Ejecta Management in a Safe Lithium Ion Battery Design

Samuel P. Russell

2024 DIERS Fall Meeting

Proposed battery storage facility in League City faces resident backlash

By Rachel Leland | 4:33 PM Mar 26, 2024 CDT
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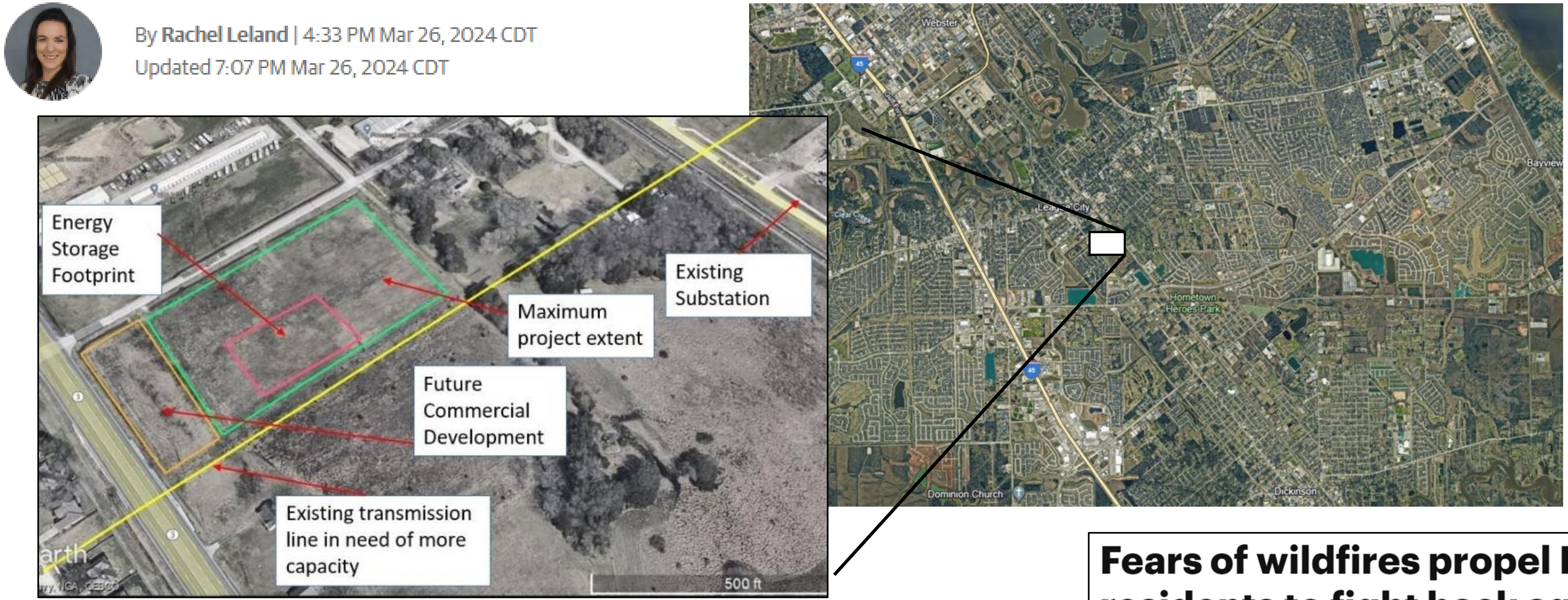


[Proposed battery storage facility in League City faces resident backlash | Community Impact]()

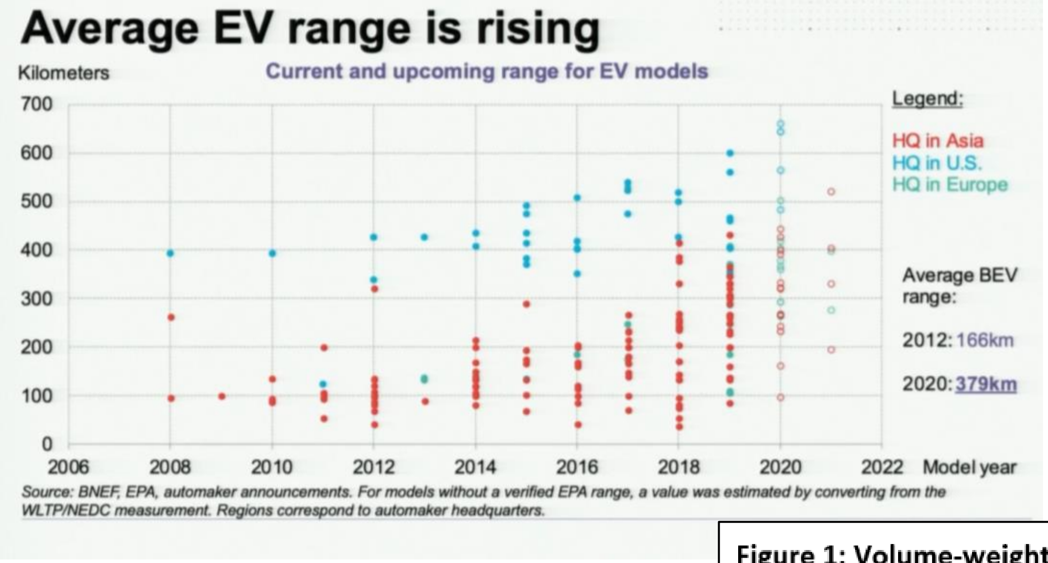
Fears of wildfires propel Escondido residents to fight back against battery storage plant

by Matt Kristoffersen
May 30, 2023 Why you can trust inewsource

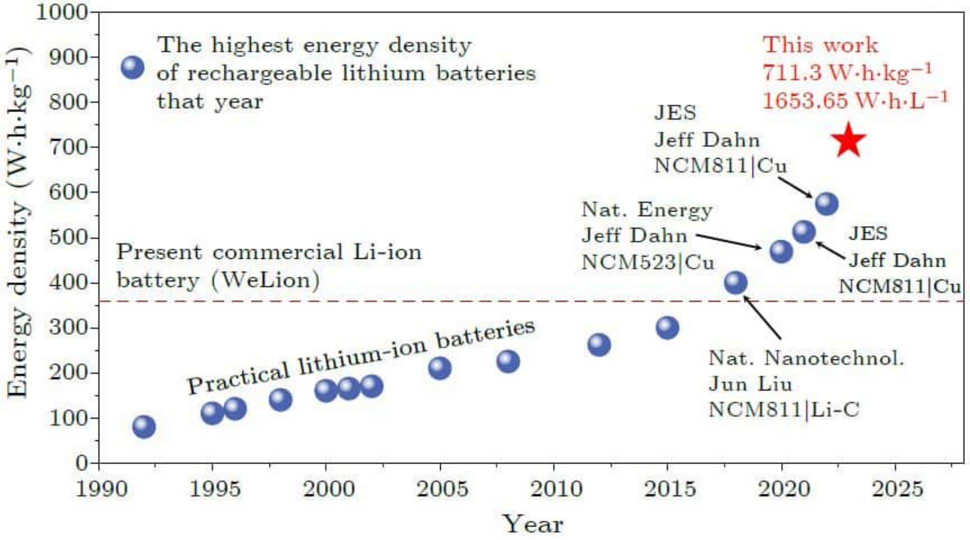
in New York City, since 2019, there have been [733 lithium-ion battery fires]() in bikes or scooters, which killed 29 people

Sherman, N. (2024). EV battery fires are on the rise. Fast Company.

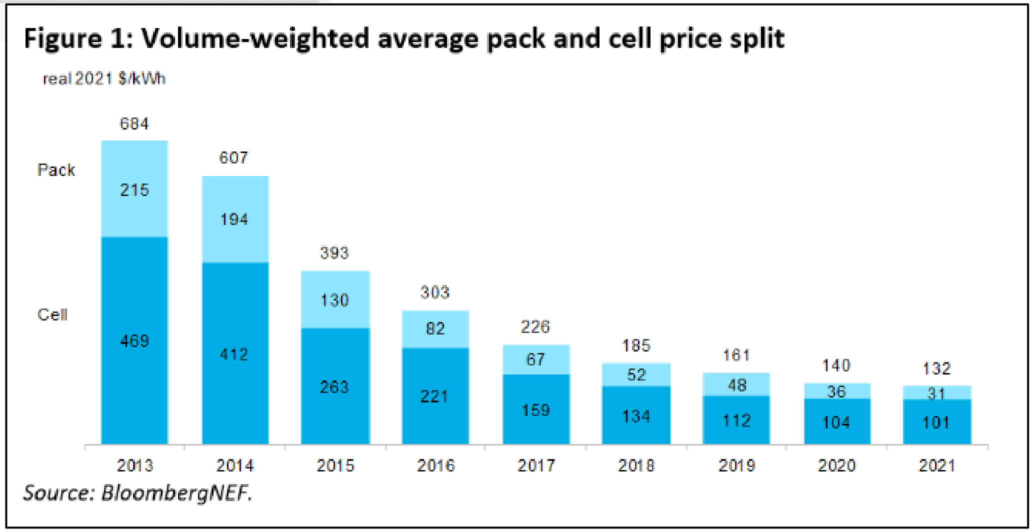
Lithium Ion is an Enabling Technology



BNEF Talk 2020: Electric Mobility: The End of the Beginning on Vimeo



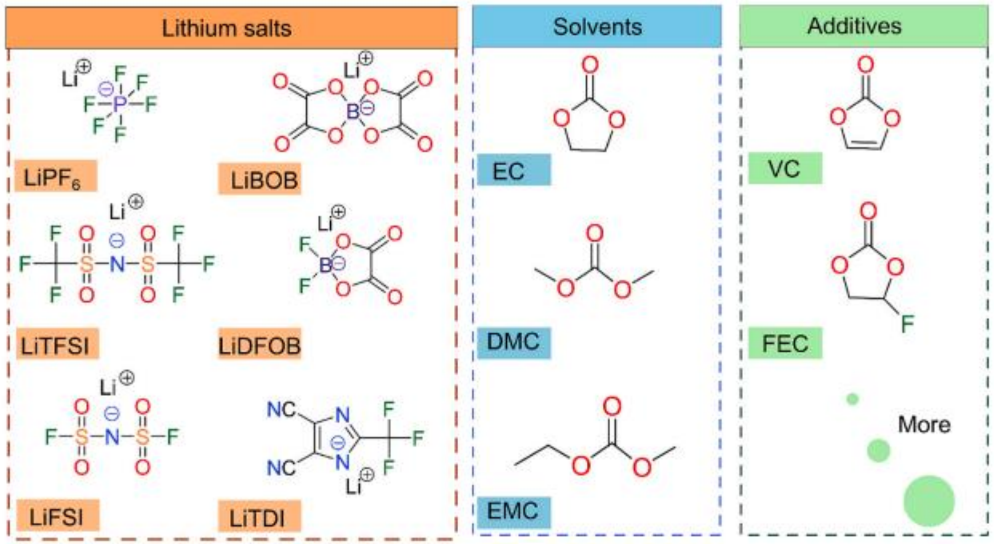
(Courtesy: B Wang) Lithium-ion batteries break energy density record – Physics World



Battery Pack Prices Fall to an Average of $132/kWh, But Rising Commodity Prices Start to Bite | BloombergNEF (bnef.com)

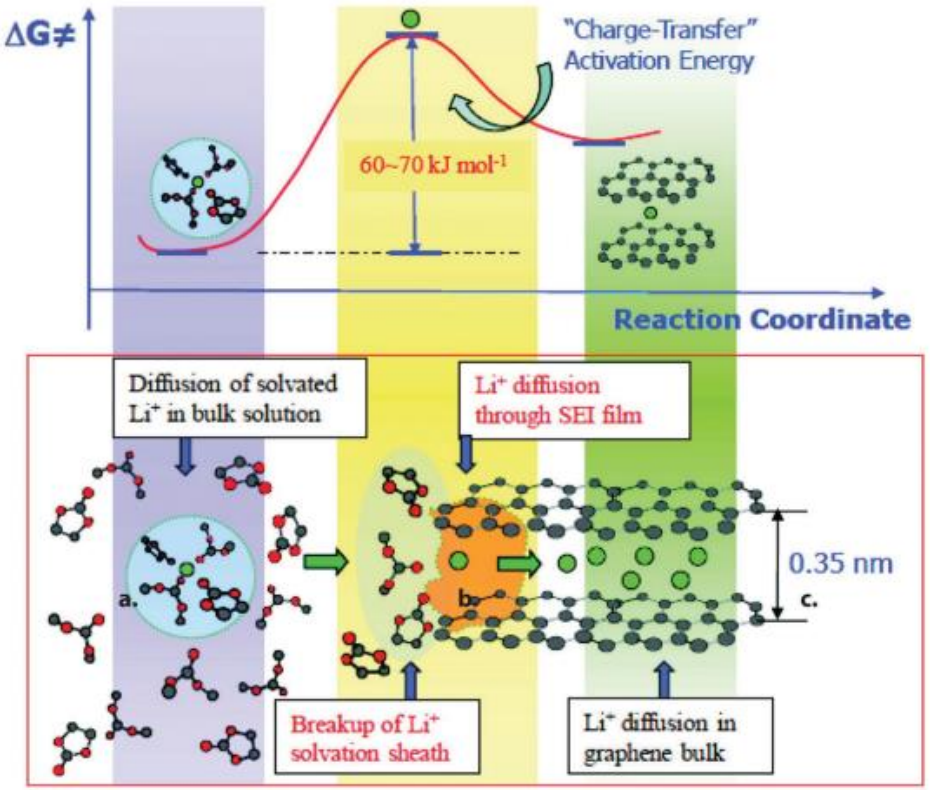
That Depends on a Flammable Electrolyte

Electrolyte Composition



Thermolytic Decomposition at ~300 °C

Ionic Shuttle



Armand, Michel, et al. "Lithium-ion Batteries – Current State of the Art and Anticipated Developments." *Journal of Power Sources*, vol. 479, 2020, p. 228708.

Hubble, Dion, et al. "Liquid electrolyte development for low-temperature lithium-ion batteries." *Energy & Environmental Science* 15.2 (2022): 550-578.

Why Worry?

Cell Safety Features

Can be Overcome in a Battery

Leading to

- Large amounts of heat
- Noxious Effluent
- Self Sustaining Reaction

CT Image provided by Glimpse Engineering, Inc (www.glimp.se)

Is Containment the Answer?

Following new data showing that ***59 percent of 2023's lithium-ion battery fires started when those batteries were not charging***, the Mayor of New York City responded on July 22, 2024 by:

- Expediting approvals of e-bike battery swapping and charging cabinets on public sidewalks
- Municipal trade-in program for replacing unsafe devices with certified, high-quality e-bikes / batteries
- A $1 million public education and awareness campaign on the dangers of unsafe lithium-ion batteries

Office of the Mayor. (2024, August 14). Mayor Adams takes new actions to prevent deadly lithium-ion battery fires.

Containment Systems for Home and School

Walmart, 16-bay Charging Cabinet

Luxor Workspaces, Secure Charging Cabinet

E-bike Fire Resistant Lithium Battery Charging Cabinet

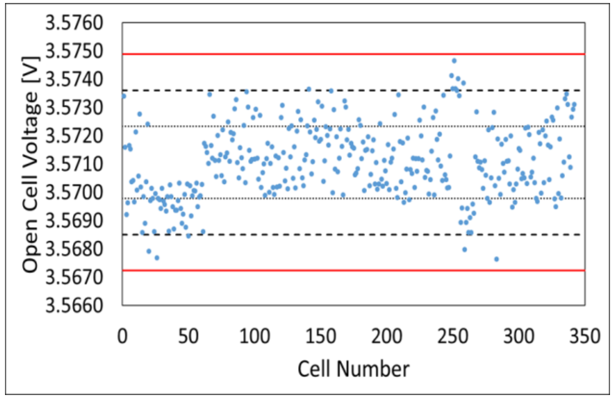
Key Features
•Fire resistant reinforced steel plate
•Fire alarm
•Charging socket
•Real time temperature monitoring
Ventilation
•Automatic temperature control exhaust system
•Electric surge protector
•Automatic fire extinguishing in future updates

E-Biles, Fire-resistant micromobility recharging cabinet.

What if Design Could Offer a Solution

Screening

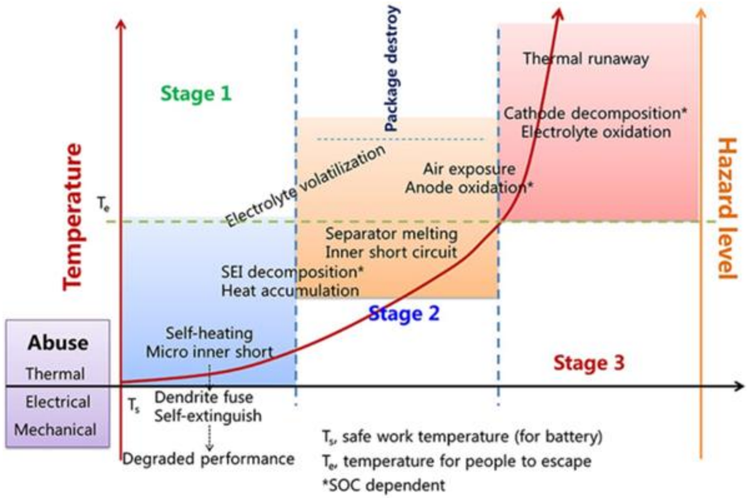
Removing Anomalous Actors
Reduces Failure Likelihood



Fortune, C., et al, *presentation*.

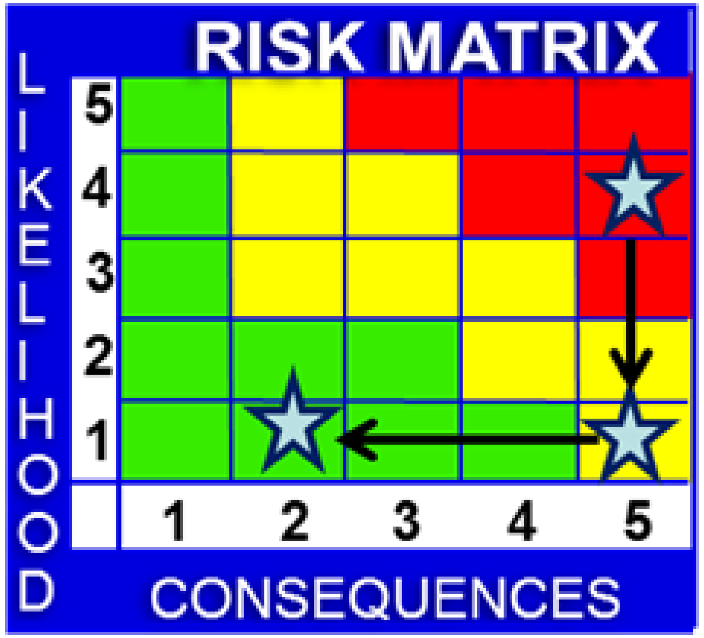
Design

Isolate Failure to a Single Cell
Reduces Failure Consequences



Wu, et al, Frontiers in Energy Research, July 2019, vol 7, article 65.

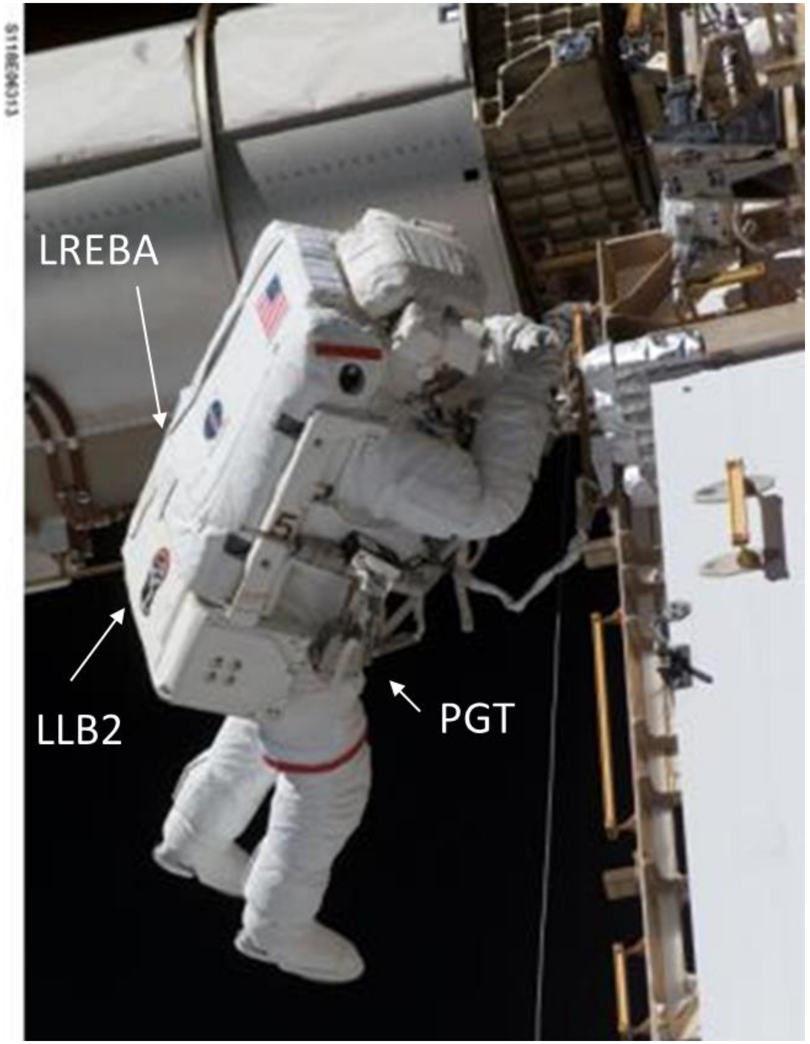
Passive Propagation Prevention



Seeking a Solution in Design

Case Study

- LREBA (0.5kWh)
- LPGT (0.1kWh)
- LLB2 (0.8kWh)



Scalability

- High Energy (1-5 kWh)
- High Power (1 kWh)
- Small Volume (0.1 kWh)

A Common Approach

Case Study

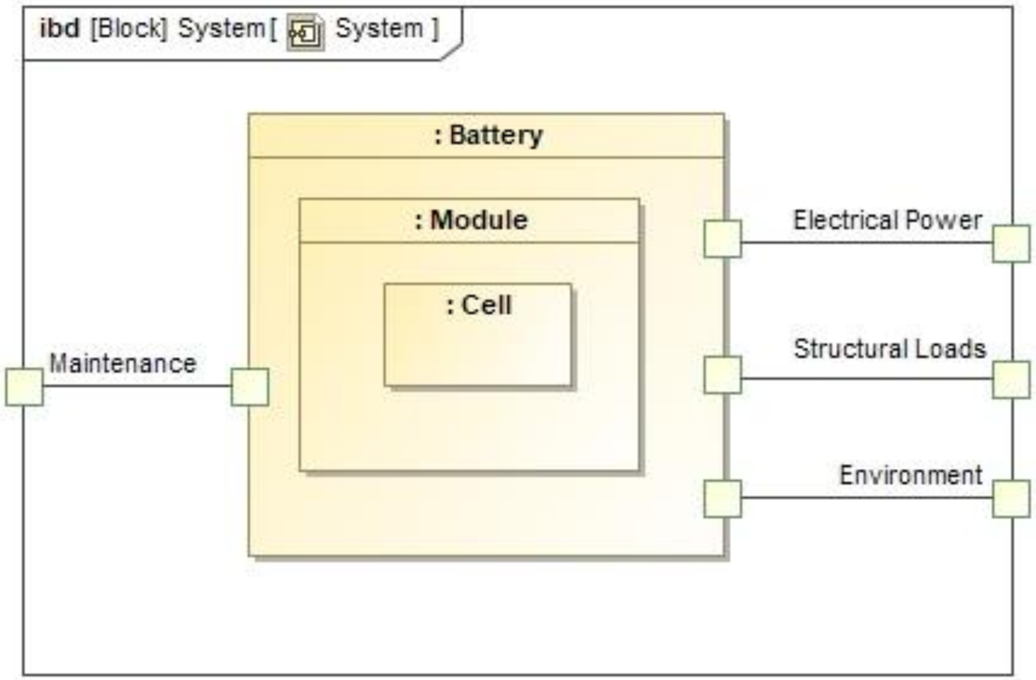
LREBA (0.5kWh)

LPGT (0.1kWh)

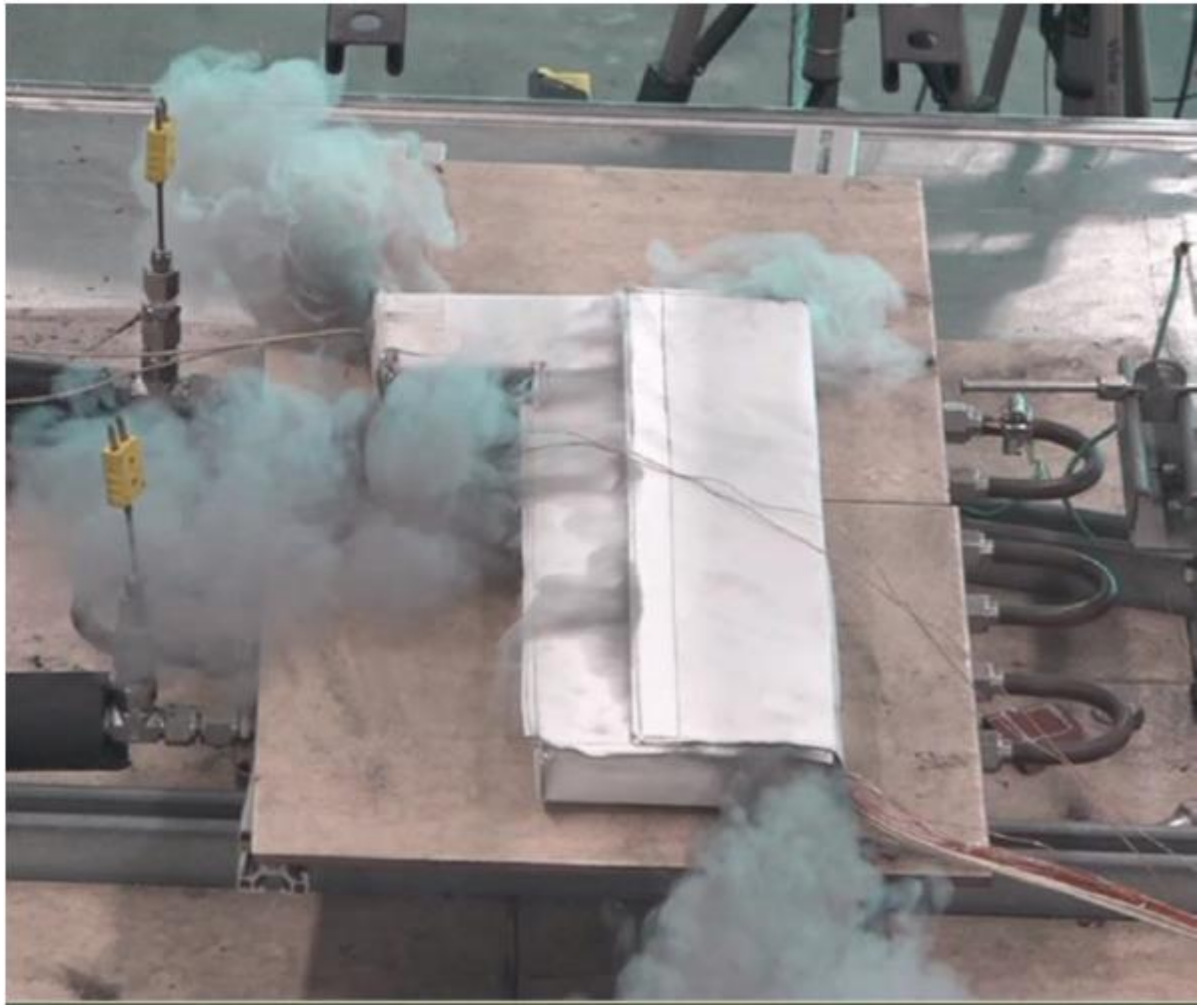
LLB2 (0.8kWh)

COTS Li-Ion Cell ($LiCoO_2$)

Physical Architecture



Redesigned to Prevent Propagation, LREBA



Iannello, C., et al, NASA/TM-2017-219649, July 2017

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 directs effluent over large housing surfaces

- Max Adjacent Cell Temp: 120°C
- Max case temp: ~60°C
- Max garment external temp: 21°C

Redesigned to Prevent Propagation, LPGT

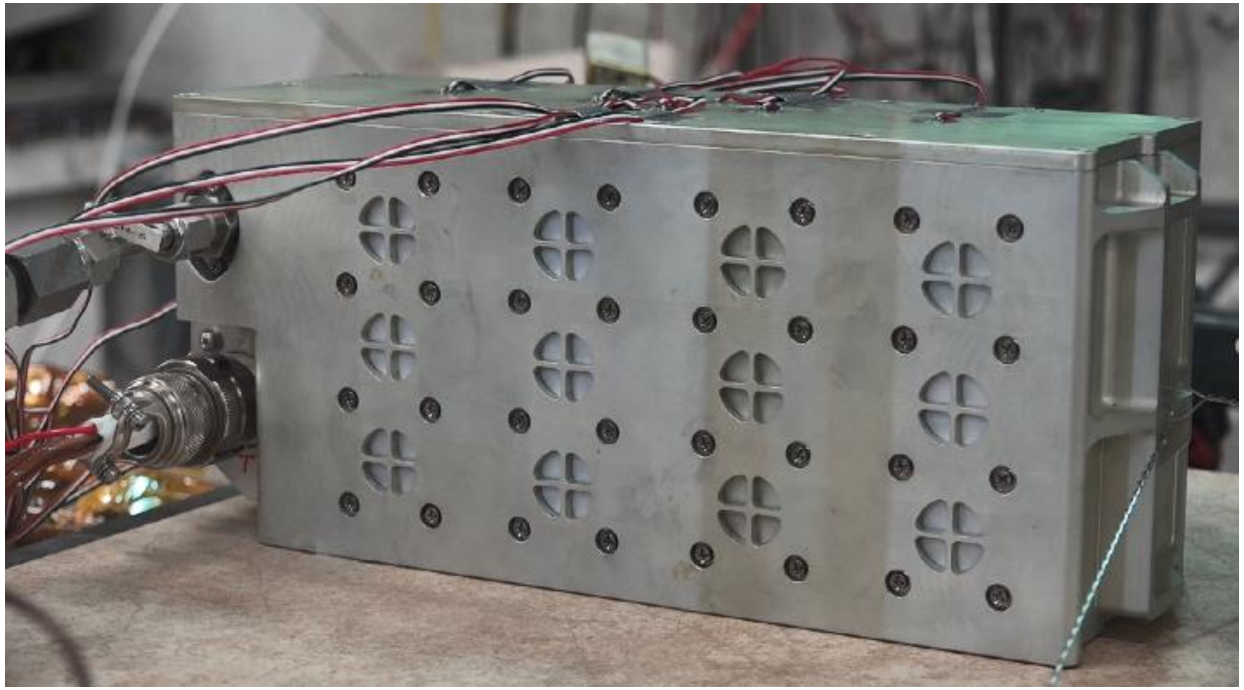
Iannello, C., et al, NASA/TM-2017-219649, July 2017

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

Redesigned to Prevent Propagation, LLB2

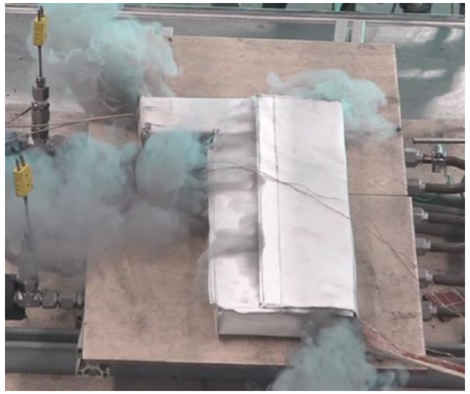
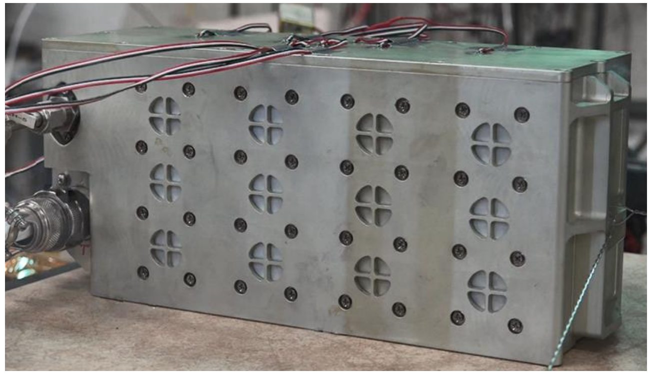


Iannello, C., et al, NASA/TM-2017-219649, July 2017

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°C
- Max case temp: 40°C

An Evolving Solution

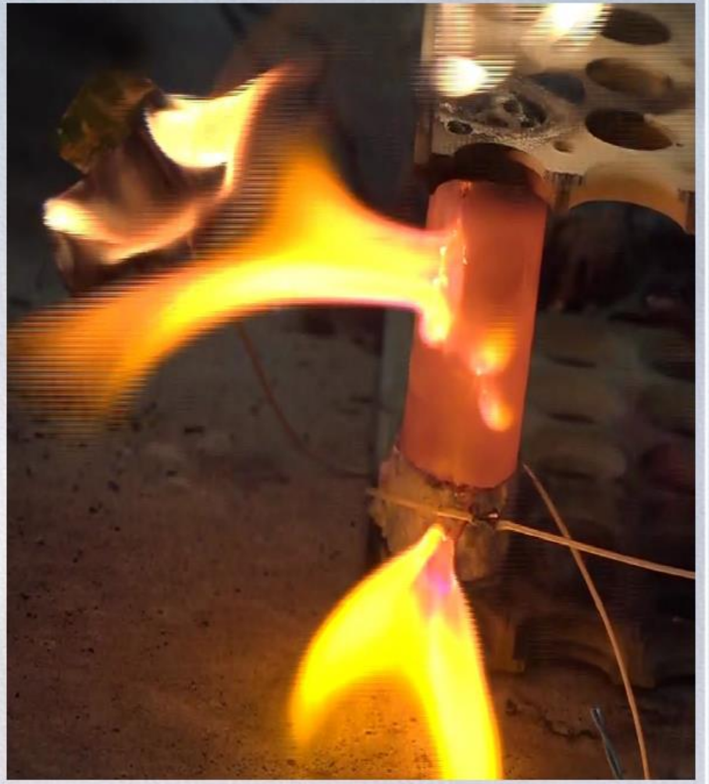
	LREBA	LPGT	LLB2
Before			
After			
	Separated and Fused Cells, External Release, Garment Wrap	*Separated and Fused Cells, Internal Expansion, Wire Mesh*	*Heat Spreading Interstitial, Fused Cells, Internal Expansion, Wire Mesh / Gore Vent*
	Max Adjacent Cell, 120°C Max Garment Temp, 21°C	*Max Adjacent Cell, 110°C Max Case Temperature, 50°C*	*Max Adjacent Cell, 80°C Max Case Temperature, 40°C*

Conclusion

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

1

- 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 and strings
  - TR cell becomes an external short to adjacent parallel cells and heats them up
  - TR cell in a string in parallel with other strings needs fusing
- 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



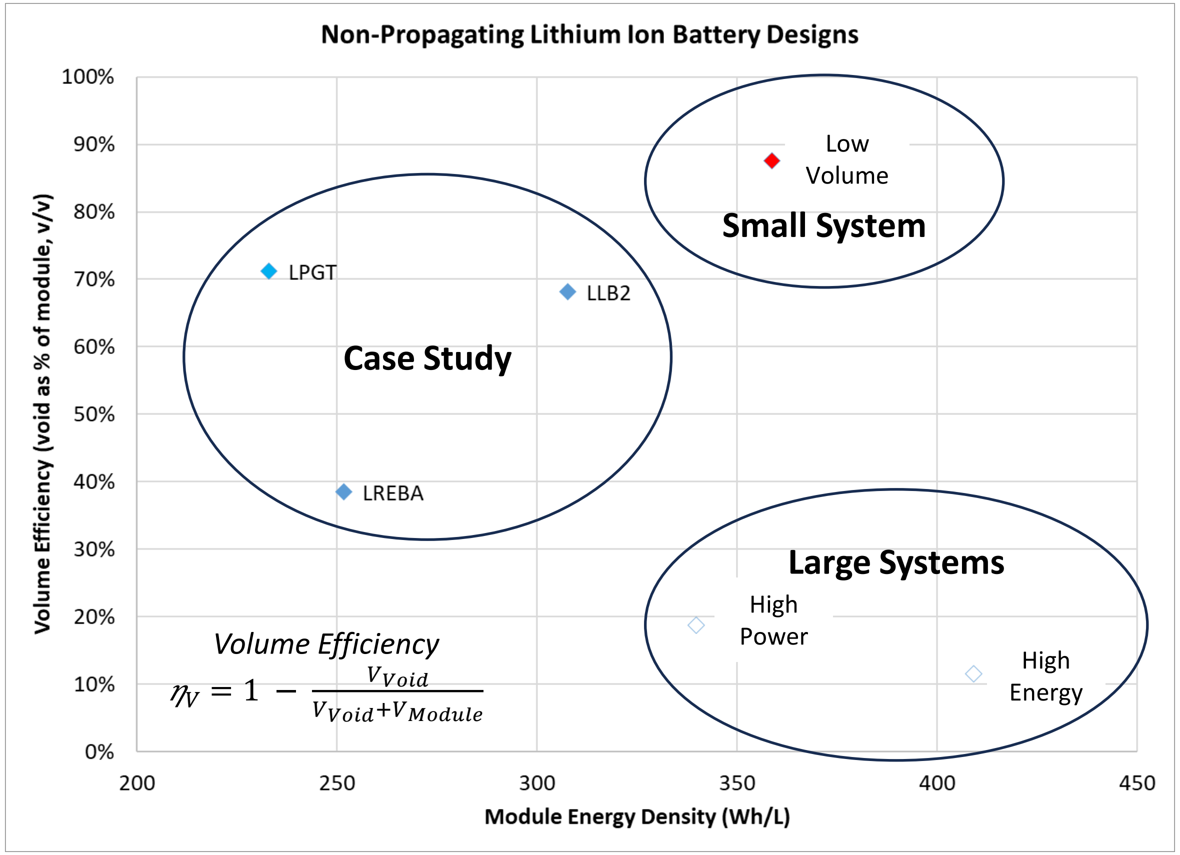
Reference: Darcy, E. C., Jacob, D., Walker, W., Finegan, D. P. & Shearing, P. Driving Design Factors for Safe, High-Power Batteries for Space Applications. in Advanced Automotive Battery Conference (2018).

Scalability

Scalability

- High Energy (1-5 kWh)
- High Power (1 kWh)
- Low Volume (0.1 kWh)

COTS Li-Ion Cell (NMC)



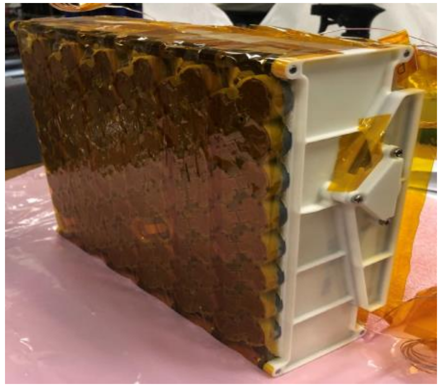
Increasing Volumetric Efficiency

Increasing Energy Density (Wh/L)

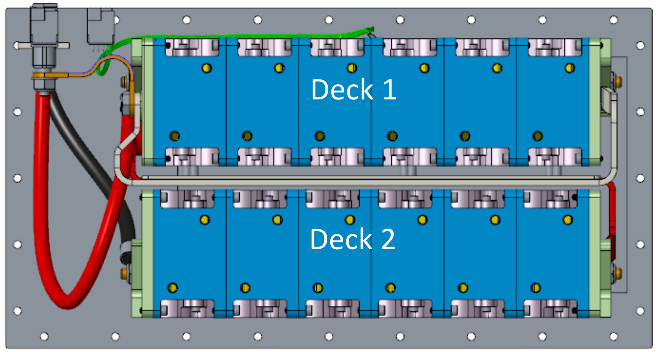
Ejecta Management in Large Systems

High Power Design

16 Cell Spline

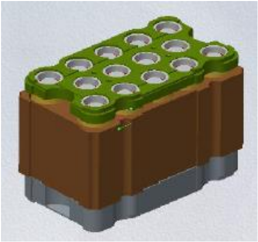


6 Spline Deck

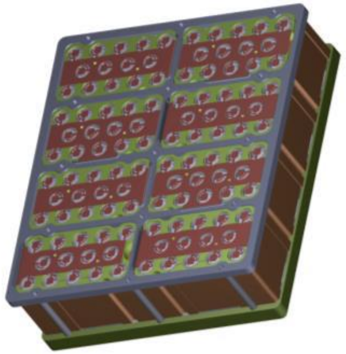


2 Deck Battery

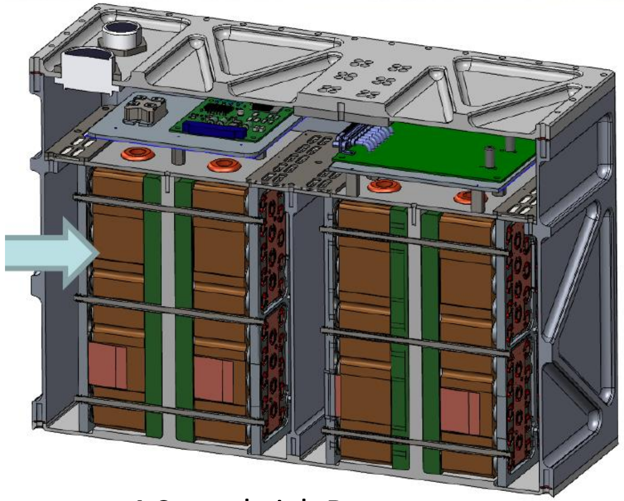
High Energy Design



14 Cell Brick



8 Brick Superbrick



4 Superbrick Battery

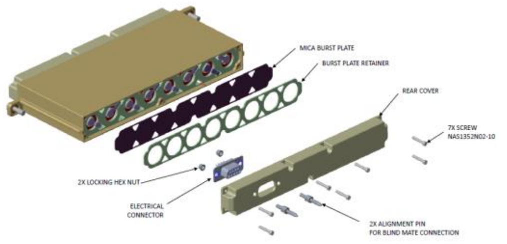
FINDINGS

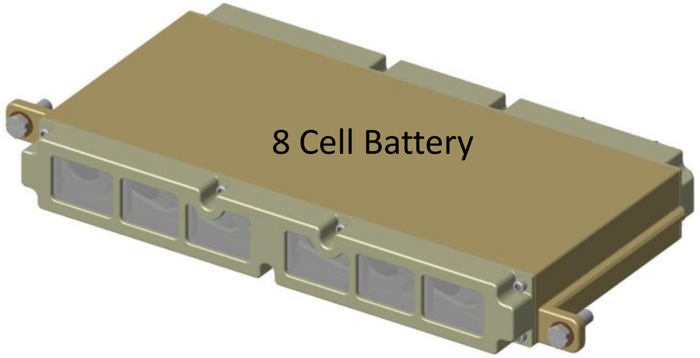
- ~6mm Vent Gap Allows Flow into Interior
- Long Path Length Increases Residence Time and Particle Retention
- Large Free Volume Reduces Gas Temperature

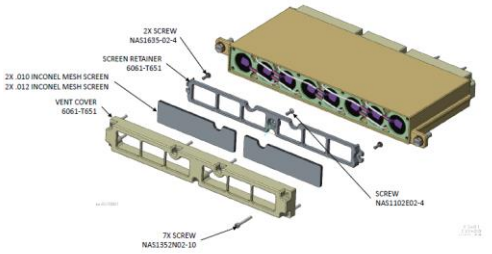
✓ *COTS Gore Vent*

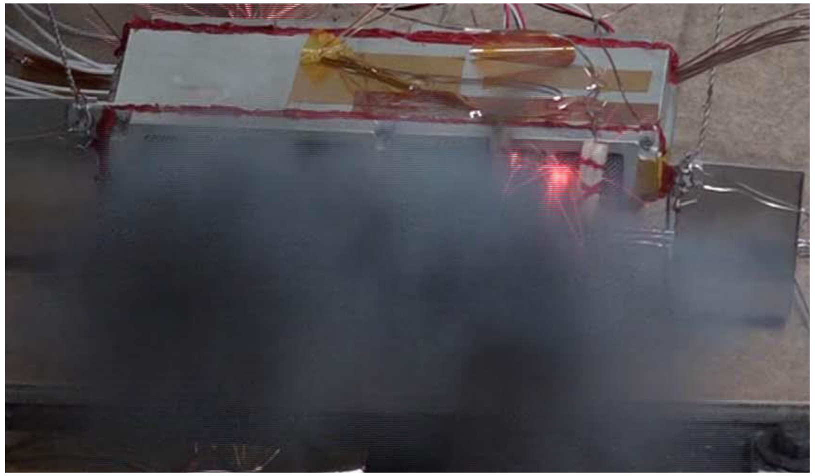
Screw-in Protective Vent

Small System









FINDINGS

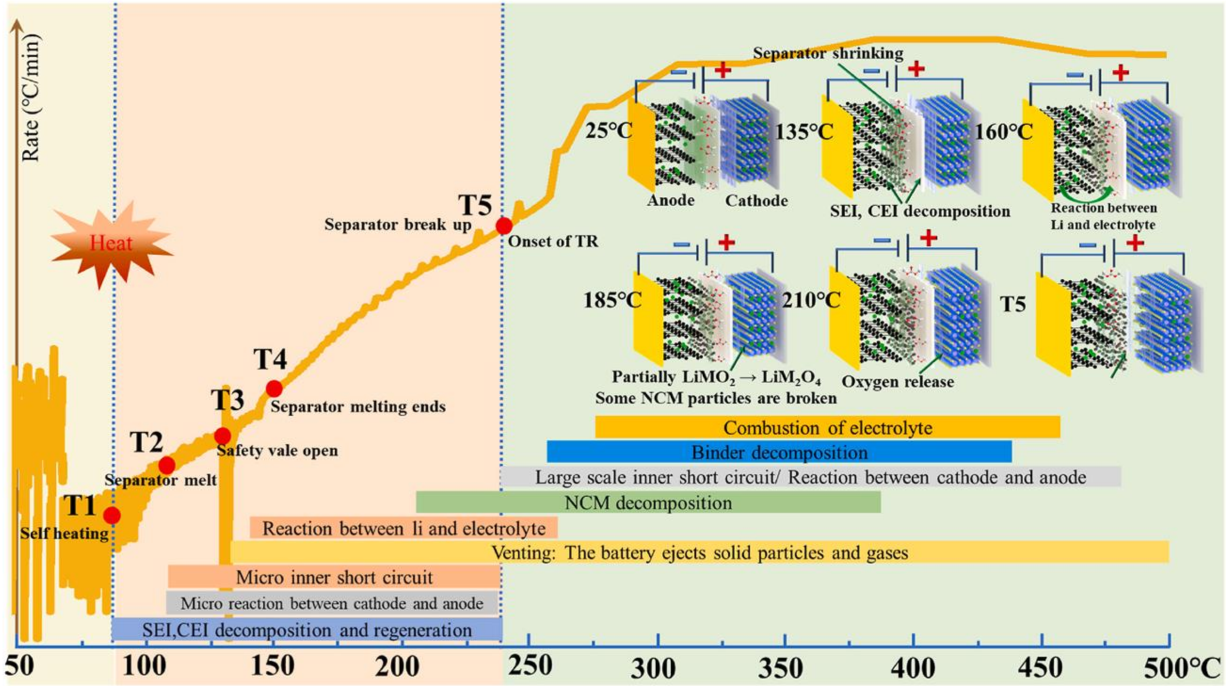
- ~6mm Gap Ejecta Gap Allows Flow into Interior
- Short Flow Path Reduces Residence Time and Particulate Retention
- Limited Expansion Volume Keeps Gas Temperature and Velocity High

X *Vaporized Gore Material*
X *Released Sparks / Flame*

Characterizing Ejecta

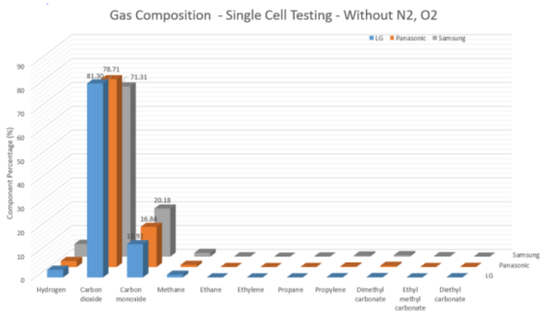
Gas Vent

Combustion



He, Tengfei, et al., *Journal of Cleaner Production* 434 (2024): 140548

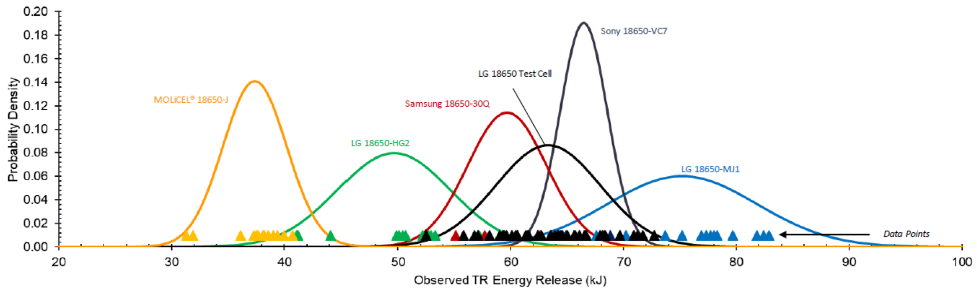
Gas Generation



Delafuente, D., IAPG-CWG, 21-22 Feb 2018

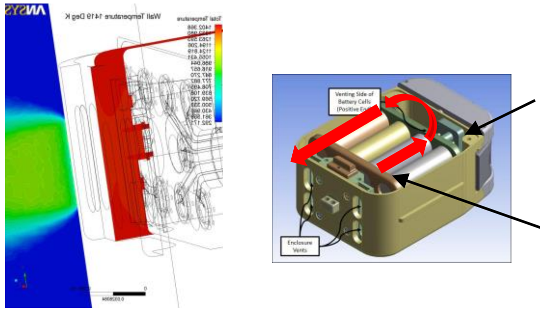
Ambient Conditions	
CO (mol%)	20+
CO2 (mol%)	70+
L/Ah (STP)	~1.8

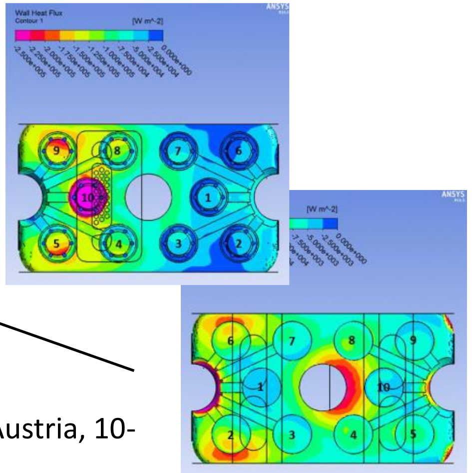
Heat Generation



Walker, William Q., et al., *Journal of Power Sources*, vol. 415, 2019, pp. 207-218.

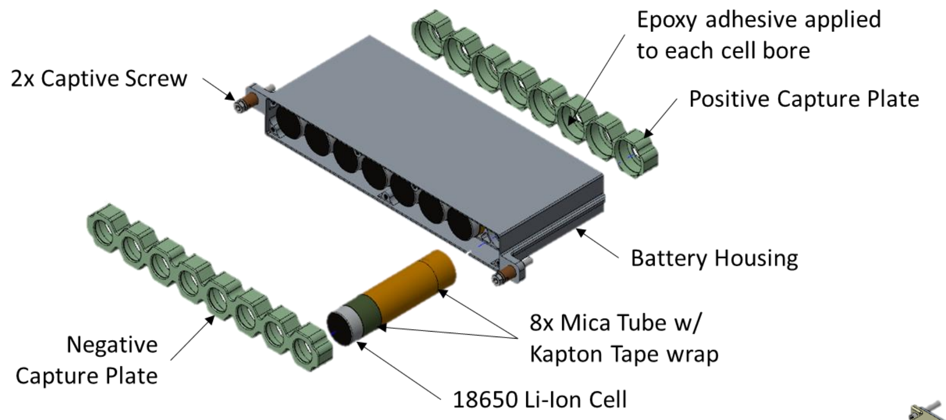
Heat Flux



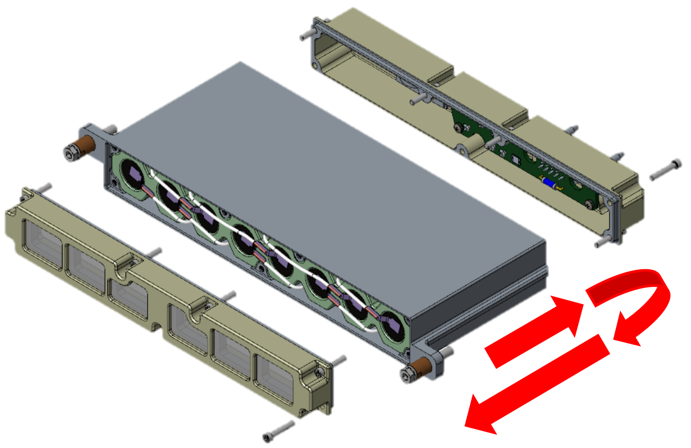


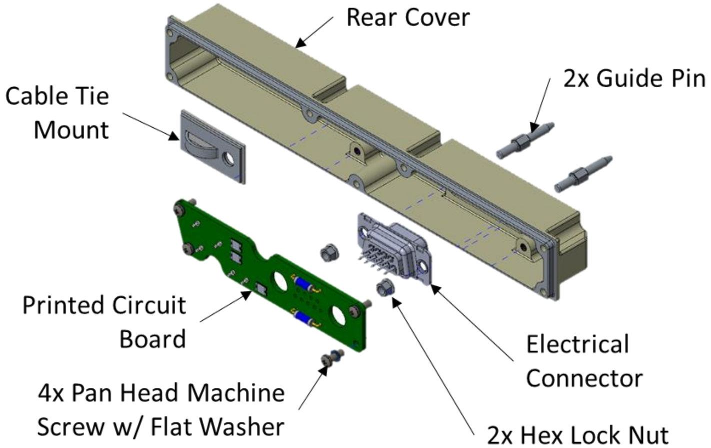
Rickman, S. L., et al., ICES-2016-009, Vienna, Austria, 10-14 July 2016

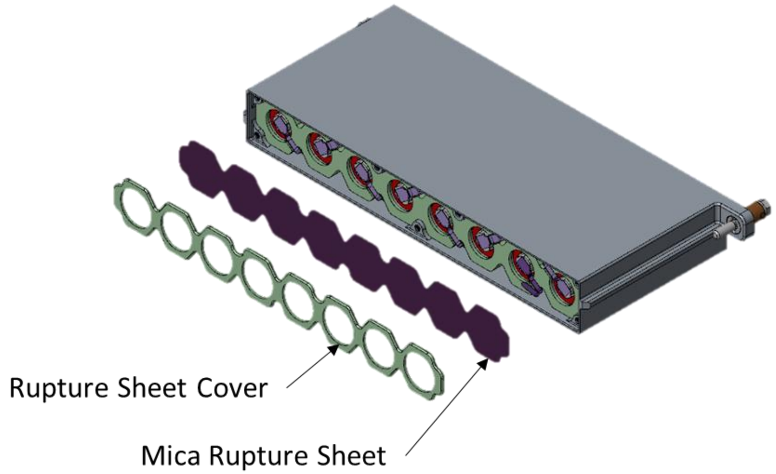
Towards an Ejecta Management Solution

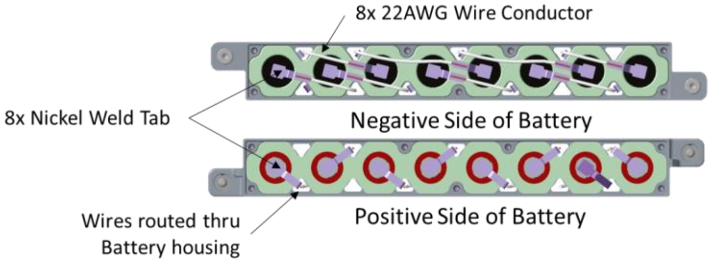


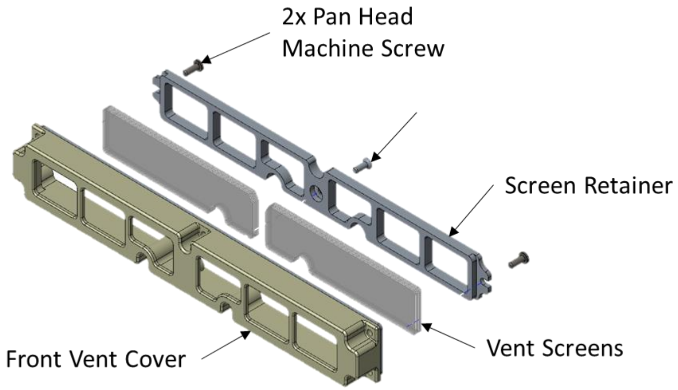
Cell Oriented for Longest Vent Flow Path



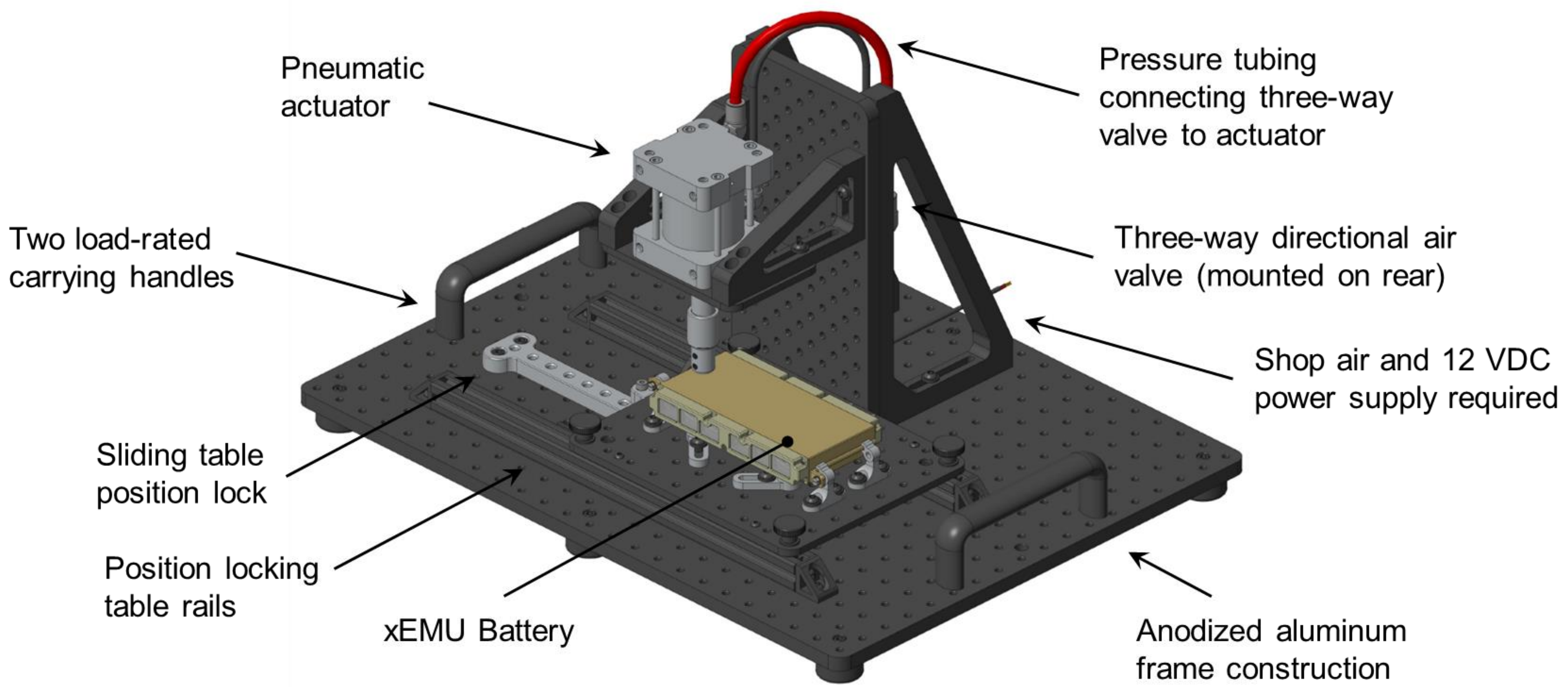






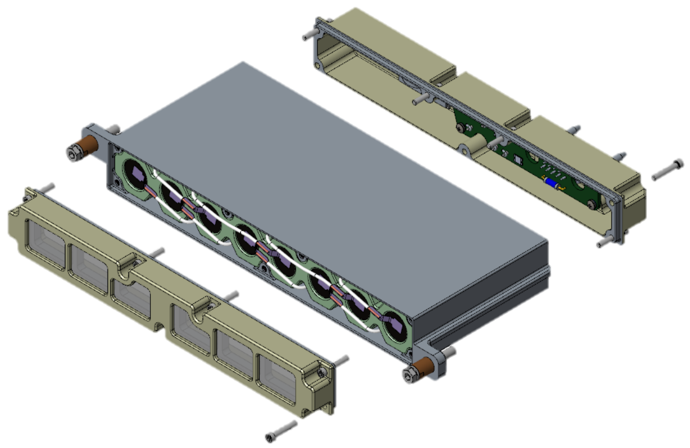


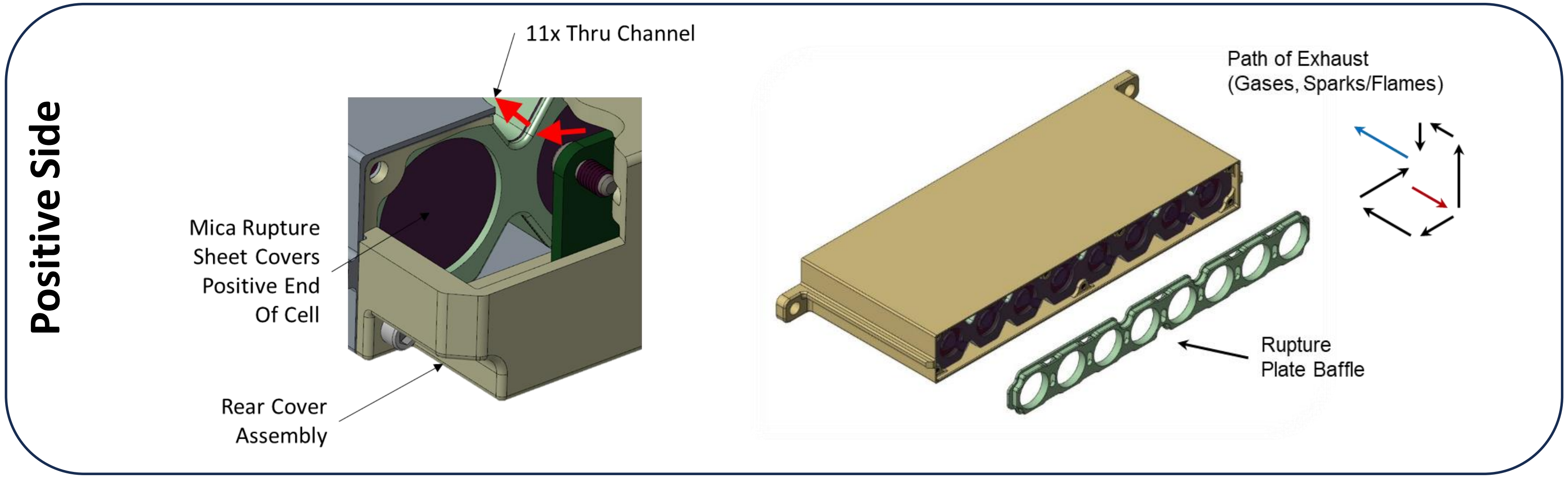
Test Method

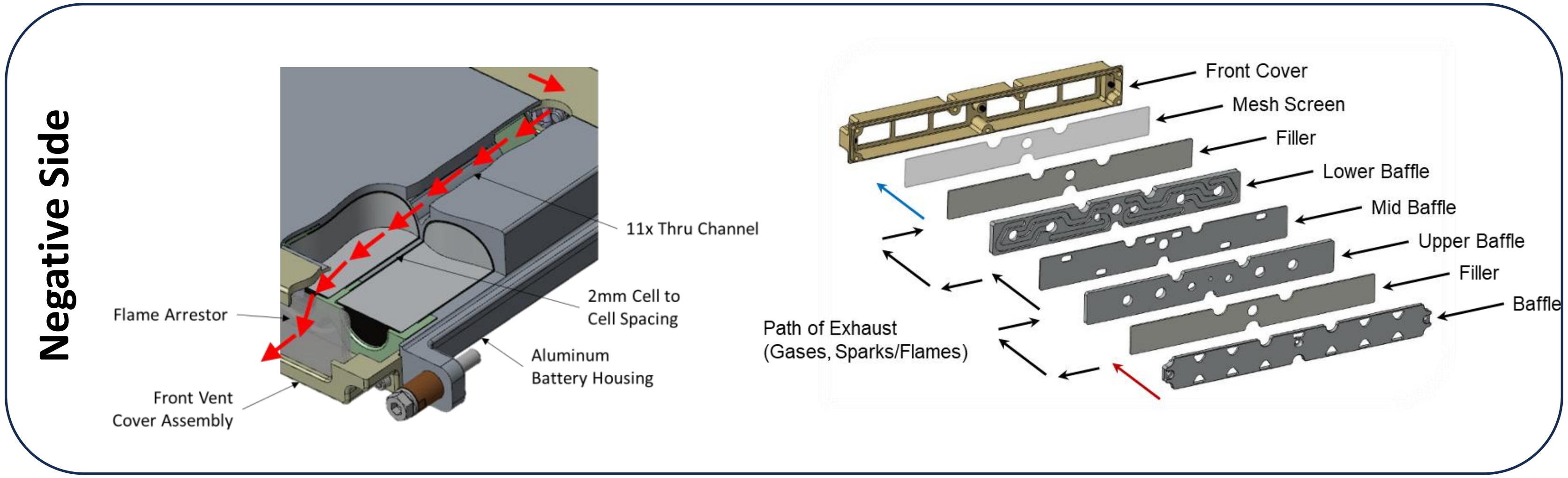


Credit: David Petrushenko, Spring/Summer 2020

Increasing Flow Resistance



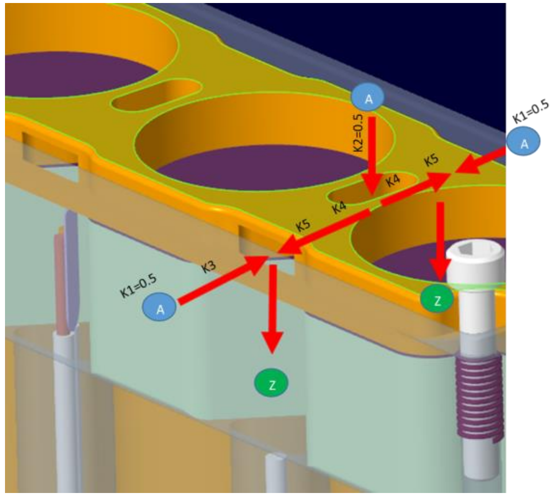


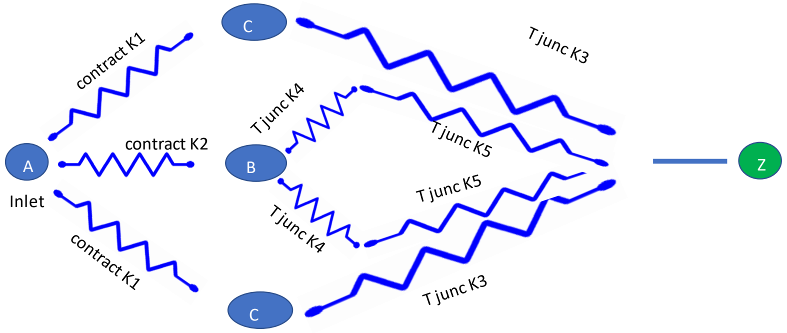


Credit: David Petrushenko, Spring/Summer 2020

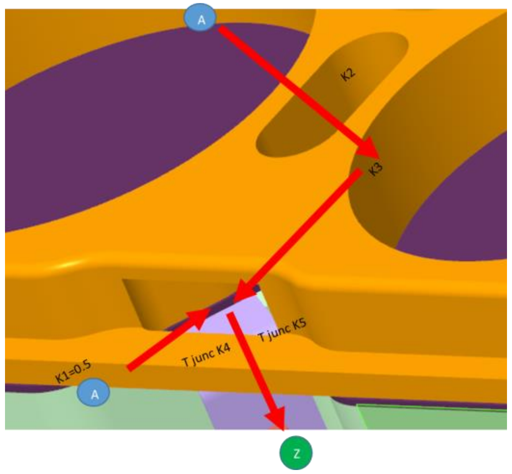
Positive Side Resistance Estimation

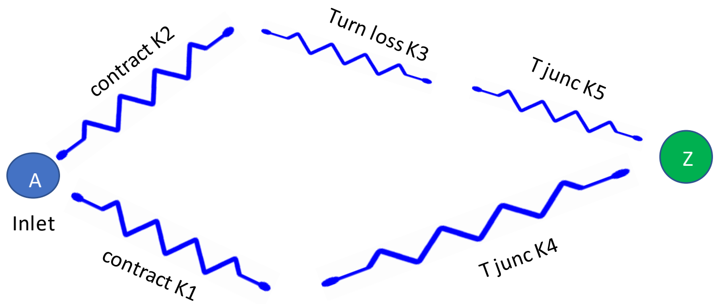
Effective resistance, with baffle





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 $\left[{}^{kg}/_{s}\right]$

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

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

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

For simple flow,

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

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

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

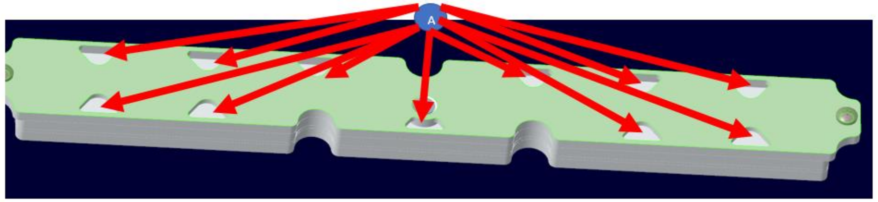
Effective resistance, assuming flow into each branch is equal,

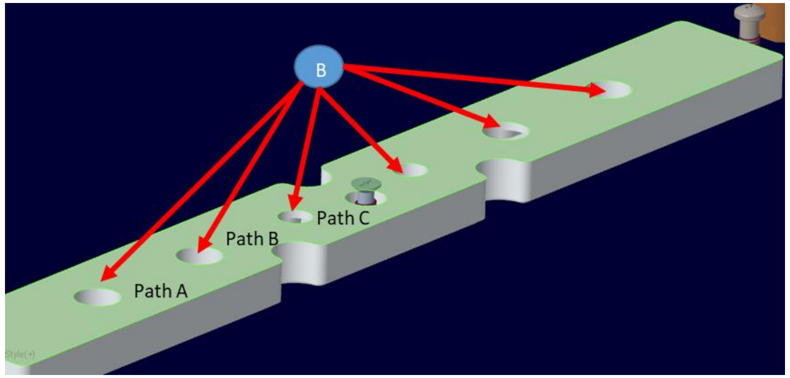
R* Baffle = 2.65x10^{8} kg/m^{7}

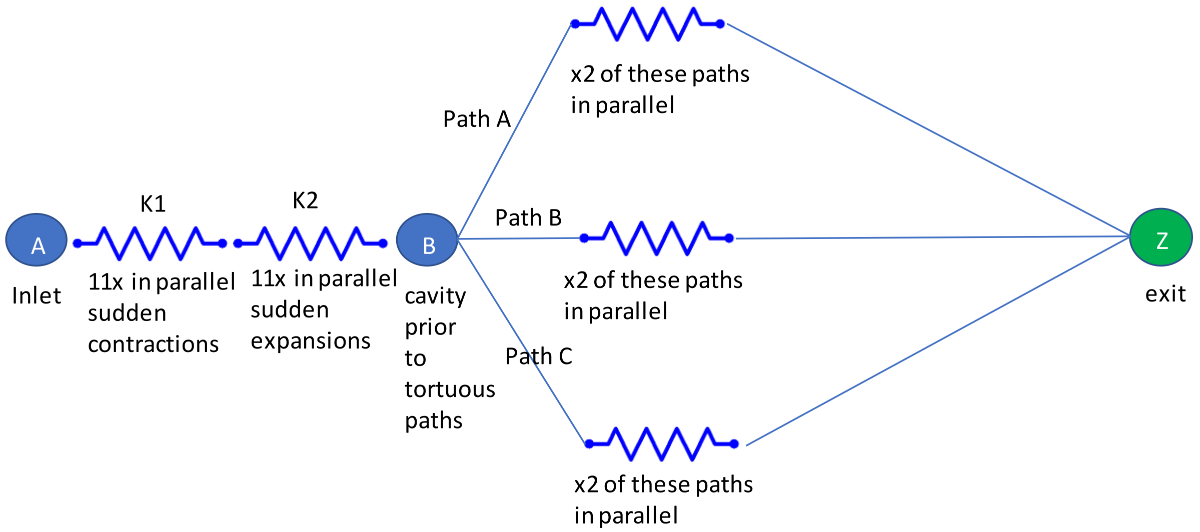
R* No Baffle = 2.80x10^{7} kg/m^{7}

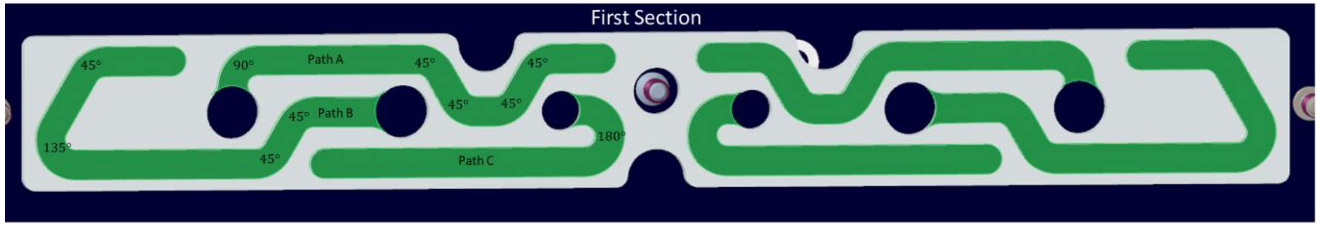
Negative Side, High Resistance Estimation

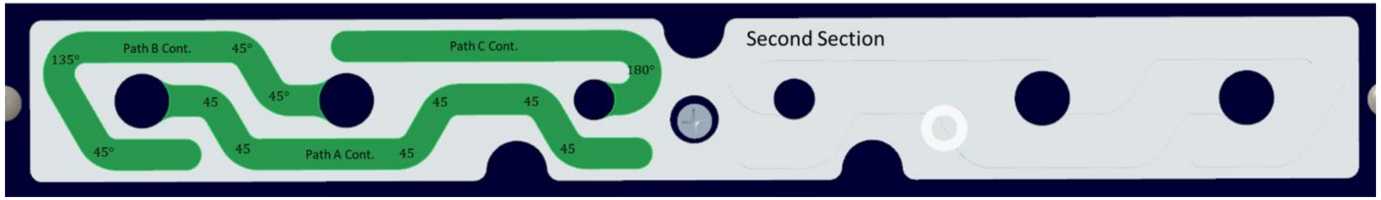
Effective resistance, negative baffle plate









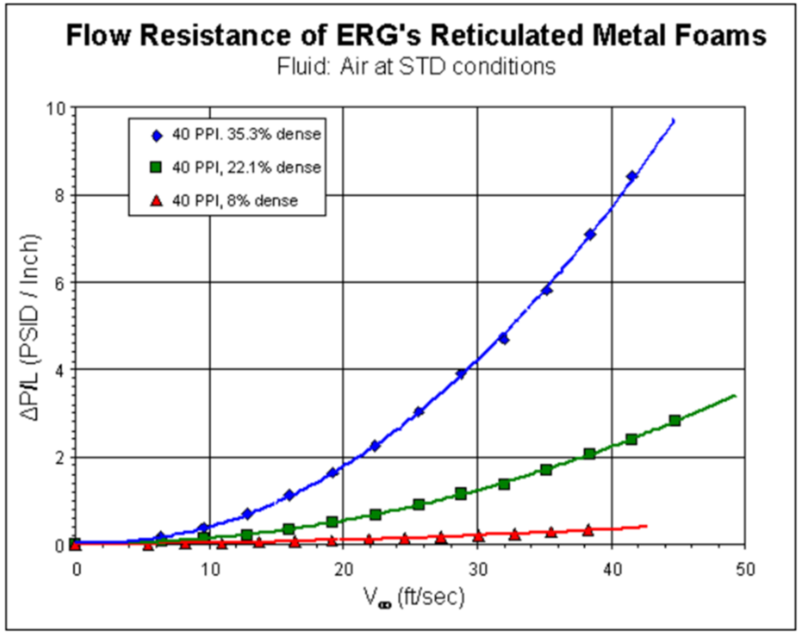


Effective resistance, assuming flow into each branch is equal,

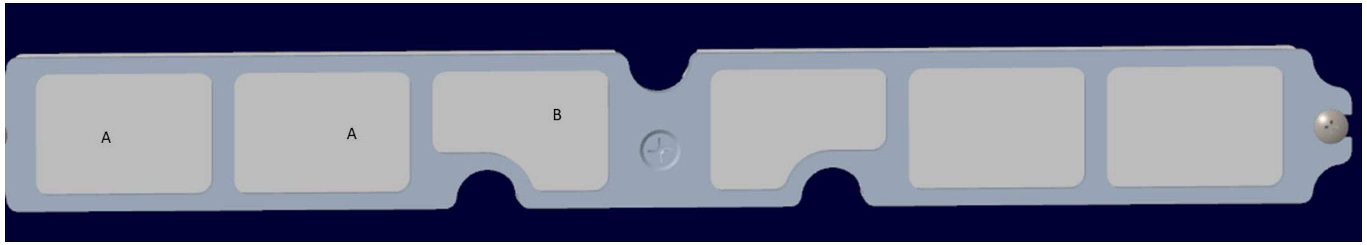
$R^* = 1.79 \times 10^{10}$ kg/m^7

Negative Side, Low 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

$R^* = 7.43 \times 10^6$ kg/m^7

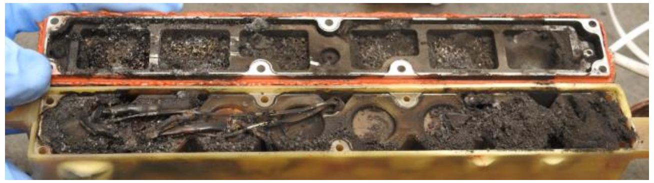
Positive Side Resistance

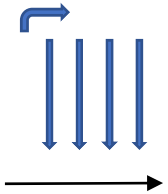
Increasing upstream resistance reduces filter performance, some sparks exit the housing

Negative Foam, no Positive Baffle

Positive Cavity

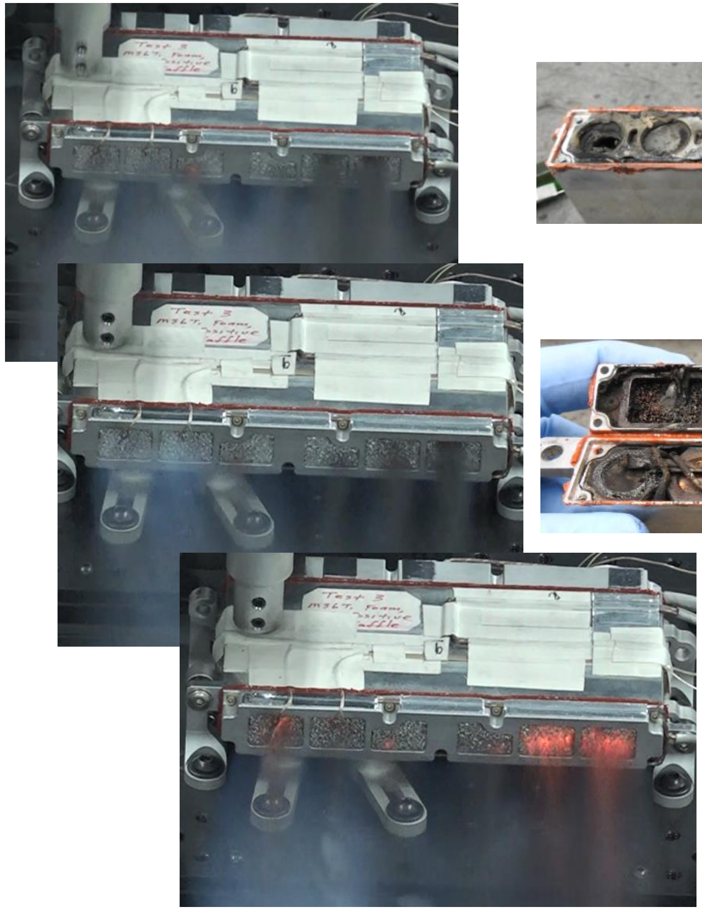
Negative Cavity





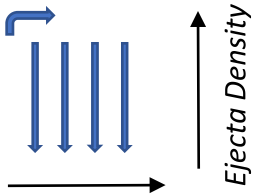
Ejecta Density

Negative Foam, Positive Baffle



Positive Cavity

Negative Cavity

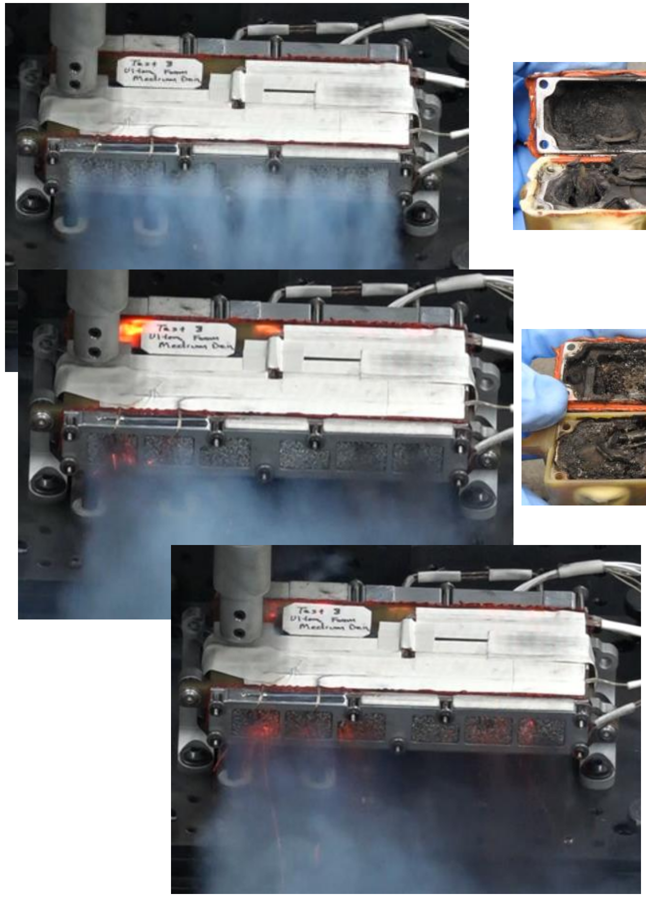


Ejecta Density

Negative Side Resistance

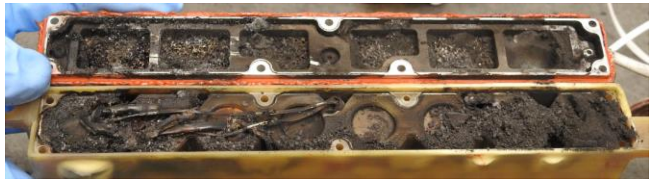
Increasing downstream resistances improves spark retention, open channels increases particulate release

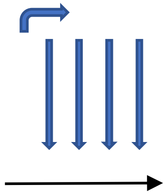
Negative Foam, no Positive Baffle



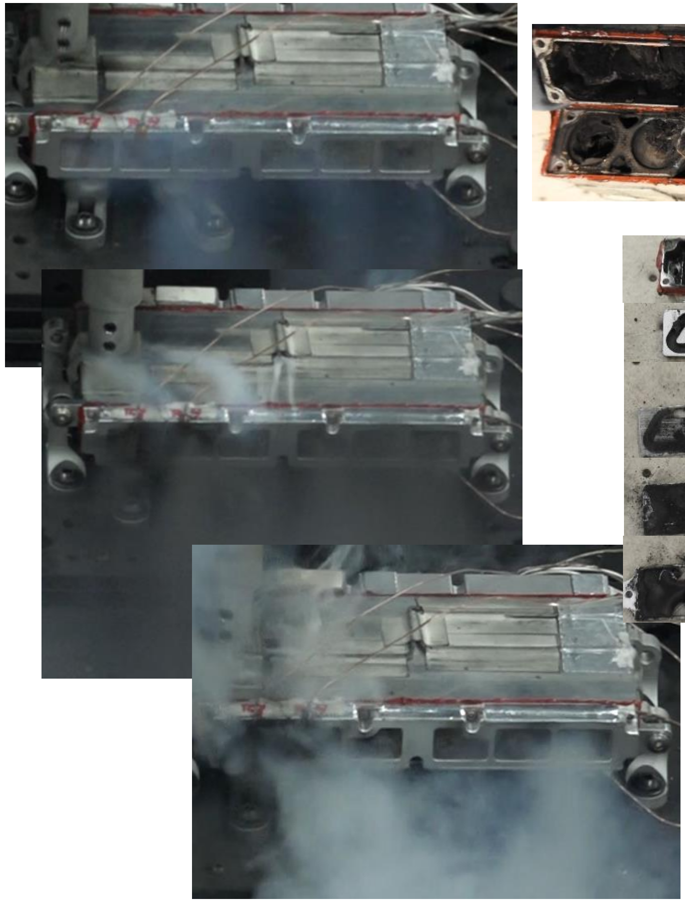
Positive Cavity

Negative Cavity



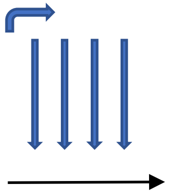


Negative Baffle, no Positive Baffle



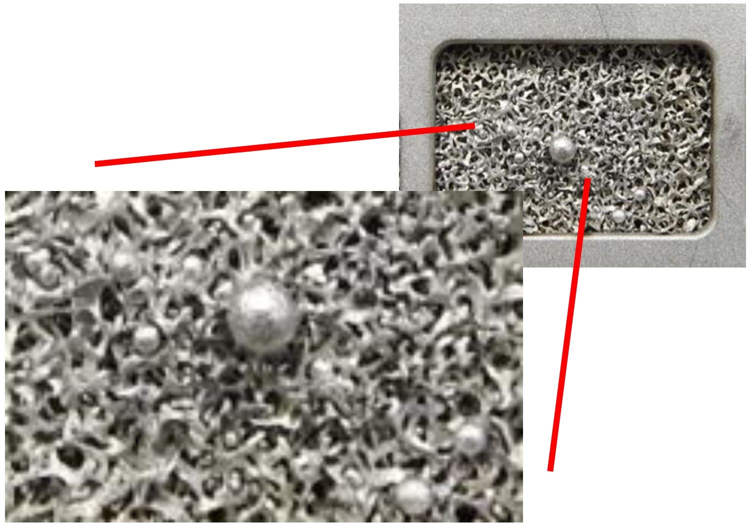
Positive Cavity

Negative Cavity

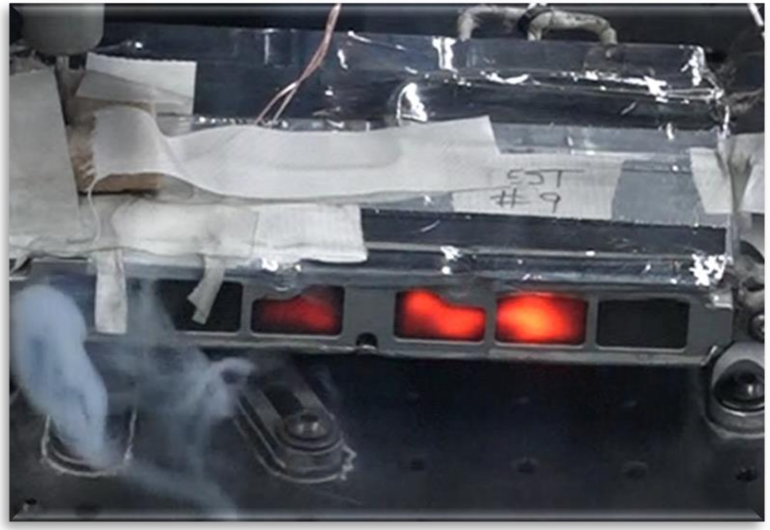


Findings

- Increasing positive side (upstream) resistance degraded filter performance
  - Reduced filter mass loading
- Selecting a material with depth improves filter performance
  - Ejecta degrades Aluminum foam, contributing to spark release (generation)
  - Ceramic materials demonstrate excellent heat tolerance but present fracture concern



Aluminum Foam

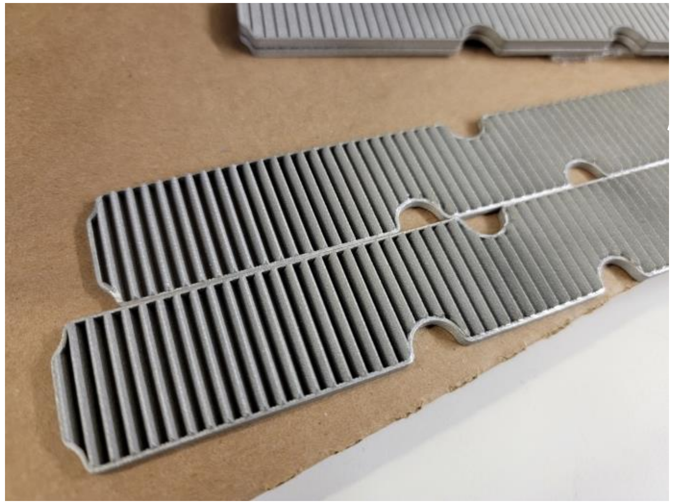


Carbon-Silica Composite

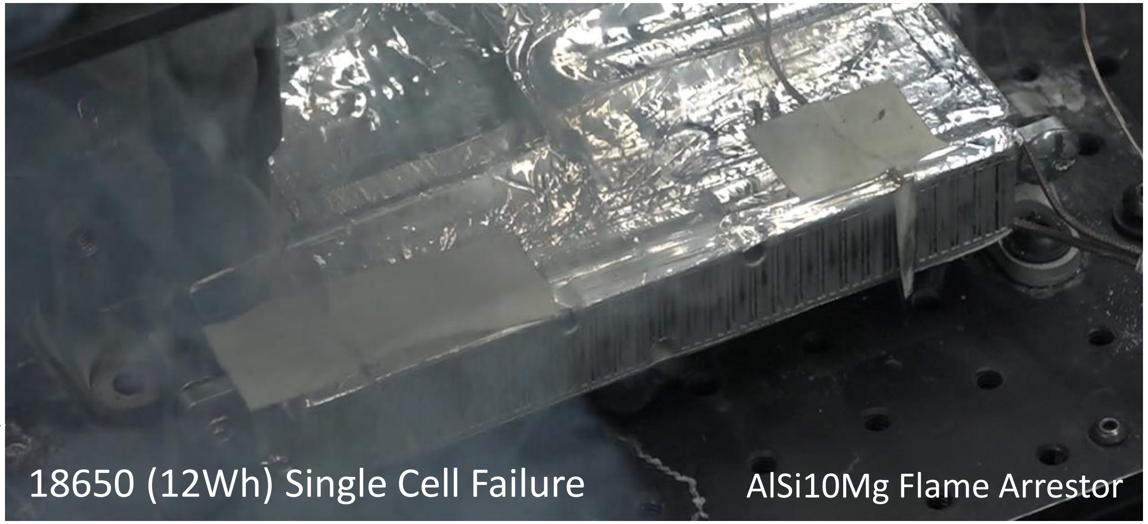
Towards a Robust Depth Filter

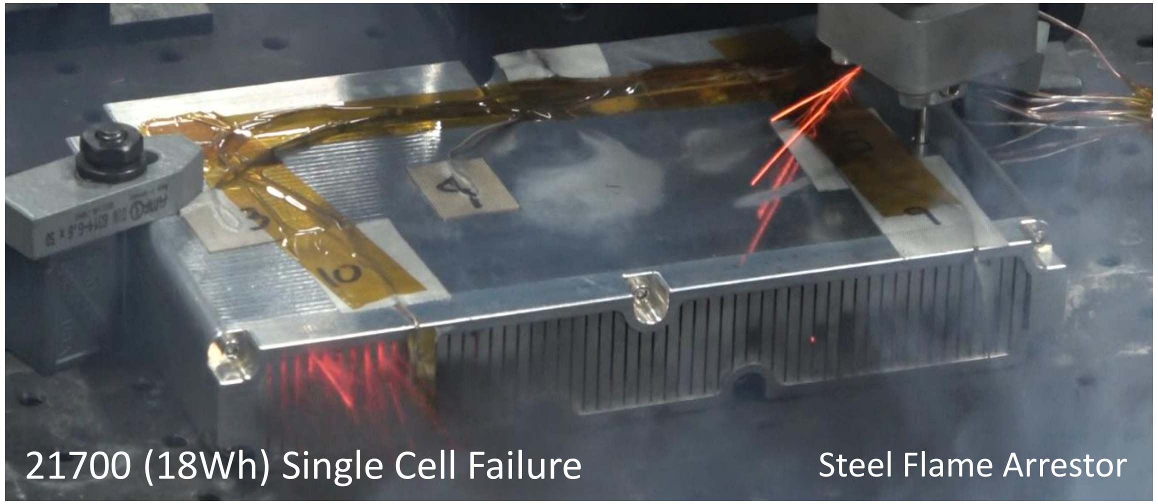
Metal Printing Enables a Wide Range of Solutions

Alternating Louvres



0.015in channel width

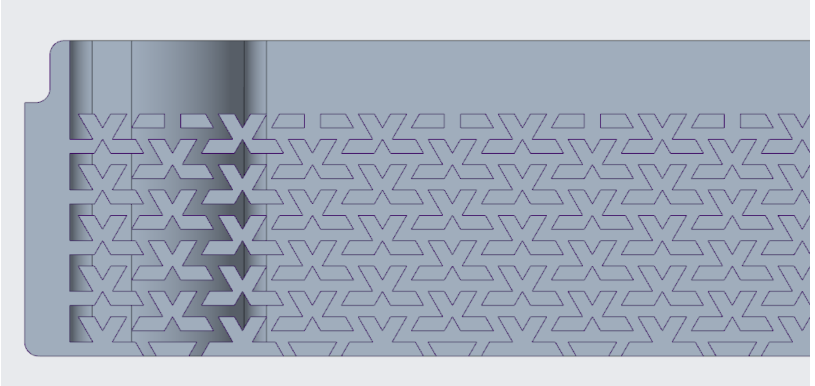




Refine Filter Relationships

- Filter Sizing Parameters
  - Porosity, Surface Area vs Ejecta Flow Stream
- Material Compatibility
  - Galvanically Stable, Enriched Oxygen Tolerant
- System Compatibility
  - Electrically Conductive, Fracture Tolerant
- Scalability Parameters
  - Chemistry, Energy Release
  - Cell Format, Volume Production
  - Battery Design, Free Volume / Path Length

More Complex Options



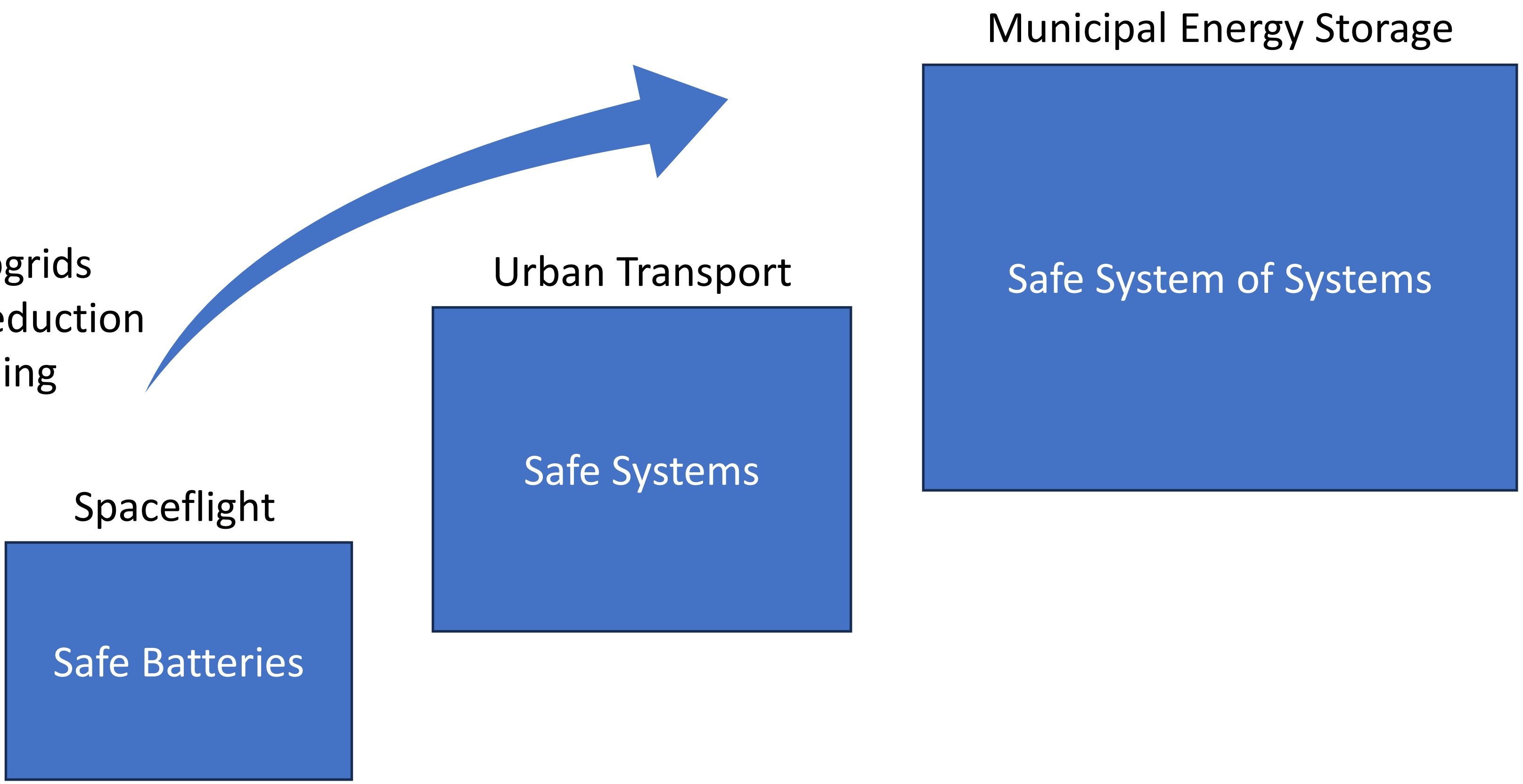
	Channel Size	Vent Area	% Sonic Flow
1	0.015 in	1.07 in^2	70 %
2	0.019 in	1.35 in^2	55 %

Could an Efficient Non-Propagating Solution Improve Adoptability and Reliability in an Increasingly Electrified Economy?

Emerging markets

- Utility Deployment
- Behind the Meter Applications
- Combined Heat and Power Microgrids
- Backup Power, Diesel Fuel Use Reduction
- Energy Storage Vision for Rebuilding
- Power Plants
- Substations
- Critical Infrastructure

[The Role of Energy Storage in Disaster Recovery and Prevention (nema.org)]



Thank you!

Catastrophic Failure of a 96-Cell Test Article

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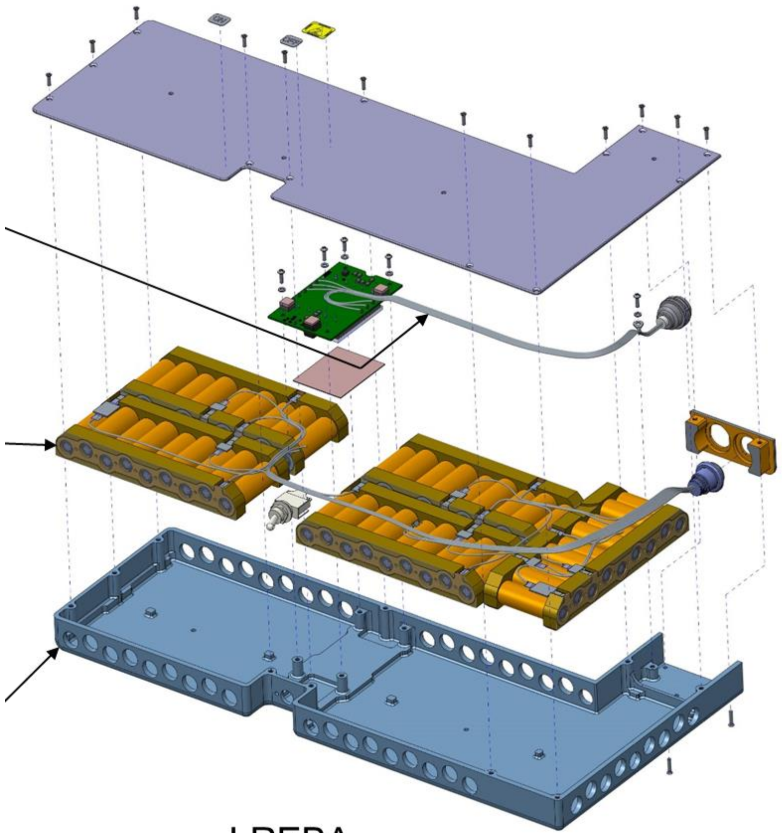
- NASA ISS EHP Program
- NASA Engineering Safety Center
- Jacobs Engineering ICA
- JSC EP DOE

Bio

Samuel Russell is a Project Manager and Systems Engineer at NASA Johnson Space Center responsible for the design, development, and sustaining of battery systems for human spaceflight. With more than twenty years of experience in propulsion and power systems, he managed the development of the first lithium-ion battery in critical human space application, helped advance propagation-resistant battery design, and managed the development of the first three propagation-resistant lithium-ion batteries in human spaceflight. In addition to leading multiple hardware development projects, he also serves as the Portfolio Manager for the NASA JSC Battery Group, overseeing battery, charger, and power supply development, engineering, test, and systems management activities. He is also responsible for battery safety requirement management and serves as a battery subject matter expert across many human spaceflight programs.

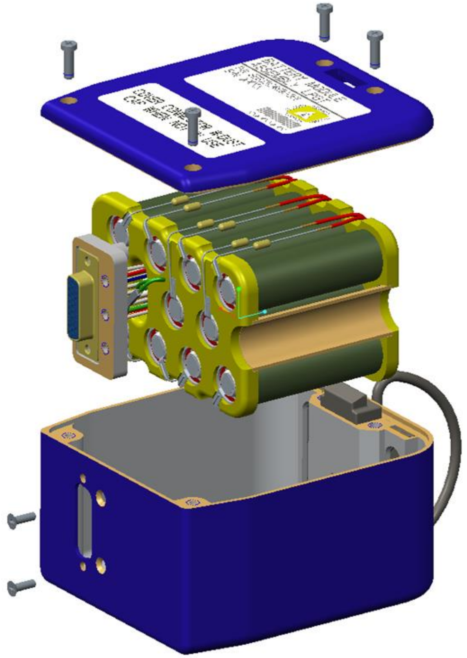
Sam holds a B.S. in Environmental Engineering and an M.S. in Materials Engineering from the New Mexico Institute of Mining and Technology, and a Ph.D. in Systems Engineering from Stevens Institute of Technology. He is a two-time recipient of the JSC Director’s Commendation Award.

Summary of Contributions



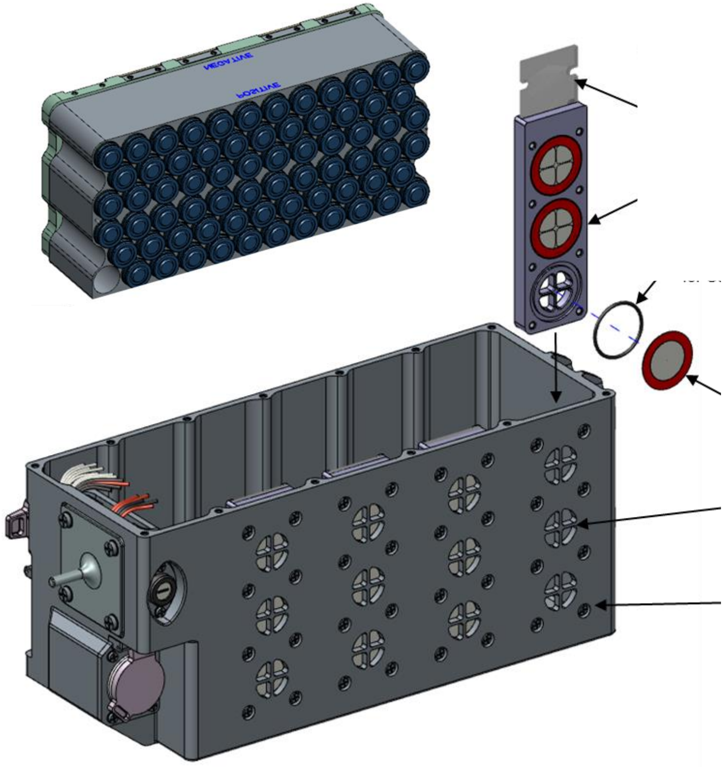
LREBA

- ✓ Cell Isolation
- ✓ Circulating Current



LPGT

- ✓ Internal Recirculation
- ✓ Flame Arrestor



LLB2

- ✓ Thermal Dissipation
- ✓ Particle Filtration

Failure Propagation in 400Wh Li-Ion Battery

Nearly 20 minutes after failure initiation