Battery Relevant Cell Side Wall Rupture Characterizations

By
David Petrushenko and Eric Darcy
NASA-Johnson Space Center

For
NASA Aerospace Battery Workshop
Final for Posting

Characterizing the Risk of Side Wall Rupture

- Side Wall Rupture (SWR) and Spin Groove Rupture (SGR) during Thermal Runaway (TR)
- Problem & Motivation
- Battery Relevant Plan & Results
  - Design 1 – Upper cell support
  - Design 2 – Upper & lower cell support
  - Design 3 – Interstitial aluminum
- Summary of results to date
- Factors driving SWR in batteries

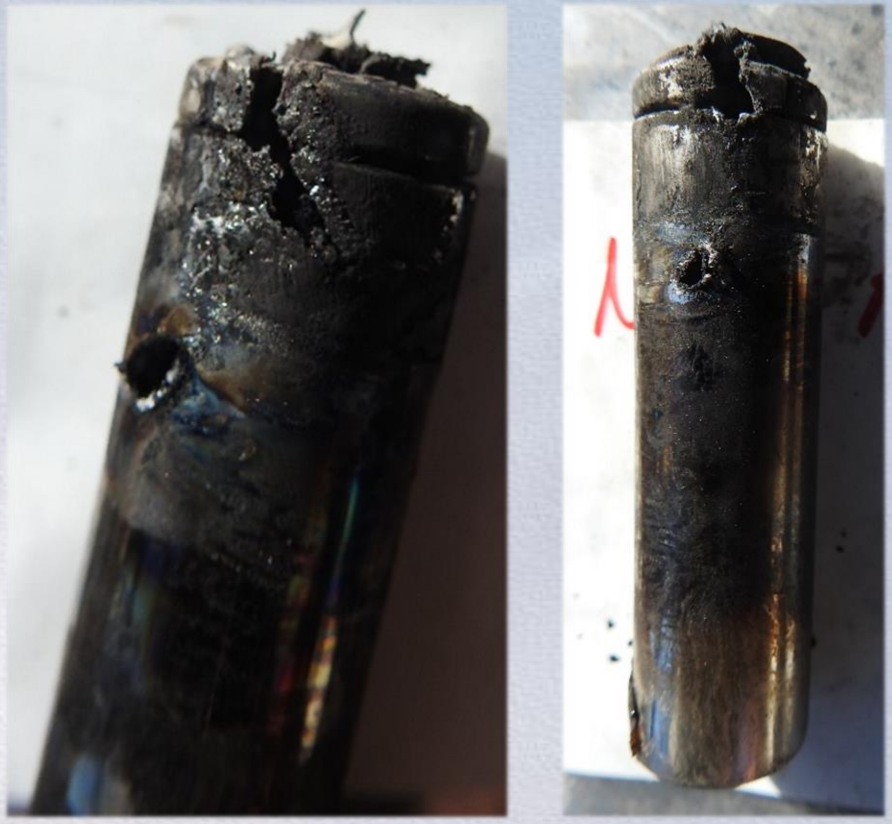


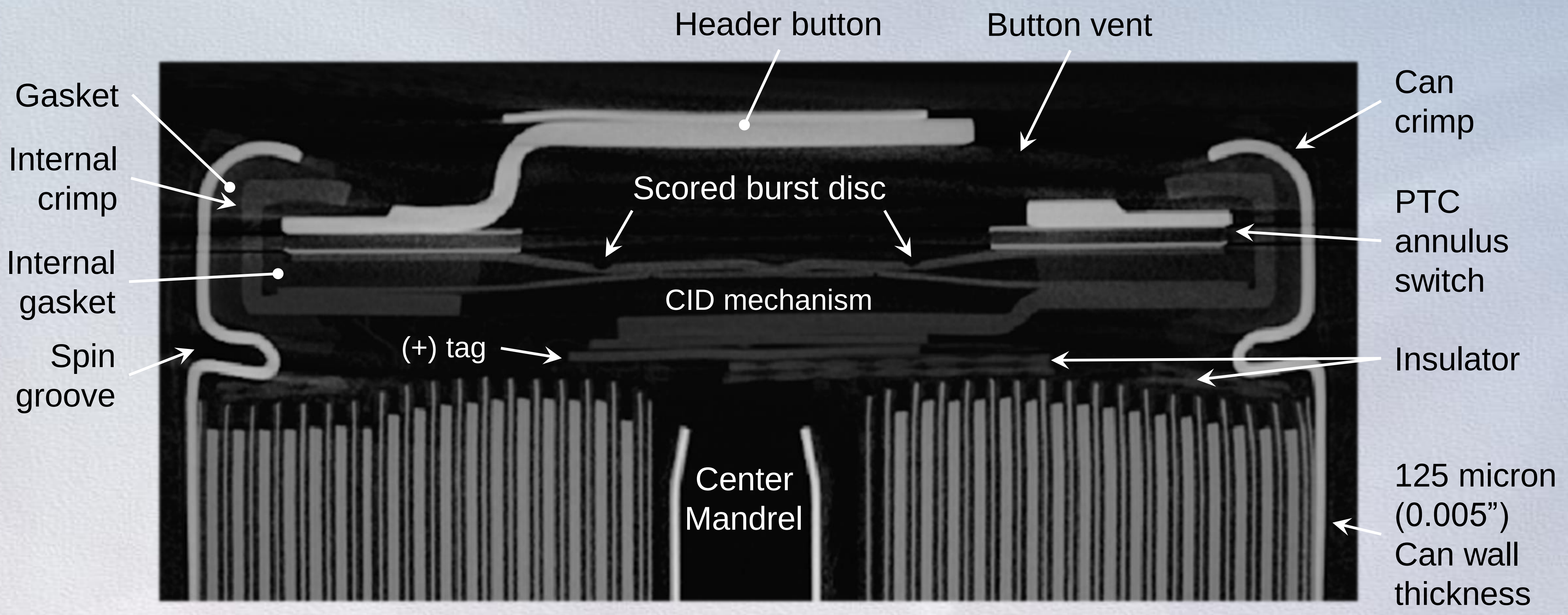
Figure: Post test photos of Panasonic NCR A cells after experiencing SWR and SGR during thermal runaway.

SWR Characterization While Unsupported (Initial Method)

Figures: Cells “cooked” in Turkey Roaster in unsupported configuration underestimate the risk of SWR

- Panasonic NCR A&B cell designs (125 µm can wall thickness) found to experience 10% SWR unsupported
- Samsung 30Q cell design (160 µm can wall thickness) found to experience 7% SWR unsupported
- **Yet, during battery PPR tests the 30Q and NCR A were found to experience much higher SWR rates ⟶ we need a much more battery relevant characterization**

Axial View - Header of NCR18650A & B Cell Designs

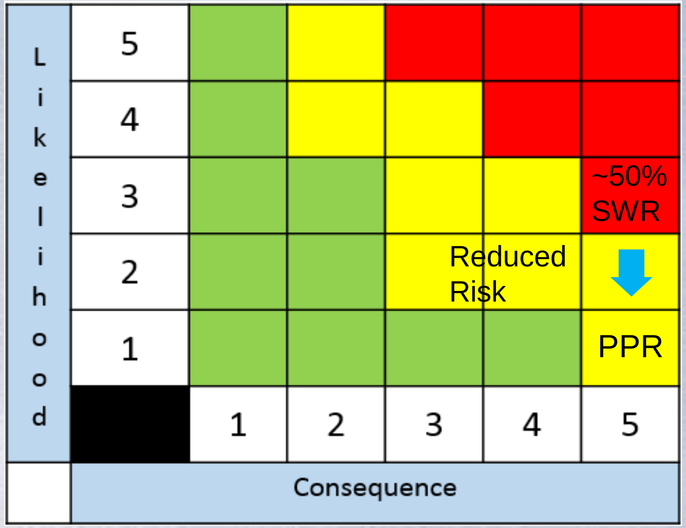


- The cell design features a double-crimp header design
- Header burst pressure of ~1000 psia (68 atm)
- **3 of 30 cells experienced side wall ruptures during unsupported oven heating to TR**

Need to Accurately Characterize the Risk of SWR

- Problem:
  - Several projects have been misled into false sense of low risk of SWR by cell-level “Turkey Roaster” characterization tests
  - This has led to costly PPR test failures
- Solution:
  - Include battery relevant structural constraints on the cells during the SWR characterization tests
  - Include enough cells to provide a statistically defendable result
- For a lot of 60,000 cells, 270 cells must be tested to achieve 90% confidence level in the results
  - Only one (1) failure allowed to reach 1 x 5 box
  - Three (3) failures allowed if testing >500 cells

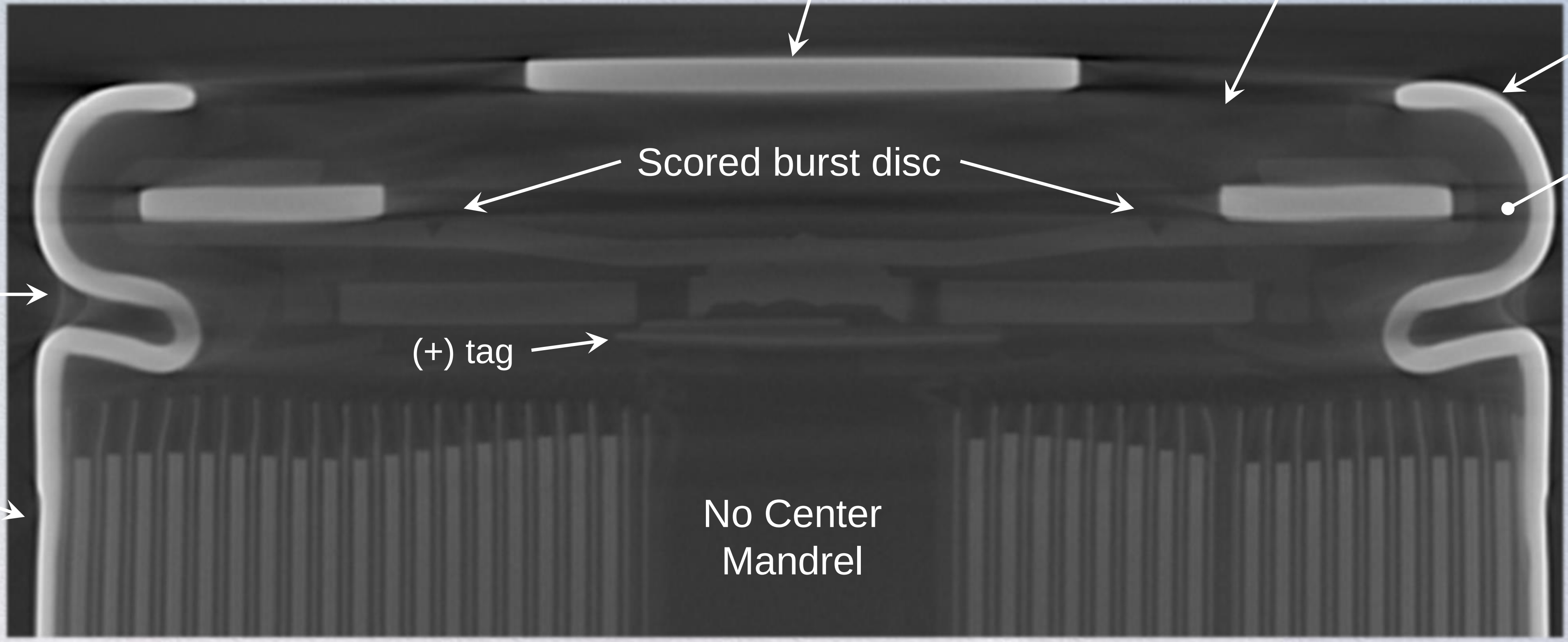
Figure: likelihood versus consequence matrix



Lot Size	Sample size	Lot Size	Sample size
131,288 +	271	7,364 – 8,255	262
46,650 – 131,288	270	6,641 – 7,363	261
28,282 – 46,649	269	6,043 – 6,640	260
20,249 – 28,281	268	5,540 – 6,042	259
15,744 – 20,248	267	5,111 – 5,539	258
12,861 – 15,743	266	4,742 – 5,110	257
10,858 – 12,860	265	4,420 – 4,741	256
9,385 – 10,857	264	4,136 – 4,419	255
8,256 – 9,384	263	4,000 – 4,135	254

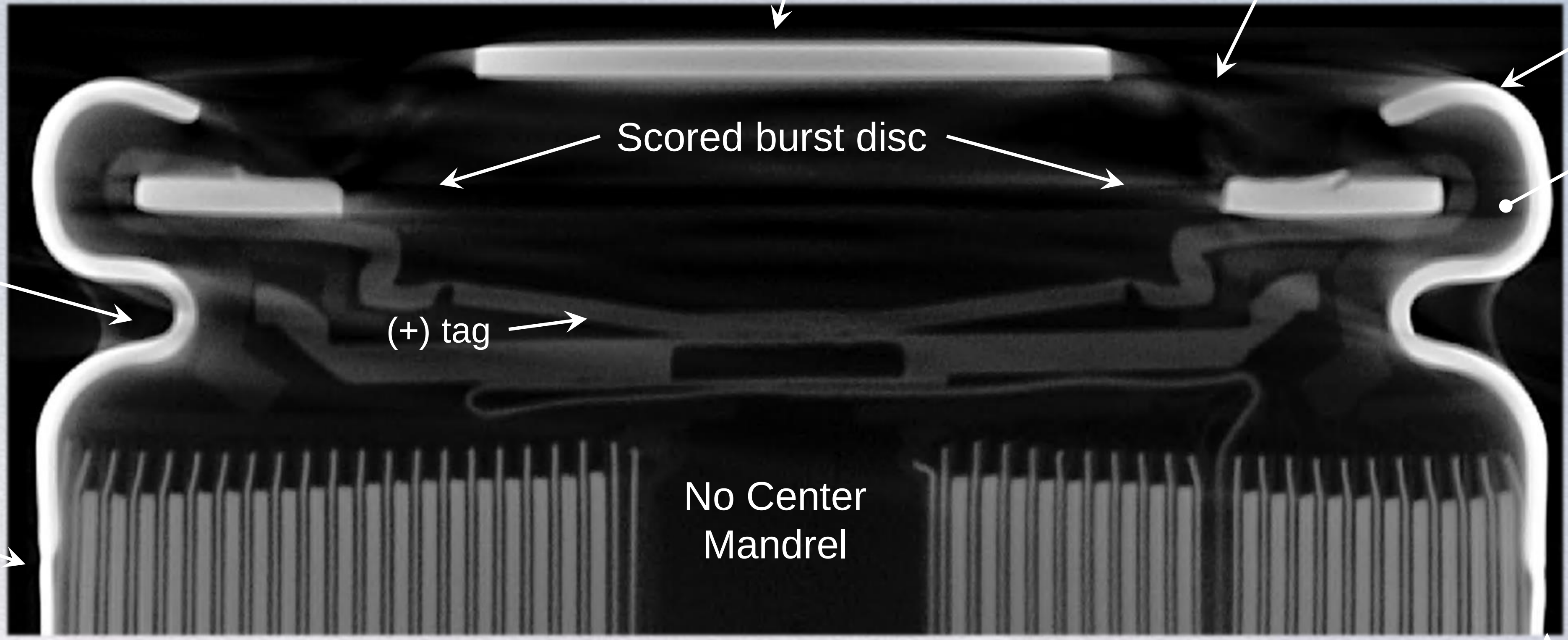
Reference: Daniel, W. W., & Cross, C. L. (2018). Biostatistics: a foundation for analysis in the health sciences. Wiley.

Axial View - Header of LG INR18650M36 Cell



- The cell design features a single-crimp header design
- Header burst pressure of ~808 psia (55 atm)

Axial View - Header of Molicel INR18650-M35A Cell



- The cell design features a single-crimp header design
- Header burst pressure of ~867 psia (59 atm)

Battery Relevant Characterization Plan

- Design relevant battery test article (BTA) that captures the salient features of how representative battery structural support the cell
  - Subscale (9 or 10 cells)
  - Full-Scale Battery Test Article (45 cells)
- Drive all cells into TR via hot plate
- Strip and examine all cell carcasses to determine risks of:
  - Side Wall Rupture (SWR)
  - Spin Groove Rupture (SGR)

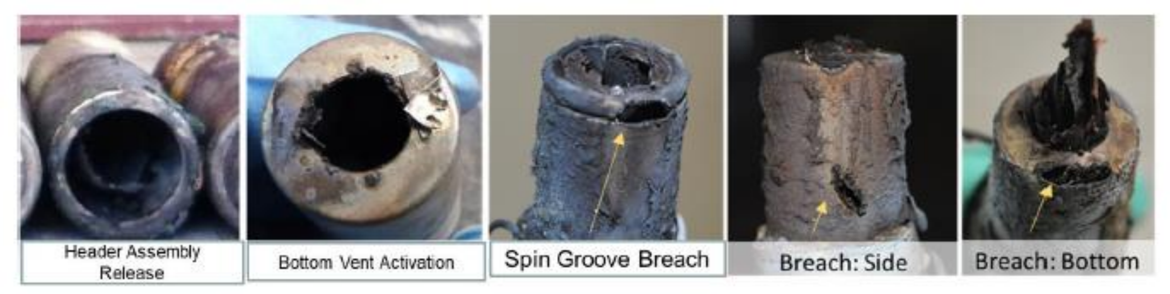


Figure: Examples of common cell failure modes after thermal runaway.

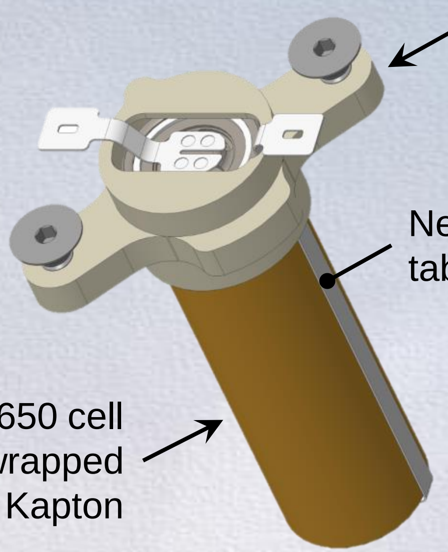
Table 1: Manufacturer, cell model, and date code:______________________________

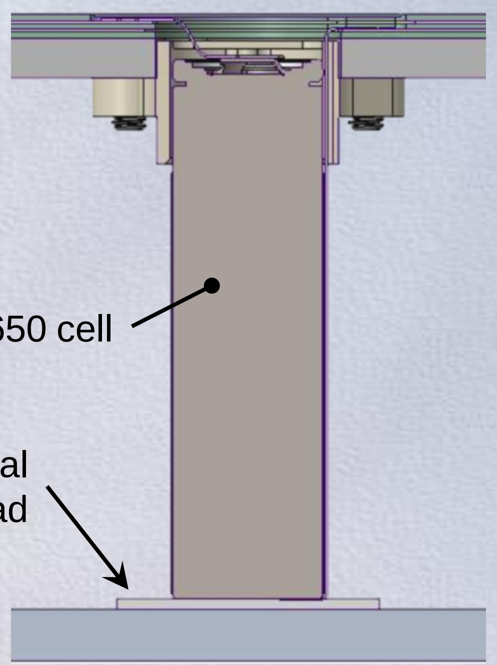
Nominal Top vent	Nominal Bottom vent	Side Wall Rupture (SWR)	Spin Groove Rupture(SGR)	Bottom Rupture (BR)	Top Rupture	JR Ejection	Header Assembly Release

Table: Cell carcasses are examined post-test and the eight (8) relevant test statistics tabulated for individual cells.

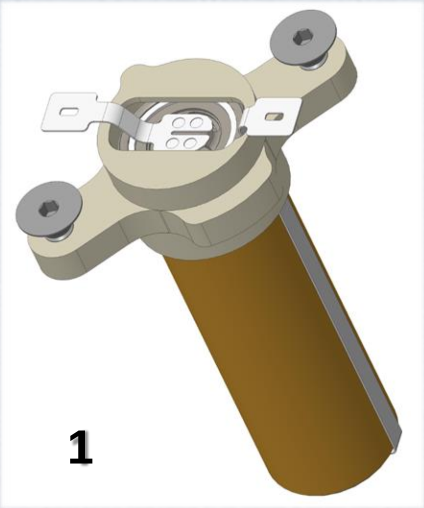
Battery Design 1 – Design Features

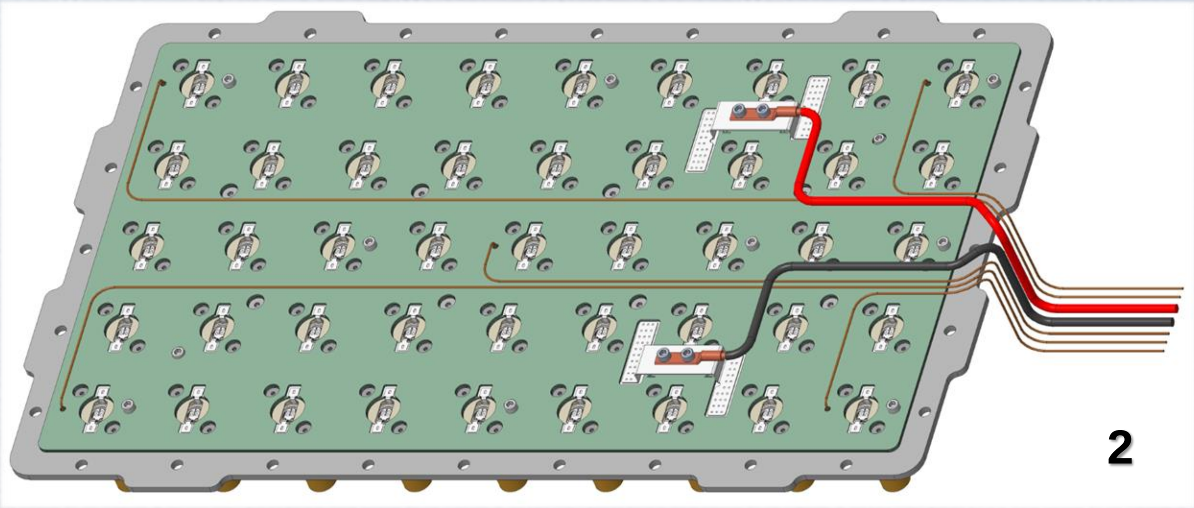
- Cell Preparation
  - Exposed cylindrical wall in Kapton tape
  - Weld negative tab (0.010” thick nickel) to cell bottom and routed axially
  - Plastic header salient features
    - Machinable plastic material matching that used in Battery Design 1
    - Upper cell support circumferential wall thickness representative of cell-cell spacing in Battery Design 1
    - Height of header matching that of Battery Design 1
  - Cell bottom squeezes same gap pad against battery bottom panel
  - Both electrical tabs are spot welded to nickel bus plates insulated with G10 panels as in Battery Design 1



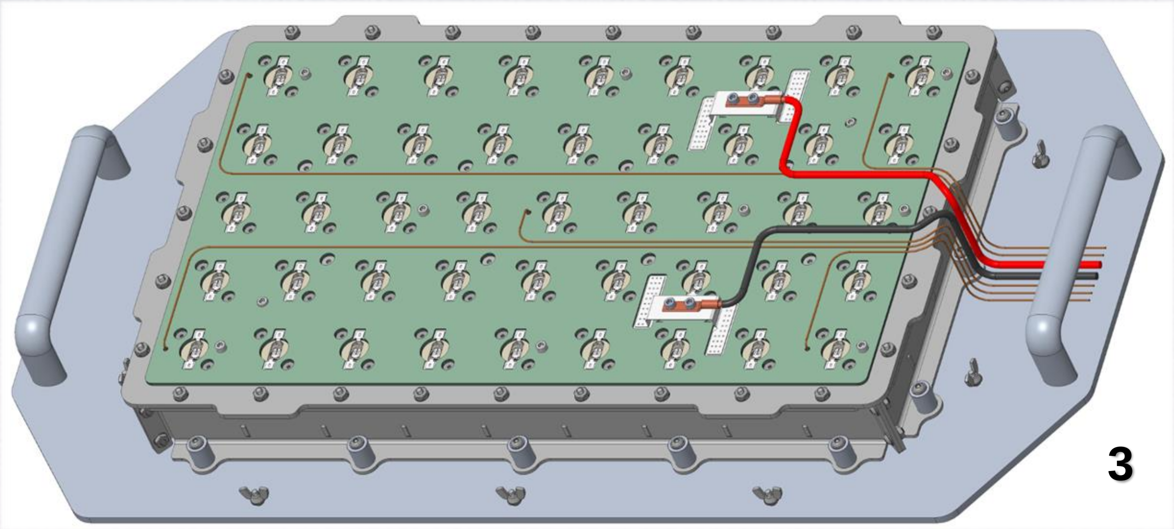


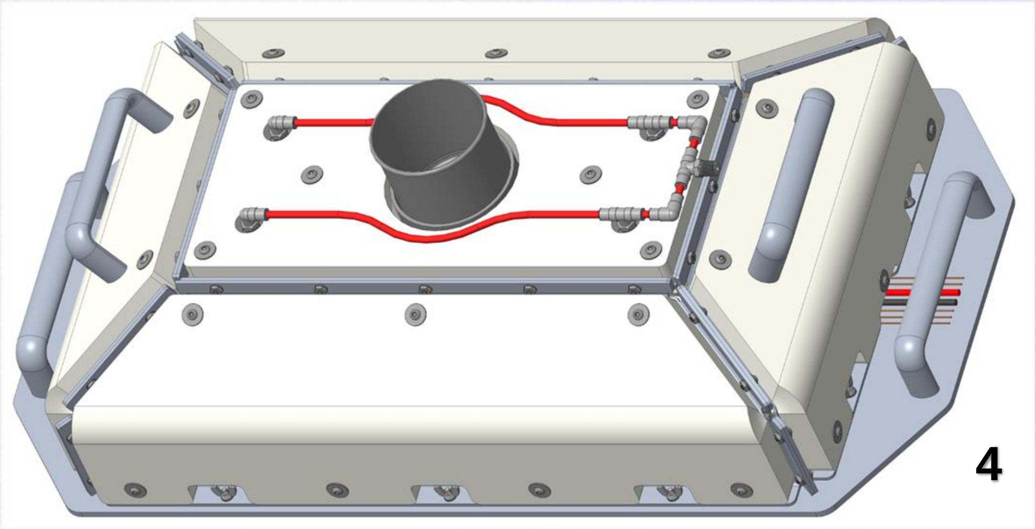
Battery Design 1 – Test Article Assembly





Figures: BTA assembly steps: (1) header and negative tab attached to cell, (2) cells attached to support plate and welded to bus plates, (3) partition and base plate assembly followed by charging, (4) fume hood attached before testing





Battery Design 1 – BTA on Hot Plate

Battery Design 1 Side Wall Rupture Test Run 2 of LG M36 Bare Cells (9/23/2021)

Pre and Post Side Wall Rupture Test Photos

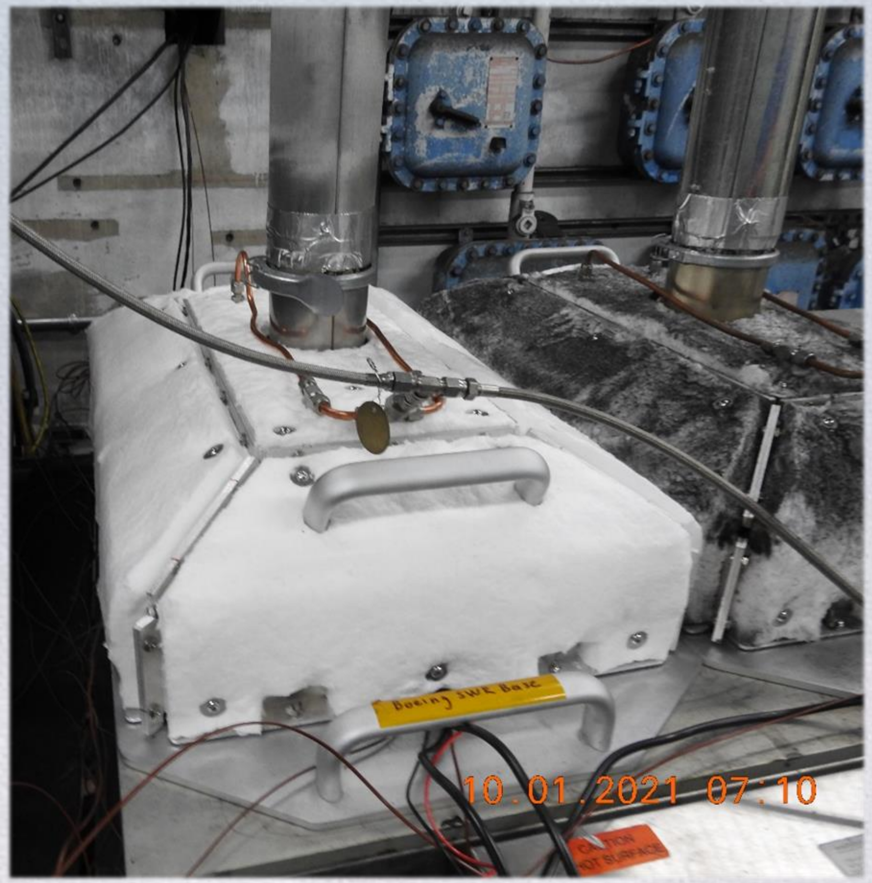


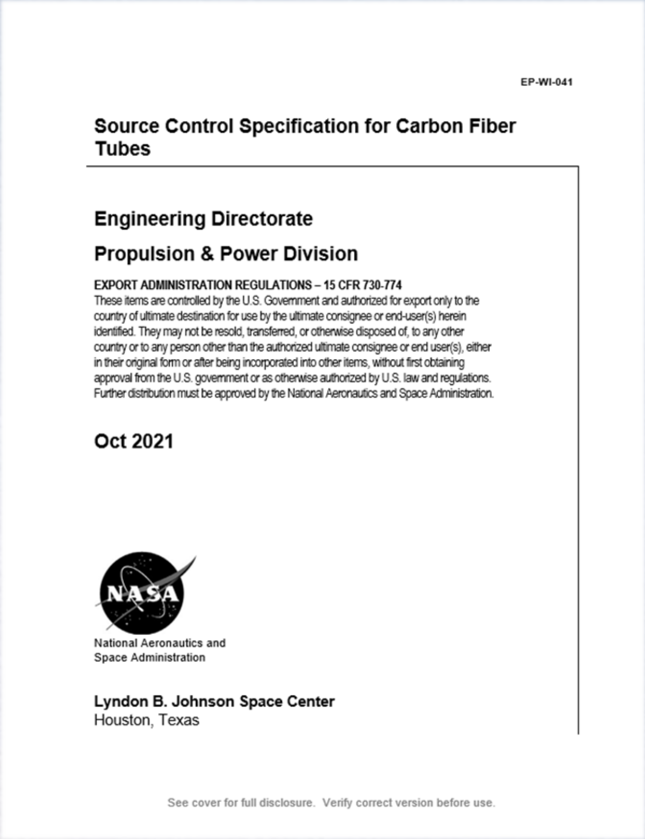
Figure: Battery Design 1 BTA on hot plate with fume hood and GN2 purge line connected.

Figure: Battery Design 1 BTA with fume hood removed following thermal runaway testing of Panasonic NCR A & B cells. Note the jellyroll ejecta material scattered throughout the top of the BTA.

Carbon Fiber Tubes Substitute for Steel Sleeves

- Steel sleeve tubes are difficult to source and control leading to the need to find an alternative sleeve reinforcement
- Carbon fiber tubes are less dense, expand very little, and are easier to make than steel tubes
- Source Control Specification, EP-WI-041, to control:
  - Design
  - Materials and Tooling
  - Assembly
  - Testing
    - Acceptance
    - Qualification

Figure: LG M36 cell with 0.012” CFT.



EP-WI-041

Source Control Specification for Carbon Fiber Tubes

Engineering Directorate

Propulsion & Power Division

EXPORT ADMINISTRATION REGULATIONS – 15 CFR 730-774
These items are controlled by the U.S. Government and authorized for export only to the country of ultimate destination for use by the ultimate consignee or end-user(s) herein identified. They may not be resold, transferred, or otherwise disposed of, to any other country or to any person other than the authorized ultimate consignee or end user(s), either in their original form or after being incorporated into other items, without first obtaining approval from the U.S. government or as otherwise authorized by U.S. law and regulations. Further distribution must be approved by the National Aeronautics and Space Administration.

Oct 2021

National Aeronautics and Space Administration

Lyndon B. Johnson Space Center
Houston, Texas

See cover for full disclosure. Verify correct version before use.

Figure: Control specification for unidirectional CFT (T700S-12E fiber, G-94 resin) and twill CFT (T300K-3K 2/2 fiber, G-94 resin)

Battery Design 1 – SWR Testing Update

- Test Runs To Date:
  - Panasonic NCR18650A with 0.018” CFT – 45 cells tested (1 BTA)
  - Panasonic NCR18650B with 0.018” CFT – 45 cells tested (1 BTA)
  - LG INR18650M36 Bare Cells – 540 cells tested (12 BTAs, first test: 9/22/2021)
  - LG INR18650M36 with 0.005” Steel Sleeve – 450 cells tested (10 BTAs, first test on 10/21/2021)
  - LG INR18650M36 with 0.012” CFT – 540 cells tested (12 BTAs, first test on 11/5/2021)
  - Molicel INR-18650-M35A with 0.012” CFT – 540 cells tested (12 BTAs, first test on 10/1/2021)
- Test Runs Remaining:
  - LG INR18650M36 with 0.005” Steel Sleeve – 90 cells
  - Molicel INR-18650-M35A with 0.018” CFT – 450 cells

Figure: Battery Design 1 BTA on hot plate prior to heating cells into thermal runaway.

Tear Down Inspection for SWR/SGR

- Destructive Physical Analysis (DPA) results to date:
  - 45 Panasonic NCR18650A + 0.018" CFT: 7 SWR, 13 SGR
  - 45 Panasonic NCR18650B + 0.018" CFT: 0 SWR, 2 SGR
  - 540 LG INR18650M36 Bare Cell: **0 SWR, 0 SGR**
  - 315 LG INR18650M36 with 0.005" Steel Sleeve: **0 SWR, 0 SGR**
  - 540 Molicel INR-18650-M35A with 0.012" CFT: 0 SWR, 1 SGR
- Remaining Cells to Examine:
  - 225 LG INR18650M36 w/ 0.005" SS tubes
  - 540 LG INR18650M36 w/ 0.012" CF tubes
  - 450 M35A w/ 0.018" CF tubes

Figure: Panasonic NCRA cell with 0.018" CFT post thermal runaway. Note the thermal abuse sustained by the upper cell support and bursting of the CFT at the seam.

Post-Test Cells Storage

Figure: Cells were bagged and serialized post test to keep ejecta with each cell for a more detailed examination.

Figure: Individual cells were placed in larger bags labeled to correspond to individual test units.

Battery Design 2 – Orion Vehicle Battery

- Battery Design Features
  - Bare cells supported by 9 mil thick 304 Stainless Steel Sleeve
  - Bottom of cell assembly epoxied to aluminum capture plate
    - 2mm spacing between neighboring cells
    - Main path of heat rejection
  - Top of cell assembly epoxied to G10 capture plate with ceramic bushing
  - Syntactic foam as interstitial material

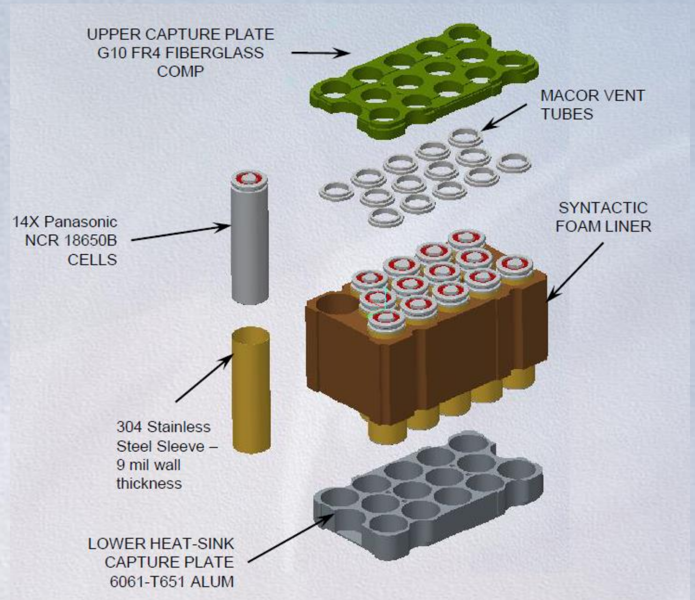


Figure: Exploded view of individual 14-cell battery bricks show with individual components.

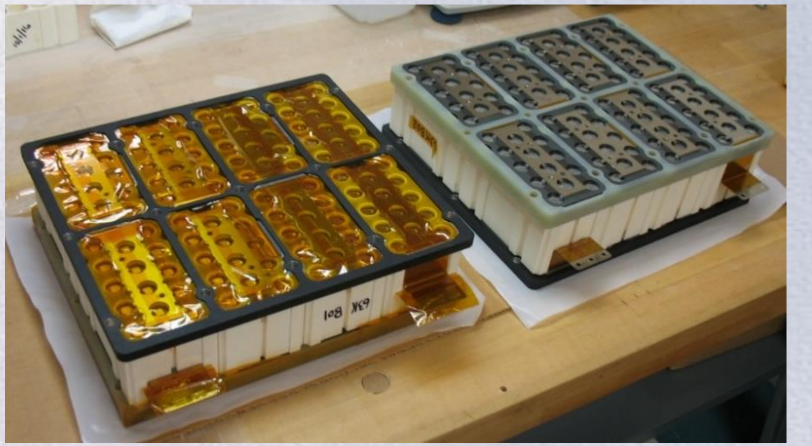
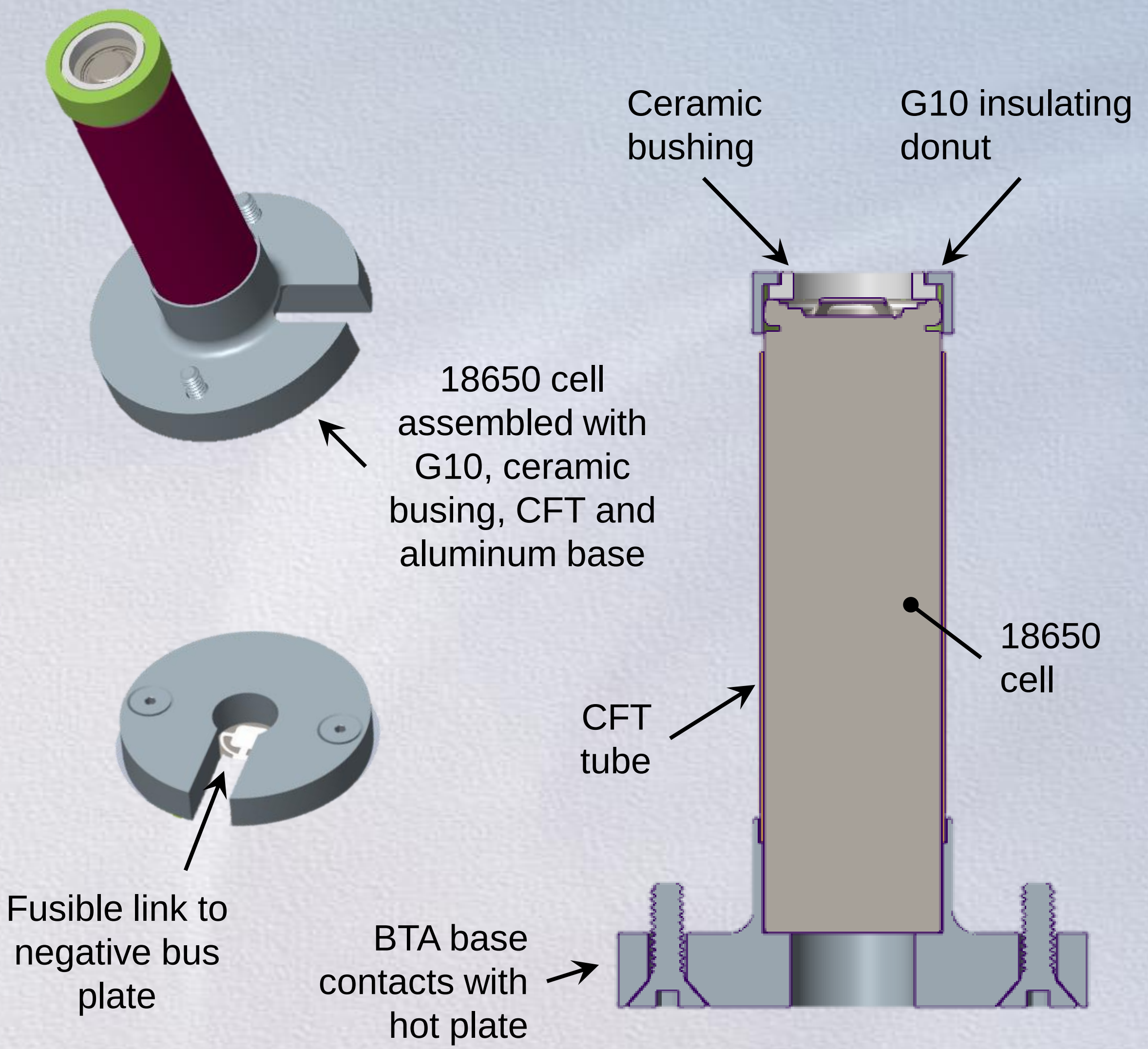


Figure: Four Superbricks connected in 14P-8S comprise single battery pack.

Battery Design 2 – BTA Design Features

- Salient Design Features
  - Ceramic bushing represented as in as-built battery
  - G10 ring sized to thinnest features in as-built batter design
  - Aluminum capture plate represented with thinnest wall features as in the actual battery design
    - Oversized base designed for rapid heat conduction to quickly drive to thermal runaway
    - Inner step added for overlap with support sleeve
  - Fusible link add
  - Both electrical tabs are spot welded to nickel bus plates insulated with G10 panels as in Battery Design 1



Battery Design 2 – Sleeve Options

Figure: Two cell configurations (1) bare LG INR18650M36 cells (no sleeve support) along with (2) Molicel INR-18650-M35A with 0.012" thick CFT prepared for testing. The CFT was manufactured in two layers: 1st layer ~0.0035" thick unidirectional, 2nd layer ~0.008" thick 2x2 twill. The two cells above were tested to compare against incumbent Panasonic NCR18650B cell design.

G10 collar with ceramic bushing

Anodized aluminum base for the cell and tube

Battery Design 2 – Test Article Assembly

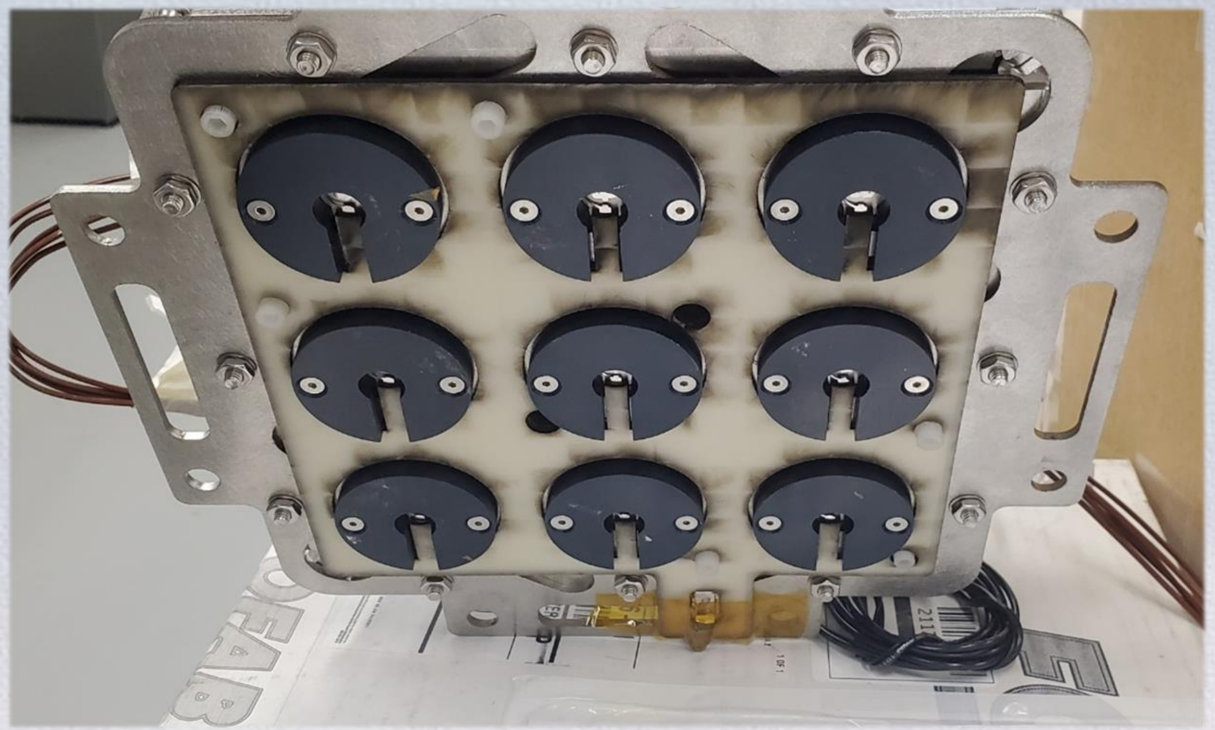


Figure: Battery Design 2 sub-scale BTA after installing cells, welding negative bus plate, and cutting fuse support material. The large diameter cell bases were designed to maximize the heat conducted from the hot plate directly to the cell via conduction.

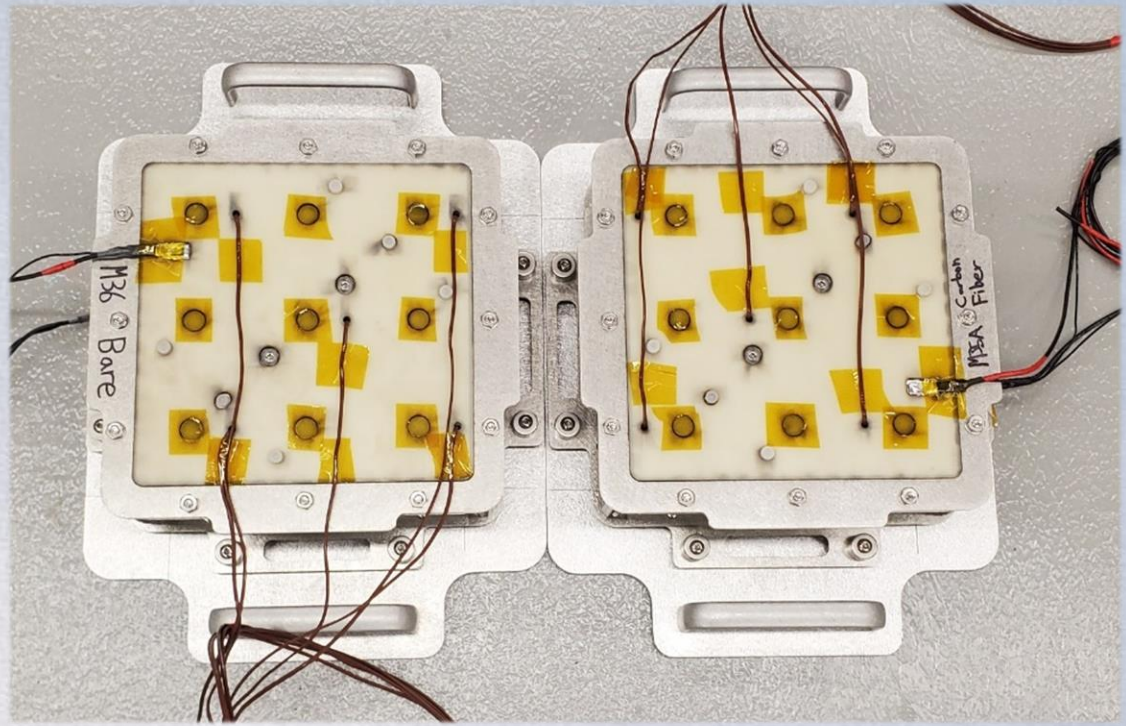


Figure: Top view of Battery Design 2 sub-scale BTAs after assembly has been complete. Five thermocouples sense temperature on the corner and center cell to determine TR and cell heating temperature distribution. The BTA is charged prior to testing and voltage is recorded during the TR test.

Battery Design 2 – Test Article Disassembly

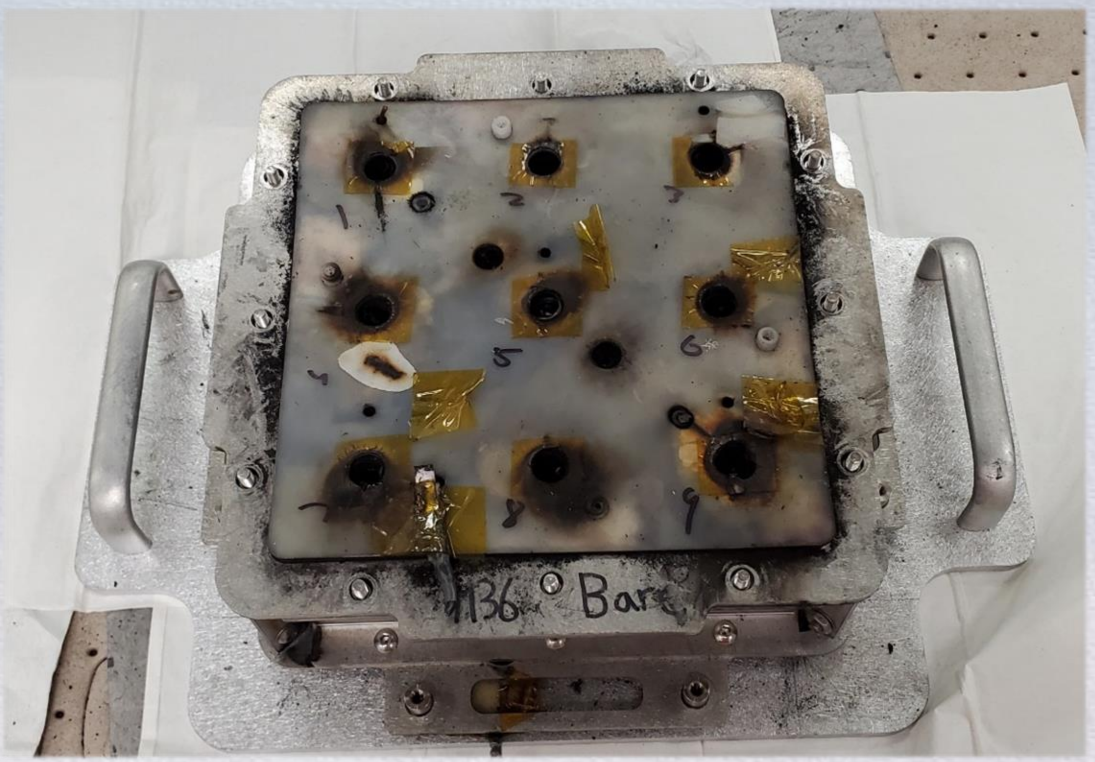


Figure: Battery Design 2 sub-scale LG INR18650M36 BTA after thermal runaway. Note that the individual mica cell covers open during the test for each individual cell to release ejecta but prevent ejecta from falling onto and influencing neighboring cells from heating/shorting.

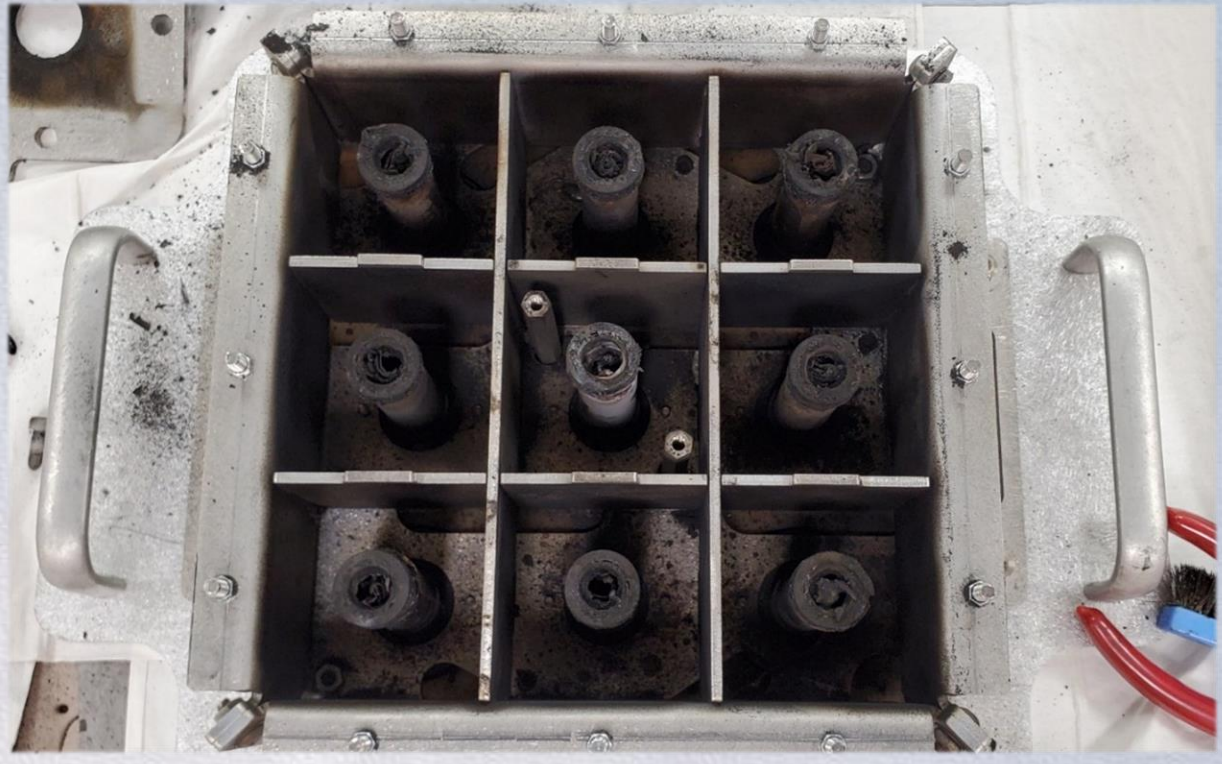
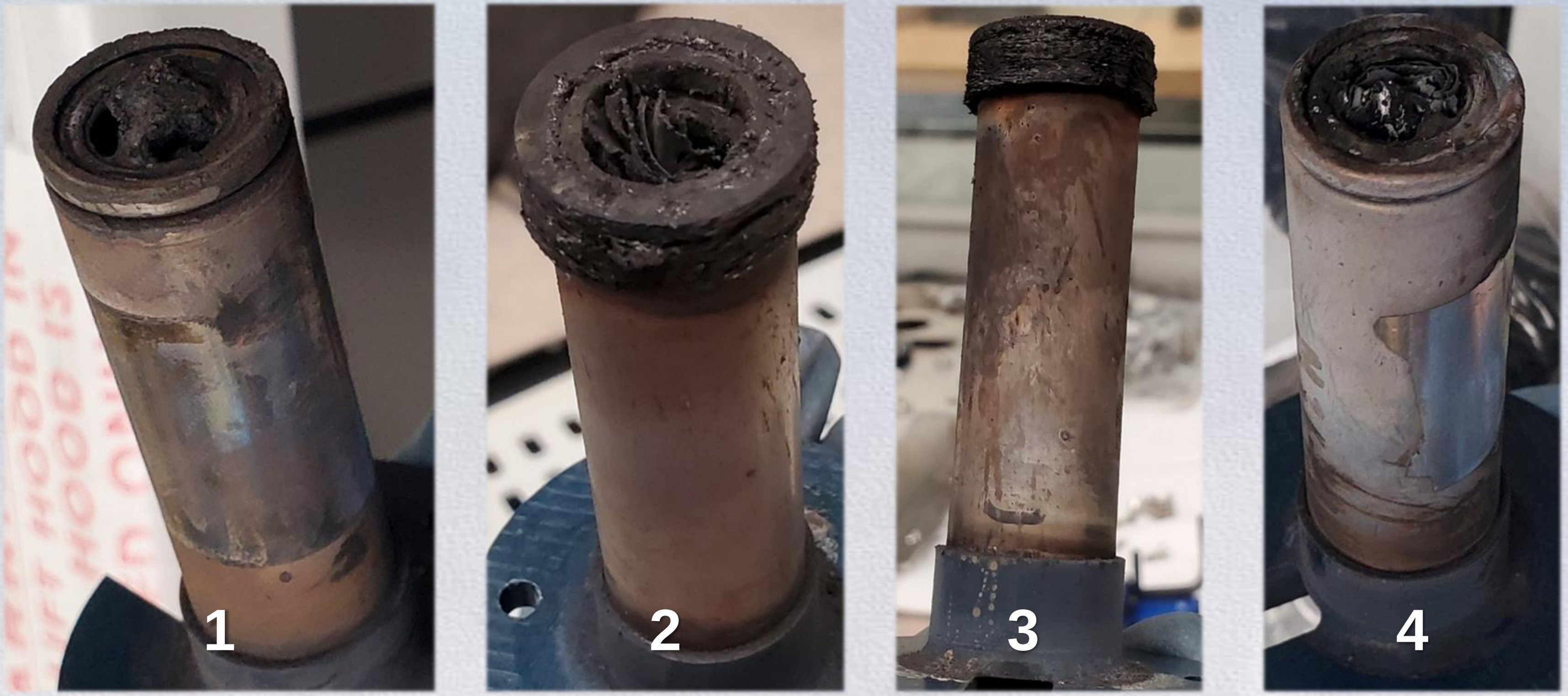


Figure: Battery Design 2 sub-scale BTAs with the upper support plate has been removed. Note that the cells are separated into grid cells to prevent cells from biasing other neighboring cells during thermal runaway. Each cell releases ejecta into its own designated volume which is guarded off from neighboring cell volumes.

Battery Design 2 – LG INR18650M36 Cell DPA



Figures: LG INR18650M36 cells from Battery Design 2 Sub-Scale BTA after thermal runaway. Note (1) header mostly in tact, (2) header completely gone with G10 still connected to the cell, (3) side view of cell with G10 burned, (4) partial jellyroll ejection and (5) G10/ceramic ring missing with top rupture of the cell. **No SWR or SGR** identified in 9-cell sub-scale BTA test.

Battery Design 2 – Moli M35A with 0.012” CFT Cell DPA

Figures: Molicel INR-18650-M35A cells from Battery Design 2 Sub-Scale BTA after thermal runaway. Note (1) G10/ceramic ring is missing and CFT is mostly in tact but split, (2) G10 is severely burned and CFT is split and burned towards the positive button of the cell, (3) G10 ring burned and CFT split but mostly in tact, (4) large split of CFT. **No SWR or SGR** identified in 9-cell sub-scale BTA test.

Battery Design 3 – Interstitial Aluminum Heat Sink

- Battery Design Features
  - Cell can walls wrapped with ¼” wide mica ribbon in barbershop pole configuration, then shrink wrapped
  - Cell assemblies epoxied to anodized heat sink bores with cells 0.020” (~0.5mm) apart
  - Cell-cell interconnects achieved with thin G10/Ni/G10 sandwich epoxied to heat sink at cell ends
  - Cell ends protected with mica covers
  - A ¼” gap between cell ends and blast plate (not shown in image) assemblies

Figure: Battery Design 3 with an interstitial aluminum heat sink with cells spaced 0.020” apart (156 cell heat sink).

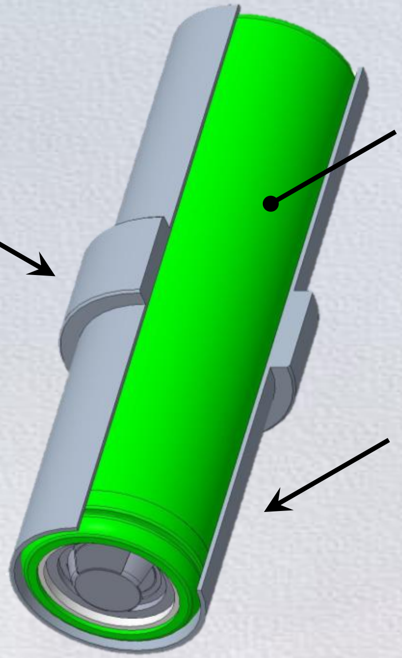
Battery Design 3 – Interstitial Aluminum Heat Sink

- Battery Design Features
  - Cell can walls wrapped with ¼” wide mica ribbon in barbershop pole configuration, then shrink wrapped
  - Cell assemblies epoxied to anodized heat sink bores with cells 0.020” (~0.5mm) apart
  - Cell-cell interconnects achieved with thin G10/Ni/G10 sandwich epoxied to heat sink at cell ends
  - Cell ends protected with mica covers
  - A ¼” gap between cell ends and blast plate (not shown in image) assemblies

Figure: Battery Design 3 with an interstitial aluminum heat sink with cells spaced 0.020” apart (156 cell heat sink).

Battery Design 3 – BTA Design Features

Clamp ring feature transfers axial forces to cell cradle (right) while providing a rigid point to secure the cell



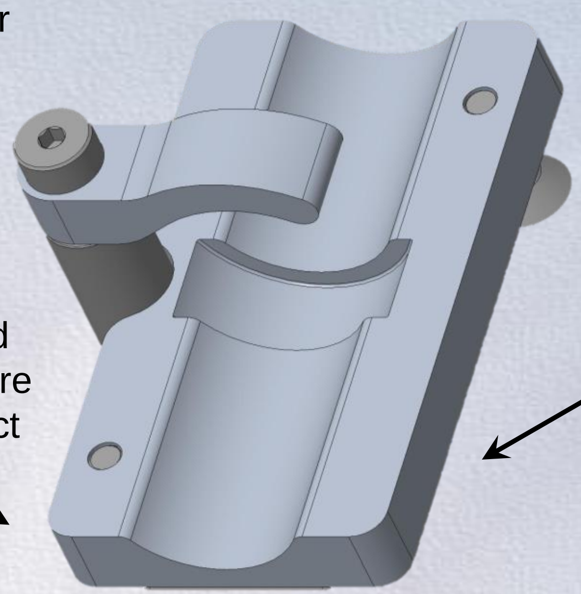
Cylindrical 18650 cells are epoxied into custom-designed aluminum cell tubes

Aluminum cell tube replicates the wall thickness (0.020”) from the battery heat sink

Figure: Cell tube assembled with 18650 cell (Note: 90º cutaway of cell tube to show cell tube cross-section profile).

Cells are secured in place with a single-fastener clamp

Thermal gap pad placed between the base plate and cradle to ensure thermal contact



Two countersink screws position and secure cradle to the base plate

Aluminum cell cradle secures the cell and transfers heat from hot plate to the cell

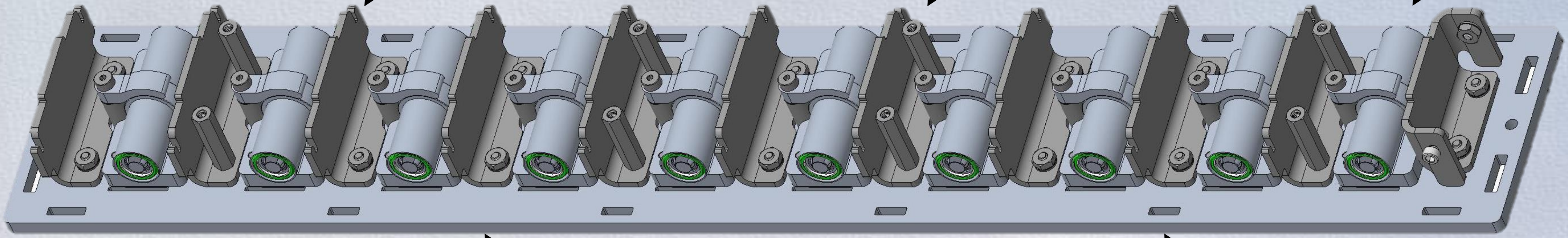
Figure: Cell clamped into the cell cradle with a single fastener. Single fastener will minimize turn-around time.

Battery Design 3 – BTA Design Features

Partitions positioned between cells prevent thermal runaway from propagating to neighboring cells

Standoffs positioned for mating with cell blast cover assembly

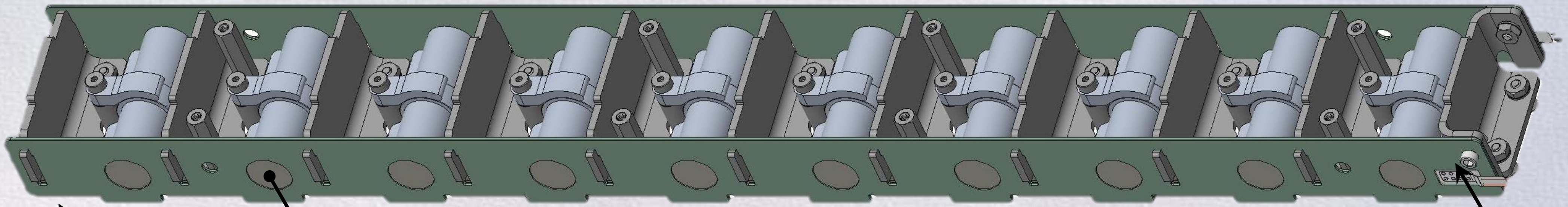
Cradle subassemblies spaced at 2-3/8” O.C.



Negative bus plate sub-assembly

Aluminum base plate onto hot plate (not shown) transfers heat to individual cells

Slot cutouts are positioned around the perimeter to support blast cover, bus plate subassemblies



Positive bus plate sub-assembly

Mica cell covers

Tabs fitting into slots in the base plate prevent the bus plates from separating away from cells during TR

Welded tabs for connecting charge wires and voltage measuring leads

Battery Design 3 – BTA Design Features

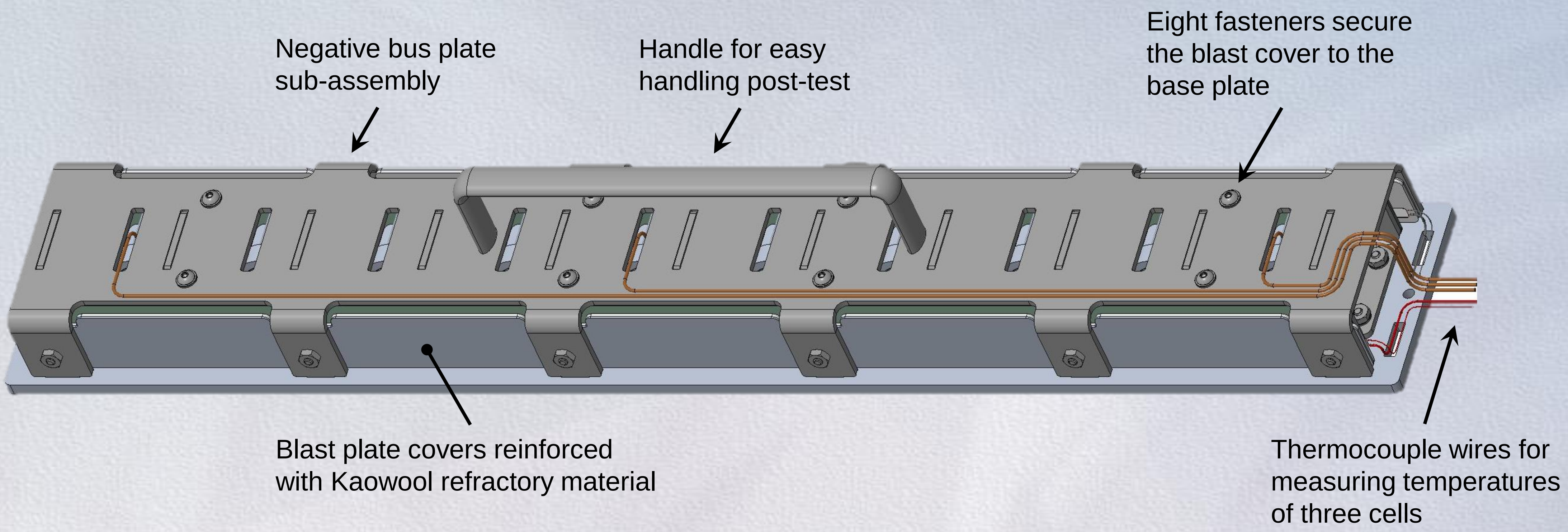


Figure: Battery Design 3 BTA designed with cells placed horizontally for a “radial” heating path to mimic heat transfer in the interstitial aluminum heat sink. During TR, a large percentage of the heat is transferred through the cell can to the neighboring cells via the heat sink which functions to disperse the sudden spike in temperature.

Battery Design 3 – Molicel INR-18650-M35A Cell DPA

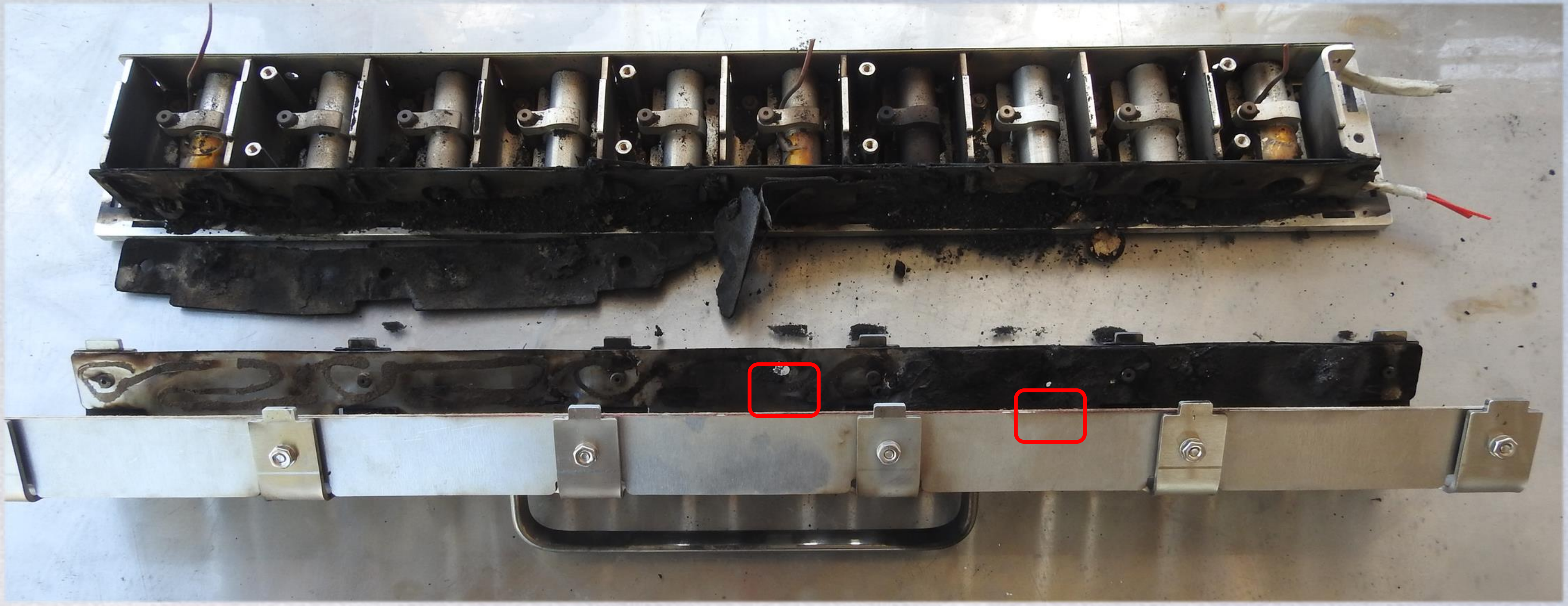


Figure: DPA of Battery Design 3 BTA with Molicel INR-18650-M35A cells with the blast cover removed. **No SWR or SGR** observed in the cells, however, two breach holes were observed in the Kaowool-reinforced aluminum blast plates.

Battery Design 3 – LG INR18650M36 Cell DPA

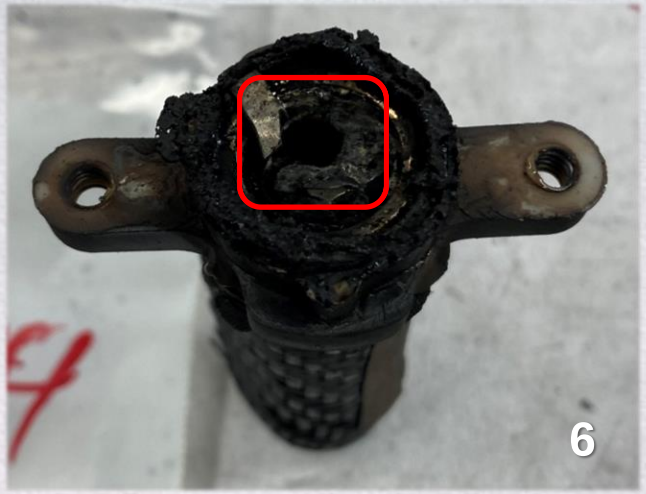
Figure: DPA of Battery Design 3 BTA with LG INR18650M36 cells with the blast cover and positive bus plate assembly removed. **No SWR or SGR** observed in the cells.

Example of Cell DPA Results

Figures: Cell #12 of BTA 18 – Molicel INR-18650-M35A Cell with 0.012" CFT after thermal runaway. Note the thermal abuse sustained by the plastic header and header rupture.

Figures: Cell #18 of BTA 18 – Molicel INR-18650-M35A Cell with 0.012" CFT after thermal runaway. Note the plastic header burn through. **No SWR or SGR observed**.

Example of Cell DPA Results



Figures: Cell #44 of BTA 18 – Molicel INR-18650-M35A Cell with 0.012" CFT after TR. Note (1, 2) tiny SGR, but not through plastic header, (5) elongated spin groove on cell with plastic header and CFT removed, (6,7) header rupture.

Summary of Results To Date

Battery Design 1 Test Article Description	Cell Quantity	Nominal Top Vent	Nominal Bottom Vent	Side Wall Rupture	Spin-Grove Rupture	Bottom Rupture	Top Rupture	Jelly-Roll Ejection	Header Release
Panasonic NCR18650 Cell with 0.018" CFT	45	2	0	**22**	**9**	4	4	4	37
Panasonic NCR18650B Cell with 0.018" CFT	45	29	0	0	**1**	0	1	0	16
LG INR18650M36 Bare Cell	540	207	0	**0**	**0**	0	321	5	24
LG INR18650M36 Cell with 0.005" Steel Sleeve	315	106	0	**0**	**0**	0	192	1	20
LG INR18650M36 Cell with 0.012" CFT	-	-	-	-	-	-	-	-	-
Moli INR-18650-M35A Cell with 0.012" CFT	538	260	0	0	**1**	0	278	0	9
Moli INR-18650-M35A Cell with 0.018" CFT	-	-	-	-	-	-	-	-	-

Table: Panasonic NCRA cell with 0.018” CFT post thermal runaway. Note the thermal abuse sustained by the upper cell support and bursting of the CFT at the seam.

Preliminary Factors Driving SWR/SGR

Cell Level:

- Energy density (> 660 Wh/L or >2.6 Ah 18650)
- Low cylindrical can wall thickness and strength
- Low spin groove/crimp area can wall thickness and strength
- High header burst pressure
- Absence a bottom vent path

Battery Level:

- Preventing cell header bursting/release
  - Impeding crimp to unfold
  - Impeding bottom rupture
- Insufficient can wall support
  - Particularly near spin groove
  - Entire can wall support required in some cell designs
- Cell can wall injury during battery assembly
  - Scoring cell wall during wrap removal or other assembly steps

Thank You!