Design Guidelines for Safe, High Performing Li-ion Batteries with 18650 cells

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Outline

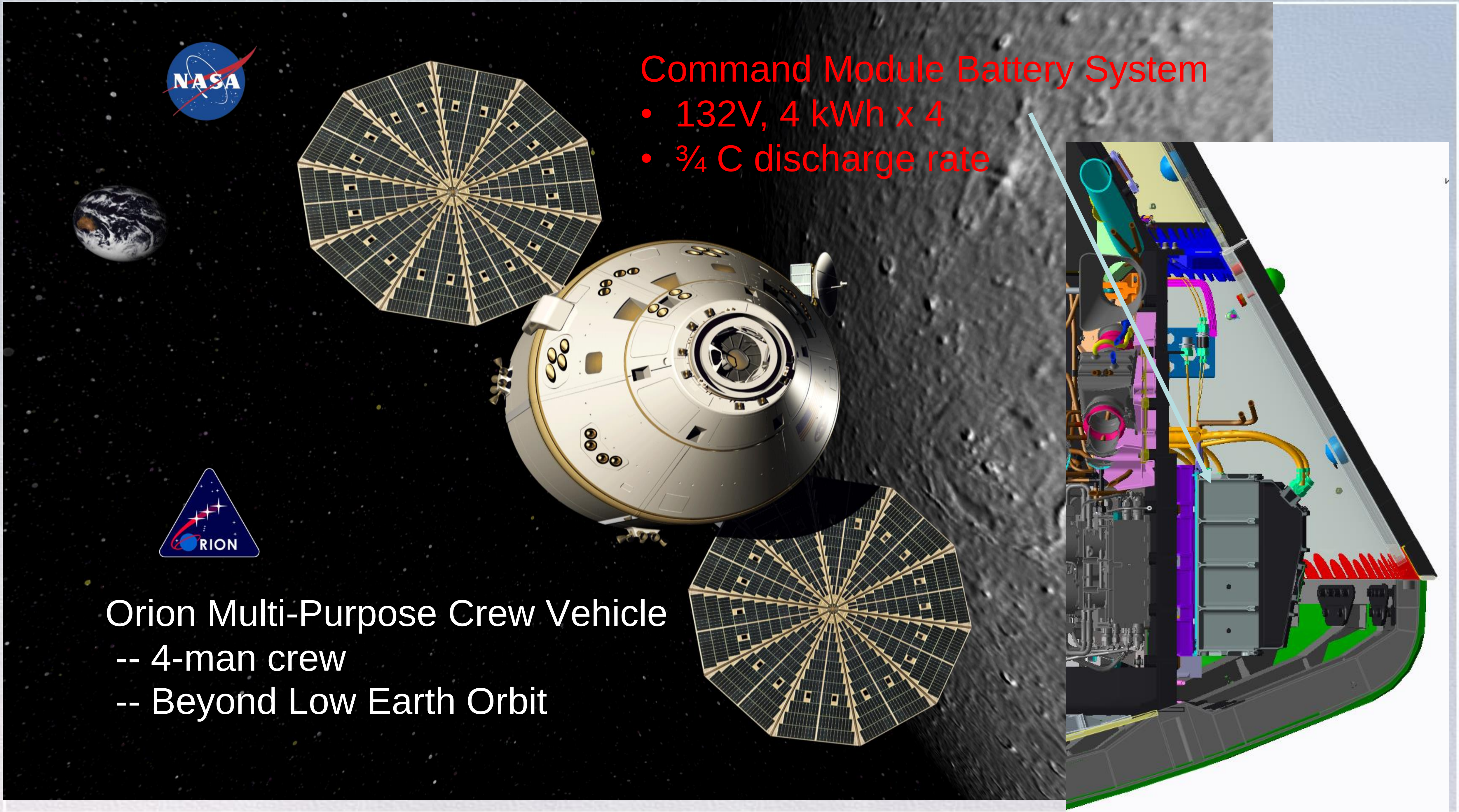
- Introduction
- Applications and Motivation
- 5 Battery Design Guidelines
- Trading thermal isolation vs heat dissipation
  - Full thermal isolation
  - Drawing heat from cell bottoms
  - Full can length interstitial heat sink approach
- Risk of side wall breaches during thermal runaway
- Insights from cell calorimetry combined with X-ray videography
- Summary

NASA-Johnson Space Center (JSC), Houston, TX

- Human spaceflight projects are led by JSC
  - ISS
  - Orion Exploration Vehicle
  - Commercial Crew
- Astronaut selection & training

Command Module Battery System

- 132V, 4 kWh x 4
- ¾ C discharge rate



Orion Multi-Purpose Crew Vehicle

-- 4-man crew

-- Beyond Low Earth Orbit

ISS Commercial Cargo/Crew Vehicles

- SpaceX Dragon Module and Falcon 9 launch vehicle
  - 28V, 26 kWh of Li-ion batteries for Dragon
  - 28V, 3 kWh of Li-ion batteries for Falcon
- Boeing CT-100 Starliner
  - 28V, 58 kWh of Li-ion batteries for command module
  - 28V, < 1 kWh of Li-ion batteries for service module
- Sierra Nevada Dreamchaser
  - 28V, 46 kWh of Li-ion batteries
  - 140V, 9 kWh of Li-ion batteries

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

High Power/Energy 18650 Cell Designs

- Specific Energy Range 259-276 Wh/kg
- Energy Density Range 704-735 Wh/L

Panasonic NCR18650GA

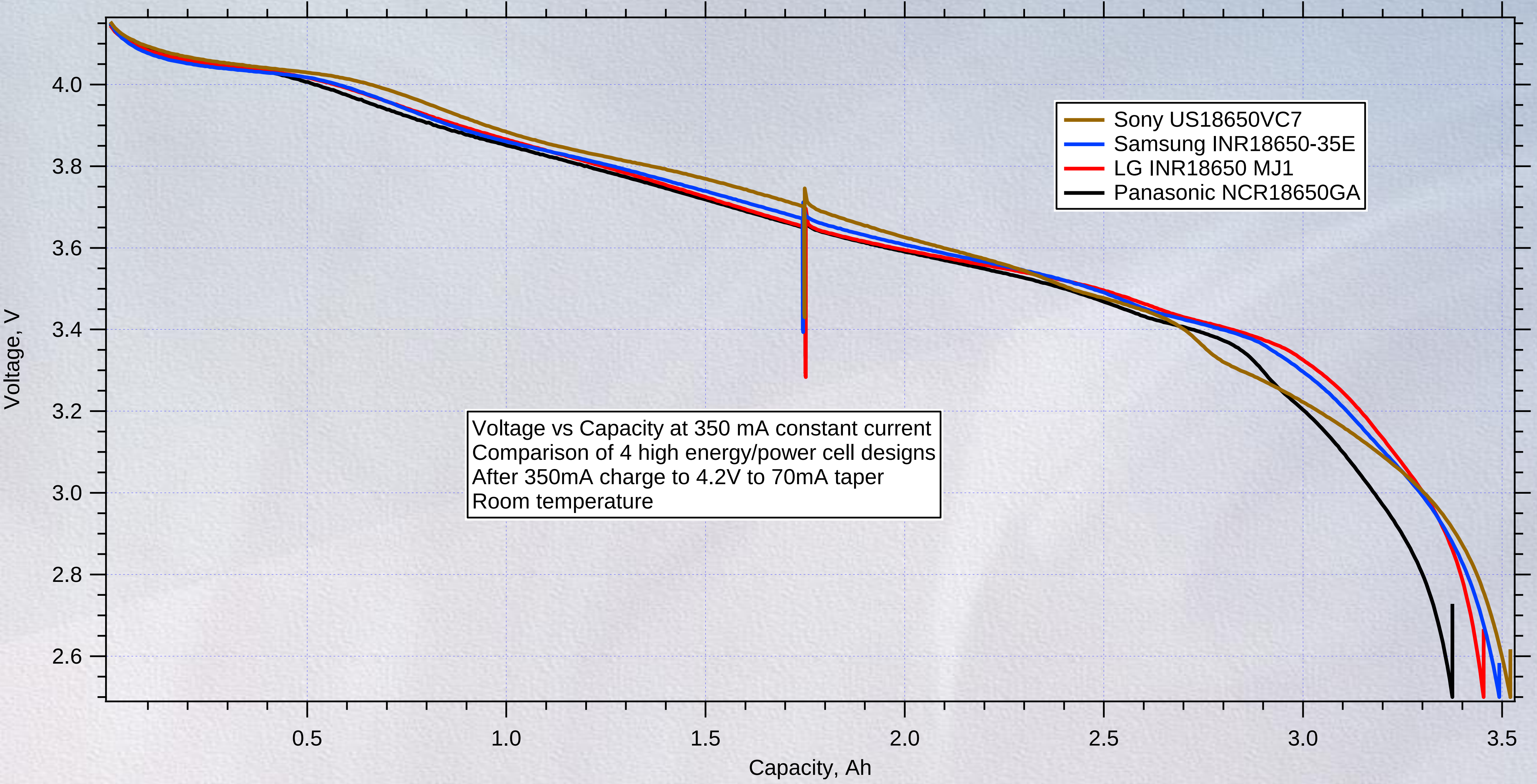
LG INR18650 MJ1

Samsung INR18650-35E

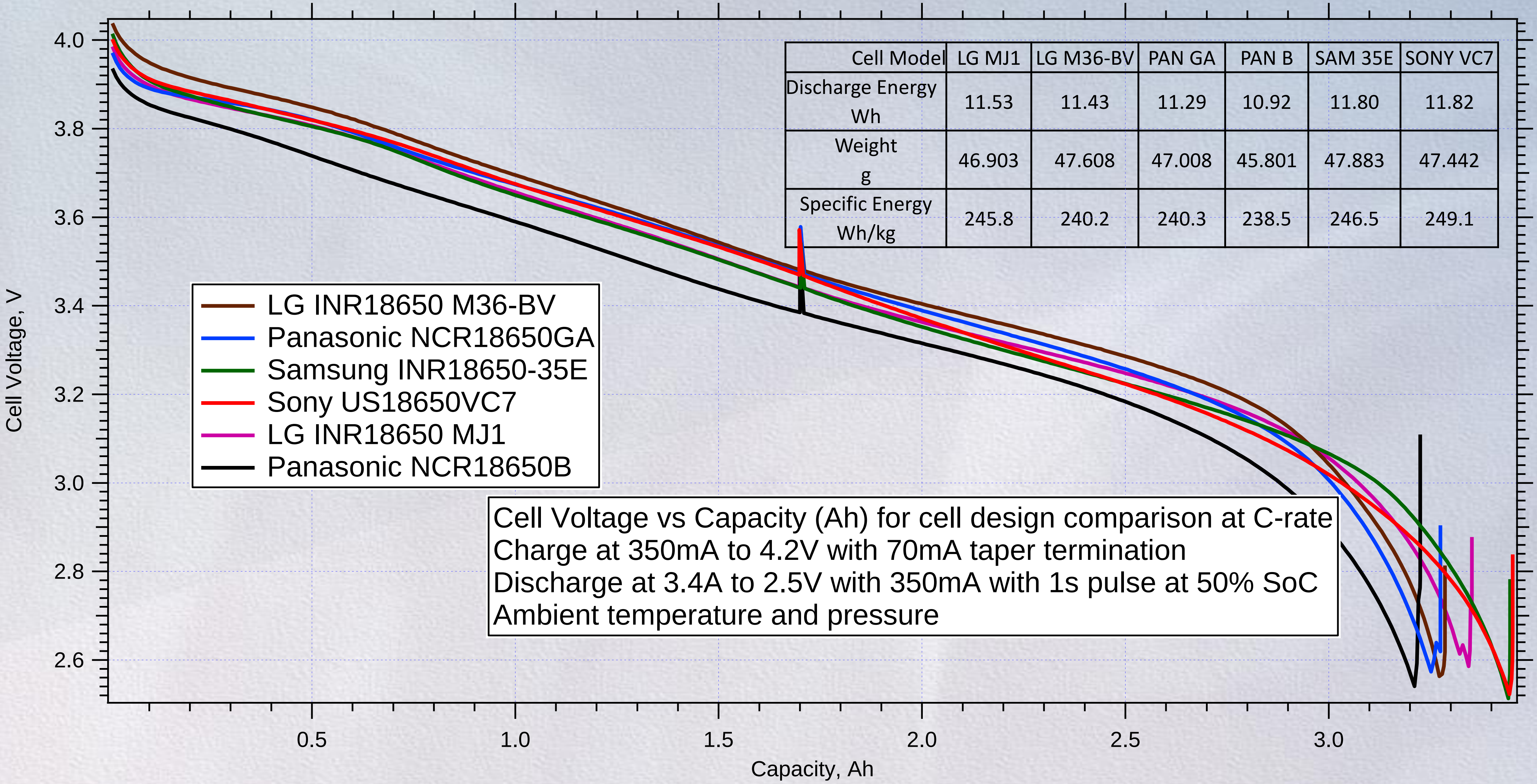
Sony US18650VC7

C/10 at RT	Panasonic NCR GA	Samsung 3.5E	Sony VC7	LG MJ1
Discharge Capacity (Ah)	3.34	3.49	3.5	3.41
Discharge Energy (Wh)	12.16	12.7	12.72	12.46
DC Internal Resistance (mohm)	38	35	31	33
Average Mass (g)	47	46	47.4	46.9
Average Volume (L)	0.0173	0.0173	0.0173	0.0173
Specific Energy (Wh/kg)	259	276	269	266
Energy Density (Wh/L)	704	733	735	720

C/10 Capacity Performance Comparison

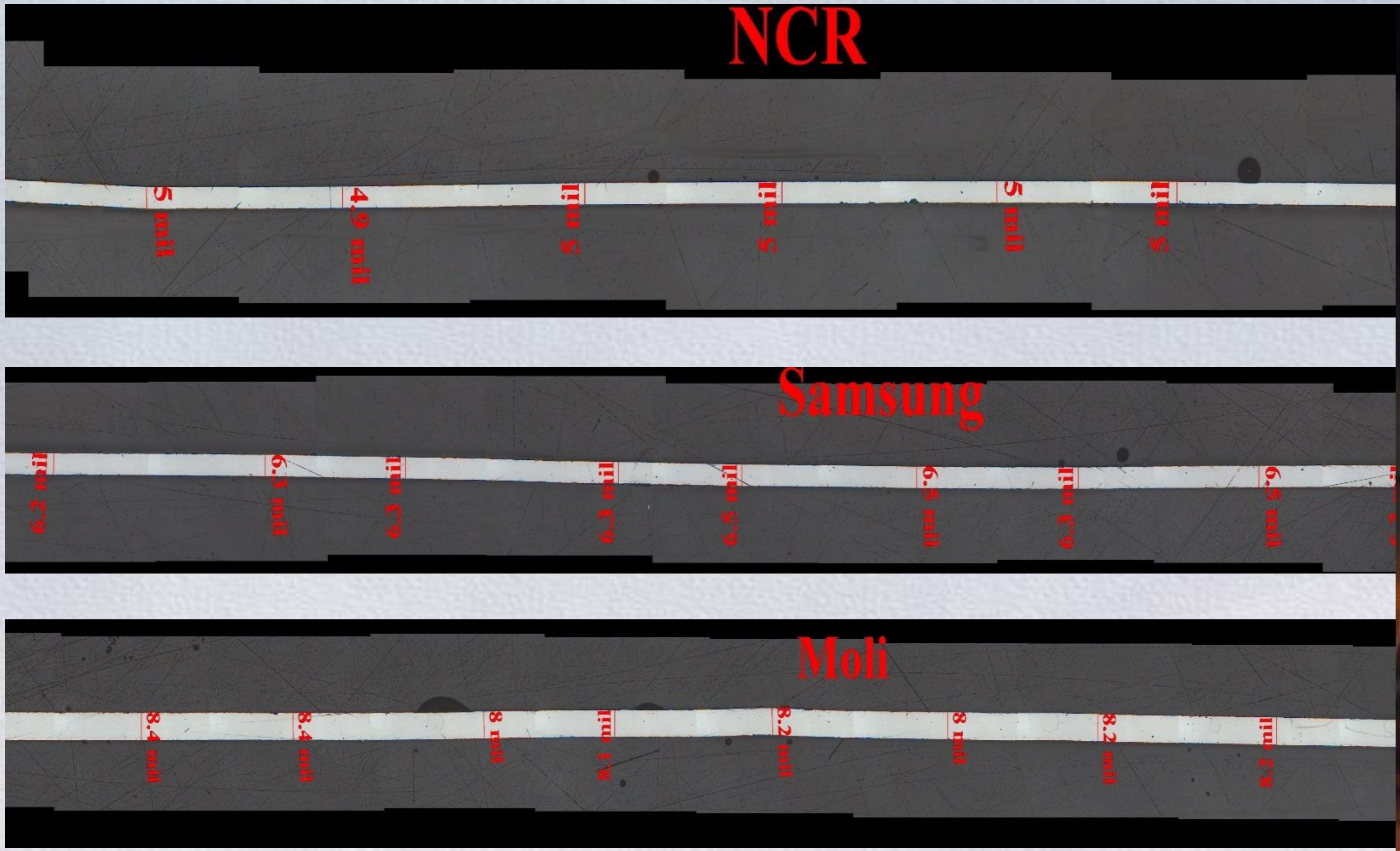


C-rate Capacity Performance Comparison



Cell Model	LG MJ1	LG M36-BV	PAN GA	PAN B	SAM 35E	SONY VC7
Discharge Energy Wh	11.53	11.43	11.29	10.92	11.80	11.82
Weight g	46.903	47.608	47.008	45.801	47.883	47.442
Specific Energy Wh/kg	245.8	240.2	240.3	238.5	246.5	249.1

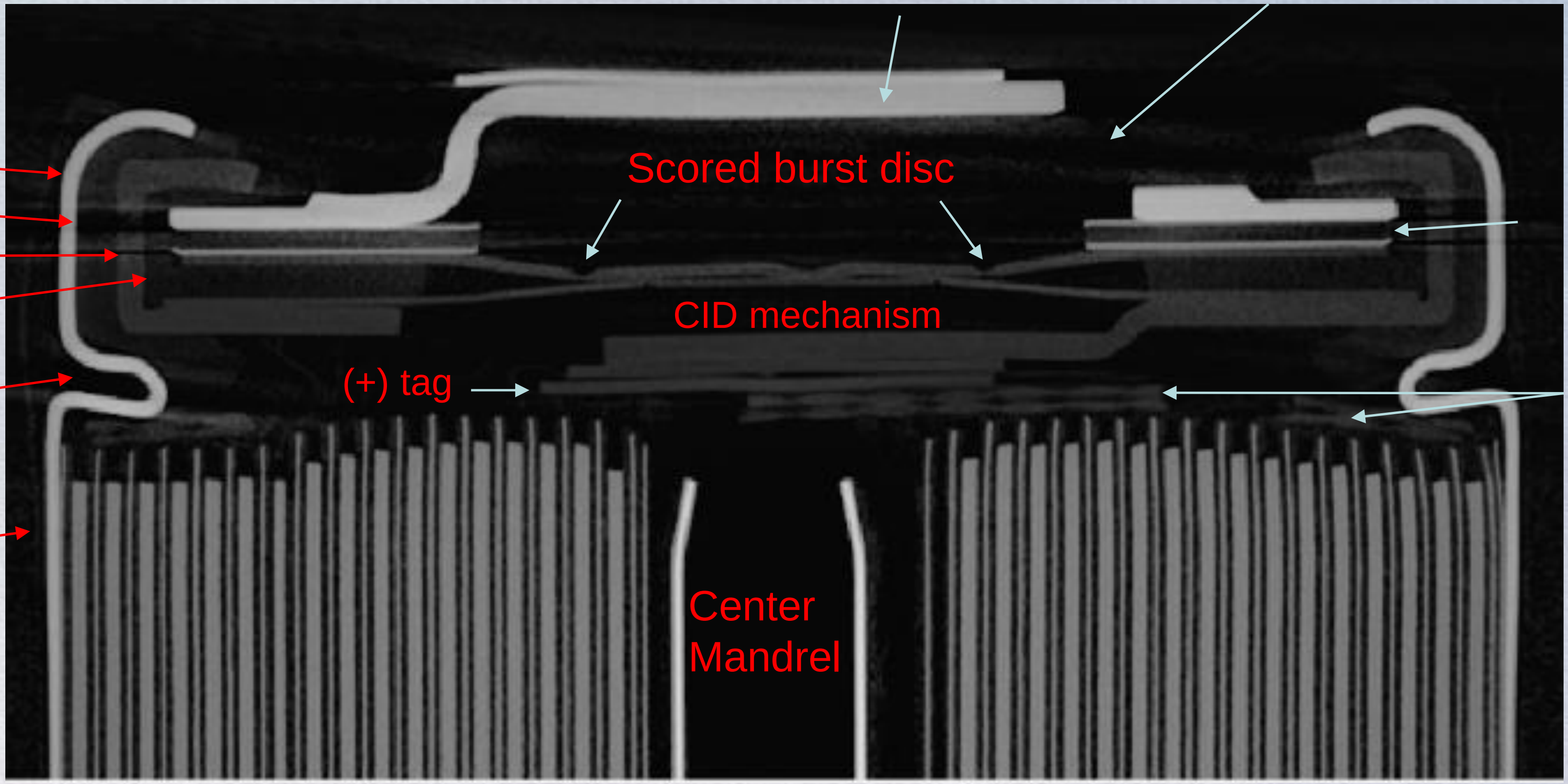
Cell Can Wall Cross Sections



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

Axial View – Header of NCR18650B Cell

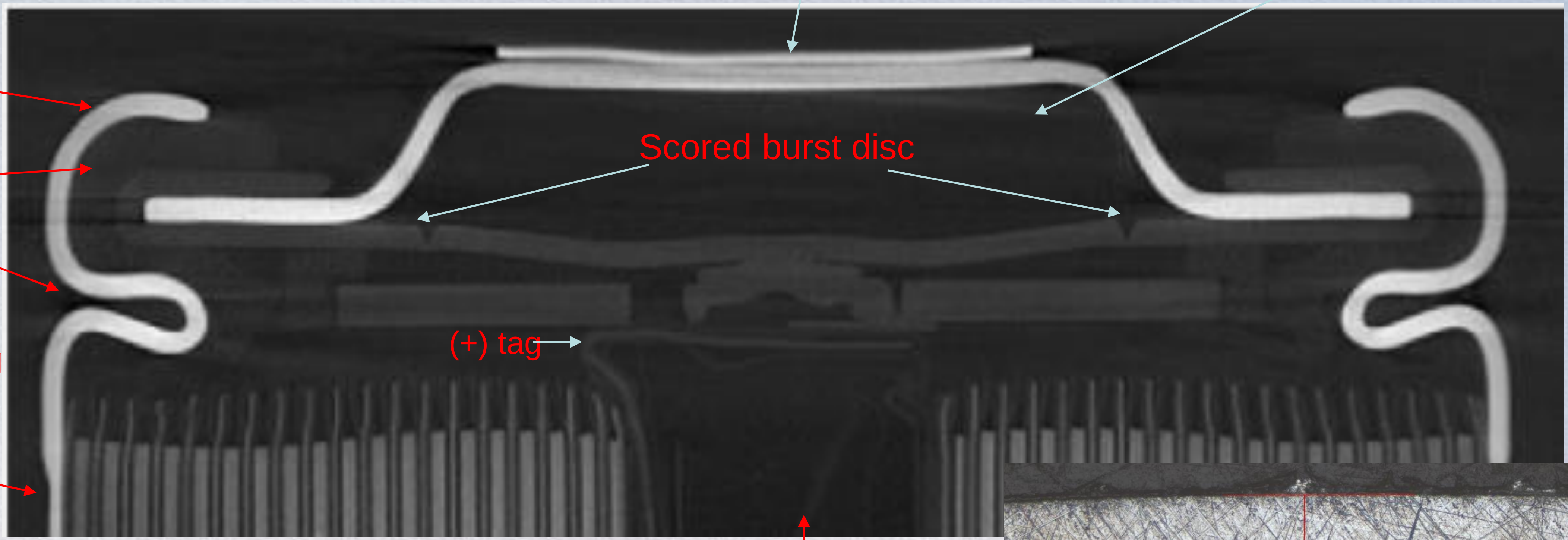


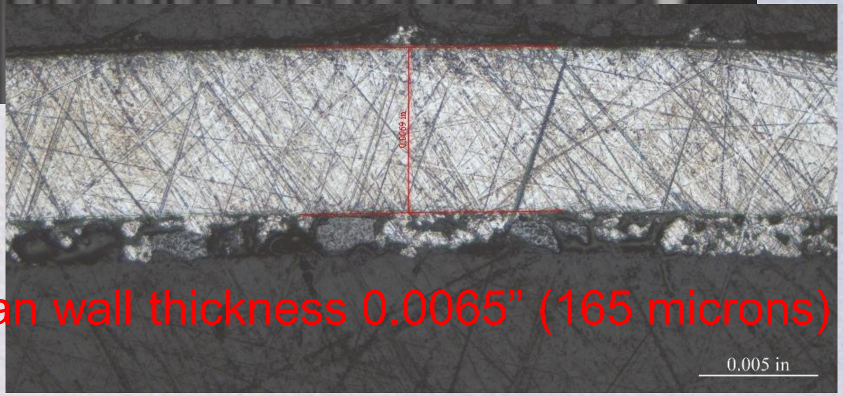
Note the double crimped header design

Burst Pressure of Crimped Header ~1000psia (68 atm)

3 of 30 cells experienced side wall ruptures during oven heating to TR

LG INR18650 MJ1 - Axial View - Header - Cell





0 of 30 cells experienced side wall ruptures during oven TR tests

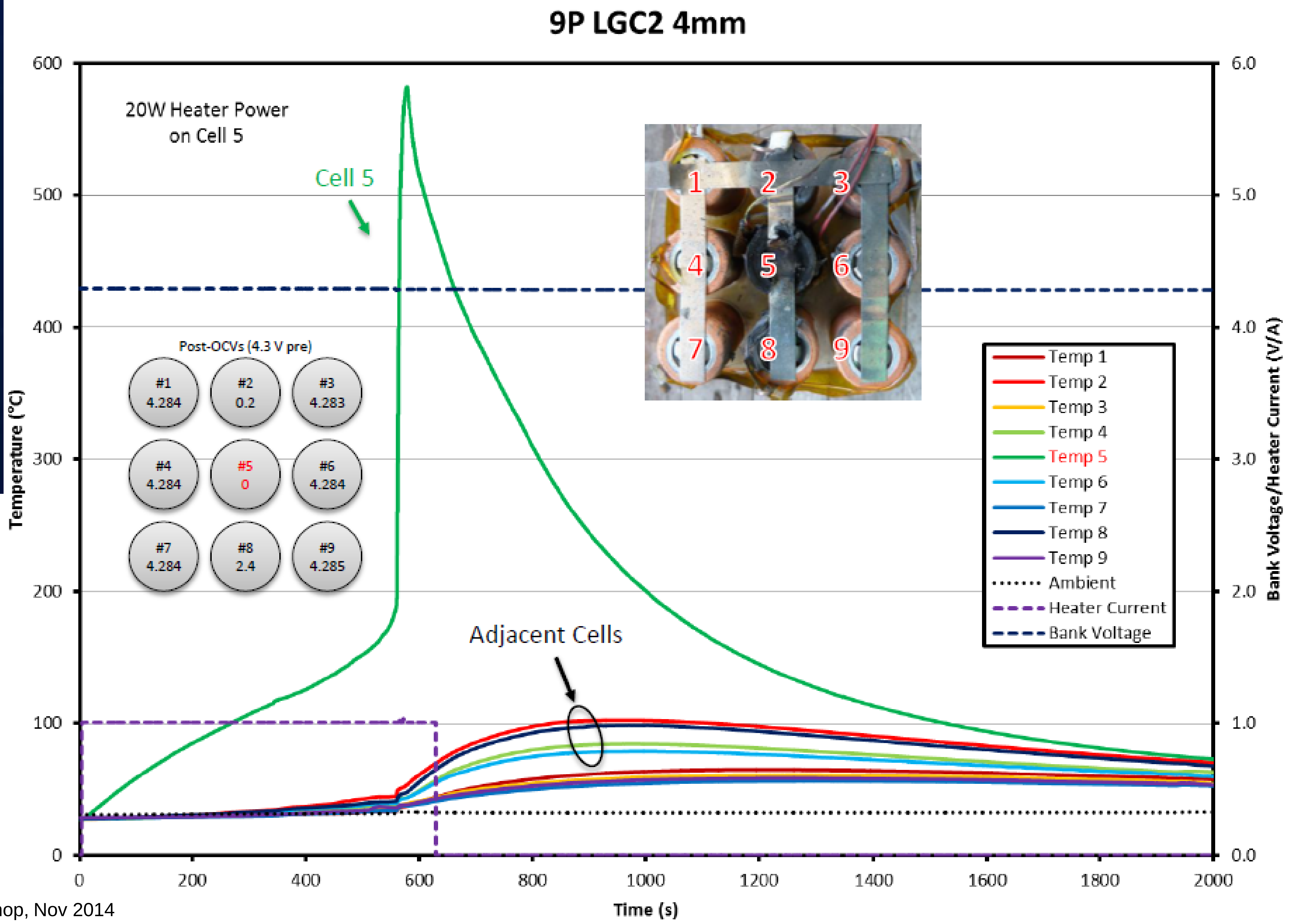
Note the single crimped header design with burst pressure ~800 psia (~54 atm)

5 Battery Design Guidelines for Reducing Hazard Severity from a Single Cell TR

- Reduce risk of cell can side wall breaches
  - Without structural support most high energy density (>660 Wh/L) designs are very likely to experience side wall breaching 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

Source: NASA NESC Task Report TI-14-00942 "Assessment of ISS/EVA Lithium-ion Battery TR Severity Reduction Measures" May 2017

Thermal Isolation Example – 4mm air spacing between cells

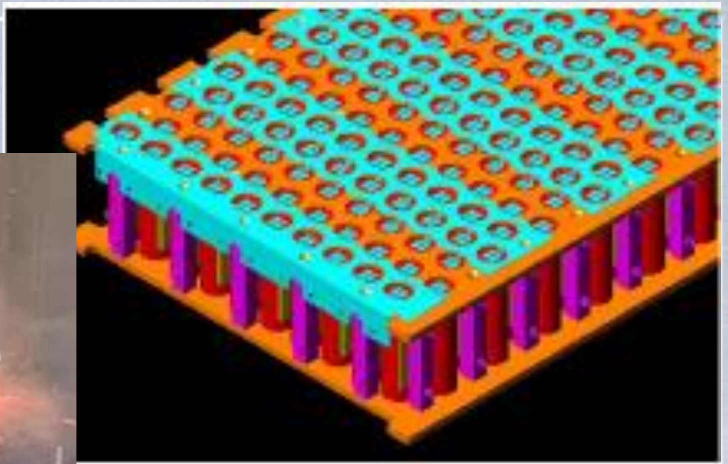


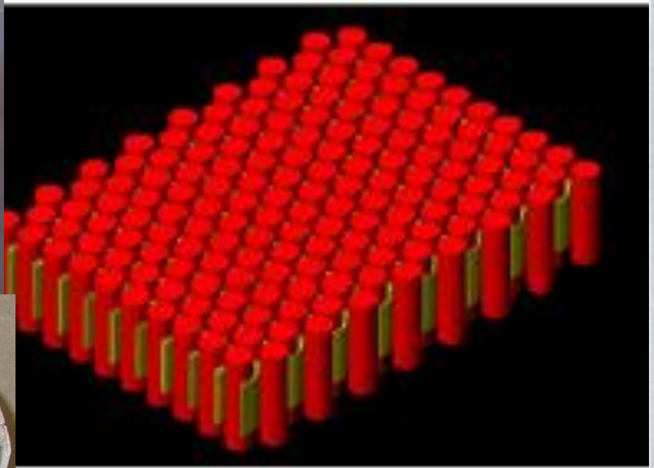
Jeevarajan[1] showed that without any heat dissipation path except through electrical parallel connections, adjacent cells get damaged (shorted) with even 4 mm spacing

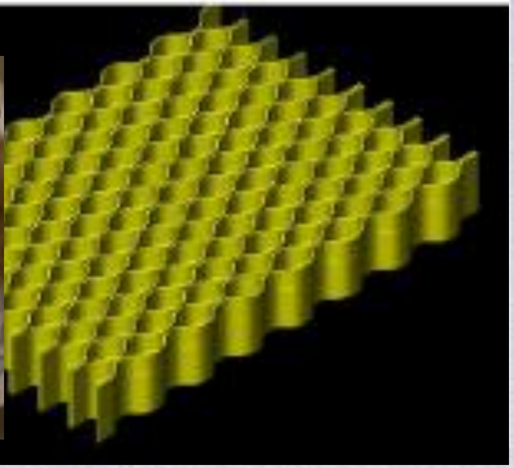
1. Jeevarajan et.al. NASA Aerospace Battery Workshop, Nov 2014

X-57 Battery Design Fails PPR Testing in 2016

- 320-cell module catastrophically fails during single cell PPR testing
  - Multiple cells propagated TR nearly simultaneously
  - DPA revealed numerous cell can side wall ruptures
- Design not following guidelines 1 and 2
  - Doesn’t protect against sidewall rupture
    - Nomex paper (yellow) is weaved in between cell can walls
    - Cell secured at their ends with G10 capture plates maybe held too tightly
  - Doesn’t provide sufficient heat dissipation between cells
    - Cell heat is dissipated through Ni bussing
    - Ni is a poor thermal conductor
- Battery redesign and retest will require trigger cells with ISC device



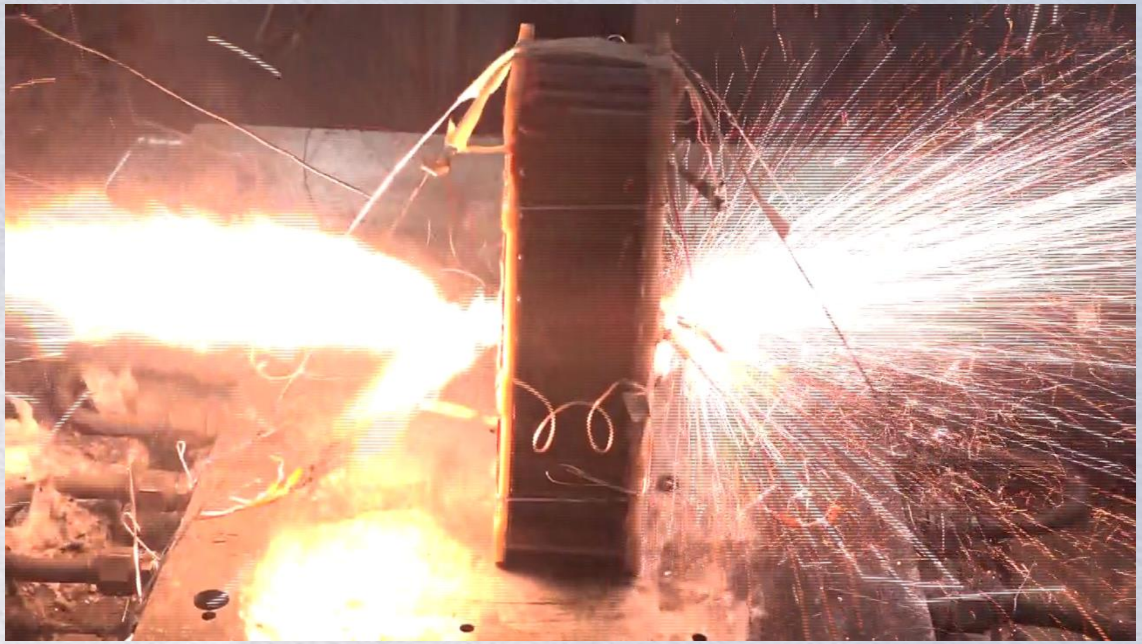




Achieving Passive TR Propagation Resistant Designs

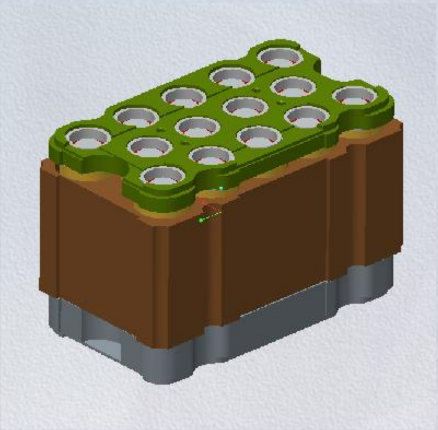
Pass/fail Criteria

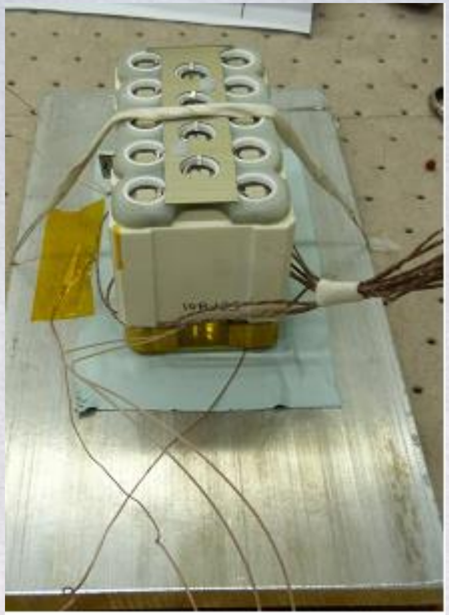
- No TR propagation resulting from the TR of any single cell location at worst case temperature and pressure conditions
- Demonstration required by test
  - Minimum of 3 tests if adjacent cells cycle nominally after the test
  - Minimum of 6 tests if in any one test the adjacent cells are damaged
    - CID opens, cell vents, or leakage
    - Charge retention (soft short)

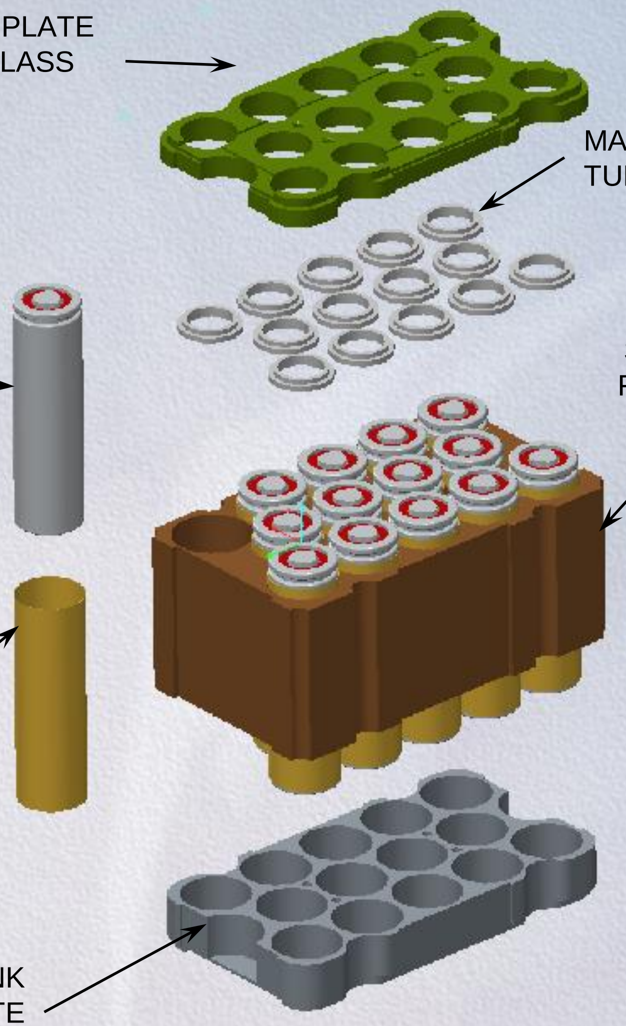


Source: NASA NESC Task Report TI-14-00942 “Assessment of ISS/EVA Lithium-ion Battery TR Severity Reduction Measures” May 2017

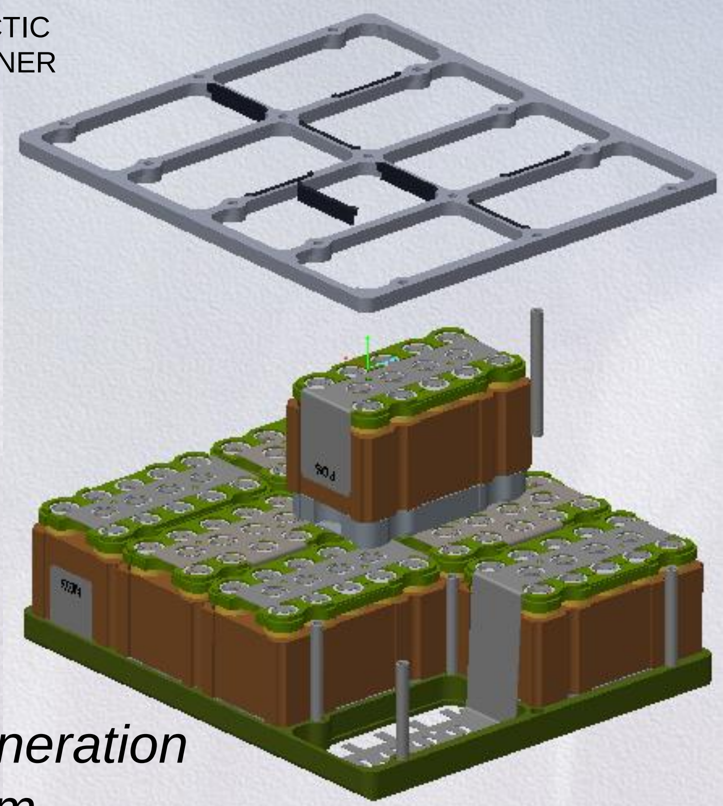
Orion Battery 14-cell Block





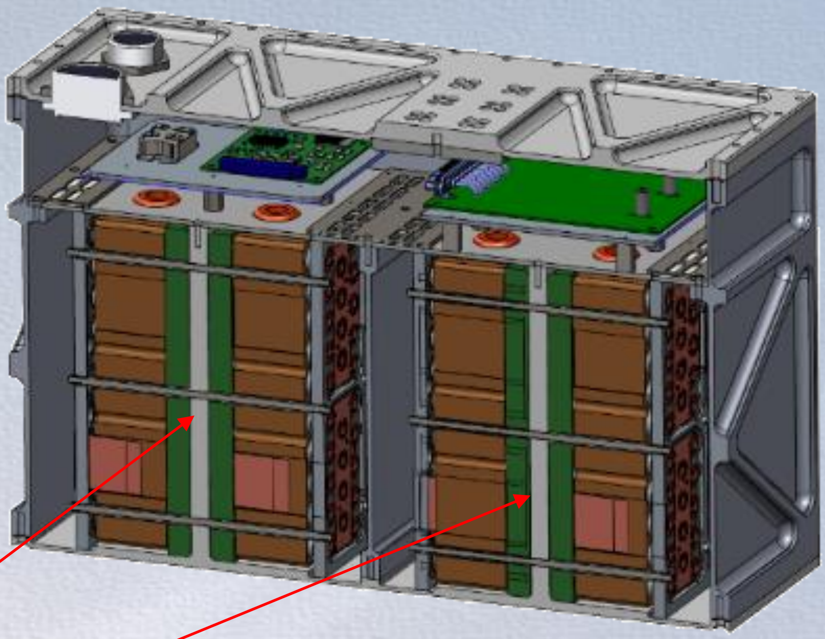


Orion 14P-8S Superbrick

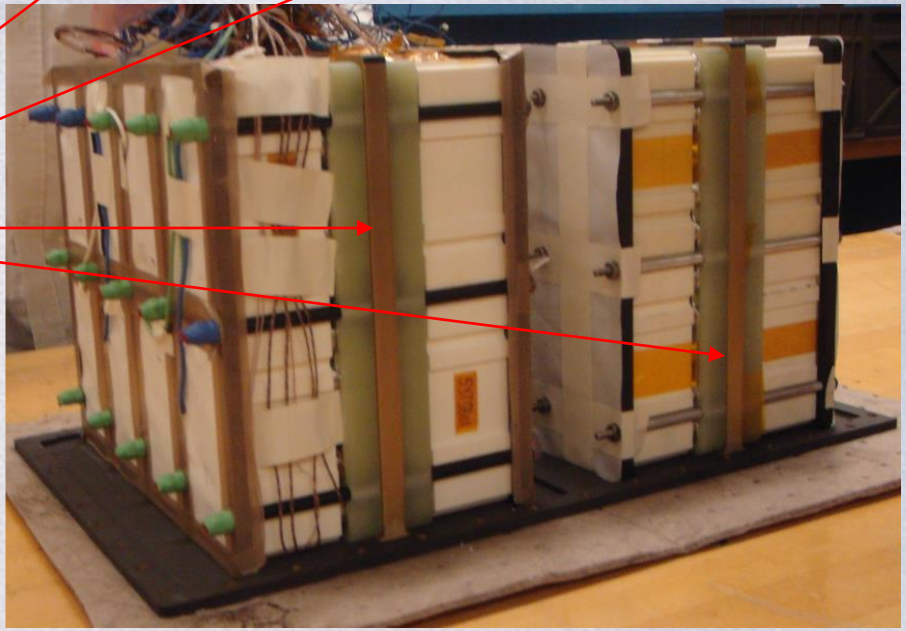


Draw cell heat generation through cell bottom

Isolating vs Providing a heat path

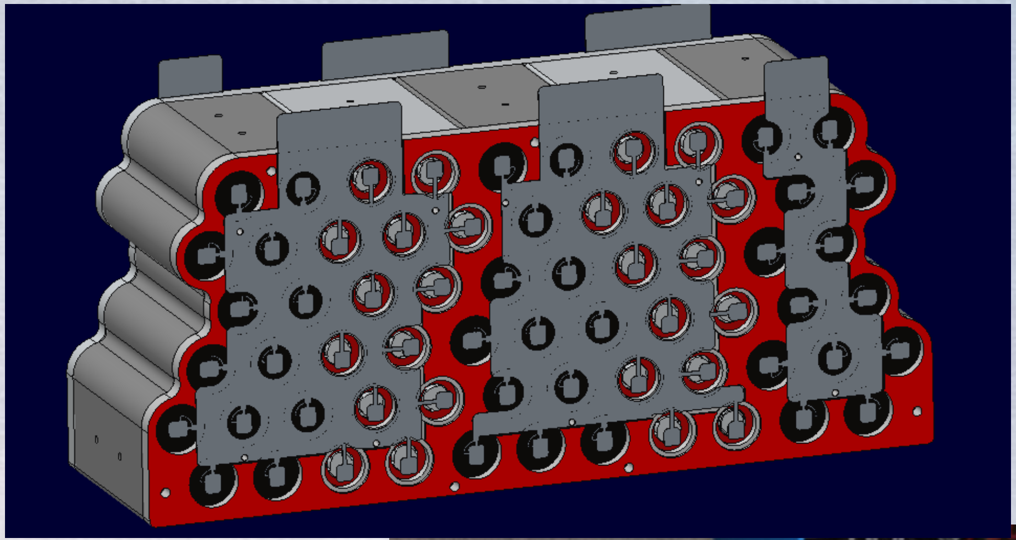


- If you thermally isolate cells (air)
  - Adjacent cell ΔT rise 80-100°C
  - ***Limited to cell designs with little risk of side wall ruptures***
  - Achieves 160-170 Wh/kg
- Orion - Partially conductive (Draw heat from cell bottom)
  - Conduct heat to divider plate
  - Adjacent cell ΔT rise 60-70°C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

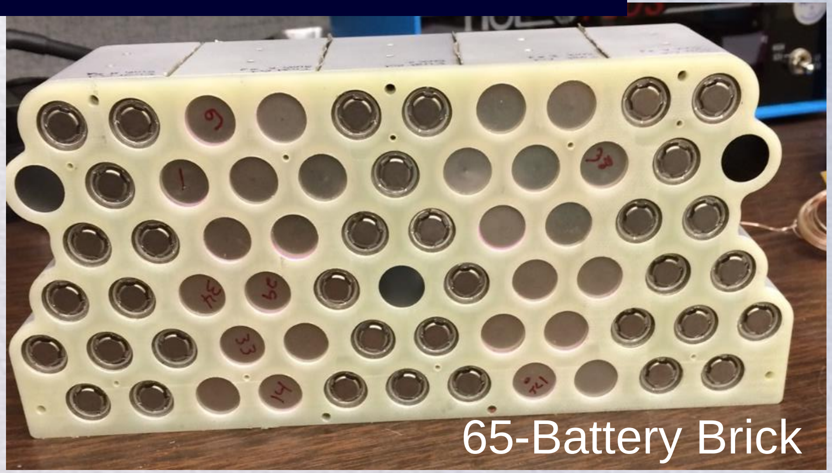


Safer, Higher Performing Battery Design

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



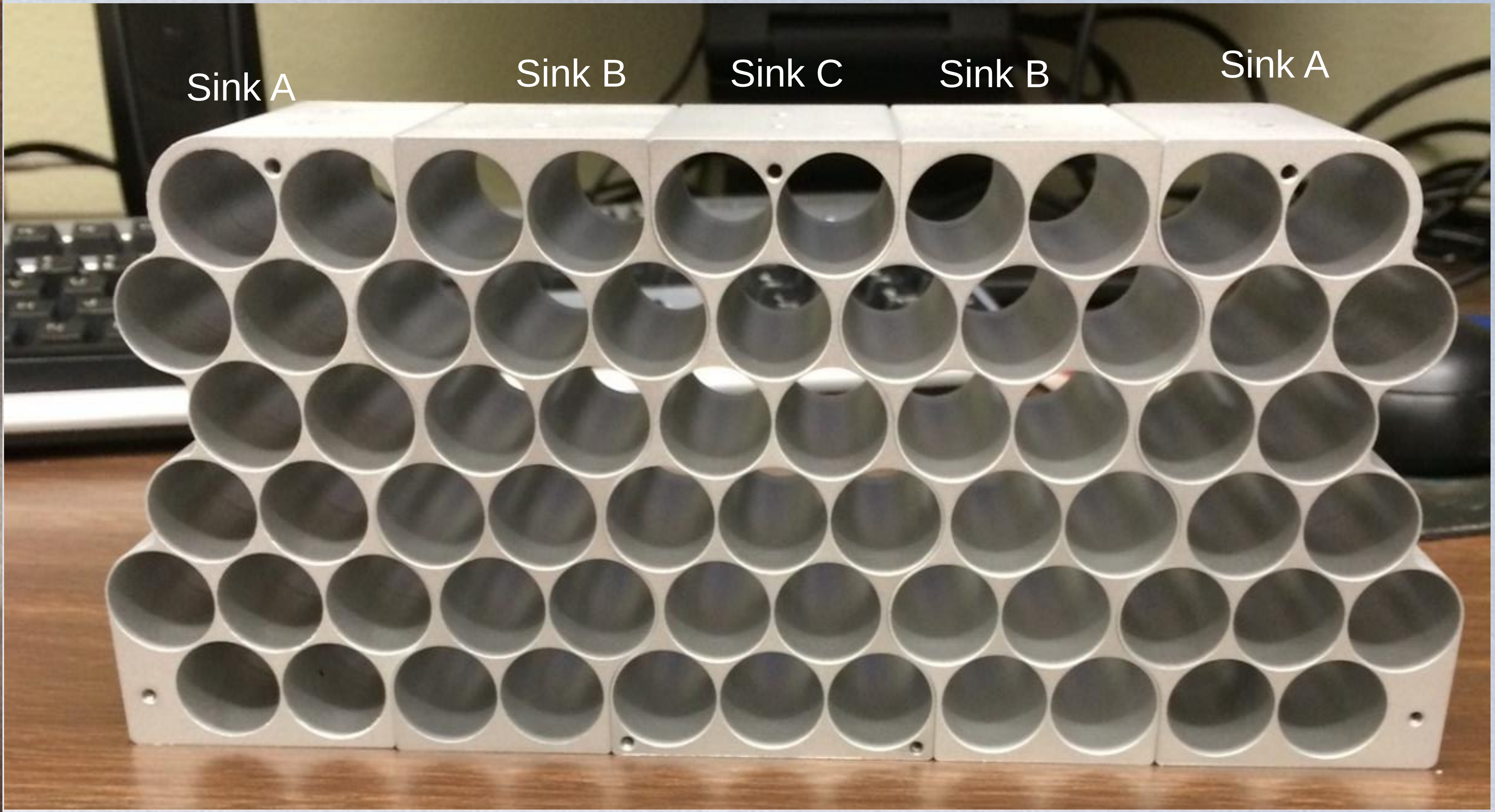
<u>Compliance with the 5 rules</u>
- **Minimize side wall ruptures** ✓
  - Al interstitial heat sink
- **No direct cell-cell contact** ✓
  - 0.5mm cell spacing, mica paper sleeves on each cell
- **Individually fusing cell in parallel** ✓
  - 12A fusible link
- **Protecting adjacent cells from TR ejecta** ✓
  - 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



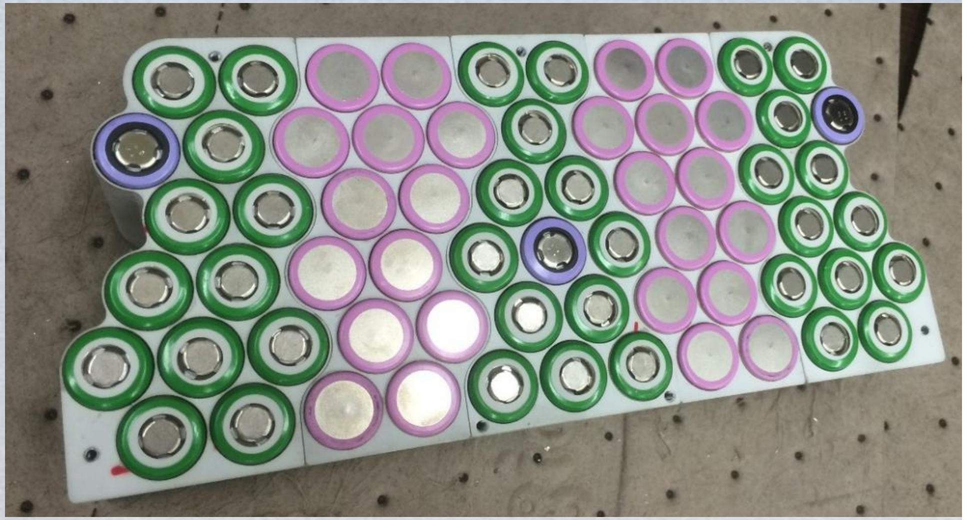
65-Battery Brick

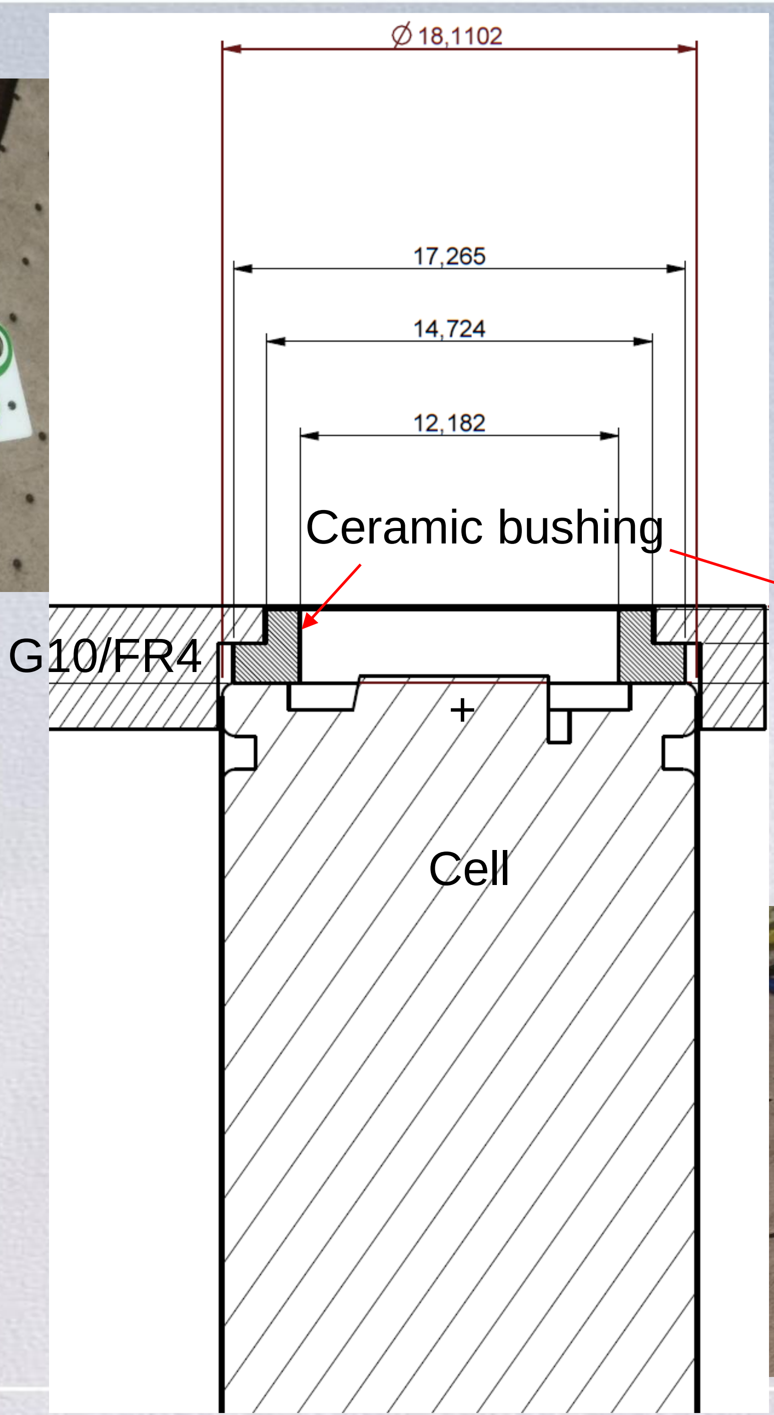
LLB2 Heat Sinks

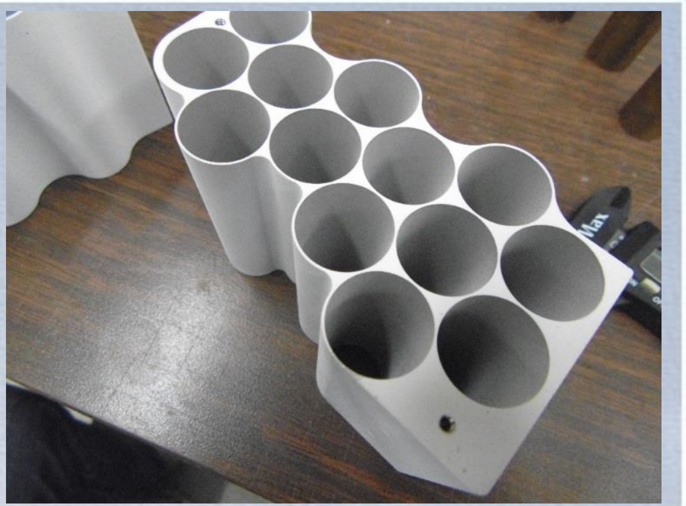
No corner cells - Every cell has at least 3 adjacent cells



0.5mm cell spacing, Al 6061T6



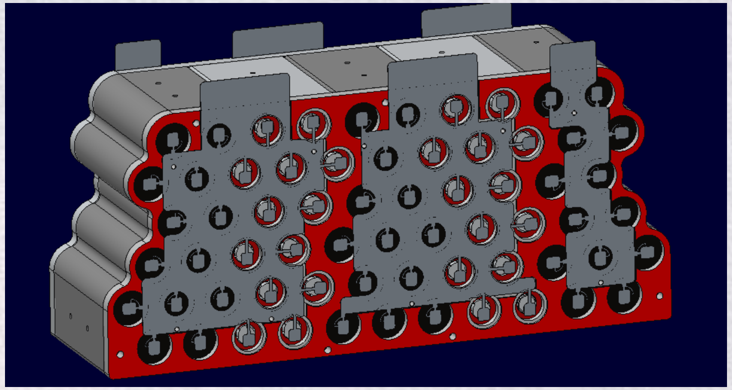




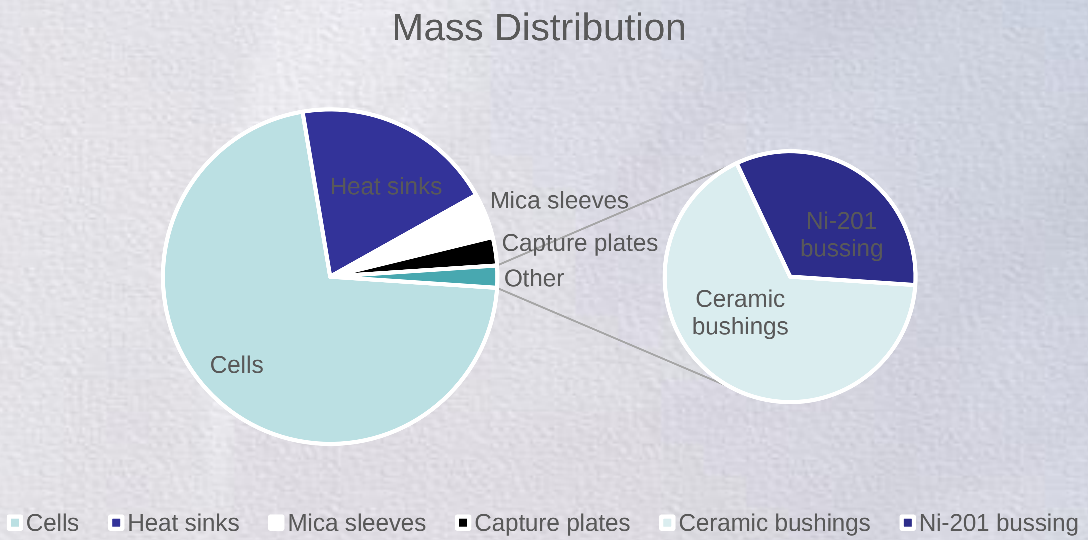
- 13P-5S Configuration with 3.4 Ah LG cell design yielding 37 Ah at 3.8 A mission rate.
- Aluminum interstitial heat sink, 0.5 mm spacing between cells
- Mica sleeves around shrink wrap, 2 FT
- The G10 capture plate houses the + and - ends of the cells and prevents the Ni bussing from shorting to the 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

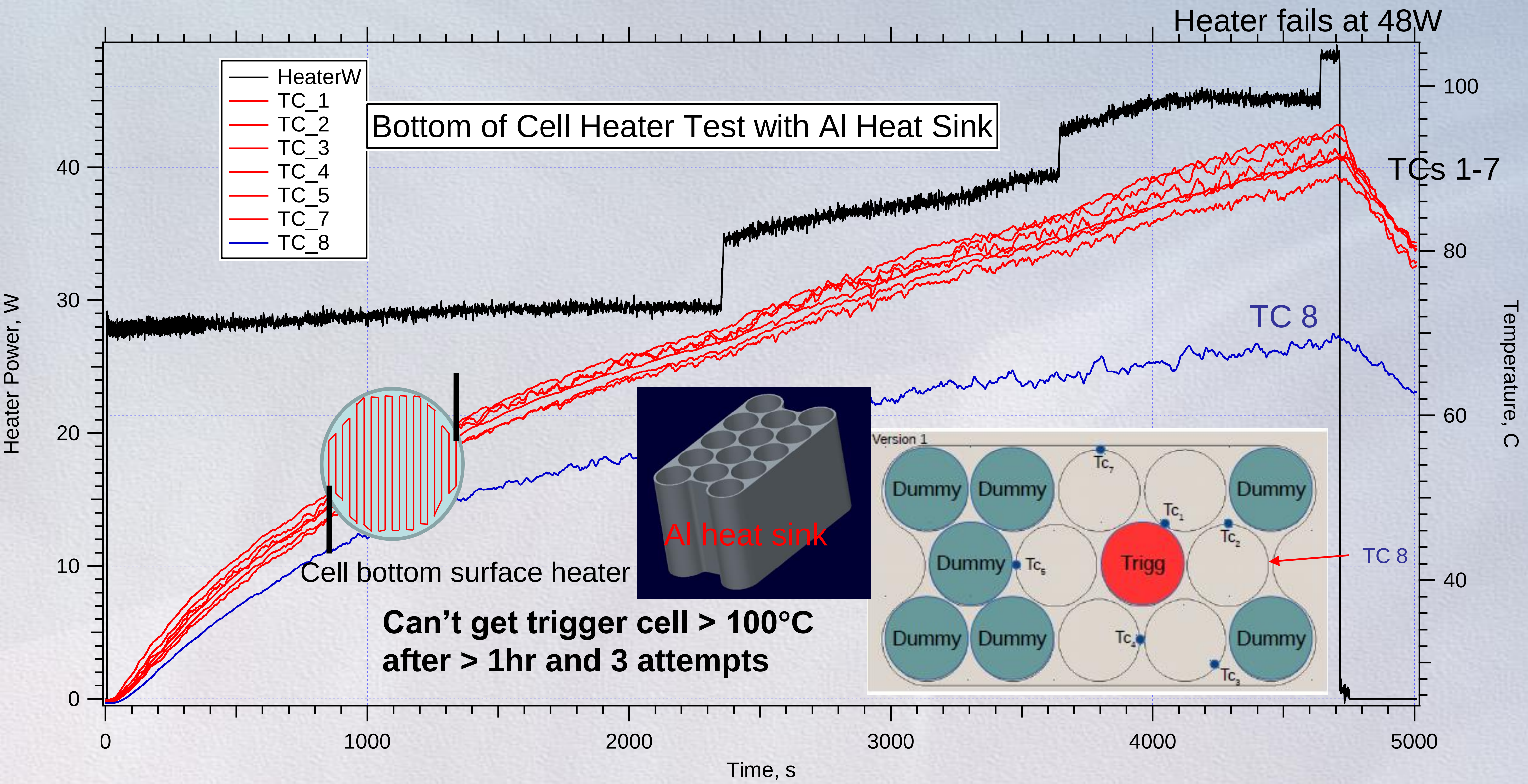
Mass Categories	g	%
3.4Ah 18650 Cells	3012.75	71.3%
Heat sinks	824.95	19.5%
Mica sleeves	182.31	4.3%
Capture plates	115.81	2.7%
Ceramic bushings	60.15	1.4%
Ni-201 bussing	29.71	0.7%
Total	4225.7	



- 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



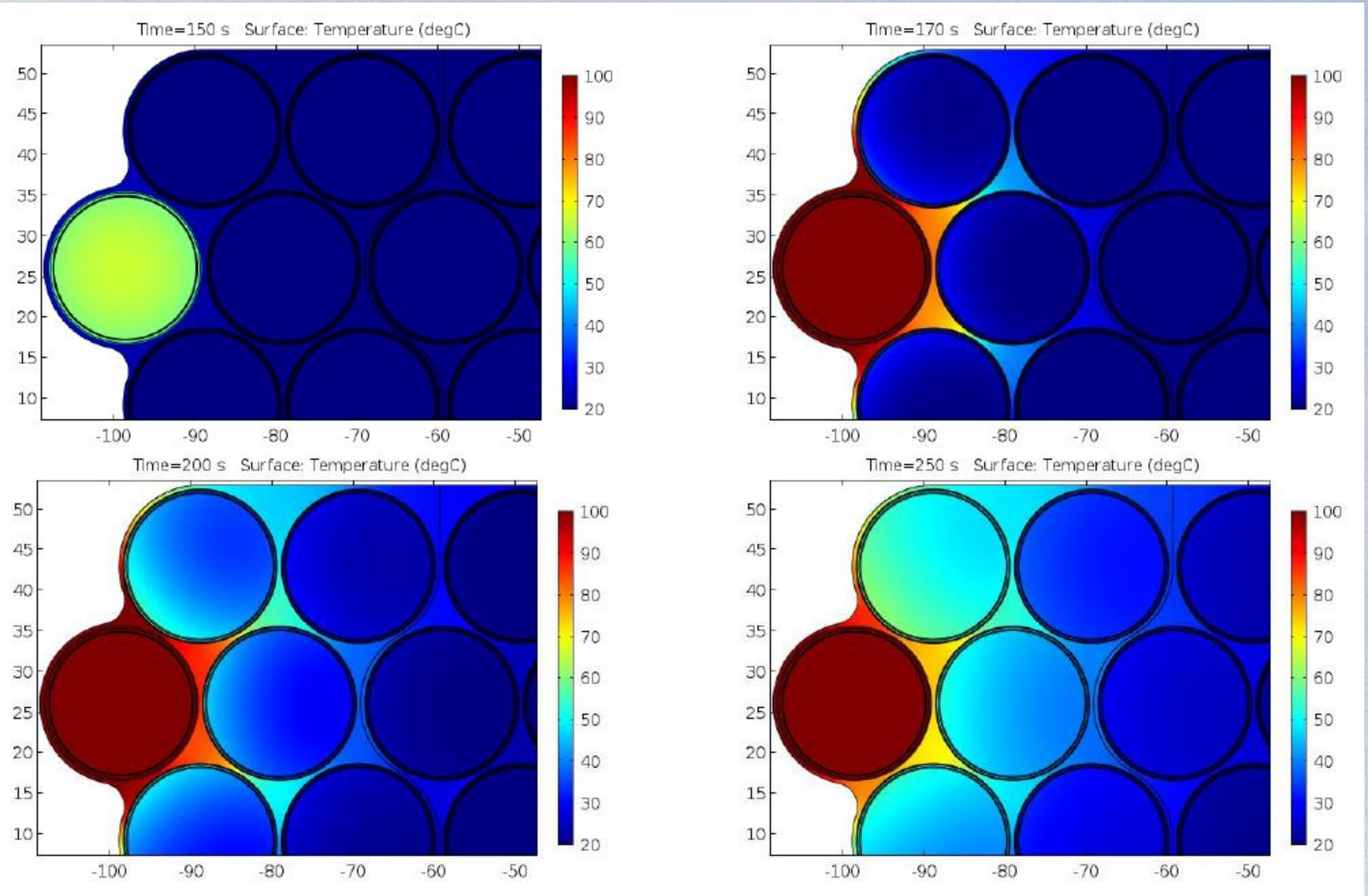
Attempts to Drive TR with Cell Bottom Heater Fails



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

Metallic Interstitial Heat Sink is Effective

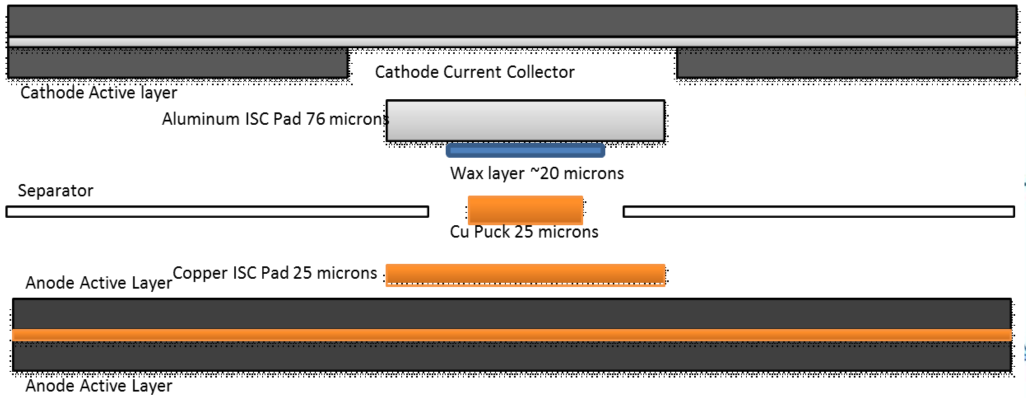
- Cell can isolated with mica paper sleeves and very small air gap
- Heat sink spreads heat more quickly through multiple layers than through mica and onto cells
- Heat from trigger cell is quickly dispersed and shared among more cells

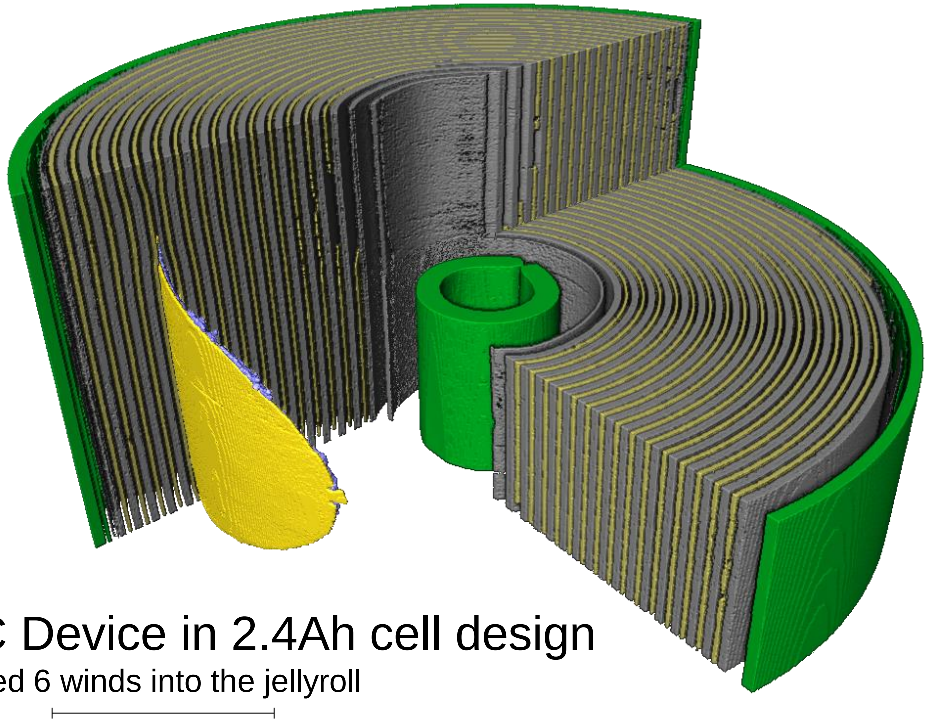


Graphic and analysis courtesy of Paul Coman

NREL/NASA Cell Internal Short Circuit Device

Active anode to cathode collector short

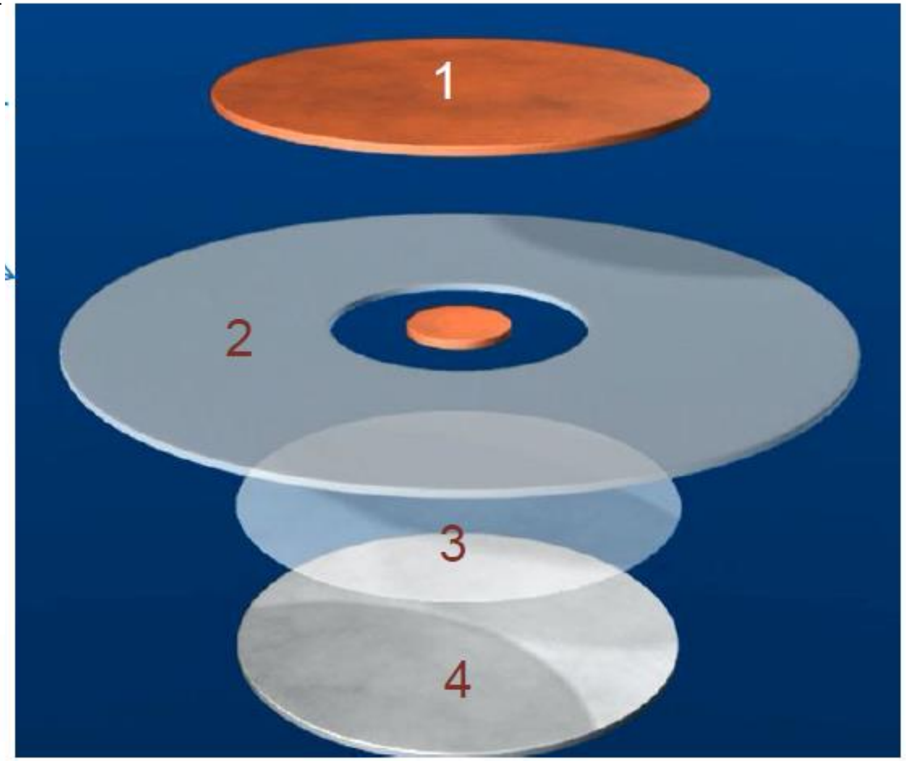




ISC Device in 2.4Ah cell design

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 issued in 2015

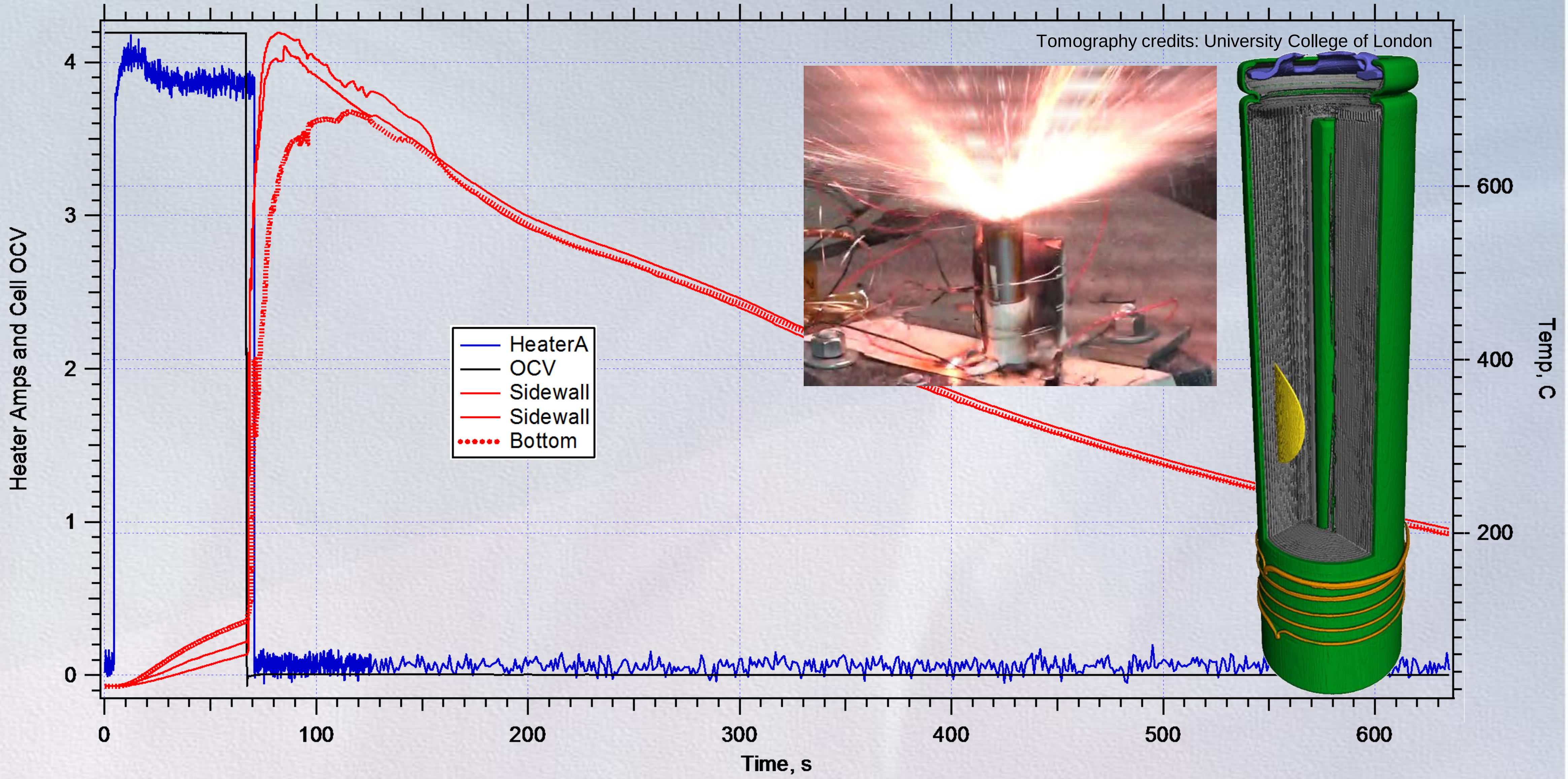
Thin (10-20 μm) wax layer is spin coated on Al foil pad

Wax formulation used melts ~57°C

Runner-up NASA Invention of 2017

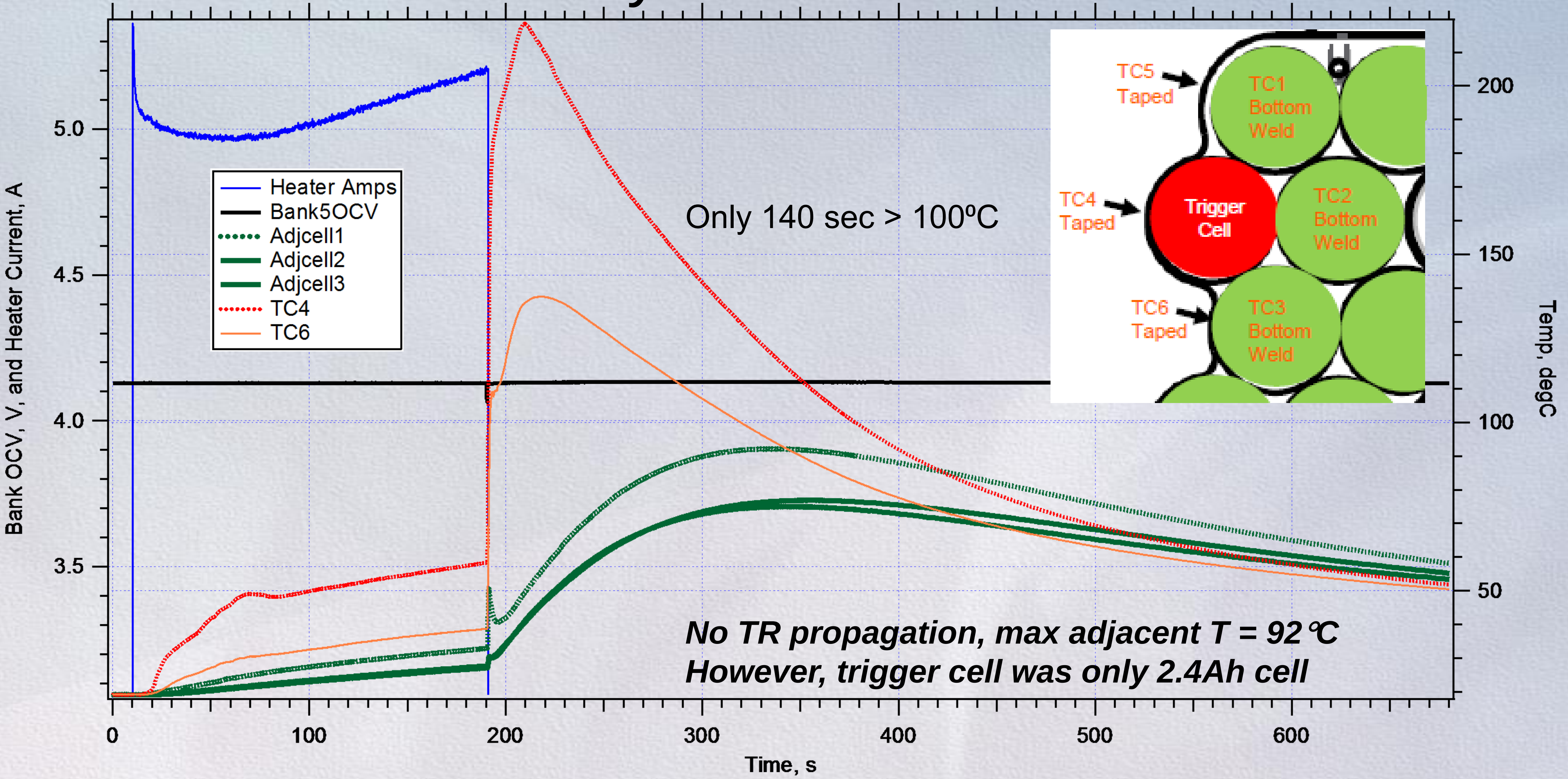
2016 Award Winner

Single Cell TR – Moli 2.4Ah with ISC Device



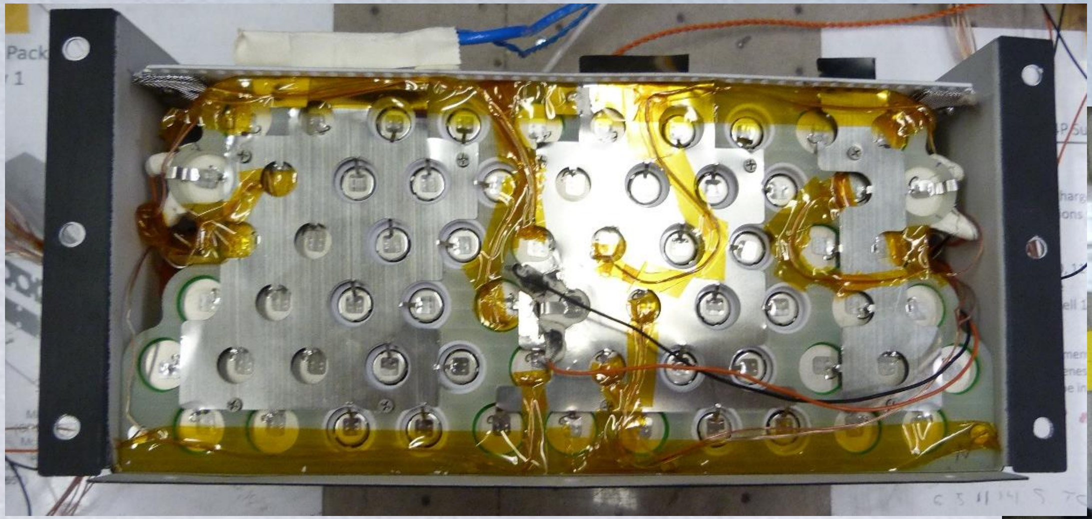
Open air test with cell charged to 4.2V and with TCs welded to cell side wall (2) and bottom (1)

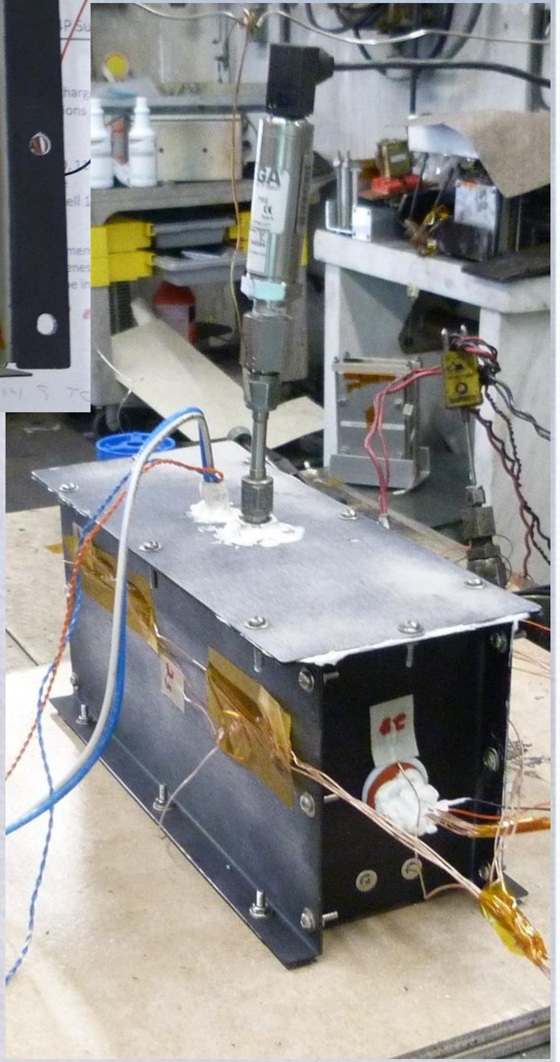
Full Scale Battery TR Test – MoliJ ISC Cell



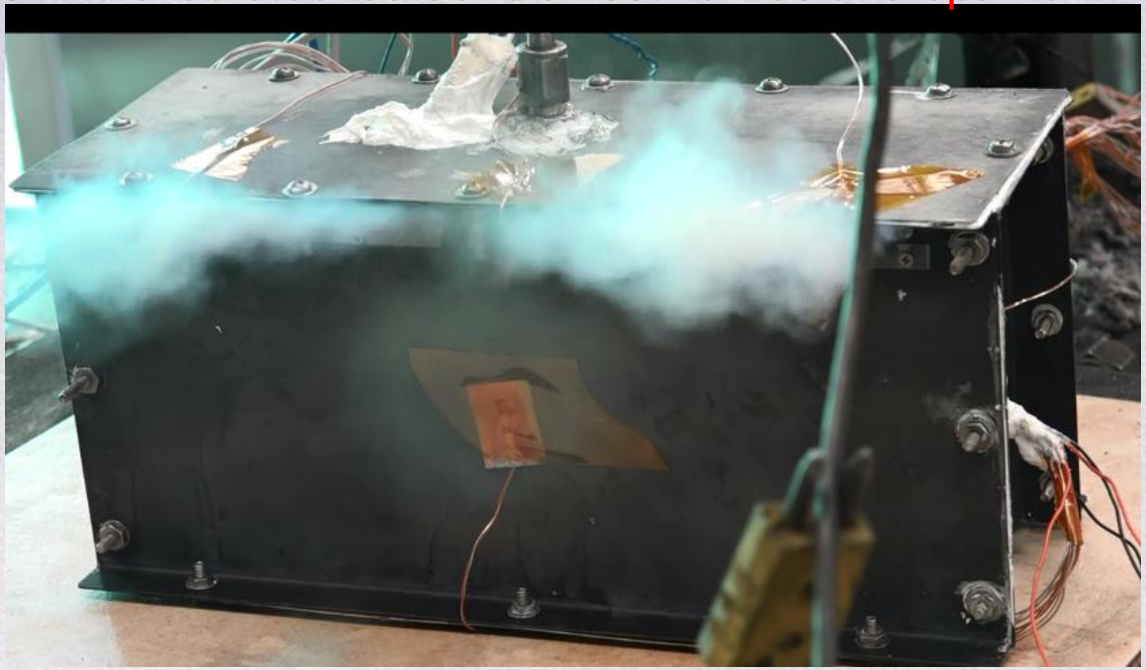
Heater power ~42W for 180s. Onset of TR (OTR) occurs 180s after power on and coincides with trigger bank OCV dip. Adjacent cell1 has ΔT = 58.9°C to max of 92.0°C, while adjacent cells 2 & 3 have ΔT = 48°C to max of 76.0°C

No TR Propagation, Only Smoke Exits Battery



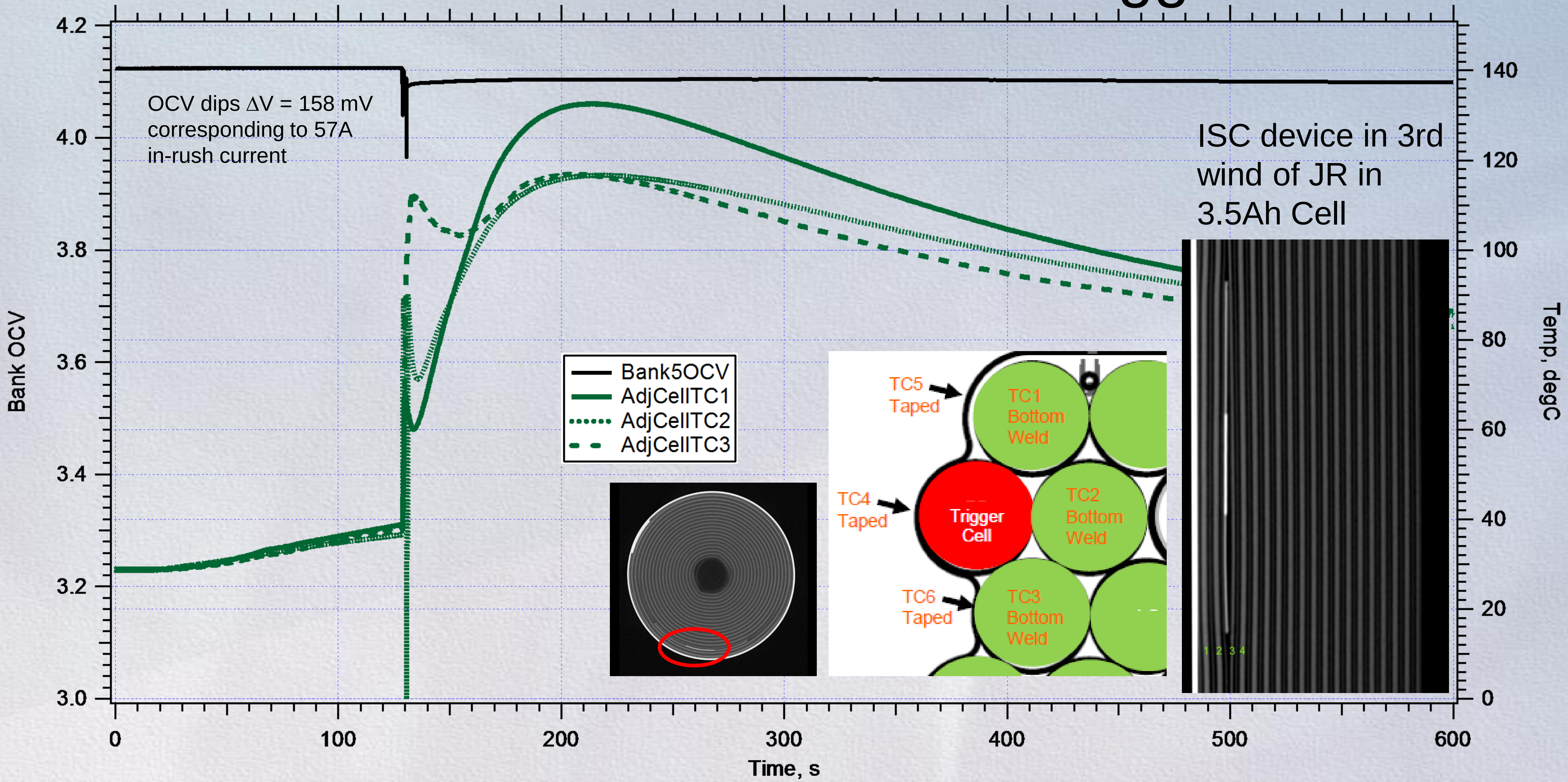


Mesh 40 & 30 steel screens arrest flames and sparks



However, trigger cell was only 2.4Ah cell

1st Test with 3.5Ah ISC Device Trigger Cell

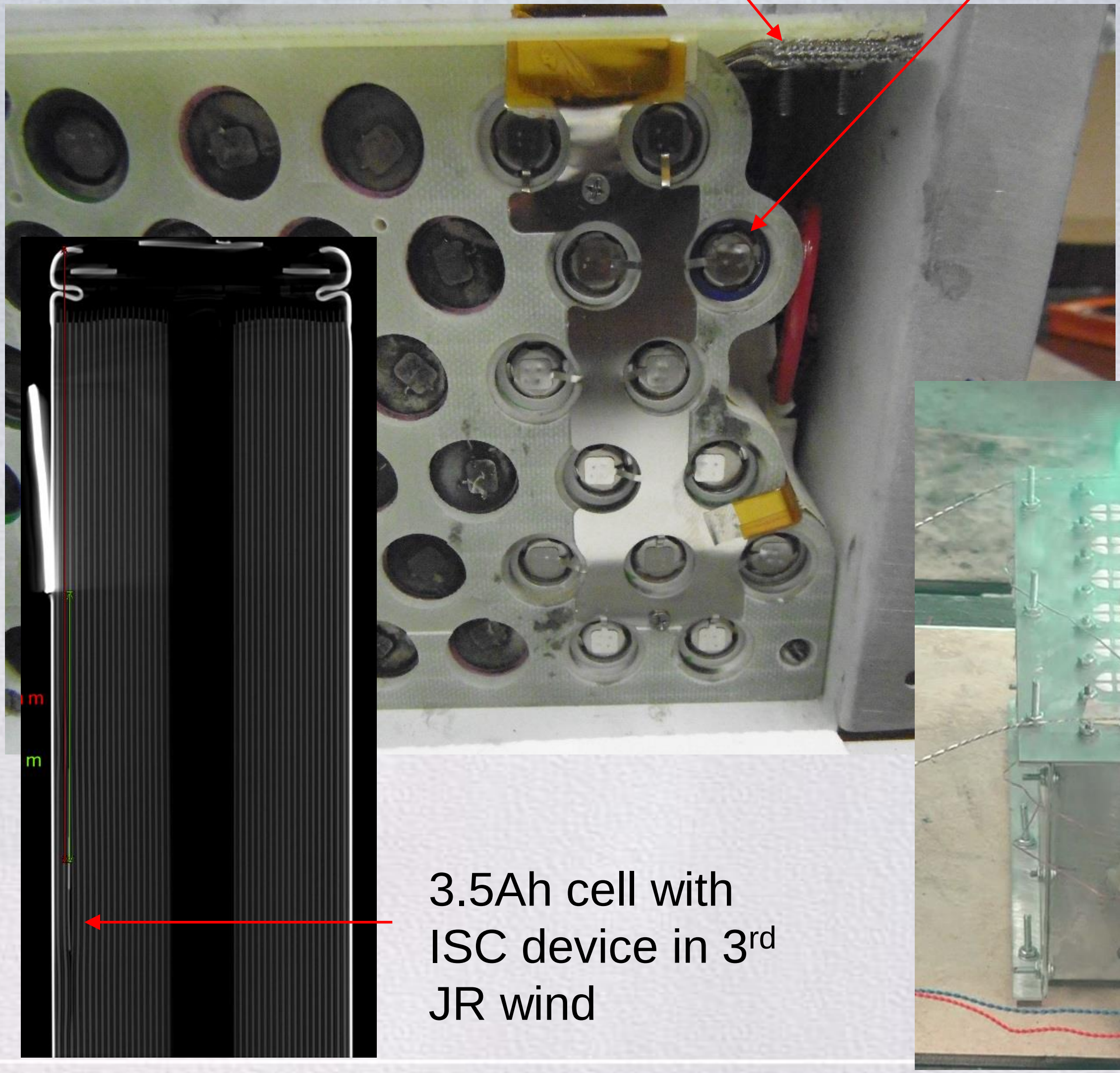


Adjacent cell temperatures TC1, TC2, and TC3 peak at 133°C, 117°C, and 117°C in 77-87s from onset temperatures of 39°C, 37°C, and 38°C for ΔT = 94°C, 77°C, and 78°C, respectively.

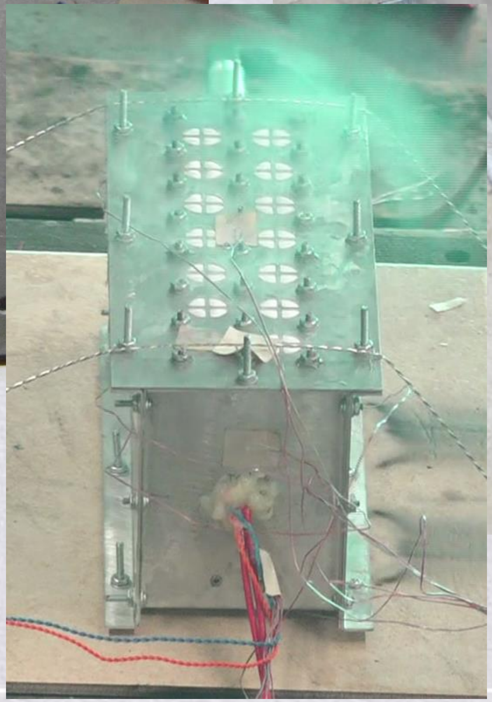
No TR Propagation – Only Clean Smoke Exits Gore Vent

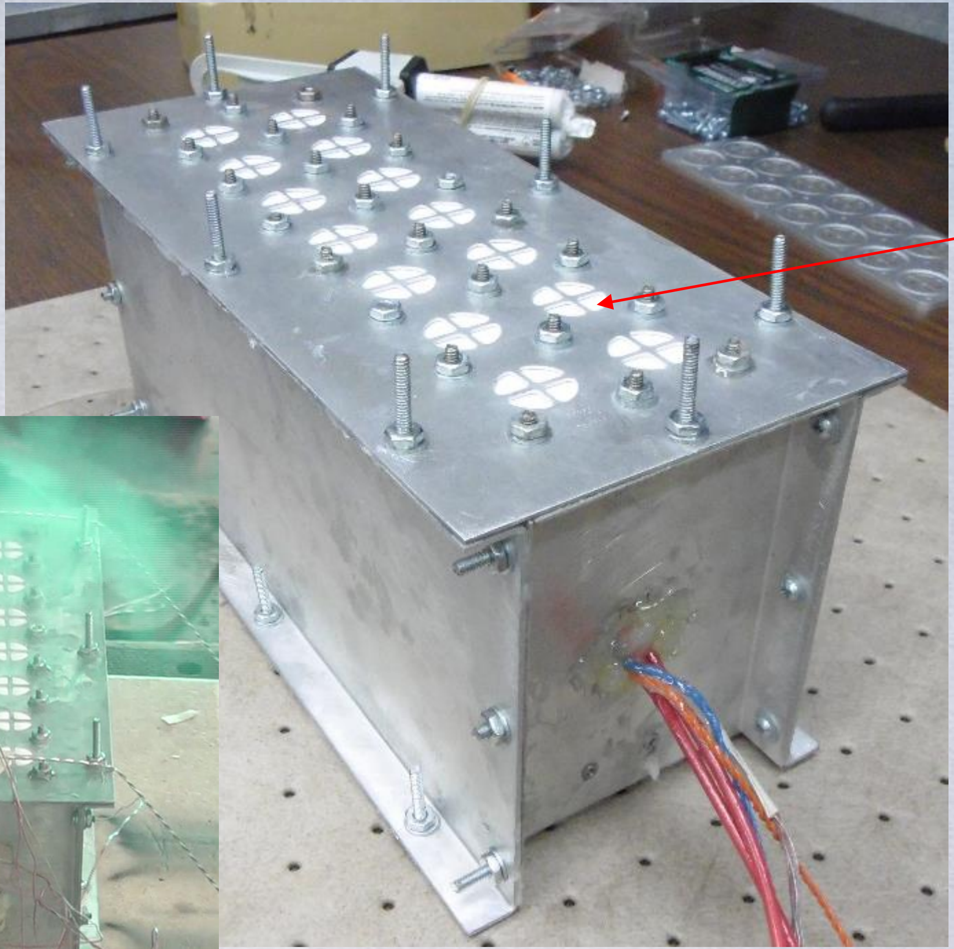
Flame arresting steel screens

3.5Ah Cell with ISC device trigger location



3.5Ah cell with ISC device in 3rd JR wind





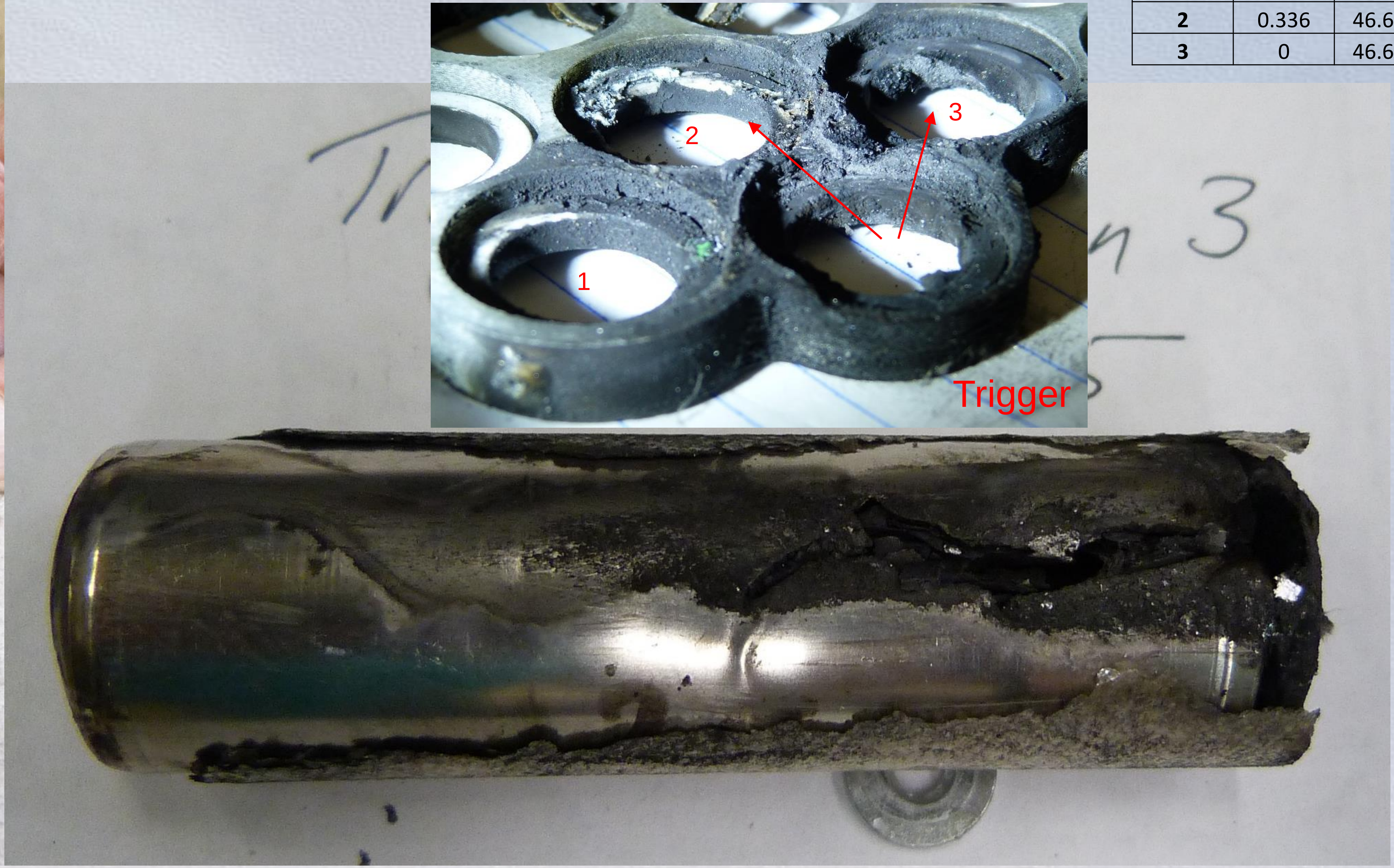
Gore fabric Vent design

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

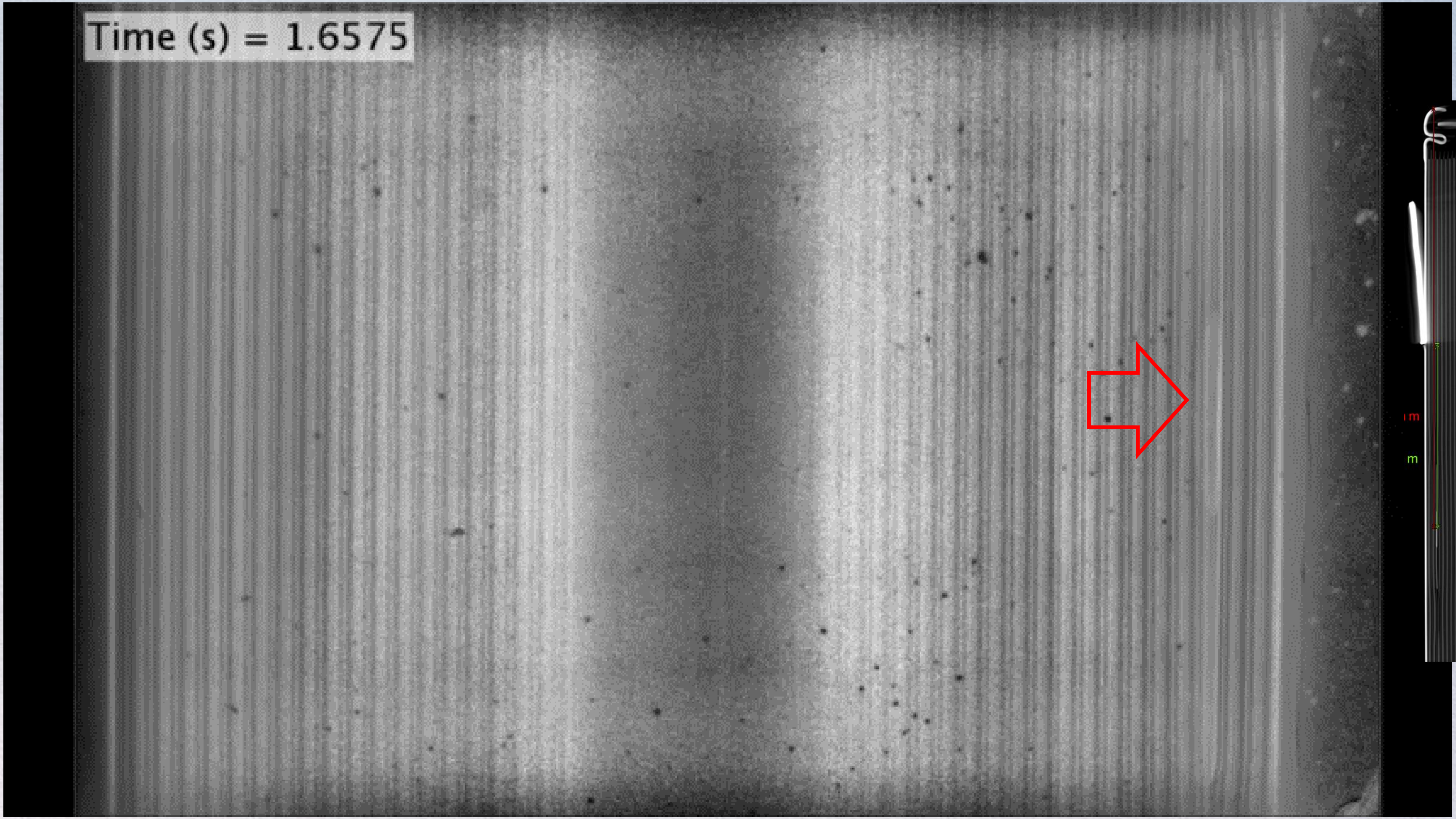
3.5 Ah Trigger Cell Experienced a Side Wall Breach

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



3.5Ah Cell #21 with ISC Device Video



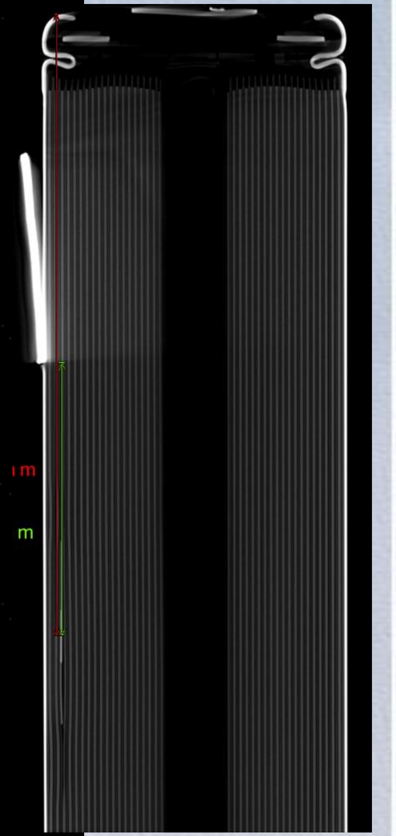
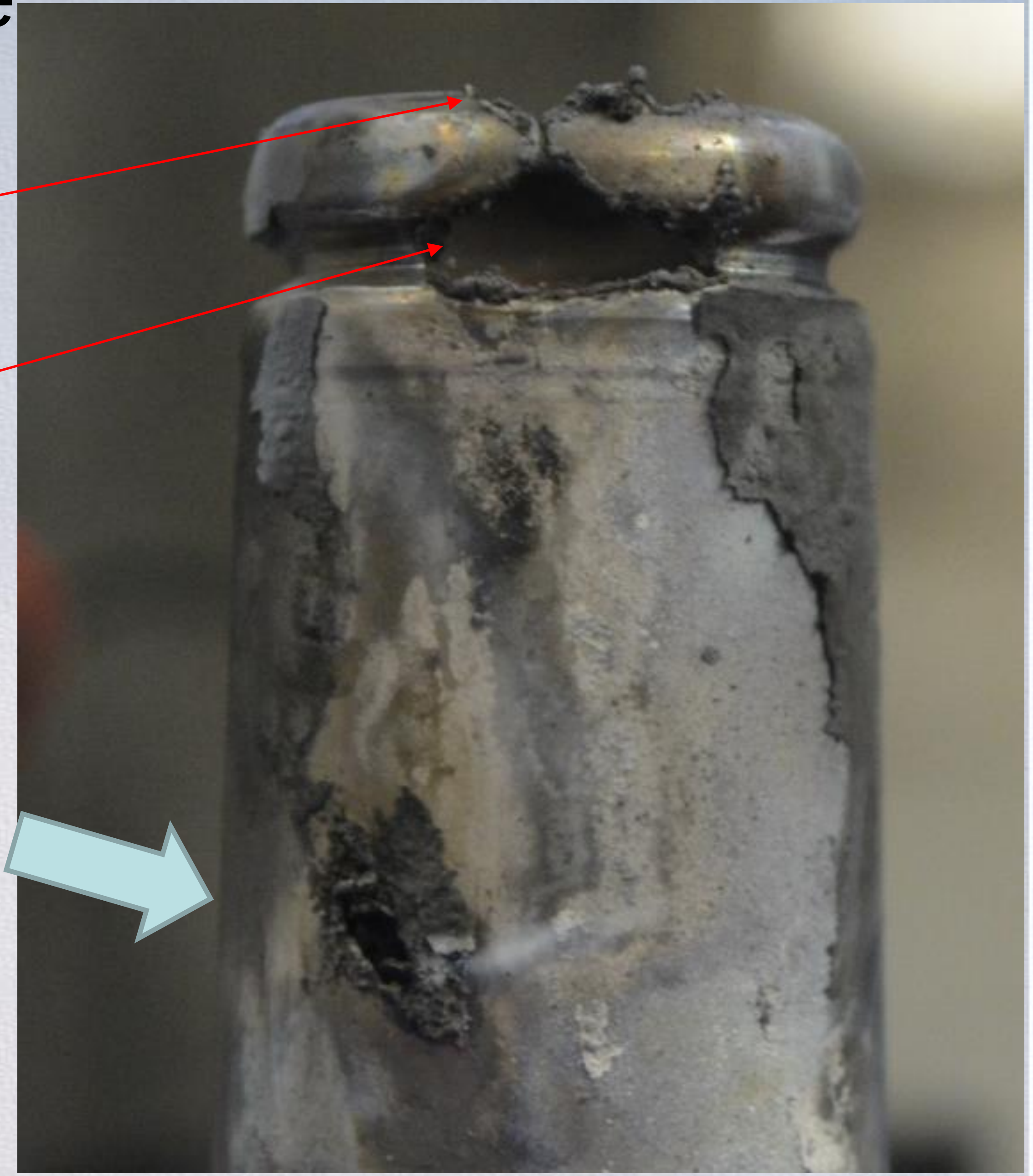


Image and video courtesy of D. Finegan, University College of London

3.5Ah Cell #21 with ISC Device

- JR ejected
- Top edge of crimp shows reflow steel
- Side wall breach in neck of crimp is clocked with ISC device
- Smaller breach in can wall is slightly off the ISC device clocking and above it



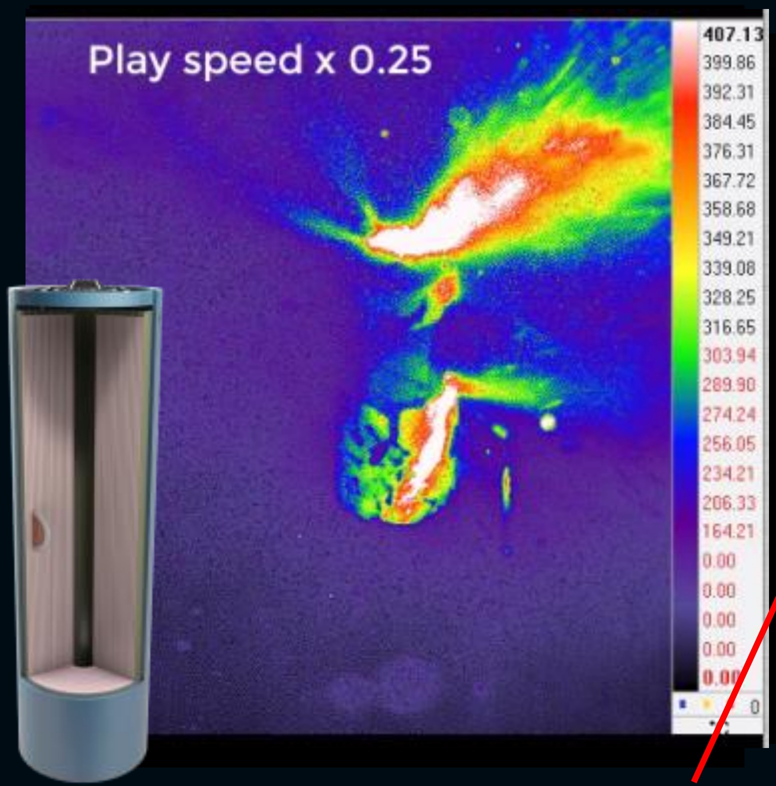
Side-wall Breach of MJ1 Cell

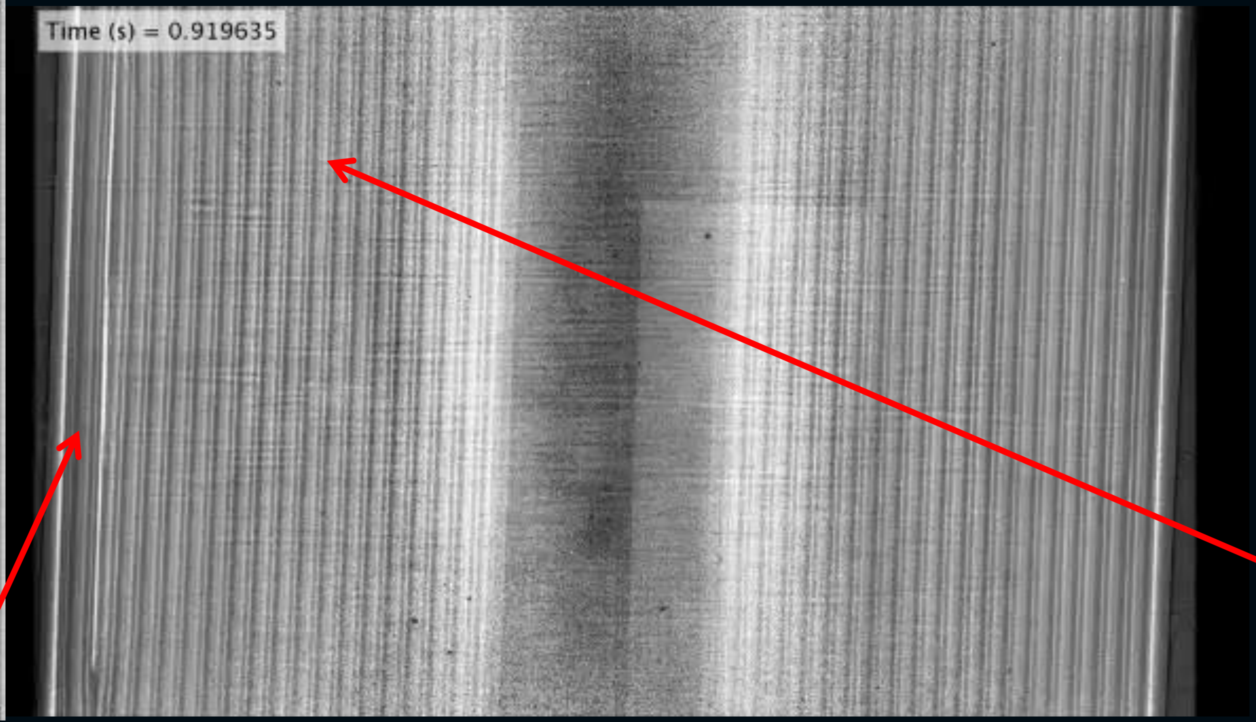
ISC device 3 winds in

Side-wall breach

Hotspot clocked with ISC device followed by side-wall breach (SWB)

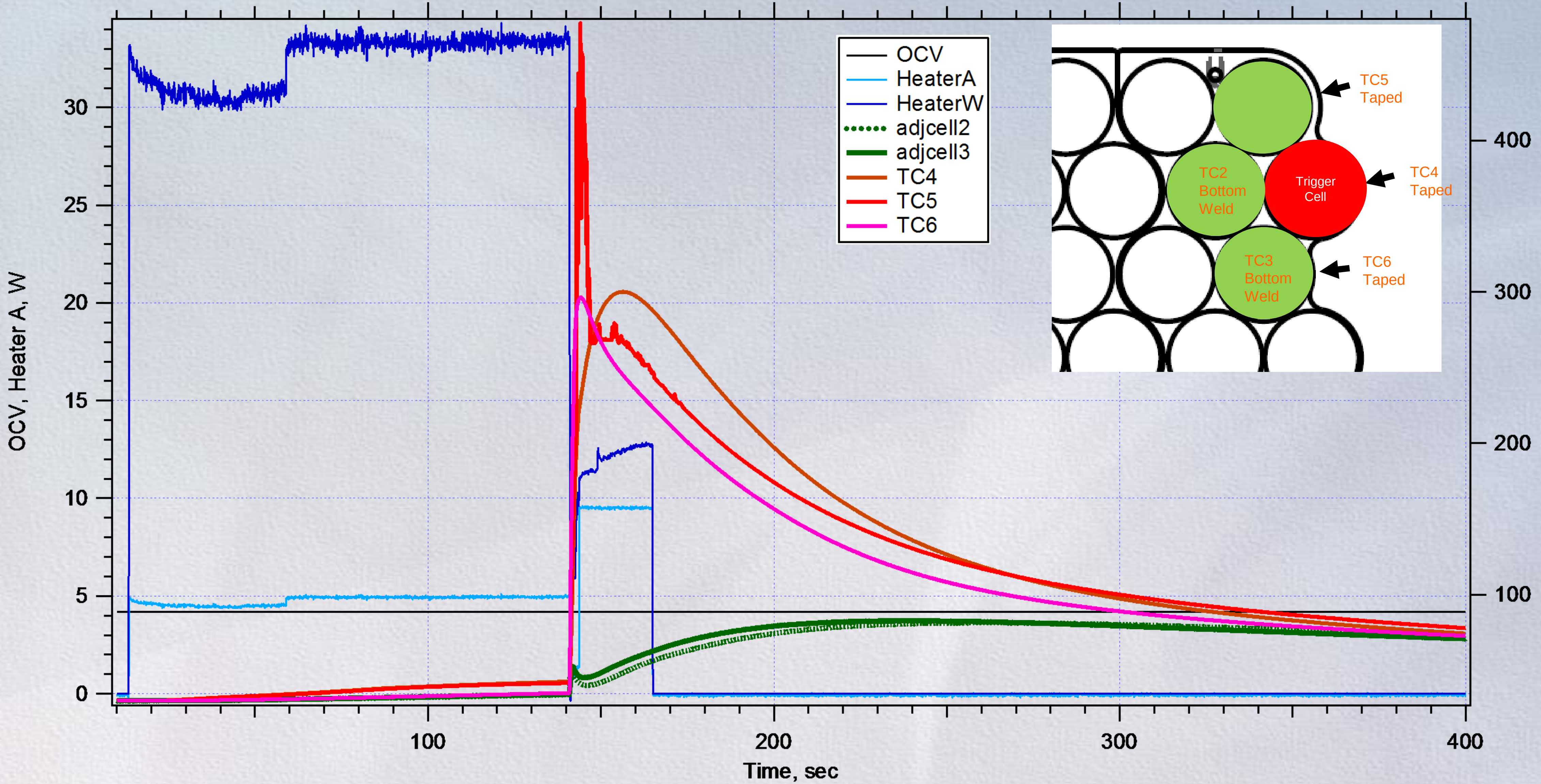
First capture of side wall breach using high speed X-ray imaging.
Bulging around the point of initiation occurs and the propagation front makes early contact with the cell casing. The direction of flow shifts towards the widening SWB.





ISC device

2^{nd} Test 3.5Ah ISC Trigger Cell – OCV, Heaters, & Interior Temps



Adjacent cell max temperatures < 83°C

Post-Test Photos – Trigger Cell

Post-Test Mass: 25.3g

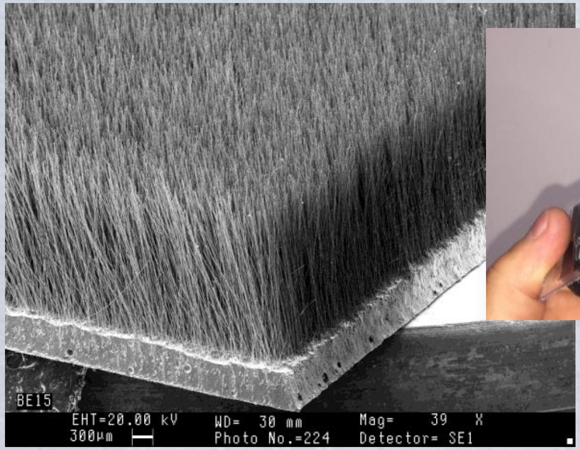
Bottom breach

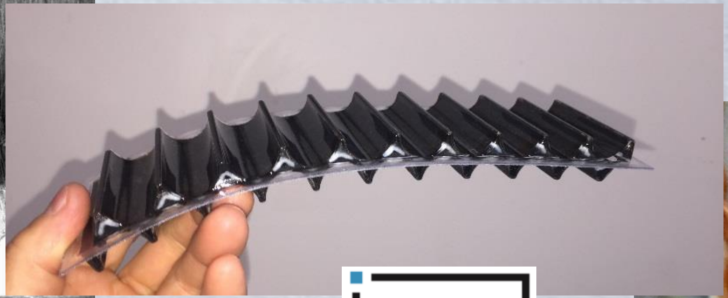
Spin groove is stretched

Findings from 2^{nd} Test with 3.5Ah ISC Trigger Cell

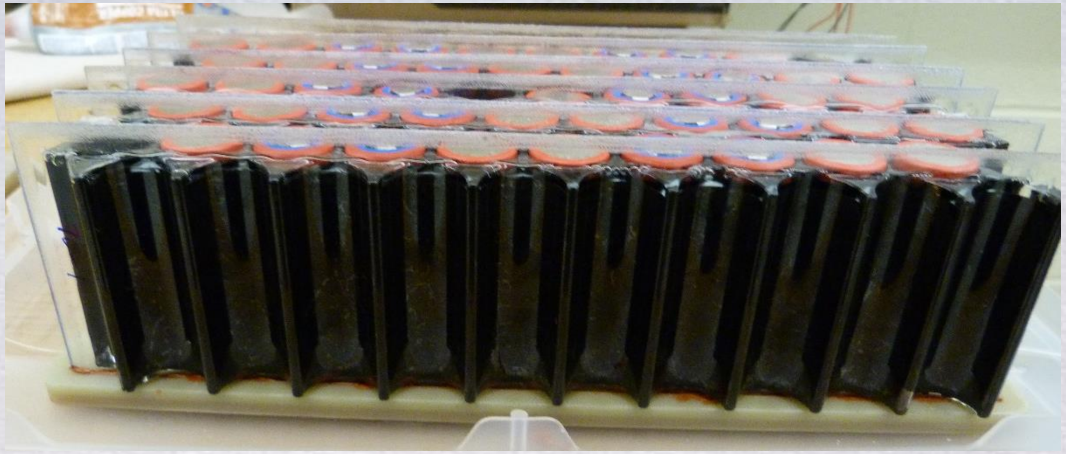
- ISC device in 3.5Ah 18650 cell triggered in 127 seconds with bottom heater at 32W average
  - Very similar initiation time (1^{st} run was in 119s)
  - Very similar biasing of adjacent cells (34-35°C) at onset of TR (1^{st} run at 37-39°C)
- No propagation of TR
  - Despite bottom breach of trigger 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 1^{st} run (77-94°C)
  - Bottom breach yields a much less severe impact than side wall breach

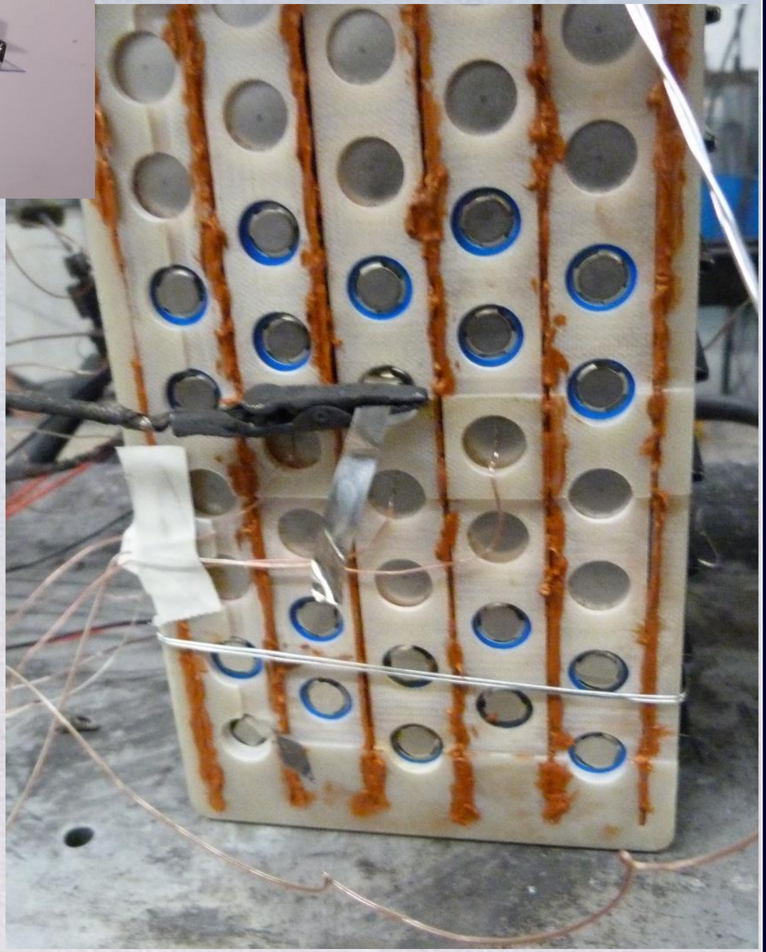
Vaporizing TR Shields 50-cell Brick Test



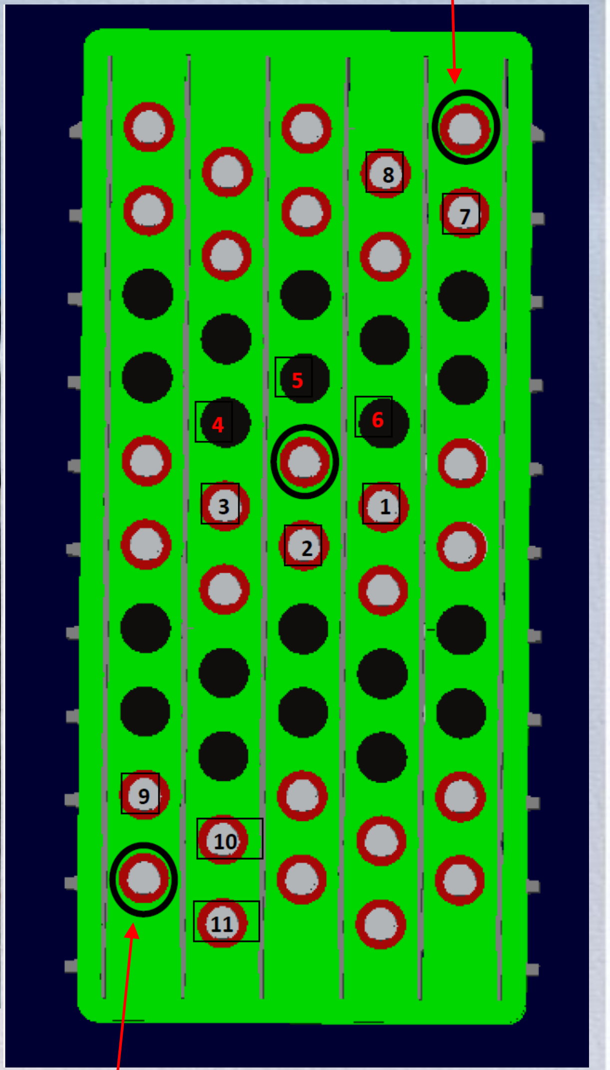


KULR
Carbon Fiber Cooling™





Trigger cell



Trigger cell

Three trigger cell locations

LG 3.3Ah with thicker can walls (250 microns) and ISC device in bottom of JR

Thermocouples welded to bottom of adjacent cells.

Comparing the 2 Interstitial Heat Sink Options

Aluminum Interstitial		
Mass Categories	g	%
LG MJ1 cells	3013	71.30%
Heat sinks	825	19.50%
Mica sleeves	182.3	4.30%
Capture plates	115.8	2.70%
Ceramic bushings	60.15	1.40%
Ni-201 bussing	29.71	0.70%
Total	4226	
Parasitic mass factor	1.40	
Brick Specific Energy	191	Wh/kg

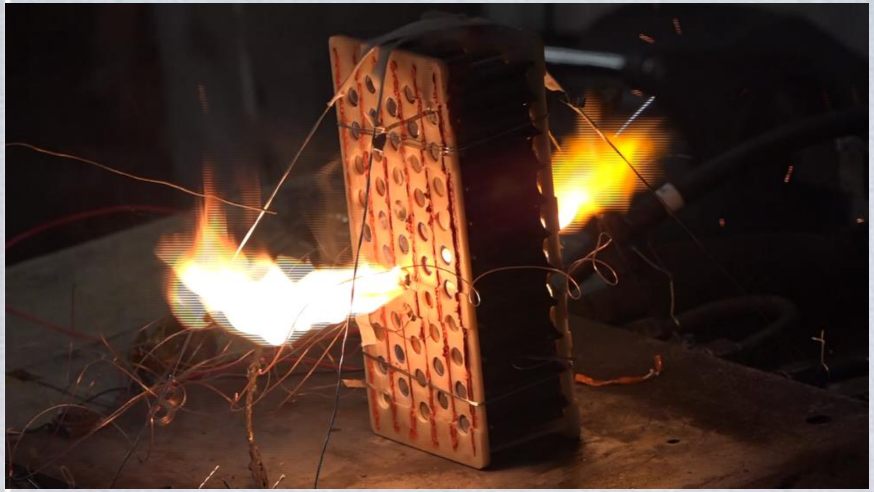
Vaporizing Interstitial		
Mass Categories	g	%
LG MJ1 cells	3013	84.81%
Vaporizing heat sinks	334.1	9.40%
Mica sleeves	0	0.00%
Capture plates	115.8	3.26%
Ceramic bushings	60.15	1.69%
Ni-201 bussing	29.71	0.84%
Total	3553	
Parasitic mass factor	1.18	
Brick Specific Energy	227	Wh/kg

KULR Vaporizing Heat Sink enables

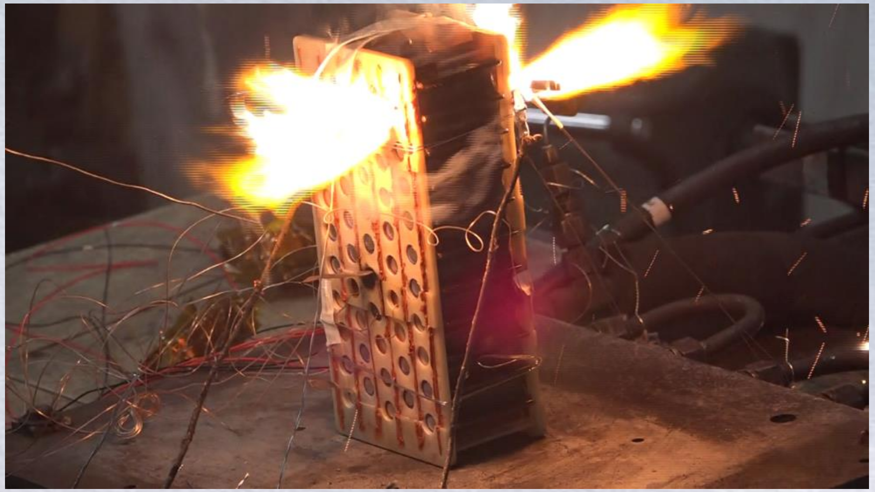
- **19% improvement in Wh/kg**
- **1.5 lbs mass savings per spacesuit battery (or 16%)**
- **For the X-57 battery (55 kWh) this would save > 101 lbs**

Video snapshots of all 3 trigger tests

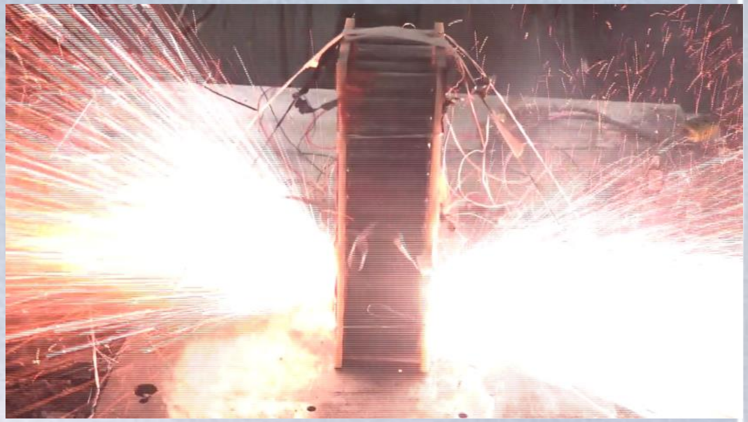
Interior trigger location



Top trigger location



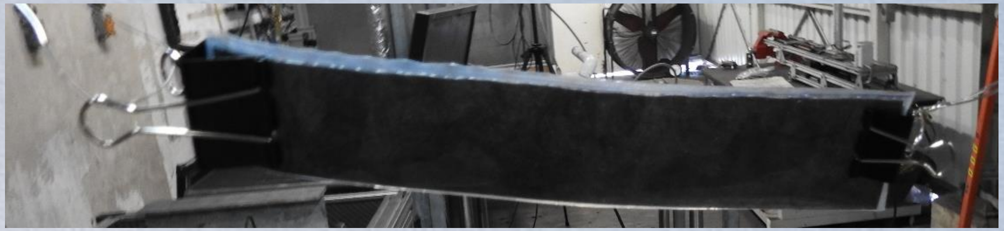
Bottom trigger location



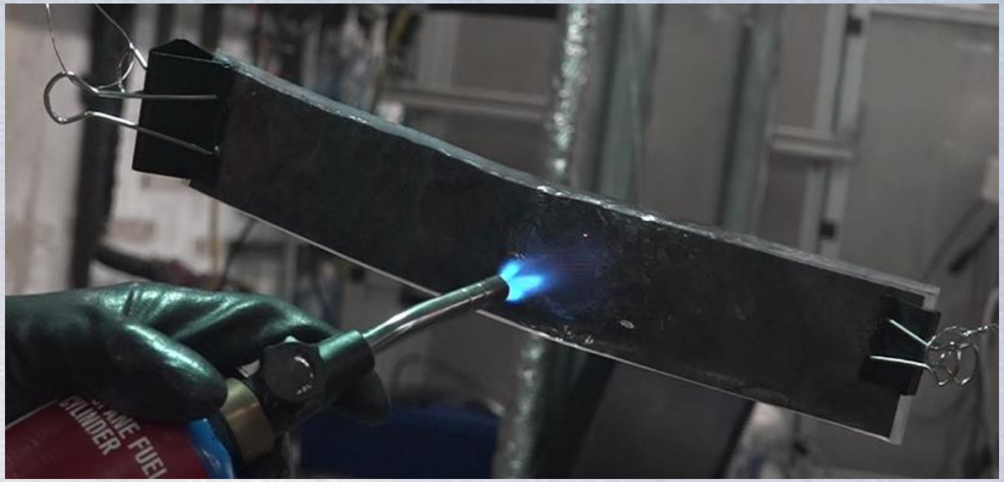
- Max ΔT on adjacent cell 40-63°C, a bit higher than with Al heat sink brick test
  - However in Al brick test 2.4Ah trigger cell vs 3.3Ah for vaporizing brick test
- All adjacent cells cycled nominally post test

Vaporizing Thermal Runaway Shields - Blow Torch Test

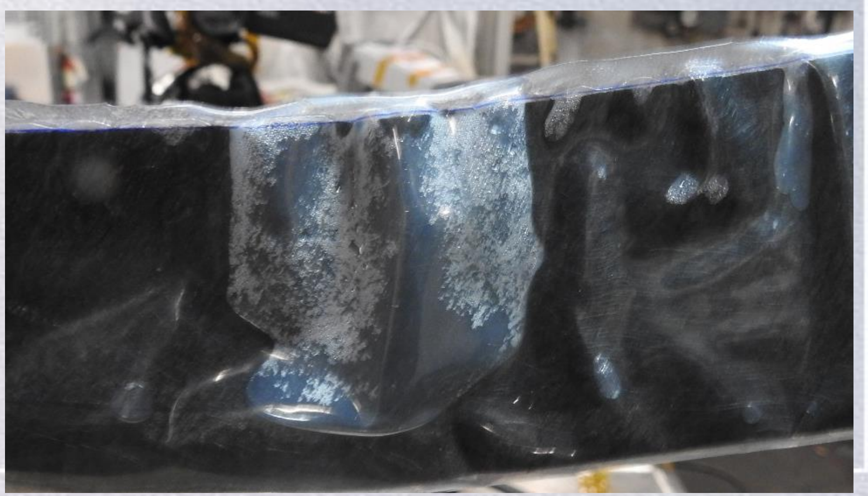
- Design
  - Highly conductive carbon fiber wick
  - Soft, thin, & compliant polyethylene enclosure & seal
  - 2mm thickness
  - Much lighter than solid Al
- Tests
  - No blow through failures after multiple direct flame impingement 10-sec blow torch exposures
  - Plastic melts, water leaks out, but wet carbon fiber layer stays intact
- Merits testing with cells likely to side wall rupture



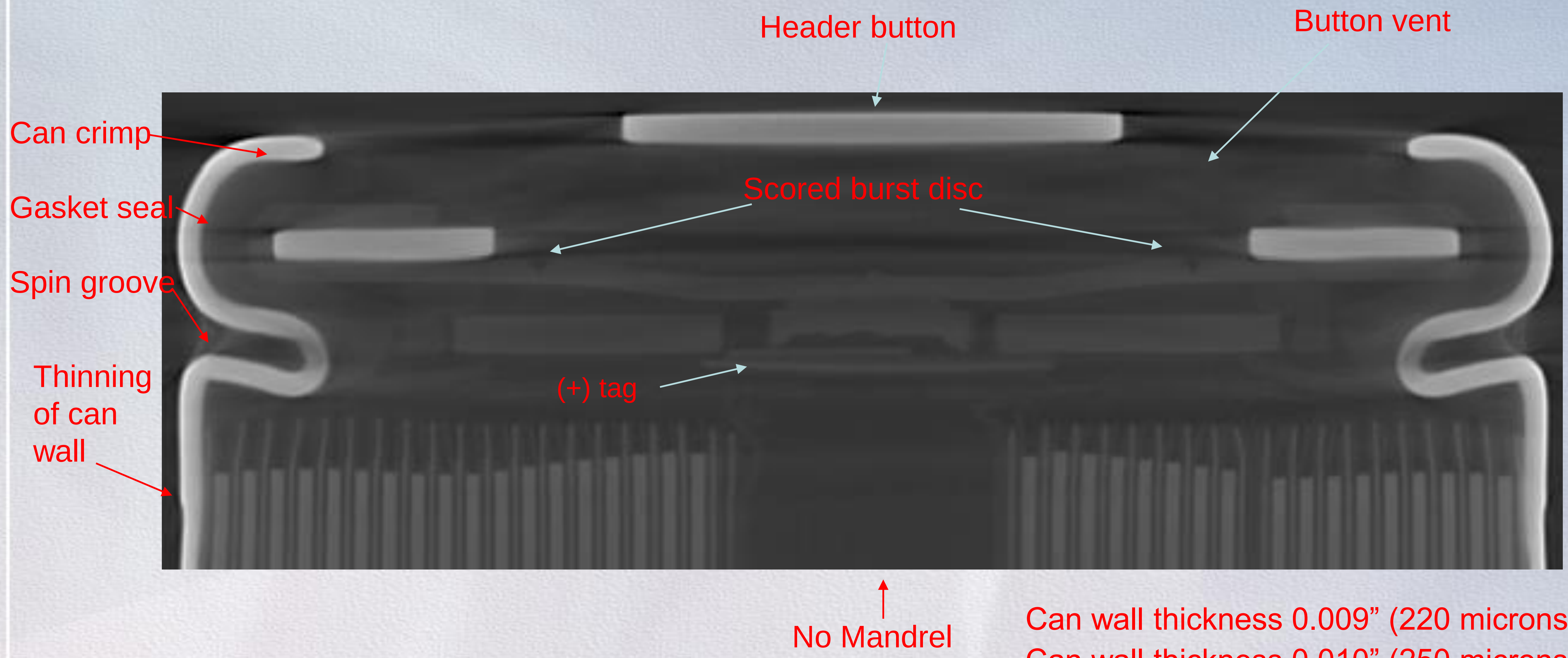
Pre



Post-
opposite
side



LG 18650 3.35Ah - Axial View - Header - Cell



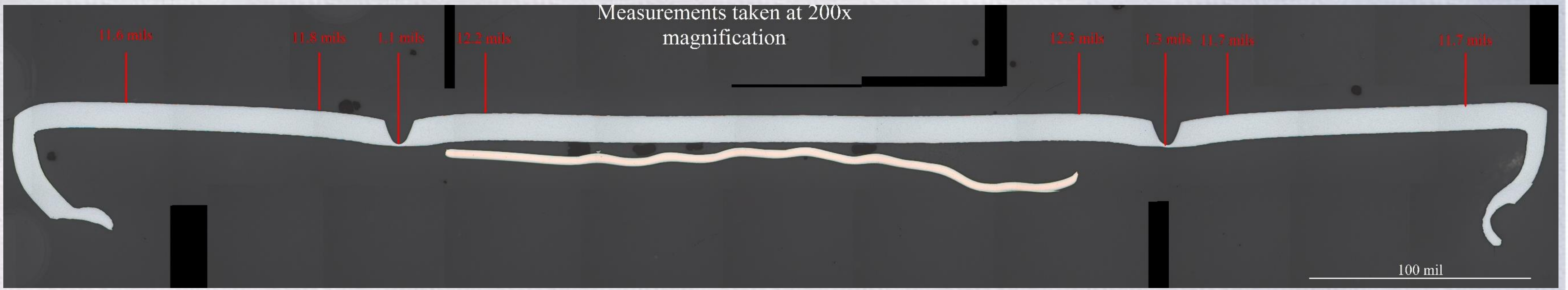
Can wall thickness 0.009” (220 microns)
Can wall thickness 0.010” (250 microns)

Note the single crimped header design with burst pressure ~800 psia (~54 atm)

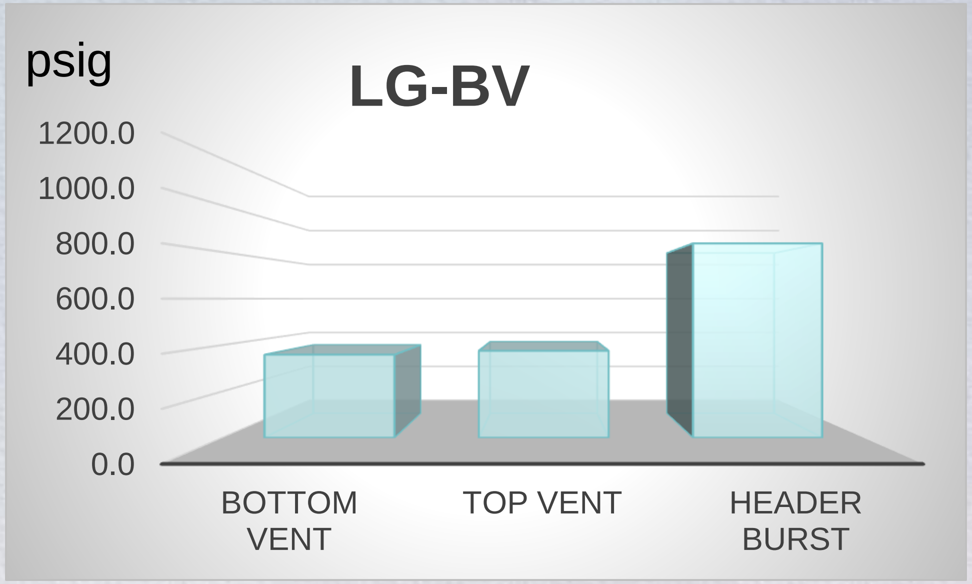
LG 3.35Ah Cell Design with Bottom Vent

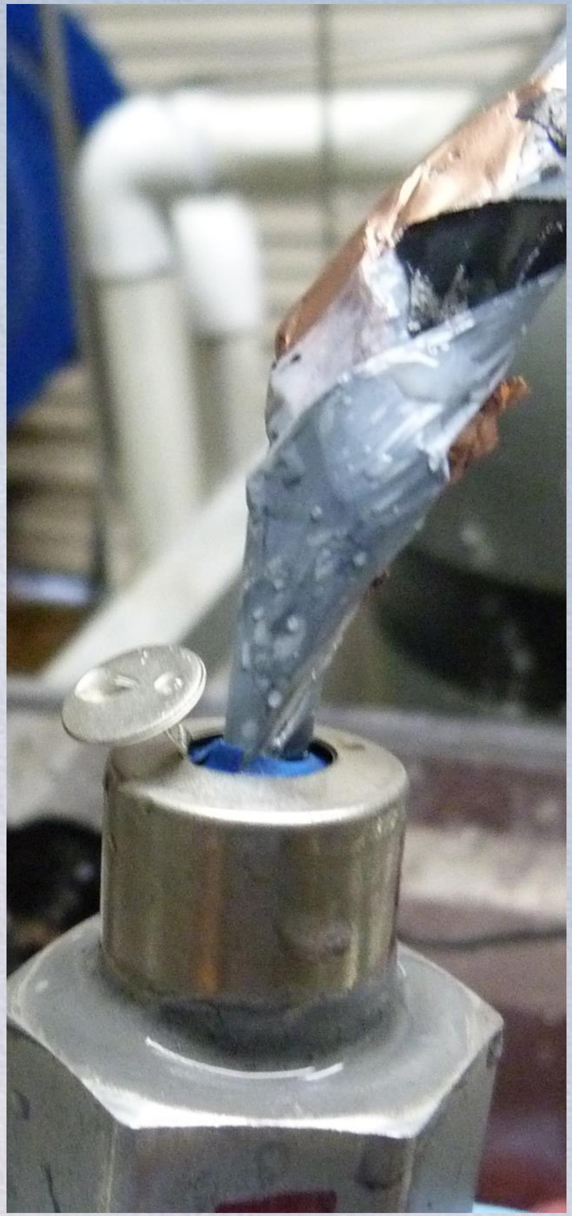
	3.50Ah vs 3.35Ah	
Diameter	max. 18.65	max. 18.45
Height	max. 65.3	max. 65.6
Wall thickness	0.15	0.22
Mass	47.0 g	47.5 g
Capacity	3.5Ah	3.4 Ah
Energy	12.7wh	12.3 Wh
Voltage	2.5~4.2	2.5~4.2
Max current	10A	10A
AC Resistance	30	23

3.35Ah cell design, a bit more power capable than 3.5Ah design



LG 3.35Ah with Bottom Vent (BV)





Bottom vent disk separates completely

Heat Distribution Calorimeter

Characterising the difference between failure types

Highlight risks associated with the spread of heat sources when cells rupture and compare to when they remain intact

Heat Distribution Calorimeter

- Measure heat output from single cylindrical cells
- **Decouple heat generated within the cylindrical casing and heat generated by ejected material**
- X-ray transparent for in-situ high-speed X-ray imaging
- Scalable to fit any cylindrical cell design
- Ambidextrous design for bottom vent cells

Bore Chamber

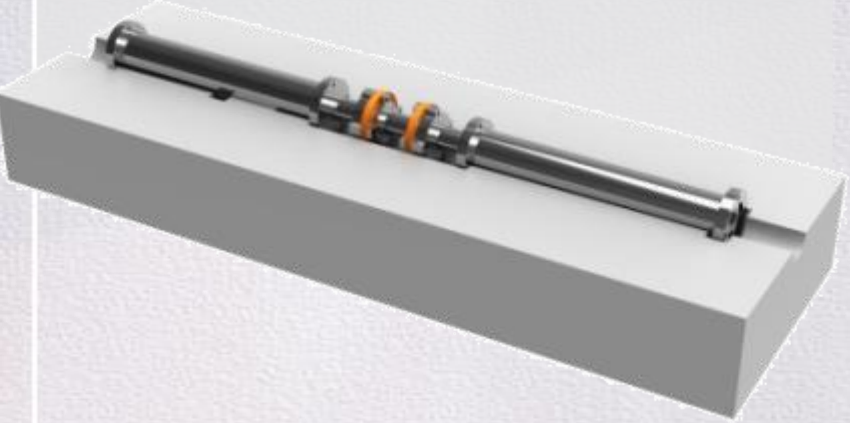
- Slows down and extracts heat from escaping flames and gas

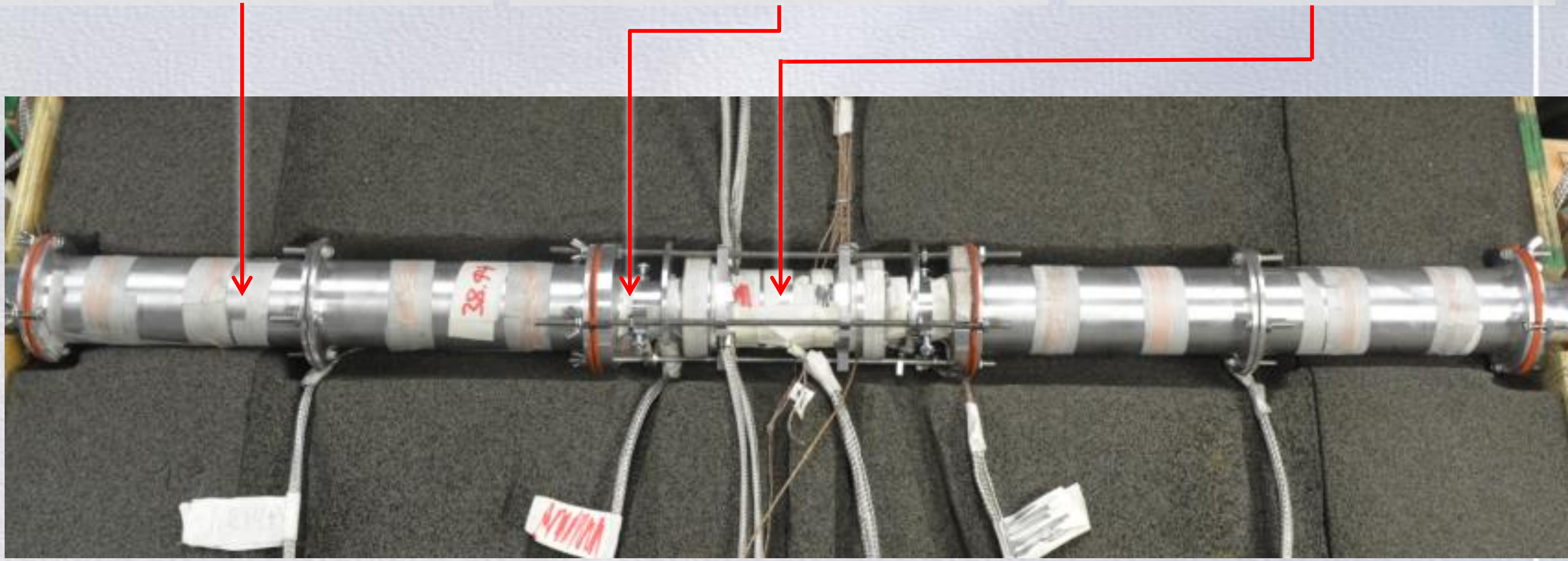
Ejecta Mating

- Captures ejected solids such as the electrode assembly
- Thermally isolated from the cell chamber

Cell Chamber

- Contains the cylindrical cell
- Includes heating system for thermally induces failure





Heat Distribution Calorimeter

Calorimetry experiments have been conducted at the NASA JSC Energy Systems Test Area (ESTA) and at the European Synchrotron Radiation Facility (ESRF) and Diamond Light Source (DSL):

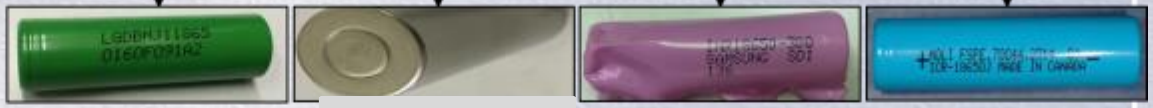
- 38 sets of data processed for successful tests processed to date
- 27 runs at the ESRF and 62 very recently performed with the new calorimeter at the DSL

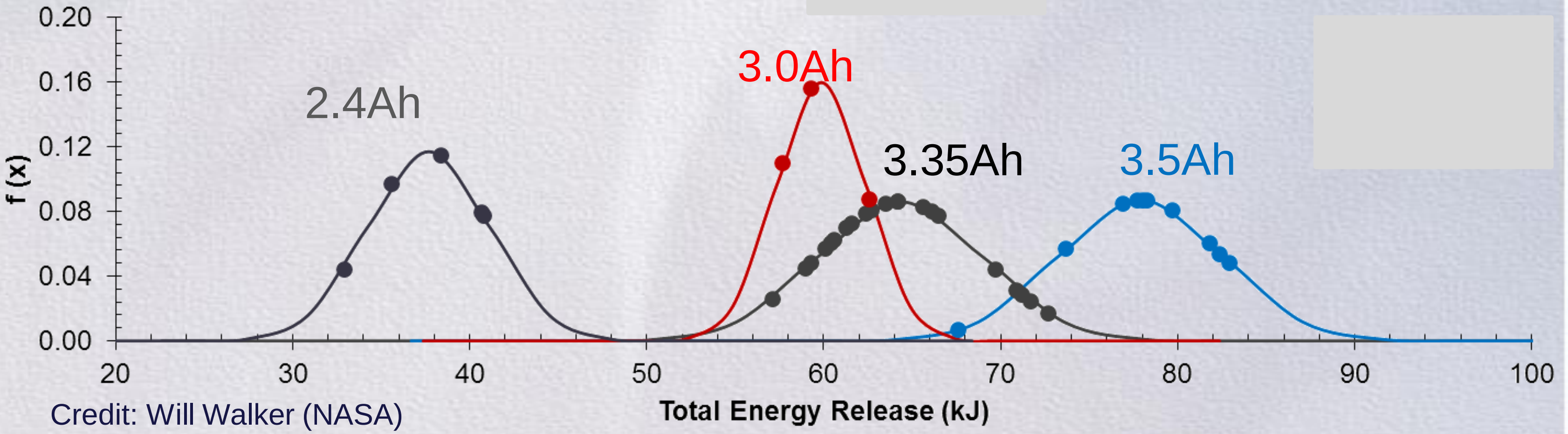
Key Findings

- Higher energy density cells released more heat
- 3.5Ah MJ1 cells generated 22 % more heat than 3.35Ah cells that have 3 % more capacity
- The distribution of heat released from ejected material and from the cylindrical body of the cell was measured
- A combination of 3.35Ah cells with bottom vents (BV) and without bottom vents (NBV) were tested

Item	Unit	LG 18650-MJ1	3.35 Ah LG 18650	Samsung 18650-30Q	Molicel 18650-J
Capacity at 100% SOC	Ah	3.43	3.35	3.0	2.3
Nominal Voltage	V	3.67	3.7	3.6	3.78
Stored Electrochemical Energy	kJ	45.3	44.6	38.9	31.3
Cell Mass	g	47	47	48	47
Special Features Tested	-	-	BV / ISC/ TCW	-	Separator
Number of Successful Tests	-	9	22	3	5
Test Facility	-	ESTA	ESRF	ESTA	ESRF

BV: Bottom Vent Cells
NBV: Non-Bottom Vent Cells
ISC: Internal Short Circuit Device
TCW: Thin Can Wall
S1 & S2: Two proprietary separators





Credit: Will Walker (NASA)

Walker, et.al, 2017 NASA Aerospace Battery Workshop, Huntsville, AL

Heat Distribution Calorimeter – 3.35Ah cells

Comparison between the heat distribution of cells with and without bottom vents

Key Findings

- **Bottom vent cells produce around 12 % less heat than non-bottom vent cells.**

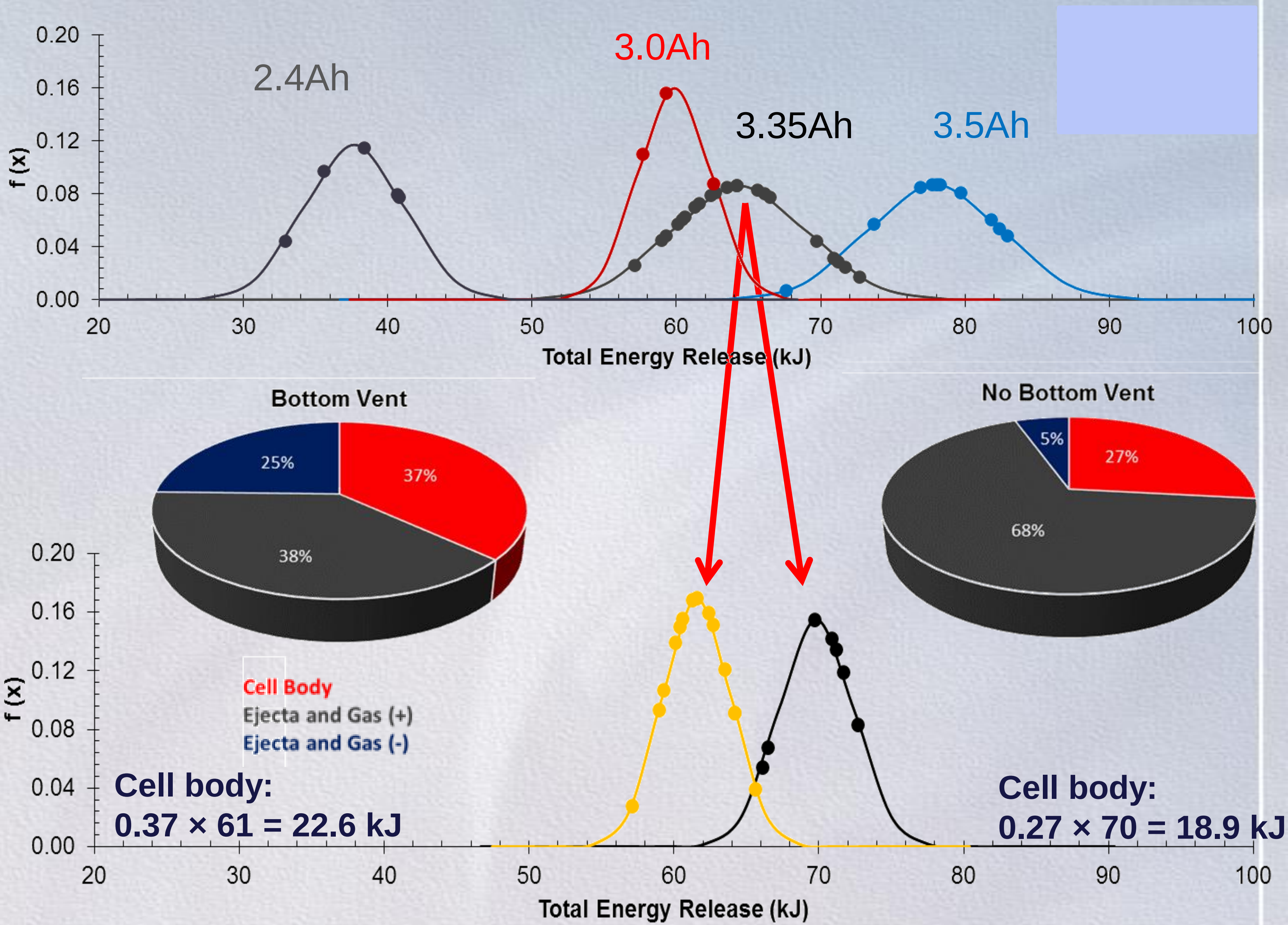
- May be due to bottom-vent cells ejecting less material and thermal runaway reactions being oxygen limited.

- A higher proportion of heat is generated within the cylindrical casing in cells with bottom vents.

- This may be due to a decreased risk of the cell bursting and ejecting the electrode assembly

- A higher proportion of heat is generated from ejected material in cells without bottom vents.

- For both cells, over 60 % of the heat generated during thermal runaway stems from ejected material.



Test Plan - Cell ISC Device Implantations

- Objective #1 is to determine the safety merits of bottom vents vs thicker can walls
  - LG Initial design (Group 1)
    - No bottom vent
    - 220 µm (0.009”) side wall
  - LG-BV (Groups 2-5)
    - Bottom vent
    - 220 µm (0.009”) side wall
  - LG-TC (Groups 6-9)
    - No bottom vent
    - 250 µm (0.010”) side wall
    - Adds 777mg vs the initial design
- Objective #2 is to determine the side wall rupture sensitivity to the location of the ISC device
  - 3 winds into middle of JR
  - 6 winds into middle of JR
  - 6 winds into top of JR
  - 6 winds into bottom of JR

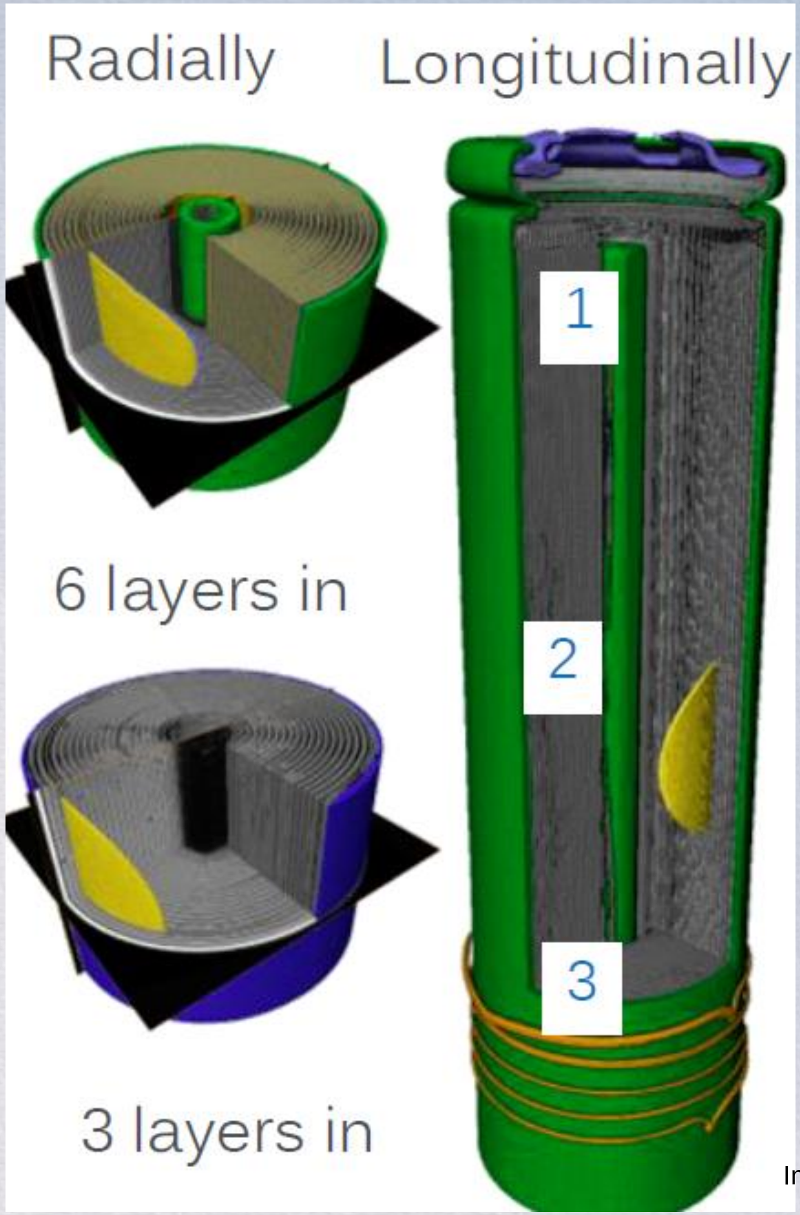
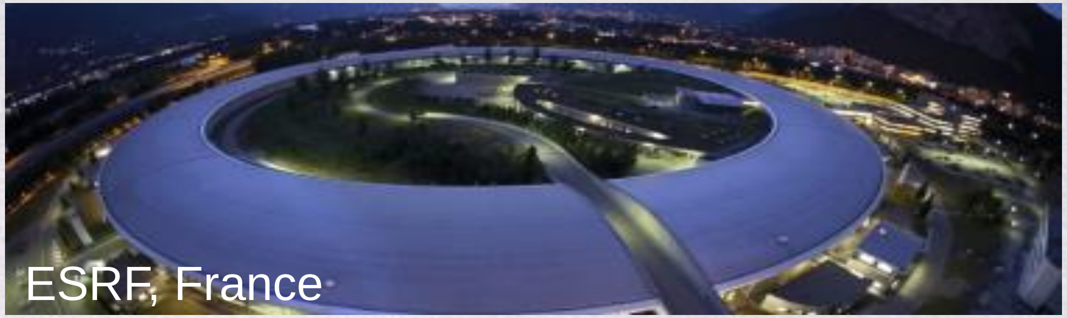


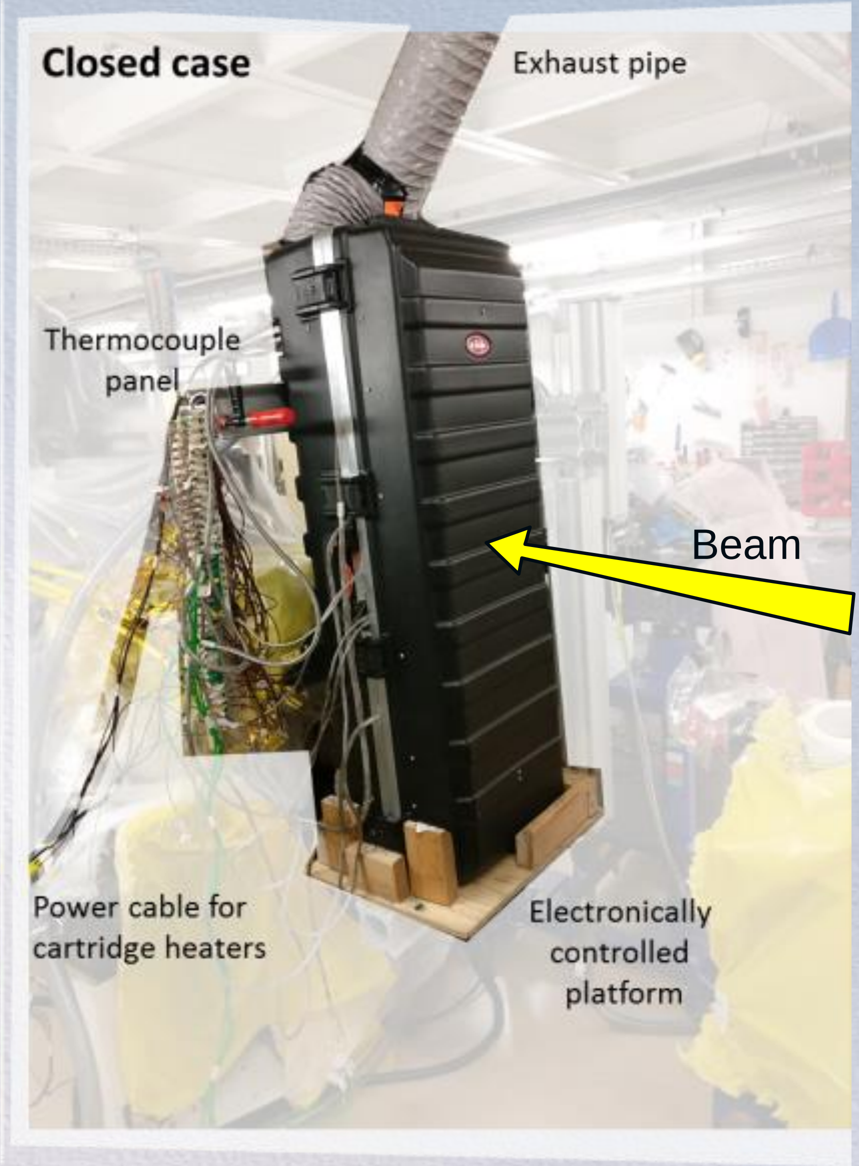
Image credit: NREL

Linking internal dynamics to external risks

High-speed X-ray Imaging

- Oct 2017: Experiment at **The European Synchrotron** (ESRF), France.
- **29 x 18650 cells** with ISC devices placed at different locations were brought to thermal runaway
- Cell design features varied; with two different wall thicknesses and w/ or w/o bottom vents
- Simultaneous high-speed X-ray imaging and single cell calorimetry
- **Aim:**
  - To link internal phenomenon with external risks and uncover conditions that lead to worst-case failure scenarios
  - Clarify the merits of bottom vents and thicker casing walls





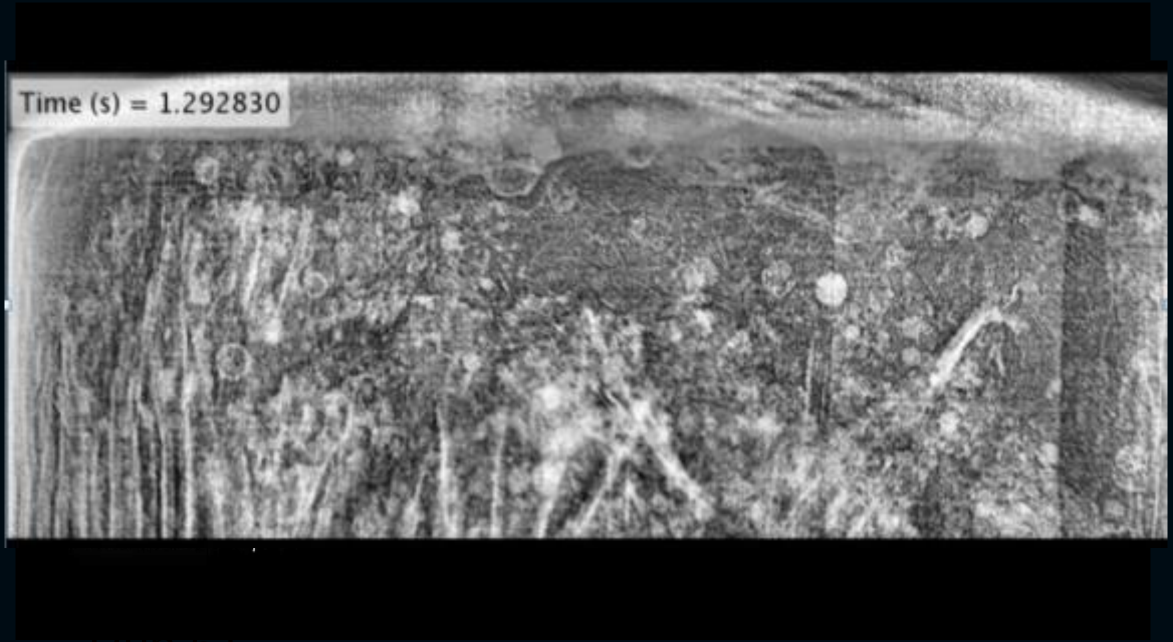
Bottom Vents: Determining Merits

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

No Bottom Vent (NBV)

Key findings

- Base-plate domes outwards as the gases and debris deflect and take a U-turn through the vacant core of the electrode assembly
- The inner winds of the electrode assembly shear and eject

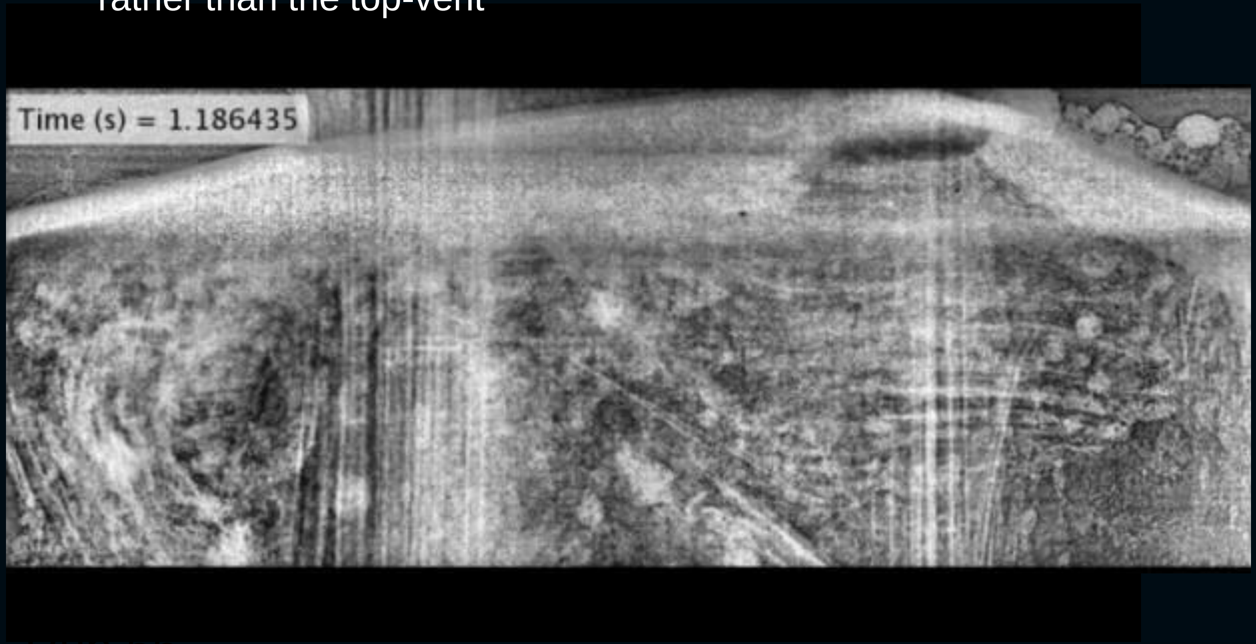


Run 51

Bottom Vent (BV)

Key findings

- Gases and debris does not take a U-turn. The residence time of reacting material is therefore less.
- The thermal mass of the base plate is reduced which may increase the risk of breach due to deflecting material
- The electrode assembly shifts towards the base-vent rather than the top-vent



Run 56

Bottom Vent vs No Bottom Vent (only 3.35Ah Cells)

- Inside Calorimeter
  - Bottom vent cells retain 54% of their mass post TR
  - While cells without BV retain only 40%
- Outside Calorimeter with circumferential heater
  - Bottom vent cells retain 50% of their mass post TR
  - While cells without BV retain only 42%
- Counting all tests
  - BV cells retain 52% vs 41% of their pre-test mass
  - Similar results inside or outside calorimeter
  - *Pictures of cell can walls, occurrence of side wall ruptures, and post test mass all suggest BV feature produces less violent TR events*

Calorimeter Runs	3.35Ah w BV		3.35Ah w/o BV	
Average (g)	25.7	54.4%	19.2	39.9%
Sdev (g)	2.7		3.1	
Count	12		8	

% of pre-test mass

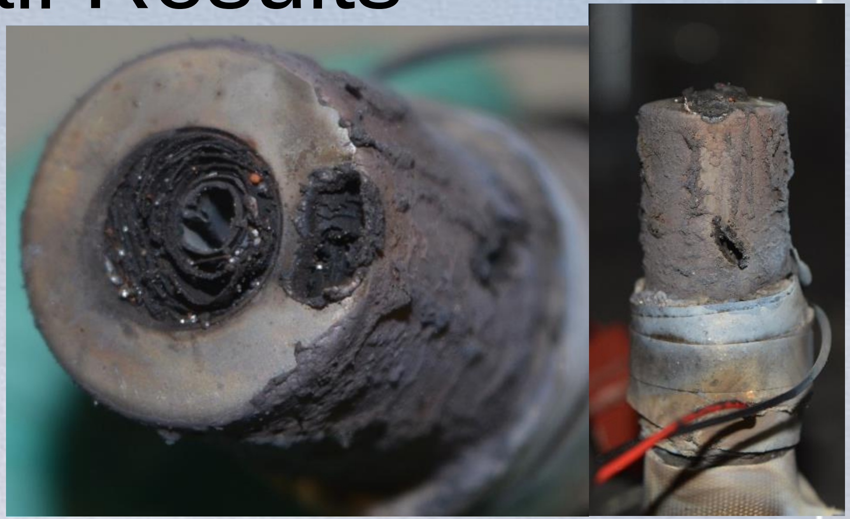
Heater Runs	3.35Ah w BV		3.35Ah w/o BV	
Average (g)	23.6	49.9%	20.2	42.0%
Sdev (g)	4.1		4.0	
Count	18		9	

All Valid Runs	3.35Ah w BV		3.35Ah w/o BV	
Average (g)	24.5	51.7%	19.7	41.0%
Sdev (g)	3.7		3.5	
Count	30		17	

Bottom Vent, Thicker Can Wall Results

- 3.5Ah LG cell design with thin can wall (165 micron) and ISC device in 3 winds into JR
  - yields > 80% chance to SWB
  - Count = 36
  - Excellent worst case trigger cell for battery testing because clocking of SWB is predictable
- 3.35Ah LG cell design with thicker 220 micron can wall **and** bottom vent
  - 1 of 31 or 3% chance of SWB
  - Risk is not eliminated
- 3.35Ah LG cell design with thickest 250 micron can wall **but no** bottom vent
  - 4 of 18 or 22% chance of SWB
  - Higher risk than with bottom vent
- Post test masses are higher for BV cells, TR appear less violent
  - 50% vs 42% of pre test mass

3.5Ah
Thin wall



The single example of SWB
3.35Ah thicker wall & BV

Examples of 3.35Ah
Thickest wall
No BV

Summary Conclusions

Heat output

- 3.5Ah MJ1 cells produce the most heat (1.72 kJ/kJ stored) whereas 3.35Ah cells produce 1.44 kJ/kJ stored.
- > 70 % of the heat output is from ejected material in the 2 cell designs cells.
- *Cells that undergo bottom breach, on average, produce less heat.*

Rupture/Breaching of 18650 cell enclosure

- Side wall, spin groove, bottom, and top cap breaching is melt-through thermal breach, not a pressure induced rupture
- 18650 cells extend by 2-3 mm during header rupture. Allowances need to be made for this extension to avoid unwanted pressure build-up and side-wall breaches.

Merits of bottom vent

- Bottom vent reduces residence time of reacting species.
- The bottom vent leads to less ejected material due to decreased flow rate, and less overall heat generation ***but*** more heat generated within the casing of the cell. This suggests that the reactions are oxygen starved.

Safe, High Performing Battery Design Guidelines

- Must address risk of side wall breaches: bottom vent, thicker can wall, & protect vulnerable spin groove area
- Provide adequate heat dissipation: conductive interstitial heat sinks along cylindrical wall (also protect against side wall breaches) are best
- Fuse parallel cells to electrically isolate internally shorted cells
- Allow hot ejected materials to disperse their energy quickly while protecting the adjacent cells
- Equip battery vent port with flame arresting features