Safe, High Power / Voltage Battery Design Challenges

By

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with contributions from and collaborations with

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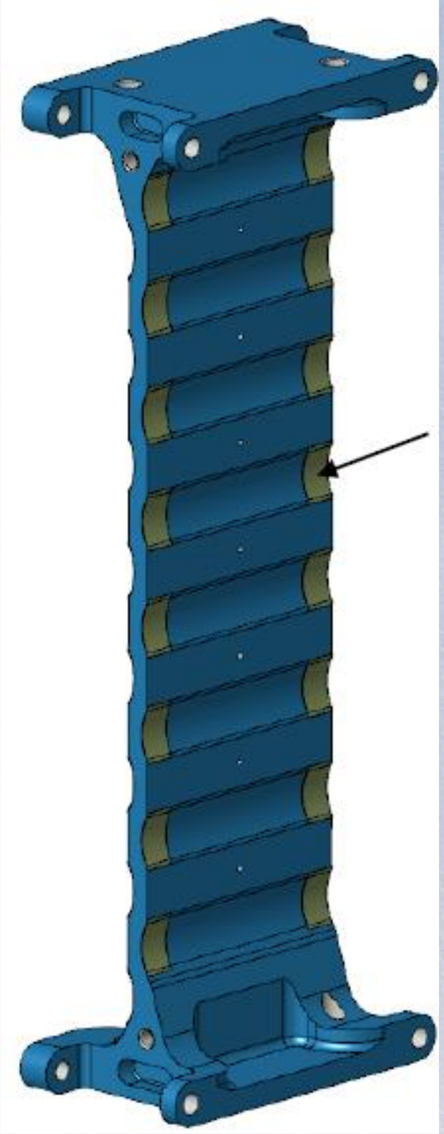
Michael Mo, KULR Technologies, San Diego, CA USA

NASA Aerospace Battery Workshop
Huntsville, AL
Nov 19, 2019

Outline

- Goals of Safe, High Power Battery Task
- Major Challenges Driving Design Decisions
  - Achieving 160 Wh/kg at battery brick level
  - Thermal management
    - Interstitial Al vs Al spine heat sinks
  - Verification of passive propagation resistance
    - 32-cell subscale test campaign and its lessons learned
    - Blast plate testing
    - Flame arresting vent port testing
    - 48-cell subscale test campaign
- Summary



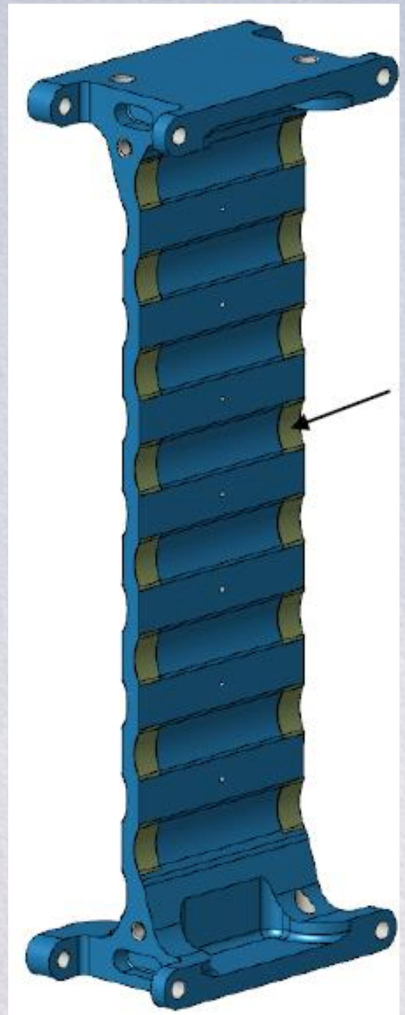
Safe, High Power Battery Task Top Level Reqts

- 100V, 2 kWh Battery Module
- Capable of 3C discharge continuous (20 minutes)
  - 100 cycles, 5 year storage life
- Capable of being connected in series and parallel as building block
- Safe
  - Resistant to single cell TR propagation
  - No flames exiting the module enclosure
  - Dead-face power connectors for electrocution hazard mitigation
  - Resistant to corona discharge hazard
- High performance (>160 Wh/kg, 200 Wh/L)
  - Using Li-ion commercial cylindrical cell technology that achieves 225 Wh/kg, 650 Wh/L at 3C

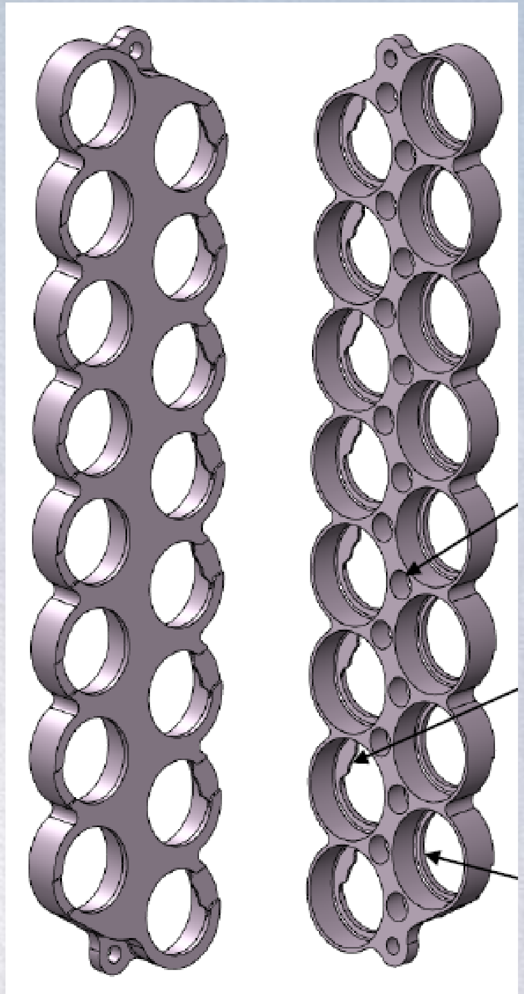
Credits: J. Darst, J. Rogers/JSC

New Approach to Improve Heat Dissipation

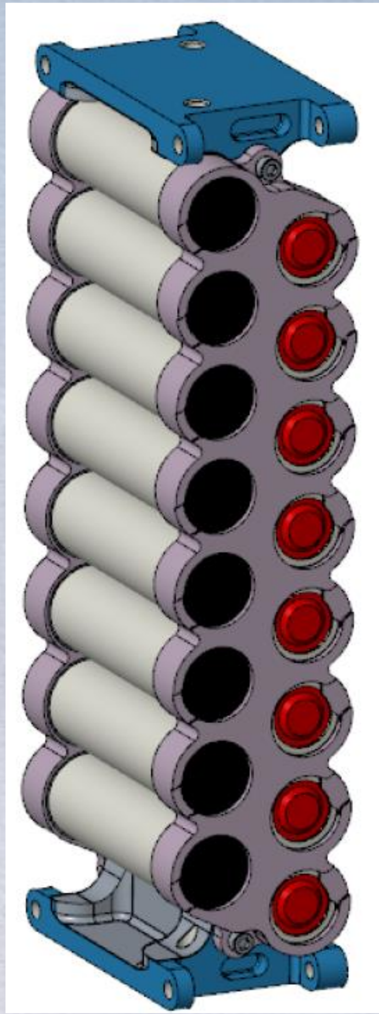
- Introduce a conductive spine to heat sink each cell and insulating gaps between pairs of vertical rows of cells
  - Improve heat dissipation to top and bottom



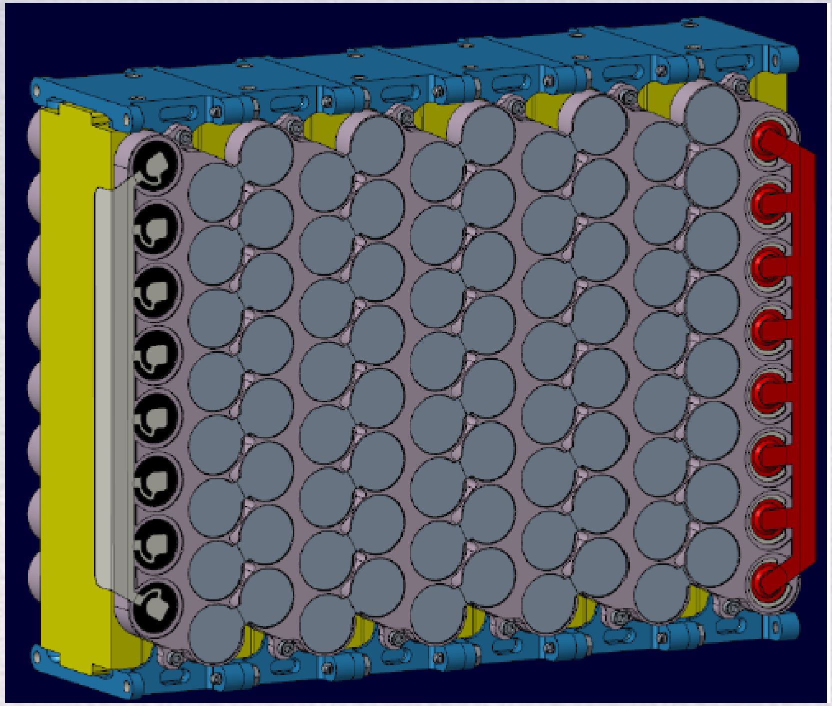
Al or OHP spine



G10 capture plates



16-cell assembly

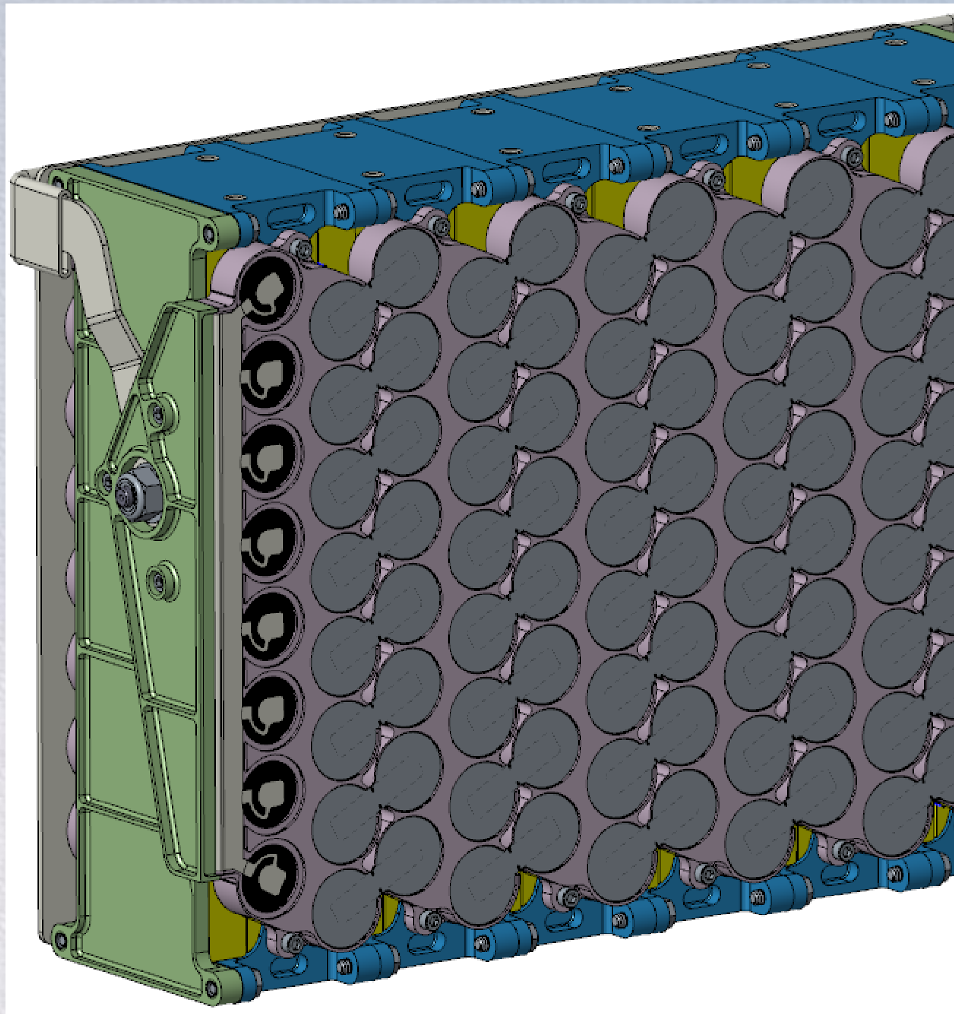


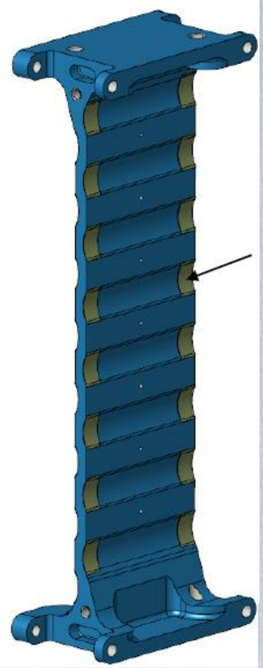
96-cell deck (1 kWh)

Spine Heat Sink Battery Mass Breakdown

Component	Material	Density	Volume	Mass	Mass
		(lb_m/in^3)	(in^3)	(lb_m)	(%)
Aluminum OHP Heat Sink Spines (Qty = 6)	Al 6061	0.0975	21.7206	2.118	15.1
SS Inserts (QTY = 88)	CRES	0.287	0.204	0.059	0.4
SS Screws/Hex Huts (QTY = 64, =2)	CRES	0.287	0.571	0.164	1.2
Blast Plate Spacers (QTY = 9)	FR4	0.067	0.027	0.002	0.0
Blast Plate	?	0.075	0.168	0.013	0.1
Capture Plates	FR4	0.067	10.21	0.684	4.9
96 Cell Deck End Plates	FR4	0.067	2.49	0.167	1.2
Ni Bussing Plates	Ni 201	0.321	0.344	0.110	0.8
Cells (QTY = 96)	Li-ION	0.0975	98.496	9.603	68.5
Mica Strips/Bus Covers	MICA	0.078	0.974	0.076	0.5
Transfer Tape (QTY = 192)	-	0.037	0.038	0.001	0.0
Steel Rings (QTY = 96)	CRES	0.287	0.288	0.083	0.6
Copper Bus Bars/Plate/Screw	Cu	0.324	1.422	0.461	3.3
Refractory Material		0.013	28.526	0.371	2.6
End Bus Plate Covers	FR4	0.067	0.84	0.056	0.4
2216 Epoxy Adhesive	Epoxy	0.048	1.104	0.053	0.4
Total	-	-	136.953	14.020	100.0

	Total Volume	Total Mass	10.6 Wh/cell	Energy Density (E_d)	Specific Energy (E_s)
BATTERY DECK	(*l*)	(*kg*)	96 cells	(Wh/L)	(Wh/Kg)
96 CELL SPINE DECK	2.244242256	6.359	1017.600	453.4269851	160.0144114





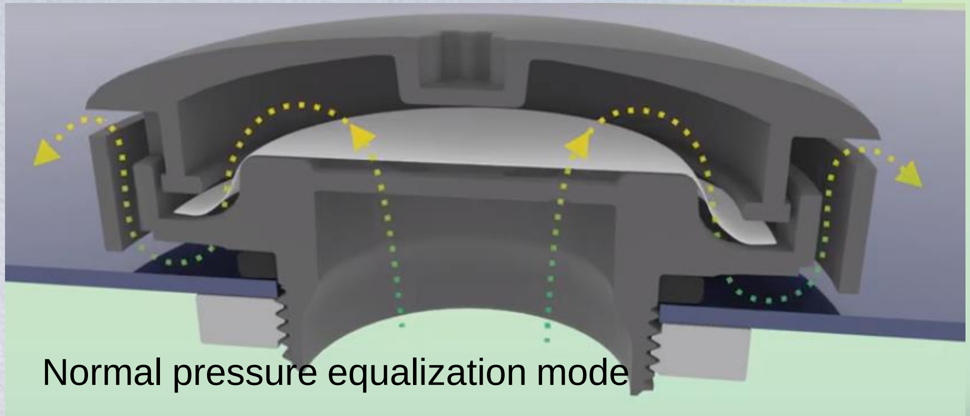
Al spine

- 96-cell deck capable of 160 Wh/kg and 3C rate with low cell-cell ΔT
- Yields a parasitic mass factor 1.39 due to 223 Wh/kg at cell level
- Using the MJ1 or GA cell designs, project specific energy of 192 Wh/kg at low rates

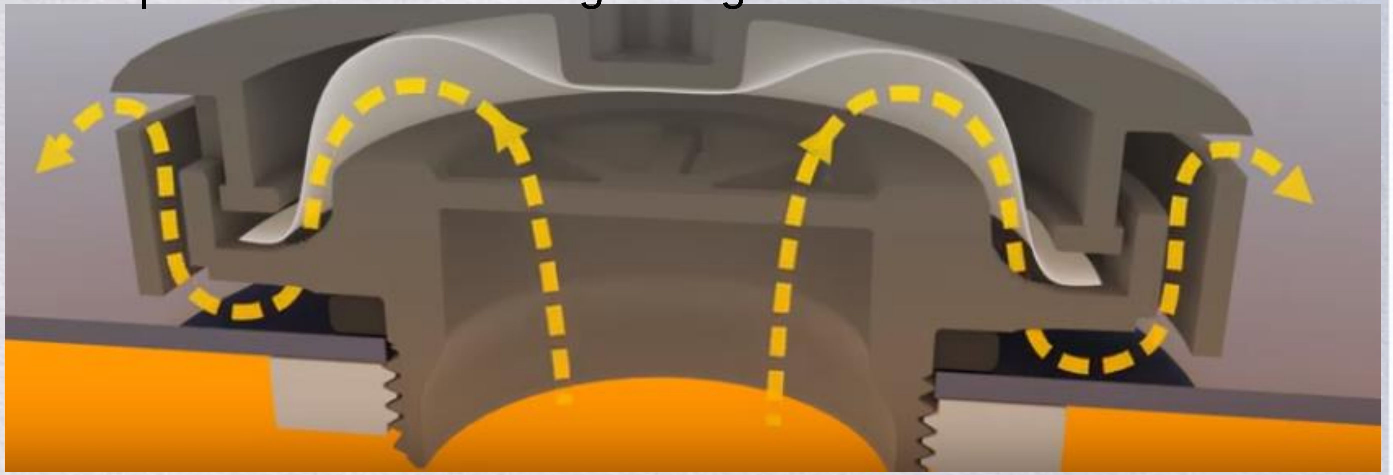
New Flame Arresting Vent Port

- Our qualified Gore vent design seals with an O-ring
  - Orion and LLB2
- High pressure TR burst can rip open the membrane
- Can a series of baffles and steel screens drop the pressure and protect the membrane?

New Gore Low Pressure Battery Vent with flexible membrane



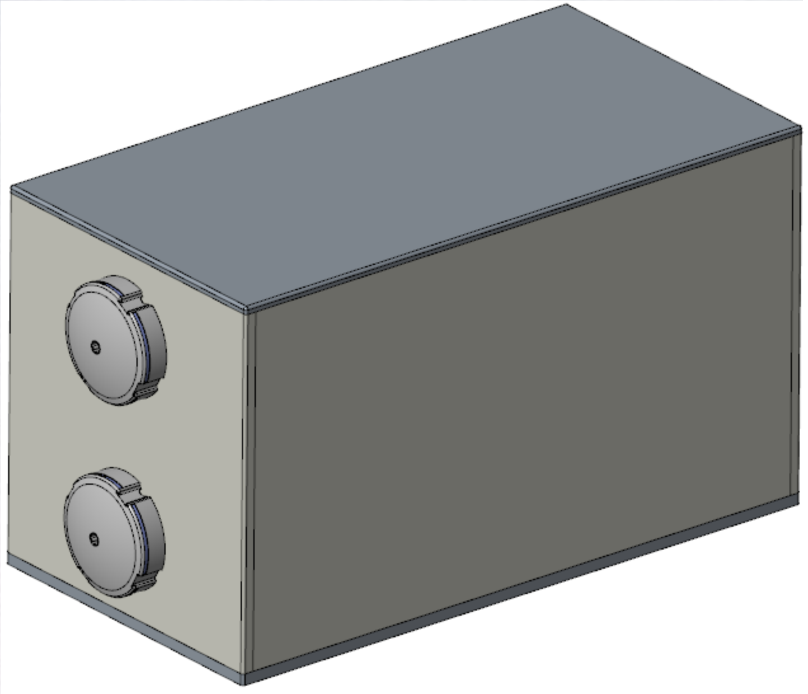
Burst pressure mode during a single cell TR



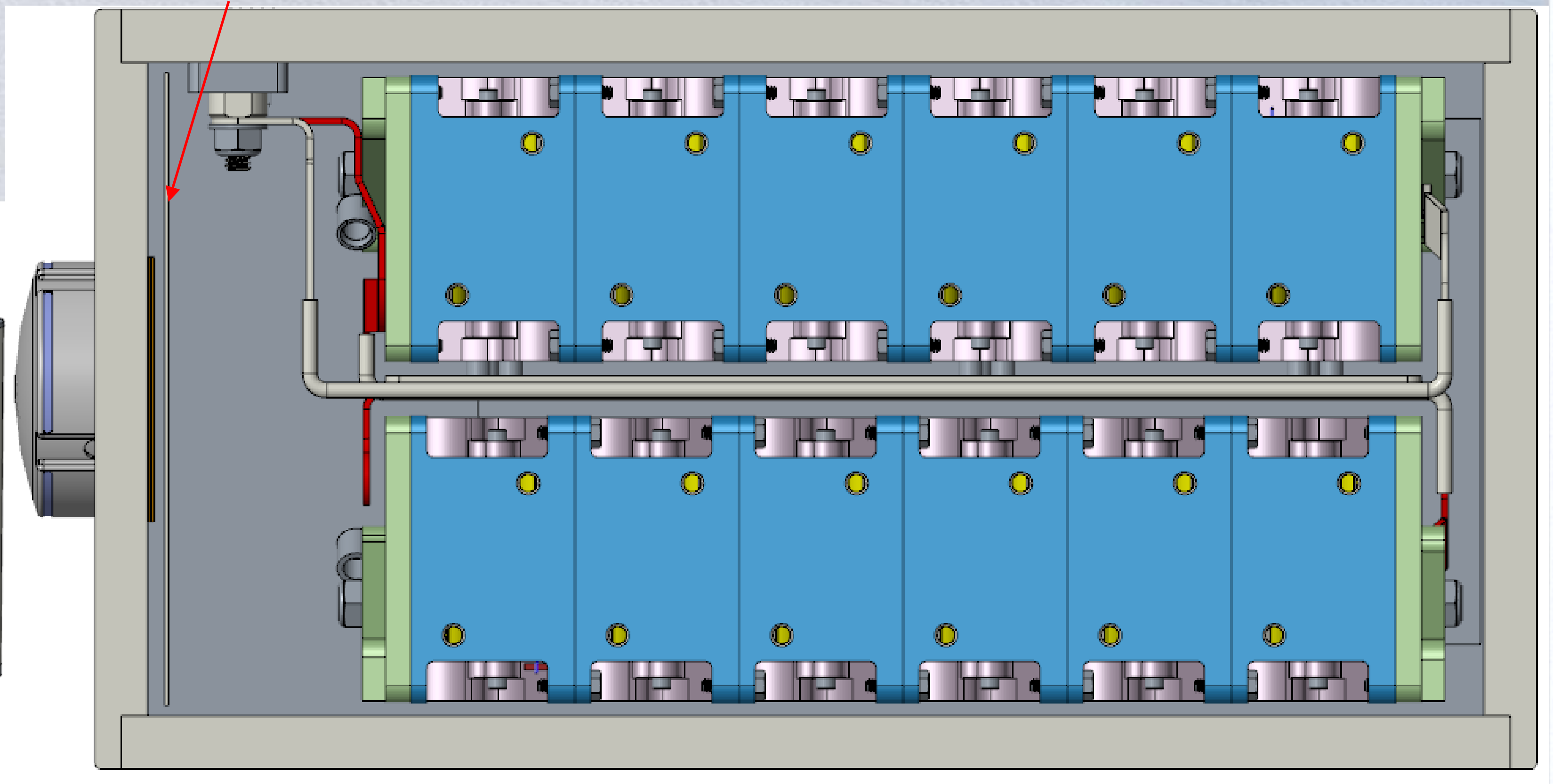
https://www.gore.com/news-events/press-release/low-pressure-evacuation-vent

Alternative Design Approach

- Baffle & steel mesh screens protect the low pressure Gore vent from direct flame/spark impingement



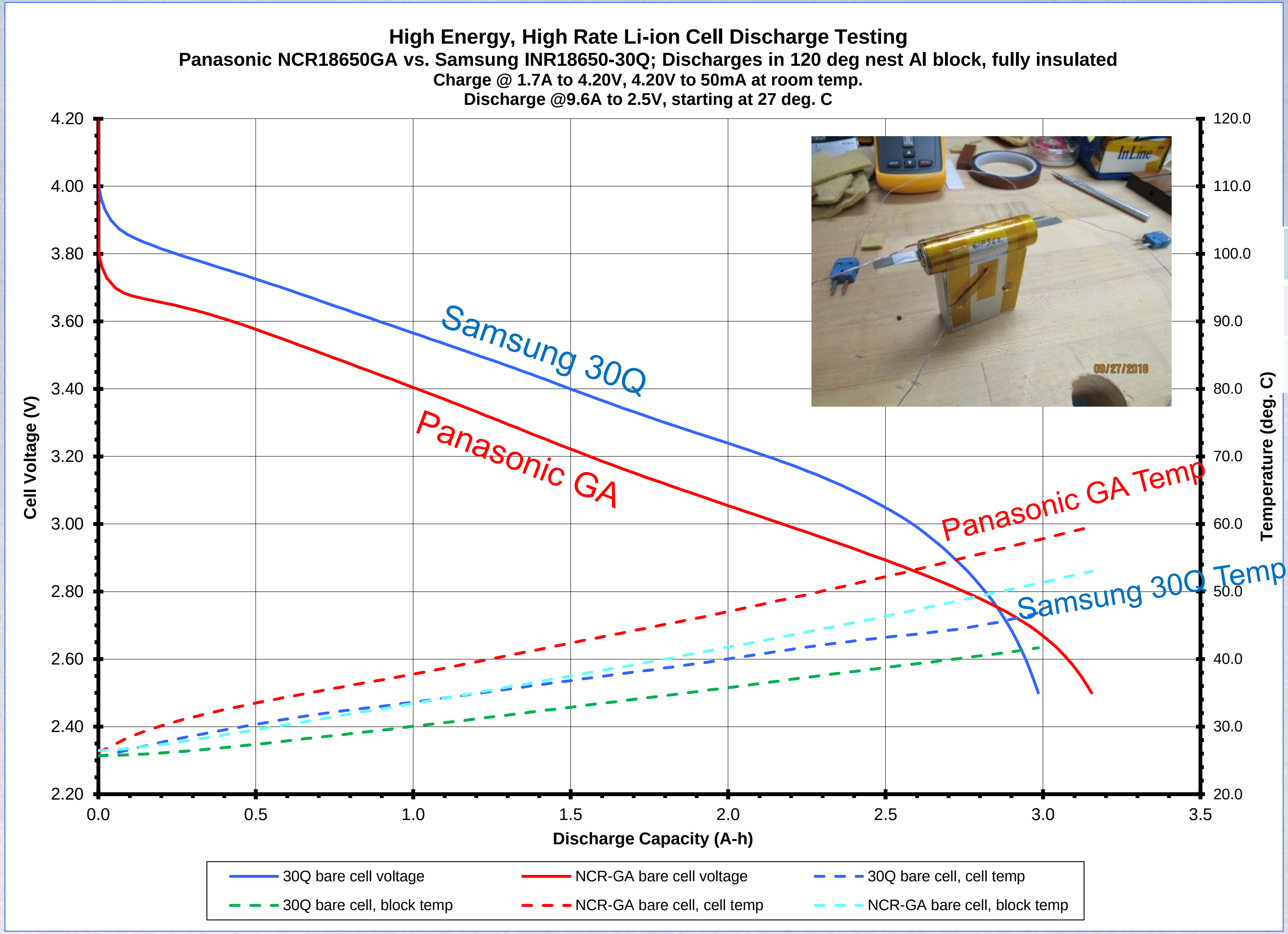
Baffle, Cu mesh, and steel screens upstream of Gore vents



High Power Cell Designs: LG HG2, Samsung 30Q

Model 18650HG2		
Nominal Capacity*(Ah, C_N)		3.0
Energy (Wh)		10.8
Dimensions	Diameter	18.3 + 0.2/-0.3mm
	Height	65.2 ±0.2 mm
Nominal Voltage*(V)		3.6
Internal Impedance**(mOhm)		14 (ave.)
DCIR(mOhm)		24 (ave.)
Designed charge current		4A

Type		
Chemistry		NCA
Dimension (mm)	Diameter	18.33 ± 0.07
	Height	64.85 ± 0.15
Weight (g)		45.6
Initial IR (mΩ AC 1kHz)		13.13 ± 2
Initial IR (mΩ DC (10A-1A))		19.94 ± 2
Nominal Voltage (V)		3.61
Charge Method (100mA cut-off)		CC-CV (4.2±0.05V)
Charge Time	Standard (min), 0.5C	134min
	Rapid (min), 4A	68min
Charge Current	Standard current (A)	1.5
	Max. current (A)	4.0
Discharge	End voltage (V)	2.5
	Max. cont. current (A)	15
ed discharge Capacity	Standard (mAh) (0.2C)	3,040
	rated (mAh) (10A)	2,983



Bare cell (no mica) comparison at RT and 9.6A

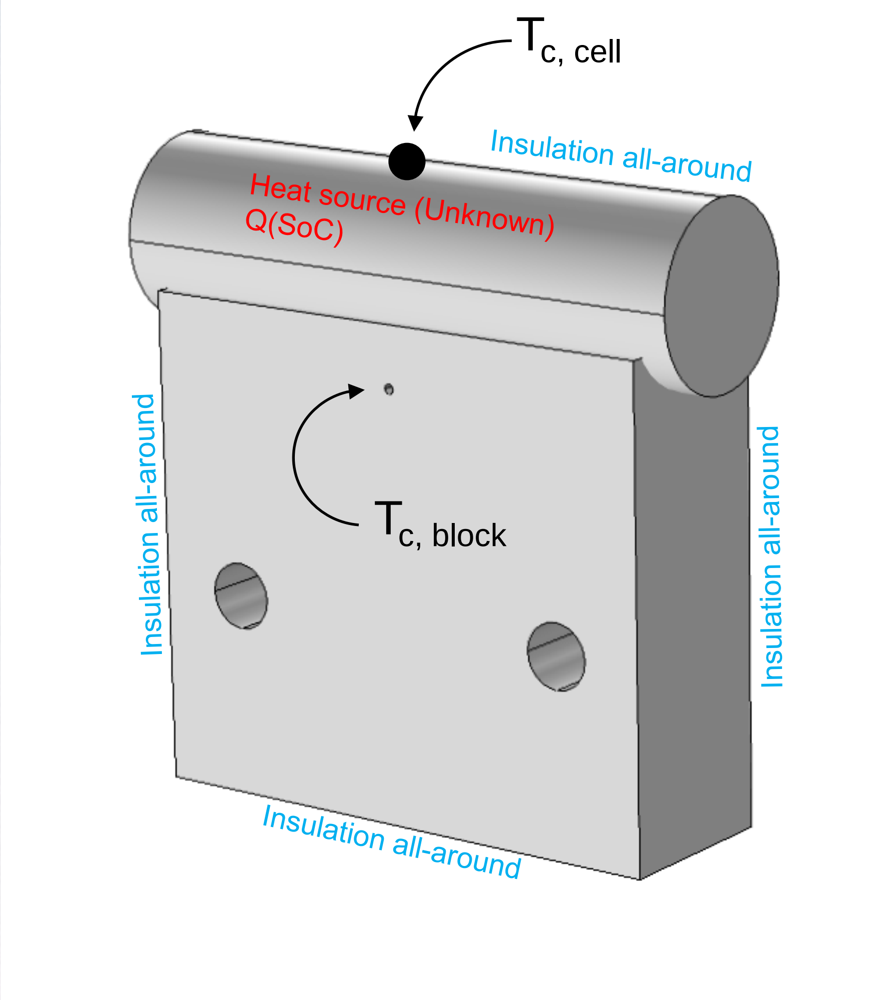
Cell Design	**Ah**	**Wh**
NCR GA	3.154	10.08
Sam 30Q	3.029	10.73

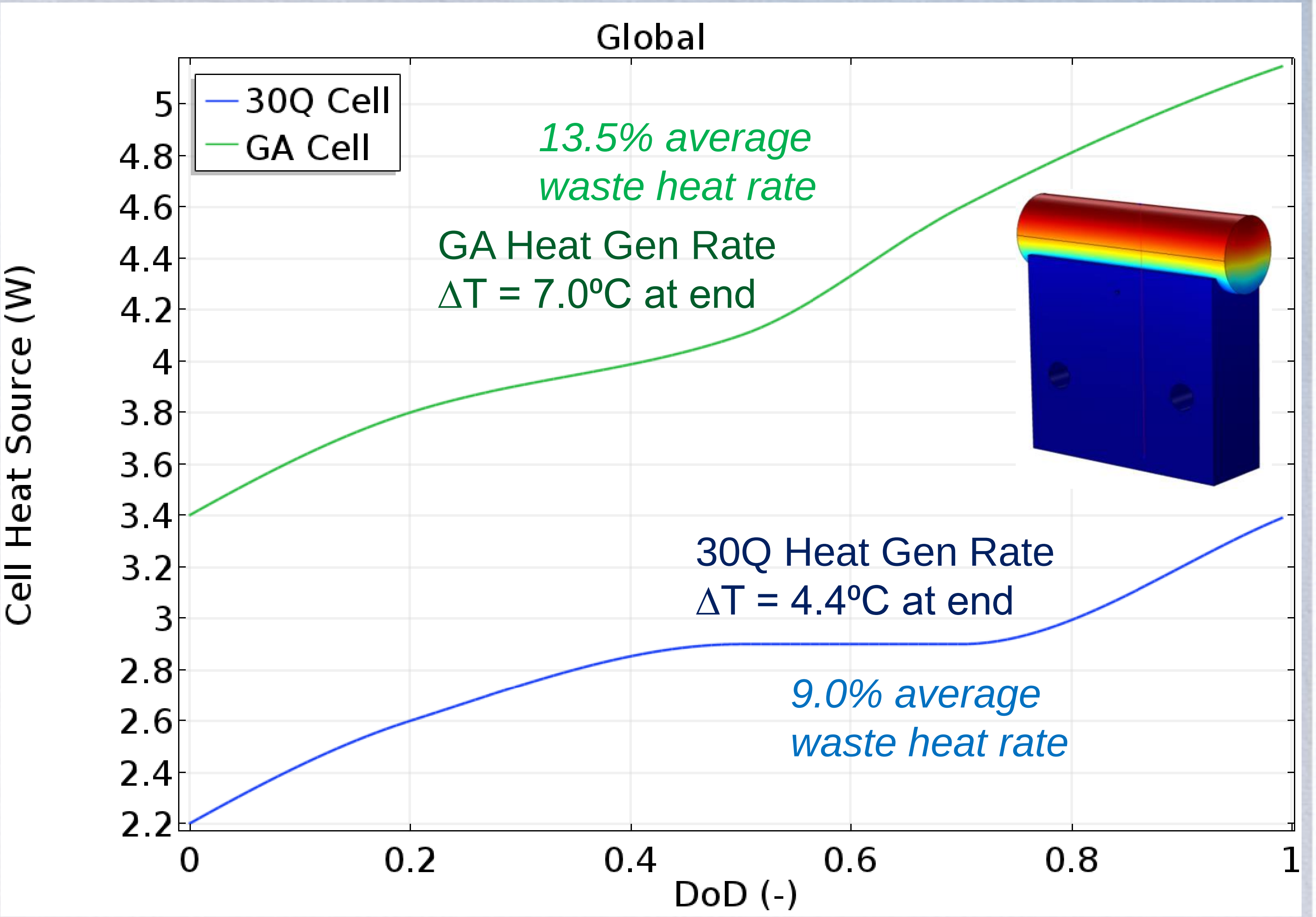
At > 3C, high power cell design (30Q) provides more Wh and less heat than higher capacity cell design (GA)

10

Analysis to Extract Cell Heat Generation Rate at 9.6A

Paul Coman & Ralph White





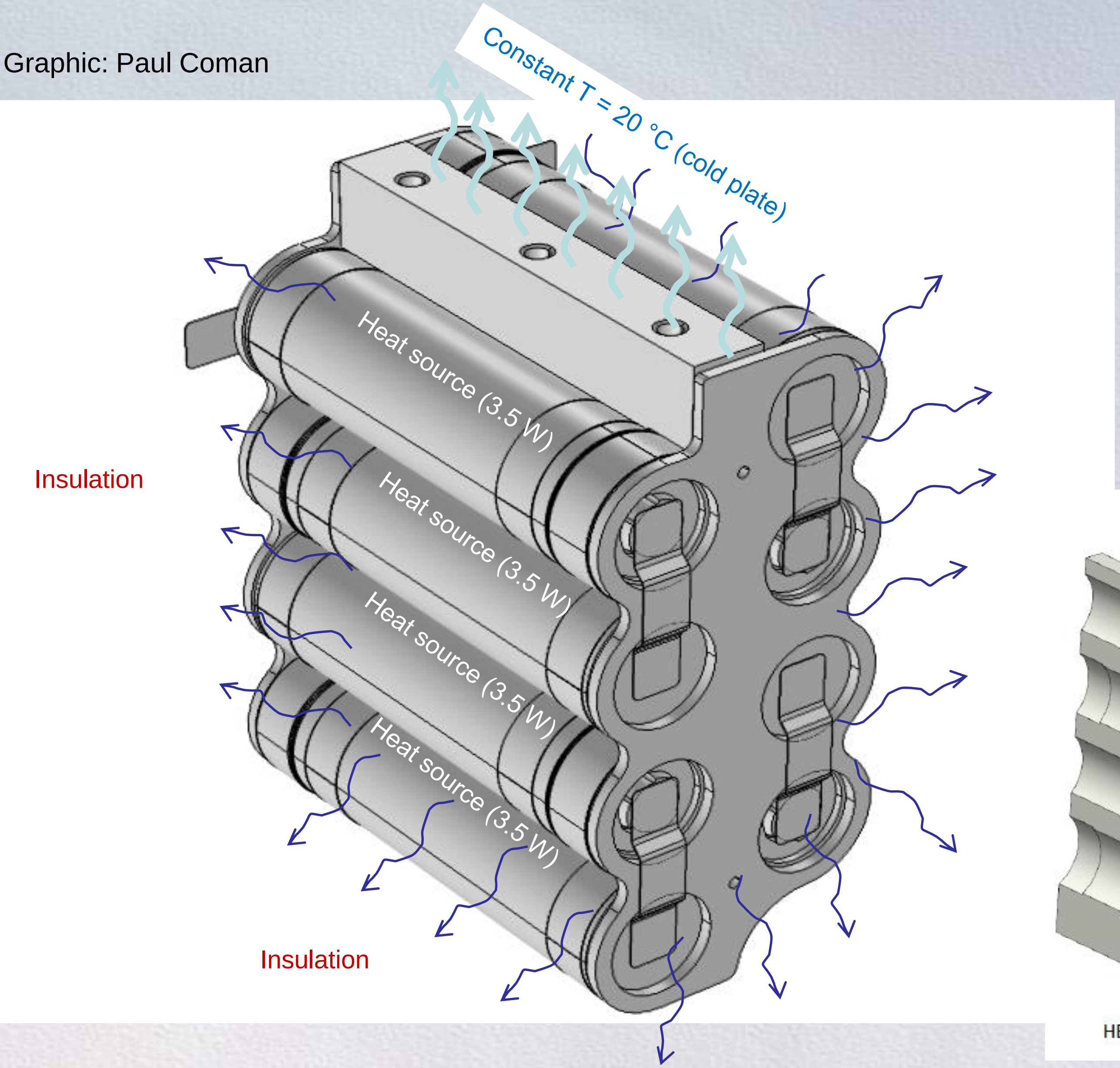
Graphics: Paul Coman

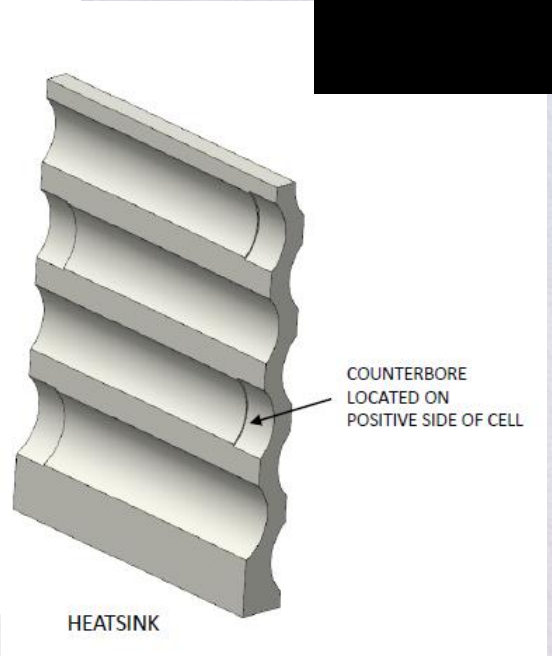
Recap of Test Findings

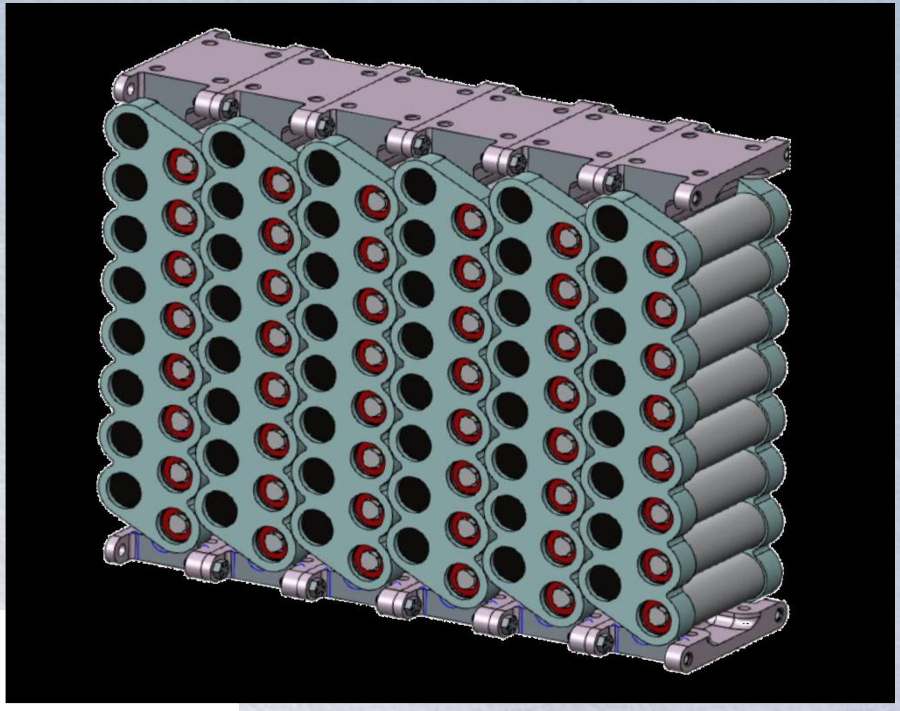
- If we improve the heat dissipation path too much and keep cells < 50ºC, high rate performance of high energy cell designs will suffer greatly
  - *Confirmed on MJ1, M36, VC7, GA, and 35E*
- However, temperature impact on 3C performance is much less with higher power cell designs
  - *Confirmed on 30Q and HG2*
- If cell has short path to heat sink, only small amount of cell surface area is needed for adequate heat dissipation
  - *This approach is more likely to prevent TR propagation*
- **We need to keep high energy cell designs in 50-70ºC range to match capacity performance of high power cell designs at ≥ 3C rates**
  - *However, energy deliver is nearly equivalent between 30Q and GA > 9A, 45ºC*
- Regardless, battery pack design will need to minimize ∆T between cells to keep them balanced

Solid Al Thermal Path 90º interface

Graphic: Paul Coman







- 90º interface with cell can wall
- Epoxy bonded interface
- With interface to battery bottom plate or cold plate
- What ΔT cell to cell will we get?

Recap of Analysis Findings

Oscillating Heat Pipes

- Heat transfer fluid encapsulated in microchannels
- Very efficient, high flux heat transfer from hot middle to cooled ends of pipe
- Greatly reduces ΔT between cells vs solid Al spines
- Significantly expands range of initial temperature operating conditions vs solid Al spines

Insignificant design factors

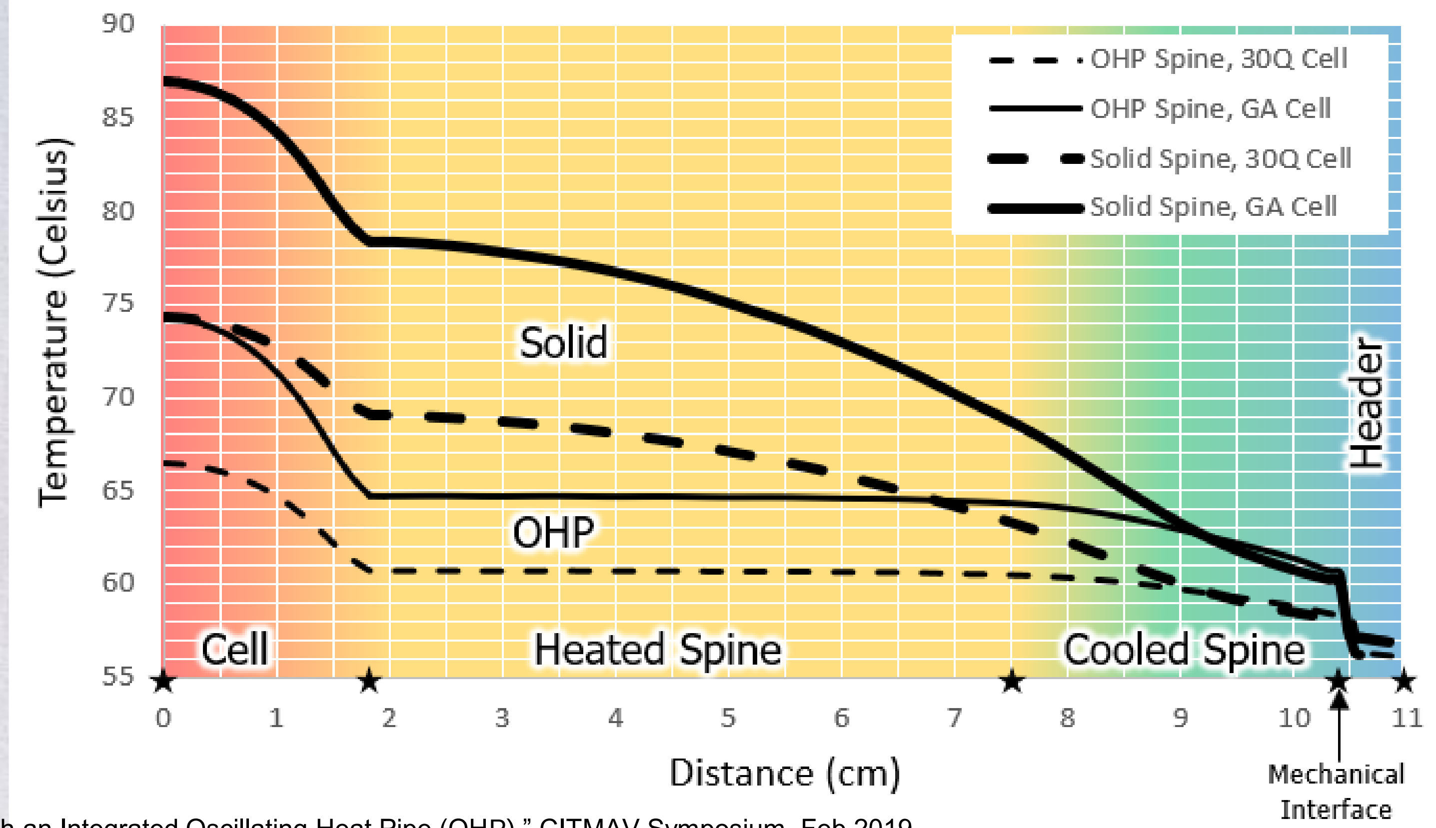
- Thermal conductivity of epoxy for cell bond
- Cell to heat sink interface area

Significant design factors

- Thermal conductivity of heat sink spine
- Reducing cell heat generation

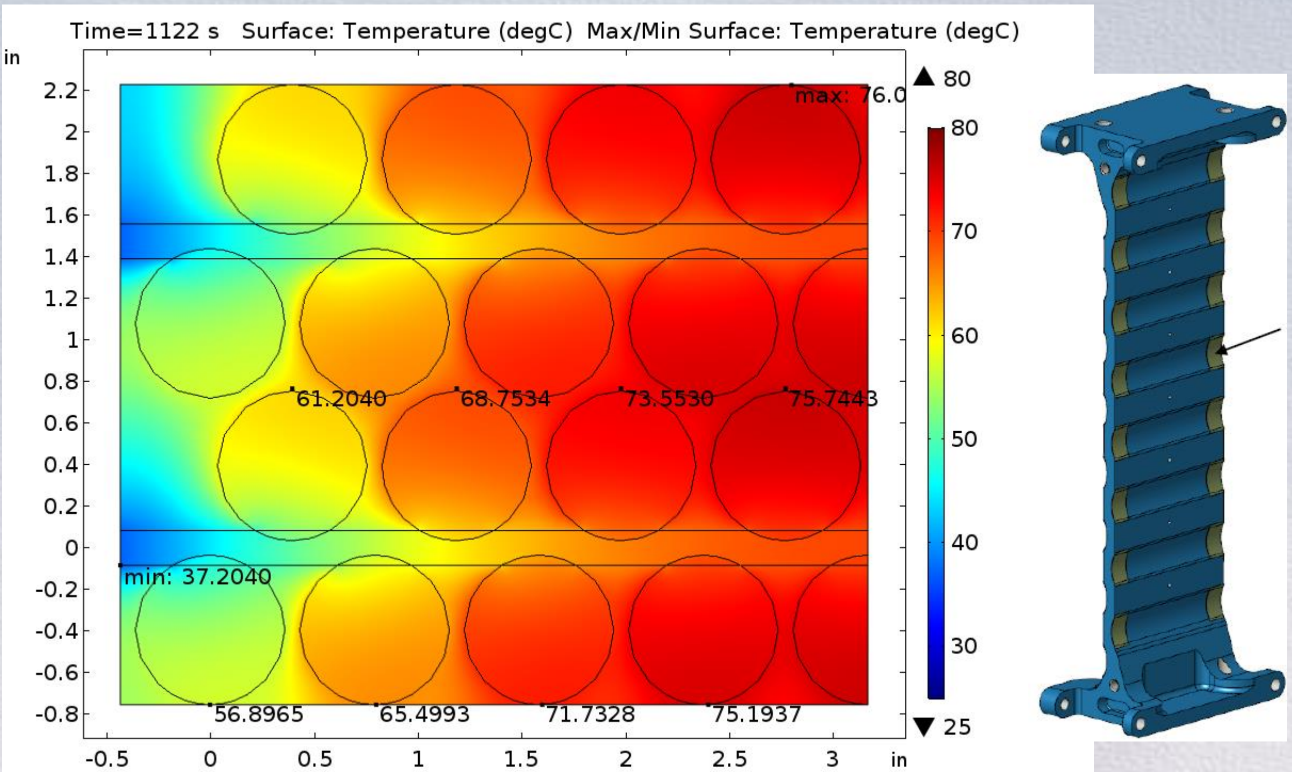
How to improve κ of heat sink spine

- ***Oscillating heat pipes***

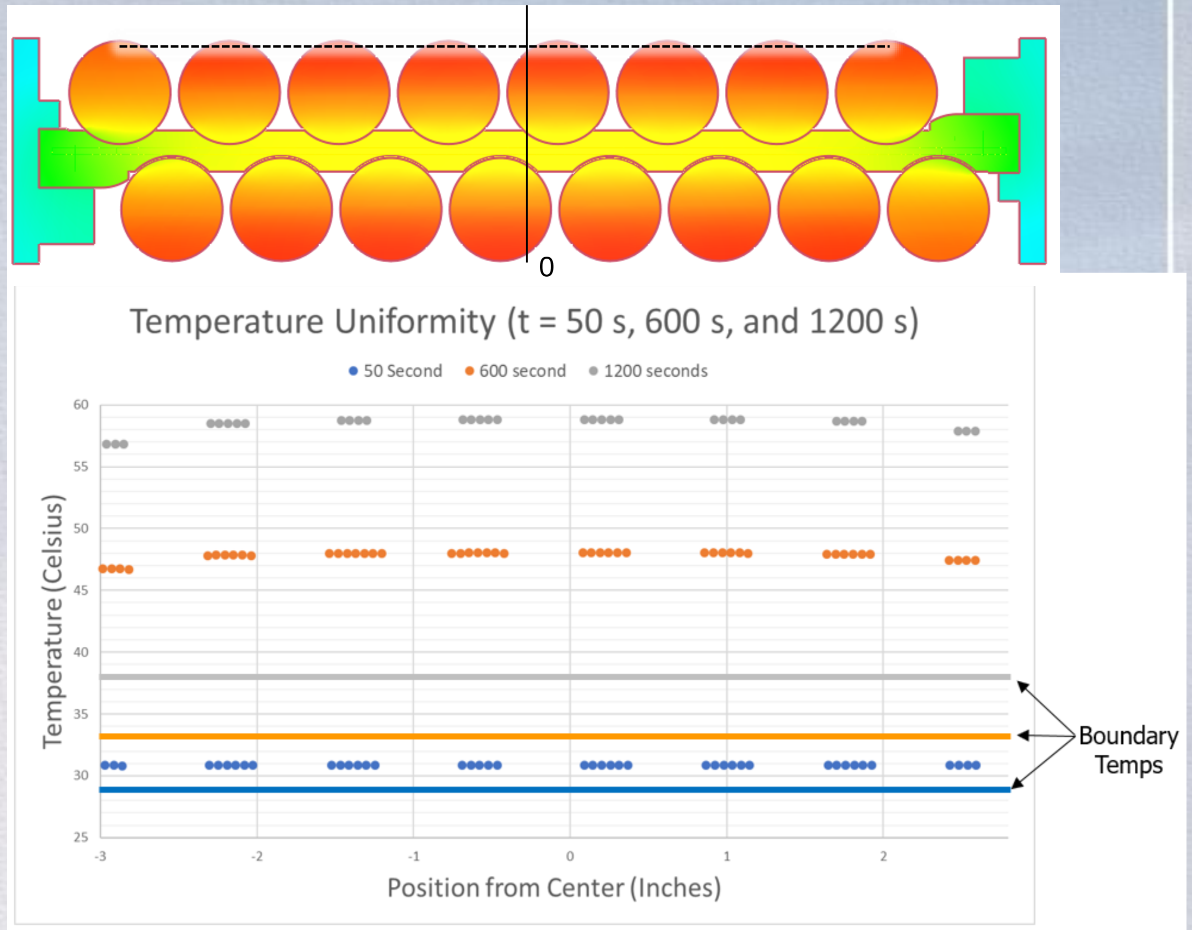


*J. Boswell, D. Pounds, B. Alexander and E. Darcy, “High Power Battery Heat Sink with an Integrated Oscillating Heat Pipe (OHP),” CITMAV Symposium, Feb 2019

Solid Al vs OHP Spine Performance



T_{max} = 76.1 °C
ΔT_{max} = 19.1 °C



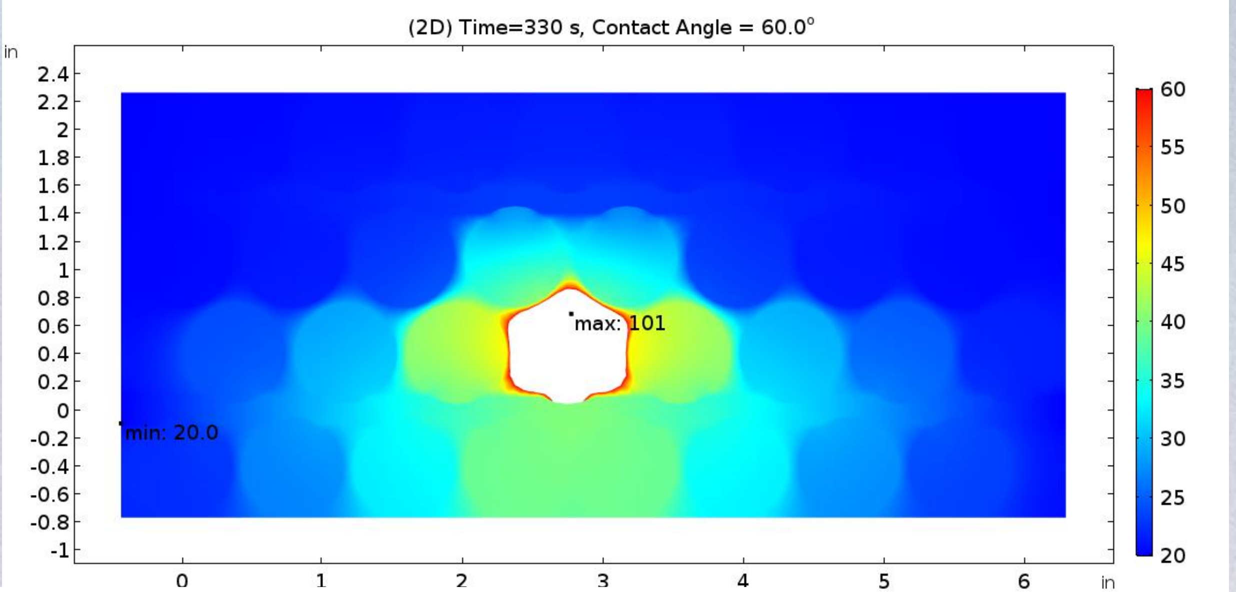
T_{max} = 59 °C
ΔT_{max} = 2.0 °C

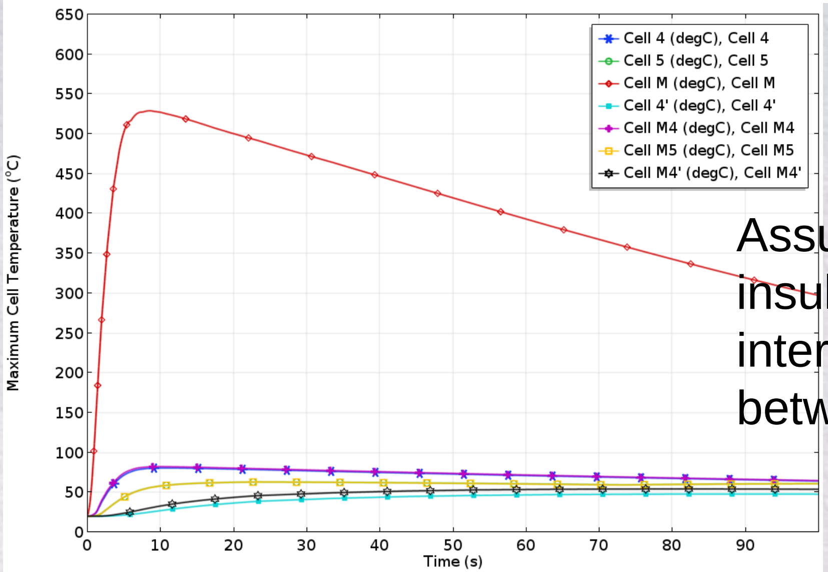
Credit: J. Boswell, D. Pounds, B. Alexander and E. Darcy, "High Power Battery Heat Sink with an Integrated Oscillating Heat Pipe (OHP)," CITMAV Symposium, Feb 2019

Credit: P. Coman, White & Associates

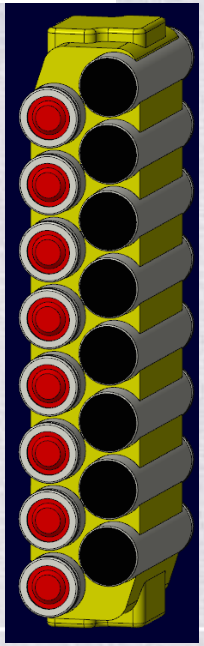
Both Are Predicted to Protect Adjacent Cells from Propagating TR

Solid Al Spine

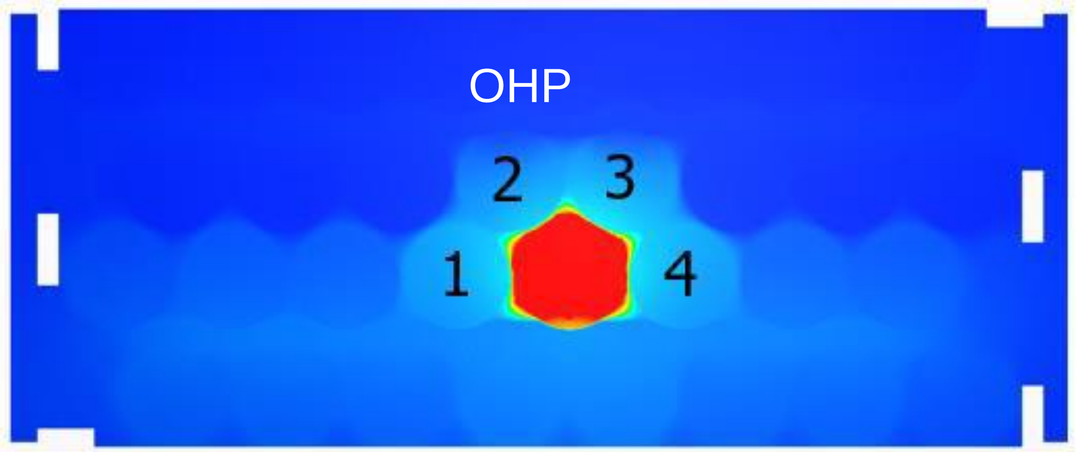


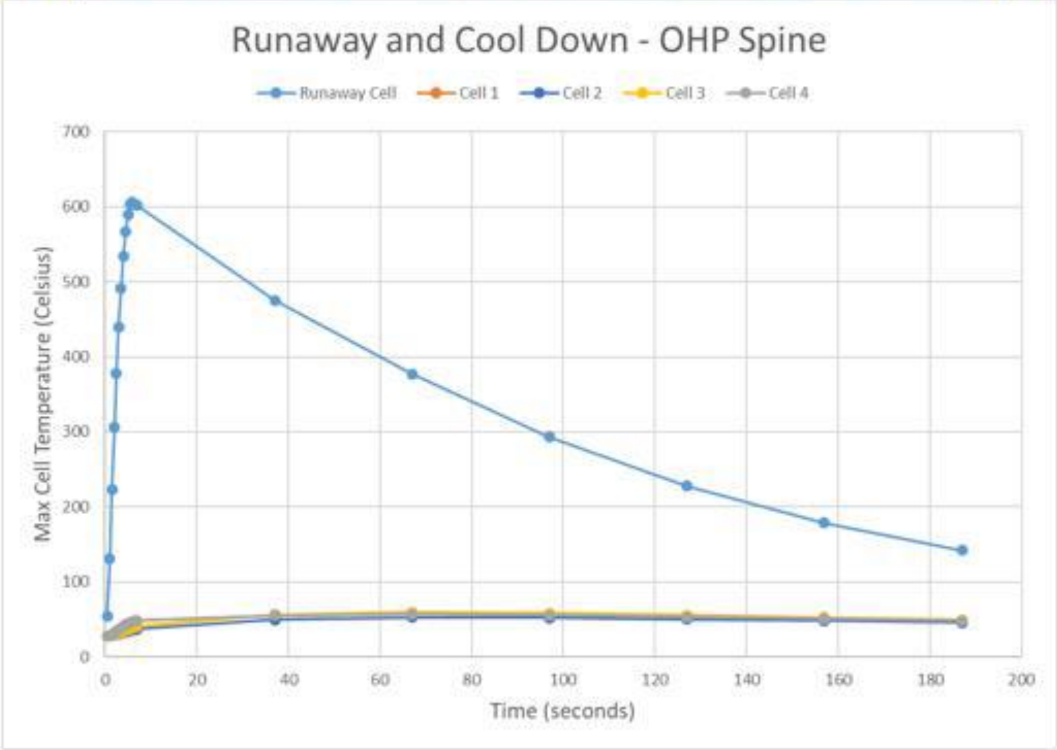


Assuming same insulating interstitial material between cells



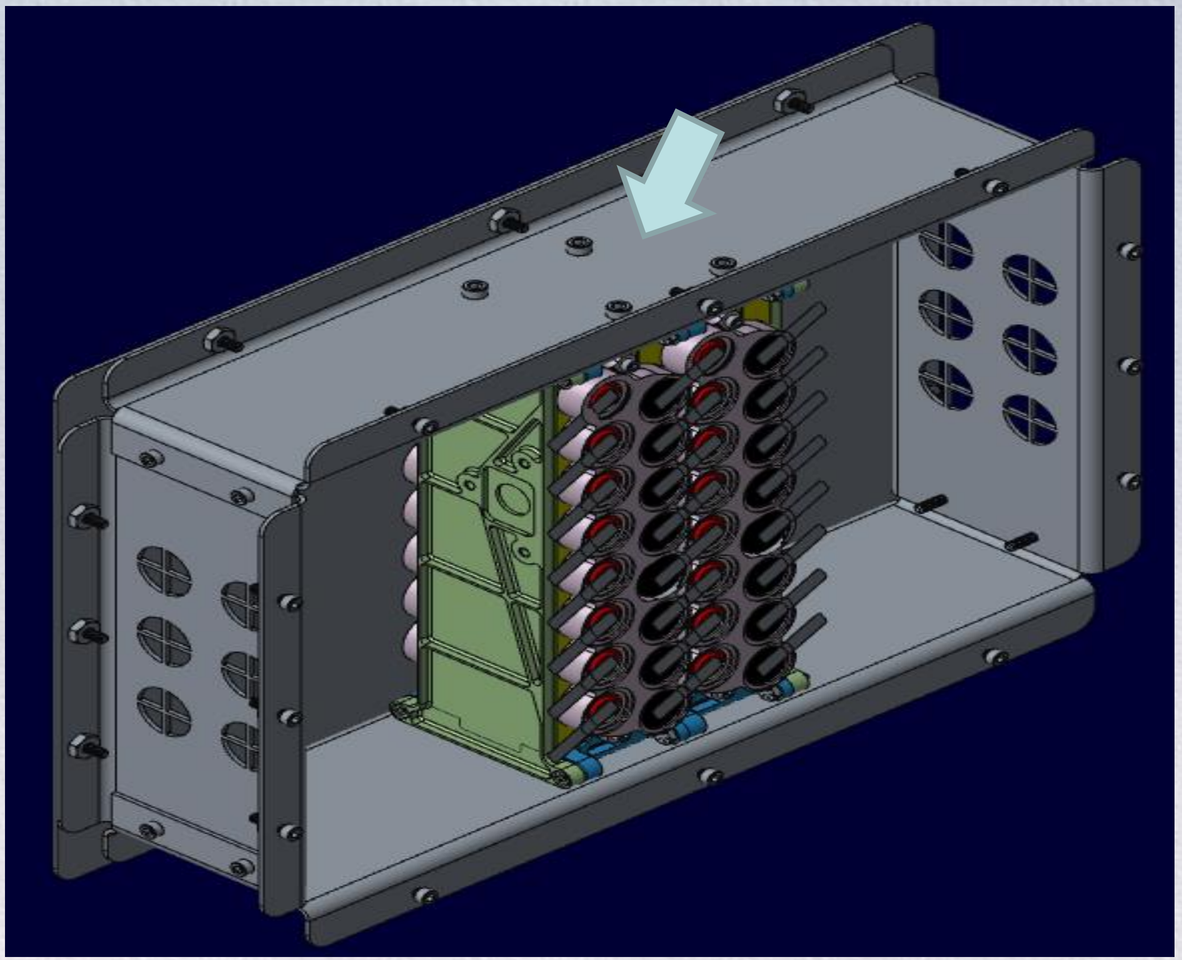
Credit: P. Coman, White & Associates





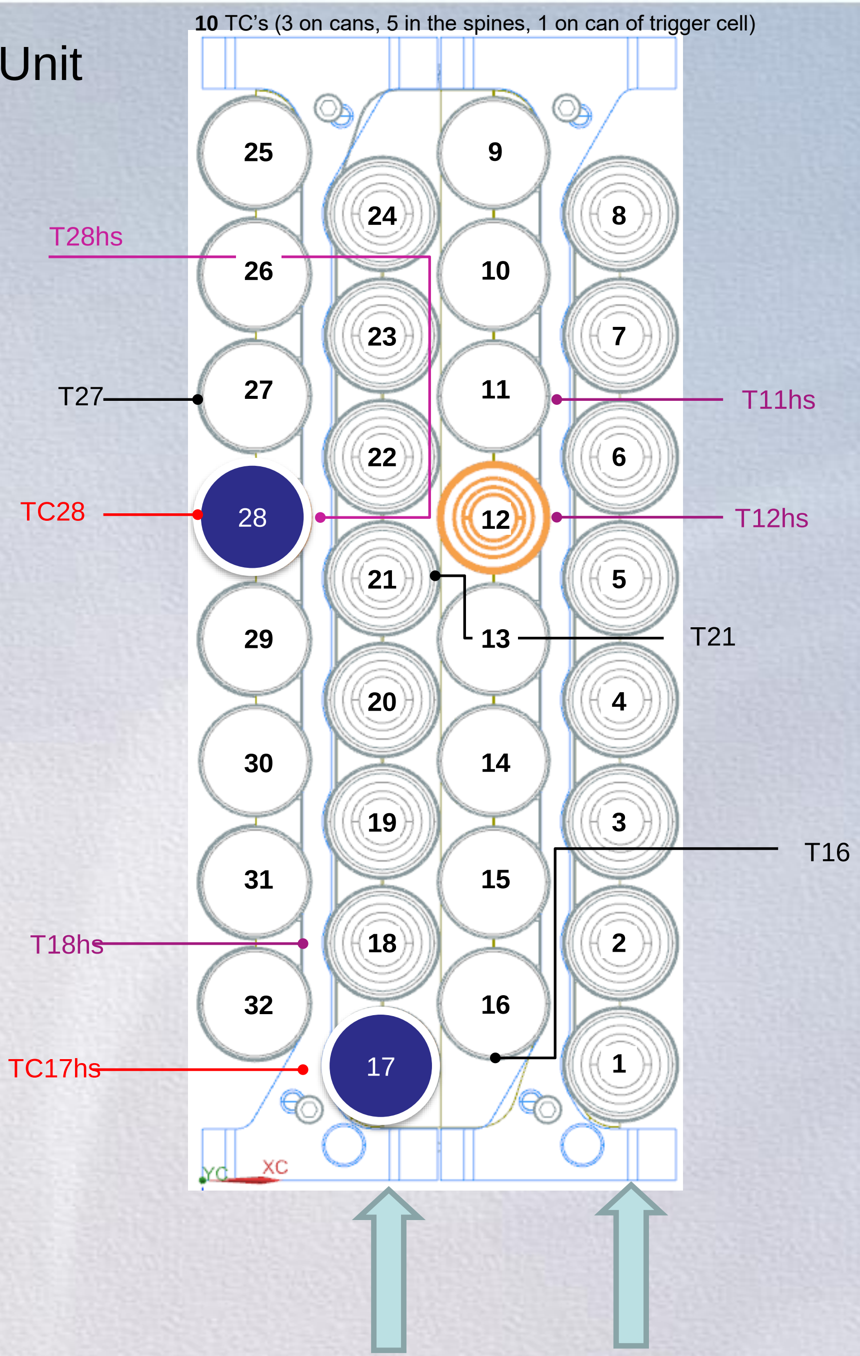
Credit: J. Boswell, D. Pounds, B. Alexander and E. Darcy, "High Power Battery Heat Sink with an Integrated Oscillating Heat Pipe (OHP)," CITMAV Symposium, Feb 2019

Fasteners were too long and damaged cells 17, 1 for sure. This caused short that involved series cells 17, 16, and 1 and activated ISCD in 17 and blew the fuse in the negative leg of that 8S string – bypassing fuse, string measured at ~11V



String at opposite end reading 27.55V as are the middle strings
Nevertheless, opposite end string is suspect and has been disconnected from the 2 middle strings which are still in parallel

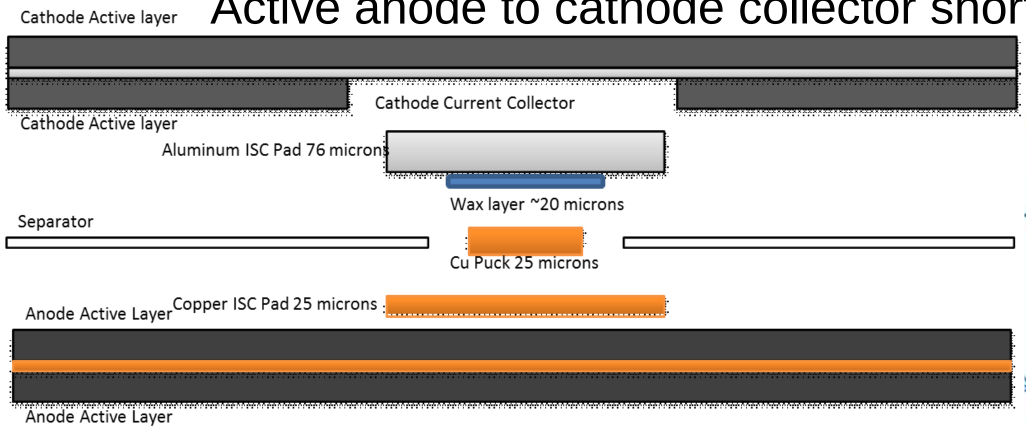
1st Unit

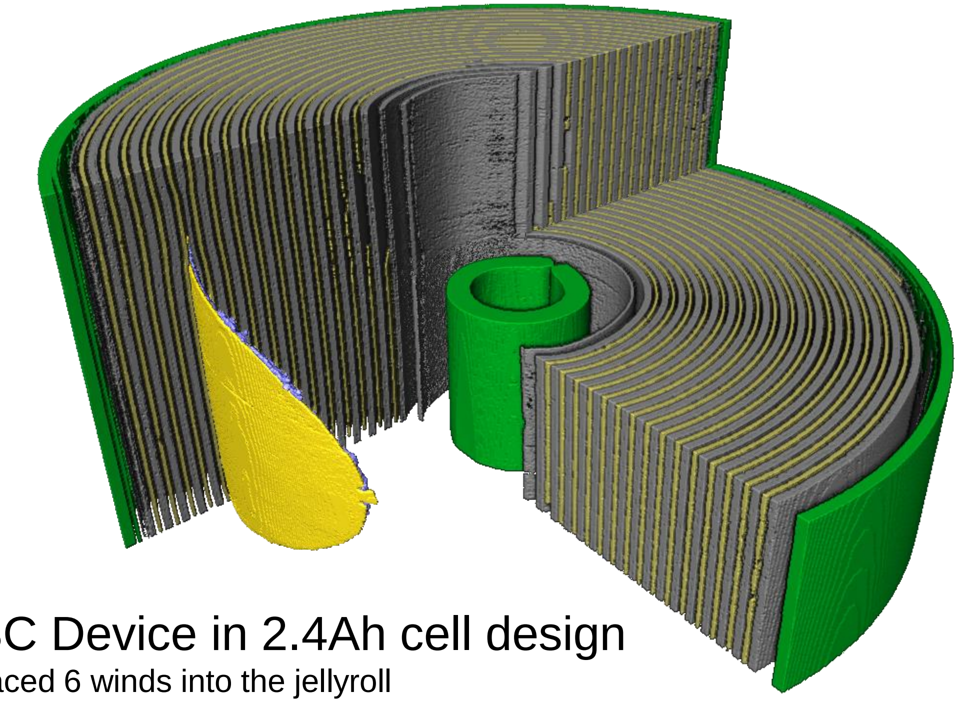


Box to spine fasteners too long

NREL/NASA Cell Internal Short Circuit Device

Active anode to cathode collector short





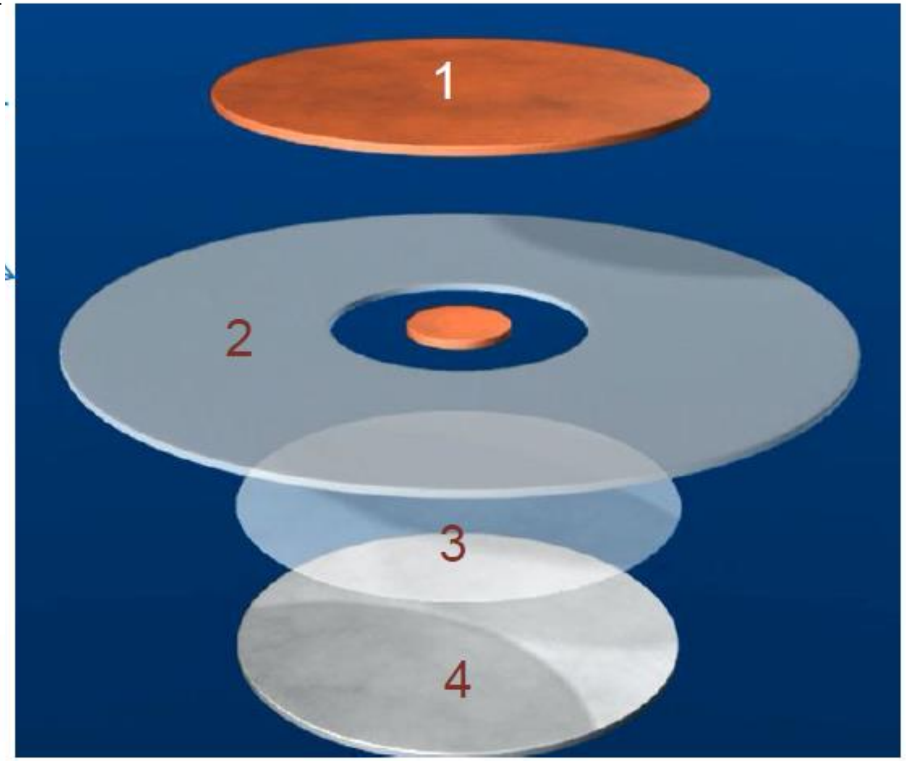
ISC Device in 2.4Ah cell design

Placed 6 winds into the jellyroll

5 mm

Tomography credits: University College of London

KULR Carbon Fiber Cooling™ Exclusive Licensee, March 2018



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

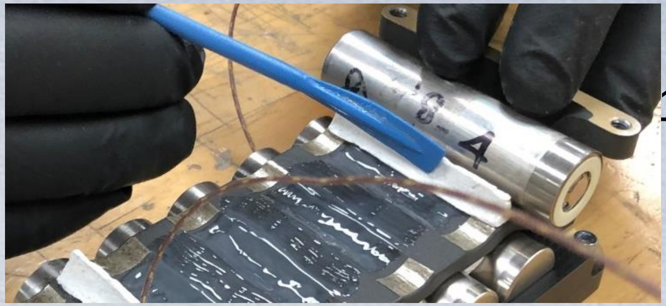
Runner-up NASA Invention of 2017

R&D 100 WINNER

2016 Award Winner

Subscale PPR Test (Assembly Details)

- Trigger cells
  - MJ1 in location 17
  - M36 (NBV) in locations 28 & 12
  - Cells clocked with ISCD aimed at adjacent cell

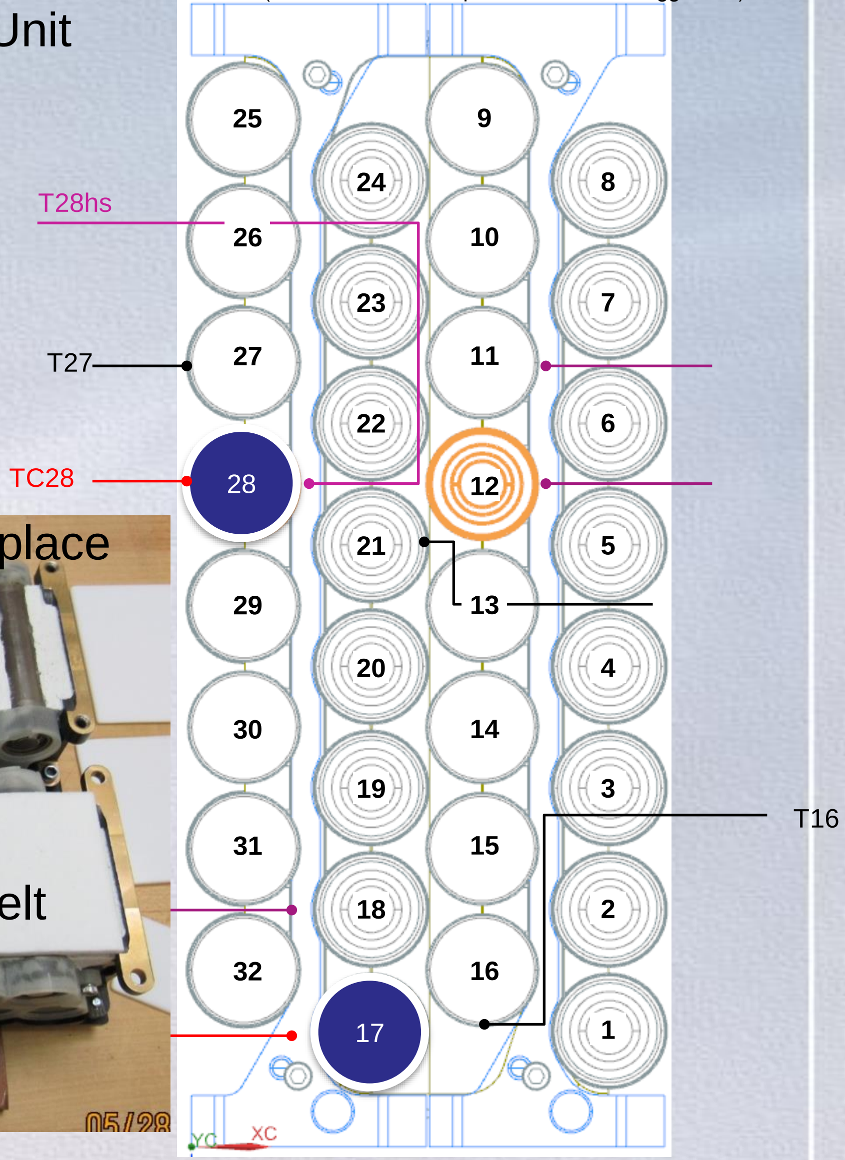


1st Unit

After welding cell interconnecting tabs

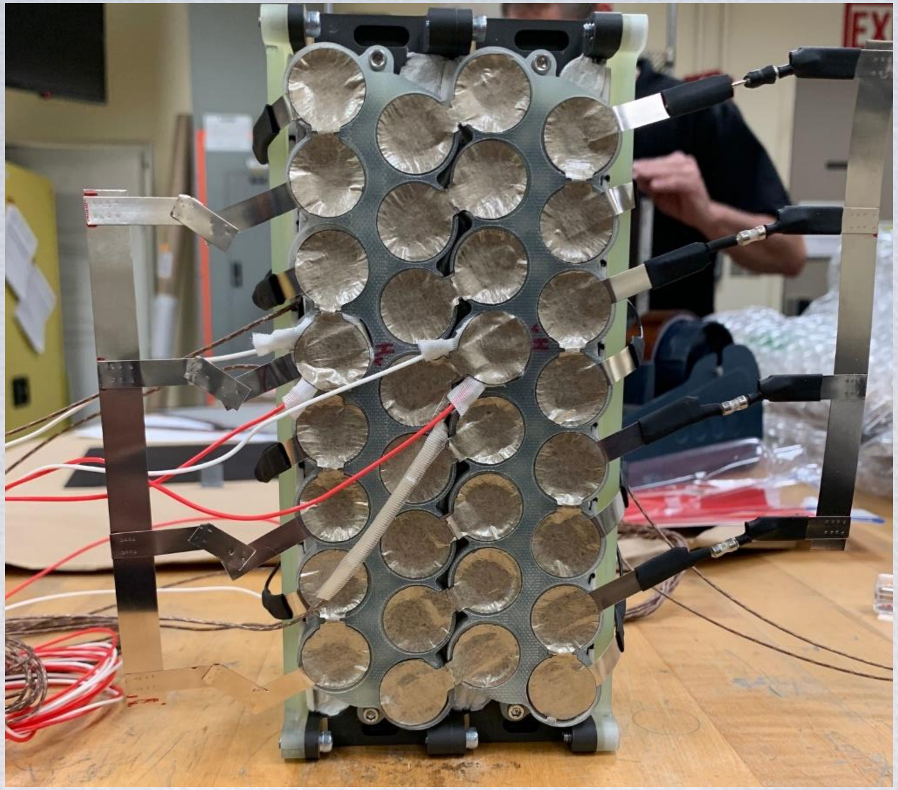
After bonding cells and capture plates

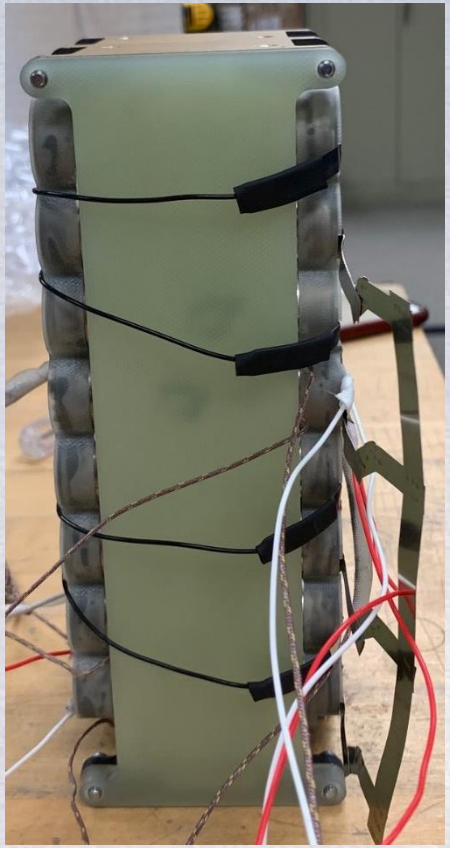
10 TC's (3 on cans, 5 in the spines, 1 on can of trigger cell)

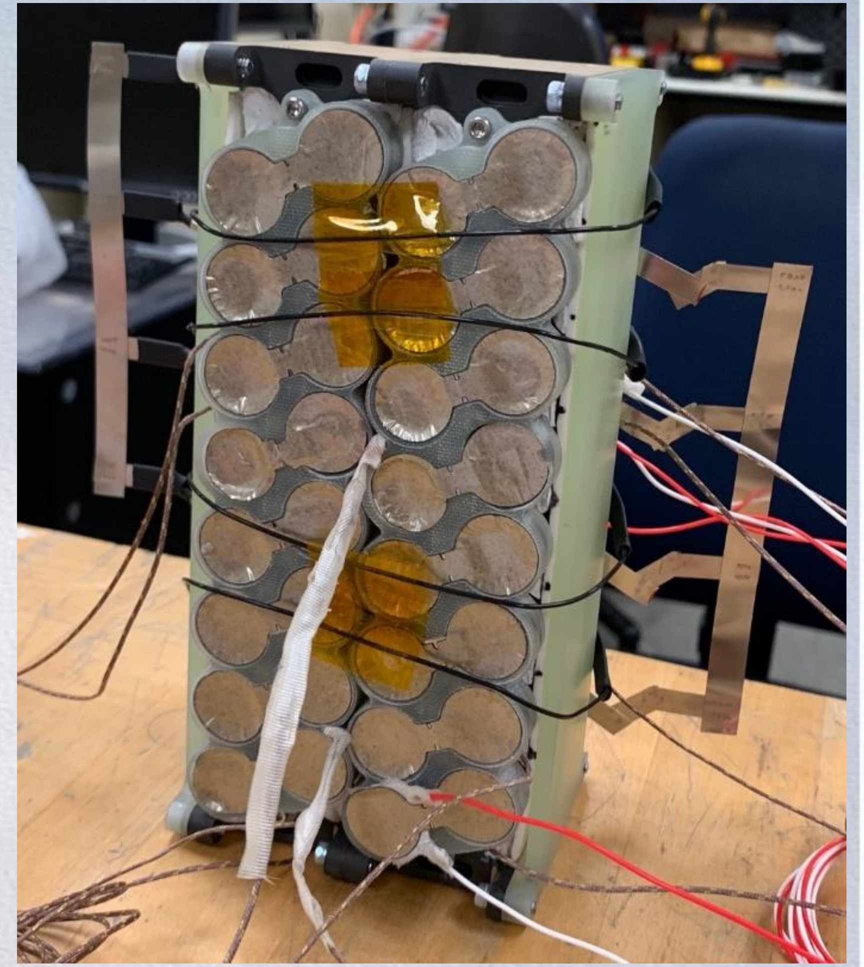


Subscale PPR Test (Assembly Details)

Connecting 4S half strings into 8S-4P topology





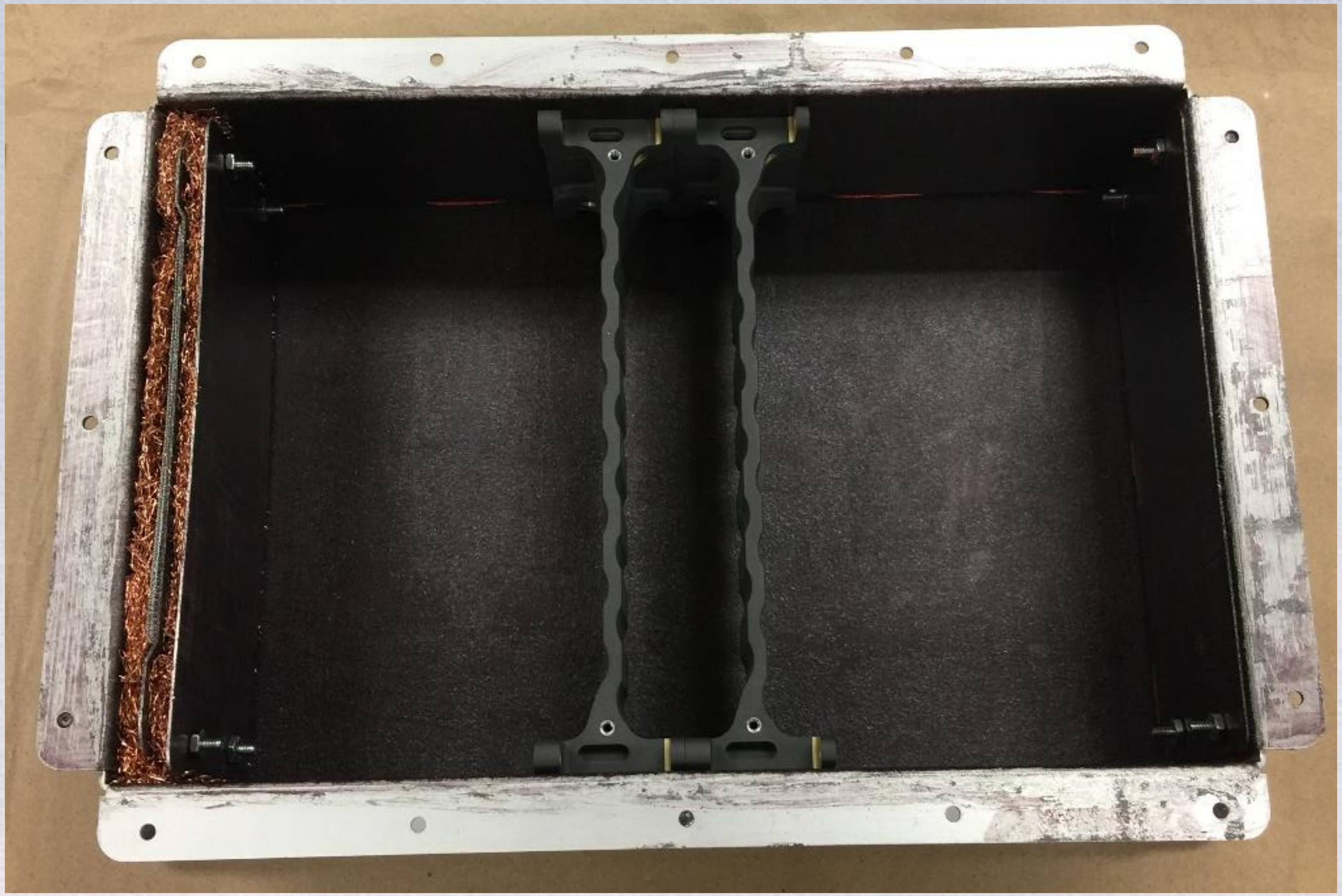


Pico fuse P/N 0275020 20A/32V, fast blow, 0.31" L 0.133" Dia

Note string fuses in (+) leg of each string as pictured, this was corrected to (-) leg prior to placing in box

Subscale PPR Test (Assembly Details)

Top and Bottom panels are 0.032” thk Al sheet metal
All interior surfaces coated with Sipiol intumescent coating

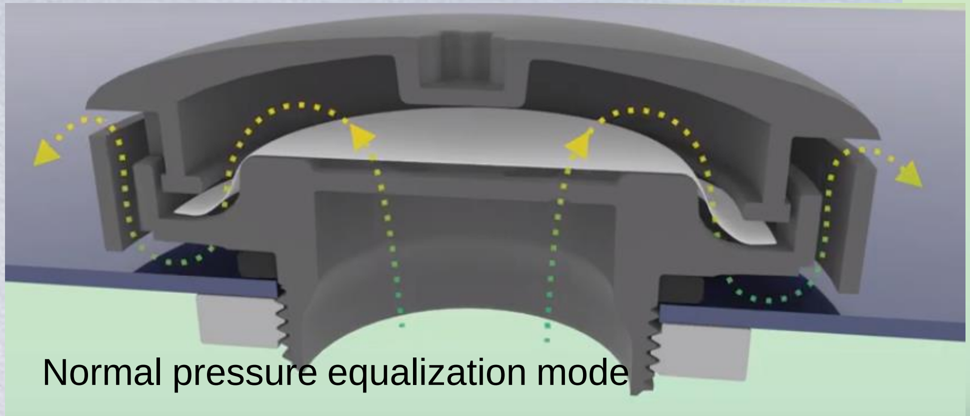


Double Gore vent panel using new flexible membrane

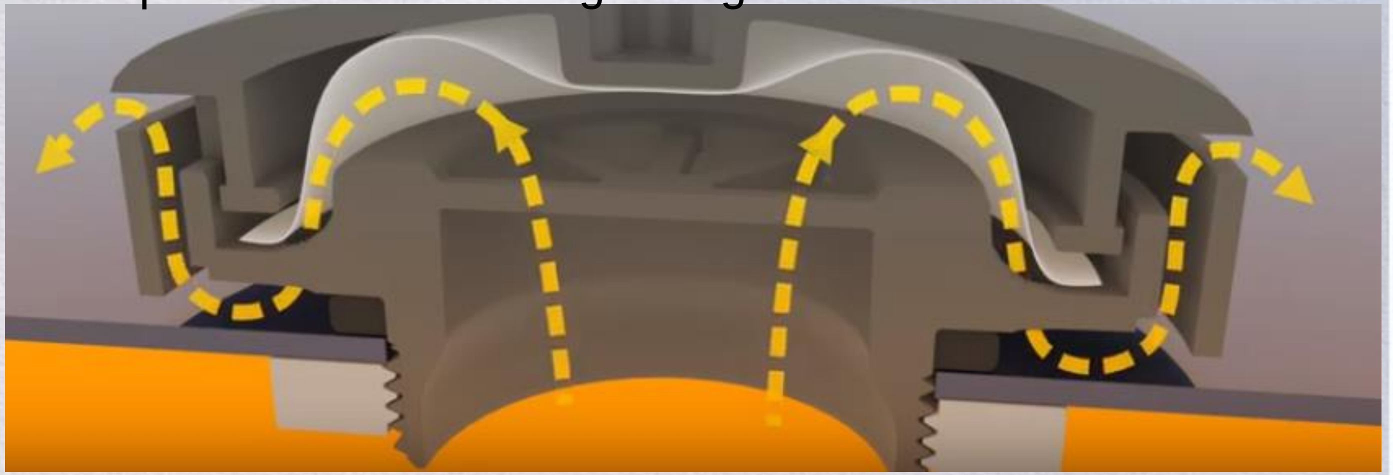
Alternate Flame Arresting Features

- Our qualified Gore vent design seals with an O-ring
  - Orion and LLB2
- High pressure TR burst can rip open the membrane
- Can a series of baffles and steel screens drop the pressure and protect the membrane?

New Gore Low Pressure Battery Vent with flexible membrane

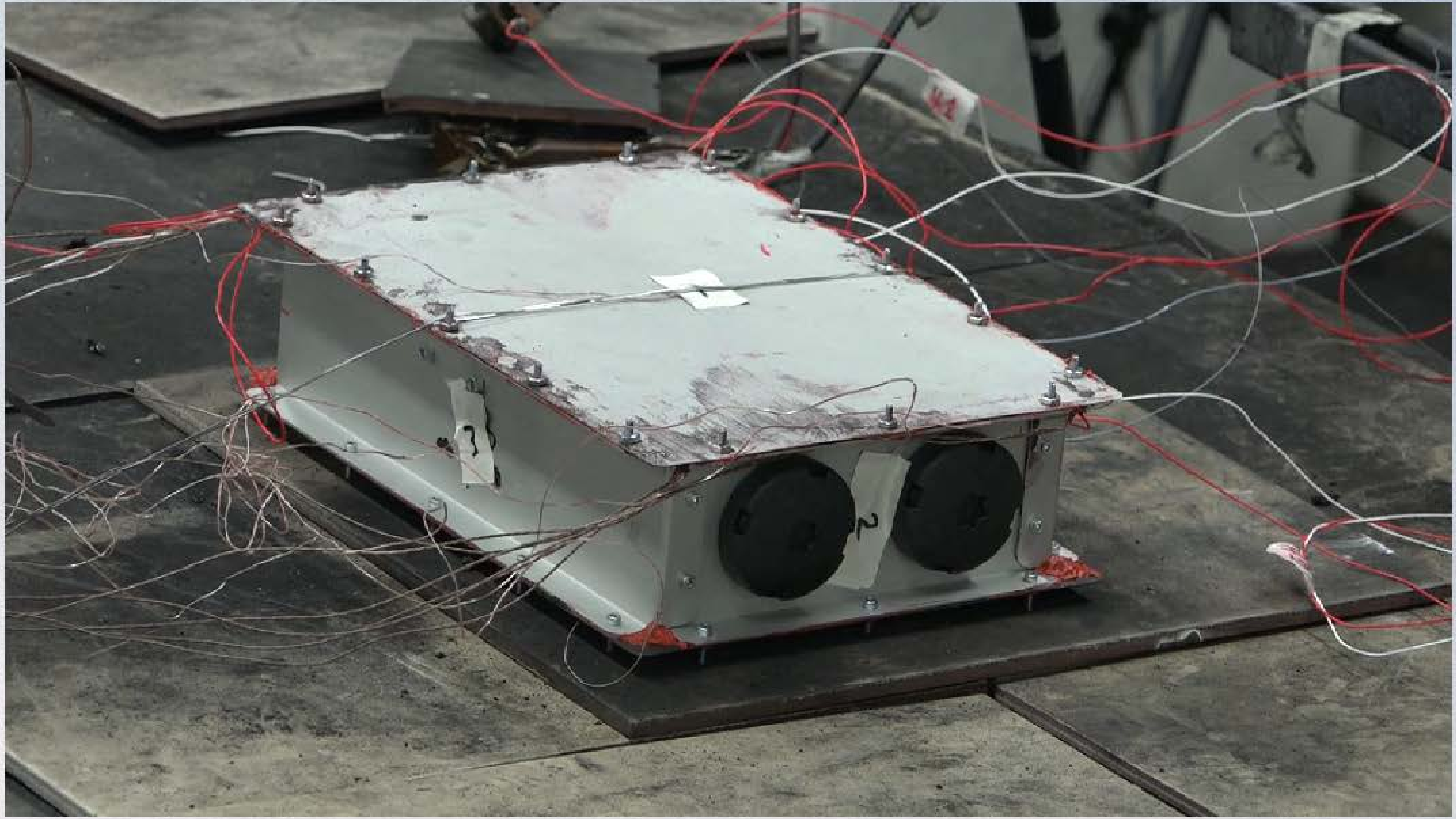


Burst pressure mode during a single cell TR

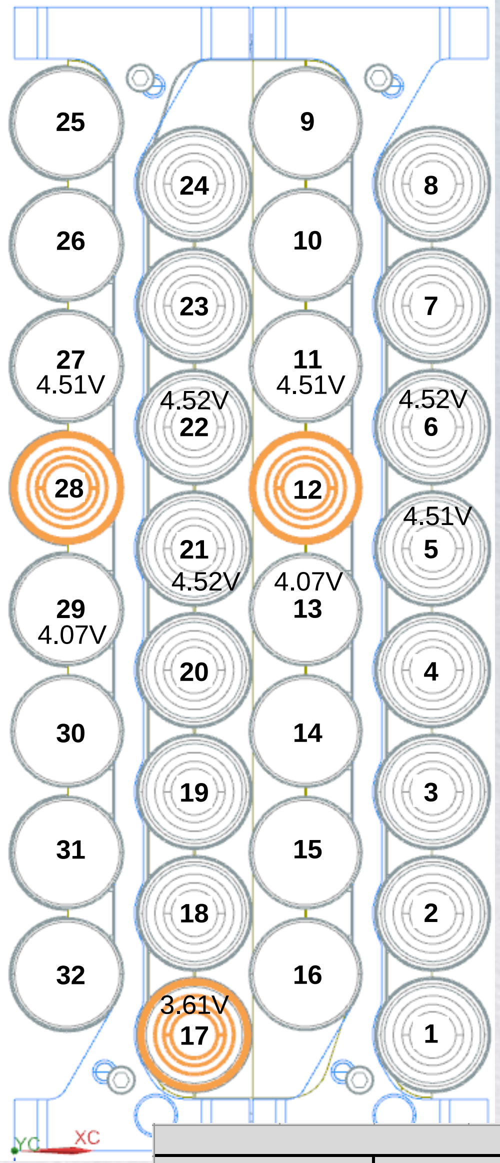


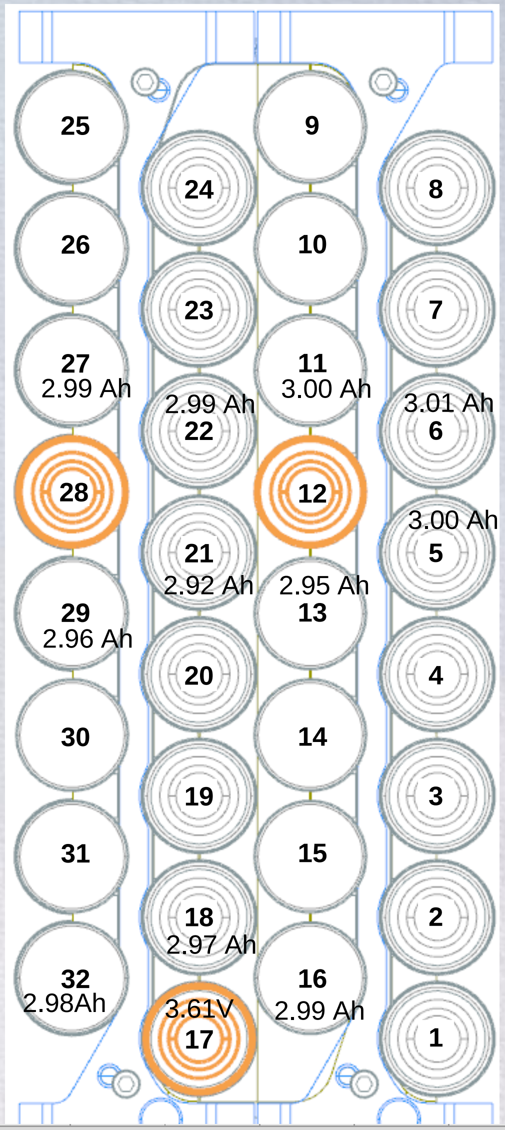
https://www.gore.com/news-events/press-release/low-pressure-evacuation-vent

Video of ISCD Cell 12 Event



OCVs and Capacities of Adjacent Cells Post Test



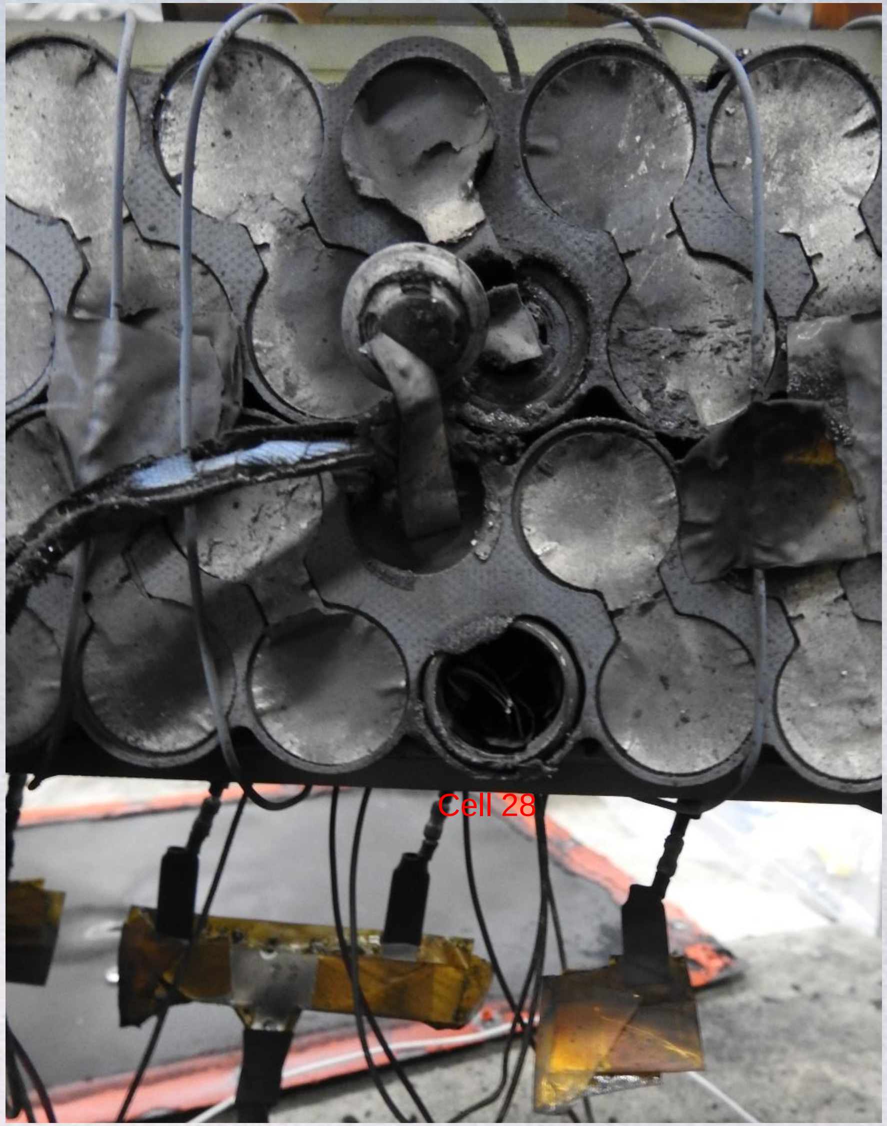


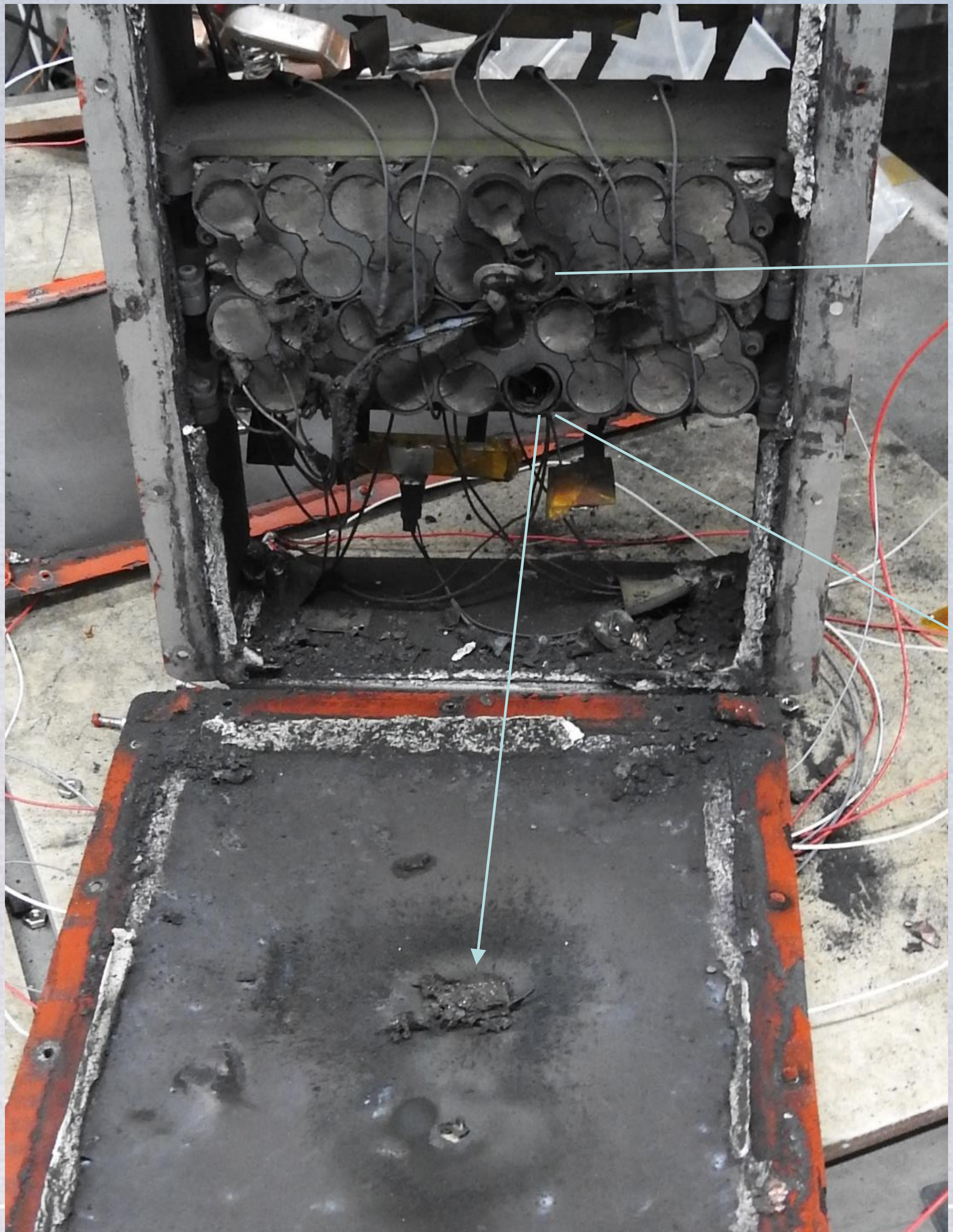
- 8S-2P battery OCV = 32.6V
  - Was charged to 33.6V prior to test
- No evidence of adjacent cell damage from OCV measurements
  - Strings will be isolated and discharged to 2.5V/cell
  - Adjacent cells capacity cycled individually at C/5 – All nominal
    - Even cells 21 and 22 adjacent to both trigger cells
- String with the 2 trigger cells was overcharged from parallel 8S string
  - Most of the balance charging appears to have occurred between TR events and may have caused the activation of 2nd ISCD cell (28)
  - Brief OCV dip on second event indicates 20A fuse blew
- Trigger cell 17 reading 3.61V

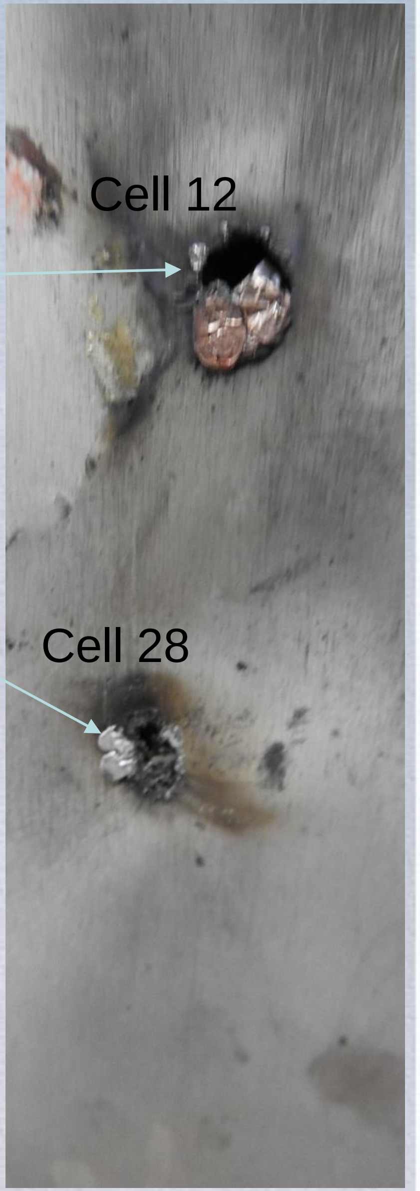
End of Cycle Values																					
SN5		SN6		SN11		SN13		SN16		SN18		SN21		SN22		SN27		SN29		SN32	
Ah	Wh	Ah	Wh	Ah	Wh	Ah	Wh	Ah	Wh	Ah	Wh	Ah	Wh	Ah	Wh	Ah	Wh	Ah	Wh	Ah	Wh
3.00	10.63	3.01	10.67	3.00	10.64	2.95	10.46	2.99	10.79	2.97	10.53	2.92	10.35	2.99	10.60	2.99	10.59	2.96	10.50	2.98	10.57

Photos Post ISCD Cell 28 Event

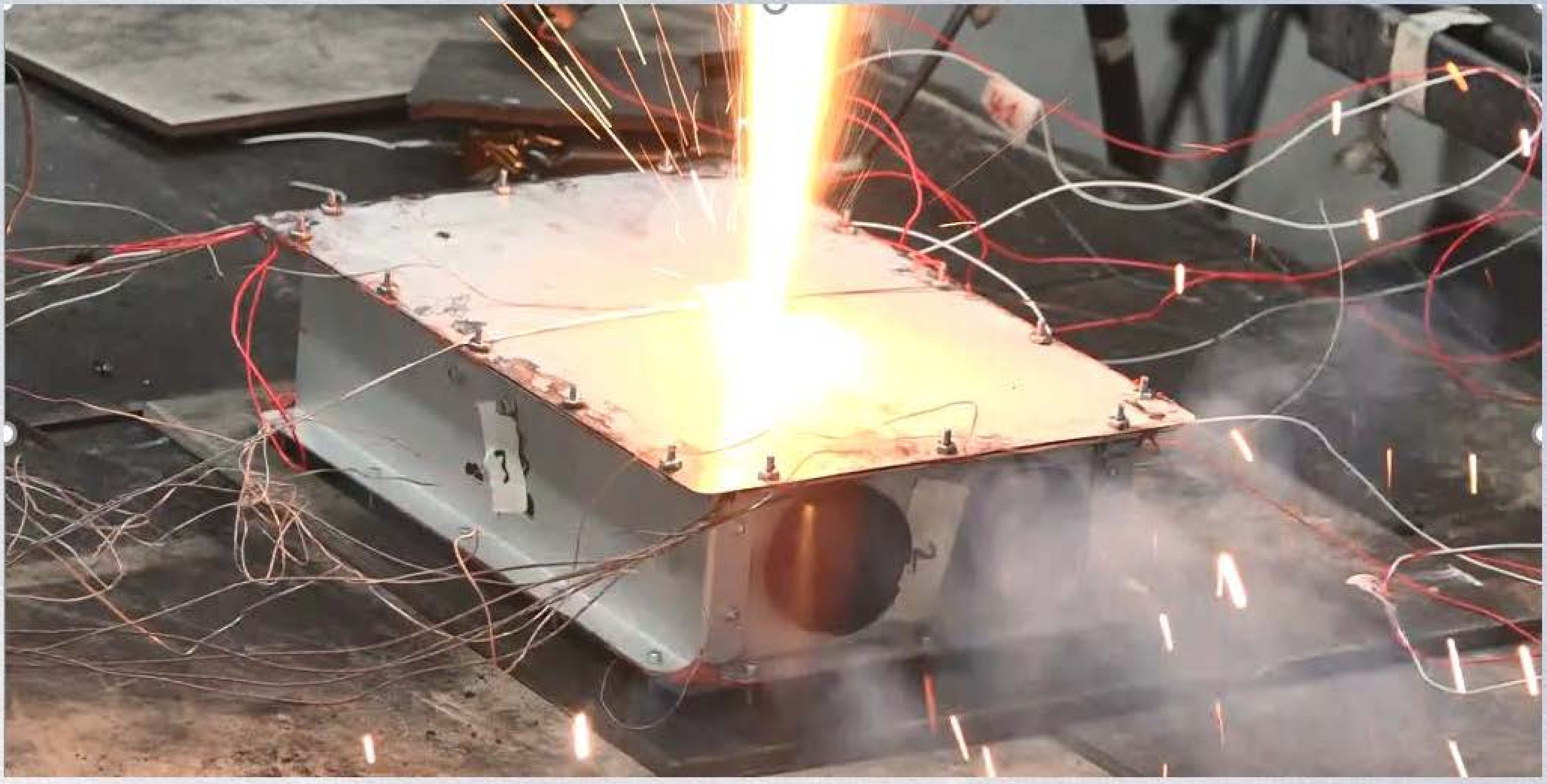
Cell 28 ejects most of its JR







0.031” (0.8mm) thk Al panel lined with Lord Sipiol FR coating is perforated by LG M36 trigger cell

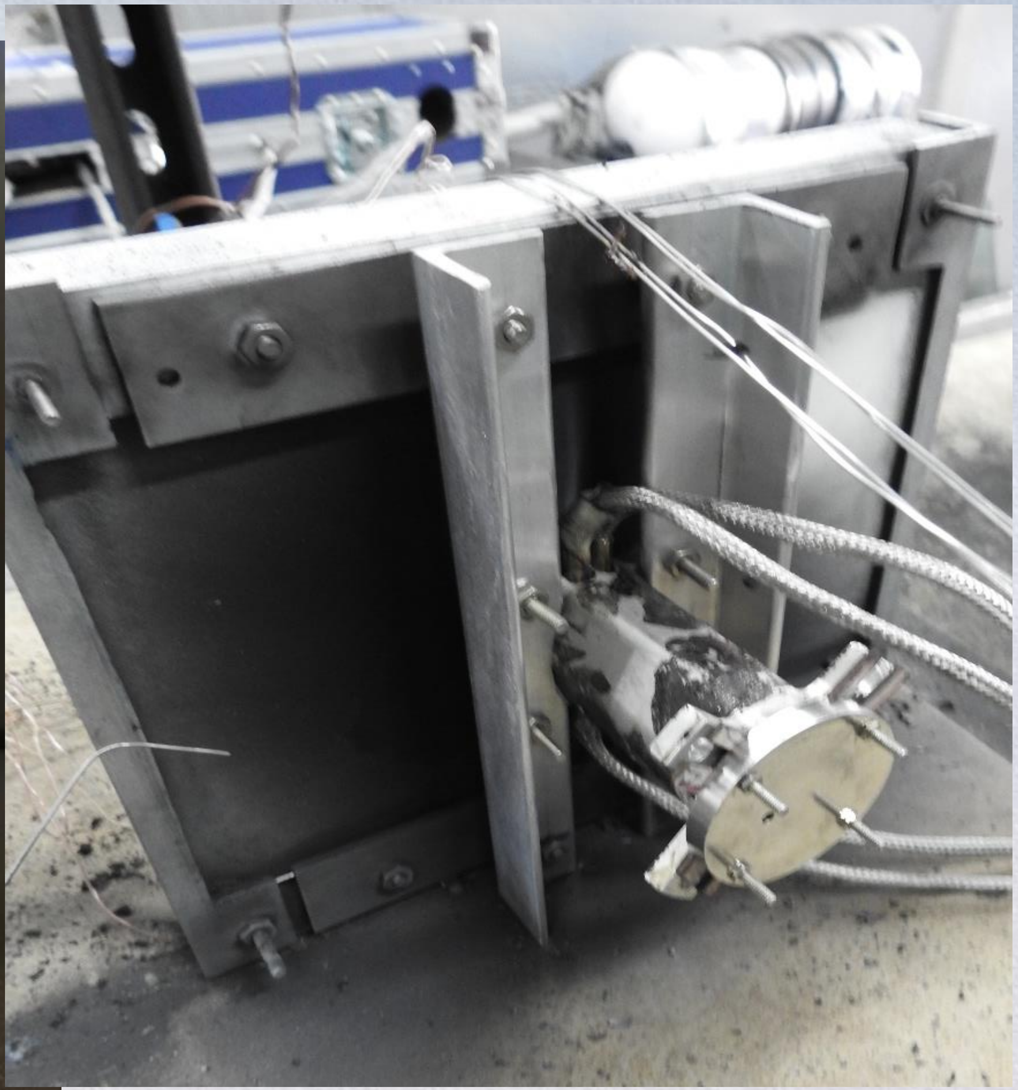


Takeaway: Blow torch testing doesn’t capture the velocity/pressure of TR ejecta materials

Preliminary Findings (Lessons Learned)

- No propagation of TR
  - Cells 21, 22 withstood 2 TR events within 512s (8.5 minutes)
  - Ceramic putty (Thermez 7020) and (EST Superwool) felt with 60º contact angle between cell and spine appears to work
- All adjacent cells appear functional
  - Capacity cycling remains to be done
- Mica dogbone covers worked
- Sipiol intumescent & anodize coatings on 0.032” thk Al aren’t sufficient
  - Blow torch testing not fully representative of cell ejecta events

Blast Plate Test Set-up

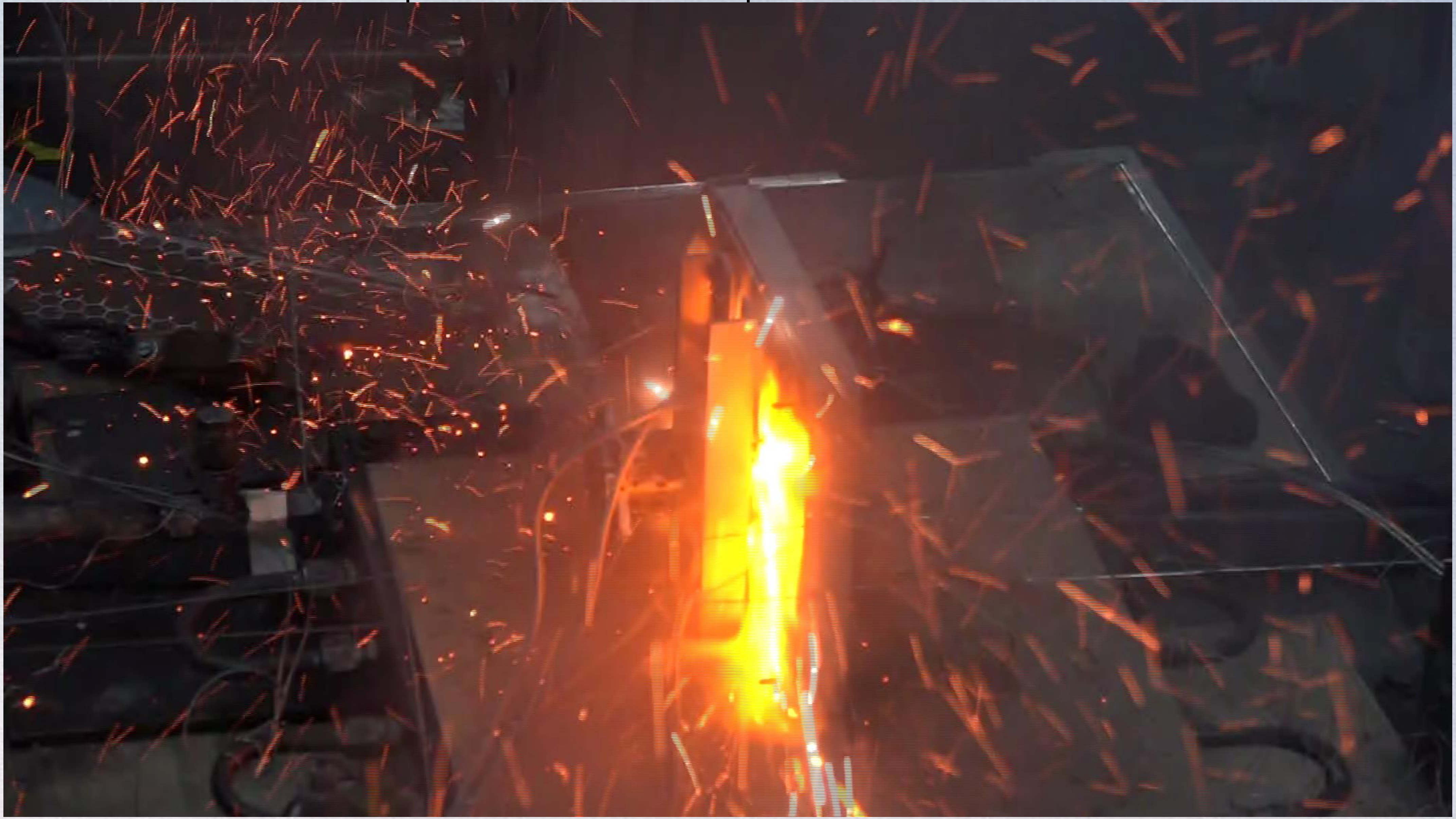


Objectives
- Test insulating/quenching layers against cell TR ejecta
- Protect 1/32” (0.8mm) Al sheet
- Adjustable gap (currently set to 6 mm

Candidate Protective Layers
Densities of 1/16” thick sheets
Kaowool 1401: 0.641 g/ml
Zircar RS200 : 2.1 g/ml
KULR TRS: 1.8 g/ml

Kaowool 1401 (1/16” thk) Run 1 – Samsung 35E

Gap measured between top of cell and Kaowool surface 6-7mm

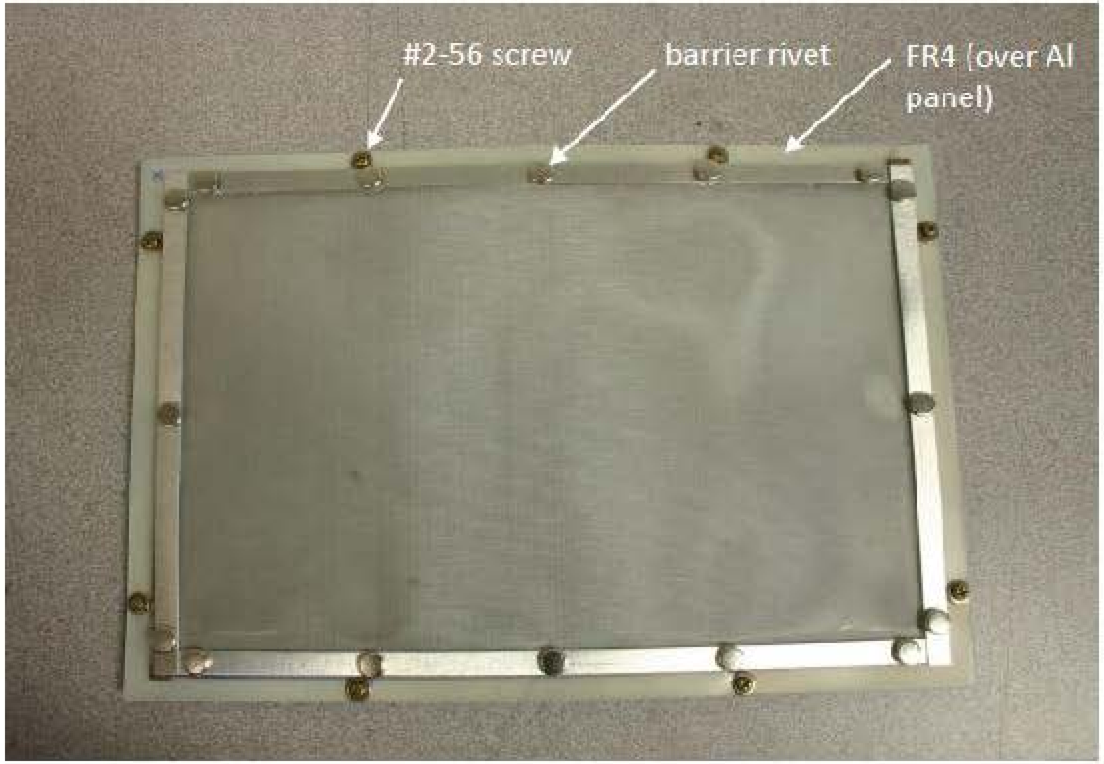


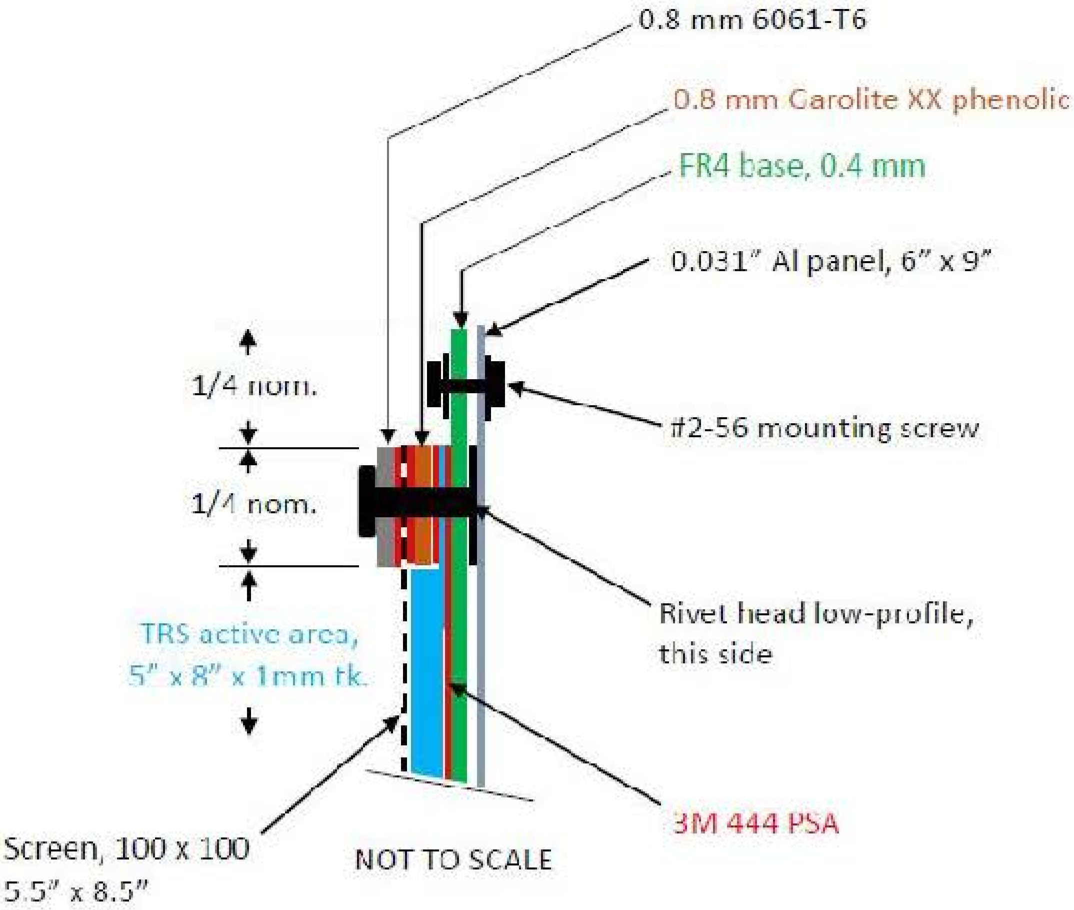
Zircar RS200 1/16” thk

Thermal Runaway Ejecta Barrier Evaluation, Round 2 Final

KULR
Carbon Fiber Cooling™

Barrier design

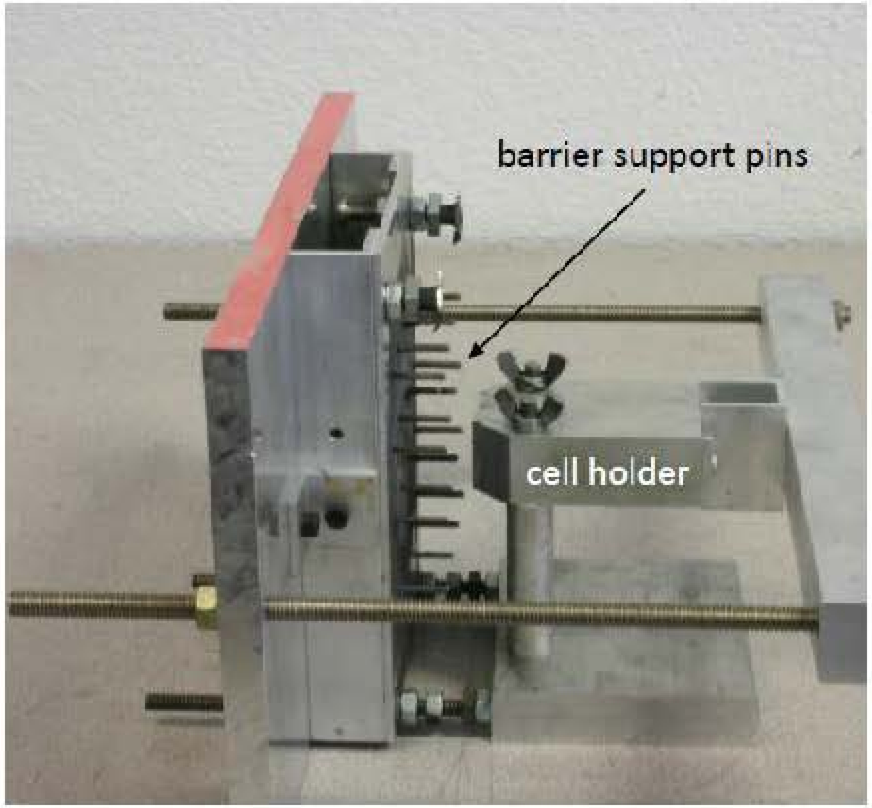




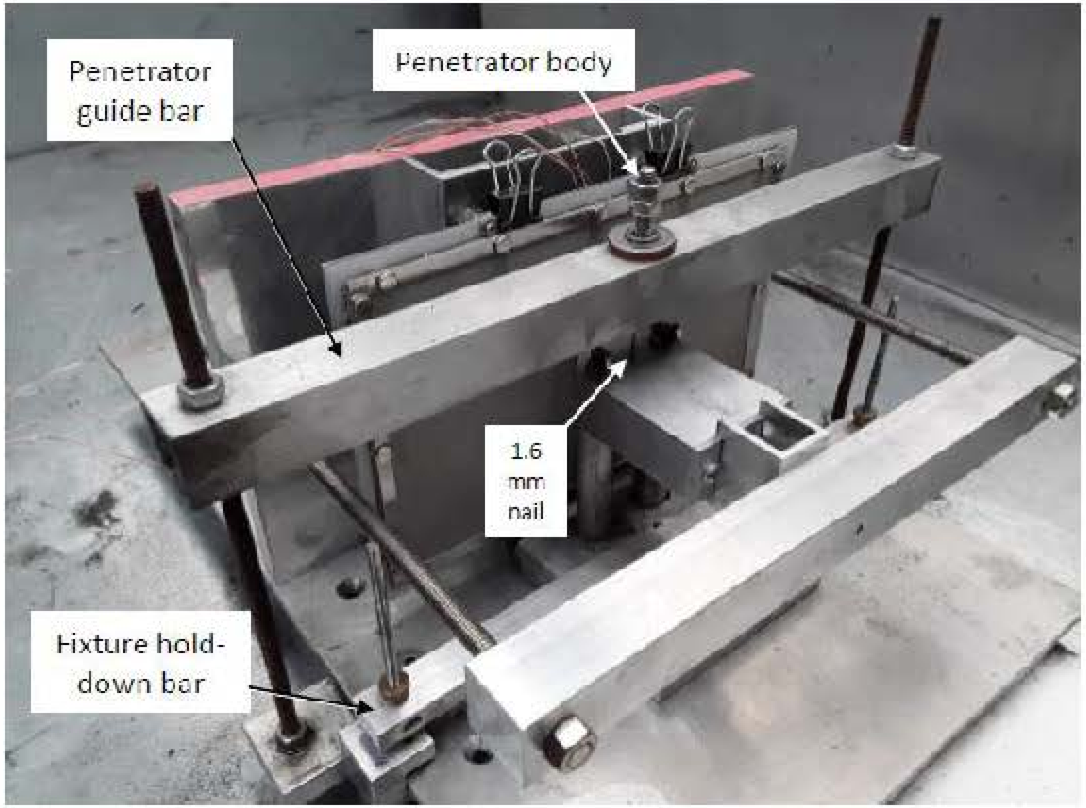
Thermal Runaway Ejecta Barrier Evaluation, Round 2 Final

Test fixture

KULR
Carbon Fiber Cooling™

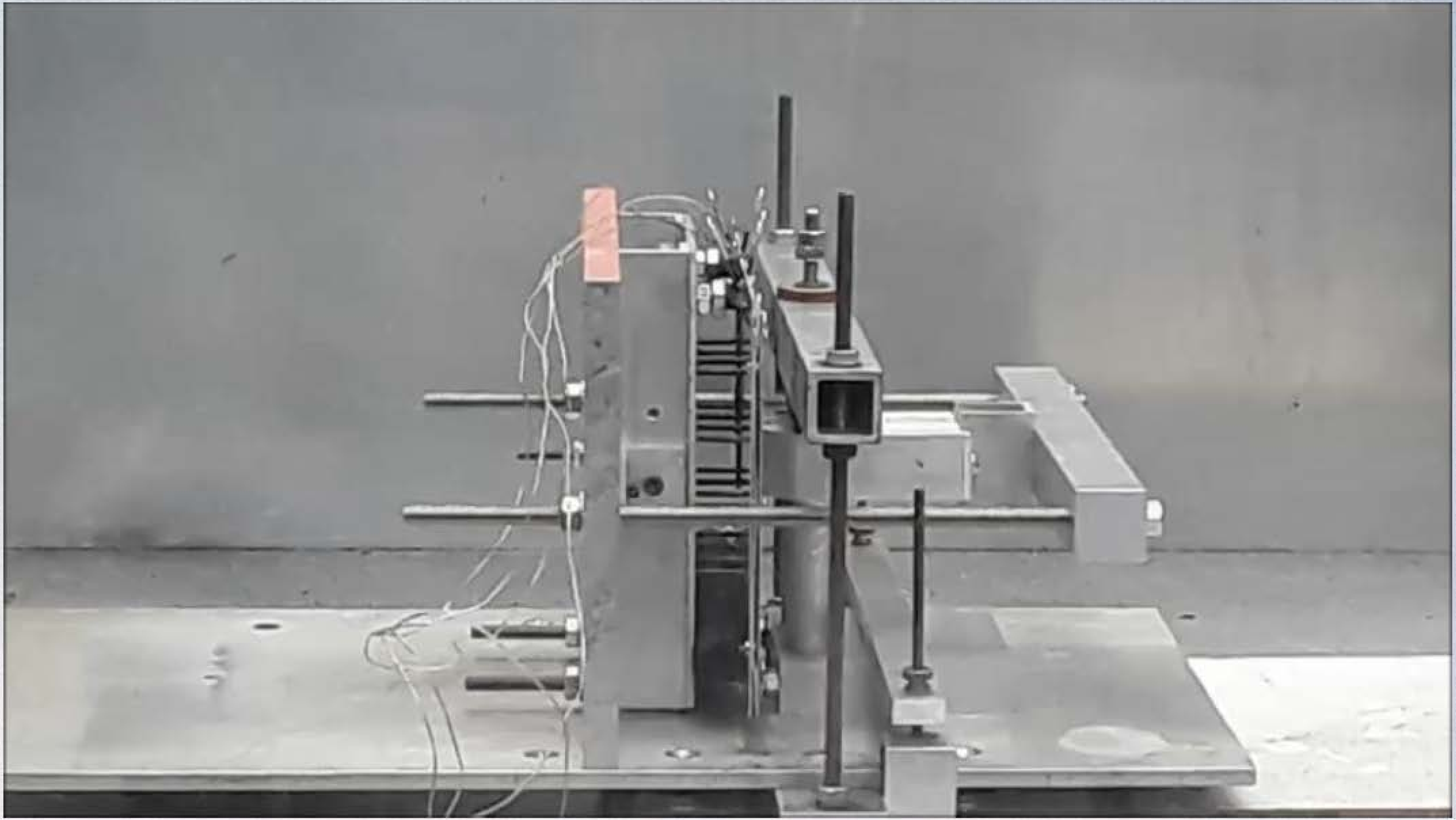


Test fixture



Fixture with barrier in position

Video of Test 1 – ¼ speed slow motion



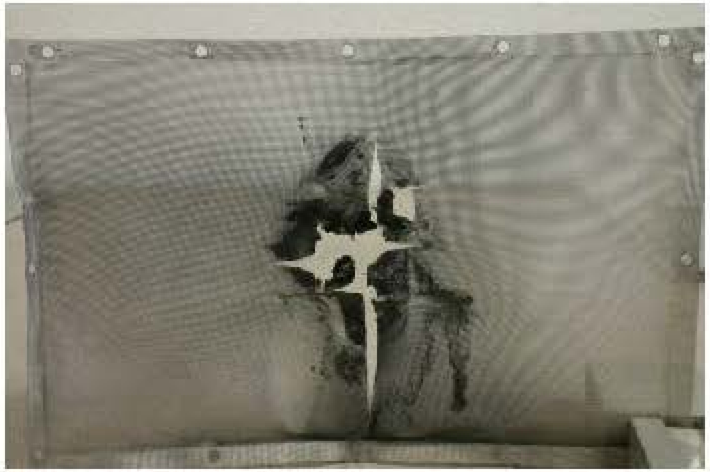
Second Test

Thermal Runaway Ejecta Barrier Evaluation, Round 2 Final

Test Screen 2-3: Post-test examination

KULR
Carbon Fiber Cooling™

Post-test: Rivets intact, FR4 failed at some screw locations.

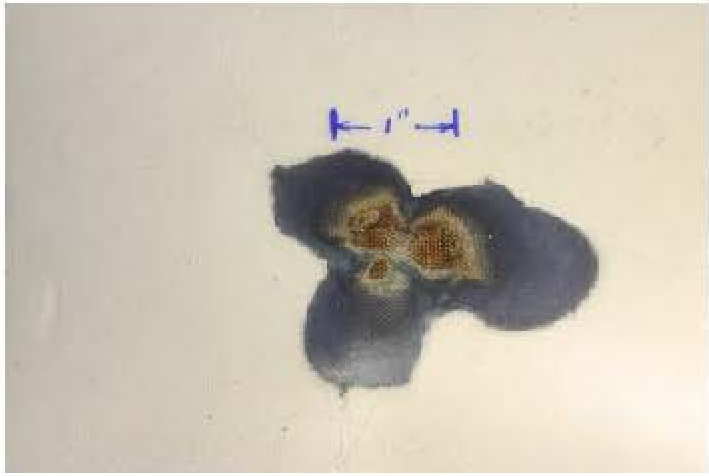


Screen alone, against white background

Screen removed

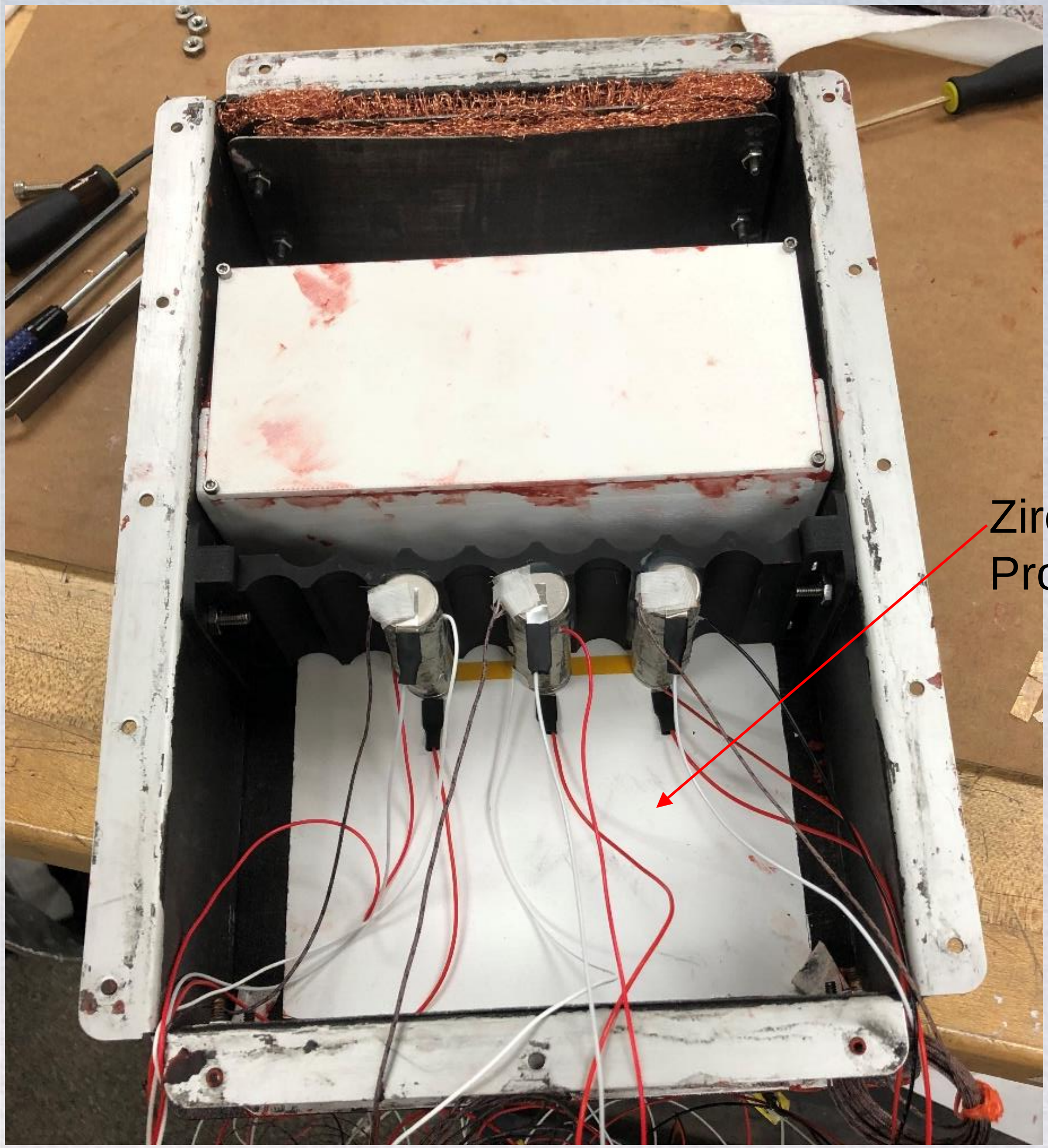
TRS top layer removed

Nomex removed



FR4 back face

Flame Arresting Vent Port Verification

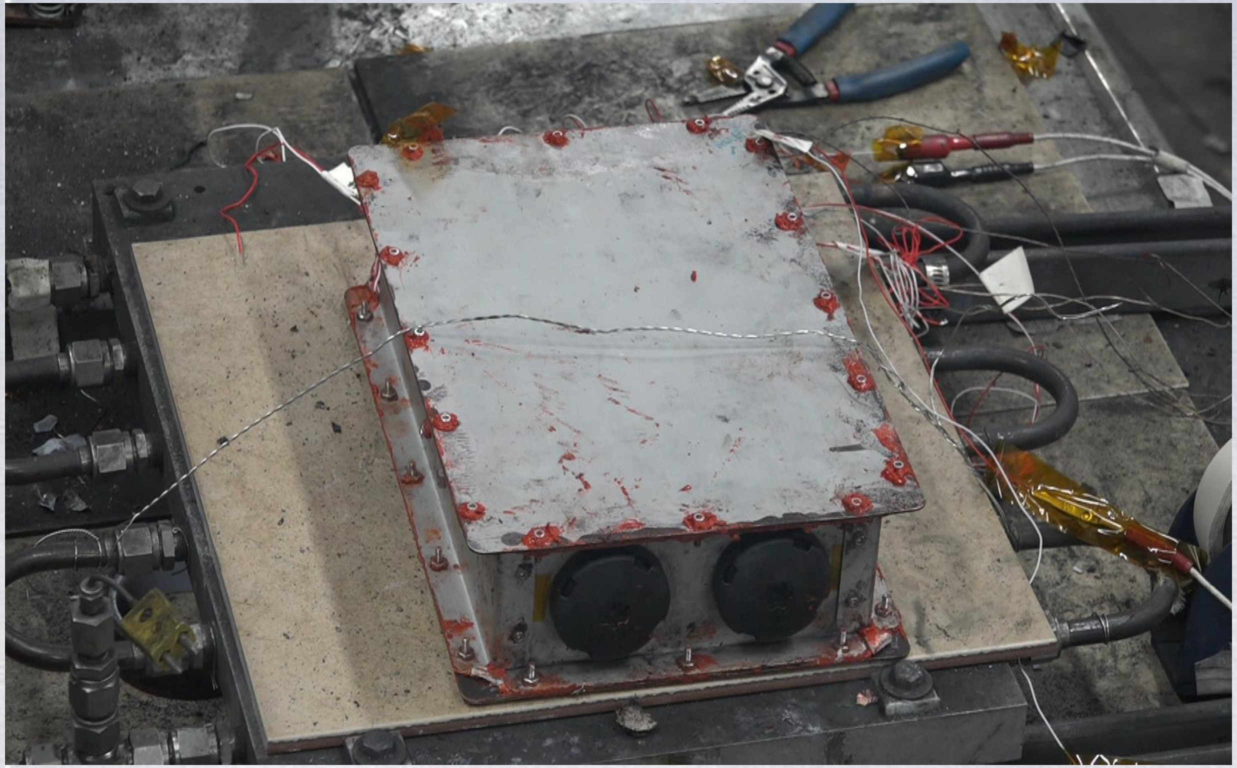


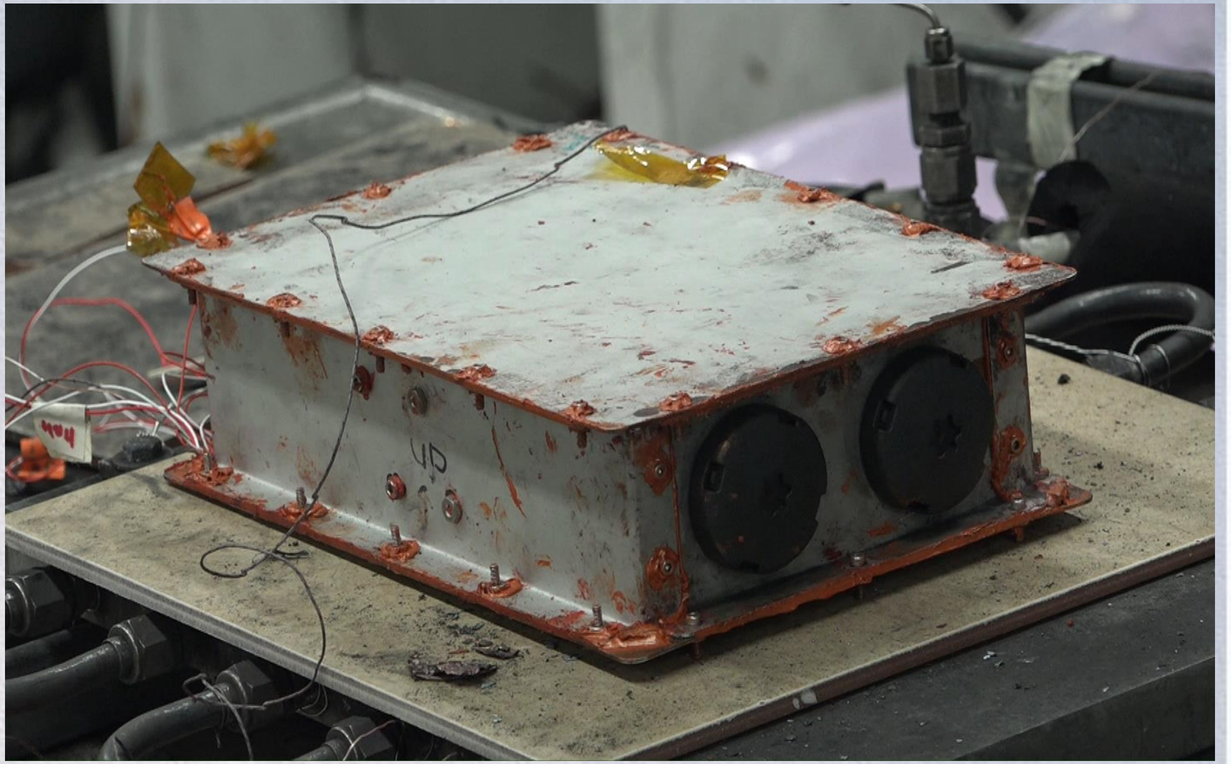
2 low pressure Gore vent ports backed by Steel screens, Cu mesh, and Al baffles

Zircar RS-200 1/16” thk
Protecting 6061-T6 Al 1/16” thk

Flame Arresting Vent Port Testing

Top and bottom panels 0.062” thk Al lined with 1/16” RS-200 Zircar

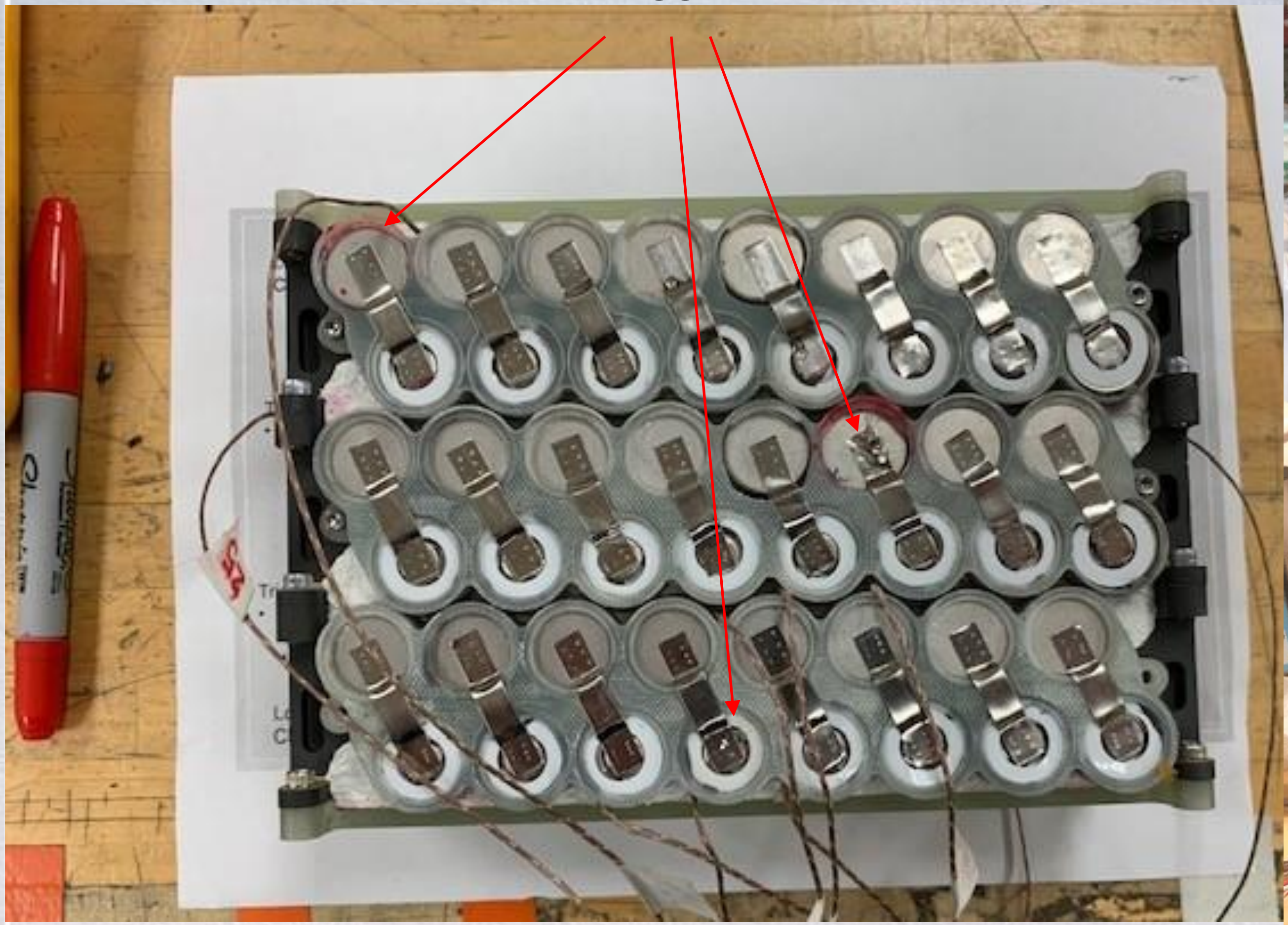


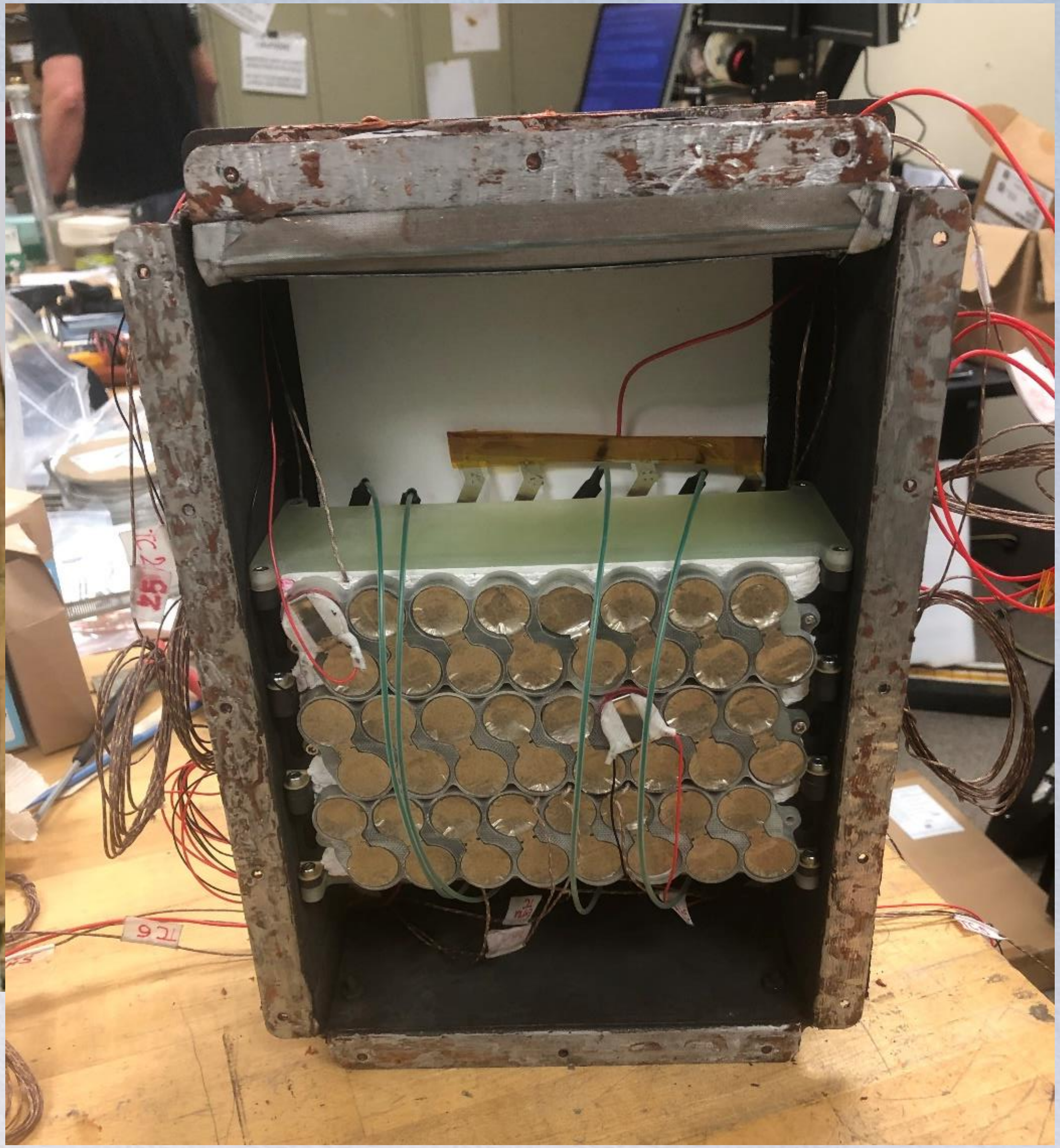


6 tests completed with no exiting flames

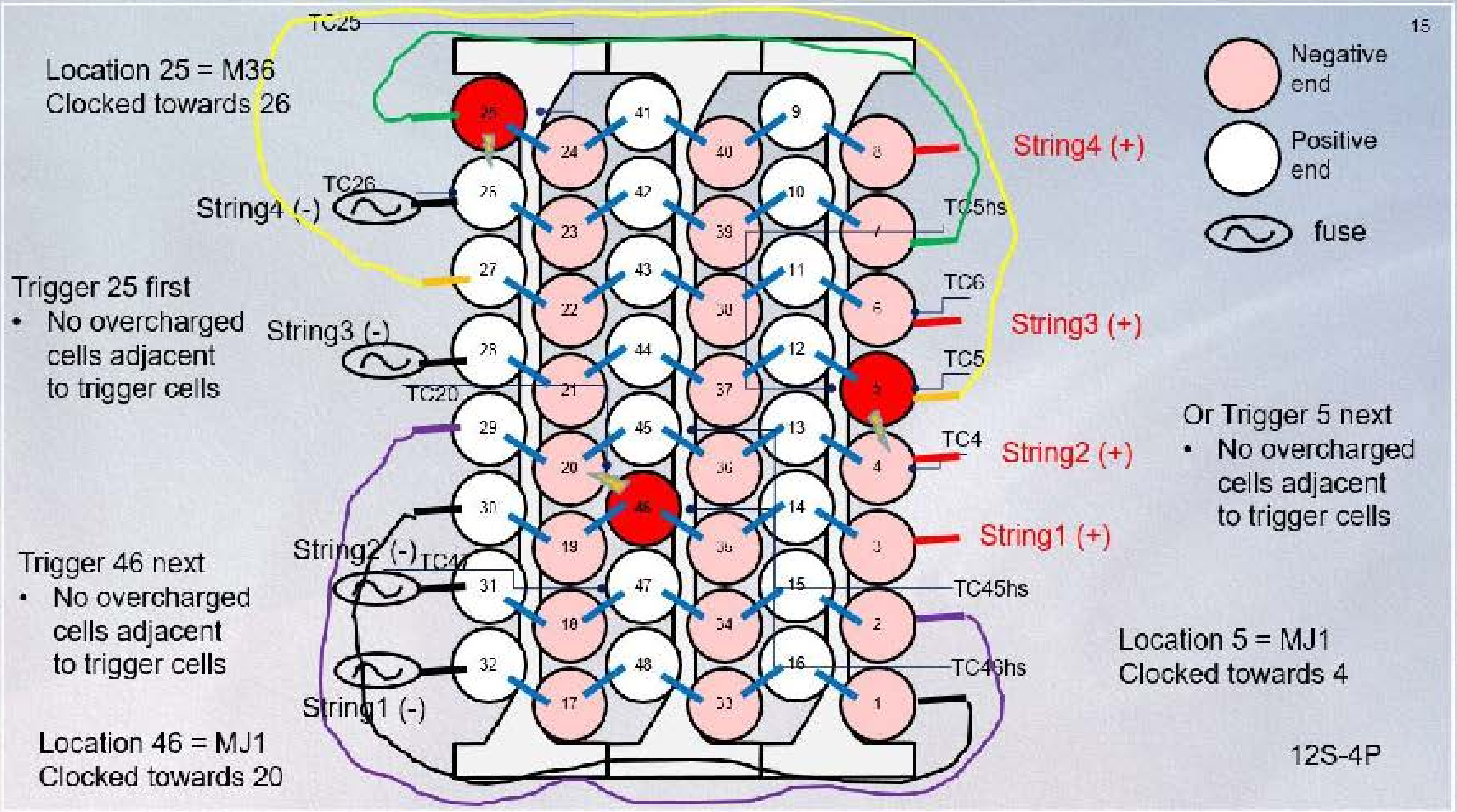
48-cell Assembly Next on Deck for PPR Testing

Trigger cells





48 cell sub-scale assembly map



48-cell subscale PPR Test 1 – Corner Trigger Cell

Zircar RS200 liner protecting the top and bottom Al panels

Post Test Examination – Corner Trigger Cell

Trigger cell

- Al 6061T6 0.031” thick panel lined with 1/16” thick RS200

No propagation of TR but adjacent cell may be damaged

48-cell subscale PPR Test 2 – Interior Trigger Cell

Kaowool material on top and bottom panels

Post Test Examination – Interior Trigger Cell

Kaowool material appears to have absorbed impact of cell ejecta successfully without perforation of the 1/32” panel underneath. Kaowool on bottom panel was intact.

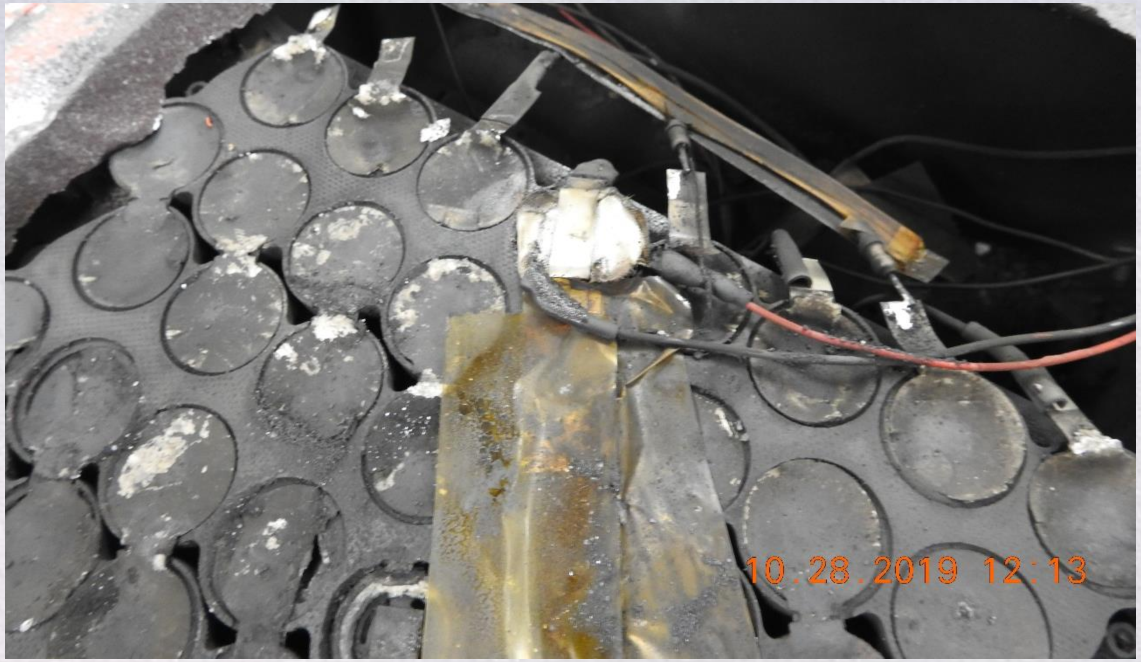
48-cell subscale PPR Test 3 – Edge Trigger Cell

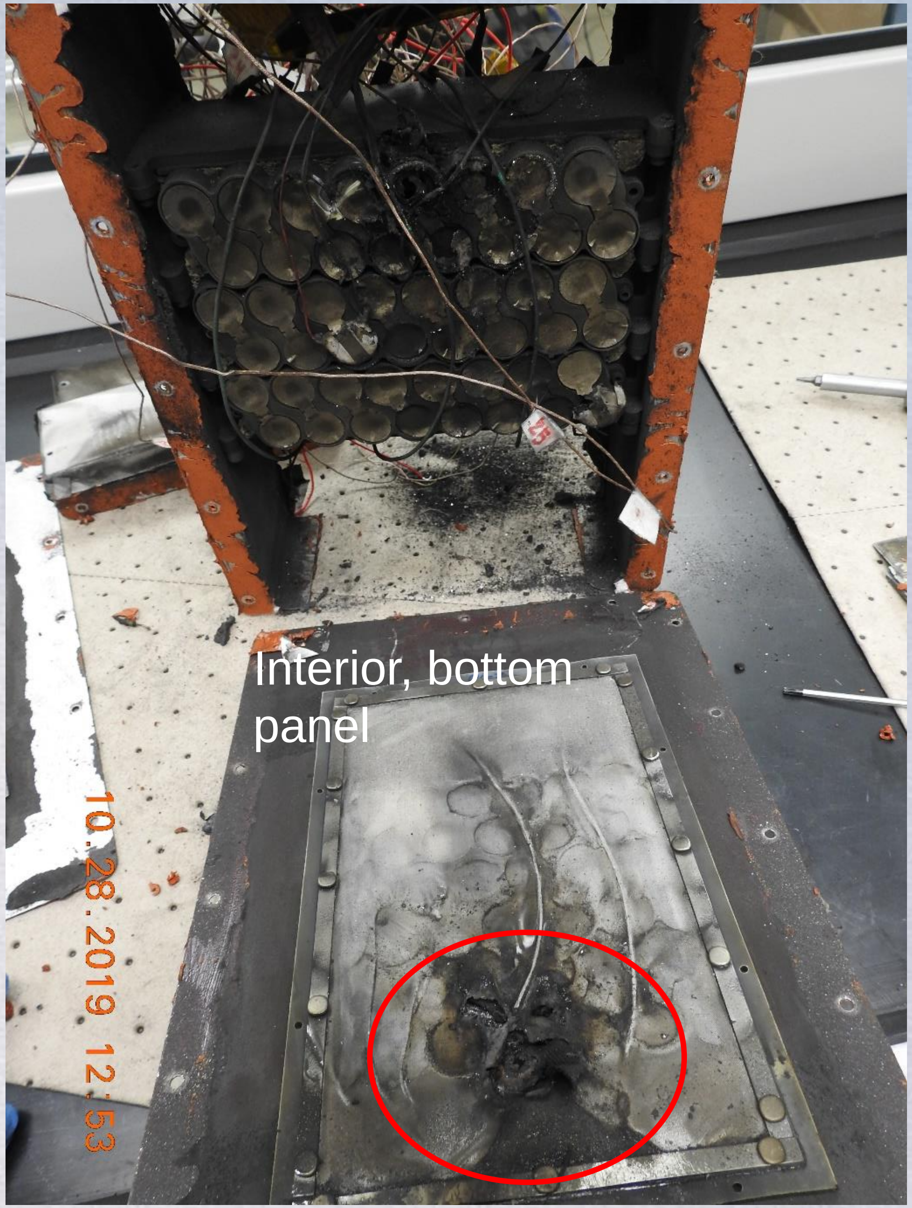
KULR TR Shields on top and bottom panels

Post Test Examination – Edge Trigger Cell

Although the top panel remained intact, the KULR panel on the bottom panel was perforated during TR of Cell 5.

This created a small hole in the bottom 1/32” panel.





Summary

- Take Away Messages
  - Safe, high power battery designs that achieve > 160 Wh/kg are predicted with
    - A high performing commercial high power 18650 cell design
    - Vulnerable spin groove of cell protected by steel ring
    - A high flux, lightweight oscillating heat pipe technolog
      - Small (60º) cell contact angle with heat sink
    - Remaining cell surfaces insulated and supported by ceramic putty
  - Subscale verification shows great promise
    - 5 single cell TR tests with no propagation
    - Light weight layering can prevent perforation of thin (1/32” thk) Al
    - Flame arresting vent port demonstrated
  - Verification testing will be completed by year end
    - 6 more full scale PPR tests
    - 3C discharge and vibration at full scale tests

- Acknowledgements
  - C. Iannello, NASA Engineering Safety Center for funding the task