SIDEWALL RUPTURE CHARACTERIZATION

21700 Cell Format

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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

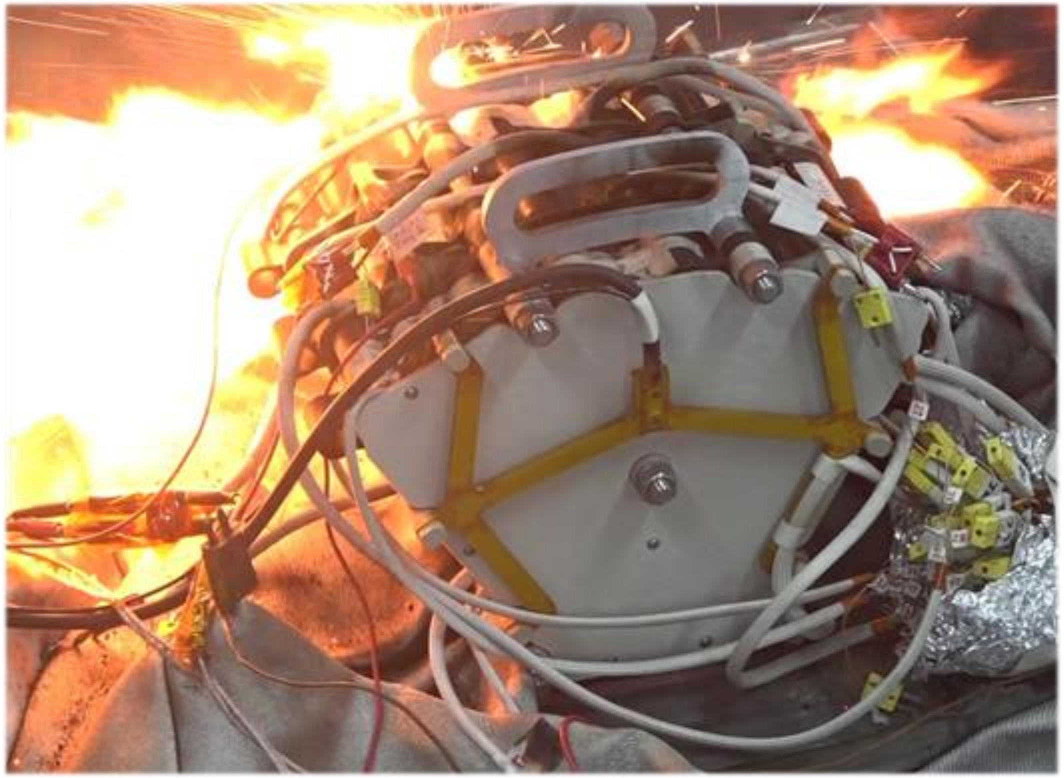


Figure: 134P-3S PPR battery pack developed by NASA successfully sustained 12 single trigger events without propagating thermal runaway

THERMAL RUNAWAY (TR) SWR VIDEO

Cell type: Li-ion 18650
Capacity: 3.5 Ah
State of Charge: 100 % (4.2 V)
Bottom vent: No
Wall thickness: Not known
Separator: Polymer
Orientation of cell: Positive end up
Location of ISCD radially: N/A
Location of ISCD longitudinally: N/A
Side of ISCD in image: N/A

Location of FOV longitudinally: Top
Frame rate: 2000 Hz
Frame dimension (Hor x Ver): 1280 x 800 pixels
Pixel size: 17.8 µm

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 cell constraints and features
2. Test 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
3. Test different cells to compare performance.

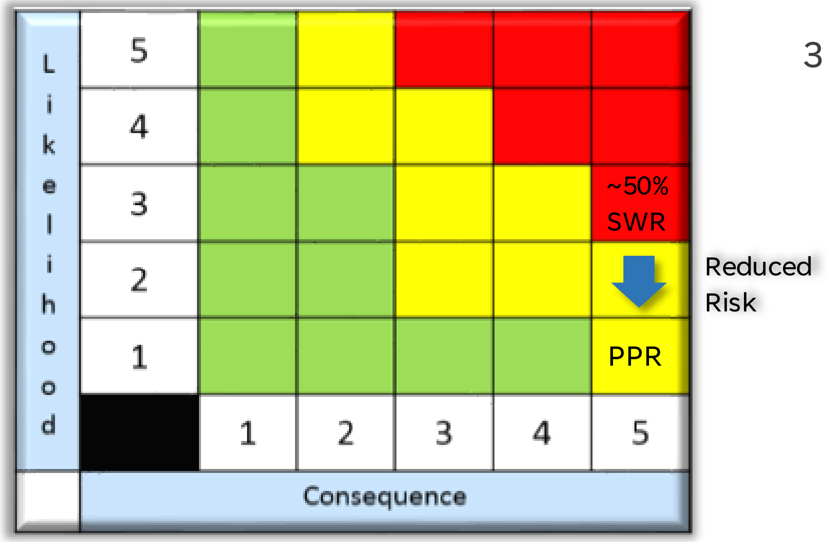


Figure: likelihood versus consequence matrix

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

TEST ARTICLE AND SET UP

21700 SIDEWALL RUPTURE TEST ARTICLE

- 10 cell test article designed to evaluate the propensity of commercial 21700 cylindrical cells to sidewall rupture during thermal runaway (TR)
- Test article designed to separates neighboring cells to prevent pre-TR biasing
- Test article captures pertinent features of the battery pack design:
  - Heat sink material and cell-to-cell wall thickness
  - Cell preparation and installation
  - Heat rejection path
  - Bus plate and blast plate features

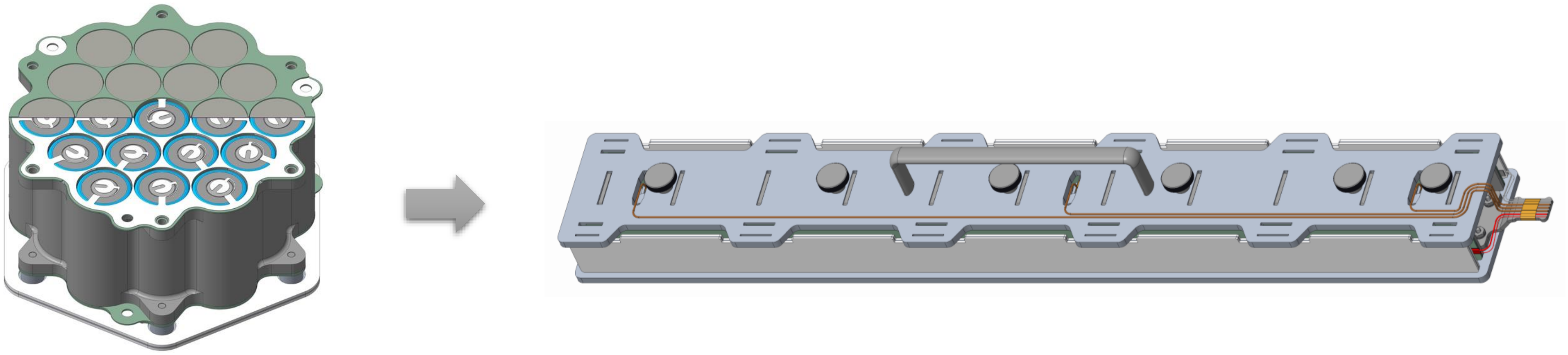
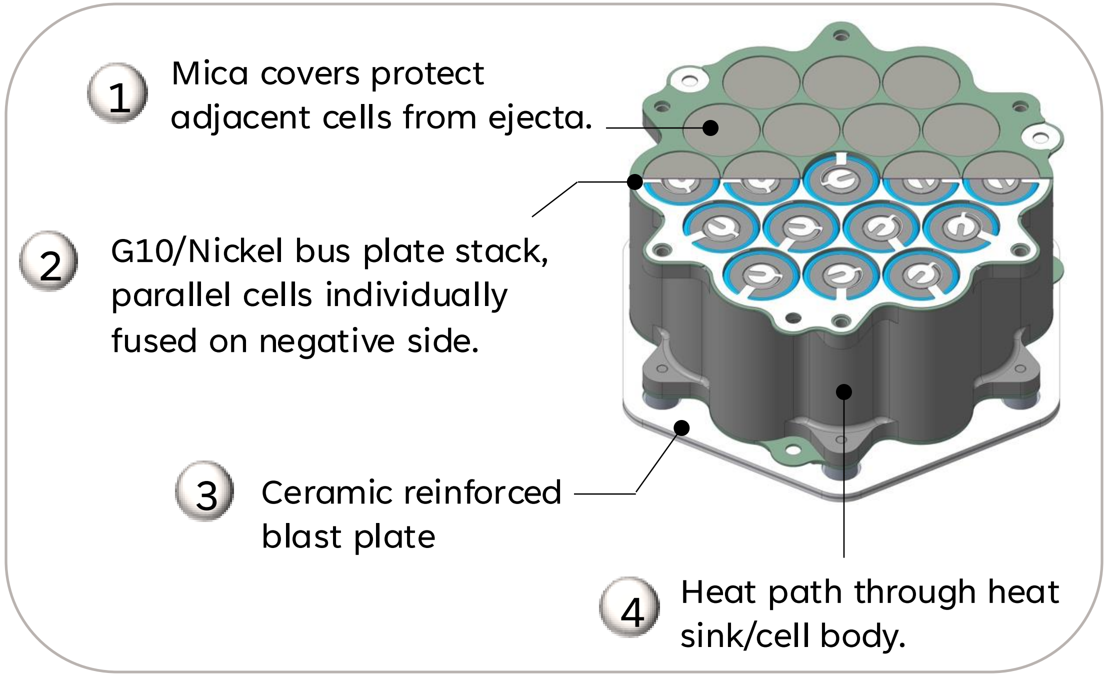
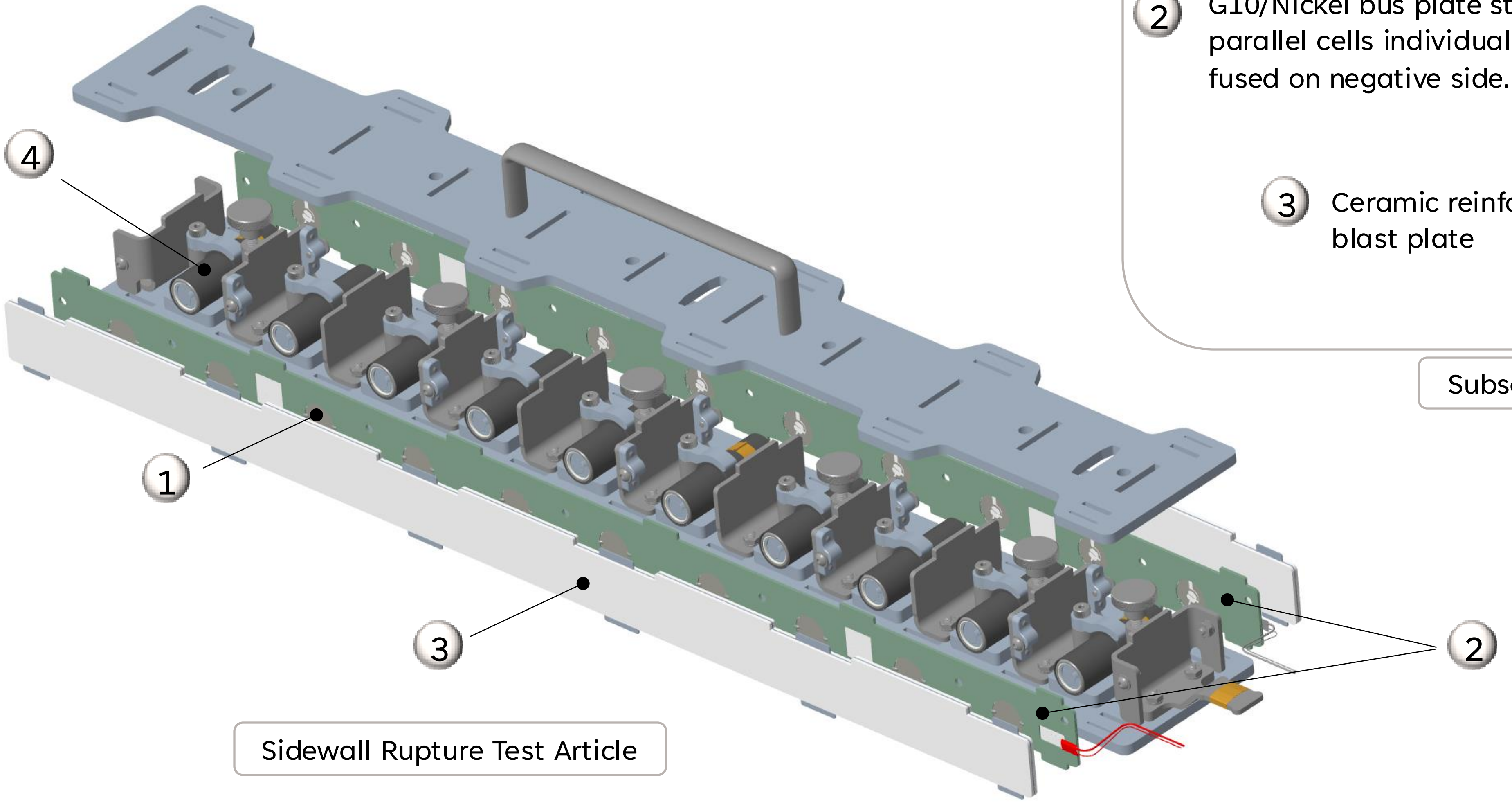


Figure: 21700 Sidewall rupture test article (right) designed to capture pertinent features of 21700 battery pack (left – subscale pack shown)

TEST ARTICLE DESCRIPTION

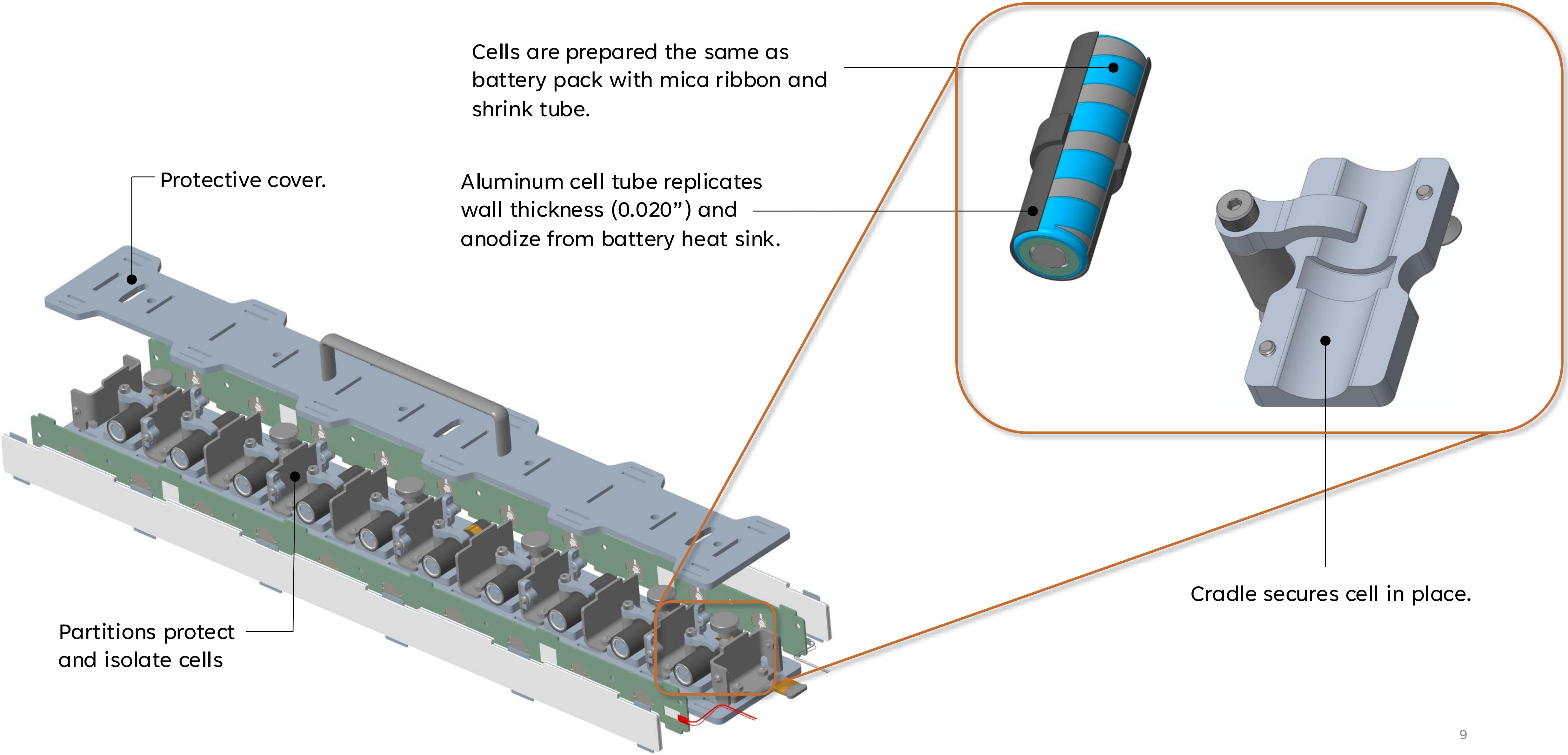


Subscale Battery Pack

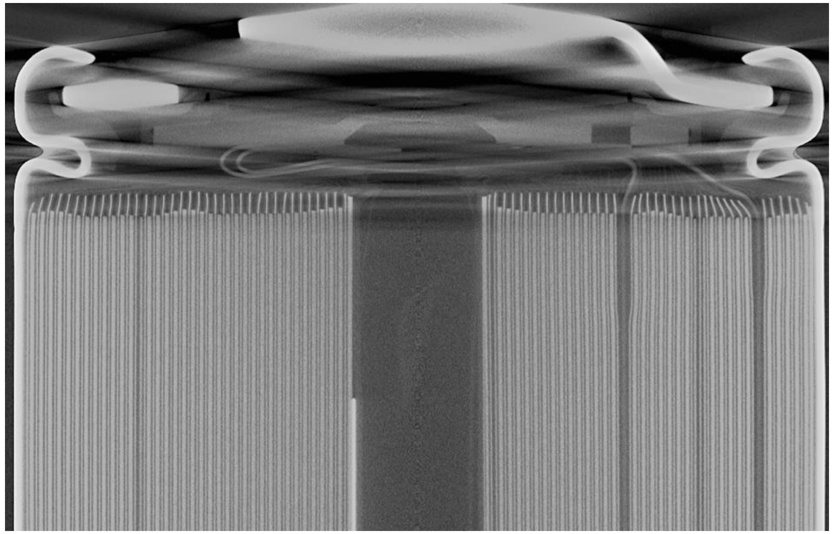
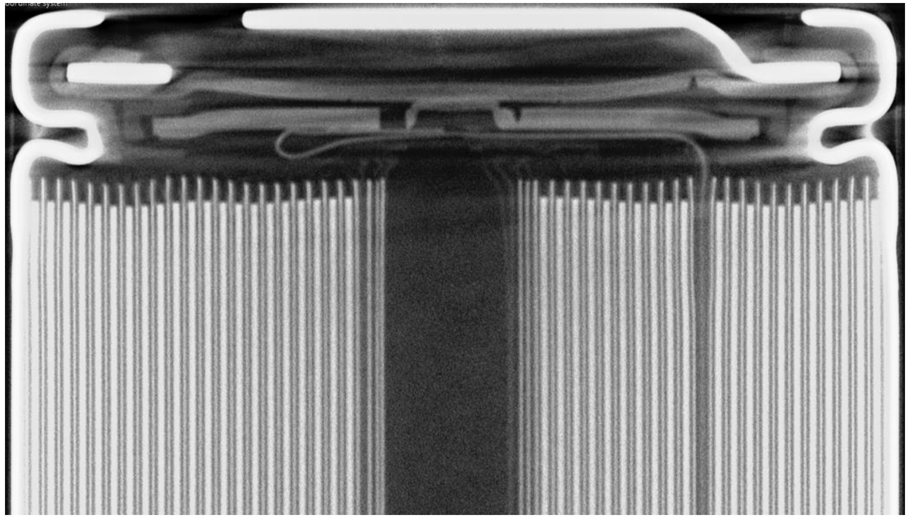


Sidewall Rupture Test Article

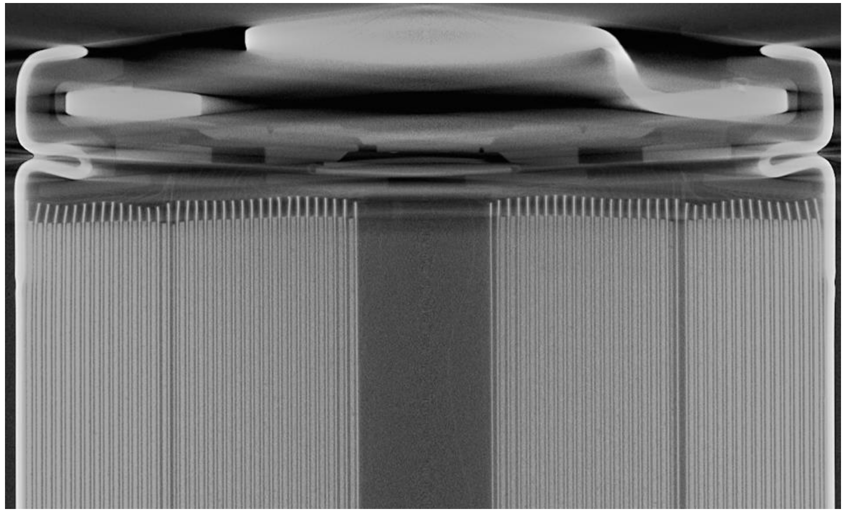
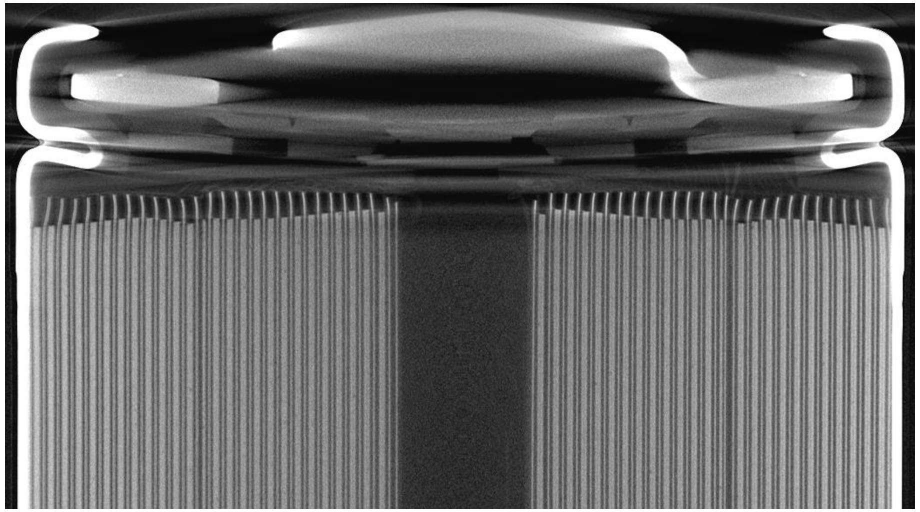
TEST ARTICLE DESCRIPTION (CONT.)



TEST MATRIX

	Molicel INR21700 P45B	LG INR21700 M52V
Nominal Energy	4500 mAh	5096 mAh
Diameter / Height	21.55 mm (Max) / 70.15 mm (Max)	21.27 mm (Max) / 70.60 mm (Max)
Can Wall Thickness	225 ± 10 microns	213 ± 10 microns
Qty. tested @ SoC	270 @ 100% (4.2V)	270 @ 100% (4.2V)
Cell CT Image		

TEST MATRIX (CONT.)

	Samsung INR21700 50S	Samsung INR21700 53G
Nominal Energy	5000 mAh	5300 mAh
Diameter / Height	21.25 mm (Max) / 70.62 mm (Max)	21.35 mm (Max) / 70.15 mm (Max)
Can Wall Thickness	200 ± 10 microns	237 ± 10 microns
Qty. tested @ SoC	180 @ 100% (4.2V)	90 @ 100% (4.2V)
Cell CT Image		

CAN WALL THICKNESS DETERMINATION

- Cell cans extracted during normal cell Destructive Physical Analysis (DPA), without the header nor bottom.
- Average can wall thickness taken using an optical microscope with ± 10 µm accuracy.
  - ➢ Note: Can thickness increase at spin groove and bottom not included in this average.

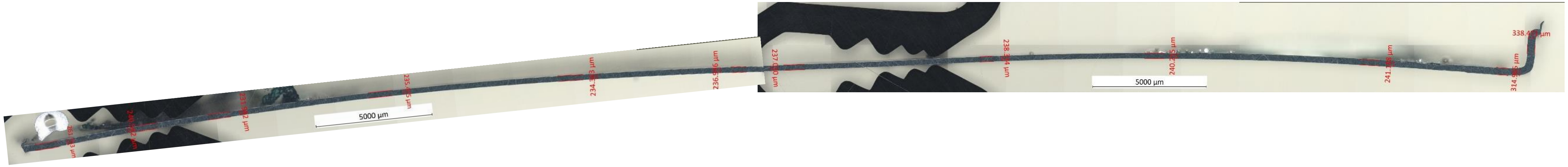
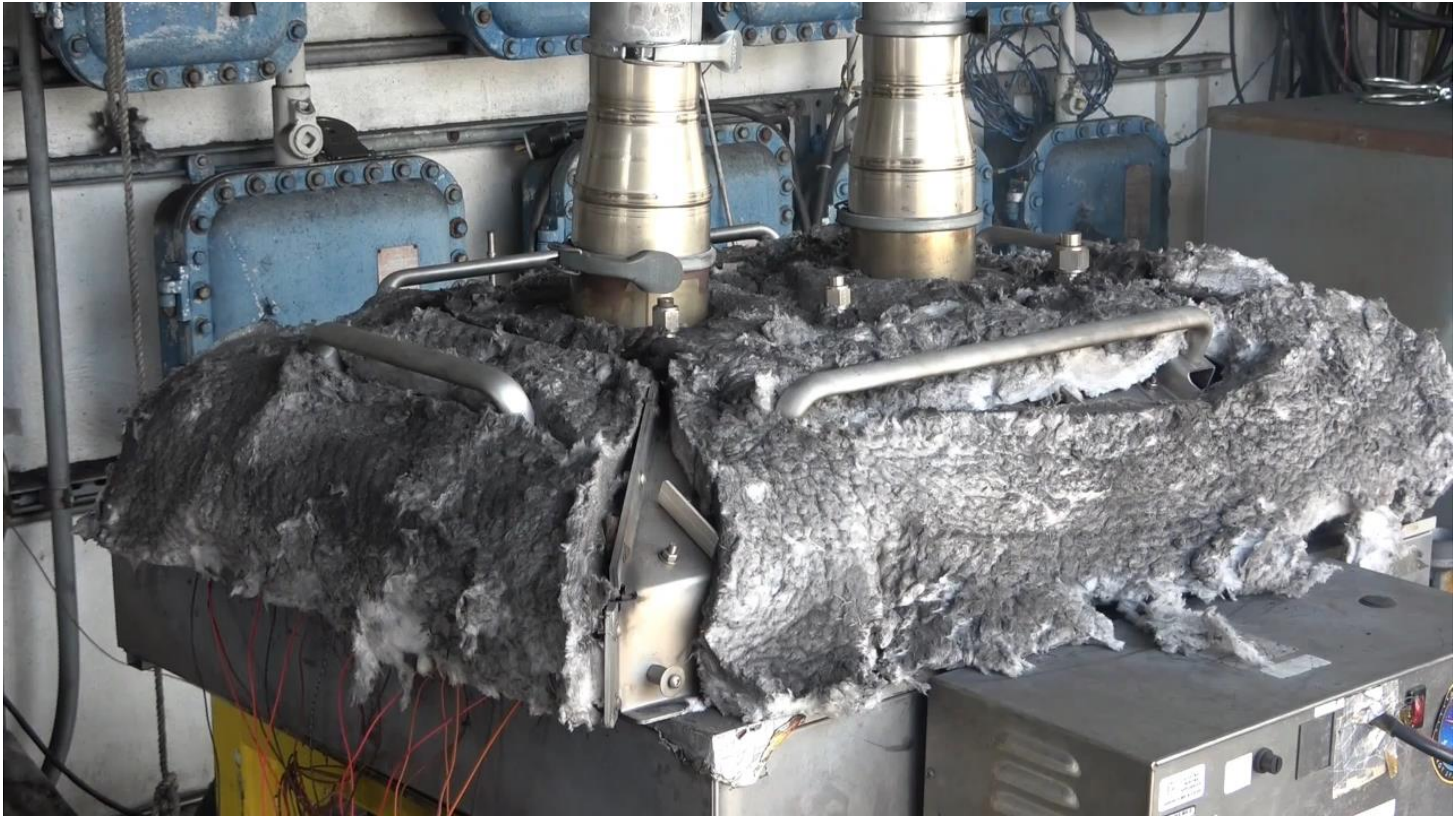


Figure: Cross section of Samsung 53G1 cell used to determine can wall thickness. Same technique used for the other cells.

TEST SETUP

Figure: A 36” X 36” hot plate is used to heat 6 test articles at a time to trigger 60 cells into thermal runaway.

TEST SAMPLE VIDEO



POST TEST SEQUENCE



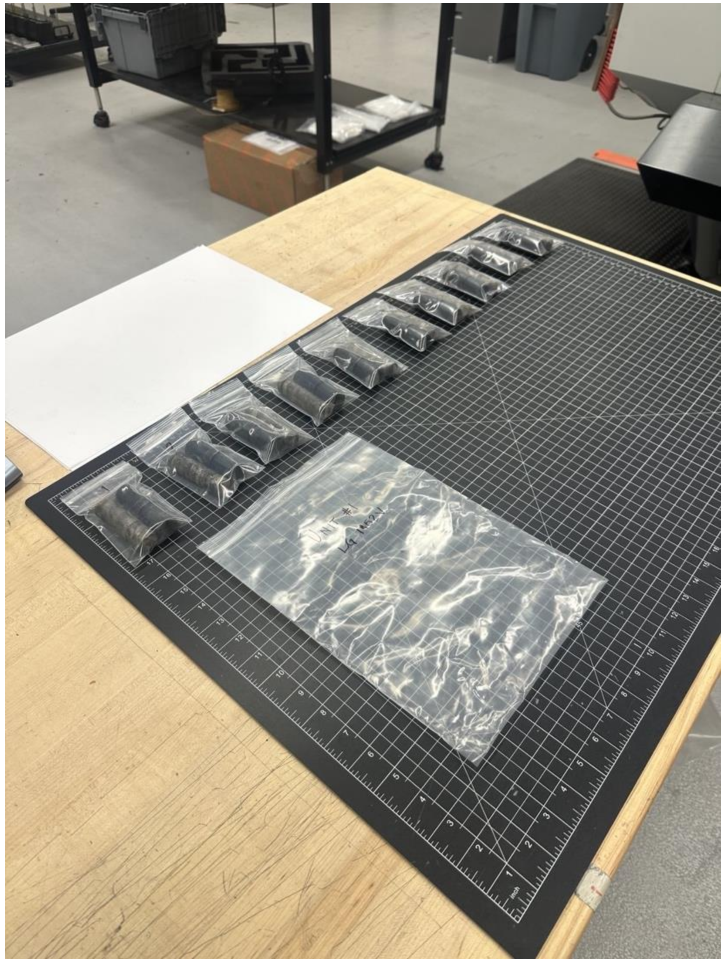


Figure: After testing, test articles are disassembled, and cells inspected and tallied individually.

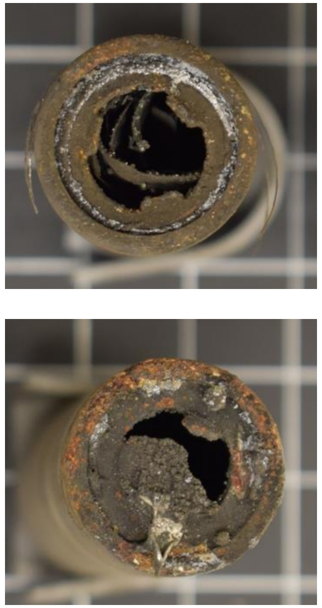
DEFINITION CRITERIA

ACCEPTABLE FAILURES

Nominal Top Vent

(NTV)

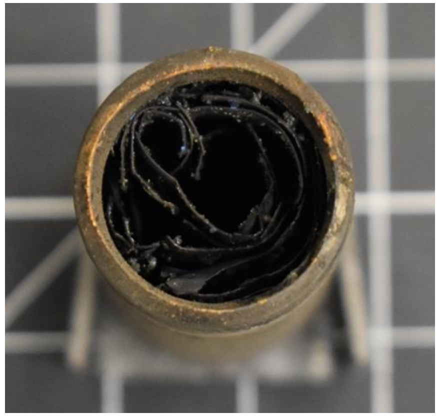
Cell vented only, no breach through the header.



Top Rupture

(TR)

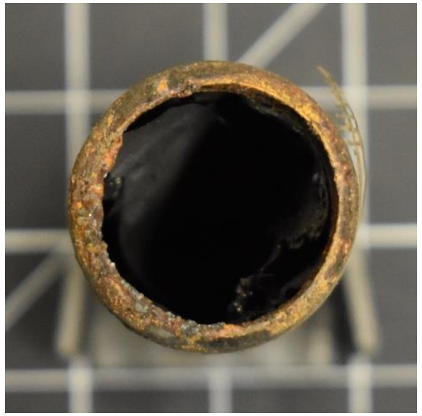
Header gets breached but some part still remains.



Header Release

(HR)

Header gets ejected in its entirety. Usually spin grooves unfolds.



Jelly Roll Ejection

(JRE)

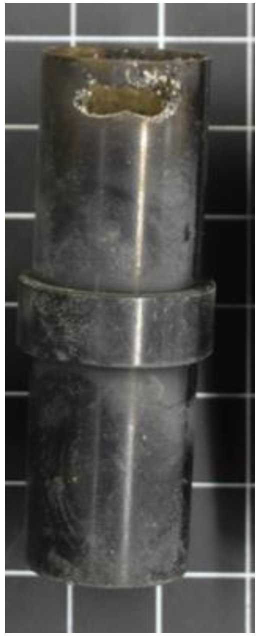
The majority (>85%) of the jelly roll gets ejected.

Bottom Rupture

(BR)

Breach through the bottom of the cell.

DEFINITION CRITERIA
UNACCEPTABLE FAILURES



Collar Breach (CB)

Breach of the aluminum cell tube.

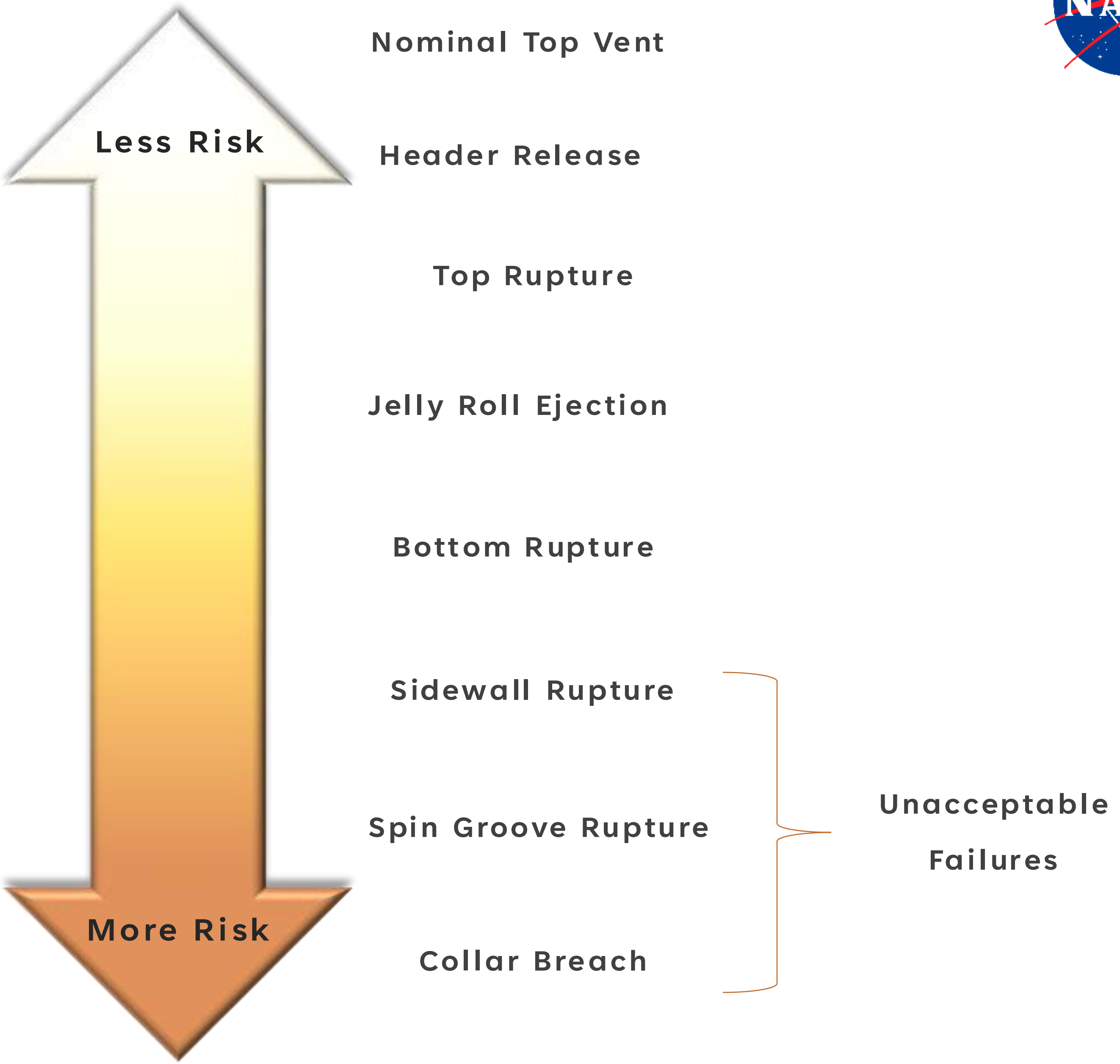
Spin Groove Rupture (SGR)

Breach through the spin groove only. Anything above or below the spin groove is considered a Sidewall Rupture.

Sidewall Rupture (SWR)

Breach through the sidewall of the cell can below and above the spin groove.

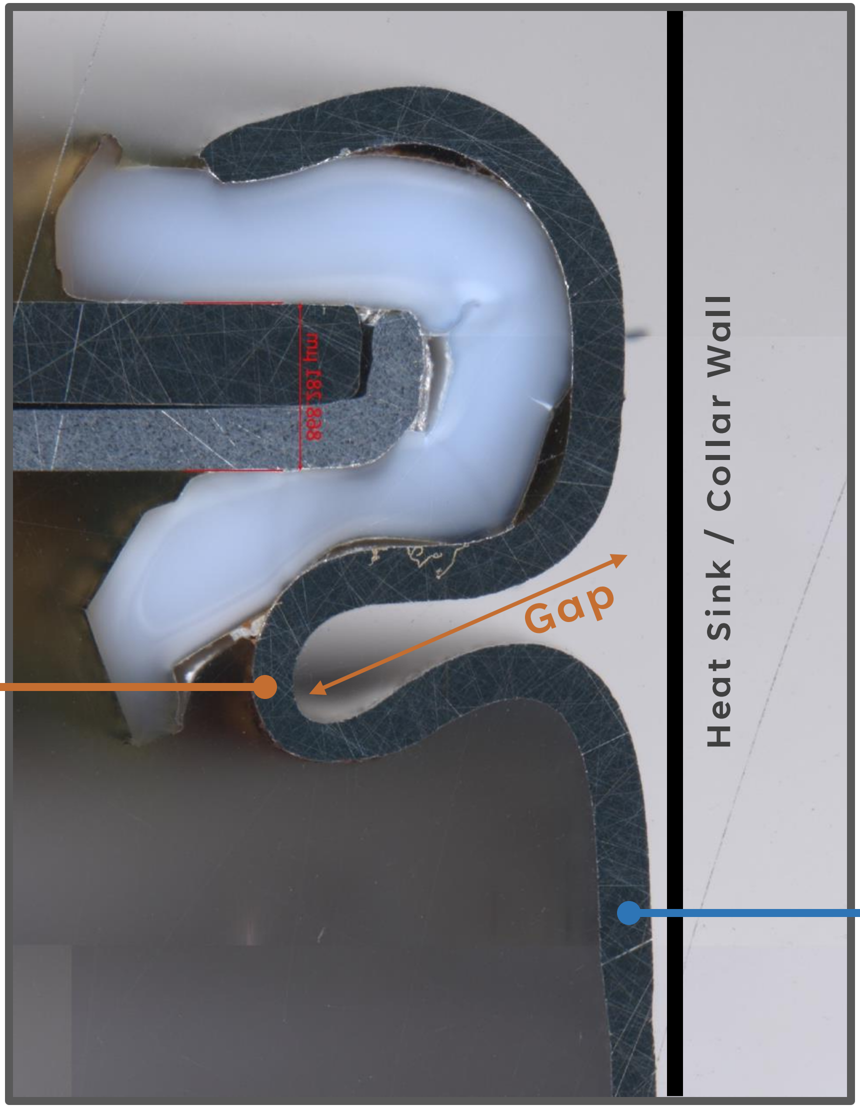
FAILURE RISK SCALE



SGR VS SWR SEVERITY

Spin Groove Rupture:

The gap between the spin groove and the heat sink/collar wall allows for the abrasive ejecta torch to develop, increasing the risk of further damage.

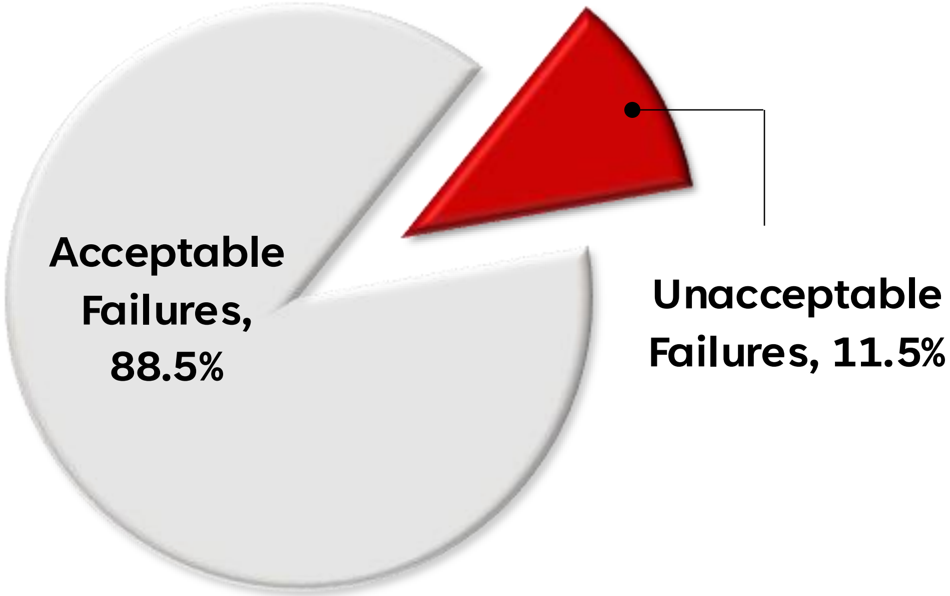


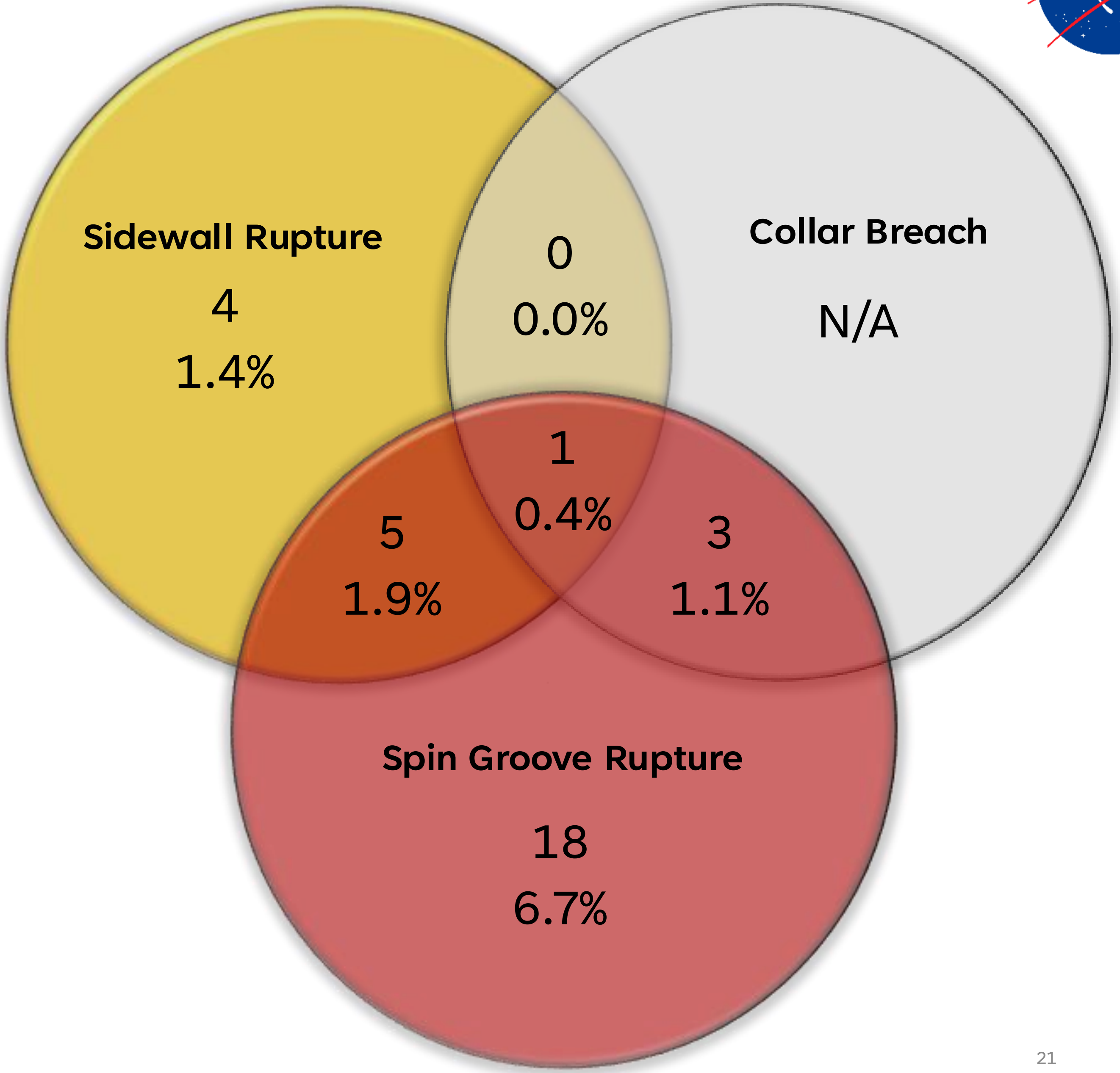
Sidewall Rupture:

Ejecta plugs the rupture against small the heat sink/collar wall, therefore preventing ejecta torch from developing therefore reducing the risk of further damage.

TEST RESULTS

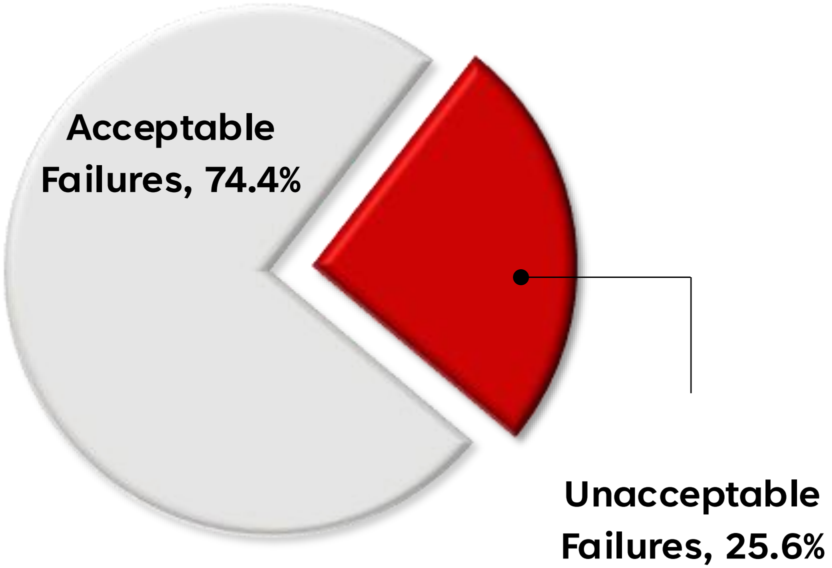
TEST RESULTS
LG M52V
270 CELLS, 100% SOC

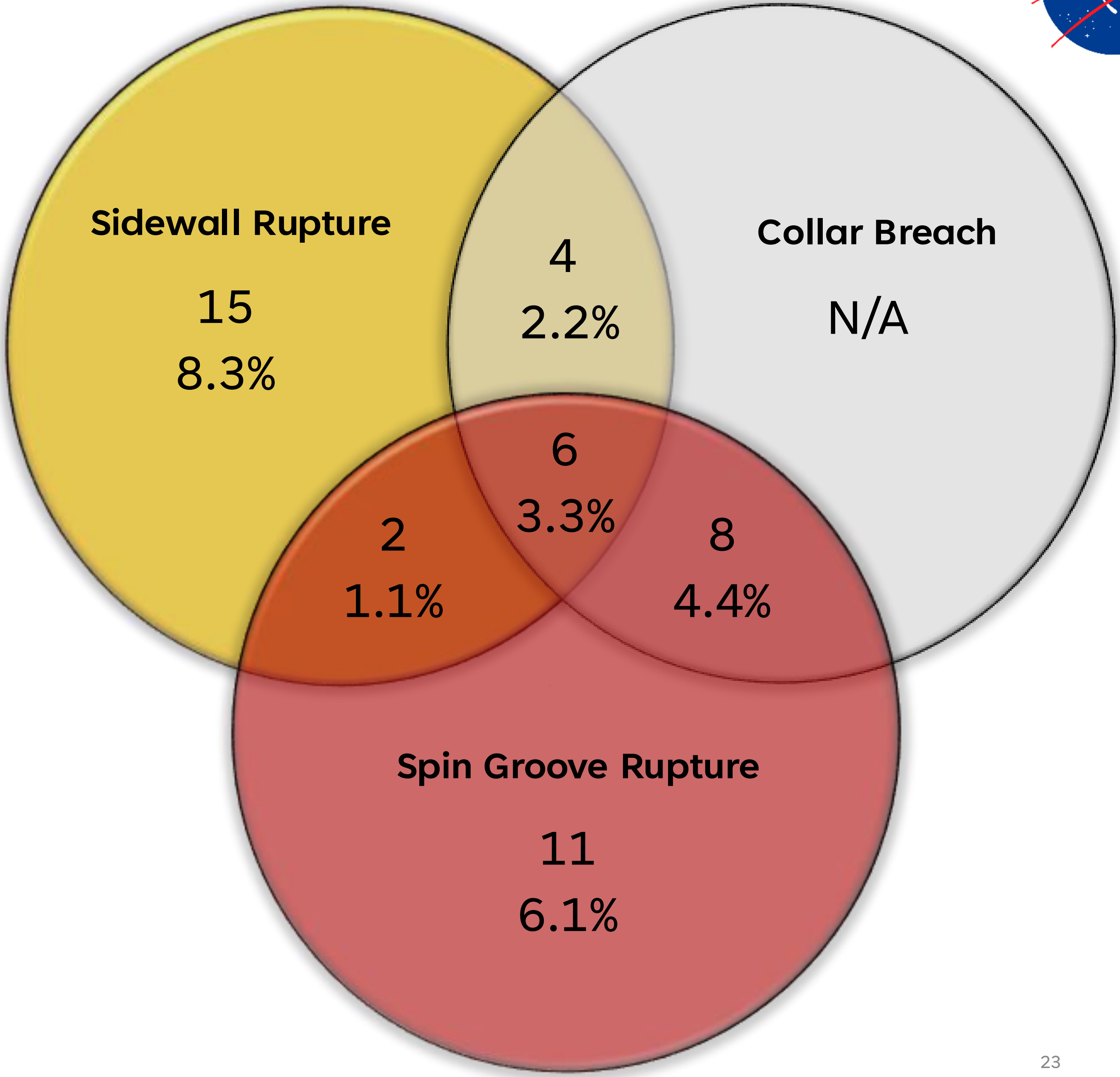




PHOTOGRAPHIC EVIDENCE - LG M52V

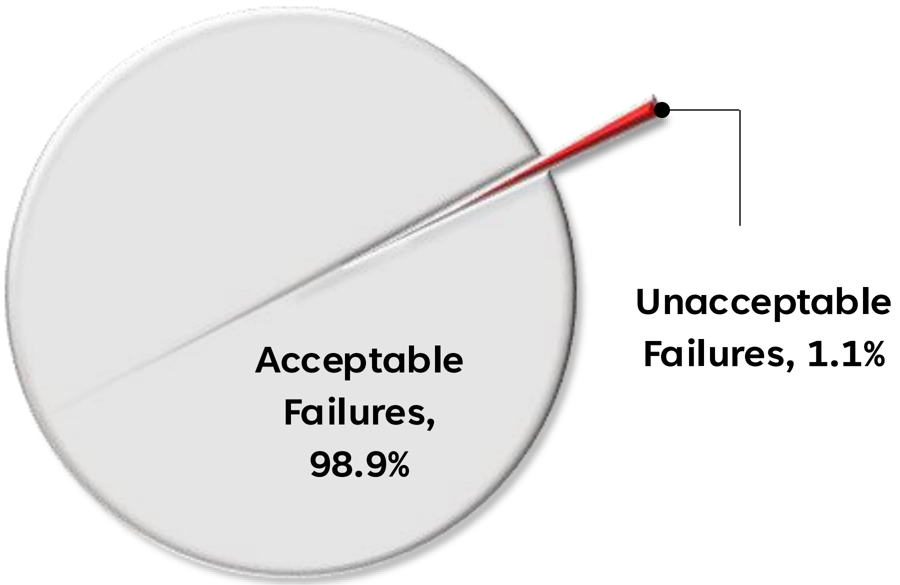
TEST RESULTS
SAMSUNG 50S
180 CELLS, 100% SOC

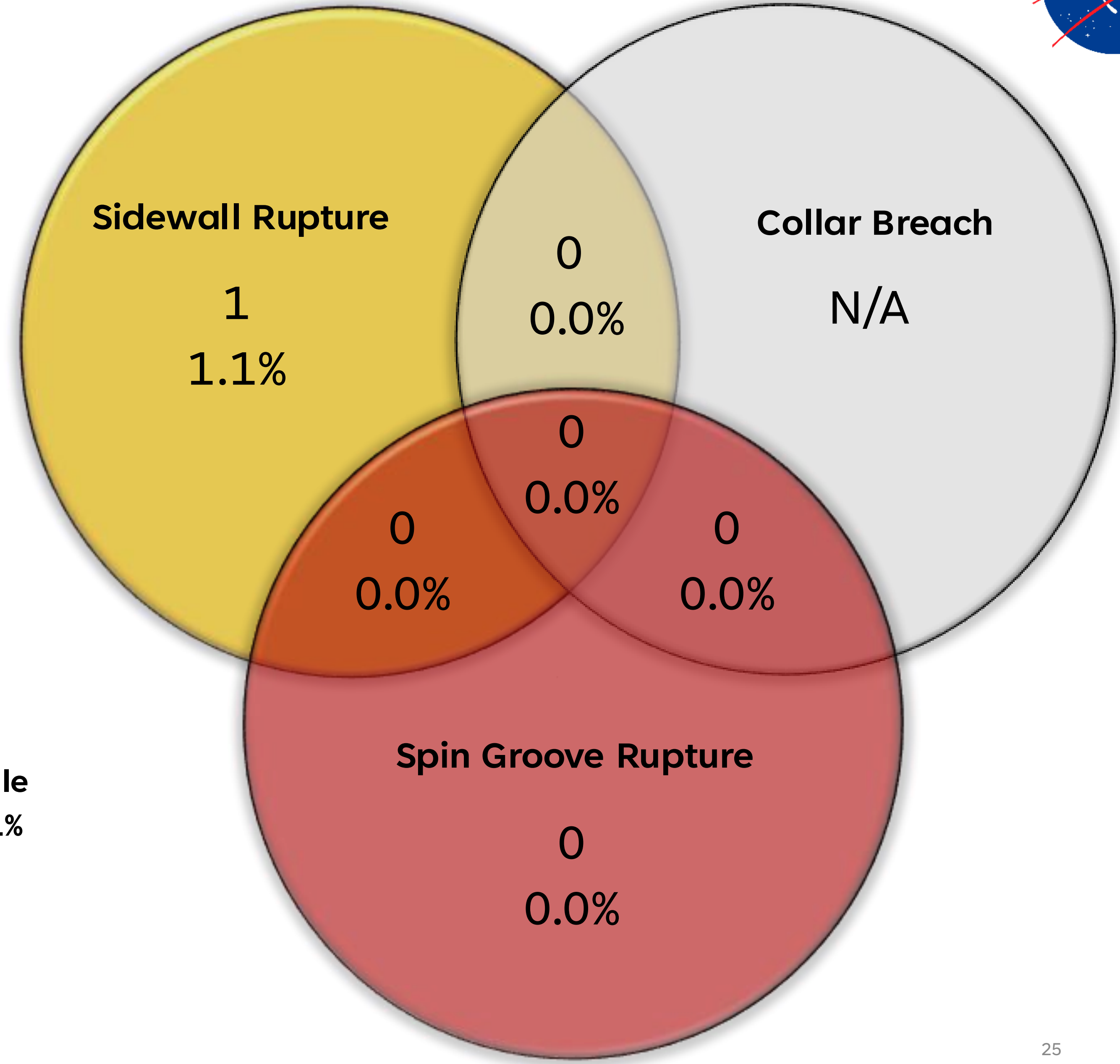




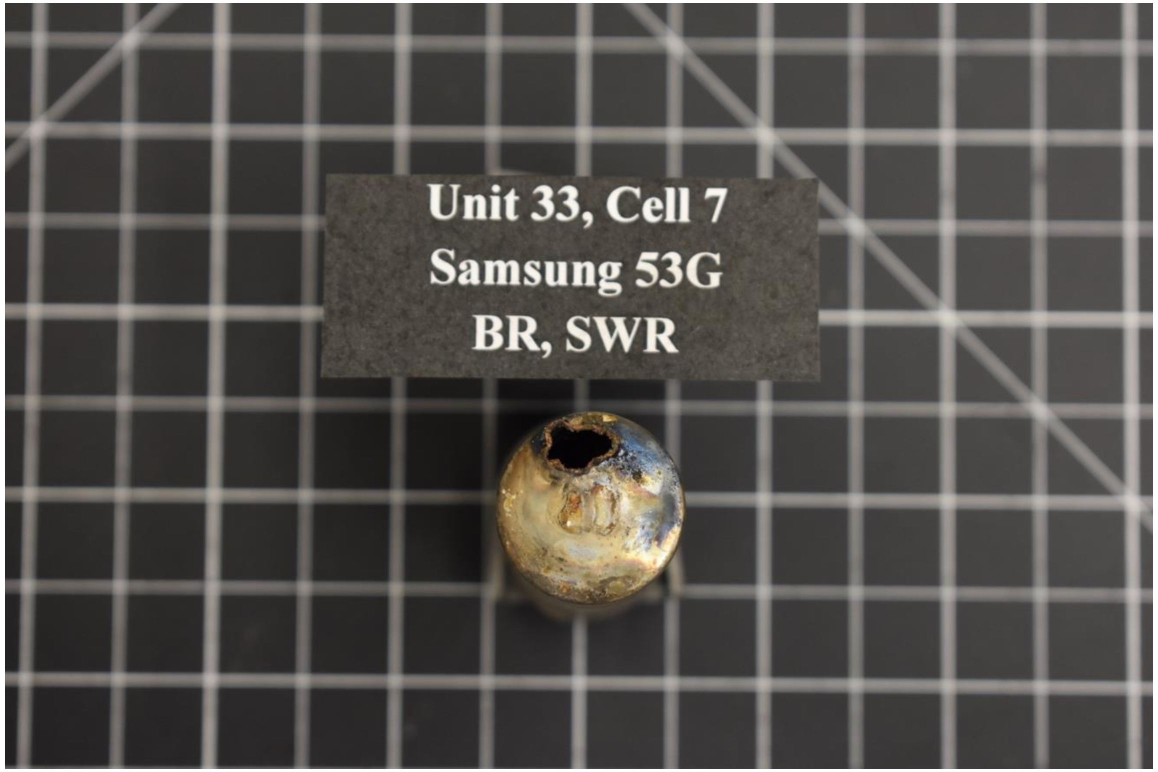
PHOTOGRAPHIC EVIDENCE – SAMSUNG 50S

TEST RESULTS
SAMSUNG 53G1
90 CELLS, 100% SOC

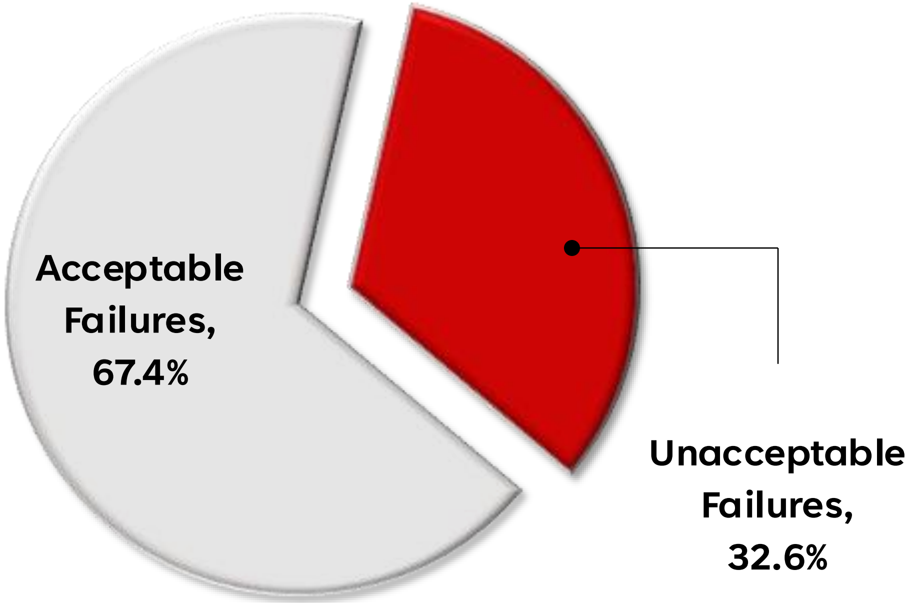


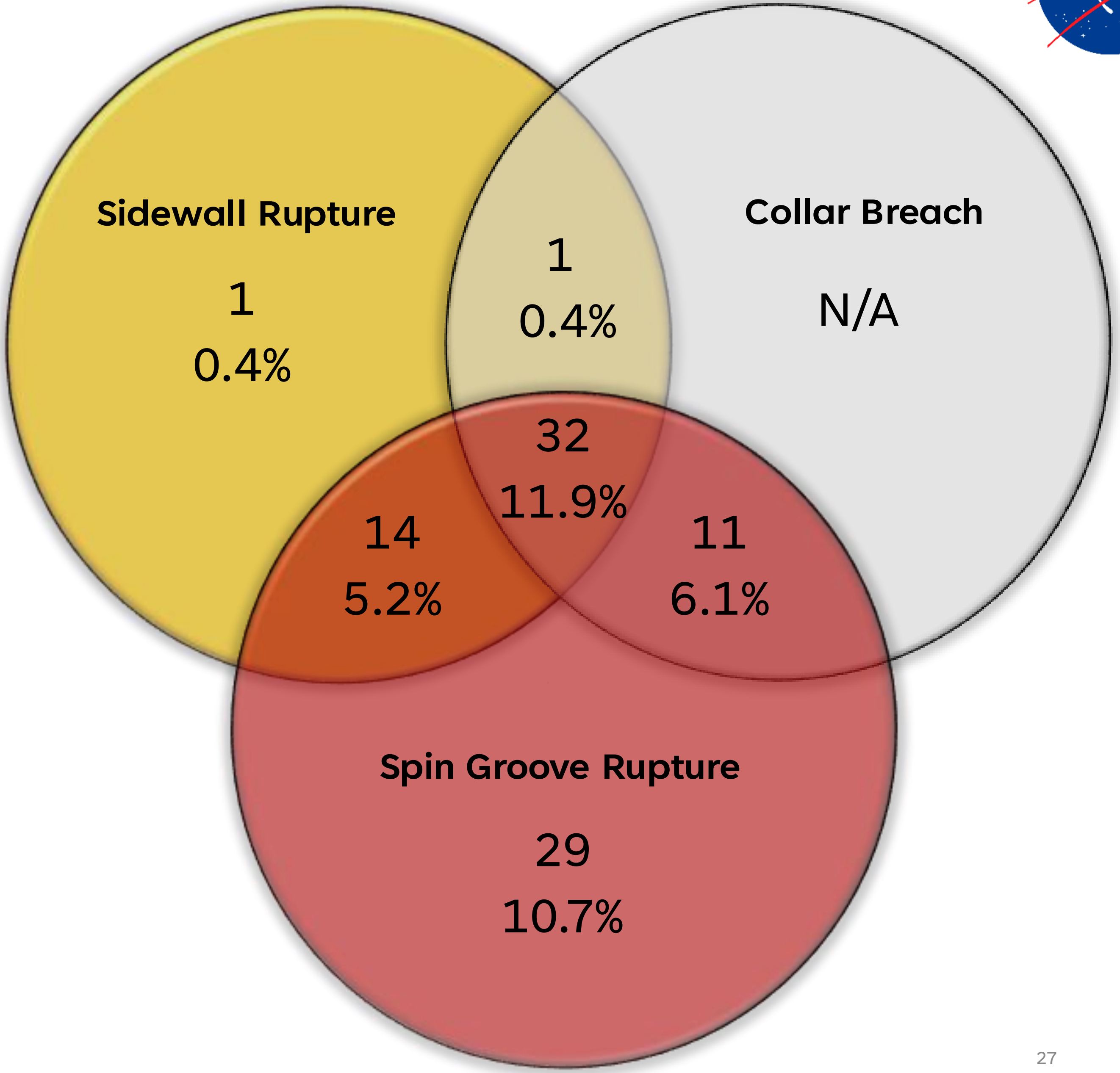


PHOTOGRAPHIC EVIDENCE – SAMSUNG 53G



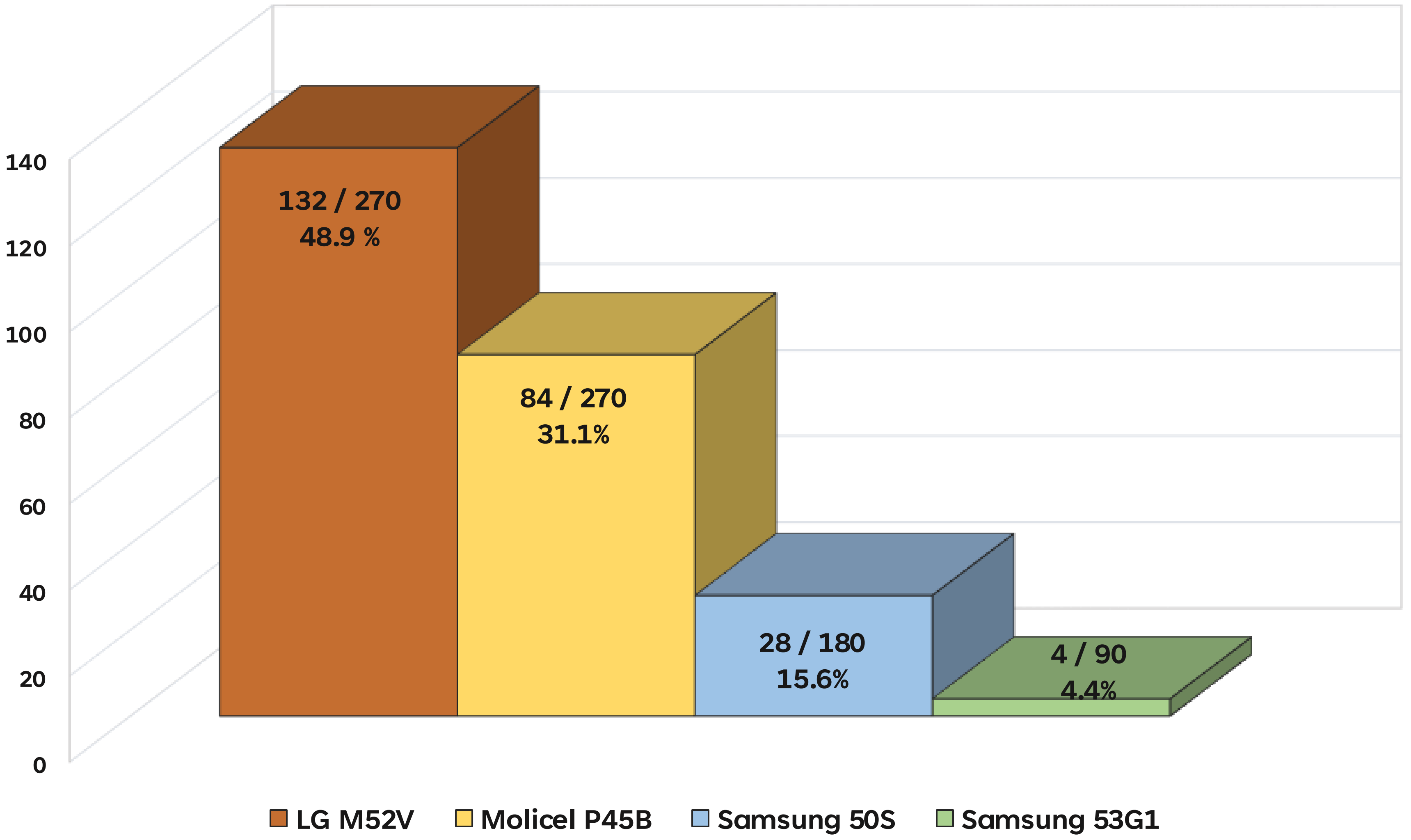
TEST RESULTS
MOLICEL P45B
270 CELLS, 100% SOC





PHOTOGRAPHIC EVIDENCE – MOLICEL P45B

BOTTOM RUPTURE RESULTS



SUMMARY OF RESULTS

1. **Samsung 53G1**: Best cell design in all aspects. Only one SWR out of 90 cells tested. Cell has the thickest can wall.

2. **LG M52V**: Second best cell in terms of SGR/SWR. Highest propensity to bottom rupture.

3. **Samsung 50S**: High propensity of SGR/SWR. Highest percentage of jelly roll ejections.

4. **Molicel P45B**: Highest propensity of SGR/SWR. Most observed at the spin groove and crimp area with a significant amount breaching through the collar.

SWR/SGR VS CAN WALL THICKNESS

SWR/SGR Robustness	Samsung 53G1 (1.1%)	LG M52V (11.5%)	Samsung 50S (25.6%)	Molicel P45B (32.6%)
	More Robust			Less Robust
	✓	✗	✗	✗
	Thicker			Thinner
Avg. Can Wall Thickness	Samsung 53G1 (237 µm)	Molicel P45B (225 µm)	LG M52V (213 µm)	Samsung 50S (200 µm)

SPIN GROOVE MEASUREMENTS

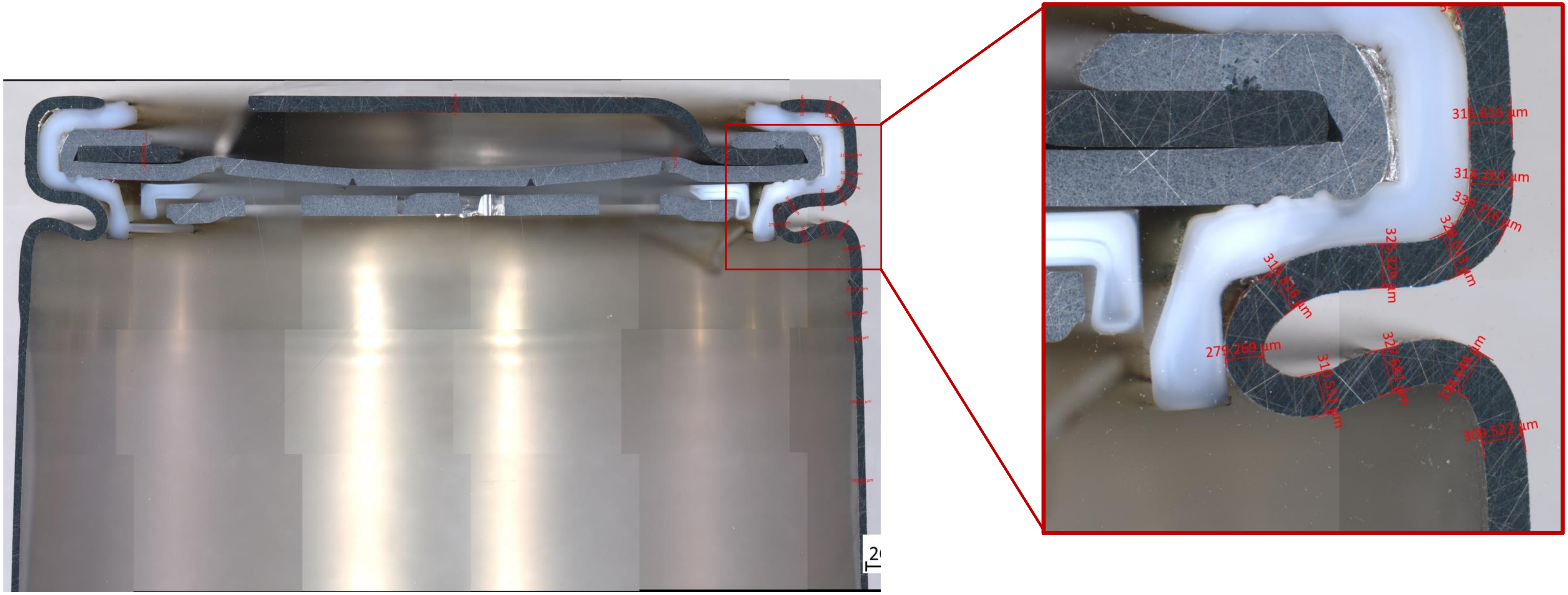
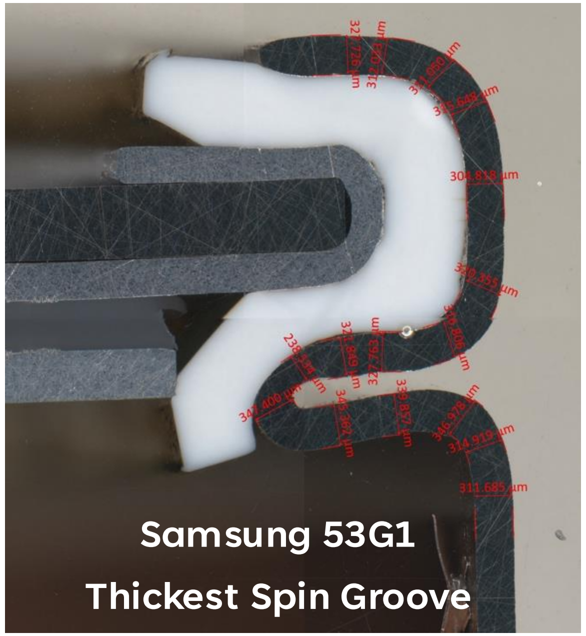


Figure: Cross section of a LG M52V cell used to determine average spin groove thickness. Same technique used for the other cells.

SPIN GROOVE MEASUREMENTS

	Samsung 53G	LG M52V	Samsung 50S	Molicel P45B
Avg. Can Wall Thickness	237 µm	213 µm	200 µm	225 µm
Avg. Spin Groove Thickness	324 µm	321 µm	271 µm	269 µm
Min. Spin Groove Measurement	239 µm	279 µm	203 µm	202 µm



Samsung 53G1
Thickest Spin Groove

Molicel P45B
Thinnest Spin Groove

SWR/SGR VS SPIN GROOVE THICKNESS

SWR/SGR Robustness	Samsung 53G1 (1.1%)	LG M52V (11.5%)	Samsung 50S (25.6%)	Molicel P45B (32.6%)
	More Robust			Less Robust
	✓	✓	✓	✓
	Thicker			Thinner
Avg. Spin Groove Thickness	Samsung 53G1 (324 µm)	LG M52V (321 µm)	Samsung 50S (271 µm)	Molicel P45B (269 µm)

SPIN GROOVE MEASUREMENTS

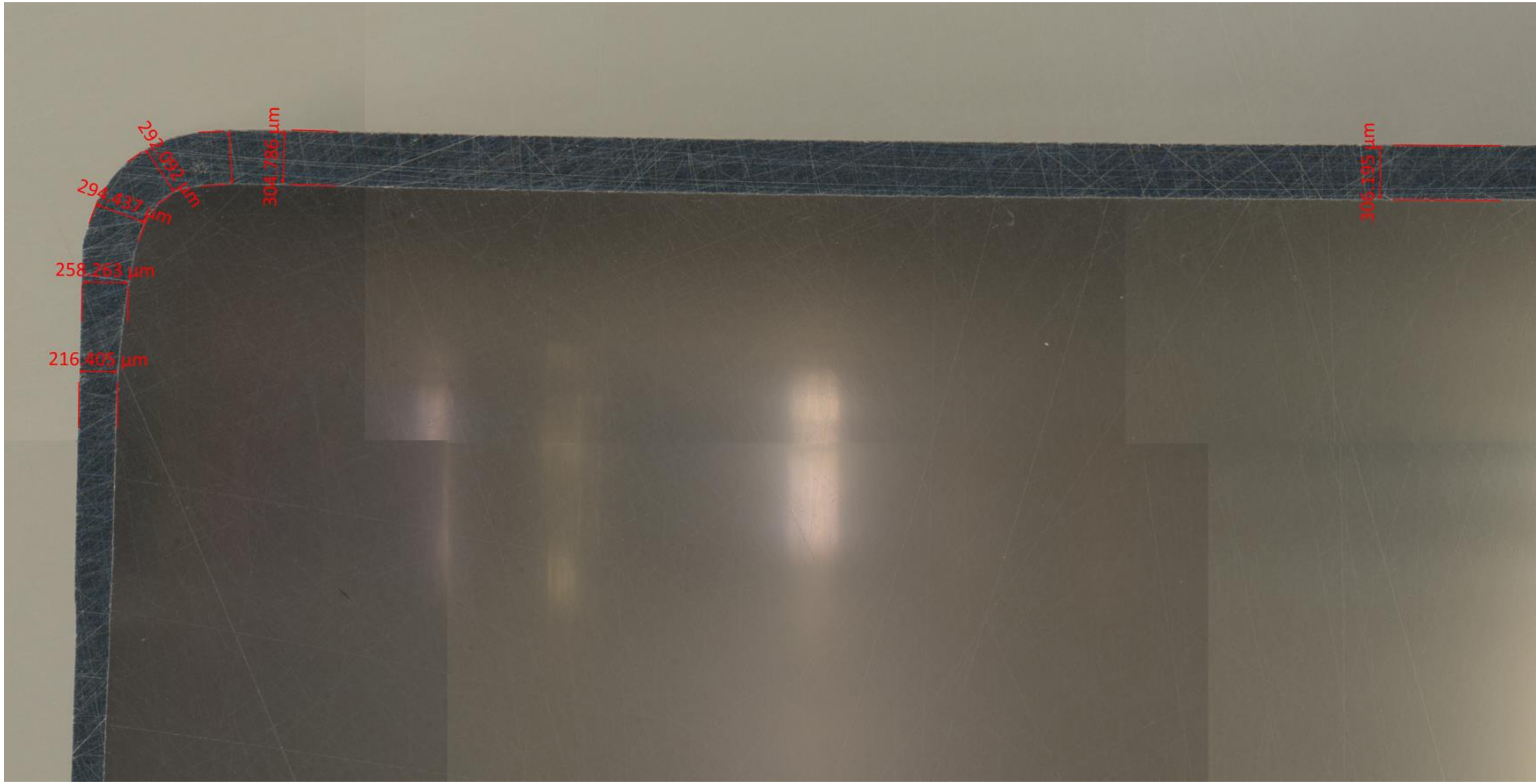


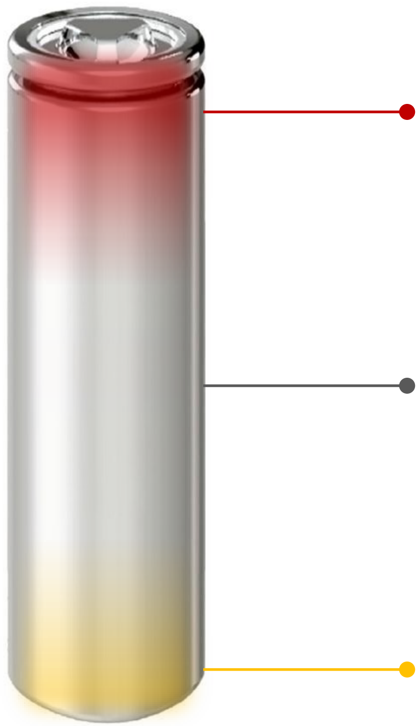
Figure: Cross section of a LG M52V cell used to determine average can bottom thickness. Same technique used for the other cells.

BOTTOM RUPTURE VS CAN BOTTOM THICKNESS

Bottom Rupture Robustness	Samsung 53G1 (4.4%)	Samsung 50S (15.6%)	Molicel P45B (31.1%)	LG M52V (48.9%)
	More Robust			Less Robust
	✓	✗	✗	✓
	Thicker			Thinner
Avg. Can Bottom Thickness	Samsung 53G1 (367 µm)	Molicel P45B (299 µm)	Samsung 50S (289 µm)	LG M52V (287 µm)

CONCLUSIONS

CELL CRITICAL FAILURE AREAS



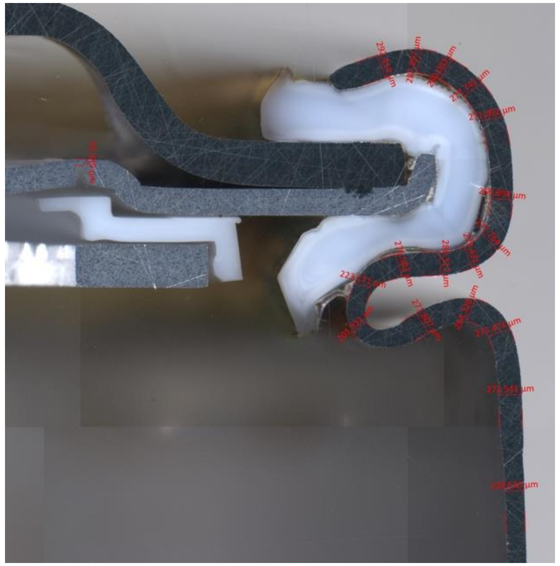
Highest Risk: Majority of unacceptable failures happen at the spin groove (SGR) and just above and below the spin groove (SWR). Most collar breaches are associated with SGR.

Lowest Risk: Very rare to see a sidewall rupture in the middle section of the cell body. Only one “split can” observed in this test series (most likely an outlier)

Moderate Risk: Some bottom ruptures happen close to the edge of the can and a few slightly breached through the sidewall. Some bottom collar breaches were observed

CONCLUSIONS

- The spin groove is the most vulnerable area of a cell.
  - Sidewall ruptures on the main can are rare, most failures happen at the spin groove and crimp
  - A thicker/reinforced spin groove and crimp strongly correlates to reduced SWR and SGR failures.
    - Can wall thickness has a smaller impact on cell robustness to SWR/SGR.



CONCLUSIONS (CONT.)

- 21700 cells are more propense to bottom ruptures than 18650 cells[1]
  - Reinforcing the cell bottom can help reduce bottom ruptures, but data suggest there are other factors that affect bottom rupture propensity.

- Other features that might affect propensity to SGR/SWR:
  - Cell constraints and support on battery pack
  - Cell design: vent pressure, crimp/header release, vent holes size, etc.
  - Other cell features such as bottom vents

- Future work: Test Molicel P45B and P50B cells with reinforced spin groove and crimp.

[1] For 18650 sidewall rupture test results, reference 2022 NASA Aerospace Battery Workshop presentation named: Lithium-Ion Sidewall Rupture Characterization with 3 Battery Designs

BACKUP SLIDES

COLLAR BREACH WITH NO SWR/SGR

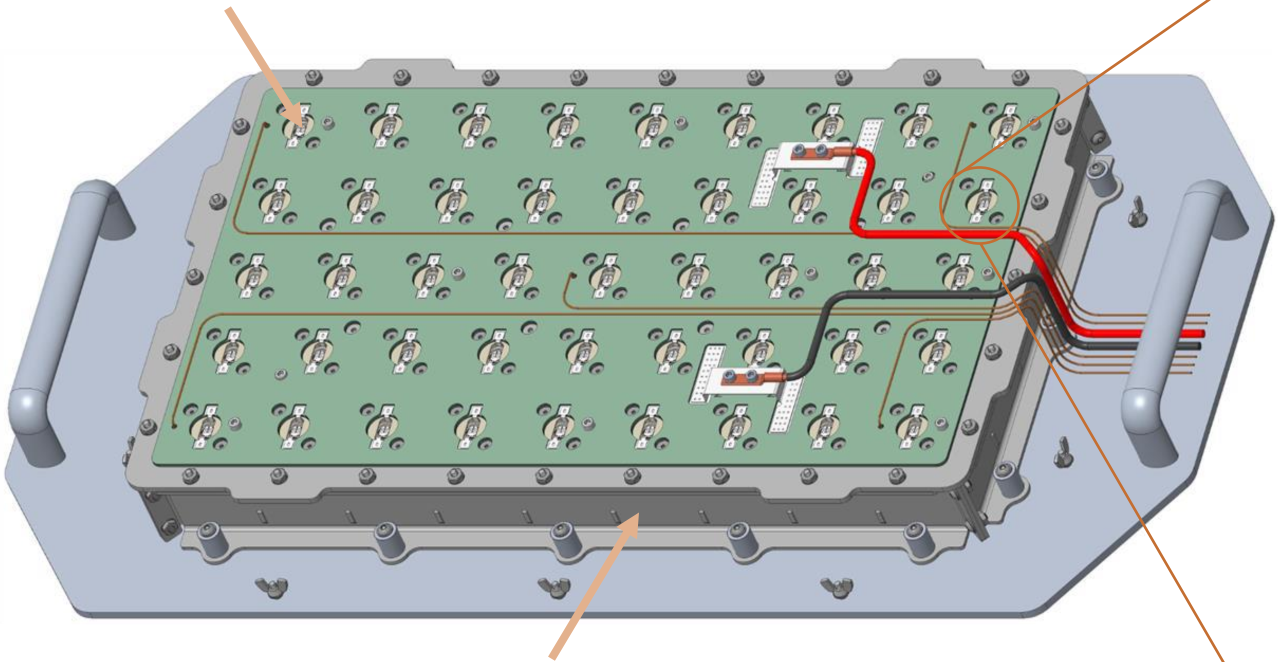
- Some cells shifted down inside the collar causing collar breaches without SGR/SWR.
  - Majority observed with header releases (indication of high kinetic TR event)
  - Recommendations: tighter process control when preparing cells, tighter collars for specific cell design, battery design feature to prevent cells from sliding out.

Example of how cell slipped inside collar during TR - Picture taken pre-cell extraction

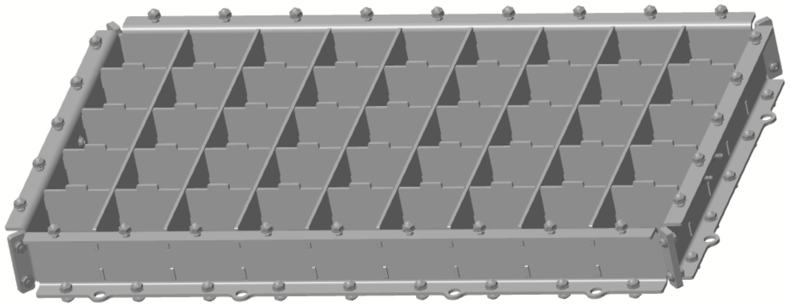
Examples post-cell extraction/inspection. Note: different cells from picture to the left.

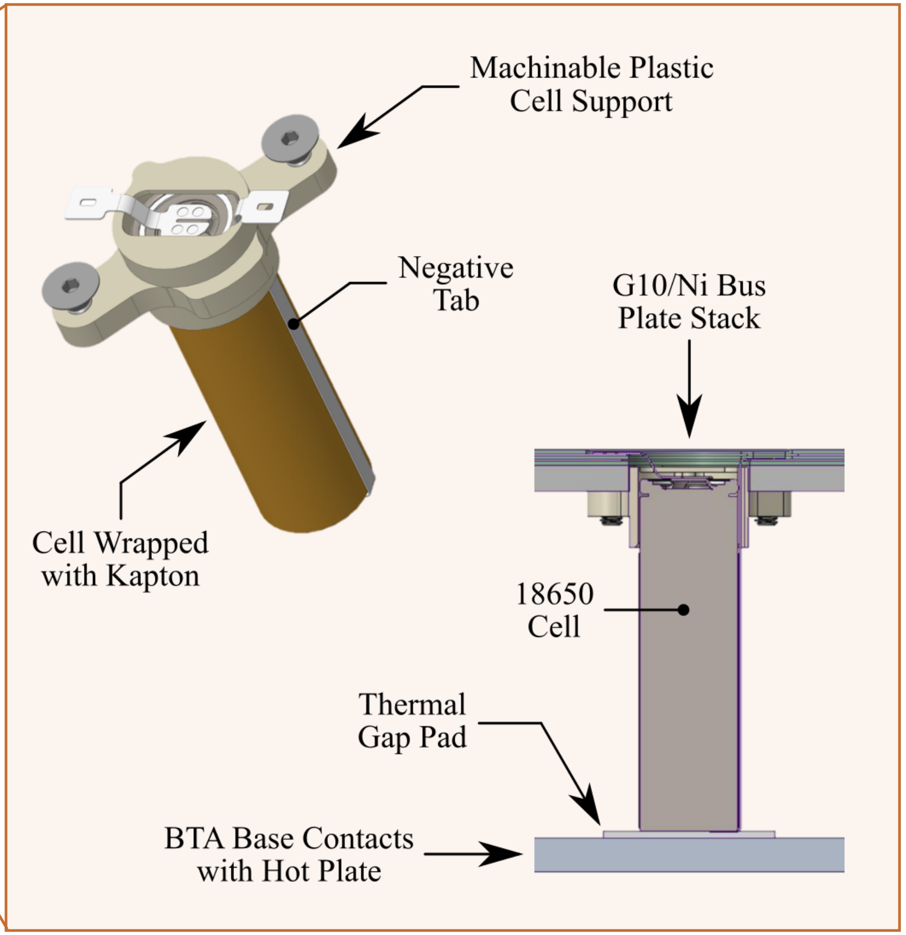
DESIGN A

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

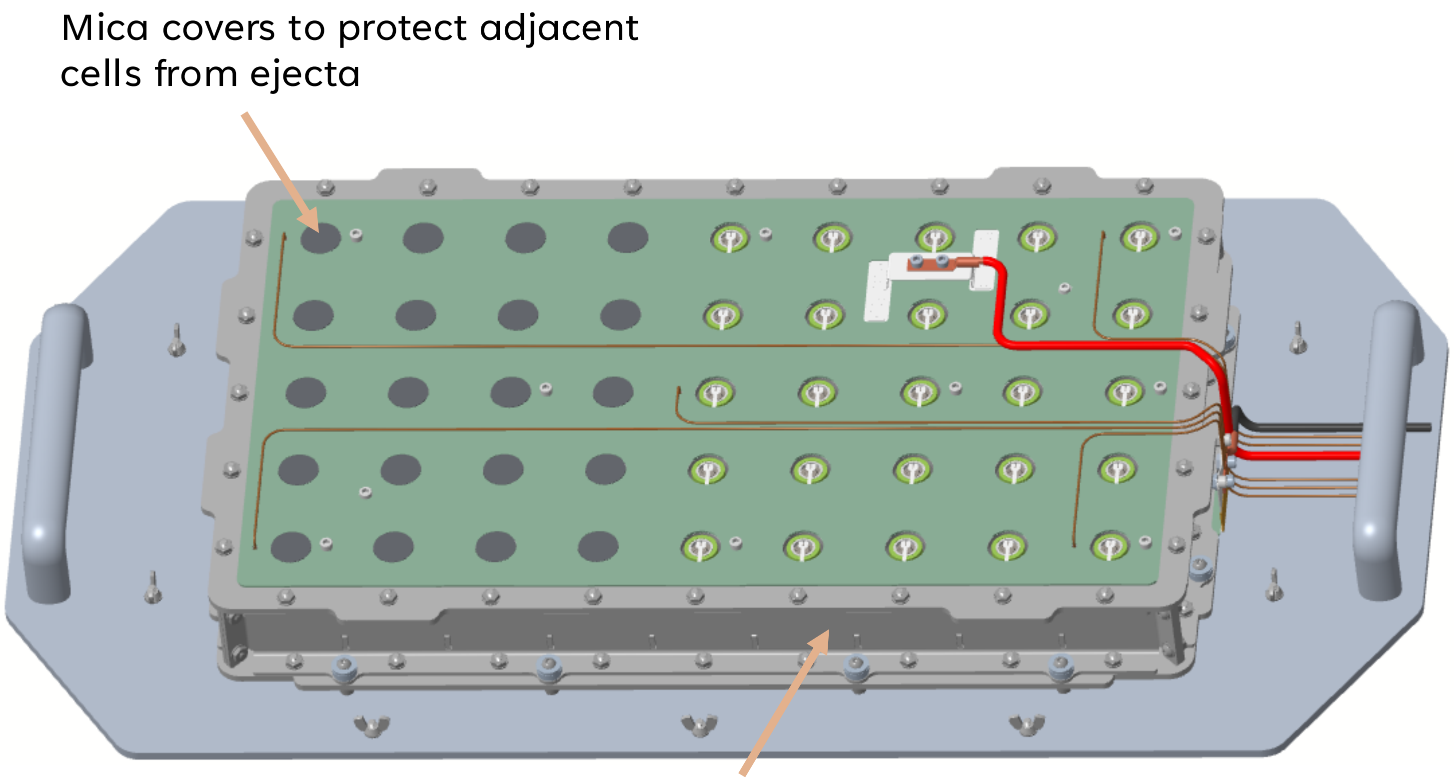


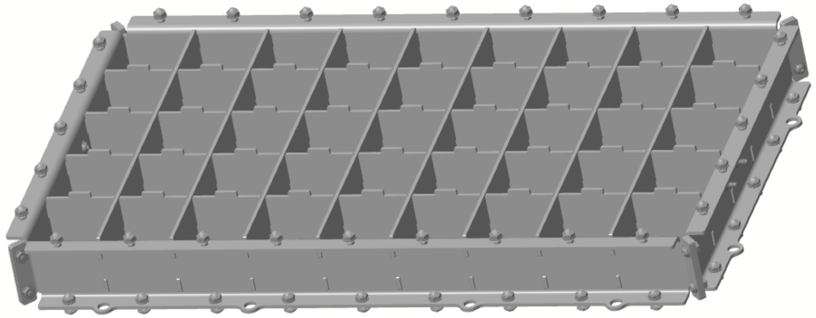
Cell Partition





DESIGN B





Salient features: Length and header constraint