Thermal Runaway Severity Reduction Assessment For EVA Li-ion Batteries

By
Eric Darcy/NASA-JSC

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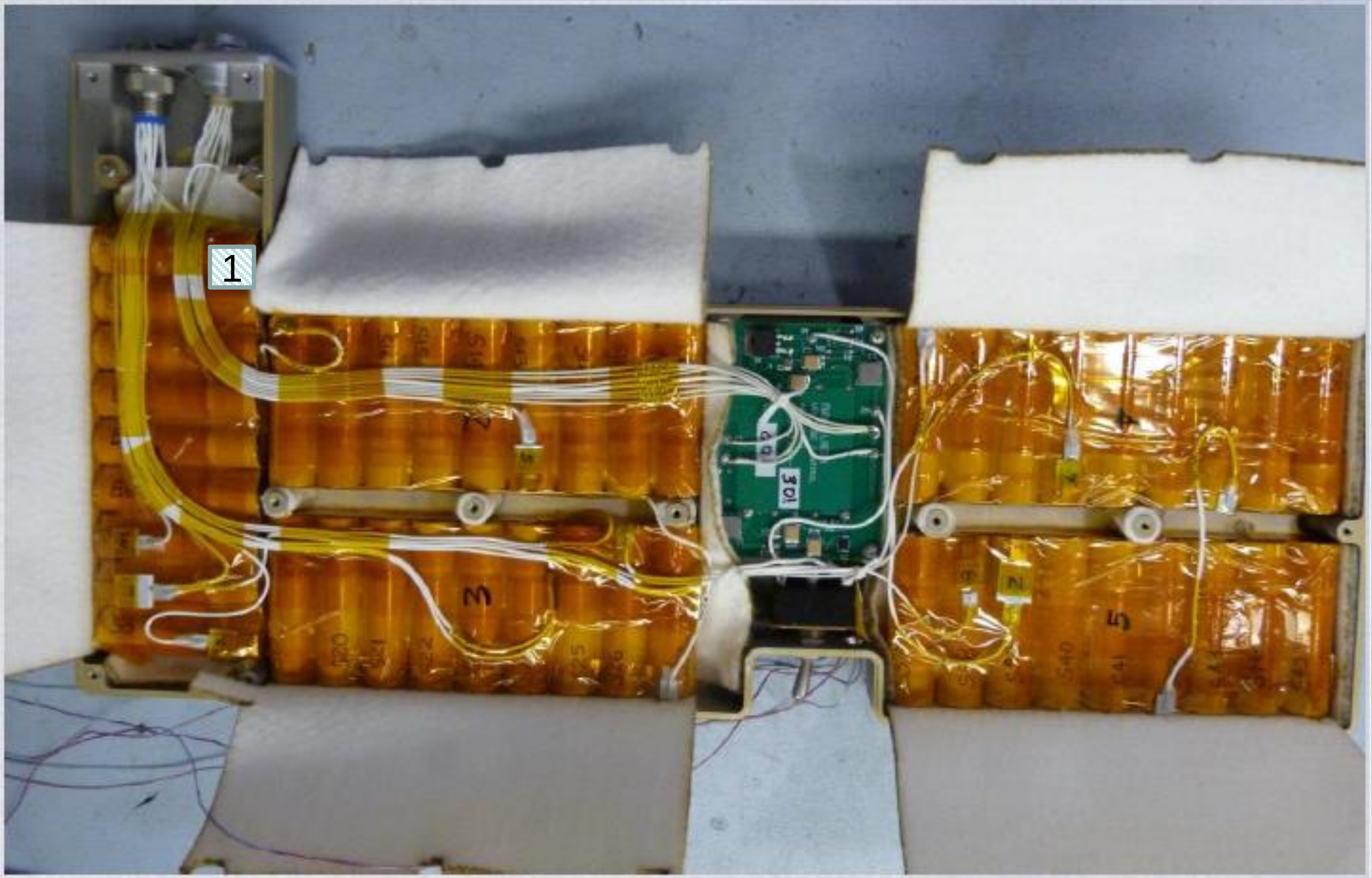
Team and Contents

- NASA Engineering Safety Center Lead Effort:
  - Paul Shack, Assessment Lead
  - Chris Iannello, NESC Technical Fellow for Electrical Power
  - Steve Rickman, NESC Technical Fellow for Passive Thermal
  - Eric Darcy, Test Lead for EVA Batteries, NASA-JSC
  - Sam Russell, Mike Fowler, Judy Jeevarajan, Craig Clark, John Weintritt, Christina Deoja and Stacie Cox/NASA-JSC
  - Rob Button, Tom Miller, Penni Dalton/NASA-GRC
  - Dan Doughty, Bruce Drolen, Ralph White, Gary Bayles, and Jim Womack/NESC Consultants
- Agenda:
  - Background on the Spacesuit batteries
  - Motivation and objectives
  - Trigger method selected and why
  - Assessments of current designs
  - Verification of subscale mitigation measures
  - Full scale LREBA with those measures leads to failure
  - Consequence of cell TR ejecta products to TR propagation
  - Full scale LREBA with adjacent cells protected from cell vent path
  - Bank test to verify benefits of cell fusing
  - Lessons learned to date

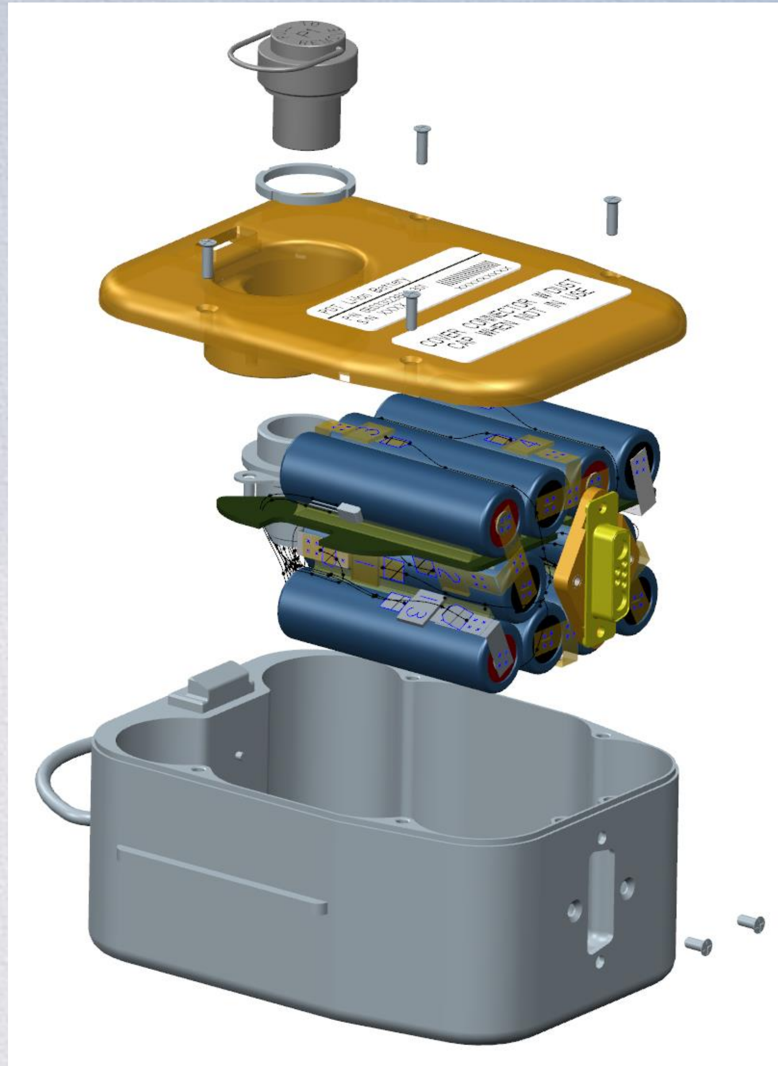
Background - Li-ion Rechargeable EVA Battery Assembly (LREBA)



9P-5S Array of Samsung 2.6Ah 18650 cells to power the spacesuit helmet lights and camera and glove heaters

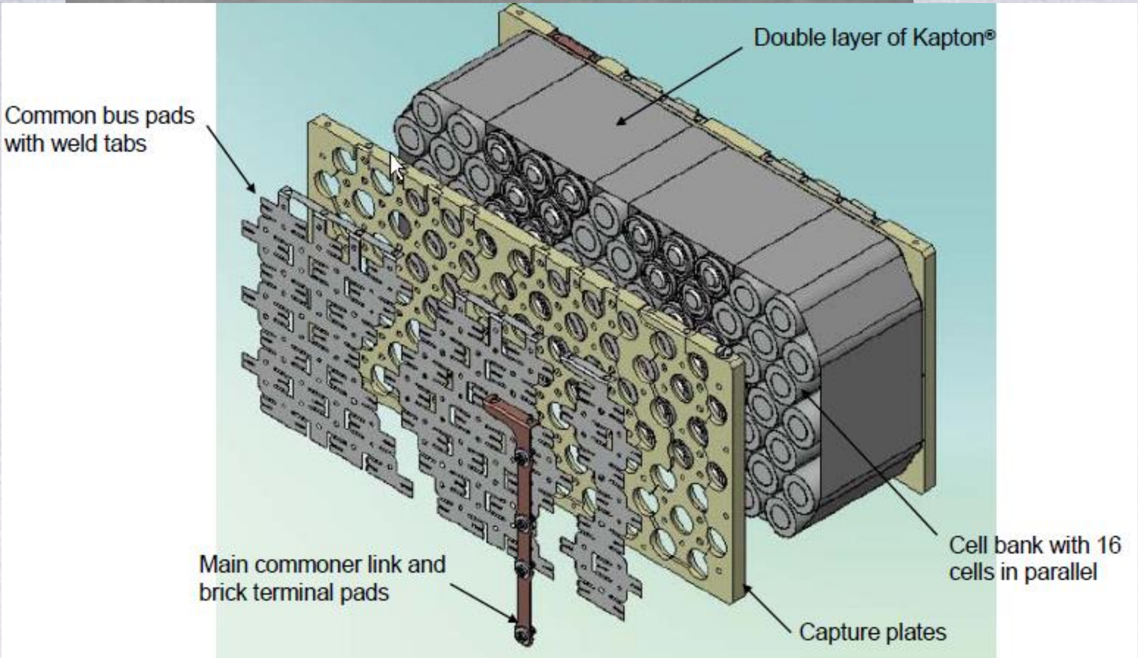
Background – Li-ion Pistol Grip Tool Battery (LPGT)

- 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



Background – EMU Long Life Battery (LLB)

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

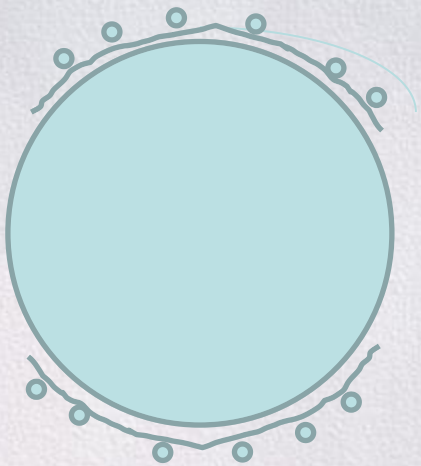


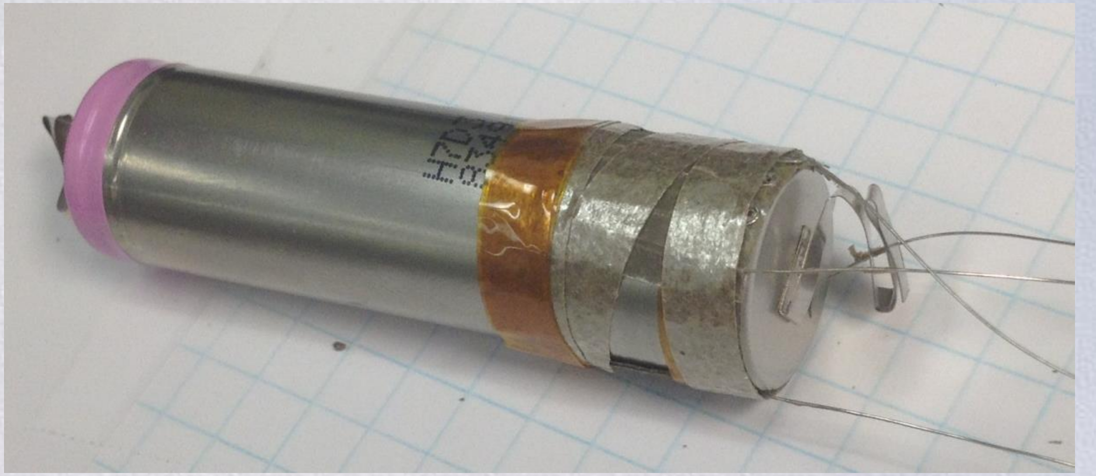
Background and Motivation

- NASA is no longer relying only on prevention measures for reducing single cell internal short hazard:
  - Cell screening known to not be fool proof against latent defects that can lead to field failures
  - Reasonable design and operational measures have been shown to reduce severity
- Revised battery safety standard (JSC 20793 RevC) requires determining the hazard by test in all designs > 80Wh and assessing possible severity mitigation measures
- This assessment is a pathfinder for that approach and will be done on 3 EVA batteries

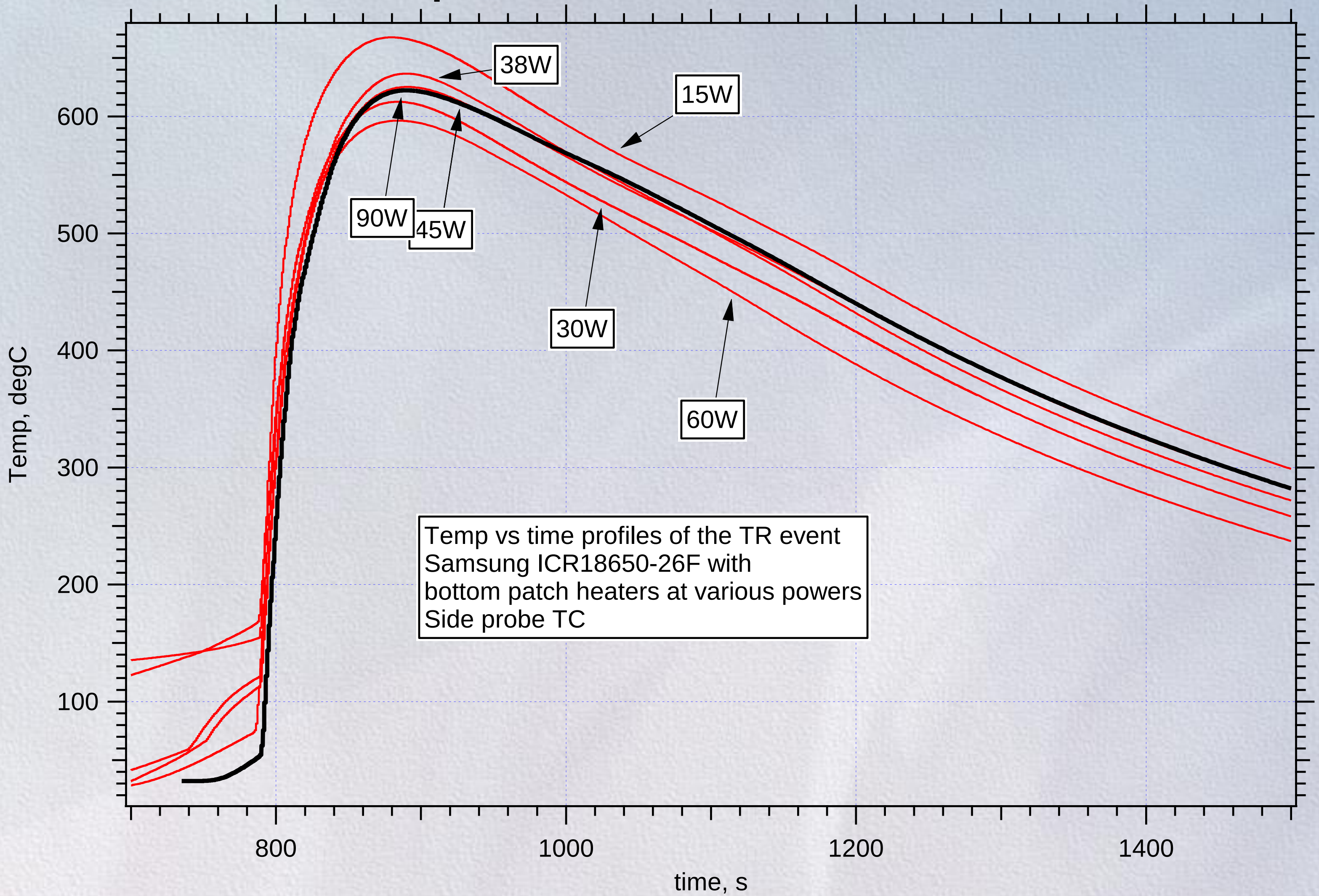
Selected Bottom Patch Heaters For Triggering TR

- 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



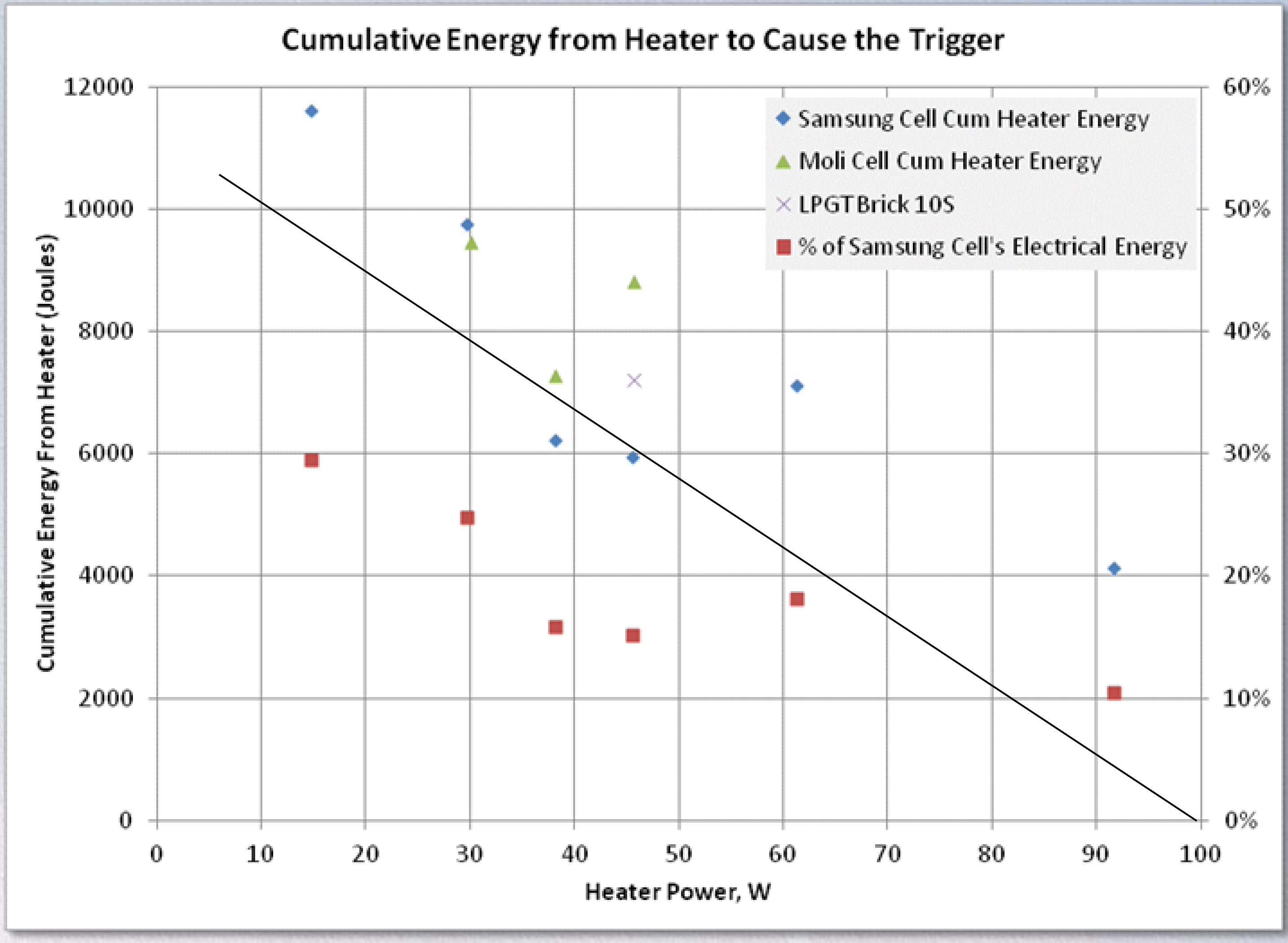


Cell TR Response vs. Heat Power



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

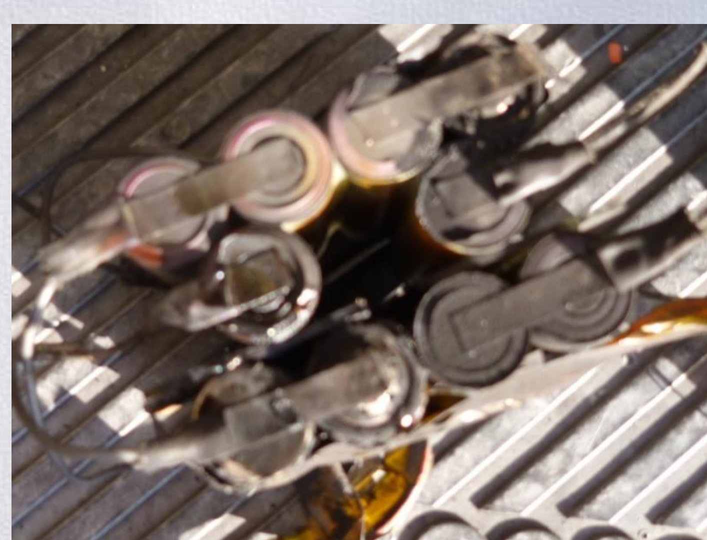
Higher W Triggers with Lower Wh Input



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

LREBA 9P Bank Test – Baseline Design

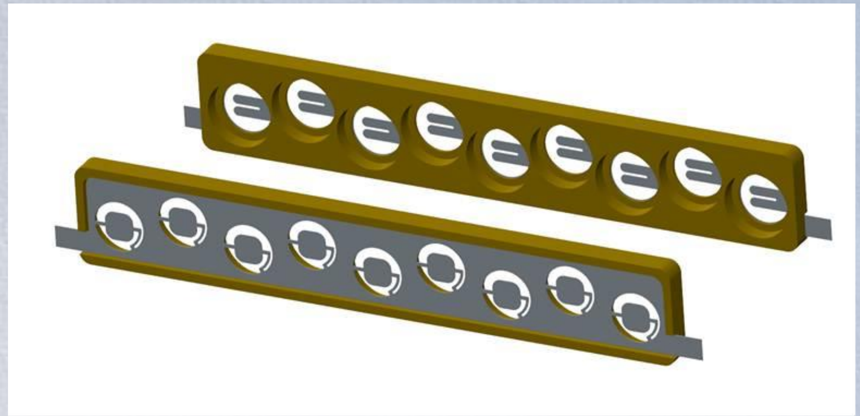
- Picket fence 9P bank with cells in axial contact and with epoxy bond line between cells:
  - End cell trigger with 45W
  - Open air environment
- Full cascade of cell TR propagation in ~10 minutes
- Similar result found with LPGT brick
- LREBA and LPGT baseline designs found susceptible to TR propagation



LPGT brick post TR Test

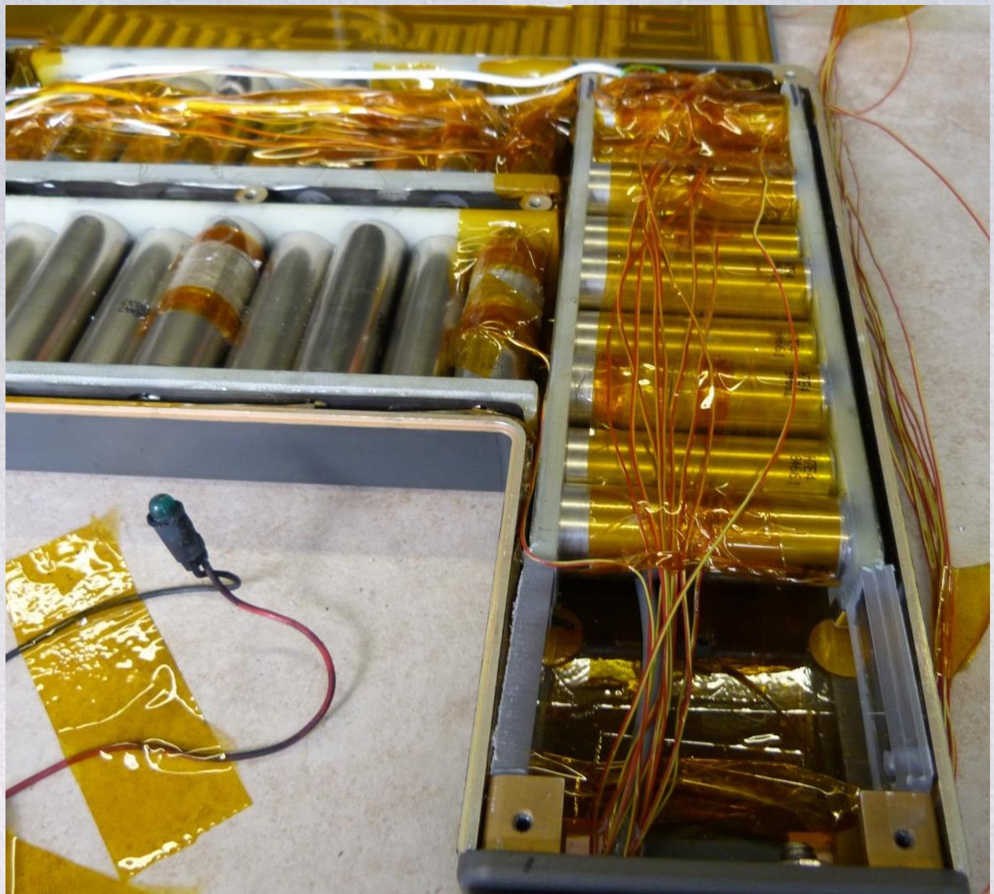
First Round of Mitigation Measures

- Ensure cell-cell spacing 1-2mm with FR4/G10 capture plates:
  - Reduce thermal conduction from cell to cell
- Integrate fusible links into Ni-201 bus plates on positive only:
  - Isolate cell with internal shorts from parallel cells
  - 15A open current
  - Reduce thermal conduction via electrical connection
- Include radiation barrier between cells in 2mm spacing design
- Test under inert gas:
  - Reduce chaos associated with burning cell ejecta
- Results:
  - No TR propagation in all 4 tests conducted in inert gas
    - Radiation barriers helped slightly
    - But spacing between cells found most significant
      - Picket fence design propagated in inert gas
  - In open air, propagation was likely because of flammable ejecta impinging on adjacent cells

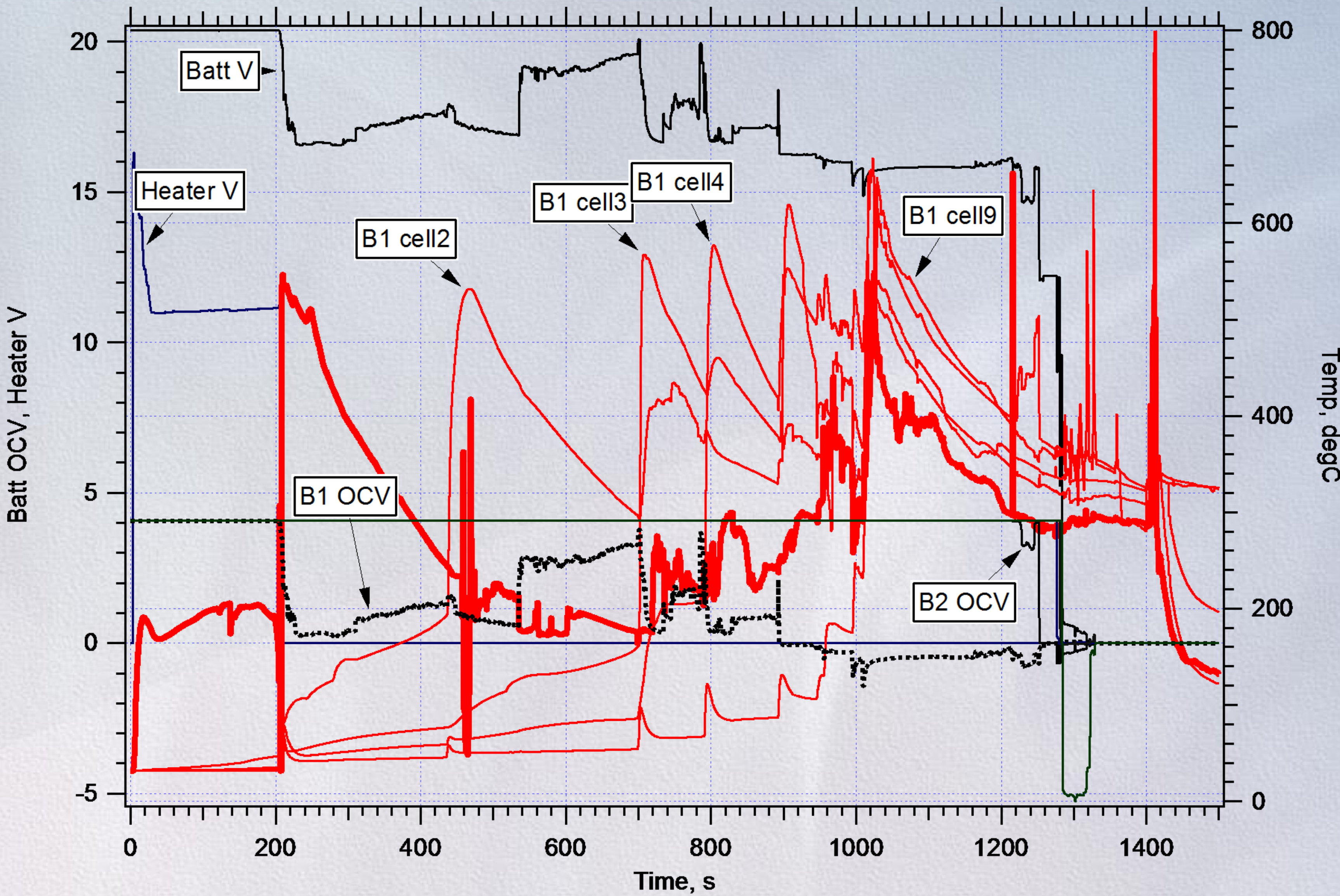


Full Scale Battery Test – Total Propagation

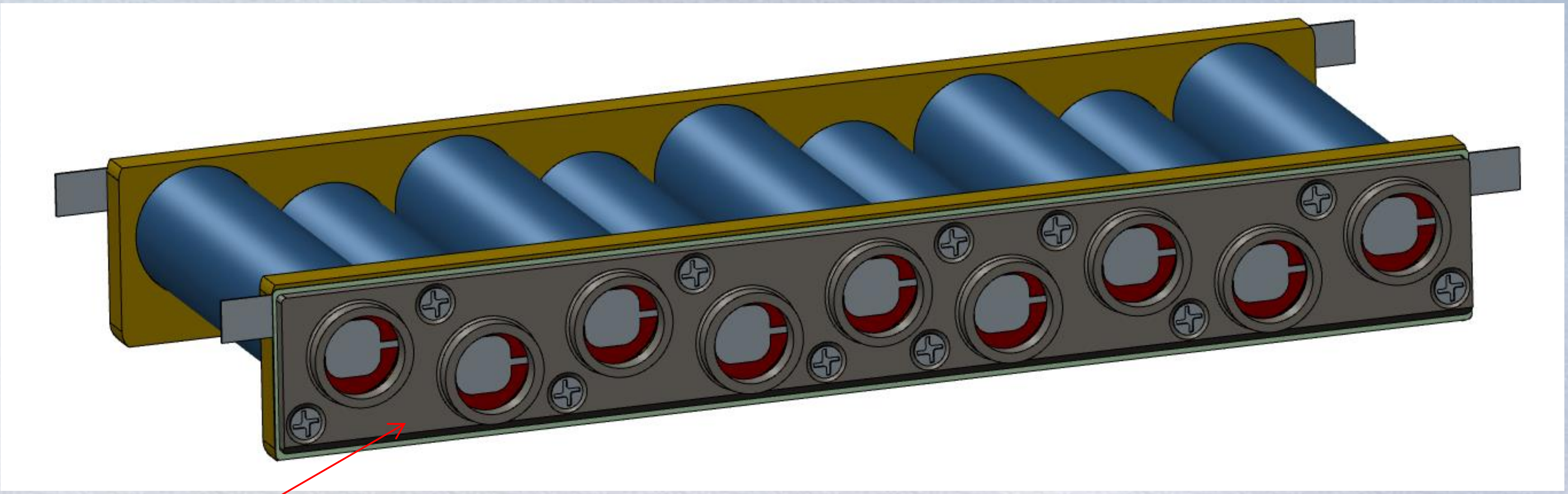
- End cell in corner of dogleg was triggered
- All 45 cells went into TR over 29 minutes
- 231 seconds from trigger cell TR to adjacent cell TR
- Flames exited housing after 5th cell driven into TR 11 minutes into the test
- Vented ejecta bypassed fusible links and created short paths



Bank 1 Experienced A Sustained Short Immediately After TR of Trigger Cell

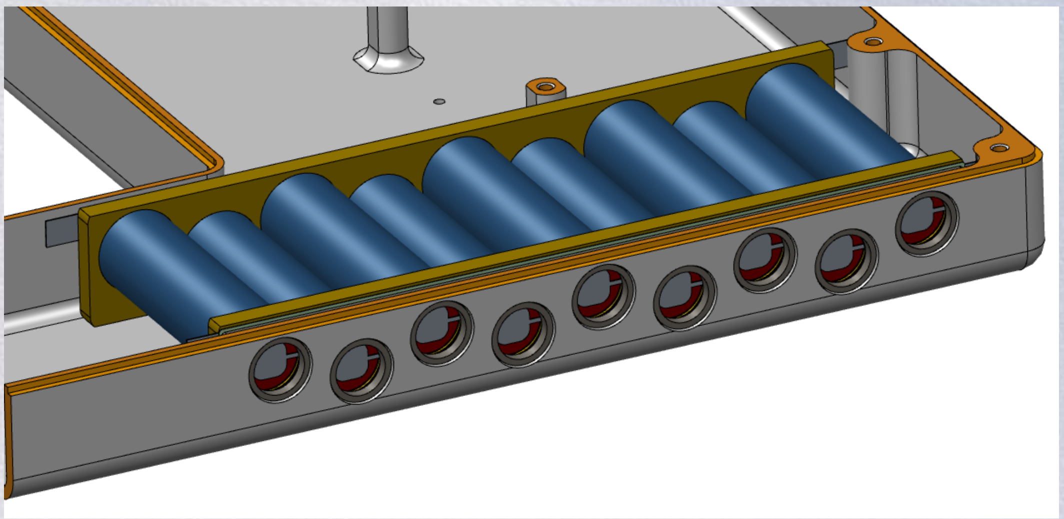


Next Full Scale LREBA Test Configuration



Cell Ejecta Exhaust Piped Top:

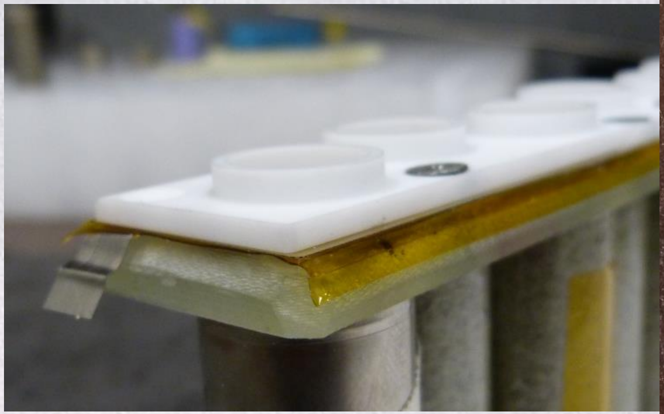
- Macor (machinable glass ceramic) with G10 gasket between Ni bus and manifold top
- Matching holes in housing for pipes
- Mica paper wrapped on cell cans
- Fusible bus bars on both positives and negatives:
    - Same 15A trip



9P bank inside LREBA housing with exhaust holes

Details of New Mitigation Features

- Gen 1 LREBA capture and Ni bus plates with same housing/lid
- Special care to avoid heater wire termination to damage cell case:
  - Added mica paper between termination and cell case
- Exhaust pipe manifold material Macor (machinable glass ceramic):
  - Very carefully fastened it to the G10 capture plate:
    - Place 3 layers of Kapton and 0.005” G10 gasket in between G10 capture plate and Macor manifold
    - Kapton layers are compliant and help seal the Macor/G10 gap
  - Al tape added top of pipes to seal pipes of non-trigger cells to fresh limit air circulation
- Added Mica paper insulation to the cell cans of non-trigger cells

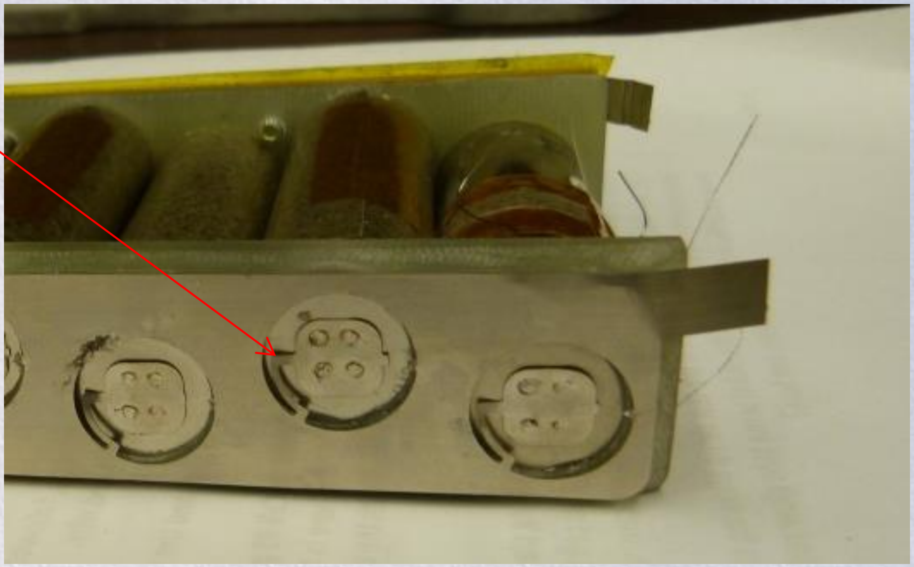


More Photos of Mitigation Features

Machinable glass ceramic (Macor®)

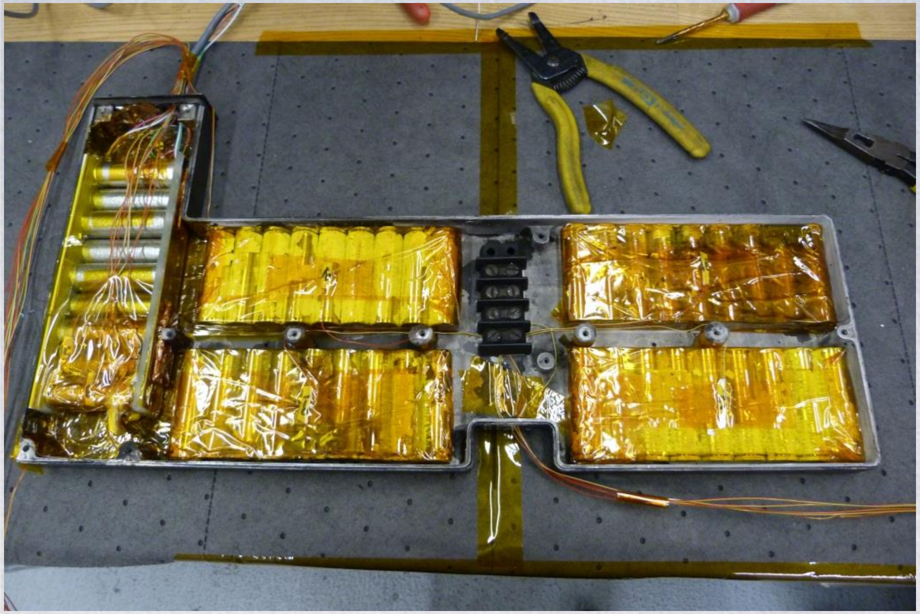
Fusible (15A) bus plates connected on both terminals

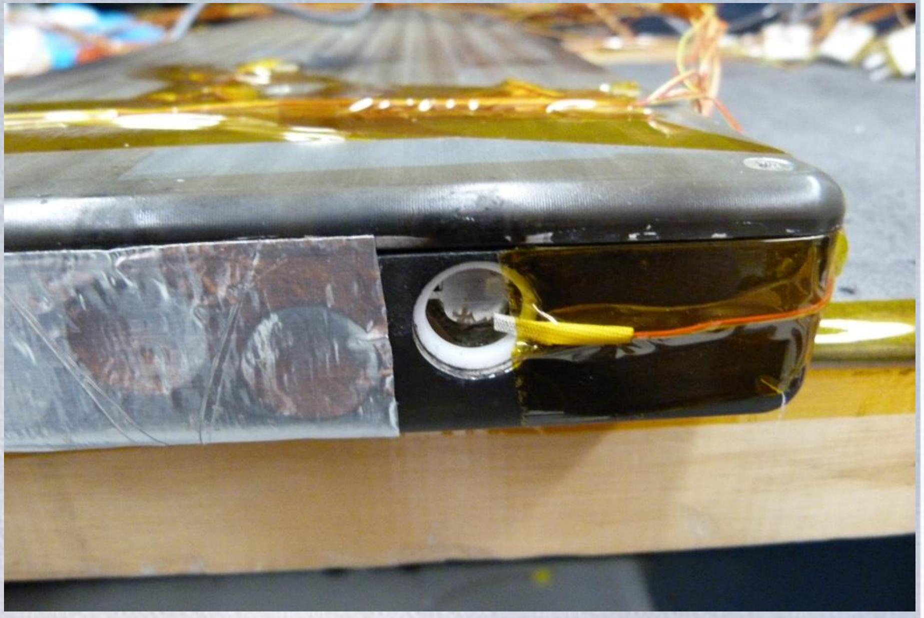
Mica paper as radiation barriers and to electrically isolate cell cans 2-8
Heater placed on end cells 1 & 9

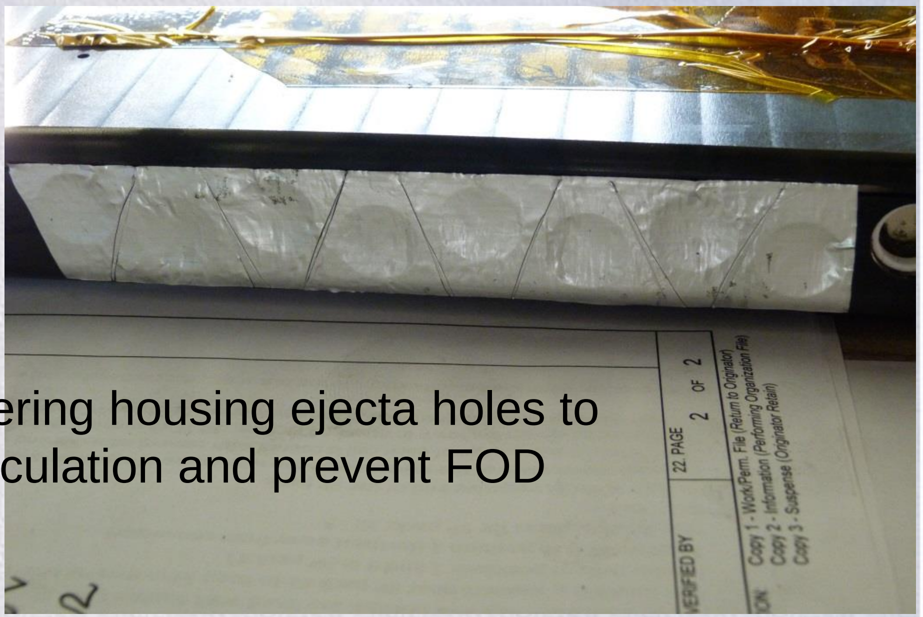


Pre-Test Photos

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

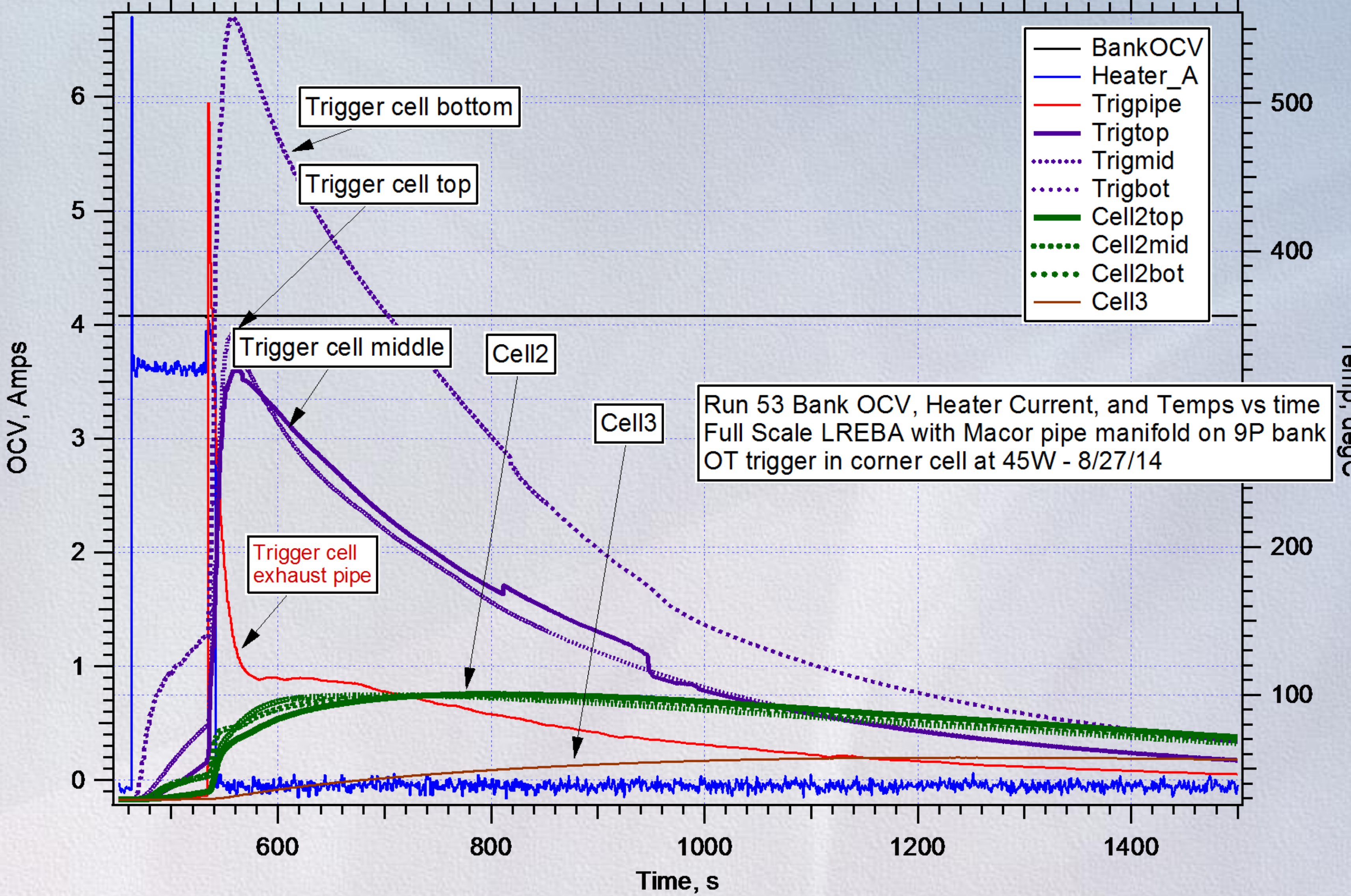






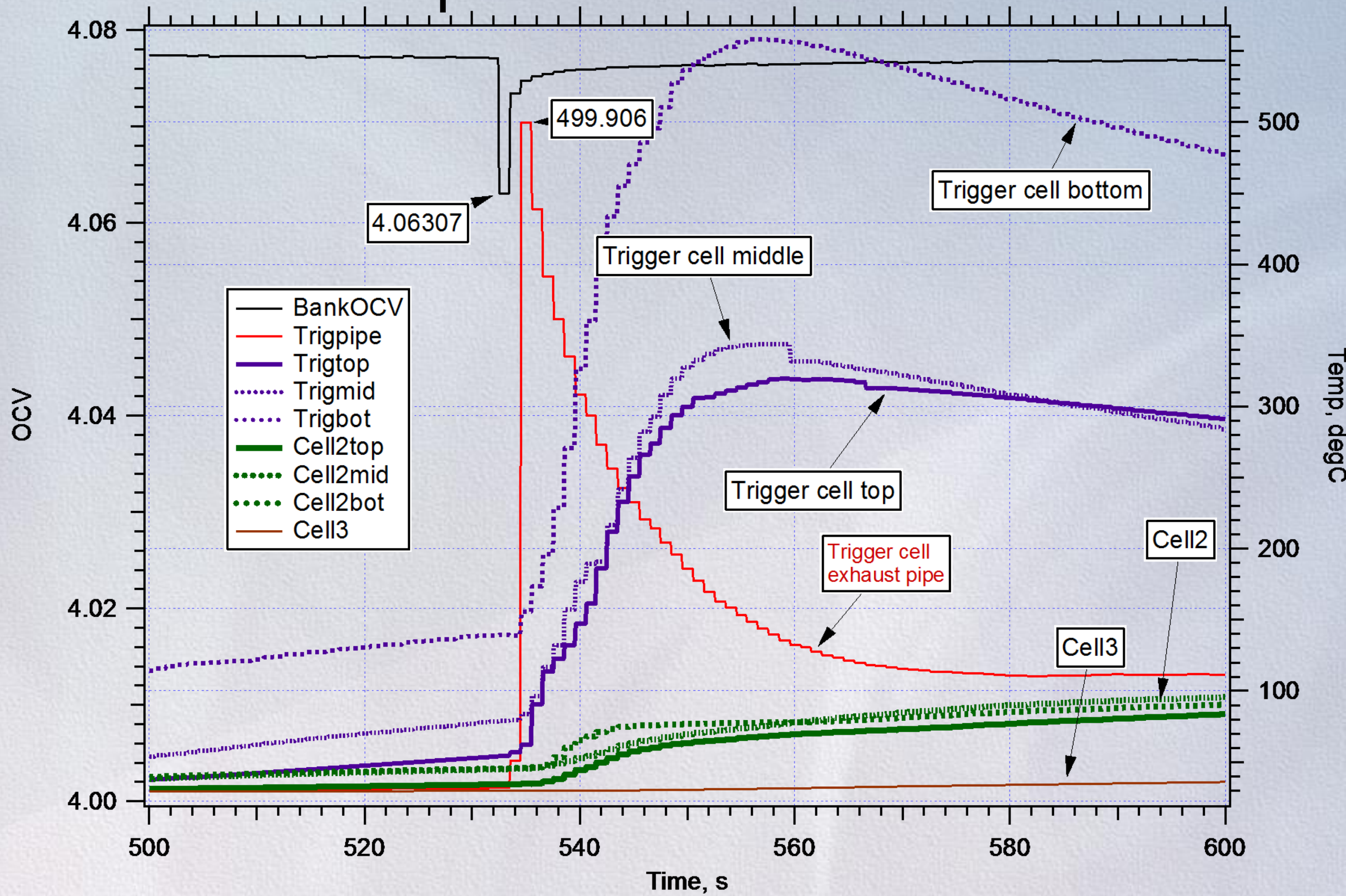
Al foil covering housing ejecta holes to limit air circulation and prevent FOD entering

No TR Propagation



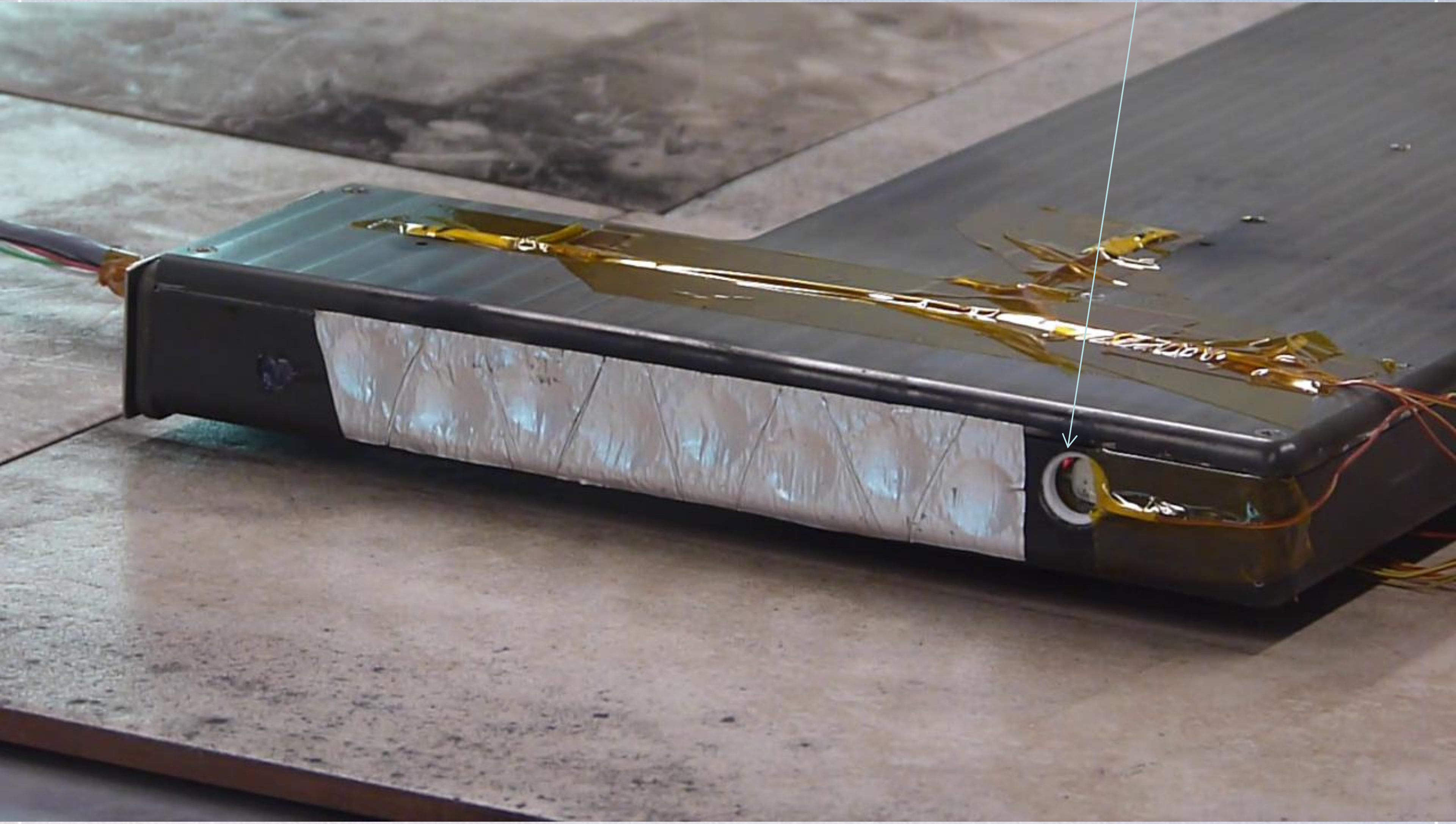
Half of heater fails open in first second, heater runs at 45W; nevertheless, TR reached in 72s. Bottom of trigger cell reaches 543°C, while mid and top get to 319-344°C. Cell 2 maxes out on all 3 TCs at 100°C.

Up Even Closer



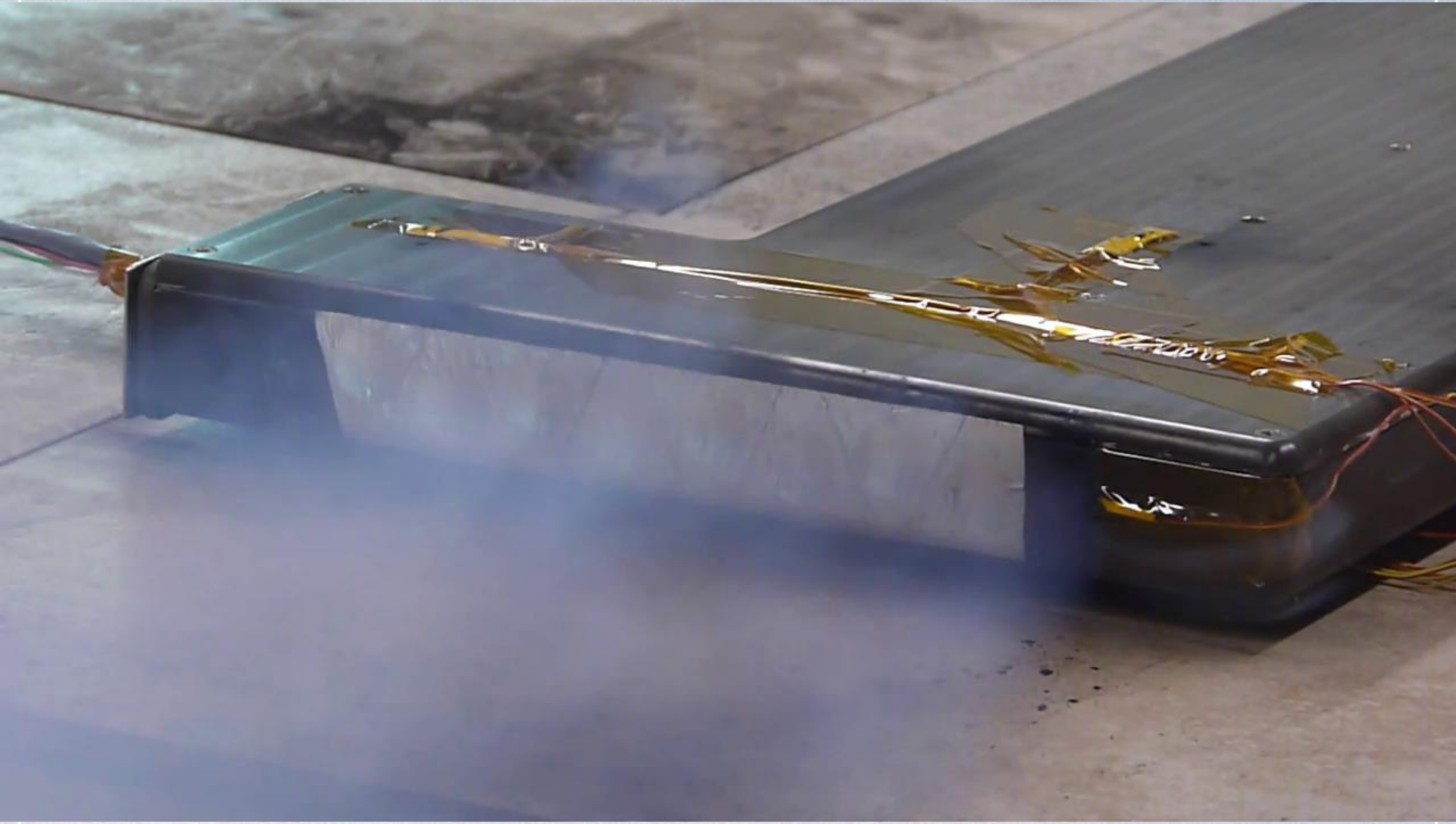
TR of trigger cell shorts the bank for ~1s, which blows open the positive & negative fuse of trigger cell, also positive link in cell 2 was found blown. The 15mV drop shown corresponds to 2.25A peak from the bank, not enough to blow 15A fusible links. But, data collected at 1Hz and may have missed true bottom of voltage dips.

Trigger Cell Positive Fusible Link Opens



At video time 13m:18s

Cell Venting

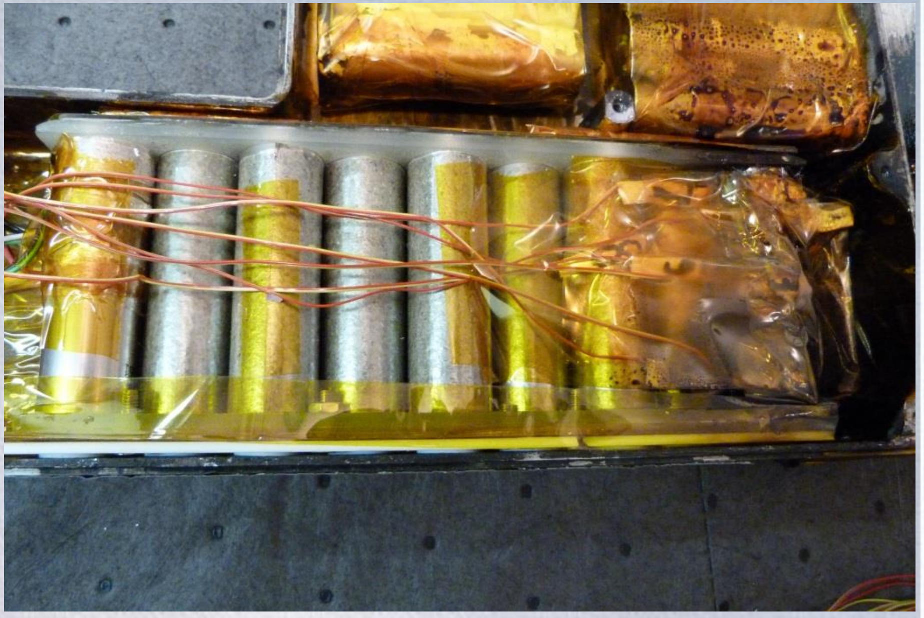


At video time 13m:19s

Trigger Cell TR

At video time 13m:20s

Post-Test Photos



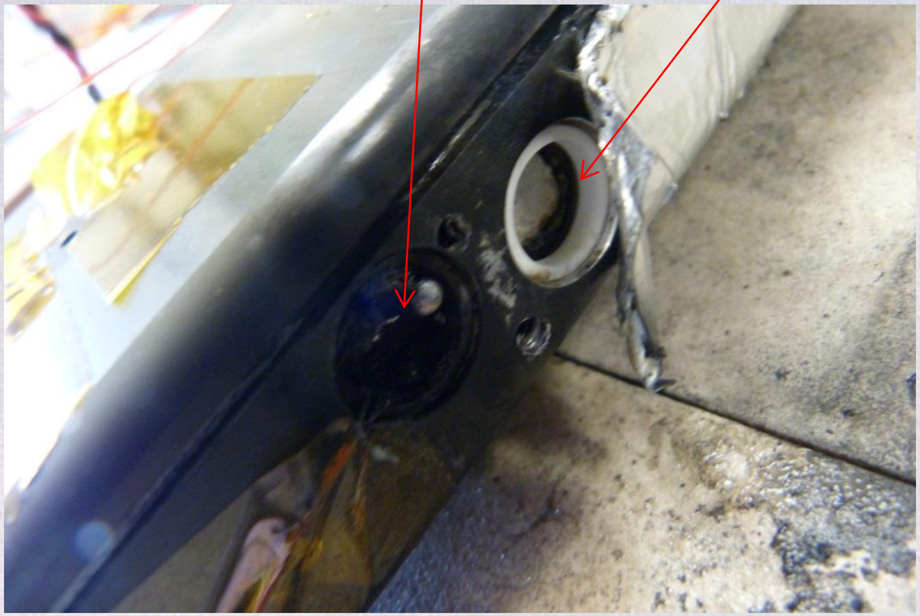
- Bank voltage at 4.07V
- Isolated Cell 2 voltage measured at 2.5V (blown positive fuse) on 8/27 and 1.1V on 8/29:
  - Internal soft short suspected
- Megaohms measured between cell 4-9 cans and housing
- Negative fuse on trigger cell also found blown

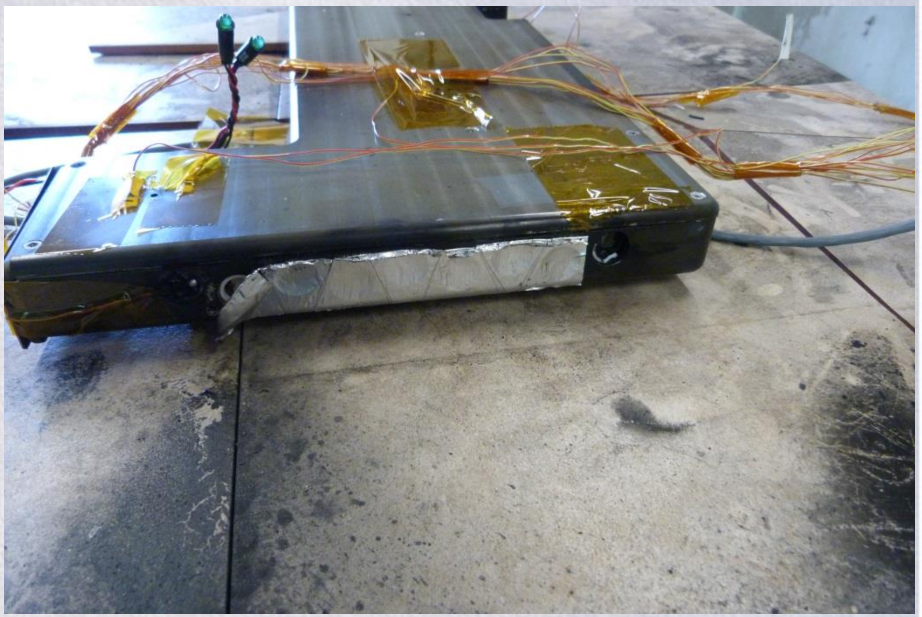
Preliminary Findings of Test

- TR of trigger cell was not uniformly hot:
  - Only bottom TC > 500°C
  - Top and mid did not exceed 350°C
- Half of heater failed, yet TR reached in 72s:
  - DPA of cell will determine if it internal temperatures exceeded melting temp of Al (660°C) and where besides the bottom
- Data was not truly collected at 10 Hz:
  - Limitation in the Labview data system makes it fail to increase data collection frequency
- Cell 2 Status:
  - Cell 2 experienced an external short sufficient to blow its 15A positive fuse
  - No TR, but it subsequently experienced a soft internal short:
    - It is hoped that DPA of cell will reveal why
    - Its hot tabs may have overheated portions of adjacent separators layers

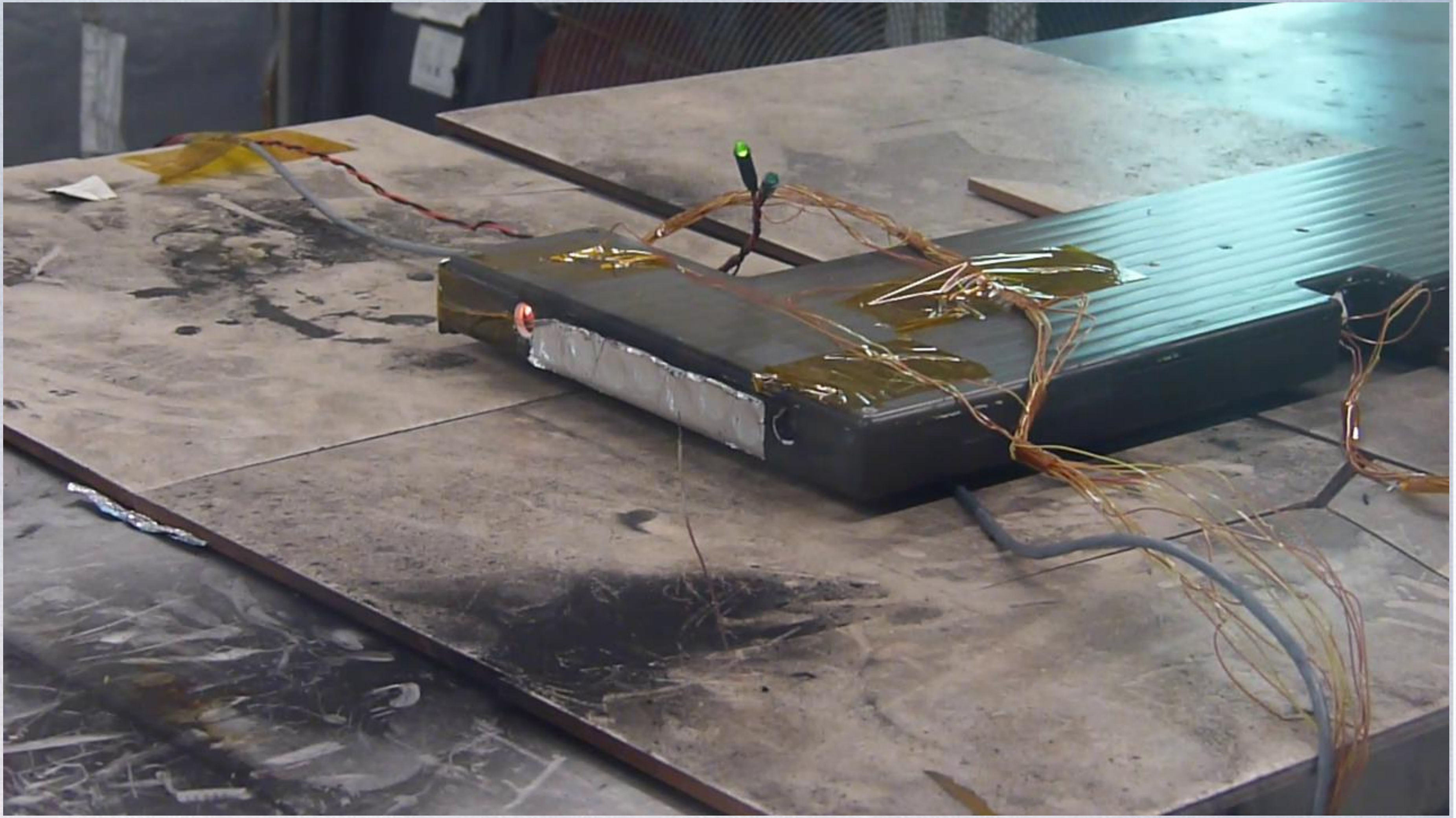
Repeat Run with Other End Cell in 9P Bank

- Trigger cell #9 with 90W
- No TR propagation, however cell 8 vented
- What measures are need to increase safety margins:
  - Capture plate G10 material switched to Macor
  - Insulating interstitial material
  - Vaporizing heat sink



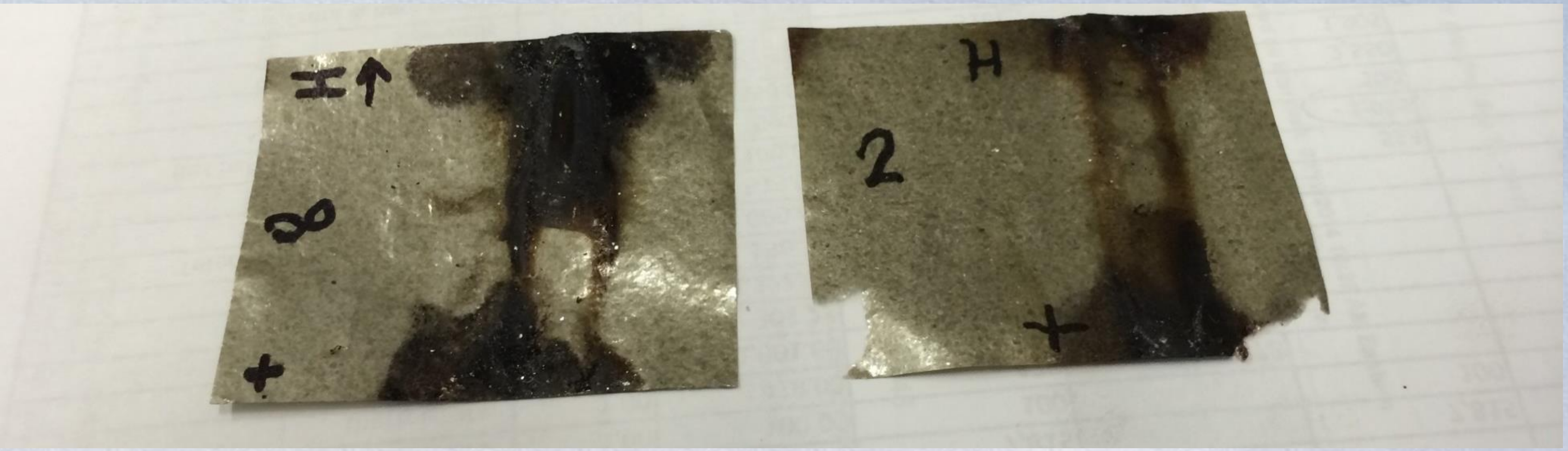


Fuse (+) on Trigger Cell Blows



63 seconds after heater is turned on and is bright for 3 seconds on video

Cell Mica Paper Wrap Heat Affected Zones

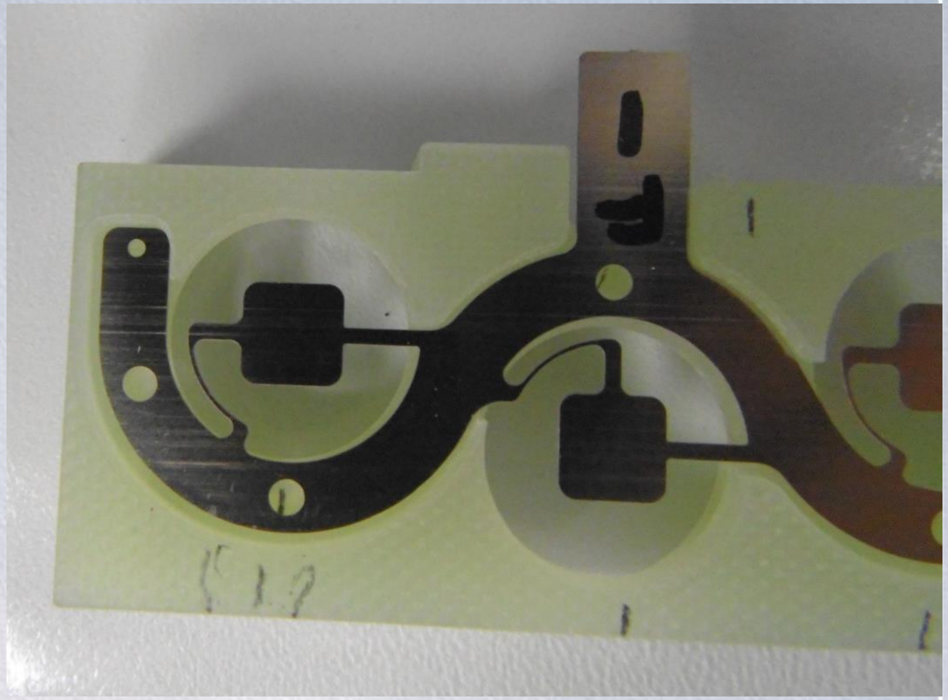


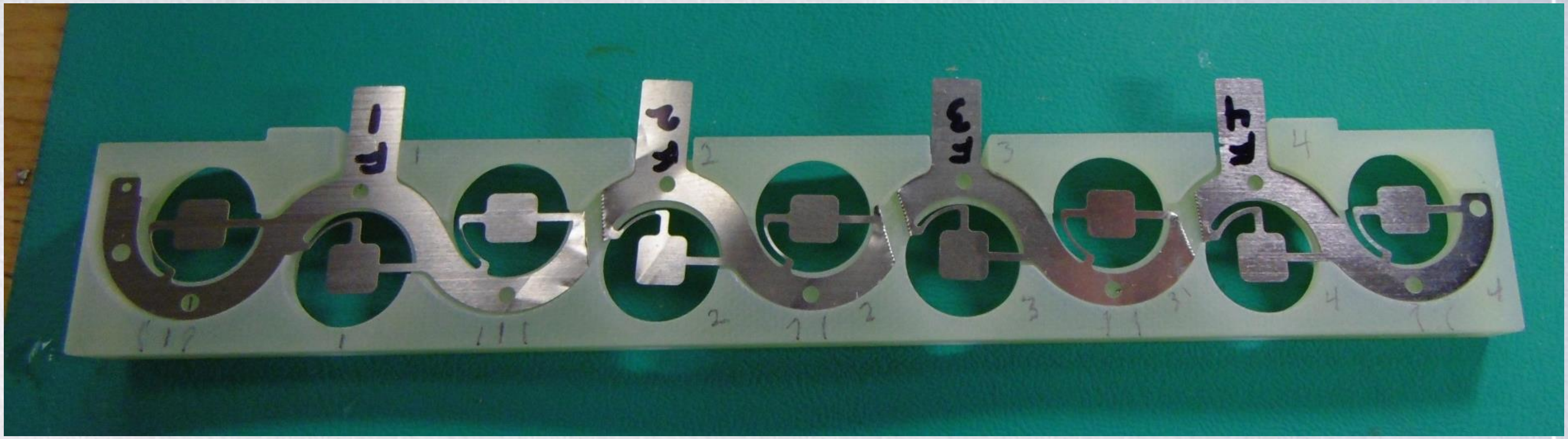
Adjacent cells 8 and 2 showing significant heat affected zones

- Burn marks indicate cell 8 was more impacted than cell 2 bottom near heater:
  - Suggest that our heater edges may be too close to the adjacent cells
  - Moving to a single 45W heater (1”x0.5”) placed on bottom side of trigger cell opposite the adjacent cell
- Burn marks on top of the mica paper similar on both cells:
  - Indicates some bypass of ejecta between the cell and G10 capture plate
  - The epoxy must be melting and may need to go to a higher temp epoxy

Fusible Link Verification Test

- Use G10 capture plates to seat the Ni bus plates and weld them to cells
- Use Ni bus tabs to put specified currents for blow tests
- Test new bus plate design at relevant conditions:
  - With cells welded to the Ni bus plates
  - 0.3mm to be tested at 8A (+ 2 reps)
  - 0.4mm to be tested at 9A (+ 1 rep)
  - 0.5mm to be tested at 11A (+ 1 rep)
  - 0.6mm to be tested at 13A (+ 1 rep)





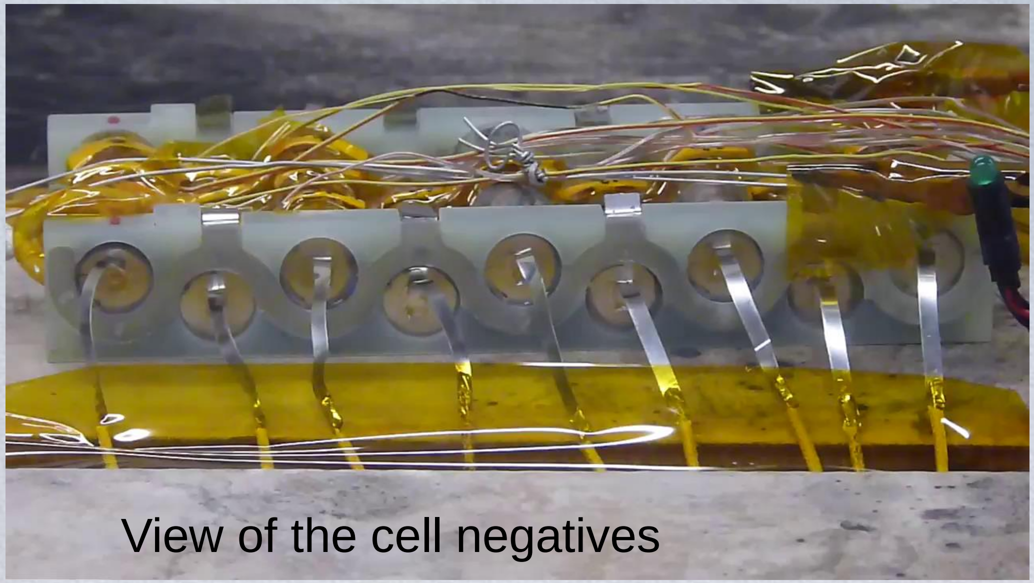
Ambient Fusible Link Blow Tests

- 0.3mm links blew at 8A in ~1s
- 0.4mm links blew at 9A in ~2-7s
- 0.5mm links blew at 11A in ~2s
- 0.6mm links blew at 13A in ~15s

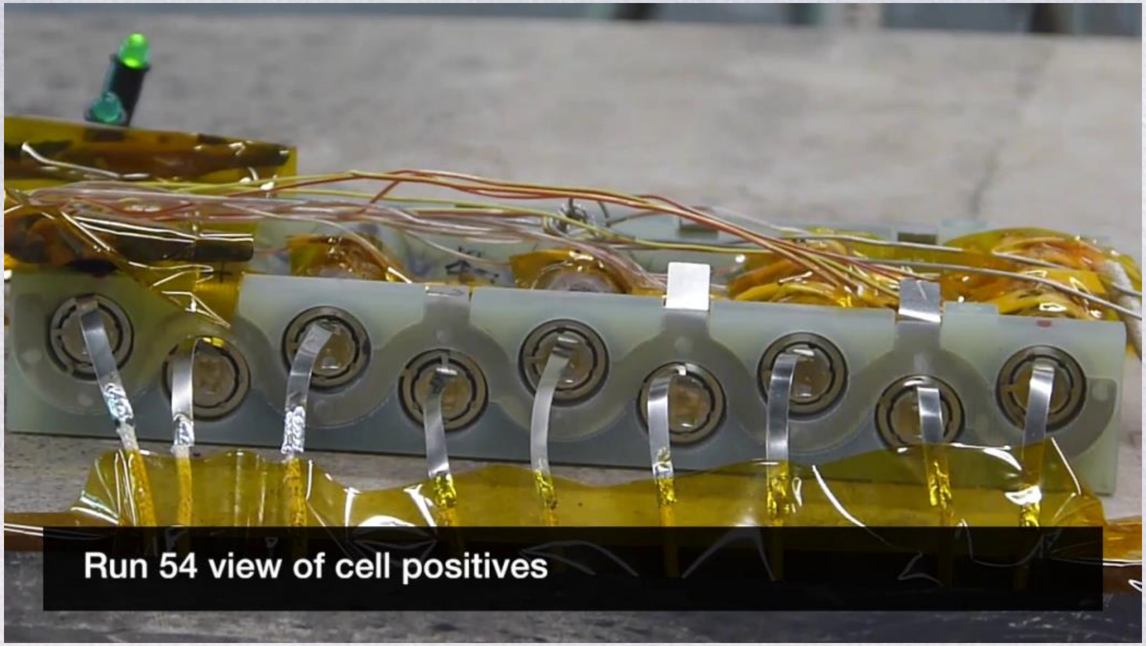
Fused open link (0.5mm)

Vacuum blow tests remain to be done

Fusible Links in Action



View of the cell negatives



Run 54 view of cell positives

- Cell voltage sense tabs routed under tile and terminated with fiberglass insulated wire
- 9P bank is immobilized with wire tie down to tile
- Heater LED functions

Notes:

- Bead of epoxy exist between each cell to promote thermal conduction
- Negative fuses are rated at 7A
- Positive fuses are rated at 8A

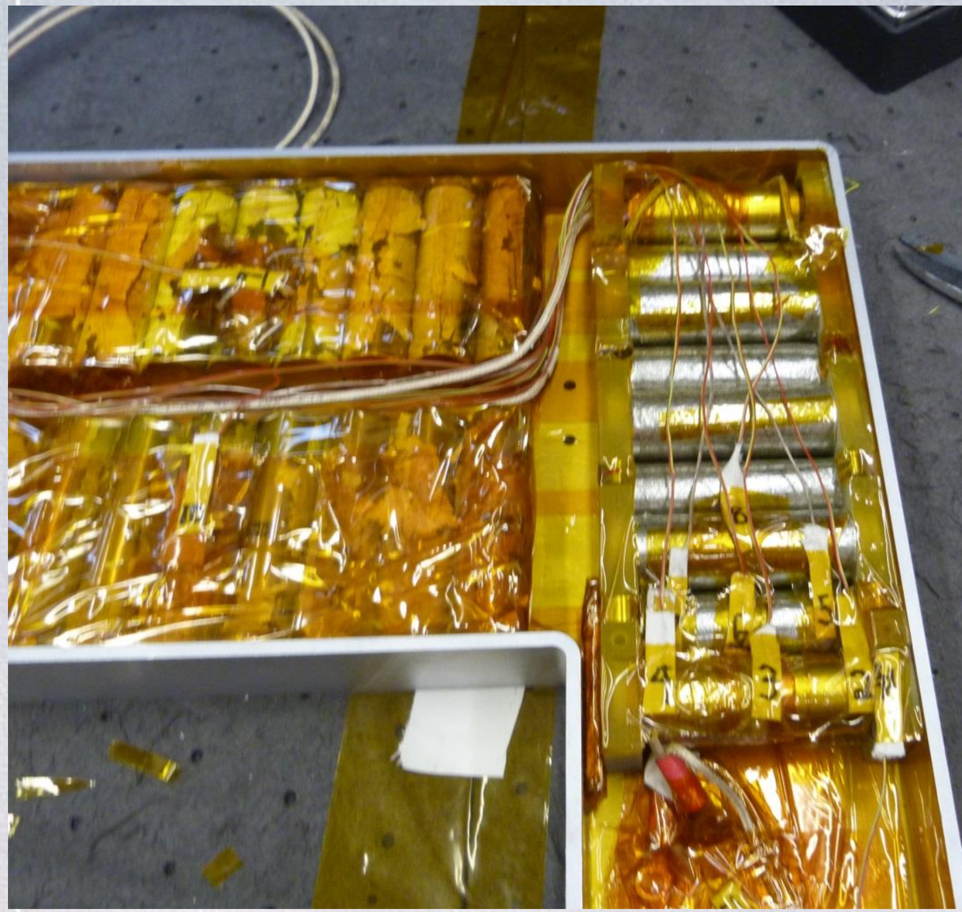
Fusible Link Test Findings

- Findings:
  - TR propagated from cell 1 to cell 7 like dominos
  - Each cell TR events was proceeded with negative fuse blowing
  - Timing of bank OCV dips coincides with video timing of fuse glowing and blowing
  - Nevertheless, we are able to deduce that short circuit currents occur during the TR propagation process and fusible links are opened and should help mitigate propagation

Lesson Learned and Next Design Iteration

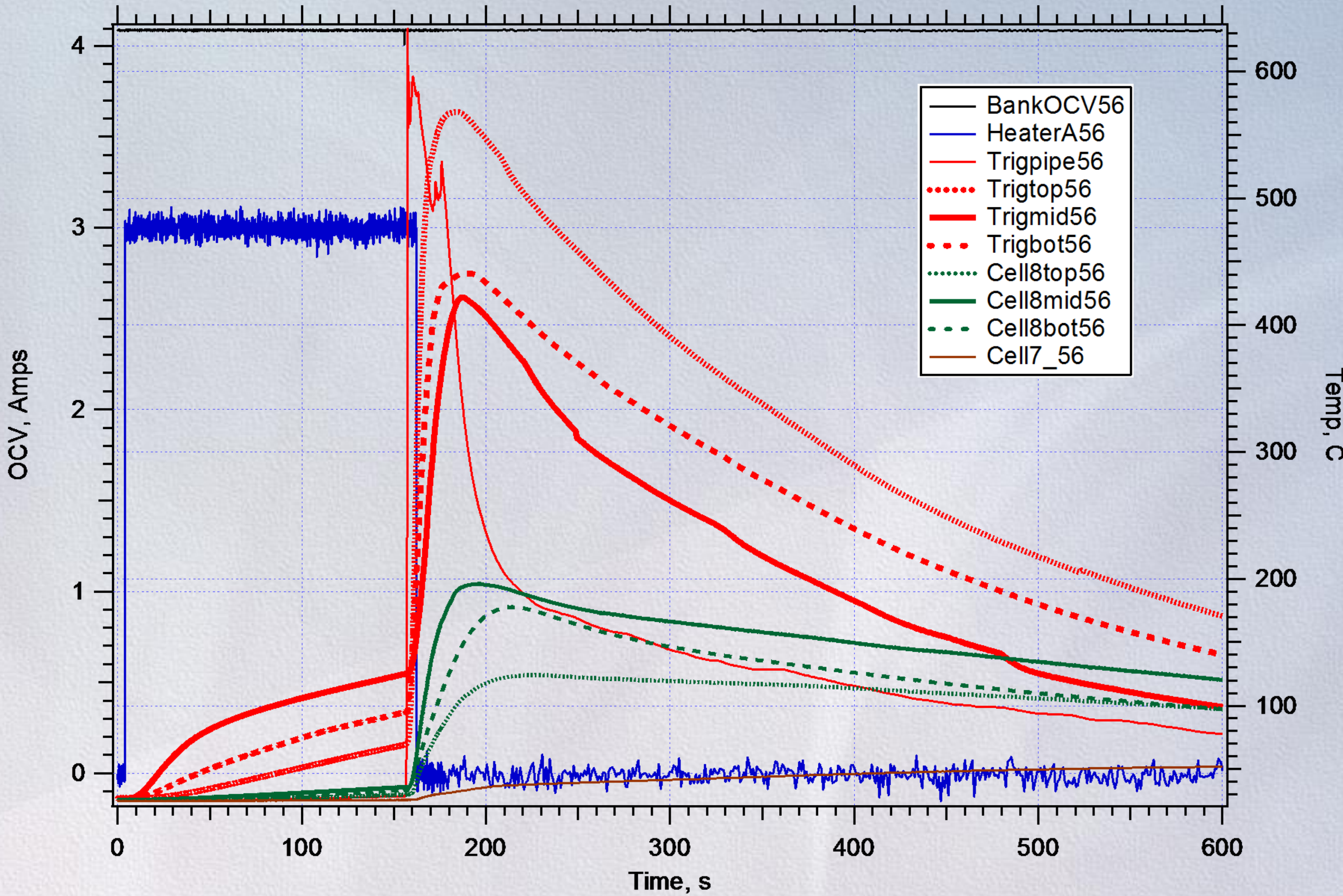
- Redesign LREBA parts
  - Locate thinner, taller heater to side opposite of cell from adjacent cell
  - Add mica half cylinder to the trigger cell to protect adjacent cell - missed
  - Use high temp epoxy to bond cells to capture plates
  - Plug all housing holes with Al foil tape
  - Route all TCs away from trigger cell
- Next run – same as previous except trigger cell 1 and add soft goods bag

Pre-Test Photos



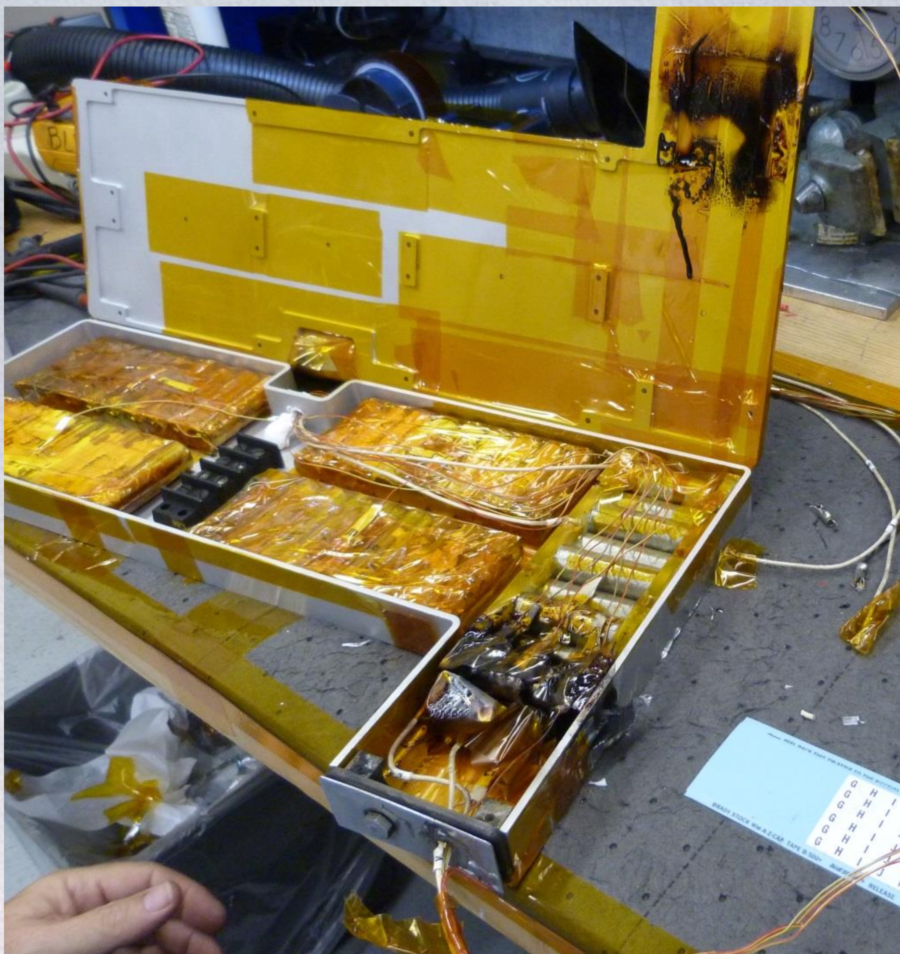
- High temp ceramic putty for gluing cells to capture plates
- TC and heater power wires routed away from trigger cell

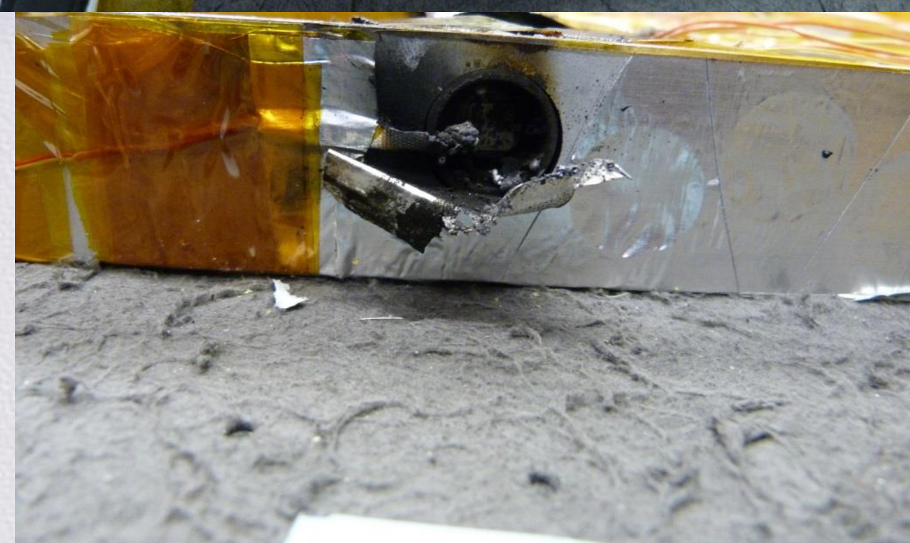
Run 56 – New Cell/G10 adhesive



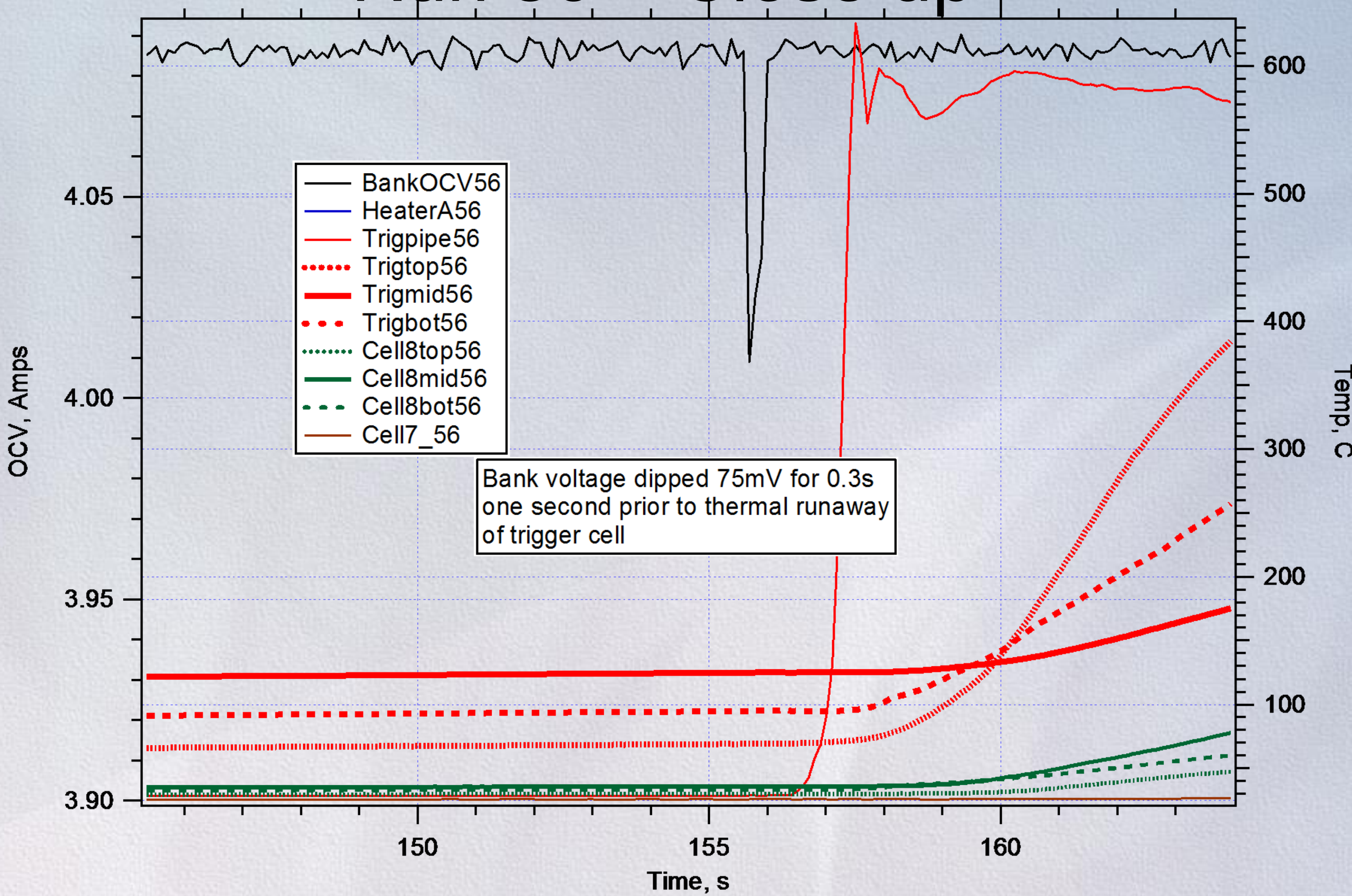
Single heater powered at 33W, caused TR in trigger cell in 153s, trigger pipe temp reached 633°C, trigger cell TCs reached 422-568°C, and cell 8 TCs reached 124-196°C, cell 7 reached 54°C

Run 56 – Post Test



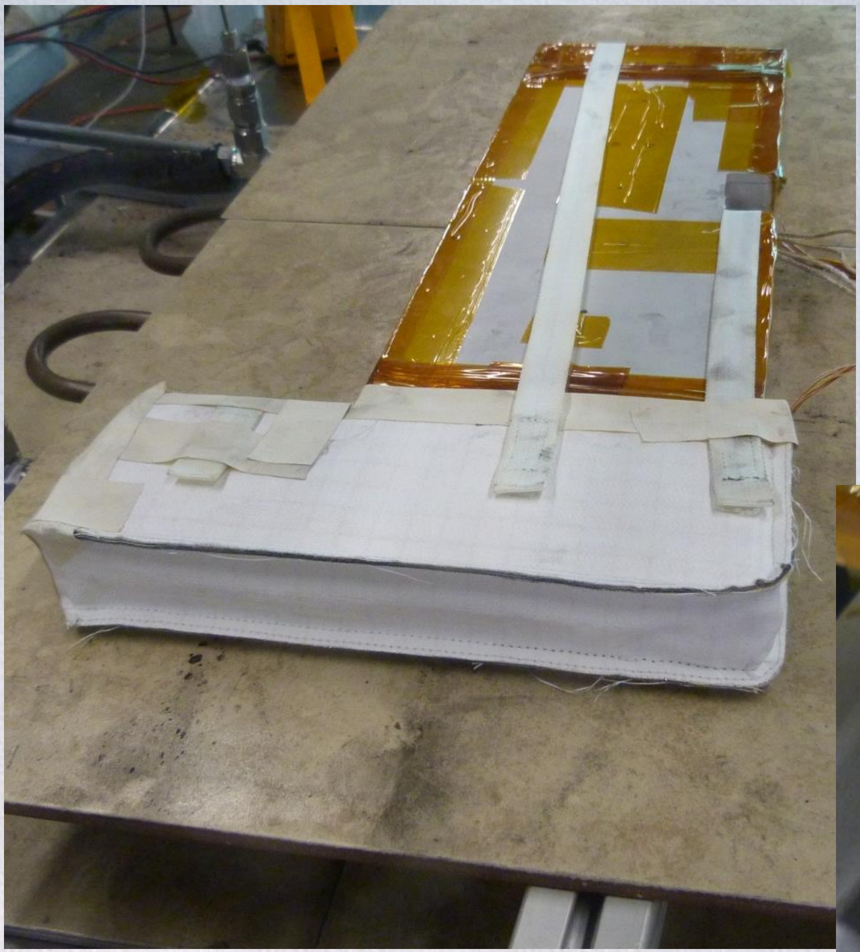


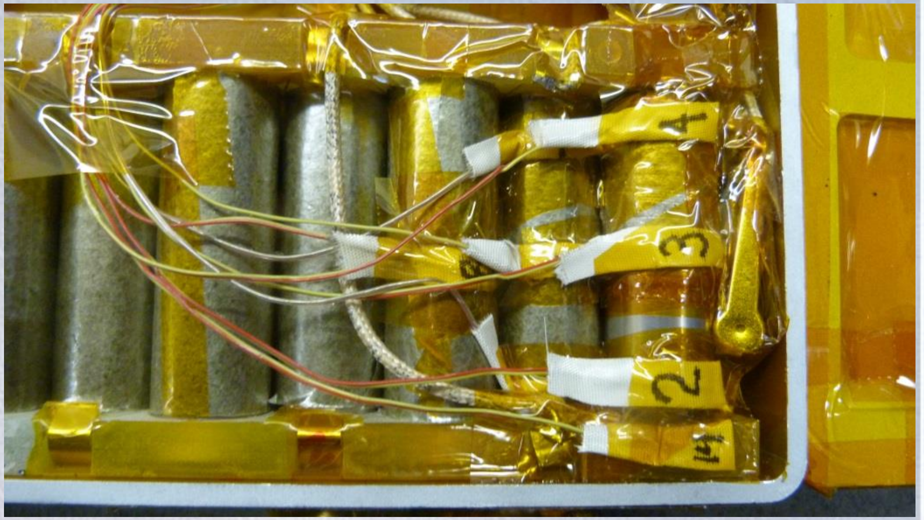
Run 56 – Close up



75 mV dip corresponds to a 10A in-rush current sufficient to blow trigger cell fuse(s)

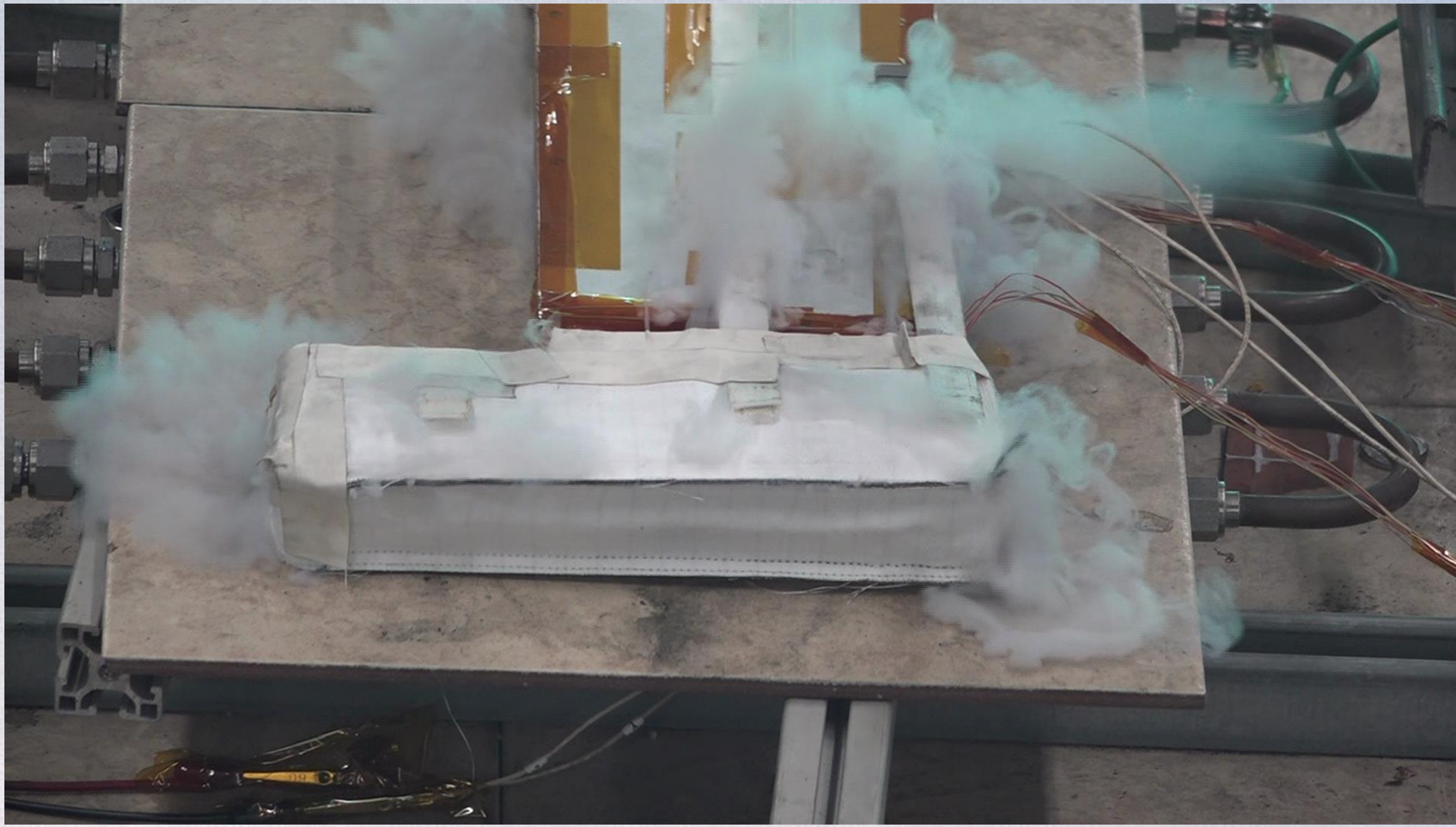
Next Run – Pre test



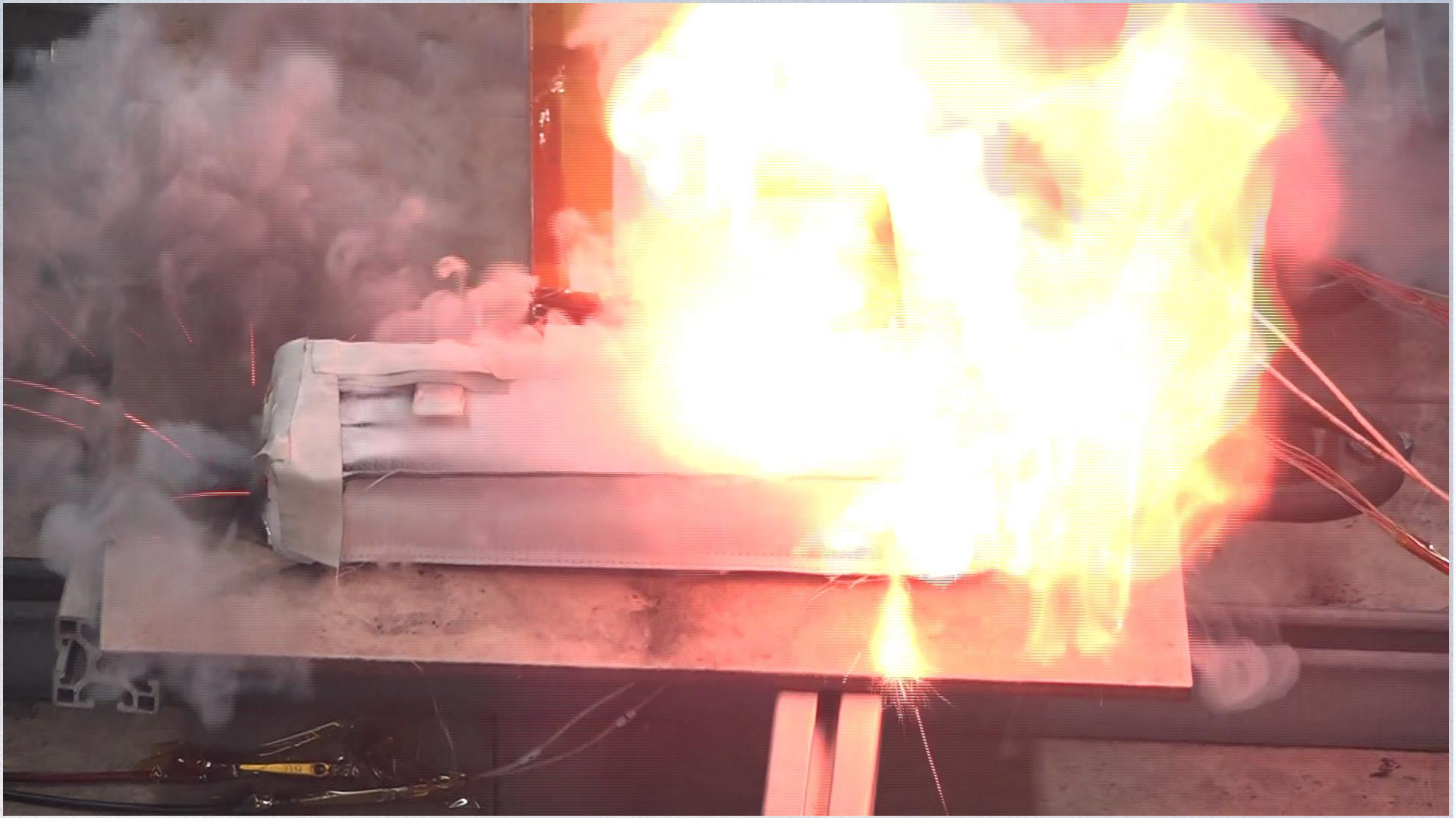


Soft goods bag added to dog leg of the battery

Trigger Cell Vents Smoke/Electrolyte



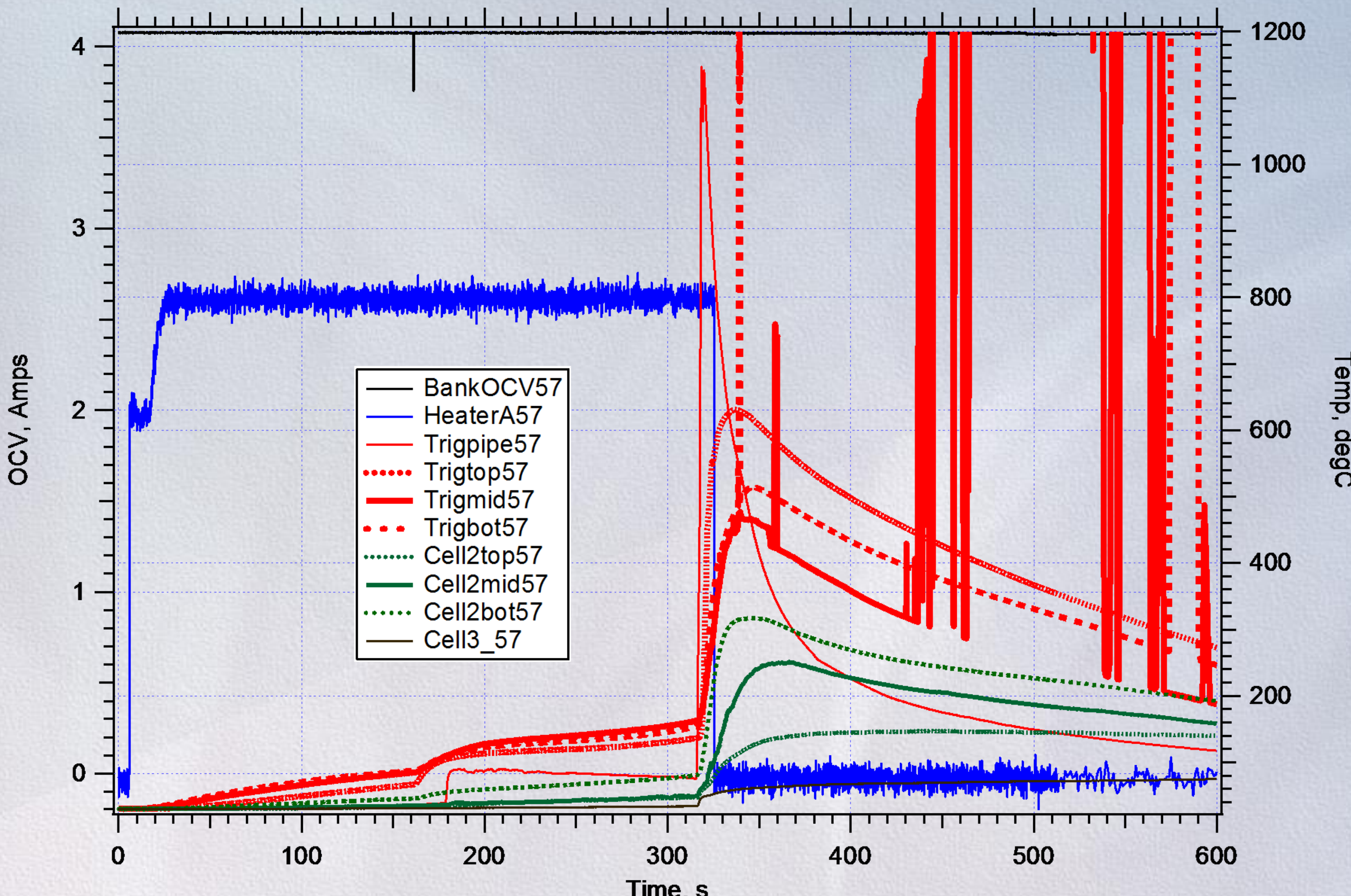
1s later, Instantaneous fireball with sparks



After 2s, Flaring

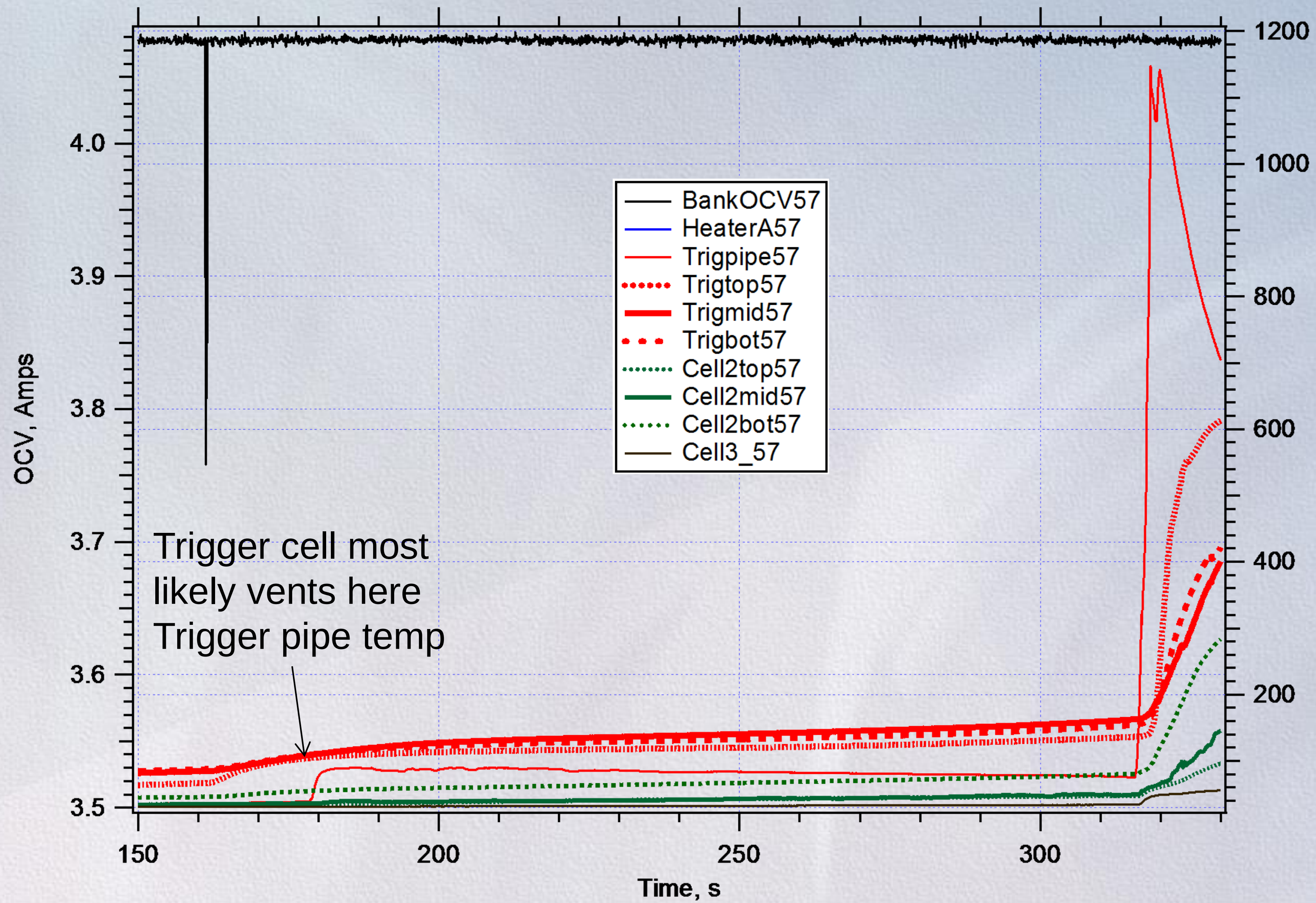
Flaring lasts for 3s, then small flame for 15s
20s from smoke vent to flame out

Overall Plot



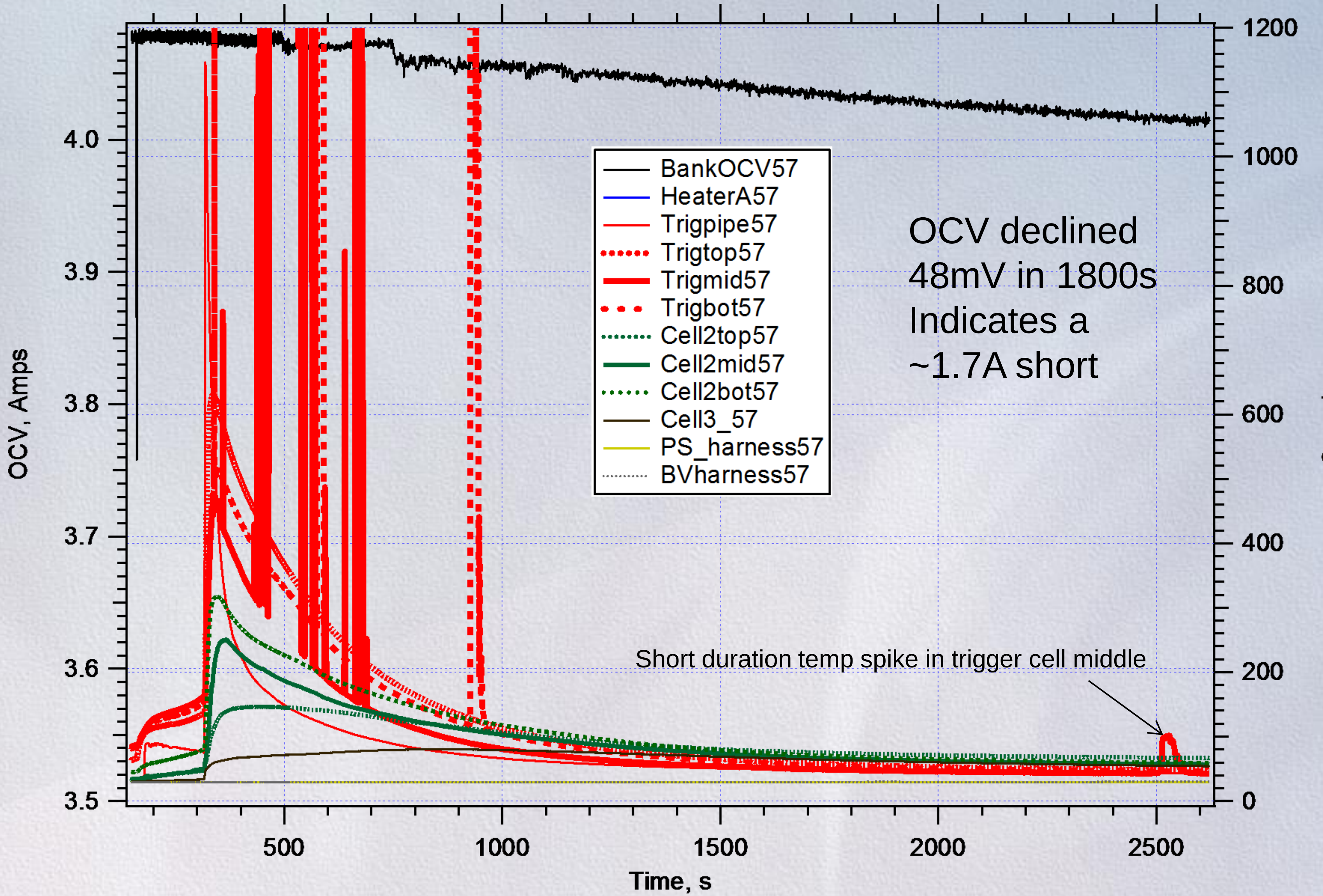
TR of trigger occurs 310s after heater on. Trigger cell max temp range from 474-631C. Cell 2 max temp range from 147-317C. Cell 3 max is 80C 600s after heater on. Trigger pipe max is 1146C.

Close Up on Short



Bank is shorted 155s after heater on, causes 8 cell bank to dip to 3.758V for 0.3s, corresponding to a 37A short fed by 7 good cells (blowing neg fuse of trigger cell)

High Impedance Short Bleed Banks

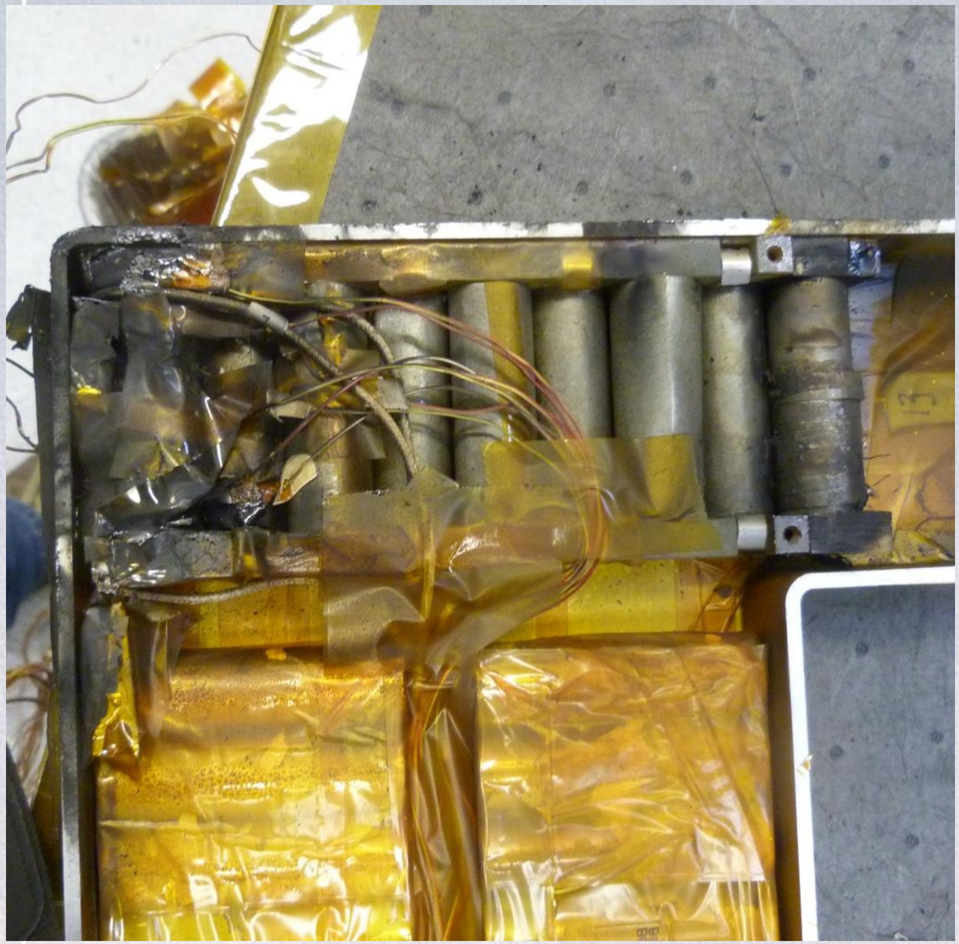


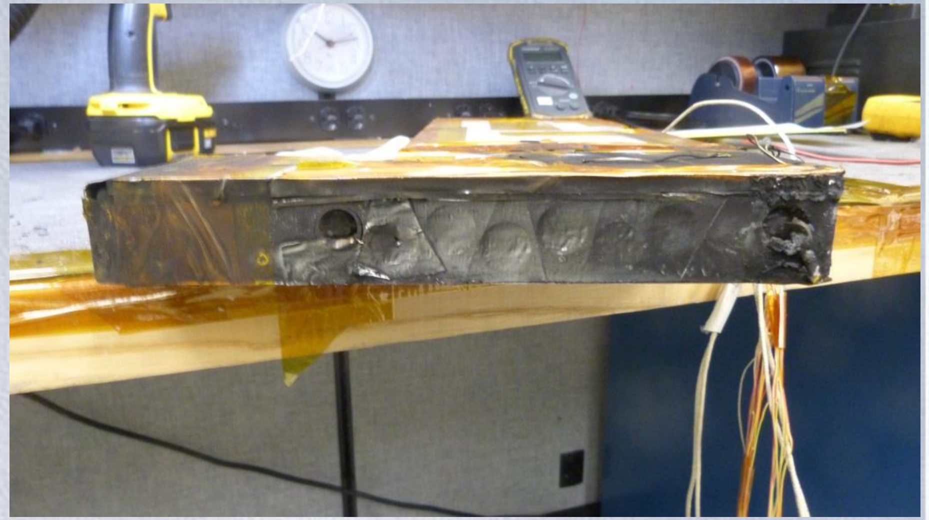
Bank at 0.27V by noon the next day and cell 2-8 fusible links intact

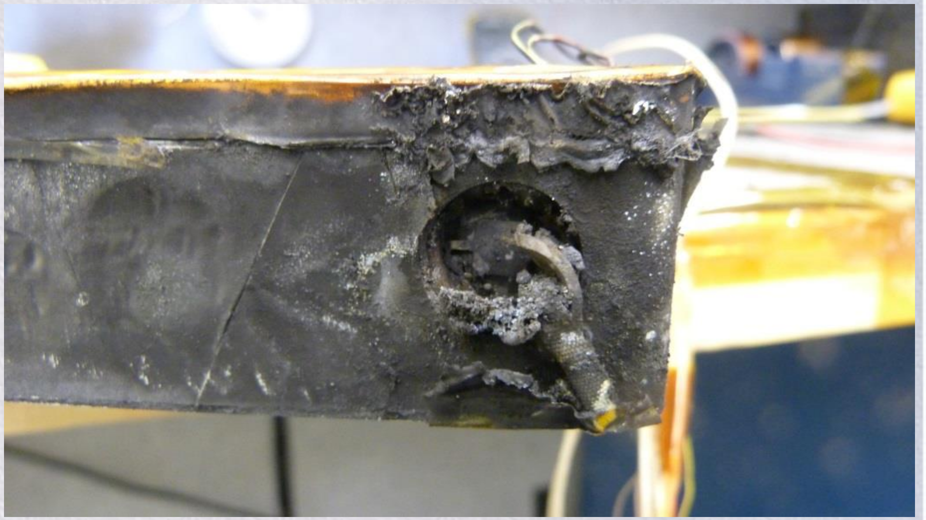
Post Test – TMG Bag

- Soft goods bag (rip stop nylon, 7 layers of aluminized mylar, and kevlar reinforced fabric) was quickly perforated by cell TR flare/flame
- Need to reinforce it with higher temperature metal foils (ex, Ni)

Battery DPA Pics





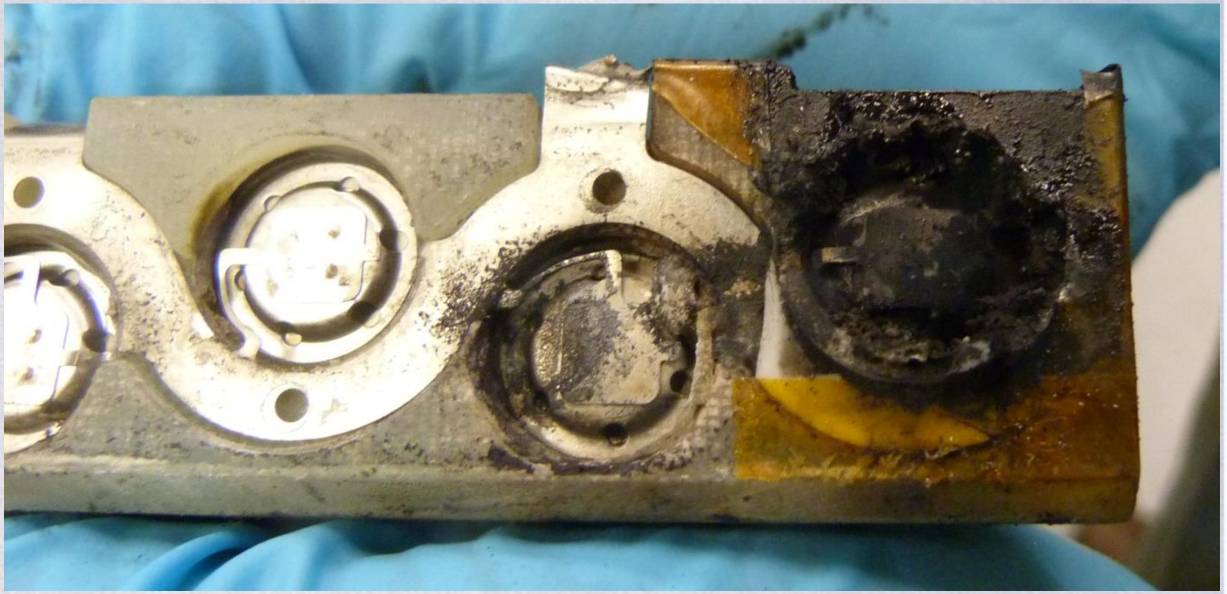


Trigger cell Macor pipe broke in pieces
No pipe on cells 2-8

Bank Examination (positive end)

Cell 1 Trigger

Intact fuse on cell 2 +
But polluted with soot



Lessons Learned To Date

- Design must prevent first TR propagation from initial failed cell:
  - Entire battery gets hotter with each subsequent cell TR event
- Limiting cell-to-cell thermal conduction appears to work:
  - Spacing out the cells ≥ 1mm is very beneficial
  - Maximizing heat conduction between cells and enclosure may also work according to modelling
- Parallel cell bussing can provide significant in-rush currents into failed cell, which gets them hot:
  - Individually fusing parallel cells is effective
- Four nearly-full scale tests with no propagation are encouraging, but more tests with reinforced soft goods bag are needed
- Managing the vent/ejecta path is critical:
  - Combustion of expelled electrolyte must 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 is needed
- Subscale test results can be misleading and no replacement for full scale test verifications

Acknowledgements

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