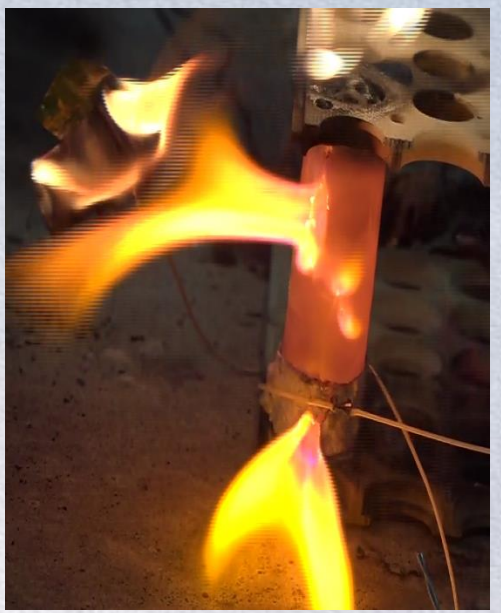
Battery Relevant Cell Side Wall Rupture Characterization



Eric Darcy/NASA JSC
David Petrushenko/White & Associates

The Battery Safety Summit
29-30 June 2021

Characterizing the SWR Risk

- Background on how we've been doing it
- Why it's not working
- Battery relevant plan
- Subscale design
- Subscale results
- Full scale plan
- Recommendations

Old Approach - SWR Characterization While Unsupported

- Test Setup:
  - Cells are charged to 4.1V.
  - Run 3 cells at a time.
  - Increase the oven temperature ~ 2-4 deg per minute until cells are going to thermal runaway.

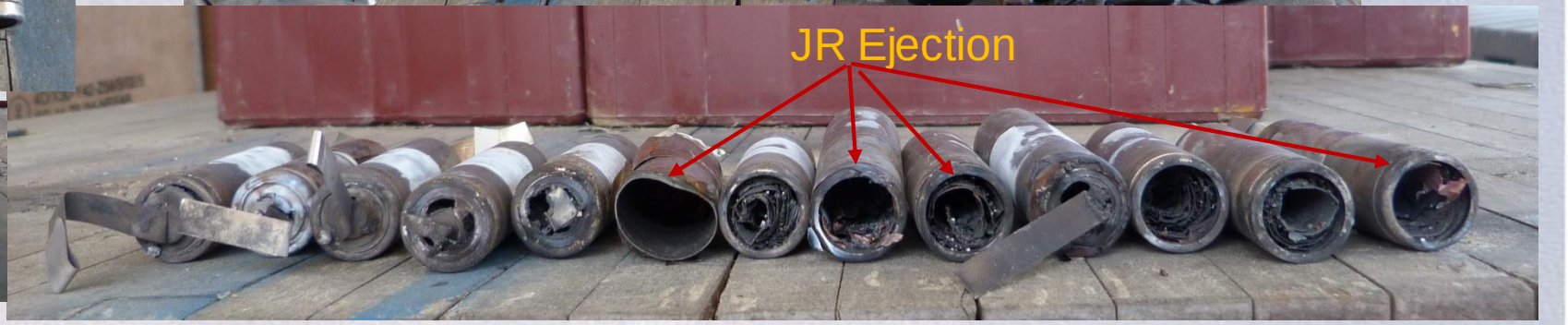
"Turkey Roaster Test"

Side Wall Rupture Testing While Unsupported (cont)

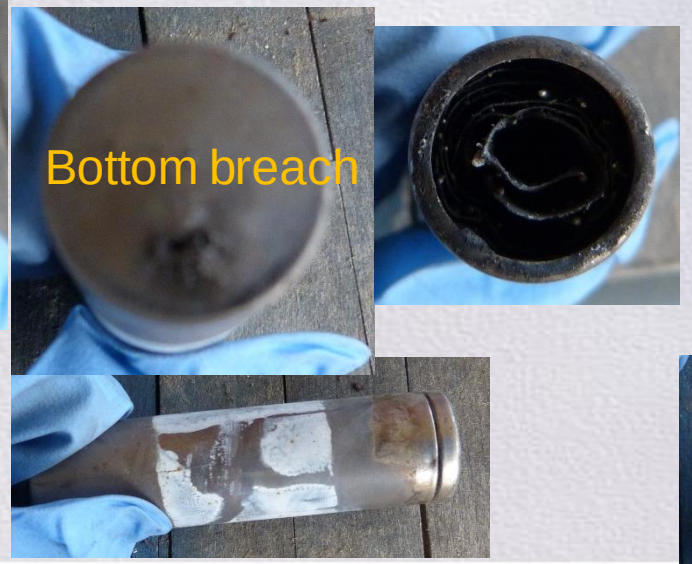
– Test Results:
  - **18 cells**
  - **2 side wall breaches,**
  - 3 bottom breaches,
  - all top vent, 10 blew off the Top Caps, 4 JR Ejection

Panasonic NCR18650B with 125 µm can wall thickness

Conclusion: SWR risk is low



Single Cell Unsupported Heat-To-Vent Test



Turkey Roaster Conclusions

- NCR18650A cell design is predisposed to side wall rupture due to
  - High energy content (> 11 Wh)
  - Thin cell can walls (125 microns, 0.005”)
  - High header crimp seal burst pressure (~1000 psia)
  - Performance is very similar to NCR18650B which experienced 3 of 30 side wall ruptures (NCR18650A experienced 2 of 18)
    - Not surprising since energy content is similar and cell construction is nearly identical
- Other cells designs with similar energy content but thicker can walls and lower burst pressure present less of a risk
  - Panasonic NCR18650GA – 0 out of 30 side wall or bottom ruptures
  - LG INR18650 MJ1 - 0 out of 30 side wall or bottom ruptures
  - Samsung INR18650-35E - 0 out of 30 side wall or bottom ruptures
  - Samsung INR18650-30Q – 2 out of 30 side wall ruptures
- However, battery TR testing has shown much higher prevalence of SWR with the NCR A and with the Samsung 30Q (X-57)
  - Hypothesis: Battery constraints on cells have big impact on results

Example of Spin Groove Breach

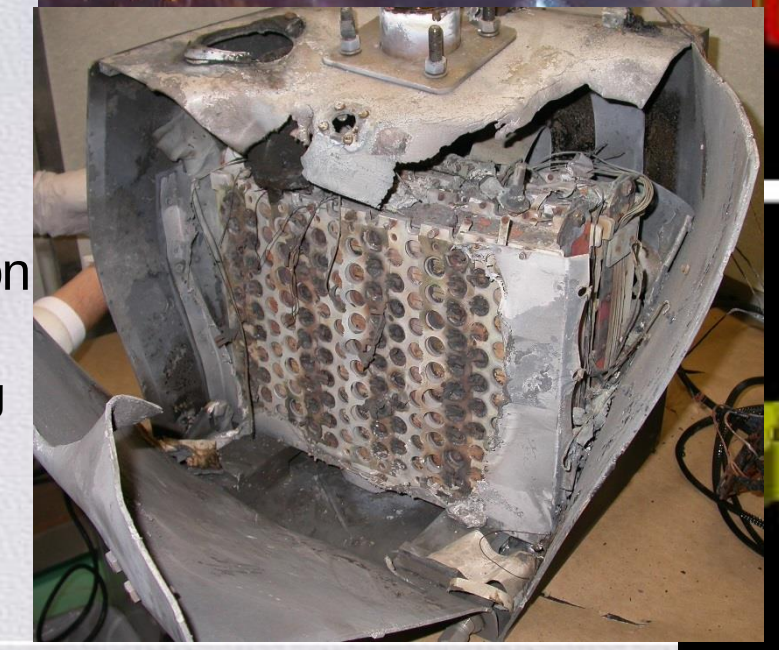
Cell type: Li-ion 18650
Capacity: 3.5 Ah
State of Charge: 100 % (4.2 V)
Bottom vent: No
Wall thickness: Not known
Separator: Polymer
Orientation of cell: Positive end up
Location of ISCD radially: N/A
Location of ISCD longitudinally: N/A
Side of ISCD in image: N/A

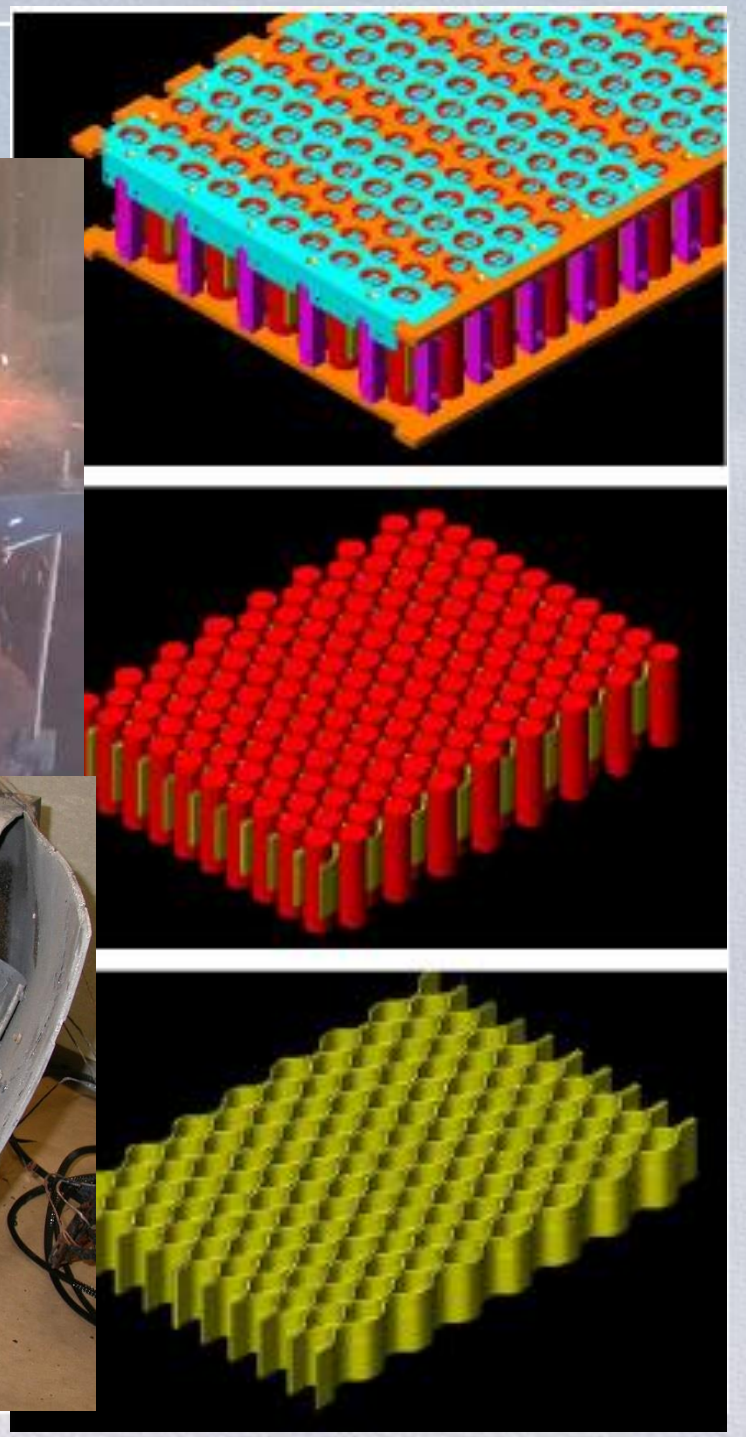
Location of FOV longitudinally: Top
Frame rate: 2000 Hz
Frame dimension (Hor x Ver): 1280 x 800 pixels
Pixel size: 17.8 µm

Credit: Donal Finegan/NREL

X-57 Battery Design Fails PPR Testing

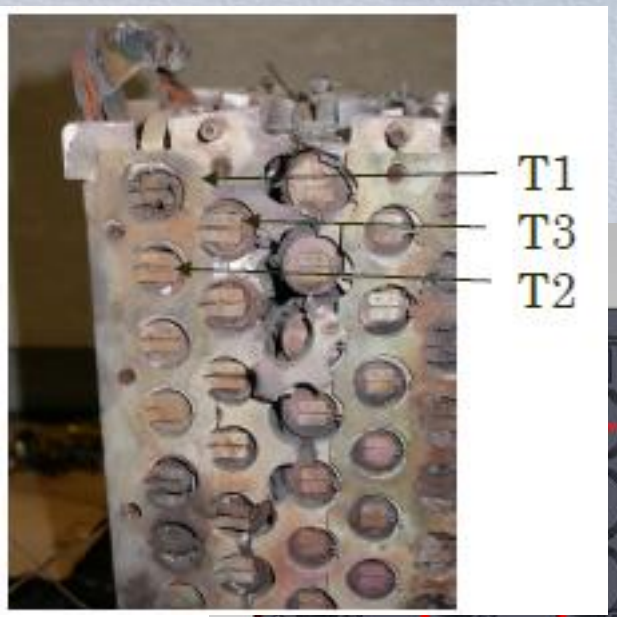
- 320-cell module catastrophically fails during single cell PPR testing
  - Multiple cells propagated TR nearly simultaneously
  - DPA revealed numerous cell can side wall ruptures (> 75%)
- Design did follow guidelines
  - Didn't protect against sidewall rupture
    - Nomex paper (yellow) is weaved in between cell can walls
    - Cell secured at their ends with G10 capture plates maybe held too tightly
  - Didn't provide sufficient heat dissipation between cells
    - Cell heat is dissipated through Ni bussing
    - Ni is a poor thermal conductor



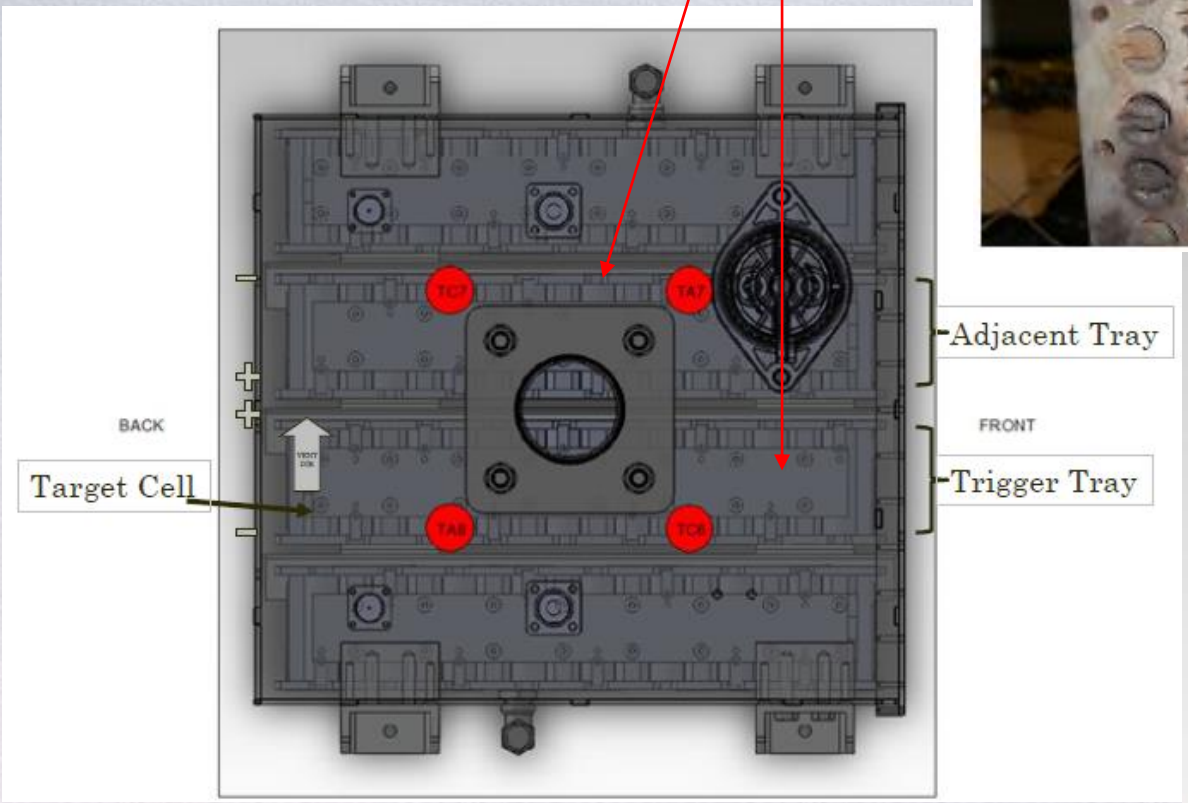


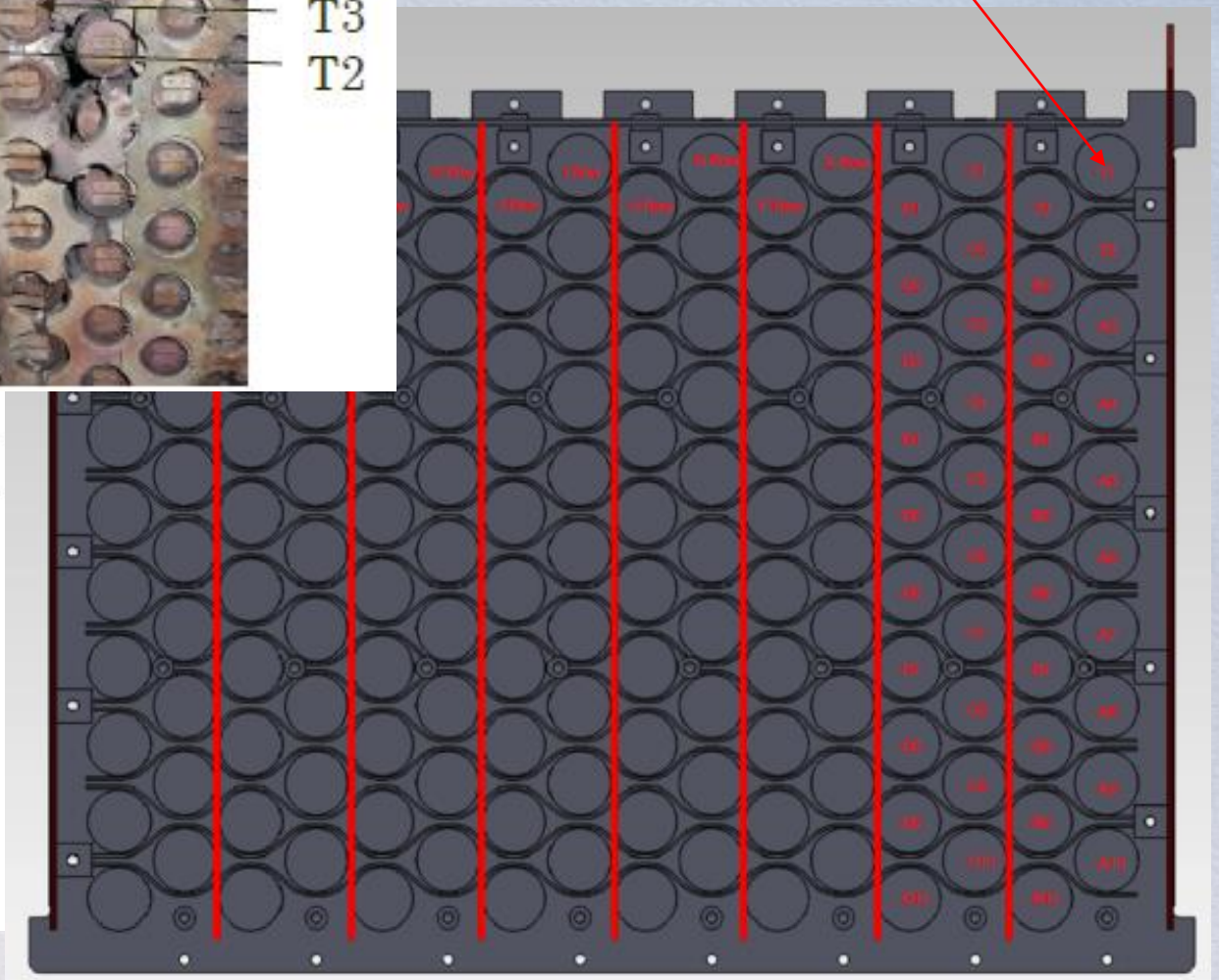
Test Method

Test battery populated with 2 cell trays positioned in the middle of battery housing
Other tray positions were empty



Corner trigger cell location





Probable Root Causes

- Side wall rupture
- Inadequate cell heat dissipation

Pictures of cells – Multiple Sidewall ruptures

T1=Trigger Cell

T2=Adjacent cell to trigger

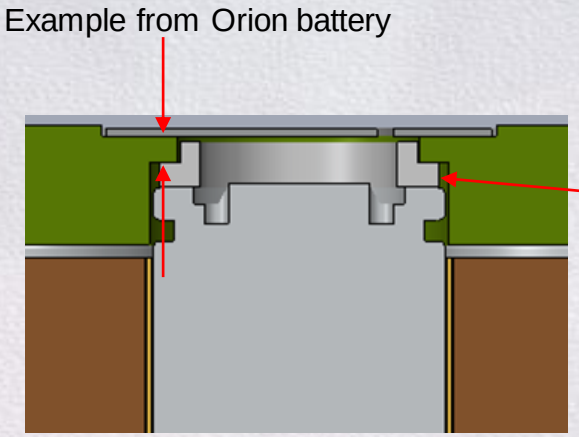
T3=Adjacent cell to trigger

T1- Side wall rupture

T2- Side wall rupture

Probable Root Causes (cont.)

- No crimp-sealed headers were allowed to burst away
  - Headers were burned through, but not ejected
- Suggests cell headers too constrained by G10 capture plates
  - Capture needs to be less structurally stiff in constraining the cell height



Example of cell after cell header burst. None occurred in this test.

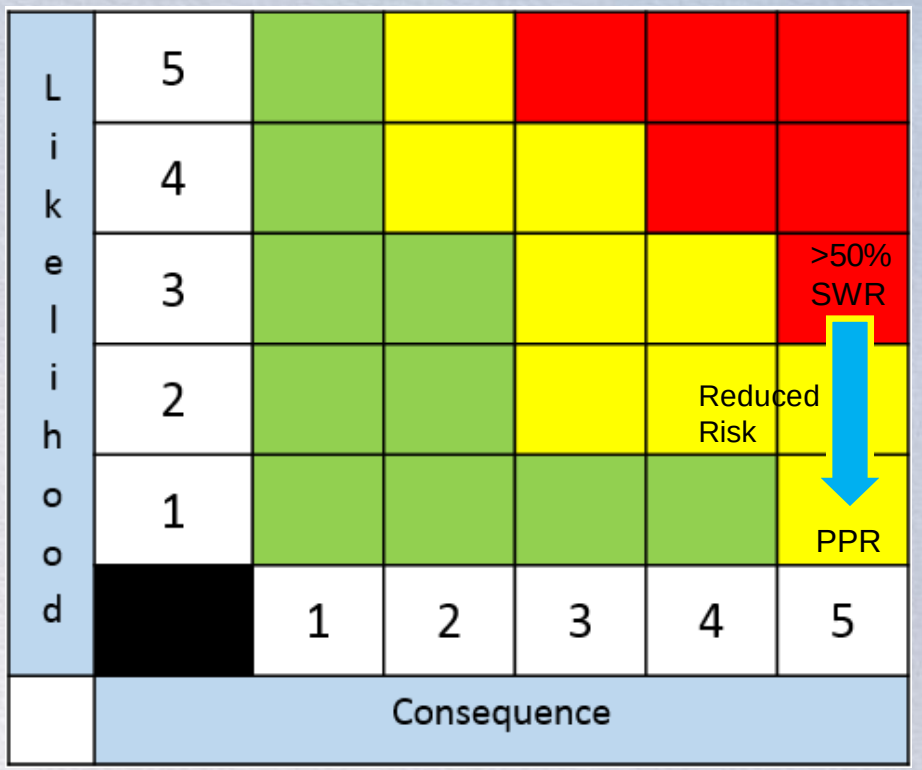
Need to Accurately Characterize the SWR Risk

Problem

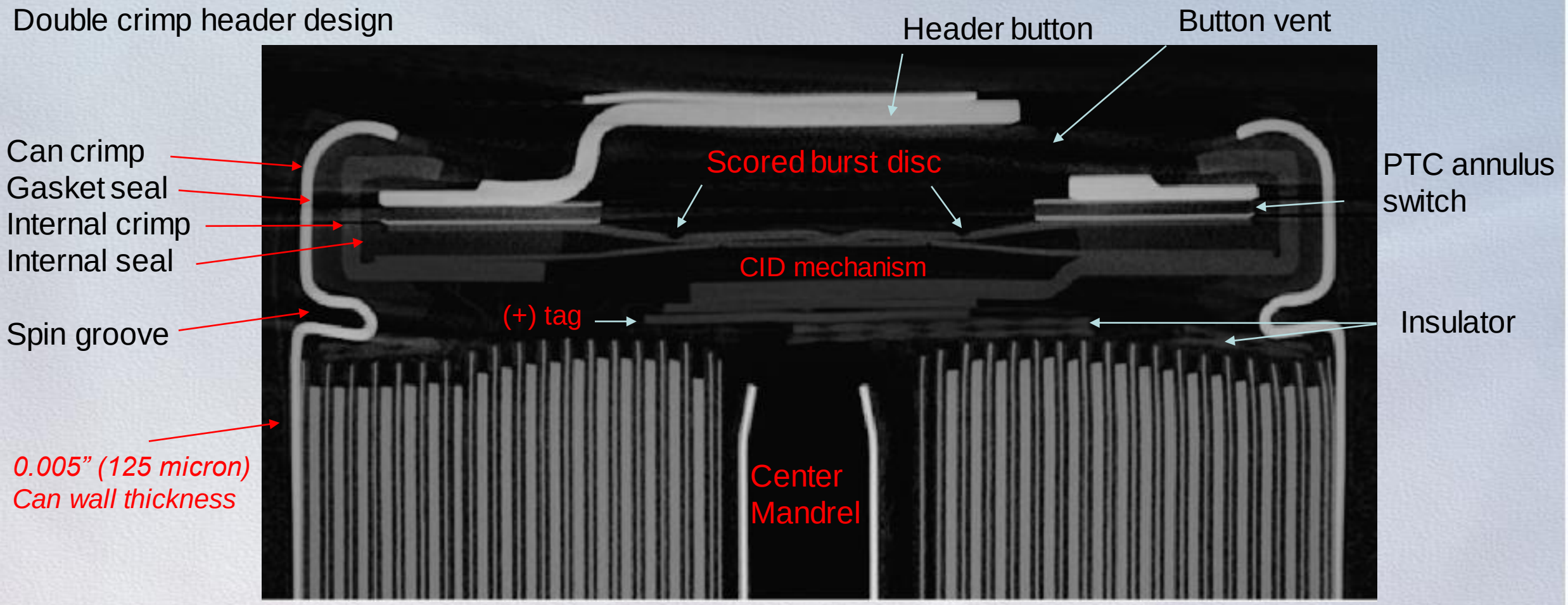
- Several projects have been misled into false sense of low SWR risk by the cell level “Turkey Roaster” characterization tests
- This has led to costly PPR test failures

Solution

- Include battery relevant structural constraints on the cells during the SWR characterization tests
- Include enough cells to statistically defendable



Axial View – Header of NCR18650B Cell

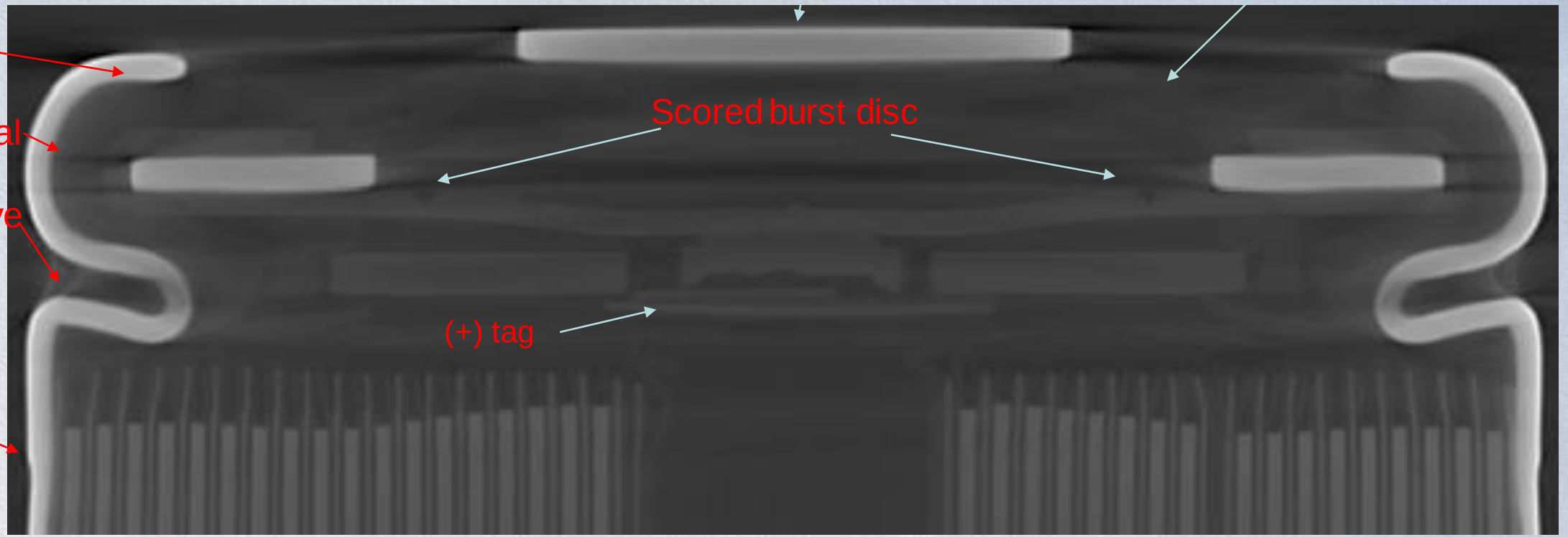


Note the double crimped header design

Burst Pressure of Crimped Header ~1000psia (68 atm)

3 of 30 cells experienced side wall ruptures during oven heating to TR

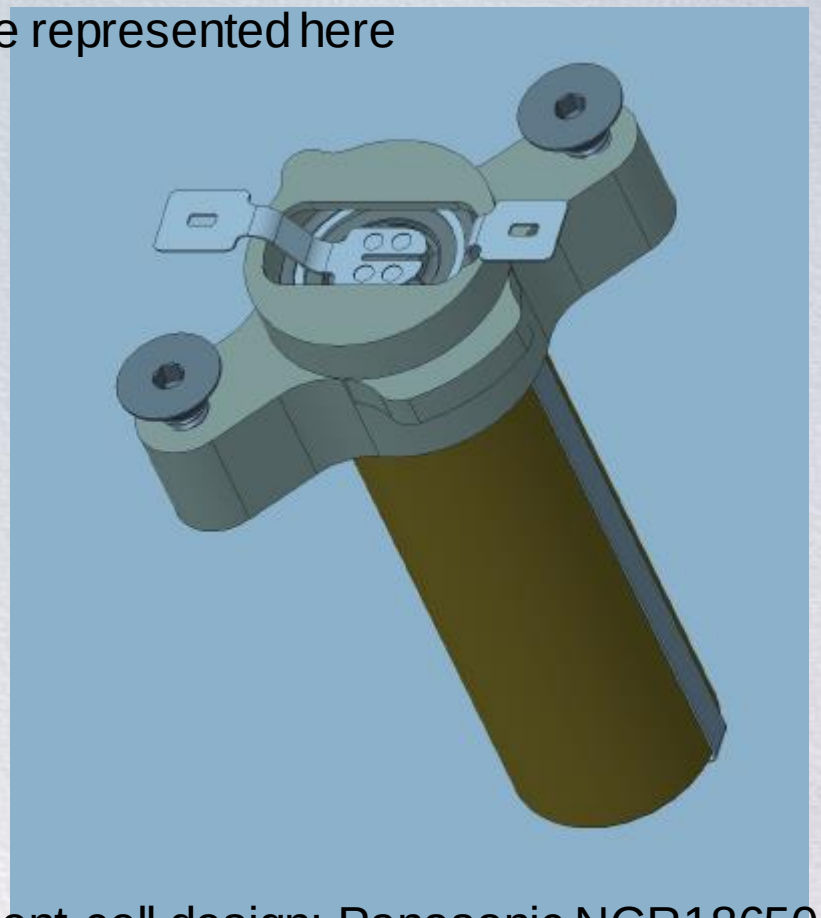
LG 18650 M36 - Axial View - Header - Cell



Note the single crimped header design with burst pressure ~800 psia (~54 atm)

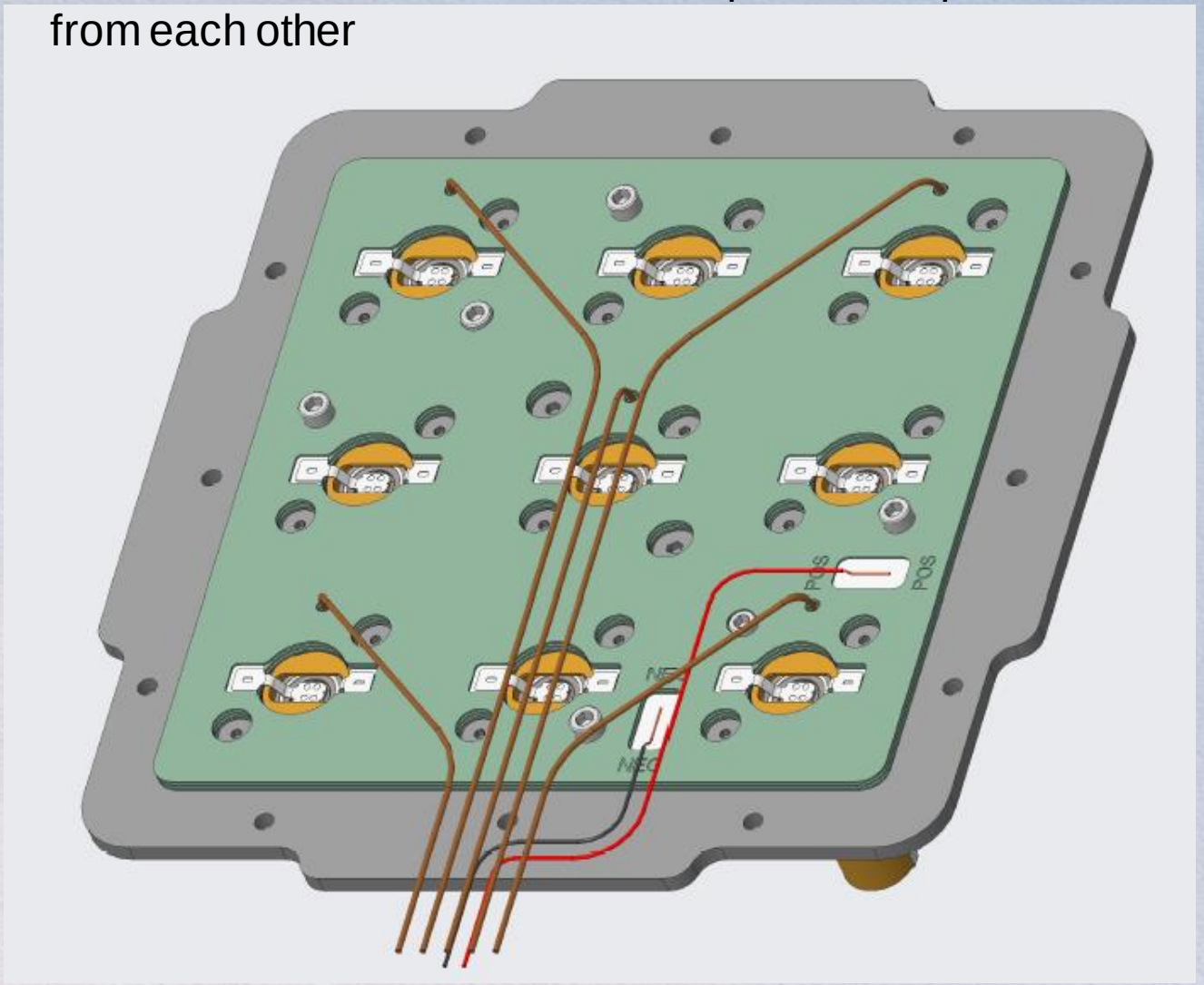
Subscale Battery Test Article

Cell is epoxied to a plastic capture plate whose salient structural interfaces on the cell are represented here

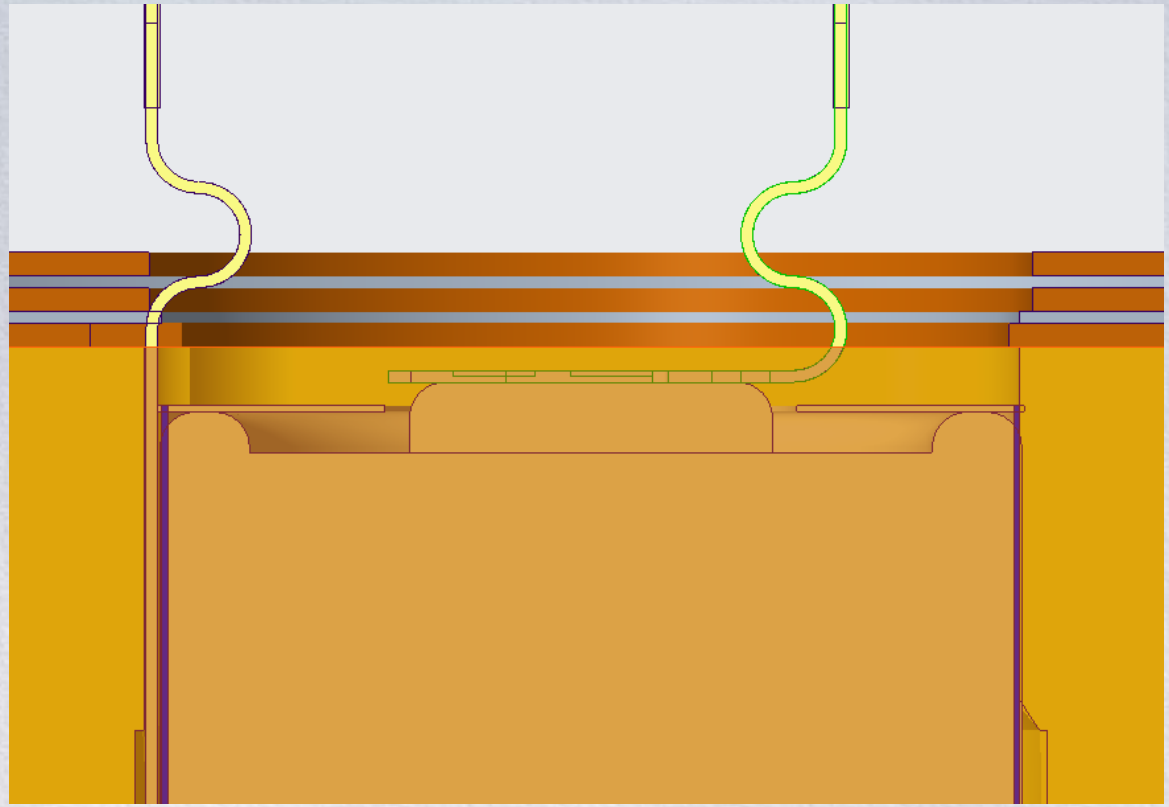


Incumbent cell design: Panasonic NCR18650A
Alternate candidate: LG INR18650 M36

9 cell assemblies fastened to steel plate and spread out from each other

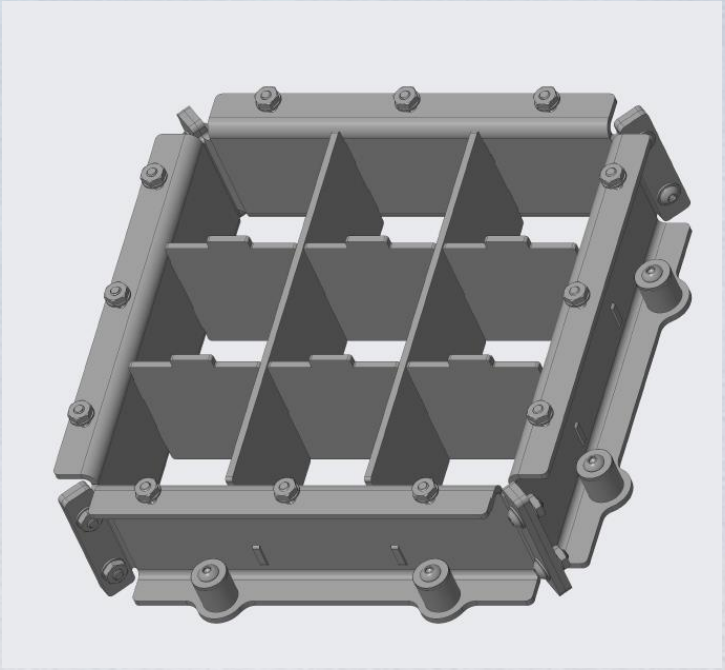


Close up of Top Layers



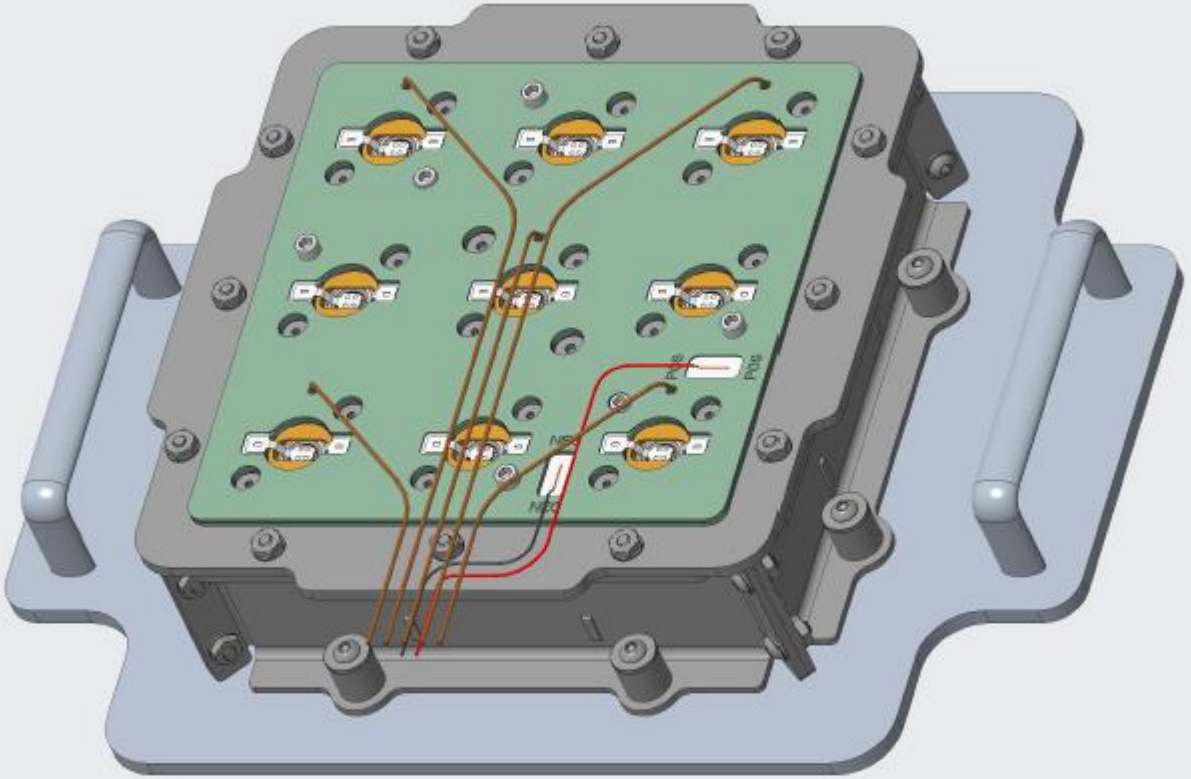
- Top insulation layer
  - 1/32” thk, G10/FR4
- Negative Ni bus plate
  - 0.005” thk
- Middle insulation layer
  - 1/32” thk, G10/FR4
- Positive Ni bus plate
  - 0.005” thk
- Base insulation layer
  - 1/16” thk, G10/FR4
- Upper Cell Support (plastic)
  - Has cell interfaces replicated, including epoxy bond surface and cell top restraining surfaces

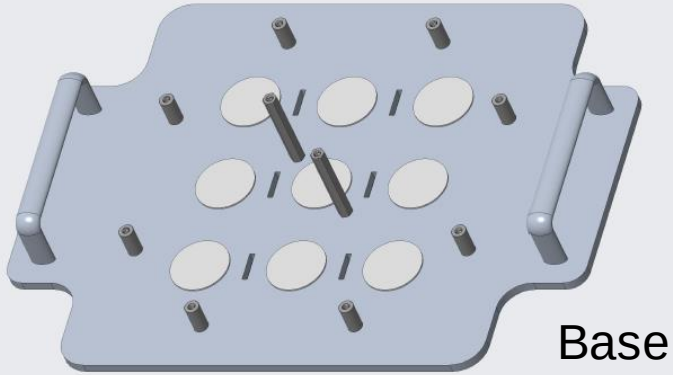
Subscale Battery Test Article



Dividing barriers prevent on cell SWR to induce similar failure on neighboring cell

Completed subscale assy

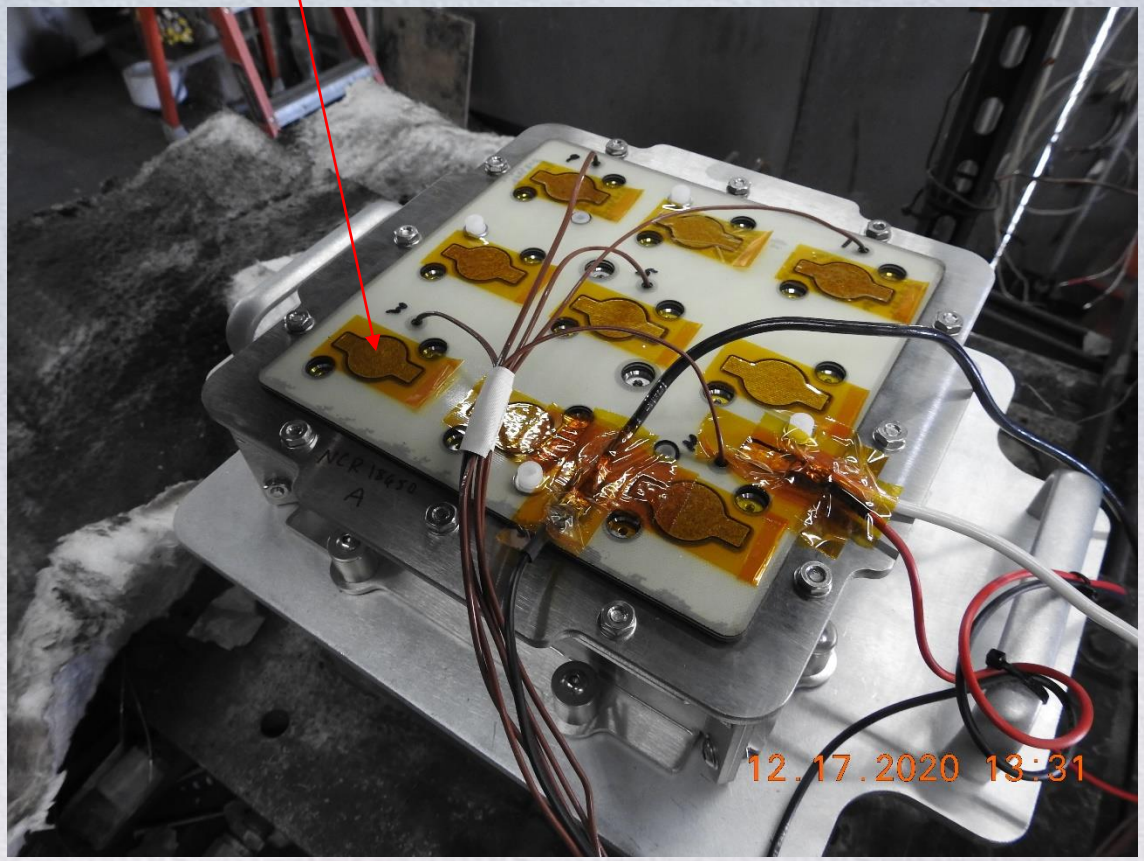




Base plate with thermal gap to represent cell interface

Pre-Test Set-up

Mica covers (9x)



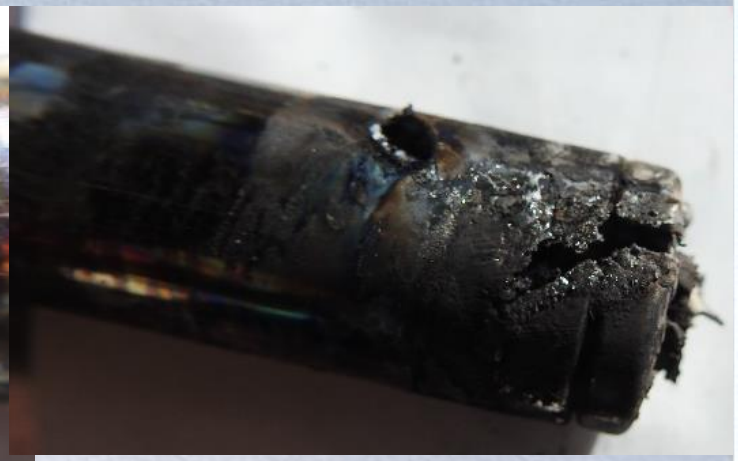
Test Video Snapshot – LG M36

Post Test

Examination M36 Cell Carcasses

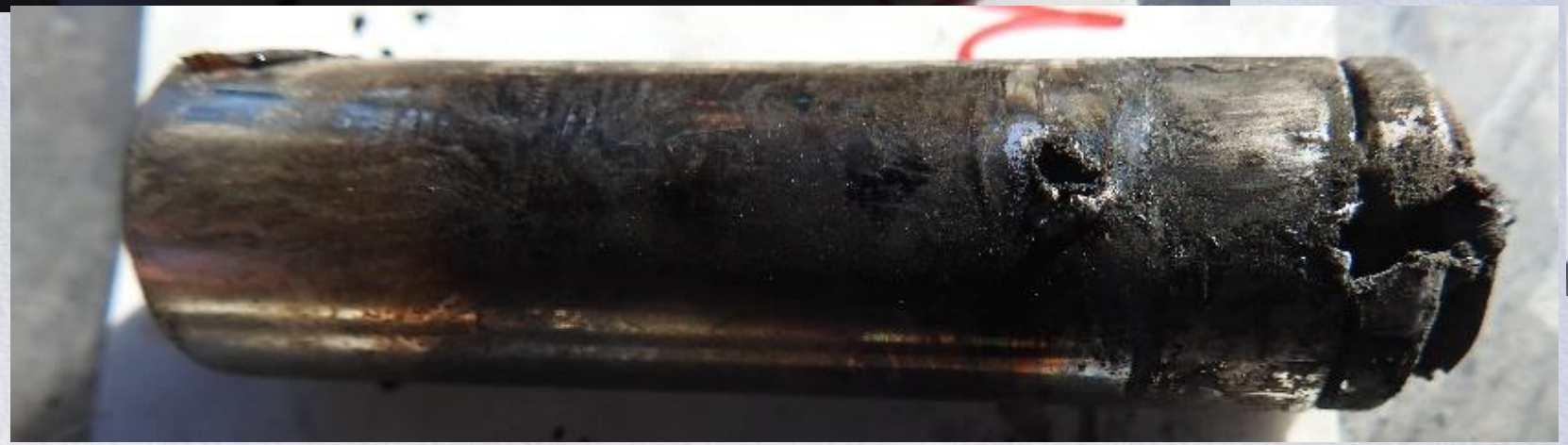
NCR A Cell TR Video Snapshot

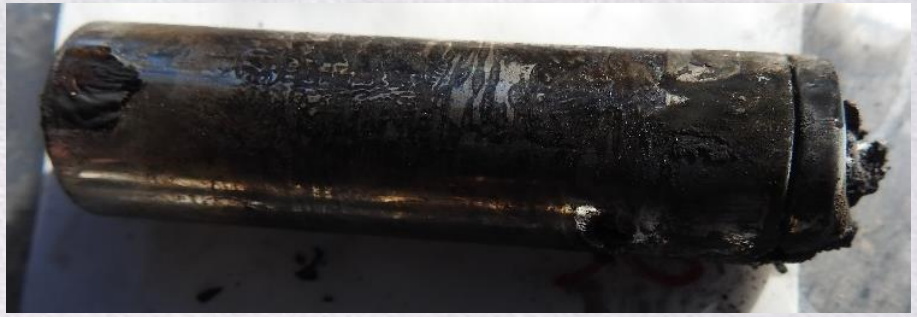
Examination of NCR A Carcasses – Cell 1



- 2 SWRs
- 2 SGRs

Examination of NCR A Carcasses – Cell 9





- 1 SGR
- 1 SWR
- 1 header breach

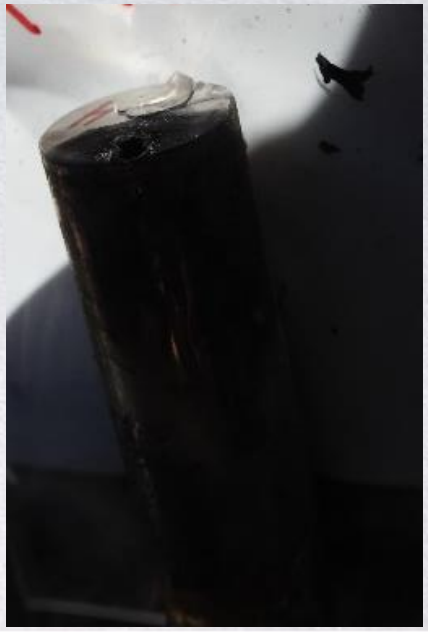
Examination of NCR A Carcasses – Cell 2

- 1 SGR

Examination of NCR A Carcasses – Cell 3

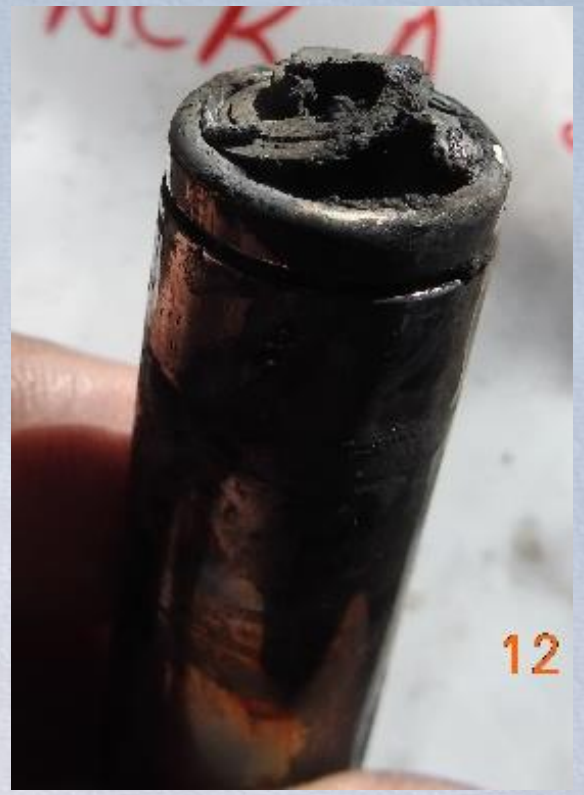
- 2 SWRs

Examination of NCR A Carcasses – Cell 4



- 1 Bottom breach

Examination of NCR A Carcasses – Cell 5

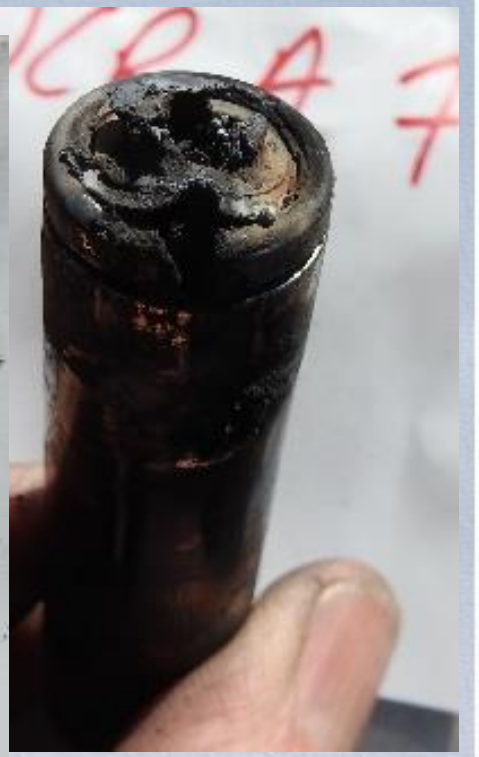


- Nominal vent

Examination of NCR A Carcasses – Cell 6

- 1 SGR
- 1 SWR

Examination of NCR A Carcasses – Cell 7



1 SWR
1 SGR

Examination of NCR A Carcasses – Cell 8

- 1 SGR

Summary of Subscale Examinations

	Post Test		Post Test	
#	M36 Mass (g)	Comments	NCR A Mass (g)	Comments
1	11.77	No SGR or SWR	26.35	2 SWR, 2 SGR
2	14.55	No SGR or SWR	23.26	1 header breach, 1 SGR
3	16.99	No SGR or SWR	24.02	2 SWR
4	13.41	No SGR or SWR	8.30	1 Bottom breach, header blew out
5	17.56	No SGR or SWR	26.84	No SGR or SWR
6	10.12	No SGR or SWR	24.06	1 SGR and 1 SWR
7	16.15	No SGR or SWR	21.67	1 SGR and 1 SWR
8	11.84	No SGR or SWR	24.02	1 SGR
9	17.81	No SGR or SWR	21.25	1 SGR and 1 SWR and header breach
	Pre-test mass 44g		Pre-test mass 44g	

SWR = Side Wall Rupture
SGR = Spin Groove Rupture

Lessons Learned

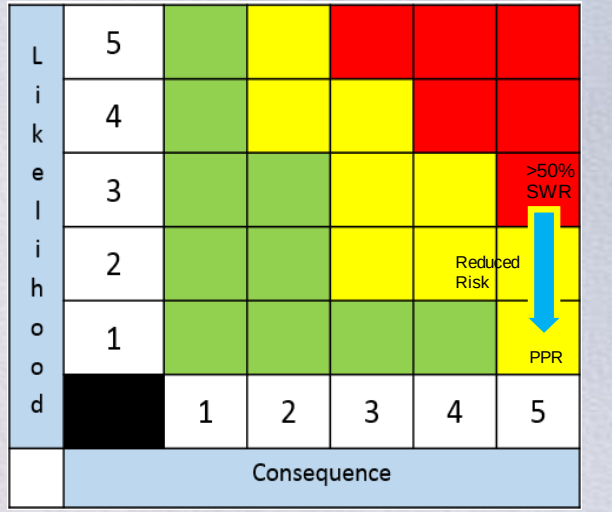
- Cell **and** battery design play a big role in side wall rupture risk
- LG M36 without steel sleeves shows promise

How Many Cells Must Be Tested to Get to 1x5 Risk?

- To get into 1x5 box with standard NASA PRA methods and a 90% confidence level, the fail rate demonstrated must be
  - None out of 200
  - 1 out of 300
  - 2 out of 400
  - 3 out of 500
- Plan is to test 540 per test configuration
- (6 test runs)

Population Proportion – Sample Size for 90% confidence level with 5% margin of error

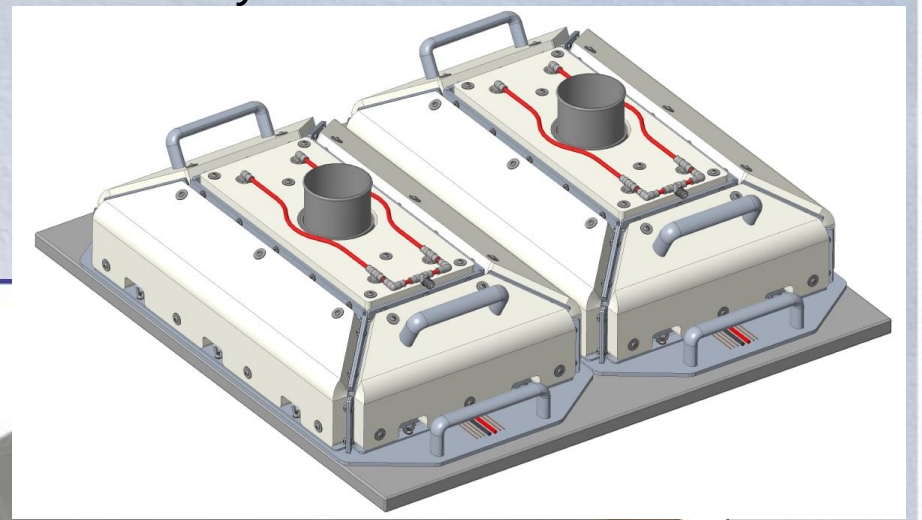
Lot Size	Sample size	Lot Size	Sample size
131,288 +	271	7,364 – 8,255	262
46,650 – 131,288	270	6,641 – 7,363	261
28,282 – 46,649	269	6,043 – 6,640	260
20,249 – 28,281	268	5,540 – 6,042	259
15,744 – 20,248	267	5,111 – 5,539	258
12,861 – 15,743	266	4,742 – 5,110	257
10,858 – 12,860	265	4,420 – 4,741	256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

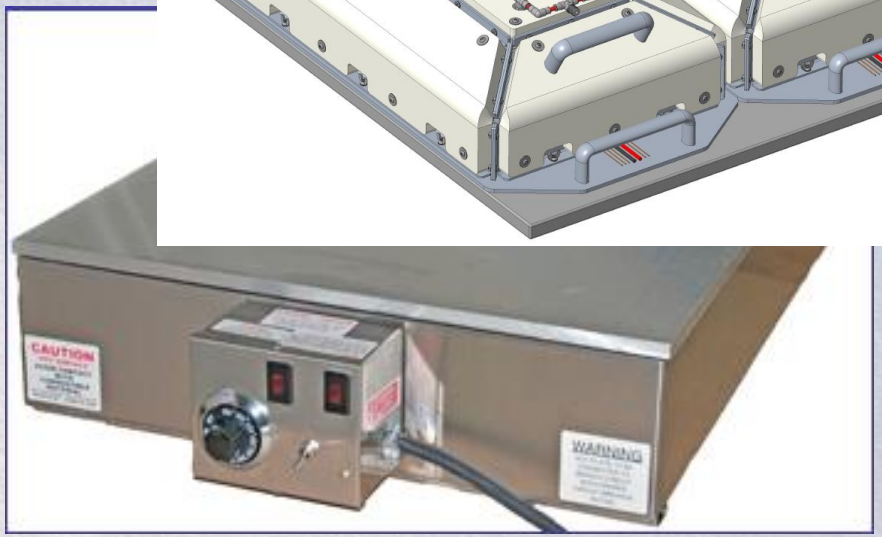


Full Scale Test Plan

- Need 90-cell battery test article or pair of 45-cell test articles (350Ah total driven into TR)
- Test Matrix
  - LG M36 bare (540)
  - LG M36 with spin groove rings (540)
  - LG M36 with 0.005” full length tubes (540)
  - Moli M35A with with 0.005” full length tubes (540)
  - Moli M35A with with 0.010” full length tubes (540)
  - Total of 2700 cells tested
  - Total of 30 test runs, 15 test days
- Compare Results vs Previous PPR test campaign
  - 6 SWR out of 13 in battery PPR tests
  - Subscale testing showed 7 out of 9 cells experiencing SWR and SGR
  - One or more of these cell/sleeve combinations should achieve lower than ≤1 in 300 or ≤3 in 500 SWR occurrences bringing risk from 3x5 to 1x5

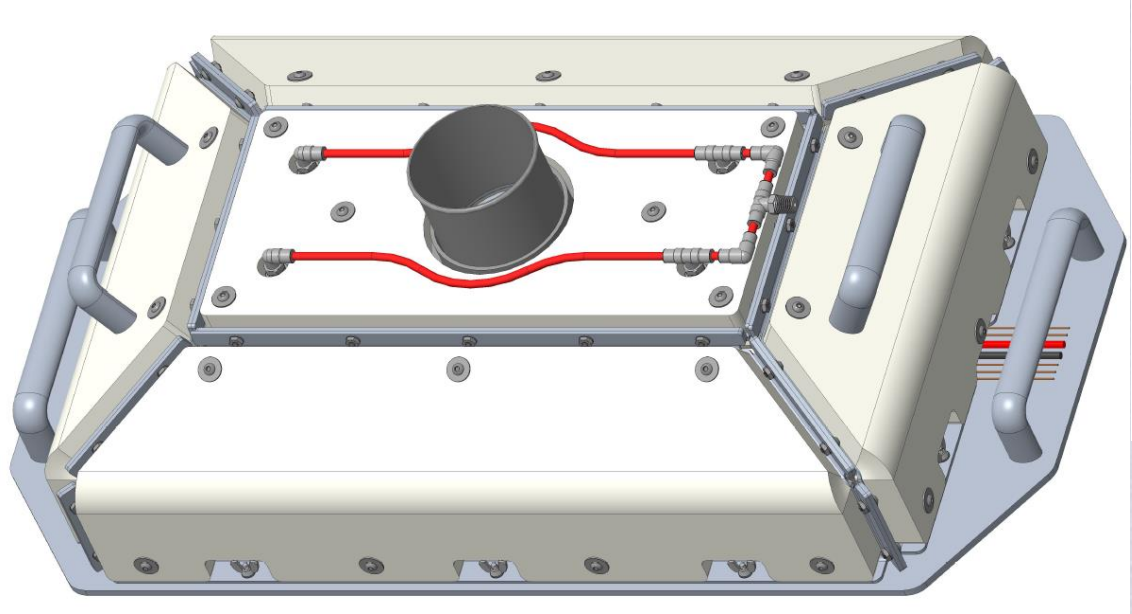
Two 45-cell battery test articles

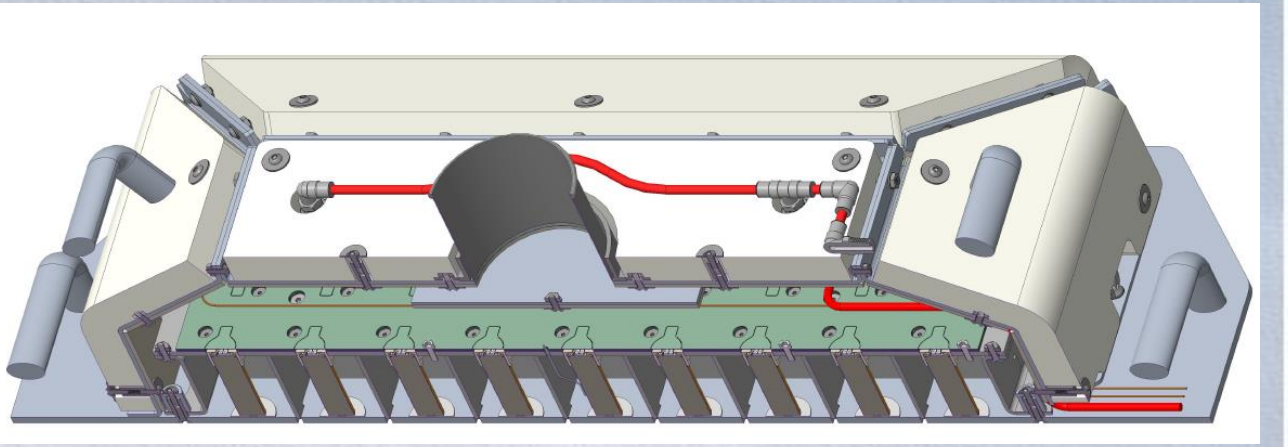


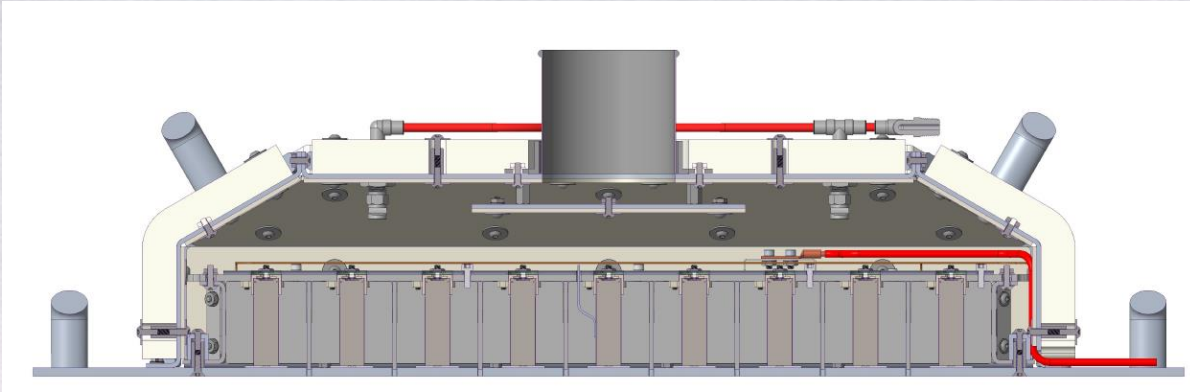


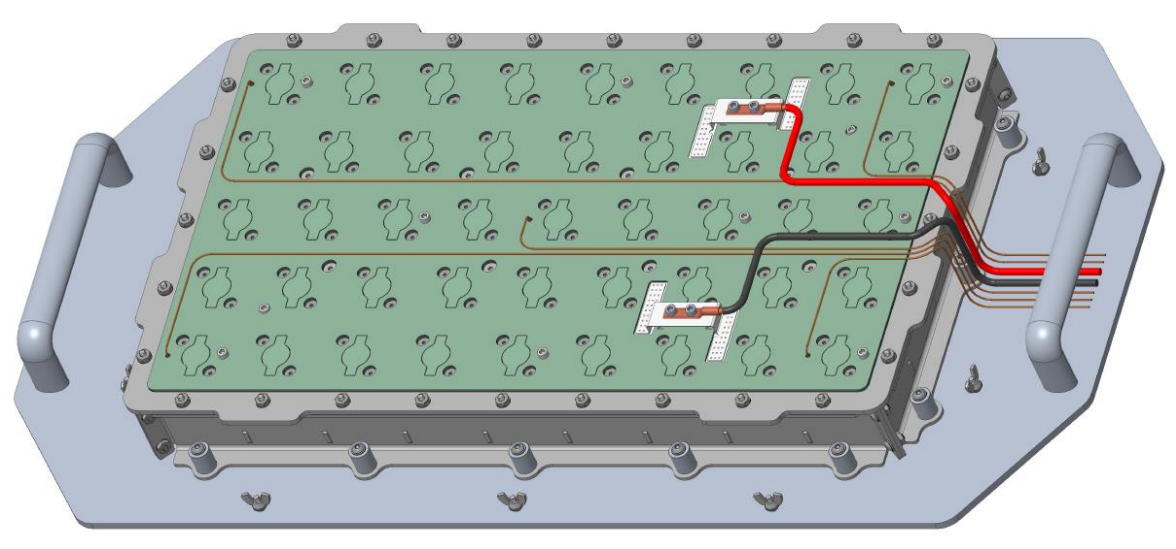
6kW Hot Plate

Full Scale Battery Test Article (45-cell)



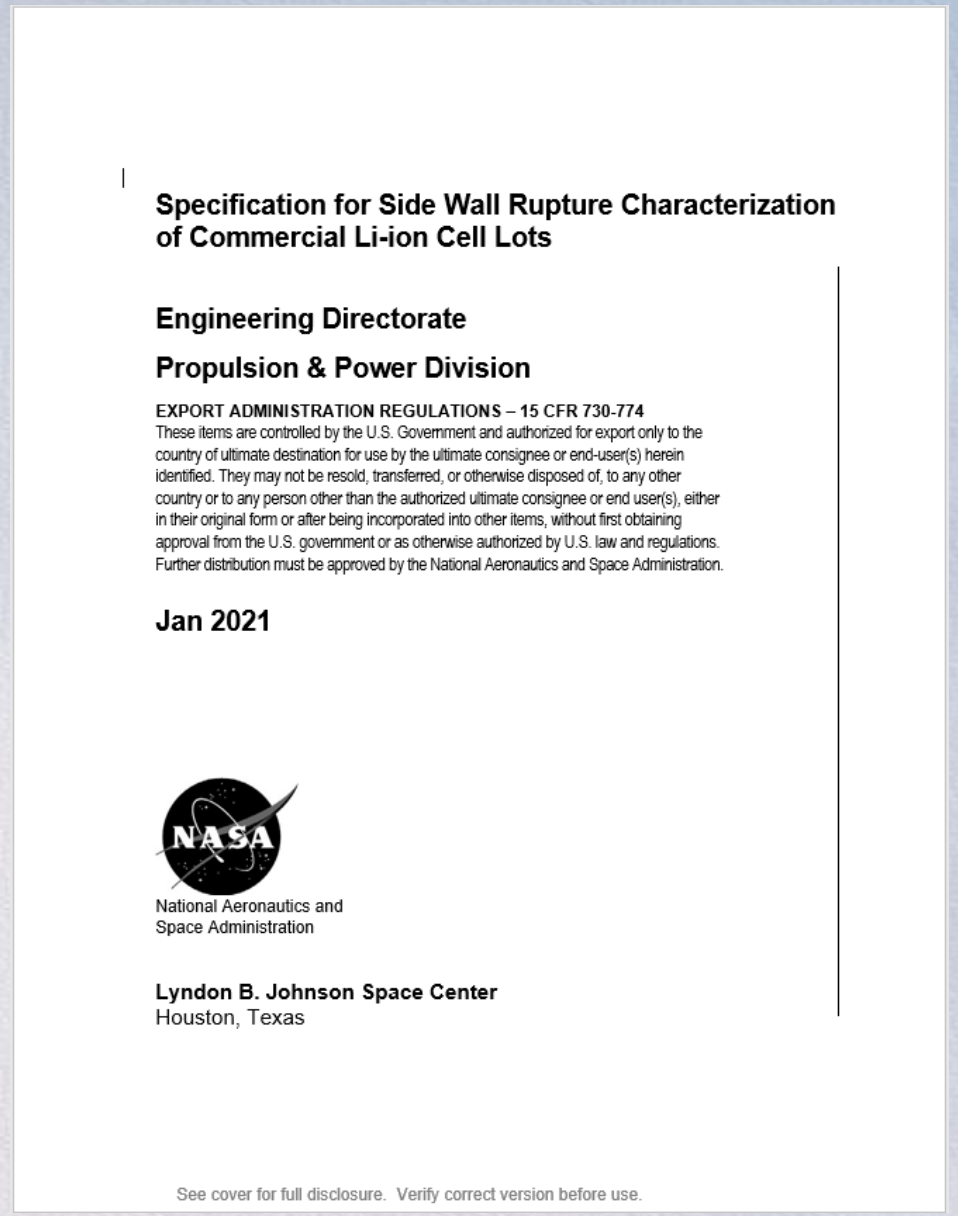






Work Instruction about to be submitted for Signatures

- EP-WI-038
- To be performed as part of Initial Lot Assessment after receipt of a cell lot
  - EP-WI-036
- Characterization of SWR risk while in battery relevant conditions
  - Must be repeated for each battery design



Specification for Side Wall Rupture Characterization of Commercial Li-ion Cell Lots

Engineering Directorate

Propulsion & Power Division

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Jan 2021

National Aeronautics and Space Administration

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Take Home Message

- Characterizing SWR with the cells unsupported can be misleading
  - Unsupported cell tests indicate low propensity
  - Real propensity to SWR is not entirely dependent on the cell design features
  - Battery constraining features on its cells have a big impact
- Accurately determining a cell design's predisposition to side wall rupture or spin groove rupture requires
  - Testing cells in battery relevant structural conditions
  - Driving sufficient cells to be statistically defendable
    - ~270 cells for 90% confidence interval