# Lithium ion Batteries Cell-to-Cell Propagation Risk for Crewed Space Flight

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**2019 European Space Power Conference**

**Juan-Les-Pins, France**

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# NASA Johnson Space Center (JSC), Houston, Texas

- Leader in Human Space Flight and Exploration
  - ISS Mission Control Center
  - Commercial Crew Program
  - Orion human exploration vehicle
- Astronaut Selection and Training Facility

# Agenda

- Introduction
- Thermal Runaway
  - Heat generation
  - Sidewall rupture
- Testing and evaluation
  - Pass/Fail Criteria
  - Understanding Margin
- Engineering a safer battery
  - Design guidelines
  - Successful solutions

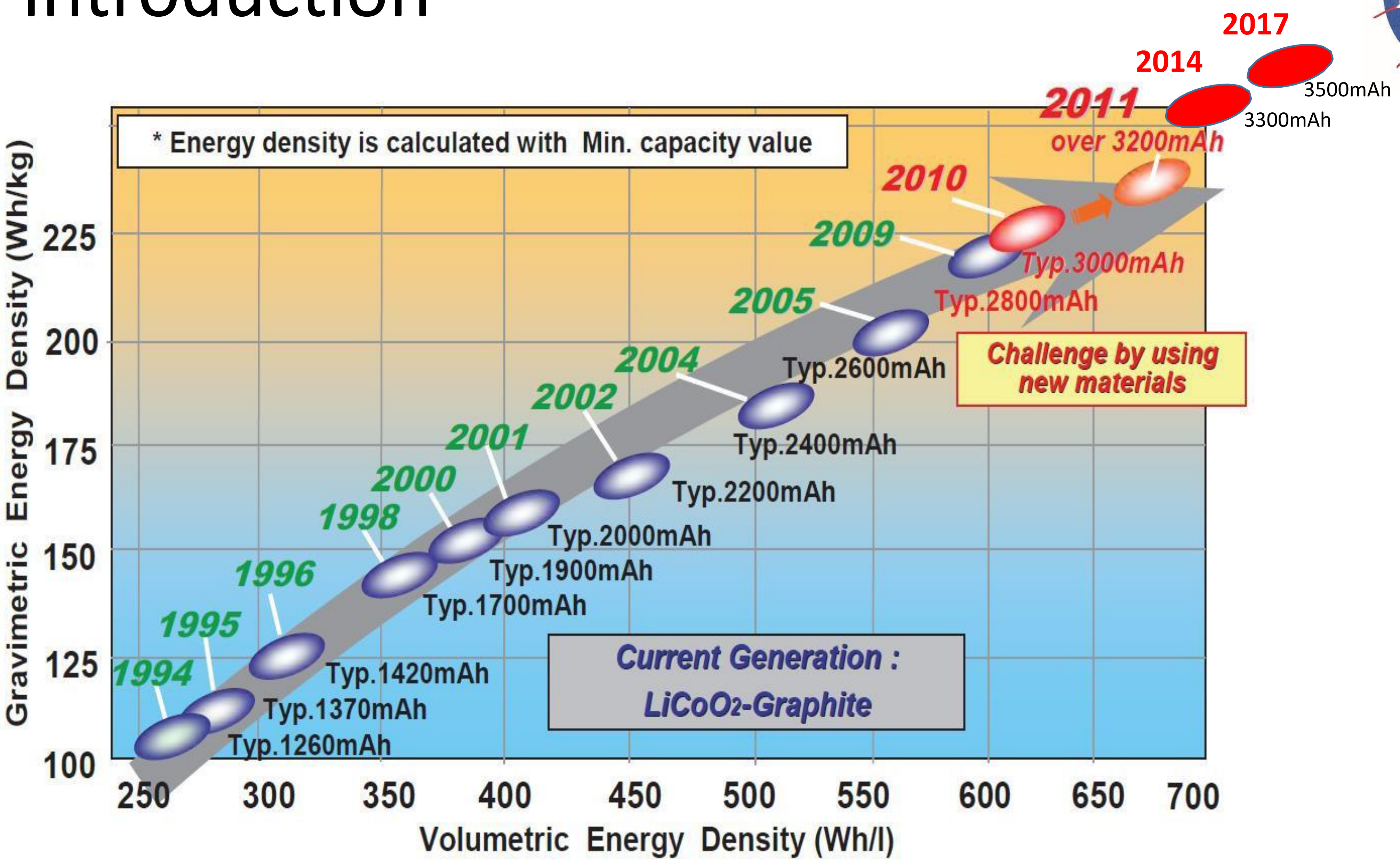
# Introduction

Lithium-ion technology has revolutionized the electronics industry including space applications

Energy content is increasing while cell level safety has not kept pace

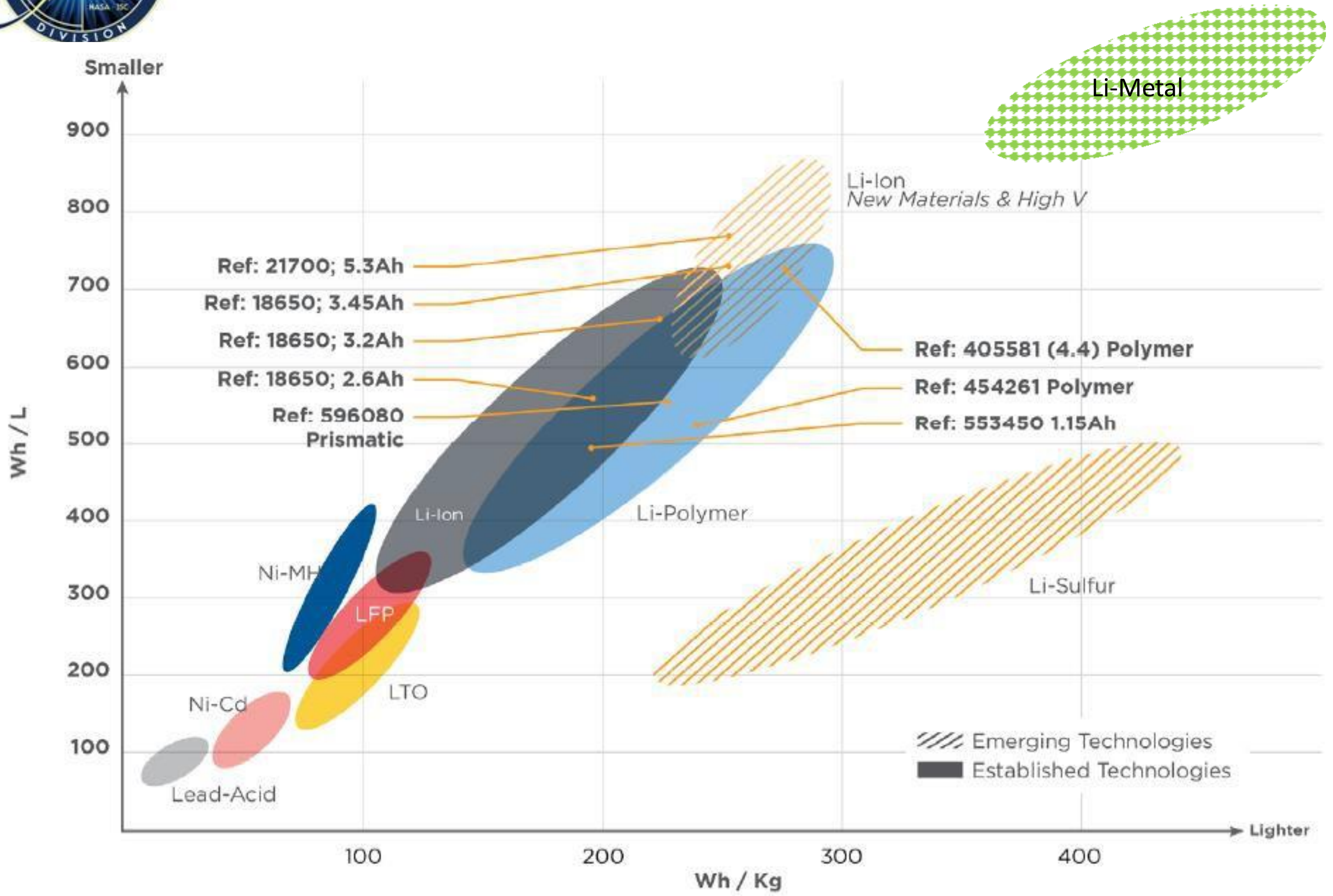
A battery fire is space poses a much bigger threat to the crew than an equivalent fire does on the ground

# Introduction




Source: Sanyo/Panasonic 2010

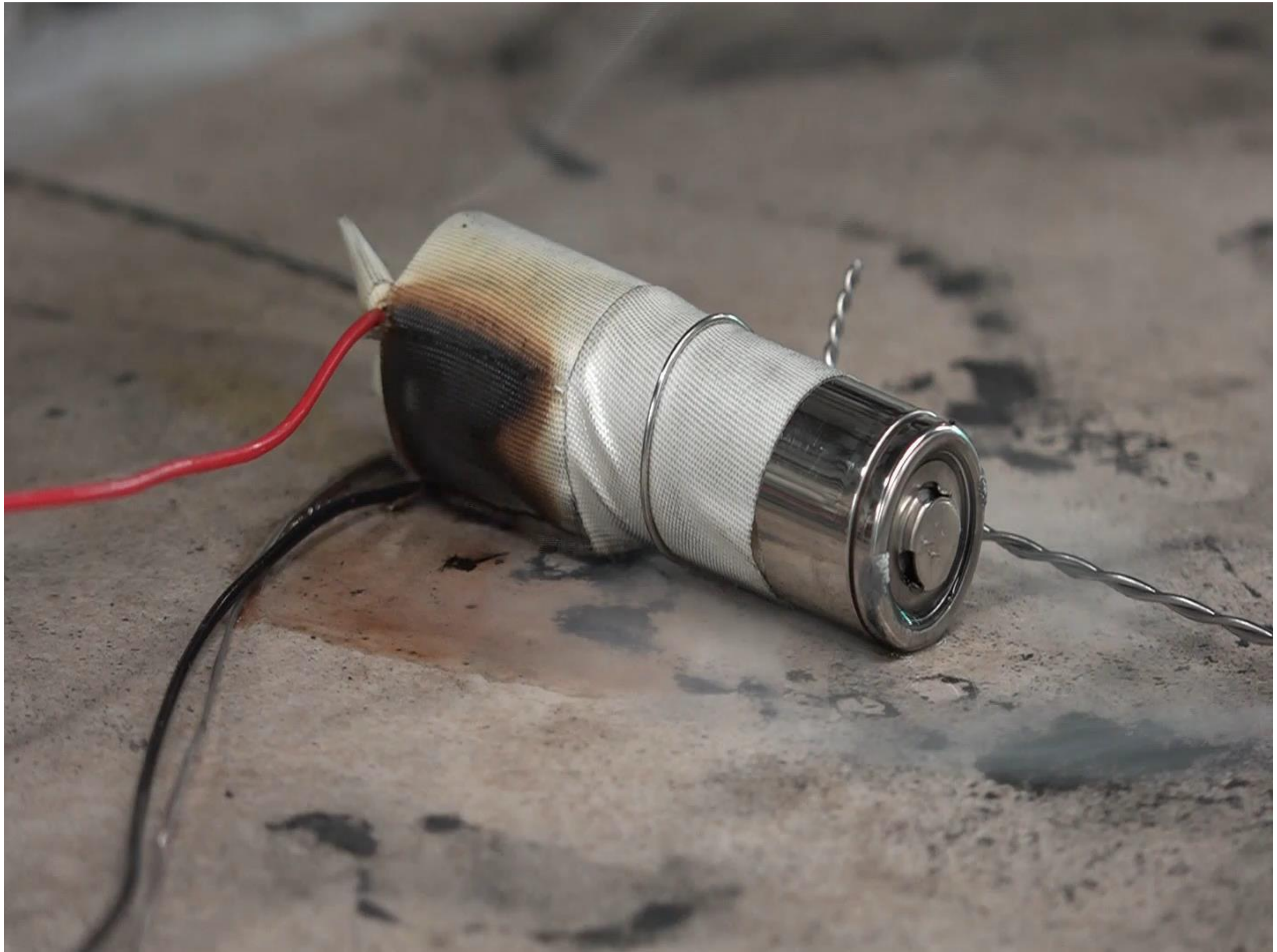
# Specific Energy and Energy Density




*Inventus Power Annual Update on Lithium Ion Battery Technology2018*

- Li-metal and Li-ion all silicon anodes are more likely the emergent technologies
  - ~400-500 Wh/kg and ~350-450Wh/kg respectively
  - Currently small scale low TRL availability but promising
  - Need lower cost and large scale to compete in commercial markets
  - Understand the safety of the emergent chemistries

# Video: 18650 Thermal Runaway



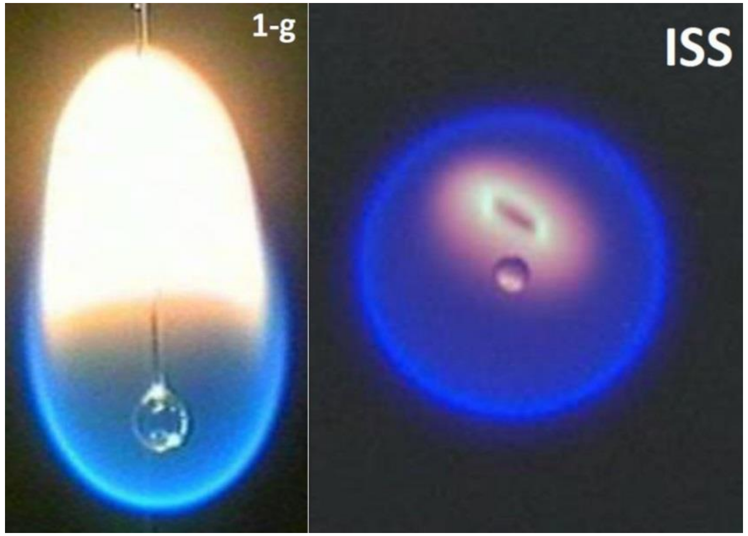
# Video: Robosimian Robot

The research was carried out at the
Jet Propulsion Laboratory, California Institute of Technology,
under a contract with the National Aeronautics and Space Administration.

Jet Propulsion Laboratory, California Institute of Technology

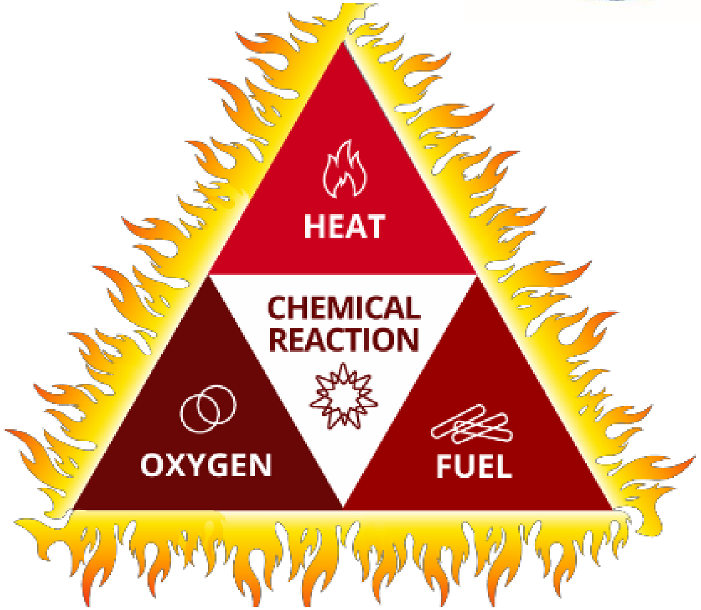
# Battery Fire Risk for Crewed Missions

- A fire can be scary on the ground but is significantly worse in space
  - Li-ion fails with force and in Zero G will propel a battery if not secured to a surface
  - Is Velcro strong enough?
- Gas generated in closed volumes
- ISS is ~800m$^3$ free volume but Carbon Monoxide (CO) is generation due to a battery fire is a significant crew risk
- ISS is good at scrubbing Carbon Dioxide ($CO_2$) but limited in scrubbing CO
  - ~80-90% of gas produced from a li-ion cell is $CO_2$ and CO
- Both $CO_2$ and CO become more of a problem on small crewed vehicles with very limited free volume



# Fire Risk of a Li-ion Battery

- Likelihood of cell going into Thermal Runaway (TR) causing a fire is estimated at 1 in 10M
  - Significantly more likely to have a random battery fire than winning the big lottery (~1:300M)
- Li-ion cell contains all the components necessary to initiate and support a fire
- In general Batteries are recalled when failure rates drop below ~1:1M
- Every year major brands recall batteries in the US and Canada
  - HP, Dell, Apple, Toshiba, Sony, Panasonic…
  - June 27, 2019 Apple recalls 500K MacBook Pro's due to battery "overheating" with



# Commercial Product Failures

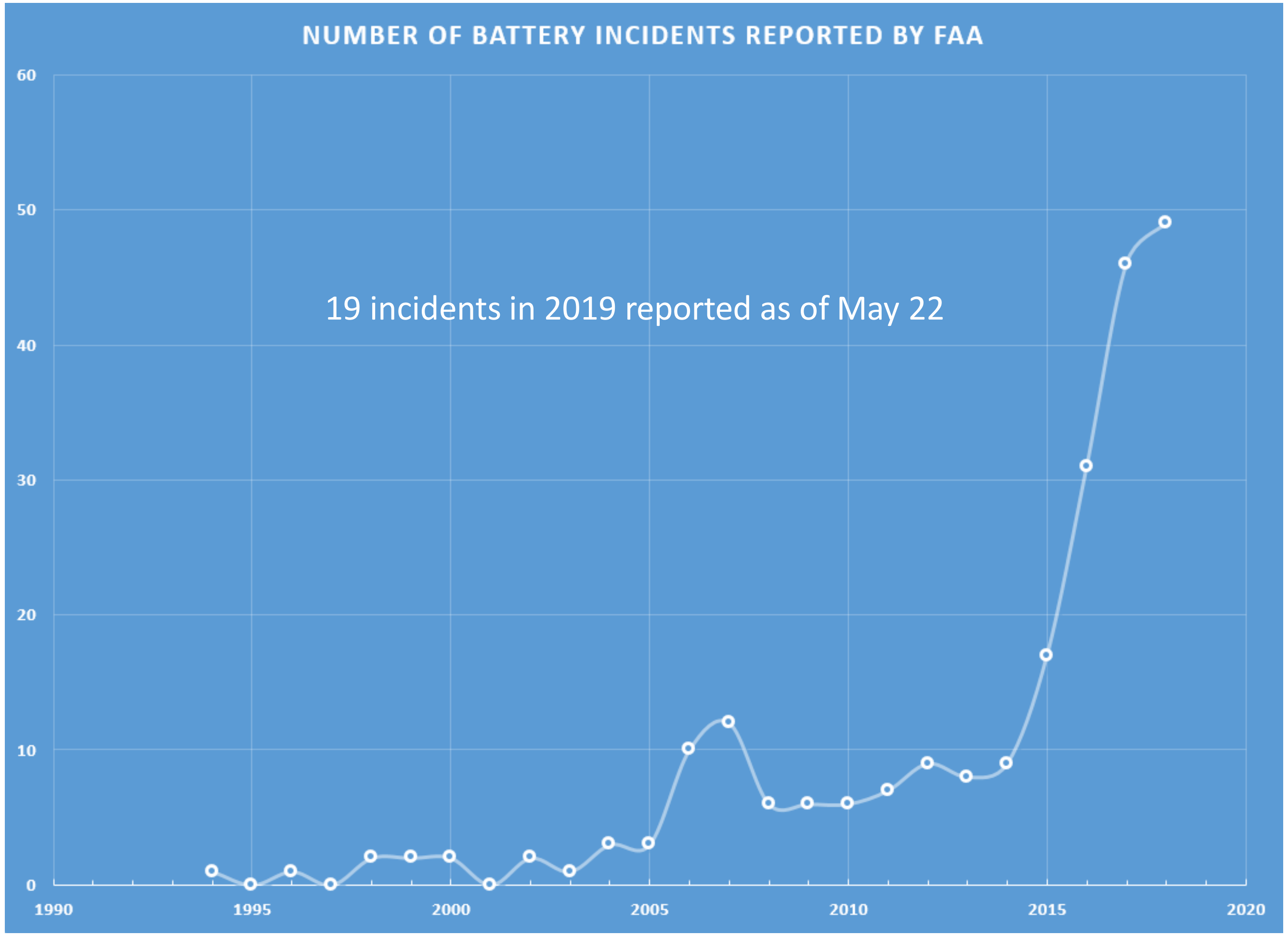
## Recalls of Li-ion Batteries: 2012-2017

| Product | # of Recalls | # Recalled |
|---|---|---|
| Hoverboard | 11 | 502,200 |
| Laptop | 11 | 498,162 |
| Flashlight/Lantern | 3 | 18,305 |
| Tablet | 2 | 83000 |
| Power Bank | 4 | 211325 |
| Charger | 3 | 684007 |
| Battery Backup | 1 | 2500 |
| Jumpstarter | 2 | 14814 |
| E-Bike | 1 | 5000 |
| UPS | 1 | 2876 |
| Cell Phone | 1 | 1920927 |
| Other* | 9 | 289692 |
| | Total | 4,232,808 |

*Other products include baby monitor, gloves, hand warmers, RC car battery pack and wireless speakers

*U.S. Consumer Product Safety Commission, Lithium-ion Battery Safety Standards for Consumer Product Import in the United States, 2017*

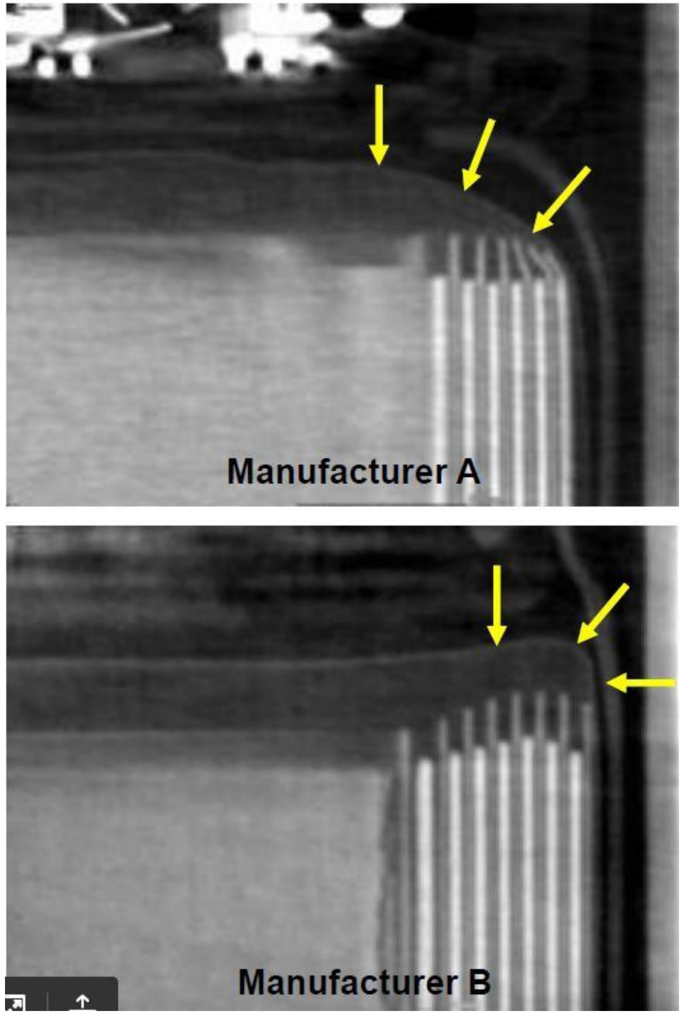
## Lithium Batteries & Lithium Battery-powered Devices Events Involving Smoke, Fire, Extreme Heat or Explosion




*FAA Battery Incident Chart as of 5/22/2019*

# Samsung Note 7

- Samsung Note 7 was down to ~1:40k when the second battery recall was initiated
- First failure mode was damage to the anode due to inadequate volume of the pouch cell
- Second failure mode determined to be welding defects on the cathode tab which were large enough to bridge to the negative tab leading to shorting




Positive Tab

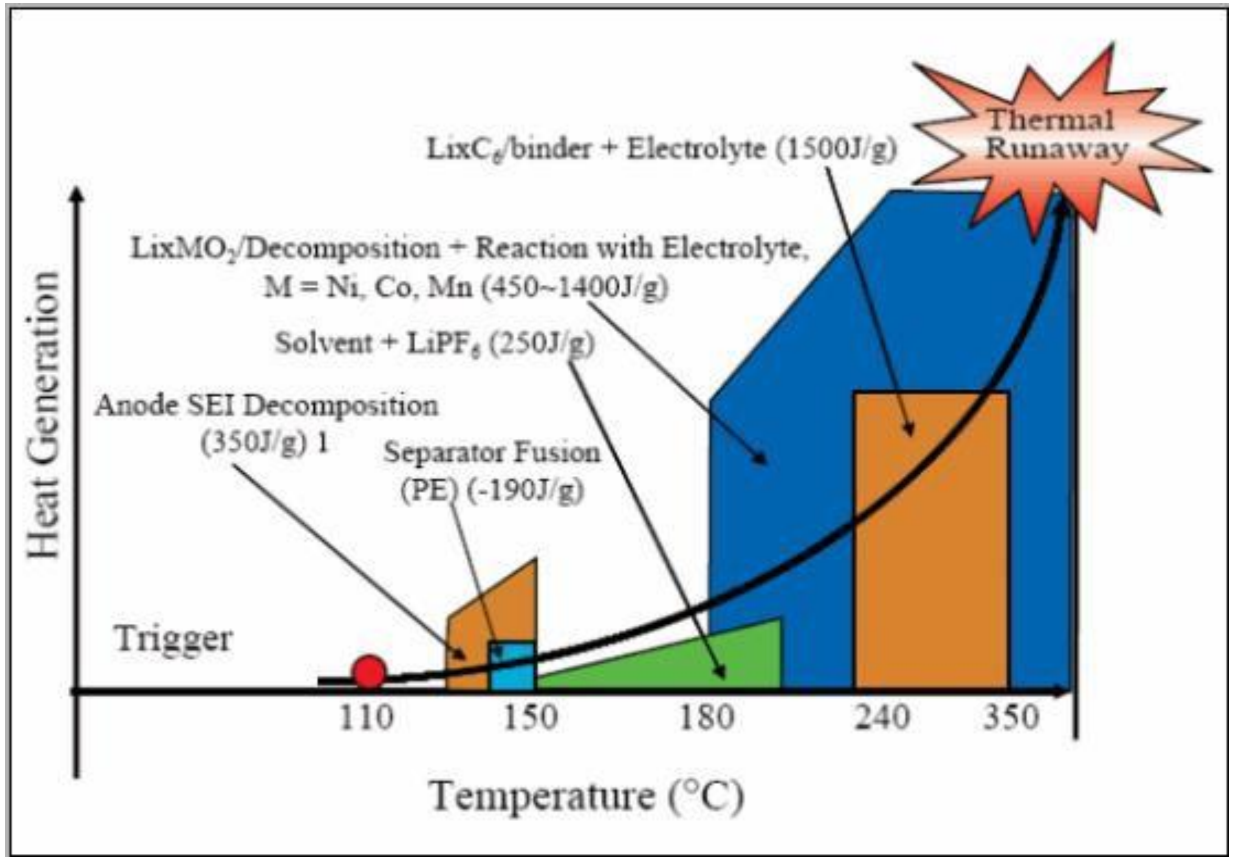
*Exponent, Samsung Recall Support Note 7 Investigation, White, K., 2017*

# 15-inch MacBook Pro Recall

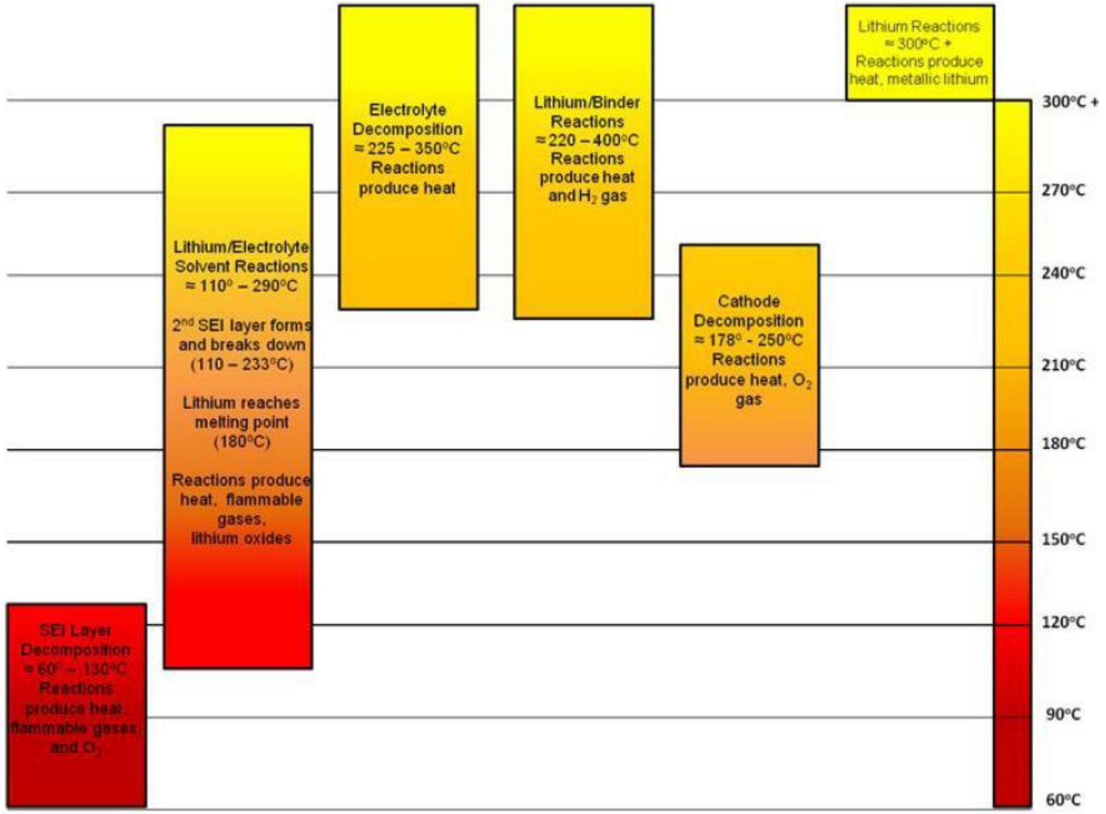
- June 27, 2019 Apple recalls 458,000 15-inch MacBook Pro in the US and Canada
- The MacBook's were sold from September 2015 through February 2017
- 26 reports of overheating
  - 5 reports of minor burn and one of smoke
  - 17 reports of minor property damage
- Approximately 1:19k incident rate
- Cause not provided in the recall notice
- To check if you laptop in included go to: https://support.apple.com/15-inch-macbook-pro-battery-recall
- This will not be last of battery recall for Apple or other manufactures
- US/CA recalls available on all products at www.cpsc.gov

# Thermal Runaway

# Li-ion Thermal Runaway (TR)




*Industrial Materials Magazine, 264 (2008) 118-122*




*NHTSA DOT HS 812 418 Report: Lithium-ion Battery Safety Issues for Electric and Plug-in Hybrid Vehicles*

# Causes of Li-ion Battery Fire

Electrical Abuse

- External Short
- Over Charge
- Over Discharge
- High Rate Charging

Mechanical Abuse

- Crush
- Drop
- Pinch

Thermal Abuse

- External Heating
- Extreme Cold

Melting Separator

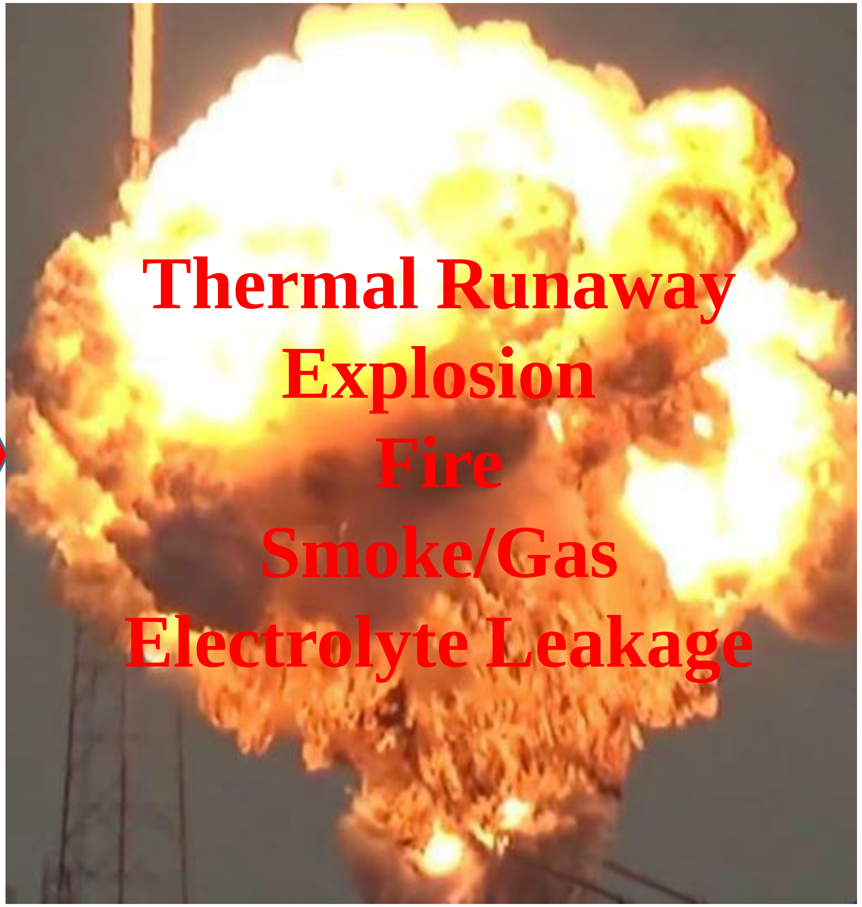
Lithium Dendrites

Lithium Plating

Copper Dissolution

Electrolyte Side Reactions

Internal Short & Excess Heat



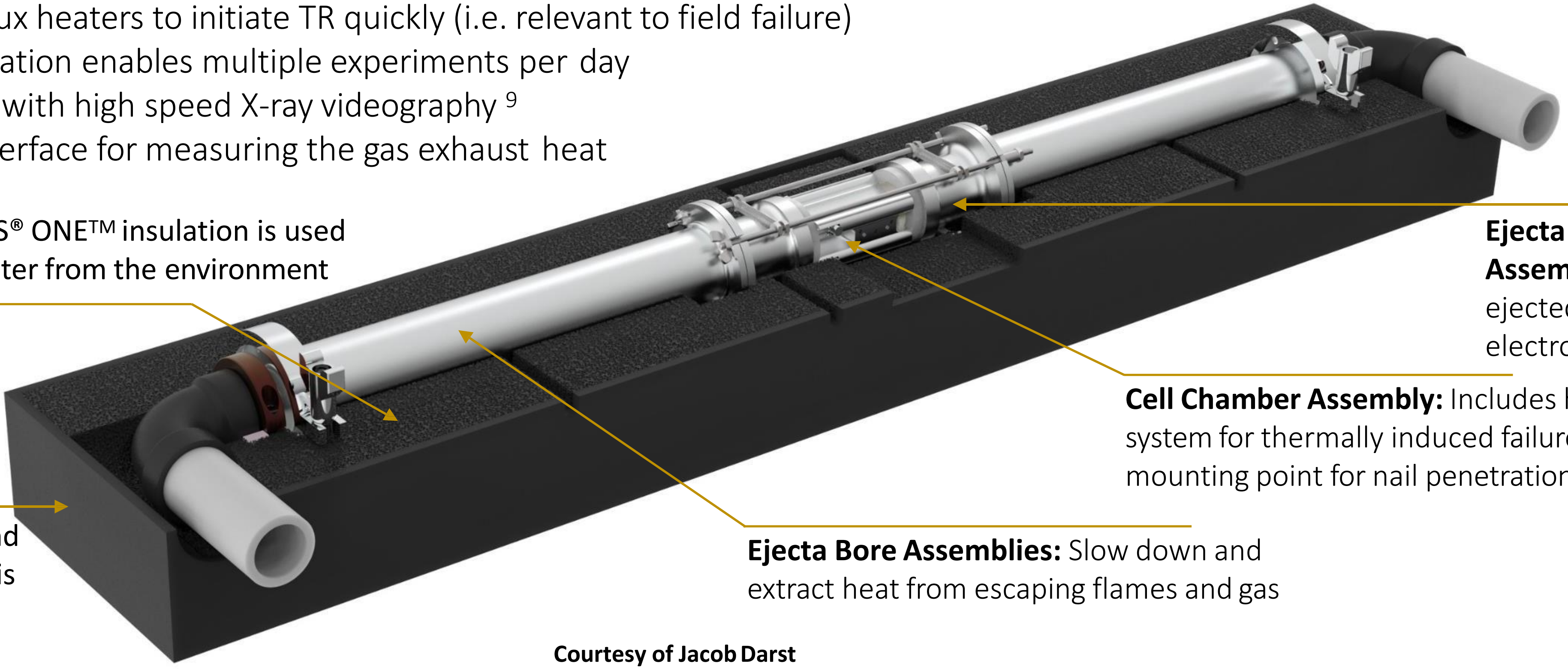

Manufacturing defects can lead directly to internal shorts

# Thermal Propagation

- Understanding of the thermal energy release of a single cell
- Cell selection is critical to designing an non-propagating battery design
  - Small cell vs Large cell formats
  - Energy density/Specific energy
- Managing the thermal environments and discharge rates during normal operations while designing for single cell thermal runaway can be challenging
  - High power systems require additional resources to manage heat loads

# FRACTIONAL THERMAL RUNAWAY CALORIMETRY (FTRC)

- **As an NESC assessment, NASA developed a new fractional TR calorimetry (FTRC) method for 18650-format Li-ion cells:**
  - Collaborators included NESC, NASA JSC, and SAIC
  - Allows discernment between (1) total heat output and (2) fraction of heat released through the cell casing vs. ejecta material
  - The energy distributions are determined by post processing temperature vs. time for each calorimeter sub-assembly (i.e. $\sigma \; m_i C_{p_i} dT_i$)
  - Ambidextrous configuration accommodates cell designs with bottom vents (BVs)
  - Uses high flux heaters to initiate TR quickly (i.e. relevant to field failure)
  - Simple operation enables multiple experiments per day
  - Compatible with high speed X-ray videography [9]
  - Optional interface for measuring the gas exhaust heat



**Insulation:** FOAMGLAS® ONE™ insulation is used to isolate the calorimeter from the environment

**Ejecta Mating Assemblies:** Captures ejected solids such as the electrode winding

**Cell Chamber Assembly:** Includes heating system for thermally induced failure and mounting point for nail penetration system

**Housing:** Lightweight and shipping ready housing is employed to support hardware mobility

**Ejecta Bore Assemblies:** Slow down and extract heat from escaping flames and gas

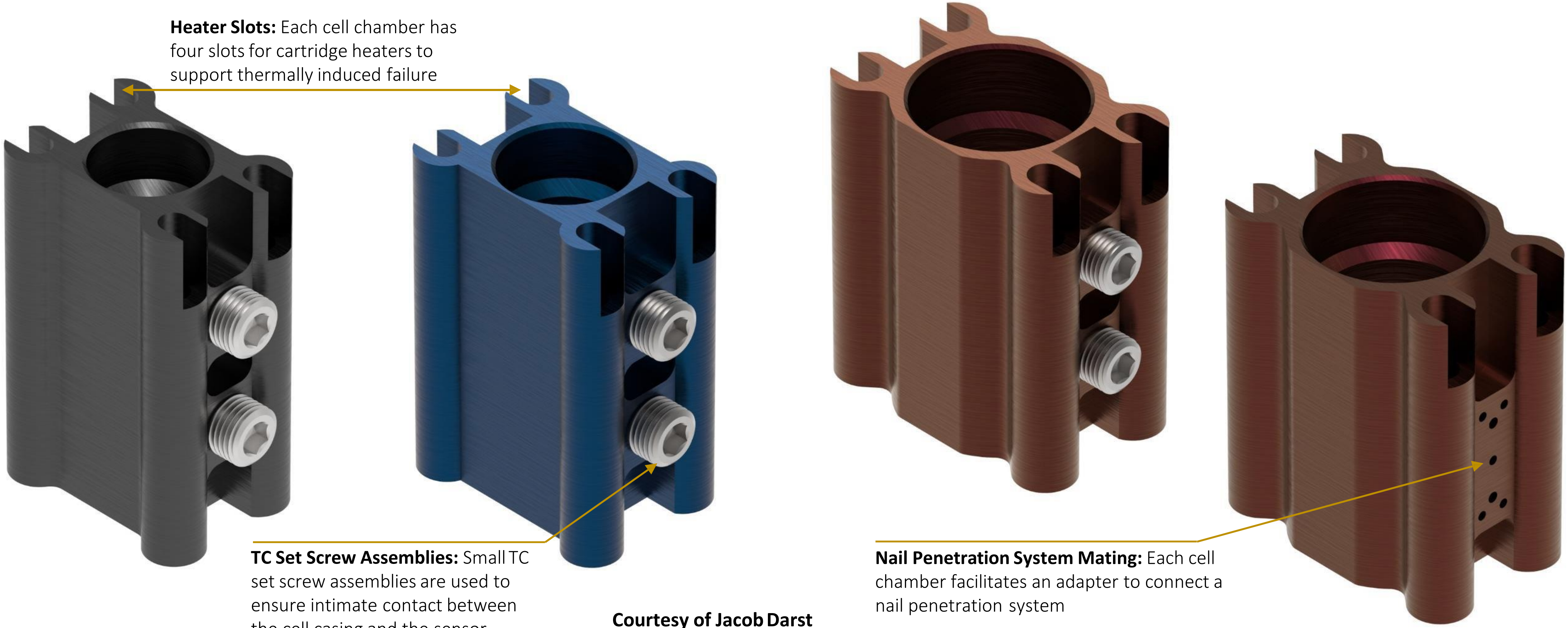
**Courtesy of Jacob Darst**

**Images submitted to Journal of Thermal Analysis and Calorimetry on May 1st 2019**

# FTRC Cell Chambers

- **The FTRC currently supports cell chambers designed for the following cell formats: 18650, 21700, and D-Cell:**
  - Utilizes the same downstream FTRC assemblies (i.e. the only adjustment to test a new cell is to swap out the cell chamber)
  - The current architecture supports cells with >5 Ah capacities
  - Stay tuned for new capabilities to support pouch cells and larger format cells…

**Heater Slots:** Each cell chamber has four slots for cartridge heaters to support thermally induced failure



**TC Set Screw Assemblies:** Small TC set screw assemblies are used to ensure intimate contact between the cell casing and the sensor

**Nail Penetration System Mating:** Each cell chamber facilitates an adapter to connect a nail penetration system

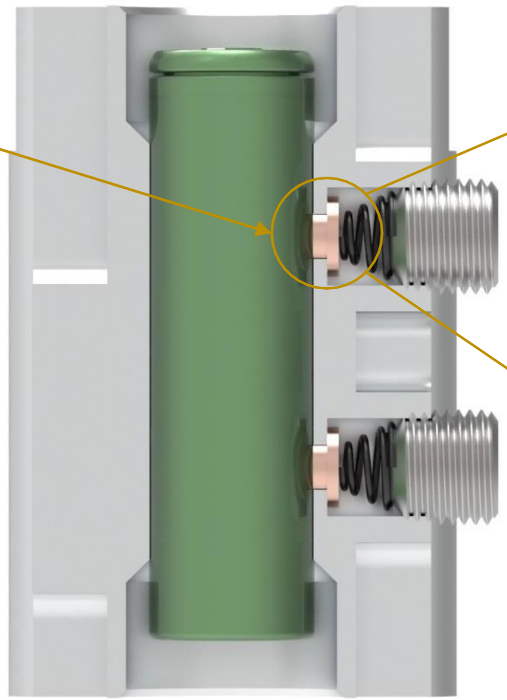
**Courtesy of Jacob Darst**

**Images submitted to Journal of Thermal Analysis and Calorimetry on May 1st 2019**

# FTRC

- **Reliable temperature measurement from the side of the cell is critical to accurate calculation of the fraction of thermal runaway energy released through the cell casing:**
  - To support temperature measurement on the cell casing without actually installing a thermocouple, the FTRC cell chambers employ plunger like set screw assemblies that contain an imbedded thermocouple
  - When released, the spring loaded set screw assembly forces intimate contact between the embedded thermocouple and the cell casing

**TC Set Screw Assemblies:** Used to maintain intimate contact between the cell casing and the thermocouple



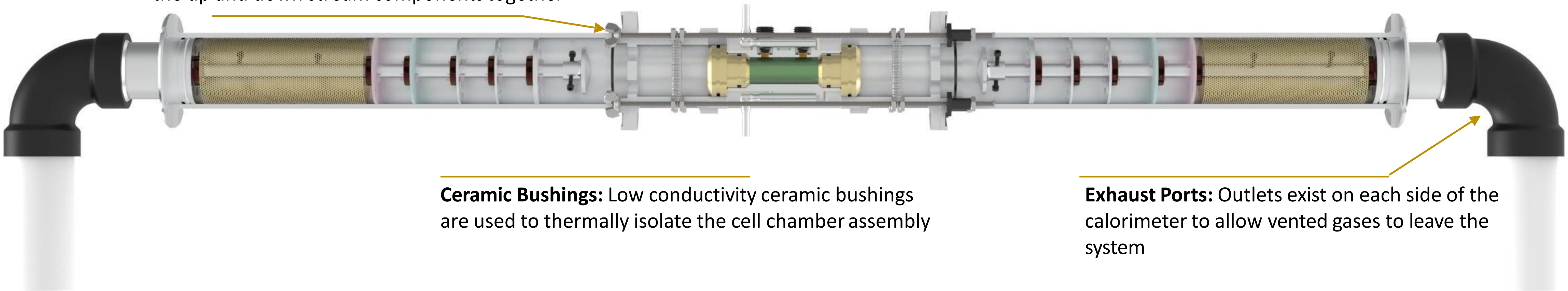
**X-Ray Image:** Image reveals the contact between the TC set screw assembly and an 18650 Li-ion cells installed in the FTRC during testing at Diamond Light Source in 2019.

**Courtesy of Jacob Darst**

**Images submitted to Journal of Thermal Analysis and Calorimetry on May 1st 2019**

# FTRC Design

- **The FTRC is designed to not only facilitate testing of different cell types, but to also help characterize directional/fractional thermal runaway failure behavior (i.e. top vent, bottom vent, ruptures from any location, et…)**
- **The cell chamber assembly is isolated from the remainder of the up and down stream calorimeter components with low conductivity ceramic bushings:**
  - Maintaining this thermal isolation is critical to our team's ability to discern the fraction of energy released through the cell casing vs. through the ejecta material
  - The ejecta mating segment is designed to capture and stop complete jellyroll ejections; with this capability, we can also determine the fraction of energy associated with an ejected jellyroll

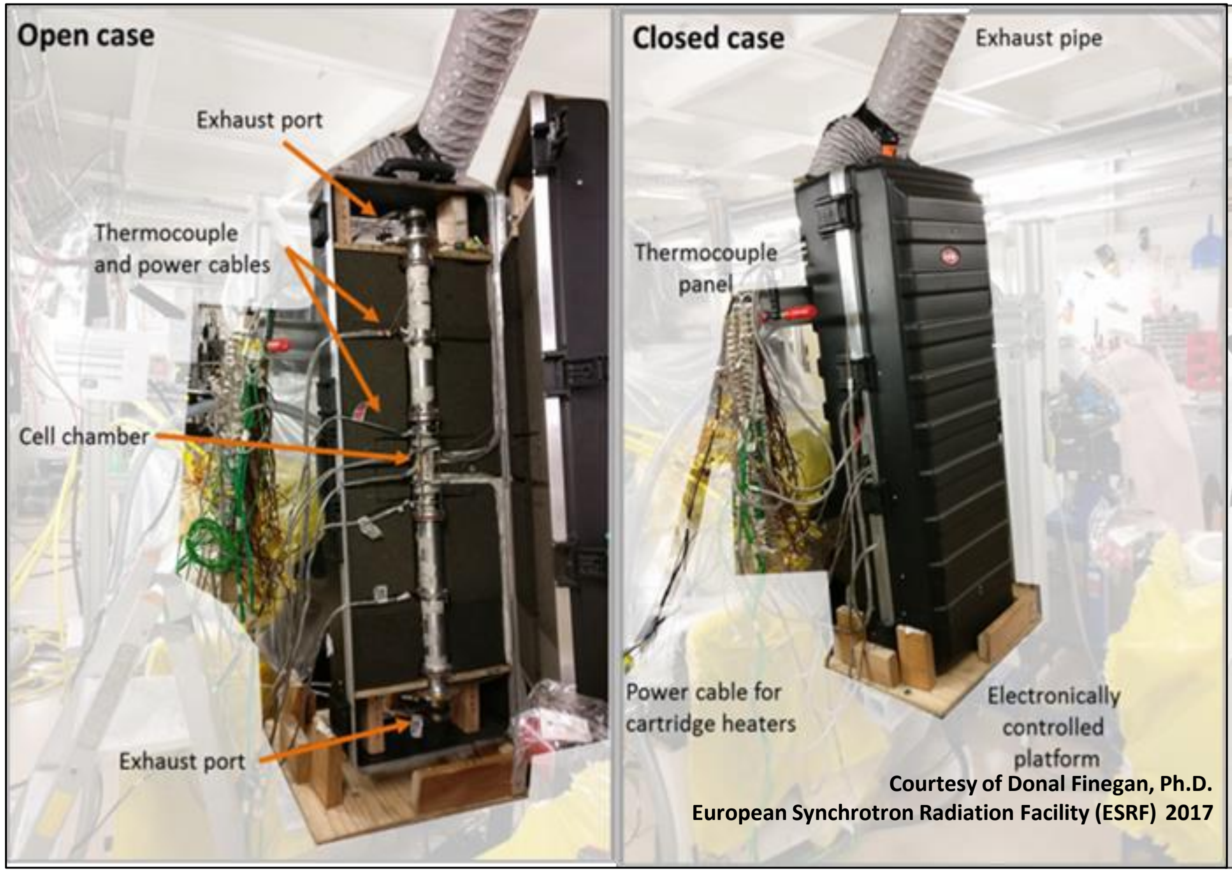



**Courtesy William Walker and Peter Huges**

**Images submitted to Journal of Thermal Analysis and Calorimetry on May 1st 2019**

# High Speed X-ray Tomography

- **Images below depict the global testing capability of the device:**
  - FTRC testing at the NASA JSC Energy Systems Test Area
  - FTRC testing at the European Synchrotron Radiation Facility (ESRF) for in-situ high speed tomography (left image)
  - FTRC testing at the Diamond Light Source (DLS) Facility for in-situ high speed tomography (right image)



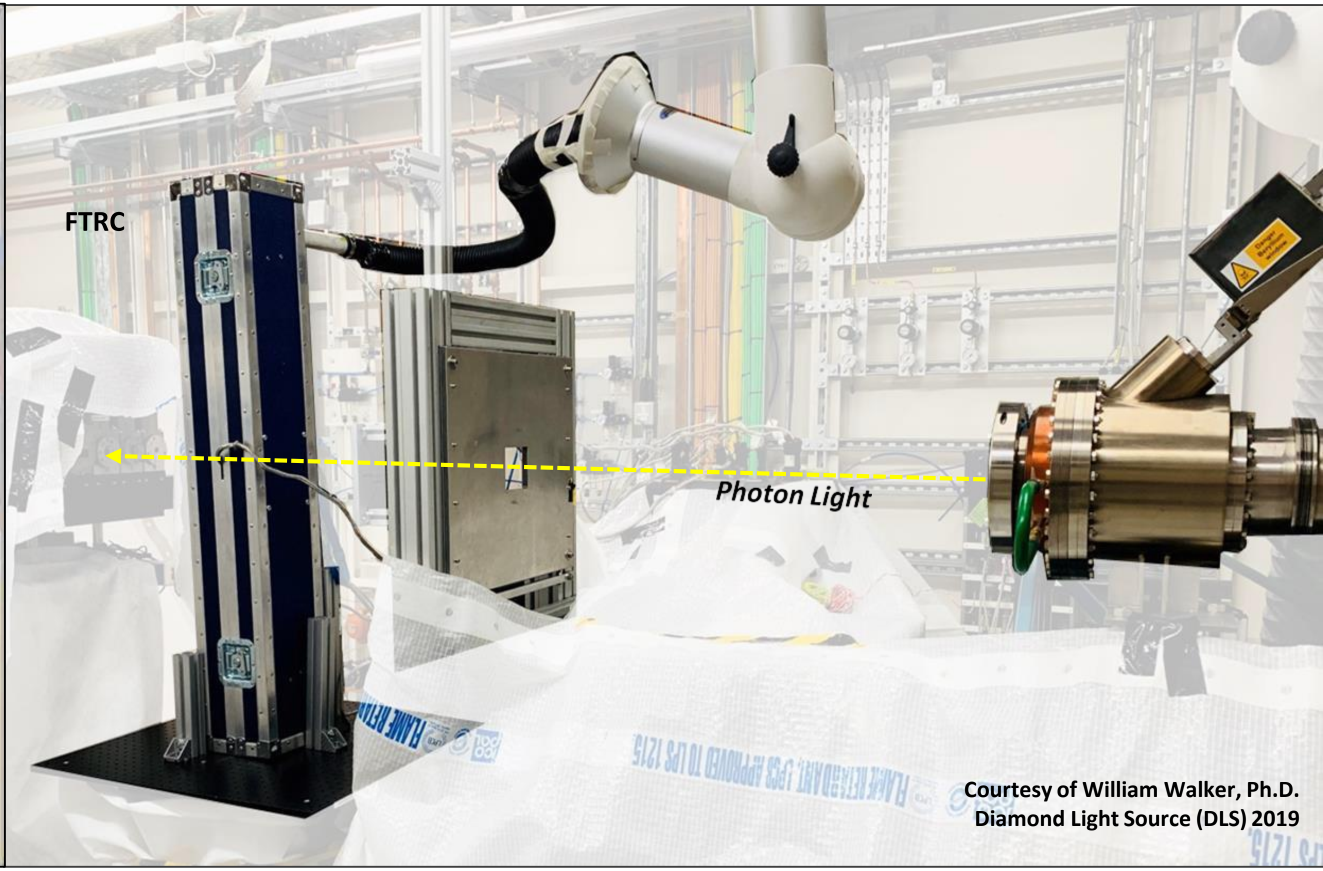
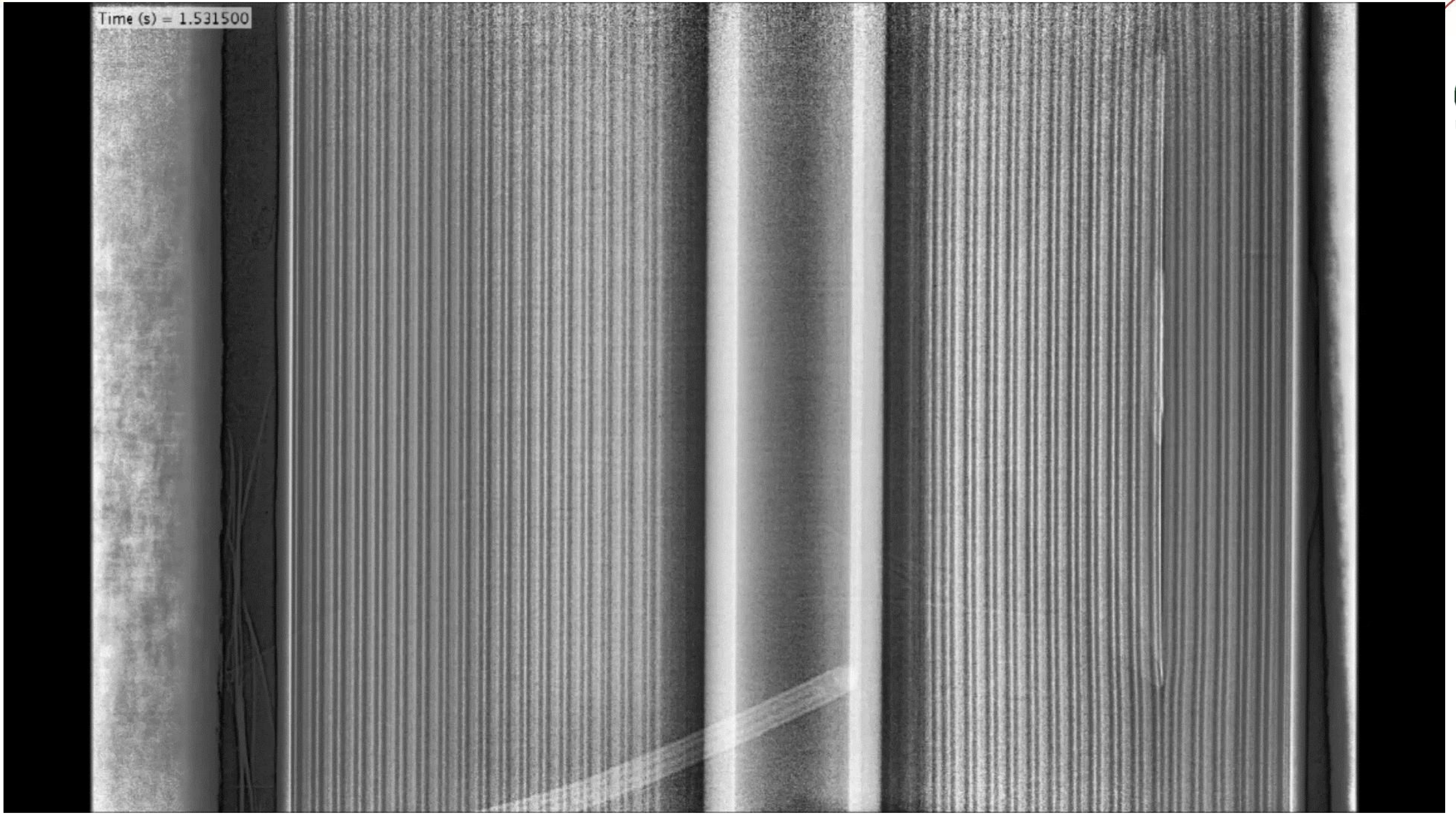
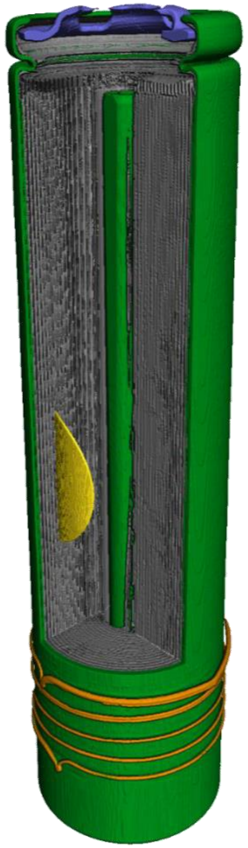




Image submitted to Journal of Thermal Analysis and Calorimetry on May 1st 2019

# EXAMPLE FTRC TESTING

# 2.4Ah Cell with ISC Device – JR Ejection



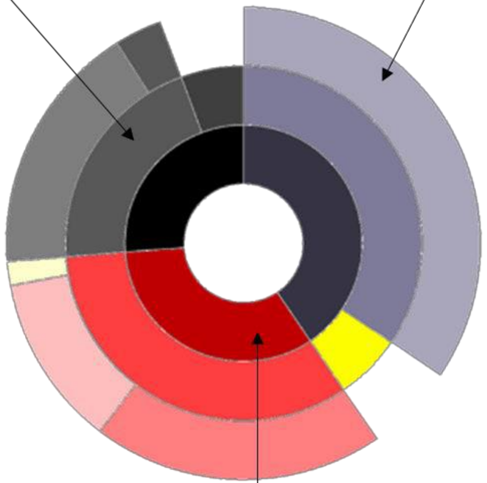



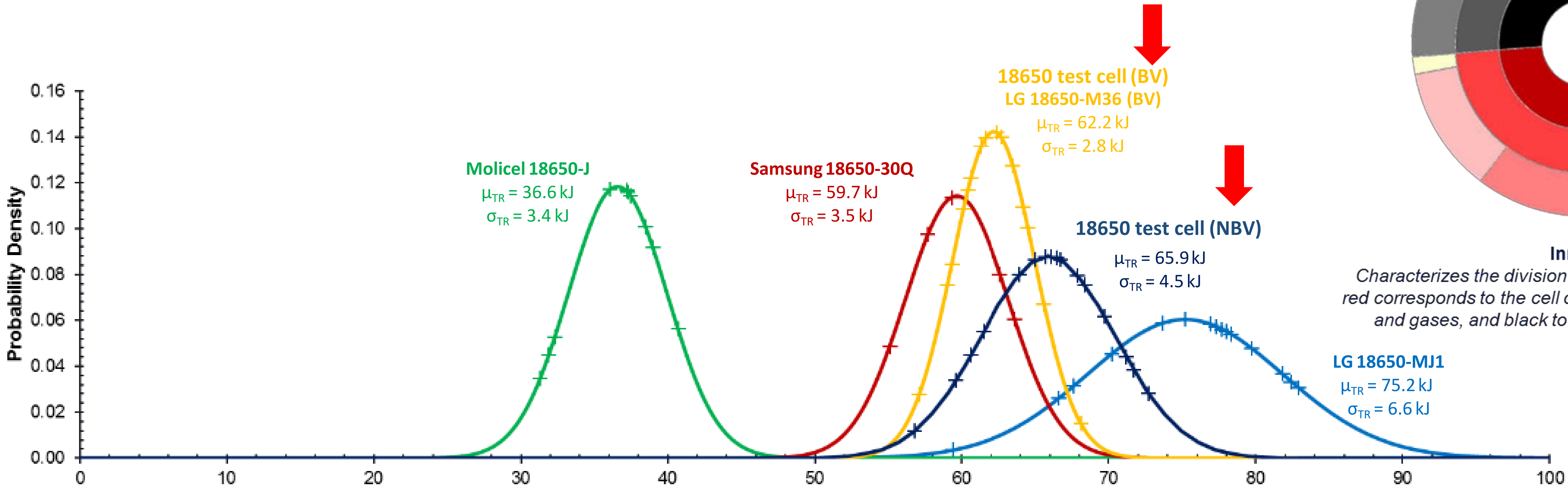
Video courtesy of D. Finegan, UCL

# Fractional thermal runaway calorimeter (FTRC)

## Statistical assessment of thermal behavior

- **The thermal runaway results for each experiment are post-processed with consideration given to the following:**
  - Total heat output during thermal runaway
  - Heat release fractions (see image on right)
  - Remaining cell mass post-thermal runaway
- **Observations from total heat output measurements:**
  - Cells with a bottom vent (BV) produce less heat than non-bottom vent (NBV) cells
  - The standard deviation for BV cells is less than NBV cells

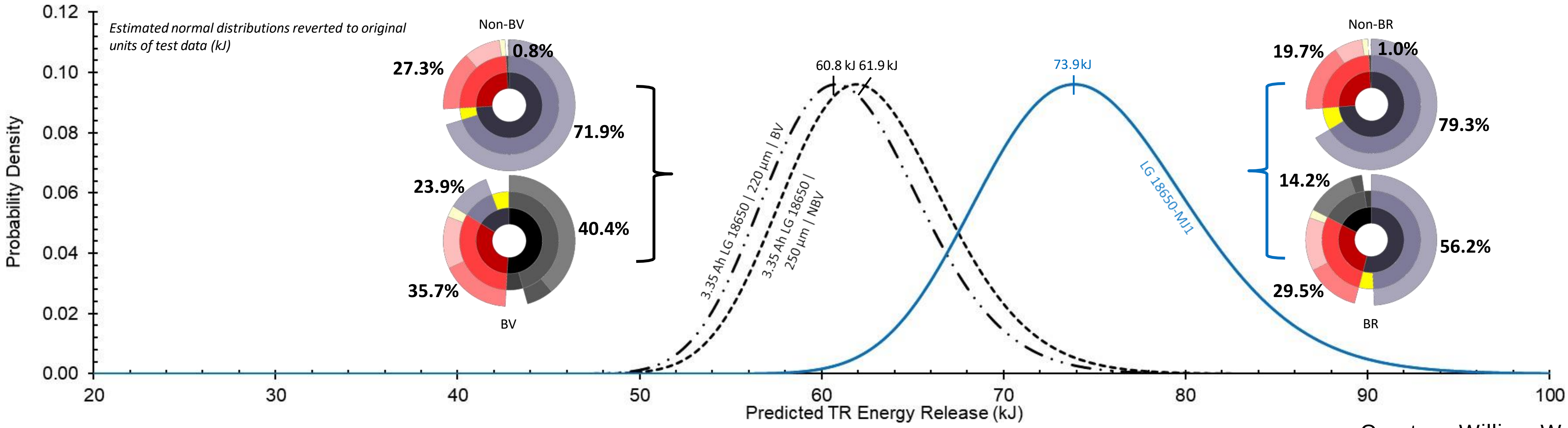




Courtesy William Walker (NASA)

# FTRC Results: Energy Release Fractions

- **The thermal runaway energy release fractions are determined for every cell configuration:**
  - Fractions can be determined from an average of all results for a given cell type or can be an average based on nominal vs. off nominal failure mechanism (e.g. difference between top vent vs. bottom rupture)
  - Fractional analysis is particularly helpful in comparing the distribution of standard vent cells to bottom vent cells
  - Standard cells typically release 20-30% through the cell casing and the remainder through the ejecta material
  - Bottom vent cells tend to release the energy in a three-way split between the casing and the top and bottom ejecta materials

- **The fractions quantify the direct impingement of energy on neighbor cells during runaway events**

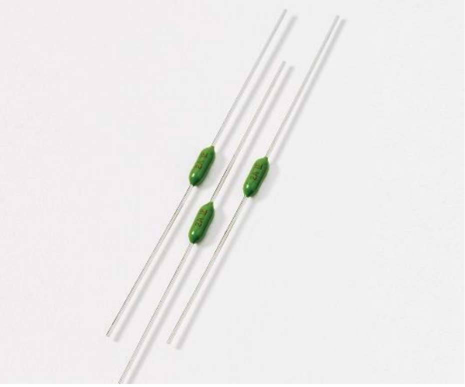


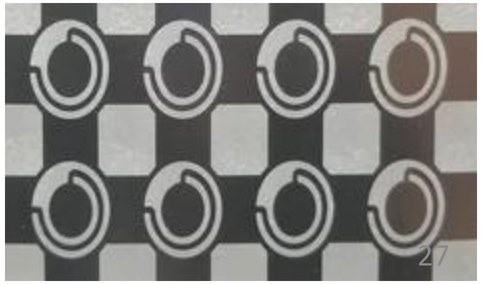

Images and data analysis submitted to J. Power Sources August 2018

Courtesy William Walker (NASA)

# Electrical Propagation

- Electrical connective in parallel can lead to propagation
  - Conduction propagation testing without electrical connectively of the battery can lead to inaccurate results
- When a cell goes into TR remaining cell carcass provides a short path with all remaining cells connected in parallel
  - The additional heat generated from cells in a hard short will cause propagation even in designs demonstrated to be successful thermally
  - CIDs are NOT effective with multiple cells in parallel
- Debris from a TR can bridge the neighboring cells leading to a soft short adding additional heat
- Solution is to fuse all cells in a parallel and between parallel strings
  - Fusing both the positive and negative connections is preferred but if only one side will be fused then select the negative side
  - Fuse should be fast blow on a hard short but leave margin for normal operations and transient loads



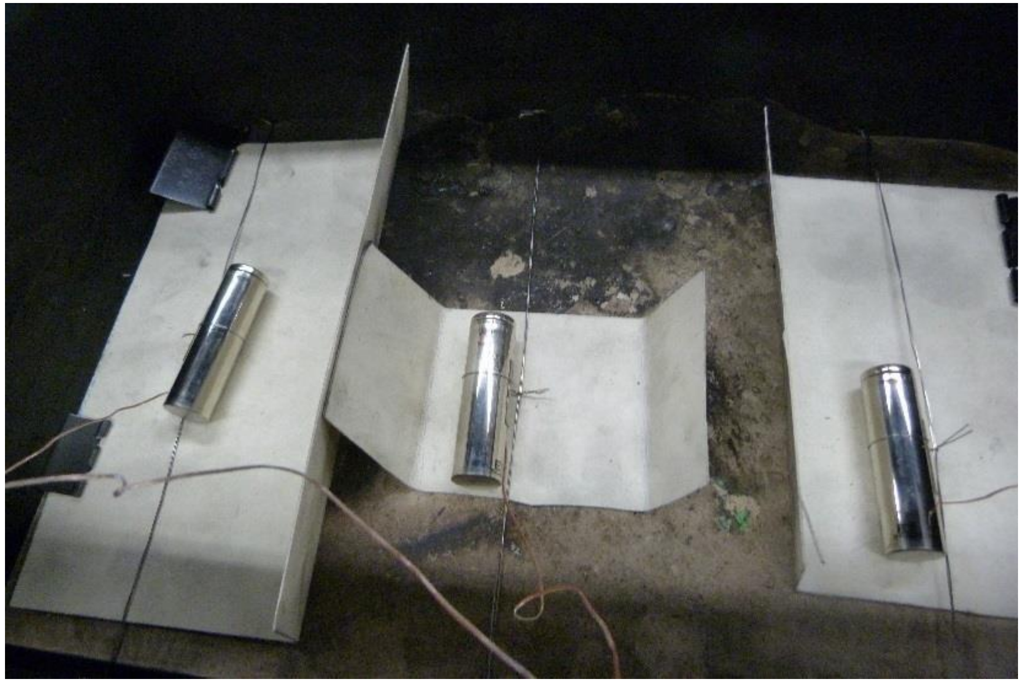


# Mechanical Failure

- Protections for both thermal and electrical propagation can be defeated by mechanical failures if not mitigated!
- Sidewall breaches (SWB) can directly imping on neighboring leading to propagation
- SWB Contributing factors include:
  - Energy content: ≥2.6Ah
  - Can wall thickness: <200 microns increased likelihood of a SWB
    - Cell cans range from ~125-250 microns thickness
    - Supported thin can wall via interstitial material
  - Header crimp compression and limited header expansion room

# Side Wall Breaching Risk

- Establish cell design's propensity for sidewall breaching failure rate
  - Unsupported can wall (bare cans)
  - Slow oven heating to TR
  - Found 10% breaching rate for the NCR18650B



# Testing and Evaluation

# Battery Classifications

Important: Battery classification should be correctly identified as soon as possible to determine necessary testing!

| JSC 20793 | JWI 8705.3 | Definition |
|---|---|---|
| Non-Critical | Low BRC | • Lowest level of hazard control that is reserved for low energy cells and battery designs for which standard emergency procedures are written and practiced |
| Critical | Medium BRC | • Typically manufactured in high volumes for the consumer<br>• Have commonly available means to help determine the reliability and safety of the products.<br>• Due the consequence of a failure, these End Items will follow a comprehensive test and validation plan |
| Catastrophic | High BRC | • Typically custom, high energy, or high power designs<br>• Due to the extreme consequence of a failure, these End Items will follow a comprehensive test and validation plan that includes testing to determine the result of single cell thermal runaway<br>• Analysis of the thermal runaway can lead to a redesign of the battery to mitigate the consequence. |

- BRC – "Battery Risk Classification" is defined in the JWI 8705.3 but will be incorporated into the SSP 51721 along with JSC 20793 Revision E and any future updates to battery procedures and guidelines
- The terms "non-critical", "critical" and "catastrophic" described above differs in context and are not to be confused with the ISRP hazard severity definitions as defined within SSP 30599, SSP 50021, and SSP 51700.

# High BRC Batteries

- Batteries within this classification do not meet the Low and Medium BRC classification and are typically custom, high energy, or high power designs
- Use Medium and High BRC Template HR (IHS# 28907)

- Requirement addition to Medium BRC Batteries
  - 5.1.5.1 – Thermal Runaway Propagation

    a. For battery designs greater than a 80-Wh energy employing high specific energy cells (greater than 80 watt-hours/kg, for example, lithium-ion chemistries) with catastrophic failure modes, the battery shall be evaluated to ascertain the severity of a worst-case single-cell thermal runaway event and the propensity of the design to demonstrate cell-to-cell propagation in the intended application and environment.

    b. The evaluation shall include all necessary analysis and test to quantify the severity (consequence) of the event in the intended application and environment as well as to identify design modifications to the battery or the system that could appreciably reduce that severity.
- Verification - High BRC End Item Thermal Runaway
  - Verification is considered successful when a Thermal Runaway Assessment with no propagation can be substantiated by: A and (B and/or C)

    A. Analysis is performed to determine whether thermal runaway with propagation can be substantiated (A)

    B. Analysis to quantify the magnitude (consequence) of the event in the intended application and environment (A)

    C. Test to quantify the magnitude (consequence) of the event in the intended application and environment (T)
- HR Battery Description Form will be attached to the unique HR and is available as an attachment to the template

# JSC 20793 Rev D. Propagation Requirements

- For batteries >80Wh no cell-to-cell propagation is permitted
  - Fire and gas produced for large batteries is catastrophic to the crew and the vehicle
  - Testing requirements provided in EP-19-001 memo
- COTS batteries are generally not designed with propagation in mind
  - Cells are closely packaged with minimal to no mitigations to prevent TR propagation
  - Only a few industries have committed to developing passively propagation resistant (PPR) batteries
- NASA has spent significant resources to develop non-propagating batteries for crewed space flight
  - Redesigned all spacesuit batteries
  - Visiting vehicle batteries required to be PPR

# PPR Test Requirement Summary

- Test setup includes full-scale battery system with electrical bussing and internal safety features intact
- Charge the entire battery to the highest flight State of Charge (SOC)
- A single cell shall be triggered into the onset of TR a minimum of 3 times
    - Locations should be chosen to evaluate each unique environment or worse case test locations
- A single, full-scale battery test article may be used for each of the three (or six) full-scale battery tests, with battery inspection, cleaning and refurbishment to occur after each test
    - No need to replace the spent/destroyed TR Trigger Cell in between tests
    - Replace or repair any flame arresting features and remove any debris that could soft-short cells

# Pass/Fail PPR Requirements

Fully Successful: The battery is fully successful and passed propagation testing if the following conditions

- Only the triggered cell(s) achieve TR
- Other cells in the battery are not damaged, vented, ignited or leaking electrolyte, the CIDs, PTCs and/or fuses have not triggered
- Neighboring cells can be cycled within ± five percent of pre-test capacity
- No flames exit the battery enclosure

Or

- No flames, sparks, gases, or fluids shall exit the containment vessel
- Exterior temperatures of the containment vessel shall not exceed 60°C

Marginally Successful: Did not have cell-to-cell propagation nor did flames exit the battery enclosure but cells were electrically damaged (minimum 6 tests required)

- Only the triggered cell(s) achieve TR
- Other cells in the battery may be damaged, vented, leaking electrolyte, CID, PTC and/or fuses have triggered
- Design assessment verifies leaked material or degraded battery performance is tolerated by the battery assembly and the adjoining system(s)

Unsuccessful: If the battery fails to meet the either fully or marginally successful criteria then the battery requires additional design modifications. The hardware provider shall repeat the full-scale battery testing until the battery design is successful

# Prevention Methods for Latent Defects

- Cell and Battery Operational & Analytical Mitigation Measures
  - Operate battery with positive margins in operating limits set by the cell manufacturer in terms of
    - Voltage
    - Current
    - Temperature
    - Cycle life
  - If not, perform the relevant testing to confirm that no failures will develop due to this type of usage during the life of the battery
  - Perform thermal analyses to confirm that positive thermal margins exists
    - Cell to cell gradients within the battery to prevent capacity/voltage imbalancing
    - Maximum and minimum temperature extremes

# Manufacturing Defects and Internal Cell Shorts

- You can not screen out all potential latent defects by acceptance testing alone!!!
  - Implementation of effective manufacturing FOD mitigation measures is key
  - Periodic line audits are a must
  - Cell DPA
- ***Take Home Message: Prevention methods are rarely 100% effective***

# Computed Tomography/Destructive Physical Analysis

- CT scan requirements
  - Able to detect metal particles 50 µm x 50 µm x 20 µm
  - Scan resolution of 70 µm minimum in the axial direction
  - Scan resolution of 50 µm minimum in the radial direction
- DPA process
  - Axial cut performed by end mill while vacuuming debris precisely cutting only the can
  - Radial cut performed manually with pipe cutter just below spin groove and just above can bottom
  - Once started, DPA must be completed within that day inside vent hood to maintain the evidence
  - Visual inspections performed throughout the disassembly process, documented with photographs, and suspect defects are sampled on SEM/EDS pucks for analysis
  - Separable components are weighed
- Perform 100 charge/discharge cycles at room temperature (3 cells per design)
  - Charge 800 mA (C/4) to 4.2V to 70 mA taper
  - Discharge 800 mA (C/4 to 2.5V with 5A, 100ms pulse ~50% SoC
  - Rationale: cycled cells are more likely to show evidence of defects

# CT Defects to Look For

a) Improper seating or pinching of the plastic seal ring .

b) Improper routing of the positive tab from the current interrupt device (CID) to the jellyroll (JR).

c) Excessive telescoping of the JR to point where anode current collector edge overlap relative to the cathode edge is non-existent in any of the JR windings either at the top or bottom. See Figure 1 for an example of nominal vs failing. See Figures 1, 2.

d) Excessive bending or deformation of the anode current collector overlap in the top or bottom of the JR. This usually comes with defect (d).

e) High density anomalies outside the JR could be indications of weld splatter. See Figure 3.

f) Internal crimp seal corrosion pitting on the inside of the can next to the seal ring (see Figure 4).

g) High density anomalies inside the JR could be indications of electrode wrinkles, foreign object debris (FOD) or native object debris (NOD). See Figure 5.

h) Anomalous can wall thin spots.

Figures 1, 2

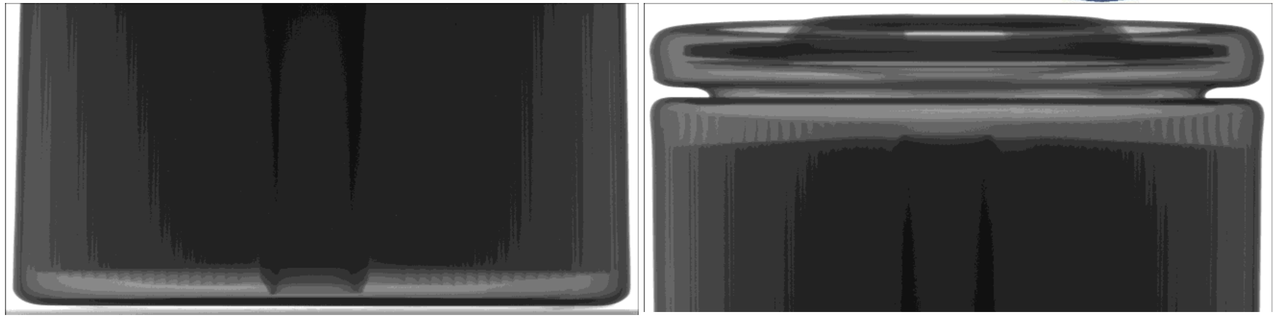


Figure 3

- Cross section of high density material on cell base insulator, possibly weld spatter from anode lead weld

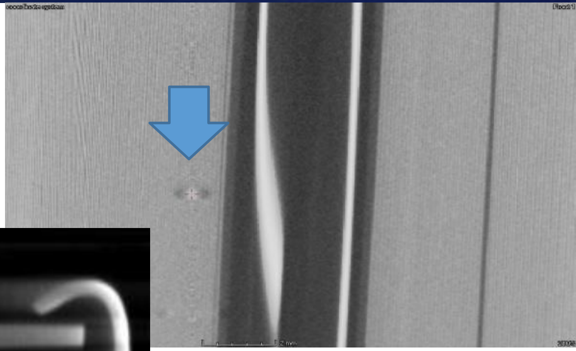
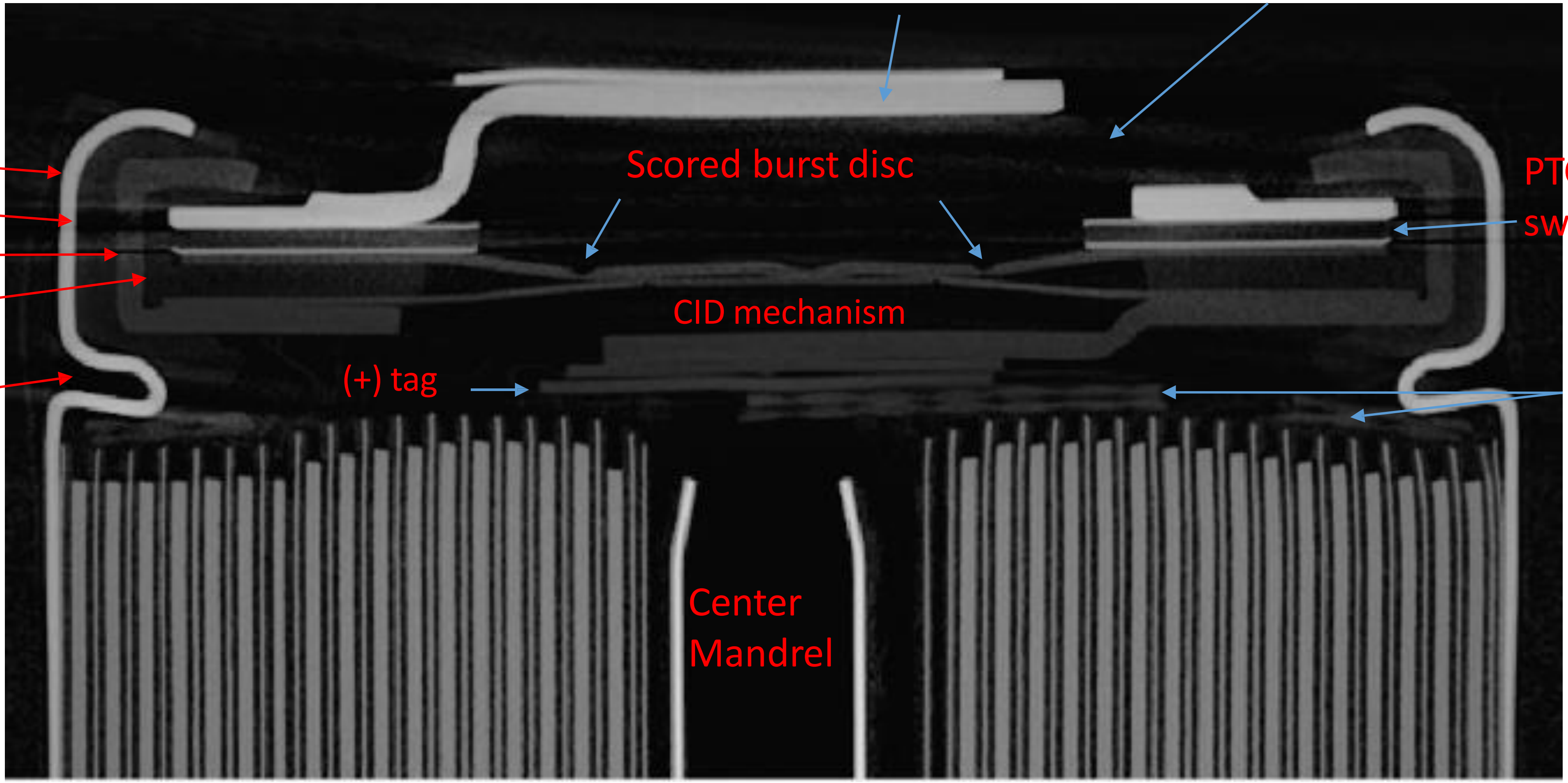


Figure 4

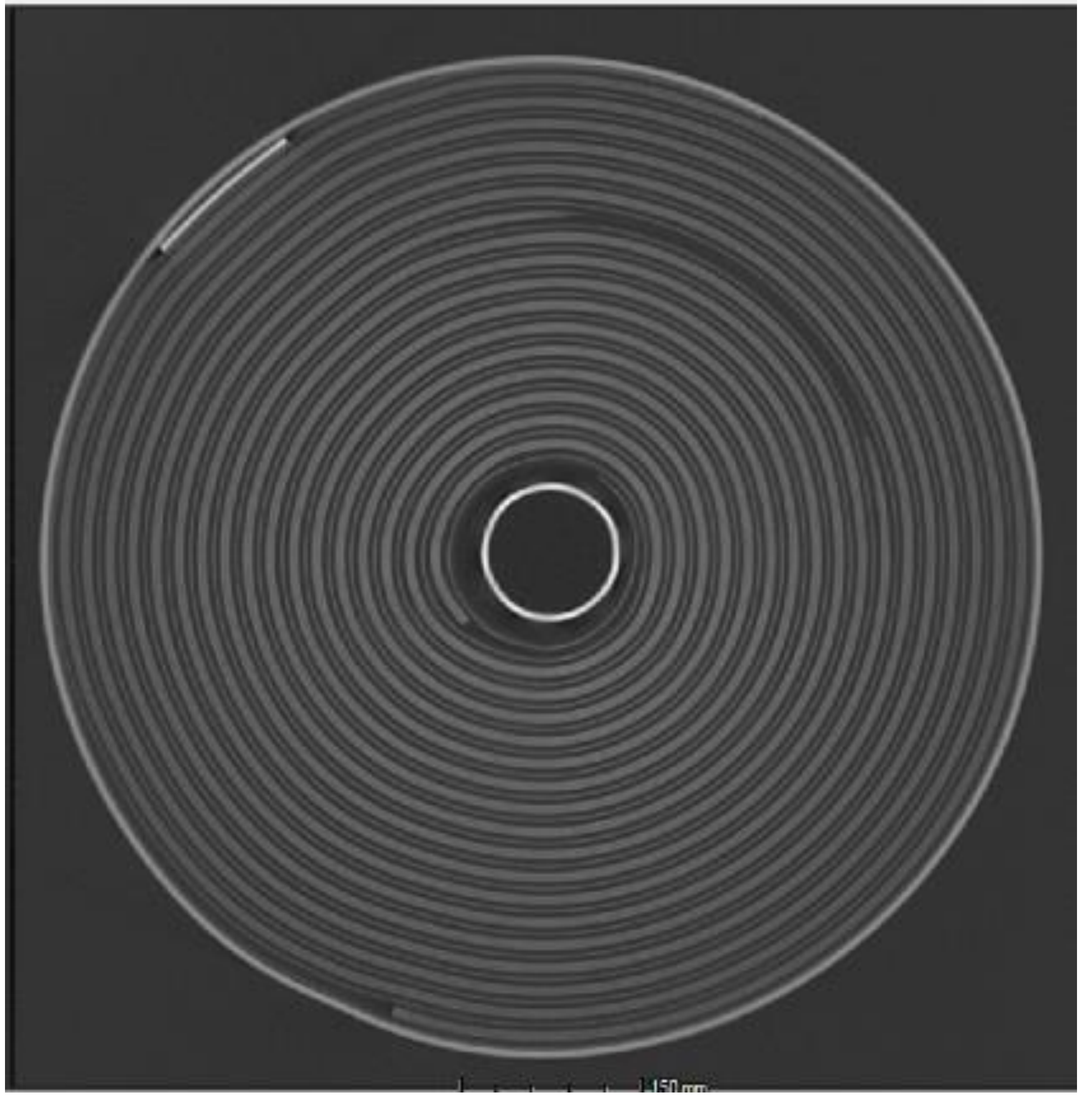
# Axial View – Header of NCR18650B

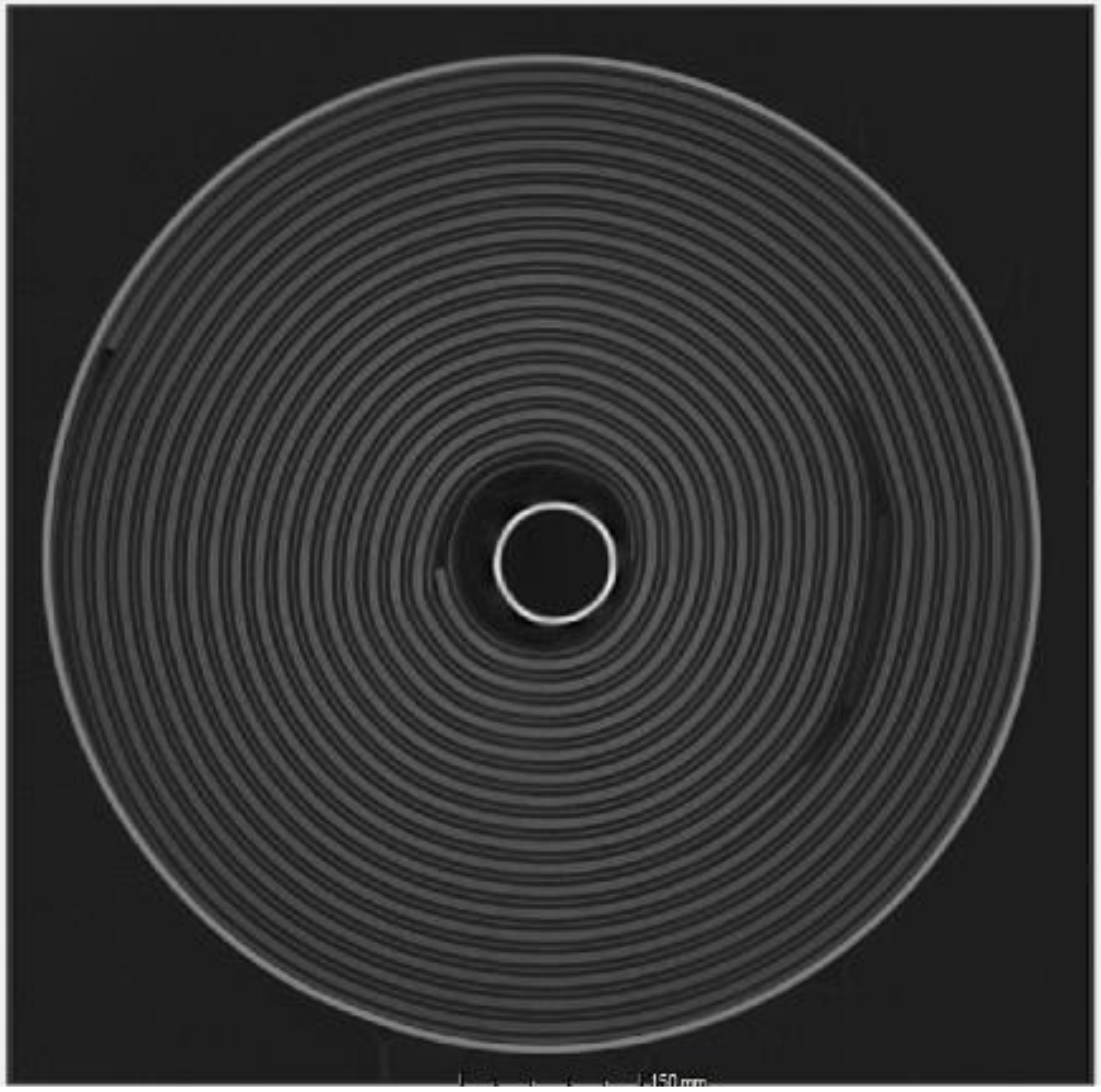
Double crimp header design




Jellyroll with anodes overlapping thicker cathodes

# Radial Views – NCR18650B





No anomalies

# DPA Defects to Look For

a) Spots in the separator where there is conductive material electrically bridging both sides. Look for any heat affected zones of the separator.

b) Dry spots or other anomalous areas of the separator.

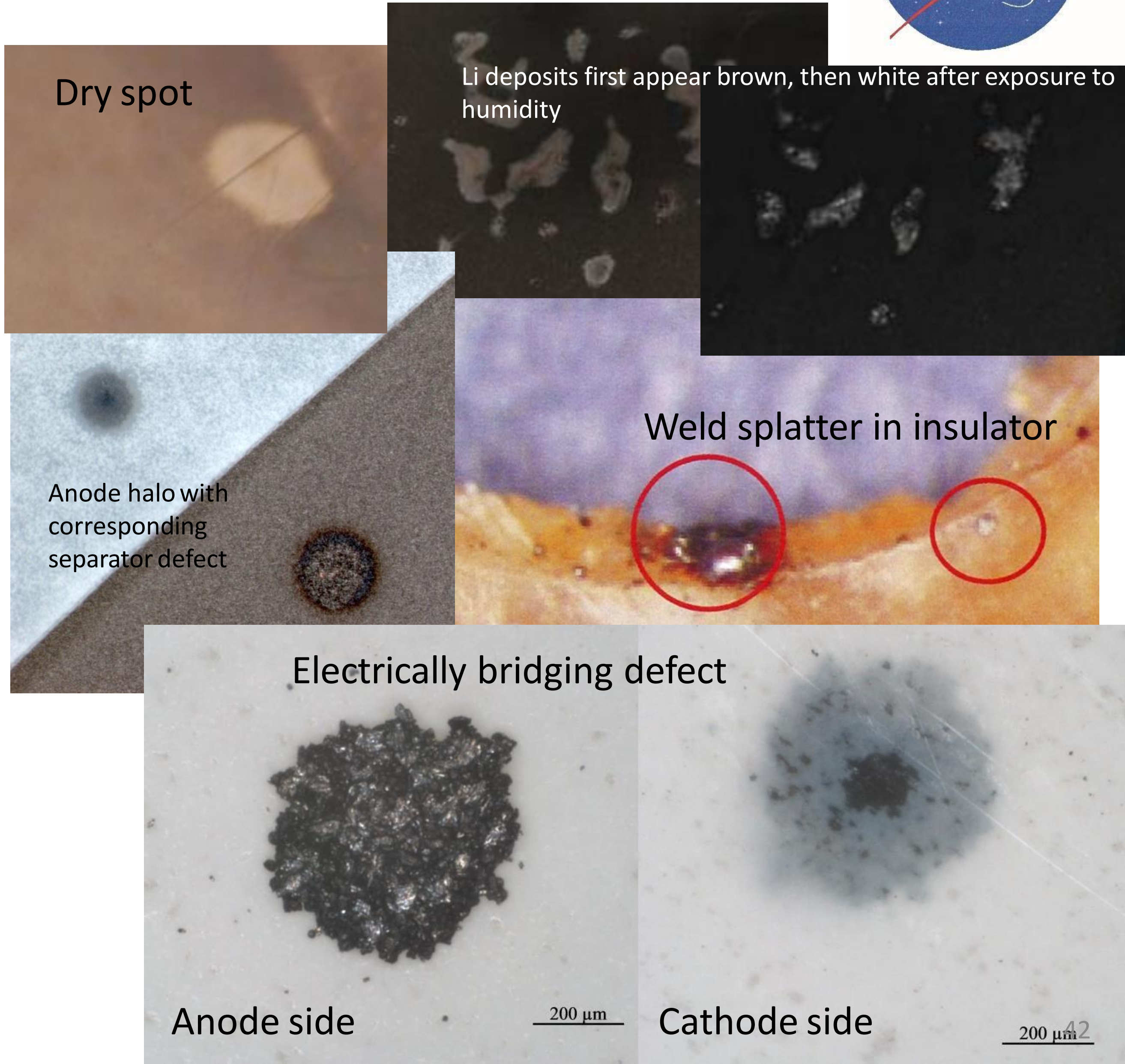
c) Lithium deposits on the anode (these will appear brown and change to white with exposure to humidity).

d) Halos on the anode surface, could be indicating a density area of active material or FOD/NOD inside the halo. If found, note its location and examine it and any corresponding heat affected zone in the adjacent separator area.

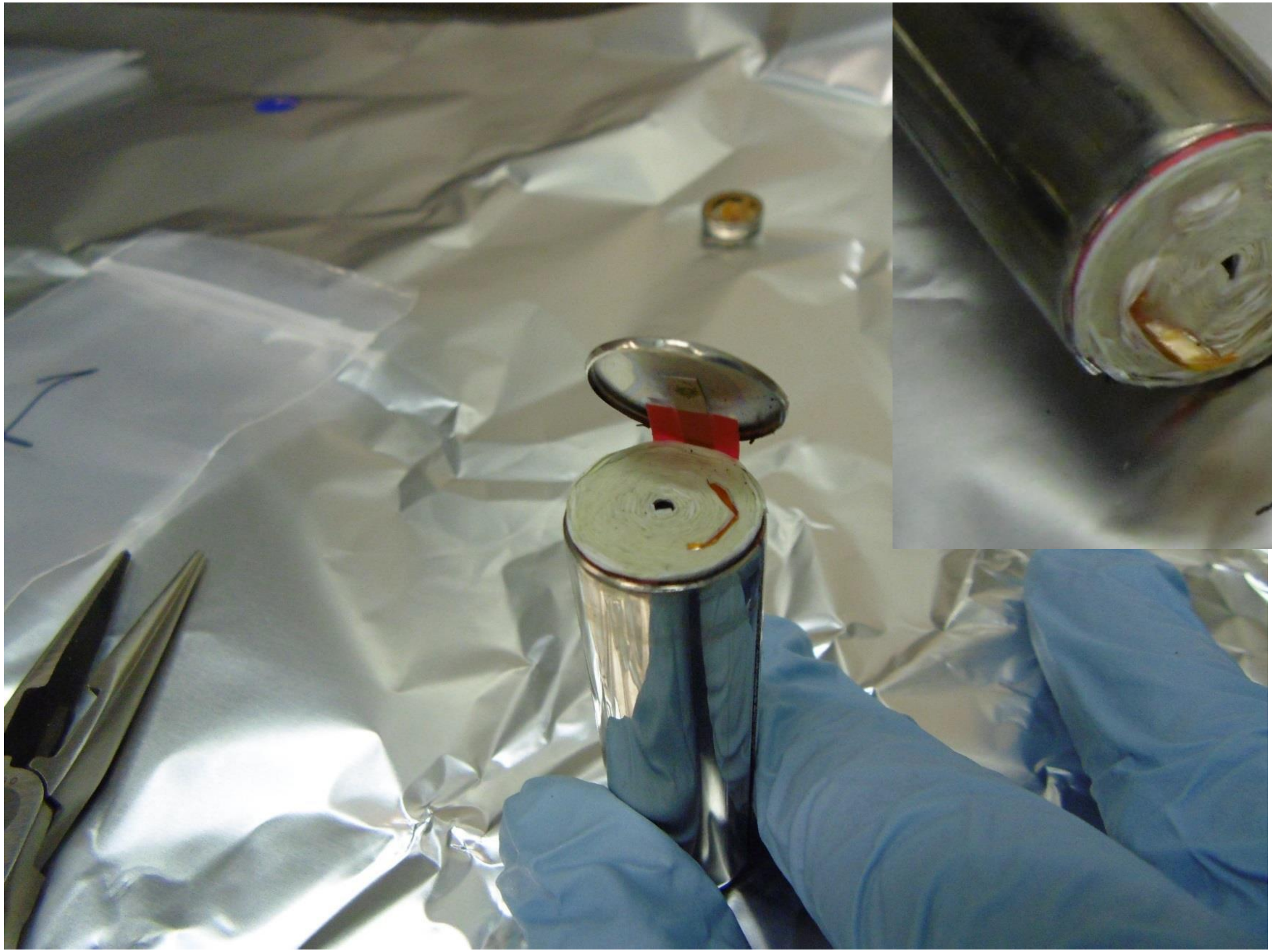
e) Examine electrode active surface area for metallic FOD or NOD. Like weld splatter. Anything that sparkles when looking at various angles. If the object moves when lightly brushed, it is probably not FOD/NOD. Refer to CT images for corroboration.

f) Any anomalous defect that merits examination by SEM/EDS shall be cut out of the electrode or separator layer and place in the SEM/EDS coupon puck.

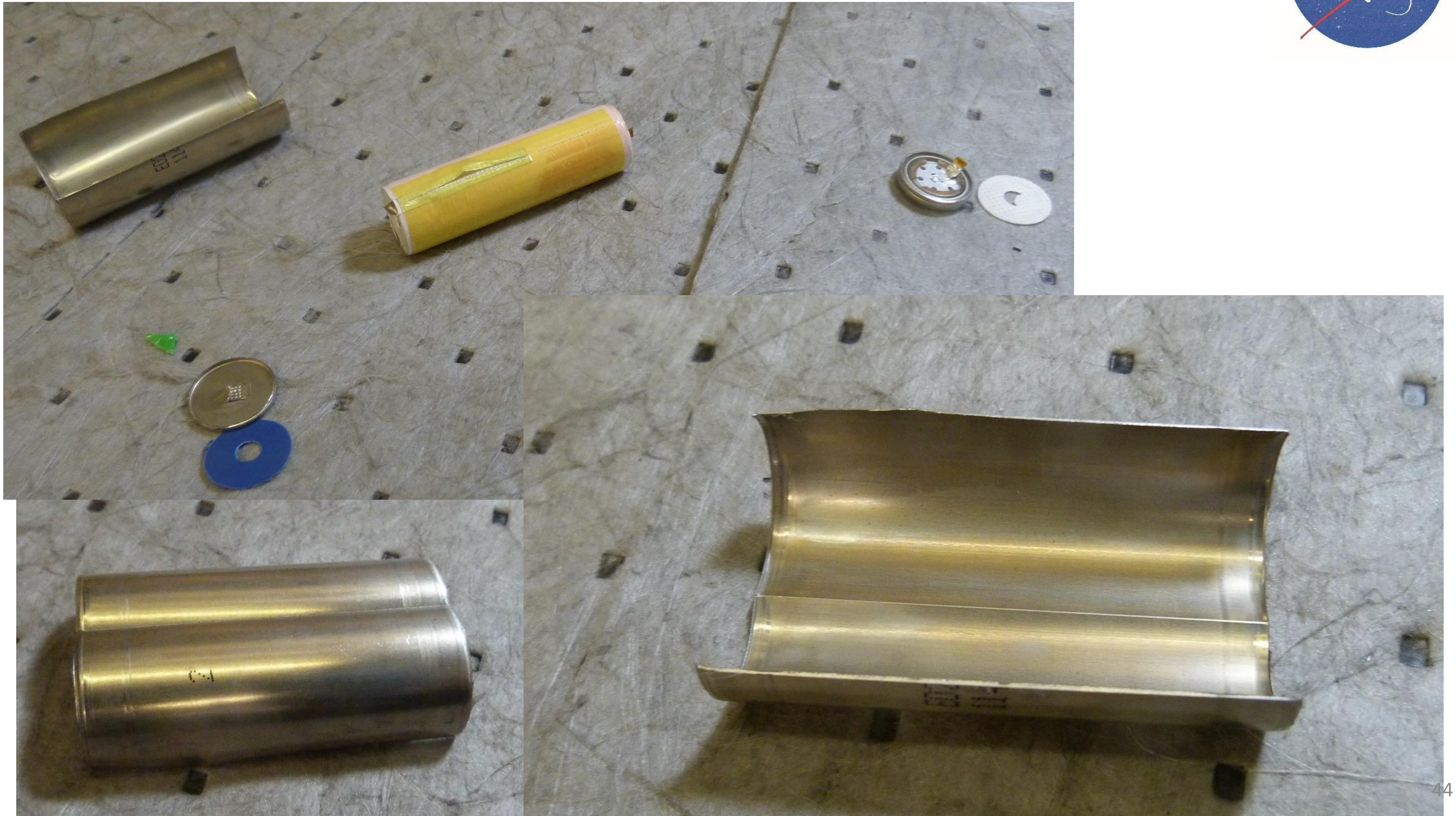
<u>*EP-WI-034 (Specification for CT/DPA of COTS Li-ion Cells)*</u>



# Bottom and Top of Jelly Roll



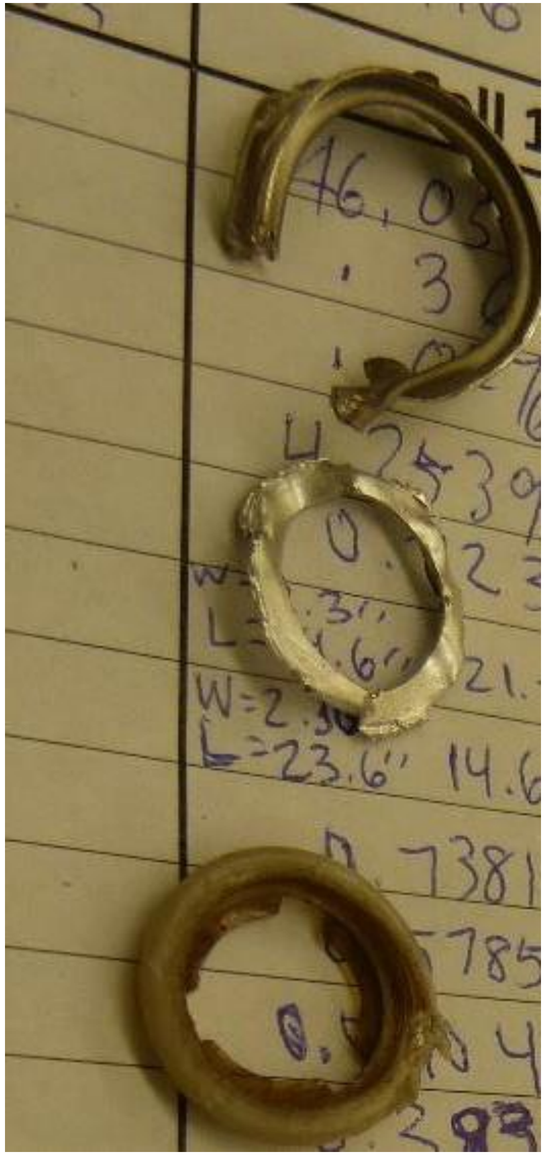
# LG INR18650 MJ1



# LG INR18650 MJ1 - Header and Bottom



Header Components



Can Wall Crimp

CID Crimp Ring

Seal Gasket

Top Cap

CID Spacer Ring

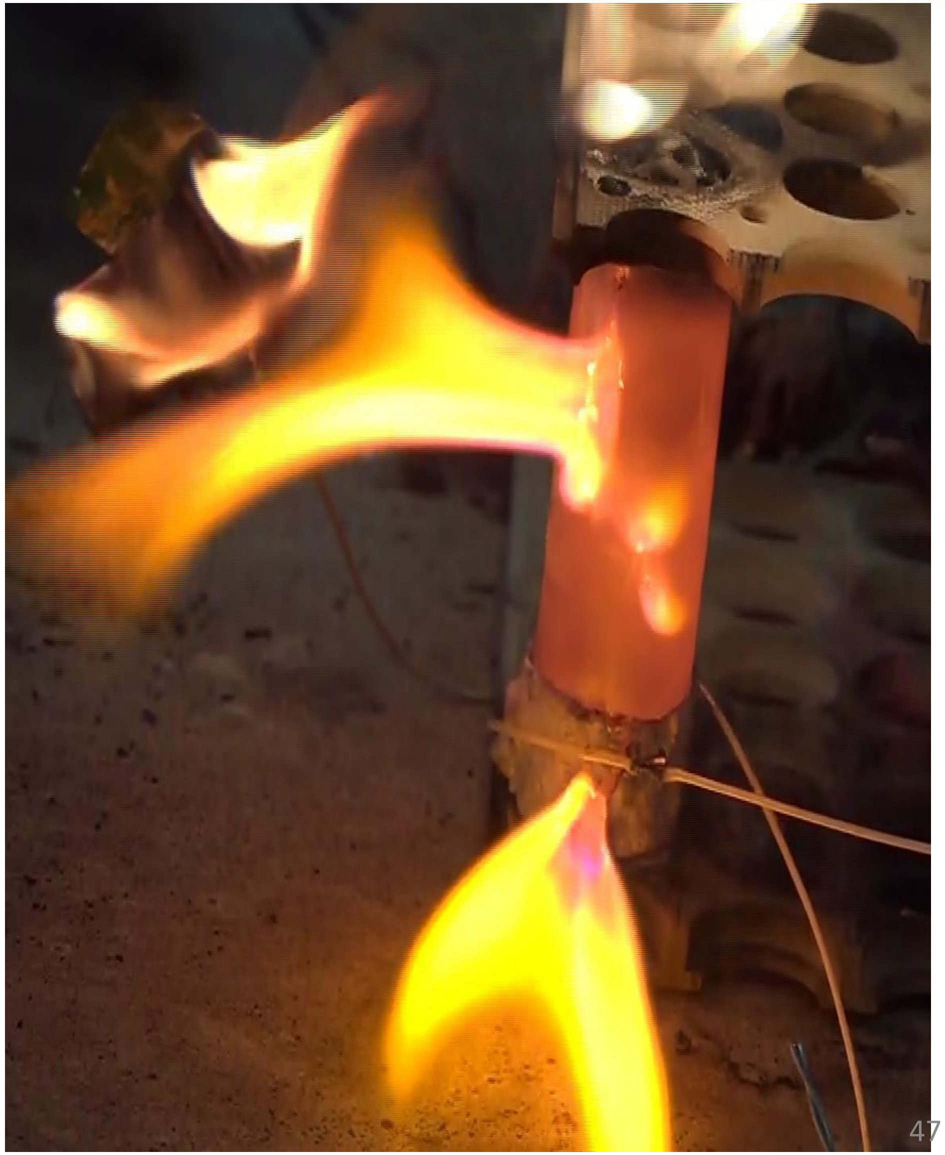
CID Scored Vent

CID Collector Plate

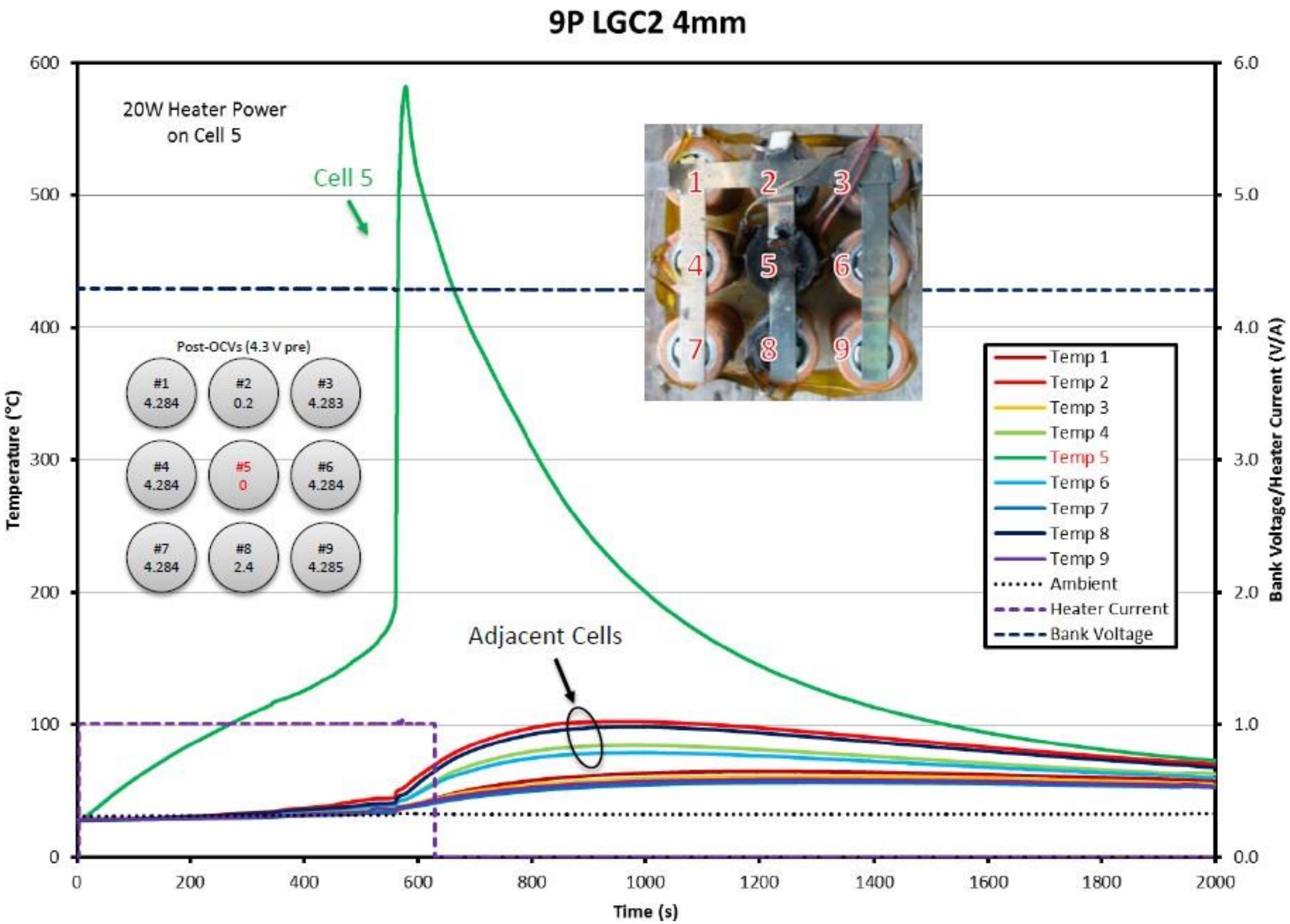
# Engineering a safer battery

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

- Prevent side wall breaches from propagating
  - 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



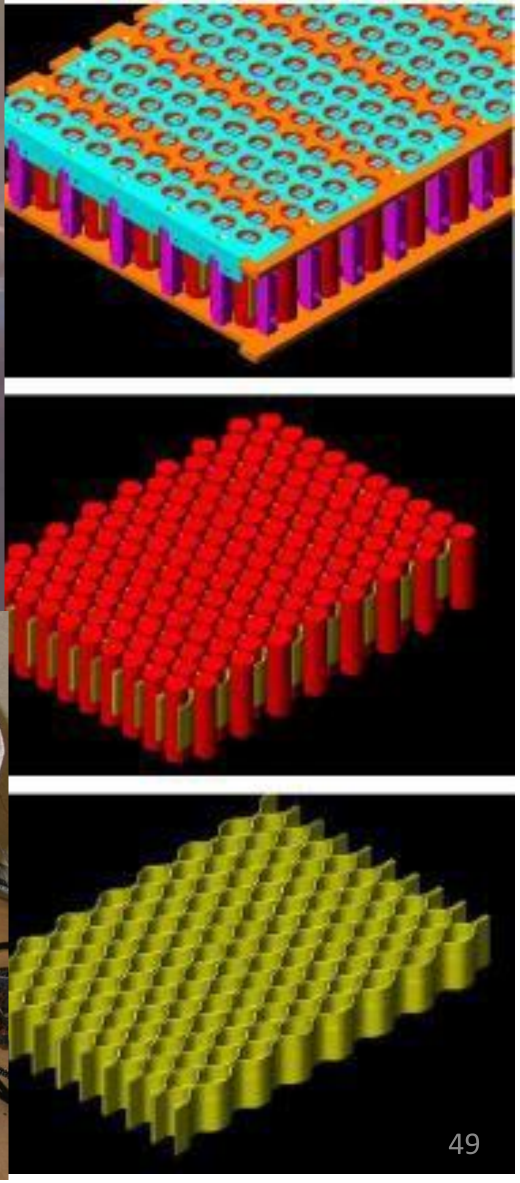
# Thermal Isolation Example – 4mm air spacing between cells

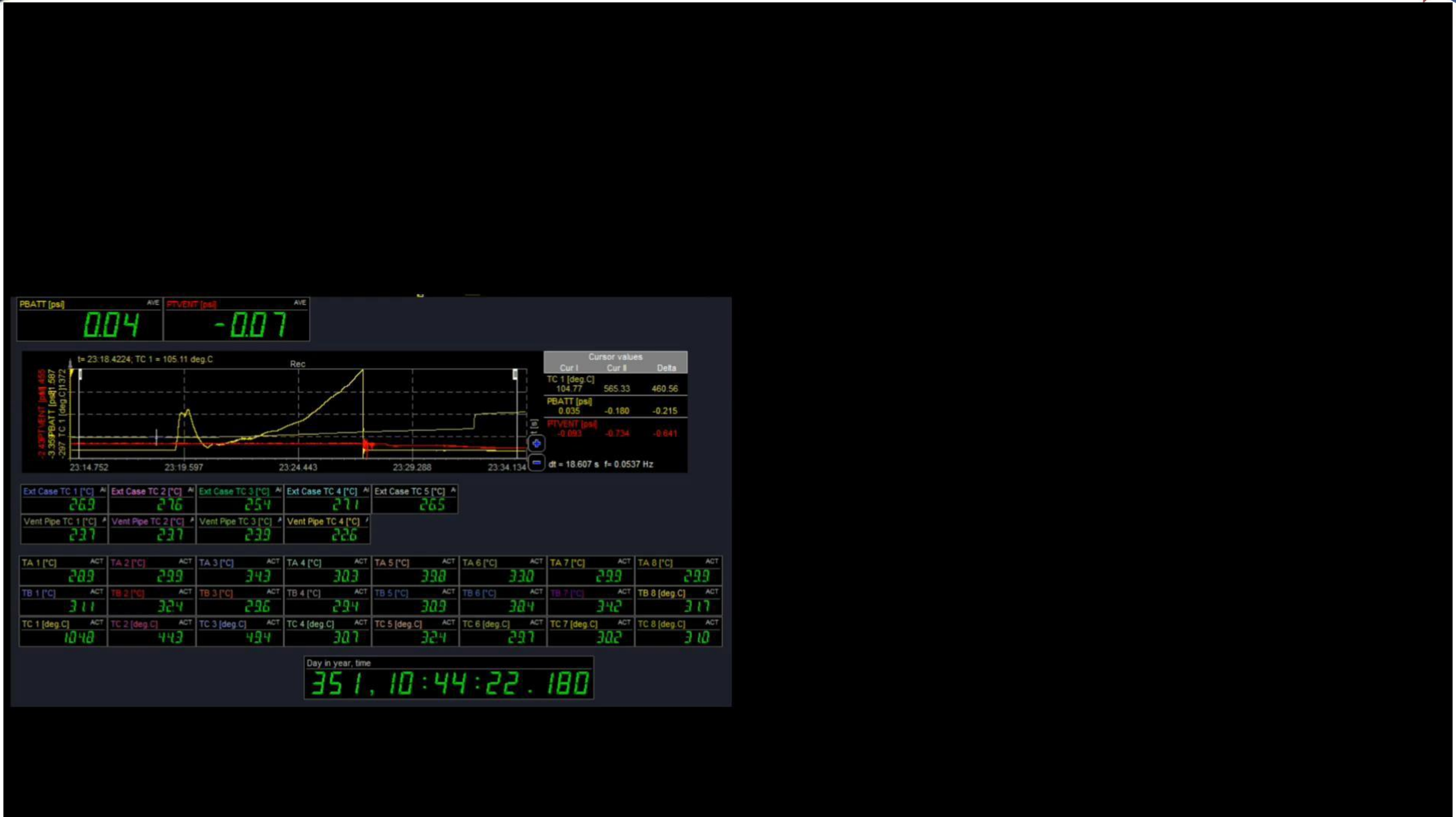

Jeevarajan et al. from 2014 Workshop showed that without any heat dissipation path except through electrical parallel connections, adjacent cells get damaged (shorted) with even 4 mm spacing, but no TR propagation.

# X-57 Battery Design Fails PPR Testing

- 4mm spacing and cell fusing to prohibit electrical propagation
- 320-cell module catastrophically fails during single cell PPR testing
  - Multiple cells propagated TR nearly simultaneously
  - DPA revealed numerous cell can side wall ruptures
- Not following guidelines 1 and 2
  - Cell can sidewall breach risk not mitigated
    - Nomex paper (yellow) is weaved in between cell can walls 4mm apart
    - 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



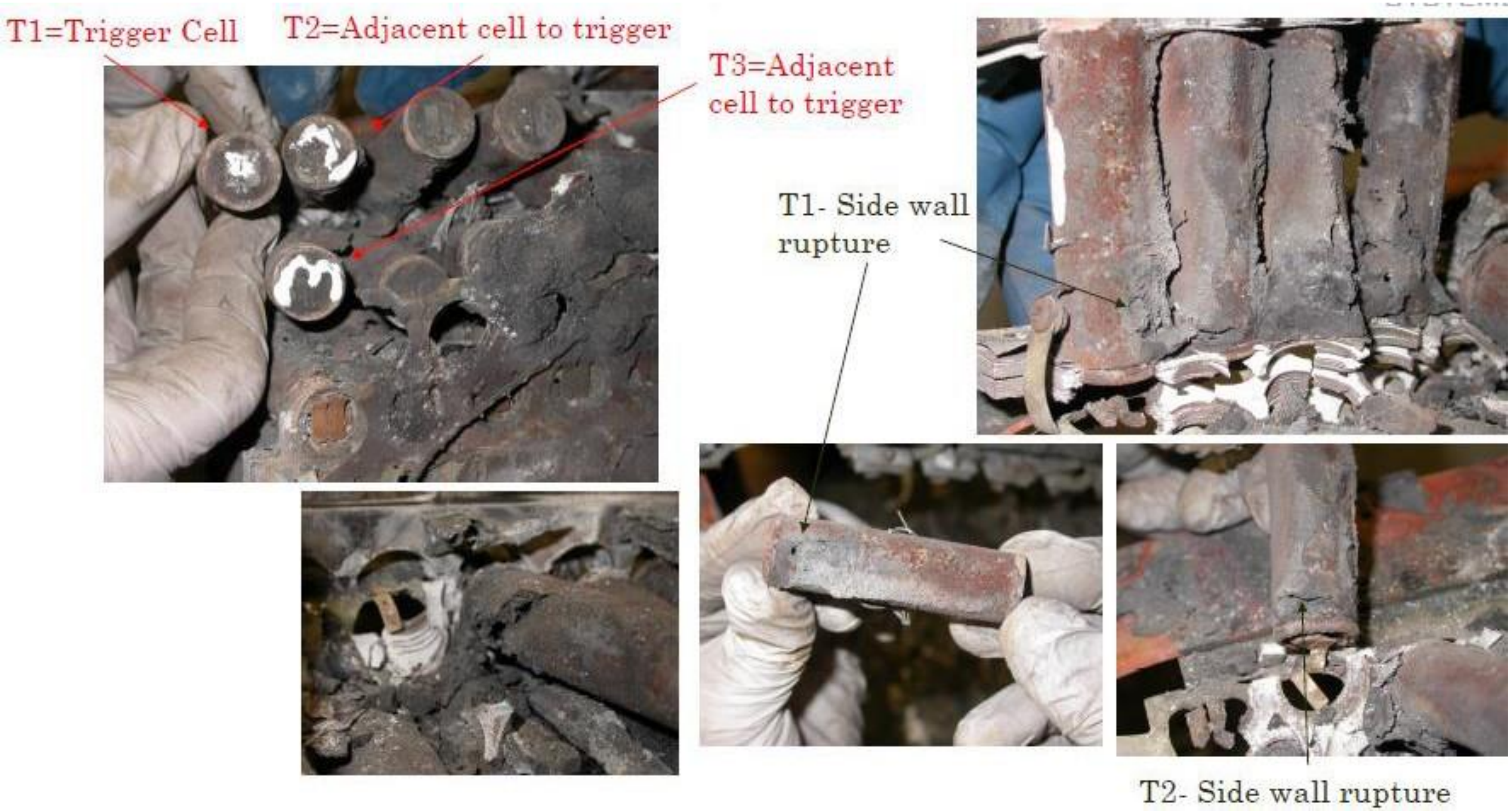
# X-57 Video



PBATT [psi]
0.04
PTVENT [psi]
-0.07
t= 23:18.4224; TC 1 = 105.11 deg.C
Rec
Cursor values
Cur I
Cur II
Delta
TC 1 [deg.C]
104.77
565.33
460.56
PBATT [psi]
0.035
-0.180
-0.215
PTVENT [psi]
dt = 18.607 s f= 0.0537 Hz
23:14.752
23:19.597
23:24.443
23:29.288
23:34.134
Day in year, time
351, 10:44:22.180

# Probable Root Causes

- Side wall breaches
- Inadequate cell heat dissipation



# Orion Large (38Ah) Cell Battery (32S1P)

<u>Compliance with the 5 guidelines</u>

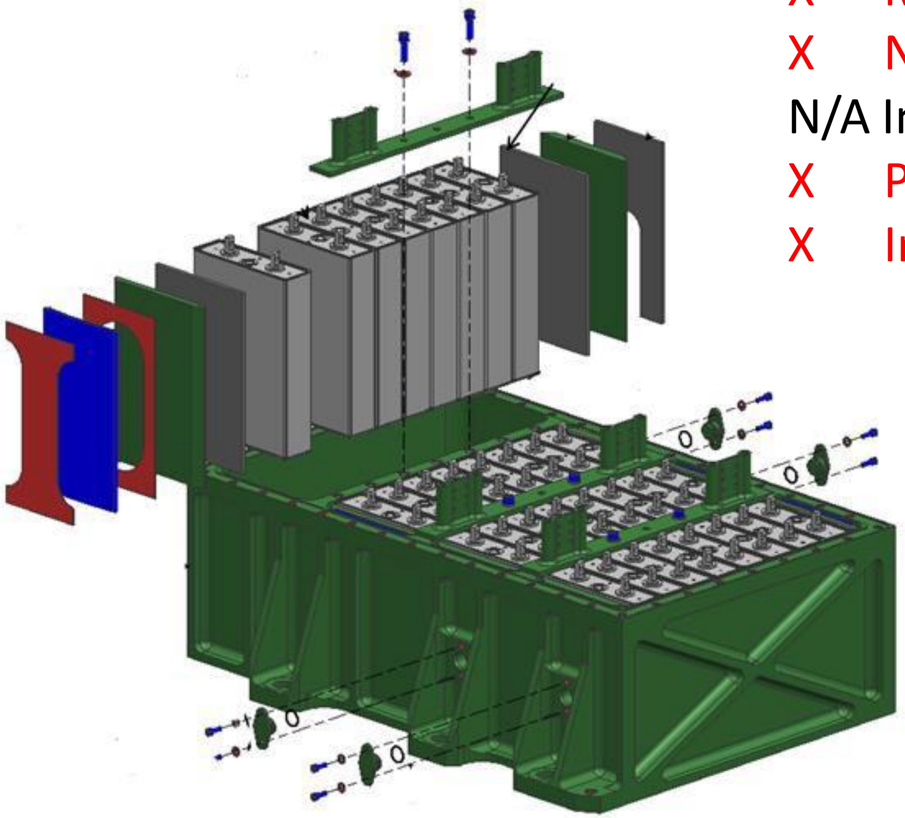
X Minimize side wall ruptures

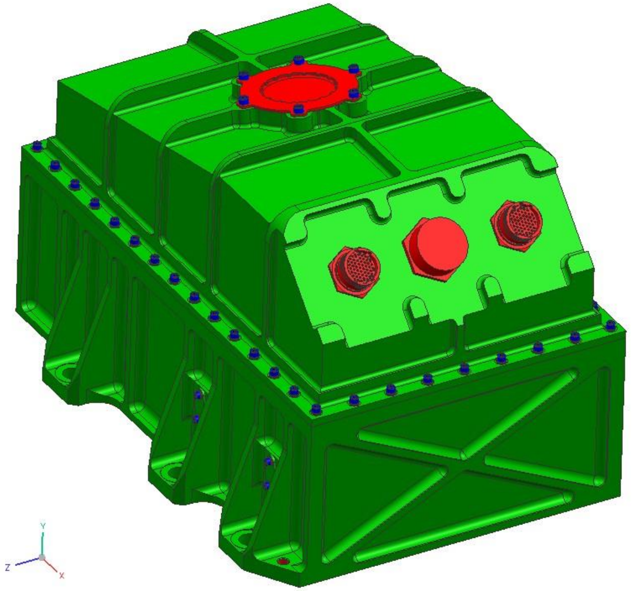
X No direct cell-cell contact

N/A Individually fusing cell in parallel

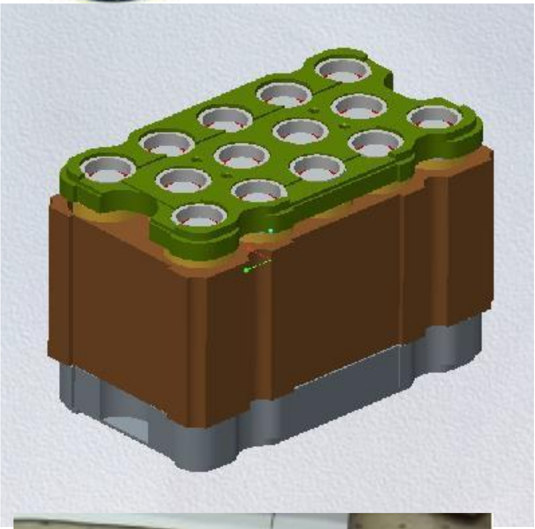
X Protecting adjacent cells from TR ejecta

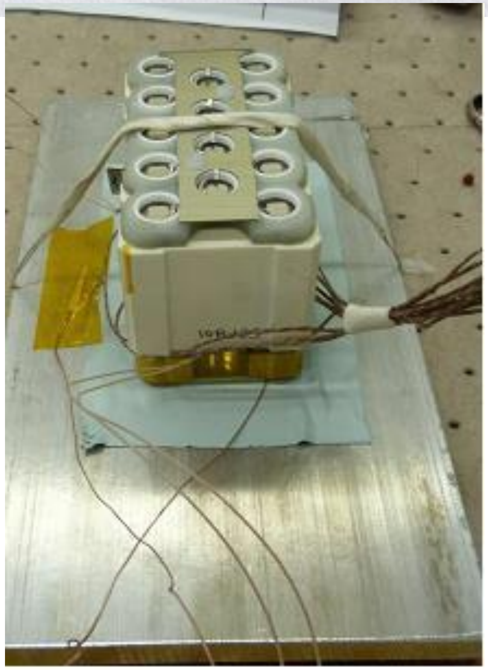
X Include flame arresting vent ports

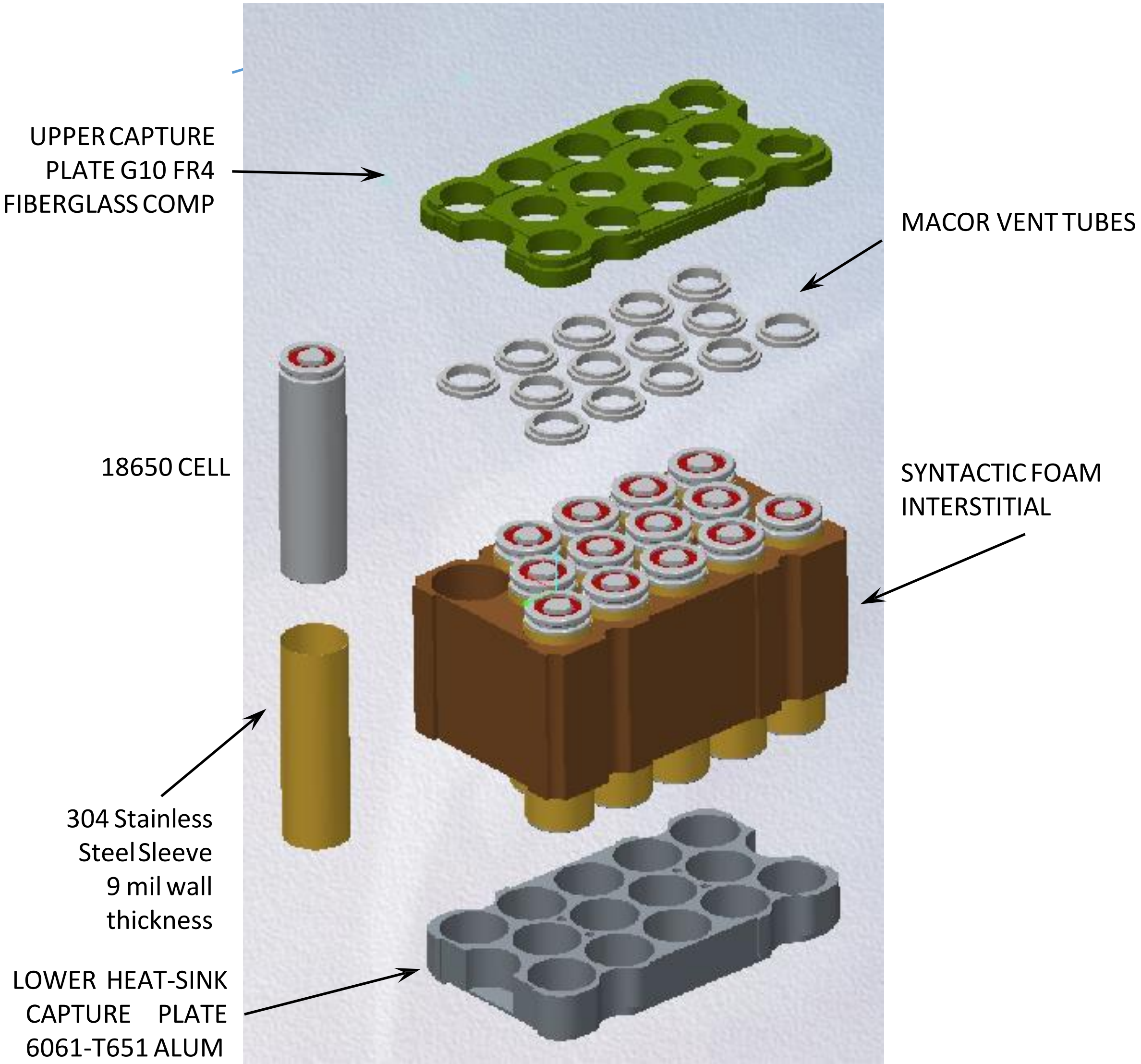




# Orion Battery

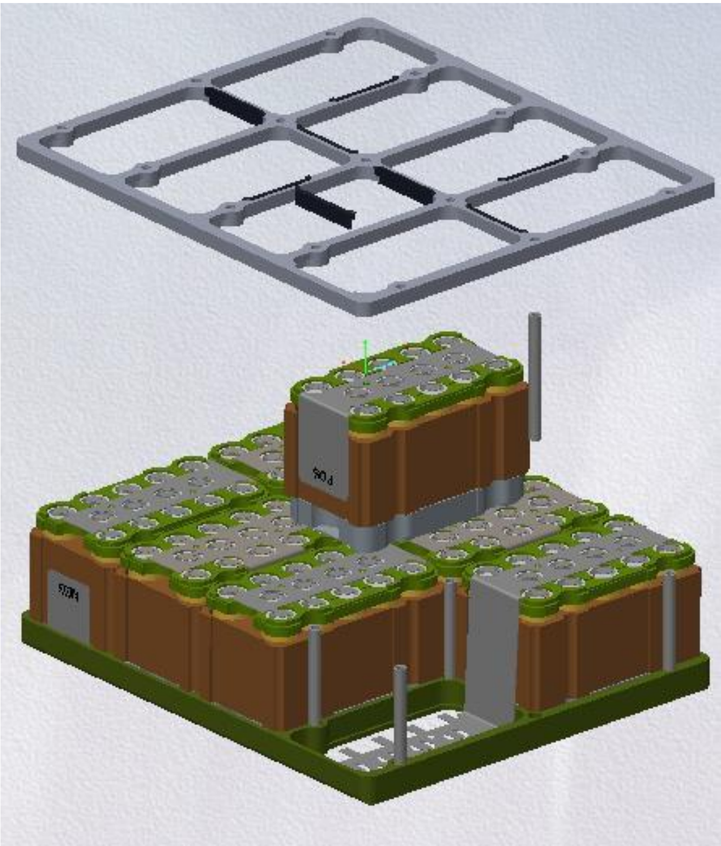







*Draw cell heat generation through cell bottom*

## Orion 14P-8S Superbrick



# Compliance Check

<u>Compliance with the 5 rules</u>

✓ Minimize side wall ruptures

- 0.009” thk stainless steel sleeves on each cell and syntactic foam to support cell can

✓ No direct cell-cell contact

- 2mm cell spacing with cell bottoms heat sunk into solid Al capture
- Uniform cell orientation allows all cell bottoms to thermally mate to thick Al heat sinking wall, which is part of housing bottom

✓ Individually fusing cell in parallel

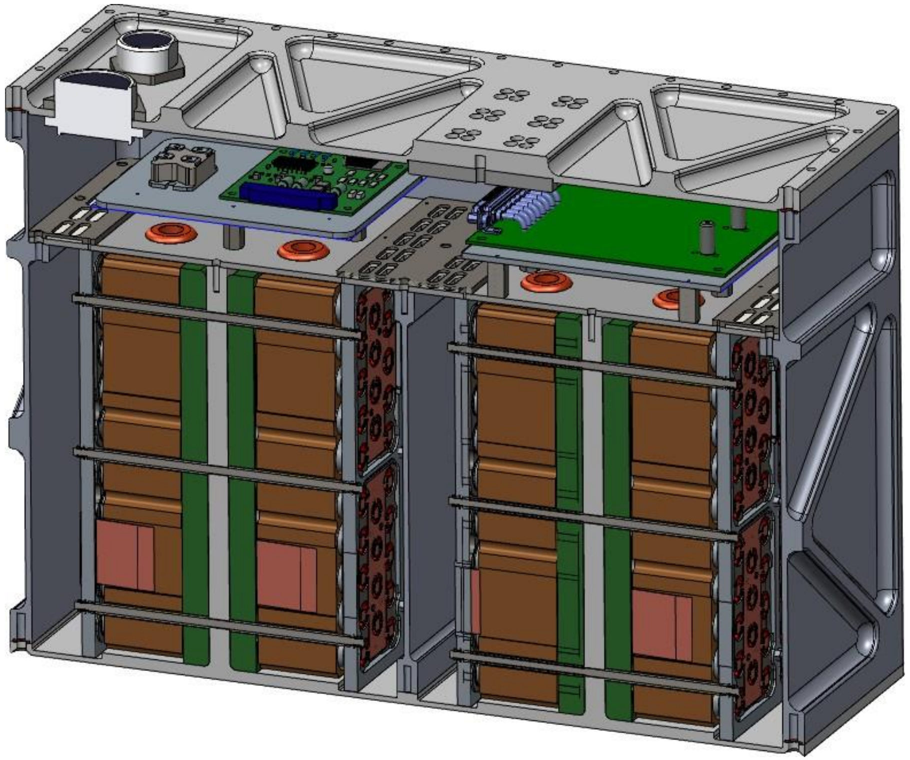
- 19A fusible links in Ni bus plates to (-) cell terminals
- Note: Cell PTC trips at 16A in 10s

✓ Protecting adjacent cells from TR ejecta

- Ceramic bushing to protect cell vent opening in G10 (+) capture plates
- Cell orientation places all cell vents towards blast wall with high temp material layering

✓ Include flame arresting vent ports

- Inside filter tray has flame arresting screens
- Battery vent ports are lined with Gore-Tex gas permeable, water impermeable layer

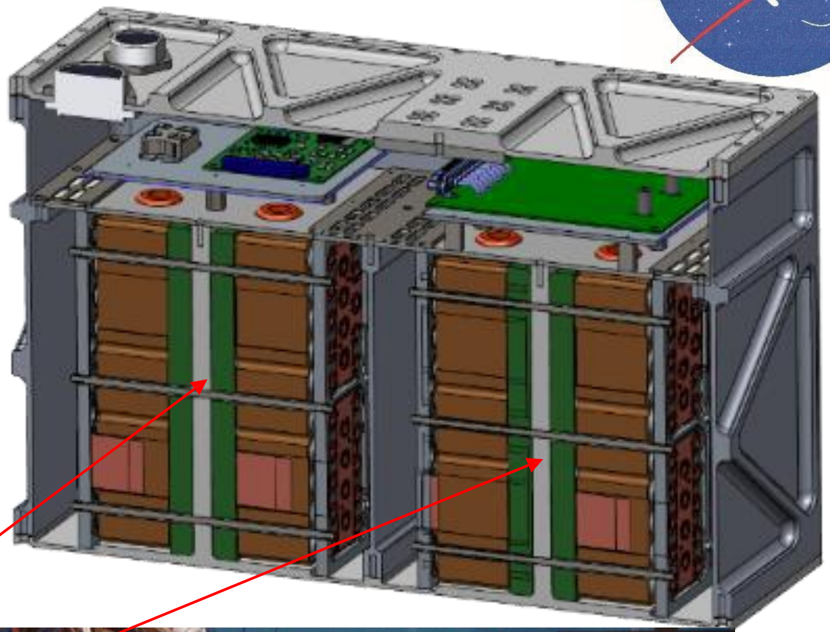


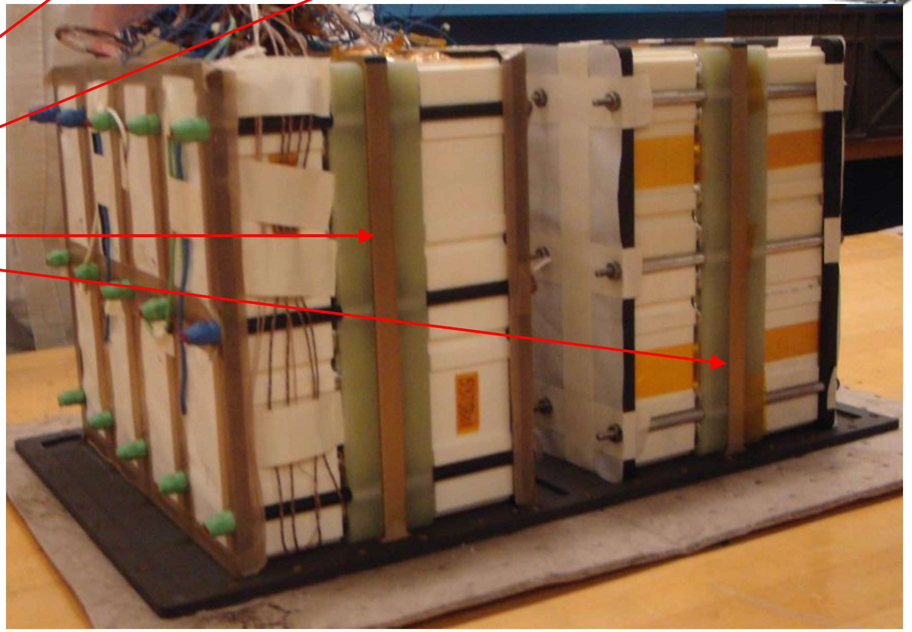
# Small Cell vs Large Cell Comparison During Single Cell TR

Above Video Feb 24 2015 Test Orion Small Cell Battery shows Five independently heater triggered cells in Proto-case housing (left frame) compared side by side with Sept 2014 Large Cell TR propagation with single cell overcharge trigger

# Isolating vs Providing a heat path

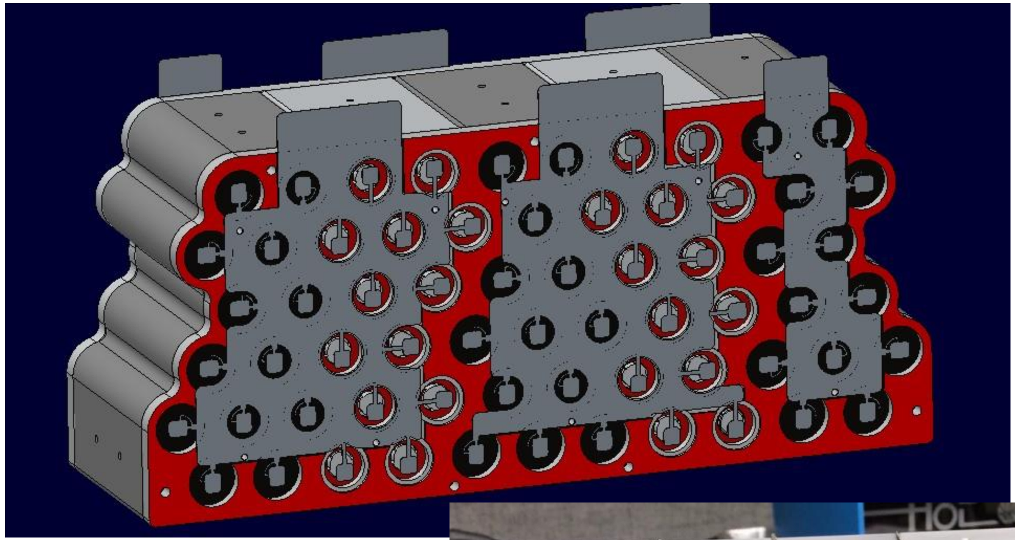
- Thermally isolate cells (air)
  - Adjacent cell ΔT rise 80-100°C
  - ***Limited to cell designs with little risk of side wall breaching*** *(180 Wh/kg)*
  - Achieves 120-150 Wh/kg
- Orion - Partially conductive (Draw heat from cell bottom)
  - Conduct heat to divider plate
  - Adjacent cell ΔT rise 50-70°C and shorter exposure
  - 14P-8S superbrick with SS sleeves achieves 140-160 Wh/kg

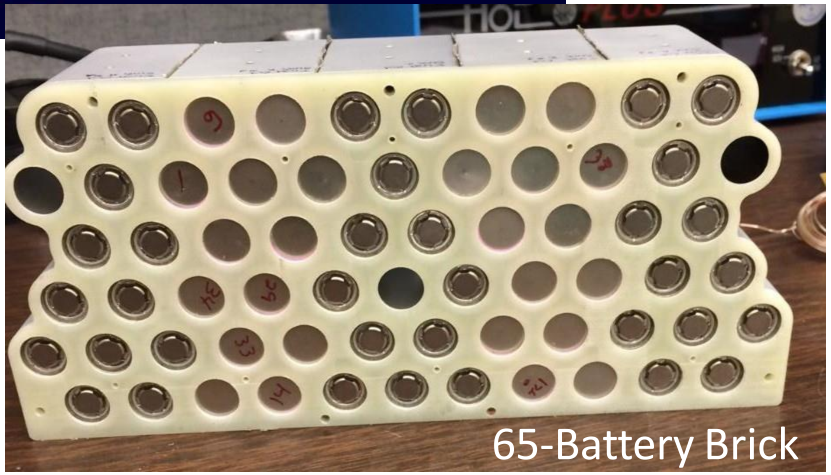




# Safe, Higher Performing Battery Design

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





65-Battery Brick

<u>Compliance with the 5 Guidelines</u>

✓ **Minimize side wall ruptures**
- Al interstitial heat sink

✓ **No direct cell-cell contact**
- 0.5mm cell spacing, mica paper sleeves each cell

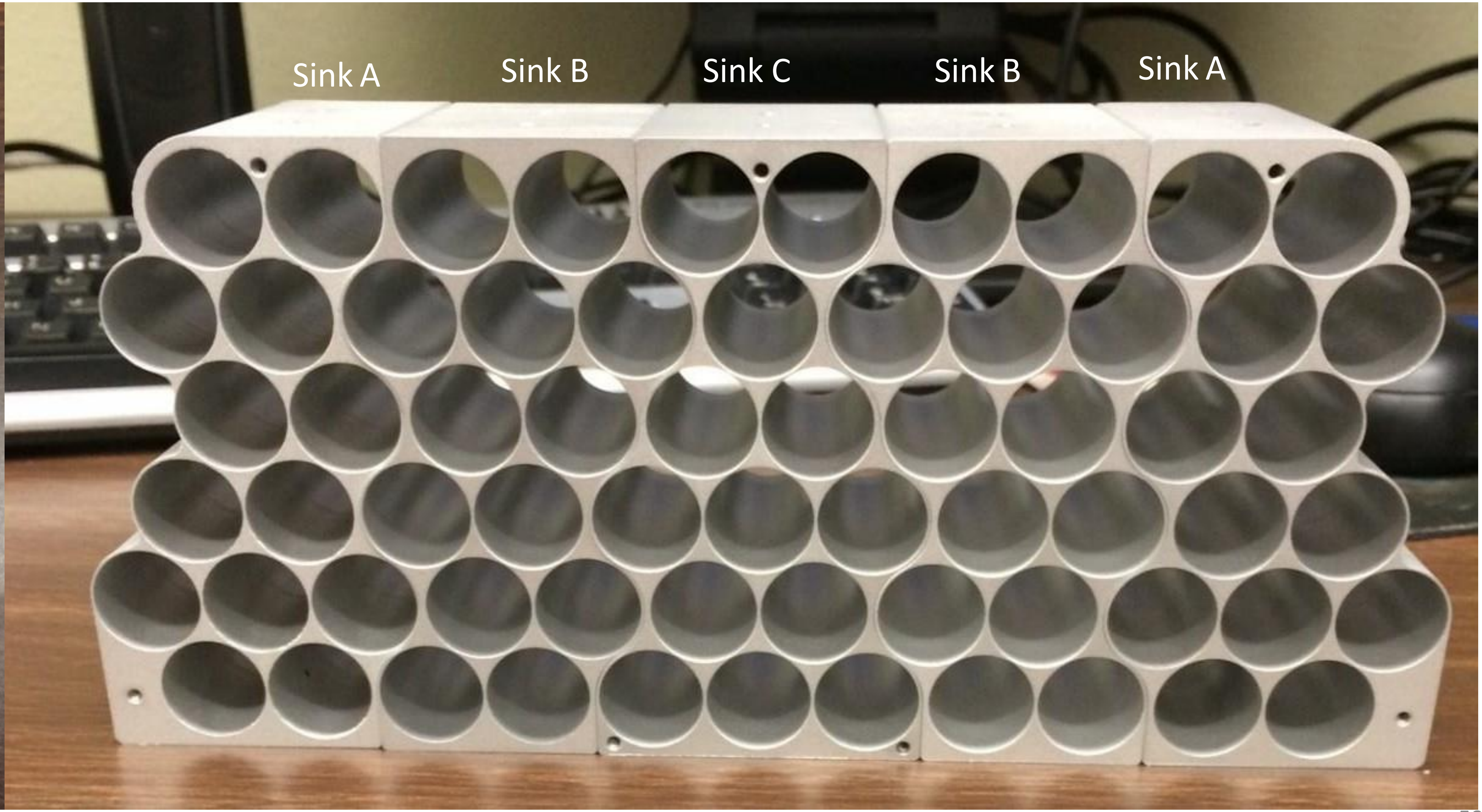
✓ **Individually fusing cell in parallel**
- 12A fusible link

✓ **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

# LLB2 Heat Sinks

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

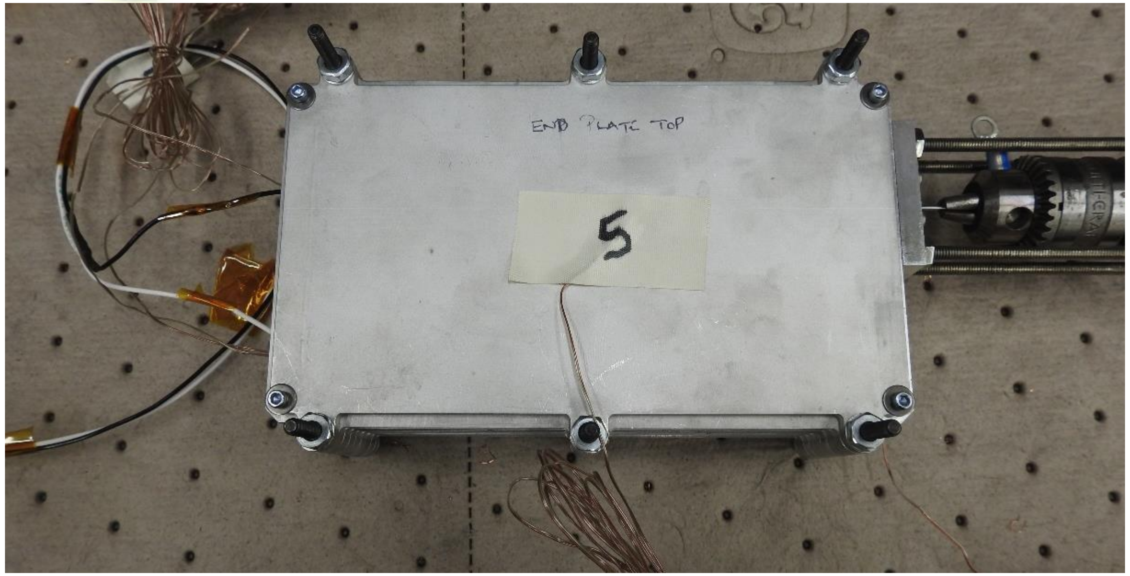
# LLB-2

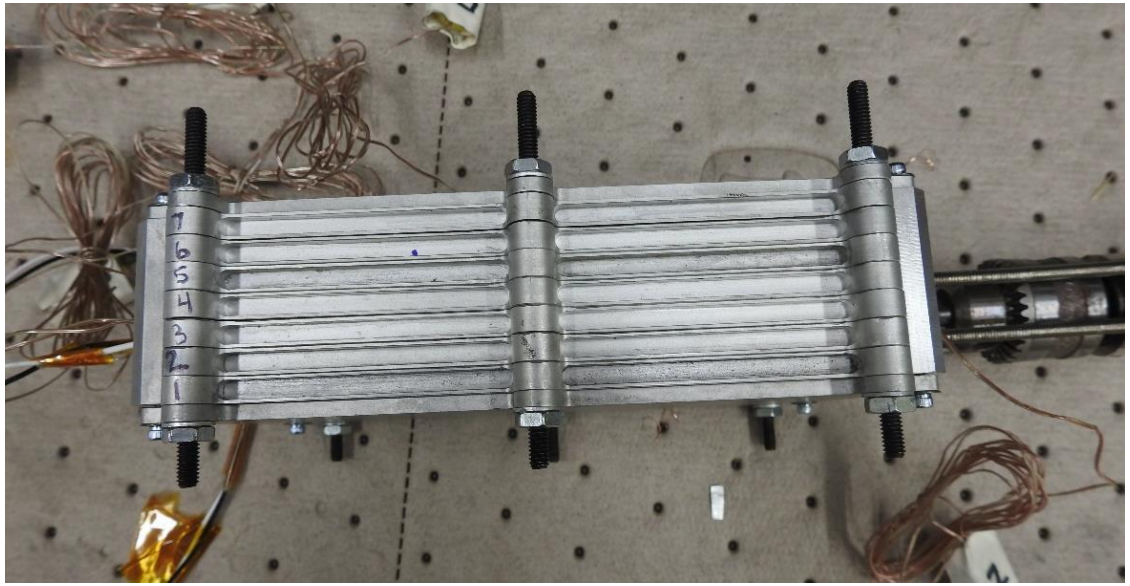
- 13P-5S Configuration with 3.4 Ah LG cell design yielding  37 Ah at 3.8 A mission rate.
- Aluminum interstitial heat sink, 0.5 mm spacing between cells
- Mica sleeves around shrink wrap, 2 FT
- The G10 capture plate houses the + and - ends of the cells and prevents the Ni bussing from shorting to the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

# Pouch Cell PPR Development

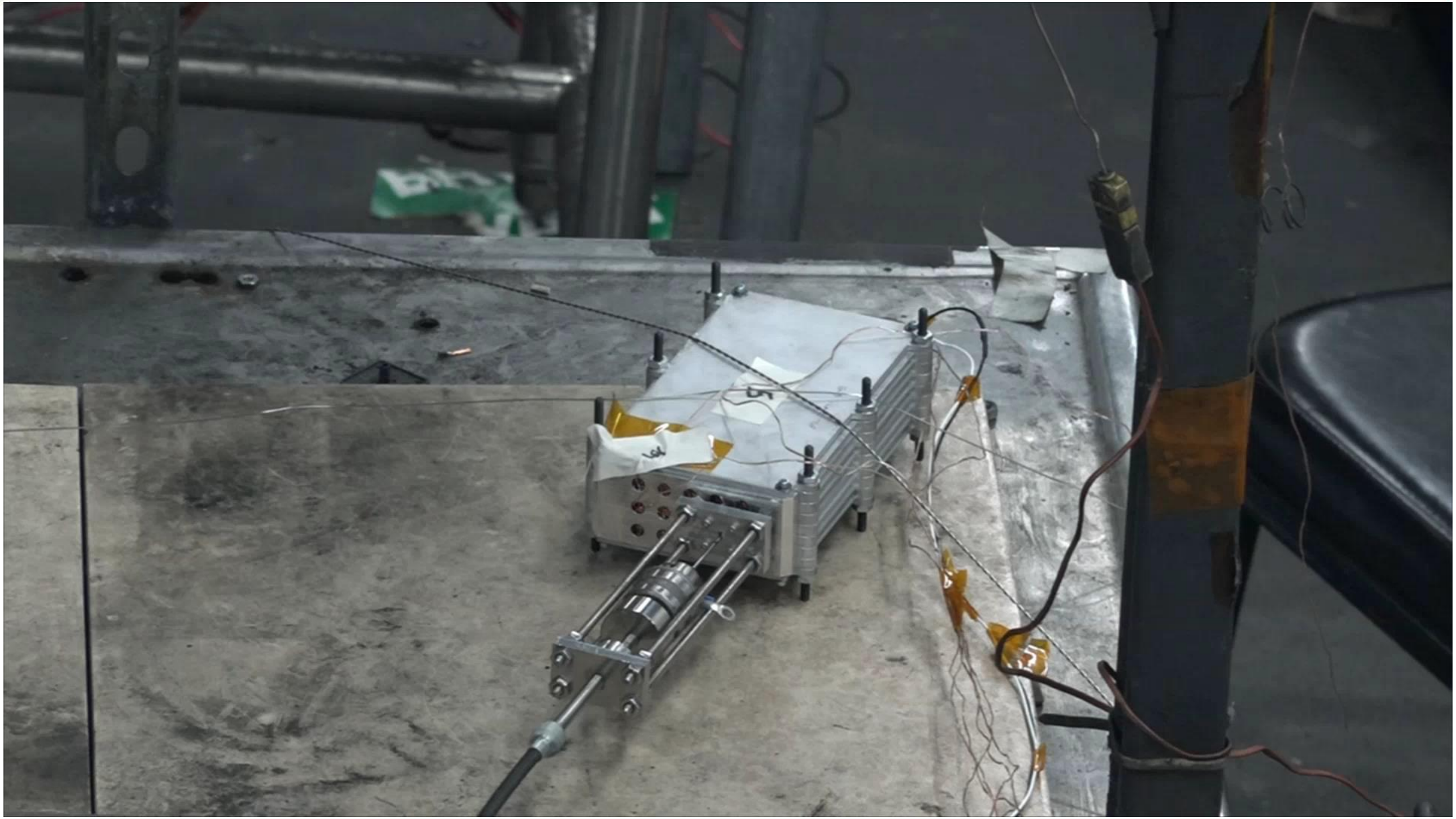
- Pouch cell market global sales is exceeding the 18650 cell format though is no cell size standards for pouch cells
  - Energy density and specific energy gap between pouch and small cell formats is closing
- What lessons learned from the 18650 battery developments can be used to transition PPR in pouch cells designs
  - ✓ Prevent side wall breaches from propagating
    - Sidewall failure will occur but which way?
  - ✓ Provide adequate cell spacing and heat rejection
  - ✓ Individually fuse parallel cells
  - ✓ Protect the adjacent cells from the hot TR cell ejecta
  - ✓ Prevent flames and sparks from exiting the battery enclosure

# Pouch Cell PPR Gen 4 Build




# Pouch PPR Video



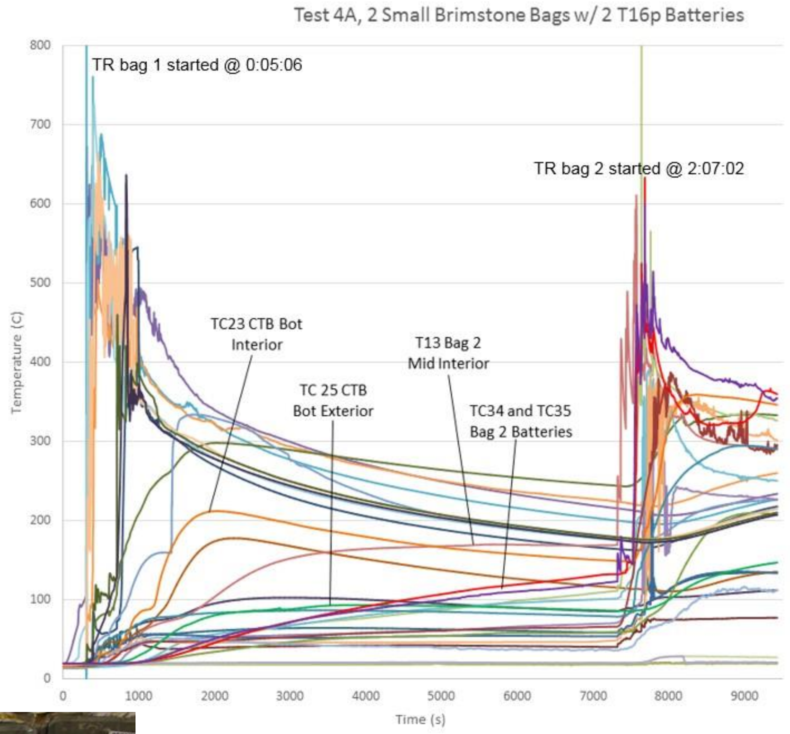
# COTS Battery Storage Bags

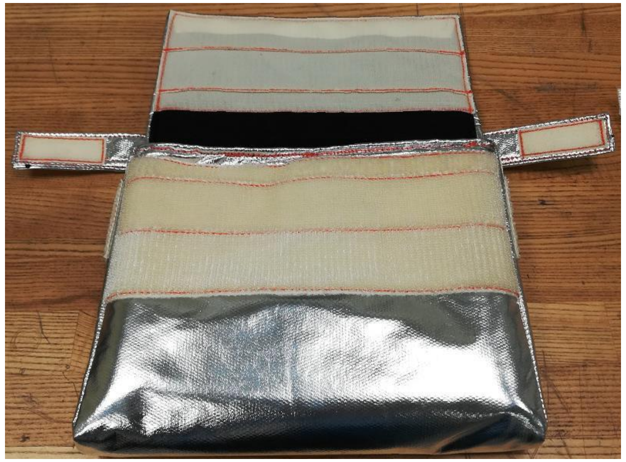
- T61p Lenovo laptop battery is heritage hardware not compliant with current standards for battery safety
- T61p is 84Wh and ISS has was storing several of these batteries in a single plastic bag and multiple would likely propagate if one had a cell TR


- How can ISS store these and other COTS batteries safely without exposing the crew to the fire?
  - Fire bags have been used by airlines recently and my be able to help NASA as well
- What about the gas produced?
  - ISS can support up to about 270Wh of li-ion before exposing the crew to excessive CO gas given the volume

# Brimstone Bags to store T61p batteries

- Idea was to store two T61ps in a storage bag, with multiple storage bags inside a Cargo Transfer Bag (CTB)
- CTB 1.0 is 19.75” x 16.75” x 9.25” made with Nomex and other flame retardant materials
- Brimstone Fire Bags (FB)
- Testing was initiated by causing a single cell to go into TR and both T61p batteries propagated inside the FB
- Bag-to-bag propagation occurred after 1-2 hours after the battery fire started in the CTB
- Localized oven effect demonstrated uneven heating inside the CTB leading to bag to bag propagation
    - The Brimstone bags increase the insulation effect of the failed battery bag with too much heat trapped



# Thermal Runaway Shields

- To circumvent the local oven effect batteries were populated in every other FB and successfully demonstrated that no bag-to-bag propagation occurred
  - The packaging in the configuration is wasteful and not ideal for ISS or other vehicles
- To prevent bag-to-bag propagation the localized heating effect had to be reduced to sufficient levels
- KULR Technologies Thermal Runaway Shield (TRS) using water in a carbon matrix as a phase change material to reduce the heat
- The TRS allowed for every FB to be populated in a CTB without bag-to-bag propagation
- FB are on HTV-8 and TRS will arrive on NG-12 to ISS

# Summary

- Follow the five guidelines as a baseline to achieving PPR
  - Prevent side wall breaches from propagating
  - Provide adequate cell spacing and heat rejection
  - Individually fuse parallel cells
  - Protect the adjacent cells from the hot TR cell ejecta (solids, liquids, and gases)
  - Prevent flames and sparks from exiting the battery enclosure
- Account for thermal, electrical, and mechanical failure modes in the design
- Verify through test at representative flight like scale that PPR has been achieved with margin