Cell Strategic Reserve – Lessons Learned

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❖ Thank you for providing the CT scan support and expertise

Outline

- JSC Cell Strategic Reserve (CSR)
  - Cell Designs in the Reserve
  - Screening Process
  - Lifecycle Quality
- Shortcomings of Visual Screening Methods
  - Example: Leaking Electrolyte on Passing Visual Inspection Cell
  - Forward Work
- Capacity vs Voltage Balance in Cell Screening

NASA’s Cell Strategic Reserve

- What is it?
    - A reserve of Li-Ion cells screened via NASA standards
    - Several cell designs are kept in stock with various key performance advantages (ex: High Energy vs High Power)
        - Molicel M35A
        - Molicel P28B
        - Samsung 30Q
        - LG M36

High Energy Cell Designs

<u>LG INR18650 M36</u>

- Previous heritage
- <u>**Superior resistance to side wall rupture**</u>
- At C/10 and room temperature
  - 270 Wh/kg, 710 Wh/L
  - ACR is 23.9 mohms
  - DCR is 29.8 mohms
- 70k lot (Nov 2020) delivered in Apr to JSC

<u>Molicel INR18650-M35A</u>

- Little previous heritage
- Same manufacturer of ICR18650J, primary power for > 25 EVAs
- <u>**Superior extreme cold performance**</u>
  - <u>**214 Wh/kg at C/20 and -20°C**</u>
- At C/10 and room temperature
  - 277 Wh/kg, 725 Wh/L
  - ACR is 24.4 mohms
  - DCR is 32.5 mohms
- 120k lot (Feb 2021) delivered in Apr to JSC

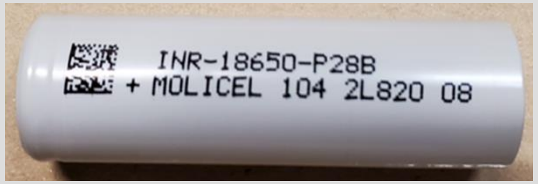
High Power Cell Designs

Samsung INR18650-30Q

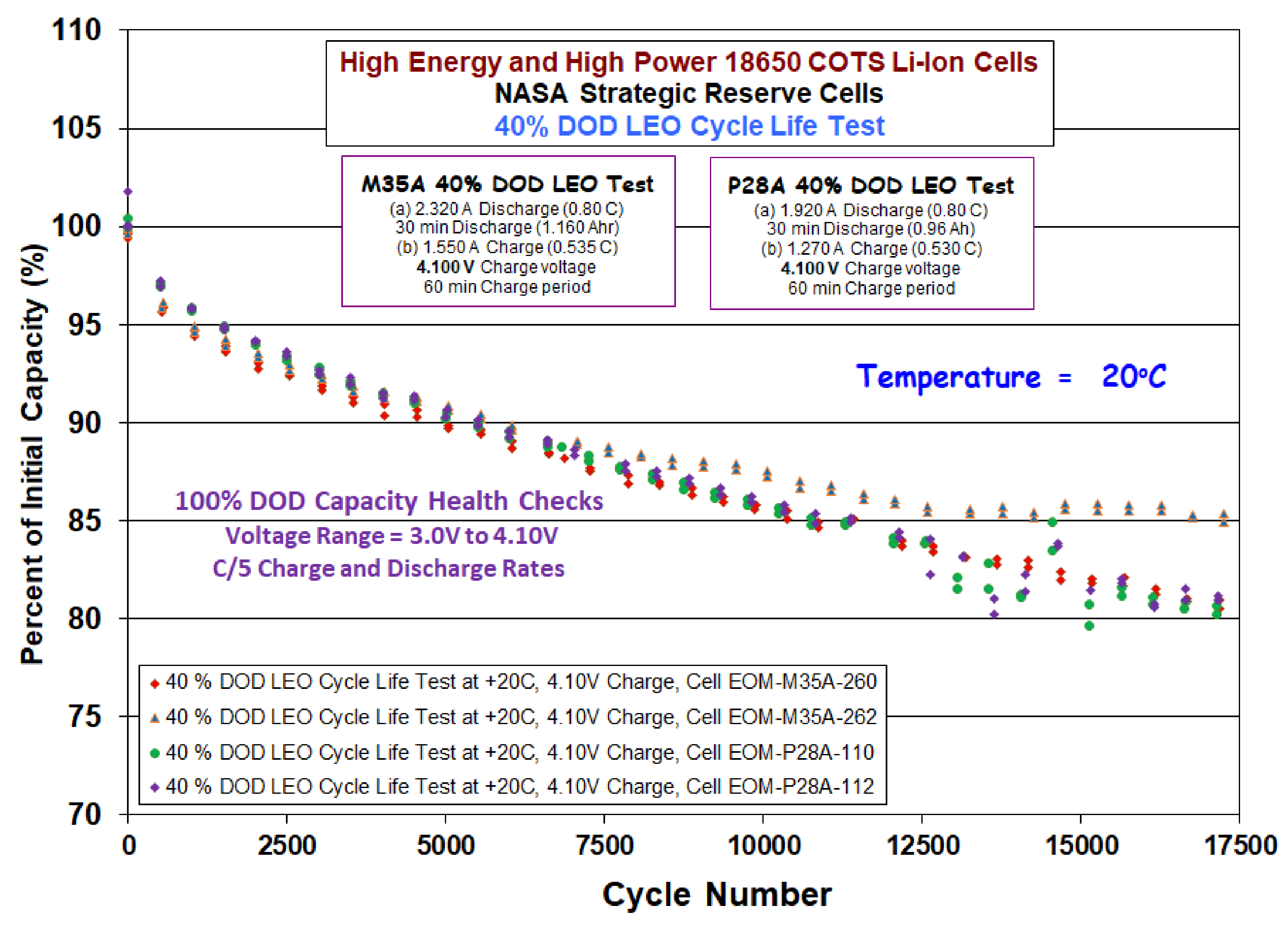
- Previous heritage
  - X-57 Electric Airplane
  - Safe high power battery demo
- At 3C and room temperature
  - 2483 W/kg, 206.9 Wh/kg
  - 6340 W/L, 528.1 Wh/L
  - 12.4 mohm ACR
  - 26.2 mohm DCR
- 60k lot (Mar 2021) delivered in June to JSC

Molicel INR18650-P28B

- No previous heritage
- Not mass produced due to 2nd cathode tab
- At 3C and room temperature
  - 2528 W/kg, 202.3 Wh/kg
  - 6376 W/L, 510.3 Wh/L
  - 9.2 mohm ACR
  - 22.3 mohm DCR
  - 5.5% waste heat – Smallest of the 4 cell types
- 60k lot (Aug 2021) delivered in Oct to JSC



Lifecycle Quality of Cells



Over 17500 cycles (3 years) to 80% Capacity Retention for Moli M35A and P28B cell designs at 40% Depth of Discharge Low Earth Orbit cycling conditions at 20°C.

Source: *"JPL Testing of COTS Li-ion Cells - NASA Strategic Reserve (10-06-2025) Rev. B"*

Calendar Life Testing

Moli P28B Cell Design

Table : Molicel INR18650-P28B Recovered Capacity and Re Results (12 mo. cycle interval)
3 cell average results as compared to 0 day baseline cycle

Capacity (avg % of baseline capacity)

SOC %	Yrs. of Storage	Temp (deg. C) 10	25	35
0	1	99.6%	99.5%	99.2%
	2	99.4%	99.3%	98.6%
	3	99.1%	98.8%	98.0%
	4			
	5			
30 (3.6V chg)	1	98.9%	98.4%	97.5%
	2	98.4%	97.4%	95.6%
	3	97.7%	96.3%	94.3%
	4			
	5			
60 (3.85V chg)	1	98.5%	97.7%	96.5%
	2	98.0%	96.6%	94.4%
	3	**97.2%**	95.4%	92.7%
	4			
	5			
90 (4.1V chg)	1	96.9%	96.7%	94.7%
	2	96.7%	94.8%	91.8%
	3	95.8%	92.9%	88.4%
	4			
	5			
100 (4.2V chg)	1	97.8%	96.6%	95.3%
	2	97.0%	95.5%	92.4%
	3	96.2%	93.5%	88.7%
	4			
	5			

Re (avg % increase from baseline Re)

SOC %	Yrs. of Storage	Temp (deg. C) 10	25	35
0	1	1.9%	3.0%	1.3%
	2	1.9%	0.3%	1.5%
	3	2.6%	0.7%	2.5%
	4			
	5			
30 (3.6V chg)	1	1.3%	1.7%	2.8%
	2	0.4%	-2.0%	4.0%
	3	1.3%	0.9%	4.5%
	4			
	5			
60 (3.85V chg)	1	3.1%	1.0%	6.4%
	2	0.4%	1.0%	9.3%
	3	**3.0%**	3.0%	14.6%
	4			
	5			
90 (4.1V chg)	1	3.0%	-1.5%	8.4%
	2	1.0%	5.2%	29.7%
	3	1.5%	16.5%	55.4%
	4			
	5			
100 (4.2V chg)	1	-1.0%	0.3%	11.8%
	2	0.2%	6.3%	46.9%
	3	2.9%	22.3%	93.5%
	4			
	5			

Moli M35A Cell Design

Table : Molicel INR18650-M35A Recovered Capacity and Re Results (12 mo. cycle interval)
3 cell average results as compared to 0 day baseline cycle

Capacity (avg % of baseline capacity)

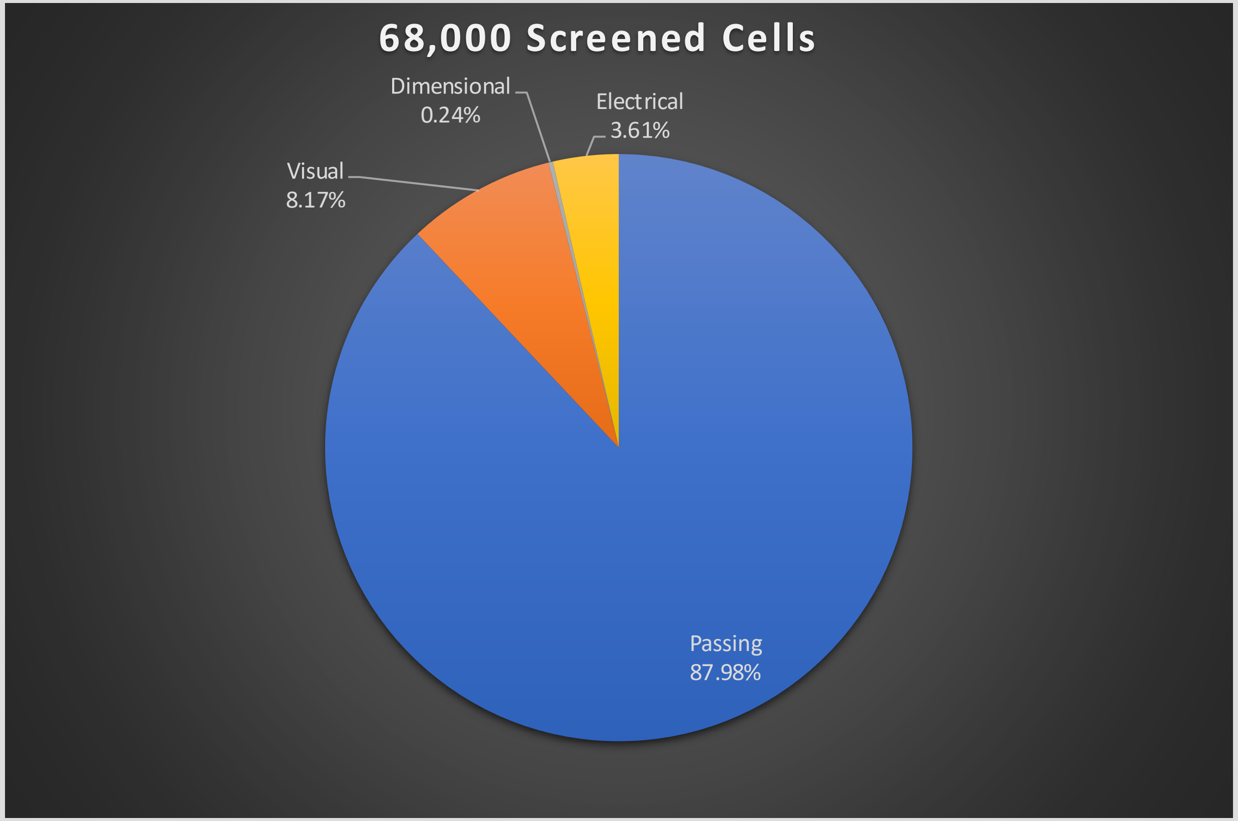
SOC %	Yrs. of Storage	Temp (deg. C) 10	25	35
0	1	100.2%	100.0%	100.0%
	2	100.0%	99.8%	99.5%
	3	99.9%	99.5%	99.1%
	4	99.7%	99.1%	98.8%
	5			
30 (3.6V chg)	1	99.2%	98.8%	98.2%
	2	98.7%	98.1%	97.0%
	3	98.3%	97.5%	96.2%
	4	97.9%	96.9%	95.4%
	5			
60 (3.85V chg)	1	98.4%	97.2%	96.4%
	2	97.7%	96.4%	95.1%
	3	97.2%	95.7%	94.1%
	4	96.9%	95.1%	93.0%
	5			
90 (4.1V chg)	1	97.0%	96.1%	95.5%
	2	95.9%	94.7%	93.6%
	3	95.2%	93.7%	92.1%
	4	94.8%	92.8%	90.4%
	5			
100 (4.2V chg)	1	97.5%	96.6%	95.7%
	2	96.5%	95.4%	93.9%
	3	95.9%	94.5%	92.2%
	4	95.4%	93.5%	90.5%
	5			

Re (avg % increase from baseline Re)

SOC %	Yrs. of Storage	Temp (deg. C) 10	25	35
0	1	-0.1%	-0.4%	-0.7%
	2	-0.1%	-1.6%	-0.1%
	3	-0.1%	-1.1%	-0.1%
	4	0.5%	-0.2%	-0.2%
	5			
30 (3.6V chg)	1	0.2%	0.5%	1.4%
	2	-0.4%	-0.1%	1.0%
	3	-1.5%	-0.3%	0.7%
	4	-0.1%	0.2%	1.2%
	5			
60 (3.85V chg)	1	0.1%	1.1%	1.7%
	2	0.0%	0.4%	1.5%
	3	0.2%	0.2%	2.6%
	4	0.5%	1.6%	4.6%
	5			
90 (4.1V chg)	1	-0.8%	-1.2%	1.0%
	2	-2.5%	-0.4%	4.0%
	3	-1.9%	1.1%	7.3%
	4	-1.3%	3.2%	13.0%
	5			
100 (4.2V chg)	1	-1.3%	-0.7%	4.0%
	2	-1.5%	1.6%	10.2%
	3	-1.5%	5.7%	16.8%
	4	-0.4%	9.6%	22.5%
	5			

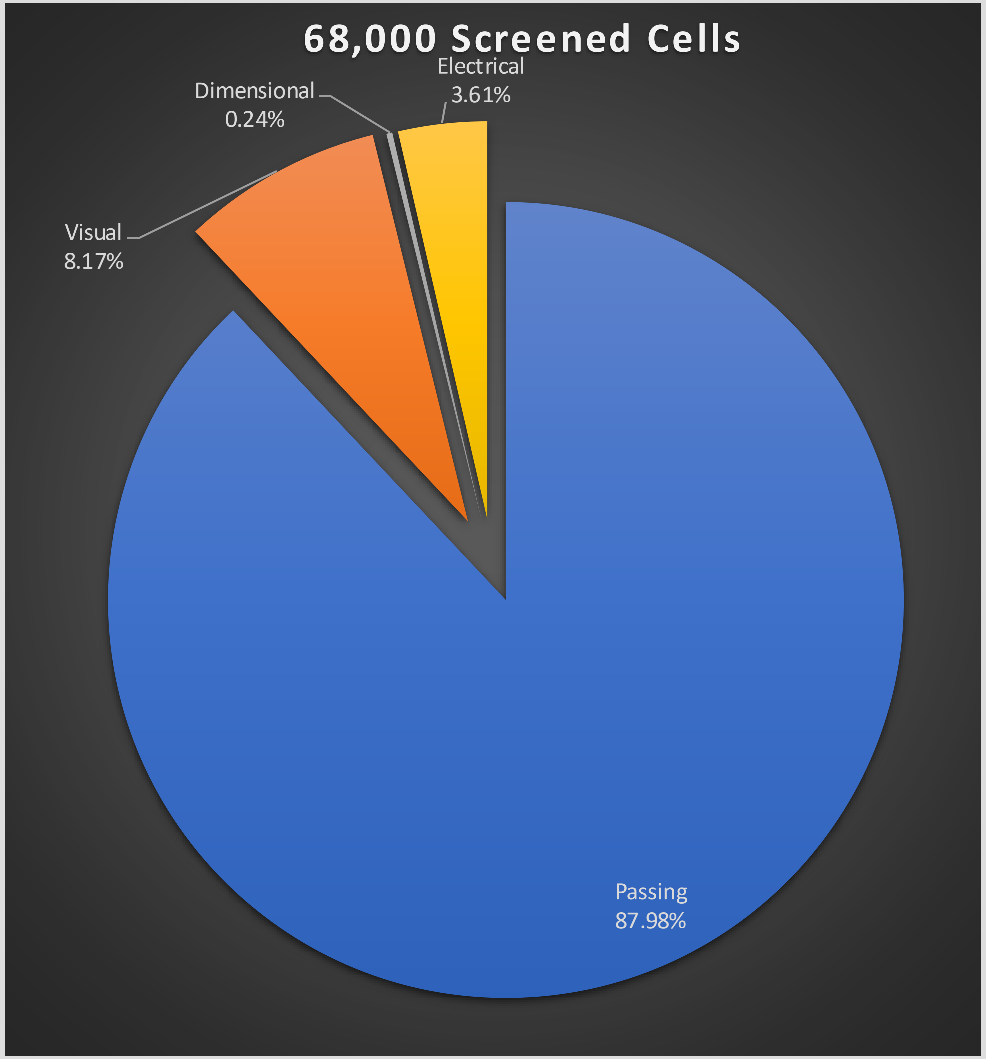
Calendar life degradation is < 1% per year at 30% SoC and room temperature and internal resistance is unchanged

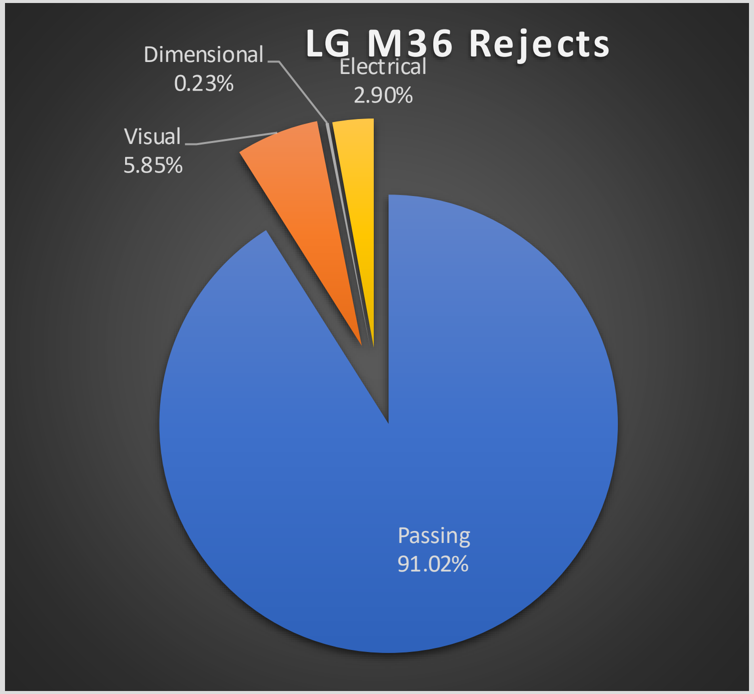
Overall Stats on 68,000 Screened 18650 Cells

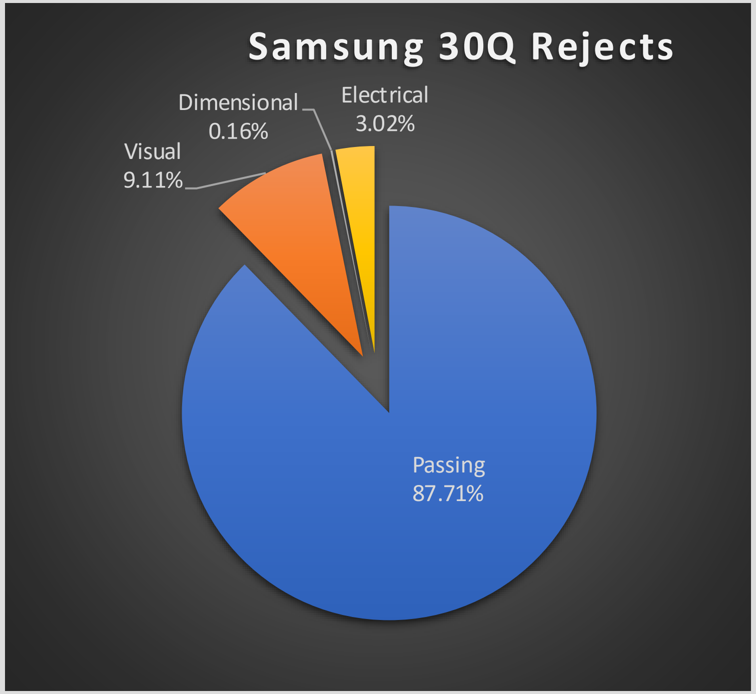


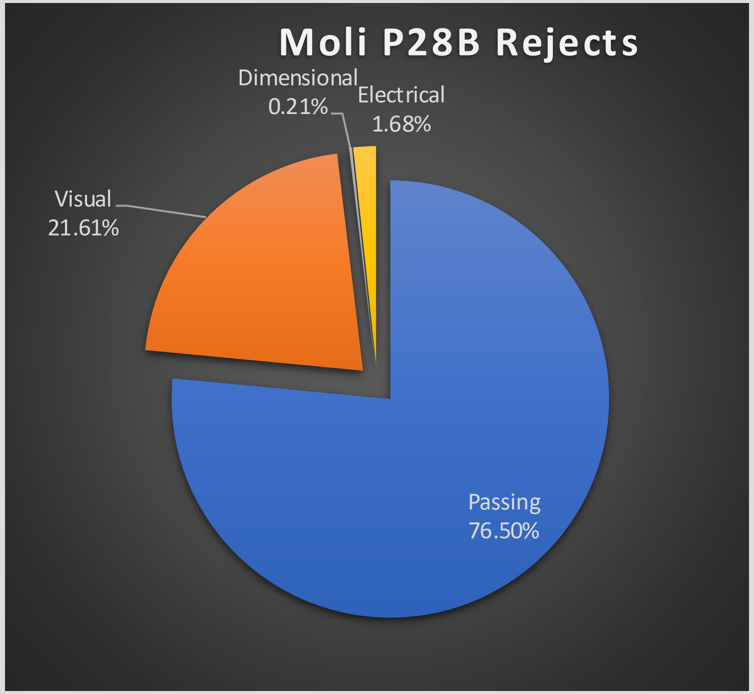
- Visual Inspection (8.17%)
  - Scratches
  - Corrosion
  - Dents
  - Cuts
  - Discoloration on weld surfaces
- Electrical (3.61%)
  - Majority due to outlying OCV
- Dimensional/Mass (0.24%)

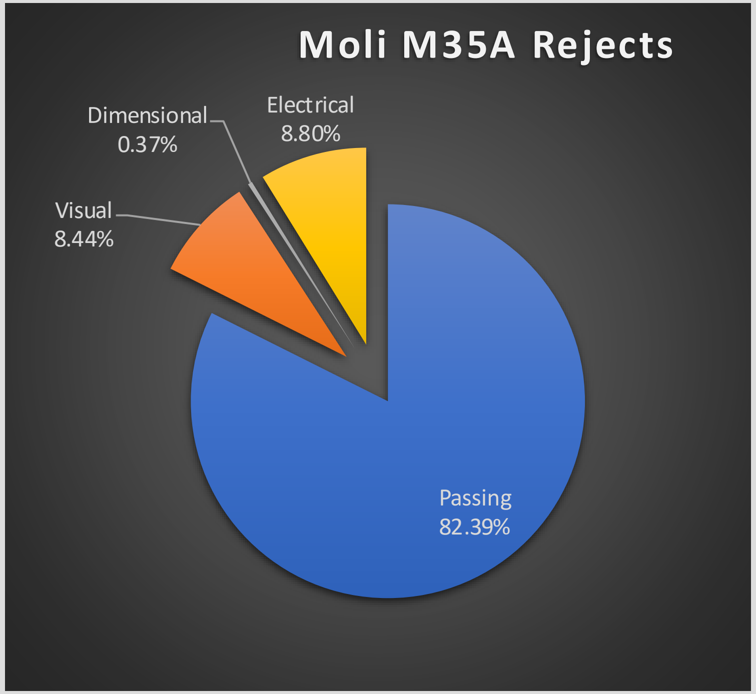
Defects


68,000 Screened Cells
Electrical
3.61%
Dimensional
0.24%
Visual
8.17%
Passing
87.98%


LG M36 Rejects
Dimensional
0.23%
Electrical
2.90%
Visual
5.85%
Passing
91.02%


Samsung 30Q Rejects
Dimensional
0.16%
Electrical
3.02%
Visual
9.11%
Passing
87.71%


Moli P28B Rejects
Dimensional
0.21%
Electrical
1.68%
Visual
21.61%
Passing
76.50%


Moli M35A Rejects
Dimensional
0.37%
Electrical
8.80%
Visual
8.44%
Passing
82.39%

Current Shortcomings of Visual Screening

1. Throughput capacity for high volume
2. Subjectivity of analysis

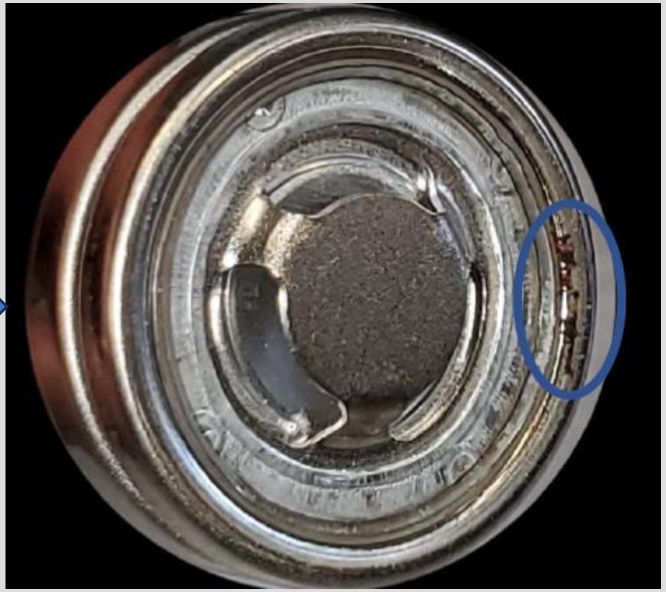
Example – Leaking P28B

Screening for Leaks

EP-WI-037B

3.7 Visual Inspection

Perform visual inspection of each cell to look for defects (with no more than 10x magnification) such as corrosion, discoloration, evidence of leakage, anomalous seal ring condition (see Figures 2-4), bulging, and physical surface damage (dings, cuts, dents, previous welds, and scratches). Objective is to identify outliers with external defects and assess the visual quality of the cell lot. If inspection shows unusual or prevalent defect(s), documentation of defect in detail and/or picture should be taken and provided to customer to confirm that defect is rejectable. This screen is required.

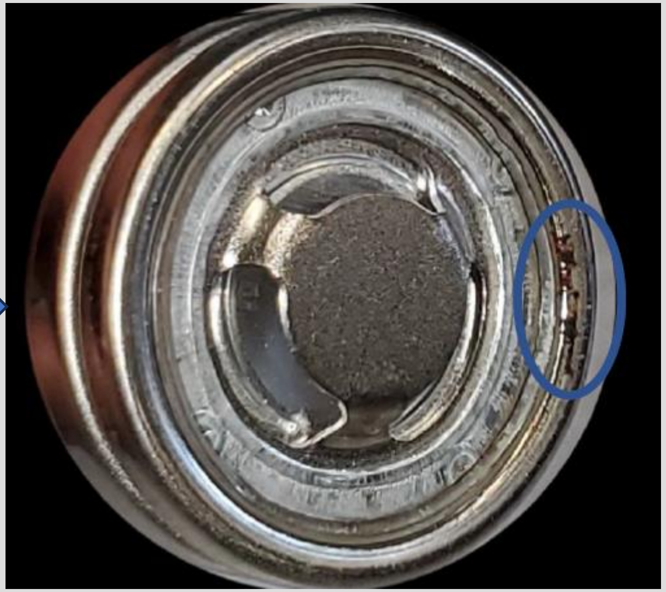


Screening for Leaks

EP-WI-037B

3.7 Visual Inspection

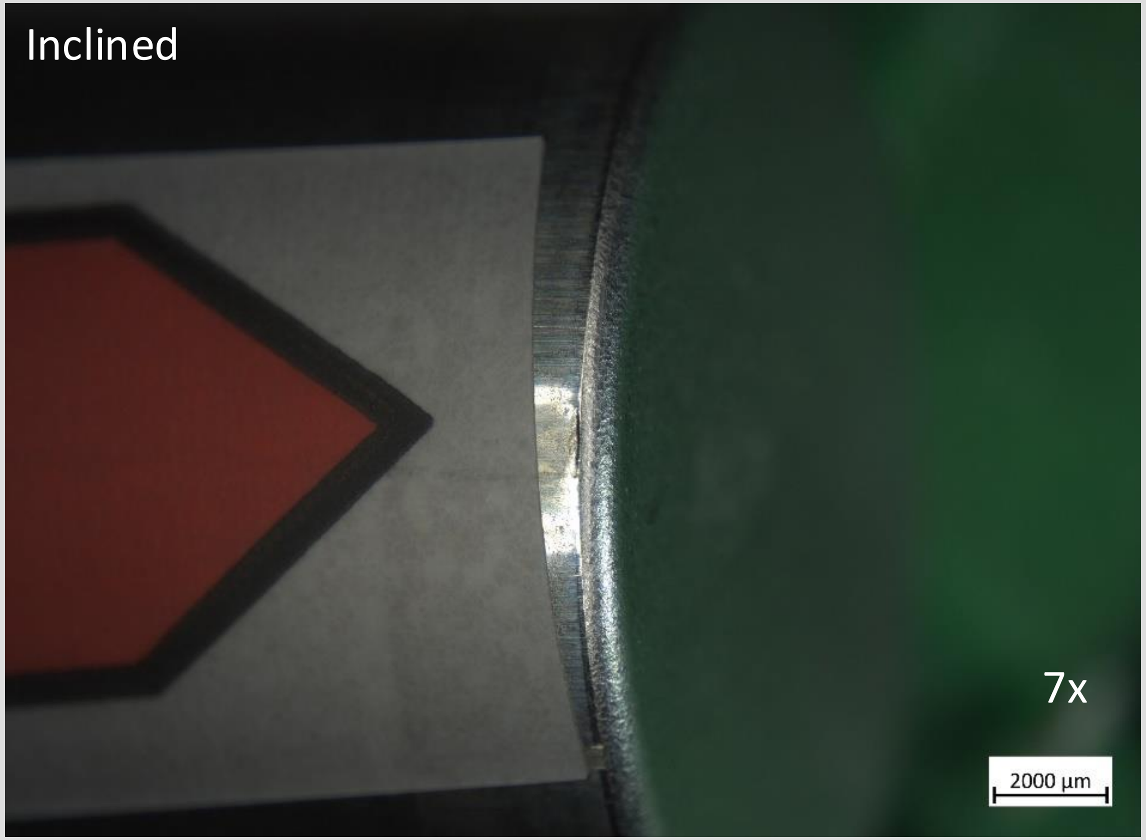
Perform visual inspection of each cell to look for defects (with no more than 10x magnification) such as corrosion, discoloration, evidence of leakage, anomalous seal ring condition (see Figures 2-4), bulging, and physical surface damage (dings, cuts, dents, previous welds, and scratches). Objective is to identify outliers with external defects and assess the visual quality of the cell lot. If inspection shows unusual or prevalent defect(s), documentation of defect in detail and/or picture should be taken and provided to customer to confirm that defect is rejectable. This screen is required.



Leaking P28B Cell

- Calendar life test cell sample was visually screened
  - Passed all cell screening from Initial Lot Assessment
- Calendar life Testing year 3
  - Lost 15% capacity
  - DCR changed +178%
  - <u>Lost 1.2g, presumed as electrolyte, but without any visual discoloration</u>
- Tried various optical methods to find a hole -> unsuccessful
  - Profilometer
  - Stereomicroscopy
  - CT scan
  - Dye penetrant analysis

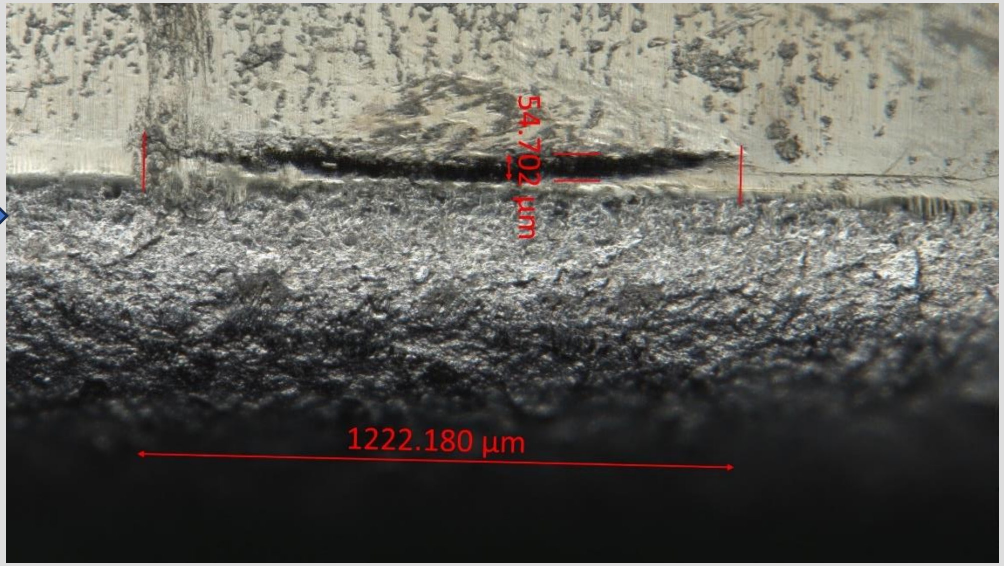
Stereomicroscope Examination



Screening for Leaks

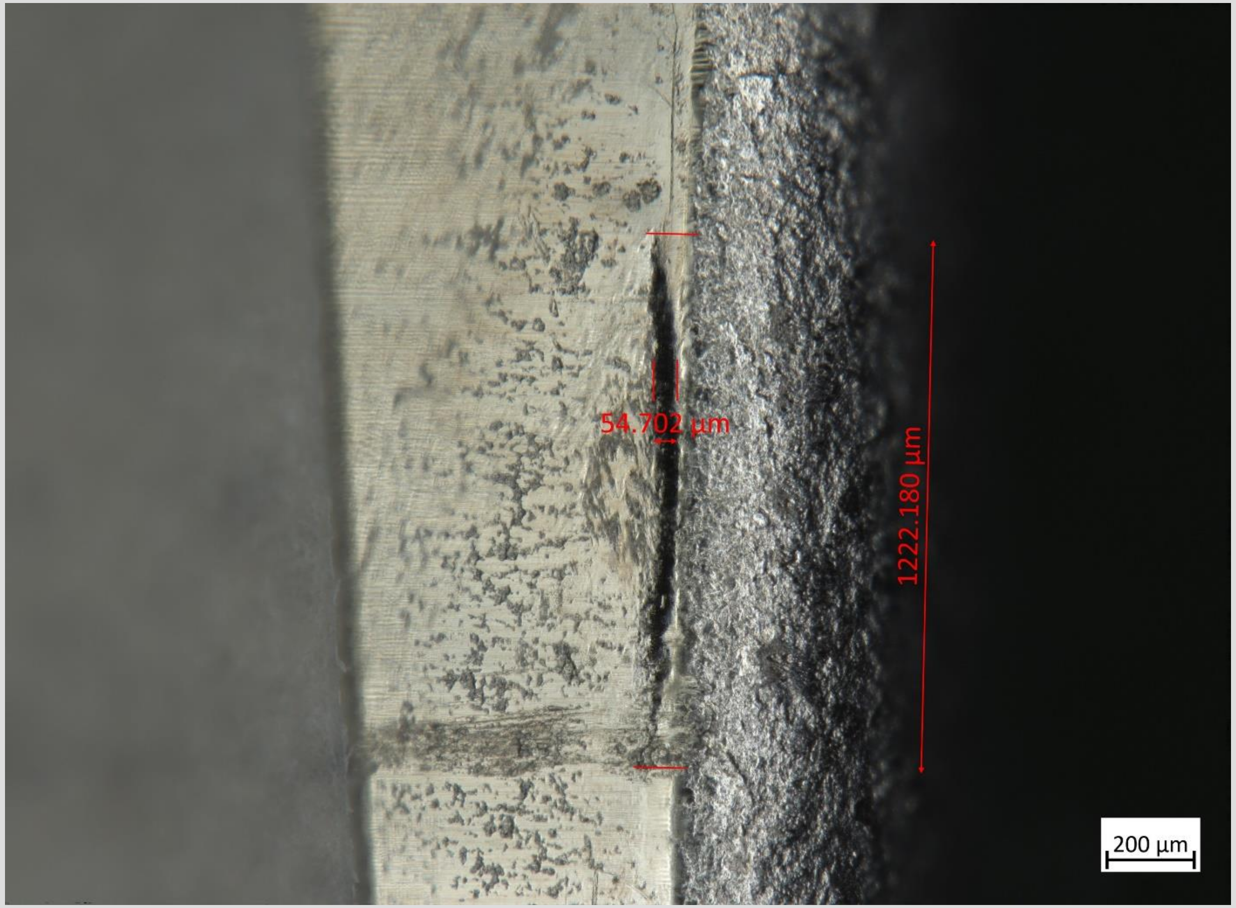
EP-WI-037B

- Electrolyte salts leaves colorful residue
- Crack may have grown in 3rd year upon capacity cycling
  - 54μm crack width at 0% SoC
  - Measured the same at 100% SoC

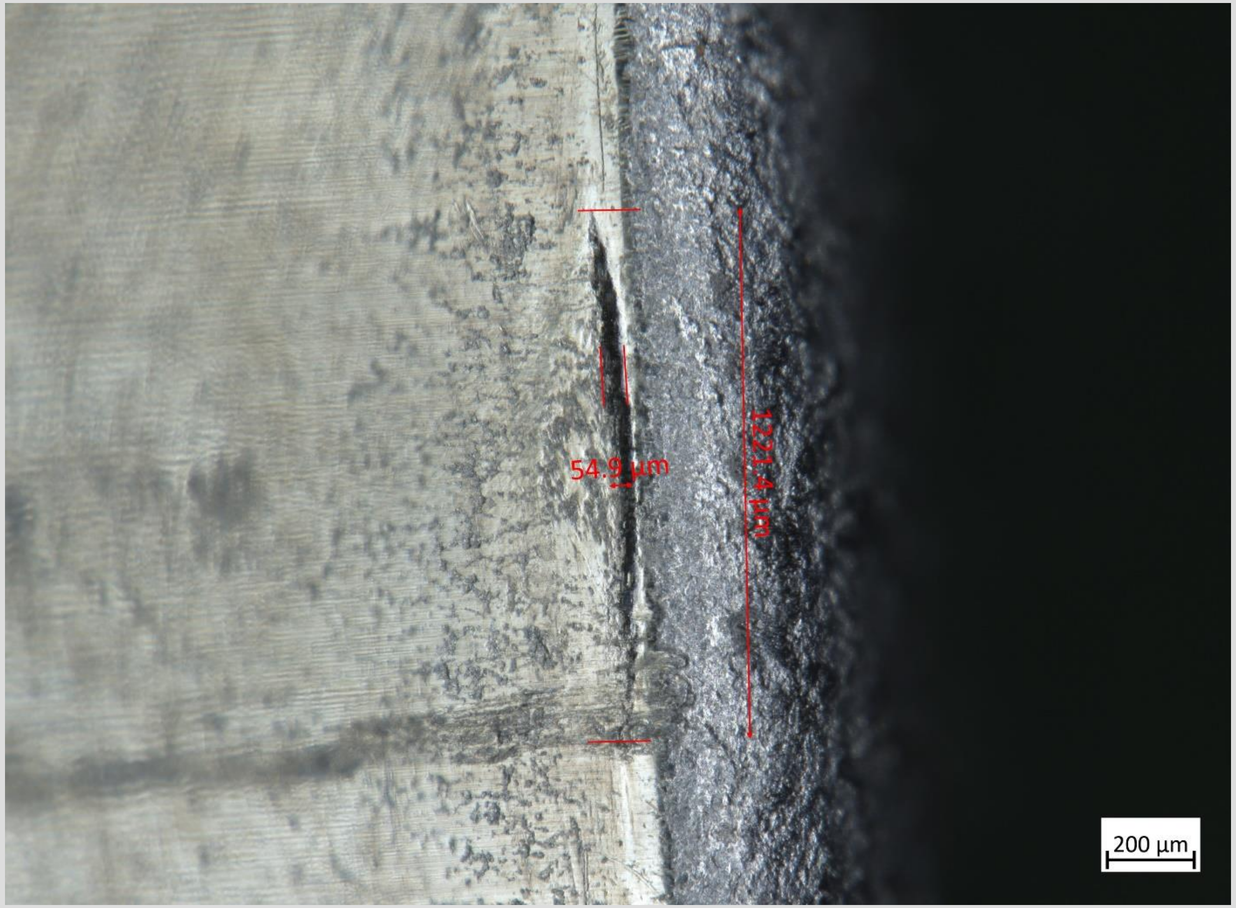


SOC Impact

OCV = 3.101V

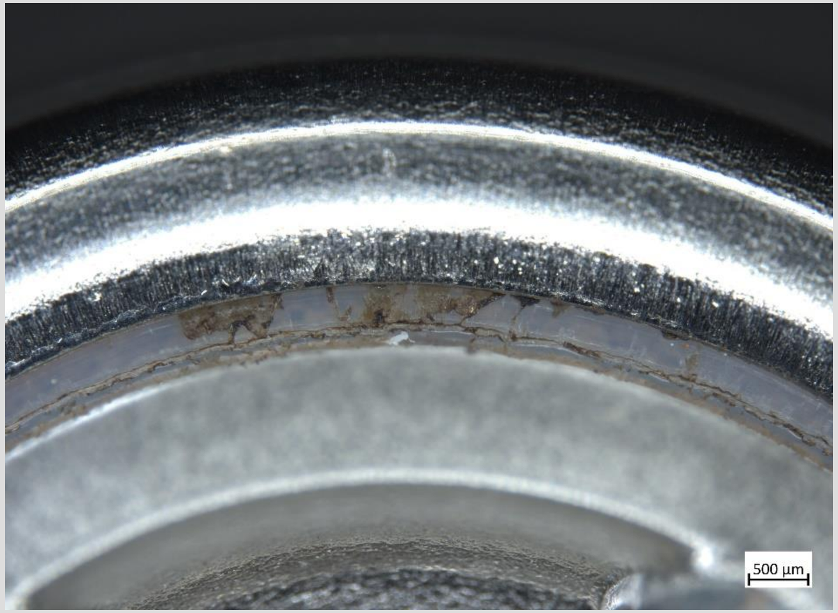


OCV = 4.109V



At 4.11V during 300mA charging, rise of $\Delta T = 9°C$ terminating charge. No odor, no discoloration

Examination of Header



Leaking P28B Cell

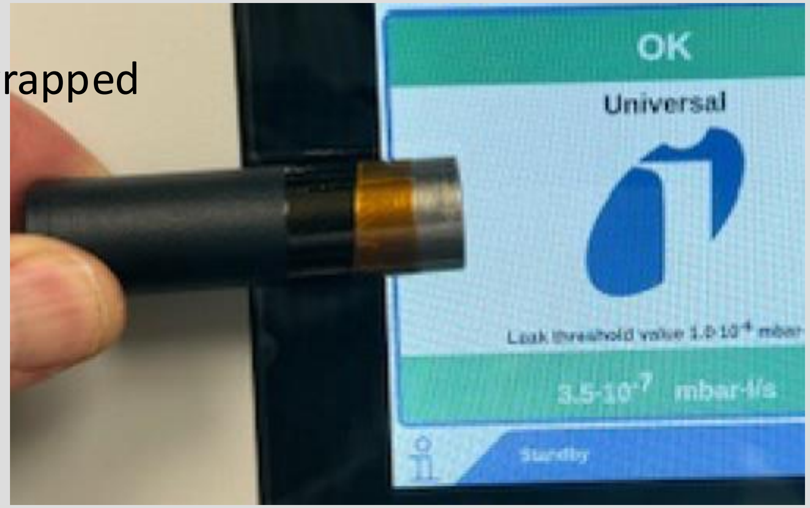
- Leak Rate Instrument
  - Inficon's ELT3000 Plus using quadrupole mass spectroscopy
    - Instrument has a leak threshold of 1.8×10^{-6} mbar*L/s for DMC (Dimethyl Carbonate)
  - Measured Leakage Rates:
    - 7.3×10^{-5} mbar*L/s
    - 1.8×10^{-4} mbar*L/s
  - Capped bottom and top of cell in various configurations, isolated leak to top of cell

Leaking P28B Cell

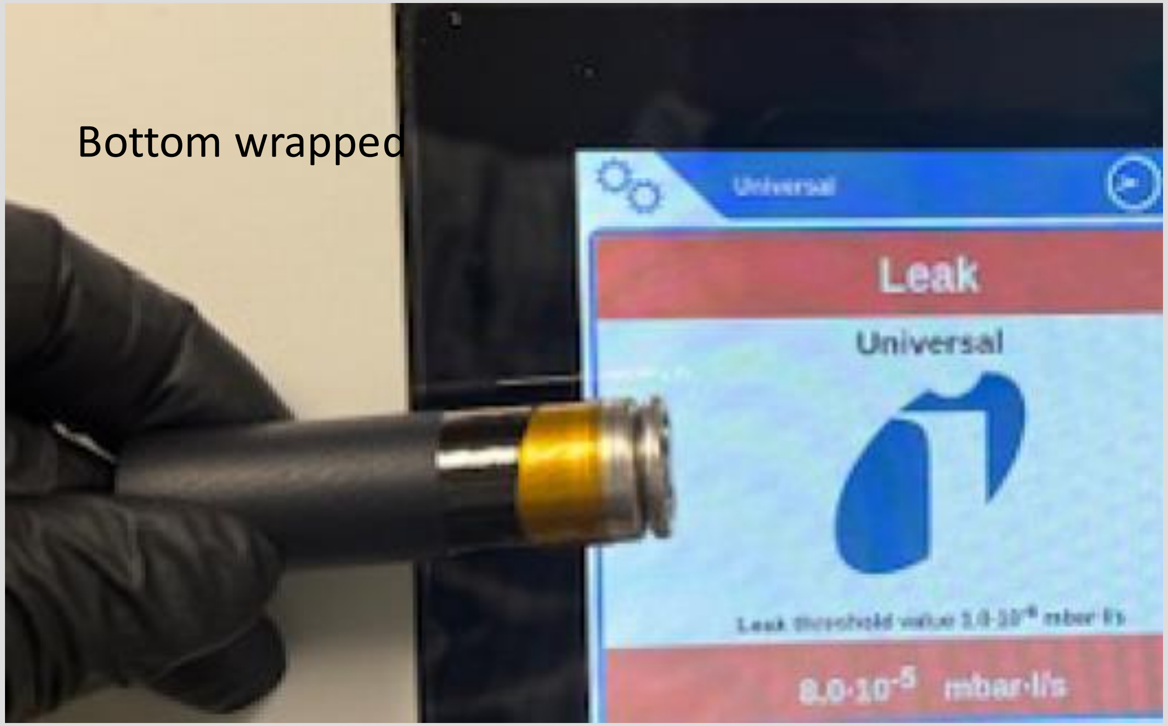
Sealing portions of the cell in latex glove fingers

Fully wrapped

Header wrapped



Bottom wrapped

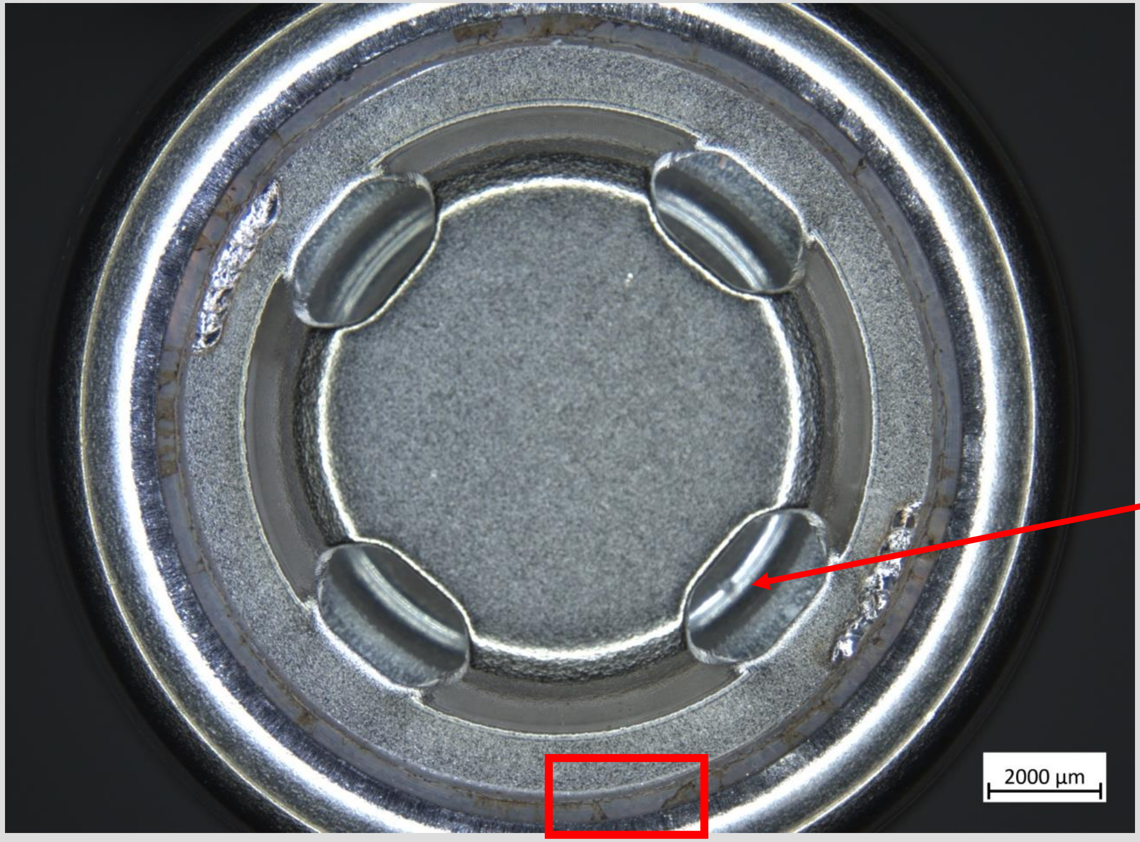


Visual Examination Pre & Post Inficon Scans

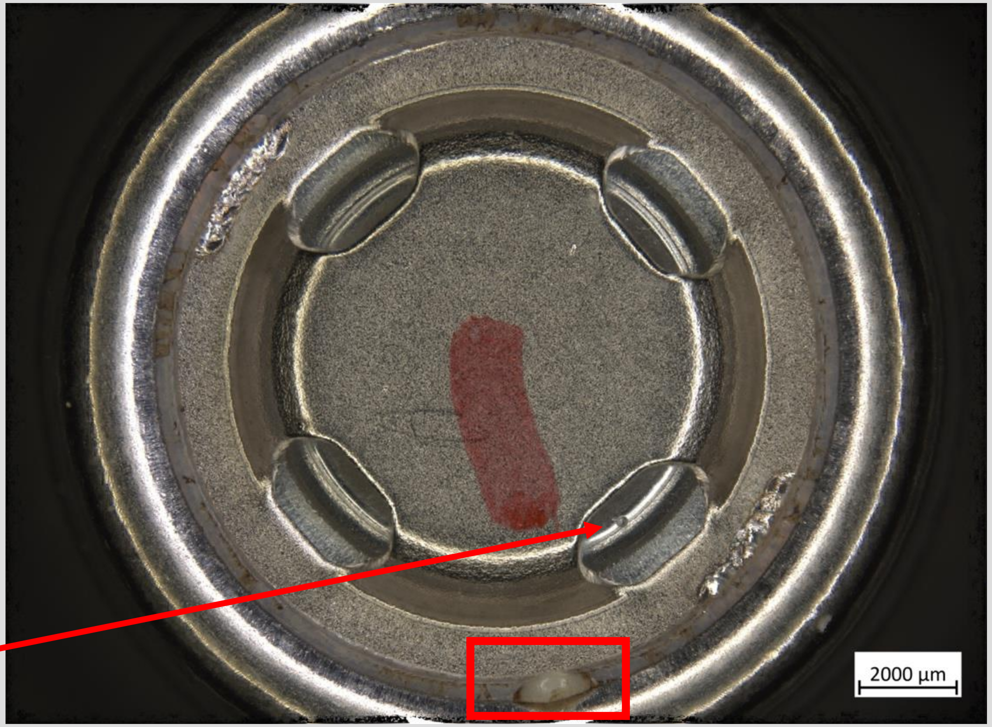
Pre-vacuum exposure from Inficon Test

Post vacuum cycle exposures

Visual Examination Pre & Post Inficon Scans



Pre-vacuum exposure from Inficon Test



Post vacuum cycle exposures

Capacity vs Voltage Balance

Cell Screening -> Pack Preparation

1. Determine cell capacity and DCR uniformity
    - Reject ± 3σ outlying cells
    - Reject lot with insufficient uniformity
        - > 5% for 6σ/μ for capacity
        - > 15% for 6σ/μ for DCR

2. Prepare cells for battery assembly with highest OCV balance at the top of charge

3. Verification of cell balance
    - Assemble screened (passing) cells into 8S battery strings
    - Charge each string fully without any cell balancing
    - Measure OCV balance at 100% SoC

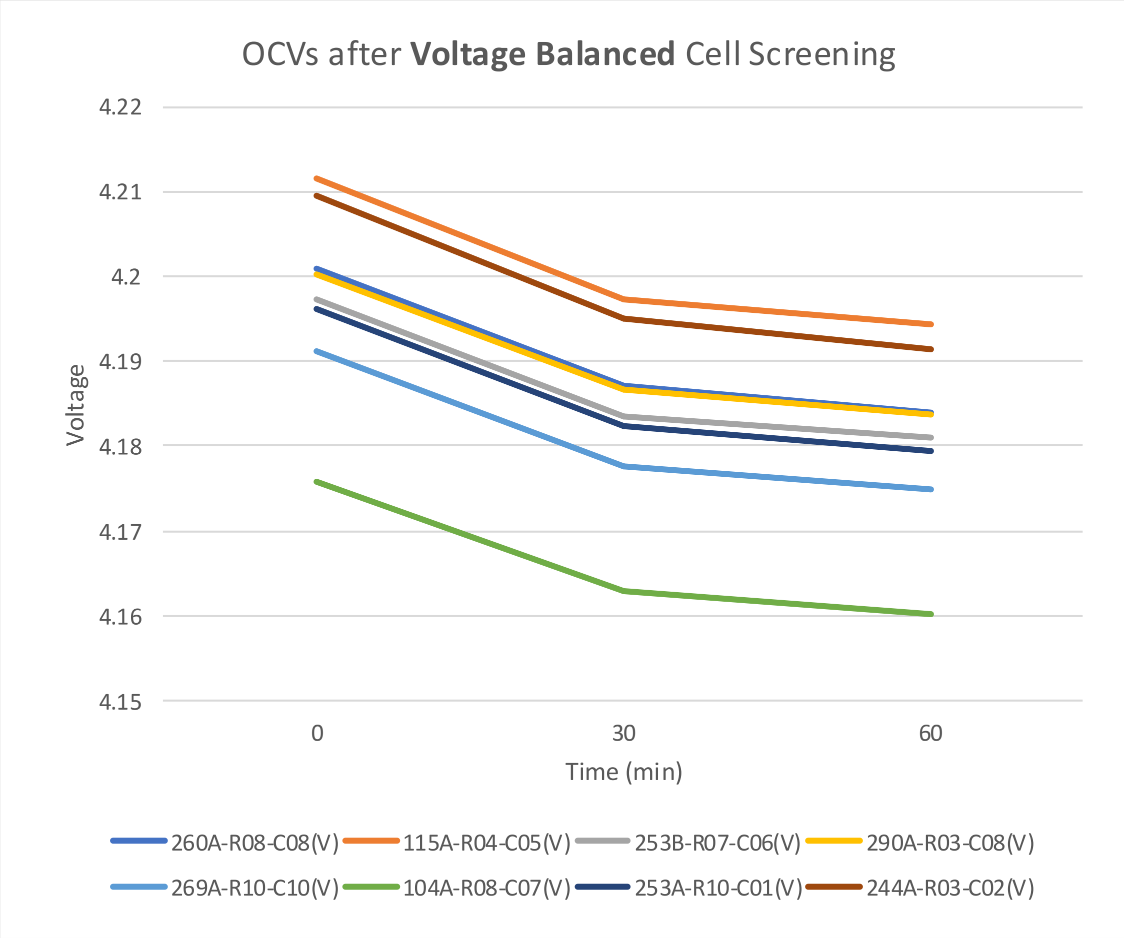
Voltage Balance Determination

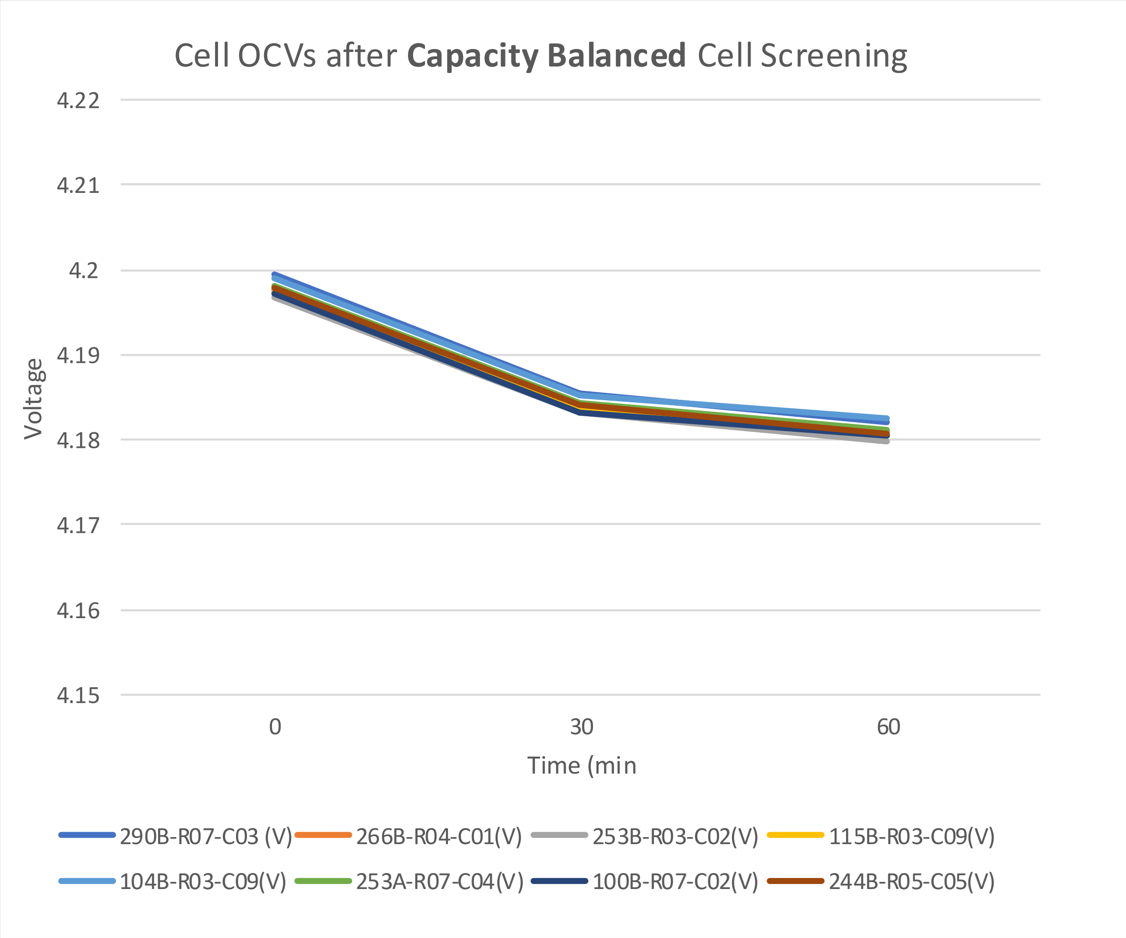
- CC/CV charge to 4.2V and C/50 taper current
- Discharge fully to minimum voltage
  - With DCR pulse at 50% SoC
  - Screen for cell capacity and DCR from this discharge
  - *This leaves the cells in voltage balance but not in capacity balance*
- Partial recharge with 10% capacity input (~10% SoC)
  - Constant current input with Ah termination

Capacity Balance Determination

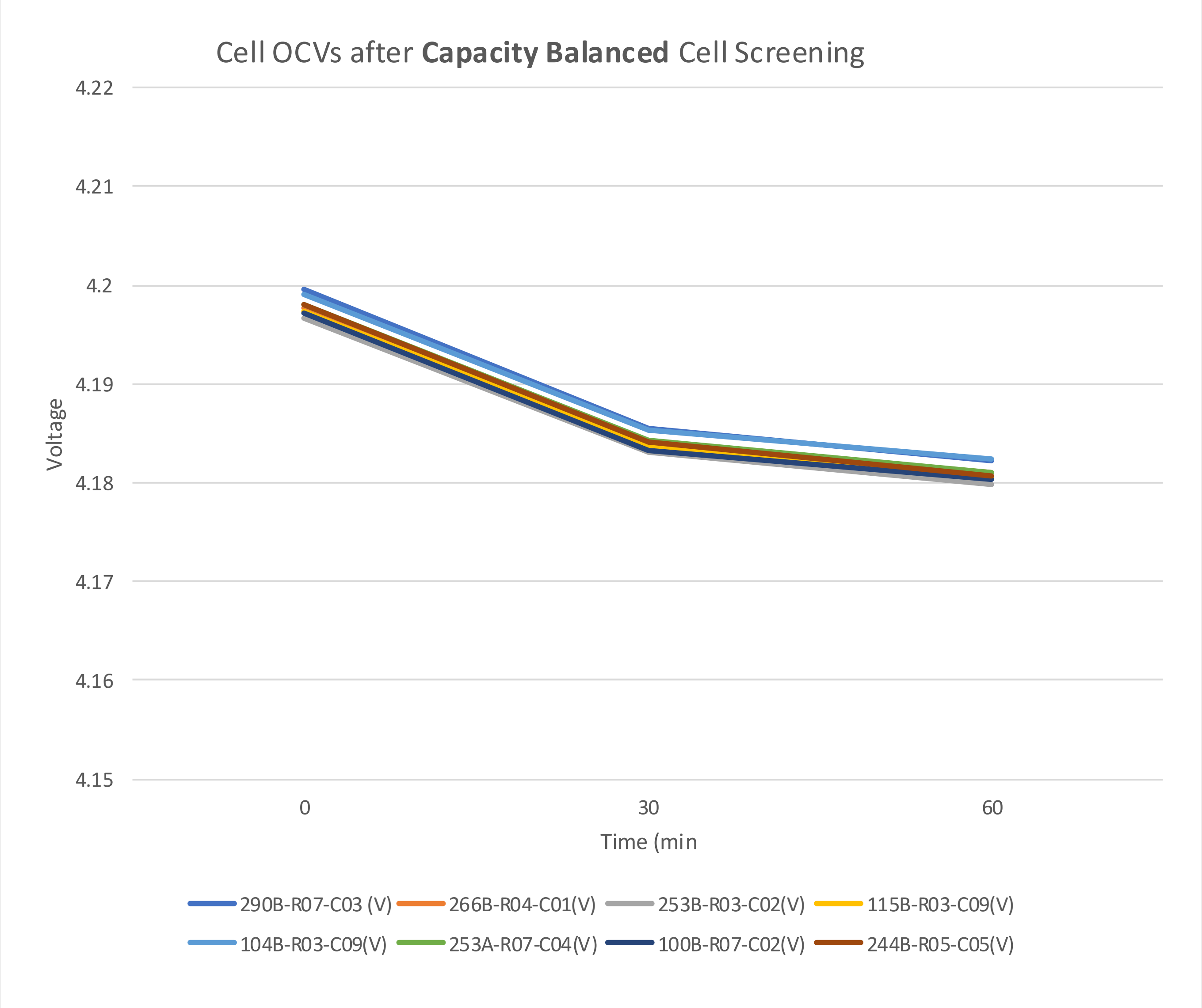
- Discharge to minimum voltage
- Full CC/CV charge to 4.2V and C/50 taper current
  - With DCR pulse at 50% SoC
  - Screen for cell capacity from the charge cycle
  - Cells balanced at the TOP of cell CAPACITY
- Discharge to 10% SoC based on capacity output
  - Remove the same Ah from each cell

Voltage vs Capacity Balance Impact on 8S Battery String at Top of Charge





Voltage vs Capacity Balance Impact on 8S Battery String at Top of Charge



Capacity balancing the SOC of cells during cell screening improves OCV uniformity from 30 to 3 mV in an 8S string.

Lessons Learned

- Capacity balanced is better than voltage balanced screening
  - Cell OCVs at top of charge are in tighter balance in series strings
- Screening cells by visual examination isn't fool proof for leaks
  - Industry standards for leak detection are under developmen
    - Inficon's leak rate instrument using quadrupole mass spectroscopy tuned for DMC solvent in Li-ion electrolyte is a leading method
  - Economic trade – Cost of screening every cell going into a battery using leak detector
  - Impact to our process is to require leak rate measurement for cell samples for
    - Initial Lot Assessment
    - Lot Acceptance Testing
  - Leave it as optional for cell screening based on risk and economics

End

The Importance of Cell Screening

Manufacturer Cell Acceptance Standards

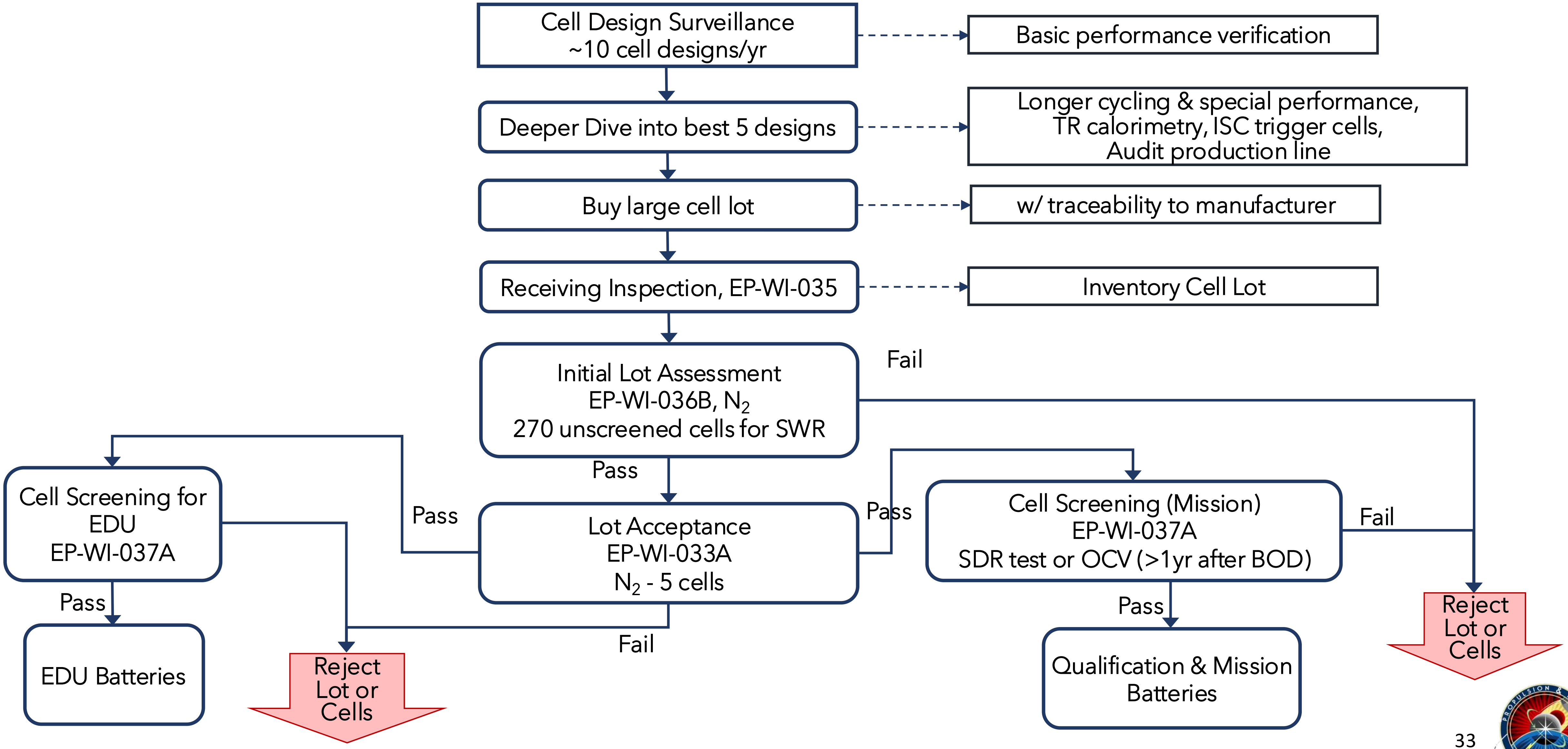
vs

NASA Flight Battery Cell Acceptance Standards

Human Rated Missions

JSC20793

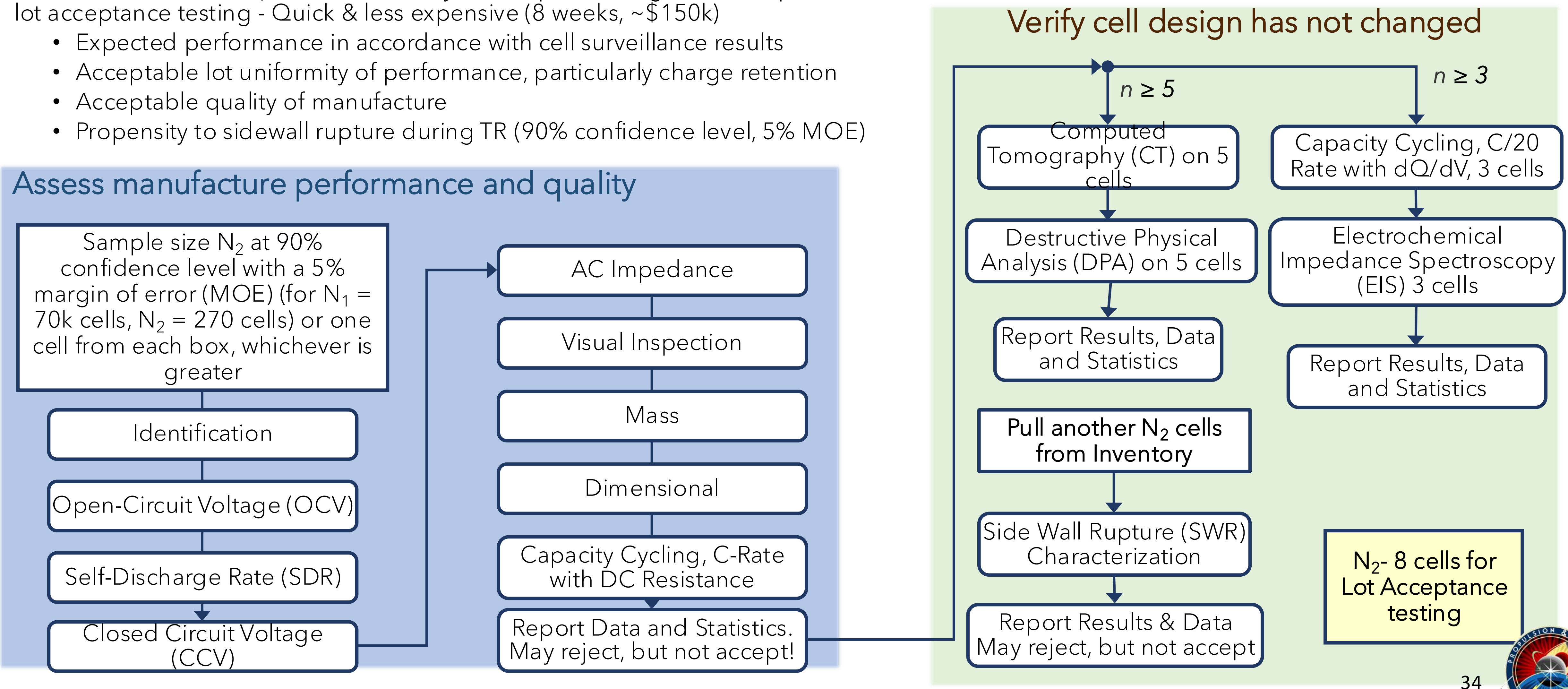
Cell Process Flow Chart



Initial Lot Assessment (ILA)

EP-WI-036 Specification for Initial Lot Assessment of Commercial Lithium-ion Cells Lots

- Determine if cell lot (N_1 lot size) is worthy before proceeding with an expensive lot acceptance testing - Quick & less expensive (8 weeks, ~$150k)
  - Expected performance in accordance with cell surveillance results
  - Acceptable lot uniformity of performance, particularly charge retention
  - Acceptable quality of manufacture
  - Propensity to sidewall rupture during TR (90% confidence level, 5% MOE)



Lot Acceptance Testing