LITHIUM-ION SIDEWALL RUPTURE CHARACTERIZATION WITH 3 BATTERY DESIGNS

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AGENDA

- Introduction and motivation
- Sidewall rupture (SWR) characterization plan
- Design description, testing, and results
    - Design A, B, and C
- Conclusions

ACRONYMS

- BR – Bottom Rupture
- BTA – Battery Test Article
- CFT – Carbon Fiber Tube
- DPA – Destructive Physical Analysis
- PPR – Passive Propagation Resistant
- SGR – Spin Groove Rupture
- SWR – Sidewall Rupture
- TR – Thermal Runaway

GUIDELINES FOR PASSIVE PROPAGATION RESISTANT (PPR) BATTERIES

1. **Reduce the risk of cell can sidewall breaches (Sidewall Rupture)**
2. Provide adequate cell spacing and heat rejection
3. Individually fuse parallel cells
4. Protect the adjacent cells from the hot thermal runaway ejecta
5. Prevent flames and sparks from exiting the battery

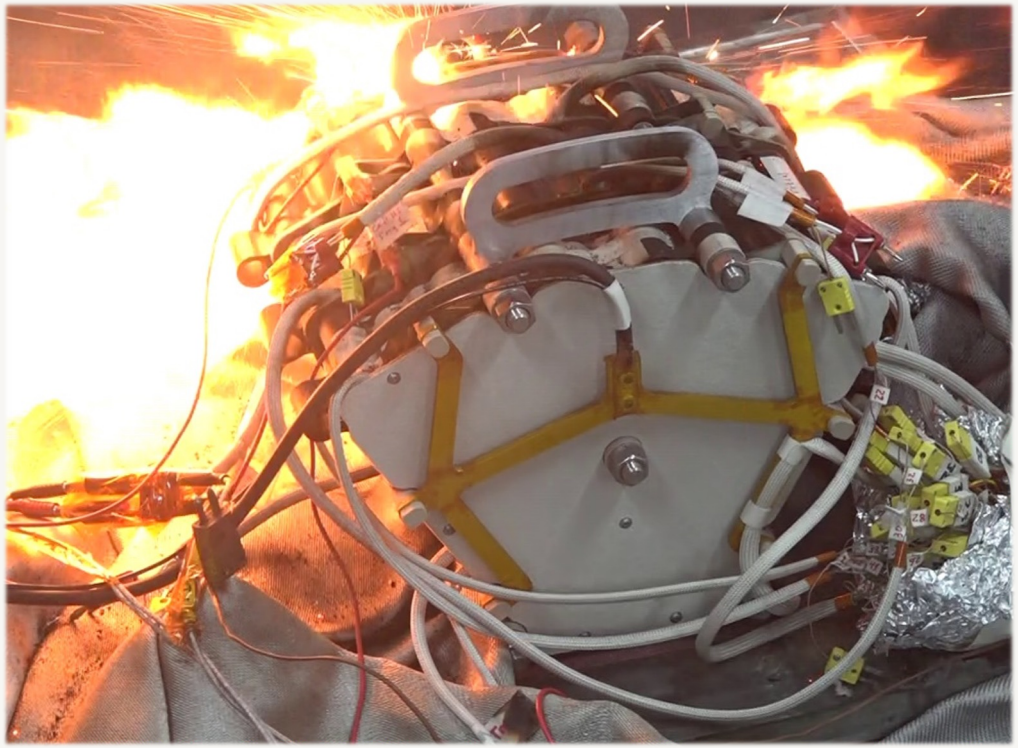


Figure: 134P-3S PPR battery pack developed by NASA successfully sustained 12 single trigger events without propagating thermal runaway

THERMAL RUNAWAY (TR) SWR VIDEO

SWR CHARACTERIZATION WITH UNSUPPORTED CELLS

CELL LEVEL TESTING

Cells triggered into TR in unsupported configuration looked promising in terms of SWR rates:

- Panasonic NCR A&B = 10% SWR
- Samsung 30Q = 7% SWR

BATTERY TESTING

When PPR tested in their battery configuration, both cells were found to experience much higher SWR rates.

SWR CHARACTERIZATION WITH UNSUPPORTED CELLS

PROBLEM

-False sense of low risk of SWR by unsupported cell-level characterization tests has led to costly PPR test failures.

SOLUTION

1. Include battery specific relevant structural constraints on the cells
2. Include enough cells to provide a statistically defendable result.

   [1]From a lot of 60,000 cells, 270 cells must be tested to achieve 90% confidence

   *Only 1 failure allowed to reach 1x5 risk level, or 3 if testing >500 cells
3. Test different cells to compare performance.

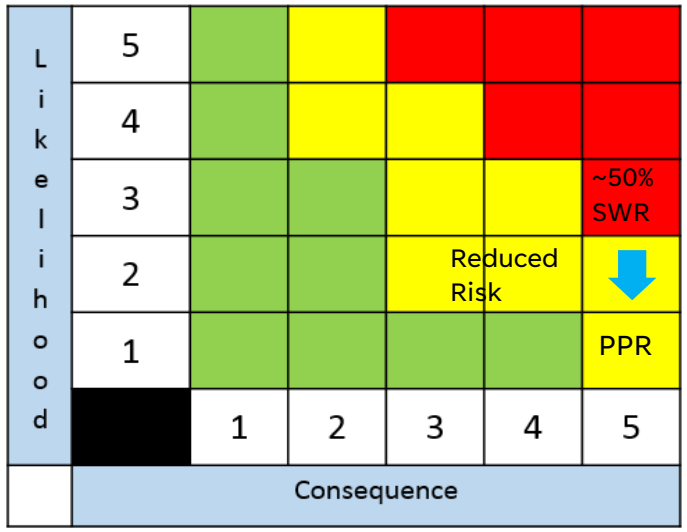


Figure: likelihood versus consequence matrix

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

CHARACTERIZATION PLAN

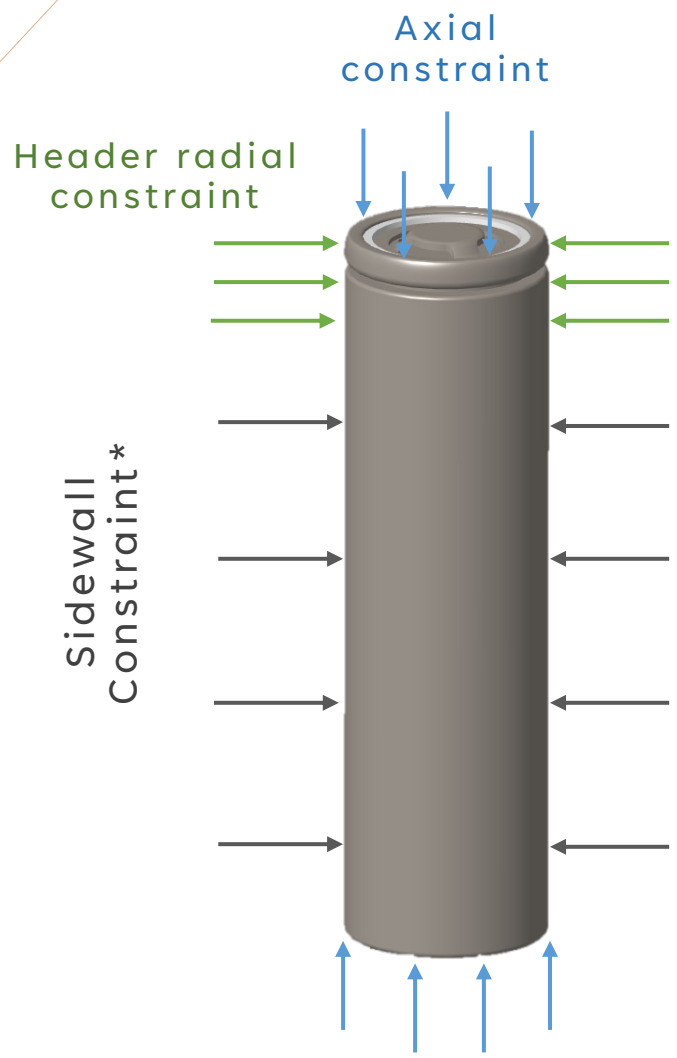
Design — Battery test article (BTA) that captures the salient features of how cells are supported on the original battery design. Test different cells.

Test — Drive all cells into Thermal Runaway via hot plate.

Data — Strip and examine all cell carcasses to determine risks of:

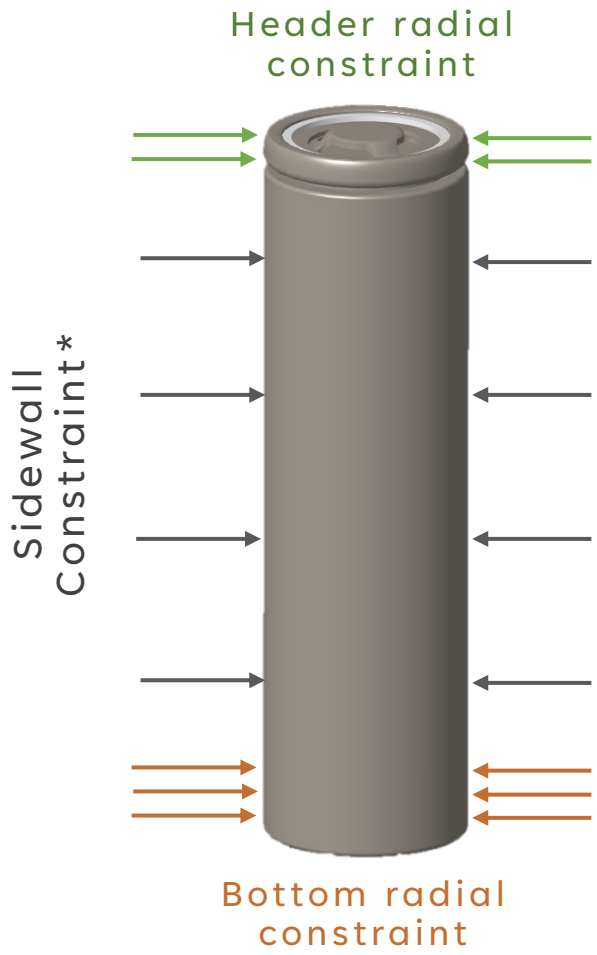
- -Side Wall Rupture (SWR)
- -Spin Groove Rupture (SGR)

SALIENT FEATURES BY DESIGN



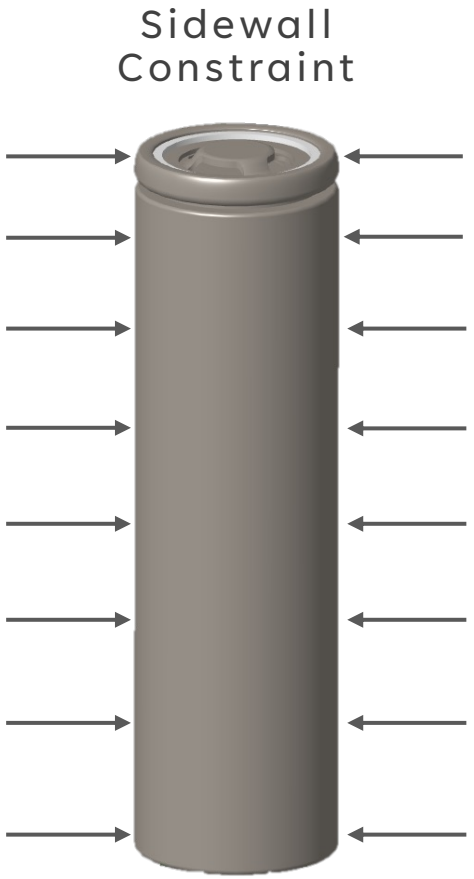
Design A

*Carbon fiber or steel tubes



Design B

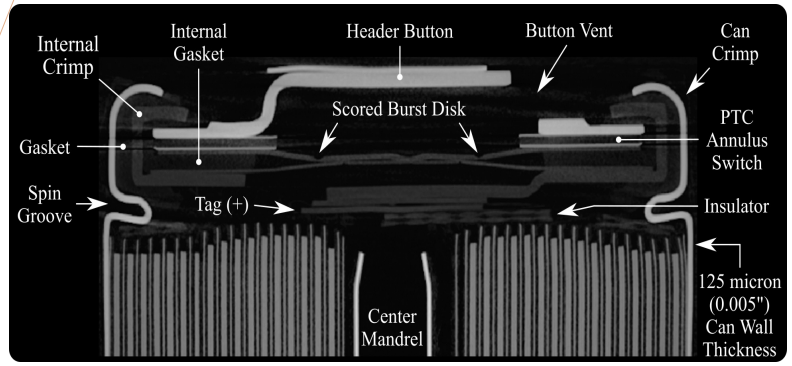
*Carbon fiber tubes



Design C

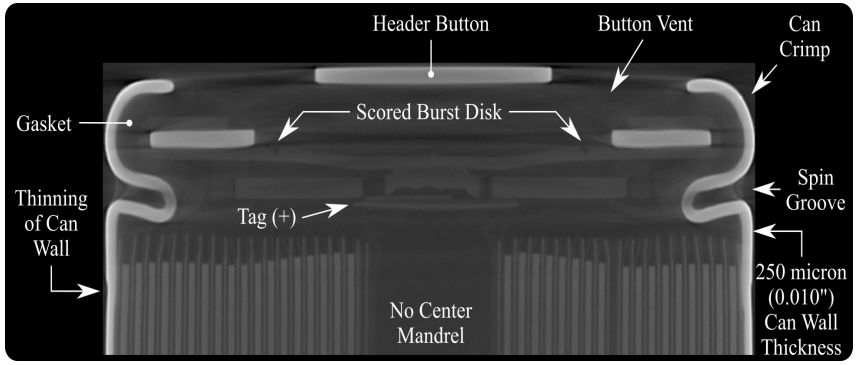
CELLS TESTED

NCR 18650 A & B



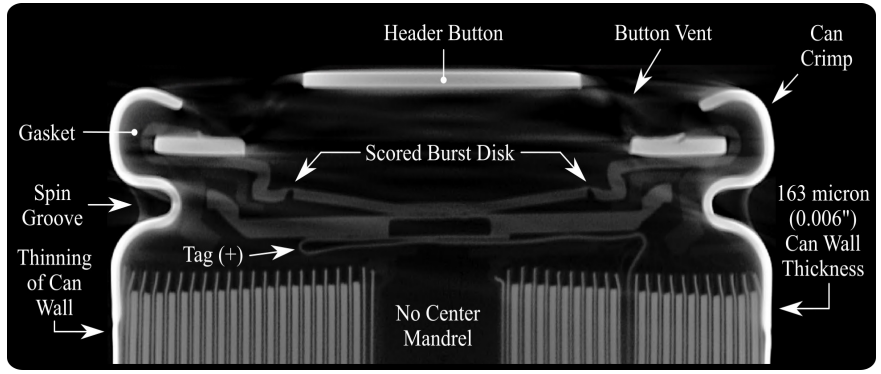
- Double crimp header design
- Header burst pressure ~1000 psia
- 0.005” Can wall thickness
- 3400 mAh

LG 18650 M36

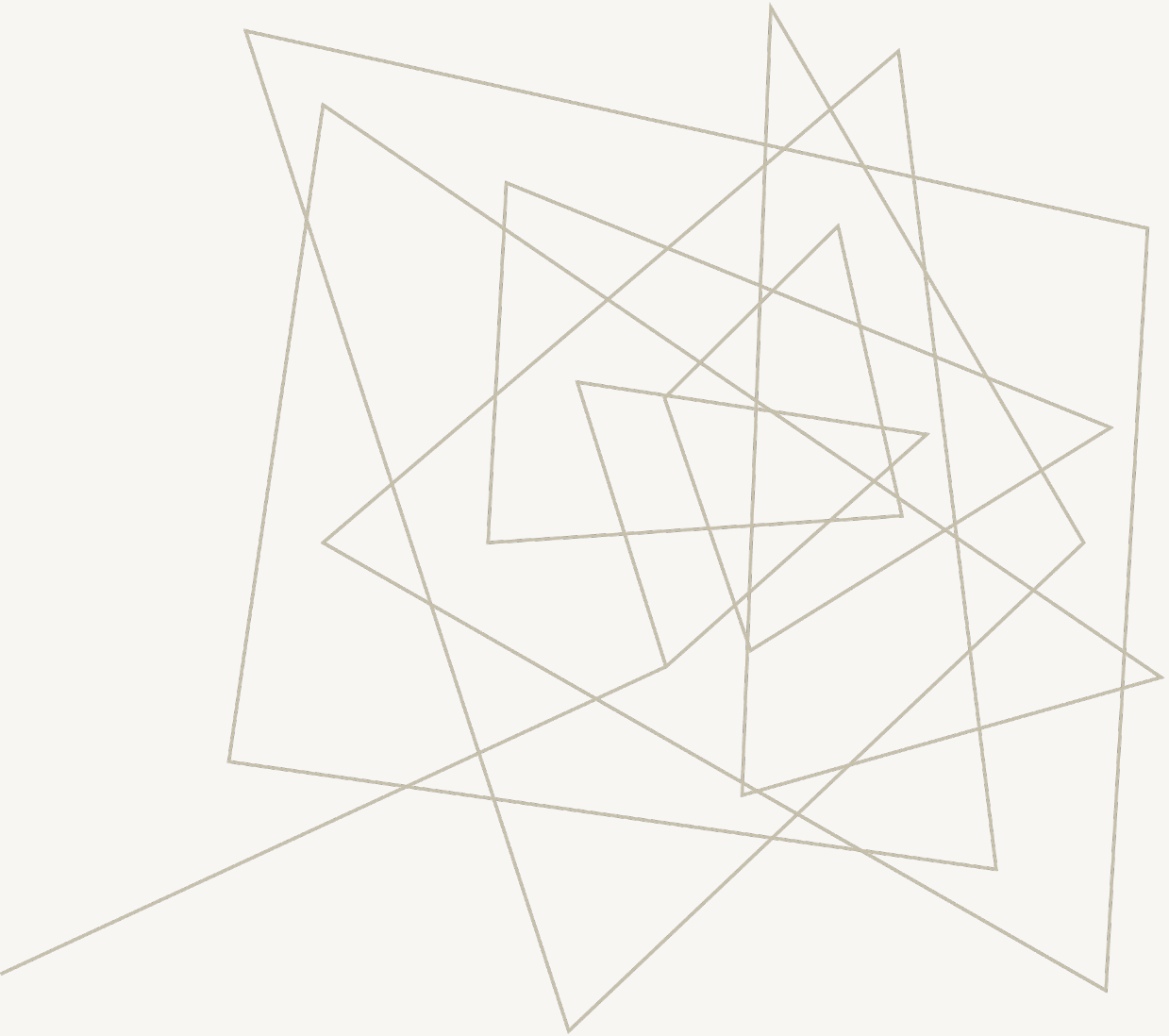


- Single crimp header design
- Header burst pressure ~808 psia
- 0.010” Can wall thickness
- 3450 mAh

MOLICEL 18650 M35A



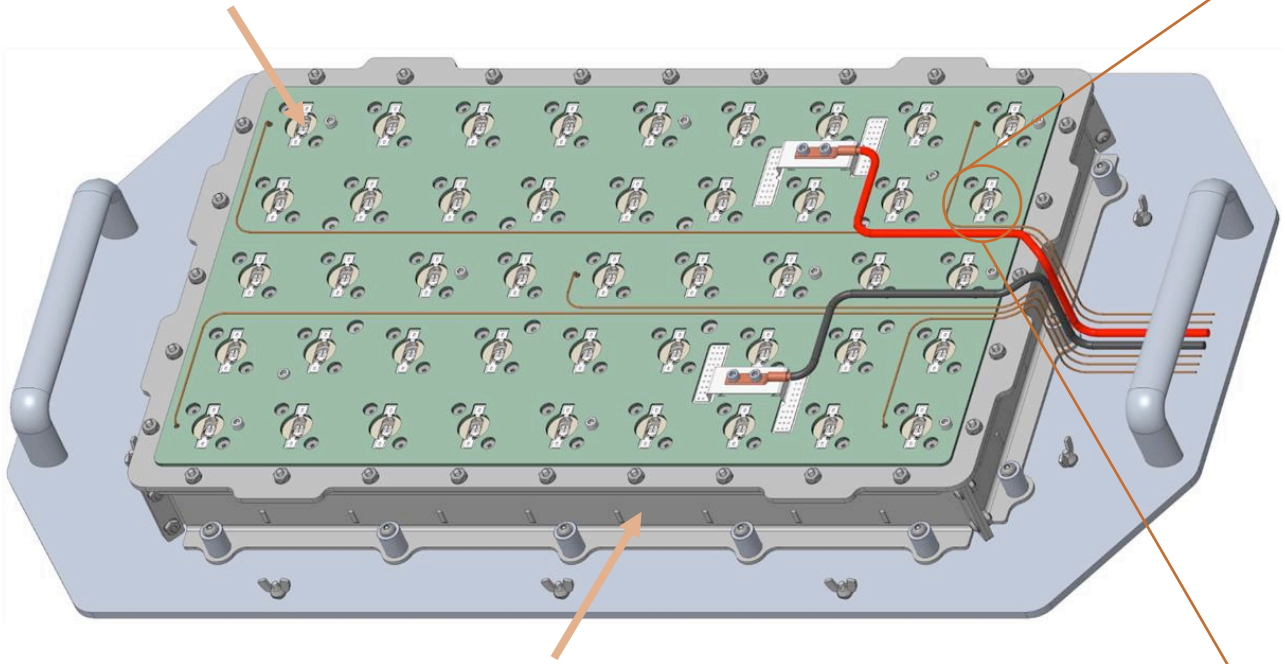
- Single crimp header design
- Header burst pressure ~867 psia
- 0.0063” Can wall thickness
- 3500 mAh



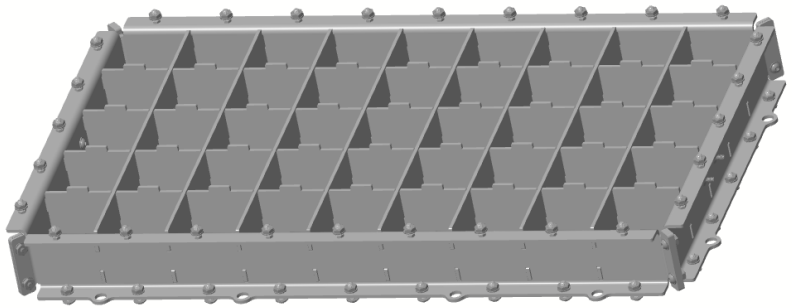
BATTERY DESIGN A

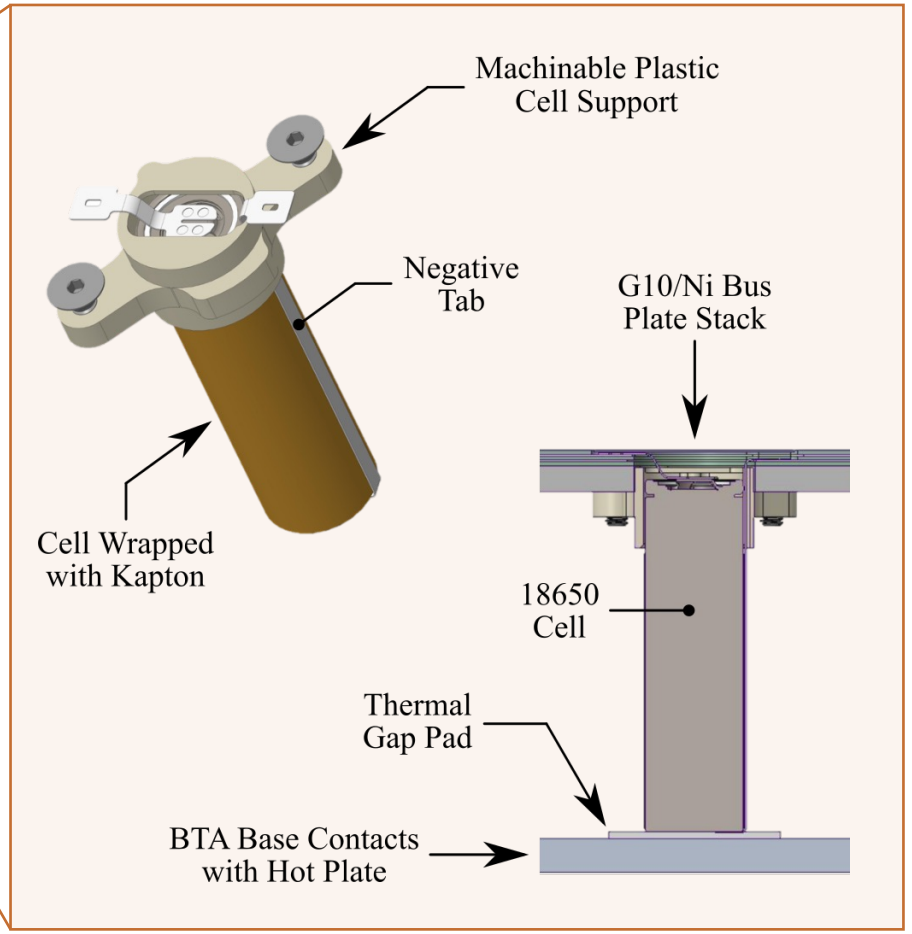
DESIGN A

Mica covers (not shown) to protect adjacent cells from ejecta



Cell Partition





CARBON FIBER TUBES (CFT) SUBSTITUTE FOR STEEL SLEEVES

- Steel sleeve tubes are difficult to source and control
- Carbon fiber tubes are less dense, and may be an alternative to steel sleeves
- Source Control Specification, EP-WI-041

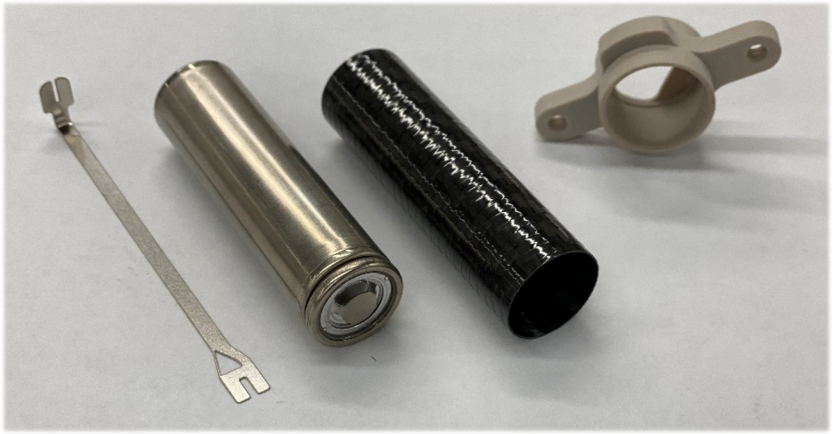
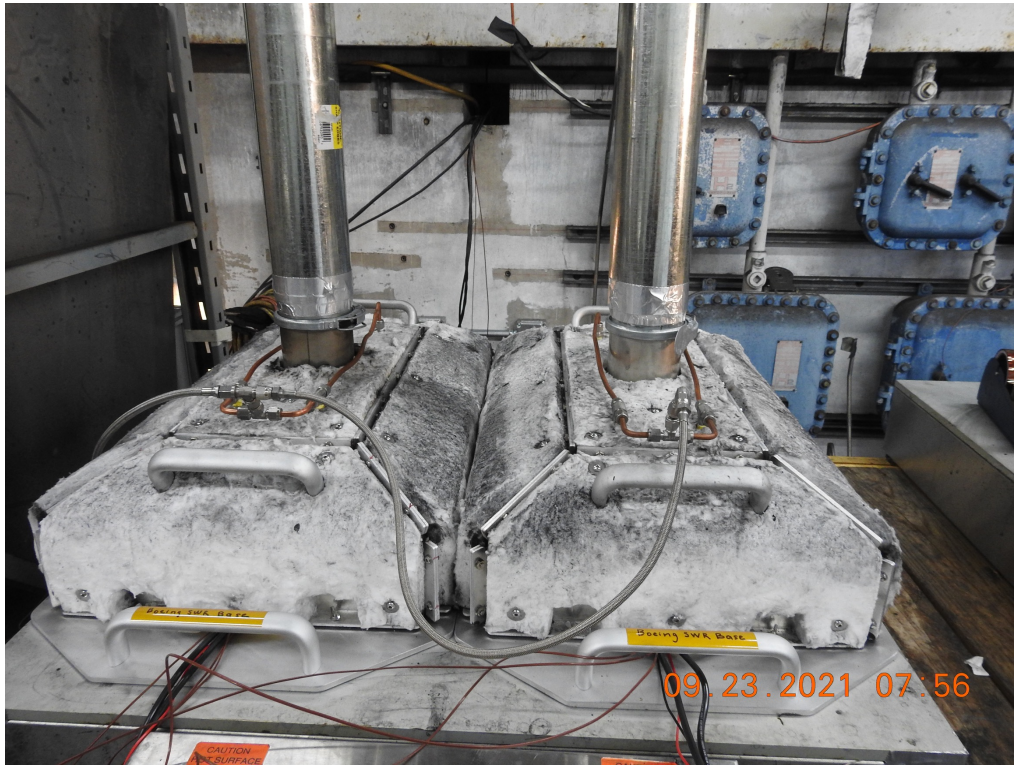


Figure: LG M36 cell with 0.012” CFT.

DESIGN A - TEST



Mica covers to protect adjacent cells from ejecta

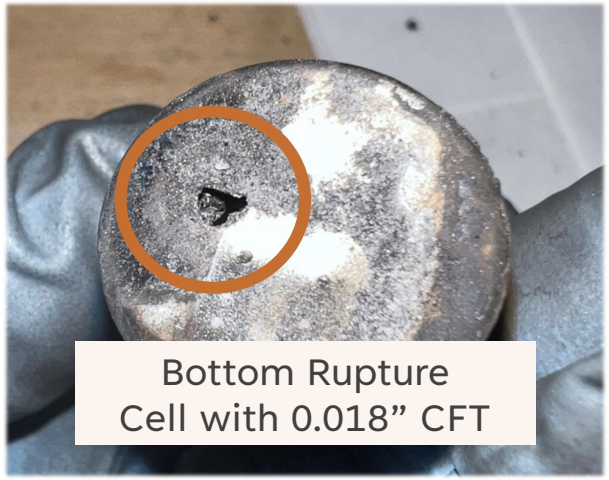
TEST VIDEO

DESIGN A - POST TEST

CELL INSPECTION – SAMPLES

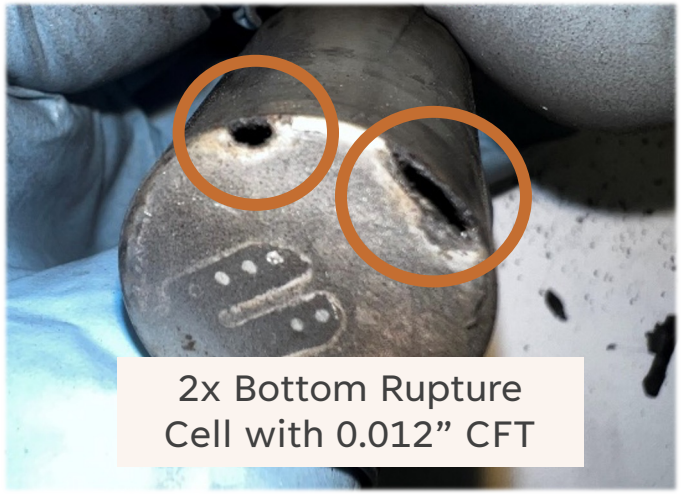
PANASONIC NCRA

Spin groove & Sidewall Rupture
Cell with 0.018” CFT

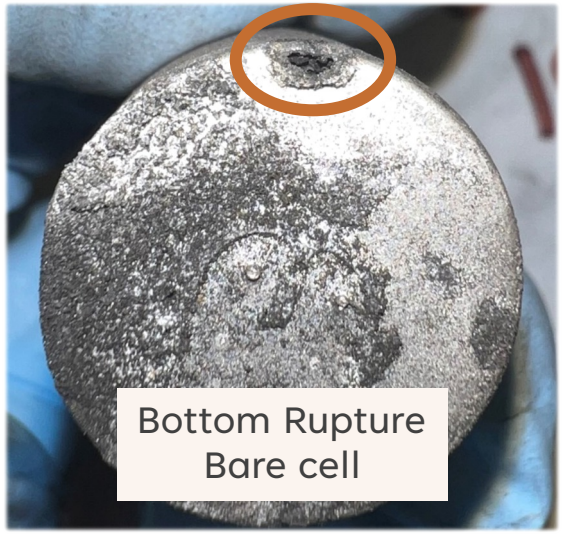


Bottom Rupture
Cell with 0.018” CFT

LG M36

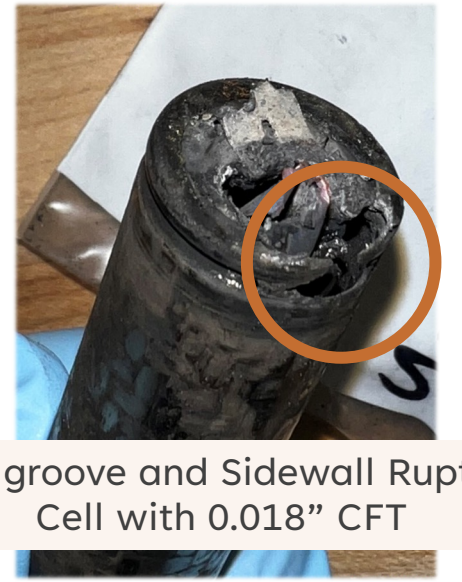


2x Bottom Rupture
Cell with 0.012” CFT



Bottom Rupture
Bare cell

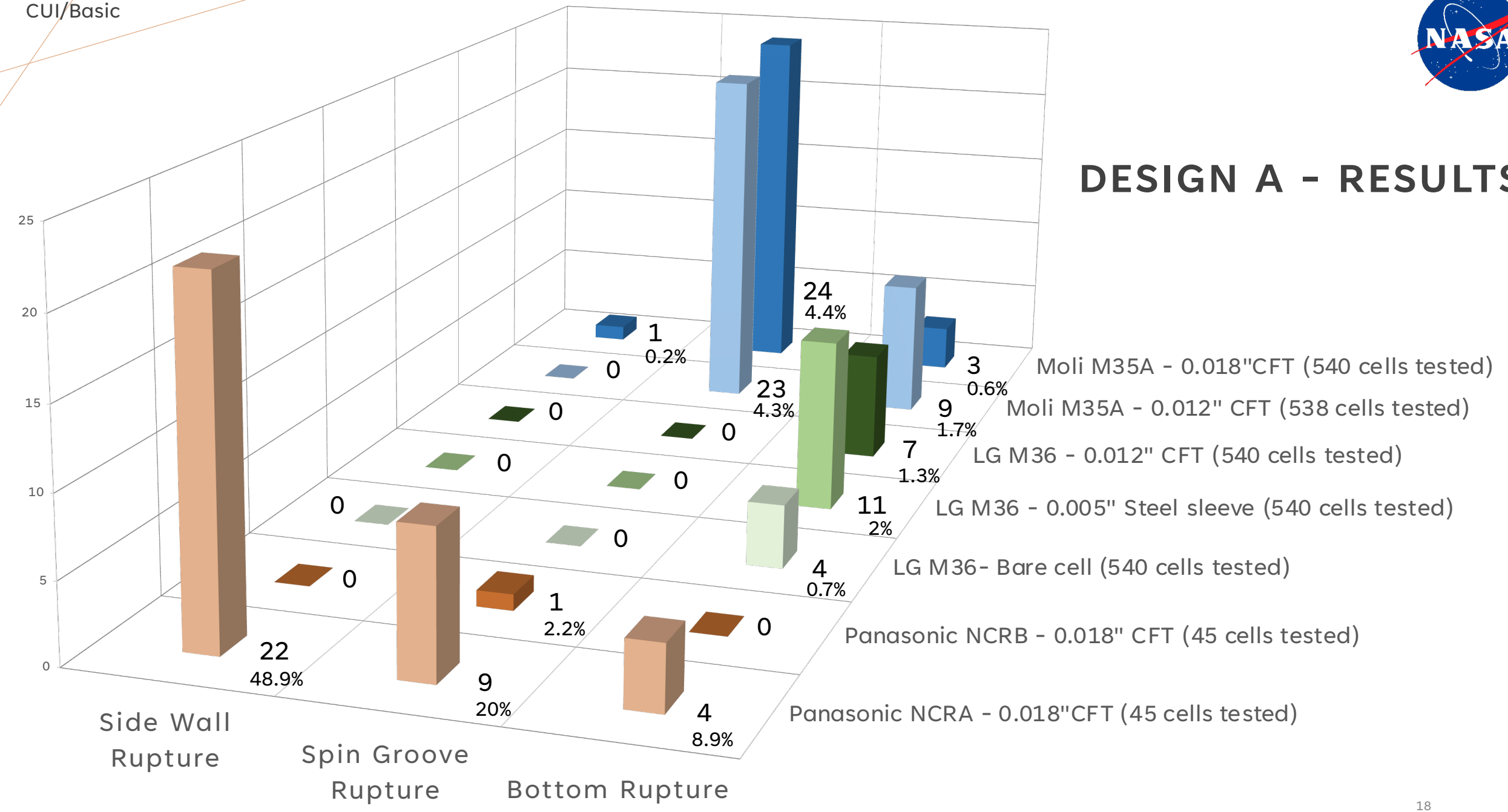
MOLICEL M35A



Spin groove and Sidewall Rupture
Cell with 0.018” CFT

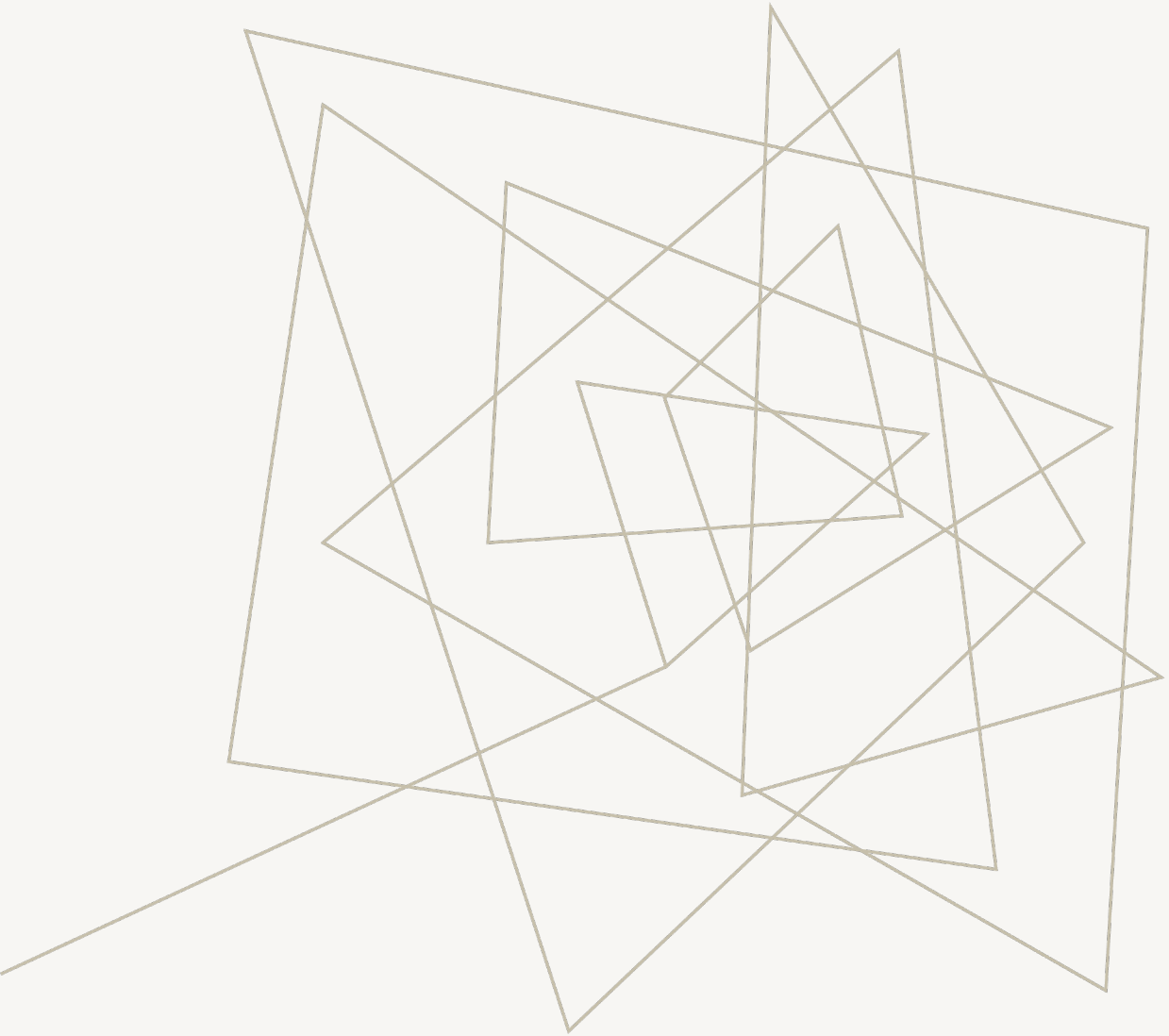
Spin groove Rupture
Cell with 0.018” CFT

DESIGN A – RESULTS



DESIGN A SPECIFIC OBSERVATIONS

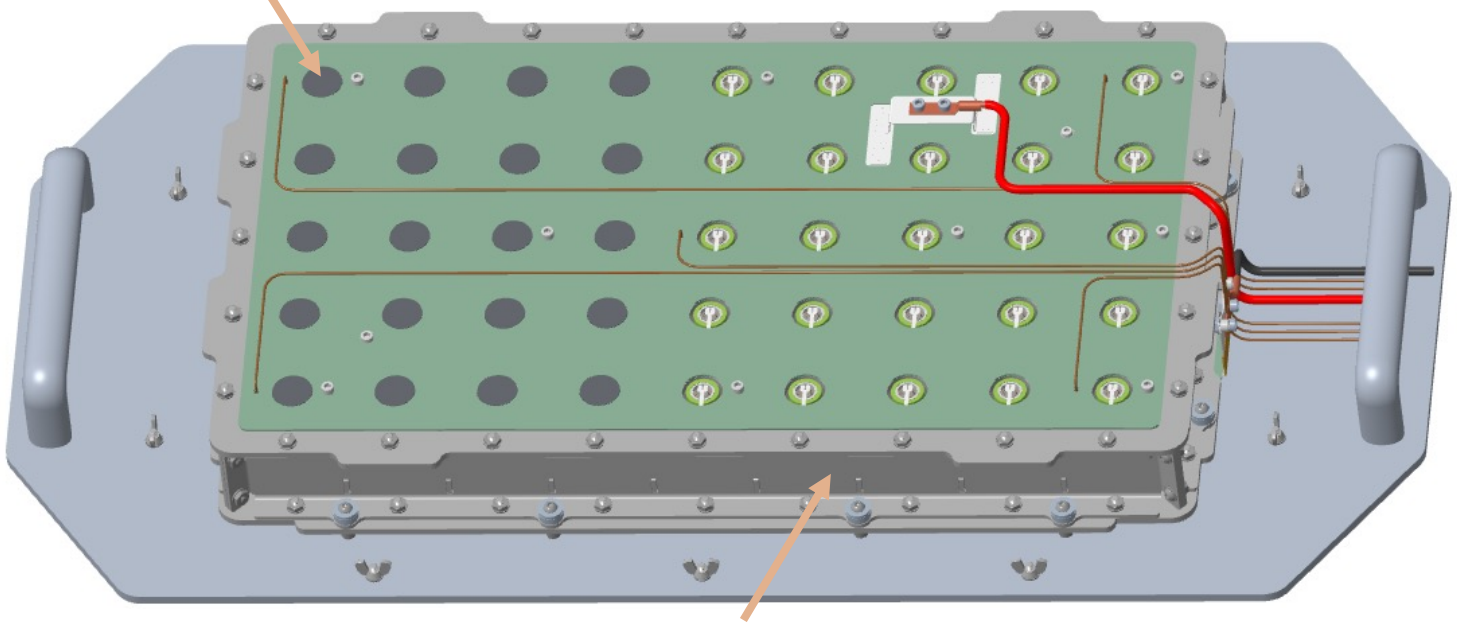
- Panasonic NCRA high propensity to SWR
- LG M36 had **NO** SWR
- Molicel M35A high propensity to SGR
- Epoxy in CFT evaporates due to high temperatures of TR. The rupture did not penetrate the CF.



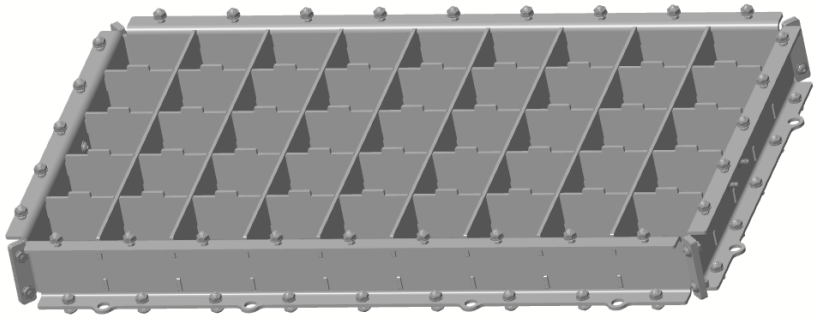
BATTERY DESIGN B

DESIGN B

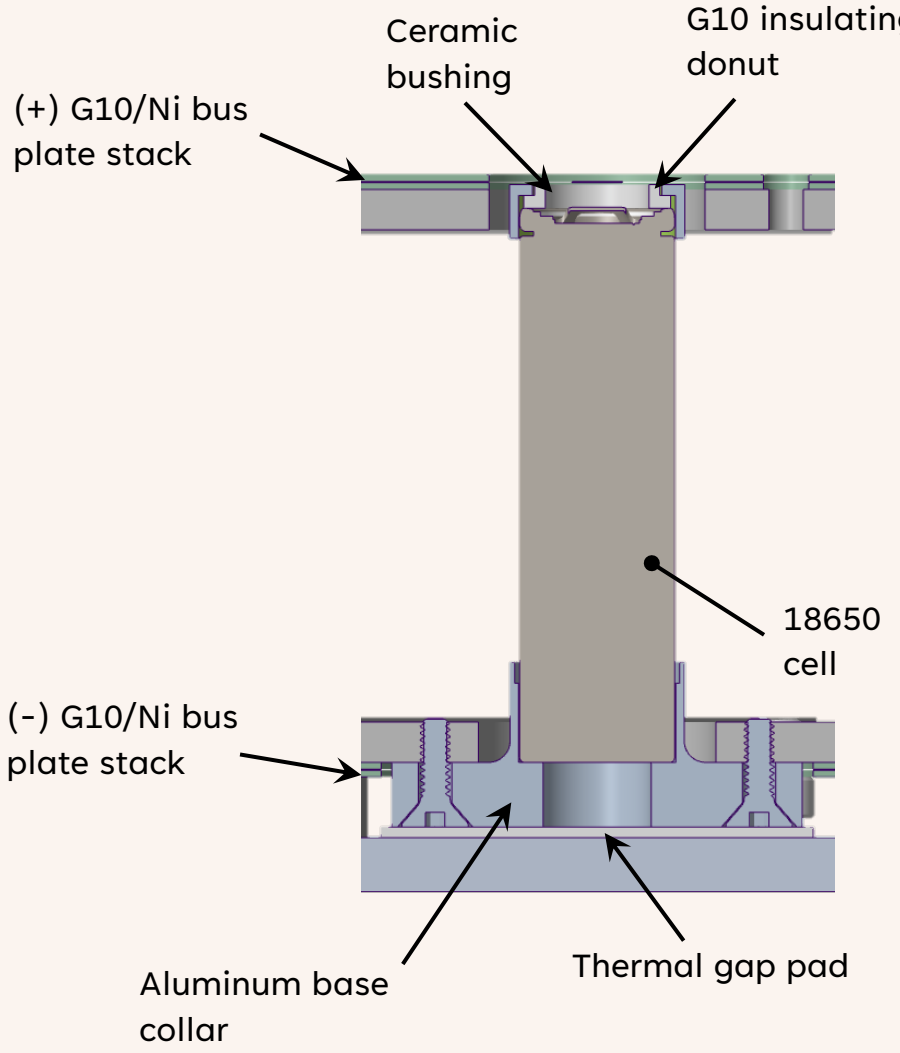
Mica covers to protect adjacent cells from ejecta



Cell Partition



Salient features: Length and header constraint

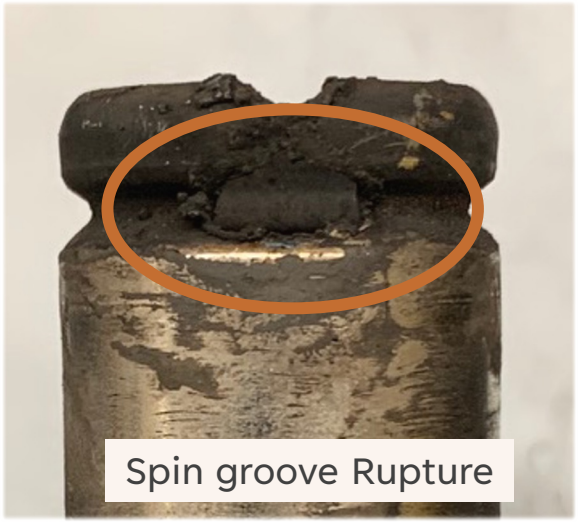


CELL INSPECTION – SAMPLES

MOLICEL M35A

INTERNAL SHORT CIRCUIT DEVICE (ISCD)

Spin groove & Sidewall Rupture



Spin groove Rupture

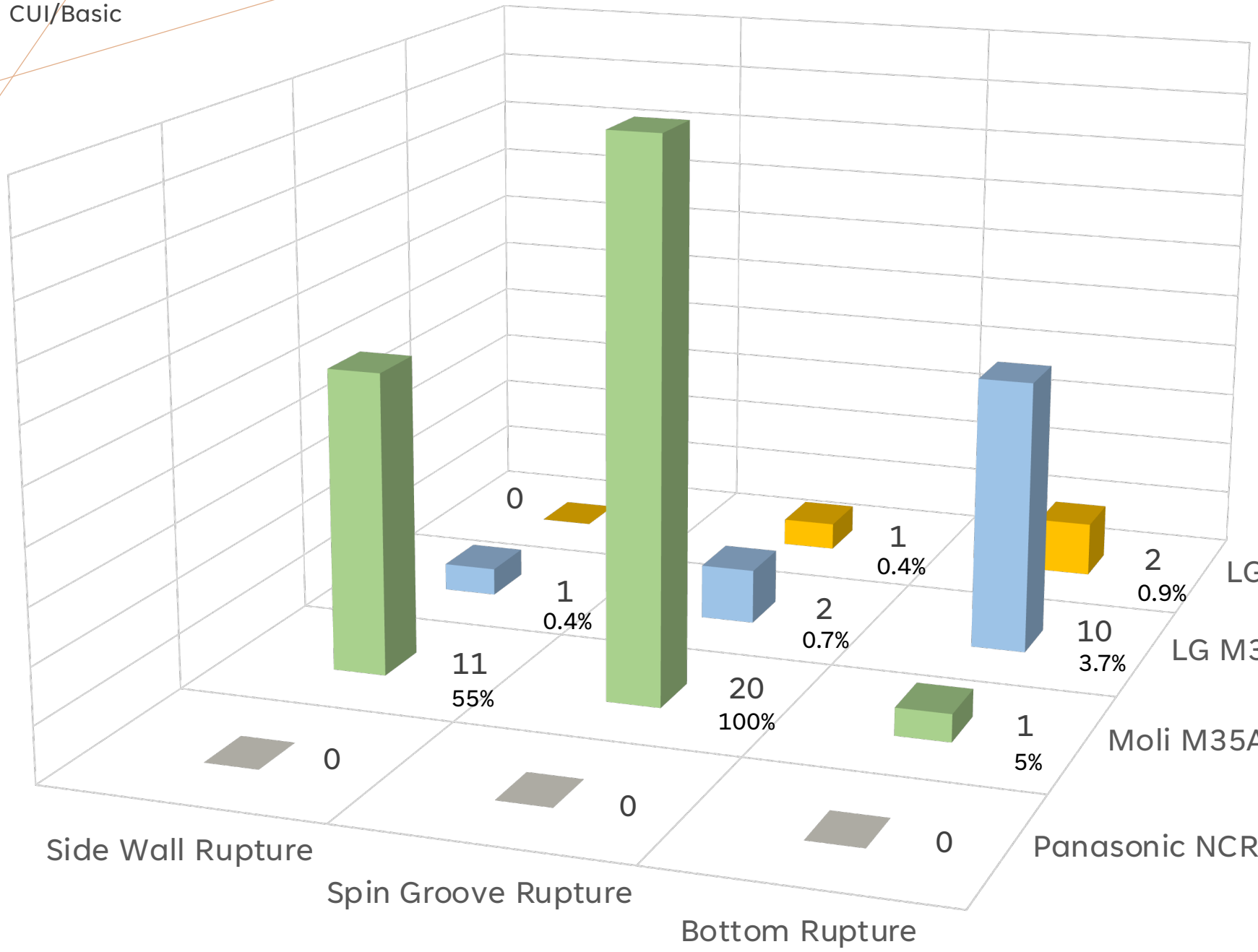
LG M36

BARE CELLS

Sidewall Rupture
✓ Only SWR from 1305 tests

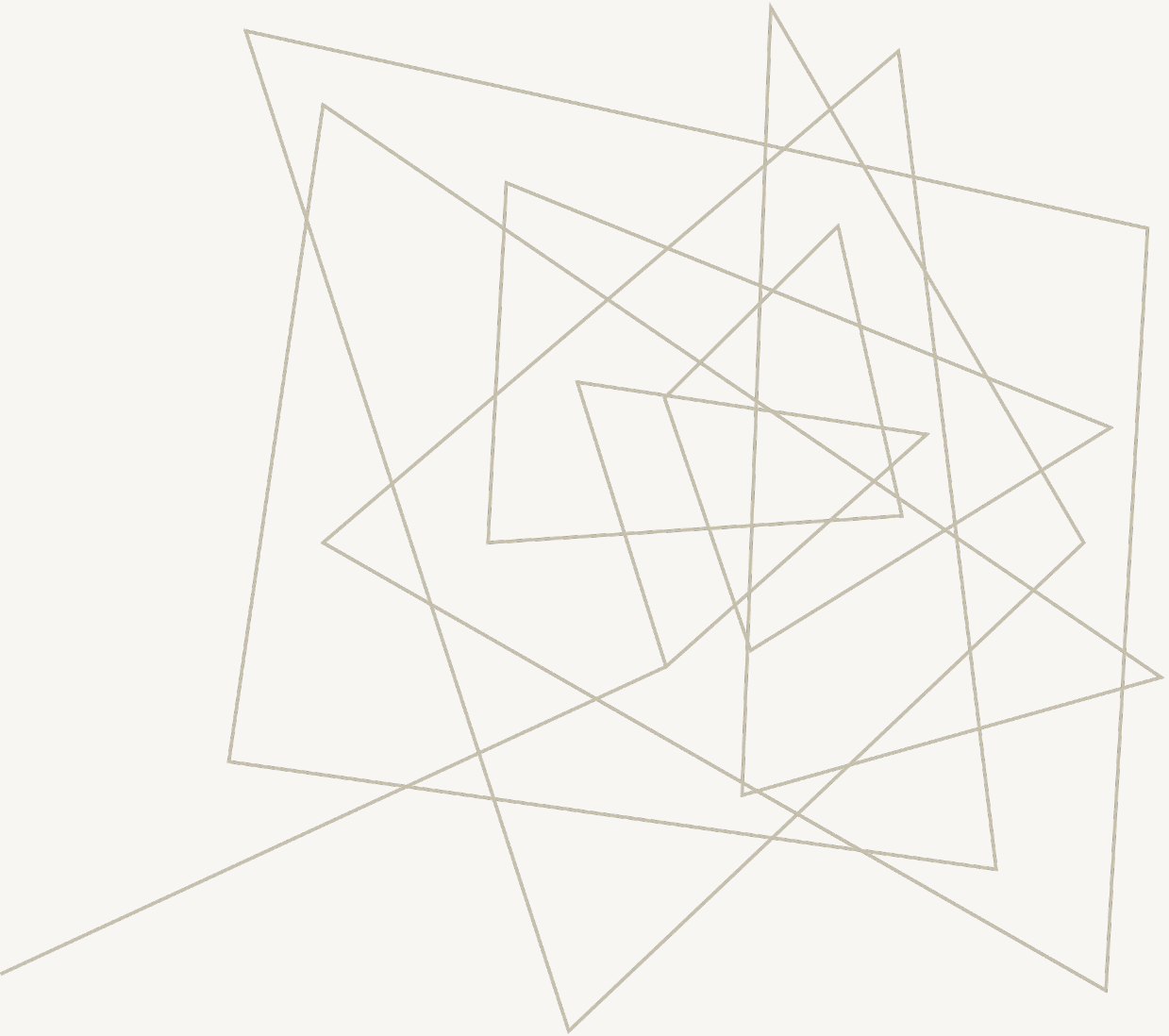
Bottom Rupture

DESIGN B - RESULTS



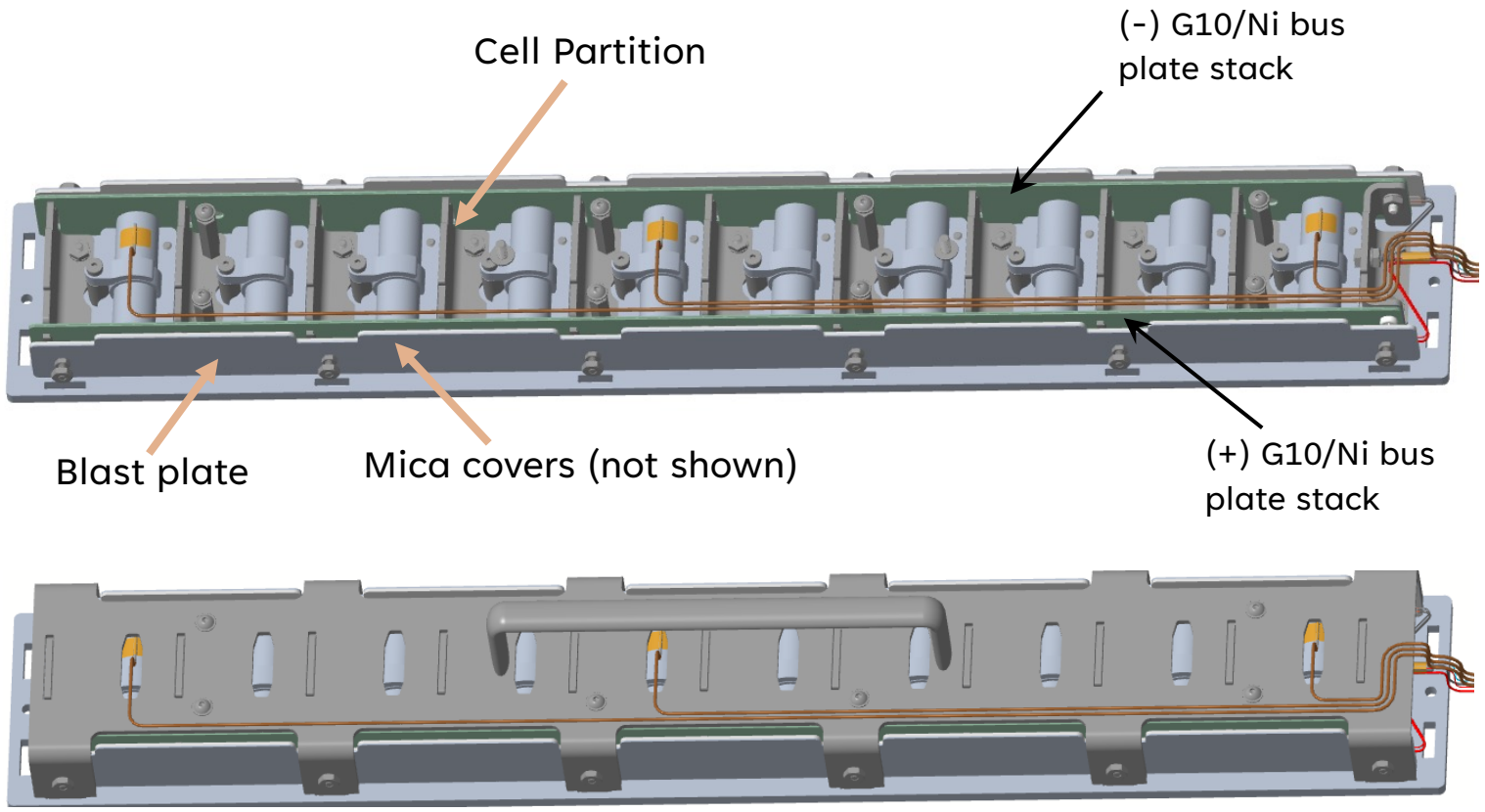
DESIGN B SPECIFIC OBSERVATIONS

- ISCD cell trigger method is more violent. All cells observed to have at least SGR
- Panasonic NCRB had no off nominal failures, but just 20 cells tested
- Epoxy in CFT evaporates due to high temperatures of TR. The rupture did not penetrate the CF.



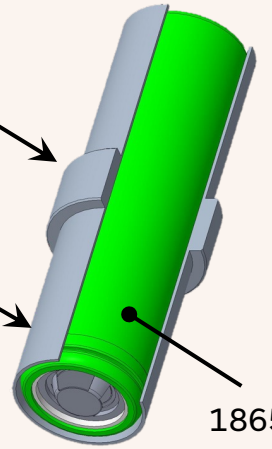
BATTERY DESIGN C

DESIGN C



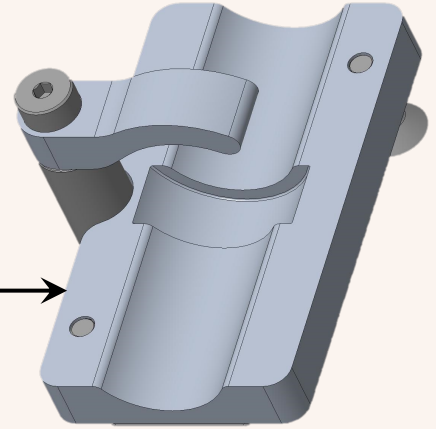
Clamp ring

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



18650 cell epoxied to Al tube

Aluminum cradle secures cell and transfers heat



CELL INSPECTION - SAMPLES

MOLICEL M35A

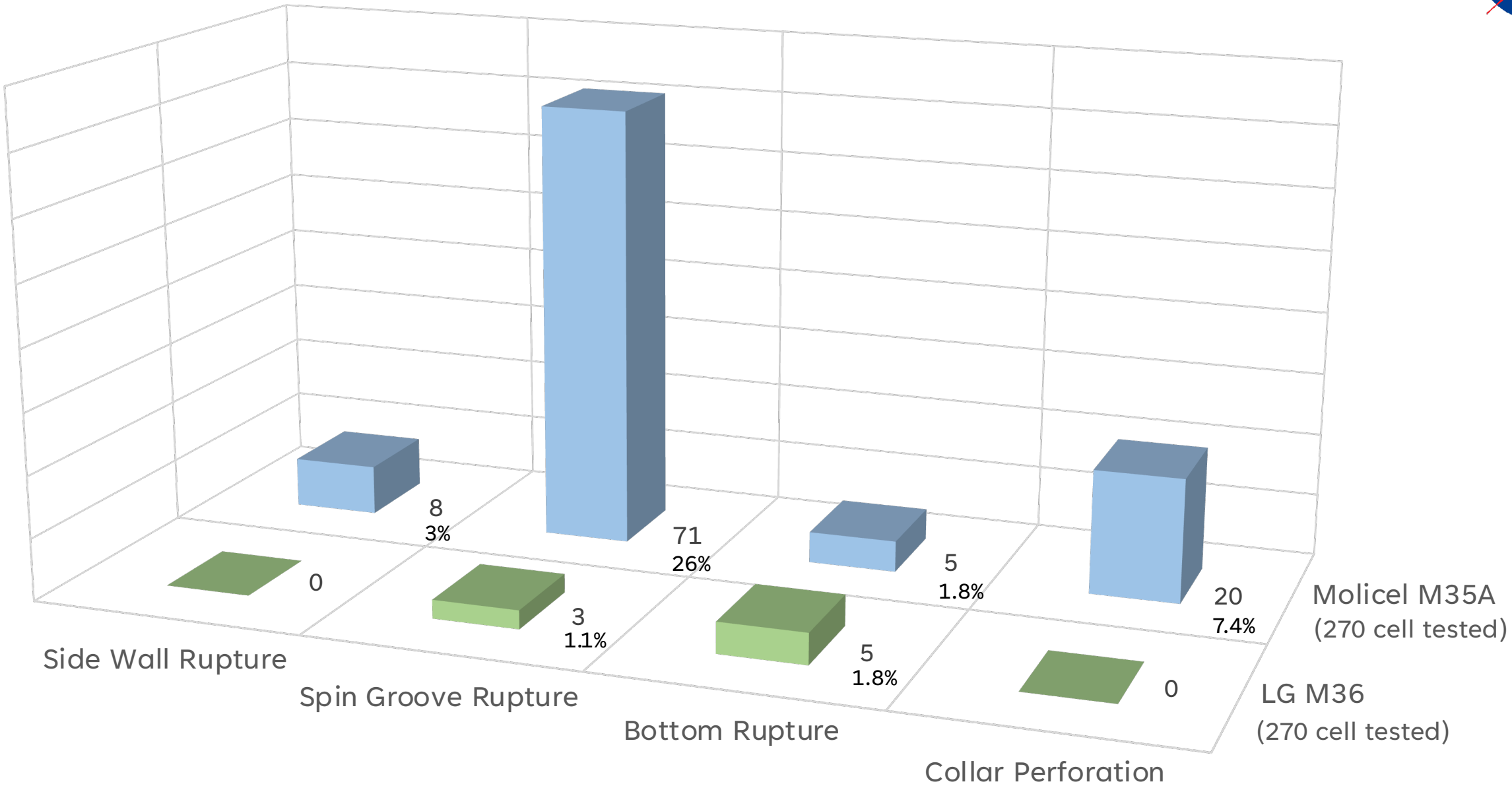
Spin groove & Sidewall Rupture with collar perforation

LG M36

2x Bottom Rupture

Spin groove Rupture

DESIGN C – RESULTS



DESIGN C SPECIFIC OBSERVATIONS

- Molicel M35A high propensity of SGR when encased in an aluminum collar
- Collar perforations occurring with Molicel M35A, none for LG36

CONCLUSIONS

PRELIMINARY FACTORS DRIVING SWR/SGR

Cell Level

- High energy density
- Low can wall and spin groove thickness/strength
- High header burst pressure
- Absence of bottom vent path
- Crimp design (double vs single)

Battery Level

- Preventing cell header bursting/release
- Insufficient can wall support
- Battery assembly/cell processing

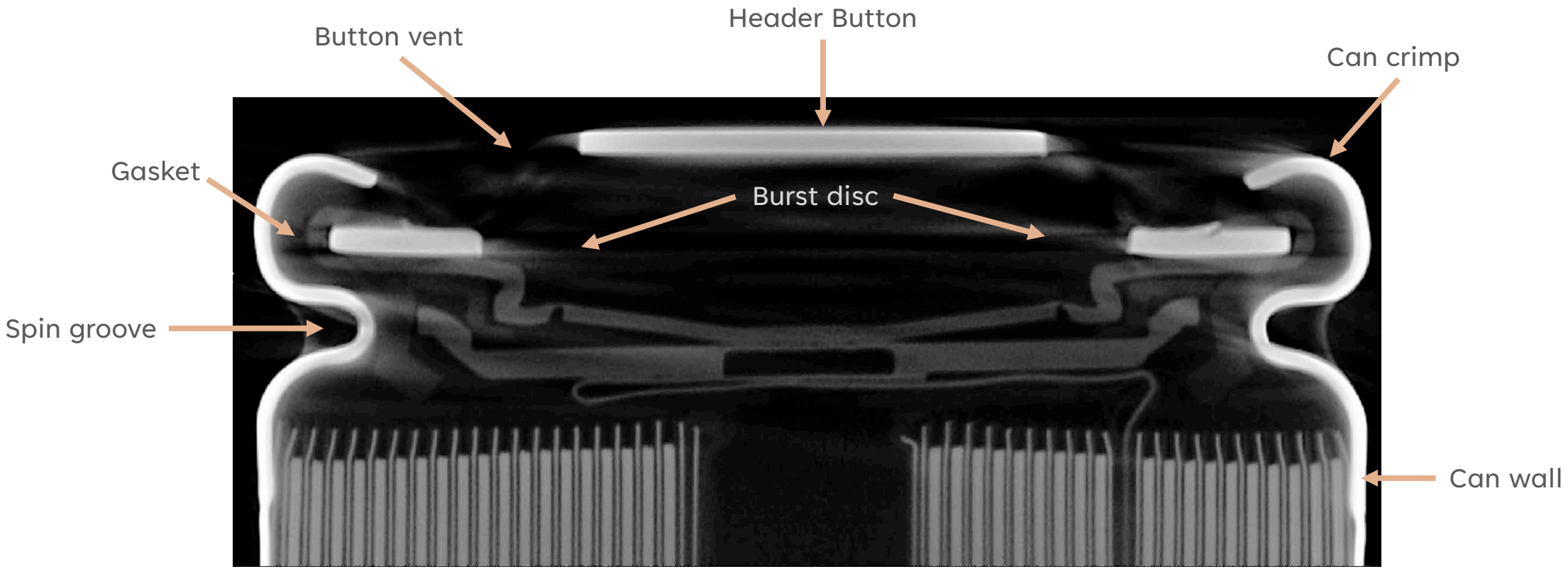
FINAL THOUGHTS

- LG M36 cells performed best against SWR and SGR in all three designs
- SWR/SGR depend on various factors, testing is critical for characterizing the risk of every unique battery design

THANK YOU

CELL ANATOMY

MOLICEL 18650 M35A



DESIGN A RESULTS

Battery Design A: Cell Description	Cell Quantity	Nominal Top Vent (NTV)	Nominal Bottom Vent (NBV)	Total Side Wall Rupture (SWR)	Side Wall Rupture Below UCS	Spin-Grove Rupture (SGR)	Bottom Rupture (BR)	Top Rupture (TR)	Jelly-Roll Ejection (JRE)	Header Release (HR)
Panasonic NCR18650A Cell with 0.018" CFT	45	2 (4.44%)	0	22 (48.9%)	[2 of 22] (4.44%)	9 (20.0%)	4 (8.89%)	4 (8.89%)	4 (8.89%)	37 (82.2%)
Panasonic NCR18650B Cell with 0.018" CFT	45	29 (64.4%)	0	0	0	1 (2.22%)	0	1 (2.22%)	0	16 (35.6%)
LG INR18650M36 Bare Cell	540	207 (38.3%)	0	0	0	0	4 (0.741%)	321 (59.4%)	5 (0.926%)	24 (4.44%)
LG INR18650M36 Cell with 0.005" Steel Sleeve	540	106 (19.6%)	0	0	0	0	11 (2.04%)	192 (35.6%)	1 (0.185%)	20 (3.70%)
LG INR18650M36 Cell with 0.012" CFT	540	236 (43.7%)	0	0	0	0	7 (1.30%)	285 (52.8%)	2 (0.370%)	28 (5.19%)
Moli INR-18650-M35A Cell with 0.012" CFT	538	260 (48.1%)	0	0	0	23 (4.27%)	9 (1.67%)	278 (51.7%)	0	9 (1.67%)
Moli INR-18650-M35A Cell with 0.018" CFT	540	369 (68.3%)	0	1 (0.185%)	0	24 (4.44%)	3 (0.556%)	161 (29.8%)	0	7 (1.30%)

DESIGN B RESULTS

Battery Design A: Cell Description	Cell Quantity	Nominal Top Vent (NTV)	Nominal Bottom Vent (NBV)	Side Wall Rupture (SWR)	Spin-Grove Rupture (SGR)	Bottom Rupture (BR)	Top Rupture (TR)	Jelly-Roll Ejection (JRE)	Header Release (HR)
Panasonic NCR18650B Cell with 0.012" CFT	25	17 (68.0%)	0	0	0	0	8 (32.0%)	5 (20.0%)	0
Moli INR-18650-M35A ISCD Cell	20	1 (5.00%)	0	11 (55.0%)	20 (100%)	1 (5.00%)	8 (40.0%)	1 (5.00%)	11 (55.0%)
LG INR18650M36 Bare Cell	270	148 (54.8%)	0	1 (0.370%)	2 (0.741%)	10 (3.70%)	113 (41.9%)	1 (0.370%)	7 (2.59%)
LG INR18650M36 Cell with 0.012" CFT	225	141 (62.7%)	0	0	1 (0.444%)	2 (0.889%)	65 (28.9%)	0	0

DESIGN C RESULTS

Battery Design A: Cell Description	Cell Quantity	Nominal Top Vent (NTV)	Nominal Bottom Vent (NBV)	Side Wall Rupture (SWR)	Spin-Grove Rupture (SGR)	Bottom Rupture (BR)	Top Rupture (TR)	Jelly-Roll Ejection (JRE)	Header Release (HR)	Collar Perforations (CP)
Molicel INR-18650-M35A Cell with 0.020” thick Aluminum Sleeve	270	113 (41.8%)	0	8 (2.96%)	71 (26.3%)	5 (1.85%)	132 (48.9%)	8 (2.96%)	19 (7.04%)	20 (7.41%)
LG INR18650M36 Cell with 0.020” thick Aluminum Sleeve	270	25 (9.26%)	0	0	3 (1.11%)	5 (1.85%)	217 (80.4%)	4 (1.48%)	28 (10.4%)	0