Challenges With Achieving >180Wh/kg Li-ion Battery Modules that Don't Propagate Thermal Runaway or Emit Flames/Sparks

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Author & Contents

- Eric Darcy, NASA-Johnson Space Center
  - Ph.D, ChE, University of Houston, 1998
  - 28 years with battery group at JSC, senior battery specialist
  - "Safe, high performance batteries for manned spacecraft" mandate
  - Specializing on reducing the severity of single cell thermal runaway (TR) hazards ever since the first 787 battery incidents after many years focusing exclusively on prevention
- Contents
  - Background on human spacecraft batteries
  - Single cell TR trigger methods selected and why
  - Design driving factors for reducing hazard severity of a single cell thermal runaway inside a battery
  - Provide medium sized battery example, LREBA
  - Summary conclusions – Preventing cell TR propagation and flames/sparks from exiting the battery enclosure is possible with minimal mass/volume penalty

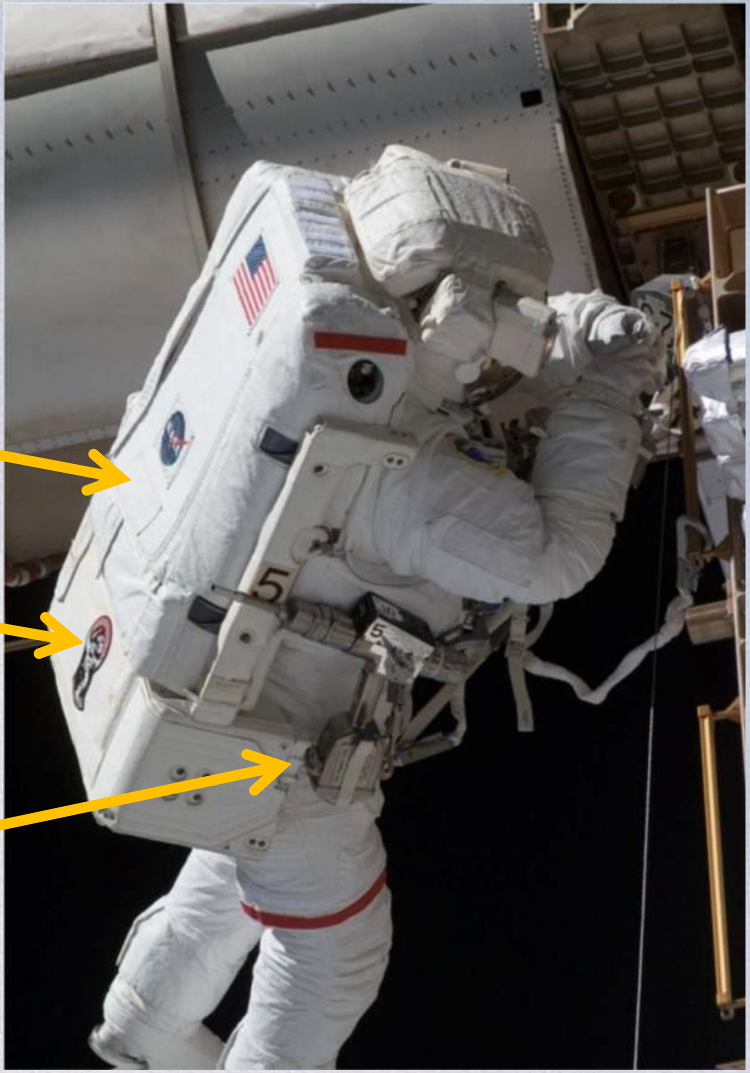
EVA Battery Overview

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



Future Applications Want > 180Wh/kg

- Other human spacecraft batteries
  - Orion
  - Robonaut
  - Advanced spacesuit

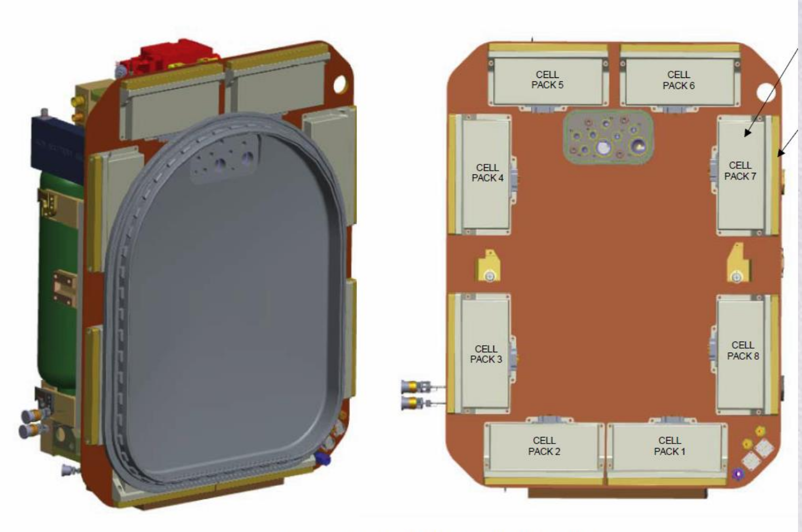
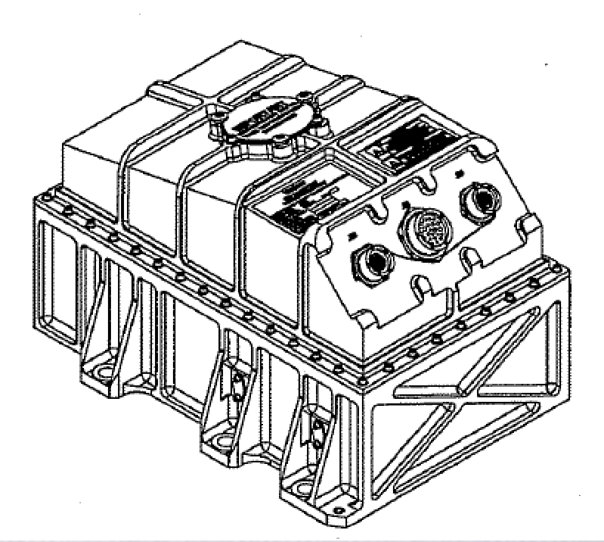


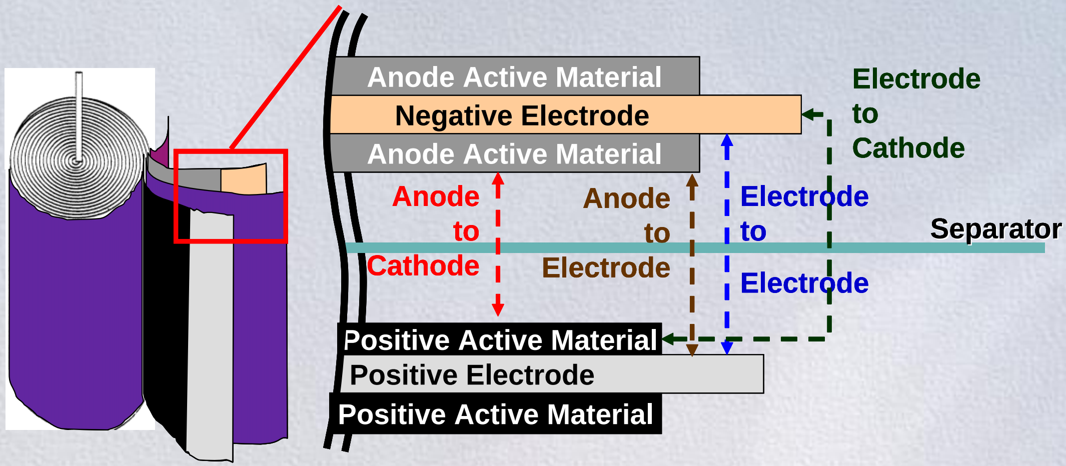
Figure 3.1-1 – PLSS 2.5 BATT-690 Layout



Objectives

•Establish an improved ISC cell-level test method that:

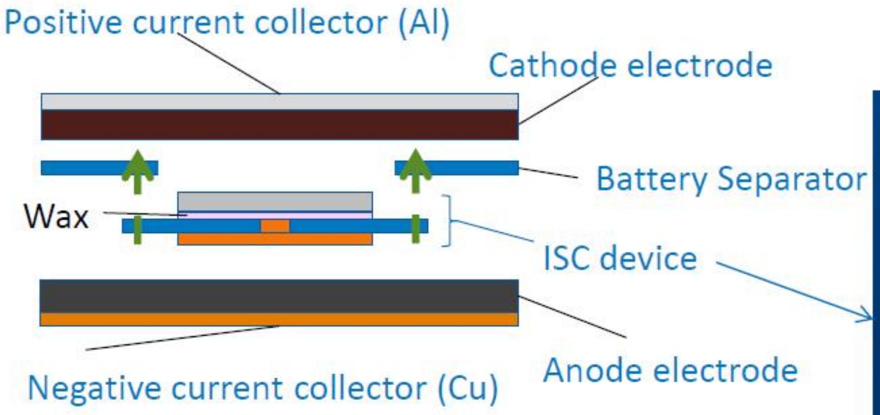
- Simulates a latent internal short circuit.
  - Capable of triggering the **four** types of cell internal shorts

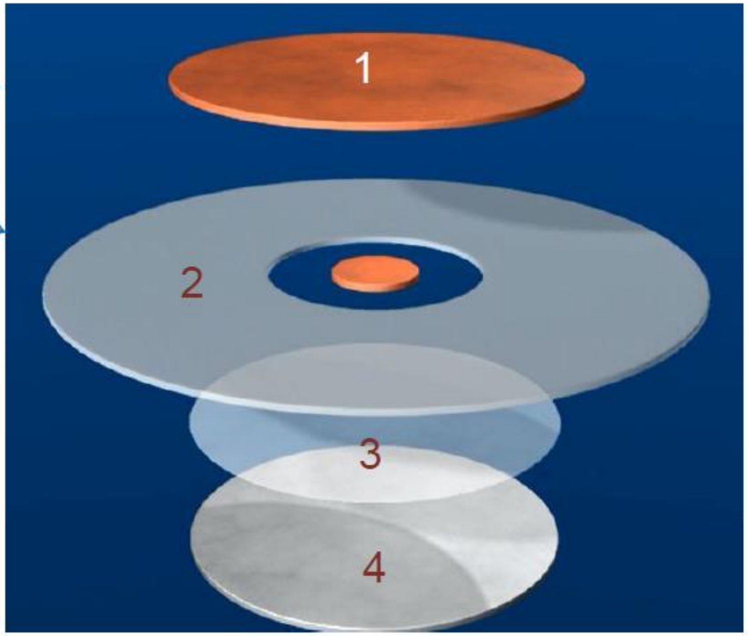


Spiral wound battery shown – can also be applied to prismatic batteries.

- Cell behaves normally until the short is activated on demand
- Produces negligible impact on cell performance
- Provides relevant data to validate cell ISC models
- Produces consistent and reproducible results
- Reliable enough for implanted cells to be built into batteries for TR propagation assessment

NREL/NASA ISC Device Design





Graphic is not to scale
and for illustration only

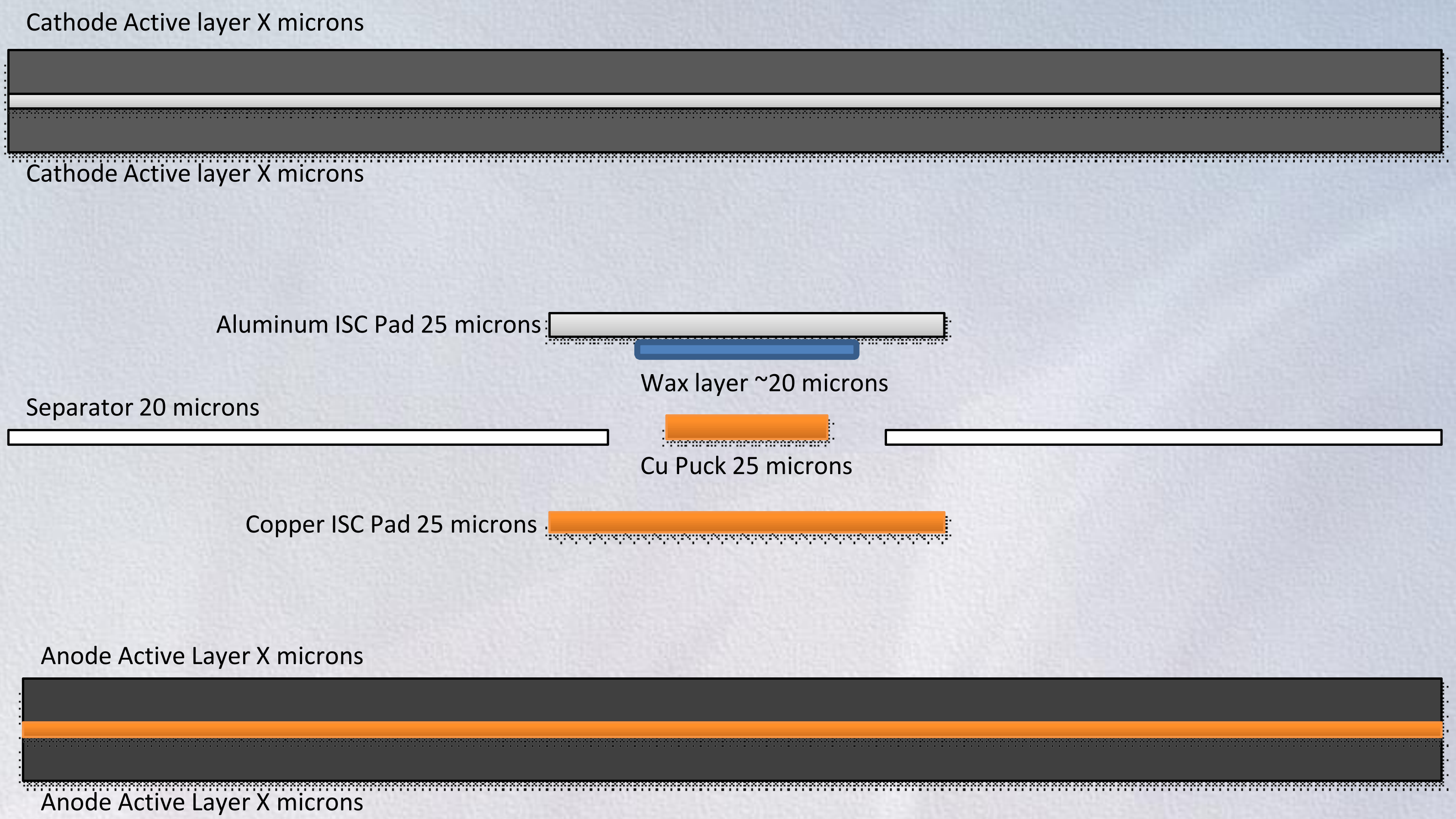
Top to Bottom:
1. Copper Pad
2. Battery Separator with Copper Puck
3. Wax – Phase Change Material
4. Aluminum Pad

Wax formulation used melts ~60°C

US Patent pending

Anode Active Material to Cathode Active Material

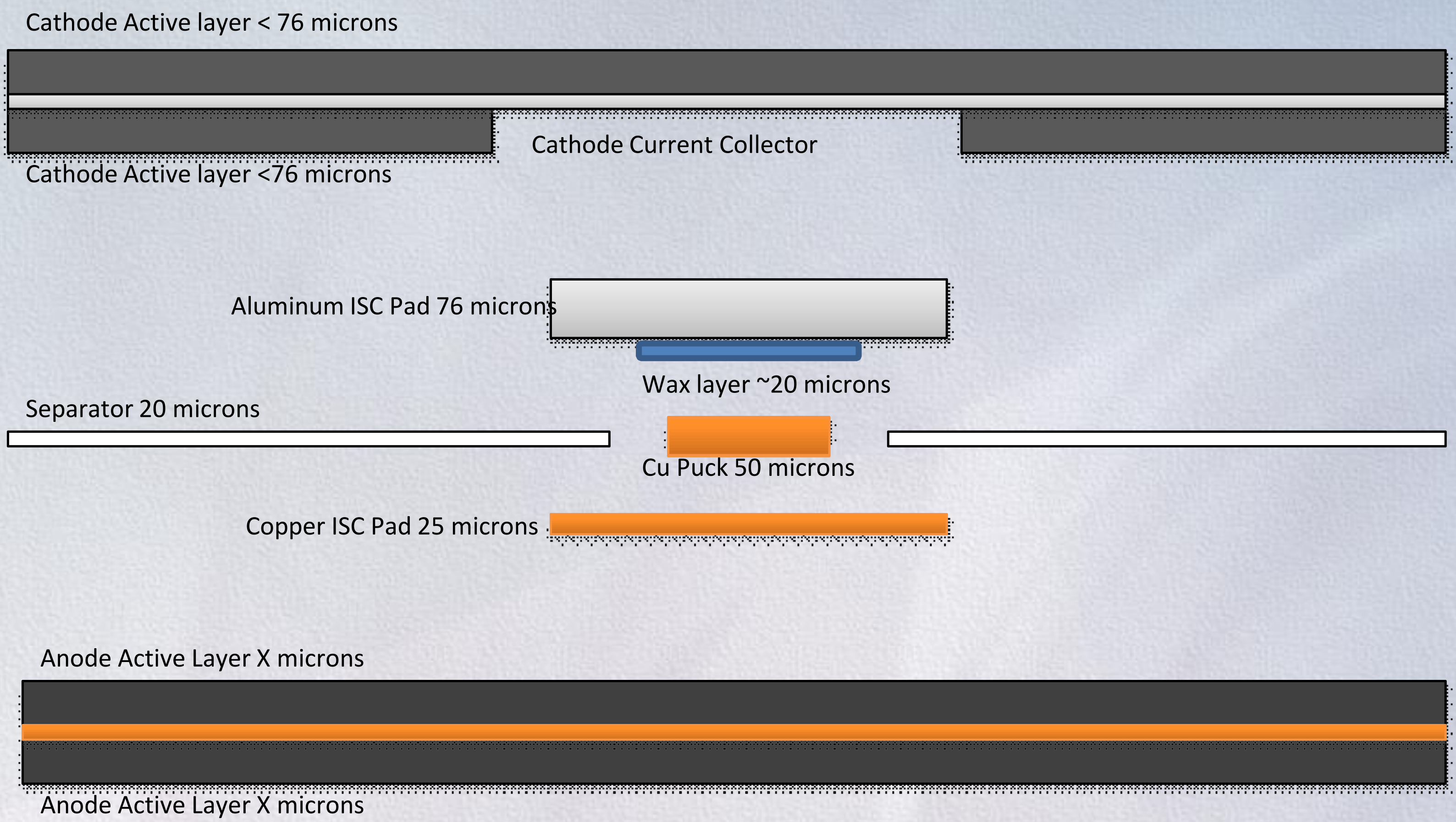
Type 1 – “Active to Active”



Note: Trials with 50 micron Cu puck produces frequent formation failures

Anode Active Material to Cathode Current Collector

Type 2 – “Active to Collector”

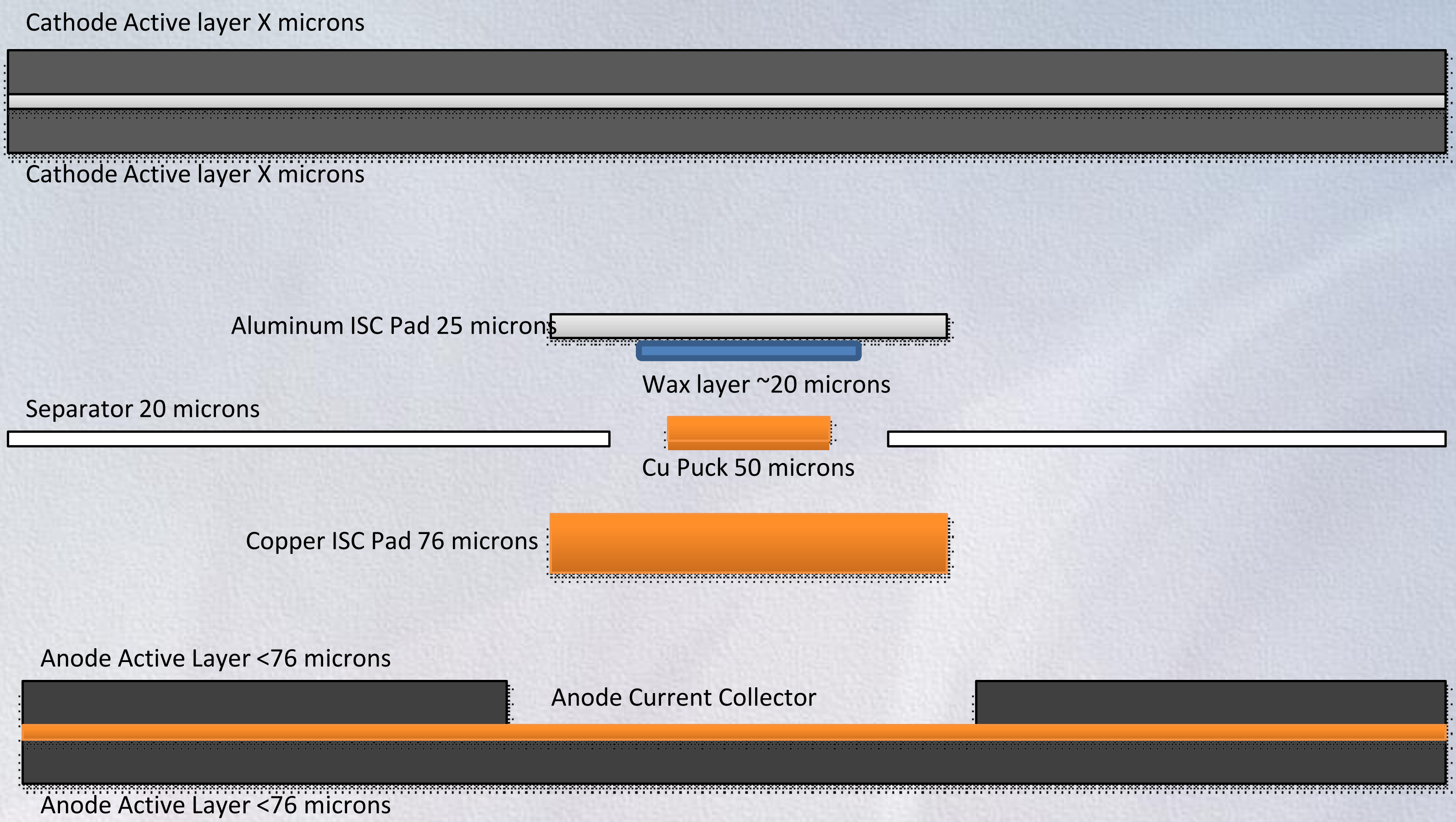


NMP used to remove active material

Note: Trials with 25 micron Cu puck produces frequent activation duds

Anode Current Collector to Cathode Active Material

Type 3 – “Collector to Active”

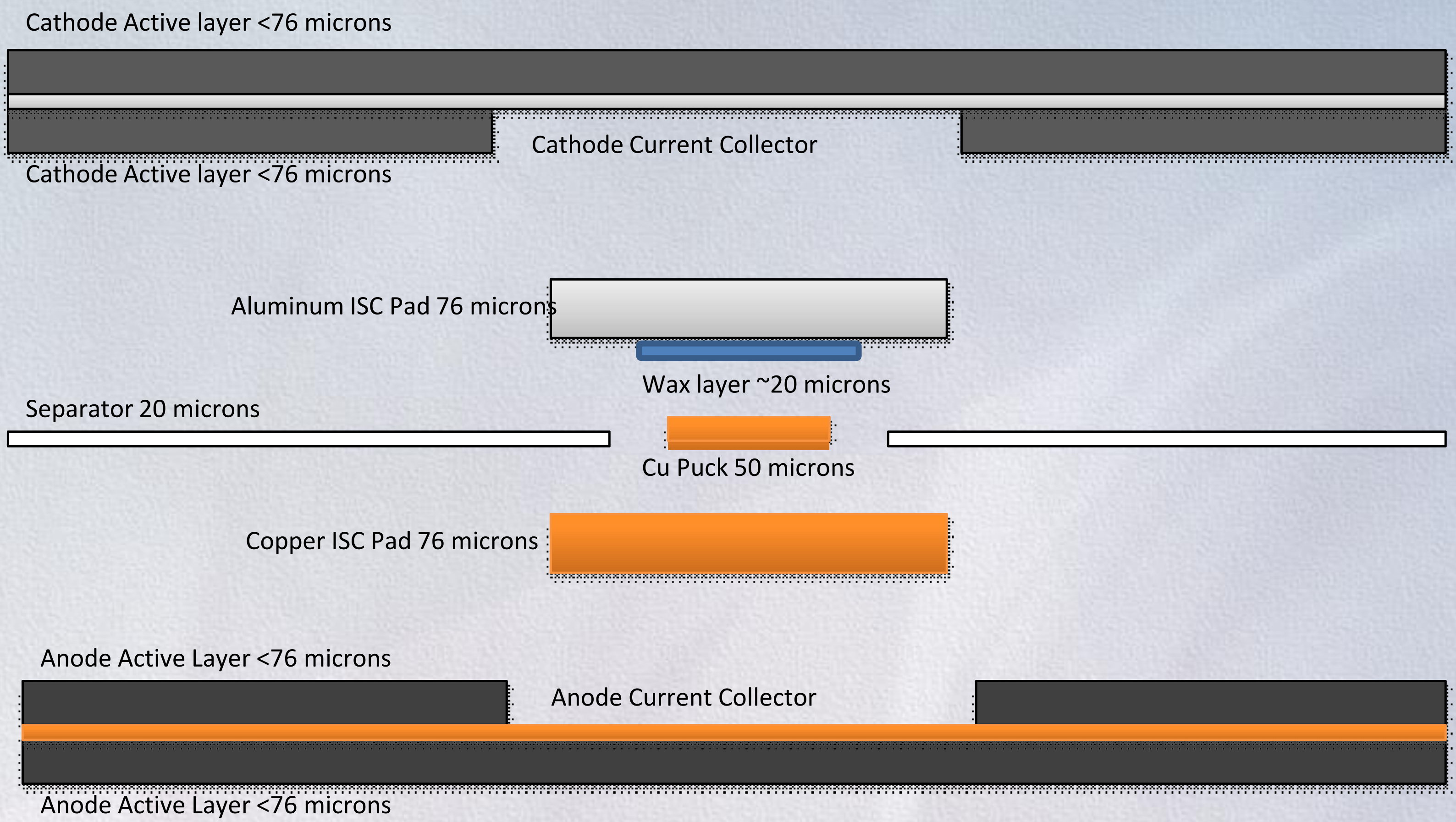


NMP used to remove active material

Note: Trials with 25 micron Cu puck produces frequent activation duds

Anode Current Collector to Cathode Current Collector

Type 4 – “Collector to Collector”

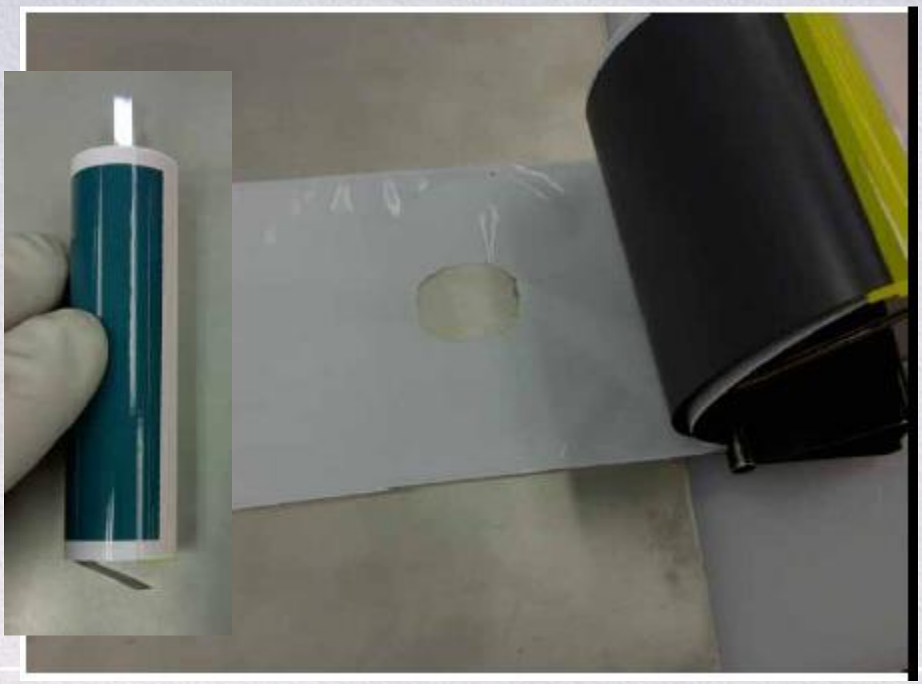


NMP used to remove active material

Note: Trials with 25 micron Cu puck produces frequent activation duds

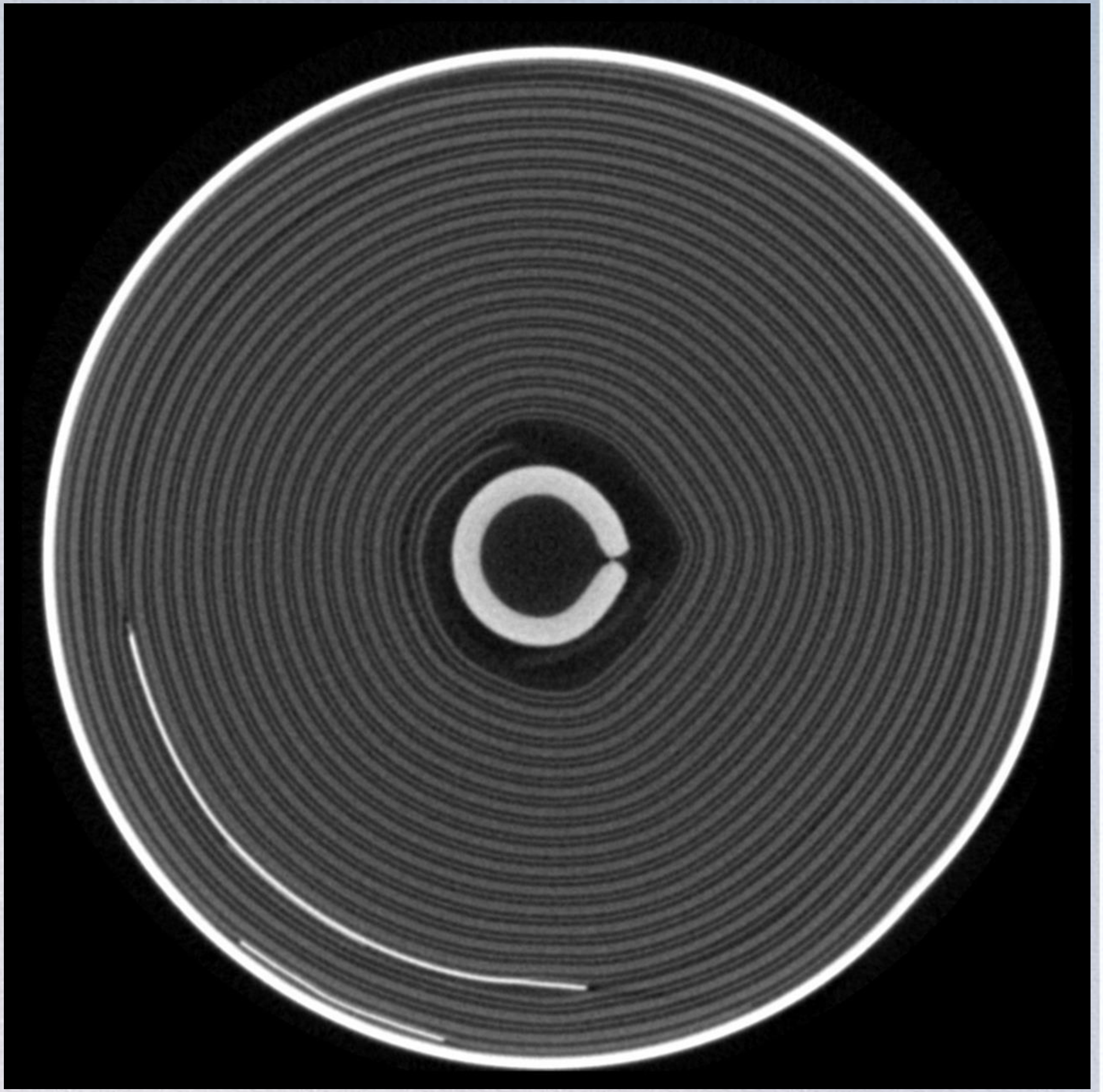
2.4Ah 18650 Cell

- NREL fabricated the ISC devices
- Partnered with E-one Moli Energy (Maple Ridge, BC) for the implantation into their 2.4Ah cells
- Moli performed cycling and activation tests
- NASA-JSC performed activation tests

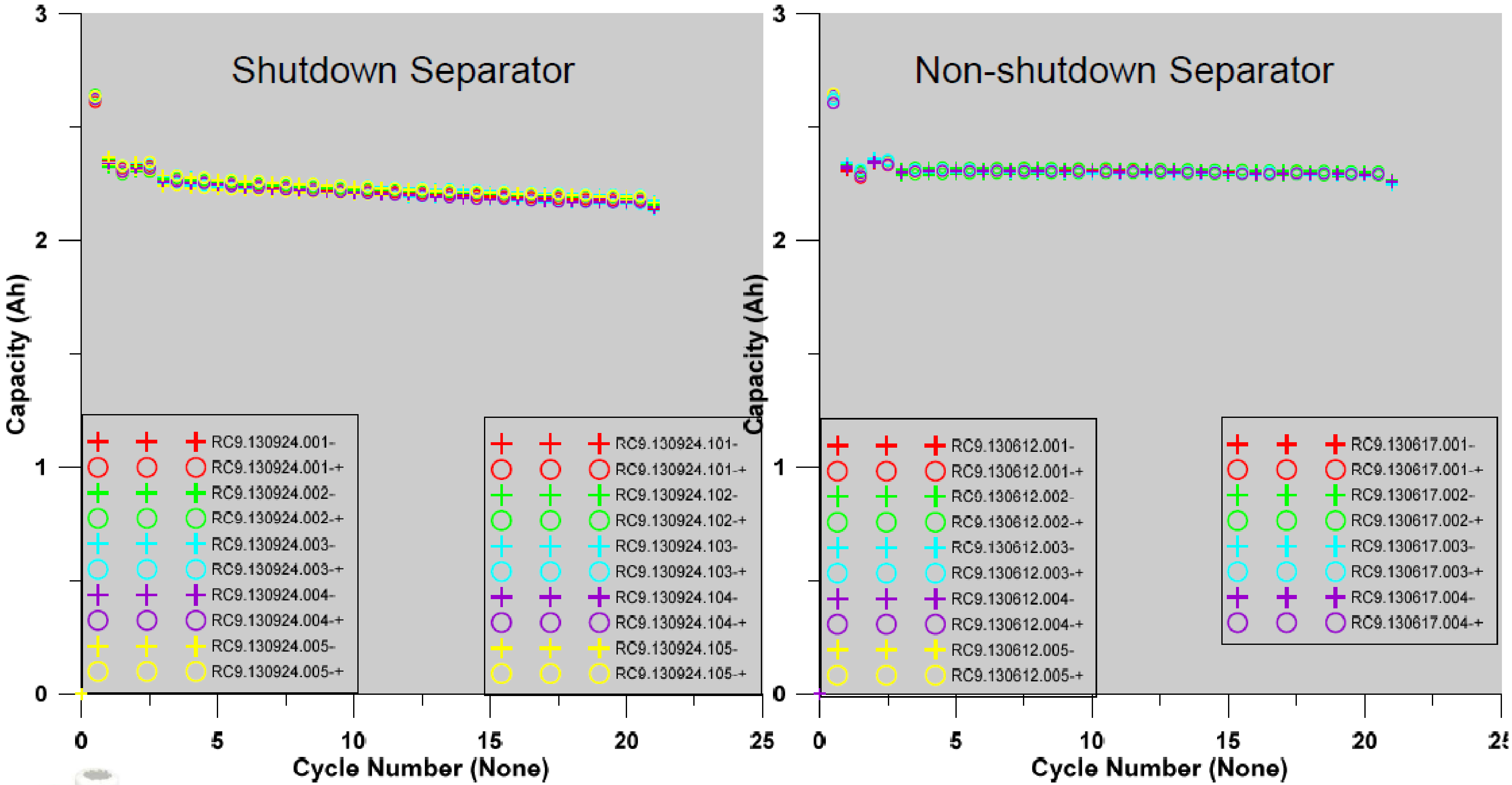


CT of ISC Device Inside an 18650

- Device implanted 3 winds into the jellyroll at mid height
- Jellyroll length did not have to be trimmed to fit into the can



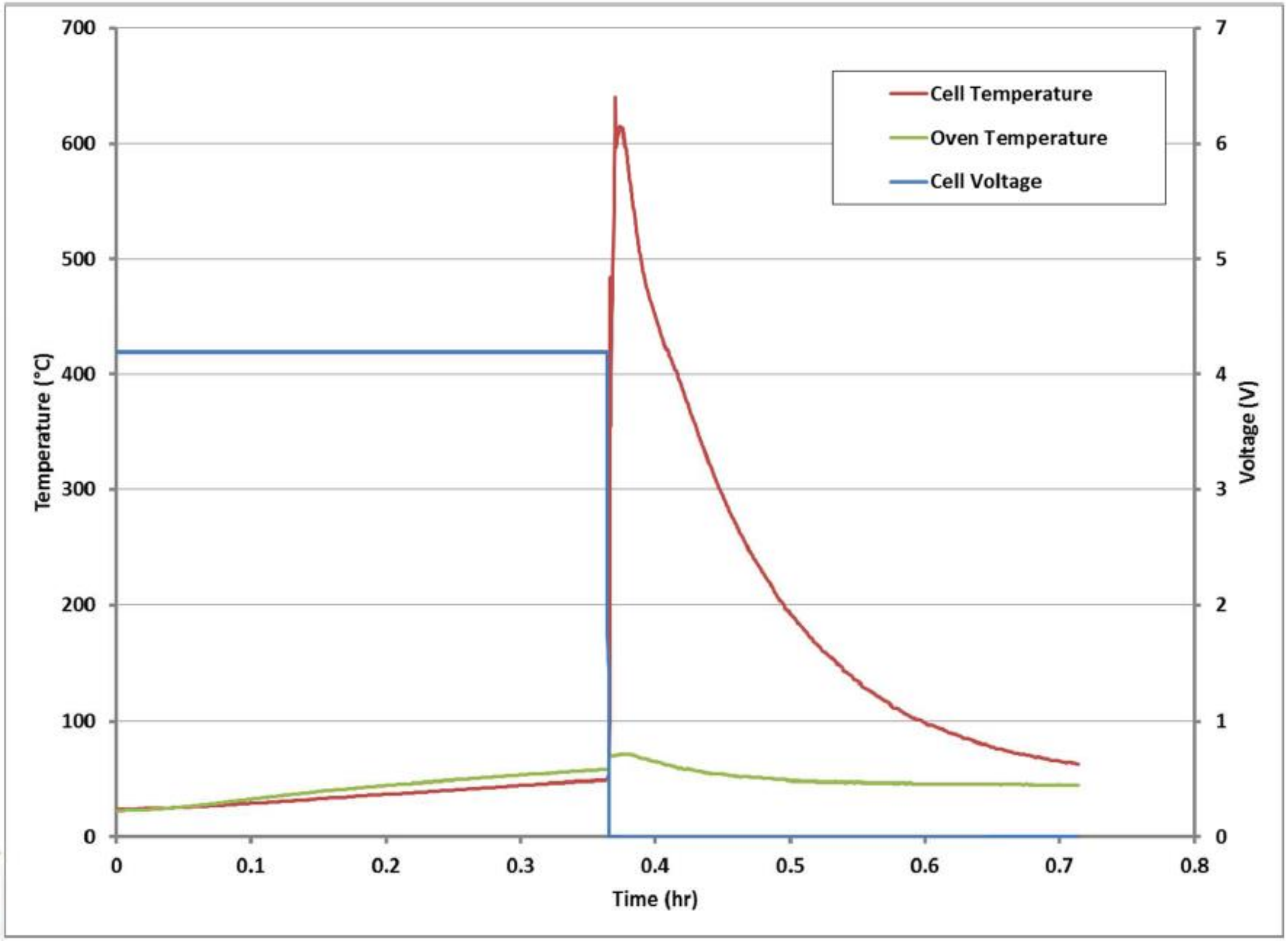
Cycle Stability



- **Cycle Stability is good over 20 cycles**
  - 1 cycle at C/2, 1 cycle at C/10, 18 cycles at 1C

Non-shutdown separator testing

MOLICEL®



Example of successful activation

100% success in 8 trials of latest batch of ISC device implantations

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

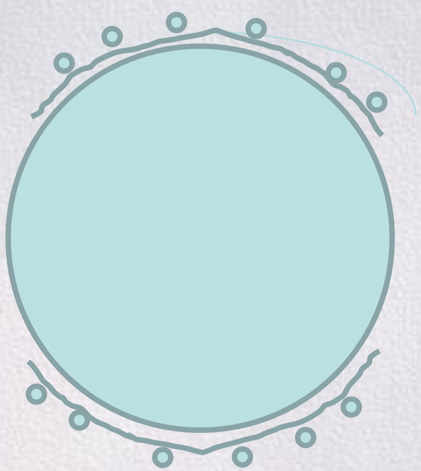
1. Nikkei Electronics, Nov. 6, 2006
2. Battery Association of Japan, Nov 11, 2008 presentation on web
3. S. Santhanagopalan, et. al., J. of Power Sources, 194 (2009) 550-557
4. Barnett et. al, Power Sources Conference, Las Vegas, NV, 2012

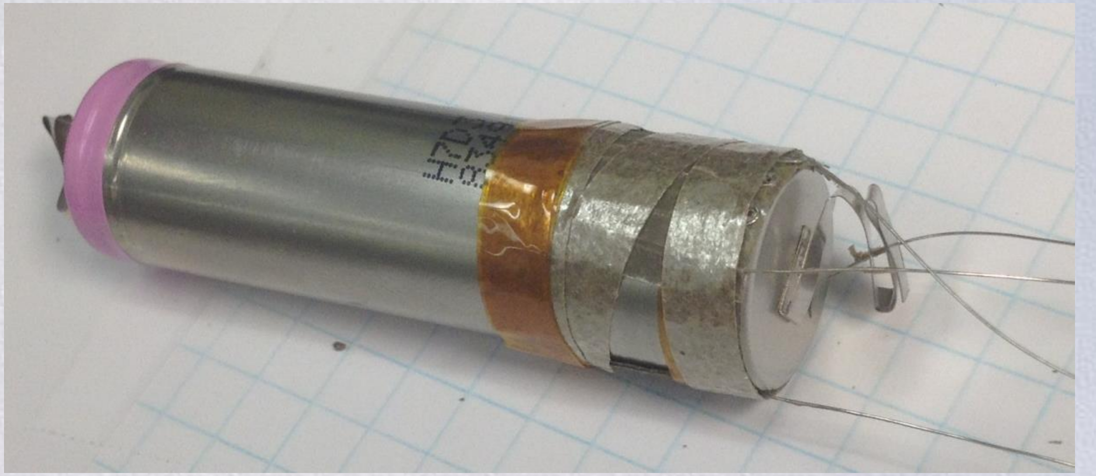
Closest Alternative to the ISC Device

- Since the On-Demand ISC Device requires implantation by a willing cell manufacturer, the best alternative trigger method is applying excessive external heat (OT) localized away from cell seals
  - Over-temperature trigger by commercial film heaters take too long because they don't provide sufficient flux (W/cm^2)
  - Custom heater is required to achieve > 10 W/cm^2
- Downsides to OT trigger method
  - Require room around surface of cell for the heater and risks biasing adjacent cells
  - For some high energy density designs, it's very difficult to trigger interior cell locations with heaters

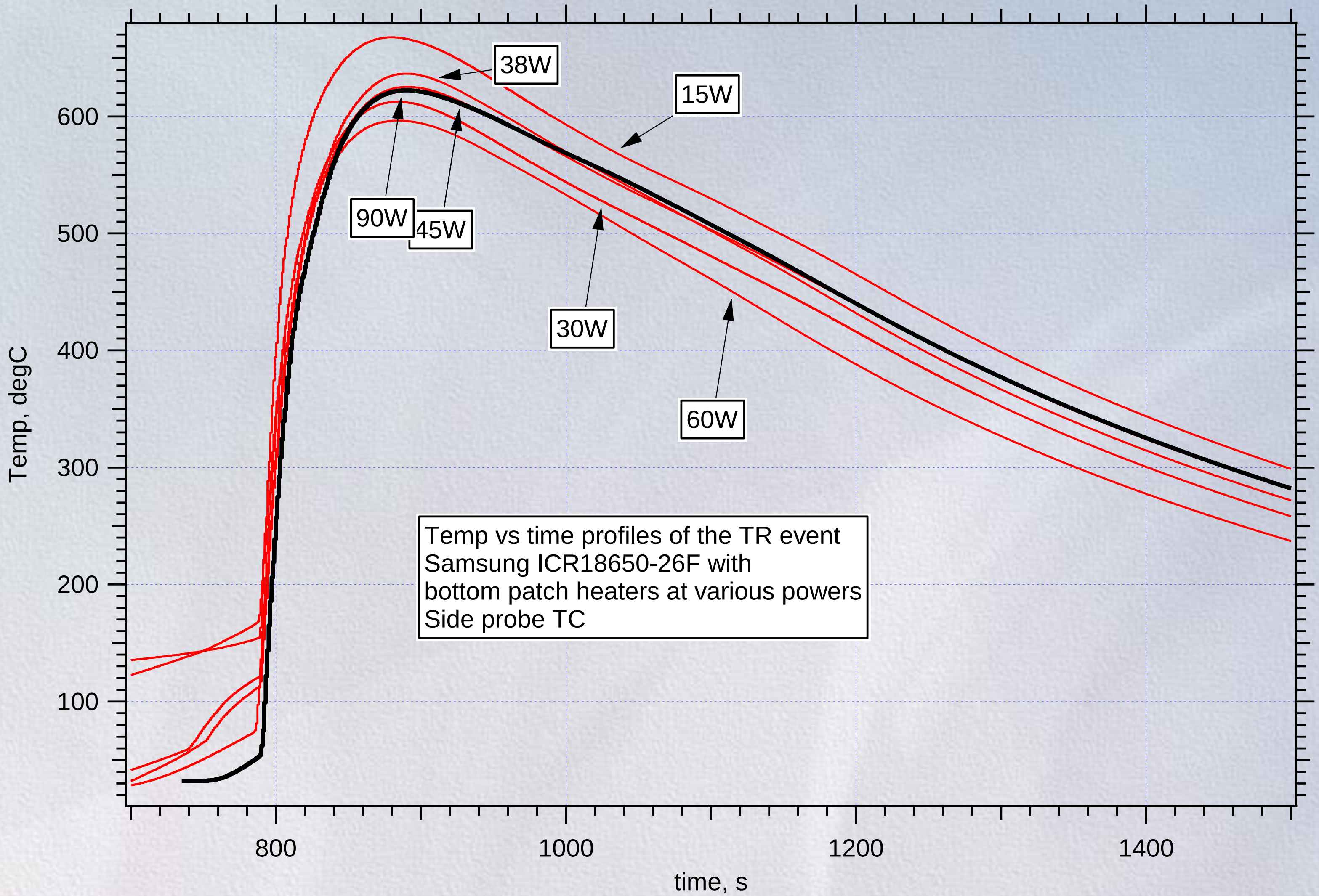
Selected Bottom Patch Heaters For Triggering TR

- Two small (3/4”x3/4”) patch heaters located on the bottom of cylindrical can
  - Nichrome wire glued to Mica paper
  - Adhered to bare can by cement bases adhesive
- Each has 6” of Nichrome wire for a total of 12” per pair
  - Pair can be powered by up to 90W
- Main benefit of design – more relevant cell internal short
  - Deliver high heat flux away from seals, PTC, and CID located in cell header
  - leaves an axial bond line undisturbed for gluing cell together in one plane
  - More likely to result in coincident cell venting and TR runaway



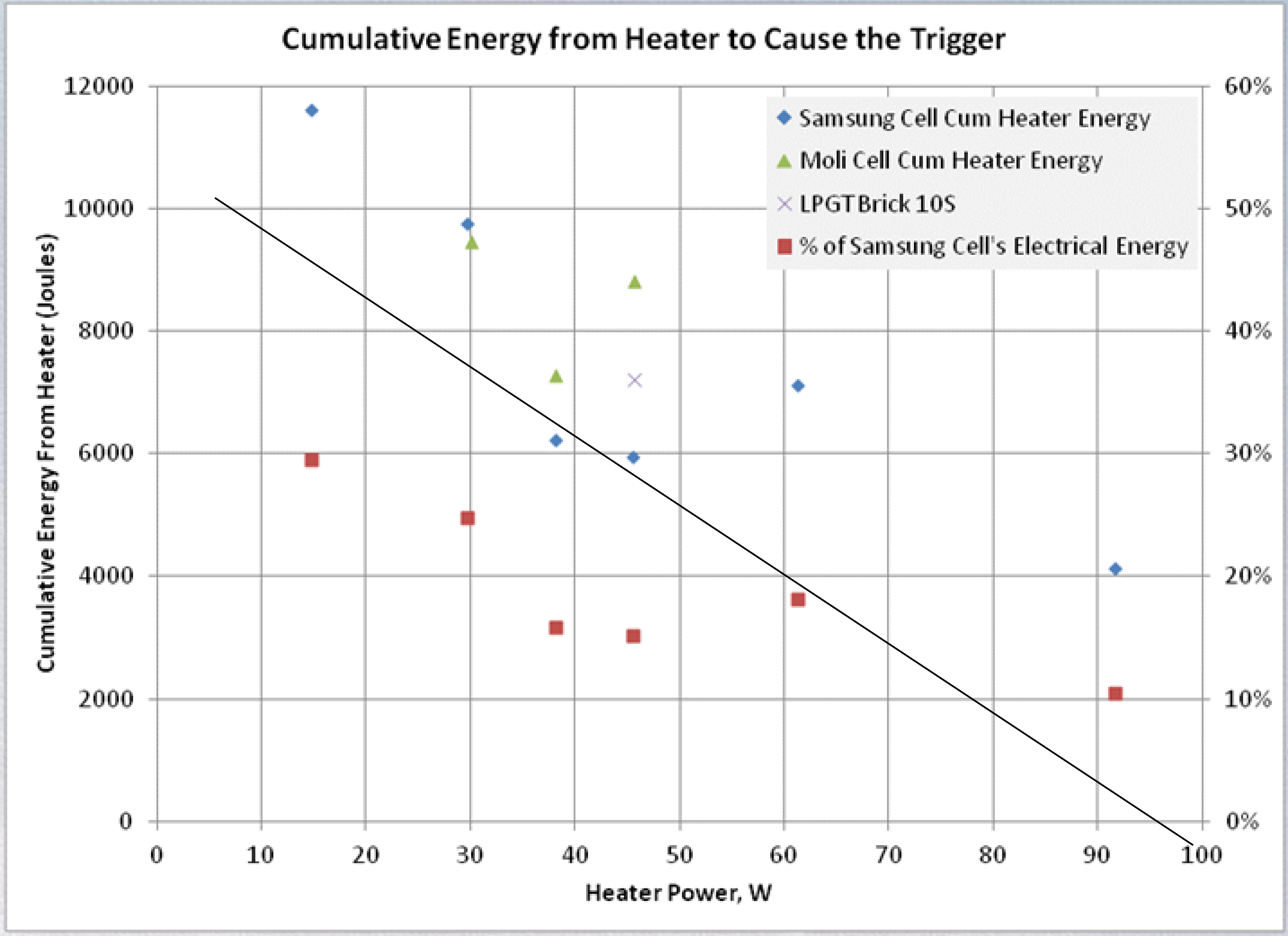


Cell TR Response vs Heat Power



- TR output heat fairly independent of heater input power
- High power preferred to reduce risk of biasing hot adjacent cells

Higher W triggers with Lower Wh Input



Plot courtesy of Bruce Drolen/Boeing

Lower Energy, Wh, input into the heater presents lower risk of biasing adjacent cells

5 Design driving factors for reducing hazard severity

- Reduce risk of cell can side wall ruptures
  - Some high energy density (>600 Wh/L) are very likely to experience side wall ruptures during TR
- Provide adequate cell spacing
  - Direct contact between cells 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)
  - 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

Cell Can Wall Cross Sections

240Wh/kg cell design averages 127 μm
ICR18650-26F (Samsung) averages 160 μm
ICR18650J (Moli) averages 208 μm

Intentionally weakening cells cans leads to ruptures

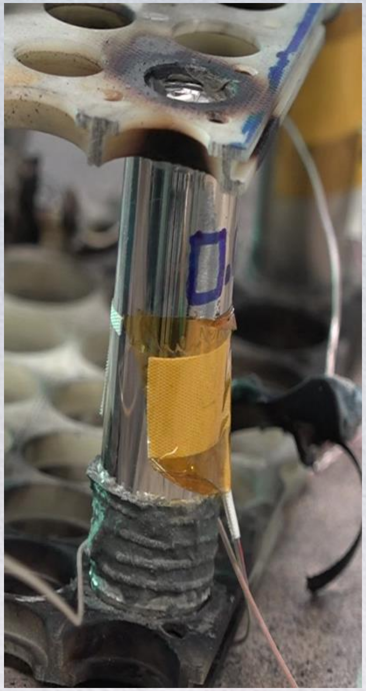
60W achieved OTR in 116s

Side wall breach achieved in weakened area and another breach in heater area

Thinned area of can
By filing down to ½ thickness

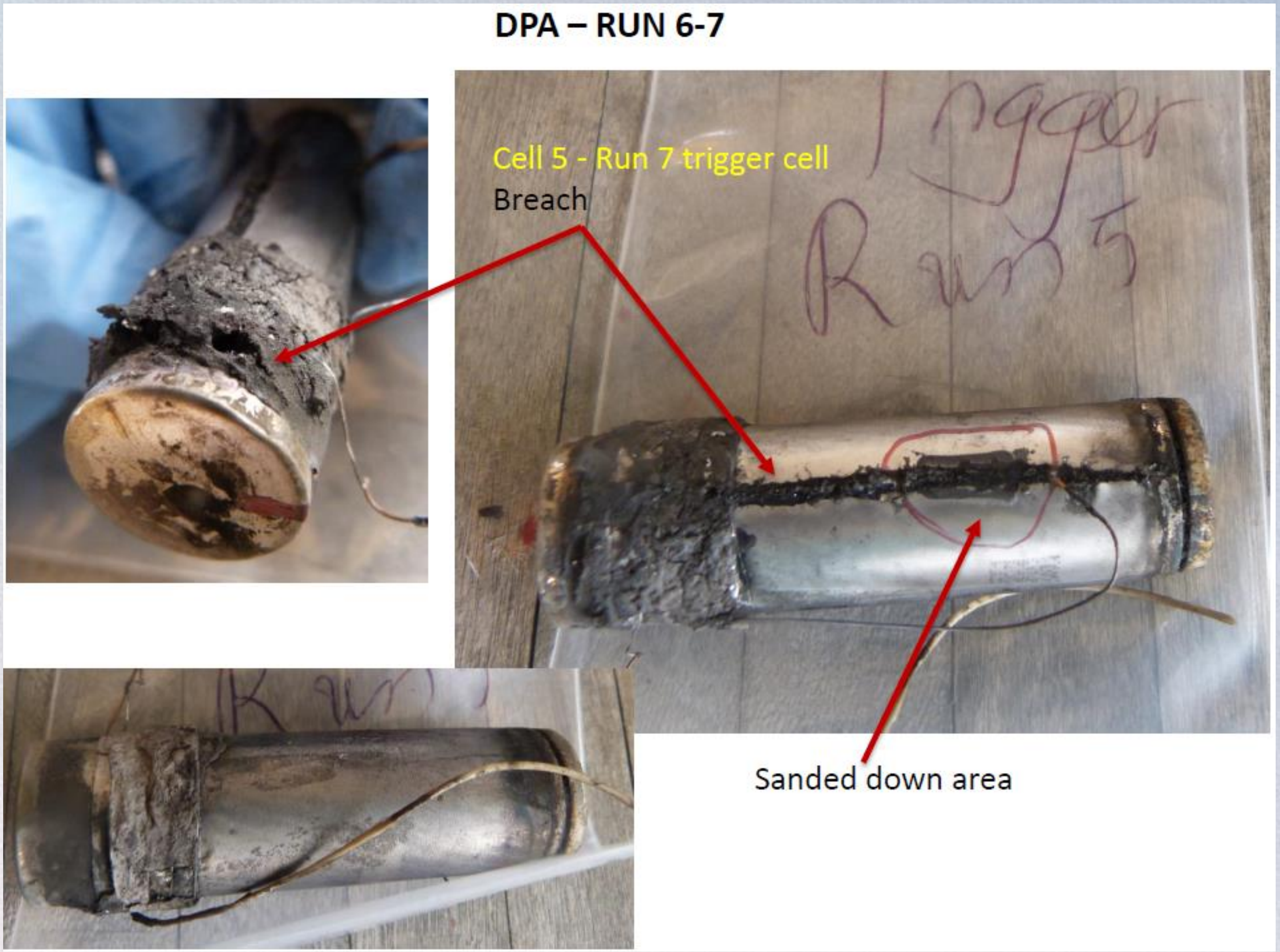
Another example with similar results

60W achieved OTR in 98s



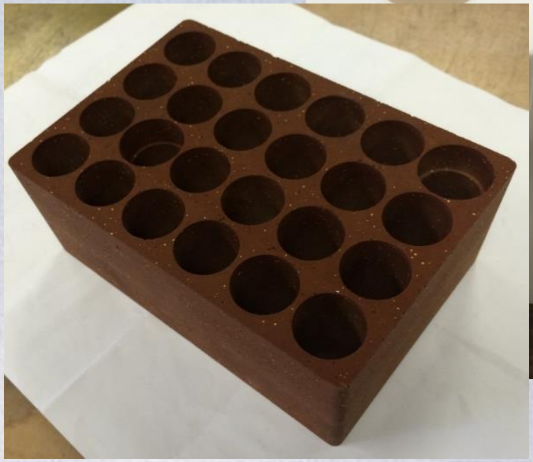
Side wall breach achieved in weakened area and another breach above heater area

Side Wall Rupture off Trigger Cell

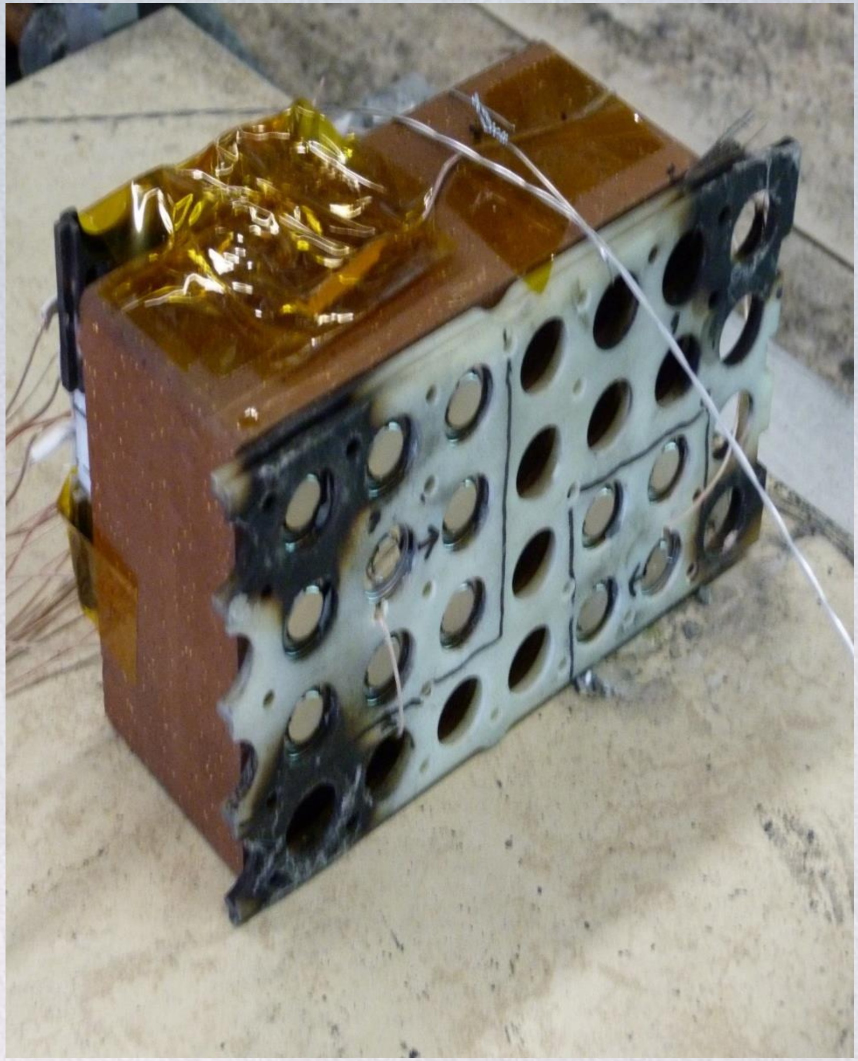


Solutions

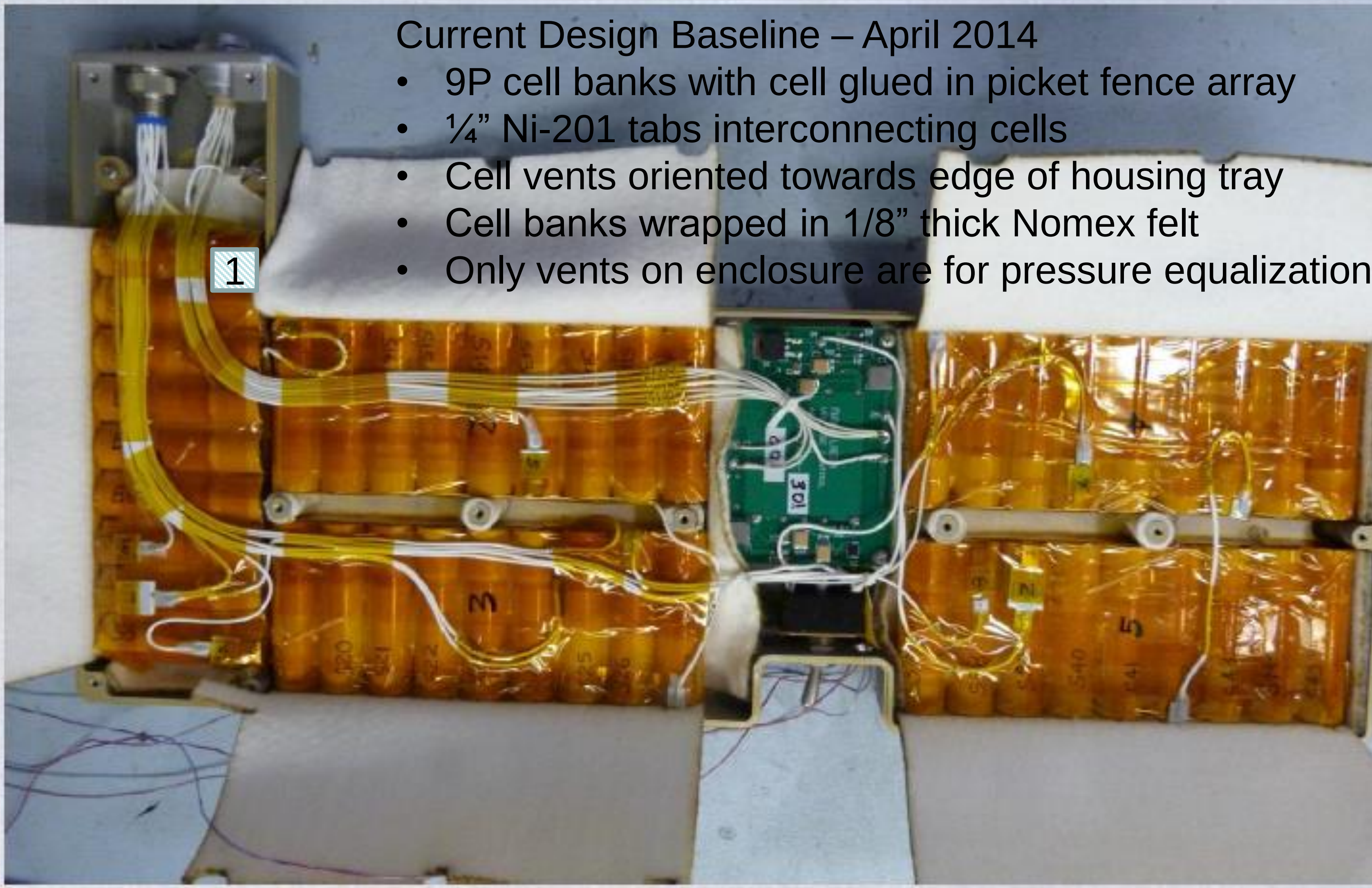
1. Don't select a design that is likely to experience side wall ruptures
2. Structurally support the can of cells likely to rupture
   - Snug fitting structural foam
   - Snug filling stainless tube

Intentionally weakened cell cans don't rupture with structural support



Background - Li-ion Rechargeable EVA Battery Assembly (LREBA)



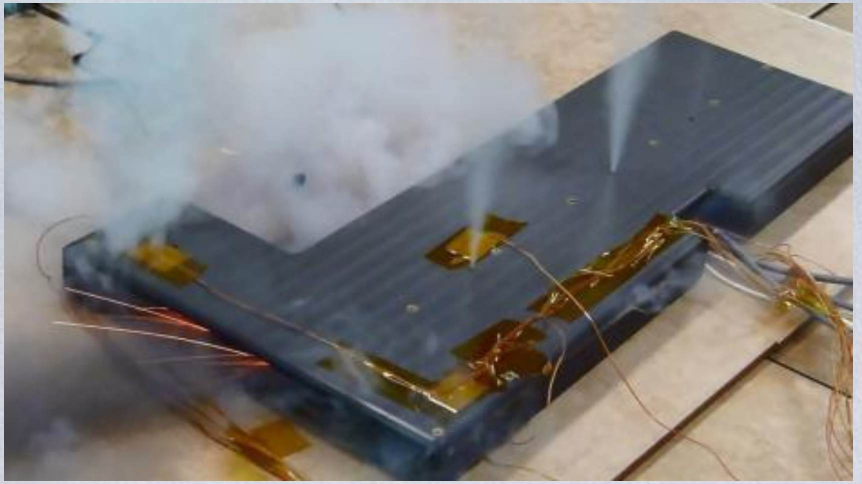
Current Design Baseline – April 2014

- 9P cell banks with cell glued in picket fence array
- ¼” Ni-201 tabs interconnecting cells
- Cell vents oriented towards edge of housing tray
- Cell banks wrapped in 1/8” thick Nomex felt
- Only vents on enclosure are for pressure equalization

9P-5S Array of Samsung 2.6Ah 18650 cell

Cell design selected because it’s unlikely to experience side wall ruptures

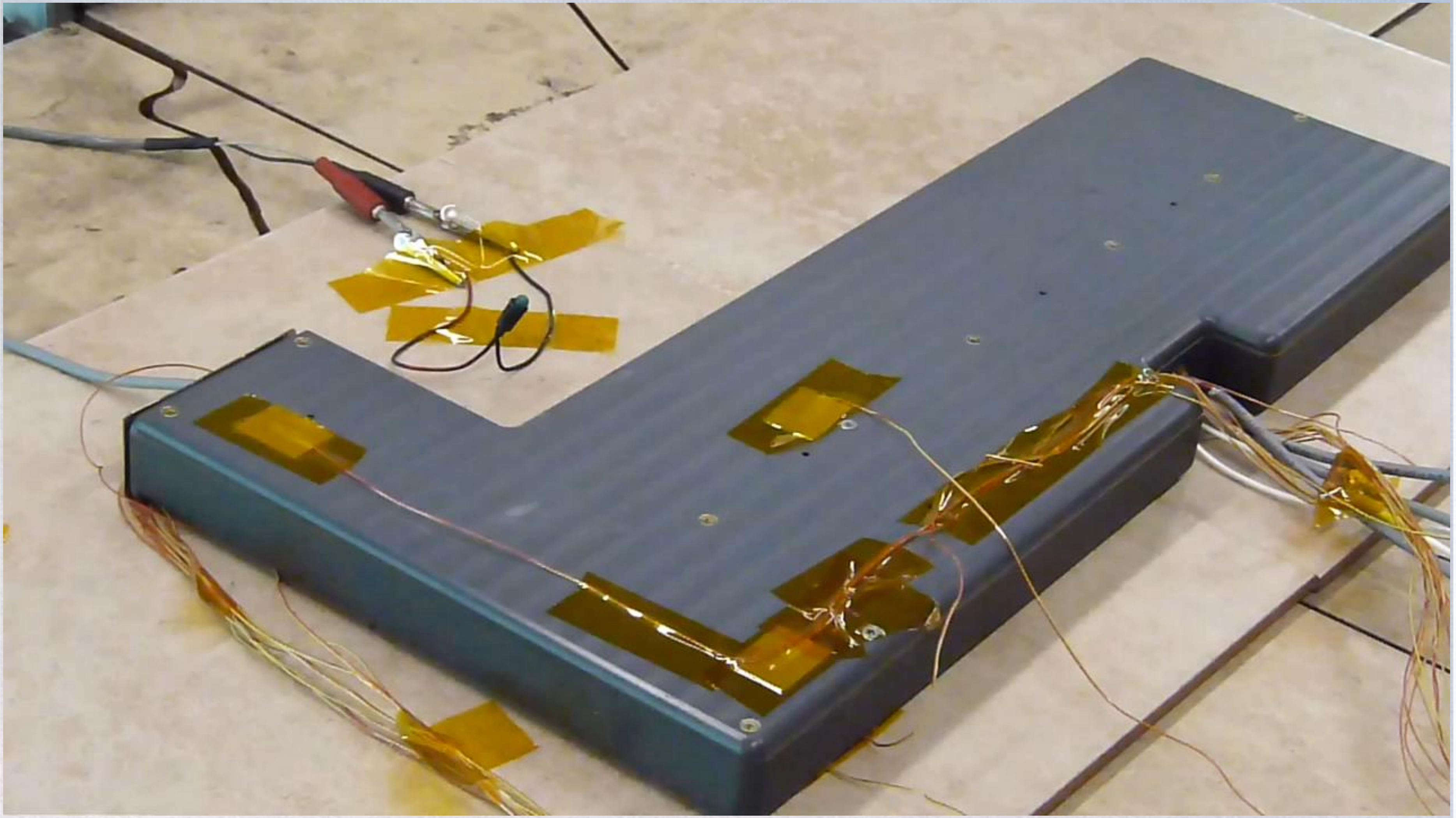
1^{st} Full Scale LREBA Test



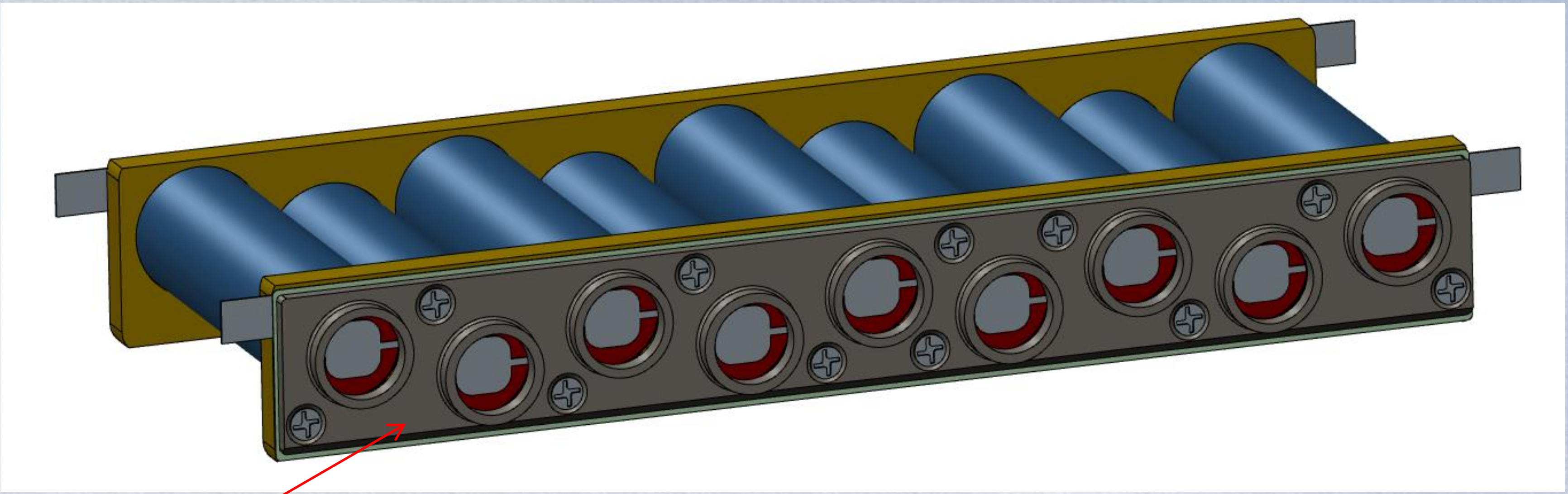
- T=5:07 min - First Cell TR
- T= 16:36 min - First flames outside housing

- T=30:28 min – During full TR Propagation
- T=34:00 min – Final TR

LREBA TR Video

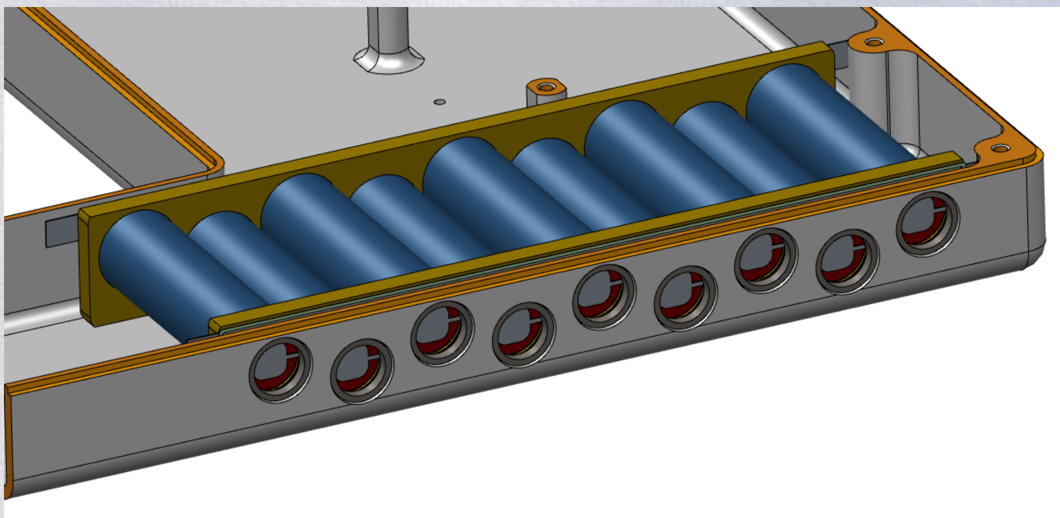


Next Full Scale LREBA Test Configuration



Cell Ejecta Exhaust Piped Top

- Macor (machinable glass ceramic)
- Matching exhaust ports in housing for pipes
- Mica paper wrapped on cell cans
- Fusible bus bars on both positives and negatives
    - Same 15A trip



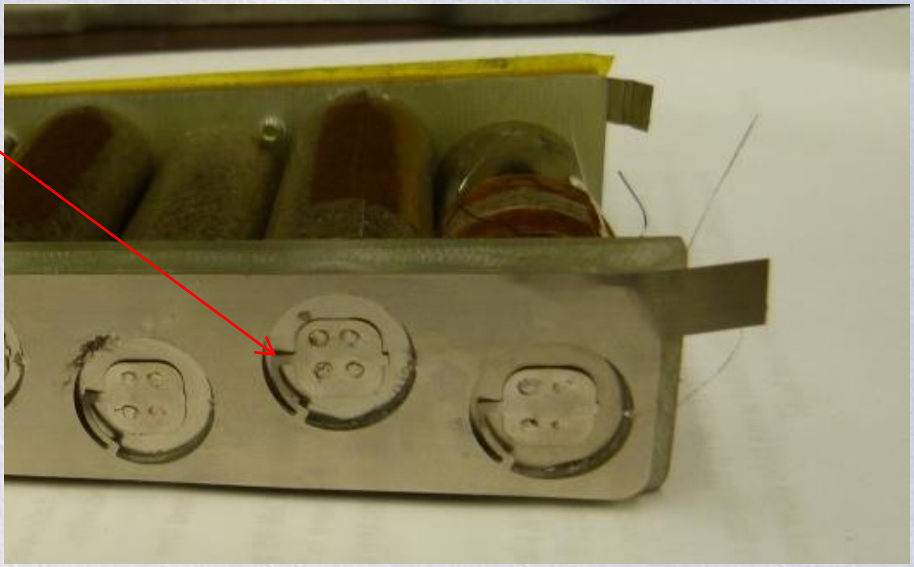
9P bank inside LREBA housing with exhaust holes

More Photos of Mitigation Features

Machinable glass ceramic (Macor®)

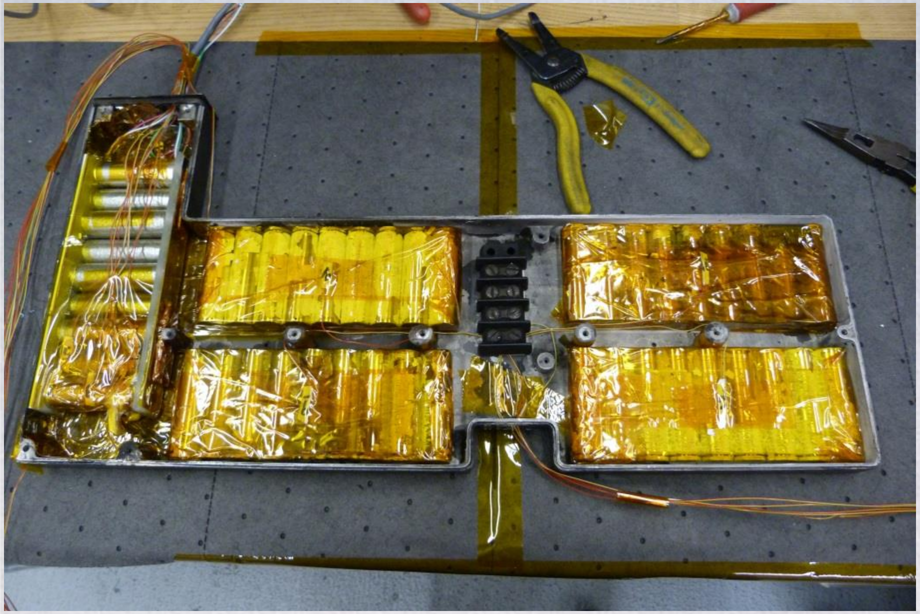
Fusible (15A) bus plates connected on both terminals

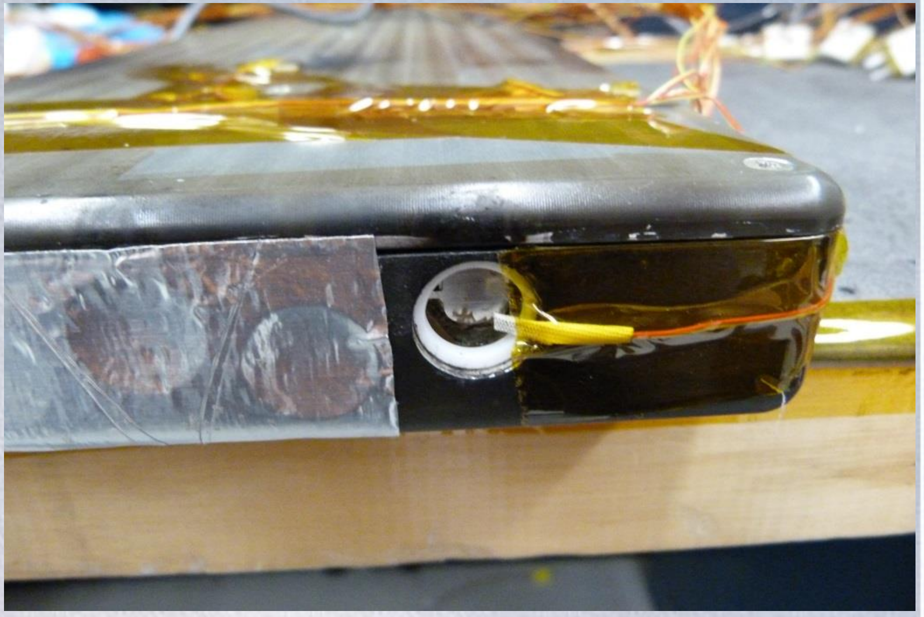
Mica paper as radiation barriers and to electrically isolate cell cans 2-8
Heater placed on end cells 1 & 9

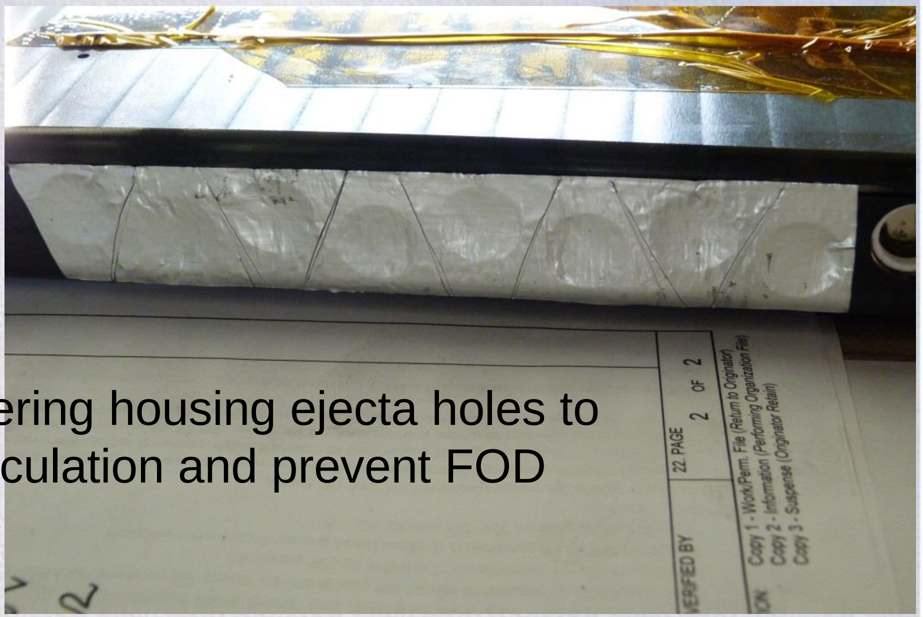


Next Full Scale Test - Pre Test Photos

One active 9P bank in dogleg with end cell trigger heaters powered at 90W
4 dummy banks uncharged to take up volume inside enclosure

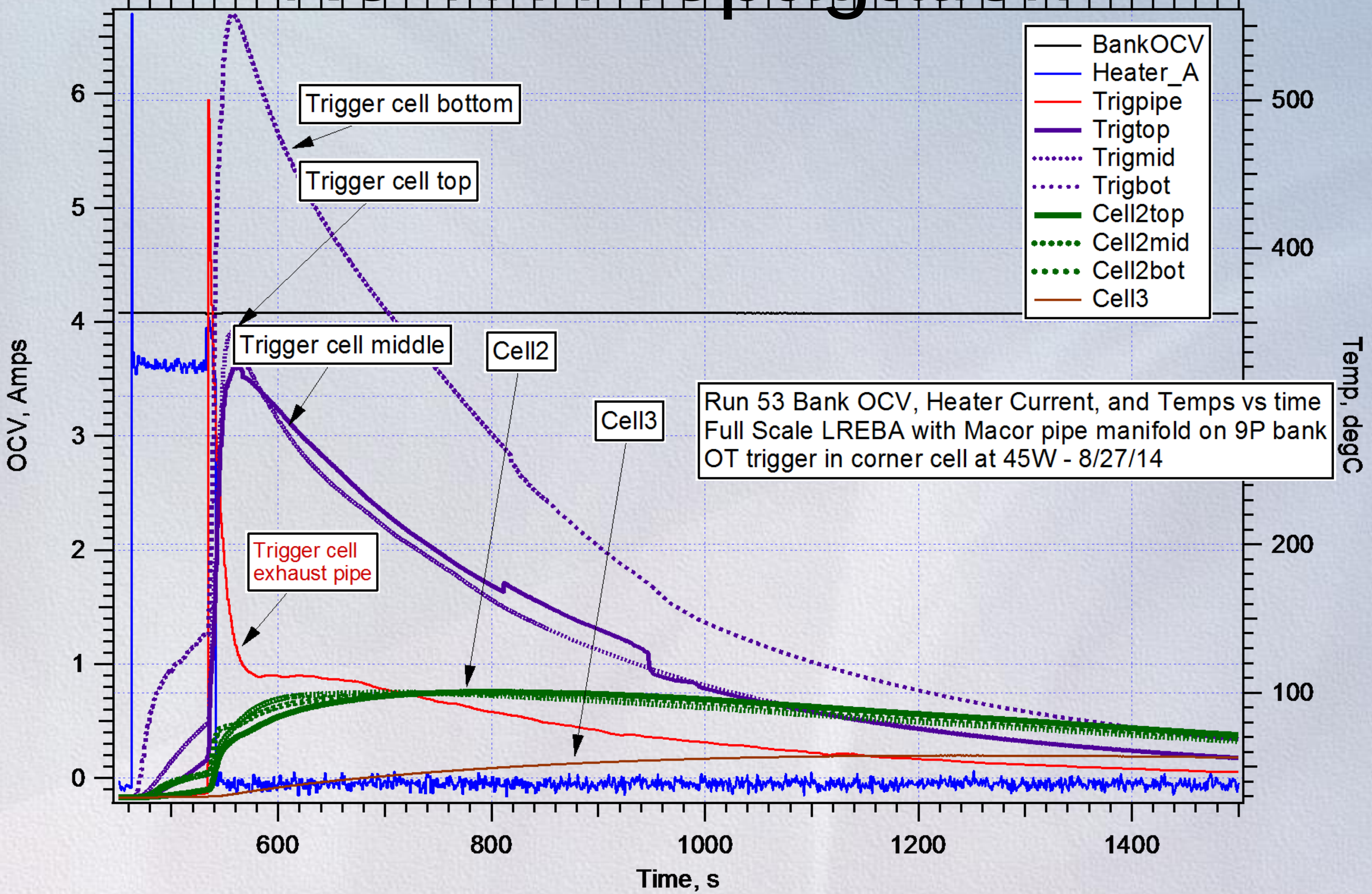






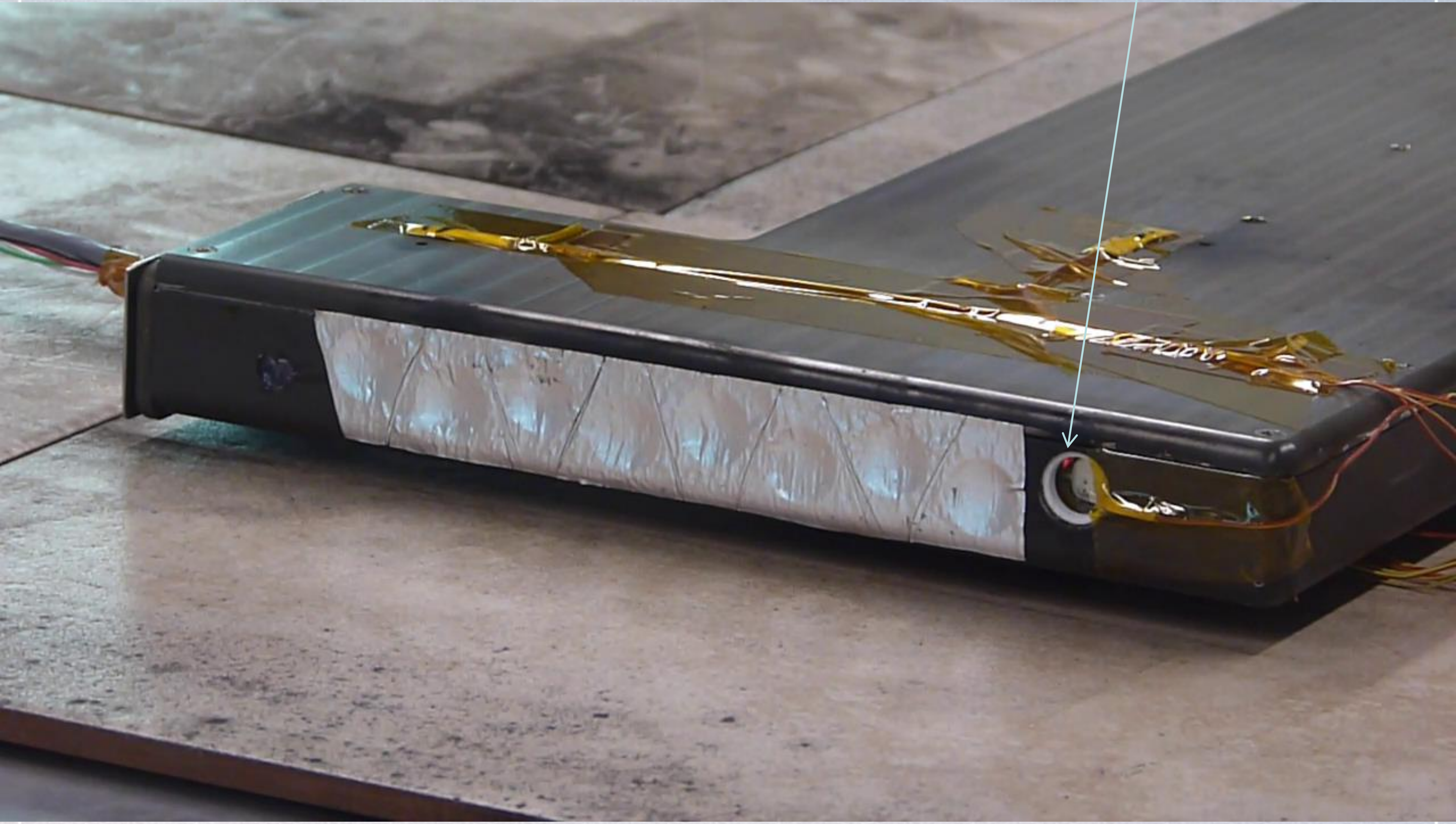
Al foil covering housing ejecta holes to limit air circulation and prevent FOD entering

No TR Propagation



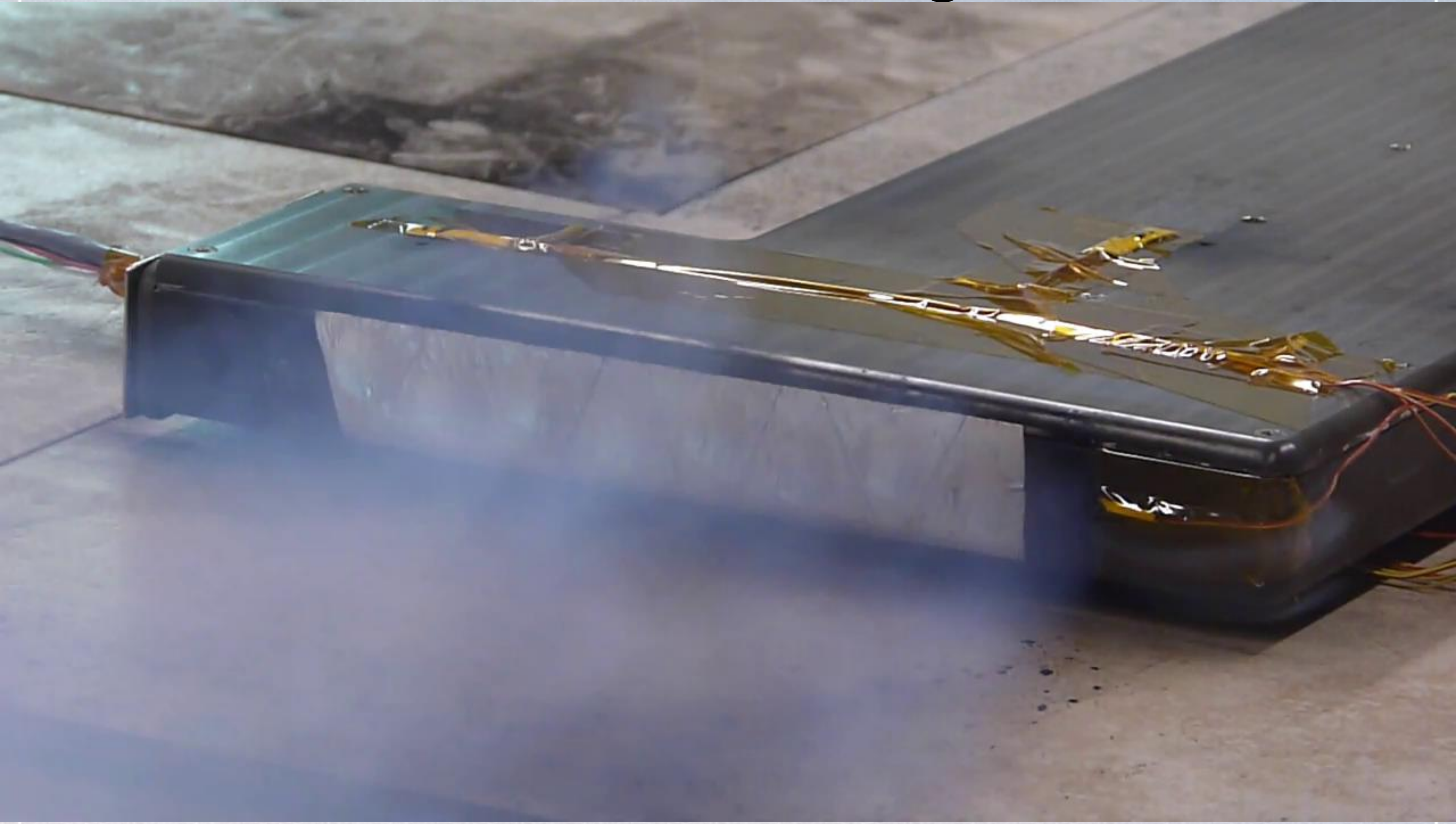
Half of heater fails open in first second, heater runs at 45W, nevertheless, TR reached in 72s. Bottom of trigger cell reaches 543°C, while mid and top get to 319-344°C. Cell 2 maxes out on all 3 TCs at 100°C.

Trigger Cell Positive Fusible Link Opens



At video time 13m:18s

Cell Venting



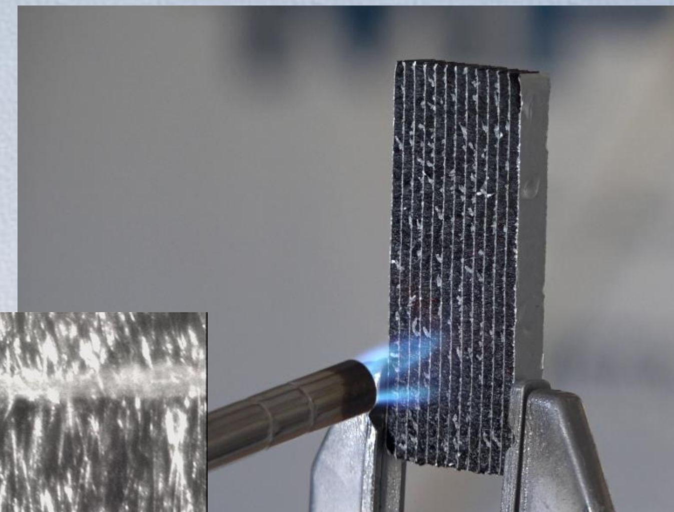
At video time 13m:19s

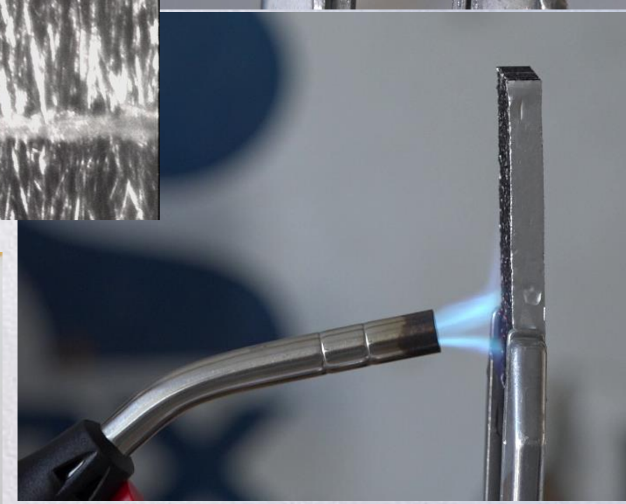
Trigger Cell TR

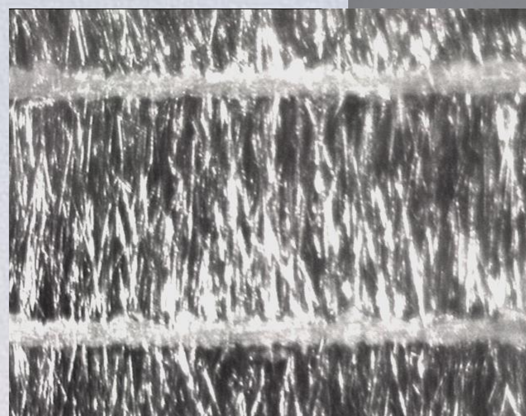
At video time 13m:20s

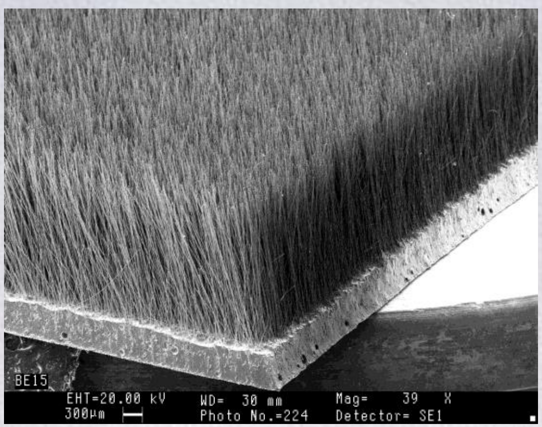
ESLI Carbon Fibercore Torch Test

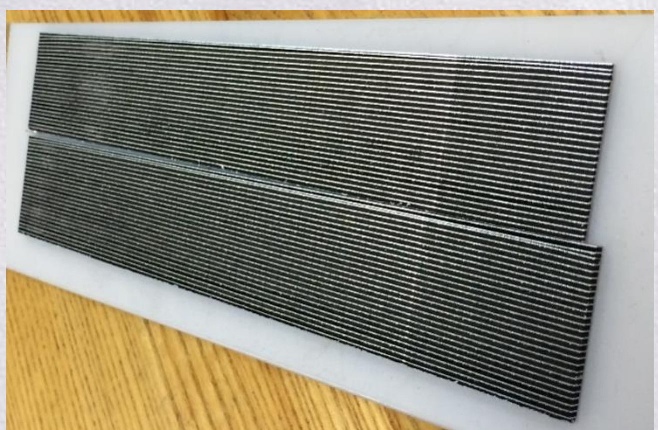
- Lightweight tiny carbon fibers glued to Al foils
  - Very surface area of very high thermal conductivity material
  - Sample tested was ¼” thick
- Blow torch flame did not penetrate through sample
  - Even after 10 second application





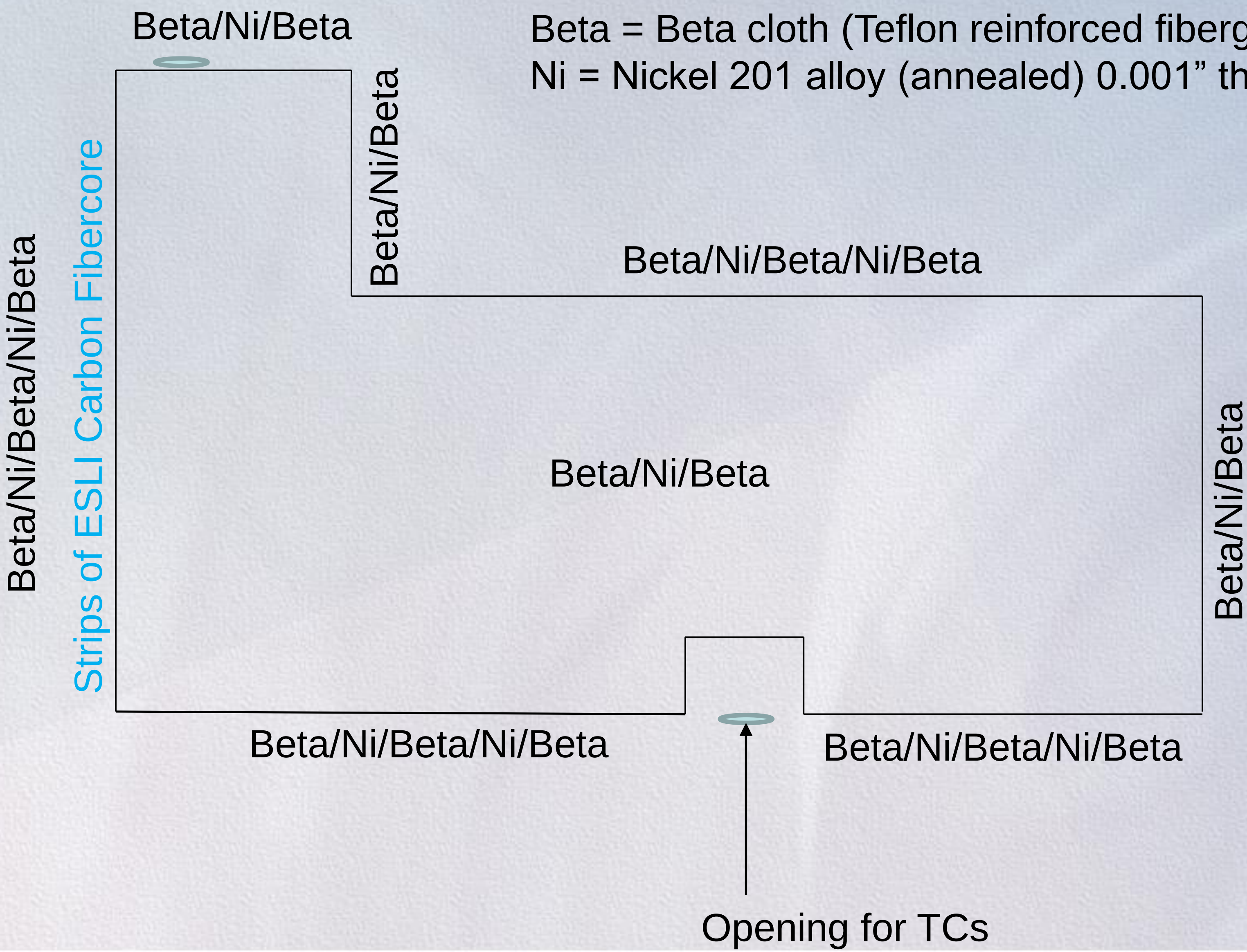






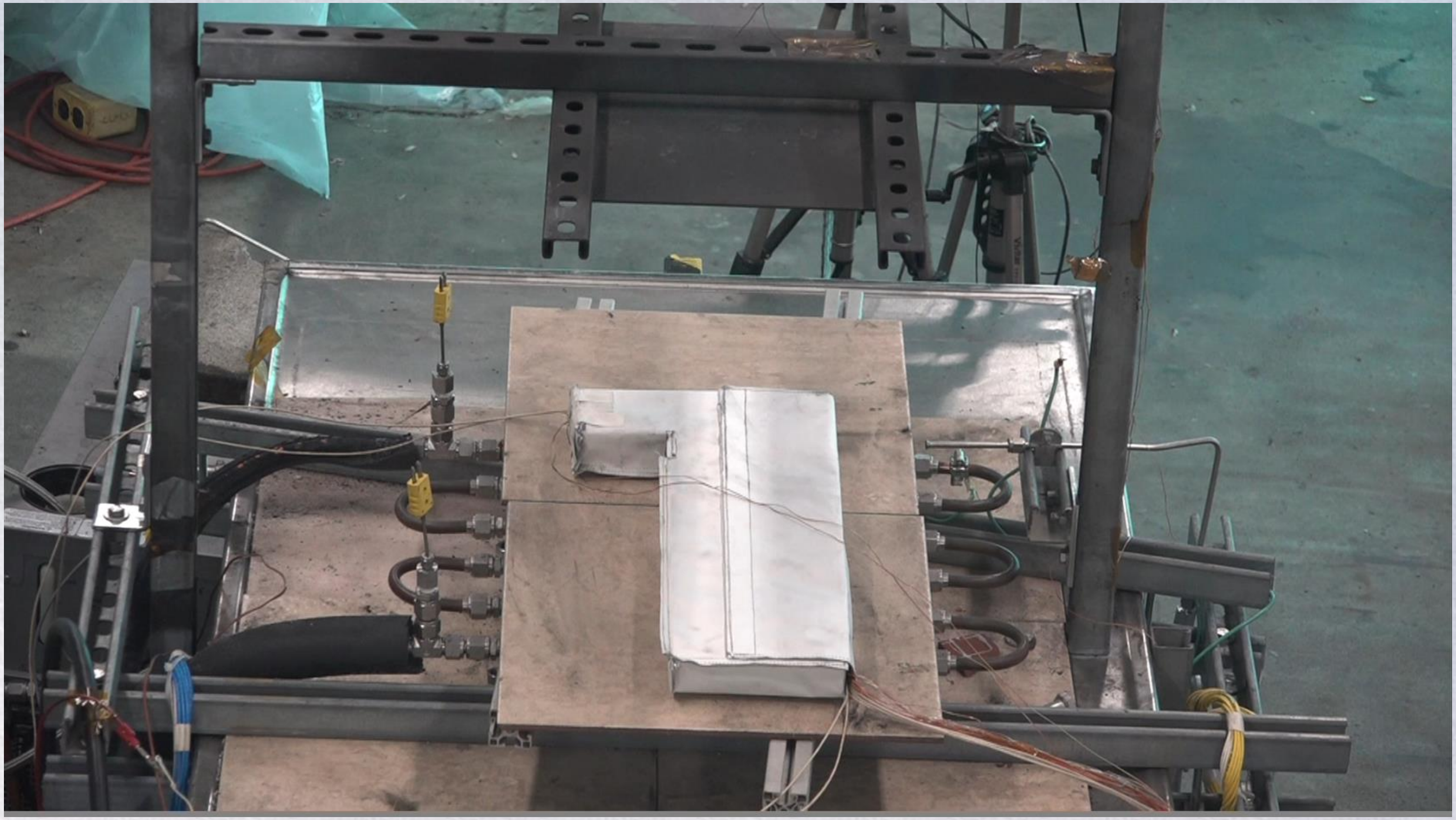
Soft Good Battery Bag Design

Beta = Beta cloth (Teflon reinforced fiberglass)
Ni = Nickel 201 alloy (annealed) 0.001" thk

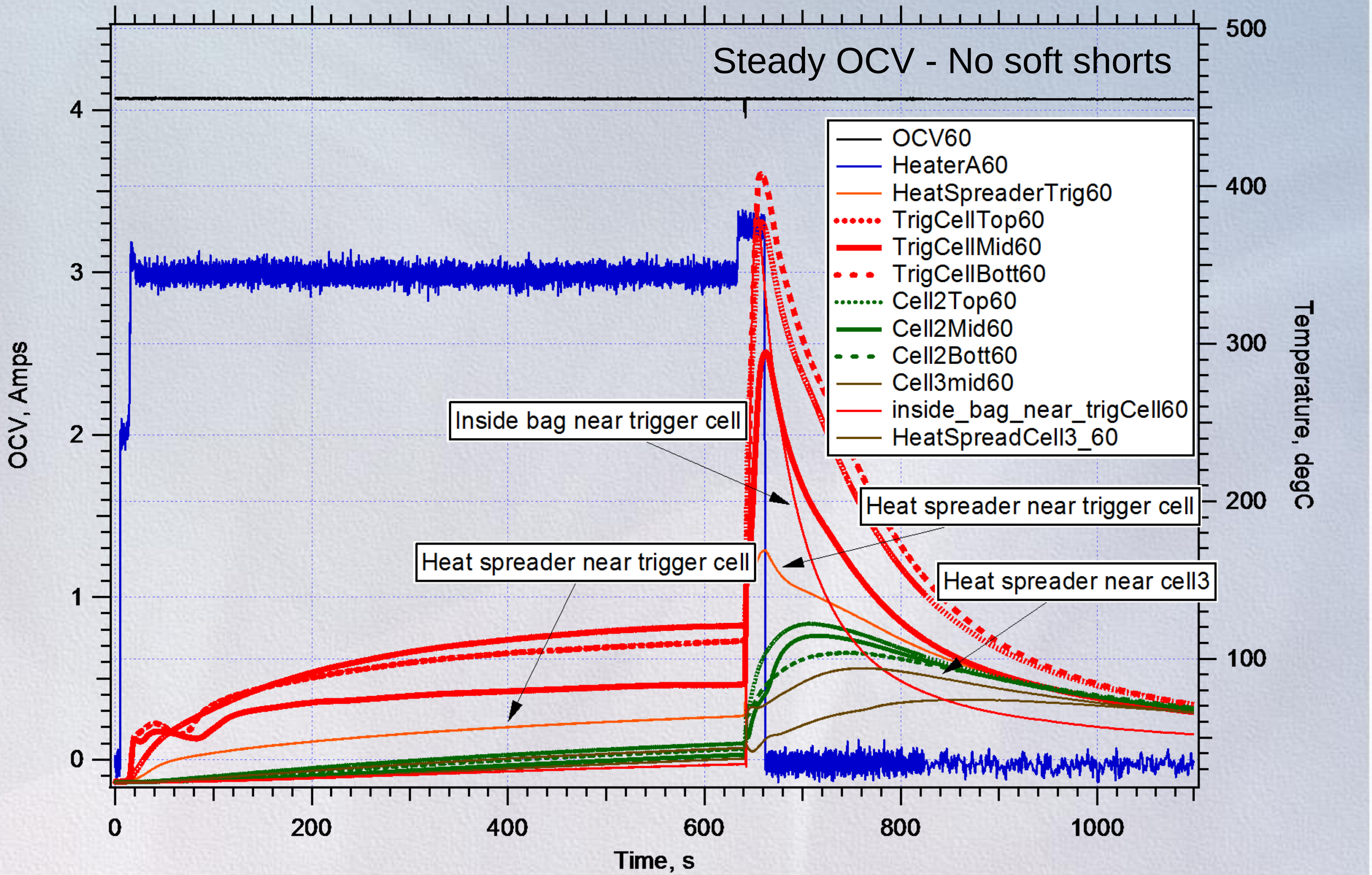


Designed LREBA - No sparks, no fire exit bag

- Bag internal layering reinforced with 4 layers of Ni foil opposing cell exhaust ports
- Bag overlap layering added at corners to prevent exiting sparks
- Heat spreader conducts heat to enclosure and reduces max temperature and duration of trigger cell

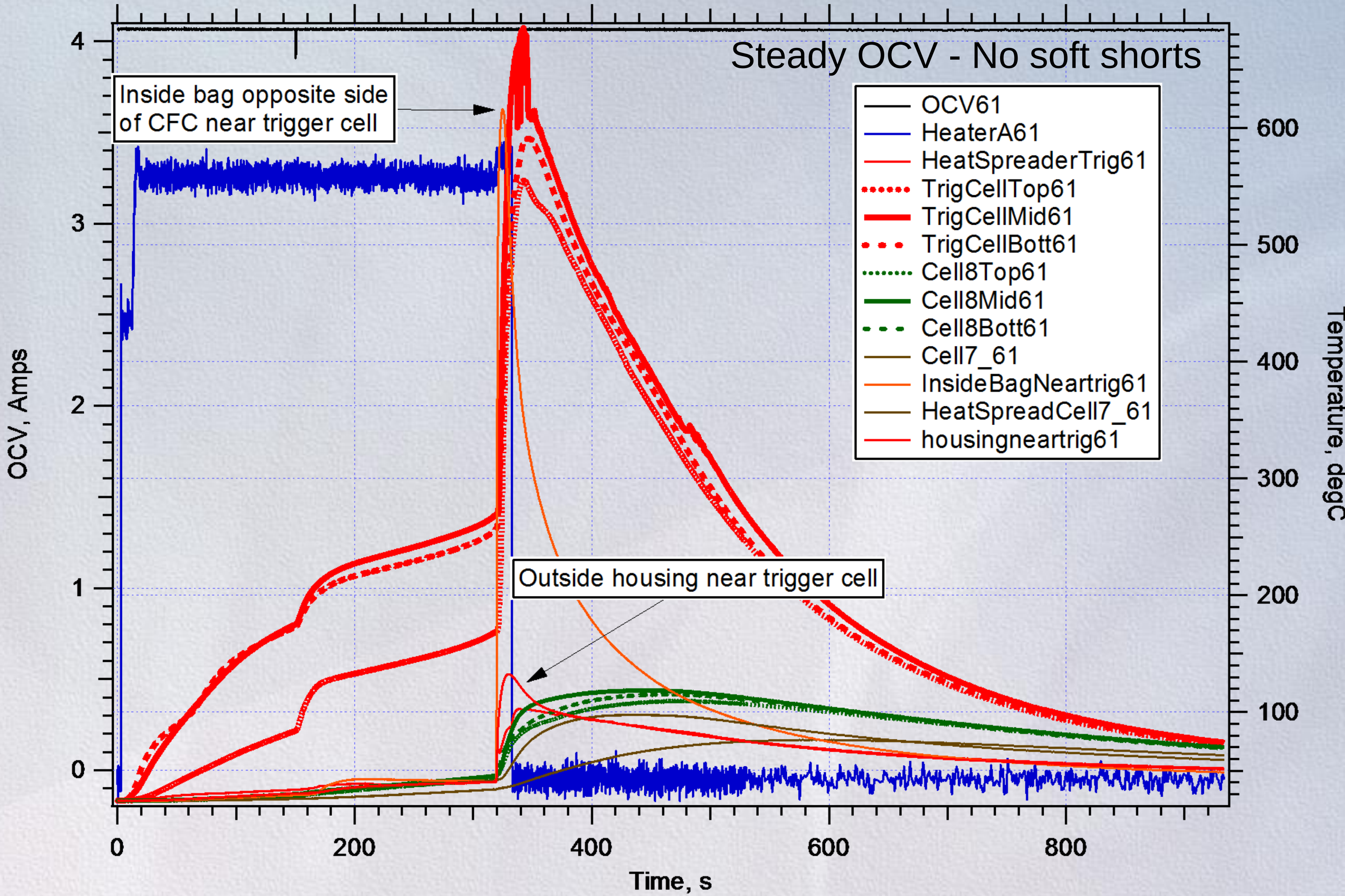


Test 1 LREBA with all features



Heater power bumped up from 45 to 55W just prior to TR, which occurs 10.6 minutes after heater turn on. Much longer to drive TR. Trigger cell max temp range is 294-408°C, Cell 2 is 104-122°C, and cell 3 reaches 74°C. Cooler Ts with heat spreader except for cell 3. The heat spreader reaches 173 and 94°C near the trigger and cell 3, respectively.

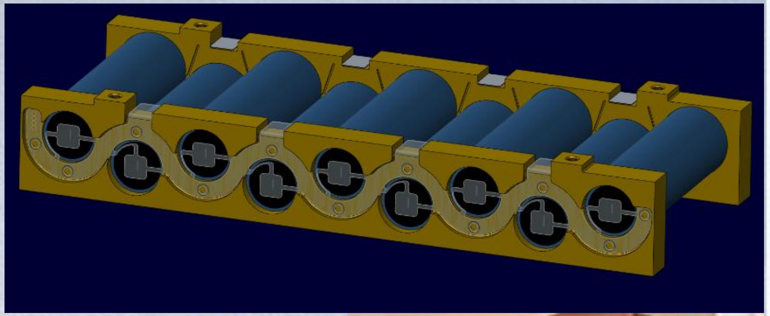
Test 2 – LREBA with all features

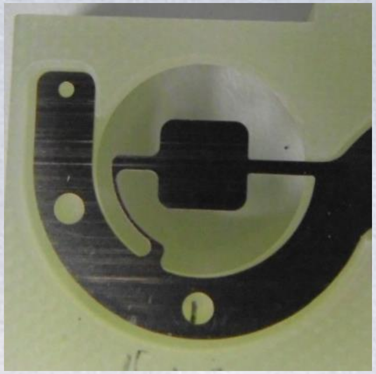


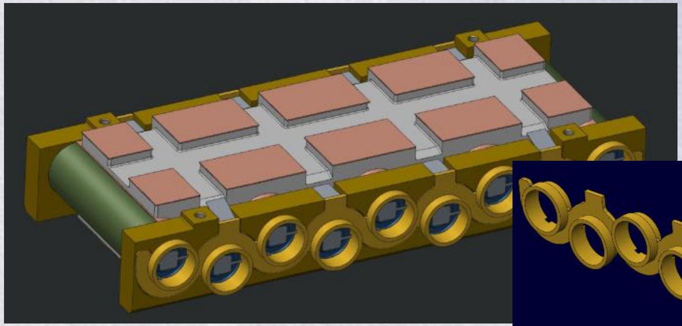
Heater set at 50W and on for 329s. TR occurs in 320s. Internal short circuit occurs 147s after heater on, possibly venting. Then TR occurs 57s later. Max Ts on trigger cell range is 555-686C, cell 8 is 110-115C, and cell 7 reaches 76C. Note that it takes 449s for max temps to cool from peak to 100C. Heat spreader does not keep trigger cell as cool, but does protect adjacent cell.

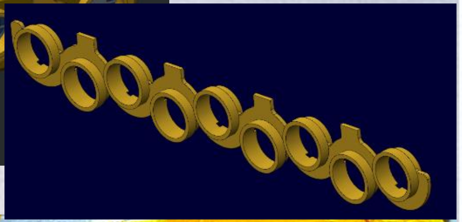
Recap of Design Features for LREBA

- Control the conduction paths
  - Ensure cells are space out ≥ 1mm
    - G10 capture plates
  - Decrease conduction of cell interconnects
    - Fusible links
  - Increase conduction to the enclosure
    - Heat spreaders and gap pads
- Limit shorting paths
  - Fusible links in the negative cell interconnects
  - Mica paper sleeves on cell cans
- Control the TR ejecta path to protect adjacent cells
  - Seal cell positives to capture plates with high temperature adhesive to prevent bypass of hot gases
  - Protect materials in ejecta path with ceramic pipes and exhaust ports
- Limit the flare/fire/sparts exiting the battery enclosure
  - Flame arresting screen to cool the hot gases leaving the battery exhaust ports
  - Soft goods bags provides tortuous path









Lessons Learned

- Design must prevent first TR propagation from initial failed cell:
  - Entire battery gets hotter with each subsequent cell TR event
- Need to prevent cell can wall from rupturing during TR
  - Structural syntactic foams or steel tubes work
- Limiting cell-to-cell thermal conduction by direct contact is critical
  - Spacing
- Limiting cell-to-cell thermal conduction appears to work:
  - Spacing out the cells ≥ 1mm is very beneficial
- Parallel cell bussing can provide significant in-rush currents into failed cell, which gets them hot:
  - Individually fusing parallel cells is effective
- Managing the vent/ejecta path is critical:
  - Combustion of expelled electrolyte must be directed away from adjacent cells with path sealed good high temperature materials & joints
  - Cell TR ejecta can bridge to adjacent cells and cause cascading shorts (suggests need for interstitial material between cells to protect cell cans)
  - Cell TR flame/flare attenuation with SS screens and carbon fibercore protected by baffle and tortuous vent path works
- Soft goods bag and conductive absorptive material prevent exiting flames
  - Additional Ni foil layers help, but flame arresting porous carbon fibercore found to be more effective
  - Porous metal screens serve as effective flame arresting screens for battery vent ports
- Subscale test results can be misleading and no replacement for full scale test verifications

Take Home Message

- Preventing cell-cell TR propagation and flames/sparks from exiting battery enclosure is possible with proper thermal & electrical design and can be had with minimal mass/volume penalty
  - First redesign took 5 months
  - Subsequent ones take less than 3 months
- Using 240 Wh/kg cell designs with the design principles presented will enable 180 Wh/kg battery solutions

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