Driving Factors for Mitigating Cell Thermal Runaway Propagation and Arresting Flames in High Performing Li-ion Battery Designs

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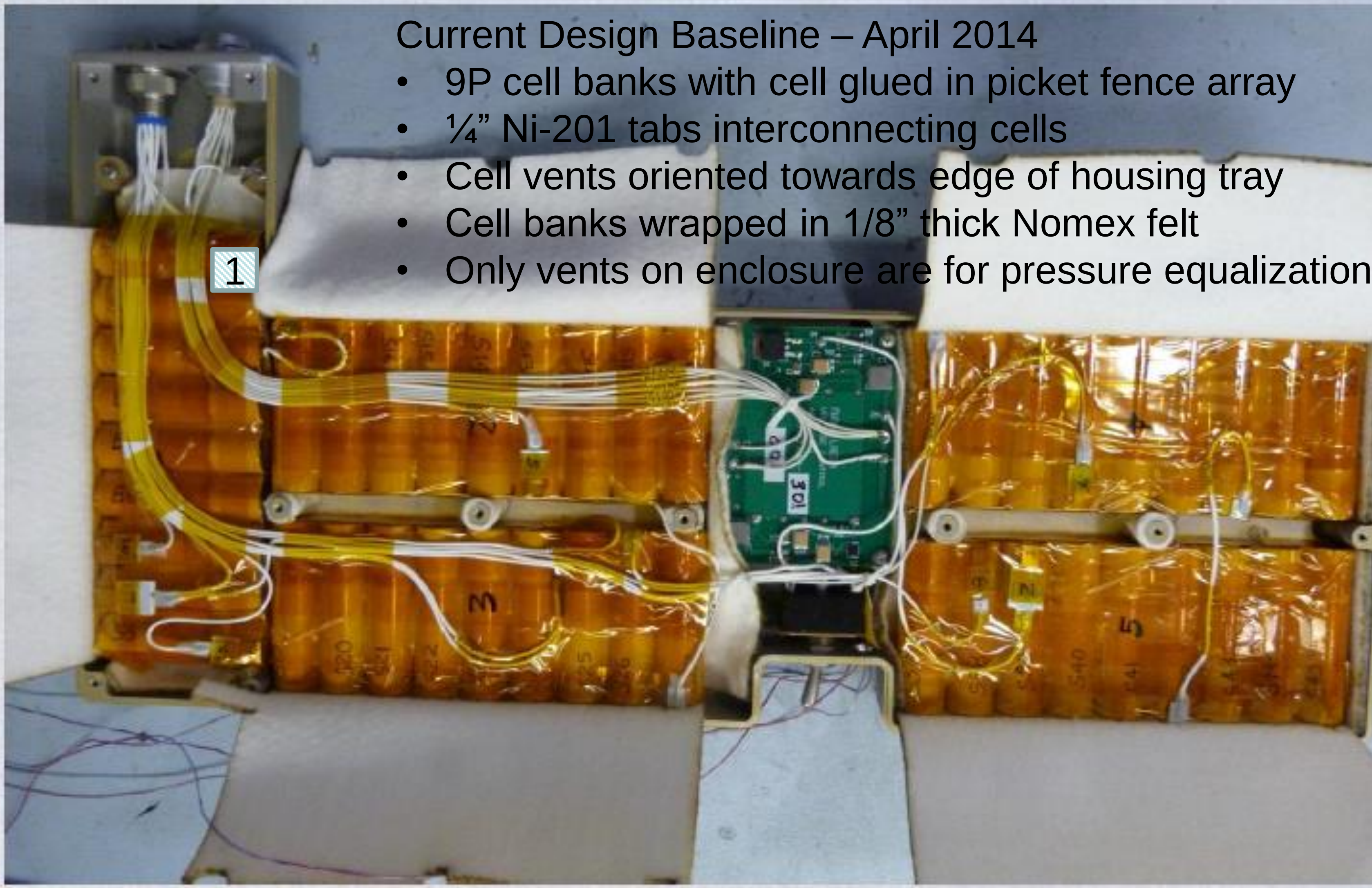
Team and Contents

- Battery Test Team (Subteam to the NESC Led TR Severity Reduction Effort)
  - Eric Darcy, Test Requestor
  - Christina Deoja, Laura Baldwin, Dereck Lenoir and Mike Salinas, Test Directors
  - Jim Rogers, Bob Bohot, John Weintritt, and Minh Tran, Battery design and assembly
  - Mark Schaefbauer, Soft Goods Design and Assembly
  - Tony Parish, Henry Bravo, Bill Holton, and Pete Sanchez, Test
- Agenda
  - Background on LREBA, LPGT
  - Single cell TR trigger method selected and why
  - Verification of subscale mitigation measures
  - Full scale LREBA with those measures leads to catastrophic hazard
  - Consequence of cell TR ejecta products for TR propagation
  - Full scale LREBA with adjacent cells protected from cell vent path
  - LREBA with severity reduction measures soft goods enclosure
  - Full scale LPGT baseline “CDR” design leads to catastrophic hazard
  - Full scale LPGT with severity reduction measures works
  - Summary conclusions – No propagation with no flames/sparks is possible with minimal mass/volume penalty

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

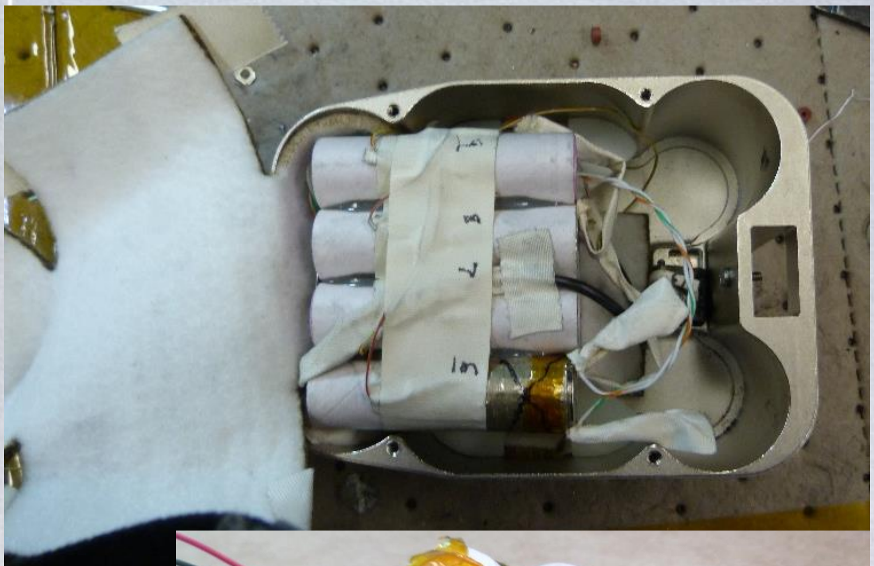
Current Design Baseline – April 2014

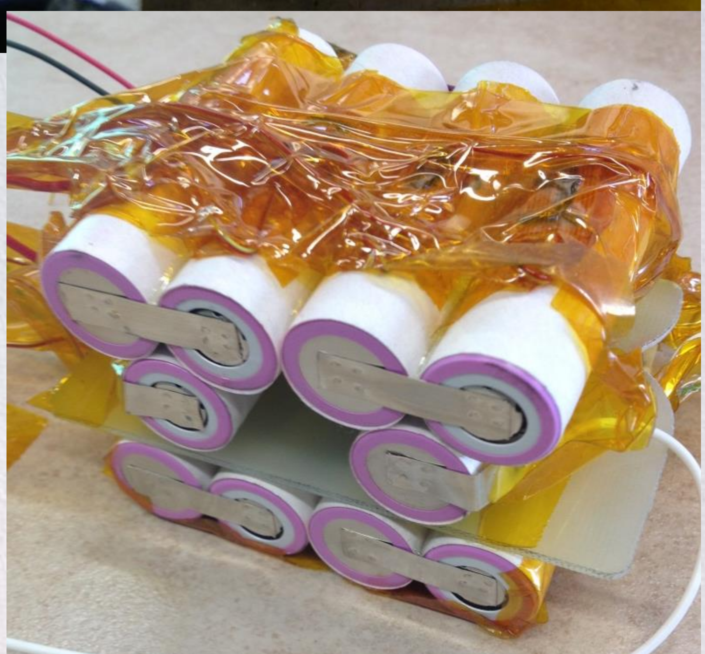
- 9P cell banks with cell glued in picket fence array
- ¼” Ni-201 tabs interconnecting cells
- Cell vents oriented towards edge of housing tray
- Cell banks wrapped in 1/8” thick Nomex felt
- Only vents on enclosure are for pressure equalization



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

LPGT "CDR" Baseline Design



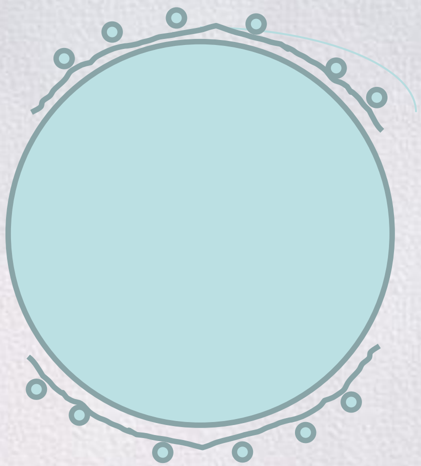


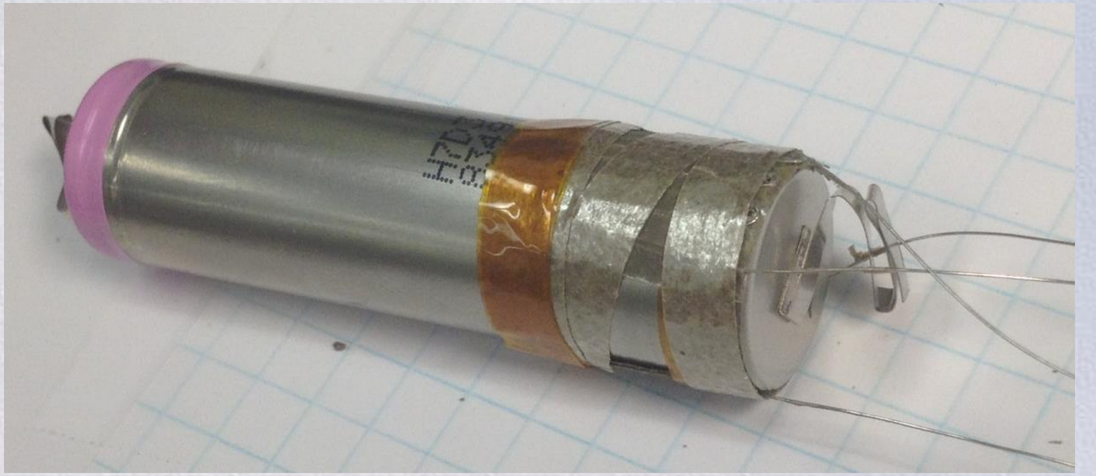
Baseline Design Features (April 2014)

- 10S array for discharge into Tool
- 2P-5S array for charging
- Cells wrapped in PVC shrink wrapped and Nomex paper tube sleeve
- Cell glued together in contact with epoxy
- ¼" wide Ni-201 tabs (0.005" thk) for cell interconnects
- No battery vent

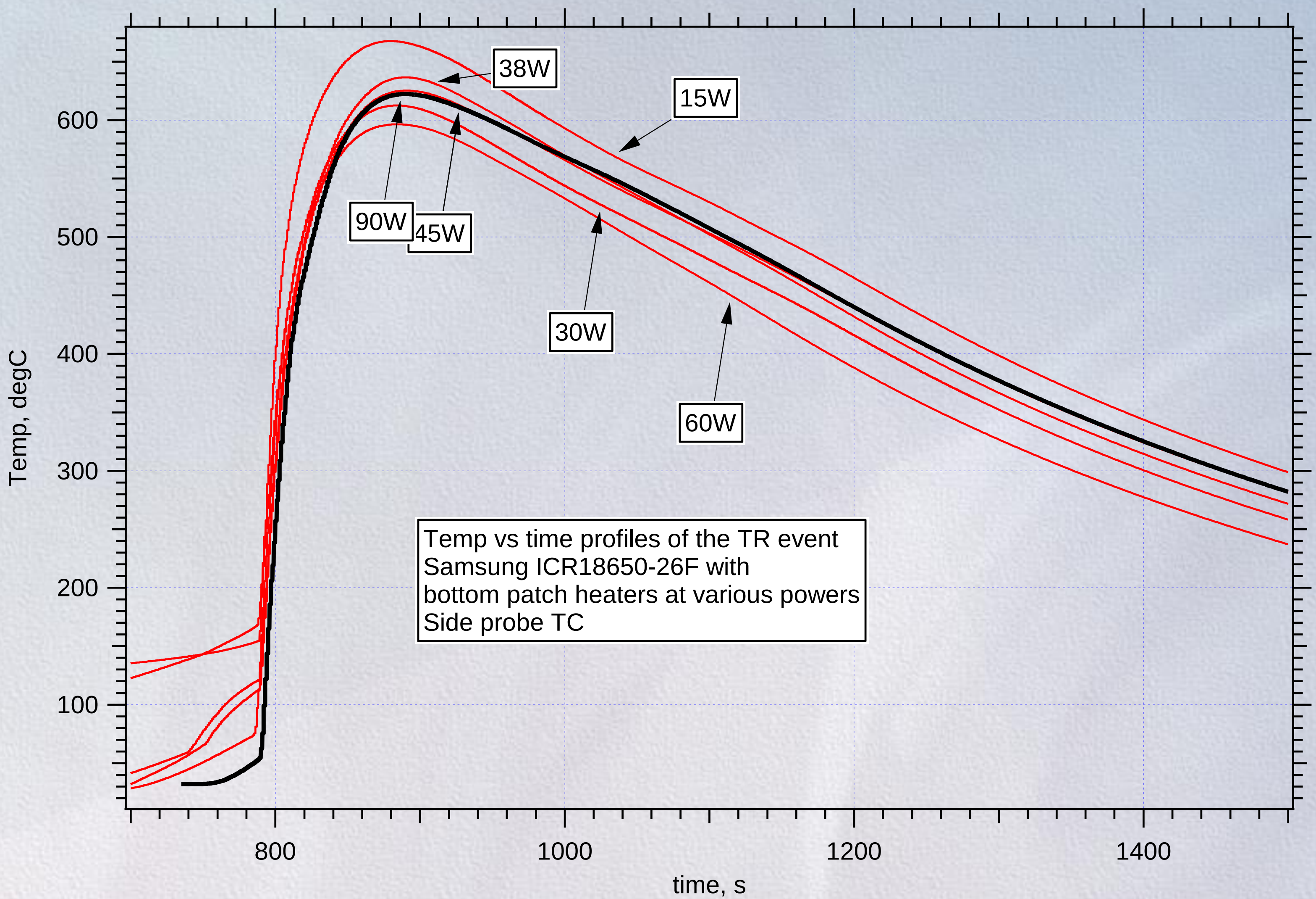
Selected Bottom Patch Heaters For Triggering TR

- 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



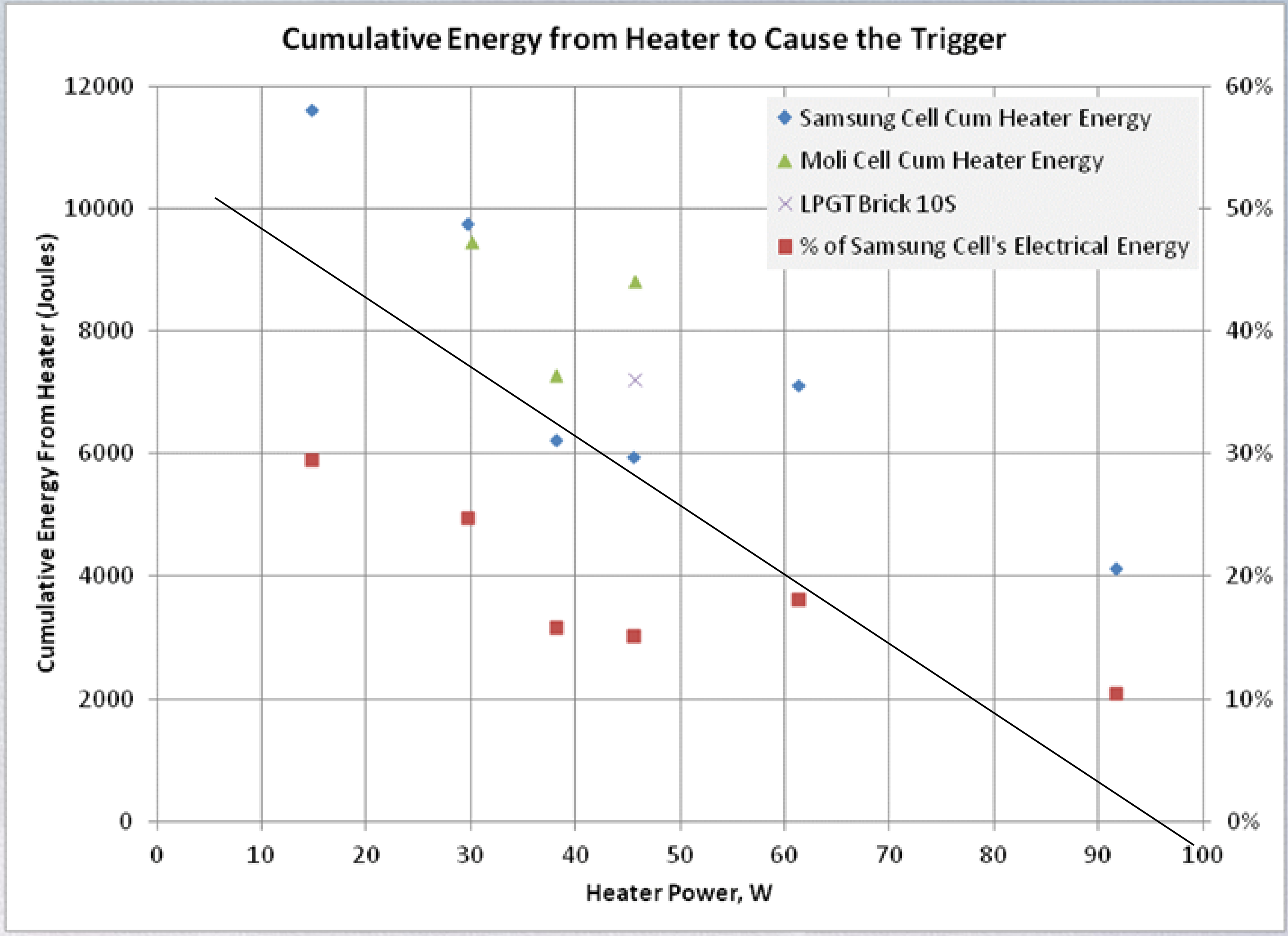


Cell TR Response vs Heat Power



- 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

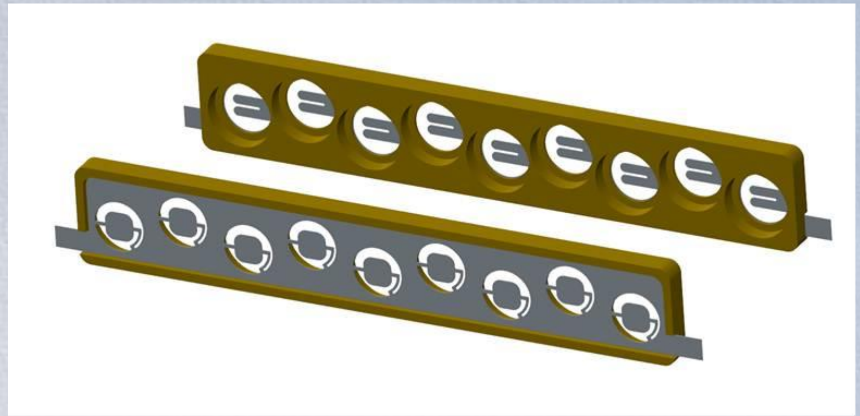
Lower Energy, Wh, input into the heater presents lower risk of biasing adjacent cells

LREBA 9P Bank Test – Baseline Design

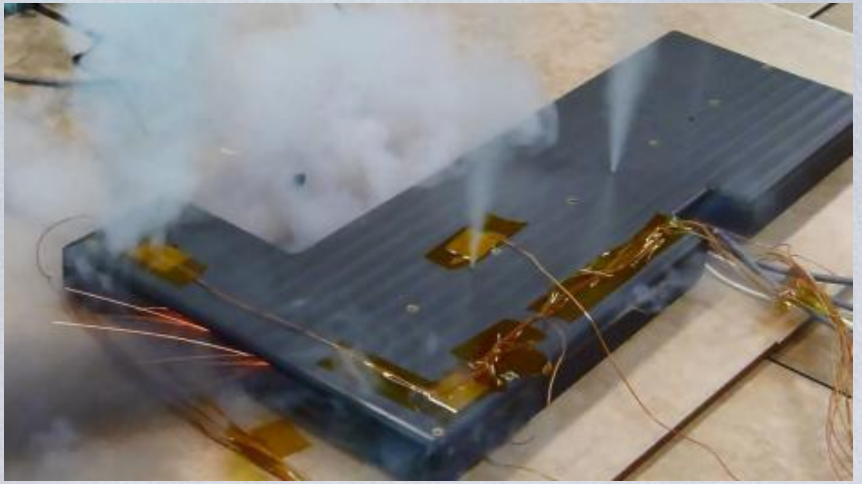
- Picket fence 9P bank with cells in axial contact and with epoxy bond line between cells
  - End cell trigger with 45W
  - Open air environment
- Full cascade of cell TR propagation in about 10 minutes

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 (electrolyte & solids)
- 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 due to flammable ejecta impinging on adjacent cells



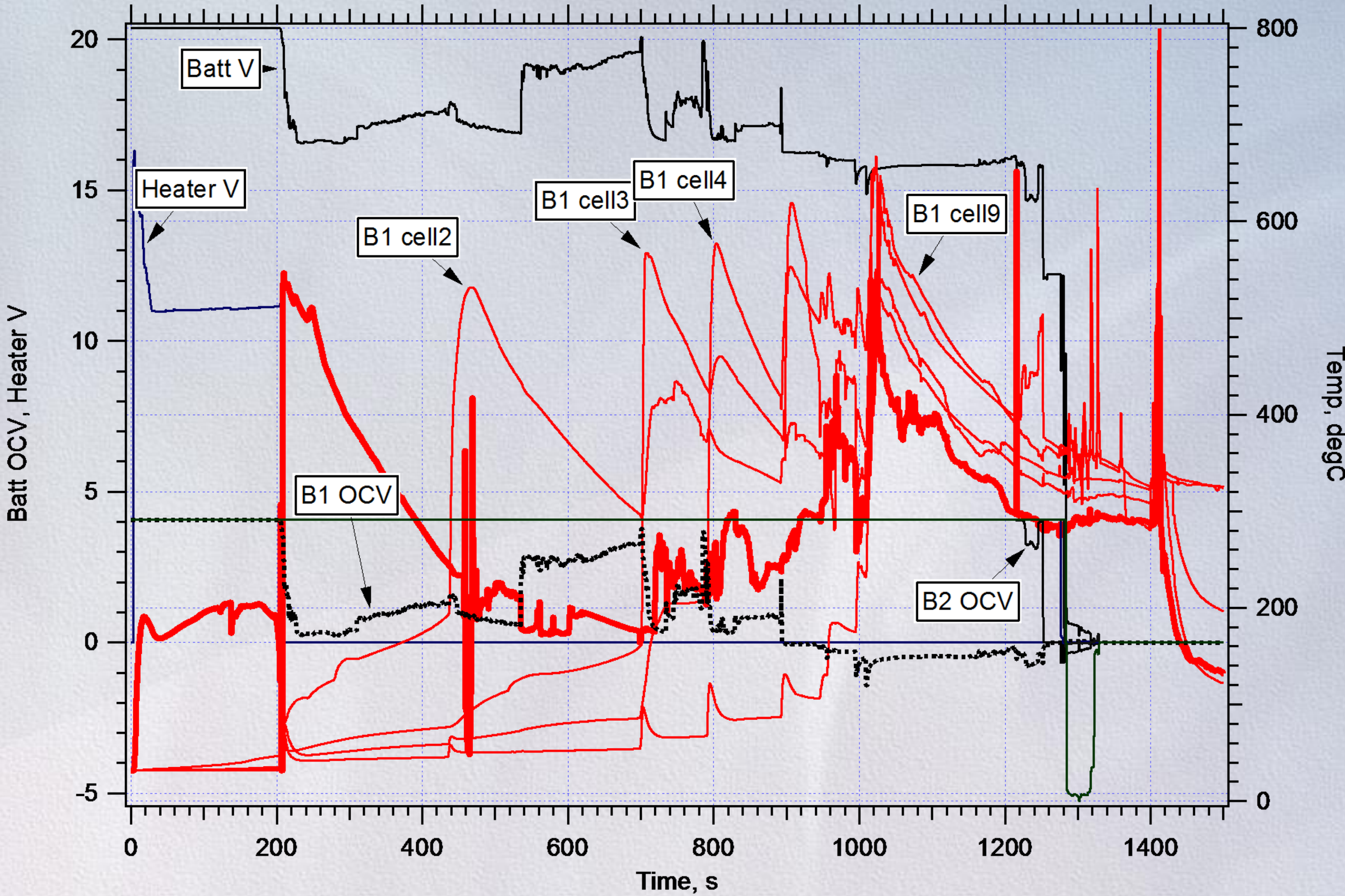
1st Full Scale LREBA Test



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

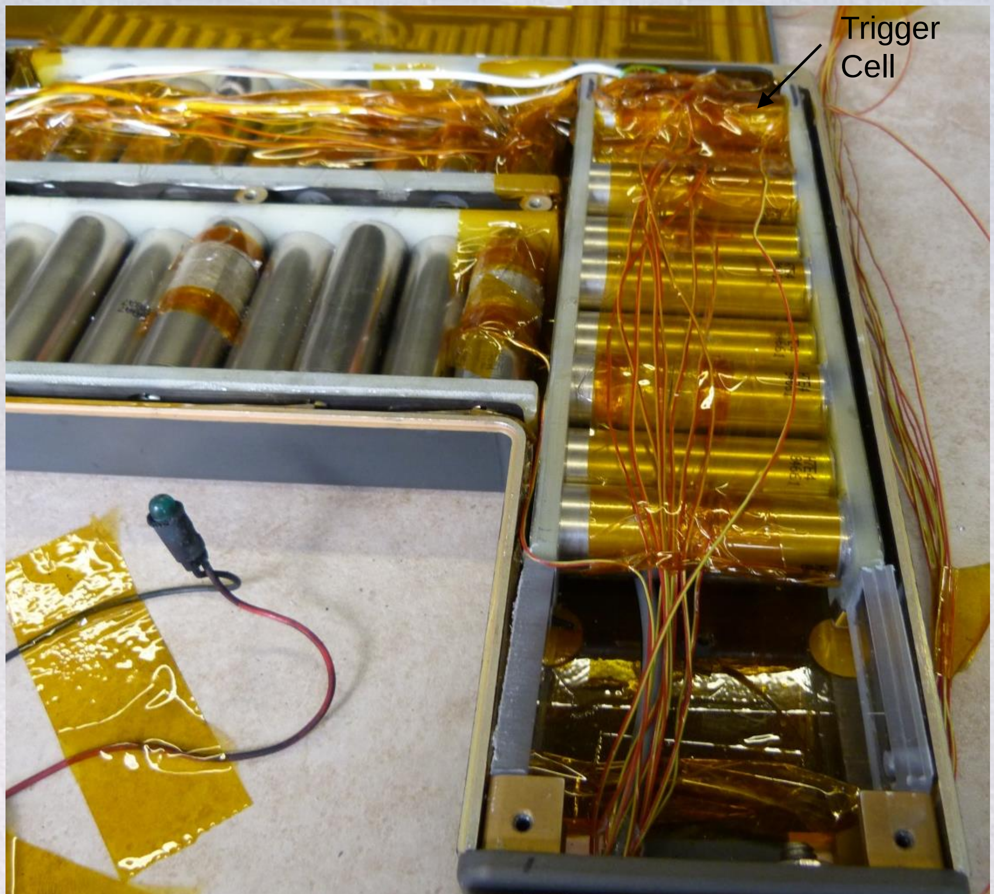
- T=30:28 min – During full TR Propagation
- T=34:00 min – Final TR

Bank 1 experienced a sustained short immediately after TR of trigger cell

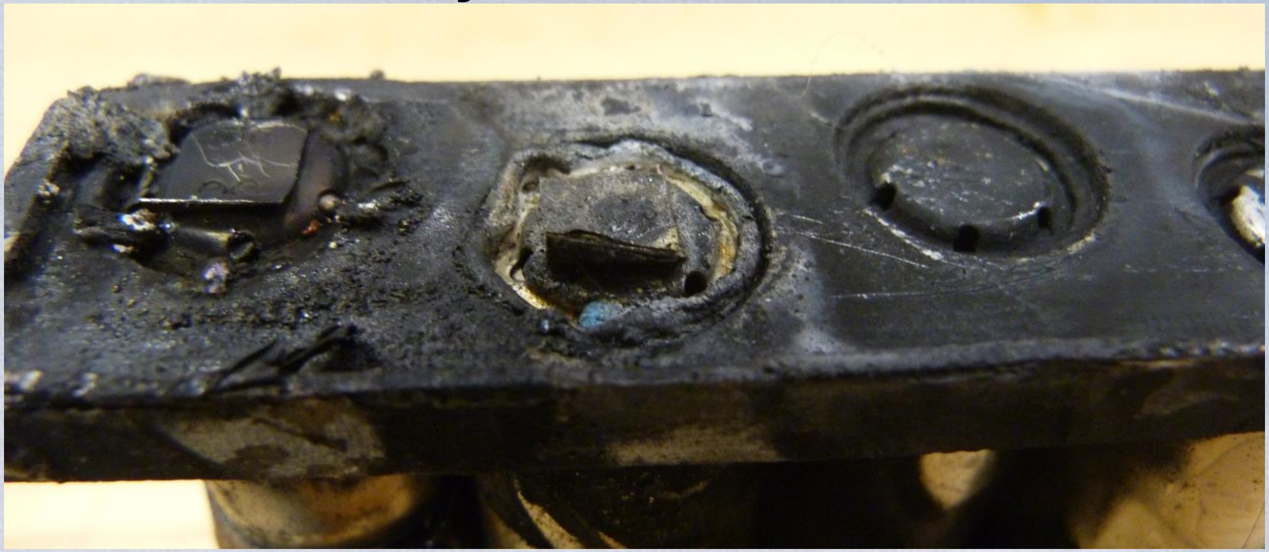


1st Full Scale Battery Test – Total Propagation

- End cell in corner of dogleg was triggered.
- All 45 cells went into TR over 29 minutes.
- *4.5 minutes 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



Cell TR Ejecta Assessment

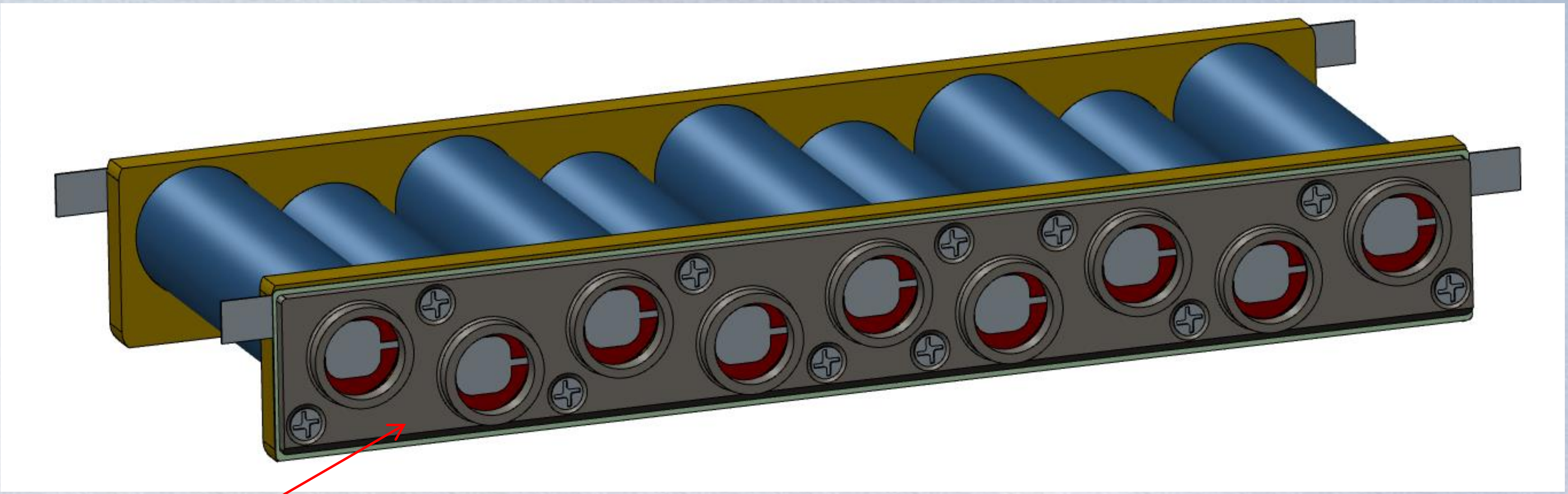


- Trigger cell next to 0% SoC cell without bus bars and with bank inside LREBA enclosure to assess if TR ejecta can electrically bridge between cells
- Cell 2 appears to have been thermally overstressed causing its sealing gasket to melt
  - This cell definitely vented, albeit without going into TR
  - Internal gas temperatures in inside LREBA enclosure exceeded 230°C
  - All other cells, #3-9 have healthy OCVs
  - Cell TR ejecta found to be electrically conductive
- Either way, it indicates that re-design features should
  - Manage the cell TR ejecta to prevent collateral damage
  - Reduce trip current of fusible links, but more importantly
  - Fusible links are more effective on negative terminal, away from vent product path

Major Contributors to Propagation

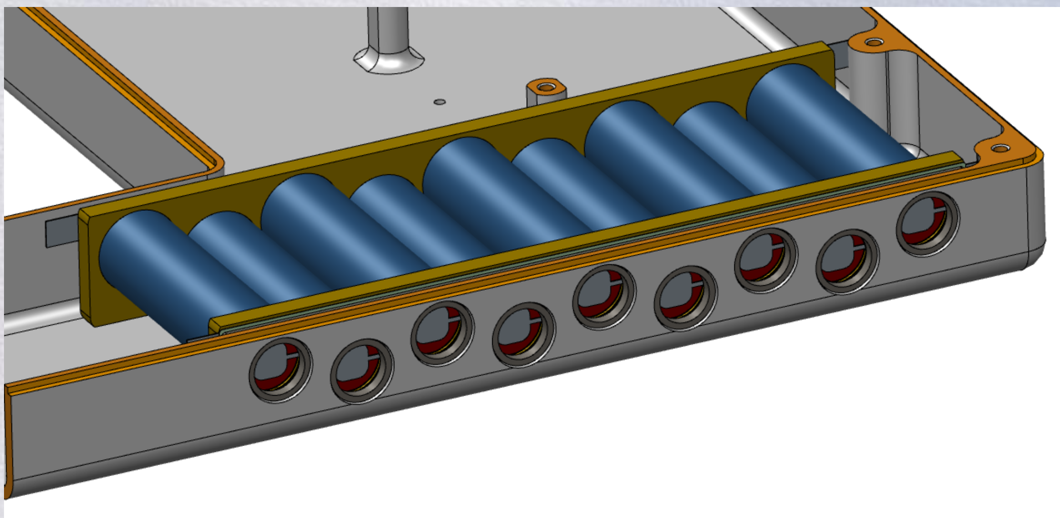
- Tests, our analysis, and other research identified three key contributors
  - Cell-to-cell heat transfer
    - Cell-to-cell conduction via contact, through structure, bonding, and electrical interconnects
    - Cell-to-cell thermal radiation found to be a contributor, but not leading
  - Electrical shorts causing adjacent parallel cell heating
  - Violent release of high temperature gas/liquids/solids (TR ejecta) with exothermic reactions
    - Bottled up in an enclosure with no place to go
- Test indicates that we must prevent the first propagation of TR, otherwise there is little hope stopping the runaway train

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



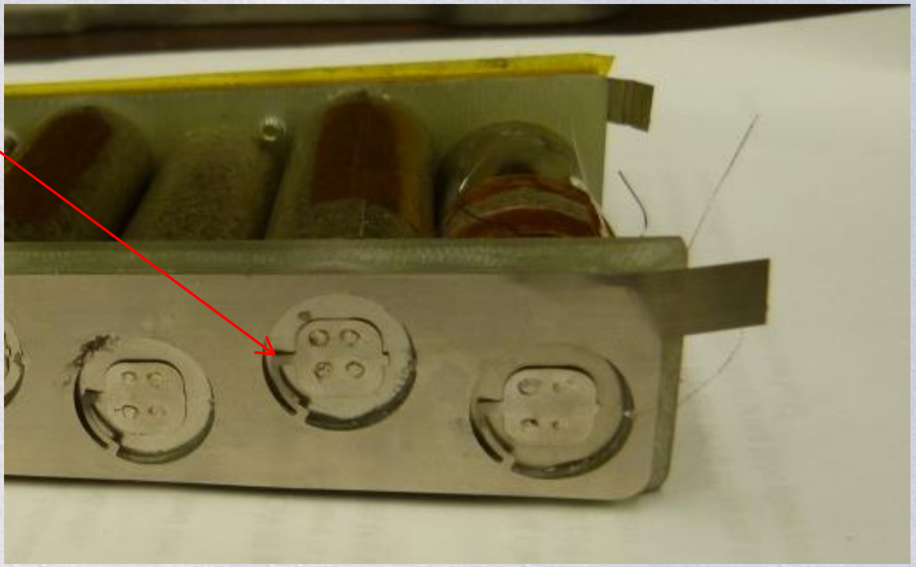
9P bank inside LREBA housing with exhaust holes

More Photos of Mitigation Features

Machinable glass ceramic (Macor®)

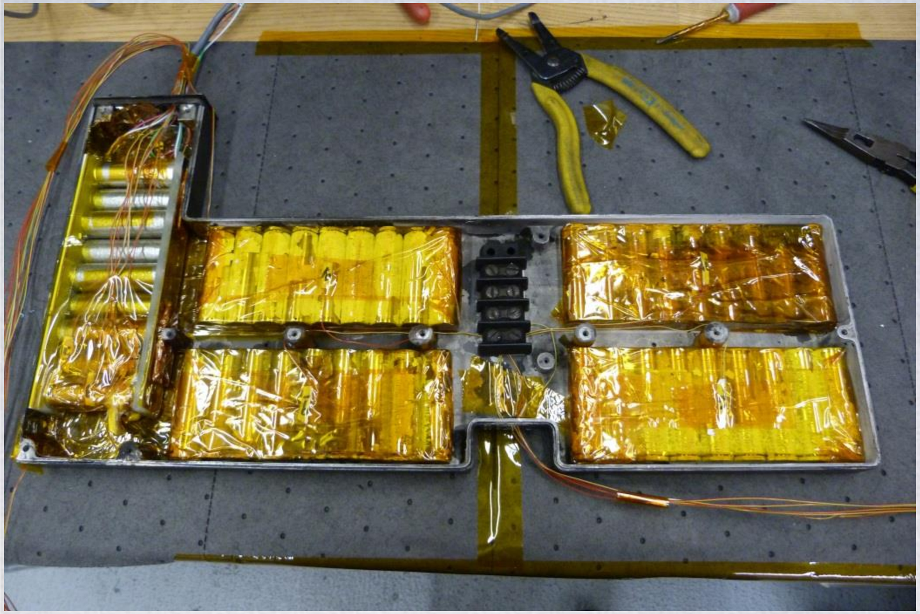
Fusible (15A) bus plates connected on both terminals

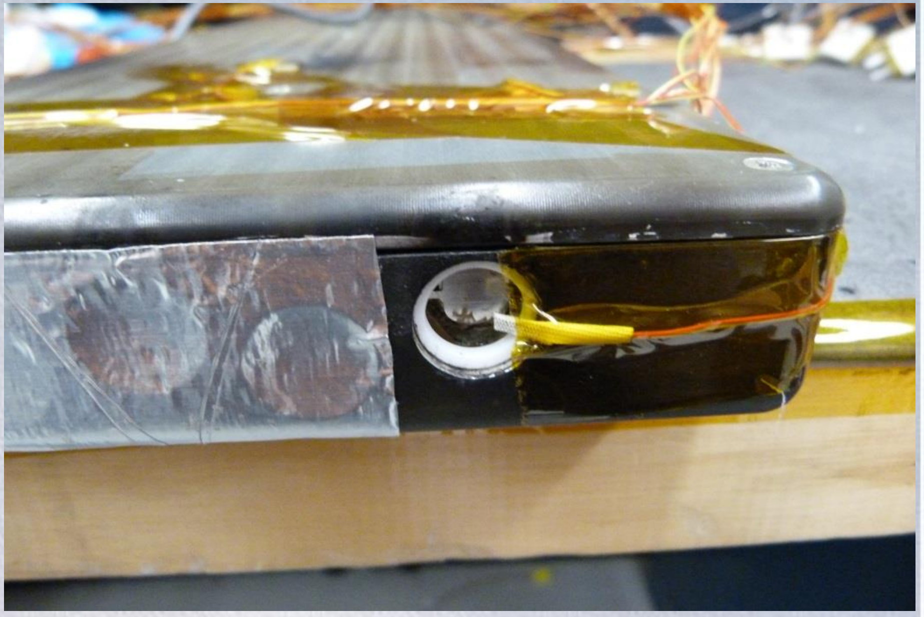
Mica paper as radiation barriers and to electrically isolate cell cans 2-8
Heater placed on end cells 1 & 9

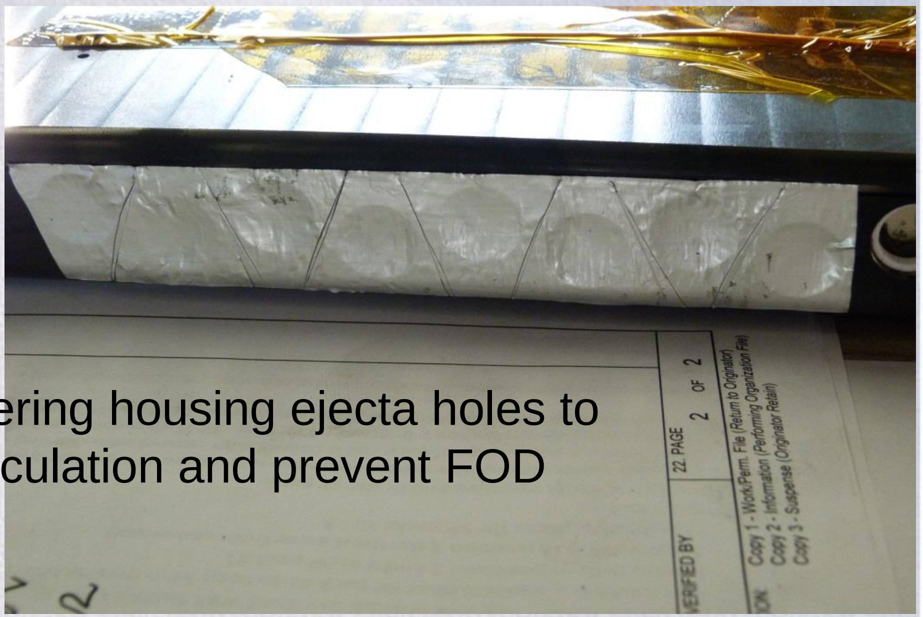


Next Full Scale Test - Pre Test Photos

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

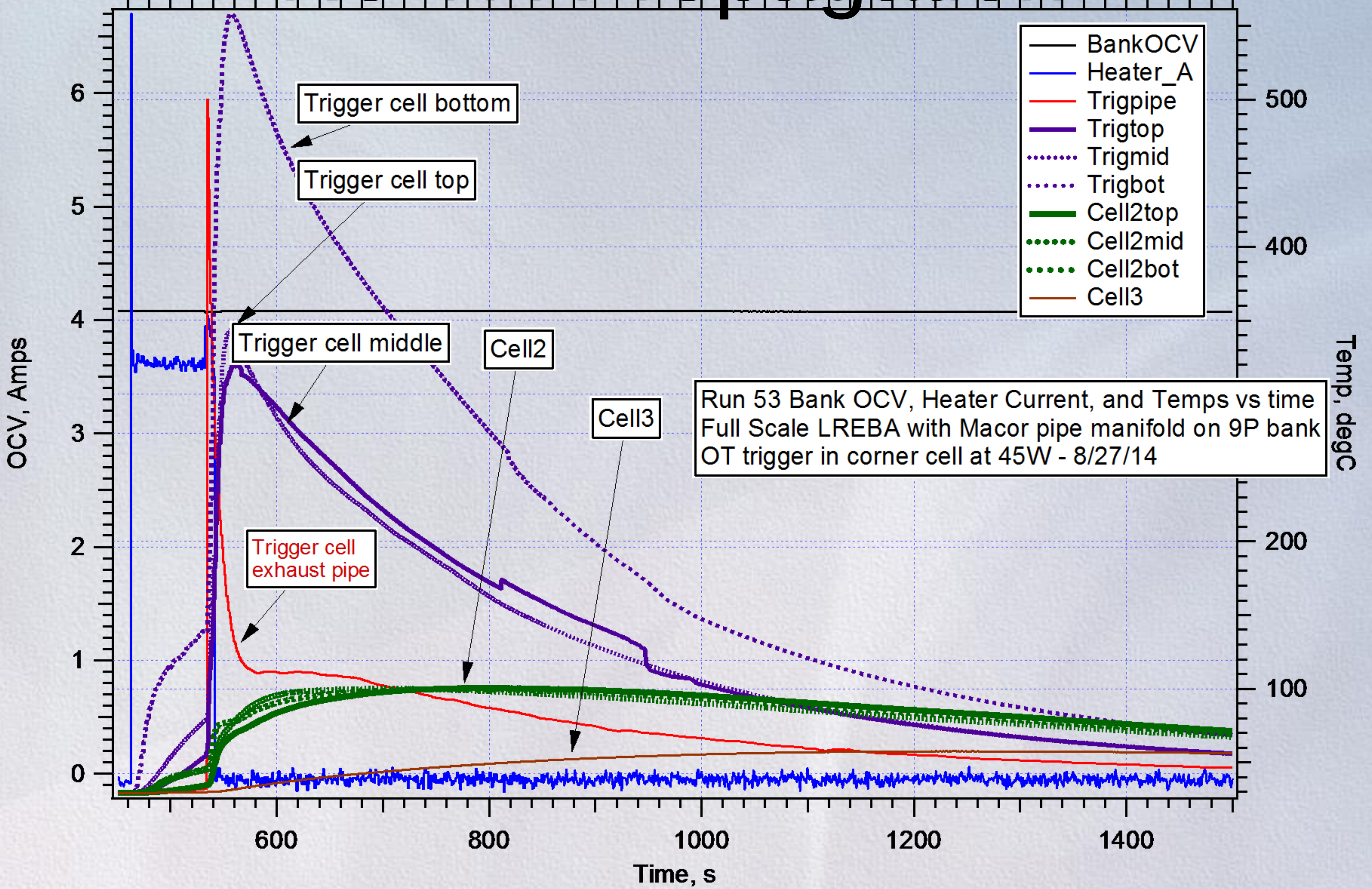






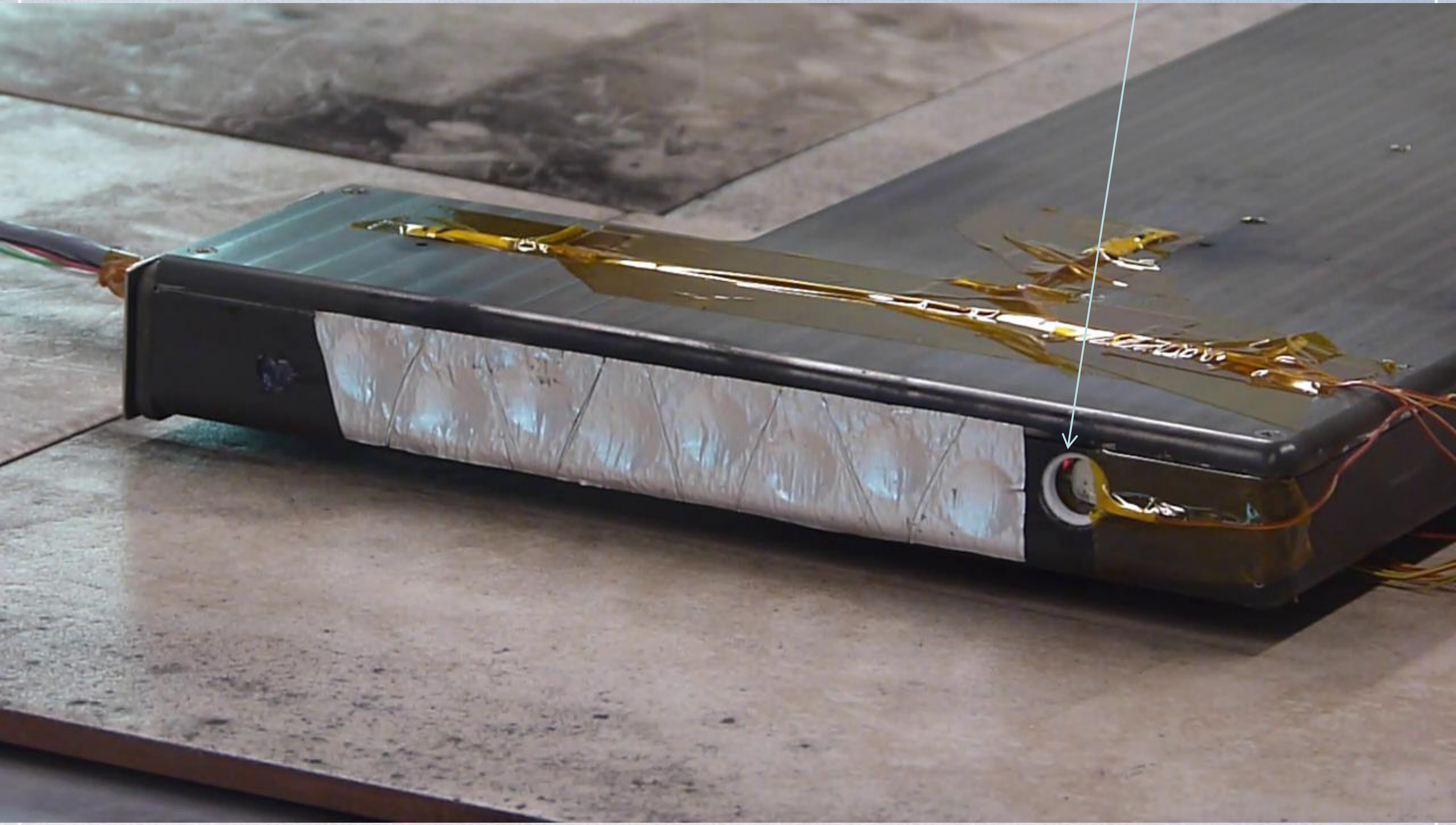
Al foil covering housing ejecta holes to limit air circulation and prevent FOD entering

No TR Propagation



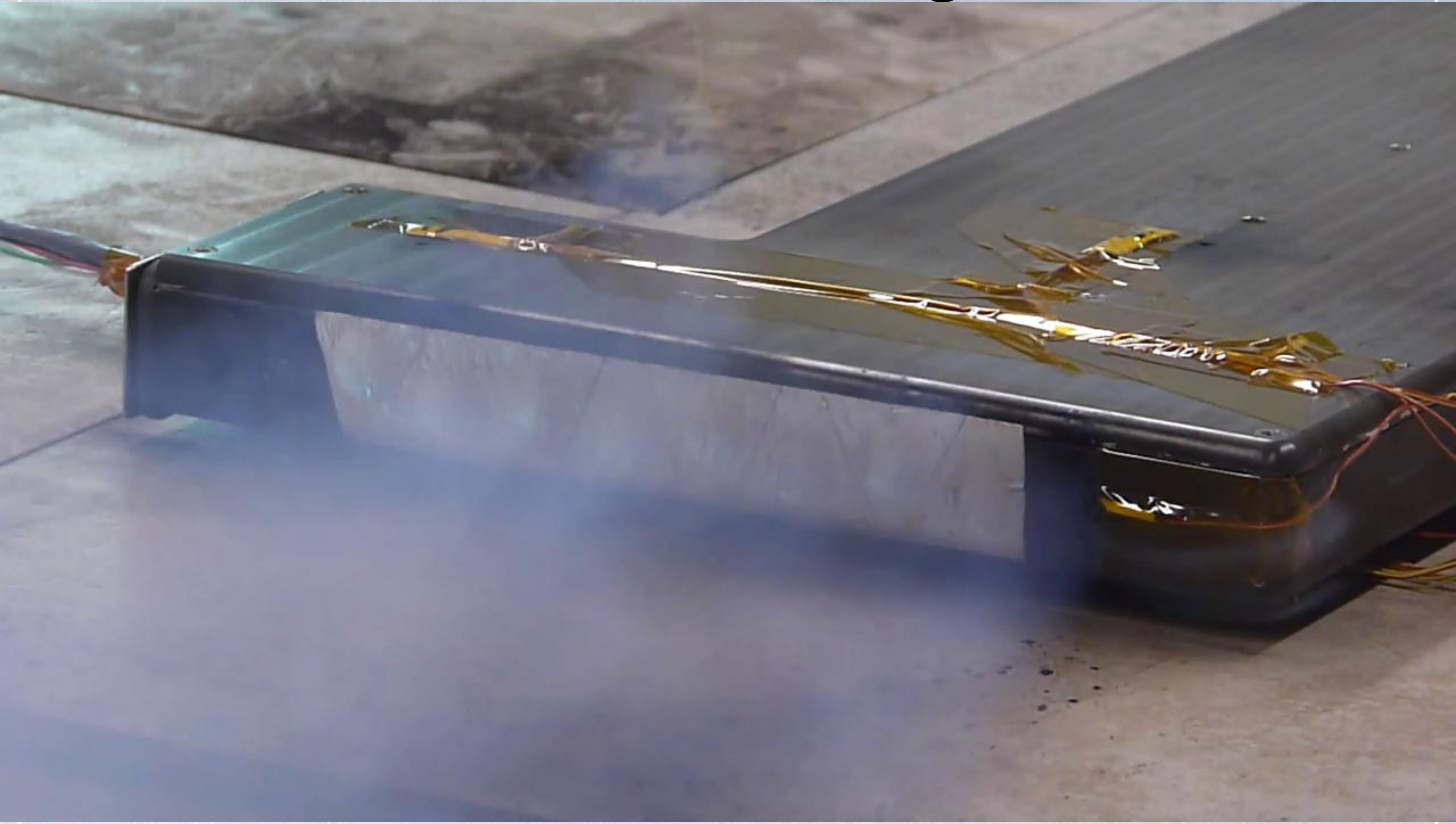
Half of heater fails open in first second, heater runs at 45W, nevertheless, TR reached in 72s. Bottom of trigger cell reaches 543°C, while mid and top get to 319-344°C. Cell 2 maxes out on all 3 TCs at 100°C.

Trigger Cell Positive Fusible Link Opens



At video time 13m:18s

Cell Venting

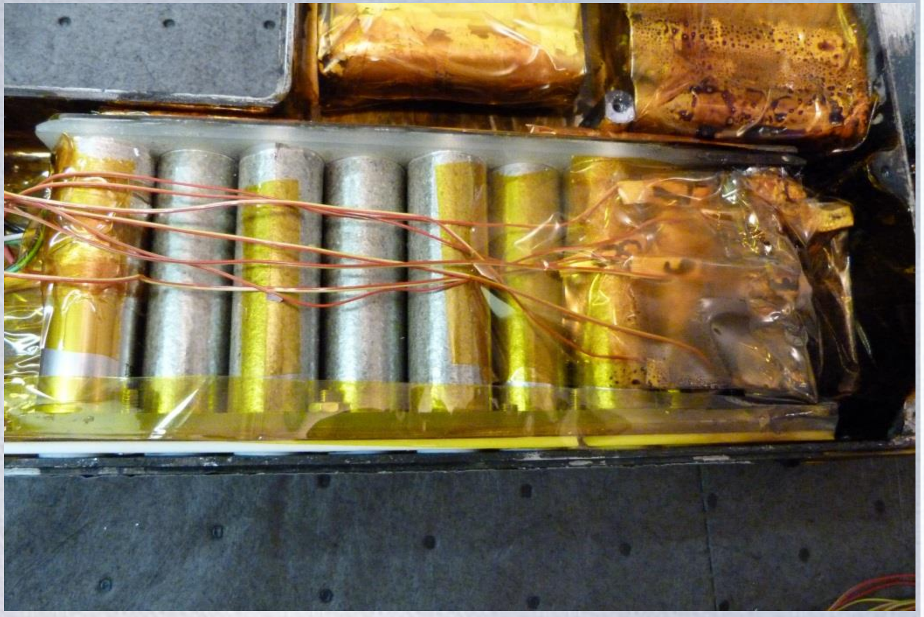


At video time 13m:19s

Trigger Cell TR

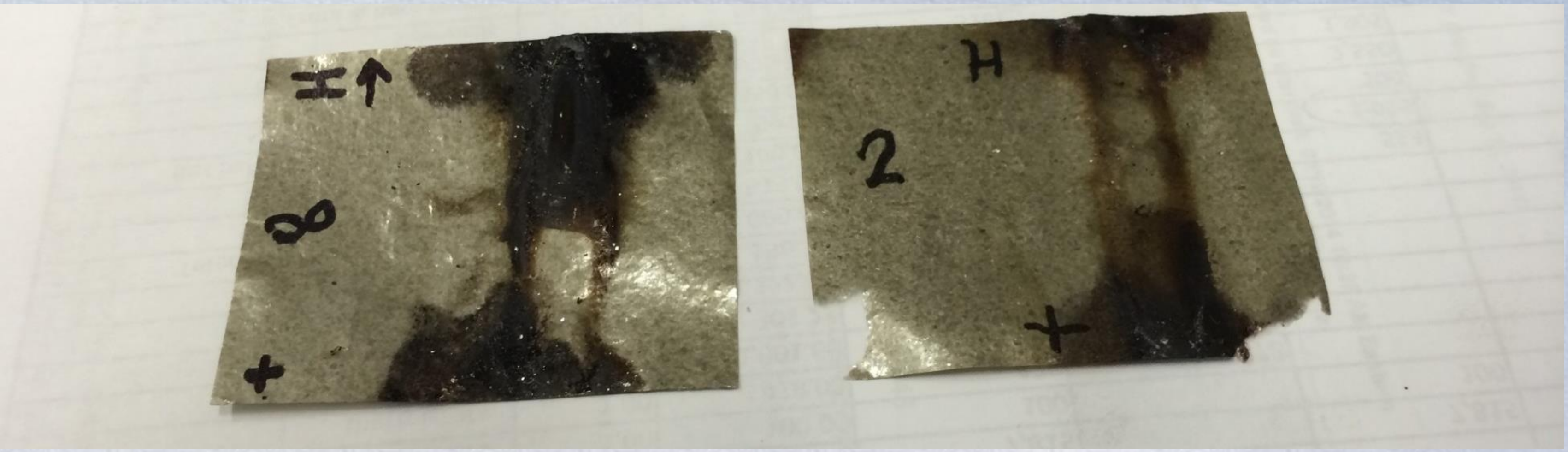
At video time 13m:20s

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

Cell Mica Paper Wrap Heat Affected Zones



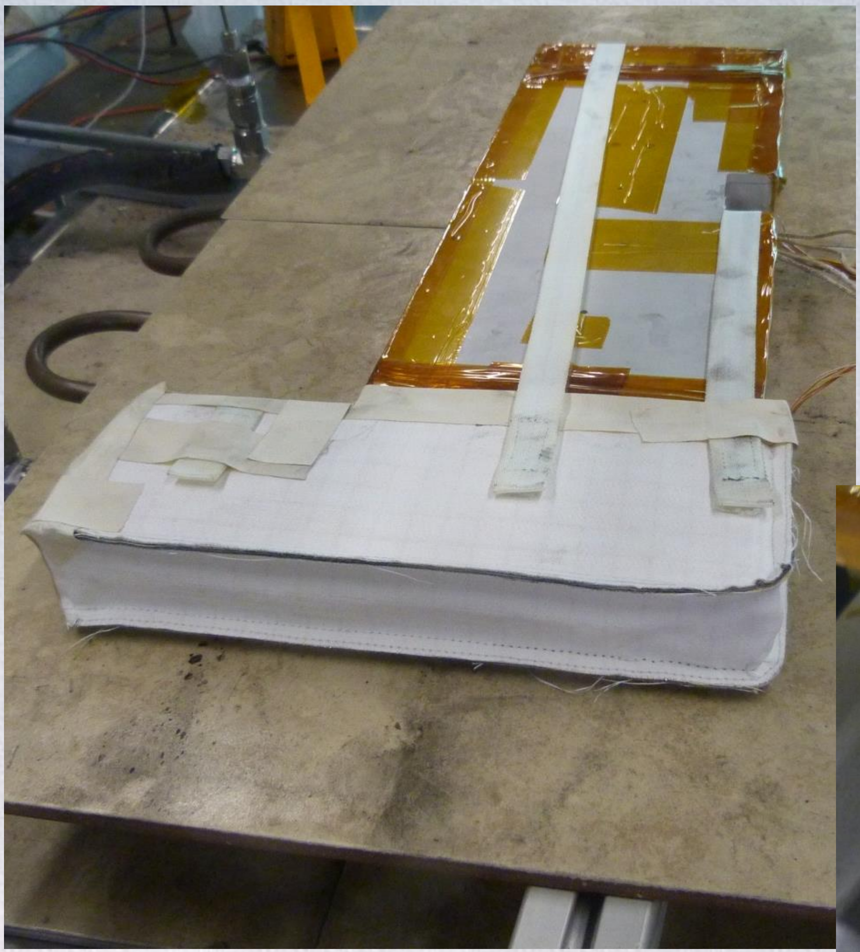
Adjacent cells 8 and 2 showing significant heat affected zones

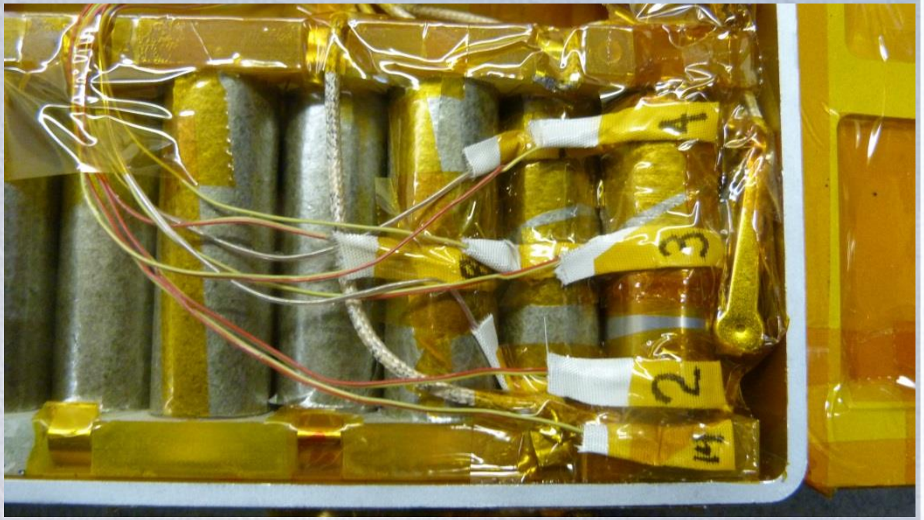
- Burn marks indicate cell 8 was more impacted than cell 2 bottom near heater:
  - Suggest that our heater edges may be too close to the adjacent cells
  - Moving to a single 45W heater (1”x0.5”) placed on bottom side of trigger cell opposite the adjacent cell
- Burn marks on top of the mica paper similar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

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
  - 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

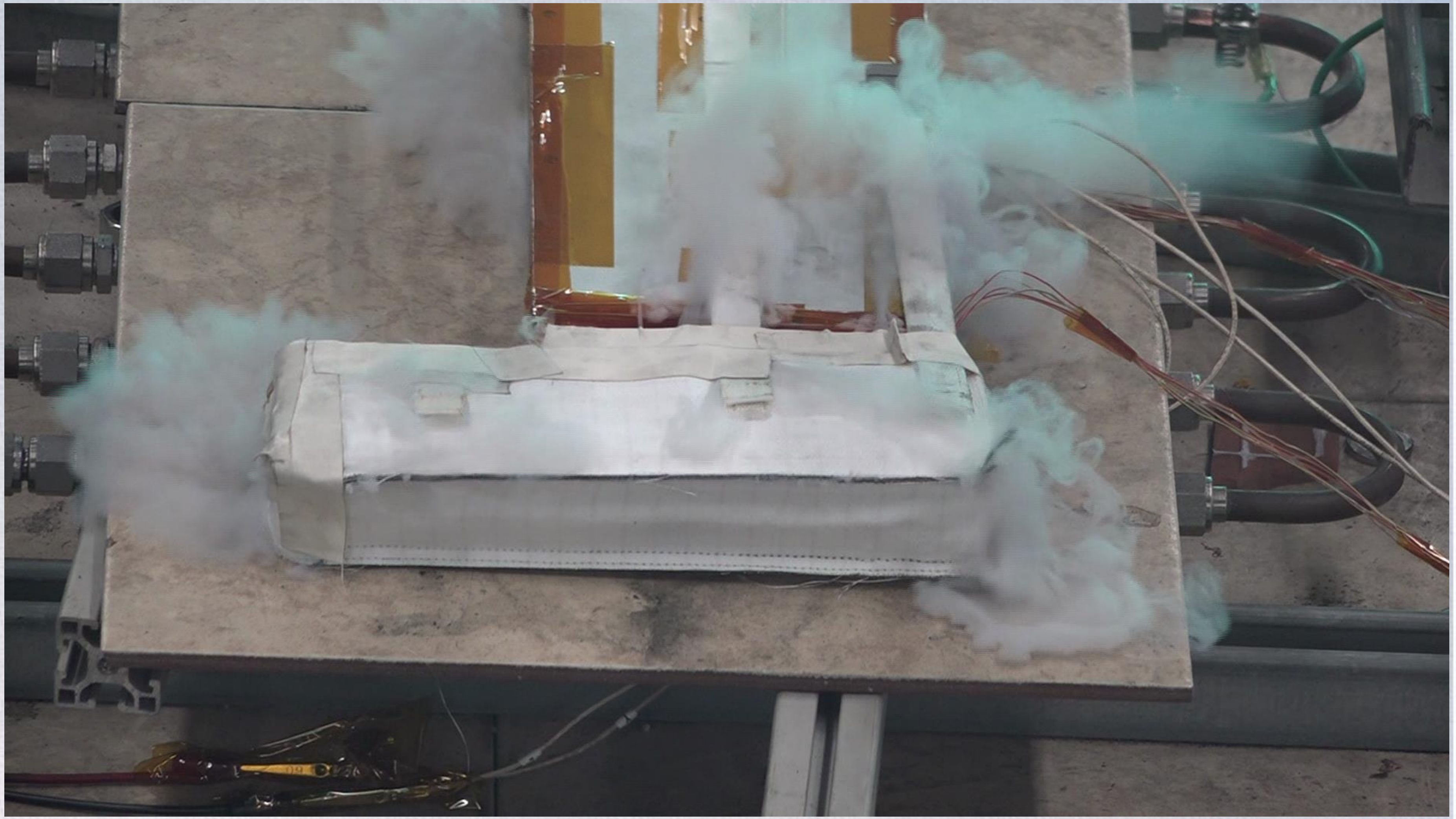
Next Run – Pre test



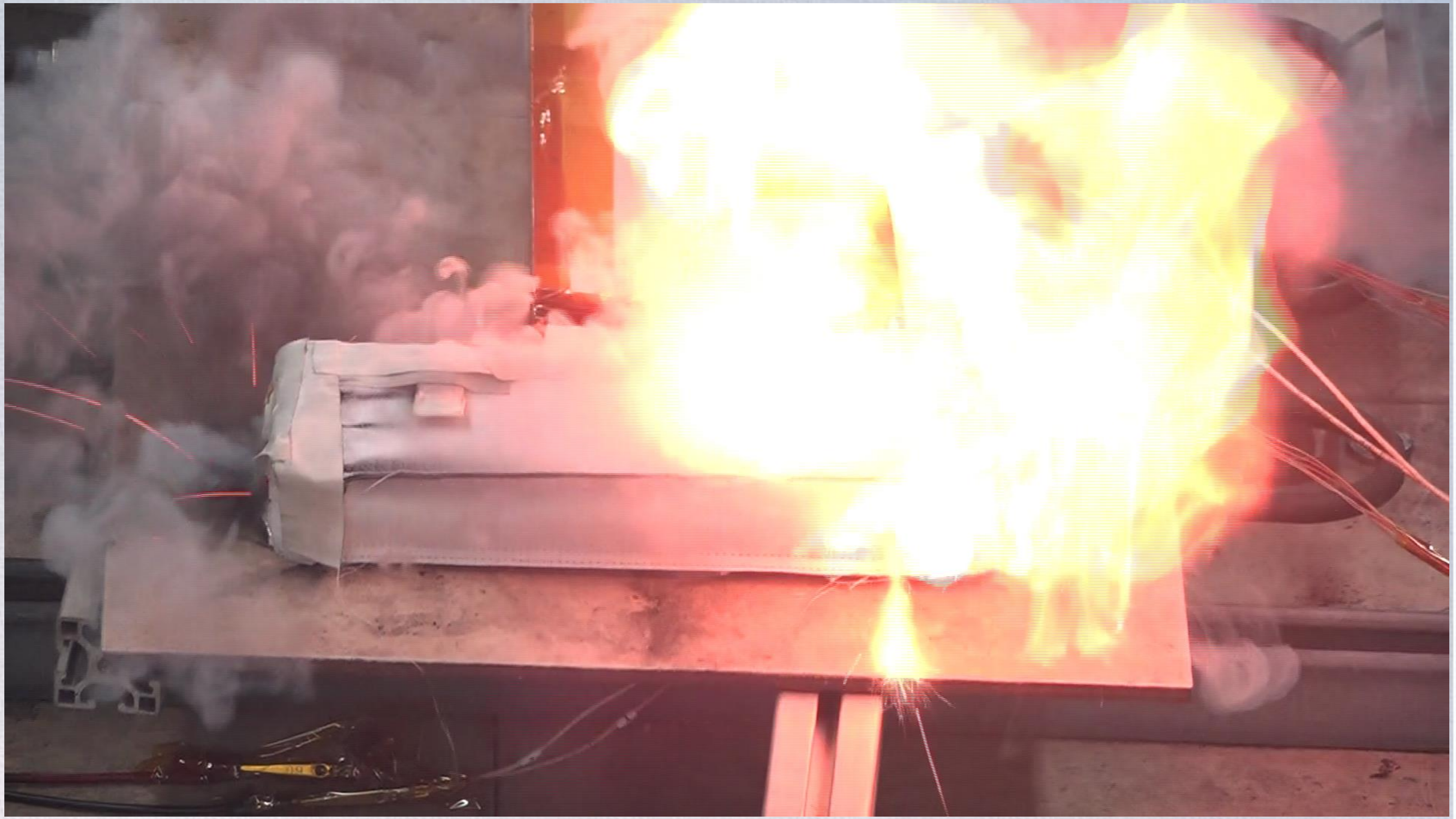


Soft goods bag added to dog leg of the battery

Trigger Cell Vents Smoke/Electrolyte



1s later, Instantaneous fireball with sparks

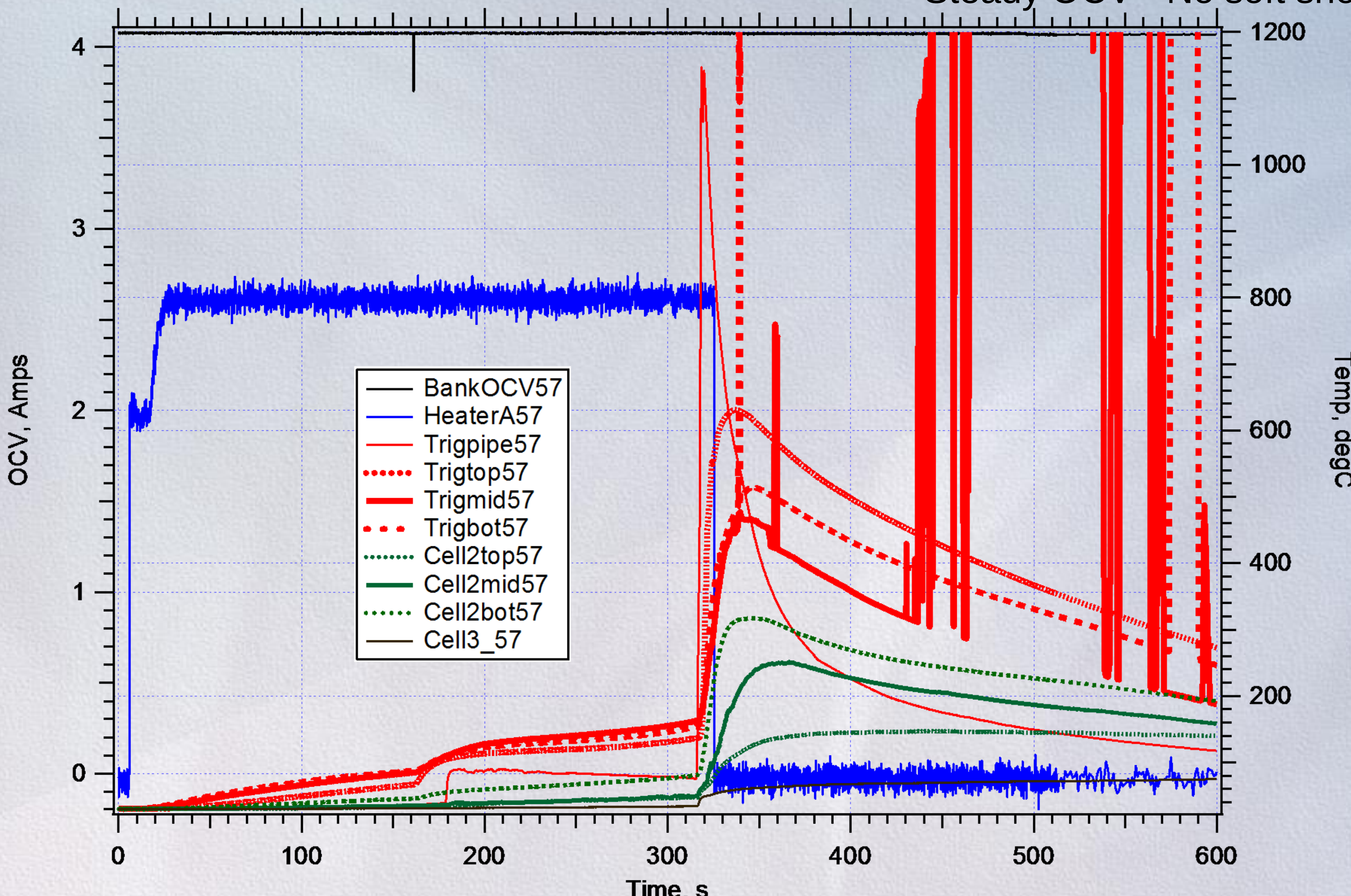


After 2s, Flaring

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

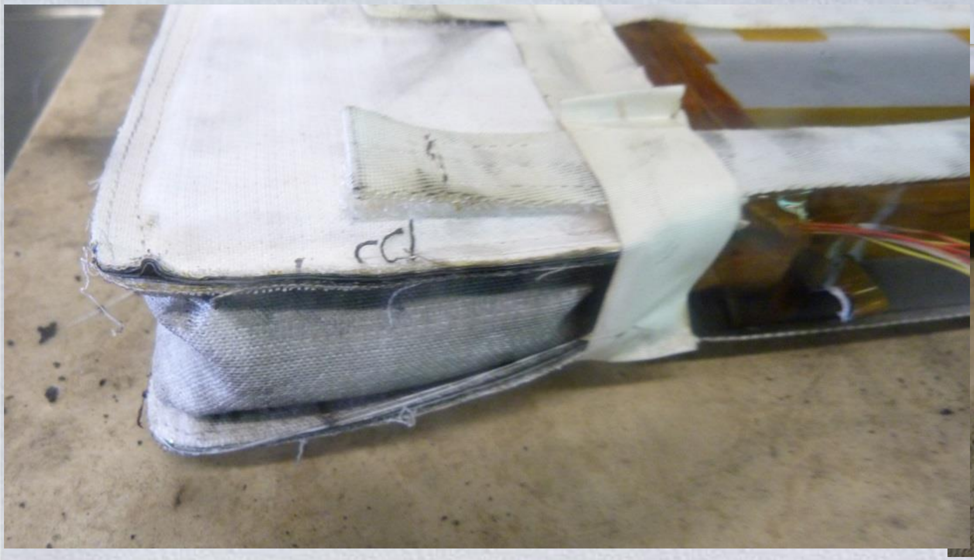
Overall Plot

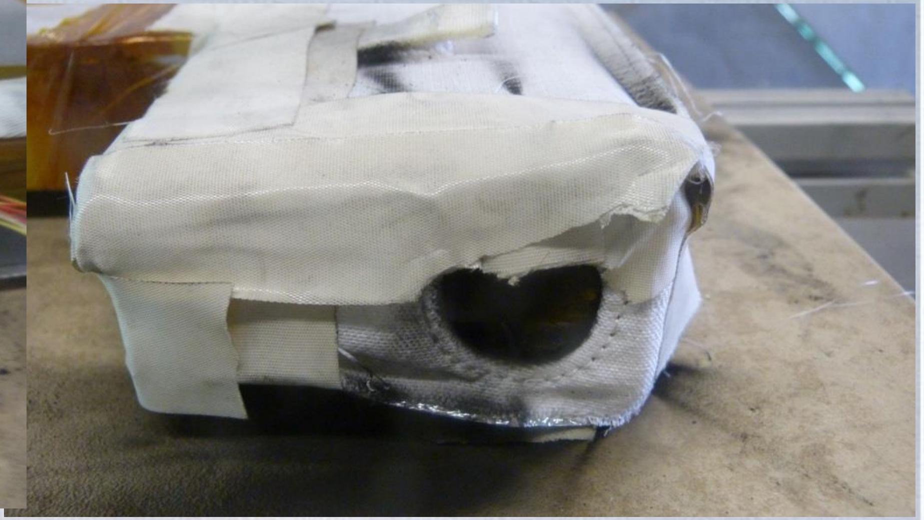
Steady OCV - No soft shorts



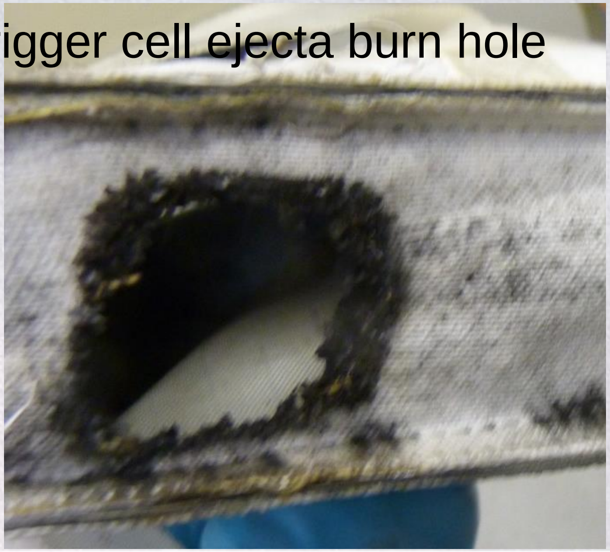
TR of trigger occurs 310s after heater on. Trigger cell max temp range from 474-631C. Cell 2 max temp range from 147-317C. Cell 3 max is 80C 600s after heater on. Trigger pipe max is 1146C.

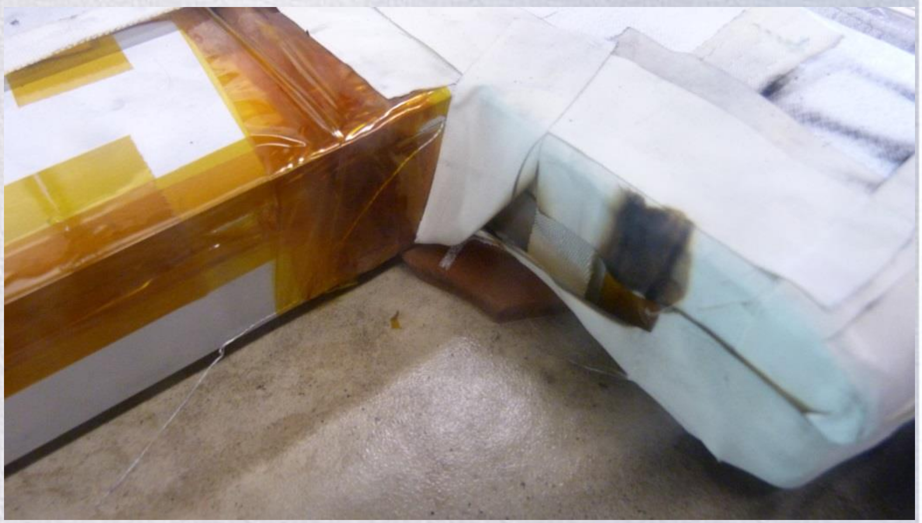
Run 57 – Post Test





Trigger cell ejecta burn hole



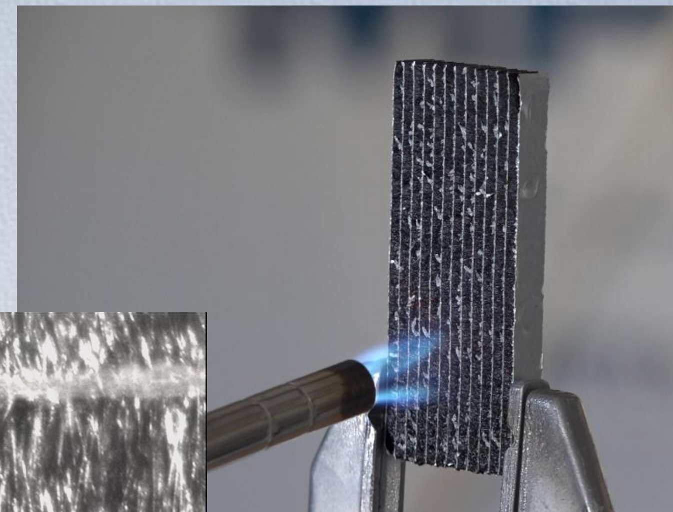


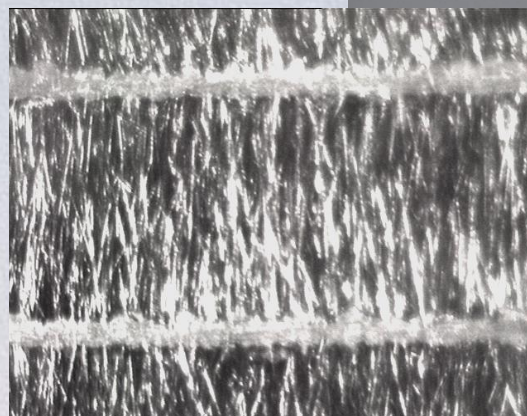
Post Test – TMG Bag

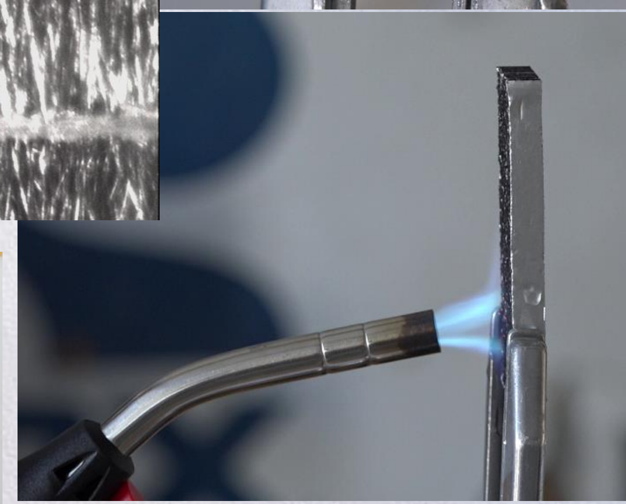
- Soft goods bag (rip stop nylon, 7 layers of aluminized mylar, and kevlar reinforced fabric) was quickly perforated by cell TR flare/flame
- Need to reinforce it with higher temperature metal foils (ex, Ni)
- Need to dissipate the heat of the flame/flare with a porous media

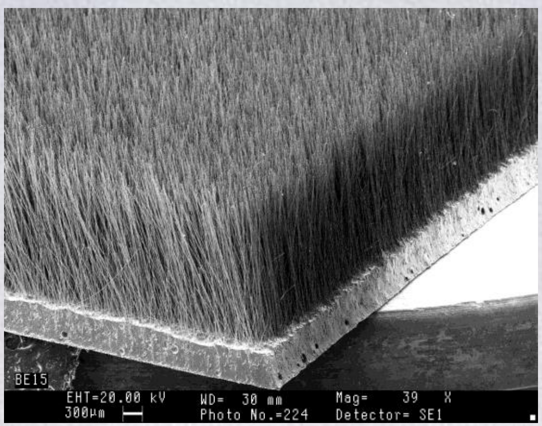
ESLI Carbon Fibercore Torch Test

- 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



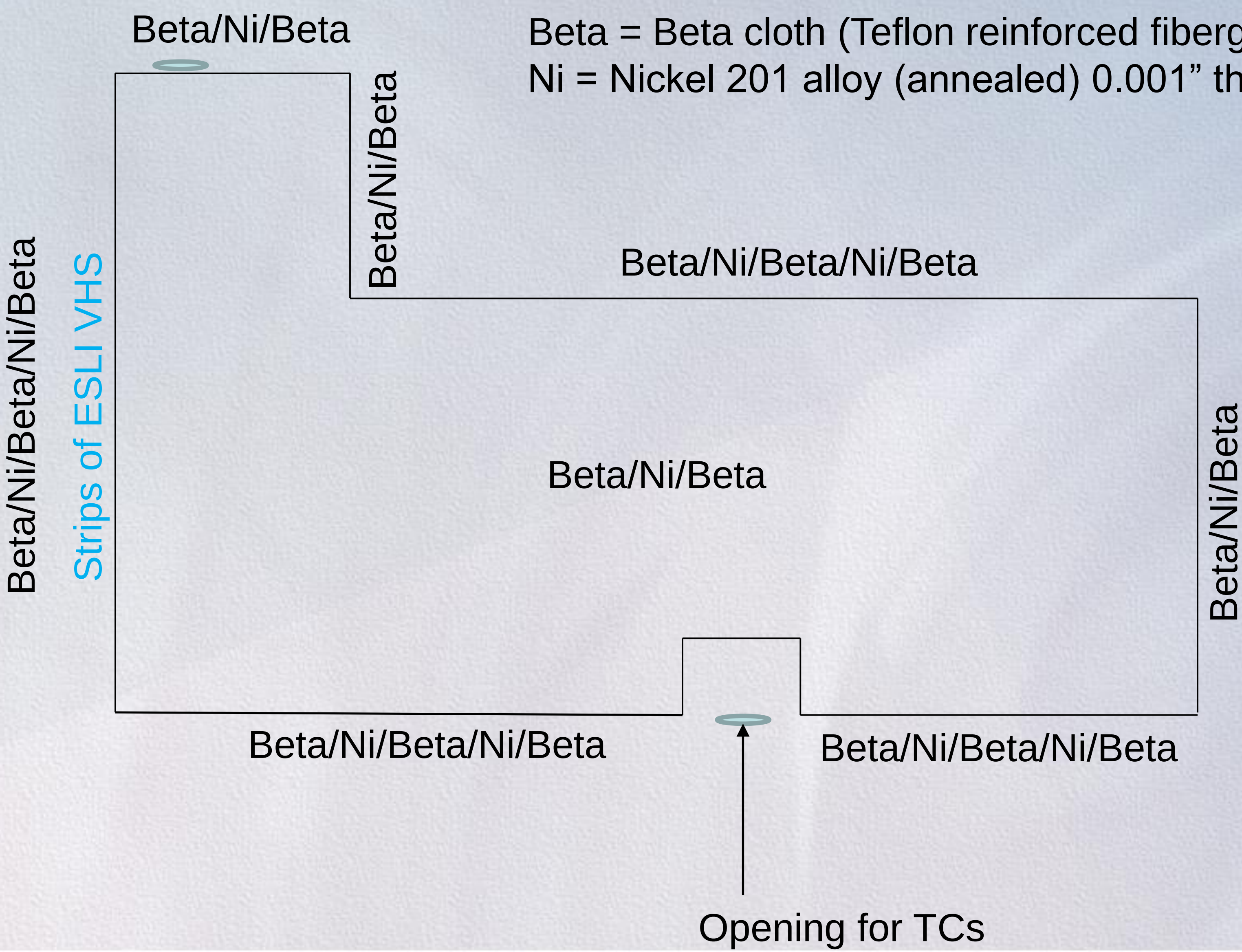




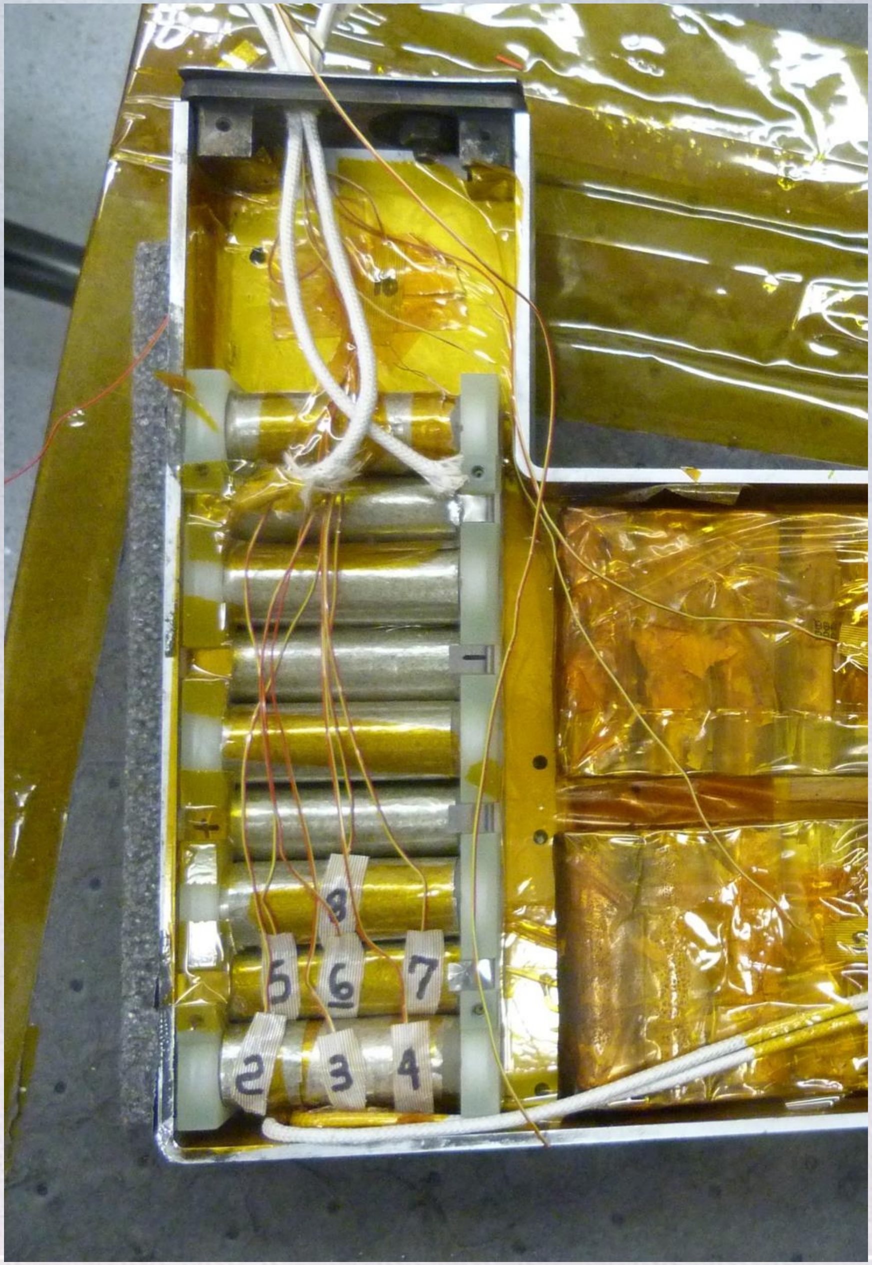


Full Bag Design

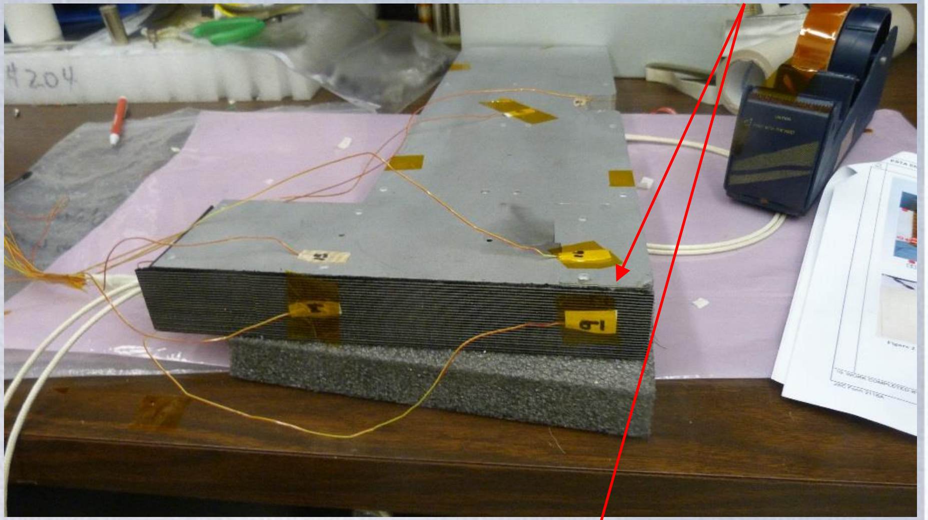
Beta = Beta cloth (Teflon reinforced fiberglass)
Ni = Nickel 201 alloy (annealed) 0.001” thk

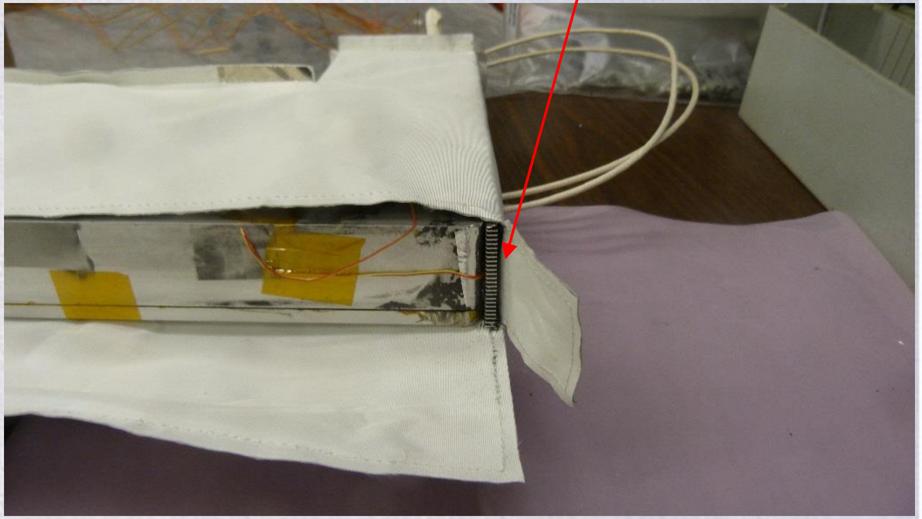


Run 58 Pre Test

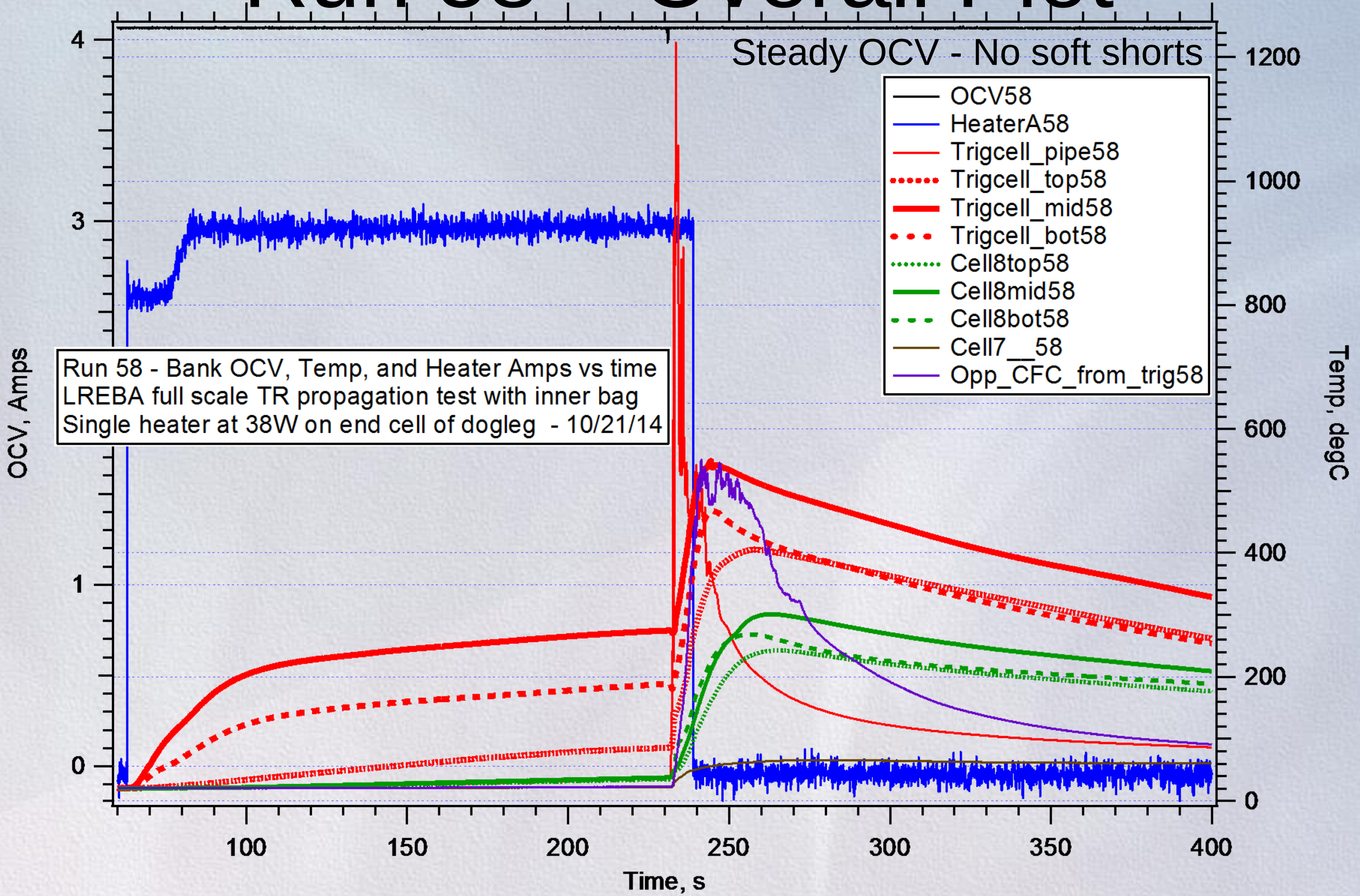


With Carbon Fibercore (CFC)



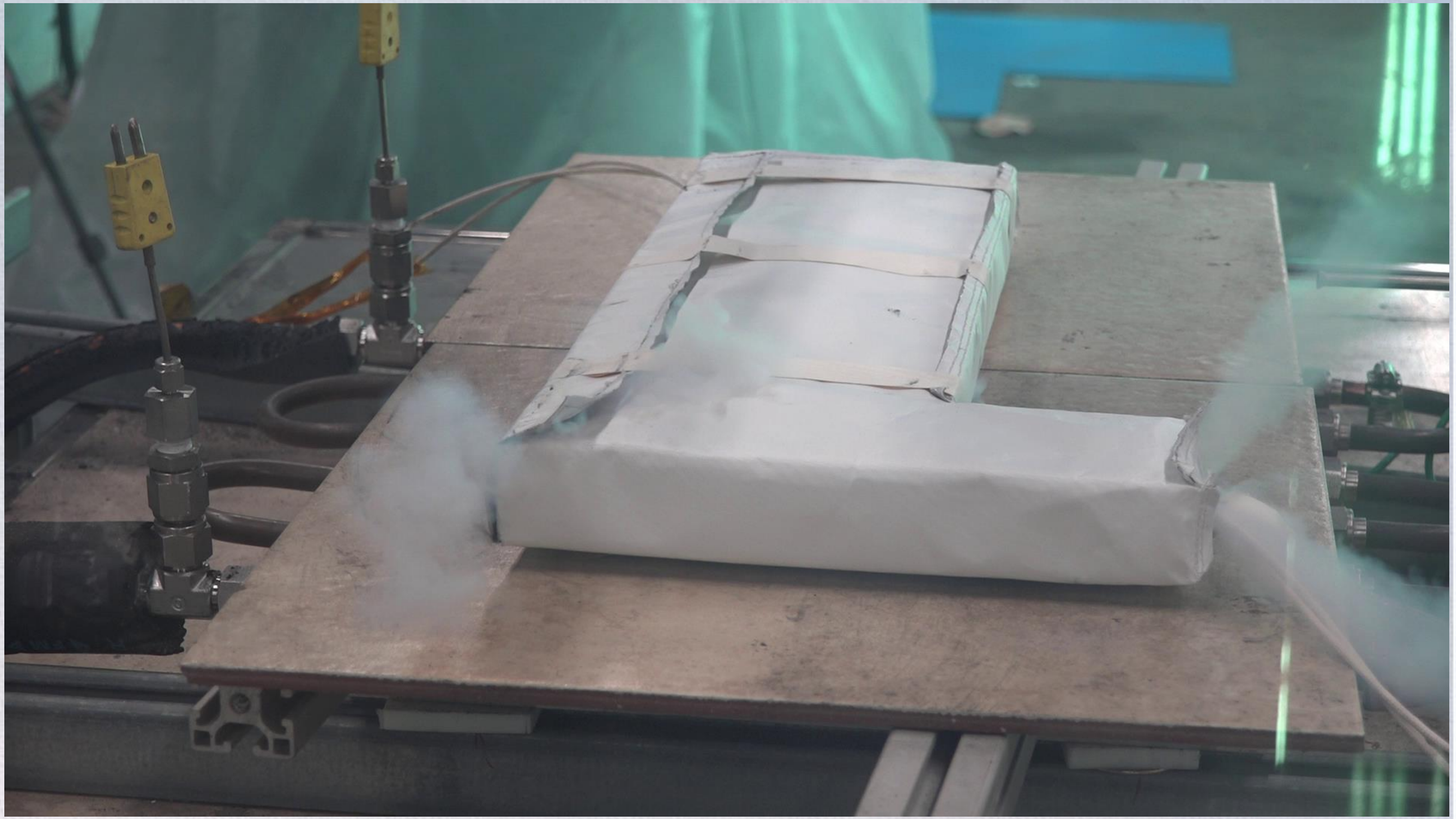


Run 58 – Overall Plot

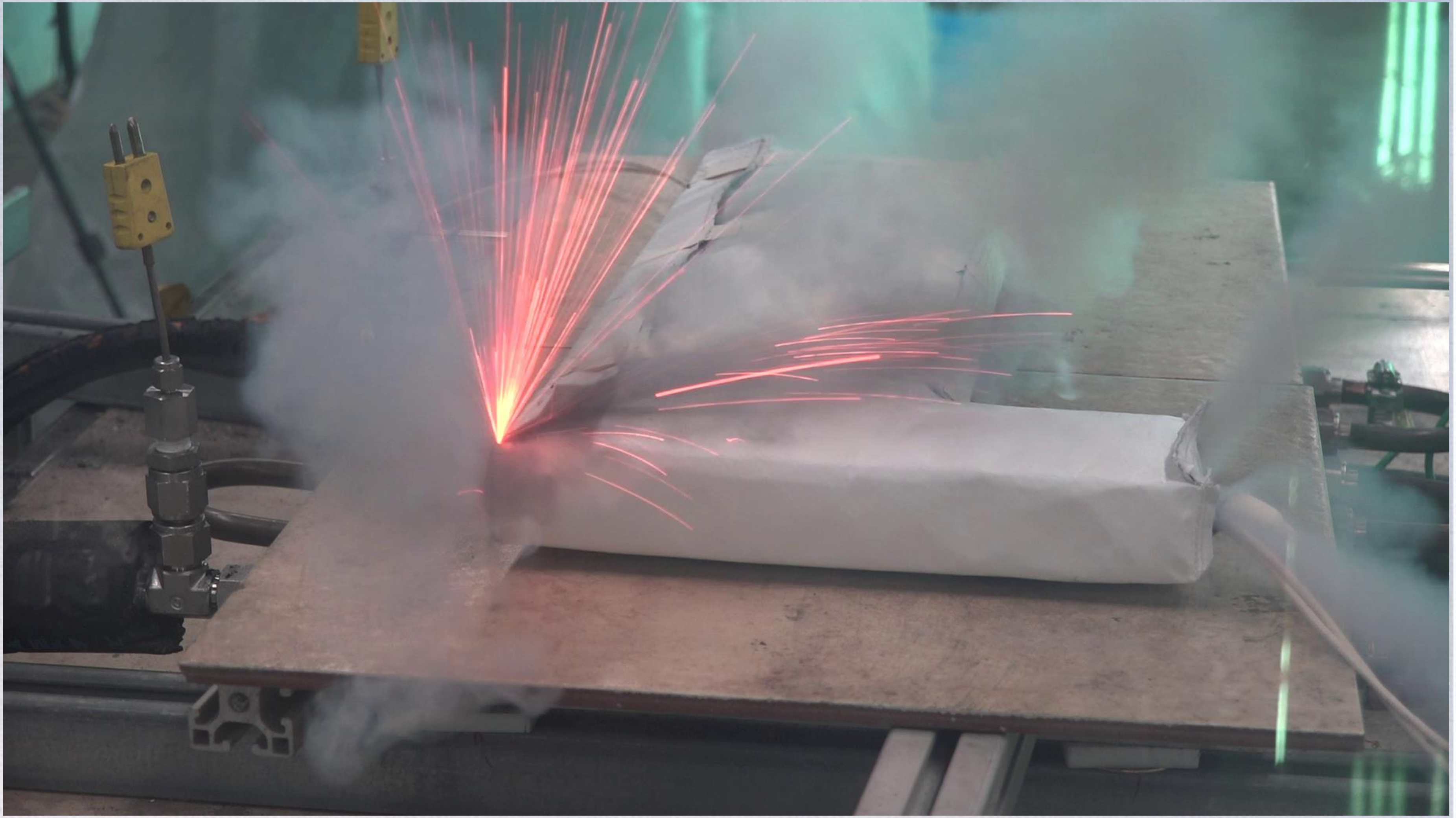


Trigger fuse blows at 168s, TR in 169s, heater left on for 176s, max temp on trigger cell pipe = 1224C

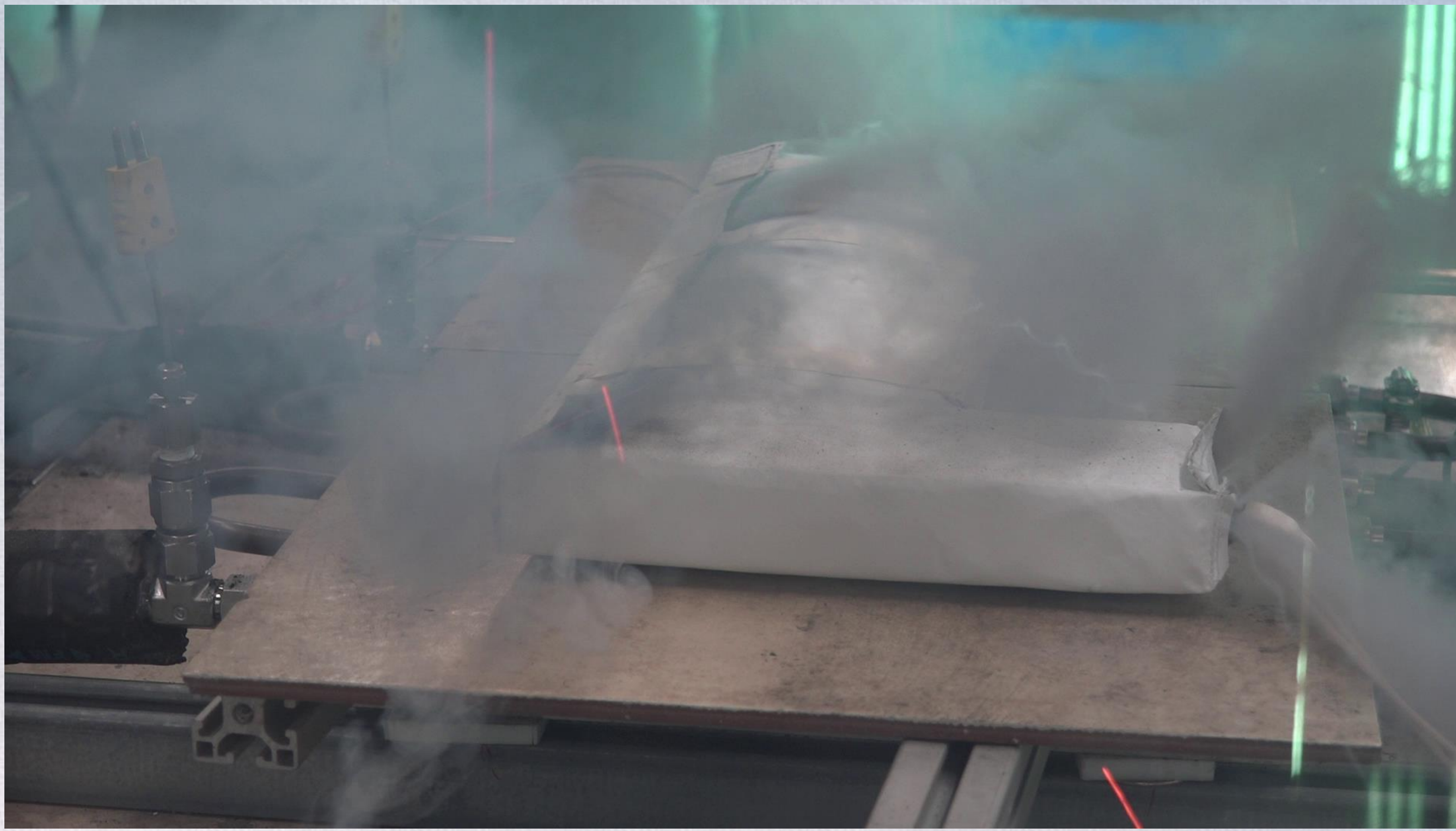
Snap Shots – Initial Vent of Smoke



1s later

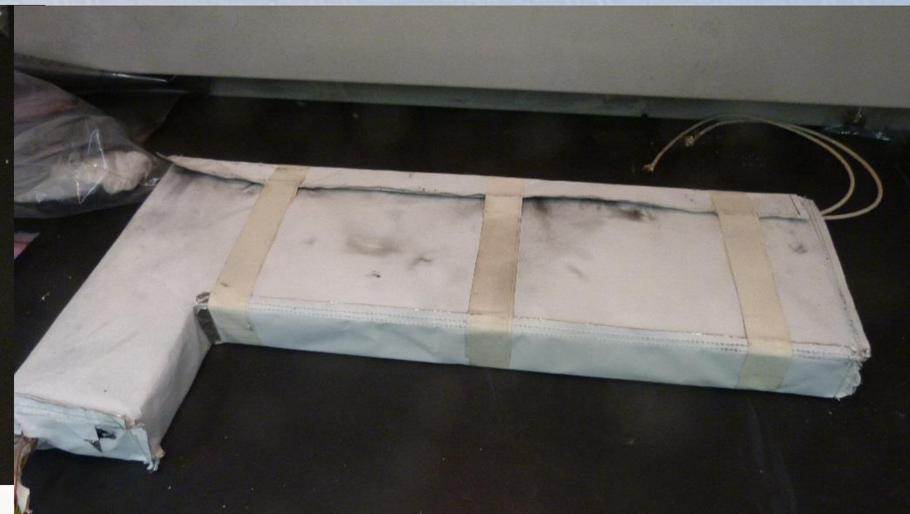


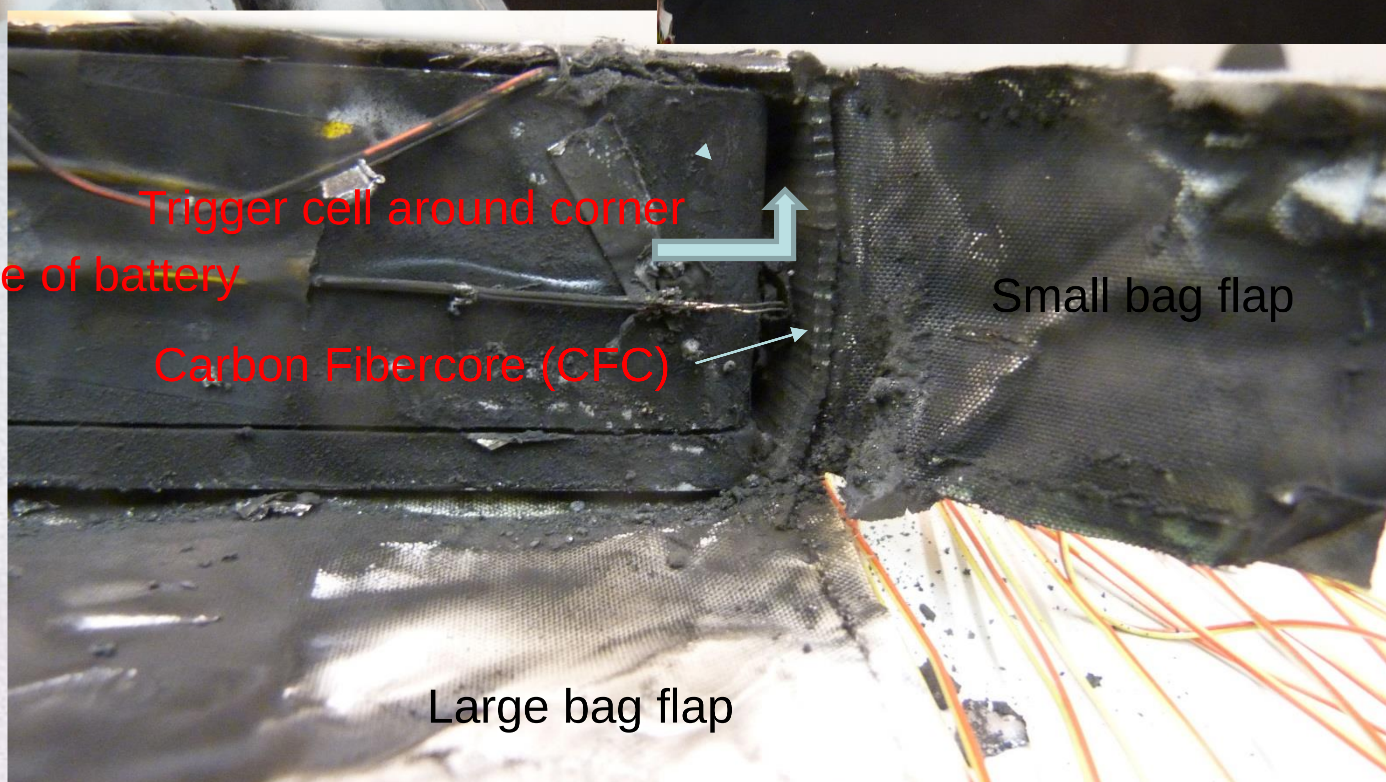
2s later



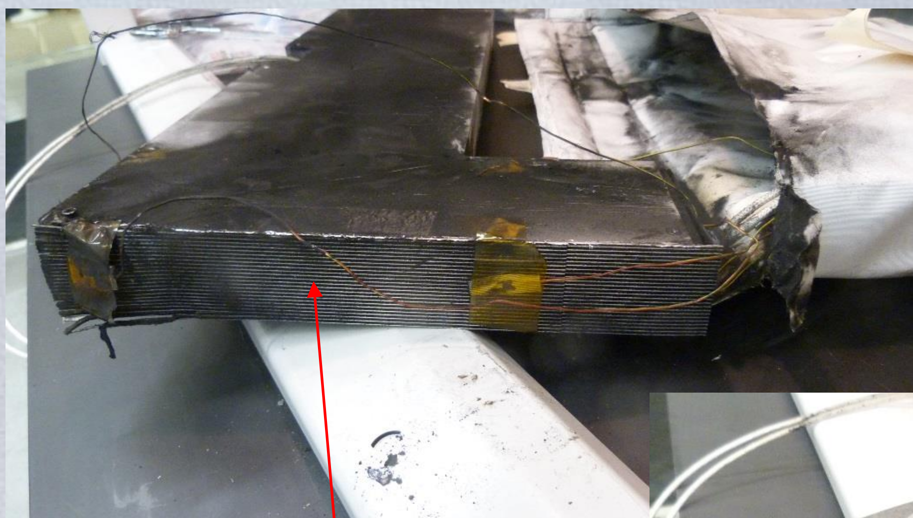
3s later

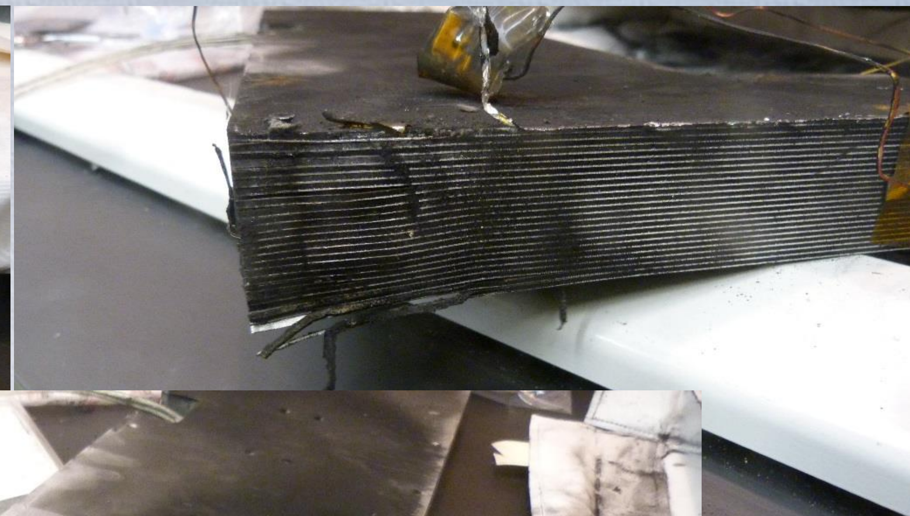
Post Pictures





Post Pictures



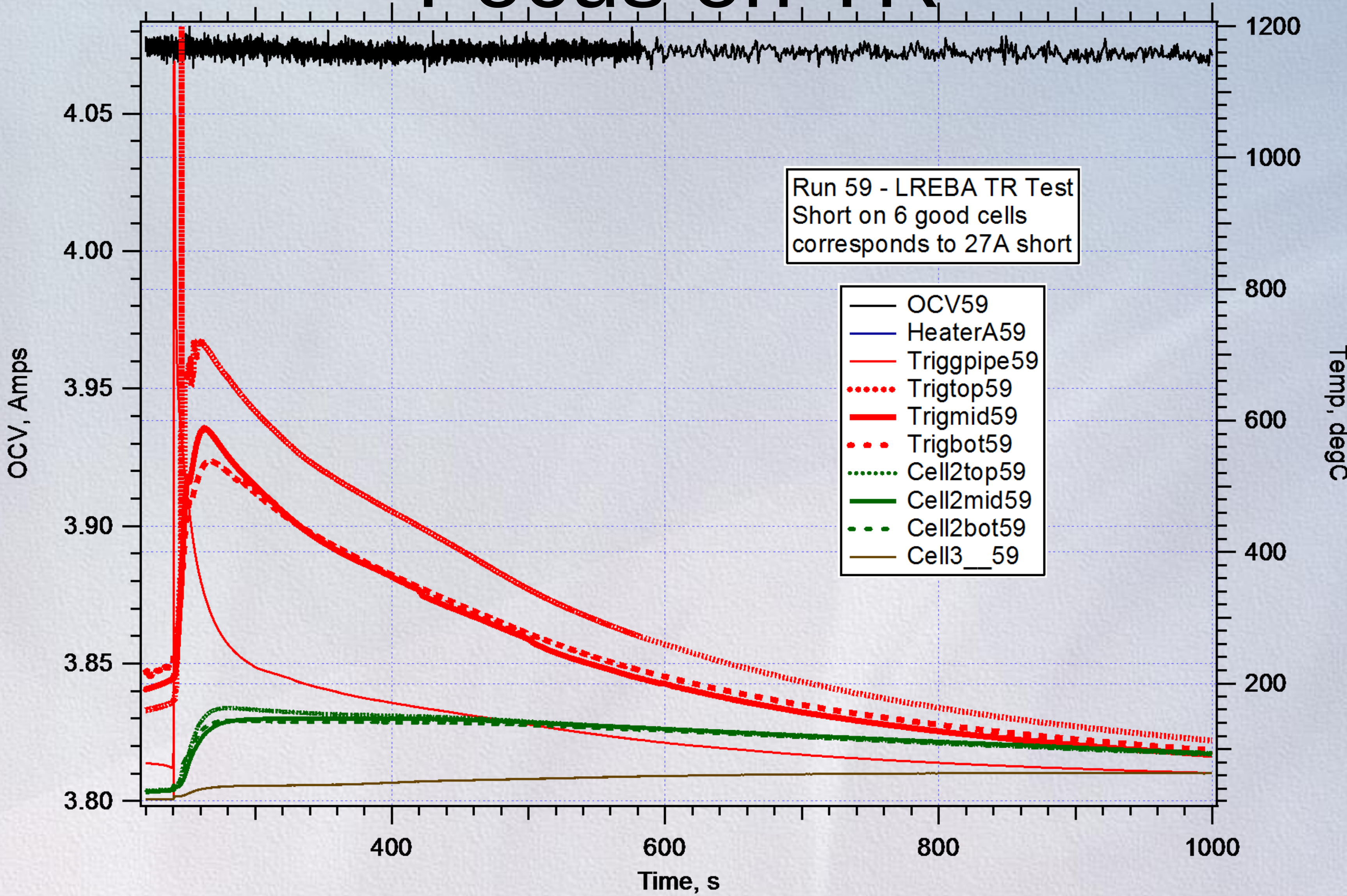


Flame arresting
Carbon fibercore (CFC)

Run 59 – Without the CFC

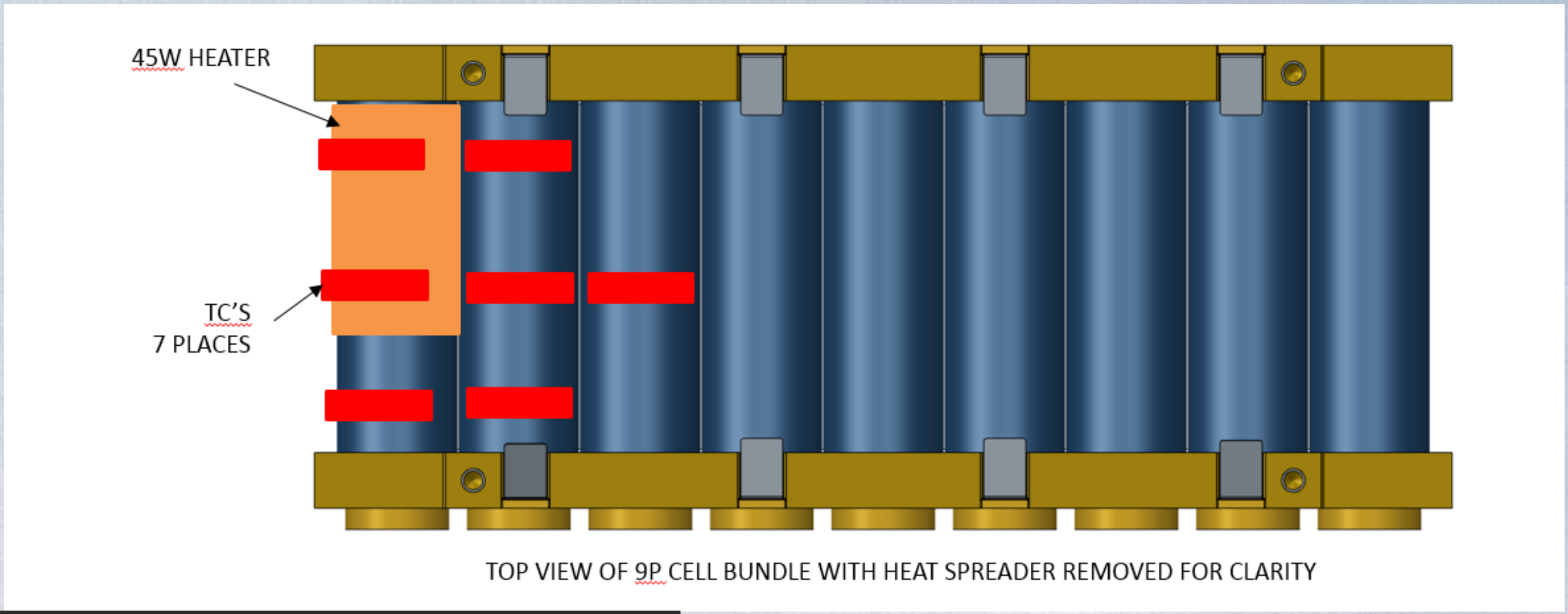
Cell TR ejecta burns right through 2 layers of Ni foil (0.001”)

Focus on TR

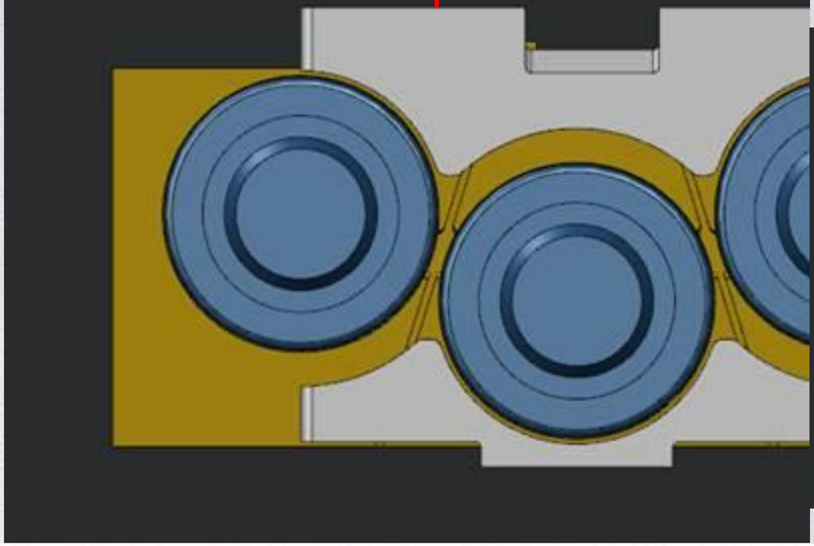


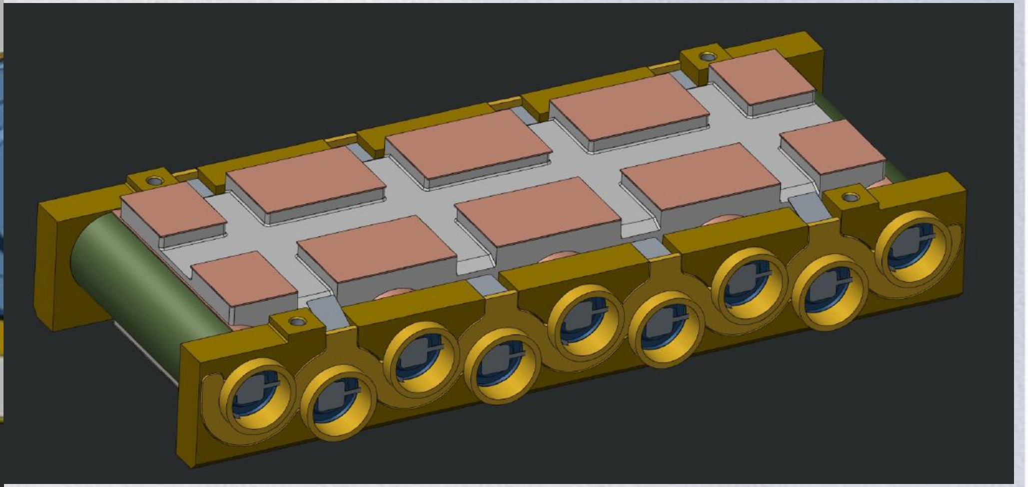
Trigger pipe reaches 1146C, trigger cell skin max T range 534-722°C,
Cell2 range 144-163°C, Cell 3 reached 64°C. Note that it takes > 800s to cool trigger cell from peak to 100°C

Al Heat Spreader (run 60-61)



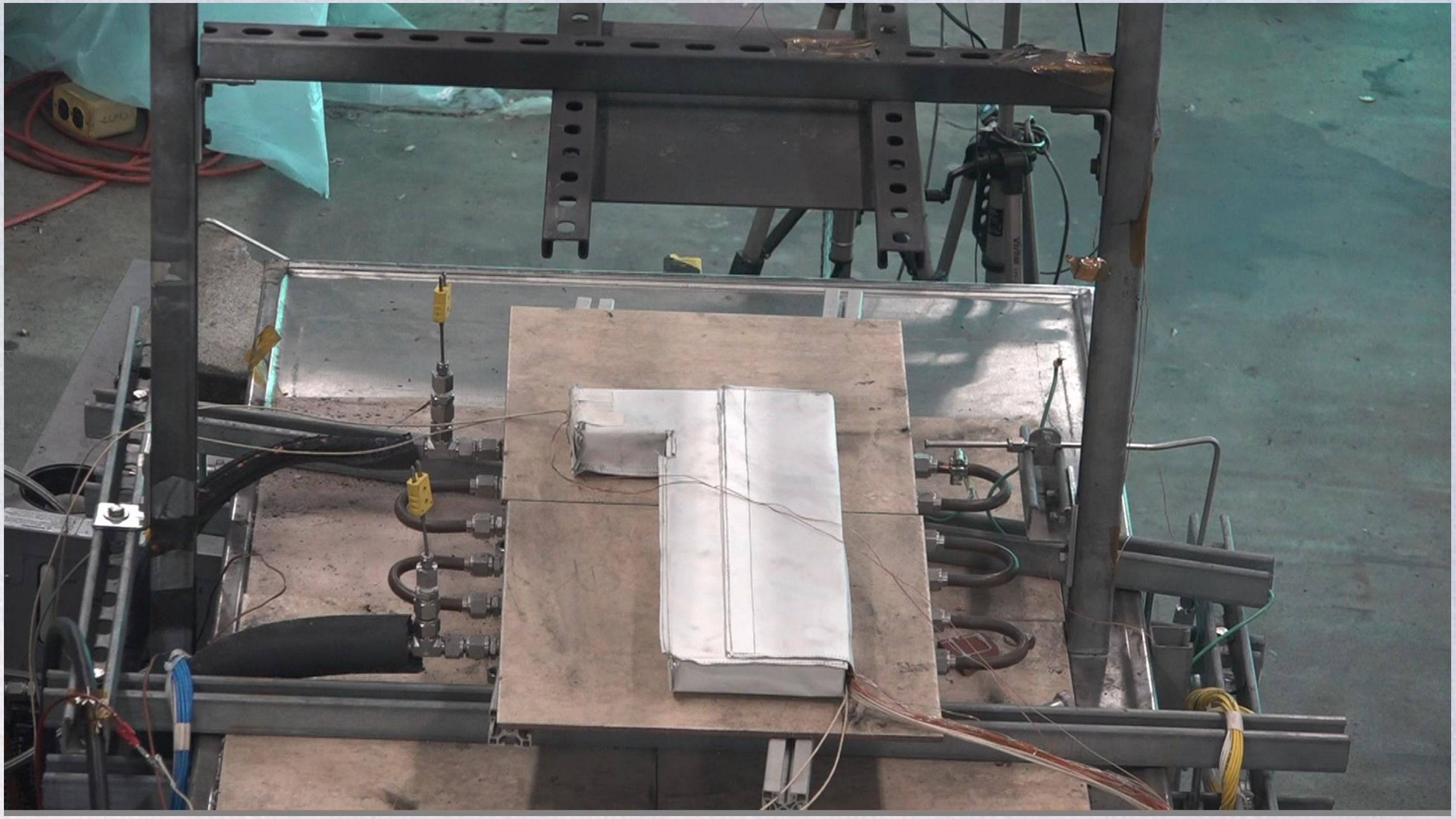
Top and bottom heat spreaders connects every other cell thermally



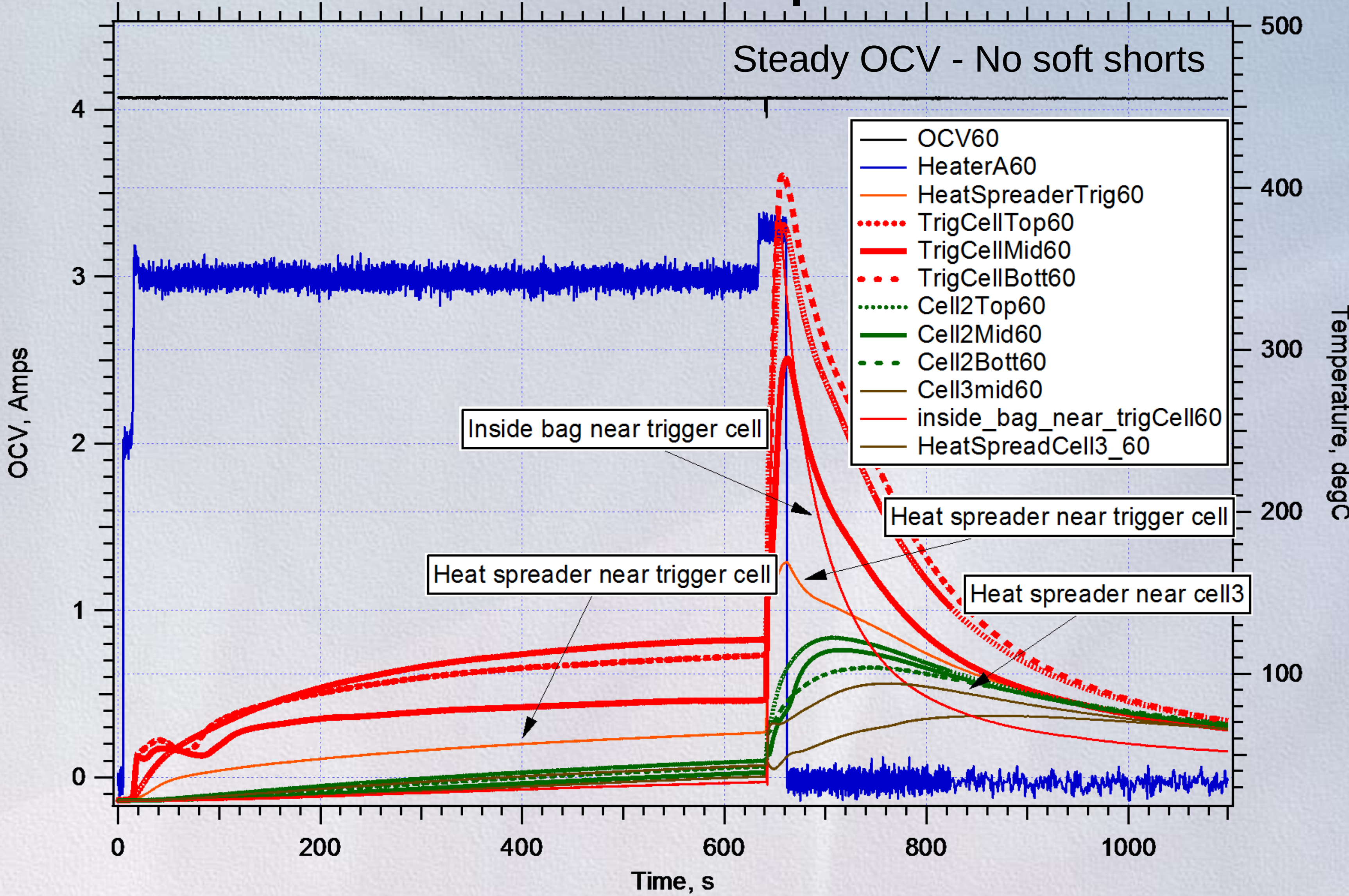


Runs 60 – 61 – No sparks, no fire exit bag

- 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

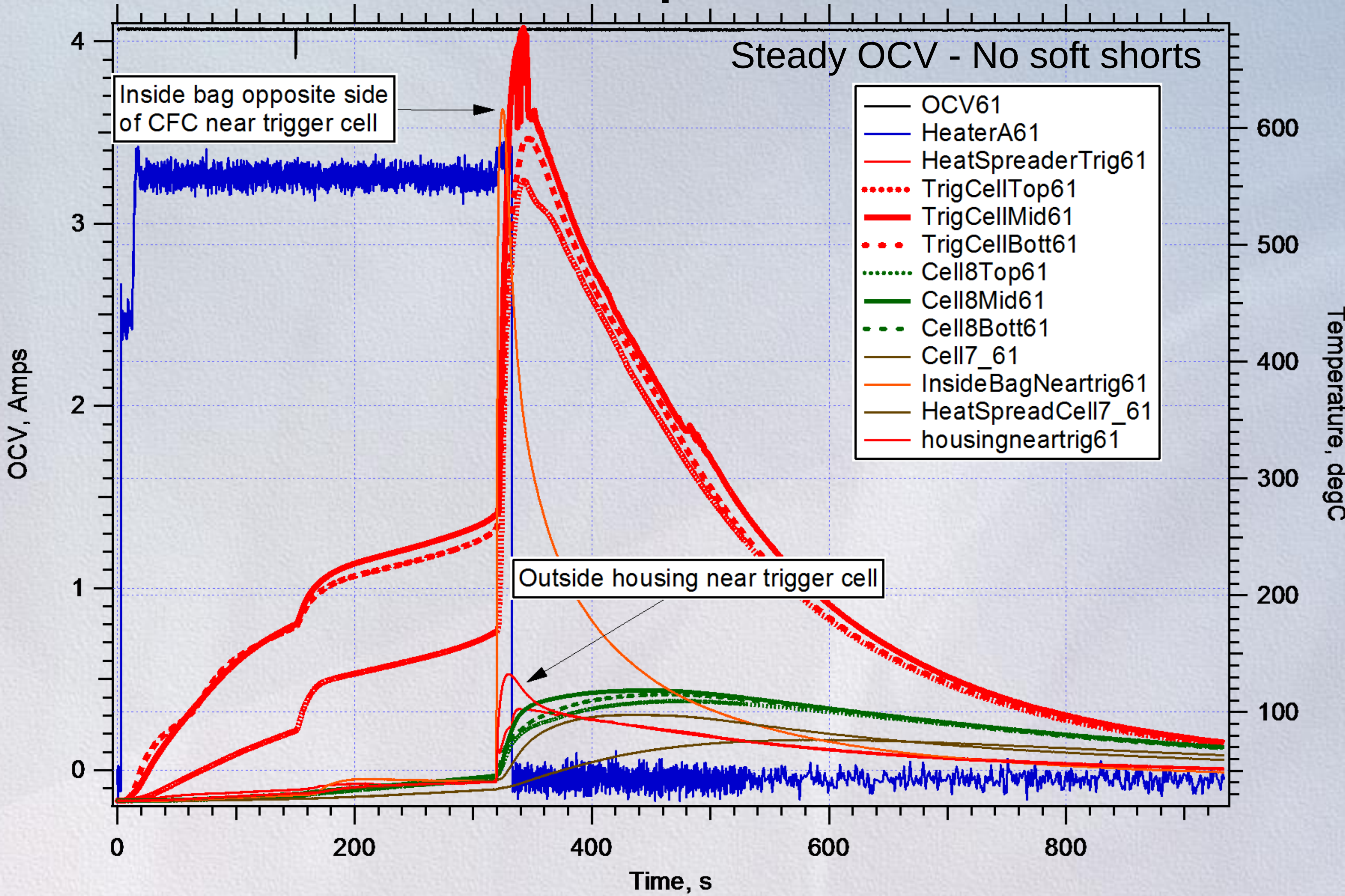


Plot of run 60 – Heat Spreader & CFC



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.

Run 61 – Heat Spreader, no CFC



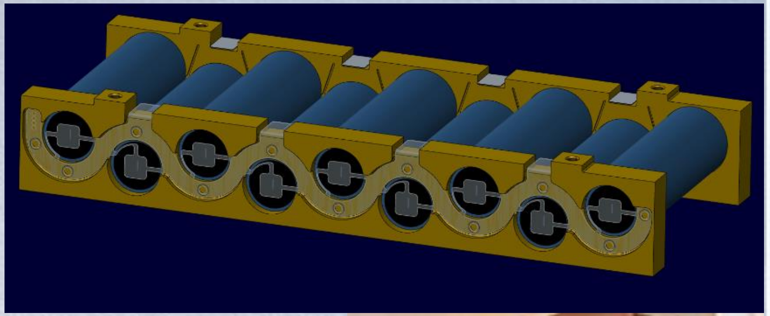
Heater set at 50W and on for 329s. TR occurs in 320s. Internal short circuit occurs 147s after heater on, possibly venting. Then TR occurs 57s later. Max Ts on trigger cell range is 555-686C, cell 8 is 110-115C, and cell 7 reaches 76C. Note that it takes 449s for max temps to cool from peak to 100C.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

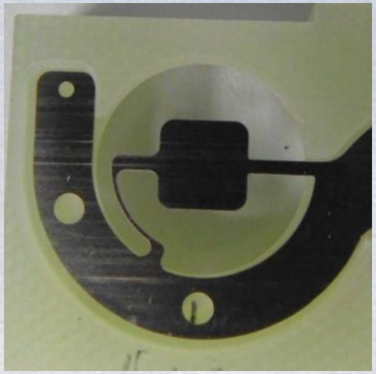
Run 61 – No CFC

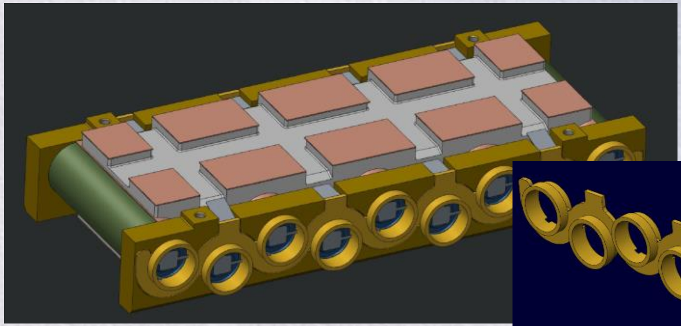
- TR ejecta burns through first Ni layer and damages second layer
- 3rd and 4th Ni layers are undamaged
- Ni melts at 1455°C
- Adjacent cells retained OCV > 4V
- DPA of adjacent cells from runs 60 & 61 indicated no heat effected zones on jellyroll plastic wrap

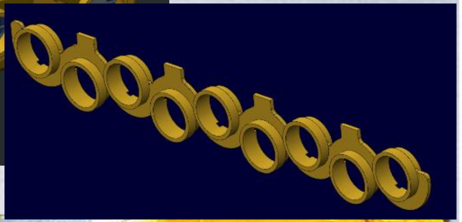
Recap of Mitigation Measures for LREBA

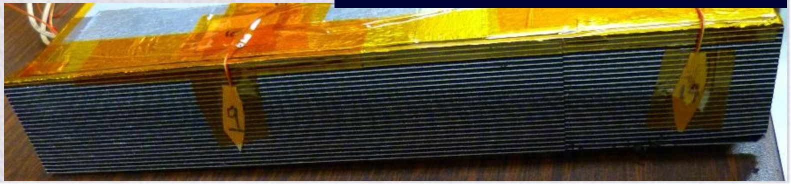
- Control the conduction paths
  - Ensure cells are space out ≥ 1mm
    - G10 capture plates
  - Decrease conduction of cell interconnects
    - Fusible links
  - Increase conduction to the enclosure
    - Heat spreaders and gap pads
- Limit shorting paths
  - Fusible links in the negative cell interconnects
  - 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



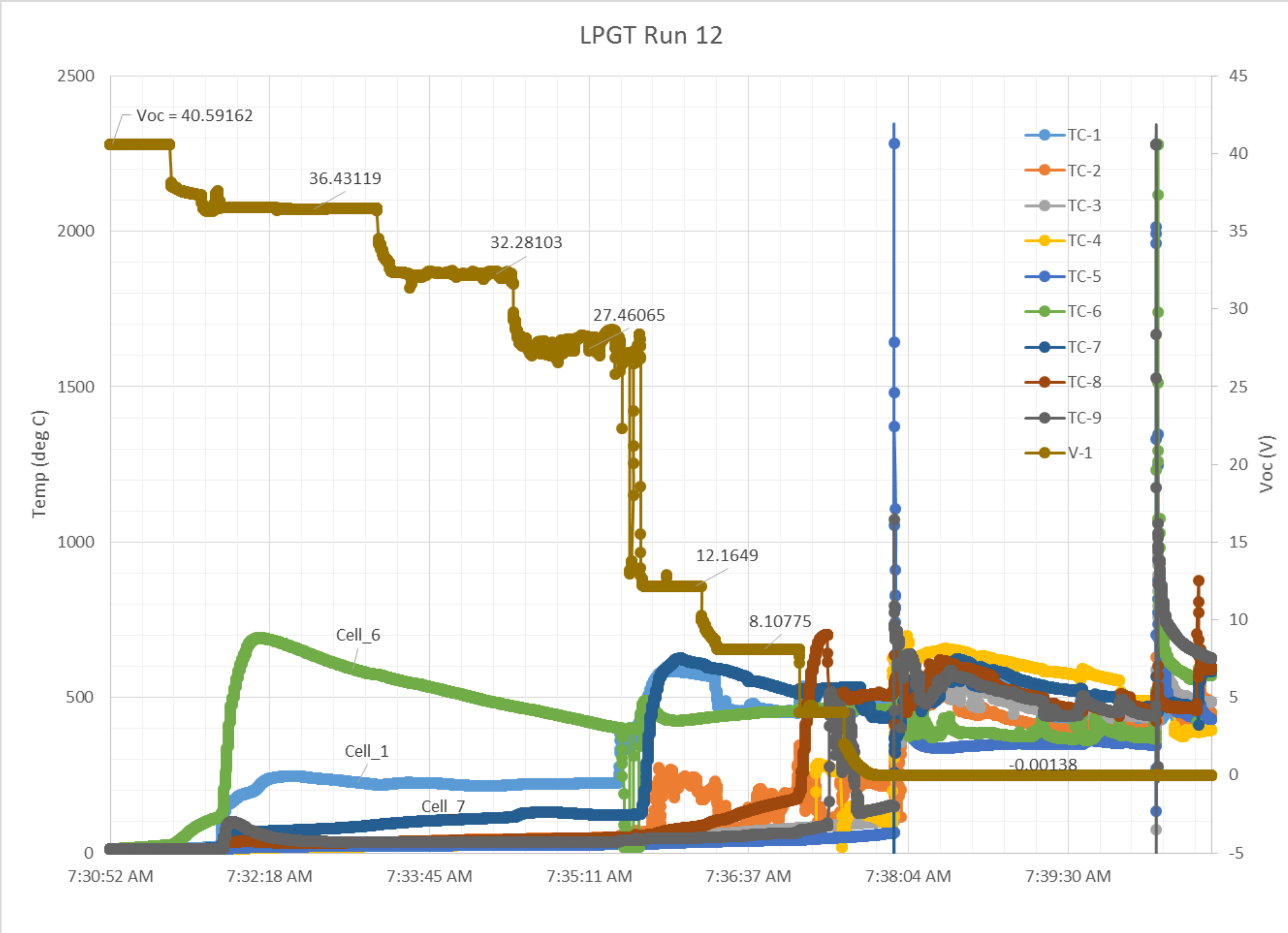








LPGT “CDR” Baseline Test



Full thermal runaway propagation to all 9 other cells over about 10 minutes with release of sparks

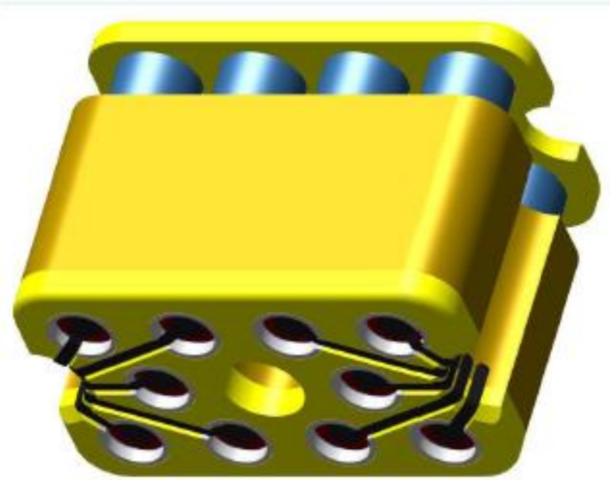
Snapshot – more sparks at 9:56

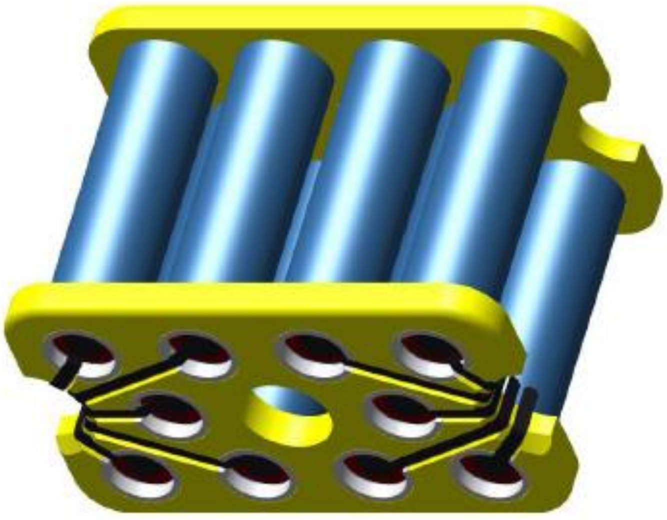
More sparks occur at 10:20, at 12:37 the supporting tile cracks, and smoldering smoke is intense for another 5 min.

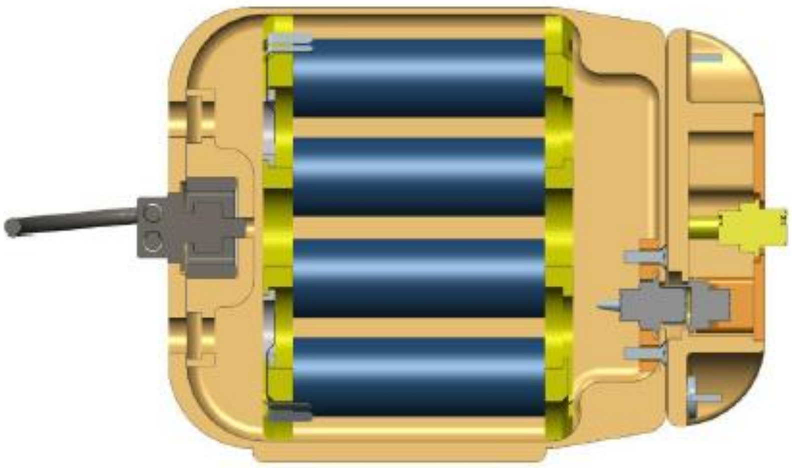
LPGT with Severity Reduction Features

Removable connector adapter

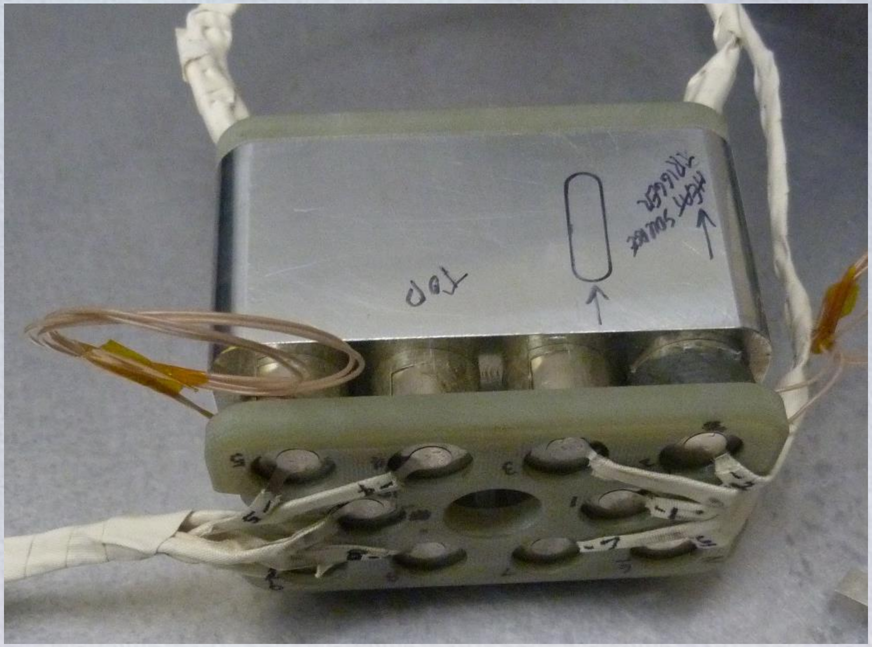
- Maintains tool-compatible configuration
- Case is sealed at tool end
- Reversed flow provides tortuous exit path

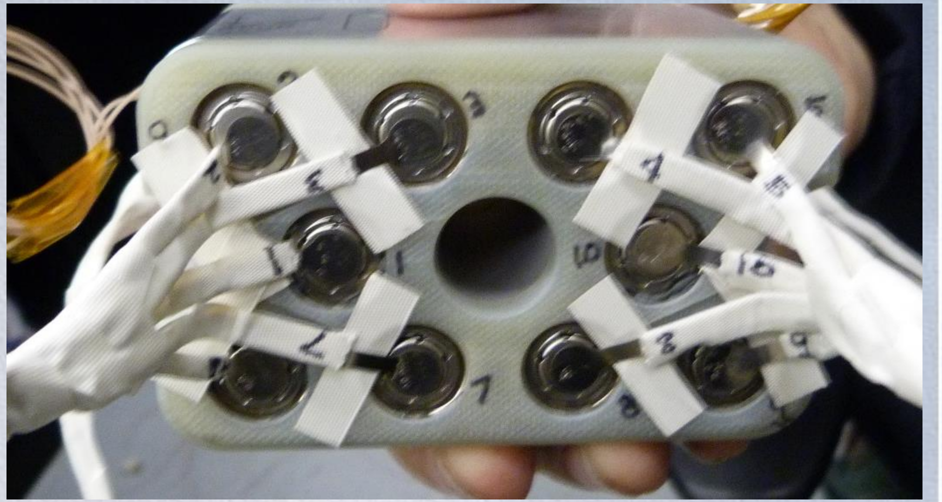


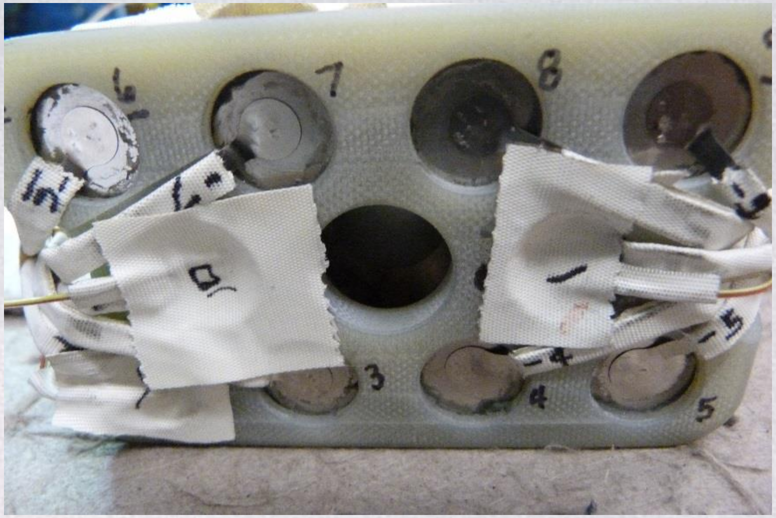




LPGT Assembly Photos



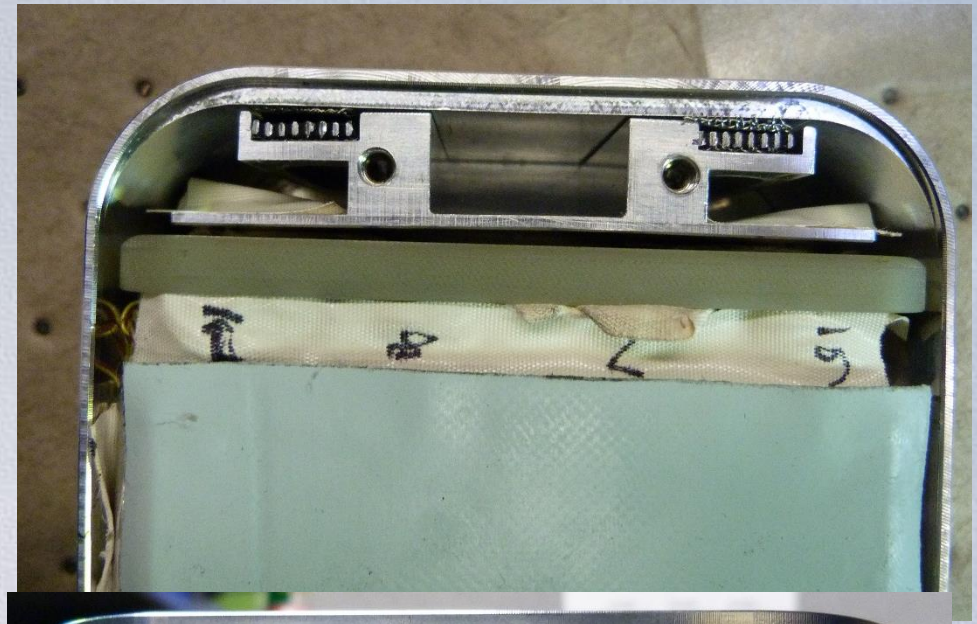


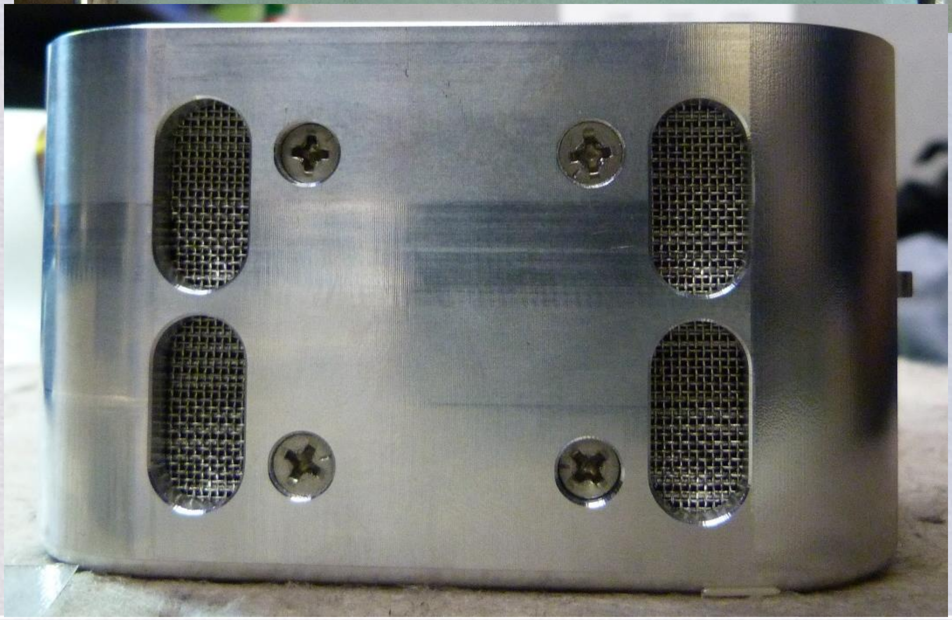


Brick Details

- Cell wrapped in 0.004” mica with ¼” overlap
- Inserted into Al heat spreader block with all cells same orientation
- Block leave ½” bottoms of cell can exposed for heaters and TCs
- Trigger cells: E2 and E10
- Adjacent cell TCs stuck through mica windows
- TCs on trigger cells placed on negative tabs
- Tab/wire/fuse assemblies routed through half cylinder cut outs and center hole of block left open

LPGT Assembly Photos



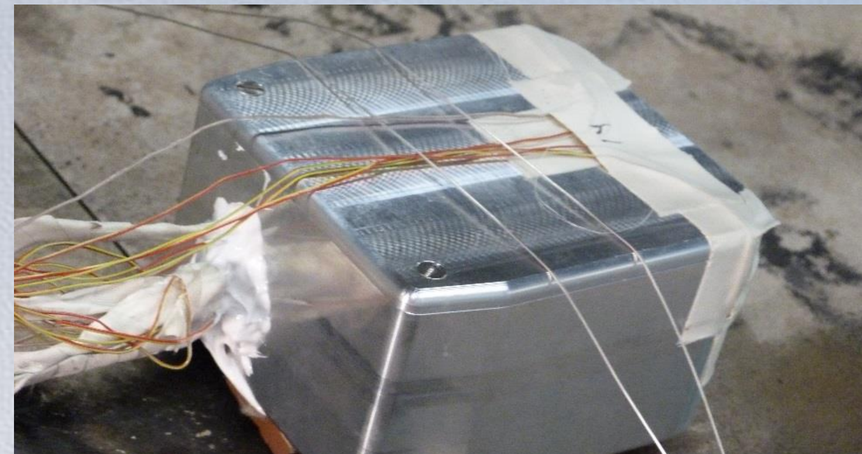


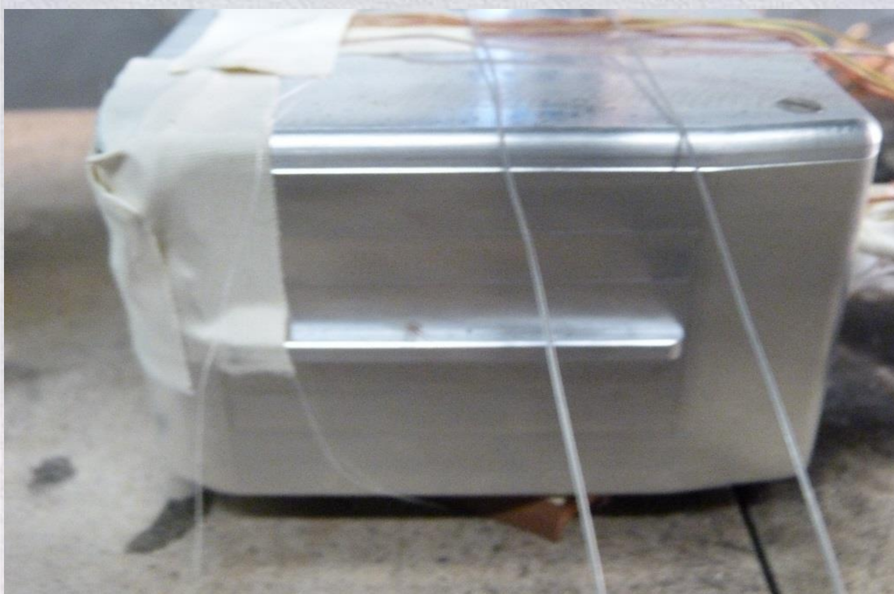
Assembly Details

- Cell vents point towards discharge connector
- Most of cell ejecta routed through center hole of heat spreader towards baffle of bracket
- 2 orthogonal layers of 1/16” CFC and 2 thin stainless screens per vent port
- Housing vent port geometry changed to provide structural support to the screens
- Only one 0.02” gap pad fit – placed between block and lid

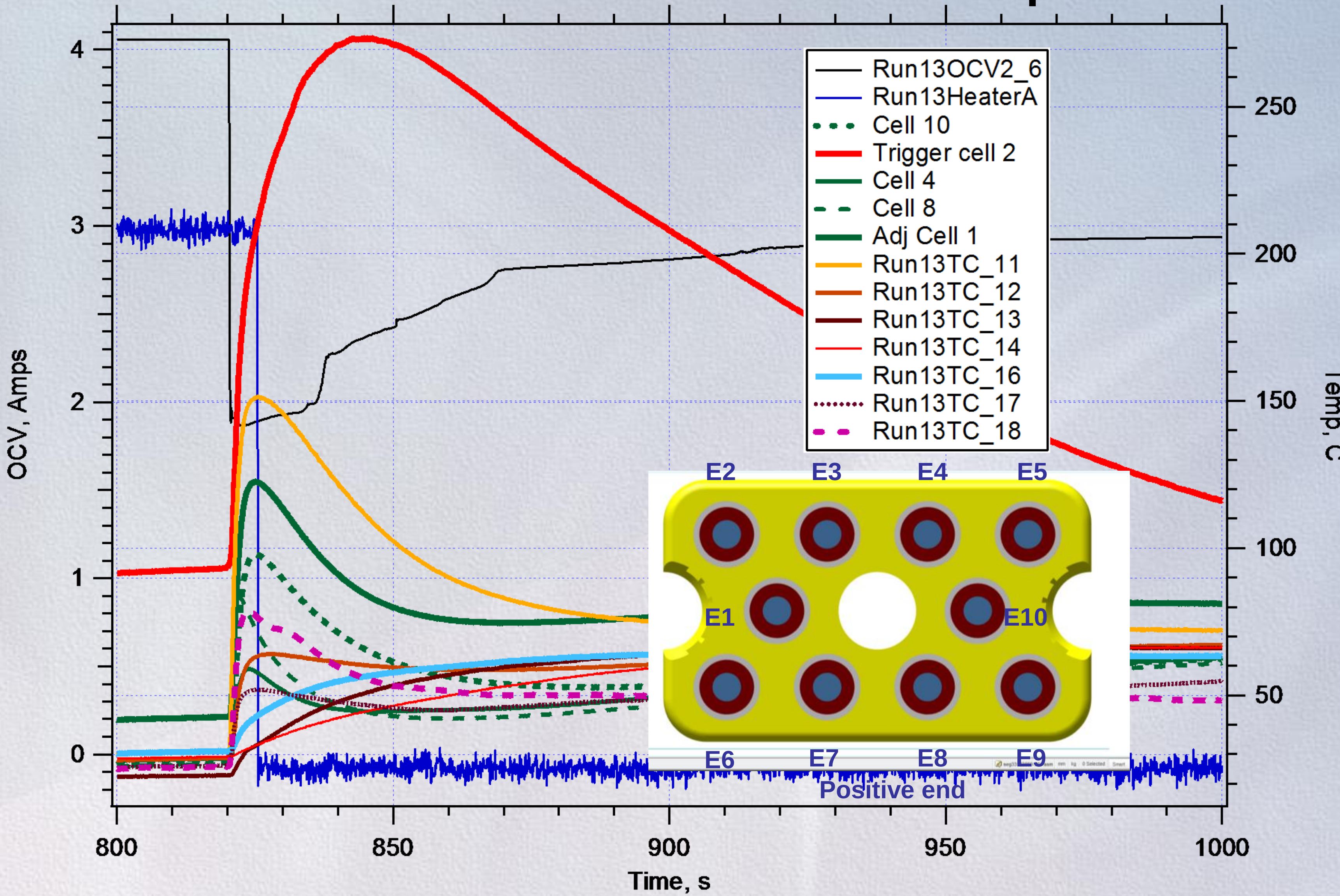
Run 13 Pre-Test Photos

- Lid/housing seated firm with four 6-32 screws
- Discharge connector opening filled with wires and sealed with caulk
- Vent ports, lid, and housing instrumented with TCs





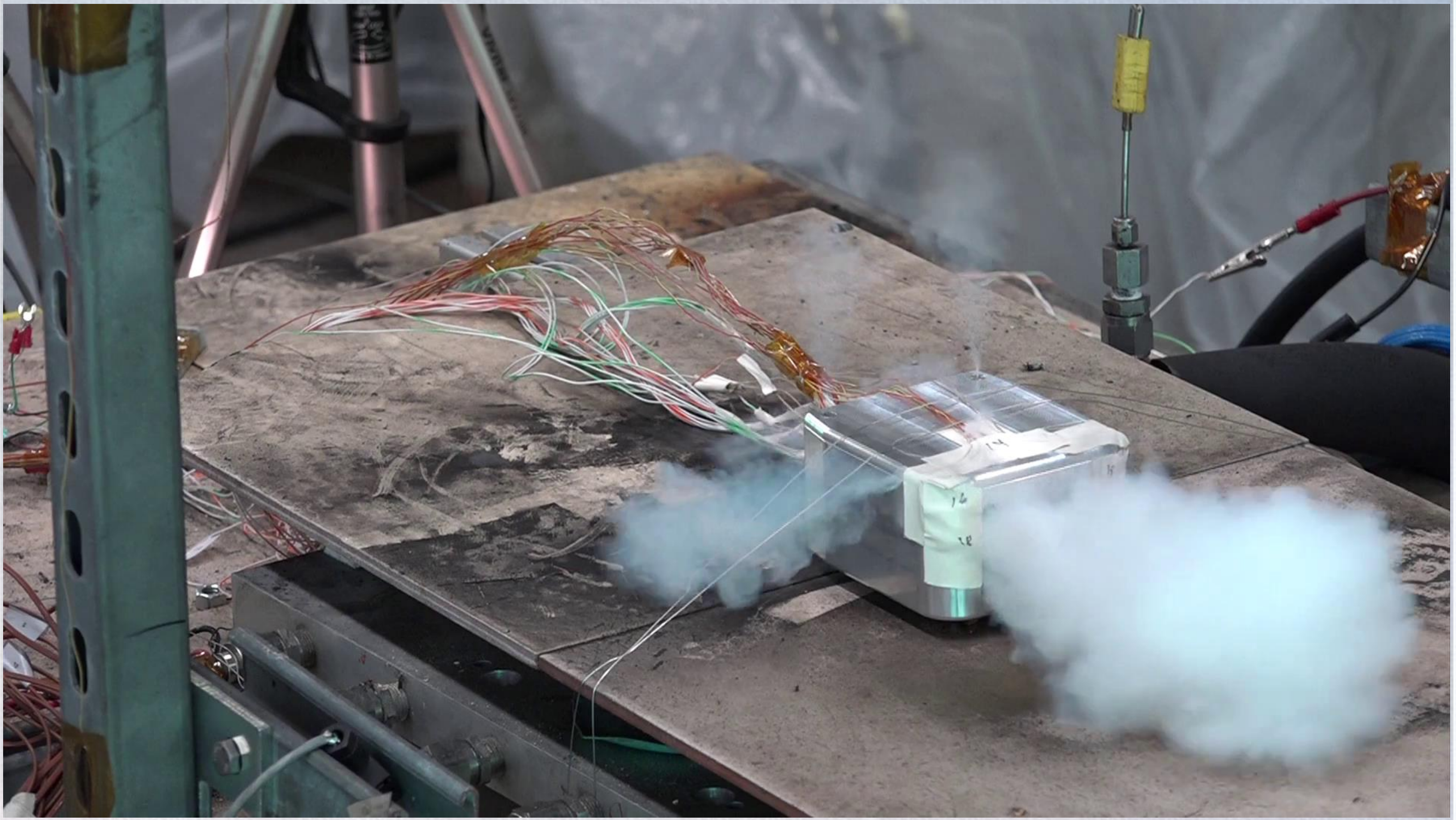
LPGT Run 13 – Close up



Unfortunately, we lost TCs of adj cell 3 and cell 6.

From hottest to colder: E2, inside near disch connector, E1, E10, E8, Trigger side vent port

Video Snapshot – No sparks



A split second after trigger cell TR, most of the vent cloud exits the vent ports, the rest exits the housing to lid joint – All adjacent cell OCVs unaffected by test

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
- Parallel cell bussing can provide significant in-rush currents into failed cell, which gets them hot:
  - Individually fusing parallel cells is effective
- 18 LREBA and 7 LPGT full scale tests with no propagation
  - Last 8 LREBA runs with interstitial materials reduced adjacent cell max temp, resulted no OCV decline even with 20% higher energy density cell design
- Soft goods bag needs reinforcements
  - Additional Ni foil layers help, but flame arresting carbon fibercore found to be more 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
- Subscale test results can be misleading and no replacement for full scale test verifications

Acknowledgements

- Chris Iannello/NASA-NESC for the vision that TR severity reduction was possible without big performance impacts and securing funding for the effort
  - Fiery 1st full scale test result
  - By end of Oct, we've achieved 8 runs with no propagation
    - Last 2 runs with no sparks, flames, or flare leaving the enclosure

Acknowledgements (cont.)

- TR Severity Reduction Team
  - Paul Shack, Assessment Lead
  - Chris Iannello, NESC Technical Fellow for Electrical Power, and Deputy, Rob Button
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