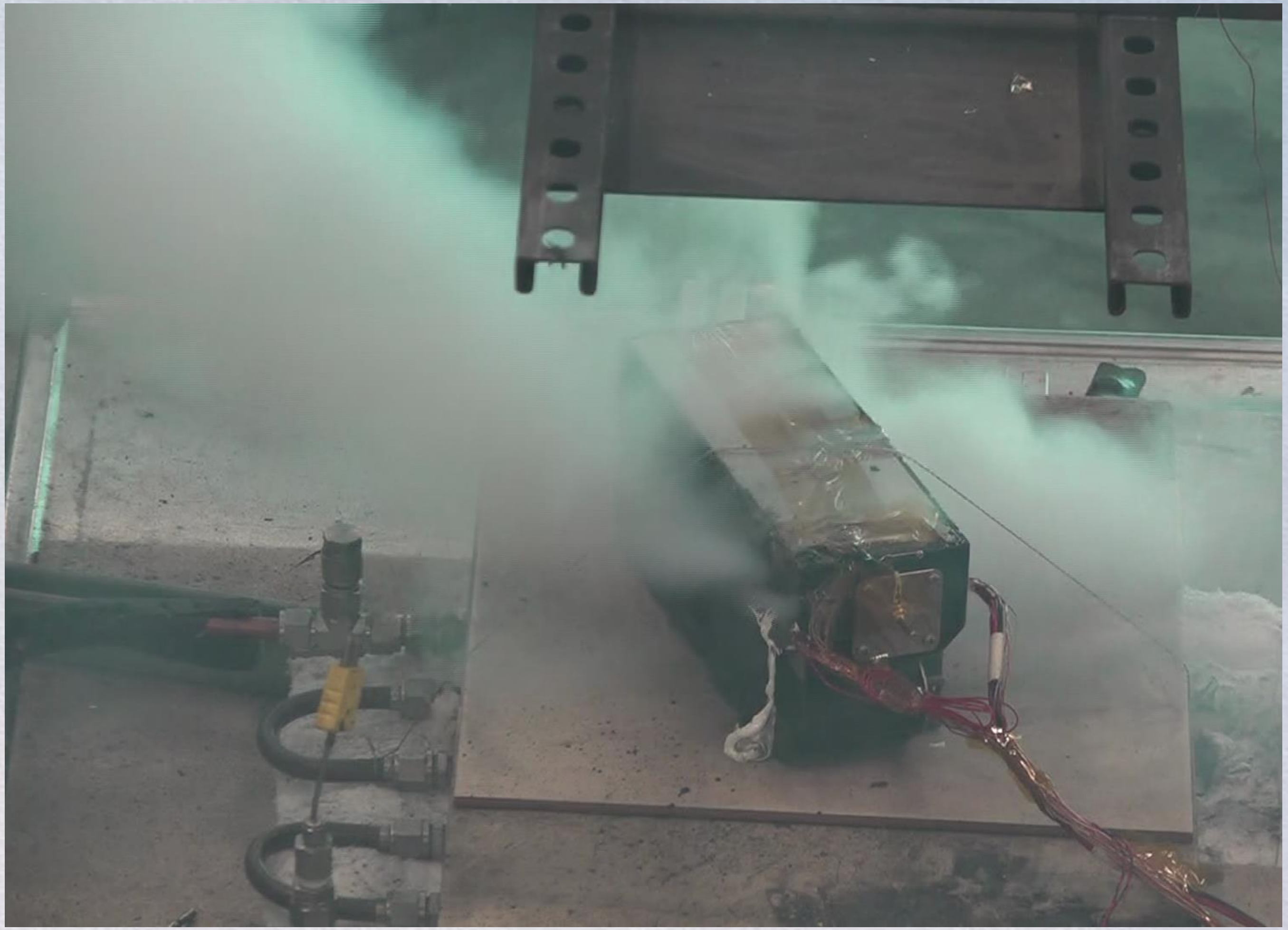
Skin TC cell location a1, a2, a3, a15, b3, c1, c16, d1, c16

Sparks



Full Blown Venting

Timeline
28:43 cell vent “pop”
29:34 initial external vent
29:49 2nd vent
30:17 3rd vent
30:30 4th vent
30:38 5th vent
30:49 6th vent followed by
Full blown vent as shown

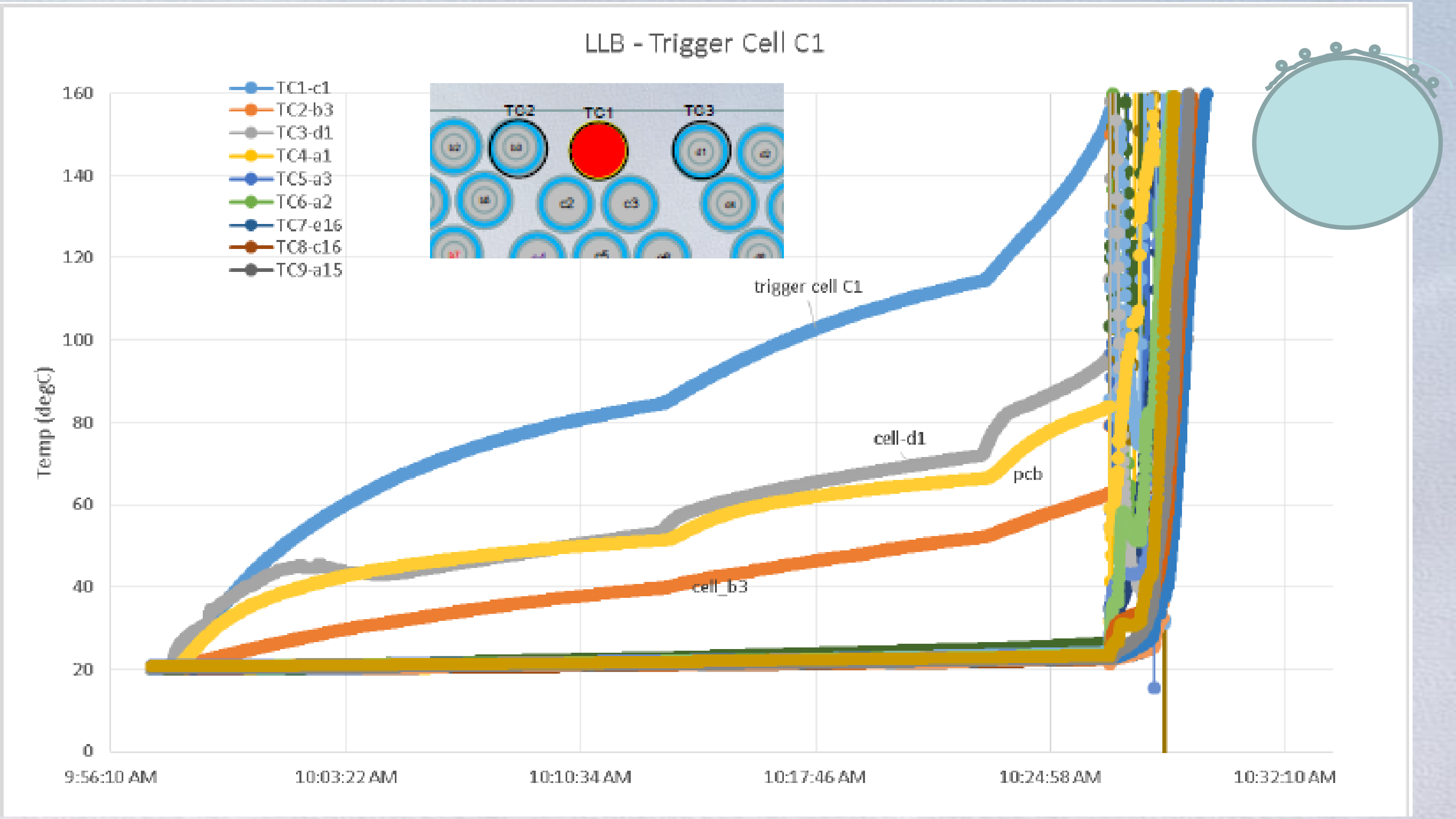


~3 minutes after initial cell vent pop

Post Morten Photos

No place for the cell TR effluent to vent

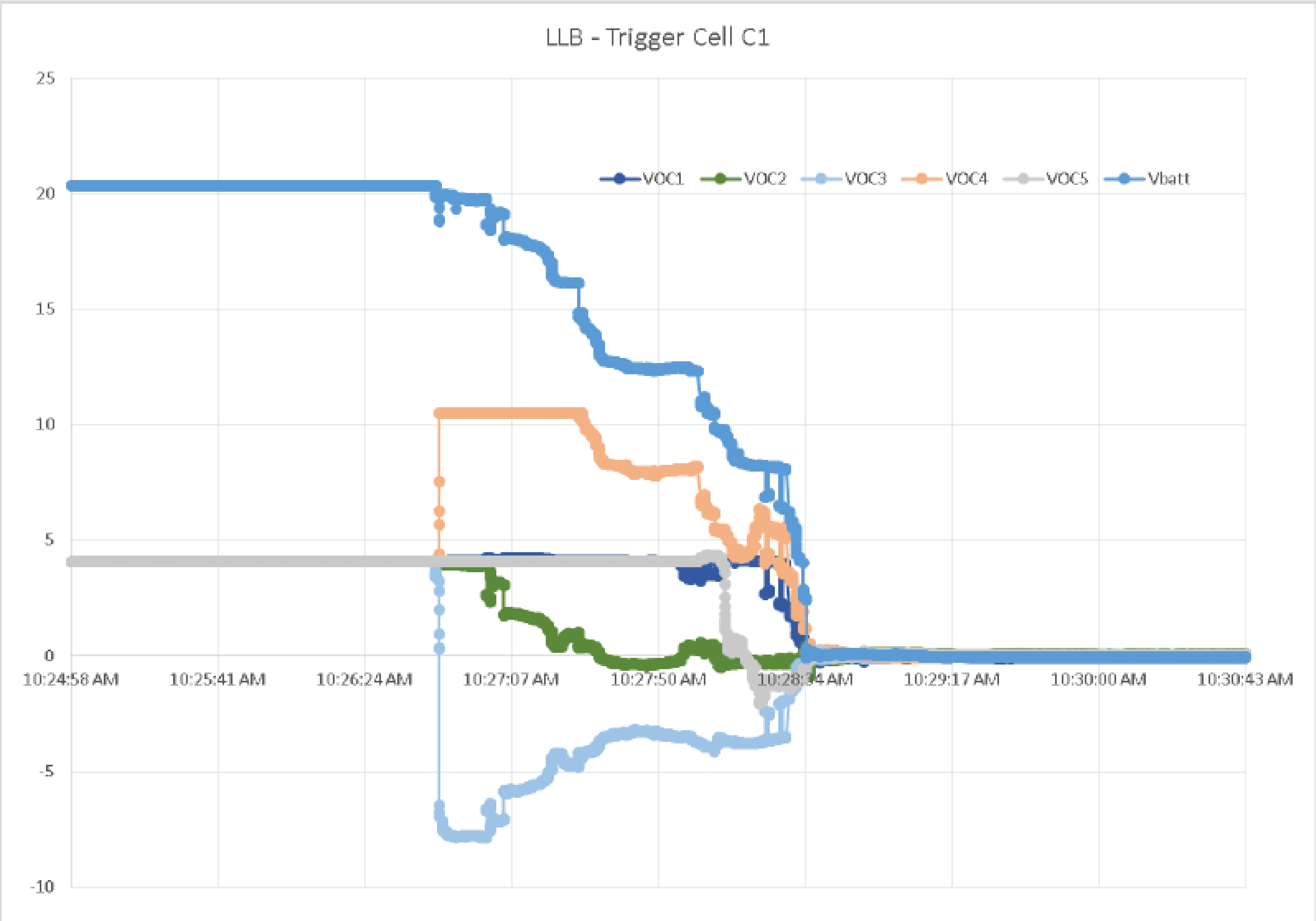
Close-up, up to OTR



Patch heater on trigger cell may have rotated towards adjacent cell d1 and away from cell b3 during battery closure rather than stay with noon clocking

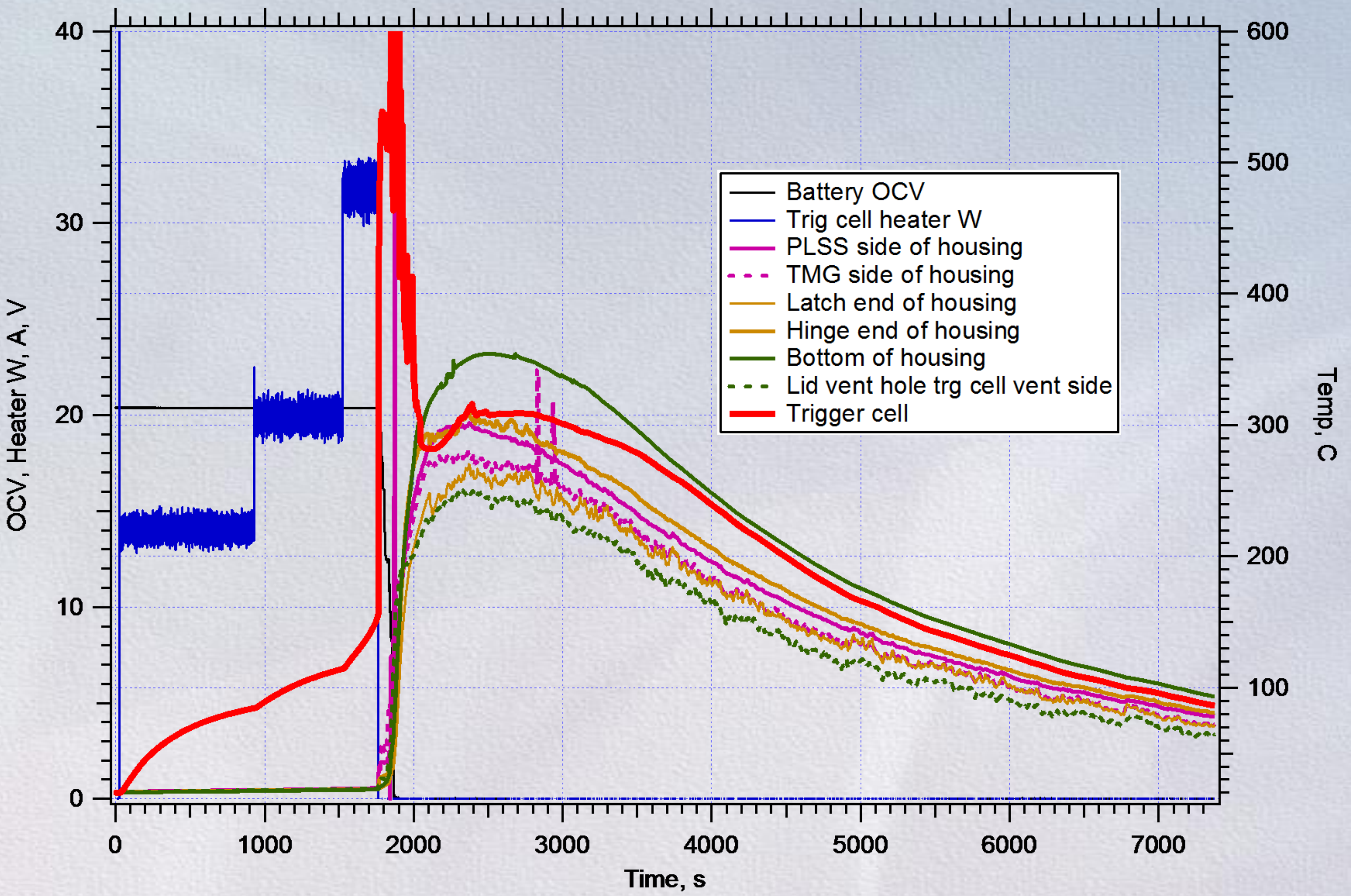
This could explain why cell d1 was tracking hotter than cell b3

Close up of the OCVs



Battery OCV degrades in steps to zero V in < 2 minutes, evidence of lots of intra-battery shorts occurring with the trigger cell and adjacent bank cells internal shorting. TR effluent produces shorting paths to brick Al side plate.

External Surface Temperatures



Bottom of housing reached 354C, top of lid near vent hole reached 248C, other surfaces were in between that range

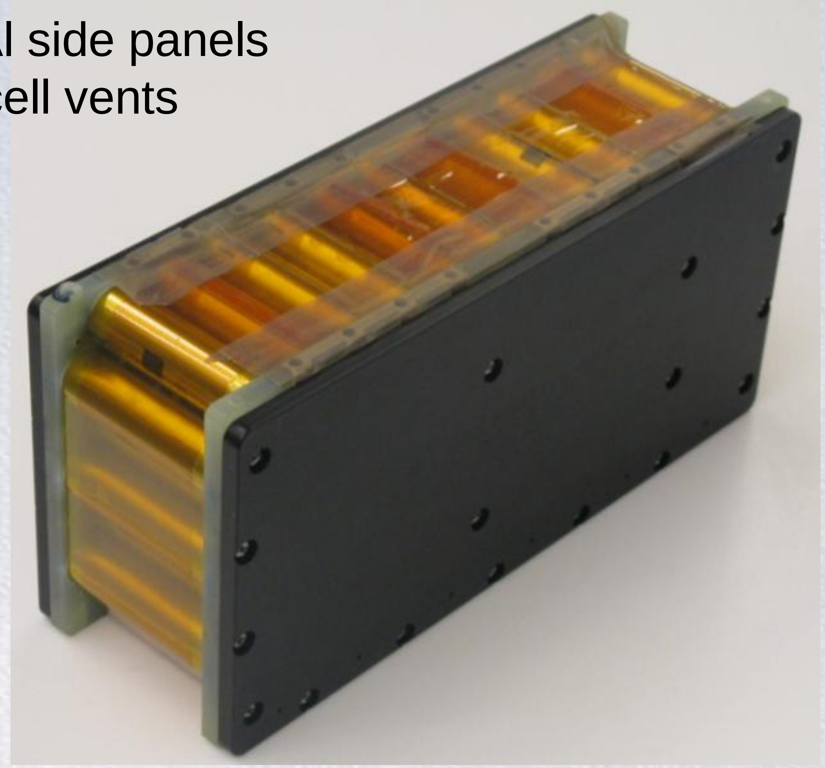
Conclusions for LLB Baseline Design

- Current LLB design behaves catastrophically to a single cell TR event
  - Cell to cell TR propagation risk is high
  - Small amount of sparks, but large amount smoke are released for > 30 minutes
  - Surface temperatures reach 250-350°C for a long time
- Weaknesses of the baseline design
  - Cell spacing ~0.5mm is too tight
  - No individual cell fuses
  - Cell TR ejecta path does not protect adjacent cells (cell cans are bare) and path is dead ended too close to cell vent
  - Battery enclosure is not properly vented with flame arresting screens

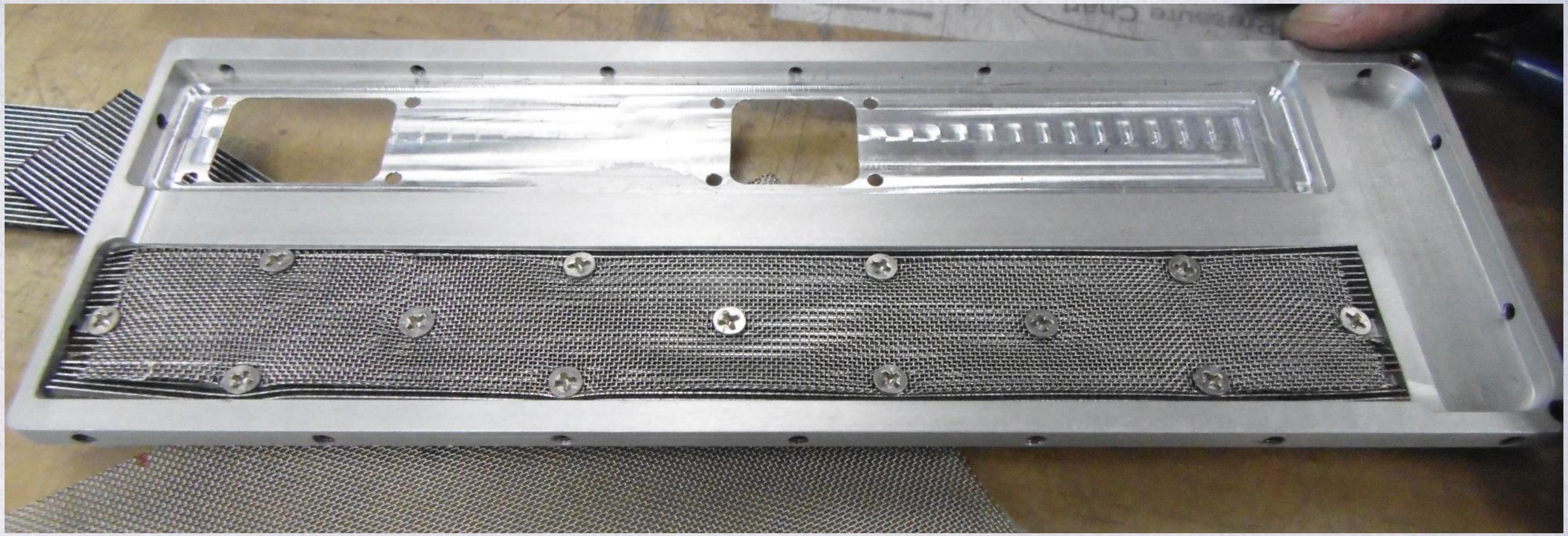
Simple Redesign Attempt

- Vent the Al side panels
- Vent the lid of the battery with flame arresting screens
- Fuse the trigger cell

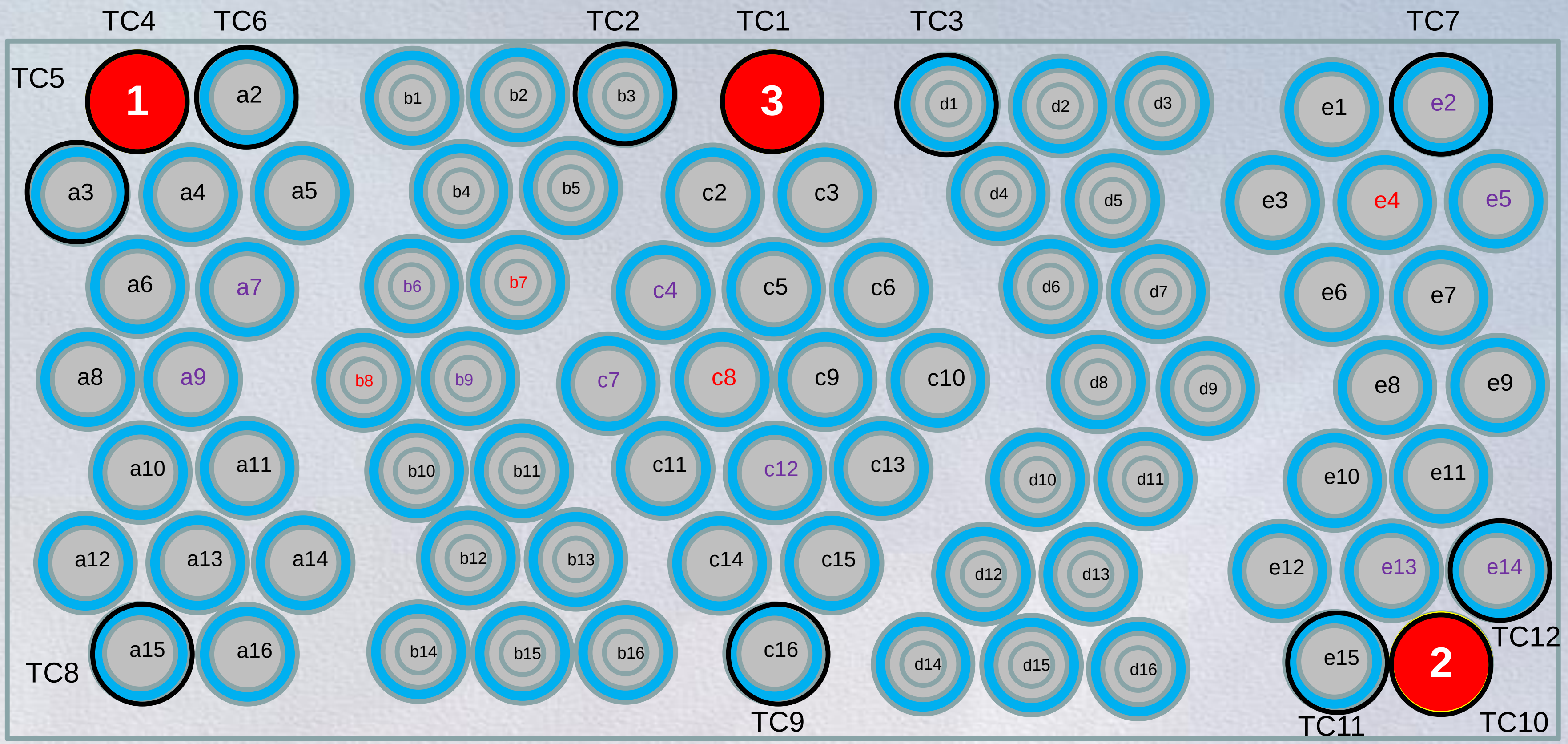
Solid Al side panels block cell vents



Modified Lid Assembly



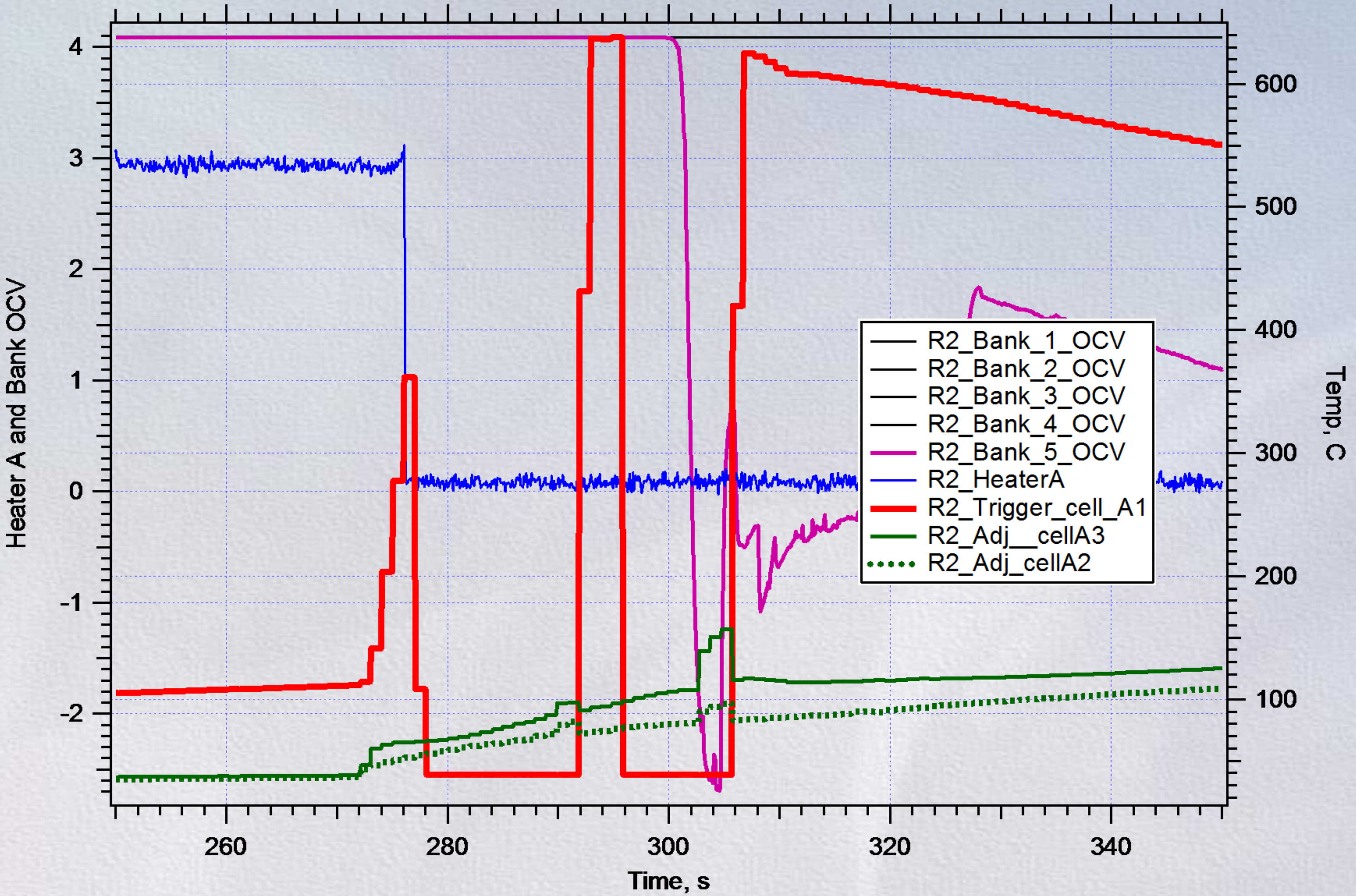
Proposed Trigger Cell & Skin TC Cell Location Map



Proposed Test Conditions

- 3 triggers shown in red at the top of the brick, ambient pressure and temperature
  - Brick reassembly
    - Before replacing the side plates, we’ll need to arm the trigger cells with fuses
    - Trigger cell 1 – negative Ni tab to cell will be snipped to isolate the cell with 45?W to heater
    - Trigger cell 2 – negative Ni tab to cell snipped and bridged with a 3A pico fuse with 45?W to heater
    - Trigger cell 3 – no Ni tab modifications, low power trigger profile (replicating baseline test conditions)

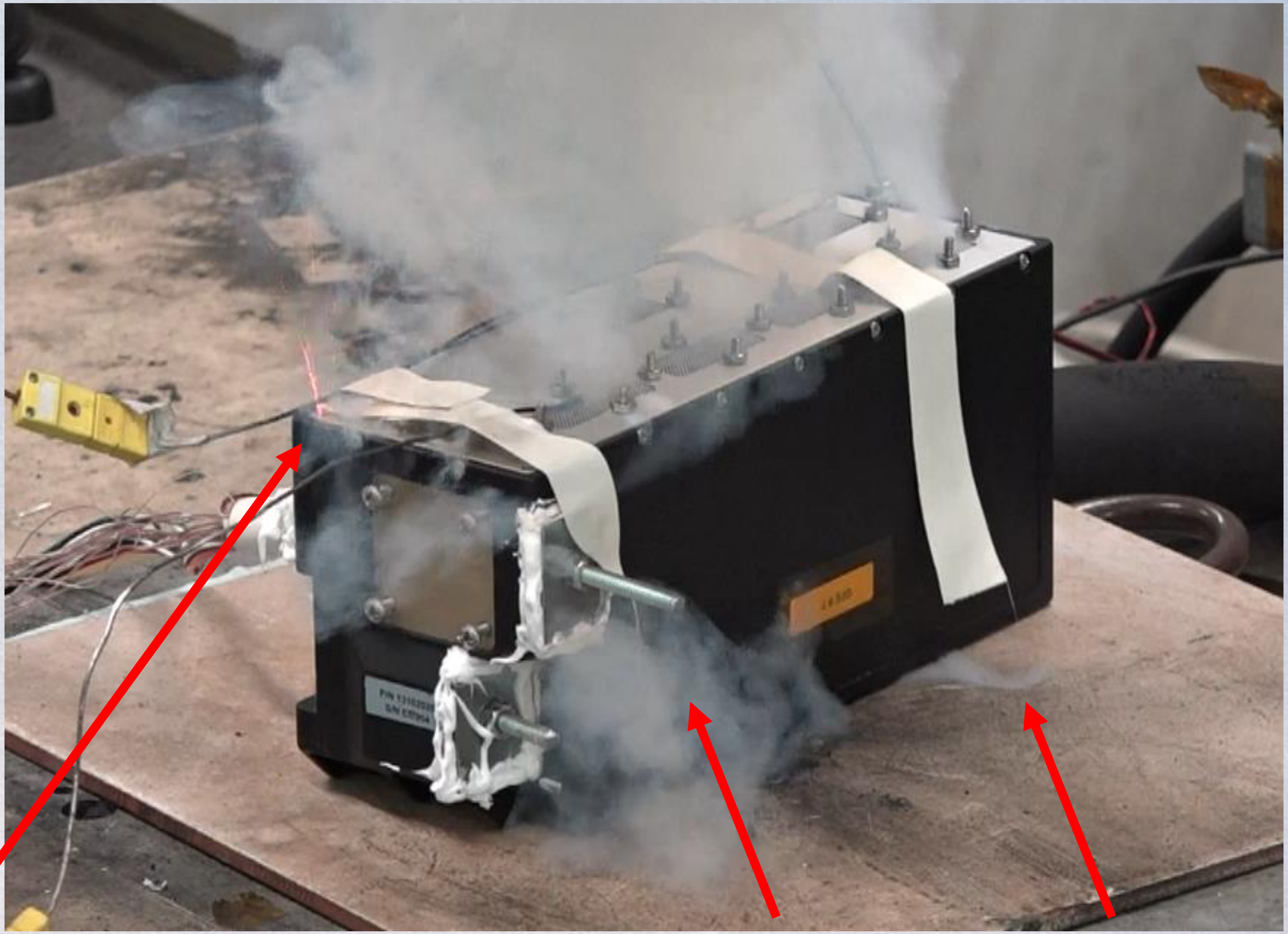
Run 2 - Close-up of TR event



Trigger cell at 114C at OTR, while adjacent cells at 43C (very little temperature biasing)
Trigger cell temp is lost during most of peak TR event for 30s, but we know max T > 625C
Max T on vent ports was 66C

Clip Highlights

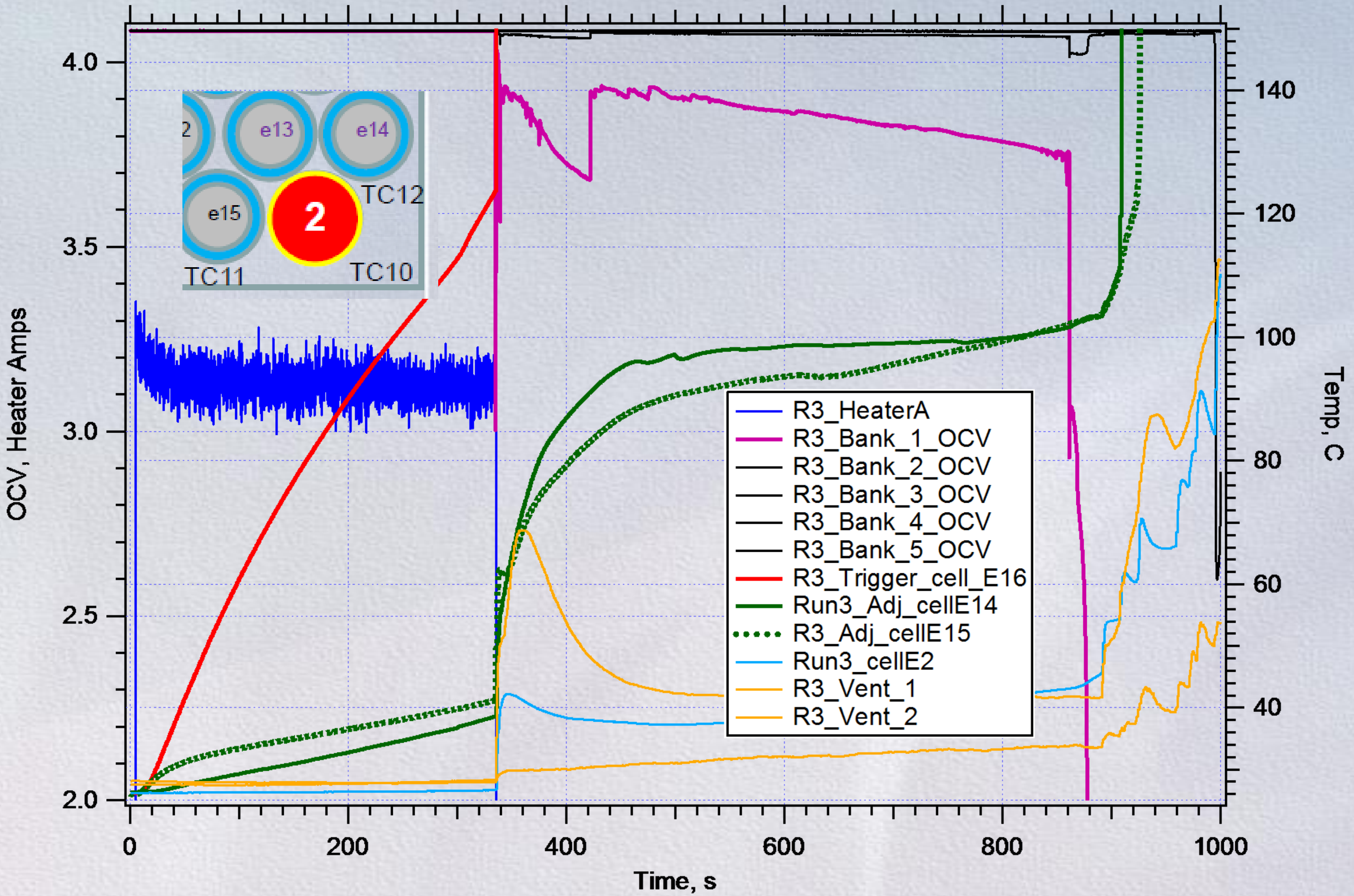
No sparks/ flames from the covered vents.



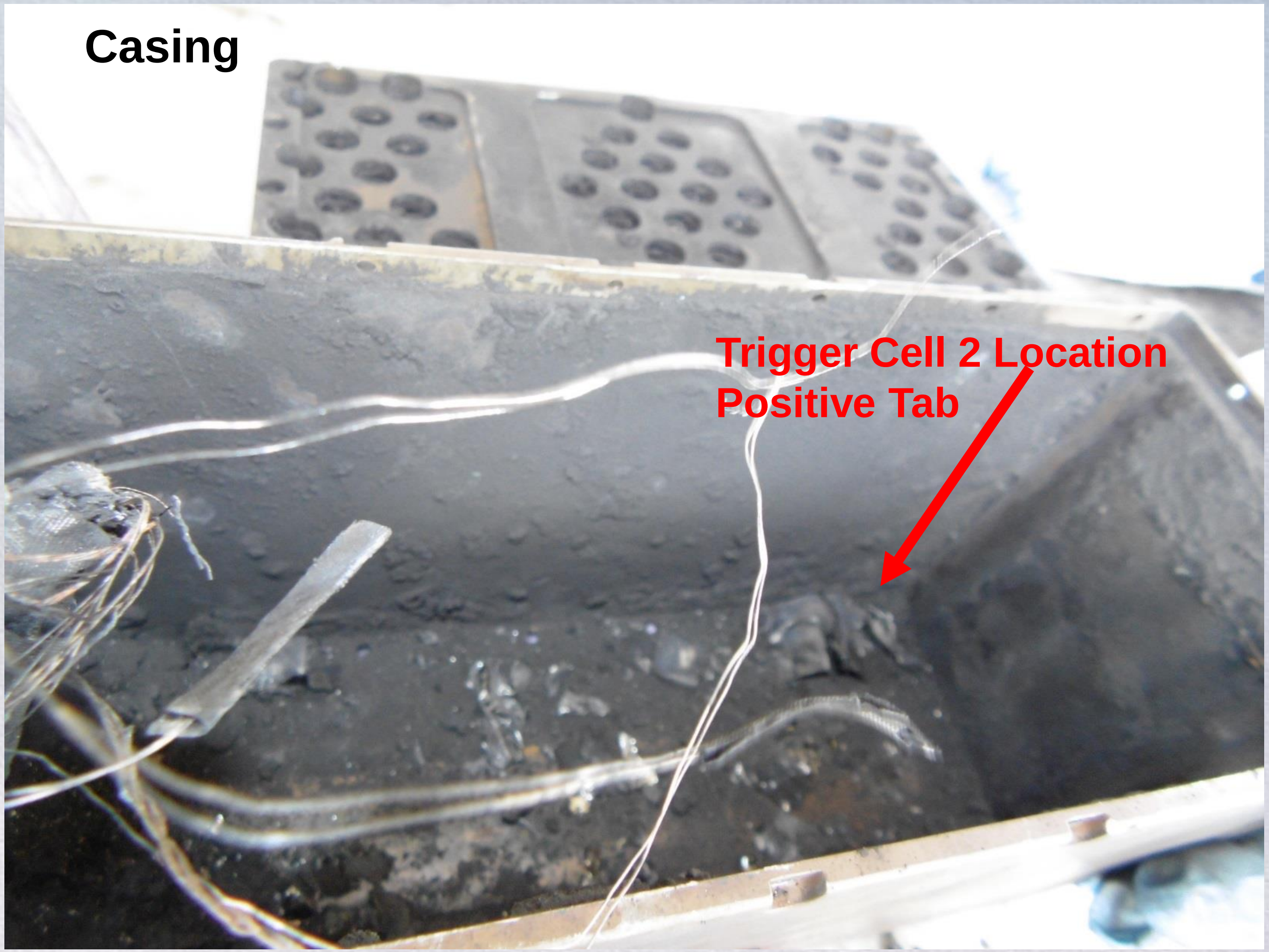
Brief sparks from trigger cell out of pressure hole

Smoke from screw-less holes and plugged holes

Run 3 – Close up on Adjacent Cells



573s between in trigger cell and adj cell E14 OTRs. During that time, low bank 1 OCV indicates circulating currents with the 15 parallel cells are slowly warming the adjacent cells. They almost plateau at 100C, but take off into OTR about 15s apart with E14 going first. First vent port max T = 69C, very similar to Run 2.


Casing
Trigger Cell 2 Location
Positive Tab

LLB Conclusions and Forward Work

- We did not propagate in Run 2 but did in Run 3.
- Lid vent ports screens were refreshed between runs and so were many TCs. The main difference between runs were the location of the trigger cells and that run 3 trigger was connected to the bus with a 10A picofuse.

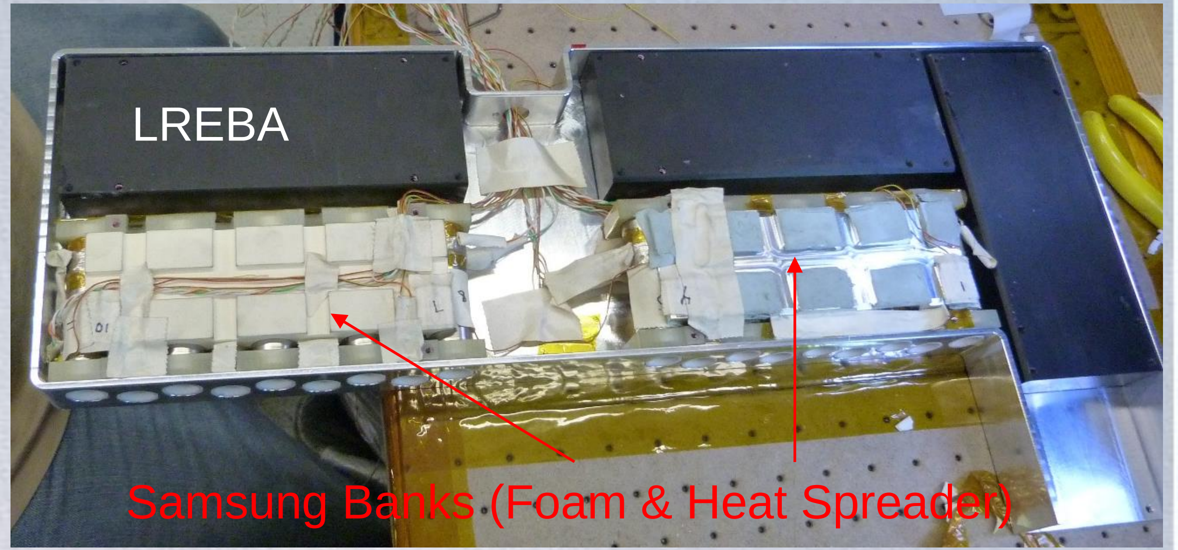
- From a quick look at the Run 3 data, reveals the following;
  - TR of trigger cell was achieved in < 330s and very little biasing of the adjacent (~40C when trigger cell went parabolic)
  - Vent port max T ~67C after trigger cell for both runs
  - Trigger cell for run 3 achieved 728°C, while in Run 2 all we know if was above 625°C since the TC was fluctuating.
  - Run 2 caused the trigger cell bank OCV to drop out and fluctuate about 30s after OTR of trigger. Run 3 caused the trigger cell bank OCV to dip to 3.0V, recover to ~3.5V. Both are indicating circulating currents, which explains why on Run 3 the adjacent cells kept getting warmer for ~9 minutes until they went.

- Adding a vent path and fusing to the trigger cells is not enough for the LLB design
  - Lack of mica sleeves on cell cans and Macor® bushings, and the tight (~0.5mm) cell spacing along with insufficient TR ejecta vent path on bottom trigger cell are the main contributors to the propagating result.
  - DPA photos indicate pooling of cell TR ejecta in between cell brick and housing wall near bottom trigger cell

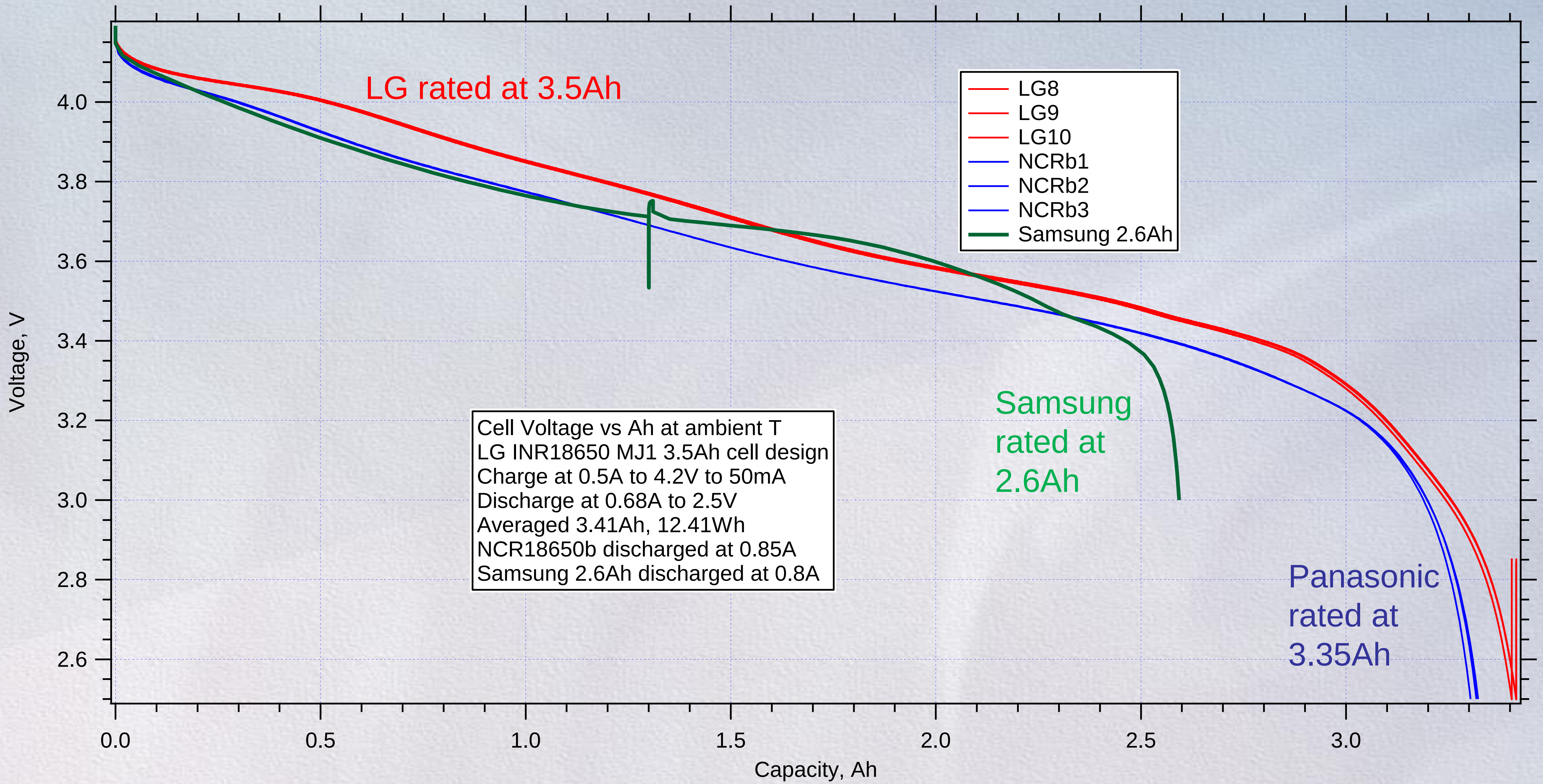
- More drastic redesign is required and should include;
  - Switching to higher energy cell design (3.35Ah vs 2.4Ah) and add features to prevent side wall ruptures
    - Reducing cell count from 80 to 65 to maximize cell spacing (~ up to 2mm)
    - Yet keep battery capacity at > 34Ah
  - Individual cell fusing integrated into bank Ni bussing
  - Interstitial material between cells
  - Improve heat sinking from cells to battery enclosure

How can we better protect adjacent cells?

- Max Adjacent Cell Temps
  - LREBA > 110C
    - No interstitial material, just mica sleeve
    - Syntactic Foam
    - Heat spreader plates
  - LPGT > 110C
    - No interstitial material, just mica sleeve
    - Partial length Al interstitial heat sink
  - LLB > 125C
    - No interstitial material, bare cells
    - Non-propagating run 2 with vented lid



High Energy Density Cell Design Comparisons

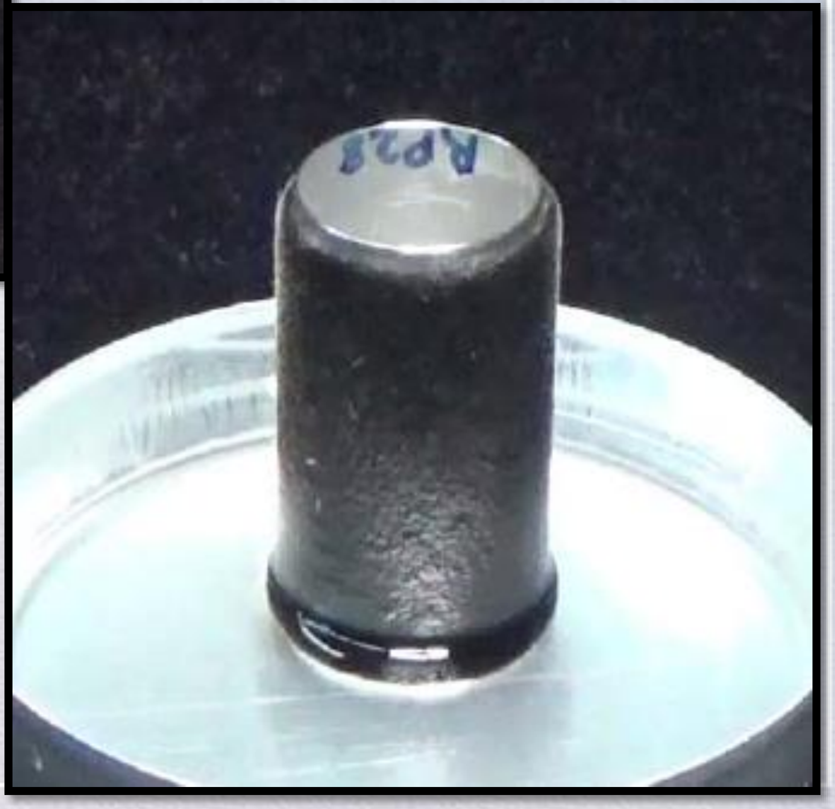


Vaporizing Heat Sink Tests

- **Goal:** Quantify benefits VHS provides over existing heat sinks
- Heat Sink designed by ESLI
- Each bore hole surrounded by carbon fiber wick
- 2 millimeter spacing between cells
- 60 g of water held within the fiber per heat sink
- Water’s latent heat of vaporization theoretically provides significant improvements over traditional heat sinks

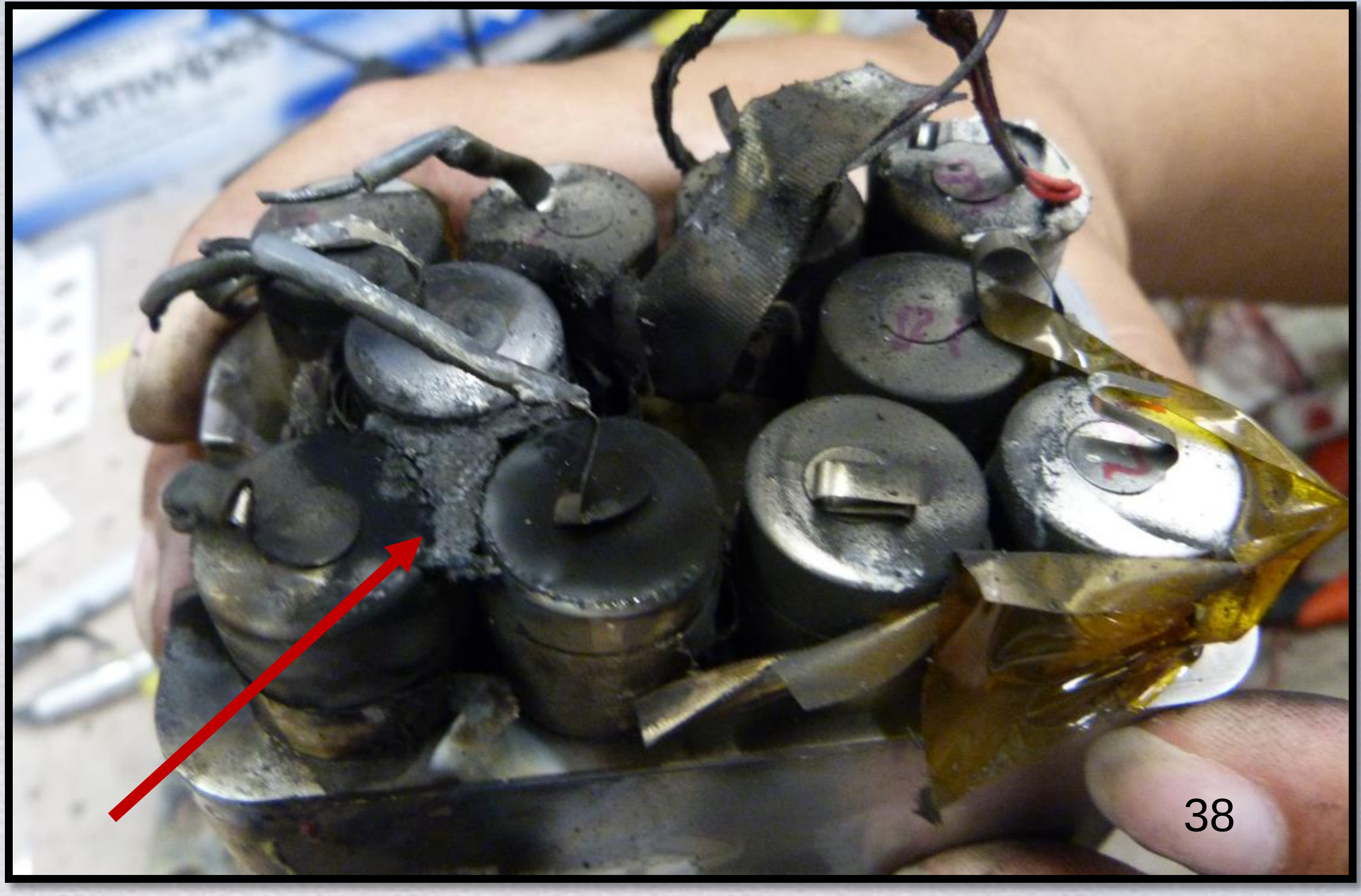
Energy Science Laboratories, Inc.

VHS cell bores leave 0.5” cell length exposed to allow for circumferential heater to placed on trigger cell



VHS TR Test with Panasonic Cells

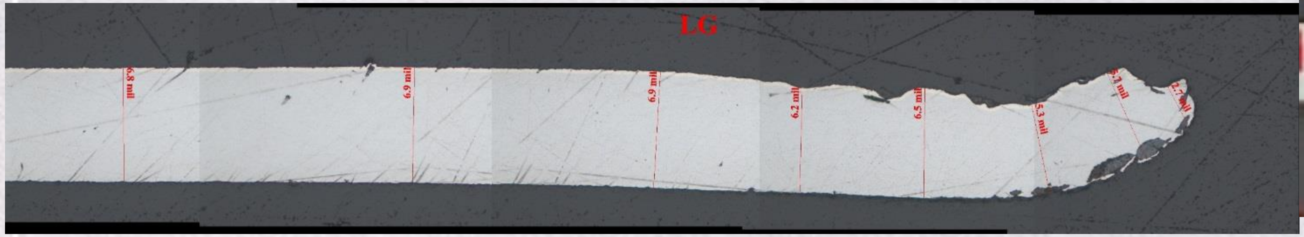
- First test conducted in N2 chamber
- Partial length VHS left 0.5” of cell bottom exposed to place heater
- Trigger cell had side wall rupture in circumferential heater area which impinged TR ejecta into adjacent cell
- Resulted in propagation to two additional cells and damaged several others



Safe, High Performing Battery Design

- Need > 250 Wh/kg, > 660 Wh/L cell designs
  - They present high risk of cell can wall ruptures
- Main contributing factors
  - High energy density
  - Fast kinetics for thermal decomposition
  - Thinner can walls
  - Strong crimp seal

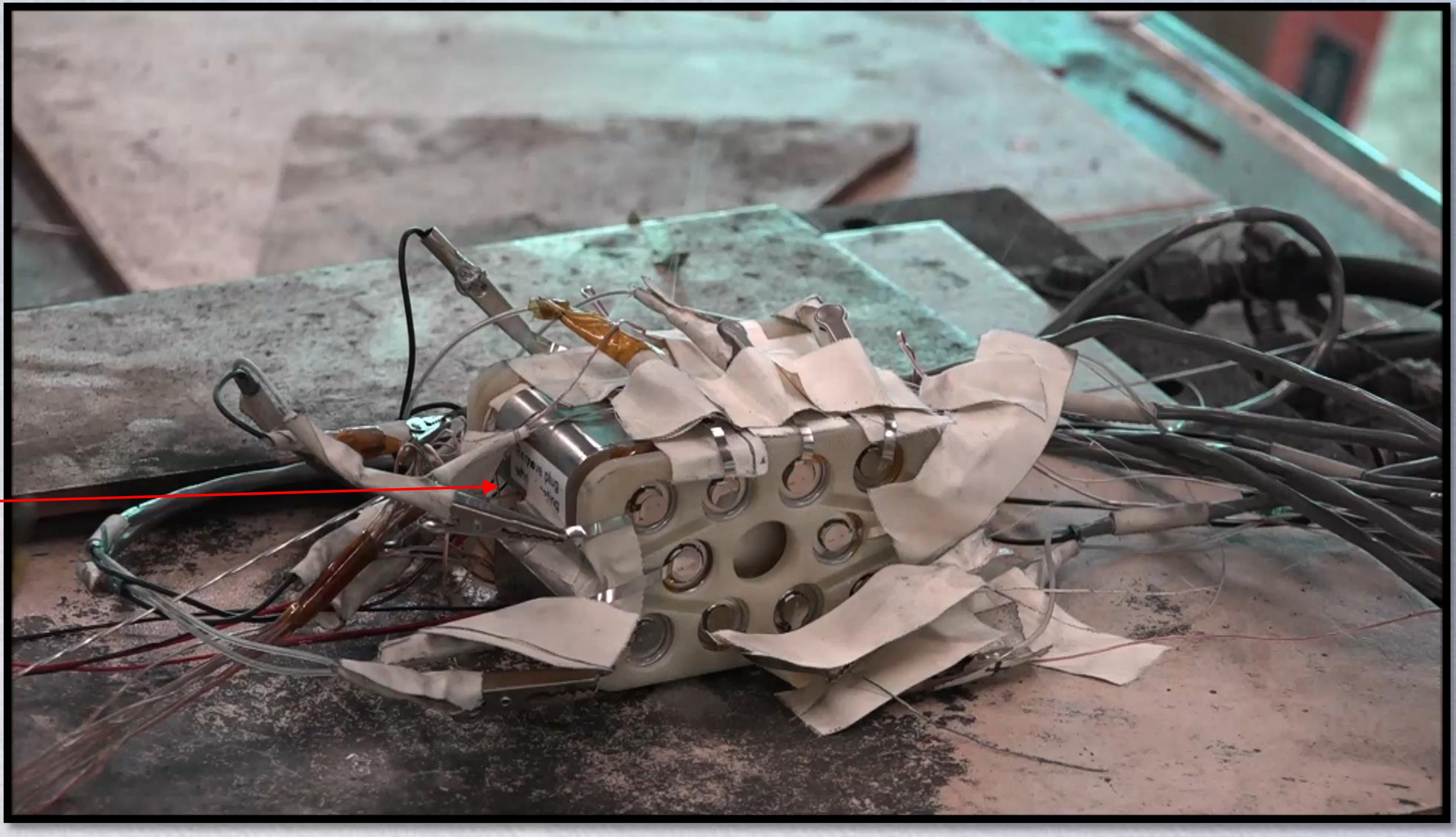
2.6Ah cell design with 0.0065” can wall



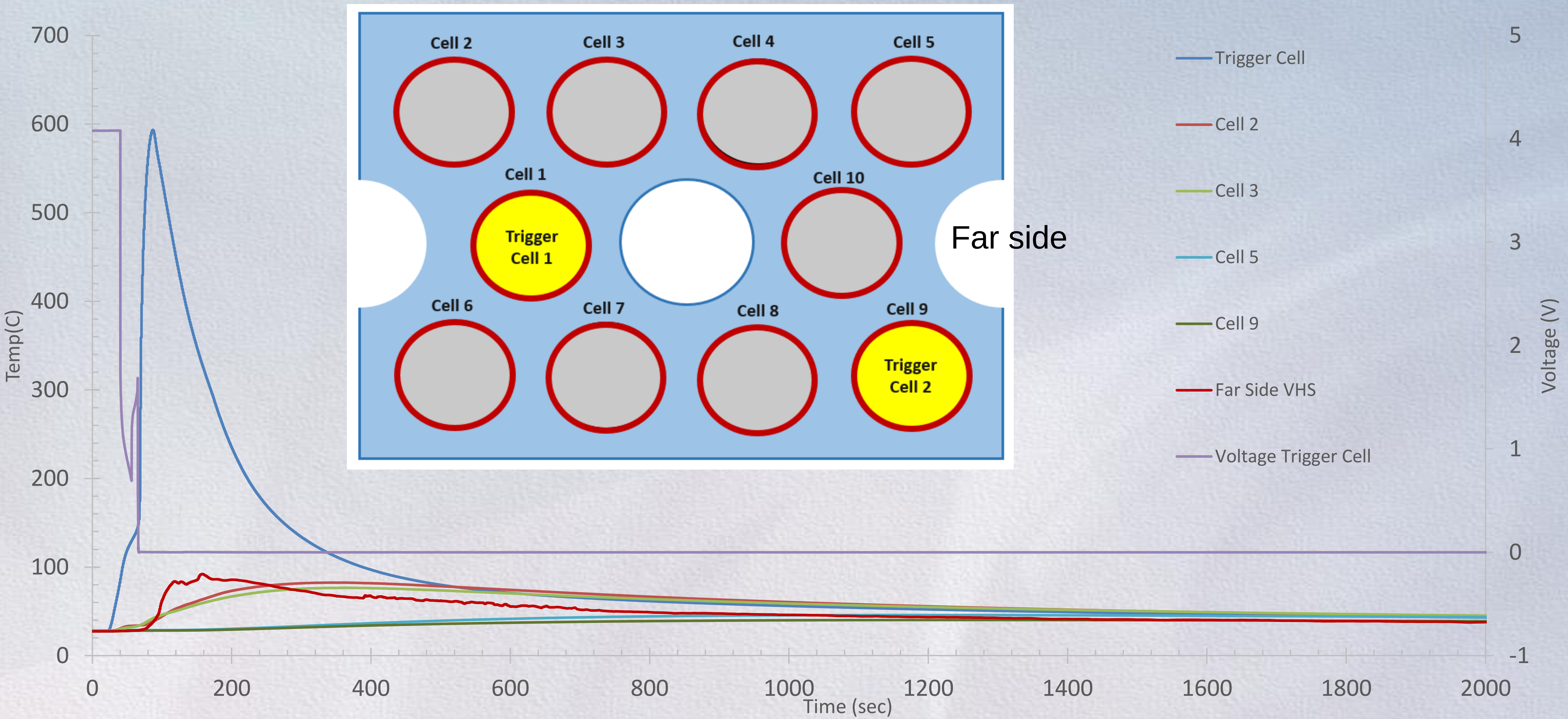
> 3Ah cell design with 0.005” can wall

VHS TR Test with Samsung Cells

- Second test conducted in open-air environment
- Samsung cells replaced Panasonic trigger cells, with same circumferential heater
- VHS succeeded in preventing thermal runaway propagation
- Liquid water and some steam exited out of open VHS vent port
- VHS lost ~1/3 of its 60g of water loading



VHS TR test with Samsung cells

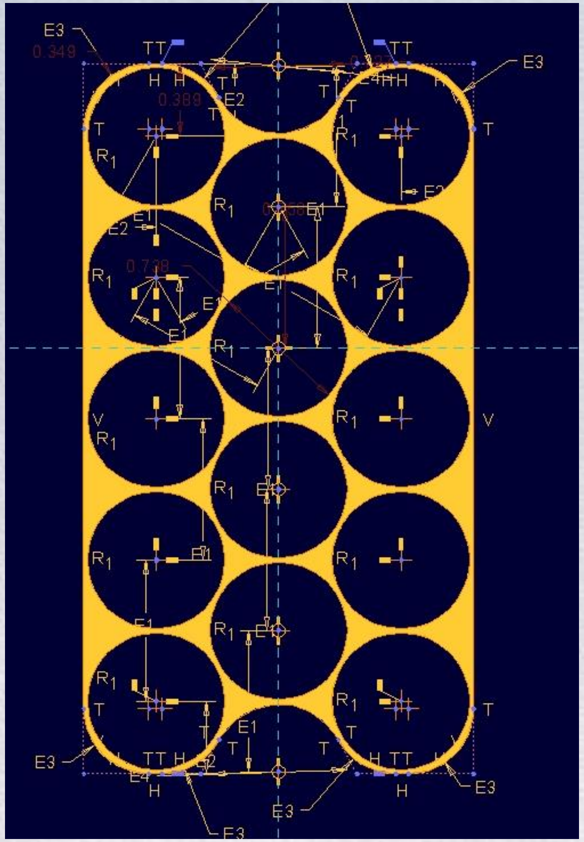


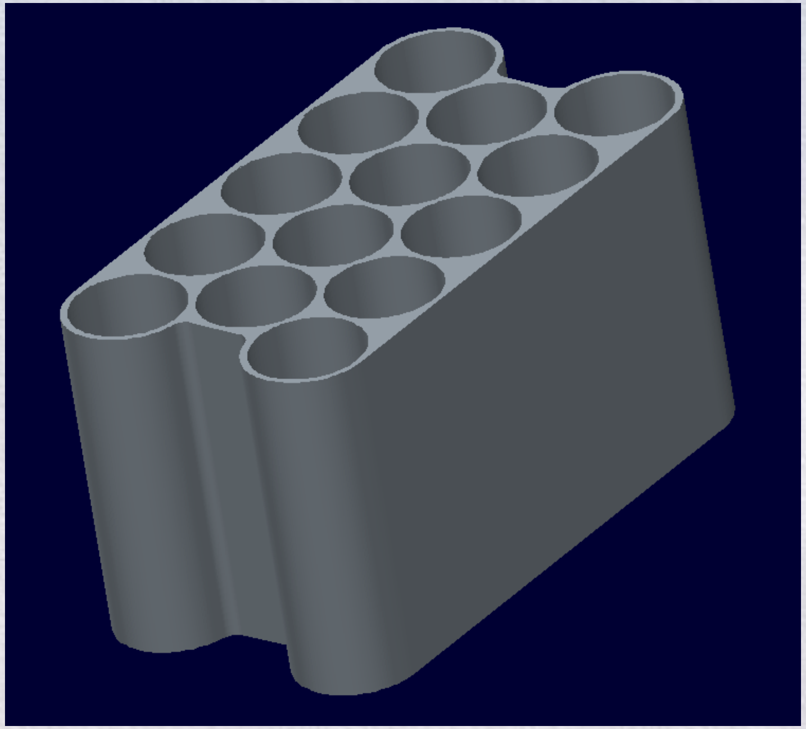
Results: Maximum adjacent cell temperature < 85°C after trigger cell 1 driven to TR

Much bigger margins than with insulating interstitial material (LPGT, LREBA, and Orion)

Conductive Interstitial Material Design

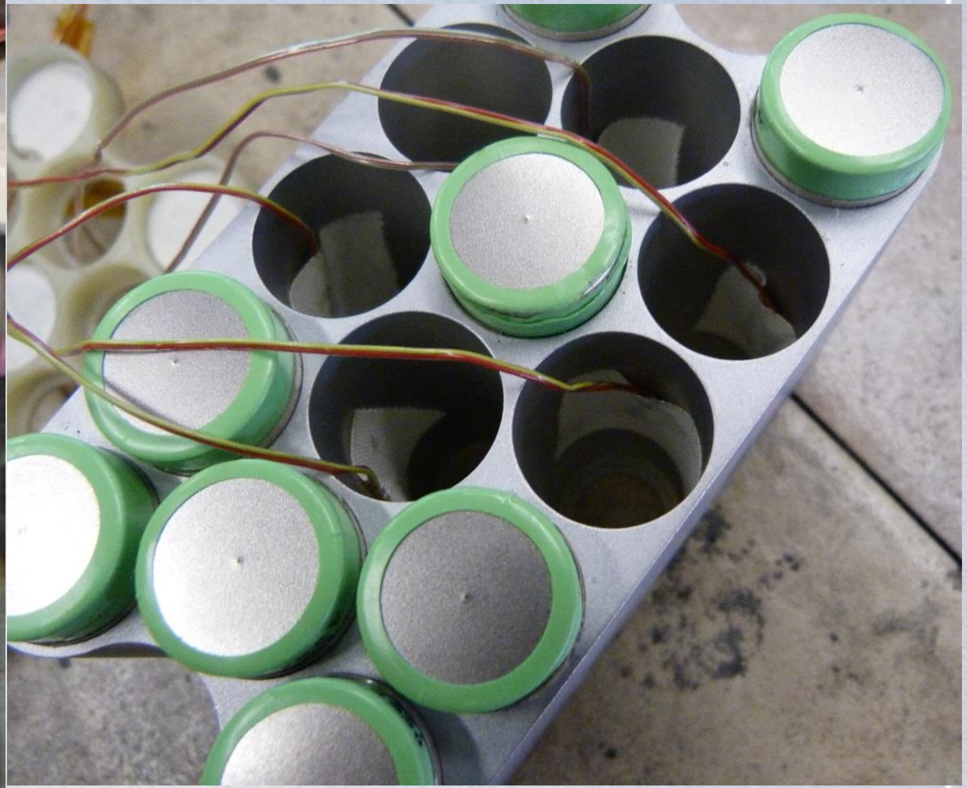
- 14 nested cells with 1mm and 0.5 mm cell spacing
- Matching G10/FR4 capture plates for the cell ends
- Initial tests done with Al 6061T6
- Cells inserted into bores with their original shrink sleeve and 100 μm mica paper sleeve





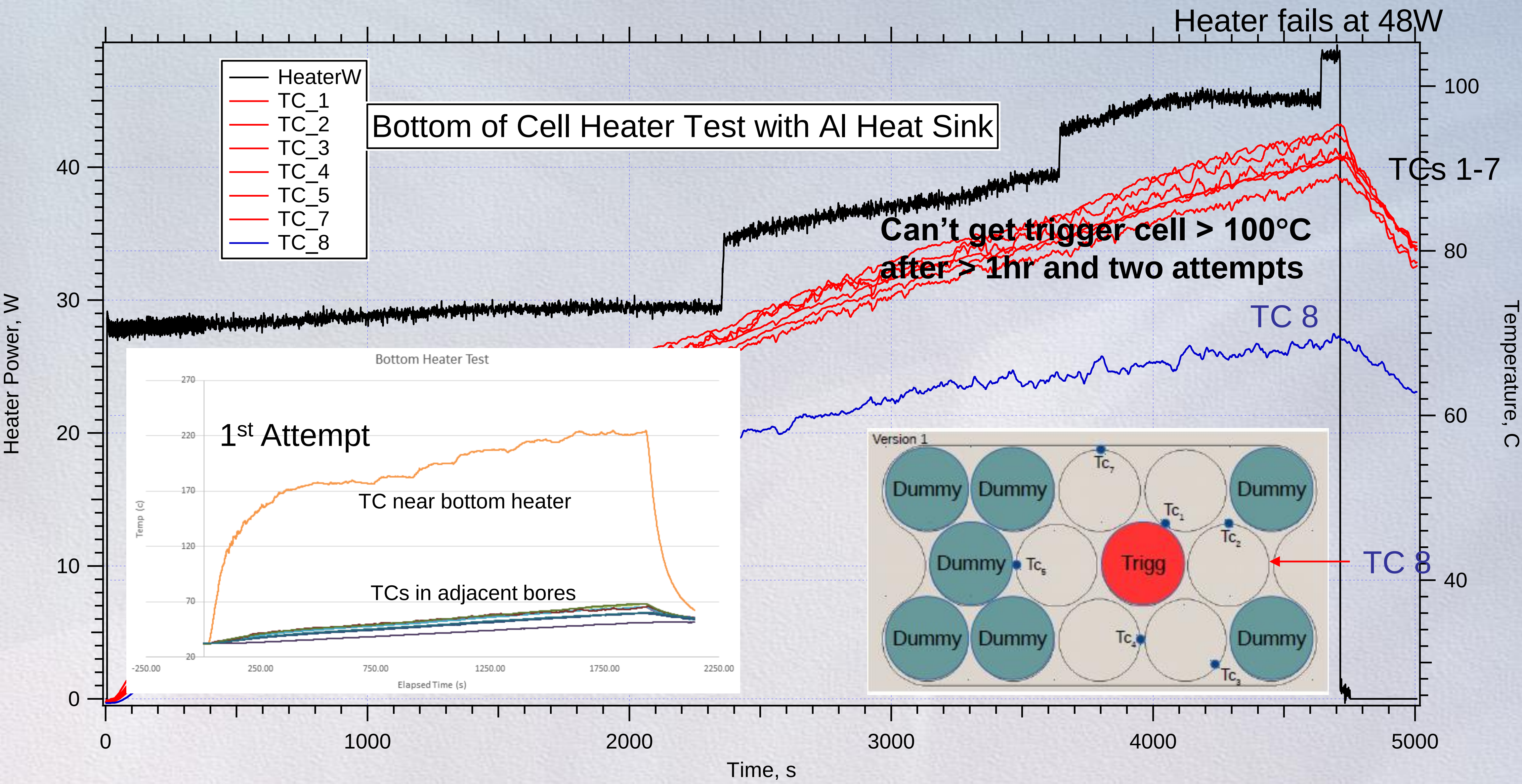
Can we drive trigger cell into TR without excessive temperature biasing of adjacent cells?

- Bottom heater was used instead of circumferential due to geometry.
- The interior trigger cell was a Panasonic NCR
- Adjacent cells were removed to allow TCs to placed in those bores
  - Non-adjacent cells (Panasonic NRCb) were fully charged and inserted to provide thermal mass
- TR was not achieved after 30 mins with bottom heater, test aborted.
- This heat sink just wicks away too much heat for cell bottom heaters!



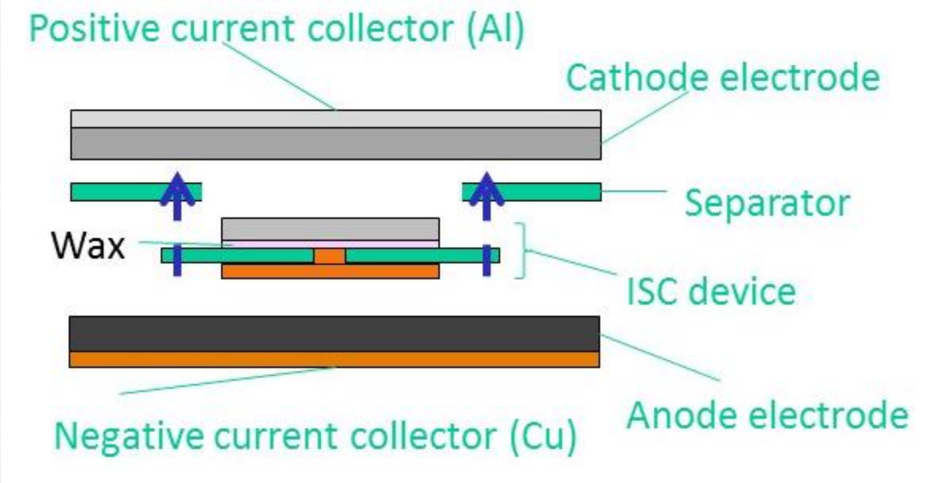
TCs in the empty adjacent cell bores
Fully charged cells in non adjacent bores

2 Attempts to Drive TR with Panasonic Cell in Al HS



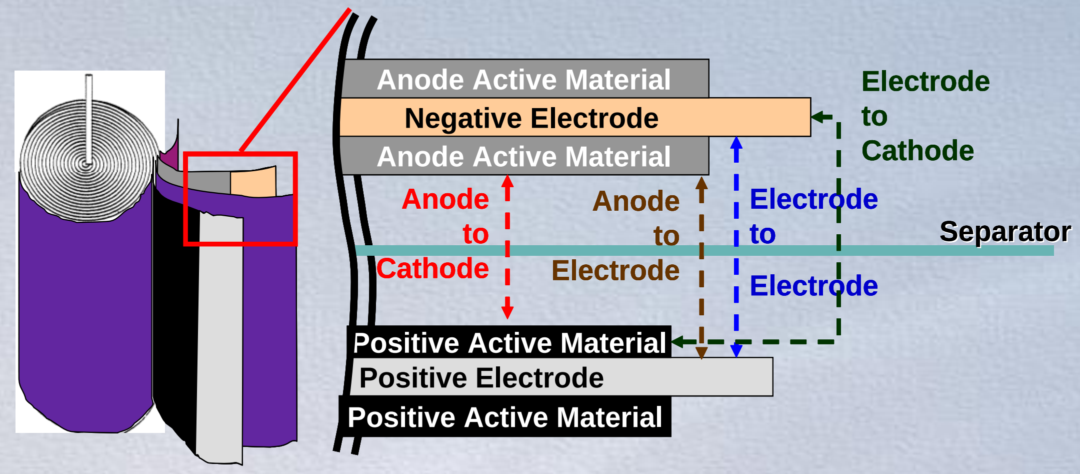
TR Trigger Methods – Which is best for battery testing?

- Conventional Methods – all with downsides
  - Electrical – Overcharge
    - Triggers at too high states of charge, with generally more violent output than ISC
    - Requires cell to be electrically isolated from parallel cells in pack
  - Mechanical – Crush or puncture
    - Compromises cell and battery enclosures
    - Difficult to do to interior cells in a pack
  - Thermal – Over-temperature exposure
    - Requires low profile custom high flux heaters
    - May interfere with cell-to-heat sink interface
    - High risk for biasing adjacent cells
    - Weakens strength of cell can prior to TR
- Implantable seeding of an ISC
  - Metallic seeding inside jellyroll (BAJ-FIST, TIAX) done on fully charged cells
    - operationally hazardous to perform
    - trigger is after many cycles (not on demand)
  - NREL/NASA implantable ISC device
    - Negligible cell performance impact
    - ***Main upside - Only battery design/test accommodation required is heating cell to melting point of wax***
    - ***Main downside – Requires a willing cell manufacturer to do the implantations***



ISC Device TR Trigger Capabilities

- Provides an improved ISC cell-level test method that:
  - Simulates a latent internal short circuit.
    - Capable of triggering the **four** types of cell internal shorts
  - Produces negligible impact on cell performance until the short is activated on demand with heating to 60C
  - Provides relevant data to validate cell ISC models
  - Can be used to verify cell design safety features (new separators, CID)
  - Produces consistent and reproducible results
  - Yields TR reliably enough for implanted cells to be built into batteries for TR propagation assessment with the following advantages
    - Minimal temperature biasing of adjacent cells
    - Trigger cell does not need to be electrically isolate from rest of the battery



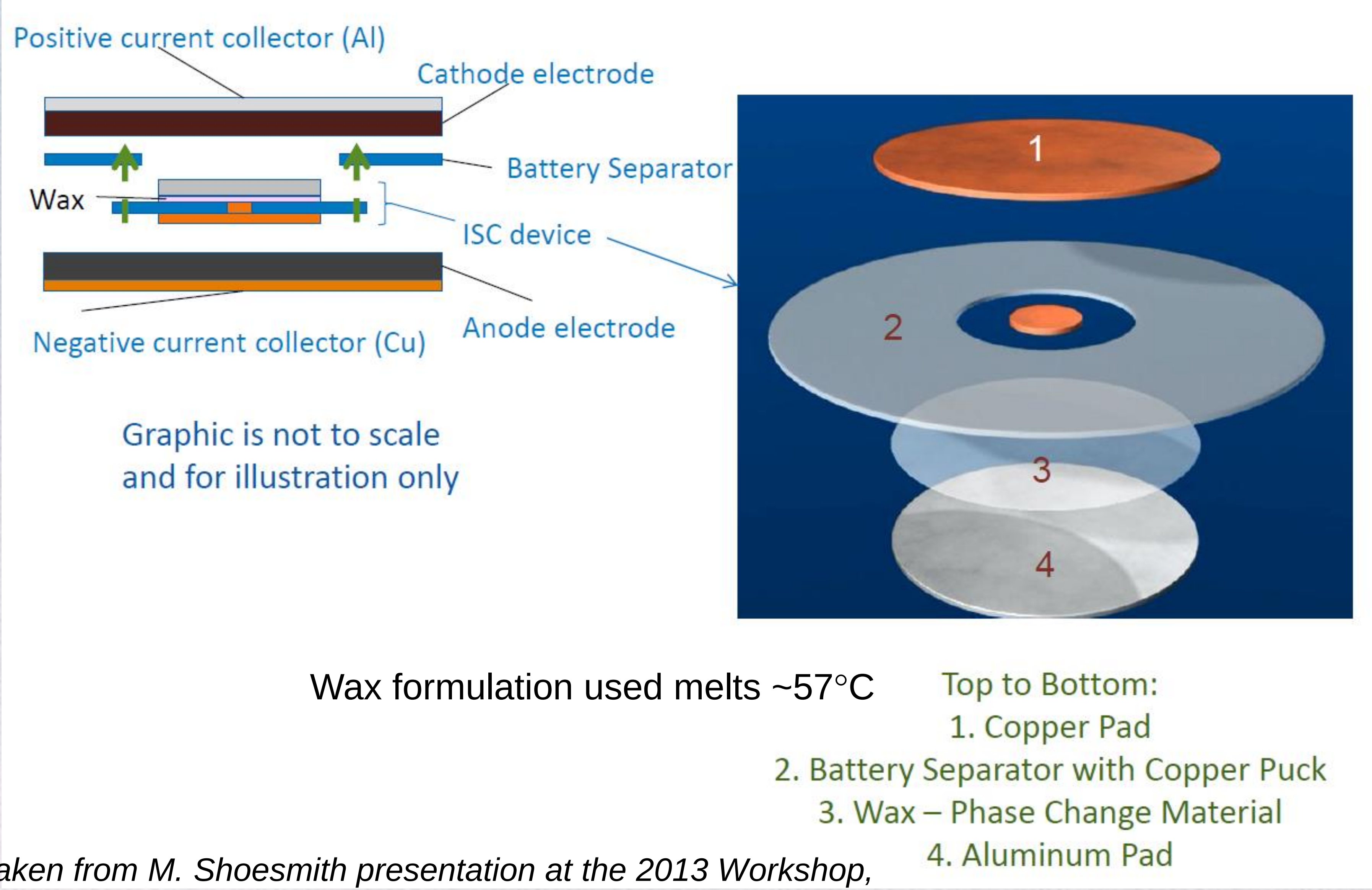
Spiral wound battery shown – can also be applied to prismatic batteries.

<u>Four Types</u>

1 – Active to Active
2 – Al Collector to Anode Active
3 – Cathode Active to Cu Collector
4 – Collector to Collector

See M. Shoesmith presentation at the 2013 Workshop, "Cylindrical Li-Ion Cell Response to Induced Internal Short"

NREL/NASA ISC Device Design



Wax formulation used melts ~57°C

2010 Inventors:

- Matthew Keyser, Dirk Long, and Ahmad Pesaran at NREL
- Eric Darcy at NASA

US Patent # 9,142,829

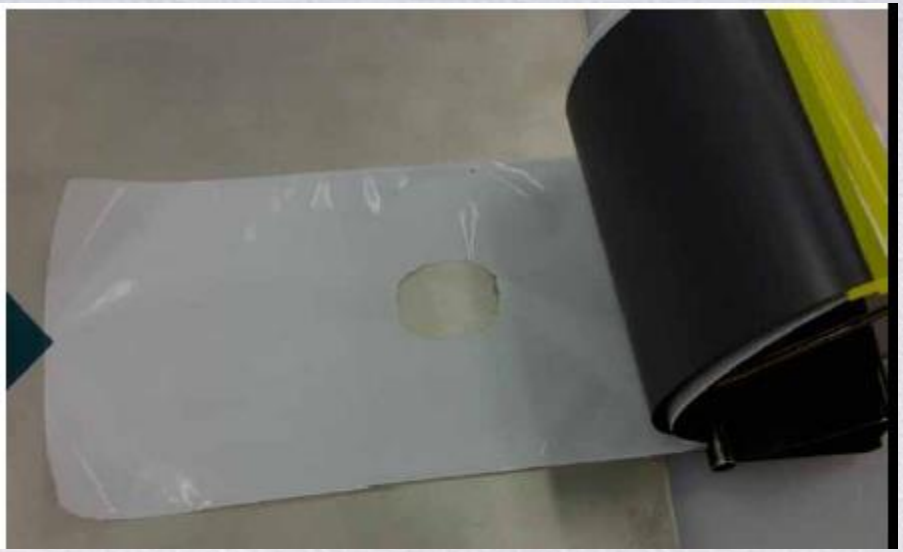
Thin (10-20 μm) wax layer is spin coated on Al foil pad

Taken from M. Shoesmith presentation at the 2013 Workshop, "Cylindrical Li-Ion Cell Response to Induced Internal Short"

Graphic credits: NREL

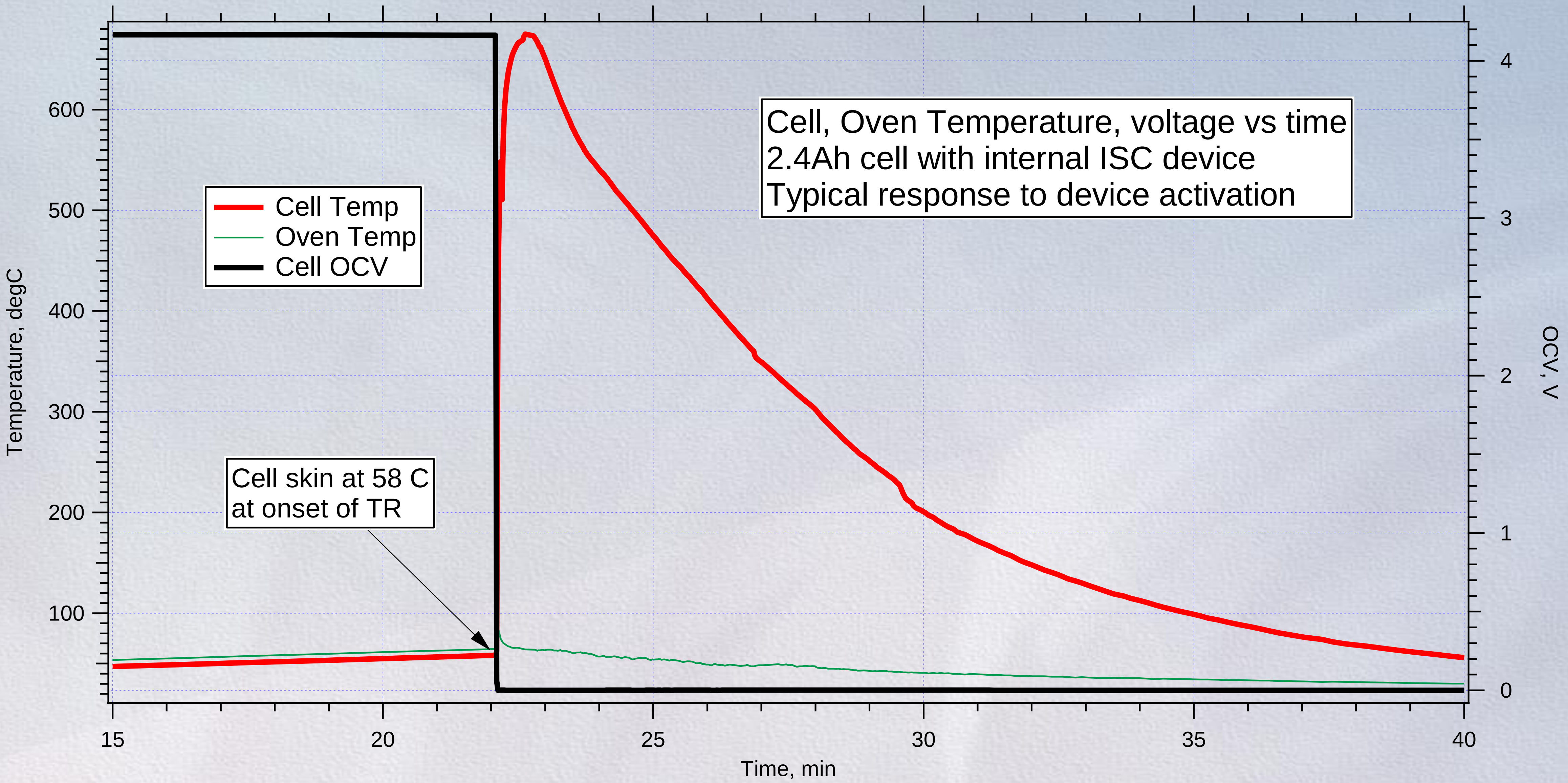
2.4Ah 18650 Cell

- NREL fabricated the ISC devices
- Partnered with E-one Moli Energy (Maple Ridge, BC) for the implantation into their 2.4Ah cells
  - Concentrated on Type II and IV shorts and with and without shutdown separator
- Moli performed cycling and activation tests
- NASA-JSC performed activation tests



Taken from M. Shoesmith presentation at the 2013 Workshop, "Cylindrical Li-Ion Cell Response to Induced Internal Short"

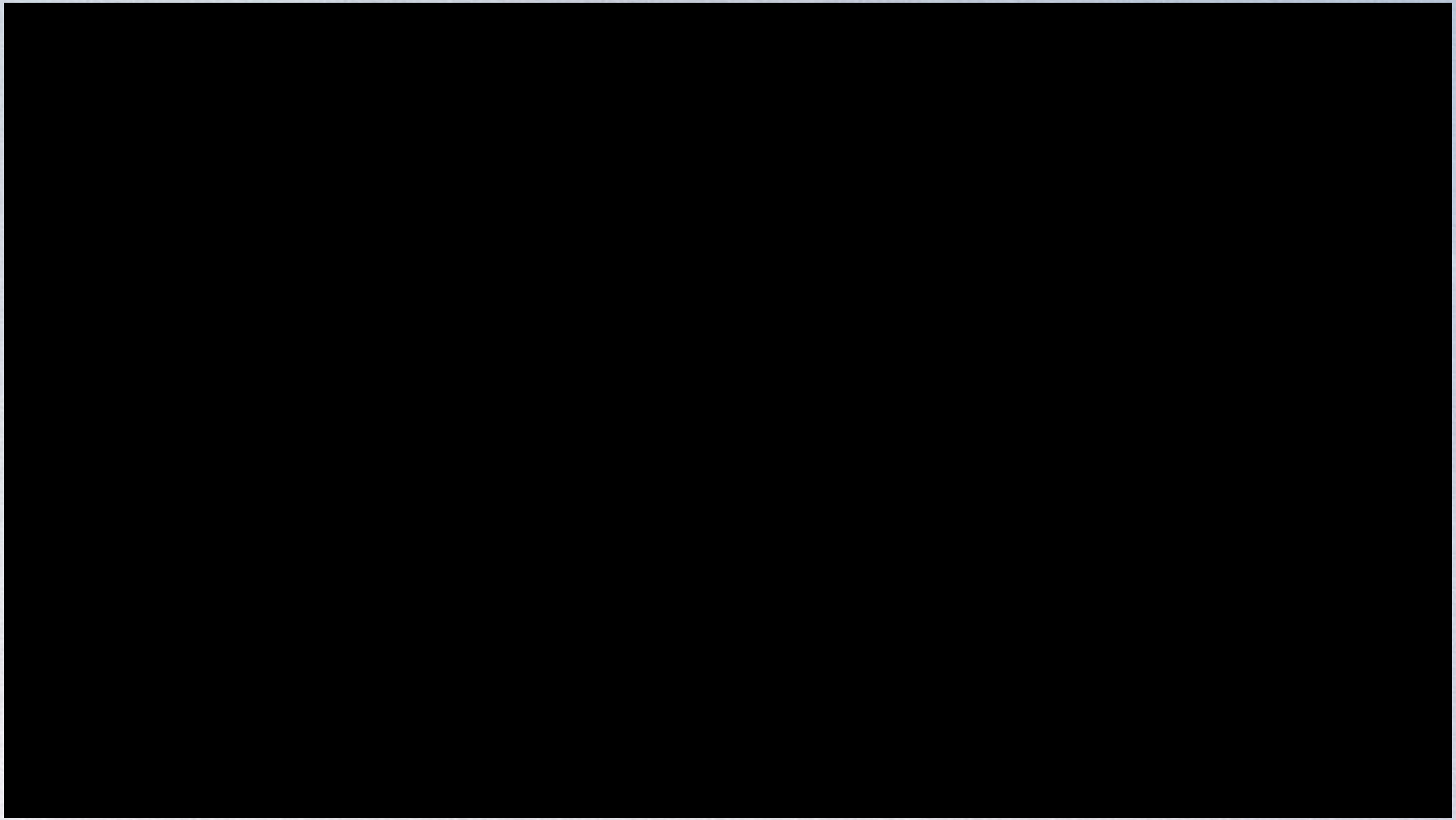
Photo credits:
Moli Energy



92% (12/13) success in producing hard shorts in trials of latest batch of ISC device implantations (9/10 at 100% SoC resulted in TR during oven exposure, 3/3 at 0% resulted in benign hard shorts)

- Note, the one dud went into TR during the post test discharge after cooling

Type 2 ISC Device in 18650 Cell



Cell assembled with non-shutdown separator – Designed to fail

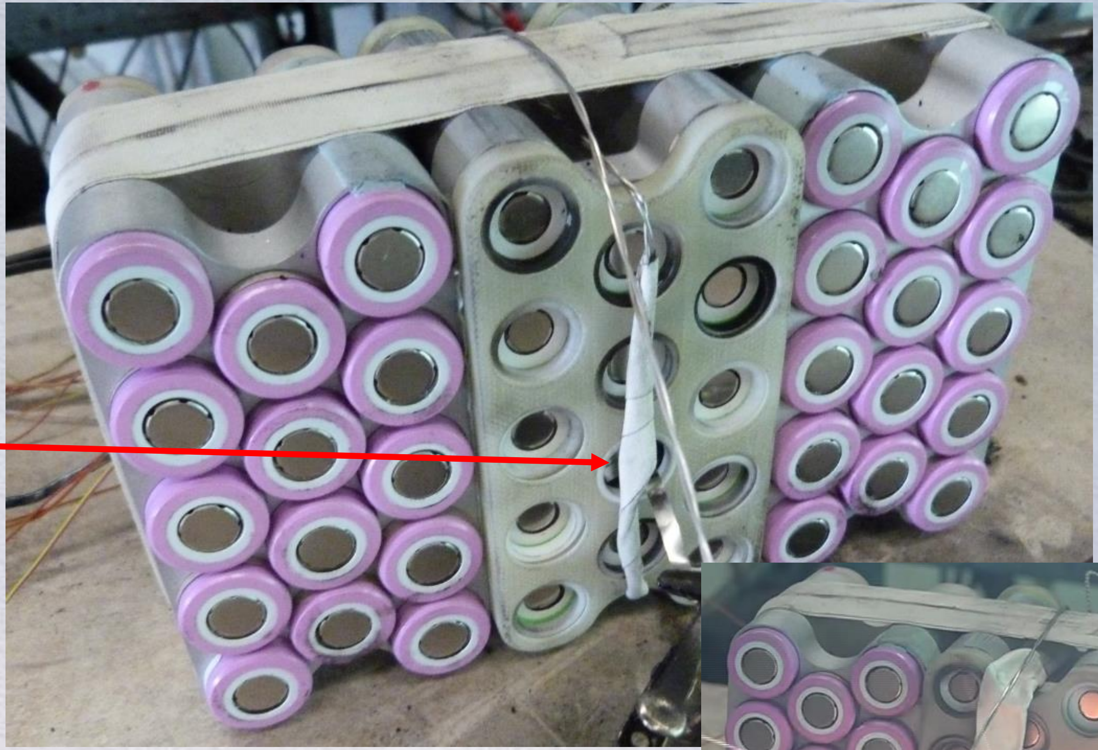
Why are Type 2 Shorts Nastier?

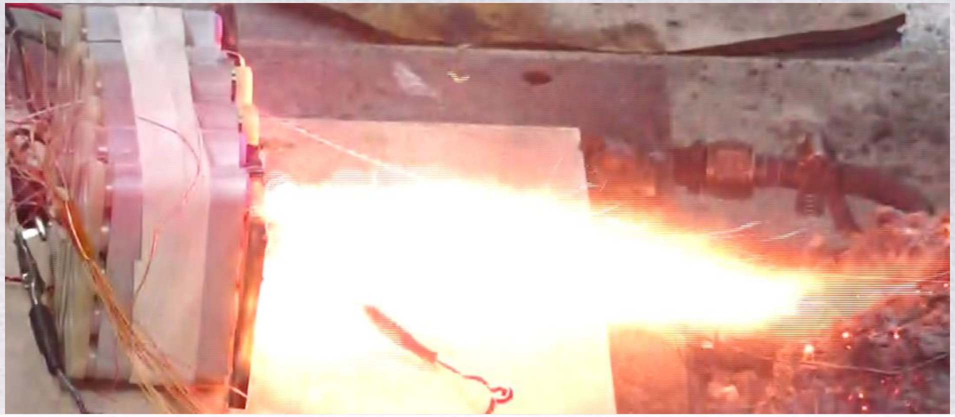
- Type 4 = Cu Collector to Al Collector
- Type 2 = Anode active material to Al Collector
  1. Sony[1] recall in 2006 was attributed to type 2 shorts
  2. Battery Association of Japan[2] replicates type 2 short and establishes test method
  3. Celgard[3] cell experiments were first to compare the 4 types of shorts and indicate the more catastrophic nature of Type 2 shorts
  4. TIAX[4] uses Type 2 short to demonstrate latency of defect during acceptance testing
- Why? One possible theory;
  - Involving carbon anode material provides the right impedance to maximize the power/energy delivered into the short
    - Type 4 shorts are lower impedance, end more quickly, and deliver less energy to the short

1. Nikkei Electronics, Nov. 6, 2006
2. Battery Association of Japan, Nov 11, 2008 presentation on web
3. S. Santhanagopalan, et. al., J. of Power Sources, 194 (2009) 550-557
4. Barnett et. al, Power Sources Conference, Las Vegas, NV, 2012

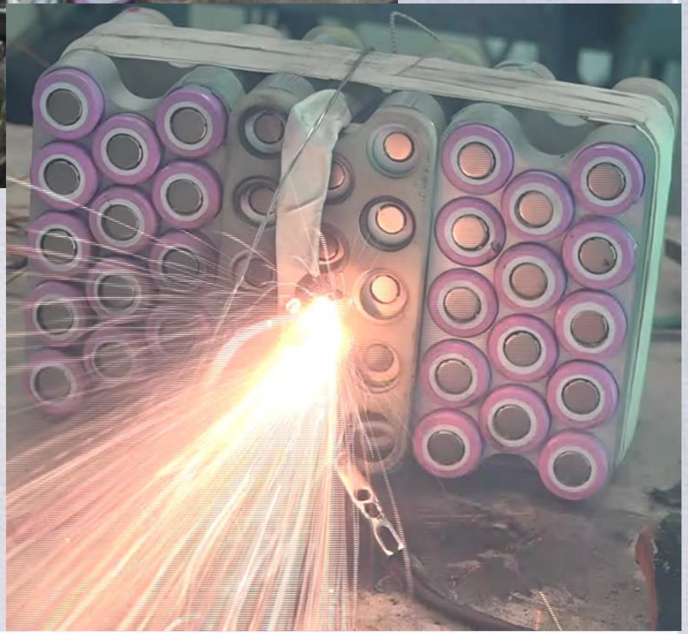
Used Moli Cell with ISC Device as Trigger Cell

- Fully populated heat sinks with fully charged Panasonic cells in middle heat sink
- Moli cell with ISC device in interior position
- Use same bottom heat to drive Moli cell to 60°C and activate ISC device

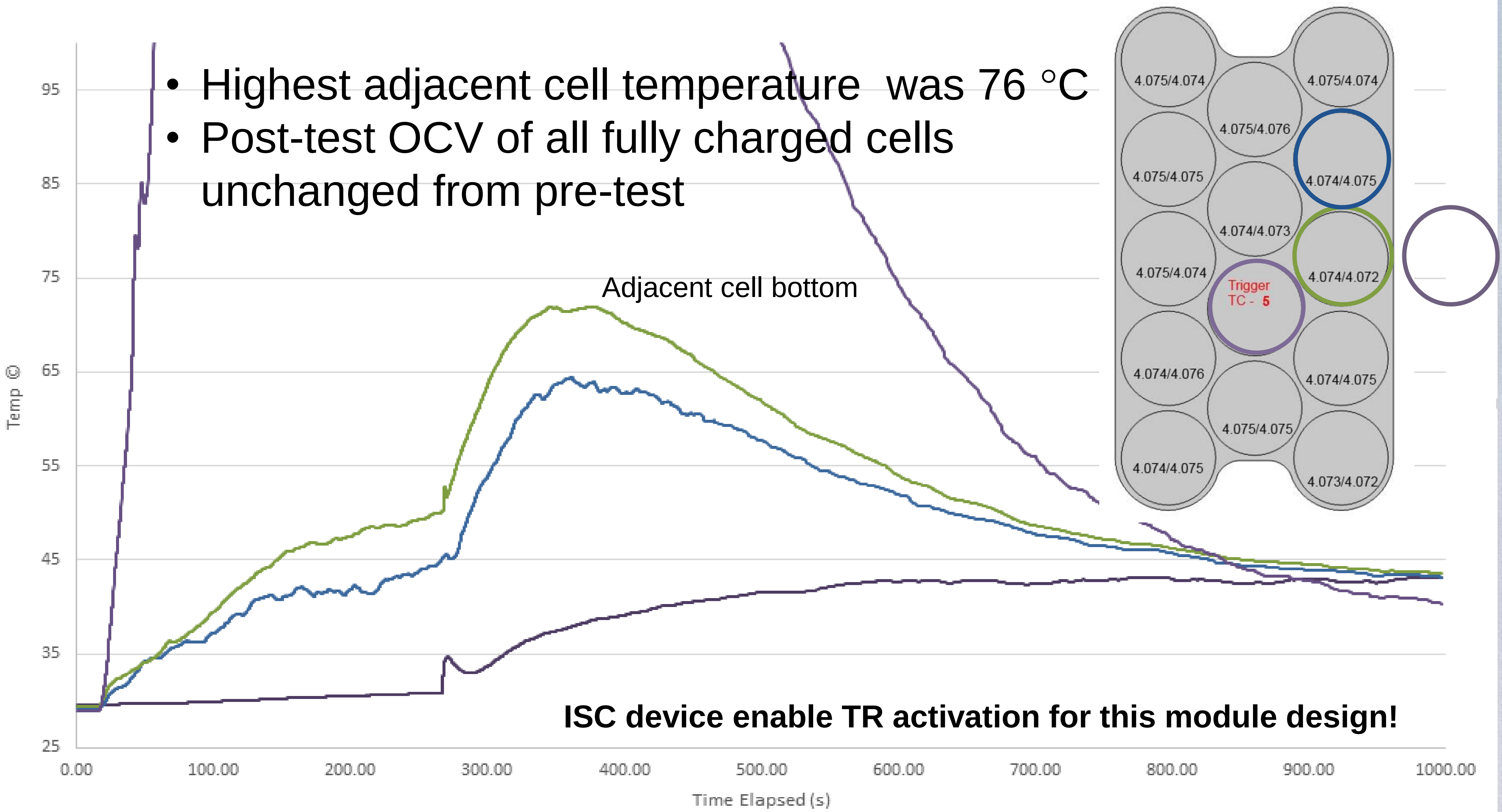




TR achieved in 3 mins in all 3 trials to date



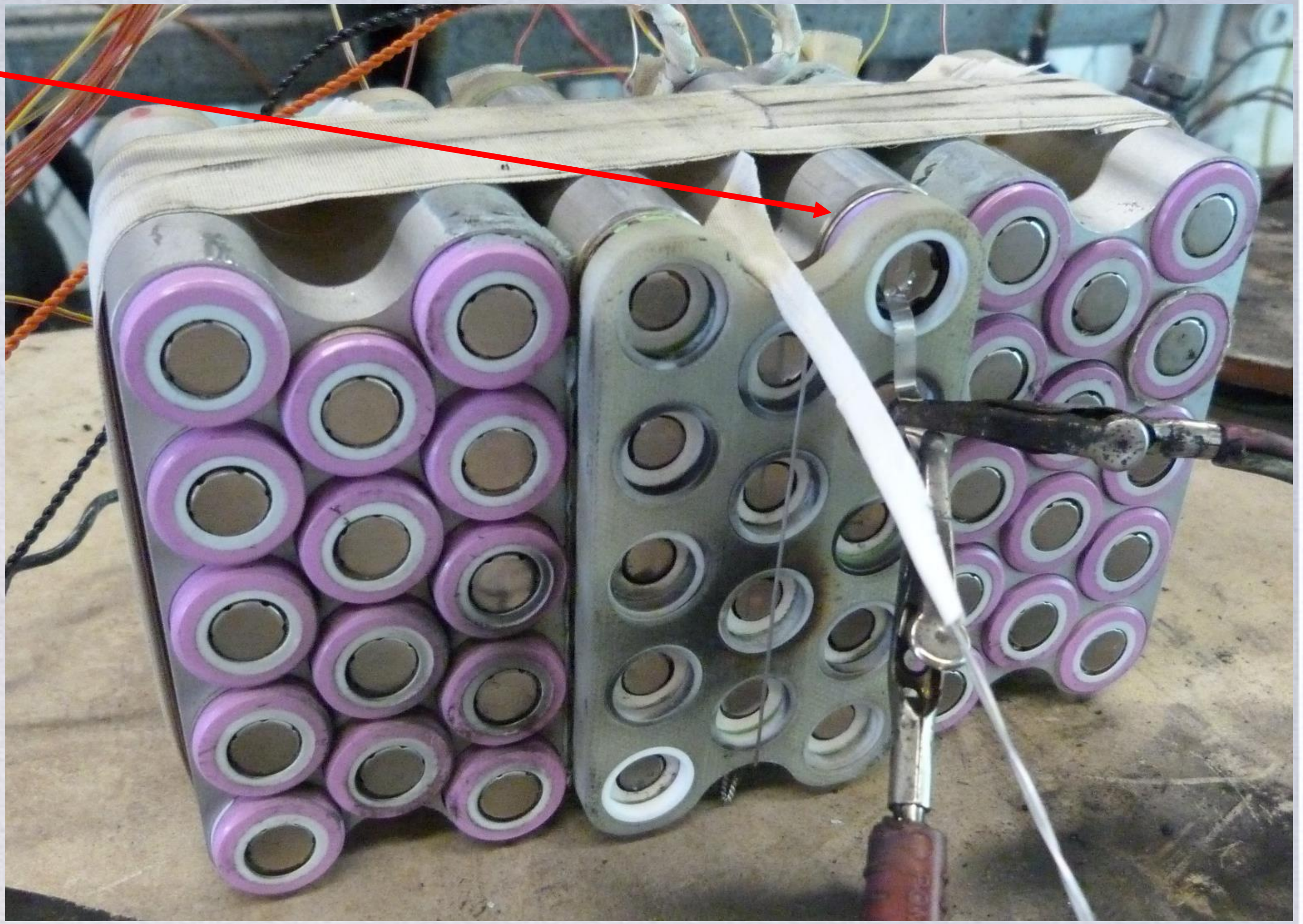
- Highest adjacent cell temperature was 76 °C
- Post-test OCV of all fully charged cells unchanged from pre-test

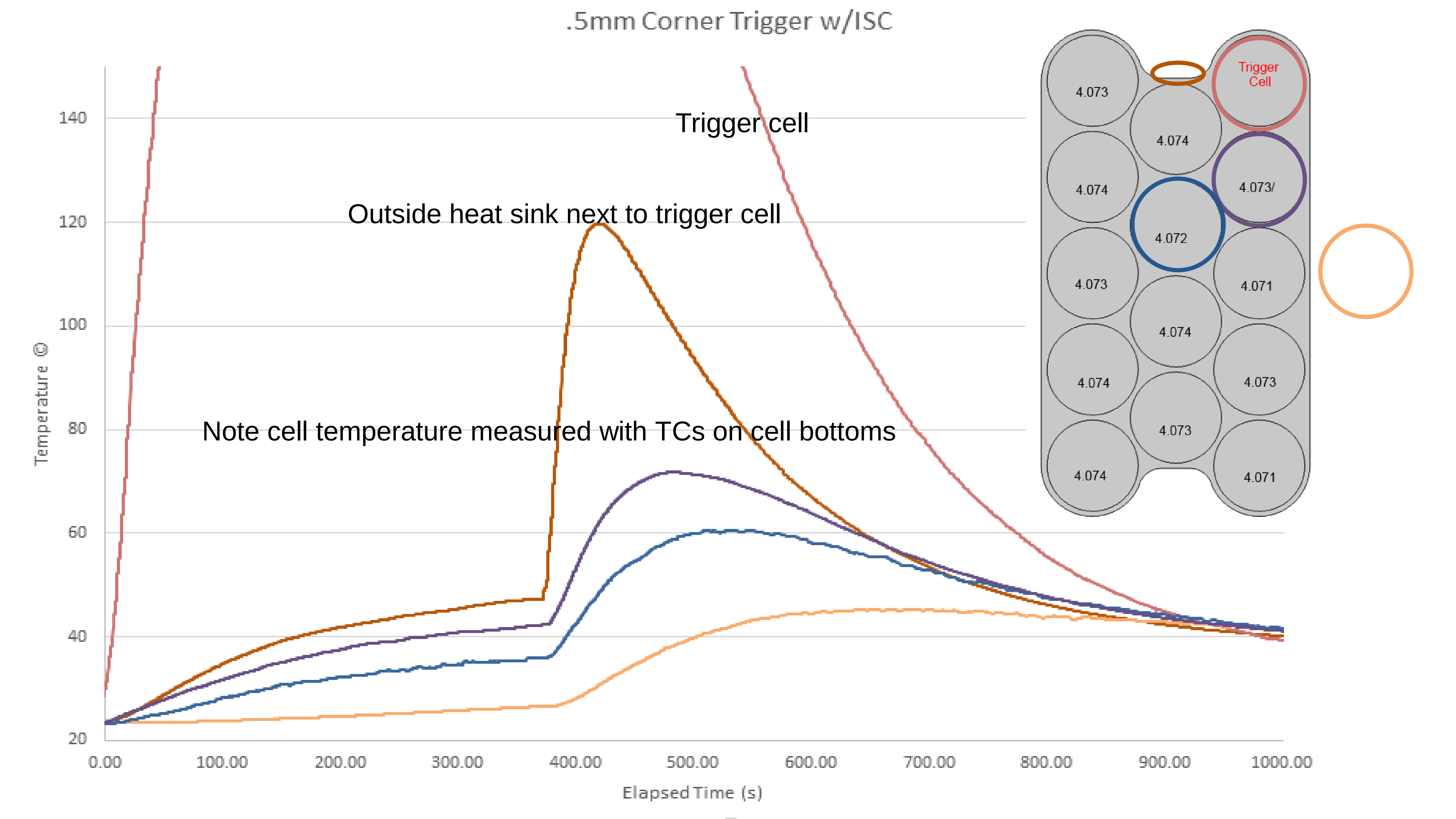


ISC device enable TR activation for this module design!

0.5mm Spacing - Moli ISC Cell In Corner Position

- Corner trigger cell position
- No propagation, venting or adjacent cell damage.
- Highest adjacent cell temperature was 72 °C!
- Pre/post OCV yet again unchanged!




.5mm Corner Trigger w/ISC
Trigger cell
Outside heat sink next to trigger cell
Note cell temperature measured with TCs on cell bottoms
Temperature ©
Elapsed Time (s)
20
40
60
80
100
120
140
0.00
100.00
200.00
300.00
400.00
500.00
600.00
700.00
800.00
900.00
1000.00
Trigger Cell
4.073
4.074
4.074
4.073/
4.072
4.073
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4.071

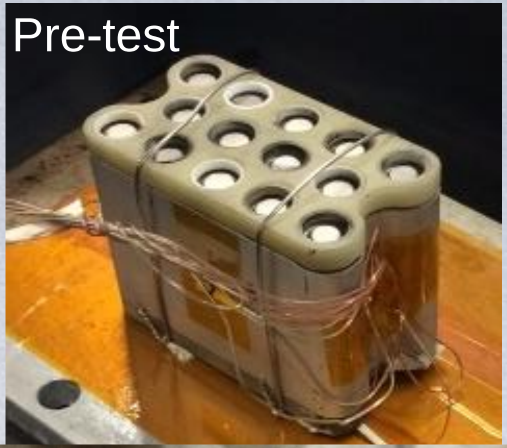
Heat Sink Prevents Side Wall Ruptures

Test Procedure

- 0.5mm cell spacing Al 6061T6 heat sink
- 5 fully charged LG 3.5Ah cells
- 9 fully discharged Samsung 2.6Ah cells
- No fully charged cells adjacent to each other
- G10/FR4 capture plates on both ends
- Macor® bushings on the positives of the fully charged LG cells
- Slow heat to vent oven test

Results

- **No side wall ruptures along the can lengths supported by the heat sink (2 tests = 10 LG cells)**
- Very little damage to the heat sink

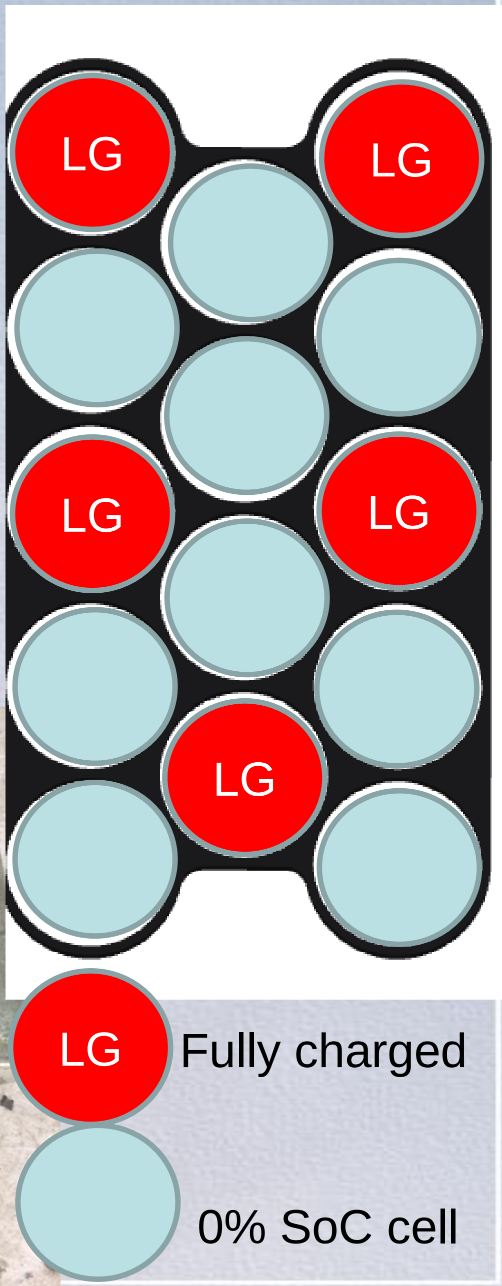

Pre-test


Post-test


Tops of LG cells


Bottoms of all the cells


Side walls of LG cells



Can we improved on Al 6061T6?

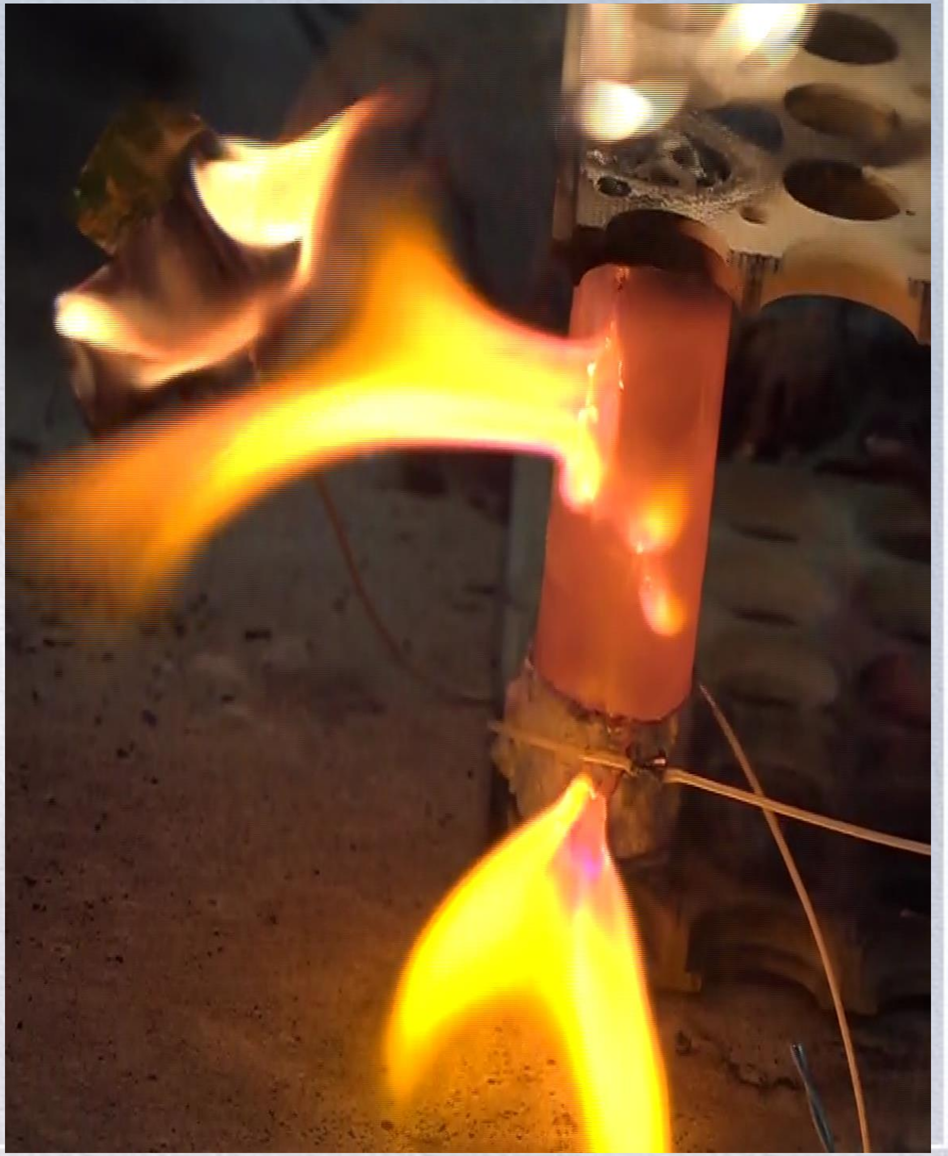
- Al 6063T6 is more thermally conductive, but structurally weaker and hard to find in thick stock
- Al-Graphite is a bit more thermally conductive, much lighter, but melts at 550C
- Be-Al alloy AM162 is most thermally conductive, much lighter, stronger, and higher melting point, but is 10x more expensive

Using 252Wh/kg NCR18650B, 14p bank assembly (with 0.5mm heat sink, capture plates, mica paper, and Macor bushings) achieving > 200 Wh/kg is possible

Material	Al 6061 T6	Al 6063 T6	AM162 (66%Be-Al)	Al Graphite
Manufacturer/Distributor			Materion	Hoffman
Thermal Conductivity (W/m*K)	167	200	246	180
Density (kg/m^3)	2700	2700	2100	2200
Sp. Heat Cap. (J/kg*K)	900	900	1653	900
Therm. Diffusivity (mm^2/s)	68.7	82.3	70.9	90.9
Melting Point (degree C)	582	616	1082	~550
CoTE (10^-6/K)	24	24	15	8
Wh/kg in 14p bank	195	195	201	202

5 Design Driving Factors for Reducing Hazard Severity from a Single Cell TR

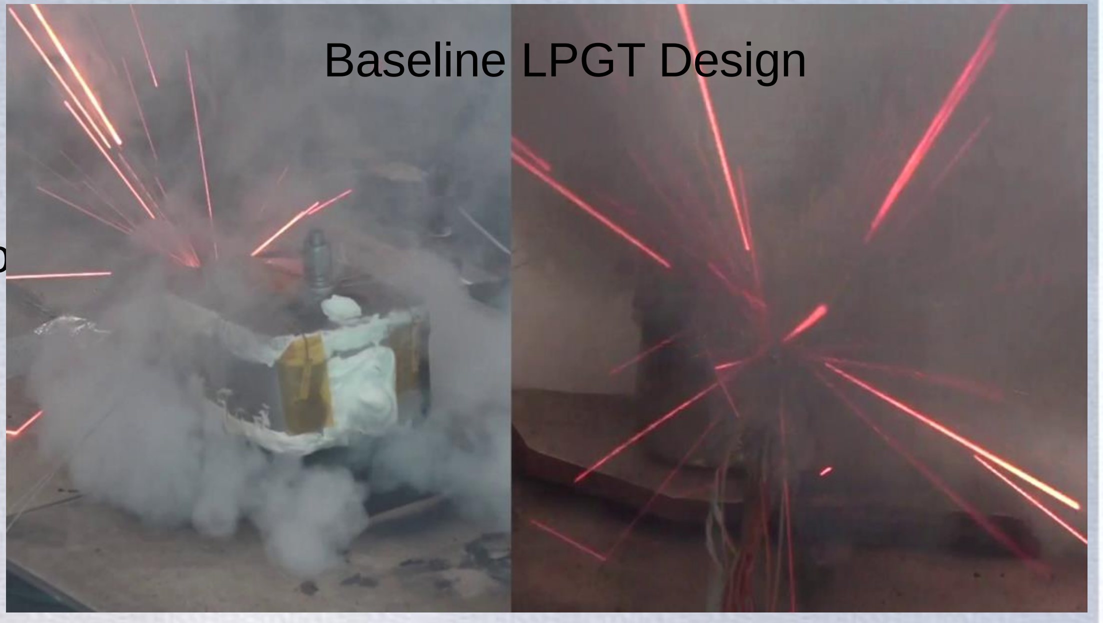
- Reduce risk of cell can side wall ruptures
  - Without structural support most high energy density (>600 Wh/L) designs are very likely to experience side wall ruptures during TR
- Provide adequate cell spacing
  - Direct contact between cells without alternate heat dissipation paths nearly assures propagation
- Individually fuse parallel cells
  - TR cell becomes an external short to adjacent parallel cells and heats them up
- Protect the adjacent cells from the hot TR cell ejecta (solids, liquids, and gases)
  - TR ejecta is electrically conductive and can cause circulating currents
- Prevent flames and sparks from exiting the battery enclosure
  - Tortuous path for the ejecta before hitting battery vent ports equipped flame arresting screens works well



Take Home Message & Acknowledgements

My Take Away

- Preventing cell-cell TR propagation and flames/sparks from exiting battery enclosure is possible with proper design features with minimal mass/volume penalty
- NREL/NASA implantable ISC device is mature and reliable fo battery TR testing
- Using >240 Wh/kg cell designs with the design principles presented will enable >180 Wh/kg battery solutions



Acknowledgements

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