Insights from Safety Tests with an On-Demand Internal Short Circuit Device in 18650 Cells

By

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Outline

- 5 Design Guidelines
- Trading thermal isolation vs heat dissipation
  - Full thermal isolation
  - Drawing heat from cell bottoms
  - Full can length interstitial heat sink approach
- Risk of side wall rupture during thermal runaway
- New cell designs with cell bottom vent from Sony and LG
  - Vent & burst pressure
  - Thermal runaway performance
- Summary of findings to date
- Future work

Some of NASA’s Future Battery Applications

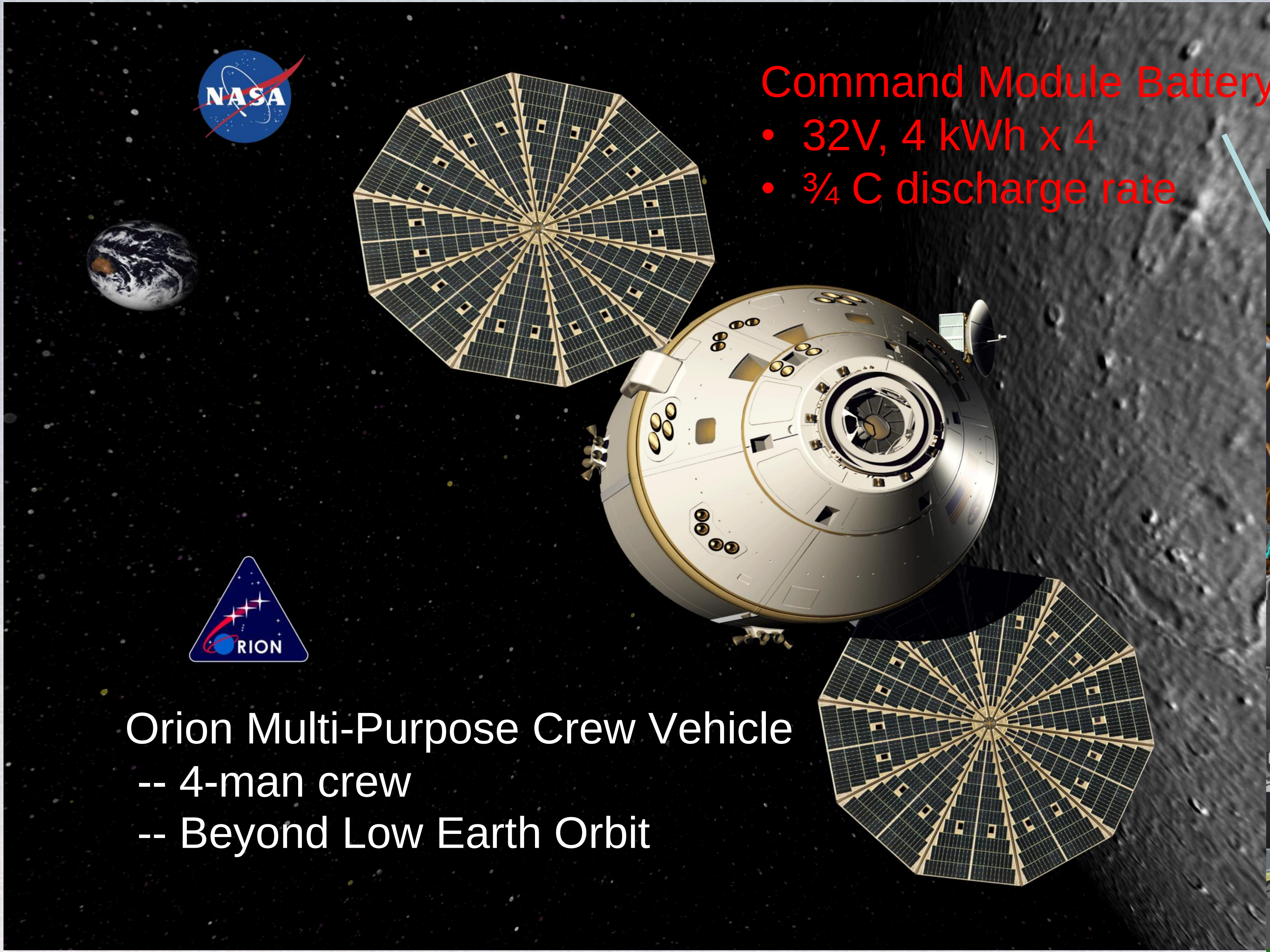
- Robonaut 2
  - To enhance and reduce frequency of manned spacewalks
  - High energy density and high specific energy battery needed
  - 90V, 4 kWh, 7 hour mission
- Mars Rover Vehicle
  - Terrestrial demonstration vehicle needing high voltage, power battery
  - 400V, 4 kWh, 1 hour mission
- Valkyrie, RoboSimian
  - Terrestrial dangerous operations robot
  - 90V, 2kWh, 1 hour mission
- X-57 Electric Plane
  - All electric aircraft demonstrating distributed electric propulsion
  - 525V, 50 kWh, 1 hour mission

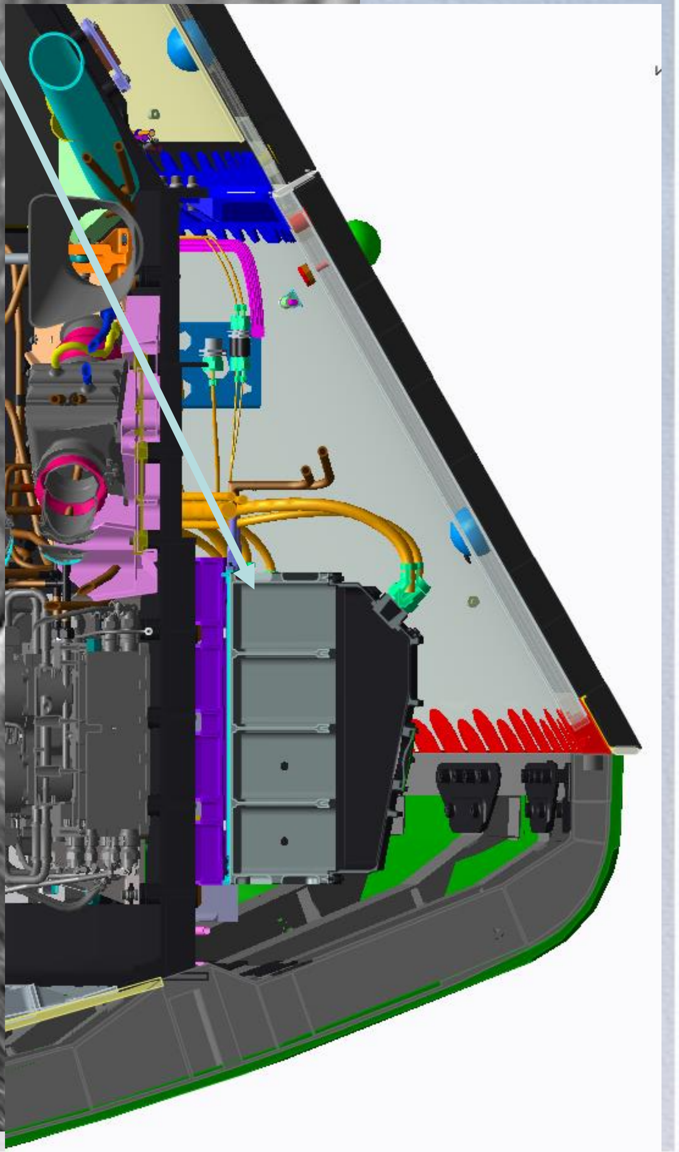
RoboSimian

X-57 Electric Plane

Command Module Battery System

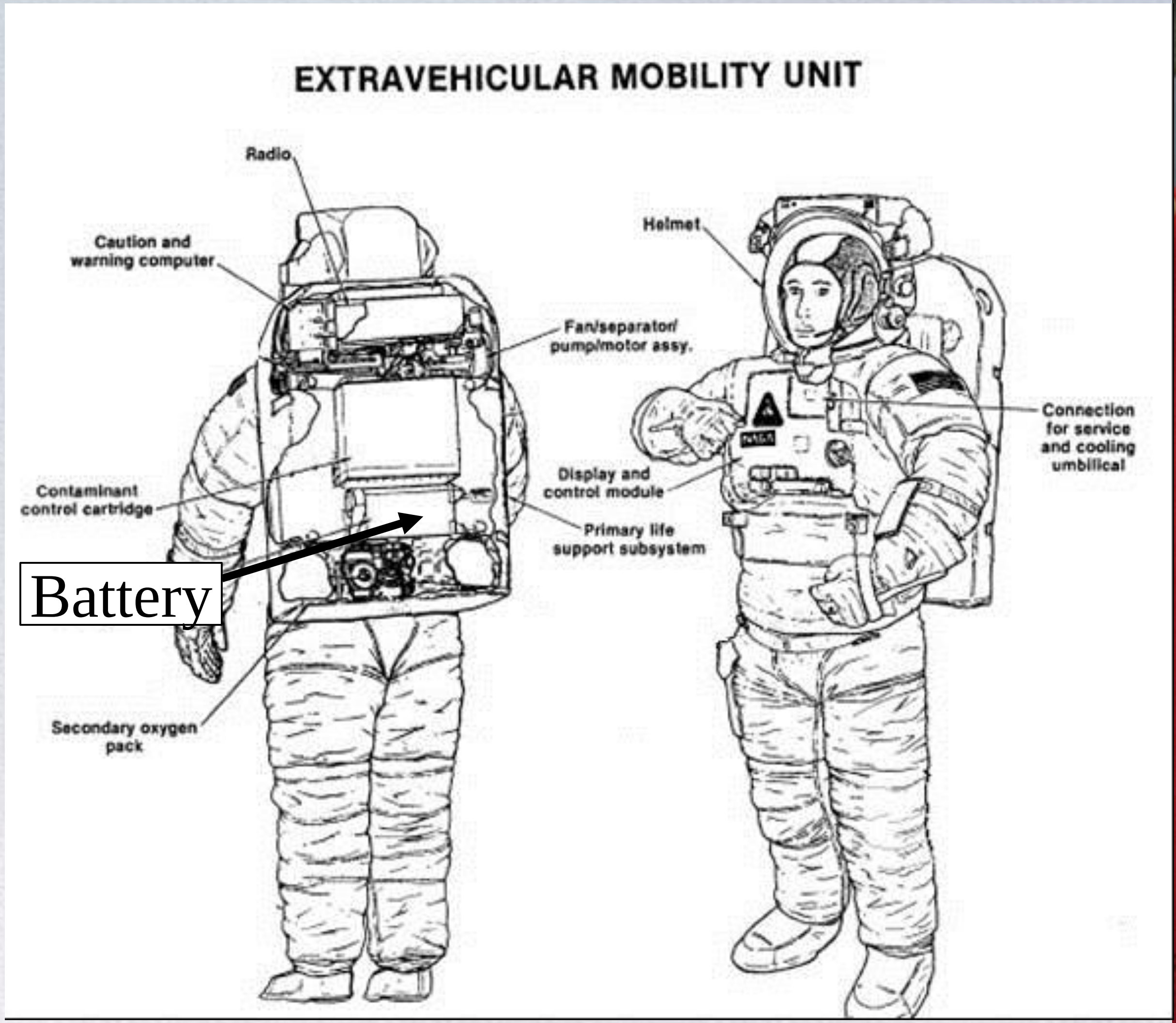
- 32V, 4 kWh x 4
- ¾ C discharge rate





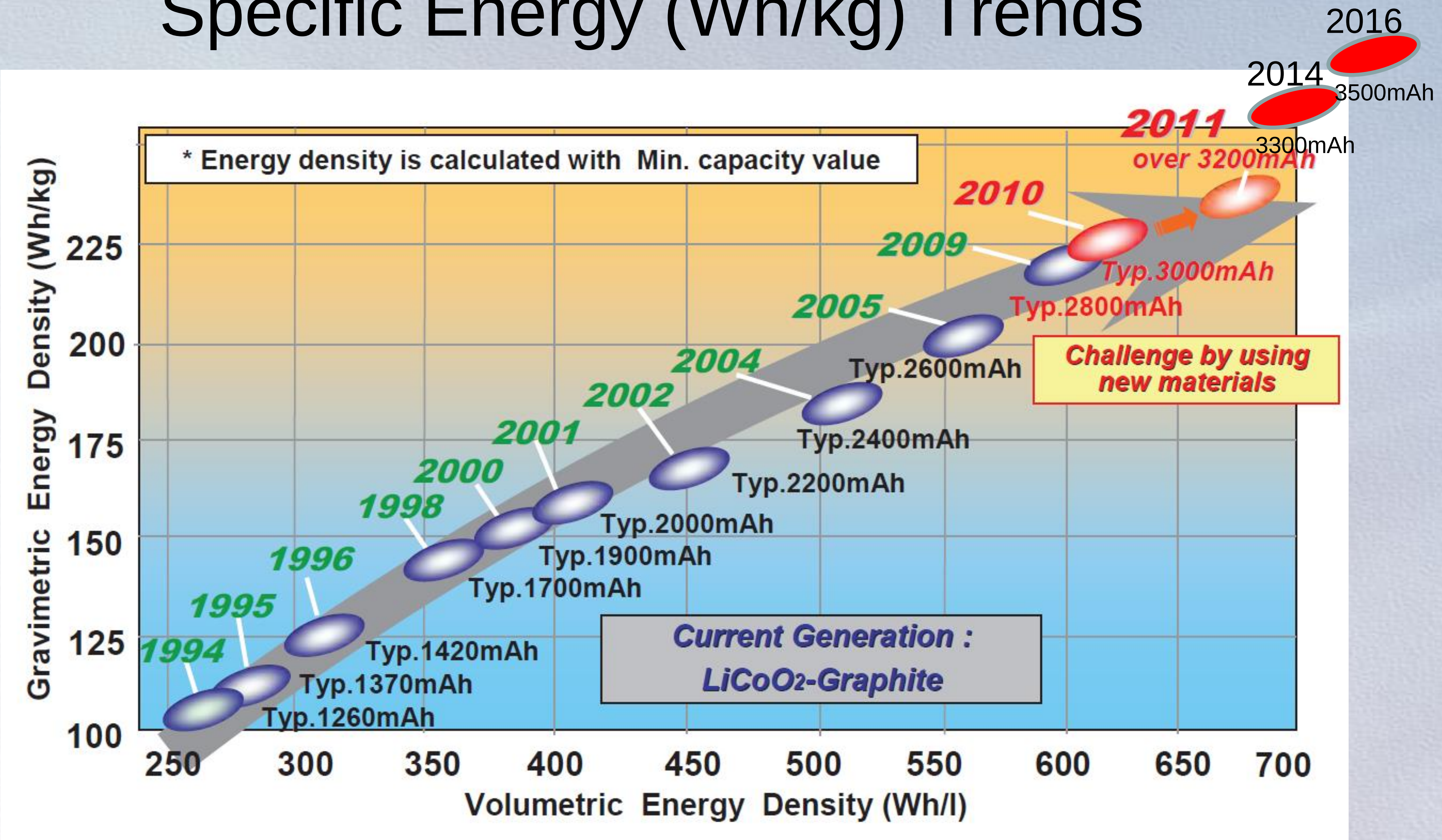
Orion Multi-Purpose Crew Vehicle
-- 4-man crew
-- Beyond Low Earth Orbit

Current Li-ion Spacesuit Battery



Used on over 22 spacewalks for far

Specific Energy (Wh/kg) Trends

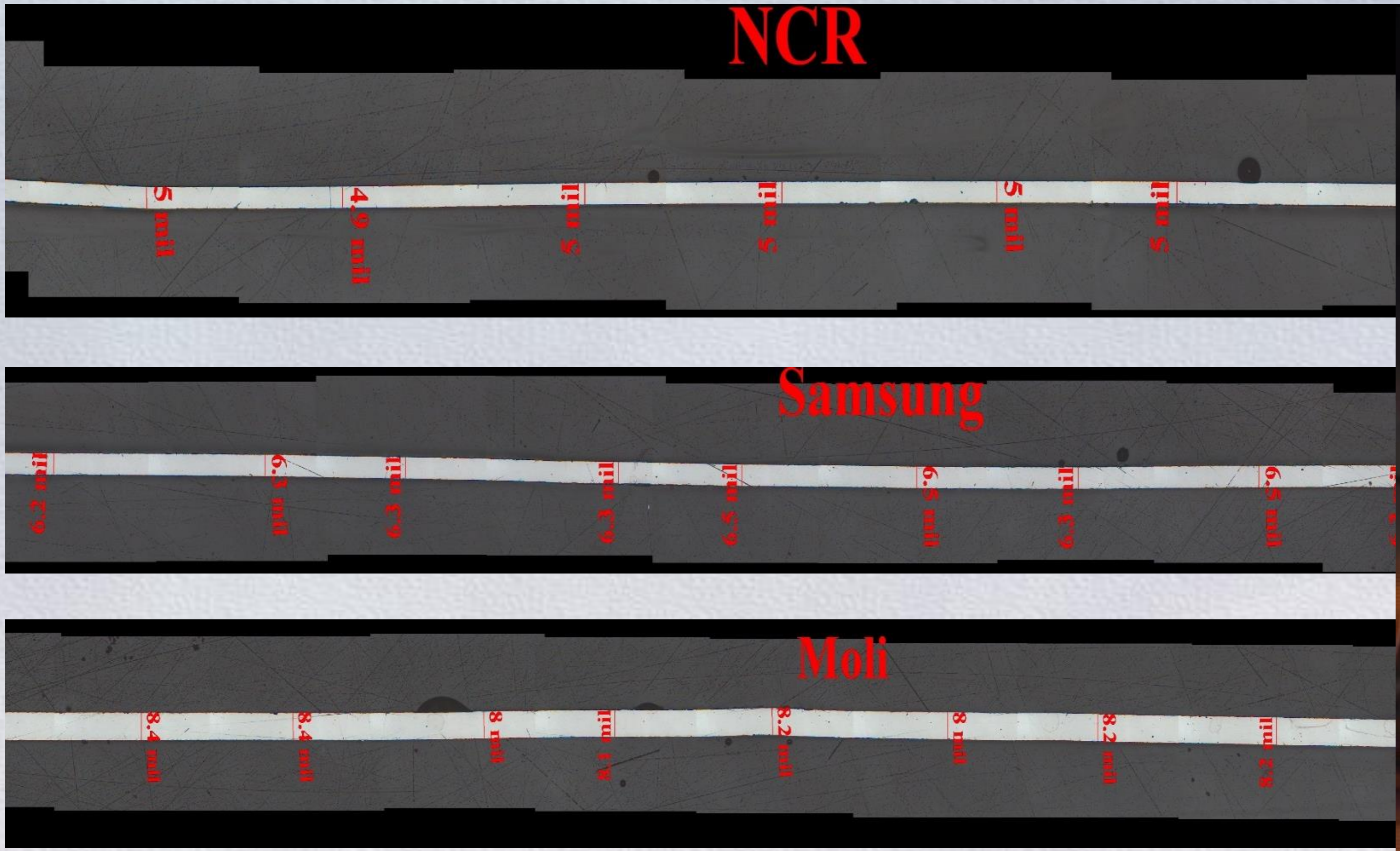


Source: Sanyo/Panasonic 2010

A high production rate design that achieves > 240 Wh/kg and > 660 Wh/L exists since 2012

Specify energy improvements are trending at 7-10% per year….should get to 300 Wh/kg by 2017

Cell Can Wall Cross Sections

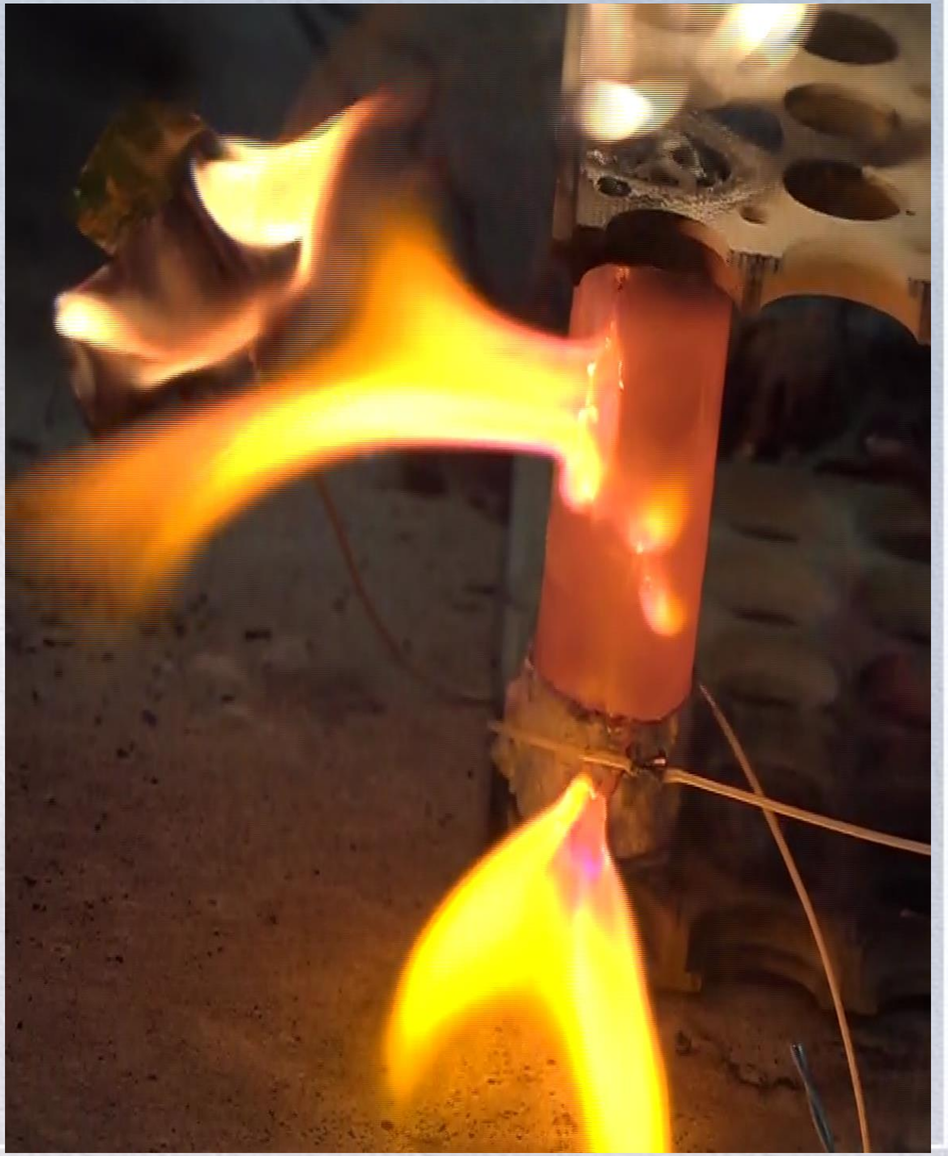


NCR18650B COTS design averages 127 μm
ICR18650-26F (2.6Ah Samsung) averages 160 μm
ICR18650J (2.4Ah Moli) averages 208 μm

Thin can wall with >660 Wh/L ➔ high propensity to side wall ruptures/breaching
Other factors include high reaction kinetics and high header crimp burst pressure

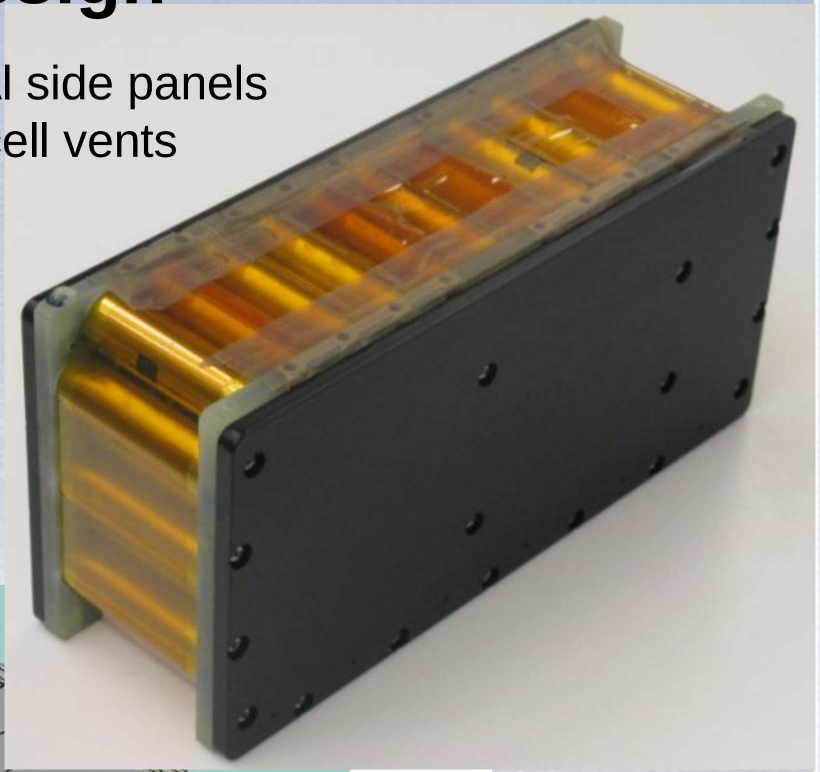
5 Design Driving Factors for Reducing Hazard Severity from a Single Cell TR

- Reduce risk of cell can side wall ruptures
  - Without structural support most high energy density (>660 Wh/L) designs are very likely to experience side wall ruptures during TR
  - Battery should minimize constrictions on cell TR pressure relief
- Provide adequate cell spacing and heat rejection
  - Direct contact between cells nearly assures propagation
  - Spacing required is inversely proportional to effectiveness of heat dissipation path
- 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
  - Provide tortuous path for the TR ejecta before hitting battery vent ports equipped flame arresting screens



Current Spacesuit Battery Design

Solid Al side panels block cell vents

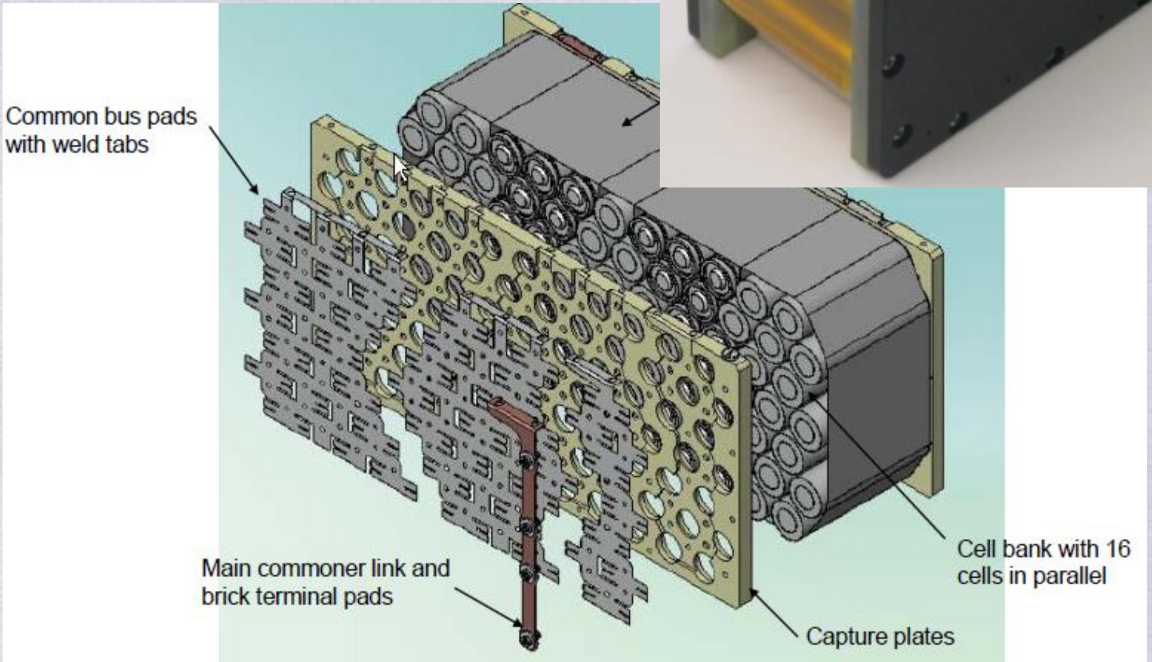


Design Features

- 80 Li-ion cells (16p-5s)
- ICR-18650J from E-one Moli Energy (2.4Ah)

Compliance with the 5 rules

- Minimize side wall ruptures ✓
- No direct cell-cell contact ✓
- Individually fusing cell in parallel ✗
- Protecting adjacent cells from TR ejecta ✗
- Include flame arresting vent ports ✗

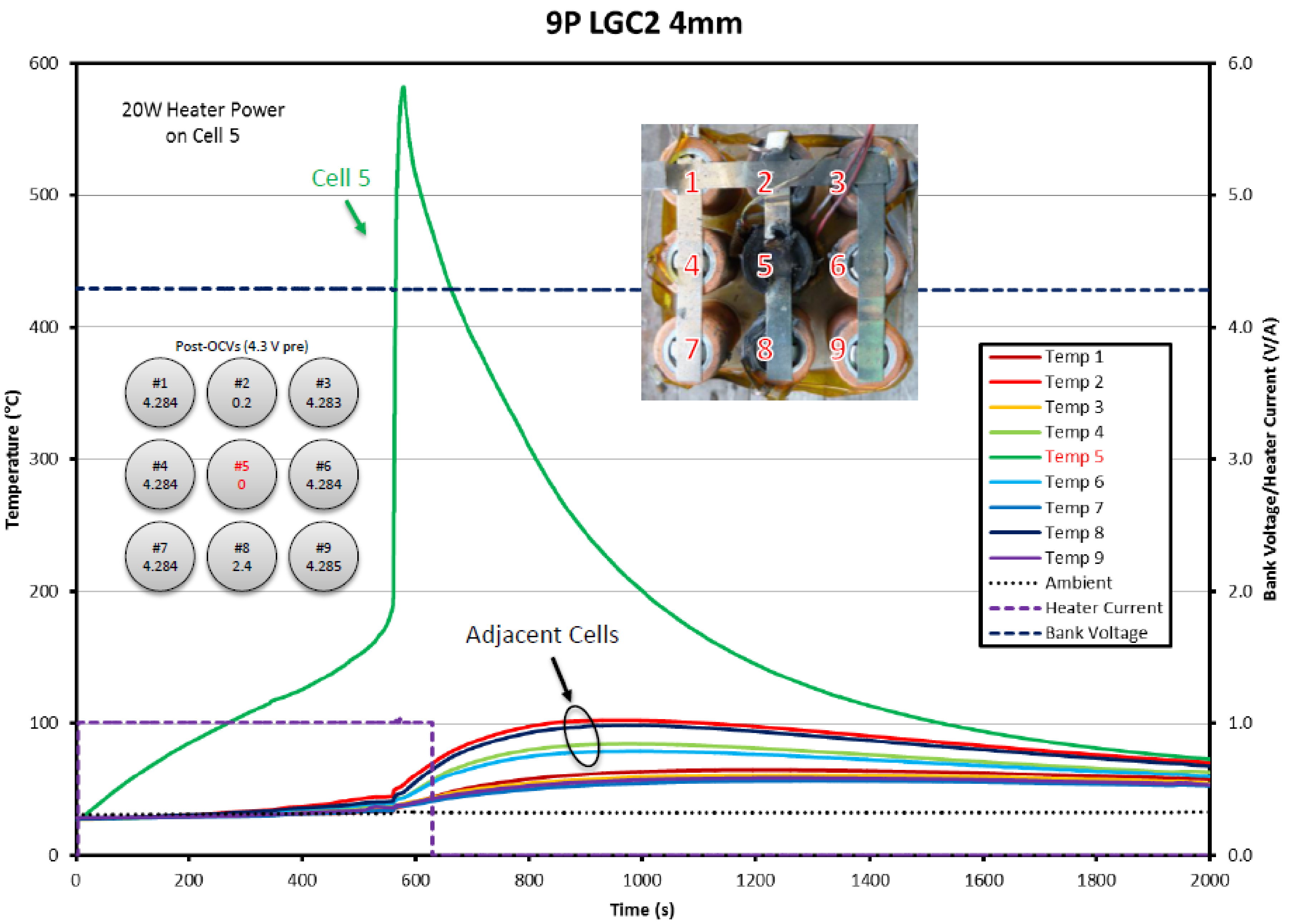


Design Propagates TR – Catastrophic Hazard

Battery external surfaces reach 350°C
Vented some sparks and much smoke for > 15 min

Thermal Isolation Example – 4mm air spacing between cells

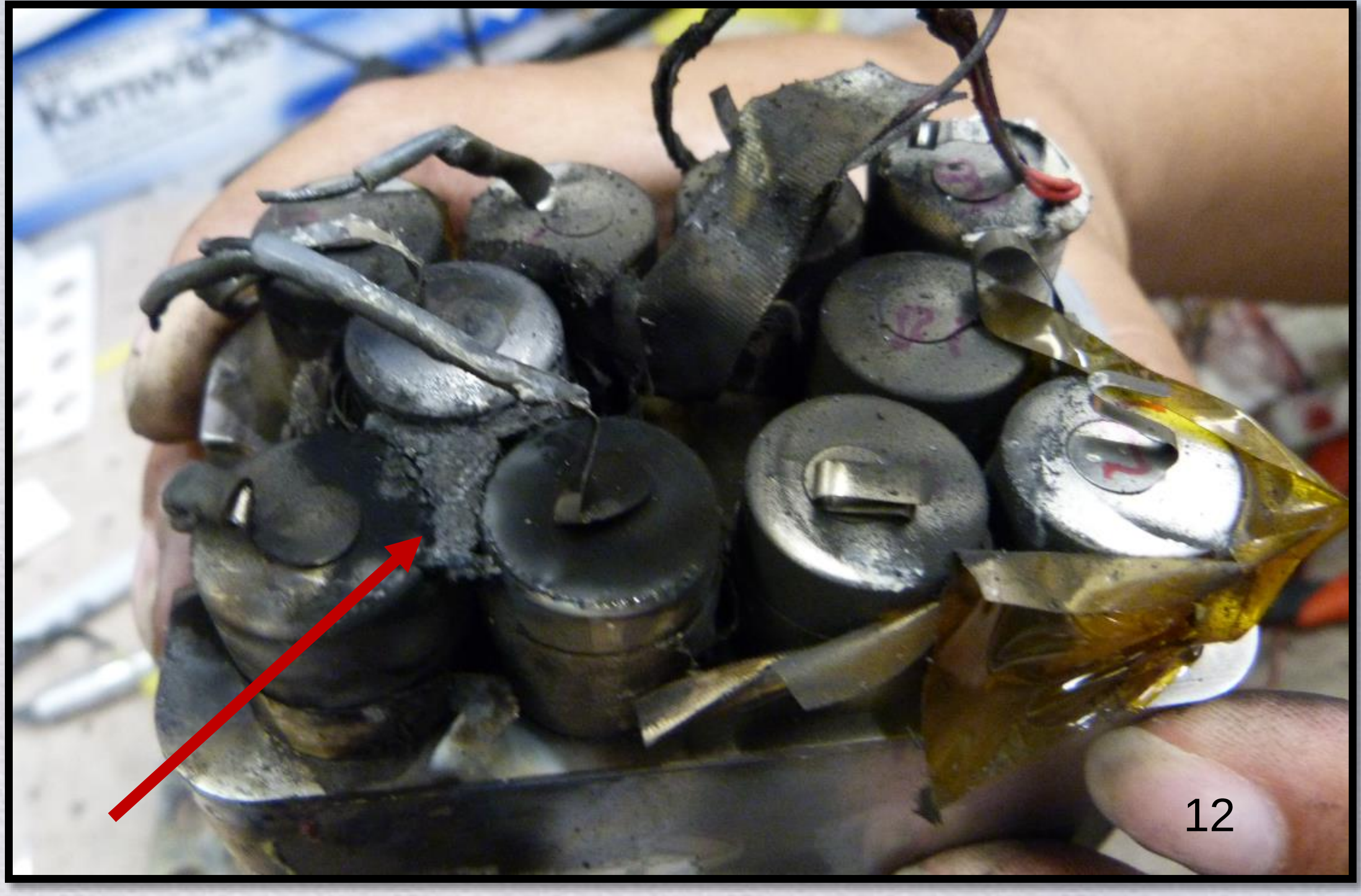
Pre-Test



Jeevarajan et al. from 2014 Workshop showed that without any heat dissipation path except through electrical parallel connections, adjacent cells get damaged (shorted) with even 4 mm spacing

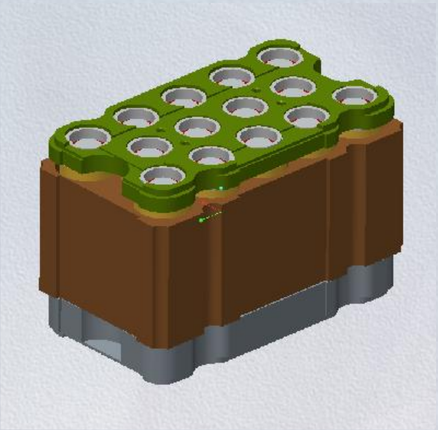
VHS TR Test with Panasonic NCR18650B Cells

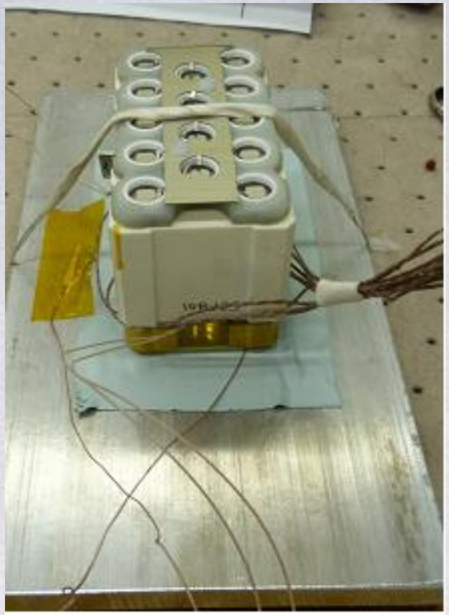
Side wall ruptures will even defeat very high flux heat rejection paths!

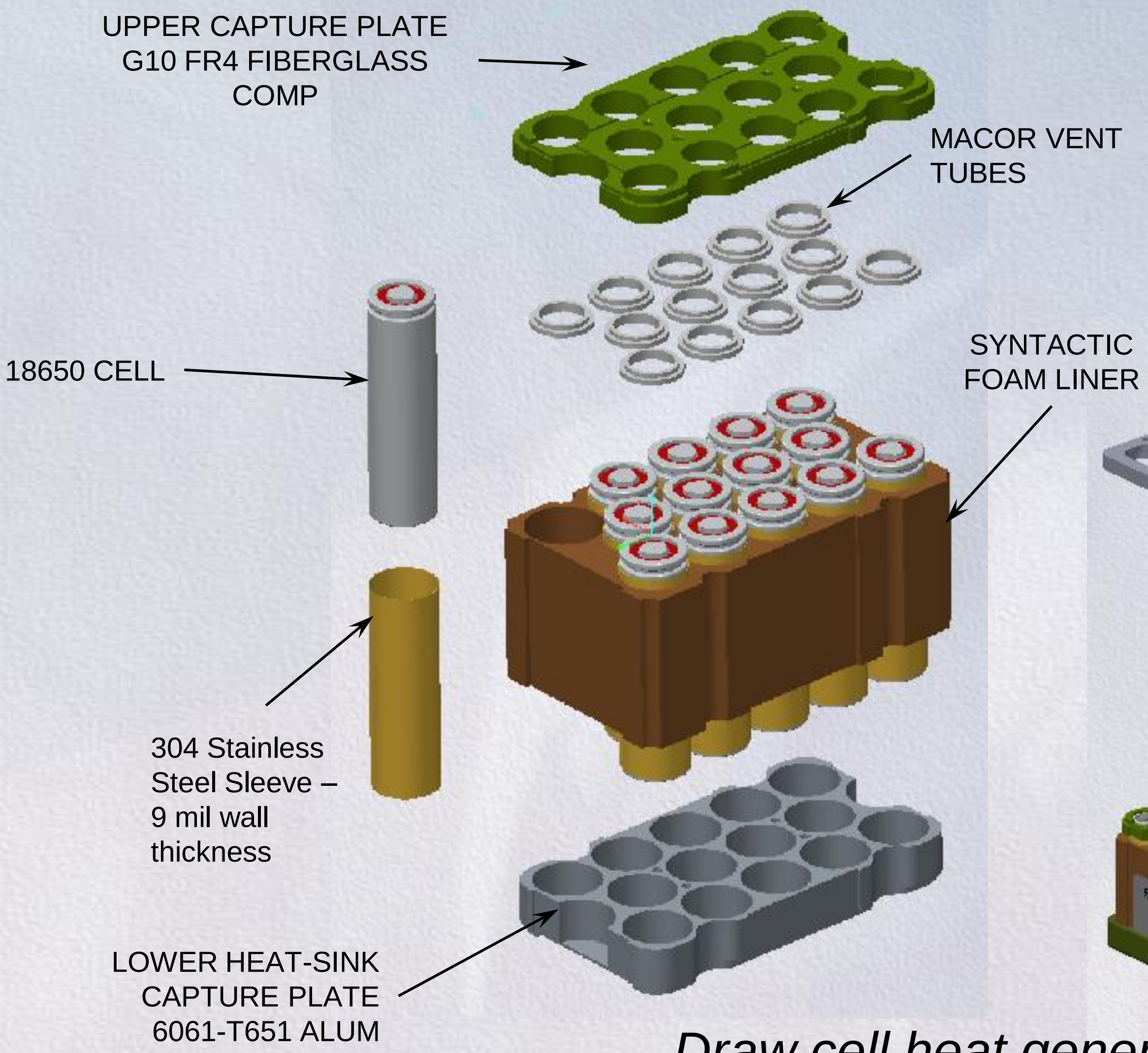


- Vaporizing Heat Sink (VHS) leaves 10mm of cell can wall bottoms exposed
- 2mm spacing between cells
- Trigger cell had side wall rupture in circumferential heater area which impinged TR ejecta into adjacent cell
- Resulted in propagation to two additional cells and damaged several others

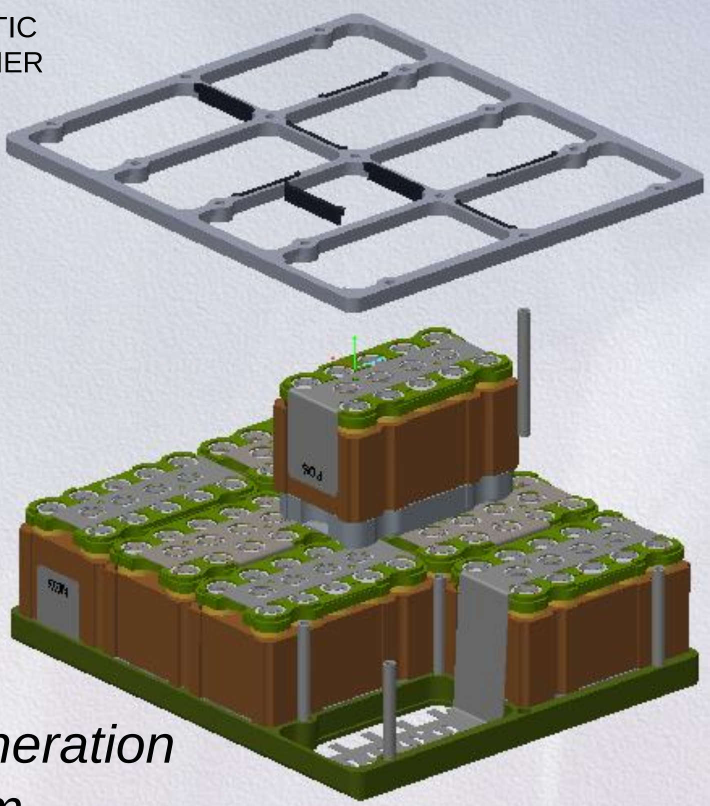
Orion Battery 14-cell Block





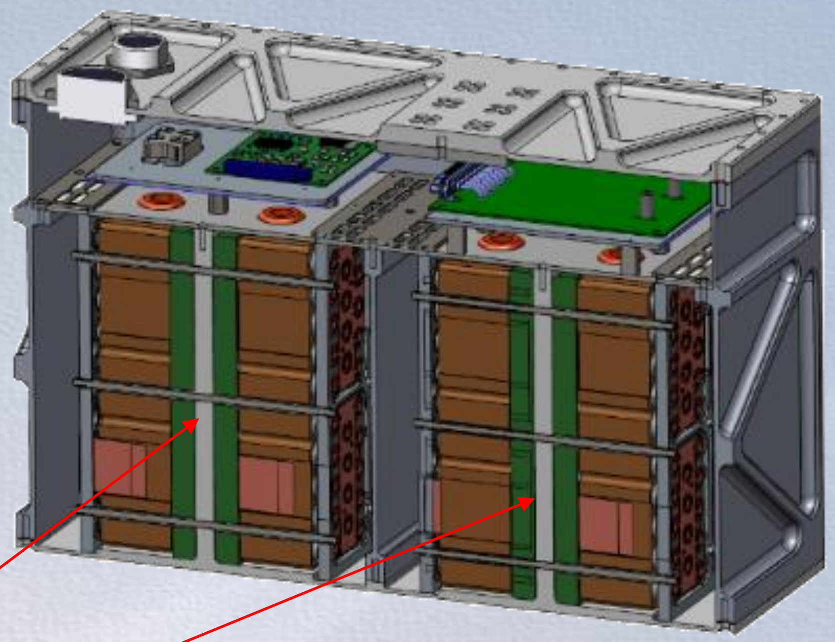


Orion 14P-8S Superbrick

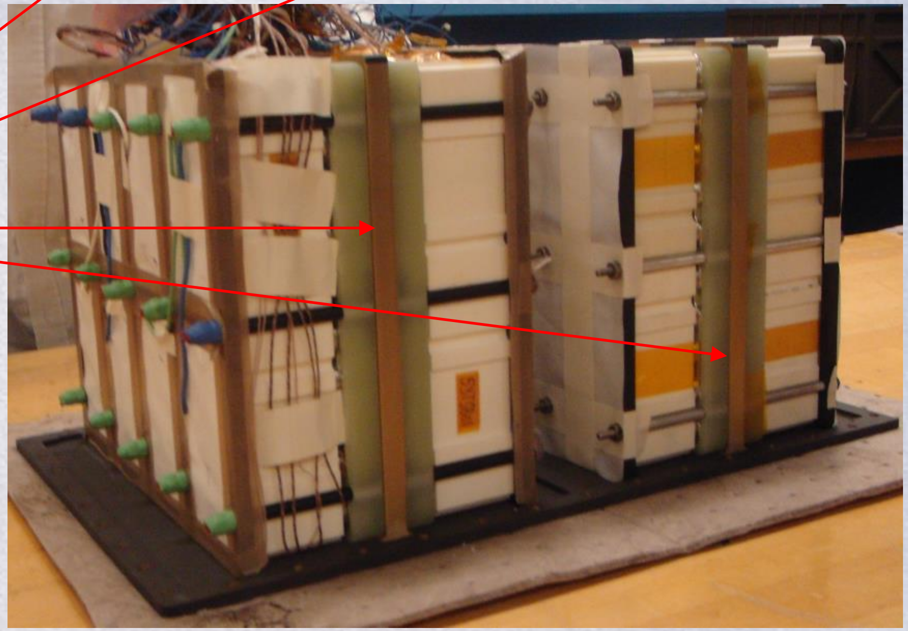


Draw cell heat generation through cell bottom

Isolating vs Providing a heat path



- If you thermally isolate cells (air)
  - Adjacent cell ΔT rise 80-100°C
  - ***Limited to cell designs with little risk of side wall ruptures***
  - Achieves 160-170 Wh/kg
- Orion - Partially conductive (Draw heat from cell bottom)
  - Conduct heat to divider plate
  - Adjacent cell ΔT rise 60-70°C and shorter exposure
  - 14P-8S superbrick with SS sleeves achieves 150-160 Wh/kg



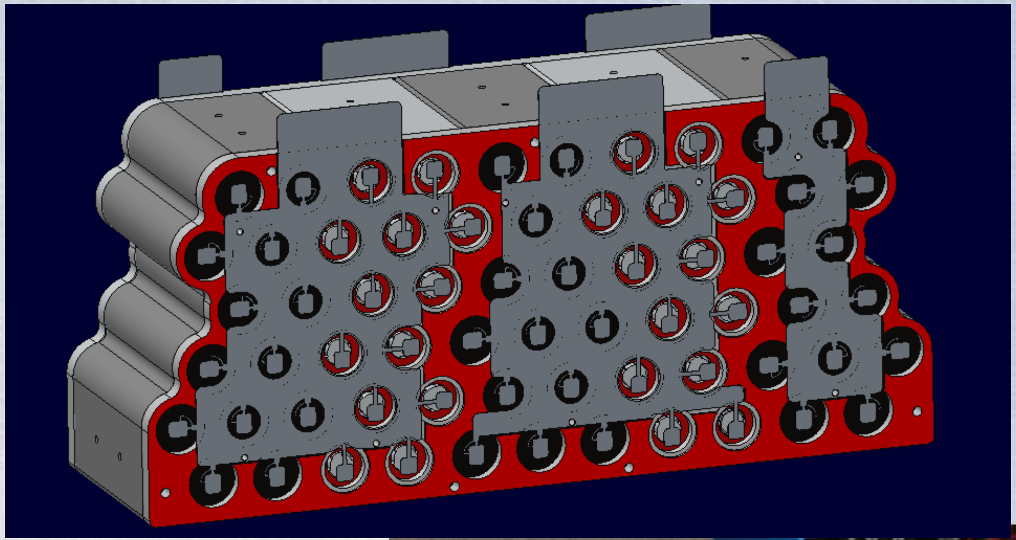
Safer, Higher Performing Battery Design

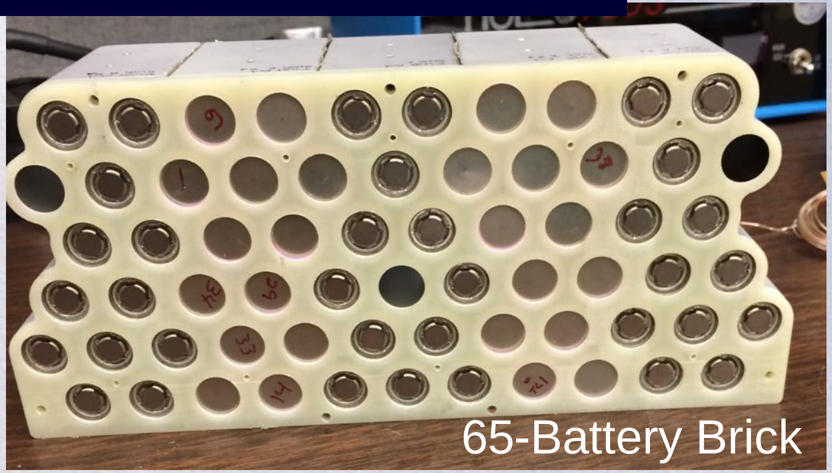
Compliance with the 5 rules

- **Minimize side wall ruptures** ✓
  - Al interstitial heat sink
- **No direct cell-cell contact** ✓
  - 0.5mm cell spacing, mica paper sleeves on each cell
- **Individually fusing cell in parallel** ✓
  - 12A fusible link
- **Protecting adjacent cells from TR ejecta** ✓
  - Ceramic bushing lining cell vent opening in G10 capture plate
- **Include flame arresting vent ports** ✓
  - Tortious path with flame arresting screens
  - Battery vent ports lined with steel screens

Features

- 65 High Specific Energy Cell Design 3.4Ah (13P-5S)
- 37Ah and 686 Wh at BOL (in 16-20.5V window)
- Cell design likely to side wall rupture, but supported

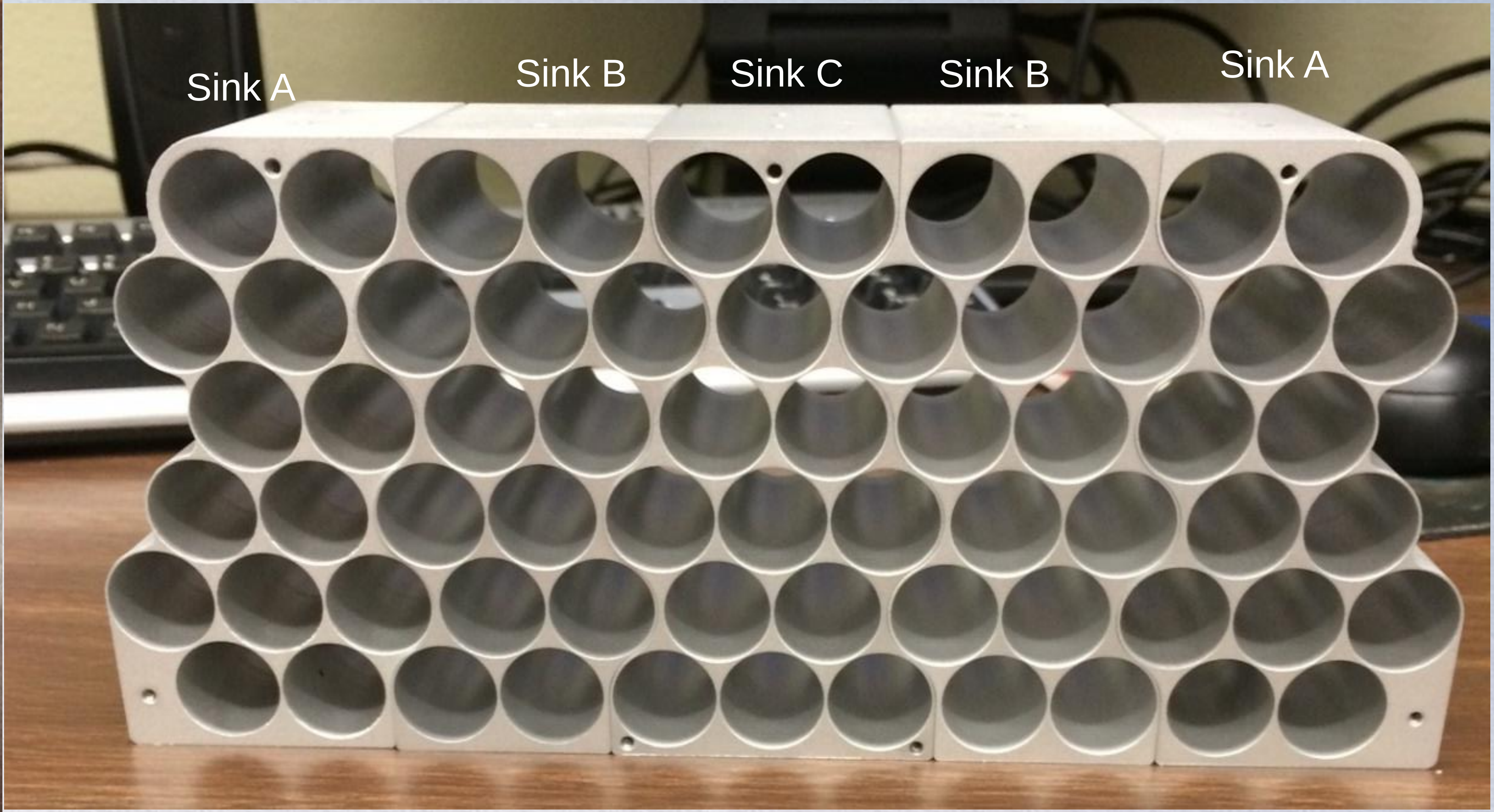




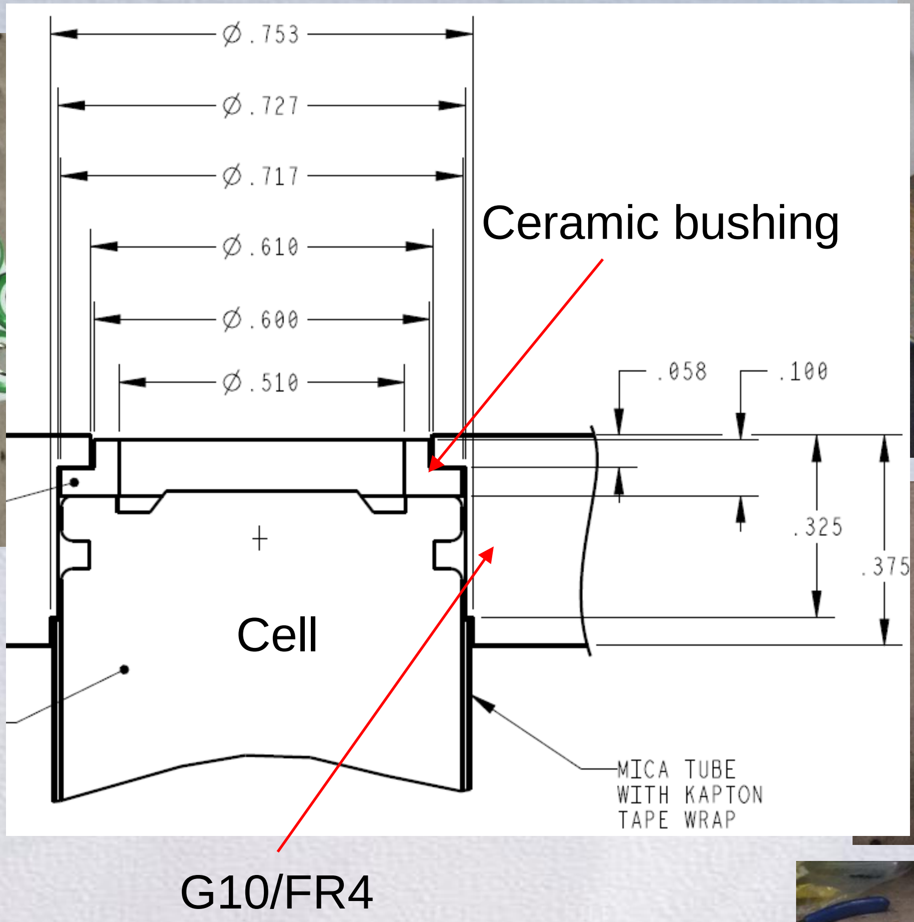
65-Battery Brick

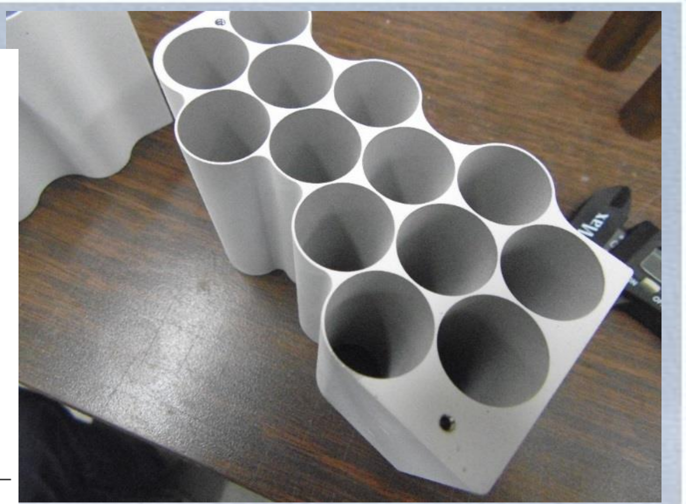
LLB2 Heat Sinks

No corner cells - Every cell has at least 3 adjacent cells



0.5mm cell spacing, Al 6061T6

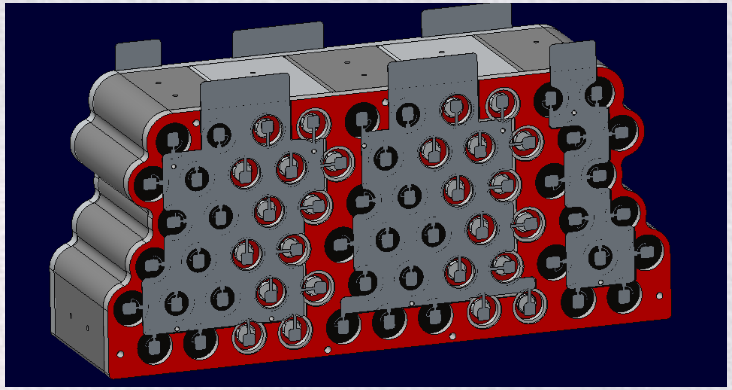




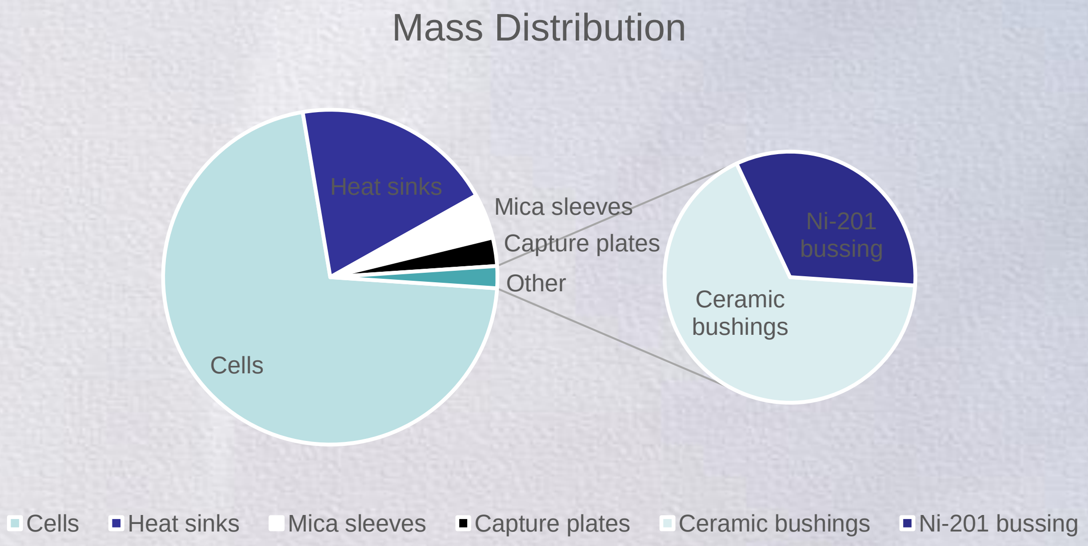
- 13P-5S Configuration with 3.4 Ah LG cell design yielding 37 Ah at 3.8 A mission rate.
- Aluminum interstitial heat sink, 0.5 mm spacing between cells
- Mica sleeves around shrink wrap, 2 FT
- The G10 capture plate houses the + and - ends of the cells and prevents the Ni bussing from shorting to the heat sinks.
- The ceramic Macor bushing acts as a chimney to direct ejecta outwards and protect the G10/FR4 capture plate

Cell Brick Assembly > 180 Wh/kg

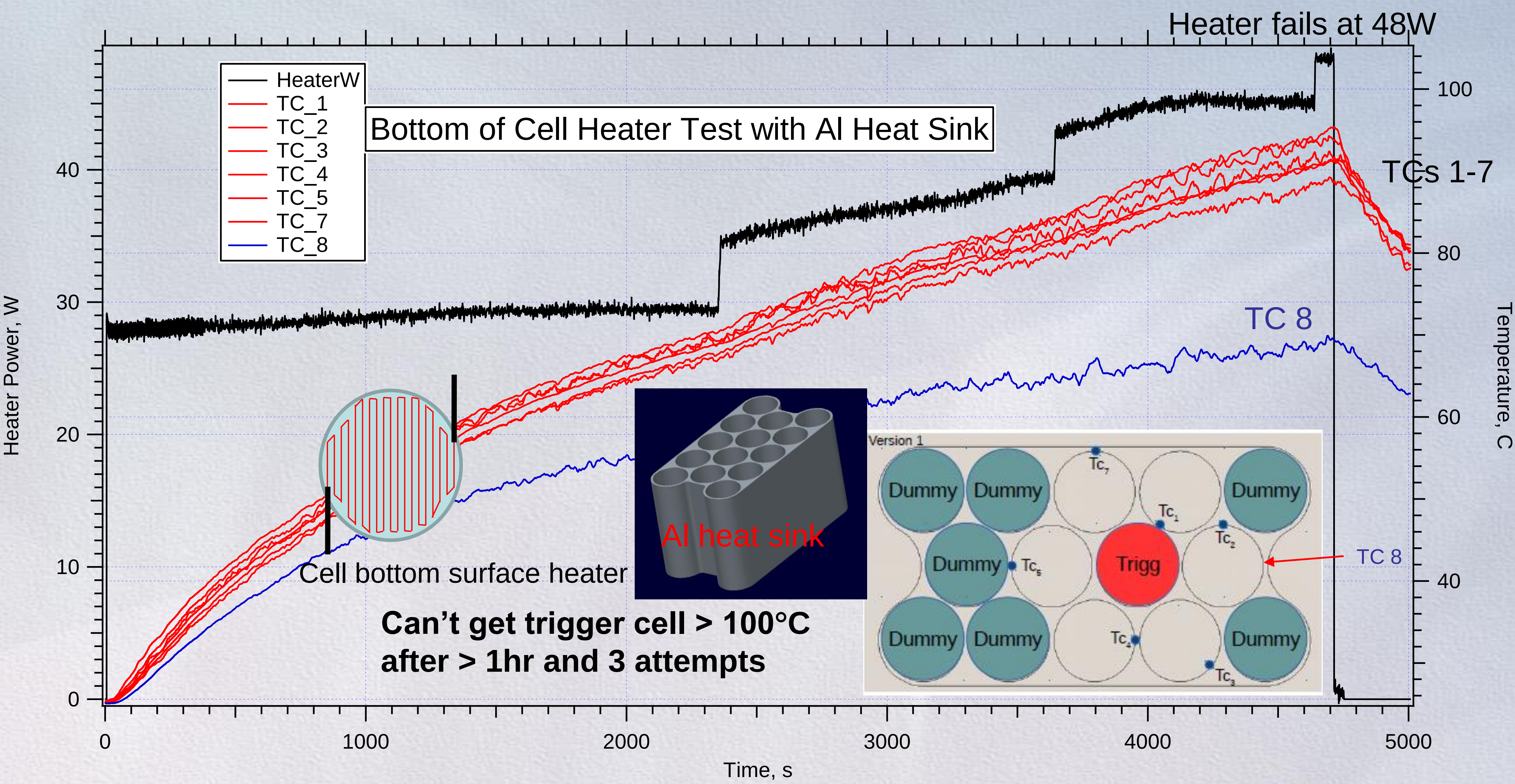
Mass Categories	g	%
3.4Ah 18650 Cells	3012.75	71.3%
Heat sinks	824.95	19.5%
Mica sleeves	182.31	4.3%
Capture plates	115.81	2.7%
Ceramic bushings	60.15	1.4%
Ni-201 bussing	29.71	0.7%
Total	4225.7	



- With 12.41 Wh/cell, cell brick assembly achieves 191 Wh/kg
  - Assuming 12.41Wh per cell
- Design has 1.4 parasitic mass factor
  - – Cell mass x 1.4 = Brick mass



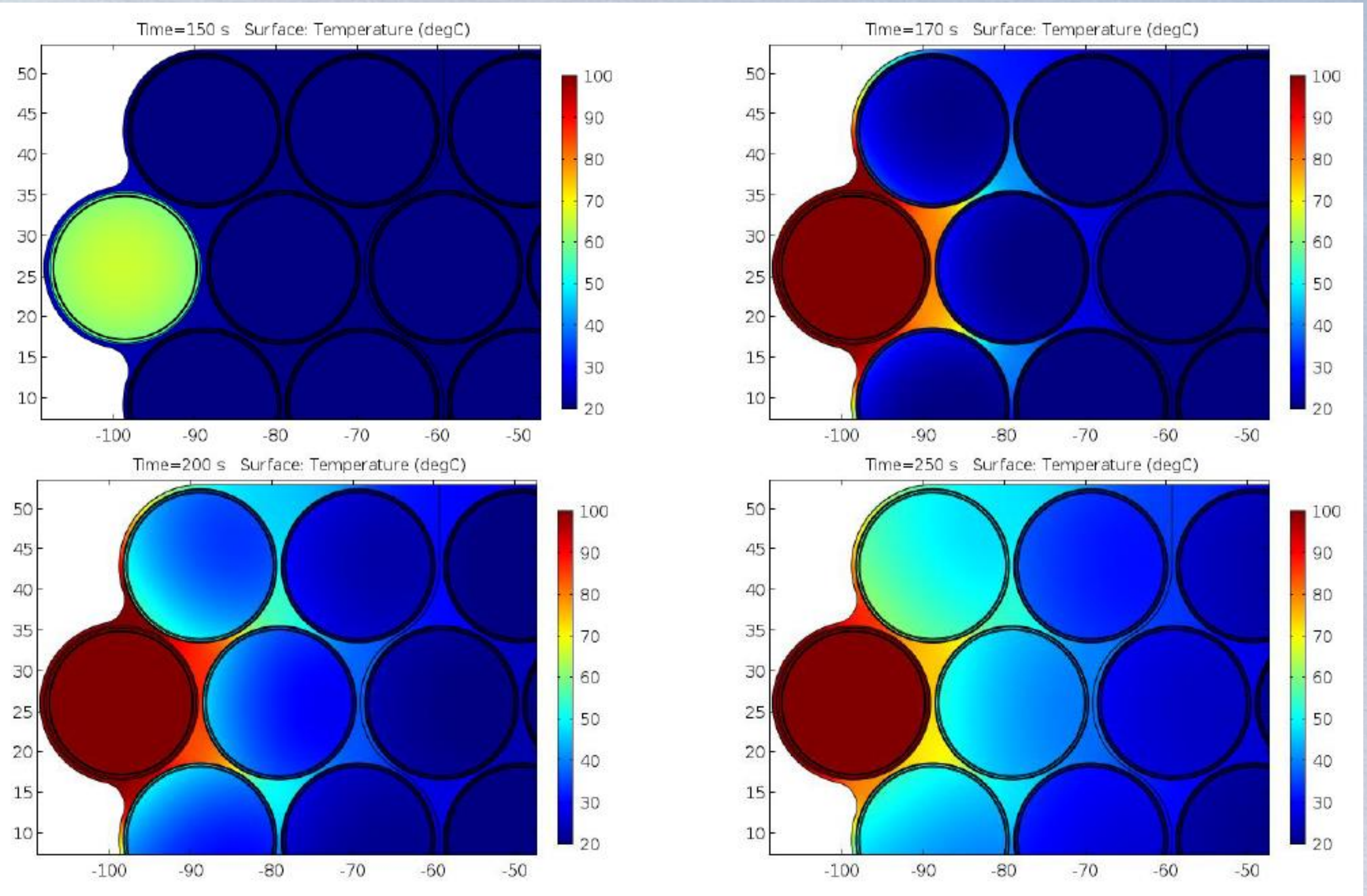
Attempts to Drive TR with Cell Bottom Heater Fails



Can't get trigger cell > 100°C after > 1hr and 3 attempts

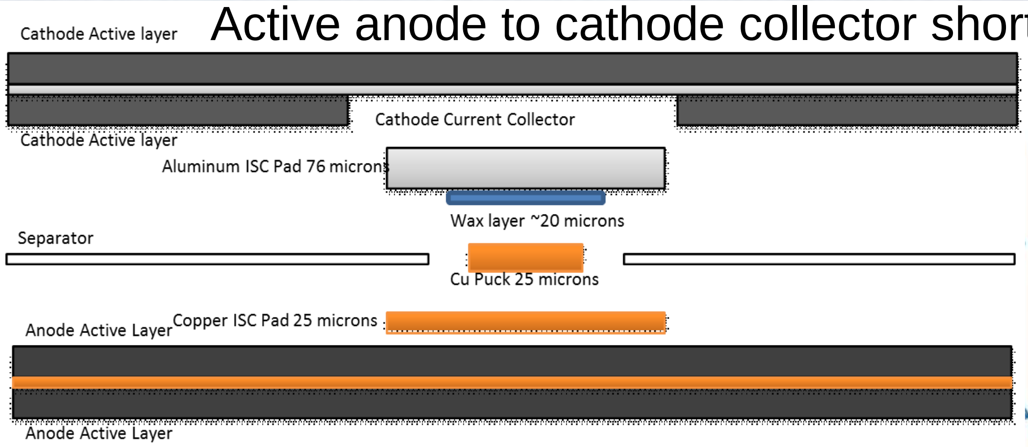
Metallic Interstitial Heat Sink is Effective

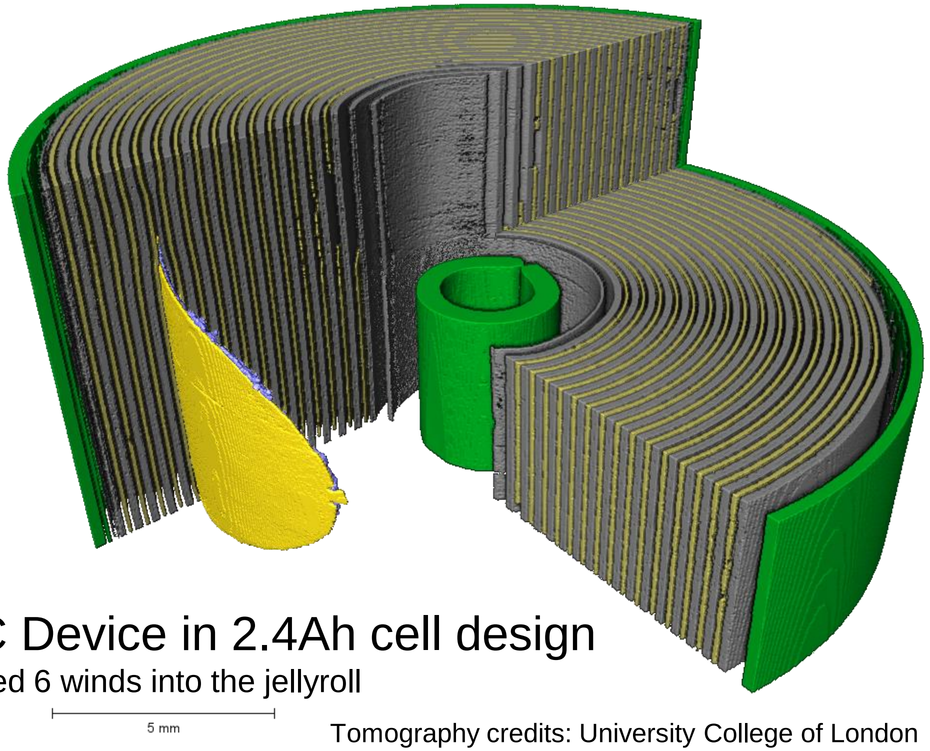
- Cell can isolated with mica paper sleeves and very small air gap
- Heat sink spreads heat more quickly through multiple layers than through mica and onto cells
- Heat from trigger cell is quickly dispersed and shared among more cells



Graphic and analysis courtesy of Paul Coman

NREL/NASA ISC Device Design

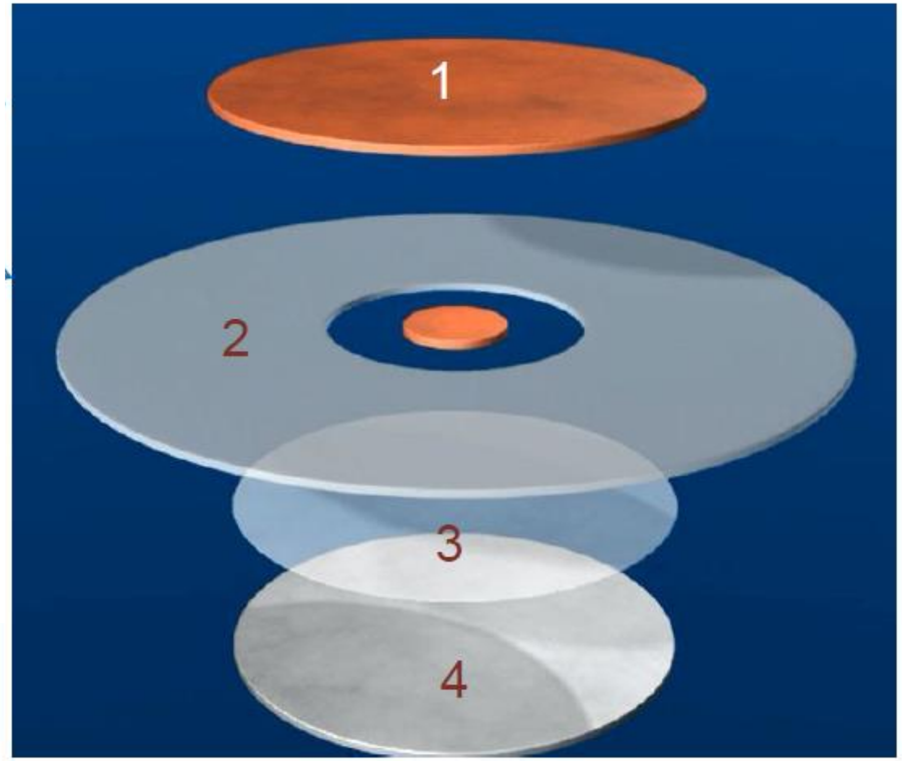




ISC Device in 2.4Ah cell design

Placed 6 winds into the jellyroll

Tomography credits: University College of London



Graphic credits: NREL

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

2010 Inventors:
- Matthew Keyser, Dirk Long, and Ahmad Pesaran at NREL
- Eric Darcy at NASA

US Patent # 9,142,829 awarded in 2015

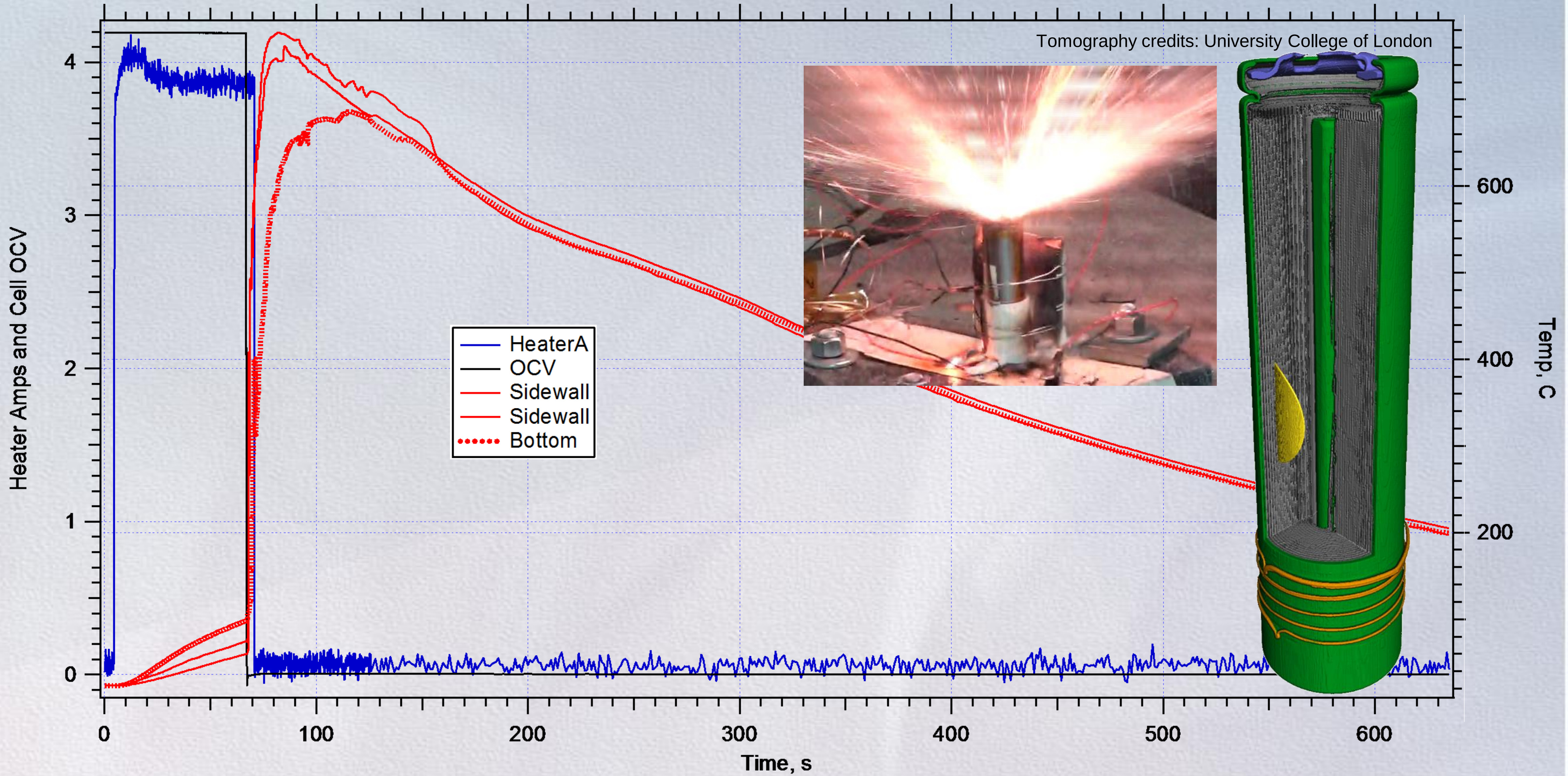
Wax formulation used melts ~57°C

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

R&D 100

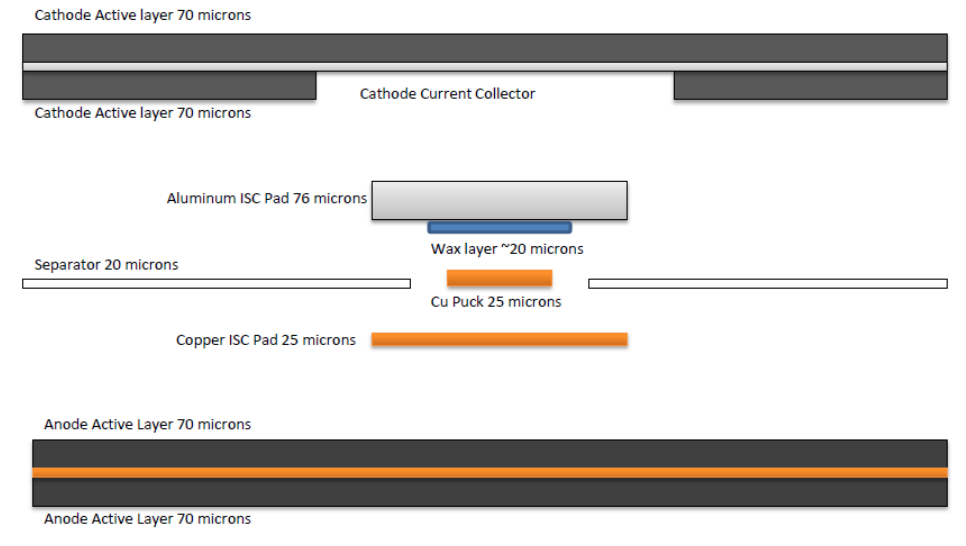
2016 Award Winner

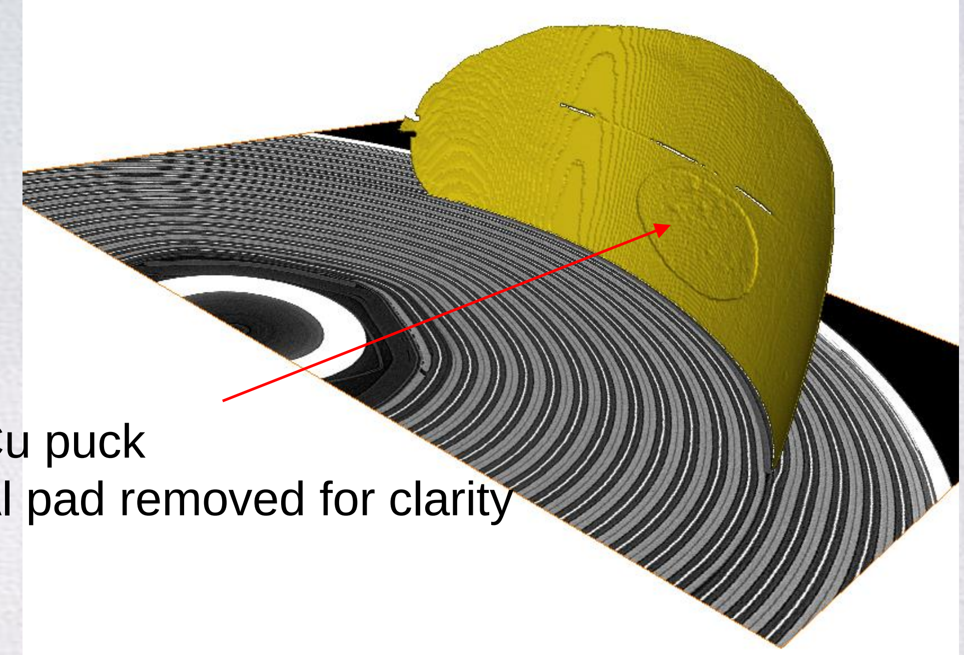
Single Cell TR – Moli 2.4Ah with ISC Device



Open air test with cell charged to 4.2V and with TCs welded to cell side wall (2) and bottom (1)

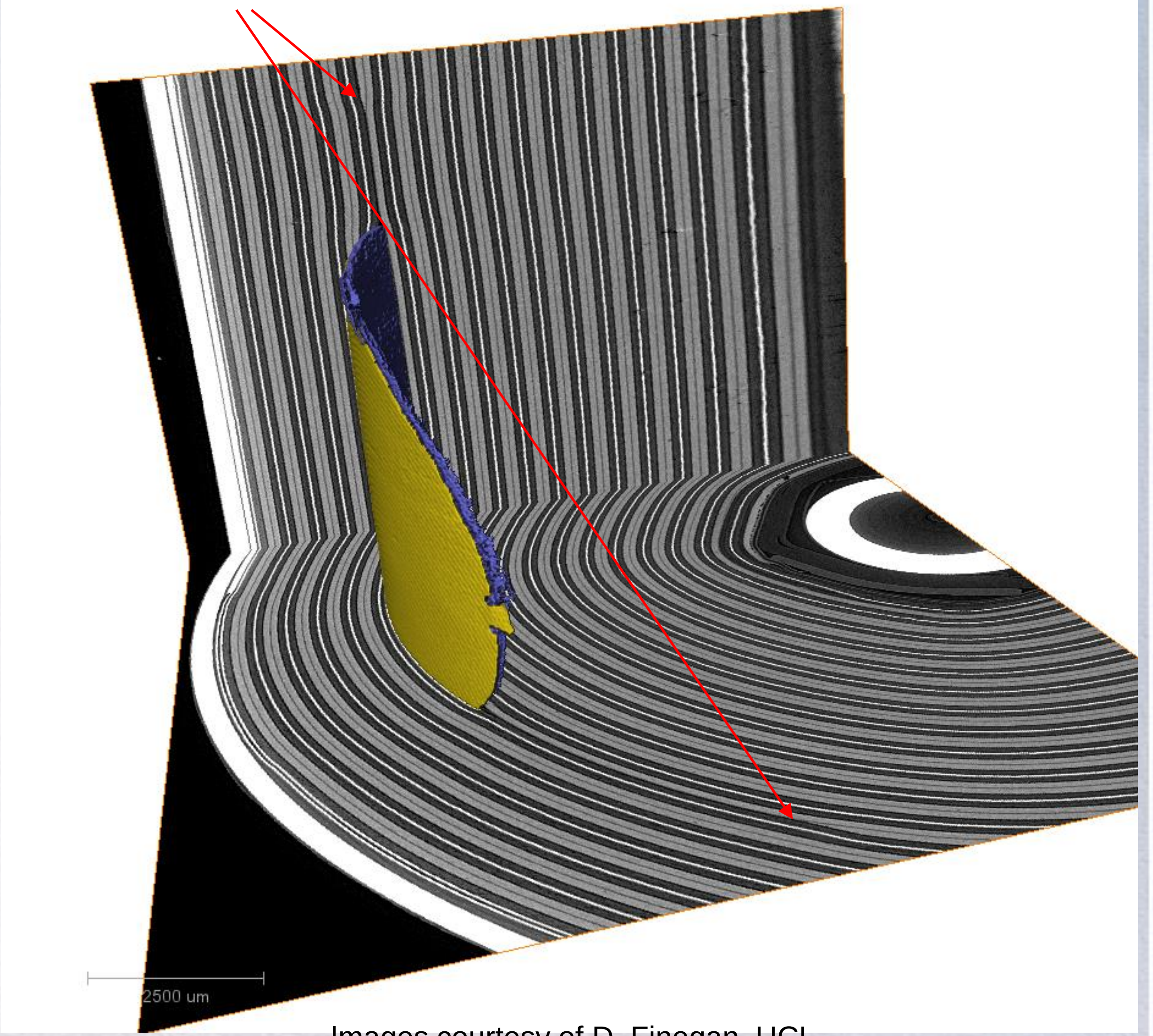
CT Images of ISC Device





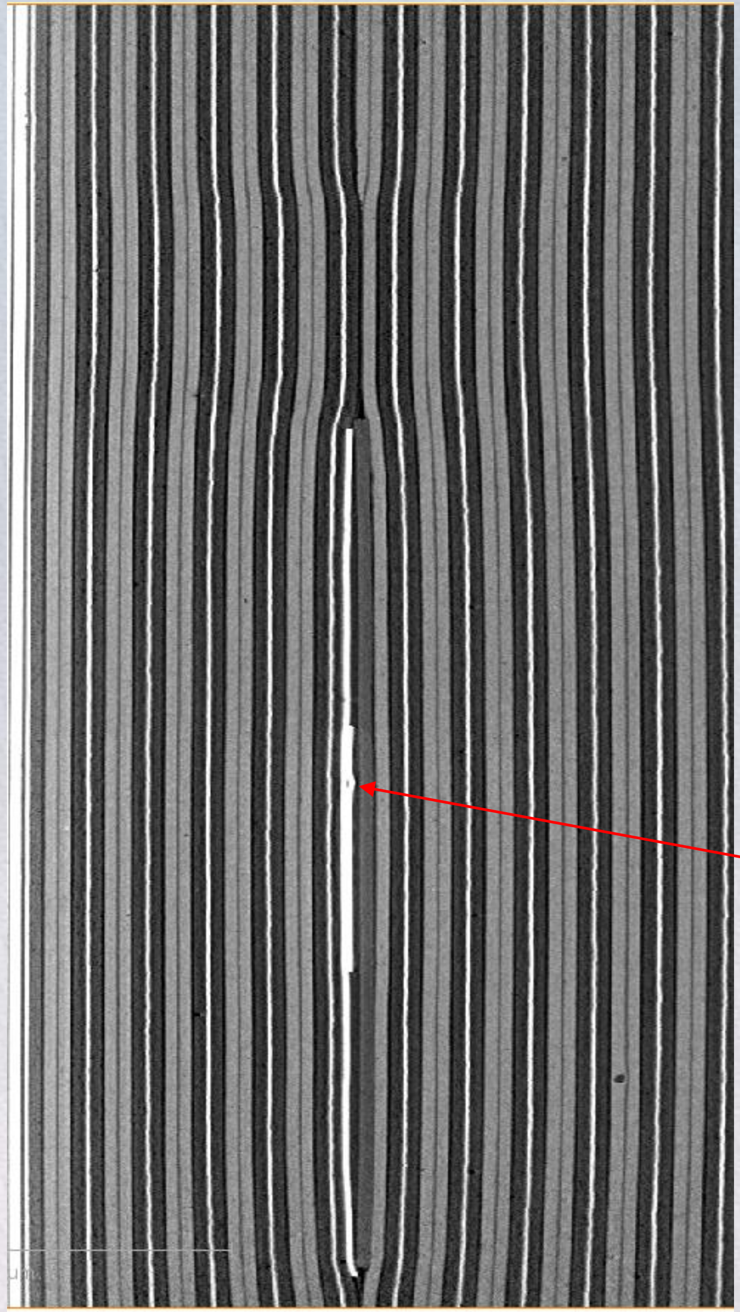
Cu puck
Al pad removed for clarity

Clearly shows that active material hole boundaries are much wider than the device



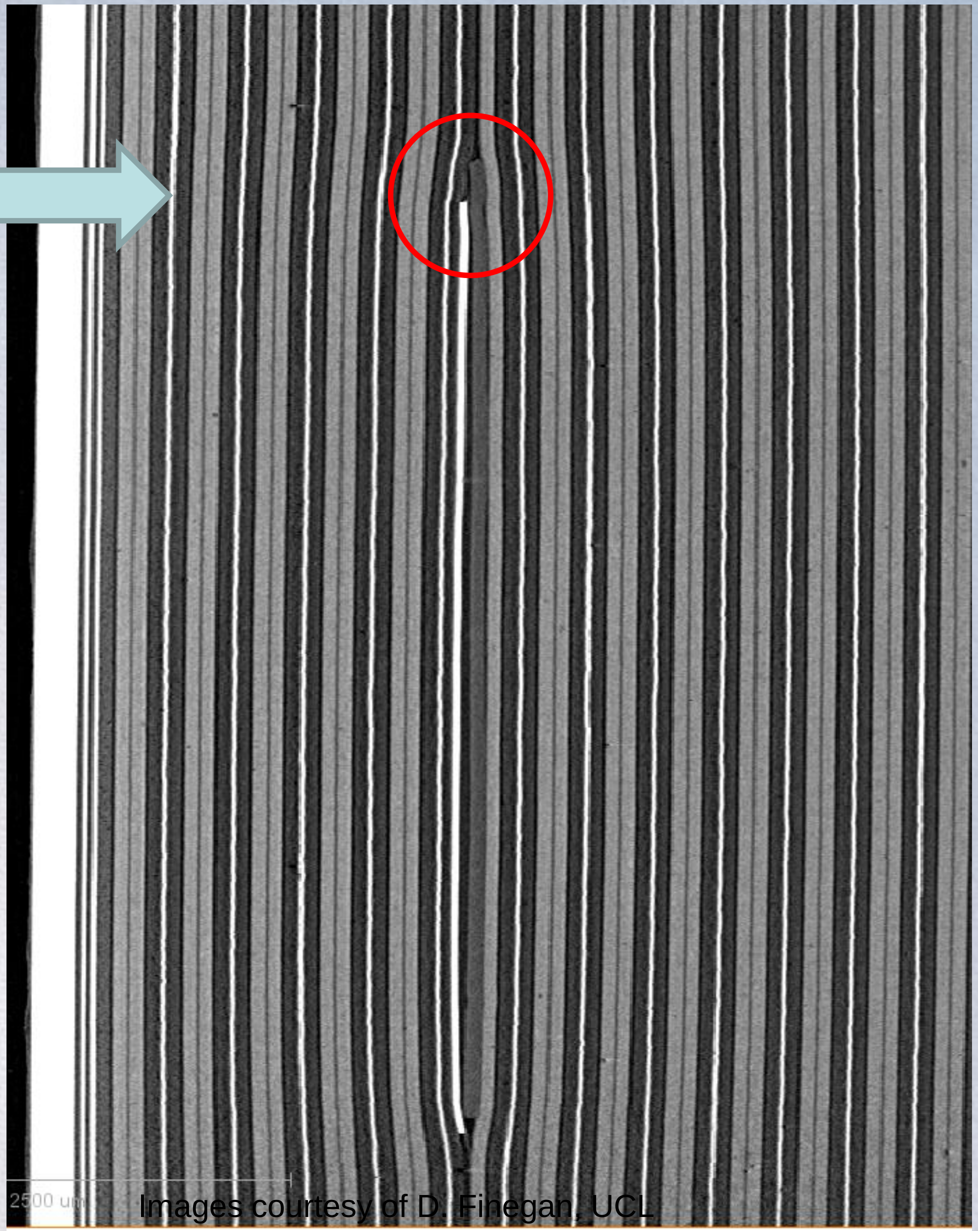
Images courtesy of D. Finegan, UCL

CT images (cont.)



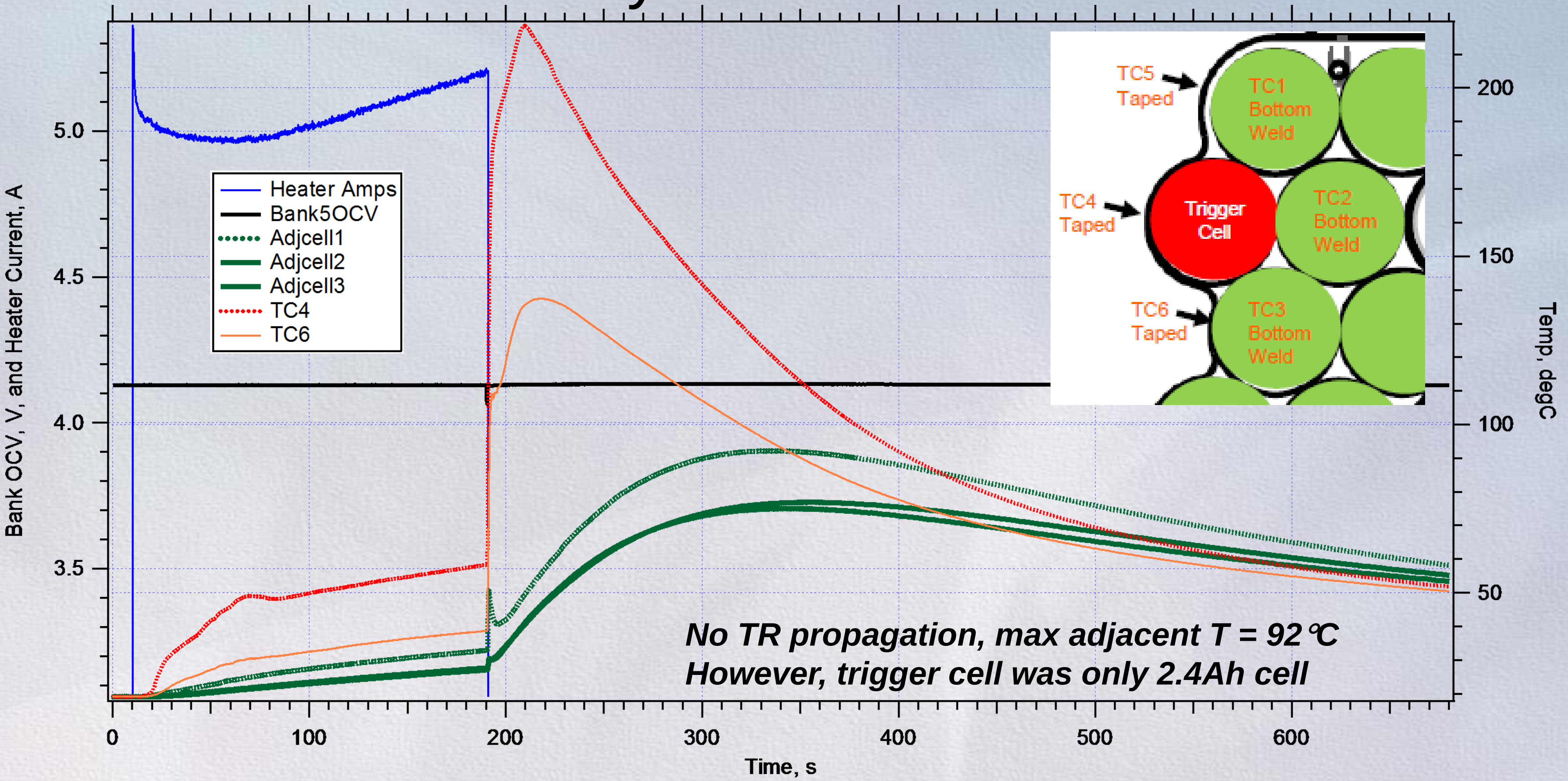
Misalignment of Cu and Al pads creates stress zones on the separator and could explain the damage initiation at the ISC device edge in some videos

Image picks up tweezer marks during fabrication on the Cu puck



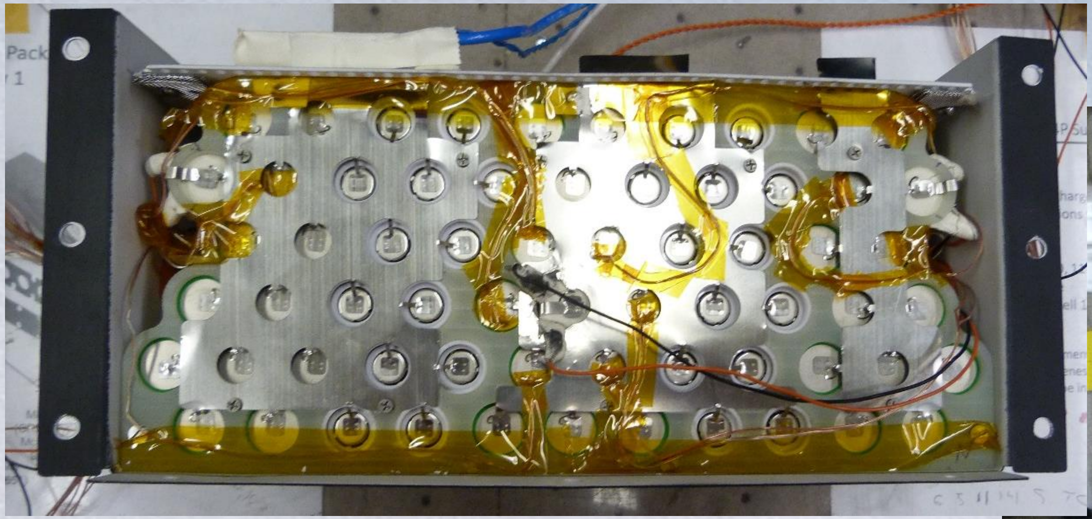
Images courtesy of D. Finegan, UCL

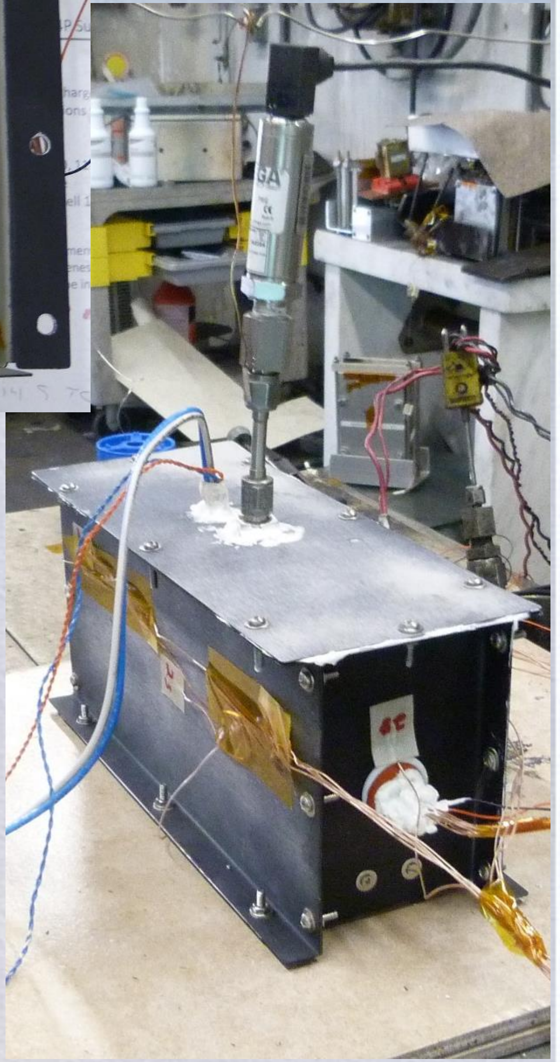
Full Scale Battery TR Test – MoliJ ISC Cell



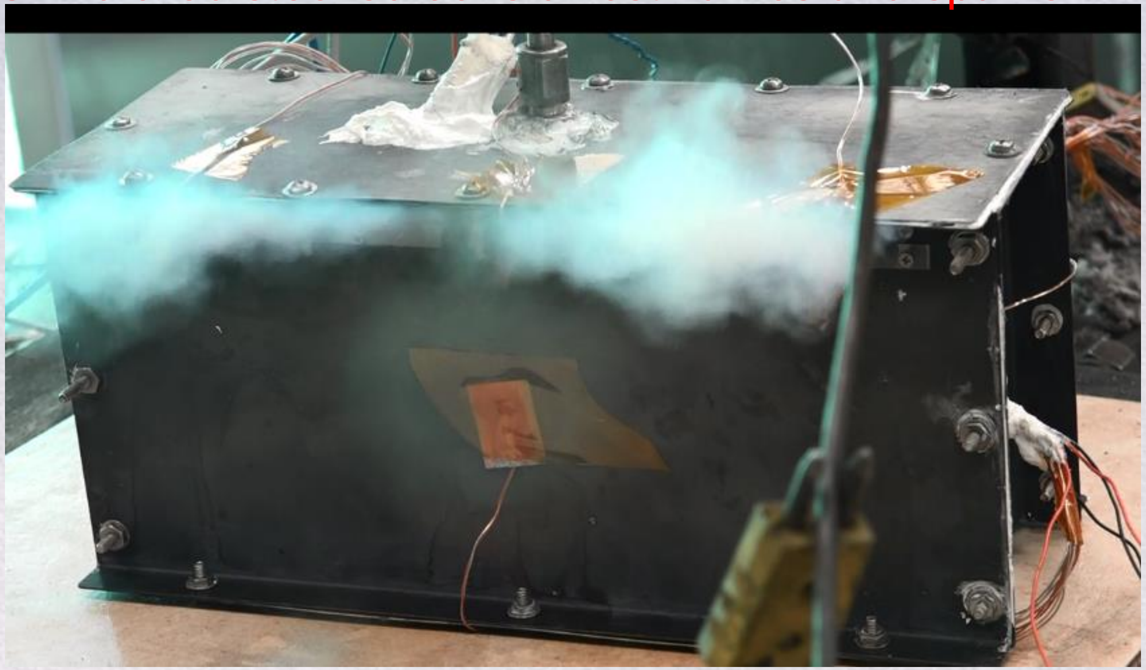
Heater power ~42W for 180s. Onset of TR (OTR) occurs 180s after power on and coincides with trigger bank OCV dip. Adjacent cell1 has ΔT = 58.9°C to max of 92.0°C, while adjacent cells 2 & 3 have ΔT = 48°C to max of 76.0°C

No TR Propagation, Only Smoke Exits Battery



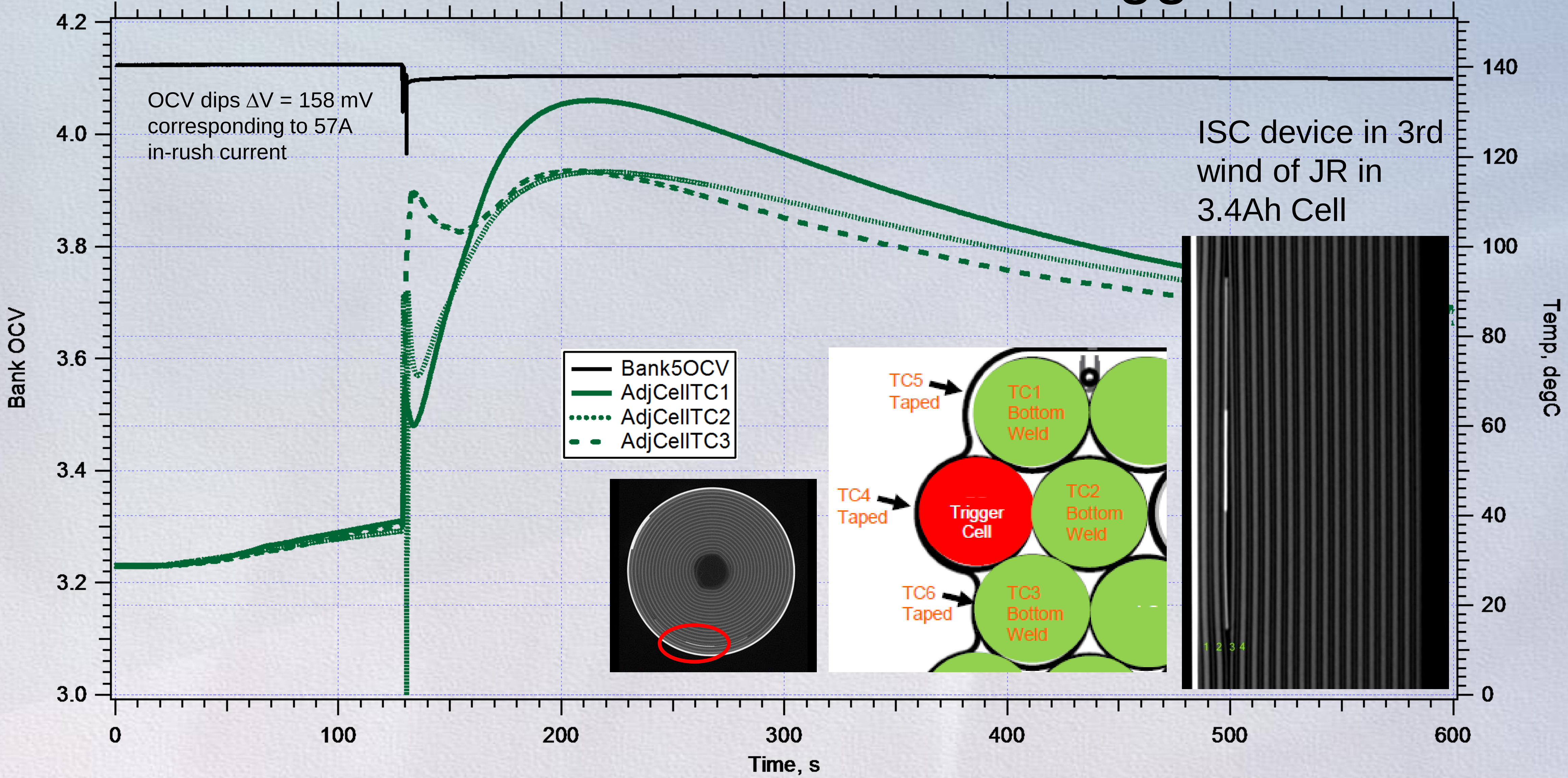


Mesh 40 & 30 steel screens arrest flames and sparks



However, trigger cell was only 2.4Ah cell

1st Test with 3.4Ah ISC Device Trigger Cell

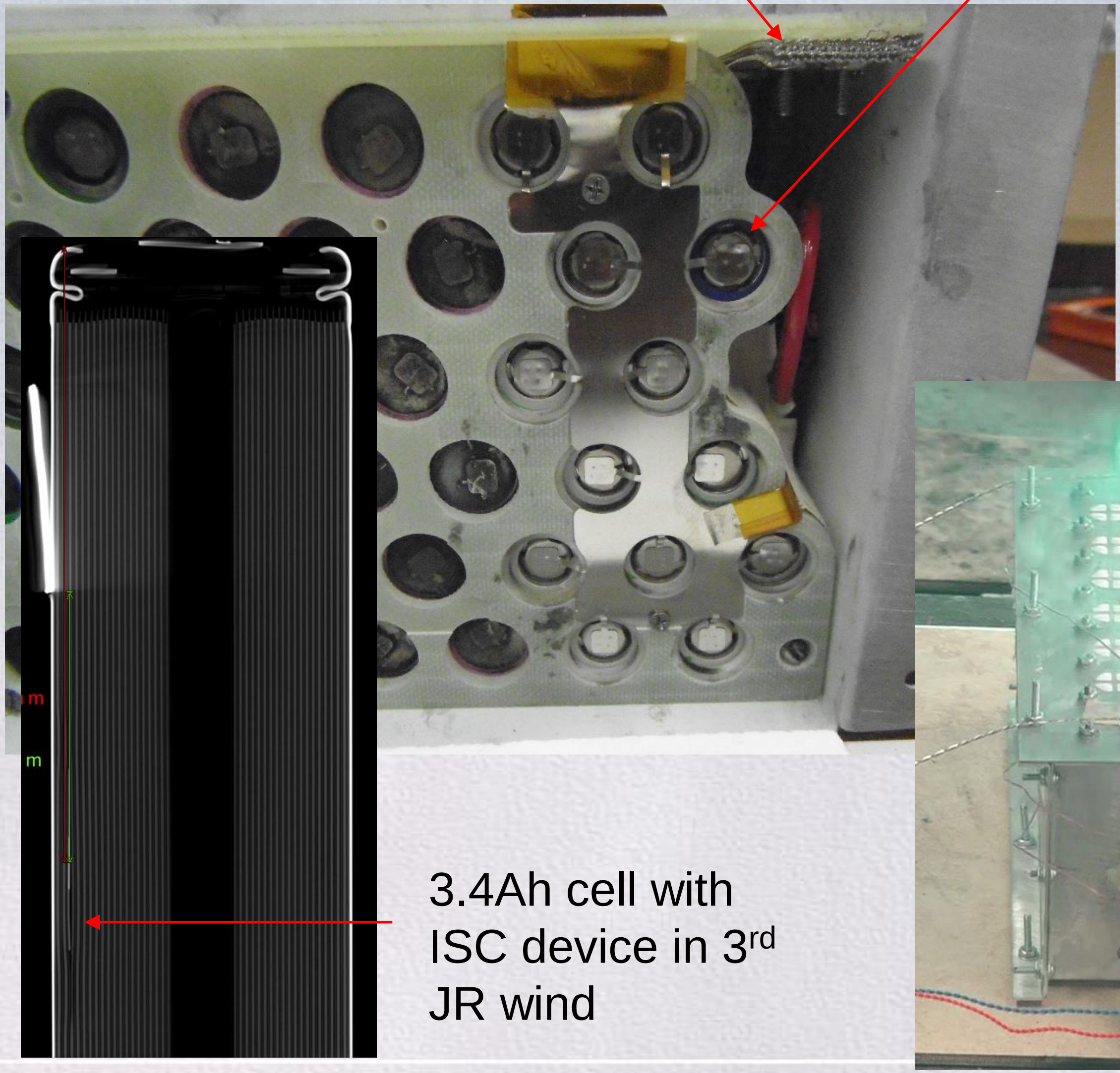


Adjacent cell temperatures TC1, TC2, and TC3 peak at 133°C, 117°C, and 117°C in 77-87s from onset temperatures of 39°C, 37°C, and 38°C for ΔT = 94°C, 77°C, and 78°C, respectively.

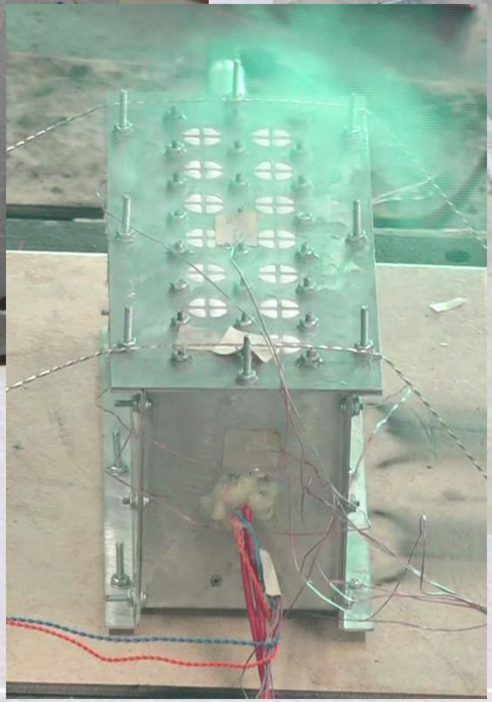
No TR Propagation – Only Clean Smoke Exits Gore Vent

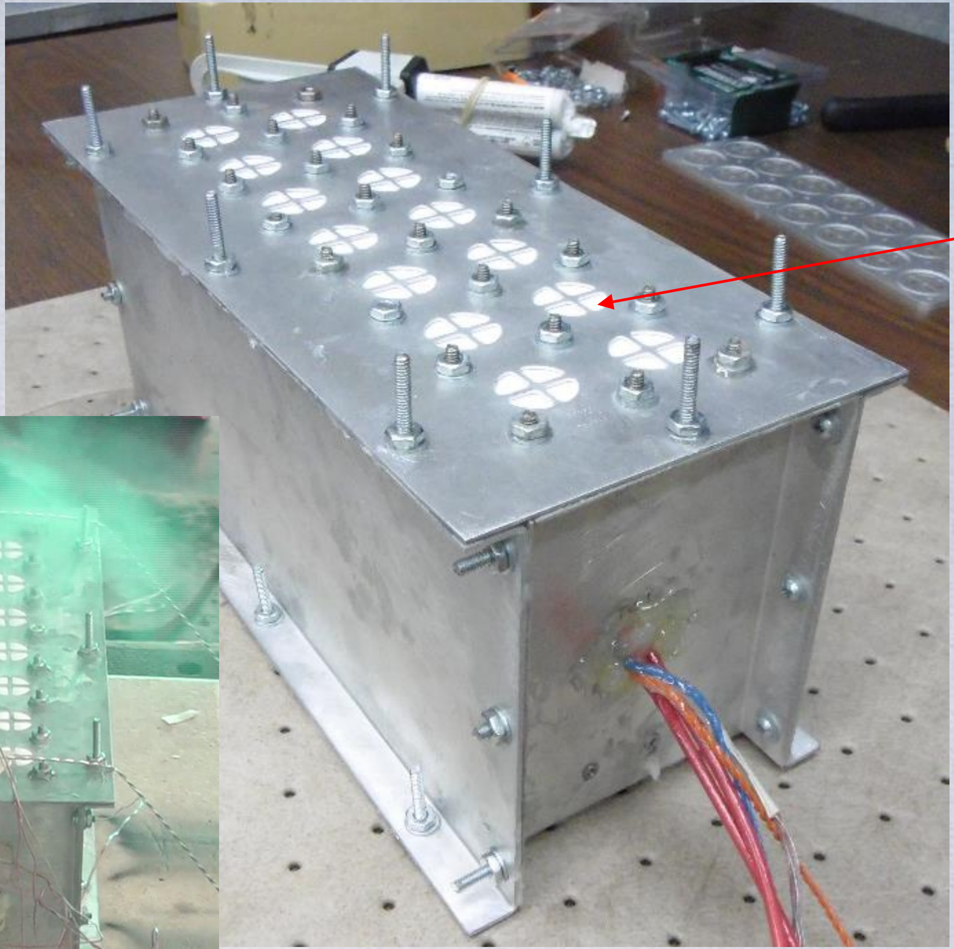
Flame arresting steel screens

3.4Ah Cell with ISC device trigger location



3.4Ah cell with ISC device in 3rd JR wind





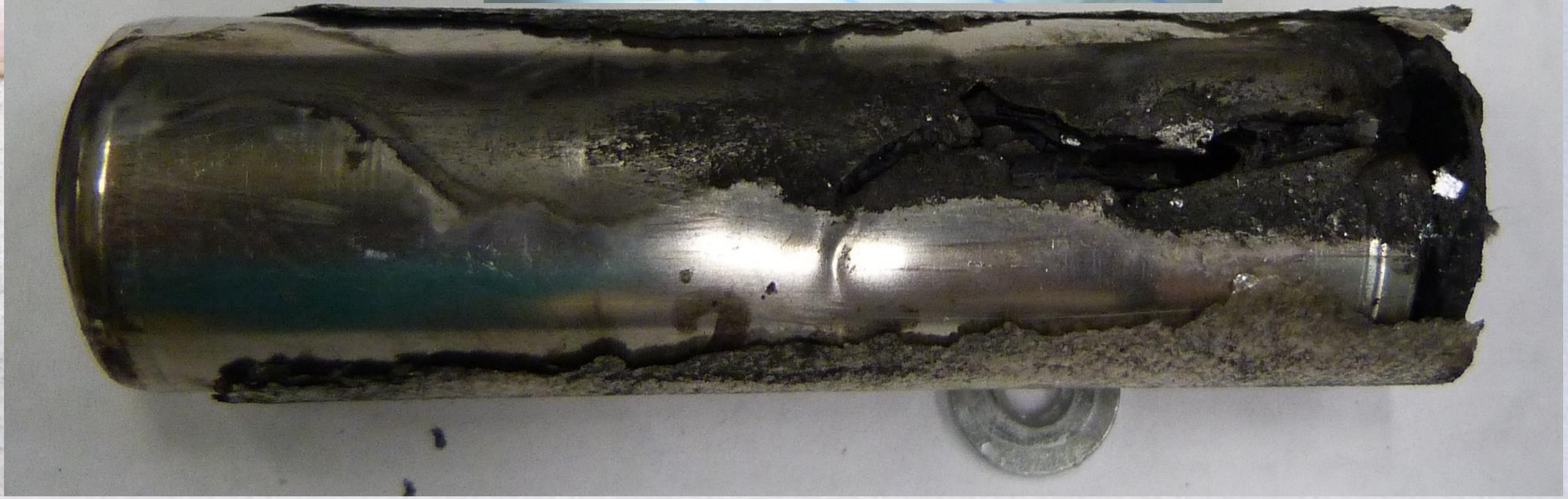
Gore fabric Vent design

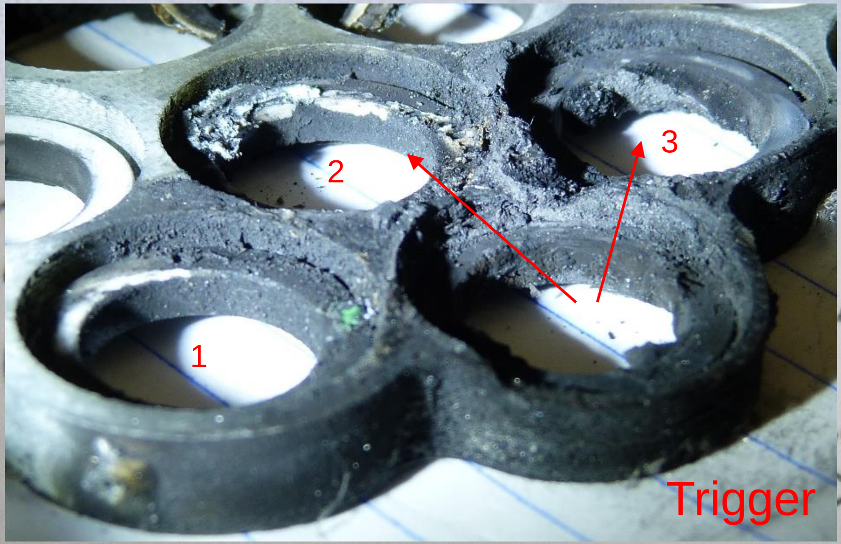
Battery bottom edge seal fails and relieves internal pressure at ~11.4 psig (0.77 bar)

3.4 Ah Trigger Cell Experienced a Side Wall Rupture

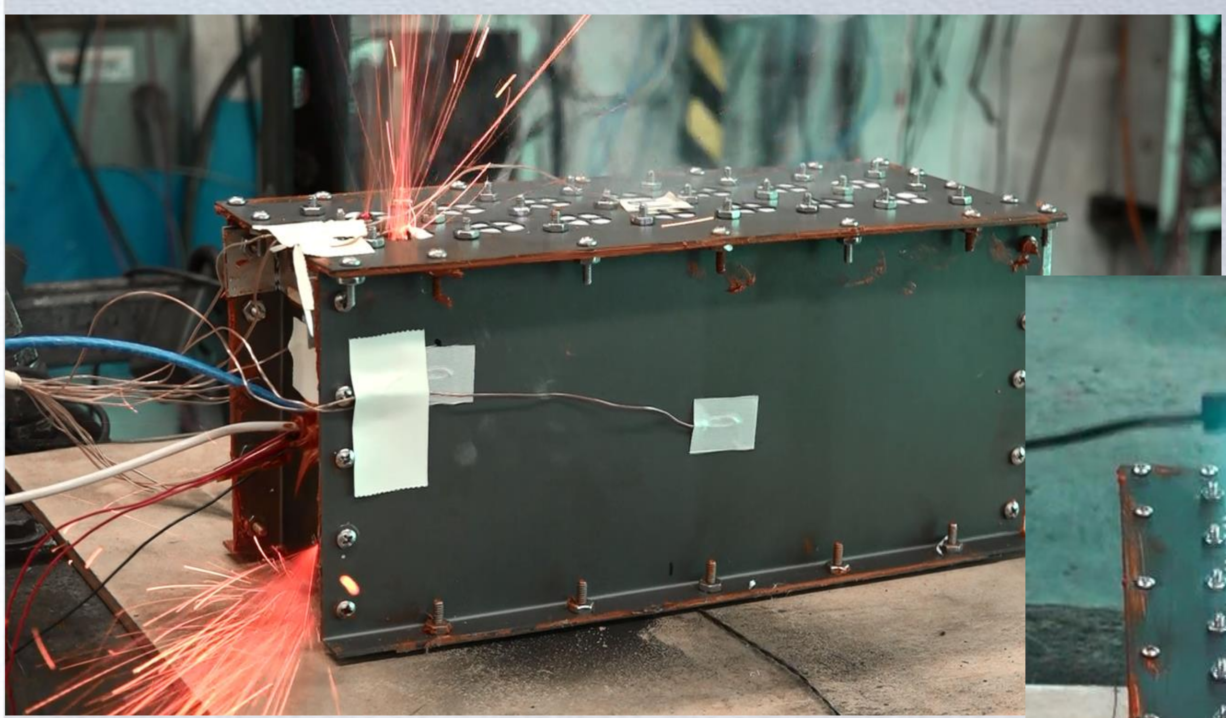
Trigger cell was a struggle to extract from heat sink.
The mica insulation was severely damaged adjacent to rupture

Cell	OCV (V)	Mass (g)
Trigger	0	17.161
1	3.474	46.801
2	0.336	46.691
3	0	46.671

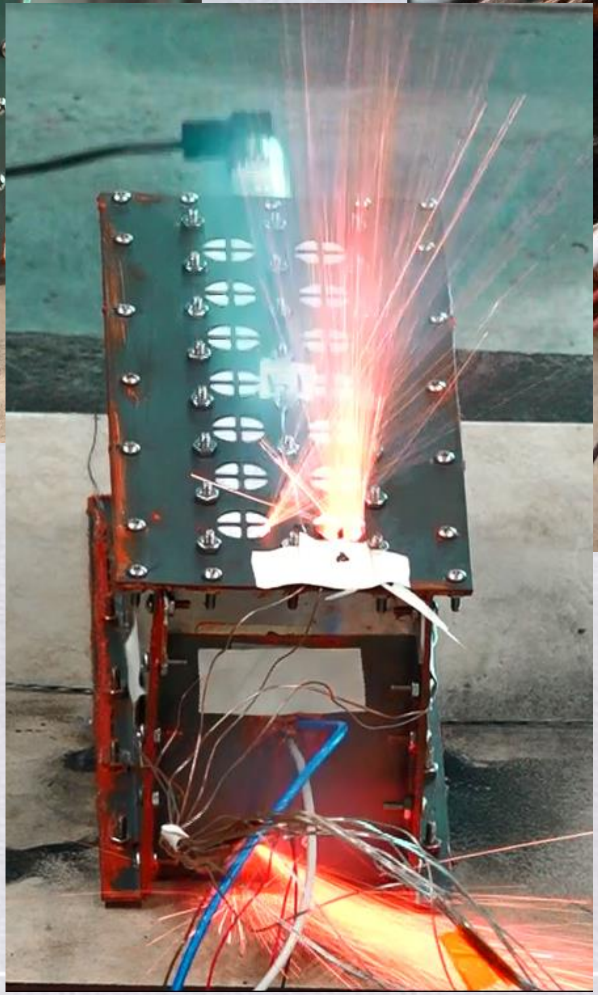


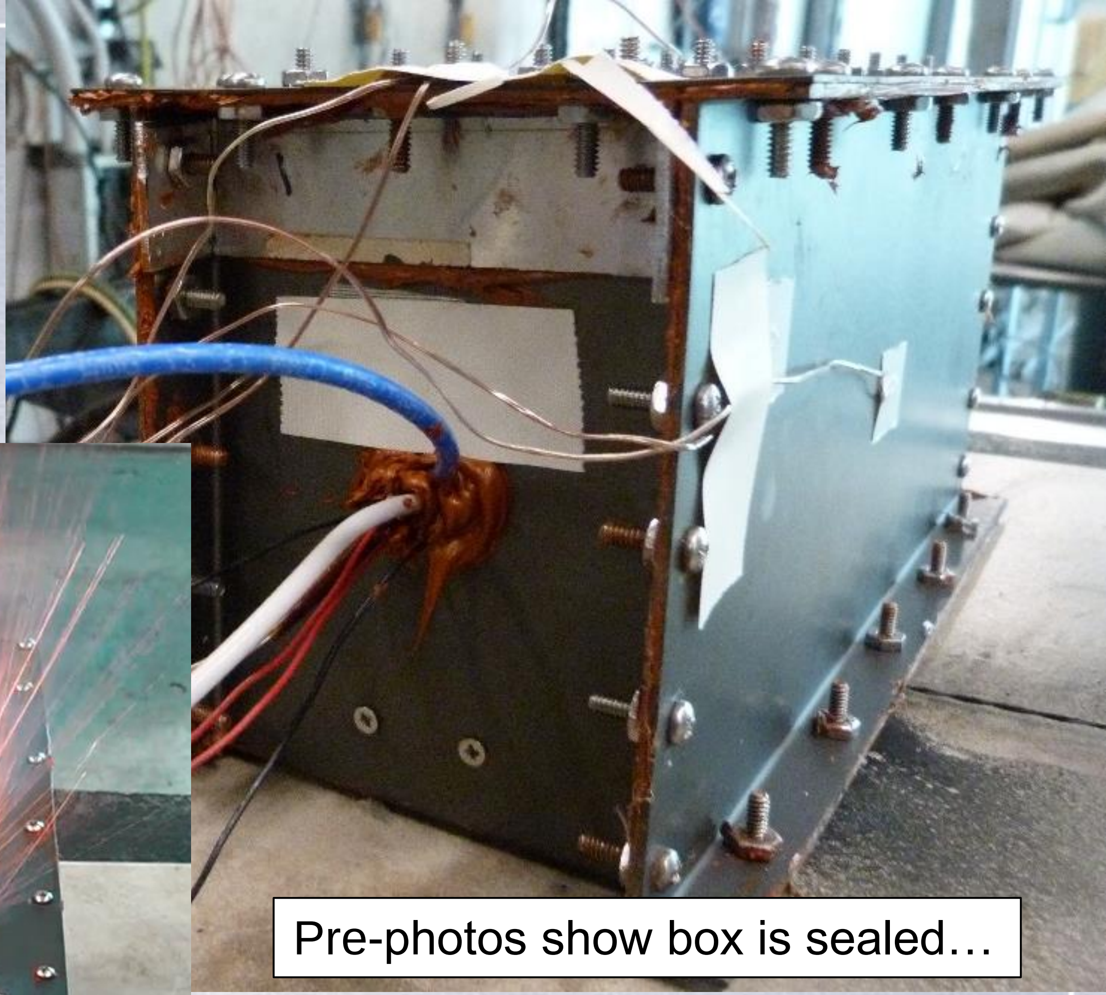


2nd Test with 3.4Ah ISC Trigger



Flames exiting from top and sides of box, less than 1 second



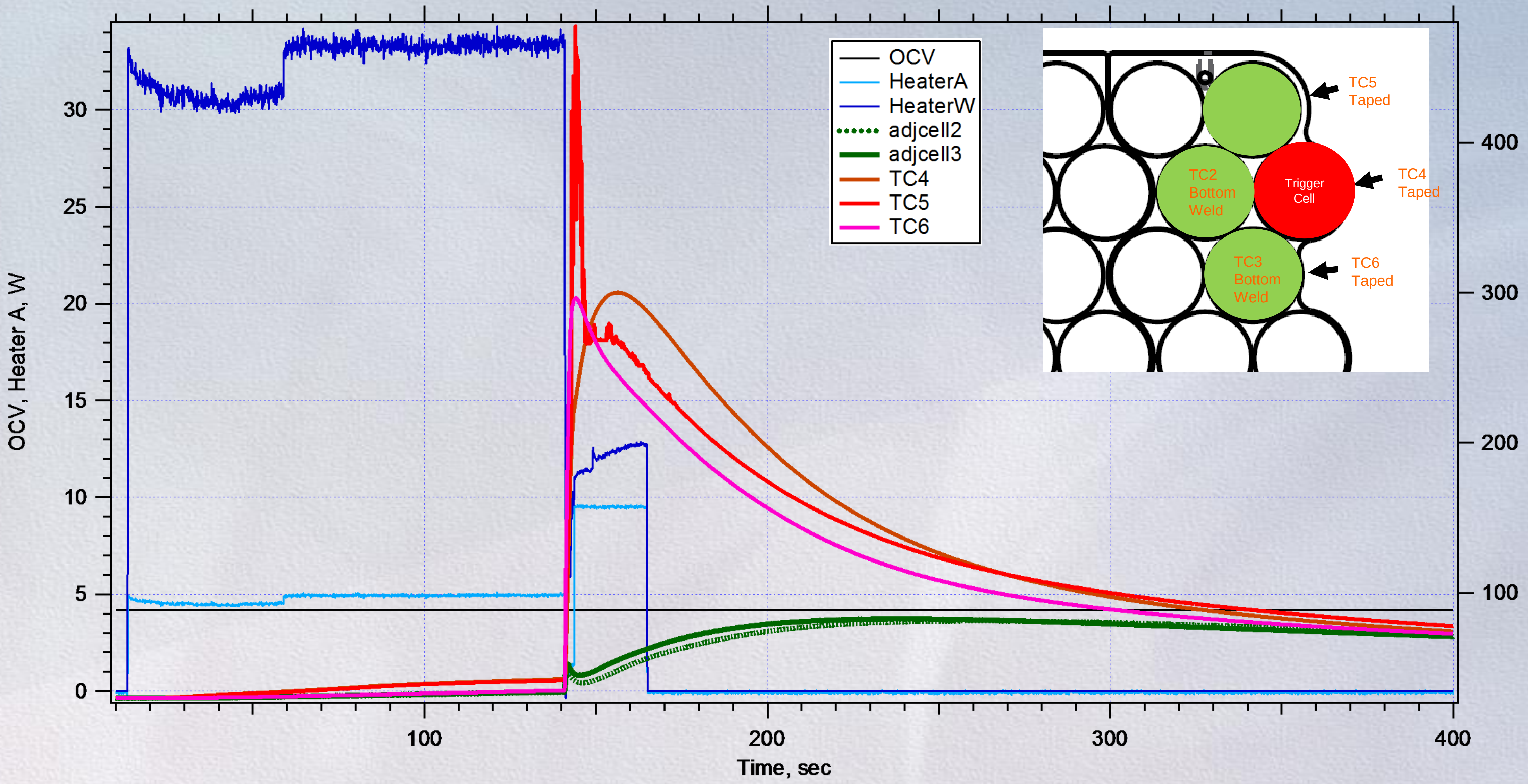


Pre-photos show box is sealed…

Cell flame path was insufficiently tortious and sparks burn through 2 Gore vents

Not enough sealant on screw and hole

2nd Test 3.4Ah ISC Trigger Cell – OCV, Heaters, & Interior Temps



Adjacent cell max temperatures < 83°C

Post-Test Photos – Trigger Cell

Post-Test Mass: 25.3g

Bottom breach

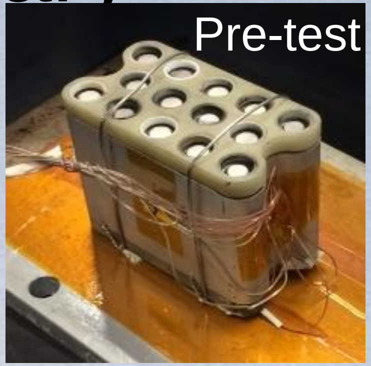
Spin groove is stretched

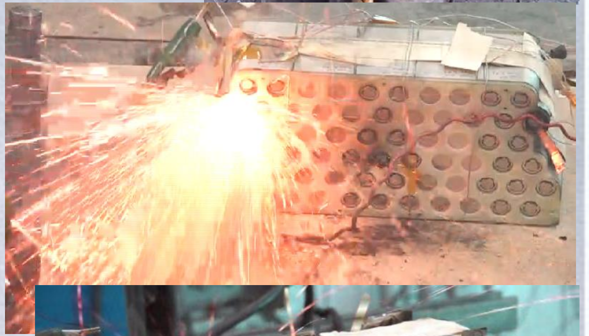
Findings from 2nd Test with 3.4Ah ISC Trigger Cell

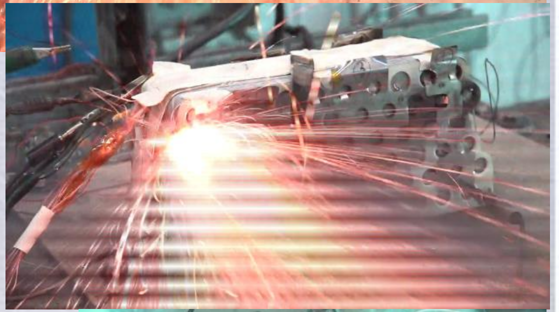
- ISC device in 3.4Ah 18650 cell triggered in 127 seconds with bottom heater at 32W average
  - Very similar initiation time (1st run was in 119s)
  - Very similar biasing of adjacent cells (34-35°C) at onset of TR (1st run at 37-39°C)
- No propagation of TR
  - Despite bottom rupture of trigger cell, which damaged the G10/FR4 negative capture plate
  - Reusing the same heat sinks from the first test – undamaged after both tests
- Max adjacent cell temperatures < 83°C
  - Adjacent cell temperature rise was 46-47°C, significantly lower than 1st run (77-94°C)
  - Bottom rupture yields a much less severe impact than side wall rupture

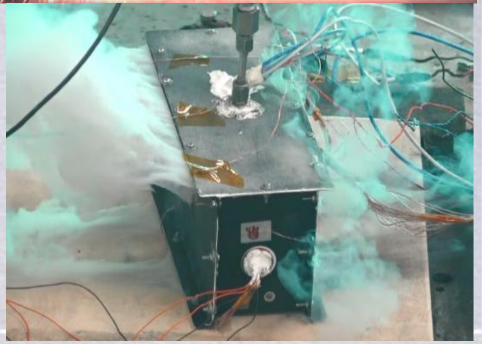
Spacesuit Prototype Battery Test Summary

- Al Heat Sink Tests
  - 4 attempts to drive > 250Wh/kg cell into TR – All failures
    - 2 with Panasonics, 2 with LGs, all with home made bottom heaters
  - 5 attempts with 2.4Ah ISC device cells – No propagation of TR
    - 1 dud and 4 success with the 2.4Ah ISC cell driven into TR
  - 2 heat to vent tests with 5 fully charged 3.4Ah cells each
    - No side wall ruptures in areas supported by the sink
- LLB2 brick tests (All six 2.4Ah ISC cells successfully driven to TR)
  - 3 no-Ni bussing brick tests
    - No TR propagation and no OCV changes to adjacent cells with excellent temp margins
      - Interior cell trigger ΔT ~ 19°C (one run)
      - Edge cell trigger ΔT ~ 42°C (two runs)
    - Interior cell trigger are less vulnerable than edge cells based on temperature rise (max-onset T) on adjacent cells
  - 3 Ni bussing (13P5S)
    - No propagation of TR, no impact on adjacent cell OCVs
    - Very good temperature margins (vs onset of TR temperature)
      - Interior cell trigger: ΔT ~ 30°C (one run)
      - Edge cell trigger ΔT ~ 48°C (one valid run)
- LLB2 full scale tests (4 runs – 2 w/ 2.4Ah, 2 with 3.4Ah ISC device implanted cells)
  - No propagation of TR (even with side wall rupture of trigger cell in 1st test w/ 3.4Ah trigger cell)
  - Maximum adjacent cell temperature rise with 2.4Ah trigger cell was 55-58°C
  - Maximum adjacent cell temperature rise with 3.4Ah trigger cell was 94°C w/ side wall rupture and 46°C with bottom rupture
  - Gore vent design needs more flame arresting protection to handle 3.4Ah cell TR output
  - Screened vents were demonstrated as a successful flame arresting solution









ISC Device Location Reveals Side Wall Rupture Risk

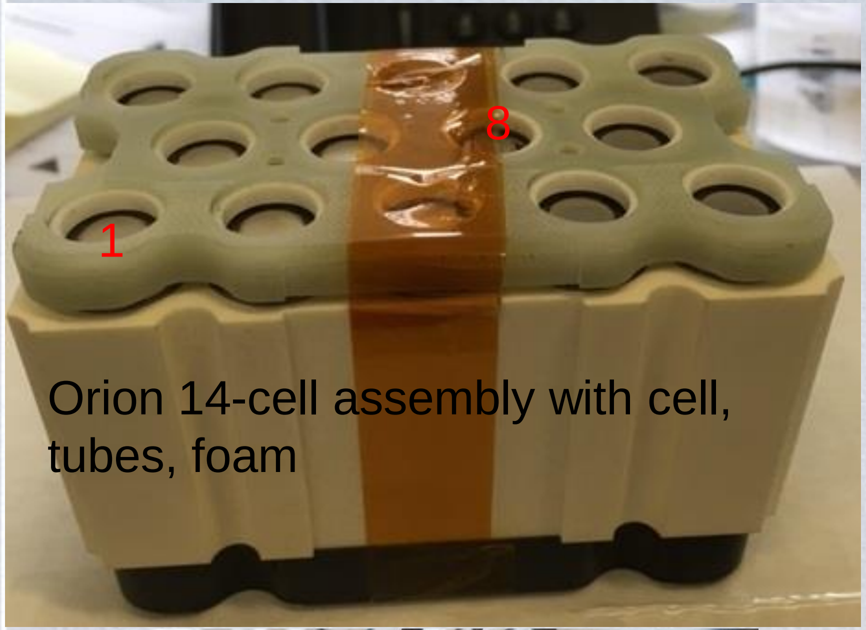
- 3.4Ah cell can thickness
  - 165 microns
  - No bottom vent
- Unsupported oven heating test
  - No side wall ruptures (30 cells)
  - Slow external heating to TR
- Unsupported circumferential heater test
  - No side wall ruptures (5 cells) at ~30W
  - 1 of 3 side wall rupture at ~60W
- With ISC device (11 tested so far)
  - 8 sidewall ruptures
    - 5 unsupported
    - 3 supported by Al interstitial heat sink
  - 1 bottom rupture
    - Supported by Al interstitial heat sink
  - 2 vented through header
    - Supported by Fe tubes

ISC device in 3rd wind

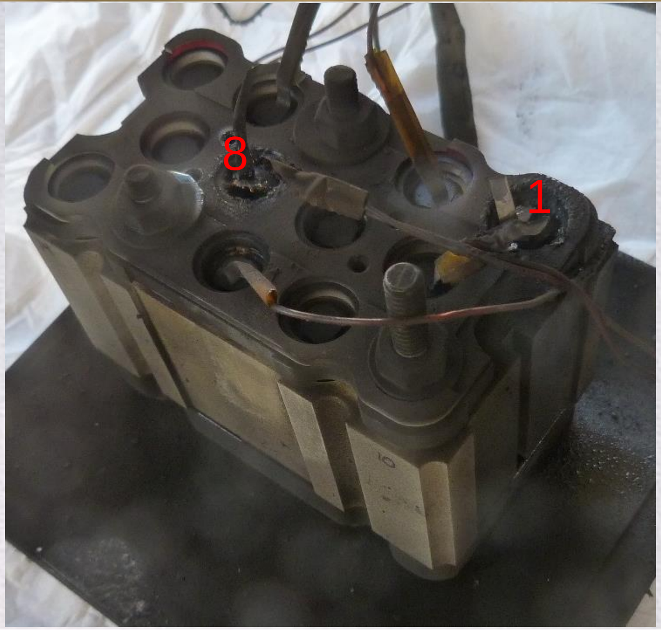
Circumferential heater near bottom of can wall

Photo credit: D. Finegan, University College of London

How Effective Are Steel Tubes?



Orion 14-cell assembly with cell, tubes, foam

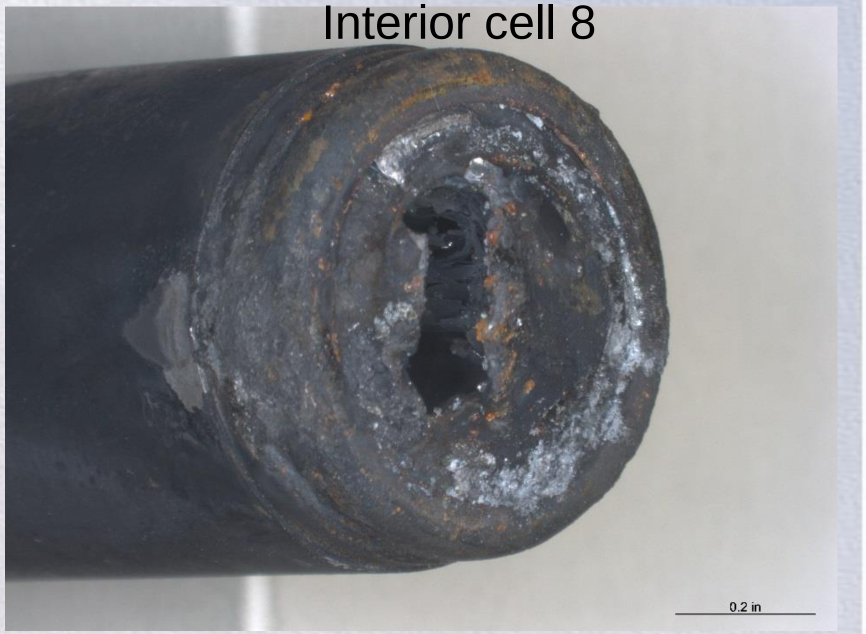


- Fully charged 3.4Ah ISC device cells in positions 1 (corner) and 8 (interior) clocked towards adjacent cells
- Block heated to > 60°C to activate ISC devices

- Corner cell wrapped with 0.015” (381 μm) SS tube experienced side wall rupture outside of tube
  - Dissection of tube found no cell can side wall ruptures inside tube area
- Interior cell wrapped with 0.009” (229 μm)
  - No side wall ruptures outside or inside tube

Corner cell 1

Interior cell 8



Summary Findings

- ISC device enables critical battery safety verification
  - With the aluminum interstitial heat sink between the cells, normal trigger cells can't be driven into TR without excessive temperature bias of adjacent cells
  - With an implantable, on-demand ISC device, TR tests show that the conductive heat sinks very effectively protected adjacent cells from propagation
    - Even with >700 Wh/L cell design experiencing side wall or bottom rupture (4 test runs)
  - 3.4Ah 18650 cell design shown susceptible to side and bottom rupture with ISC device
    - Note that no side wall ruptures occurred during slow heat to TR testing (unsupported, 30 cells tested)
- High heat dissipation and structural support of Al heat sinks show high promise for safer, higher performing batteries
  - Battery brick design achieving > 190Wh/kg demonstrated to be safe
- Preliminary results on bottom vents are inconclusive
  - TR testing with ISC device is needed

Future work

- Will examine impact of the location of the ISC device in the JR
- Will examine merits of cell designs with bottom burst disk vent feature to reduce side wall rupture risk
  - Is it a better solution than thicker can and/or lower header burst pressure?

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