Recent Developments in Safe Lithium Ion Battery Design for Human Space Flight

UCSD NANO/CENG Seminar

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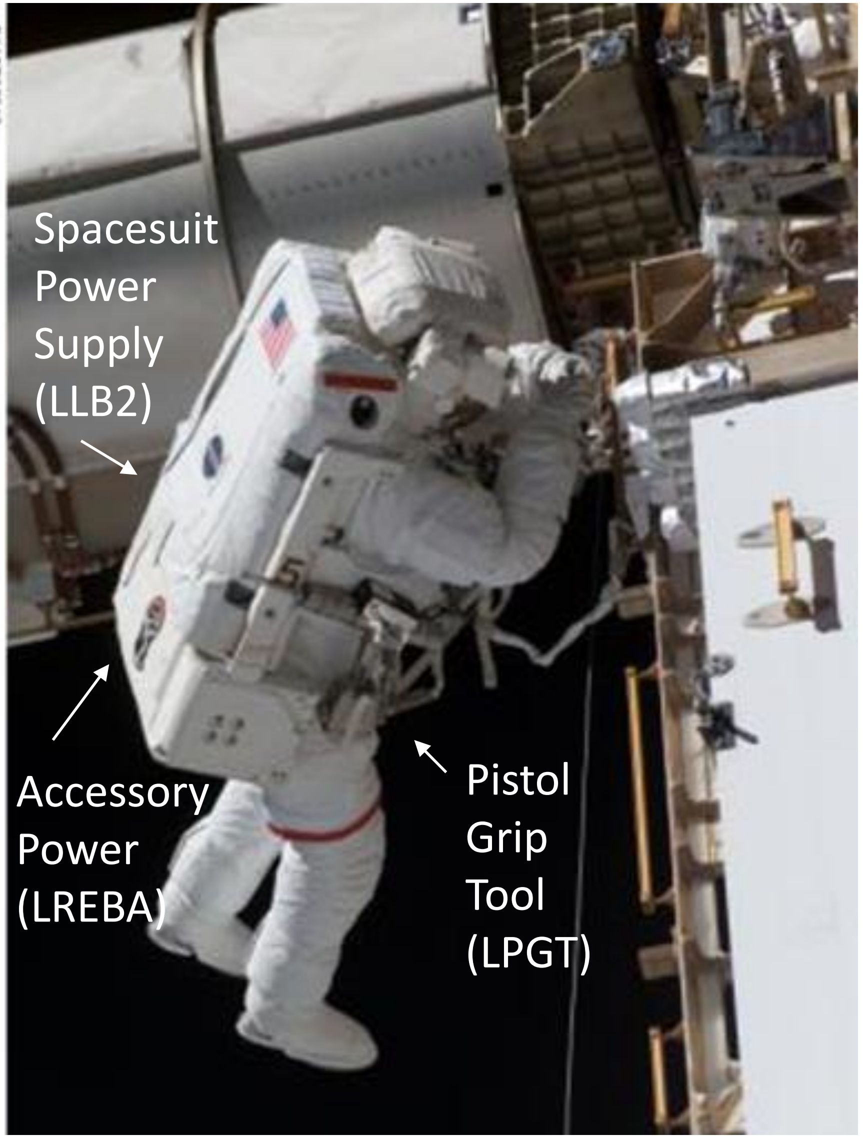
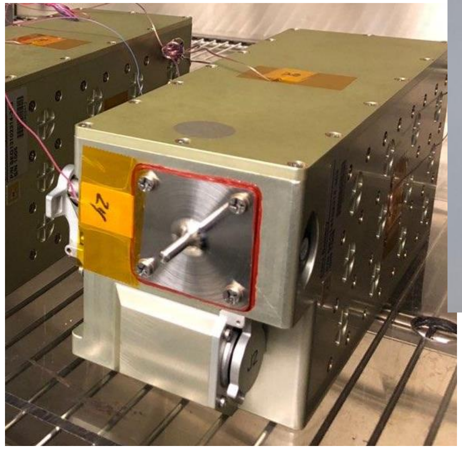
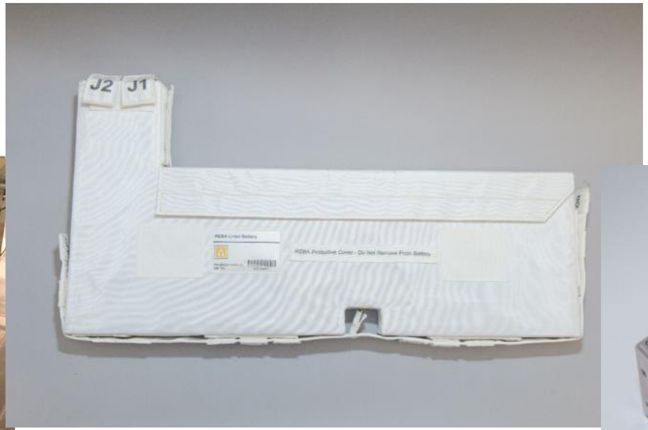
Lithium Ion Power on NASA's Spacesuit



LLB2





LREBA

LPGT

Battery Characteristic	LLB2	LREBA	LPGT
Cell Type	18650	18650	18650
Cell Rated Capacity (Ah)	2.60	2.60	2.60
Battery Topology	14P-5S	9P-5S	2P-5S
Battery Operating Voltage Range (V)	15.5 - 20.5	15.5 - 20.5, 13.5	15.5 - 20.5
Battery Capacity (Ah)	36.40	23.4, 16.38	5.20
Battery Specific Energy (Wh/kg)	98.88	96.20	85.13
Battery Energy Density (Wh/L)	182.99	111.86	79.50
Operating Temperature Range (°C)	0 to 45°C discharge	3 to 56°C	EVA sink 234F

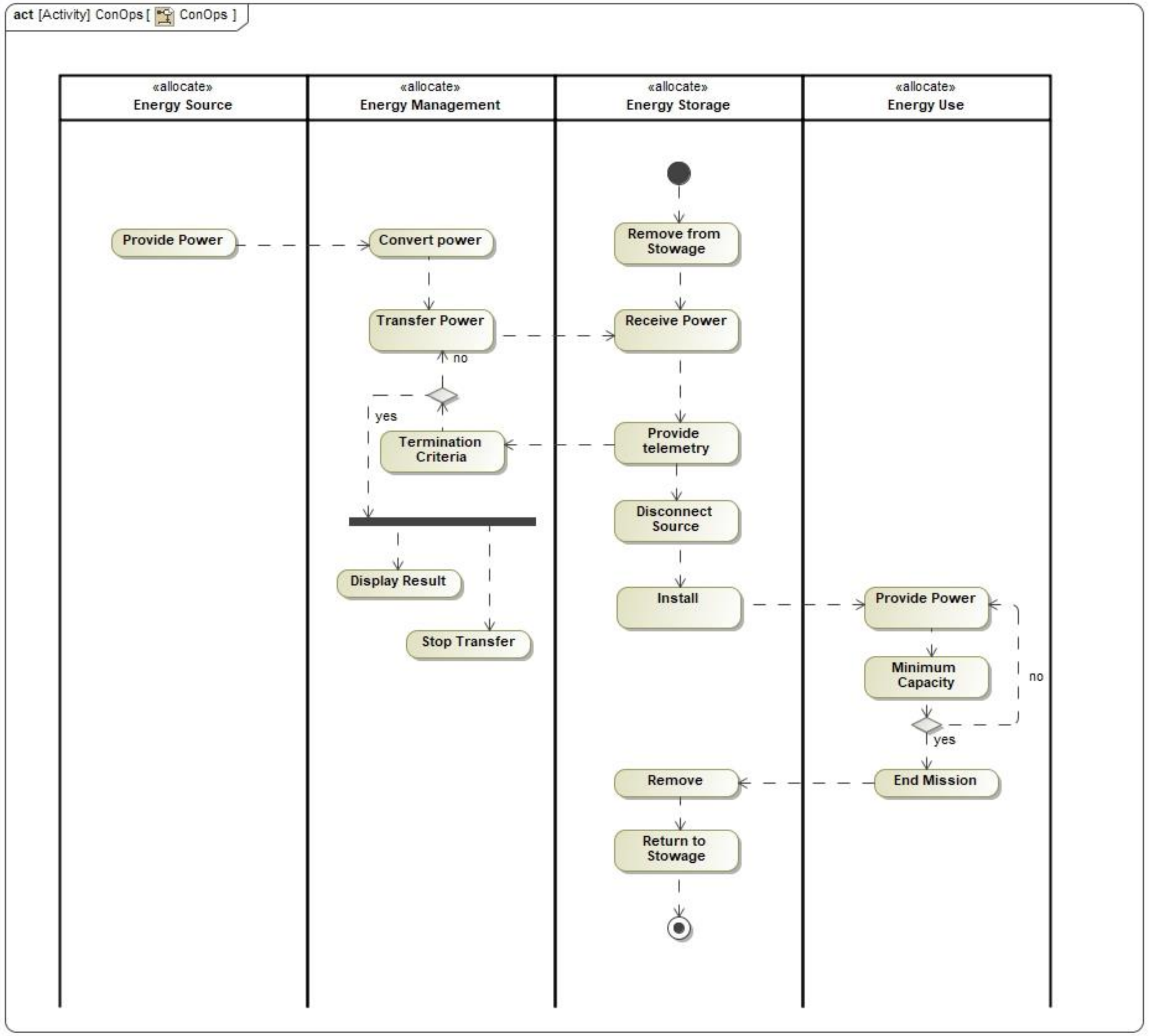
EVA Battery Concept of Operation

ConOps is common for EVA Batteries

- Designed to survive abuse
- Receive charge from dedicated charger
- Charger is designed to prevent abuse
- Service in pressurized environment
- Installed in thermally managed location
- Discharge at vacuum conditions
- Removed and stowed when not in use

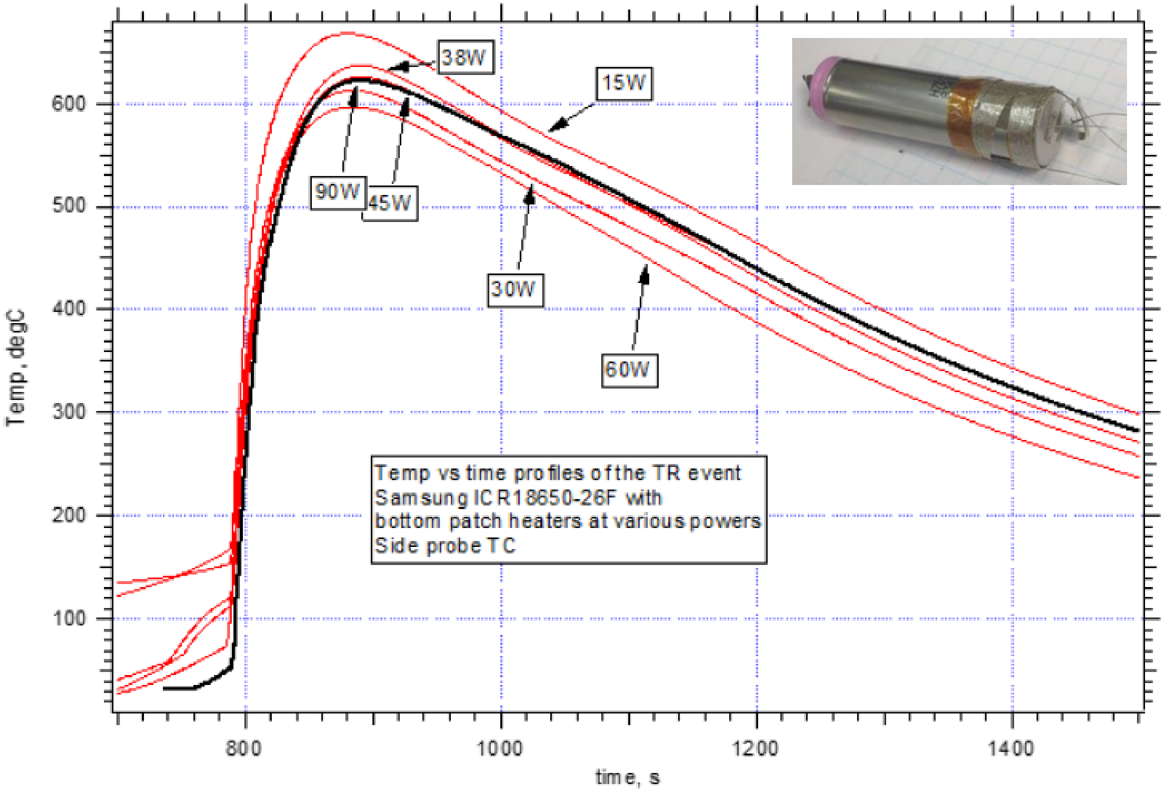
Allocating charge protection functions to the charger, and manifesting spare batteries, maximizes mission reliability

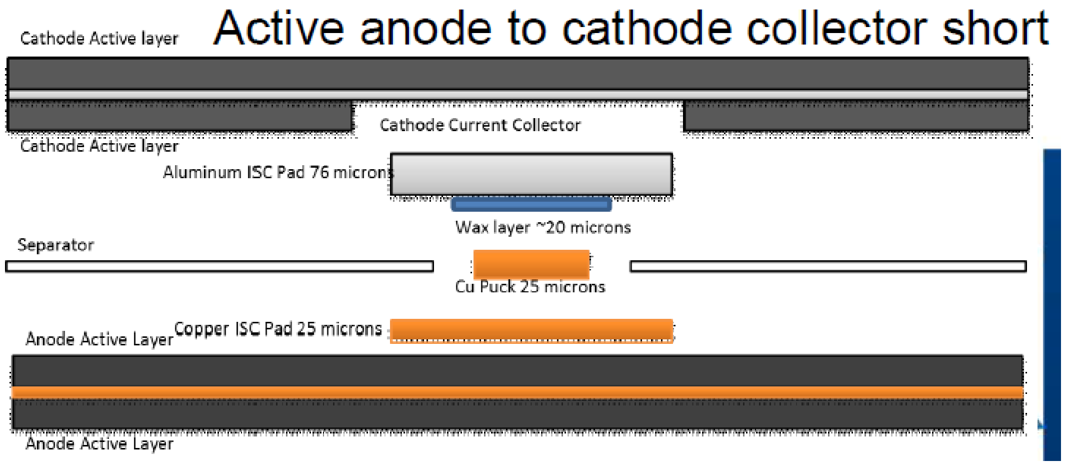
Rigorously managing stowage SOC has enabled 7+ years of continued use with >95% capacity retention when operating between 3.1-4.1V per cell over ~25 cycles

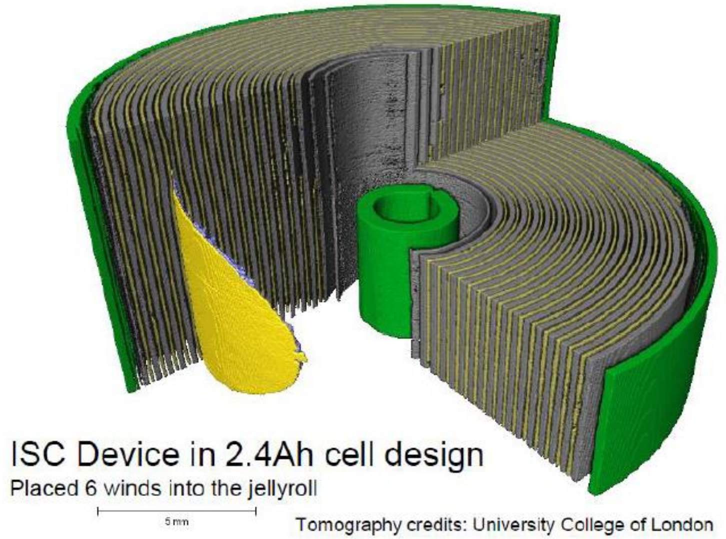


Initiating Thermal Runaway in a Li-Ion Battery

Initiating TR requires separator failure.
Internal Short Circuit device improves failure fidelity and reduces thermal bias compared to a patch heater.





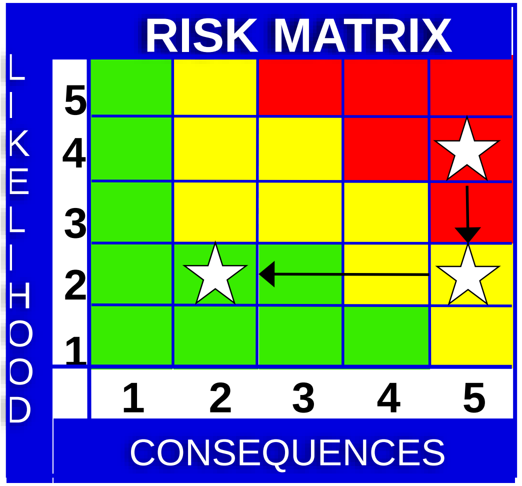


Iannello, C., et al, Assessment of ISS/EVA Li-Ion Battery TR Severity Reduction Measures, NASA/TM-2017-219649, July 2017

Preventing Propagation Improves Battery Safety

Conventional battery design methods failed catastrophically due to single cell thermal runaway event.
Failure event continued for up to 20 minutes, resulting in uncontrolled release of combustion products and case temperatures in excess of 250°C.

DESIGN STRATEGY



Risk values are notional

Screening reduces failure probability.
Preventing propagation reduces failure consequence.

Failure images from: Iannello, C., et al, NASA/TM-2017-219649, July 2017

Passive Propagation Resistance Design Guidelines

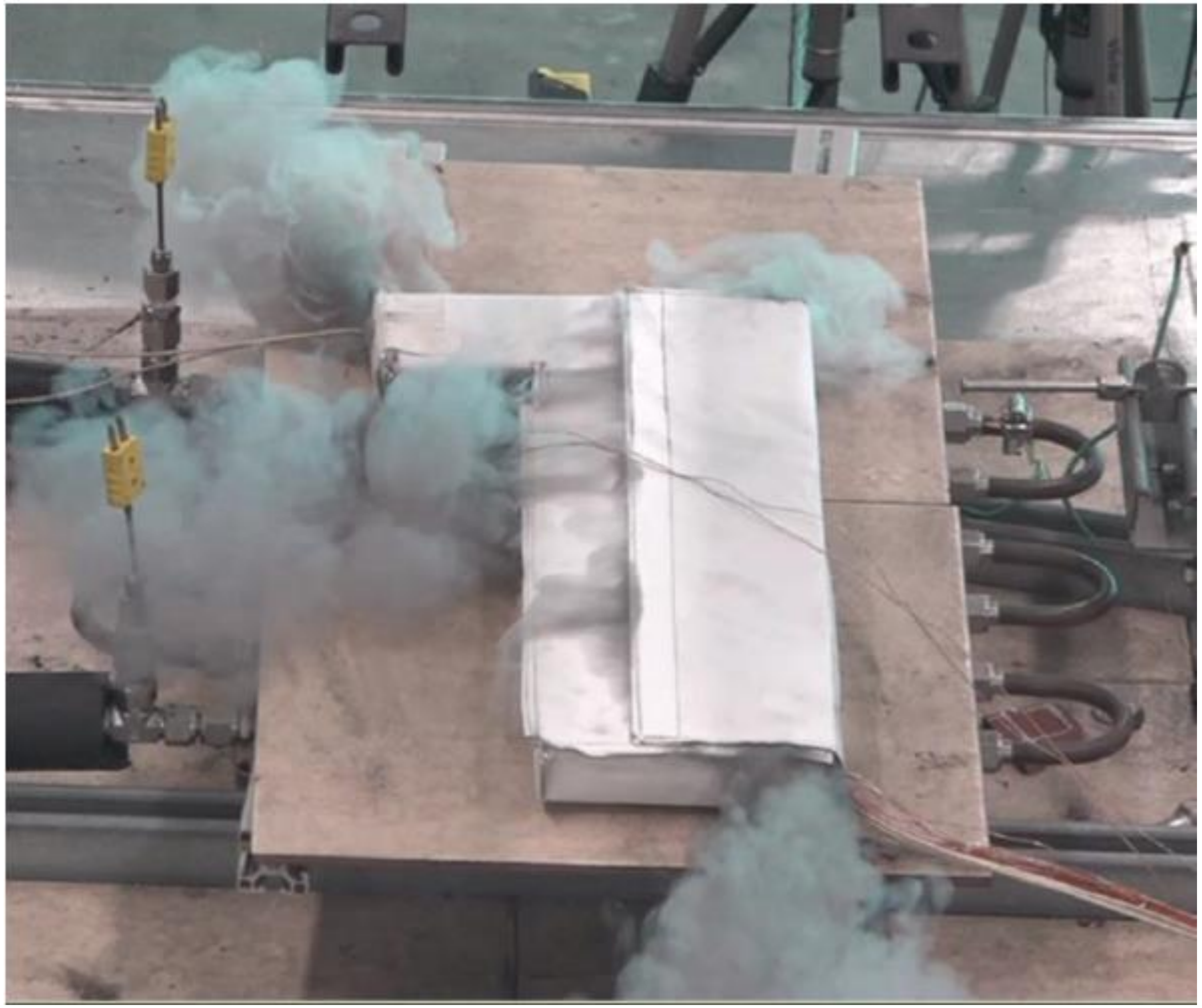
30

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

Darcy, E., Safe, High Performing Battery Designs, Battery Technology and Safety for Crewed Space Applications, Mar 2017

Redesigned to Prevent Propagation, LREBA



Propagation Resistant EVA Battery Pathfinder

- Separating cells reduced direct thermal transfer
- Fusing cell interconnect prevents circulating current between parallel cells
- Overboard vent prevents direct exposure to high energy ejecta
- Reinforced garment direct effluent over large housing surfaces

- Max Adjacent Cell Temp: 120^{o}C
- Max case temp: ~60^{o}C
- Max garment external temp: 21^{o}C

Iannello, C., et al, Assessment of ISS/EVA Li-Ion Battery TR Severity Reduction Measures, NASA/TM-2017-219649, July 2017

Redesigned to Prevent Propagation, LPGT

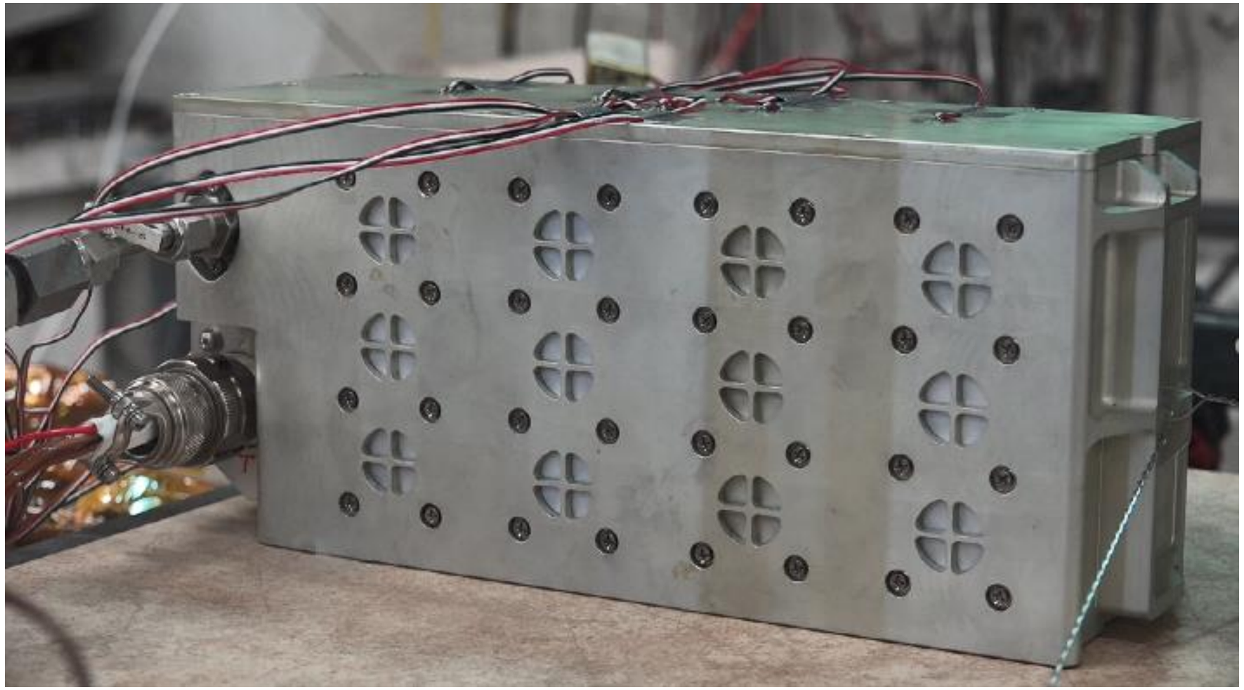
Lowest Volume EVA Battery

- Separating cells reduced direct thermal transfer
- Fusing cell interconnect prevents circulating current between parallel cells
- Ejecta flow path tortuosity reduces thermal and kinetic energy
- Screened vents prevent spark/flame release

- Max Adjacent Cell Temp: 110^{o}C
- Max case temp: ~50^{o}C

Iannello, C., et al, Assessment of ISS/EVA Li-Ion Battery TR Severity Reduction Measures, NASA/TM-2017-219649, July 2017

Redesigned to Prevent Propagation, LLB

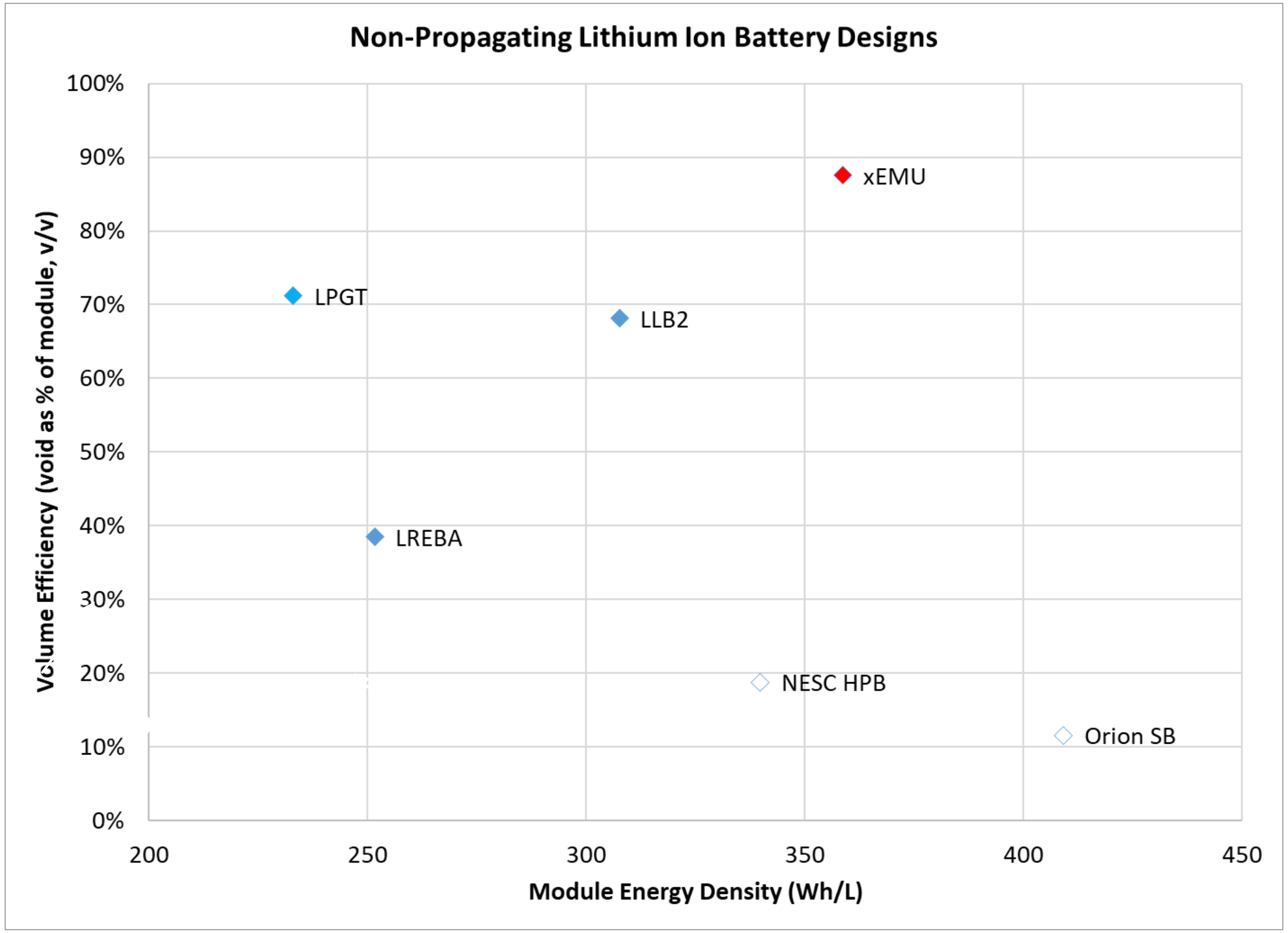


Most Dense EVA Battery
- Separating cells reduced direct thermal transfer
- Rate limited heat spreader dispersed heat across all cells
- Fusing cell interconnect prevents circulating current between parallel cells
- Ejecta flow path tortuosity reduces thermal and kinetic energy
- Screened vents prevent spark/flame release
- Filtered vents reduce particulate release

- Max Adjacent Cell Temp: 80^{o}C
- Max case temp: 40^{o}C

Iannello, C., et al, Assessment of ISS/EVA Li-Ion Battery TR Severity Reduction Measures, NASA/TM-2017-219649, July 2017

Non-Propagating Batteries Designed by NASA JSC



Volume Efficiency = $\eta_V = 1 - \frac{V_{Void}}{V_{Void}+V_{Module}}$

Plot compares volumetric efficiency and energy density of propagation resistant batteries.

Unlike the EVA batteries, the open symbol designs have a much greater specific energy density, but are significantly larger resulting in more void volume for ejecta management but a greater demand for active cooling.

The xEMU battery is pushing the limit on void volume.

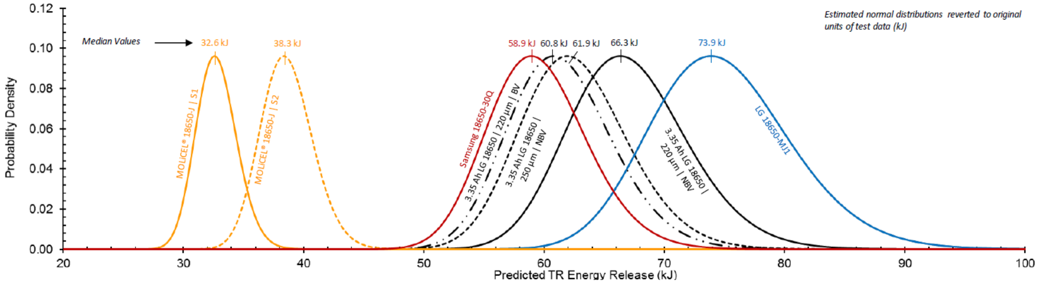
xEMU Cell Selection

Cell selected based on energy available at mission rate, cycle life, and heat release during TR.

CANDIDATE CELLS AT BEGINNING OF LIFE (BOL)

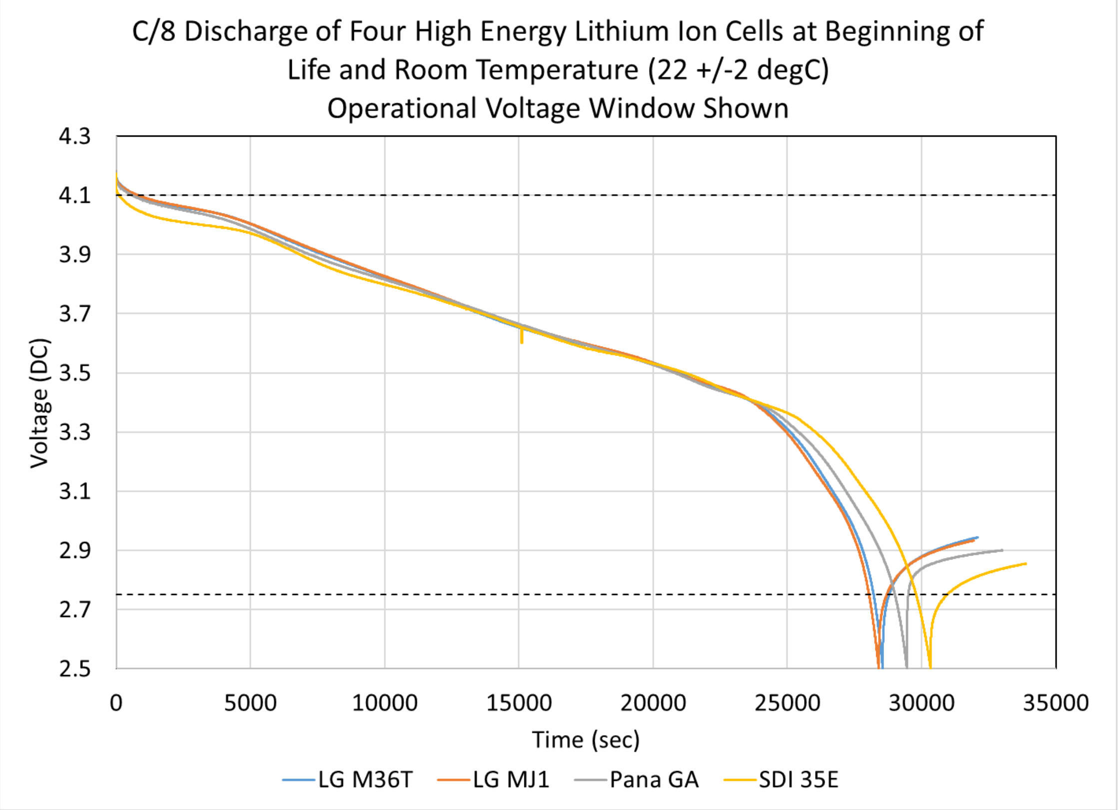
Cell	Datasheet (Ah/Wh)	C/8 Discharge (Ah/Wh)	TR Energy (kJ)
LG Chem INR18650 MJ1	3.5/12.7	3.1/11.2	75/62
LG Chem INR18650 M36T	3.4/12.5	3.1/11.3	65
Panasonic NCR-18650GA	3.4/12.4	3.2/11.6	~65
Samsung INR18650-35E	3.4/12.4	3.3/12.1	~55

FRACTIONAL TR CALORIMETER SAMPLE DATA



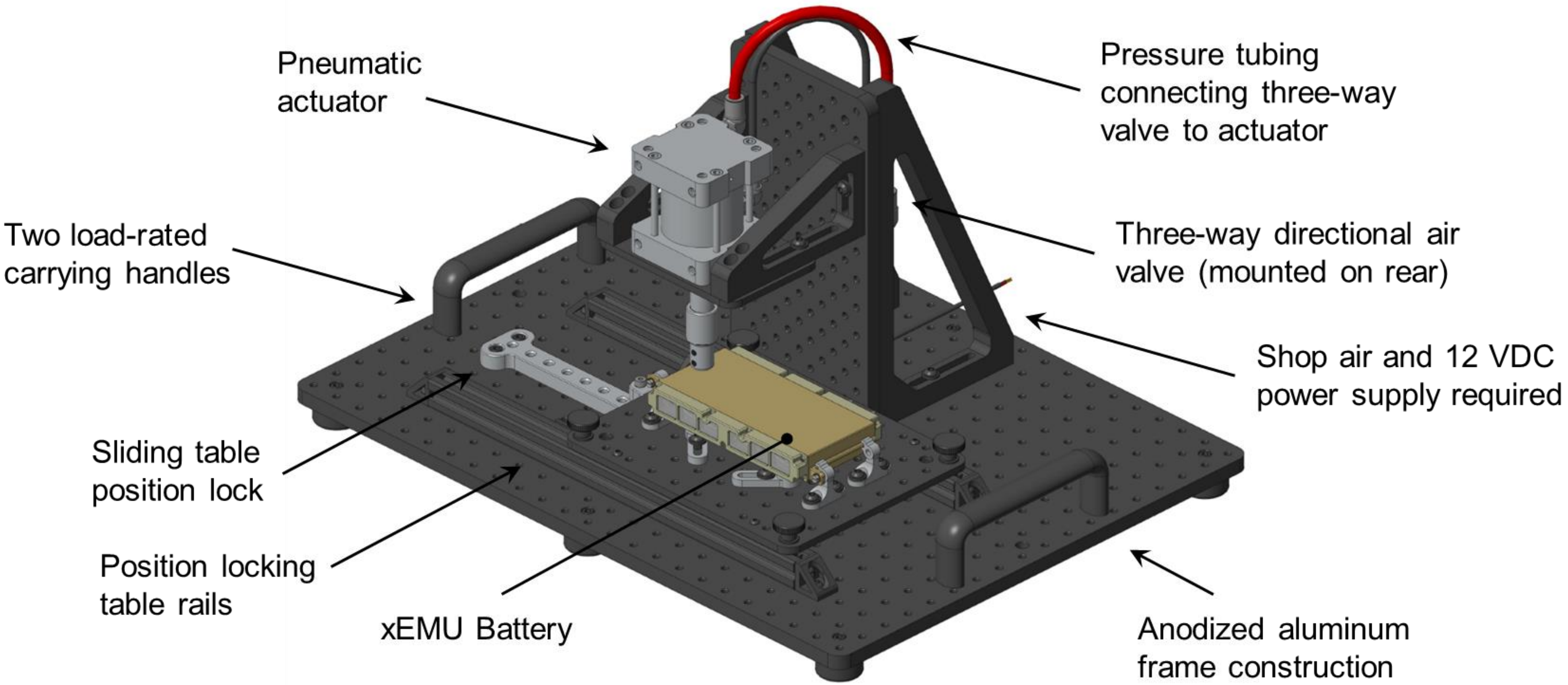
Walker, W., et al. Journal of Power Sources 2019: 207-218

MISSION RATE CONSTANT CURRENT DISCHARGE PERFORMANCE



Low Cost, Quick Turn TR Test System

A nail pin test rig was designed and assembled to reduce ISC consumption and improve test turn-around time.
Final design will be tested with ISC-implanted trigger cell.

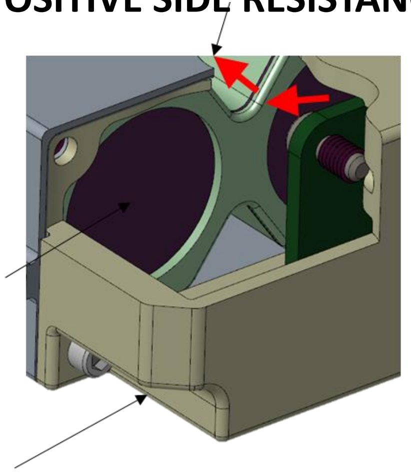


Credit: David Petrushenko, Spring/Summer 2020

Considered Location of Flow Resistance

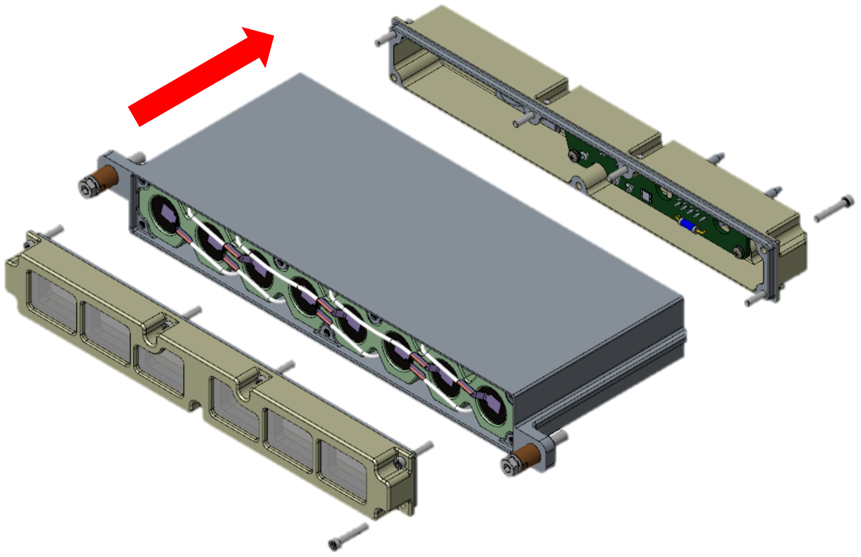
Design has survived multiple sidewall ruptures and over 20 TR events without propagation, but expelling particulate could be problematic in the intended application.

POSITIVE SIDE RESISTANCE



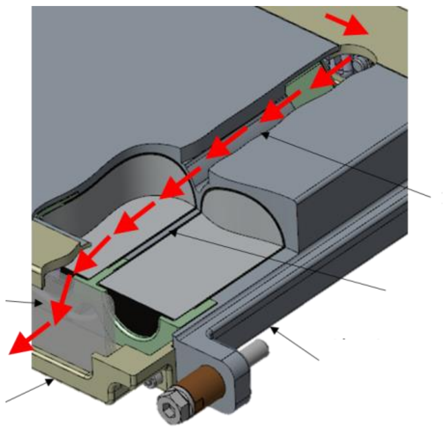
Options Considered:
- Baffle
- No Baffle

CELL ORIENTED FOR LONGEST VENT FLOW PATH



While some analysis has been performed, results are primarily evaluated qualitatively

NEGATIVE SIDE RESISTANCE

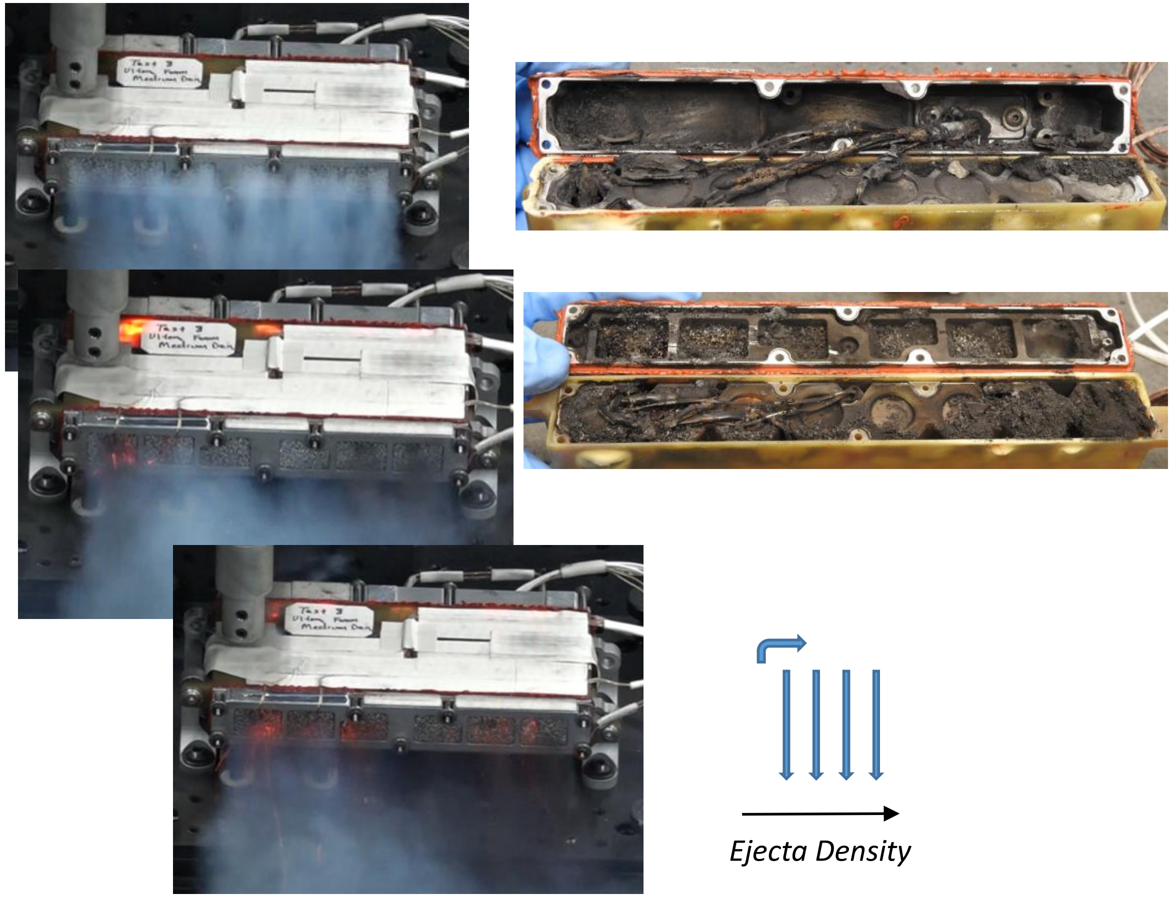


Options Considered:
- Baffle with Filler
- Baffle without Filler
- Two Foam Materials
- Various Foam Density

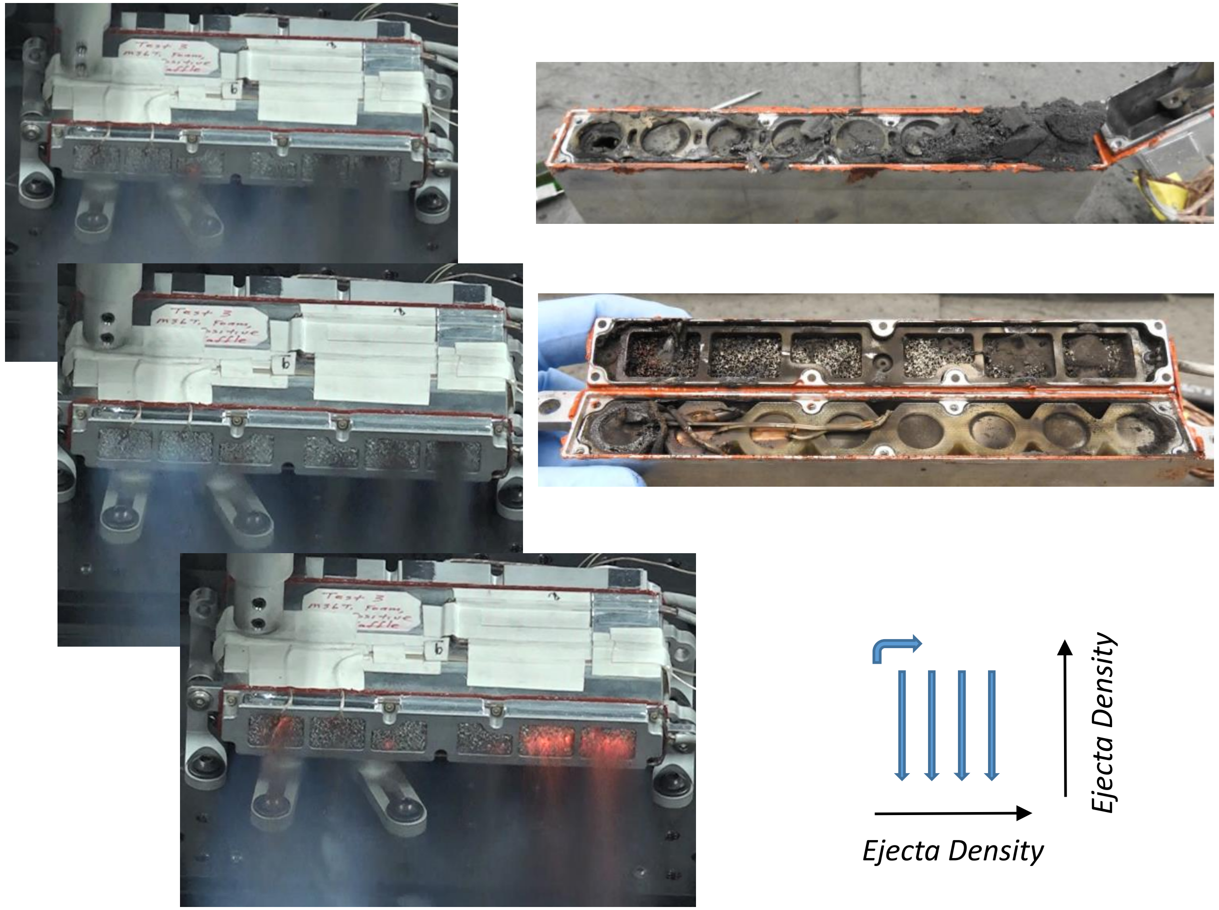
Effect of Upstream Resistance

Including upstream resistance reduces filtering efficiency of the foam, some sparks exit the housing.

NEGATIVE FOAM, NO POSITIVE BAFFLE



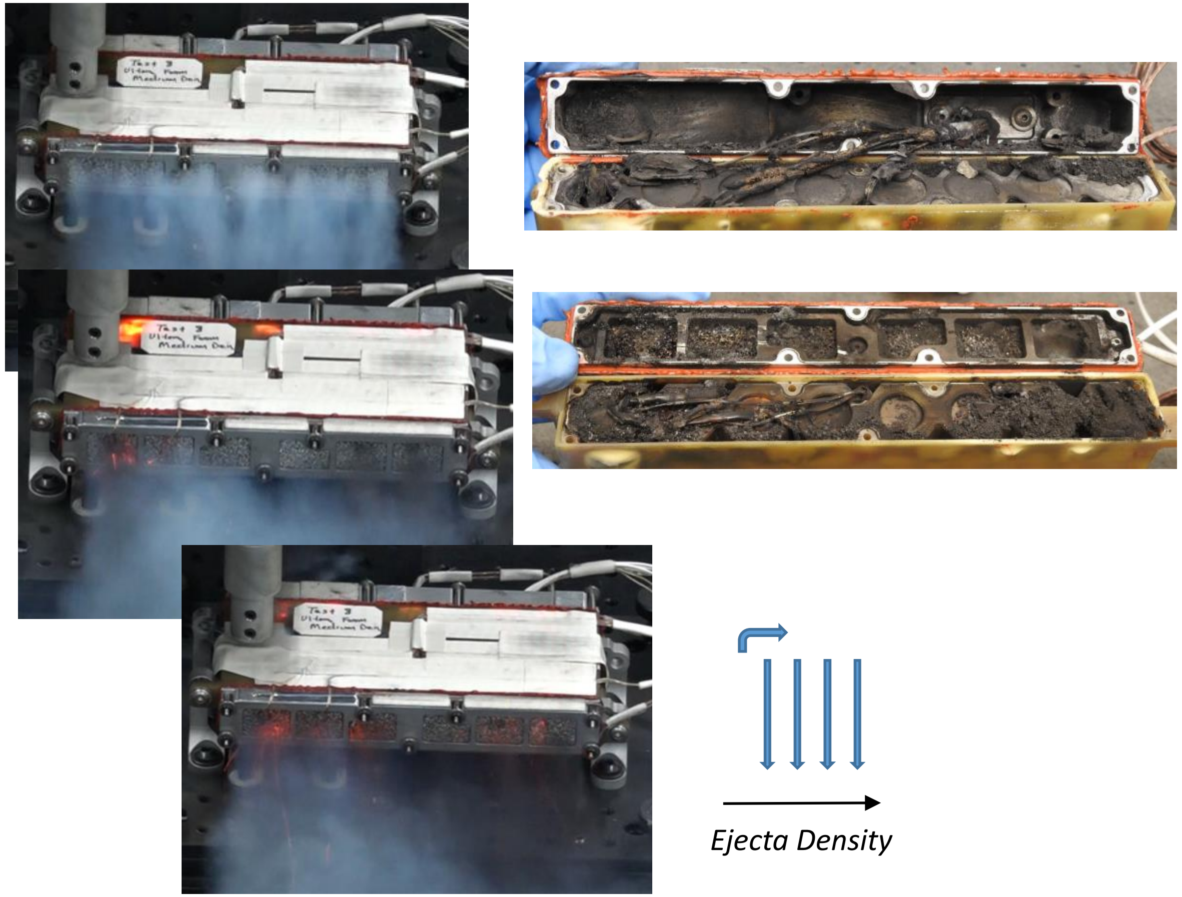
NEGATIVE FOAM, POSITIVE BAFFLE



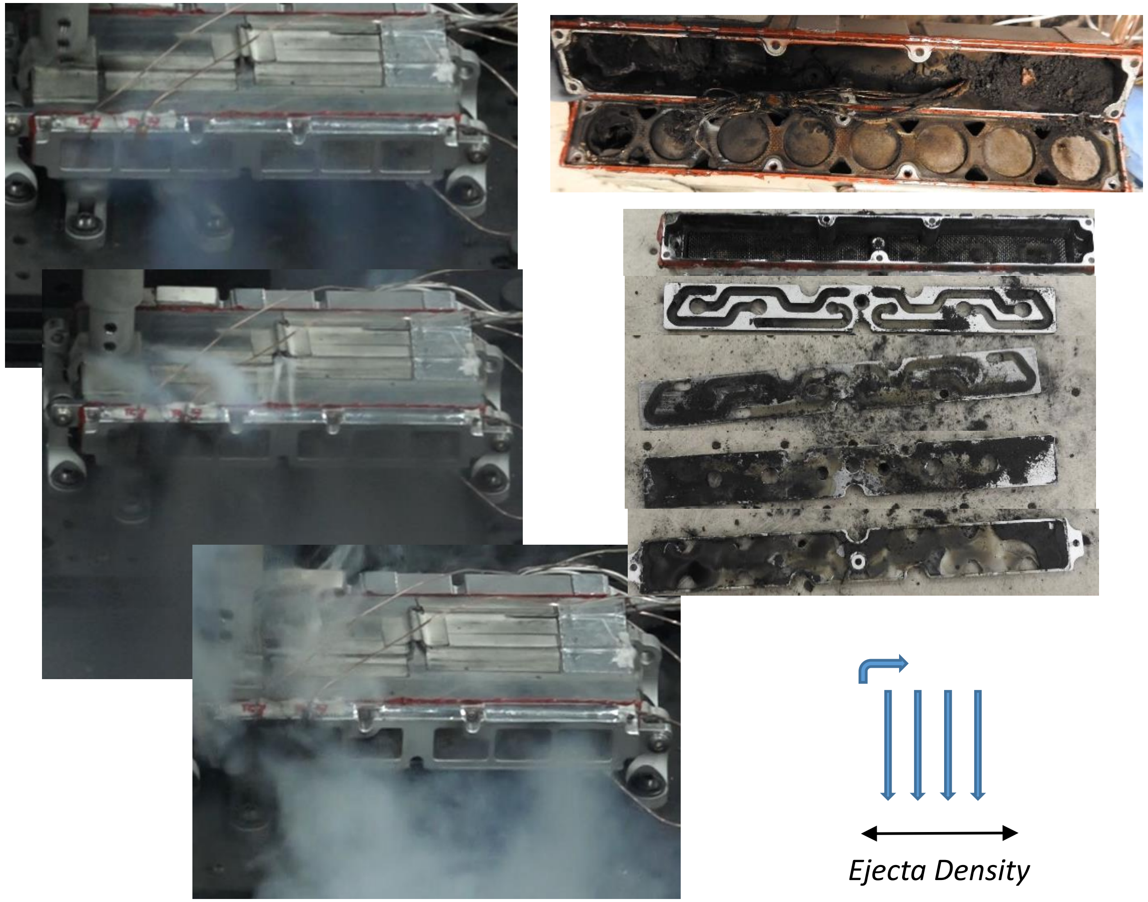
Effect of Downstream Resistance

Increasing downstream resistance improves spark retention but releases particulate.

NEGATIVE FOAM, NO POSITIVE BAFFLE



NEGATIVE BAFFLE, NO POSITIVE BAFFLE



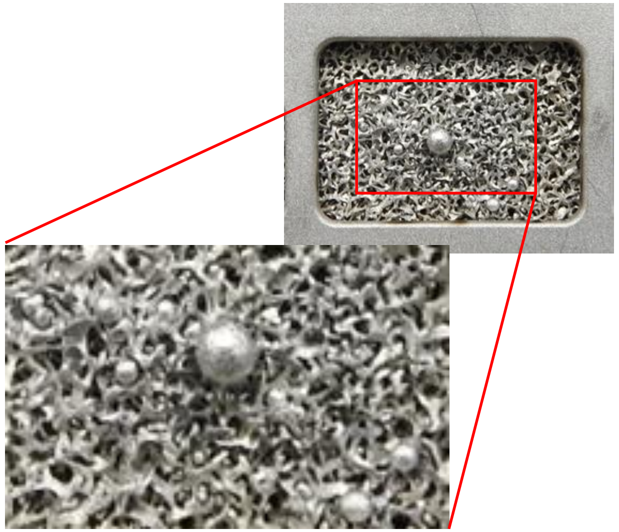
Interim Findings and Forward Work

Interim Findings

Finding 1. Allocating resistance over path length reduces particle retention
Finding 2. Filter media needs to tolerate ejecta exposure without melting

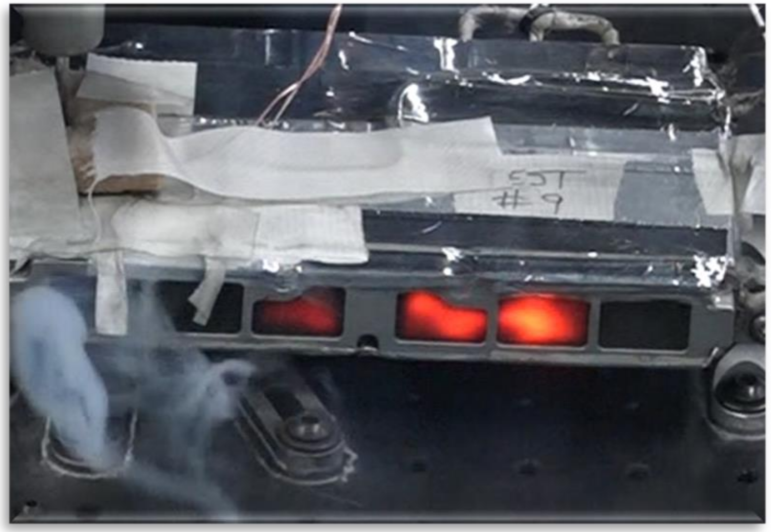
Sum R*	Neg Baffle	Neg Foam
Pos Baffle	1.82×10^{10}	2.72×10^{8}
Pos No Baffle	1.80×10^{10}	3.54×10^{7}

Selected material needs to tolerate high temperature and provide $R^* > 10^7$



Forward Work / Results

- Develop a high temperature tolerant, light weight 'depth filter'
- Establish upper limit for TR impulse for chosen material
- Ceramic material appears promising but requires impact protection



Acknowledgements and Questions?

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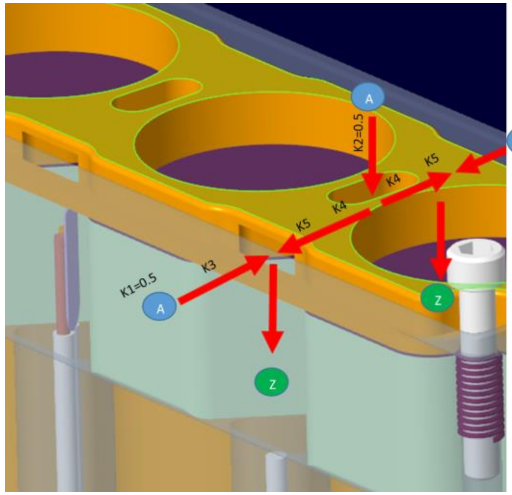
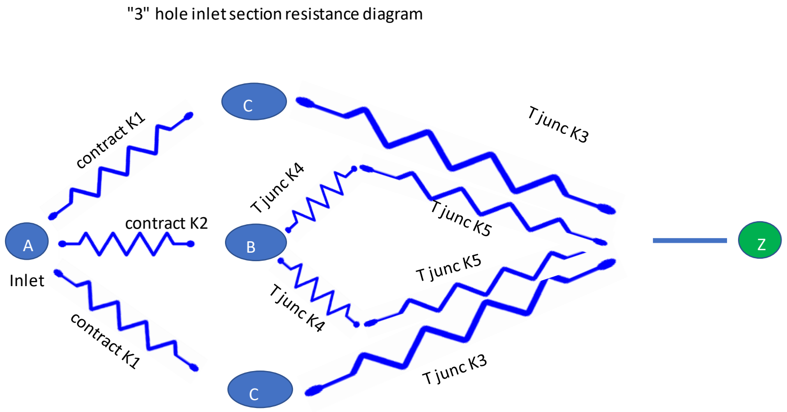
Special thanks to **Eric Darcy, James Rogers, Bob Bohot, and the EVA Battery GFE Team**/NASA JSC, **David Petrushenko**/Univ. South Carolina, **Zoran Bilc**/NASA JSC, and the **ESTA Test Team**, including Yaramy Trevino, Dereck Lenoir, Nhi Hua, Tony Randall, Oscar Huerta, Adan Garza, and many others. Thanks also to **Chris Iannello, Gary Bales**, Steve Rickman and the PPR Development Team/NASA NESC, Jacob Darst and David Delafuente/NASA JSC, the xEMU PLSS leadership team, Colin Campbell, Carly Meginnis, and Erika Jimenez/NASA JSC.

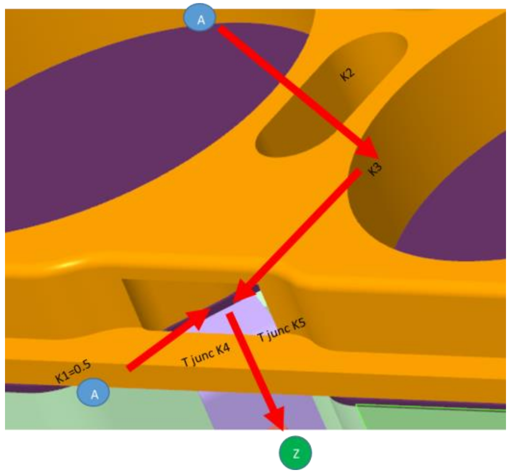
Positive Side Resistance Estimation

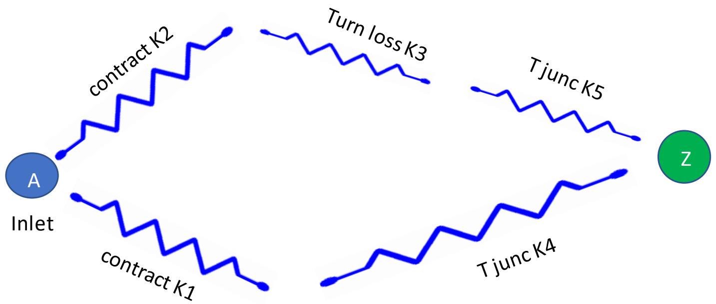
Effective resistance, with baffle





Effective resistance, without baffle





Assuming smooth pipe, turbulent flow:

$$\dot{m} = \rho\, \dot{V} = \frac{\dot{V}}{v} = \rho\, A\, \vec{V} = \frac{A\, \vec{V}}{v}$$

where: $\dot{m}$ is the mass flow rate $\left[\mathrm{kg}/\mathrm{s}\right]$

$\dot{V}$ is the volumetric flow rate $\left[\mathrm{m}^3/\mathrm{s}\right]$

ρ is the density $\left[\mathrm{kg}/\mathrm{m}^3\right]$, v is the specific volume $\left[\mathrm{m}^3/\mathrm{kg}\right]$

$\vec{V}$ is the velocity $\left[\mathrm{m}/\mathrm{s}\right]$, A is the flow area $\left[\mathrm{m}^2\right]$

For simple flow,

$$\Delta h = \Delta p/\rho g = f(l/D)(v^2/2g)$$

it follows that $\Delta h = R^* q_V^2$

$$R* = K\frac{\rho}{2A^2}$$

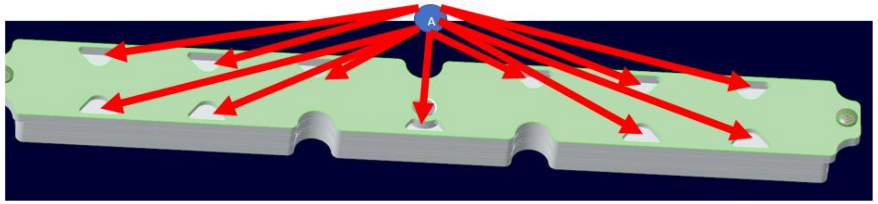
Effective resistance, assuming flow into each branch is equal,

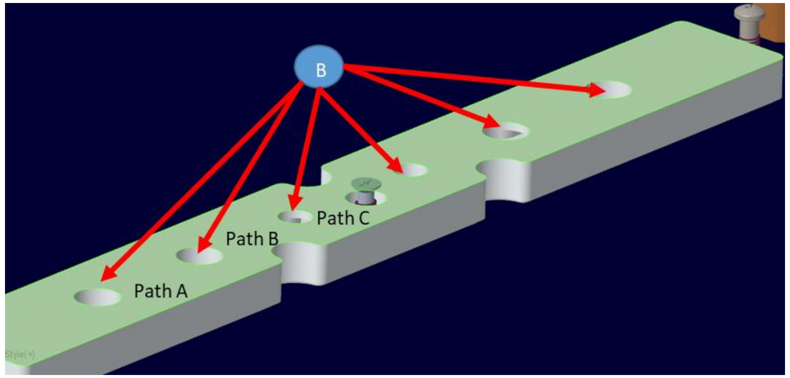
R* Baffle = 2.65x10^8 kg/m^7

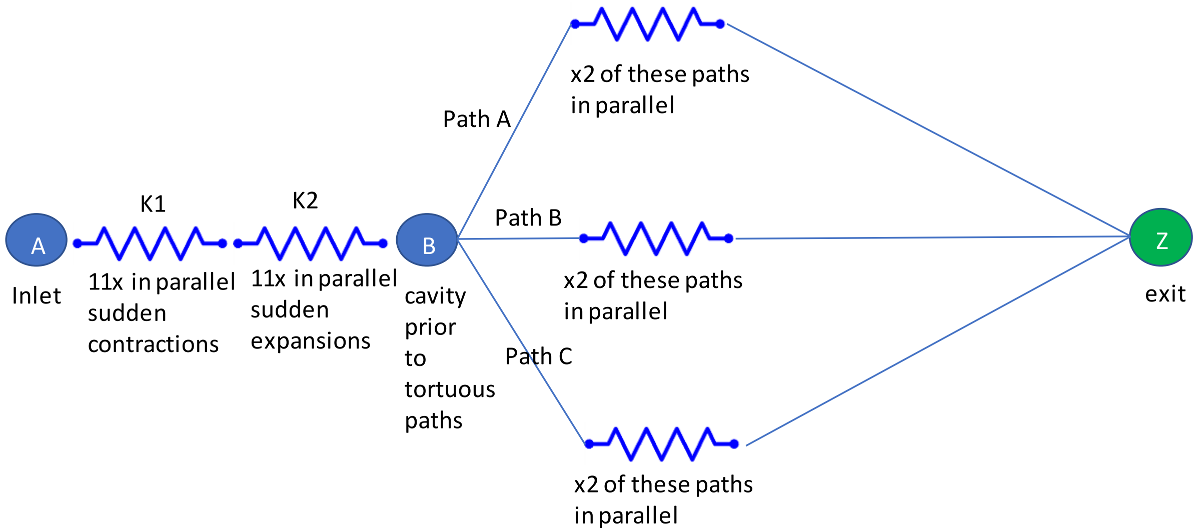
R* No Baffle = 2.80x10^7 kg/m^7

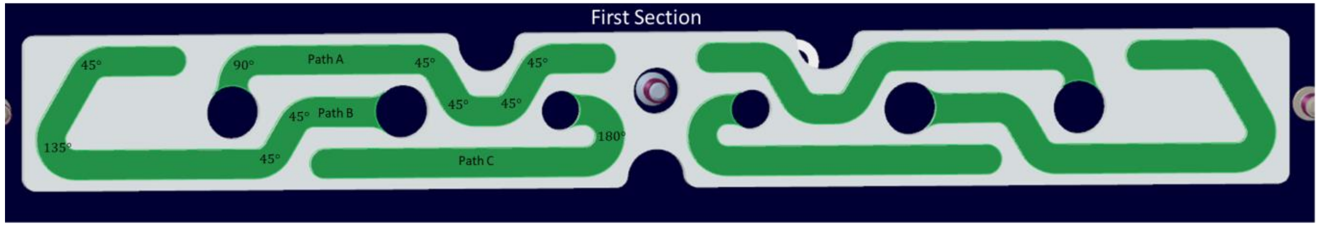
High Negative Side Resistance Estimation

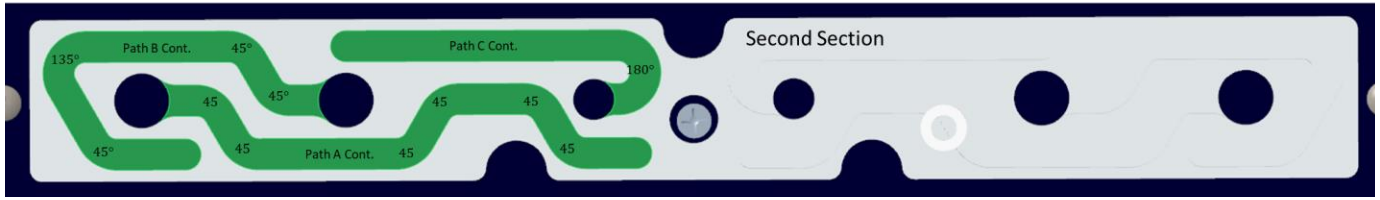
Effective resistance, negative baffle plate









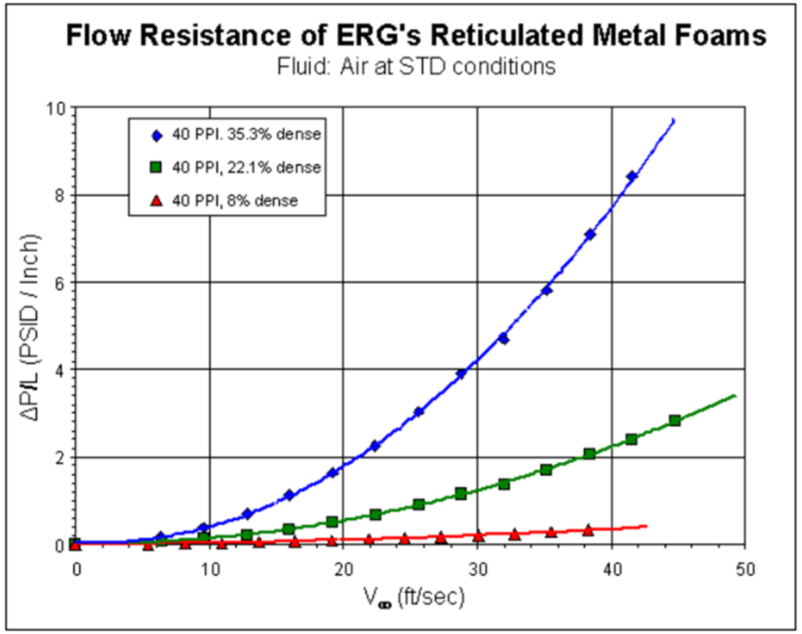


Effective resistance, assuming flow into each branch is equal,

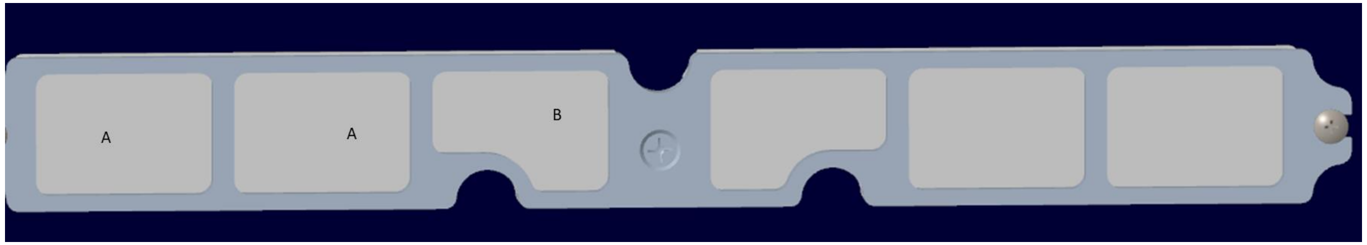
$R^* = 1.79 \times 10^{10}$ kg/m^7

Low Negative Side Resistance Estimation

Effective resistance, exit filter (aluminum foam)



http://ergaerospace.com/



Assuming max flow rate and air at STP

$$K = \frac{2 * \Delta P}{\rho v^2}$$

foam thickness (in)		0.12
foam thickness (m)		0.003048
gas velocity assumed (ft/s)		38
gas velocity assumed (m/s)		11.58
density assumed air STD (kg/m3)		1.22
Pressure drop at given velicty (Pa)		330
Calculated K factor for foam		4.034289

Effective resistance for 0.12in thick foam

R* = 7.43x10^6 kg/m^7

Resistance Estimate Summary

Sum R*	Neg Baffle	Neg Foam
Pos Baffle	$1.82x10^{10}$	$2.72x10^{8}$
Pos No Baffle	$1.80x10^{10}$	$3.54x10^{7}$

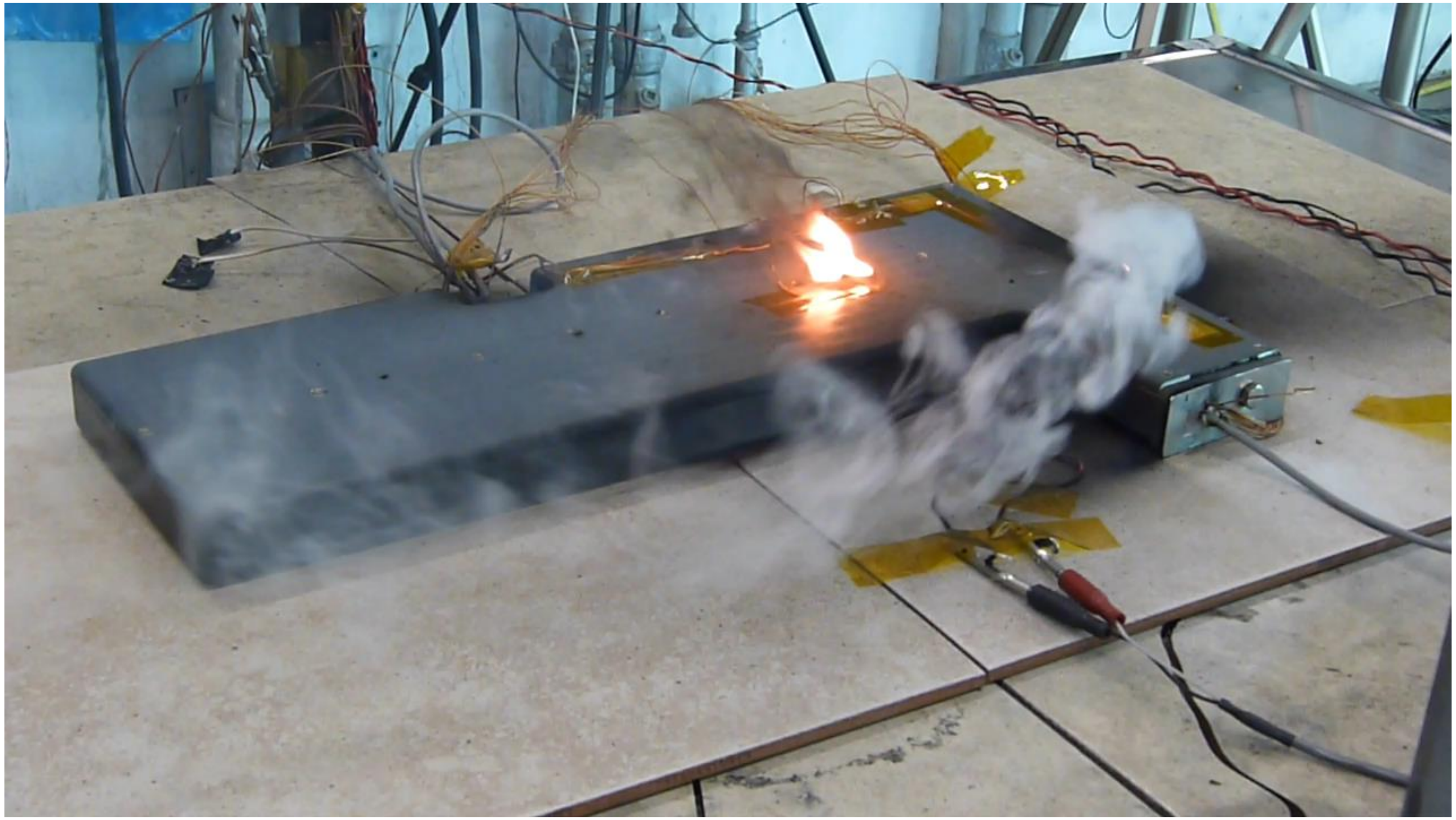
Selected material needs to tolerate high temperature and provide $R^{*}>10^{7}$

Test Videos

- LREBA, Run 1 – Baseline design, prior to implementing propagation prevention measures
- LLB2, Run 2 – flight design, ISC trigger cell
- xEMU, Run 3 – Restrictive Positive Side Baffle, Negative Side Foam Only
- xEMU, Run 8 – No Positive Restriction, Negative Side Foam Only, Ultem2300 Housing
- xEMU, Run 6 – No Positive Restriction, Negative Baffle Only
- xEMU, Run 9 - No Positive Restriction, Slightly thinner Negative Baffle Only

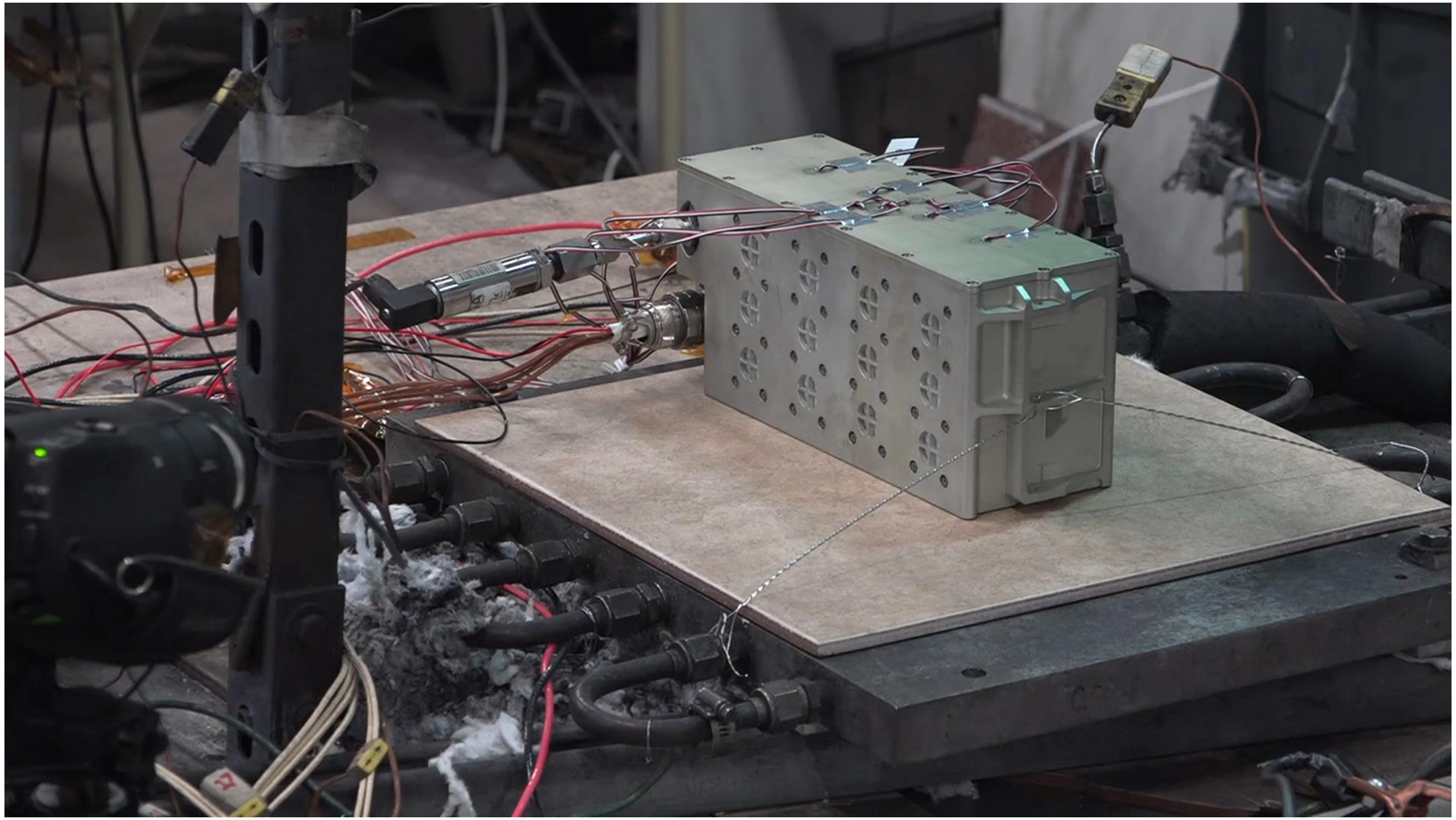
LREBA Baseline Design, Patch Heater, Run 1

This snippet was taken ~20min after trigger cell failure.



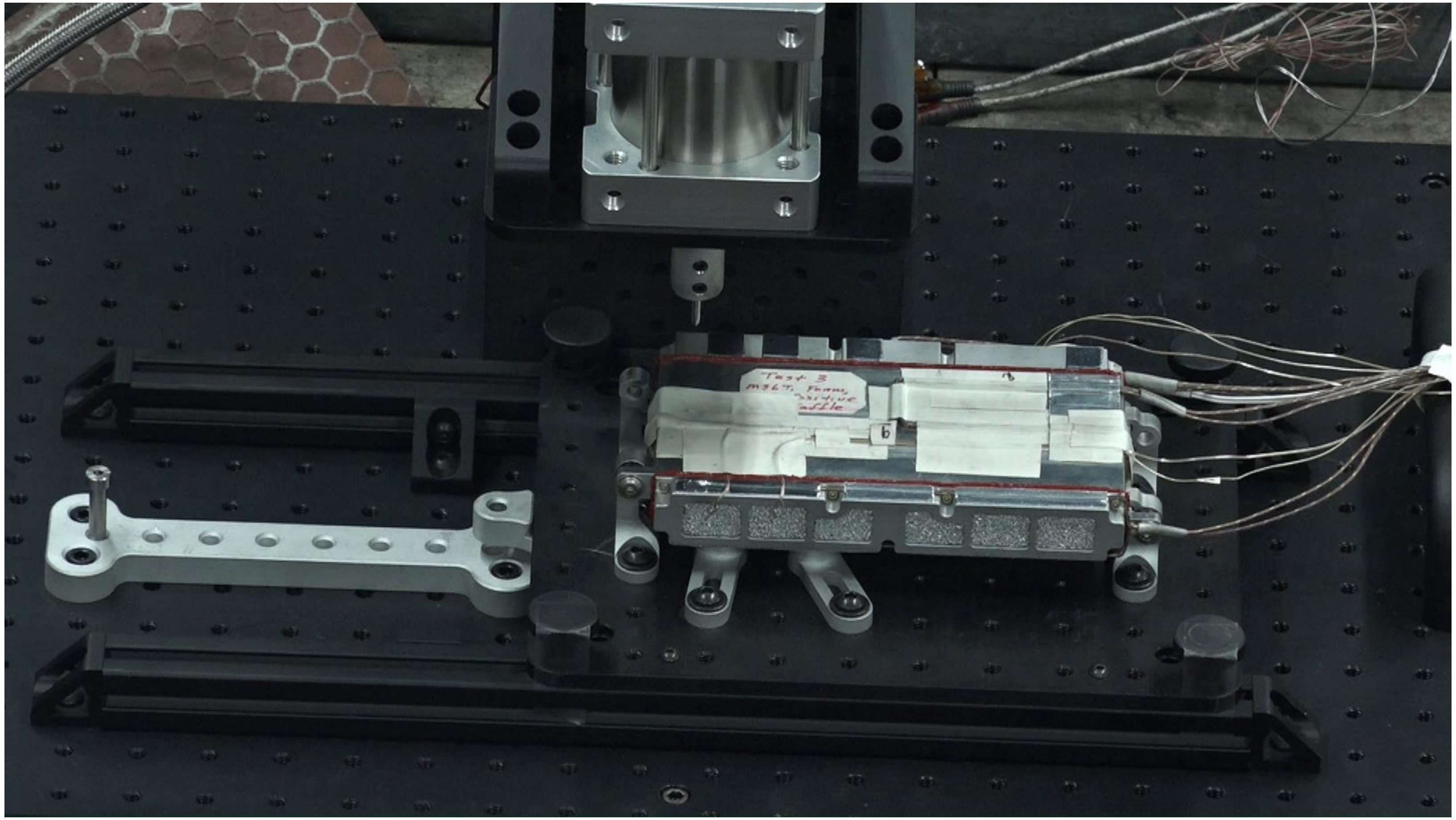
LLB-2 Flight Design, ISC Run 2

Flight design confirmation test.



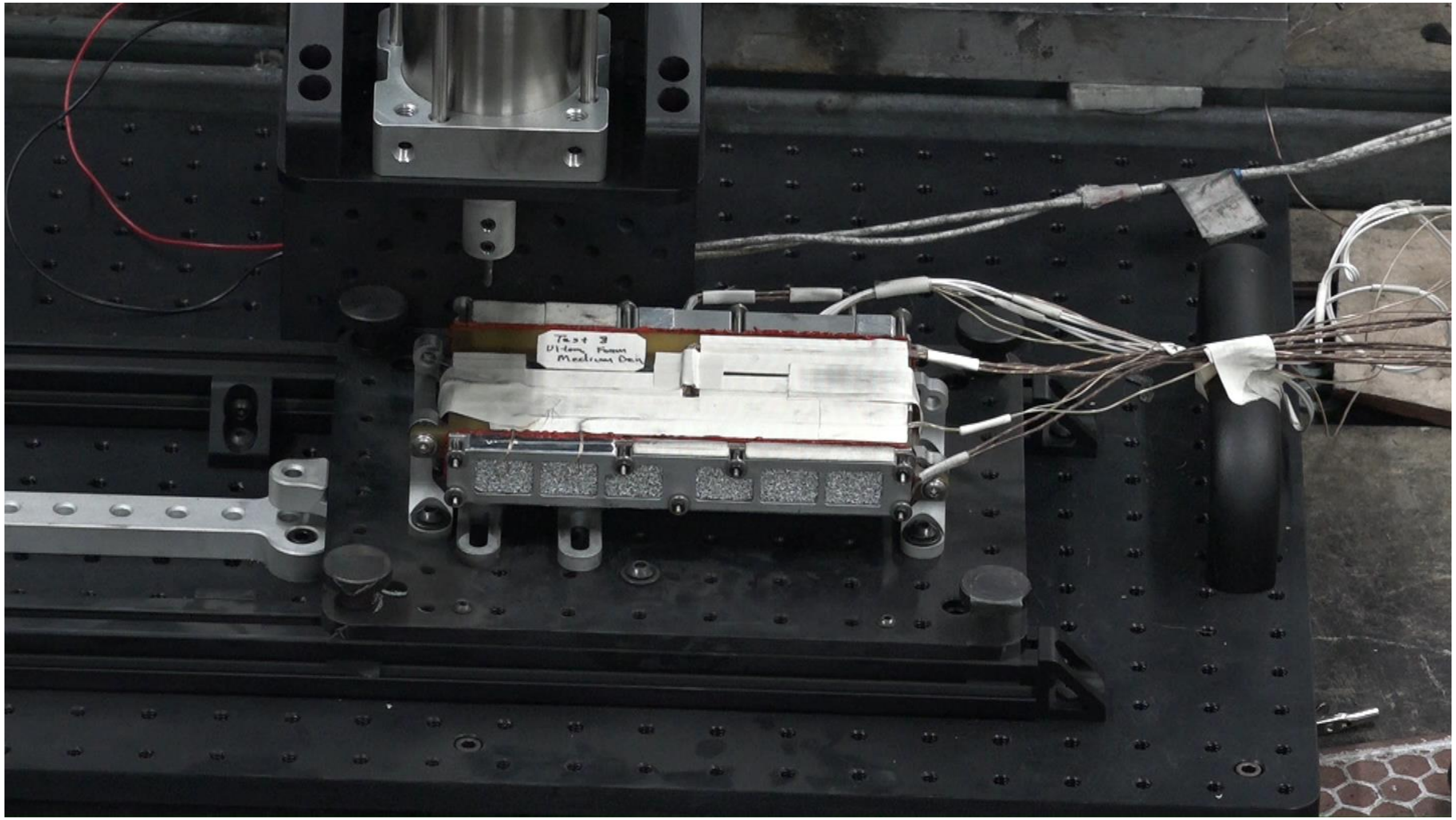
Nail Pin Campaign, Test 3

Restrictive Positive Side Baffle, Negative Side Foam Only. Sum R* = ~10^8 kg/m^7



Nail Pin Campaign, Test 8

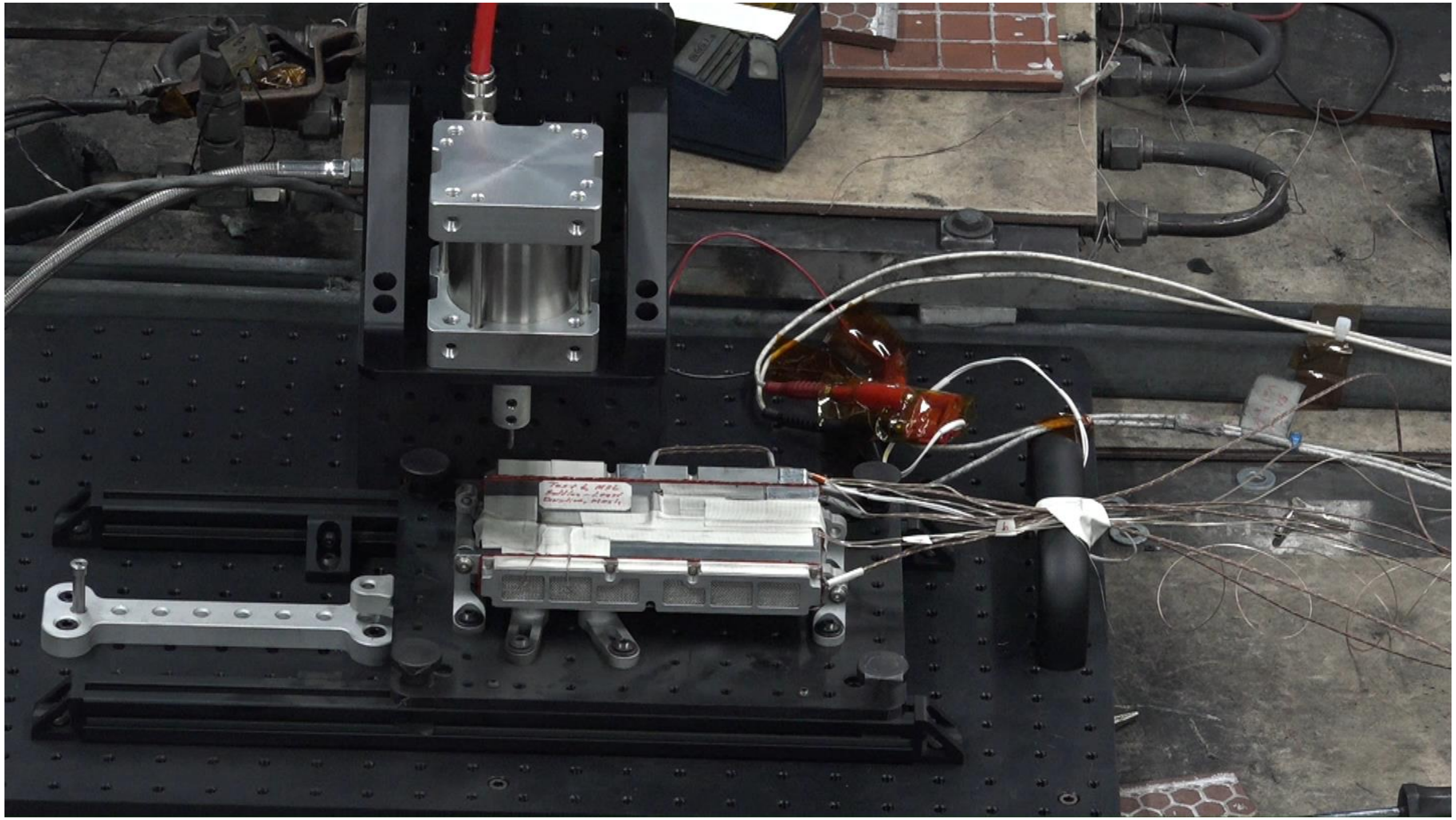
No Positive Restriction, Negative Side Foam Only, Ultem2300 Housing. Sum R* = ~10^7 kg/m^7



Nail Pin Campaign, Test 6

No Positive Restriction, Negative Baffle Only.

Sum R* = ~10^{10} kg/m^7



Nail Pin Campaign, Test 9

No Positive Restriction, Slightly thinner Negative Baffle Only. Sum R* = ~10^{10} kg/m^7