

COTS Li-ion Strategic Reserve Update



By

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NASA Aerospace Battery Workshop
For 2021 Workshop Posting**

Agenda

- Problem & Solution
 - Why do we need to act strategically?
- COTS cell design surveillance
 - What cell designs are most promising?
- Acquisition and receipt of cell lots
 - How best to procure and receive them?
- Initial lot assessment sample test
 - Quickly determine if received lot has merit for proceeding
- Lot acceptance testing (destructive sample)
 - Fully characterize the performance, safety, and quality of the lot
- Flight cell screening
 - Reject all outlying cells such that passing cells are well matched
 - Rapid soft short detection methods
- Sustaining plan
 - How does the reserve become a sustainable operation?

Problem & Solution

- Problem
 - Buying, screening, and certifying numerous COTS cell lots with only enough cells for each individual project is not efficiently utilizing our resources
 - We are unable to buy the best cells with small orders
 - Some of our primes and subcontractors are making costly mistakes/omissions in screening and certifying for manned space applications
- Solution
 - Entice cell manufacturers to sell directly to us for just a few large quantity cell lot orders and get the best quality designs for maximum benefit to our programs
 - Control how they are bought, screened, certified, and stored to prevent future cell level issues, anomalies, failure investigations, and risky battery designs



Selected High Energy Cell Designs

LG INR18650 M36

- Previous heritage
 - 250 μm can wall
 - Safety fully characterized by JSC
 - Multiple variations beam tested in FTRC
 - 3 batches of ISCD trigger cells delivered to JSC
- 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



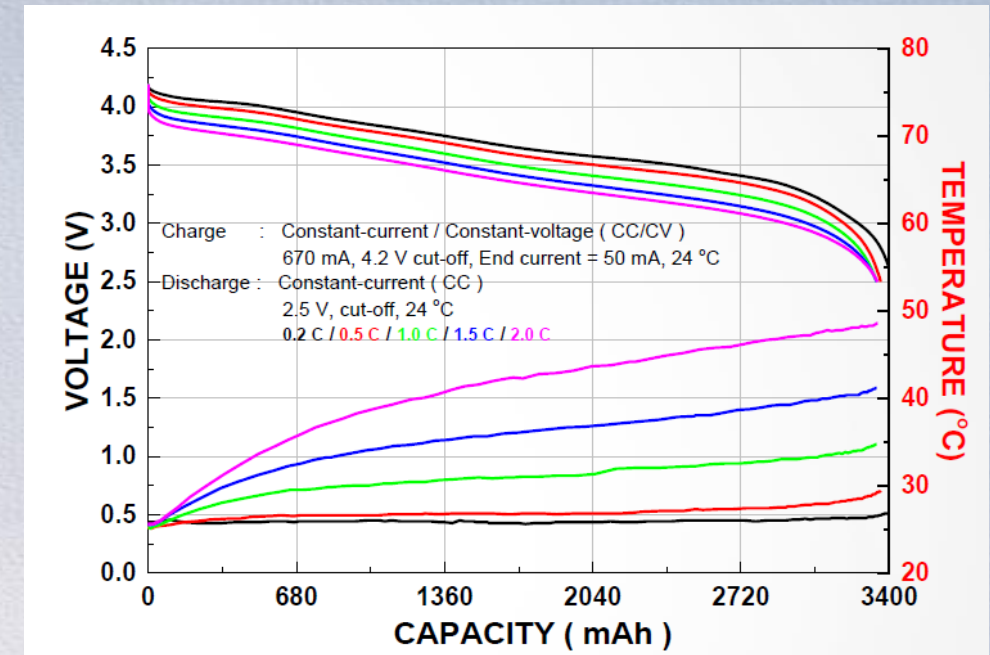
Moli INR18650-M35A

- Little previous heritage
 - Same manufacturer of ICR18650J, primary power for > 25 EVAs
 - Superior extreme cold performance
 - 214 Wh/kg at C/20 and -20°C
 - Multiple batches of ISCD trigger cells delivered to JSC
- 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



First Lot Procured for Strategic Reserve – Delivered in Apr 2021

LG INR18650 M36 rated at 3400 mAh



- Thickest can wall (250 micron), least susceptible to side wall breach (SWB)
- Lowest thermal runaway heat energy release of high capacity cells
- Reliable supply chain with lot traceability
- Availability of trigger cells with internal short circuit device (ISCD) implanted, avoid applying excess energy to battery system with traditional external heating during propagation testing.
- Good energy capacity performance at room temperature vs. other high energy cells that require elevated temperature (>50 °C) to reach rated capacity at high power levels
- No bottom vent

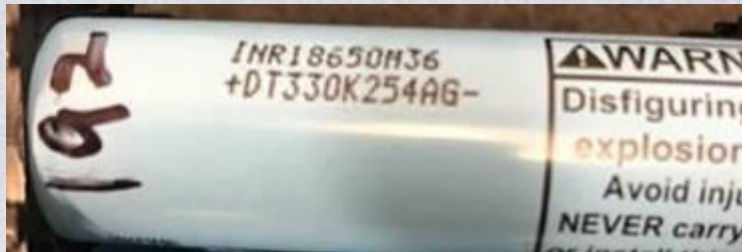
LG INR18650 M36

Qty 19,200



24 Nov 2020 Date Code Translation of T329

Qty 50,800



25 Nov 2020 Date Code Translation of T330

Other Markings:

D: Production Site – Ochang, Korea

K24, K25: Lot numbers

4: Production Line: Ochang Factory #4

A2, AG: serial number

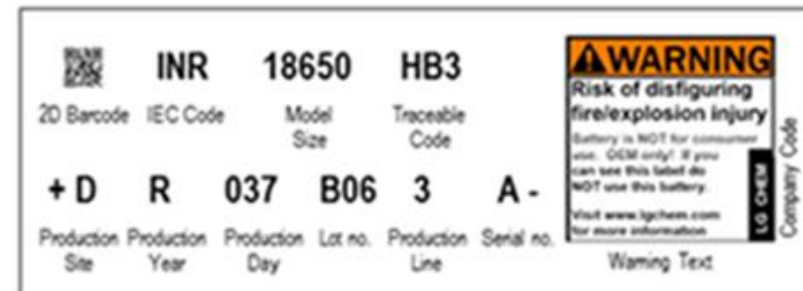
NAVSEA contract with ADS

- Awarded in Aug 2020
- 70,000 cells delivered on 16 Mar 2021 to PCTEST
 - 20k for NAVSEA, 50k for NASA

PCTEST completes Receiving Inspection per EP-WI-035

PCTEST completes sections 3.0 per EP-WI-036A

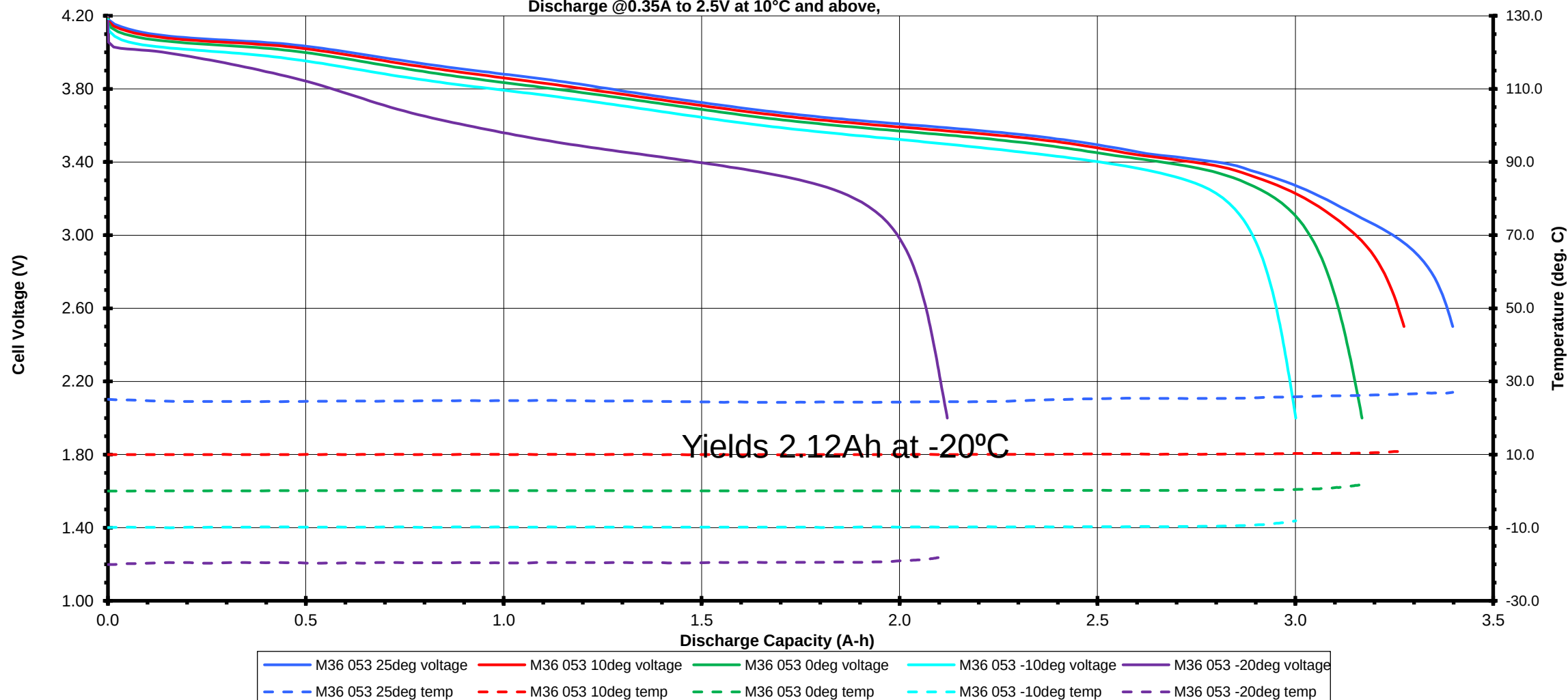
- 350 cell random sample
- Remaining cells shipped and arrived at JSC on 6 Apr 2021



LG M36 Capacity Cycled in 25 to -20°C temp range

LG Chem INR18650 M36 Cell Discharge Temperature Testing
Typical Profiles From 3 Cells Tested; Charge and Discharge at Specified Temp.
Testing at 25, 10, 0, -10, and -20°C; Charge @ 0.35A to 4.20V, 4.20V to 50mA
Discharge @ 0.35A to 2.5V at 10°C and above,

SRI Data



New High Energy Cell Design

MOLICEL®

LITHIUM-ION RECHARGEABLE BATTERY

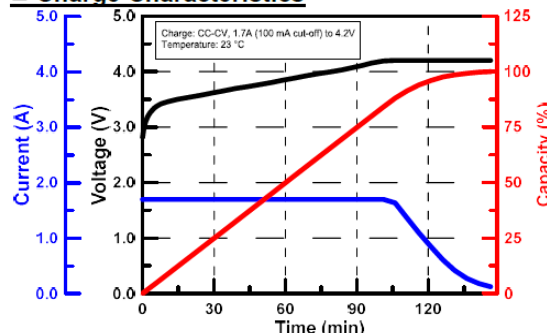
CELL CHARACTERISTICS

Capacity	Typical	3500 mAh
	Minimum	3350 mAh
Cell Voltage	Nominal	3.6 V
	Charge	4.2 V
Continuous Charge Current	Standard	1.7 A
	Maximum	1.7 A
Charge Time	Standard	2.5 hr
Continuous Discharge Current	Standard	1.7 A
	Maximum	10 A
Ambient Temperature	Charge	0°C to 60°C
	Discharge	-40°C to 60°C
Energy Density	Volumetric	700 Wh/l
	Gravimetric	250 Wh/kg

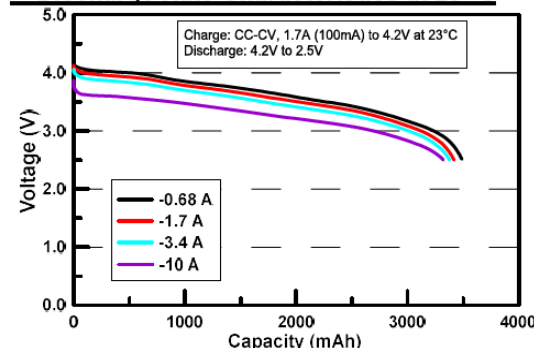
PHYSICAL CHARACTERISTICS

PRODUCT DATA SHEET MODEL INR-18650-M35A

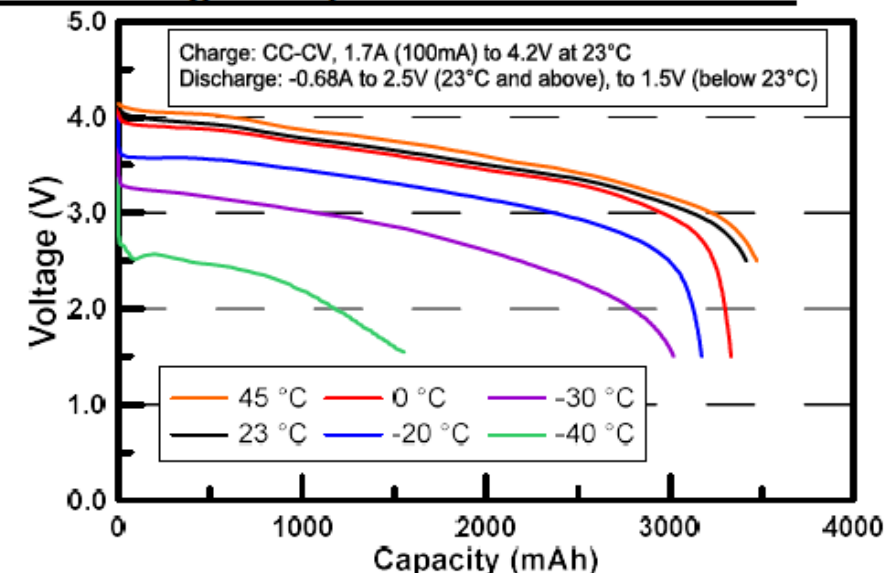
Charge Characteristics



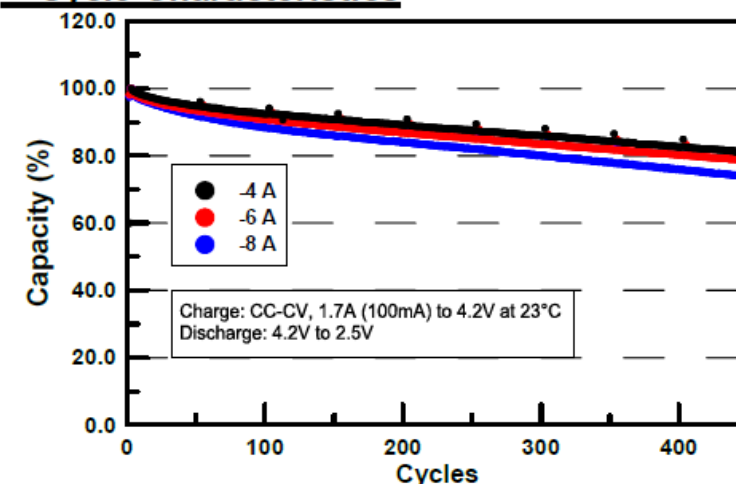
Discharge Rate Characteristics at 23 °C



Discharge Temperature Characteristics



Cycle Characteristics



- In mass production in Taiwan since 2019
- Lot of 120k cells delivered in Apr 2021
- ISC Device trigger cells delivered and more coming

Moli INR-18650-M35A

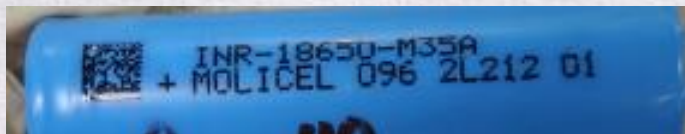
Date code	Total Per Datecode	Total Sample for ILA
L212	45016	229
L213	33171	169
L214	15482	78
L215	25731	124
Total	119,400	600

L212 translates to 12 Feb 2021

L213 translates to 13 Feb 2021

L214 translates to 14 Feb 2021

L215 translates to 15 Feb 2021

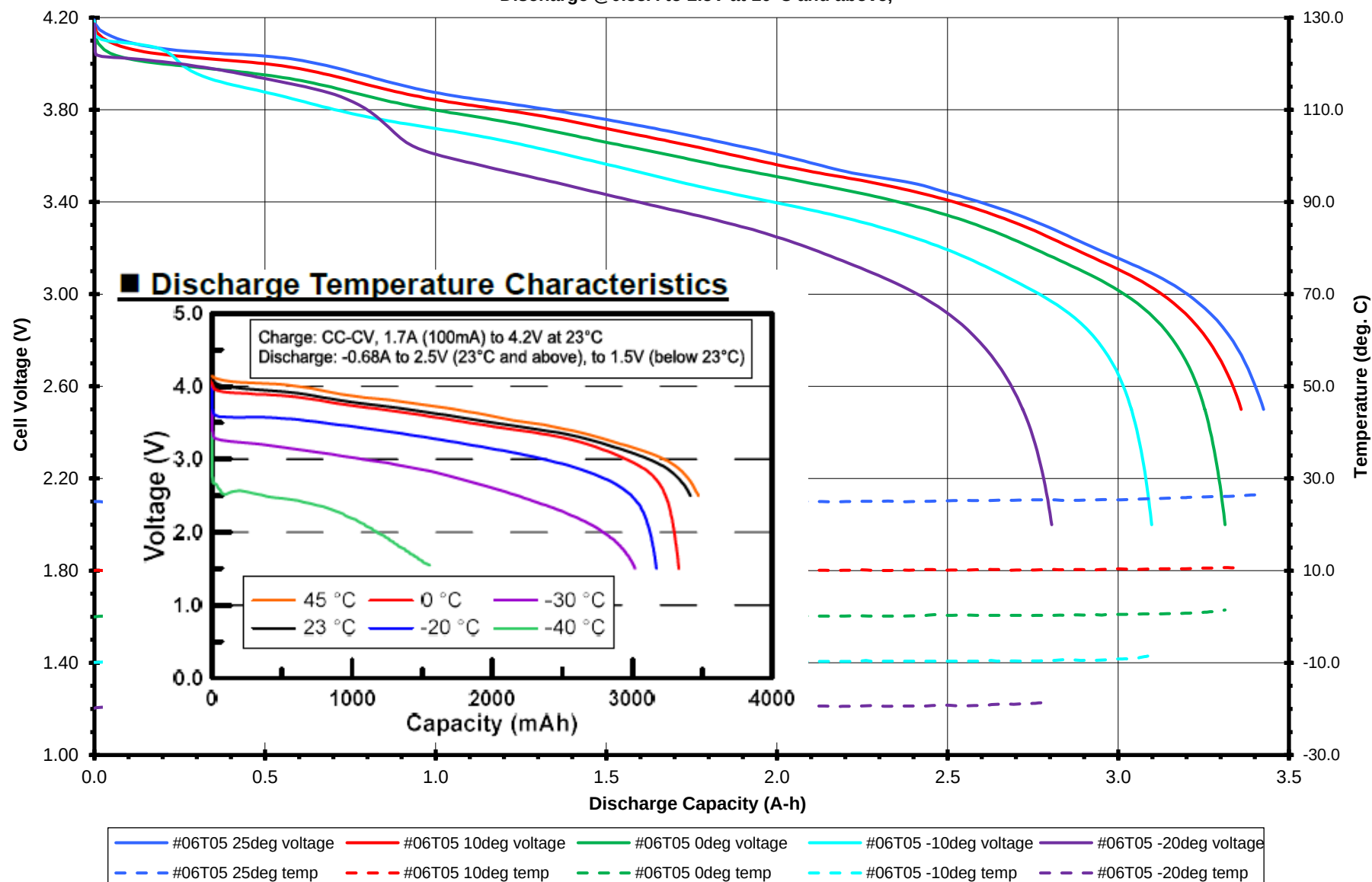


NASA and Navy cells will mostly come from Feb 12-13 lots (78,585) with balance of 1415 coming from Feb 14. The 40k KULR cells will come entirely from Feb 14-15 lots (41,415)

- 60k purchased through 80NSSC21P0774 contract with Moli
- Awarded on 13 Jan 2021
 - 2 consecutive date codes
- Navy buys 20k cells, KULR buys 40k cells
- 2 consecutive date codes to NASA cells
- 120k cells shipment changed to air cargo through 80NSSC21P1454 contract with KULR
- Cells have to be repackaged for air cargo limiting boxes to 180 cells (vs 200 capacity)
 - Cells arrive at JSC on 1 Apr 2021
- ILA performance uniformity contract (80NSSC21P1451) with PCTEST
- 600-cell random sample package and shipped to PCTEST and damaged by loose cells in boxes
 - 2nd 600-cell random sampled shipped with more secure shipment

Molicel INR18650-M35A Cell Discharge Temperature Testing
 Typical Profiles From 3 Cells Tested; Charge and Discharge at Specified Temp.
 Testing at 25, 10, 0, -10, and -20°C; Charge @ 0.35A to 4.20V, 4.20V to 50mA
 Discharge @0.35A to 2.5V at 10°C and above,

SRI Data



Datasheet conditions

- All charging at 23°C and C/2 to 4.2V to 100mA
- Discharge cut-off at 1.5V for runs below 23°C
- -20°C discharge yields 2.8Ah to 2.0V cut-off pt

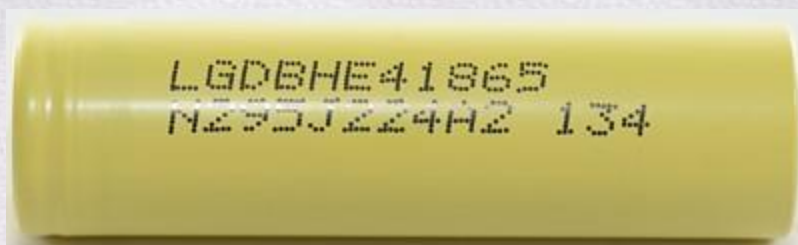
Our test conditions

- All charging/discharging at same temperature and C/10
- -20°C discharge cut-off at 2.0V yields 2.8Ah, 9.67 Wh
 - 214 Wh/kg

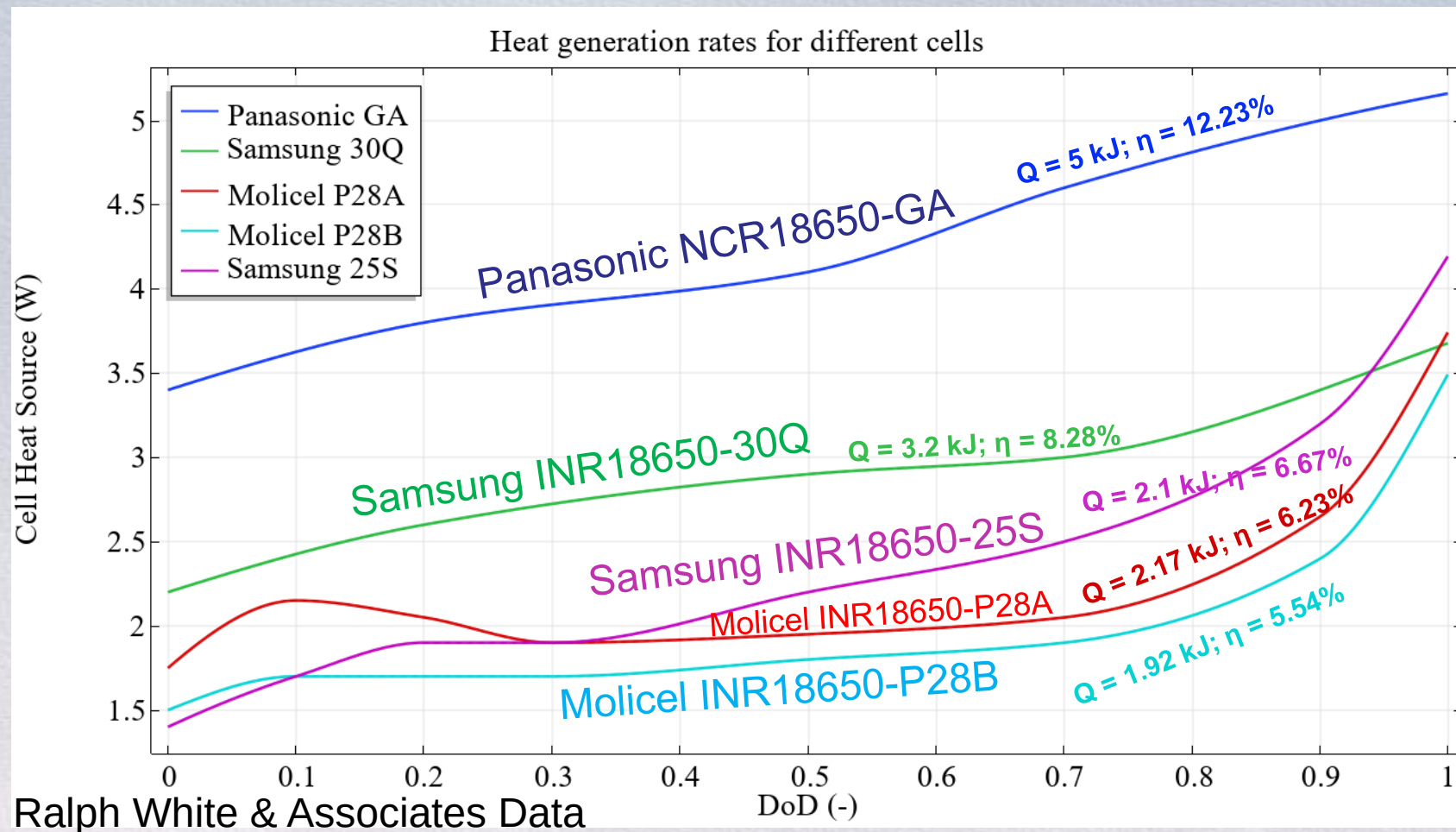
High Power Cell Designs

Capacity	LG	Molicel	Murata	Samsung
~3.0Ah	INR18650 HG2	INR18650-P28A	US18650 VTC6	INR18650-30Q
~2.5Ah	INR18650 HE4	INR18650A	US18650 VTC5A	INR18650-25S
~2.0Ah	INR18650 HD2C	IHR18650C	US18650 VTC4	INR18650-20S

- 3.0Ah cell designs rated for 15-20A max continuous
- 2.5Ah cell designs rated for 20A max continuous
- 2.0Ah cell designs rated for 20A max continuous with less heat



Heat generation different cells at 9.6A



GA>30Q>25S>P28A>P28B in waste heat generation at 3.0C (GA) to 4C (25S) discharge rates



P28B
Double
Positive
Tab

Only the P28B meets < 6% NASA Reqt

Selected High Power Cell Designs

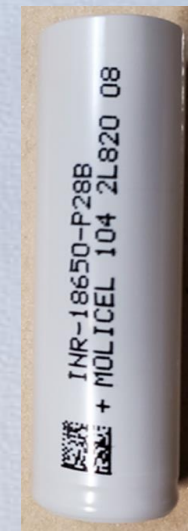
Samsung INR18650-30Q

- 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
 - 8.3% average waste heat
- 60k lot (Mar 2021) delivered in June to JSC



Moli 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/kg, 510.3 Wh/L
 - 9.2 mohm ACR
 - 22.3 mohm DCR
 - 5.5% waste heat
- 60k lot (Aug 2021) delivered in Oct to JSC



SAMSUNG 30Q Details

Qty 60,000



NASA contract 80JSC021P0024 with KULR Technologies

- Awarded in Apr 2021
- 60,000 cells delivered on 21 Jun 2021 to JSC
- NASA completed Receiving Inspection per EP-WI-035
- PCTEST completes sections 3.0 per EP-WI-036A
 - 300 cell random sample for ILA complete
- LAT on-going

- 2019 Batch Translation Information below

Batch No. Information



1. Batch No. : ERJA35E6I505

E : Line
 R : Cell Type (R: Cylindrical P: Prismatic)
 J : Year (A: 2010 ~ J: 2019)
 A : Internal Control No.
 35 : Cell Model No.
 E : Version
 6 : Month (1~C)
 I5 : Serial No.
 05 : Internal Control No.

- Cell Batch Date code translates to Wk 10 March 2021

SAMSUNG SDI				
Model	INR18650-30Q	Capacity	3000 mAh	
Batch No	RRLA30Q39C03	A39 3	Rank	A
Q'ty	200 PCS	Date	2021/03/22	
Remark	SOC 30% / Made In China			
Tracking	 RRLA30Q39C03AB041			

B

Moli INR-18650-P28B



Datecodes

L818 translates to 18 Aug 2021

L819 translates to 19 Aug 2021

L820 translates to 20 Aug 2021

60k purchased through 80JSC021P0019 contract with Moli

- Awarded on 17 Feb 2021
- 3 consecutive date codes (8/18, 8/19, 8/20)

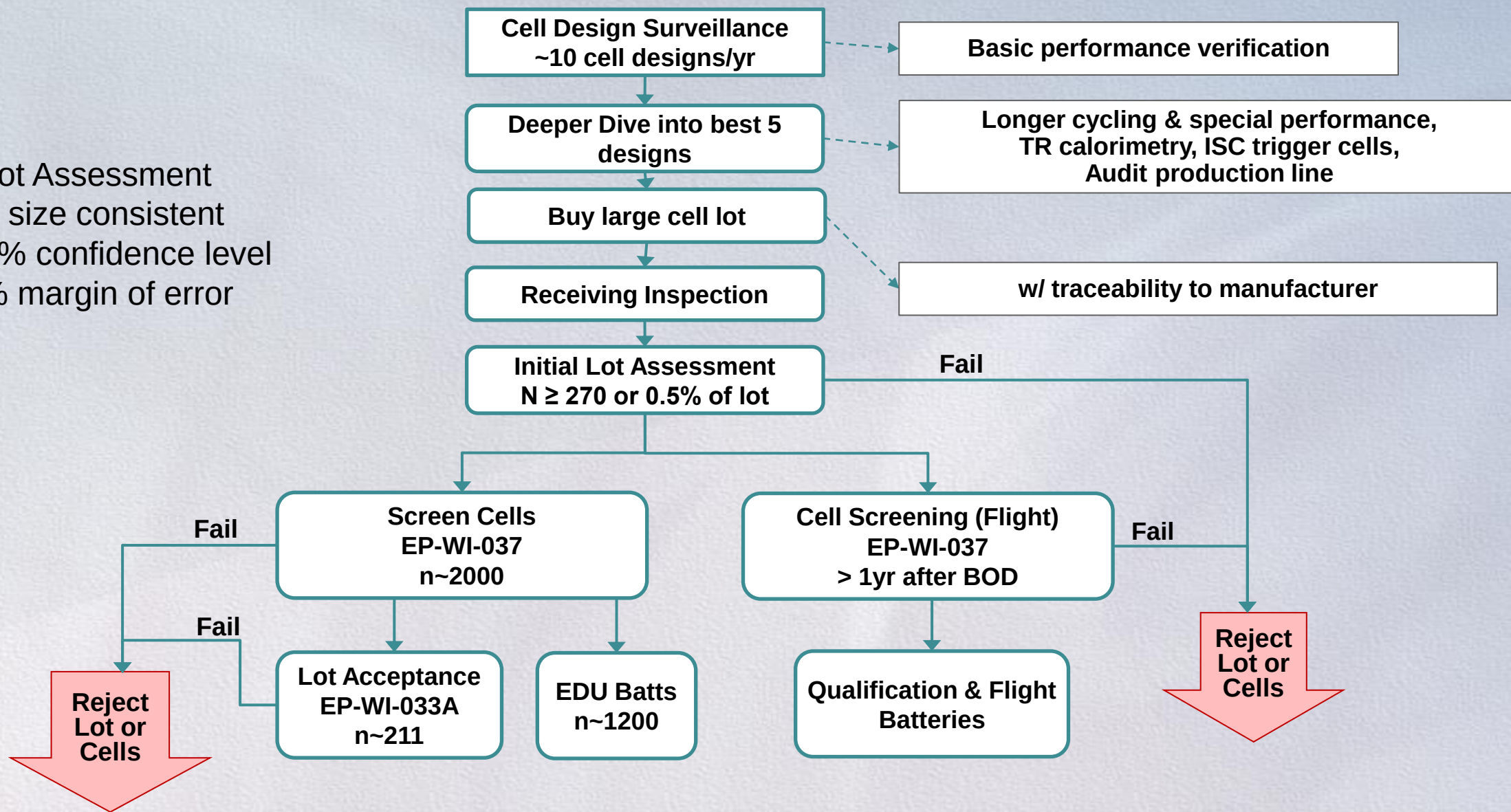
60k cells shipment changed to air cargo through 80NSSC21P2711 Mod P00001 contract with Moli

- Cells have to be repackaged for air cargo limiting boxes to 180 cells (vs 200 capacity)
- Cells arrive at JSC on 8 Oct 2021 on multiple ILA performance uniformity contract (80NSSC21P1854) with PCTEST
- Samples currently under test

Datecode	Cell Qty Per Datecode
L818	18,959
L819	15,399
L820	25,642

NASA-NAVSEA Process Flow Chart

Initial Lot Assessment
sample size consistent
with 90% confidence level
with 5% margin of error

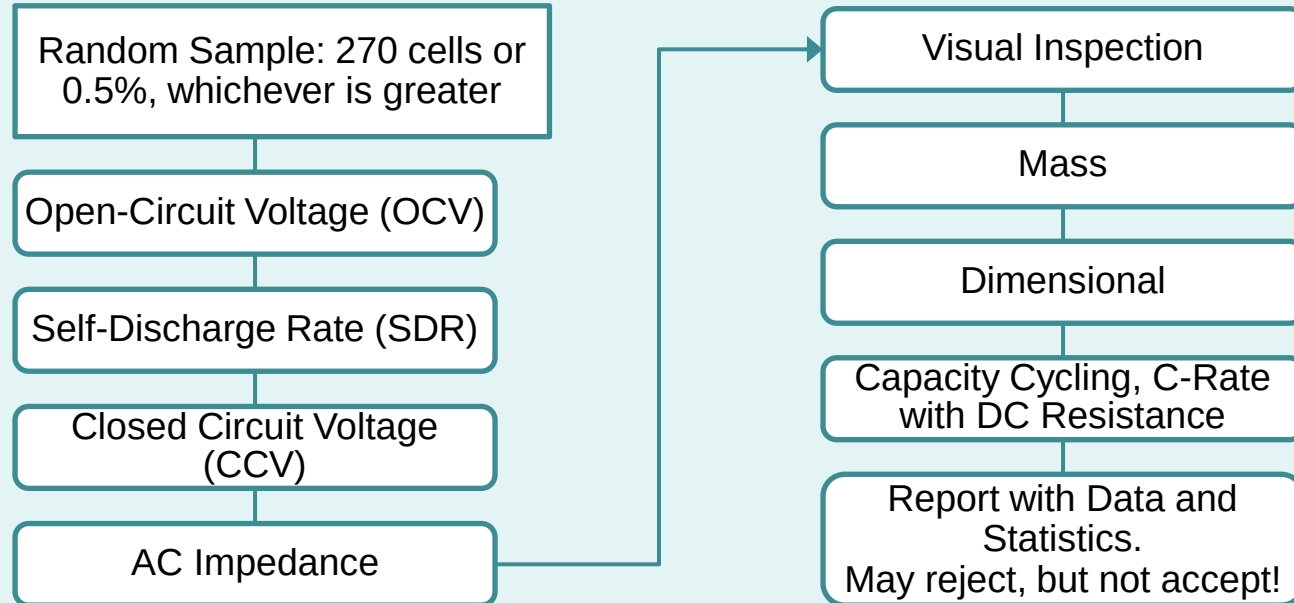


Initial Lot Assessment (ILA)

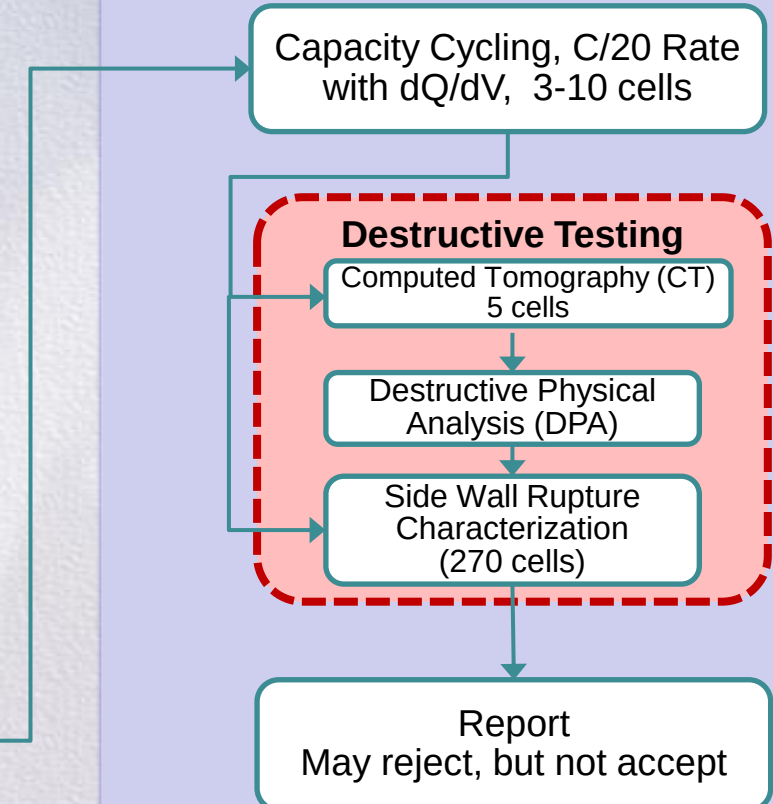
EP-WI-036 Specification for Initial Lot Assessment of Commercial Lithium-ion Cells Lots

- Determine if cell lot is worthy before proceeding with an expensive lot acceptance testing
Quick & less expensive
 - 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

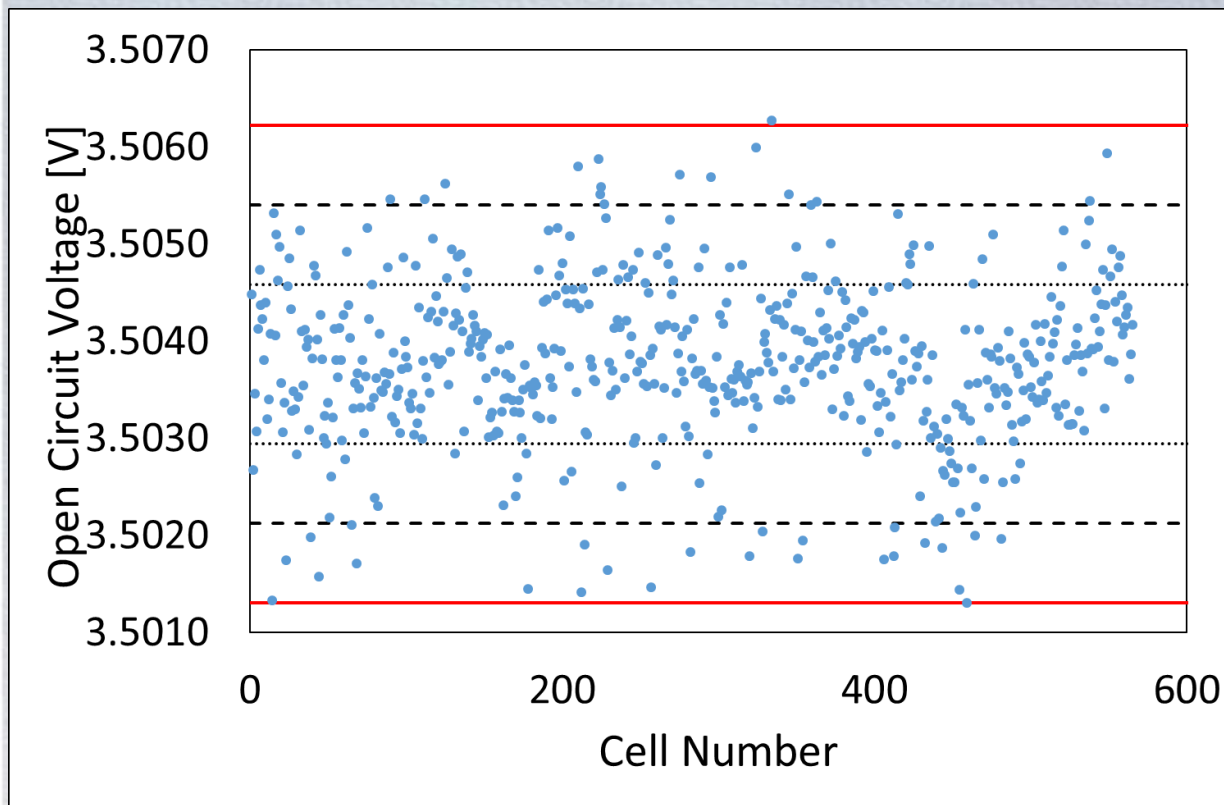
Assess manufacture performance and quality



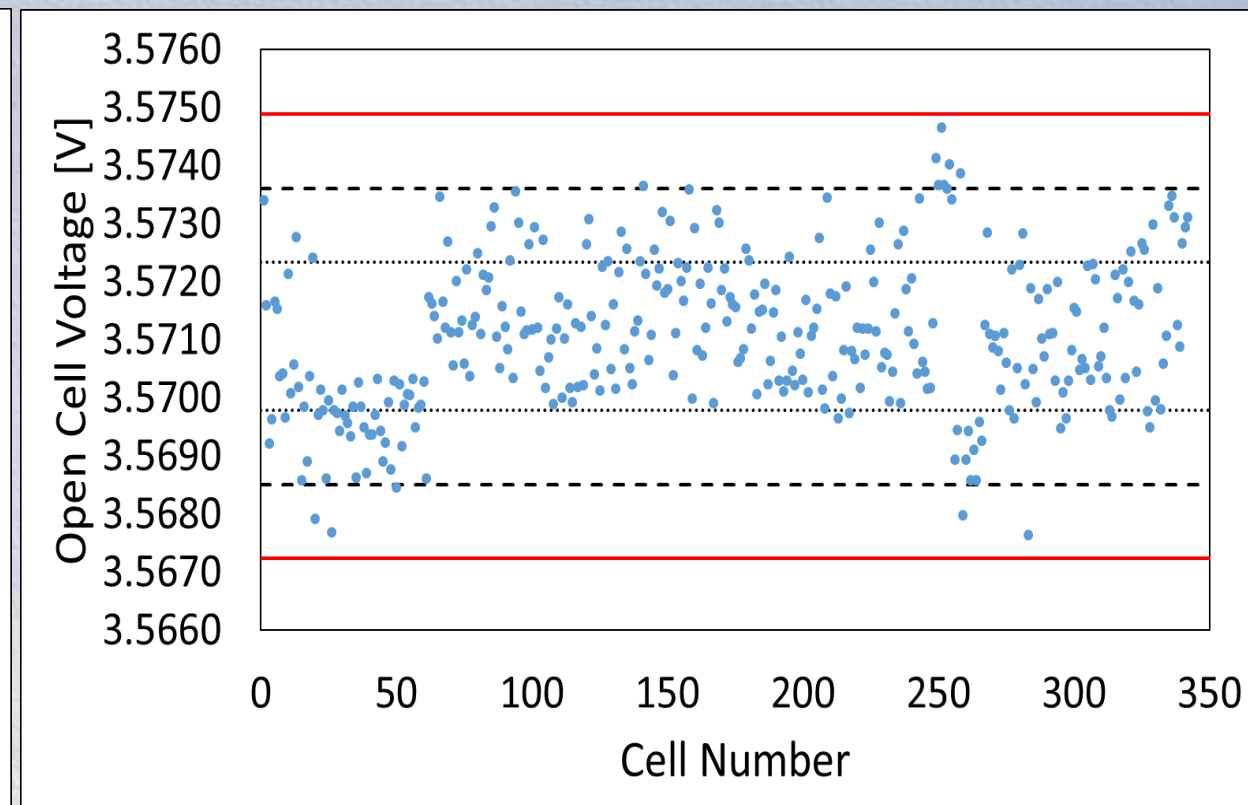
Verifies if cell Lot operates as in previous designs



OCV Comparison of High Energy Cells



M35A



M36

Both cells sampled at 3-4 months after their date code

Parameter	M35A OCV	M36 OCV
6 σ Range (% of mean)	0.14	0.21

OCV Comparison

Parameter	M35A OCV	M36 OCV
	[V]	[V]
Average [X]	3.5038	3.5711
st.dev [σ]	0.0008	0.0013
st.dev (%)	0.02	0.04
Min	3.5011	3.568
Max	3.5064	3.575
Range	0.005	0.007
Range (%)	0.15	0.20

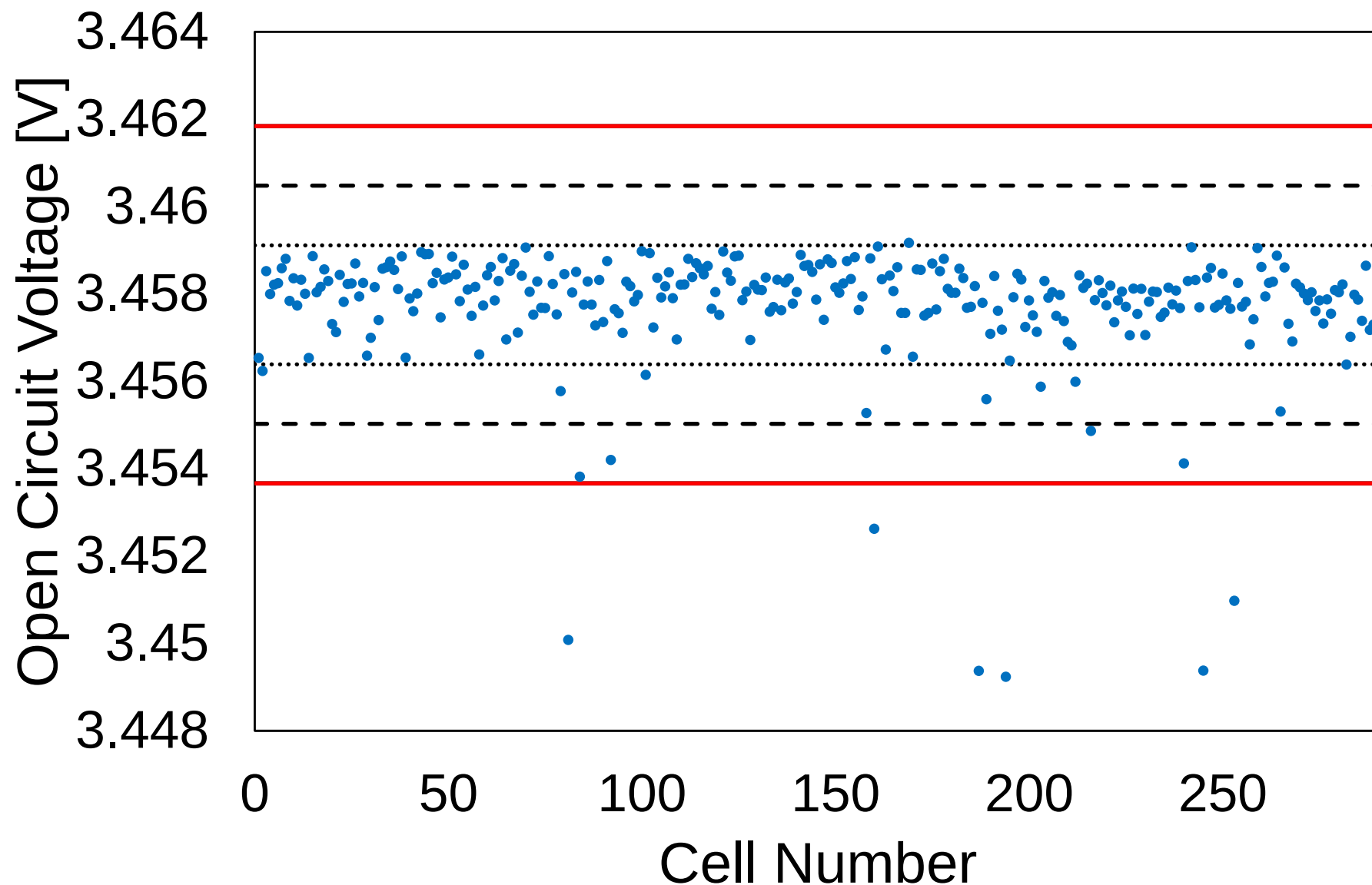
M35A: 27 outliers
removed after 2 scrubs

M36: 8 outliers removed
after 2 scrubs

X-3 σ	3.5012	3.567
X+3 σ	3.5063	3.575
6 σ Range	0.0051	0.0076
6 σ Range (%)	0.14	0.21
Low Rejects	2	0
High Rejects	2	0
Total Rejects	4	0
Count	569	342
Total Rejects (%)	0.70	0.00

Both cells sampled at 3-4
months after their date code

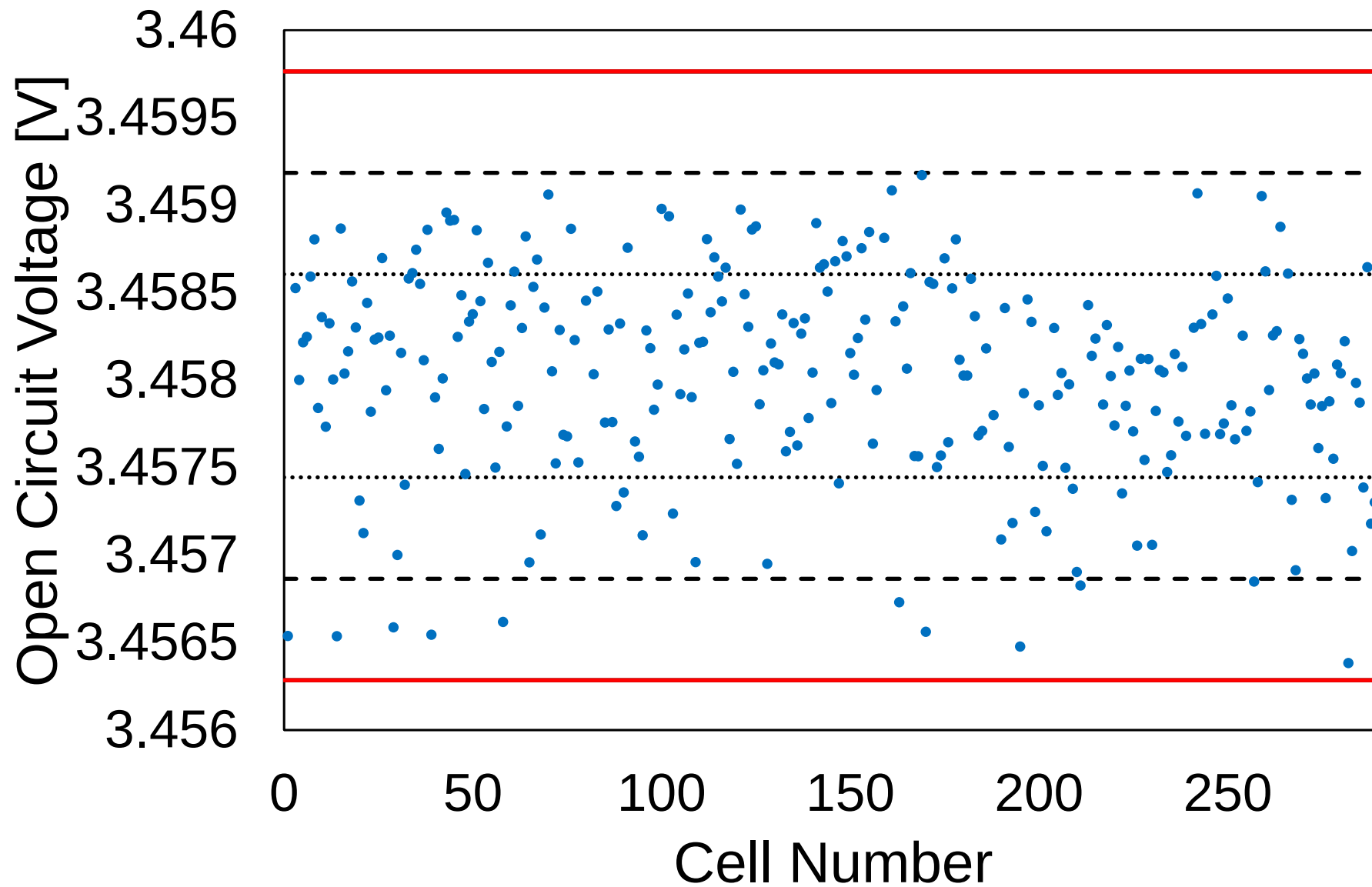
Samsung 30Q - As received OCV – 290 cells



Parameter	OCV
	[V]
Average [X]	3.4578
st.dev [σ]	0.0014
st.dev (%)	0.04
Min	3.449
Max	3.459
Range	0.010
Range (%)	0.29

X-3σ	3.454
X+3σ	3.462
6σ Range	0.0082
6σ Range (%)	0.24
Low Rejects	6
High Rejects	0
Total Rejects	6
Count	290
Total Rejects (%)	2.07

Samsung 30Q OCV – 4th Scrub

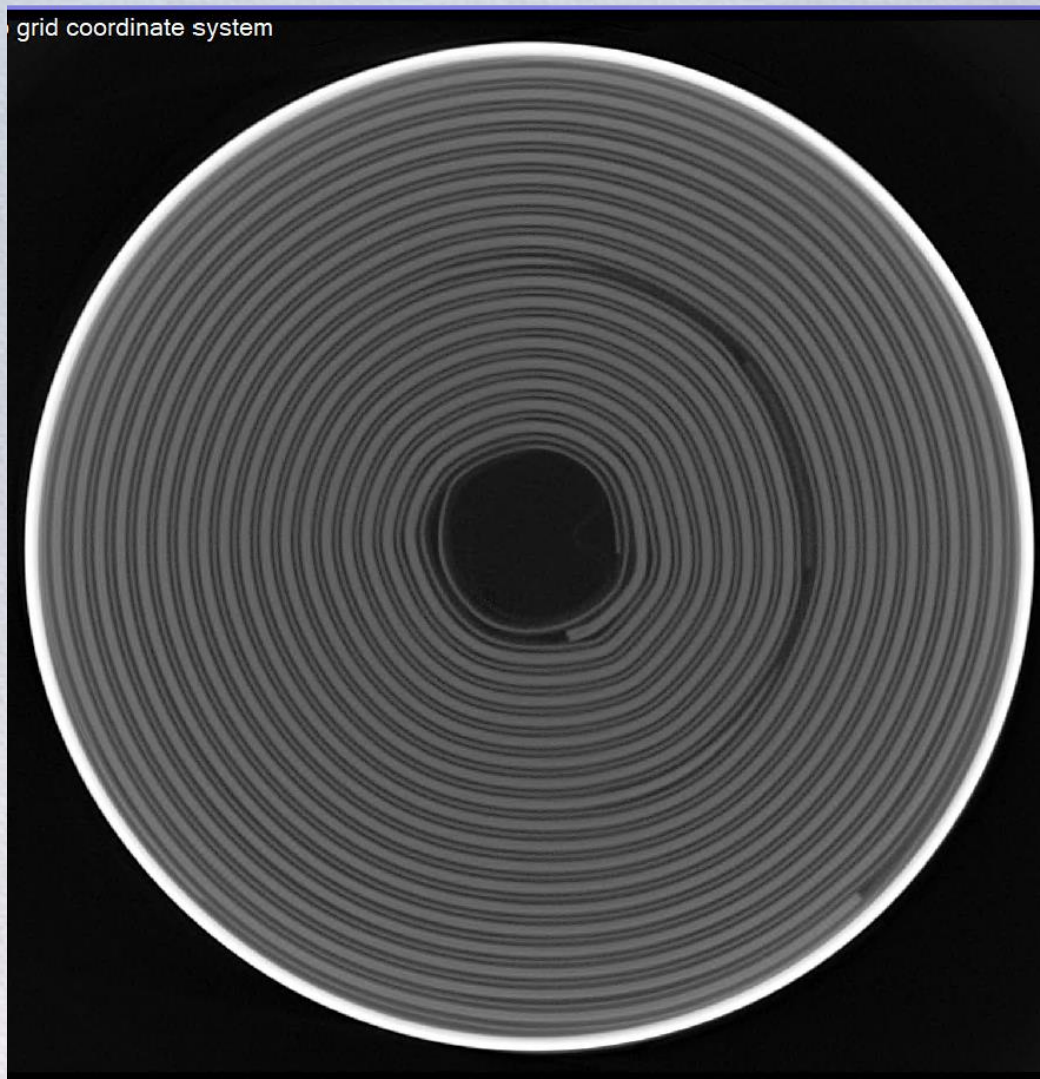


Parameter	OCV
	[V]
Average [X]	3.4580
st.dev [σ]	0.0006
st.dev (%)	0.02
Min	3.456
Max	3.459
Range	0.003
Range (%)	0.08

X-3σ	3.456
X+3σ	3.460
6σ Range	0.0035
6σ Range (%)	0.10
Low Rejects	0
High Rejects	0
Total Rejects	0
Count	272
Total Rejects (%)	0.00

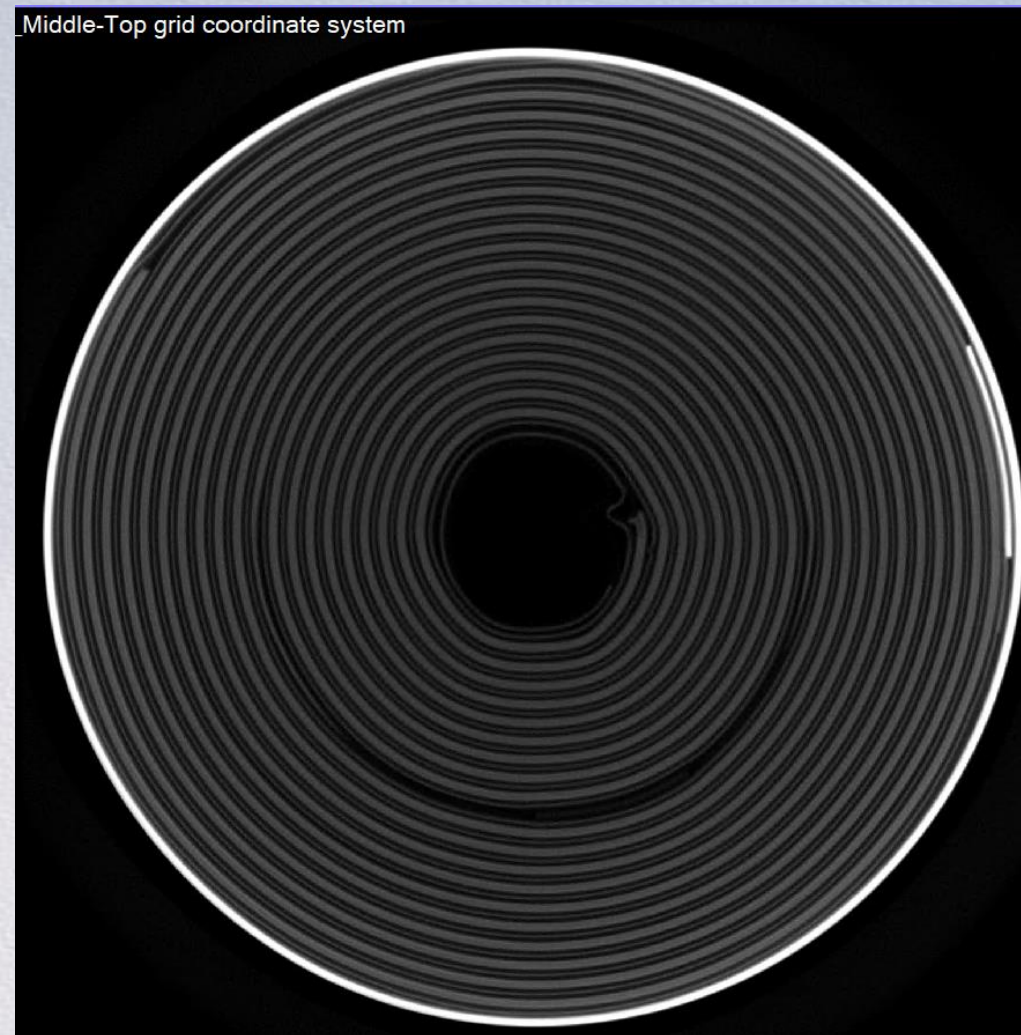
After removing 18 low rejects, tightest 6σ%

Radial CT Comparison – High Energy



LG M36

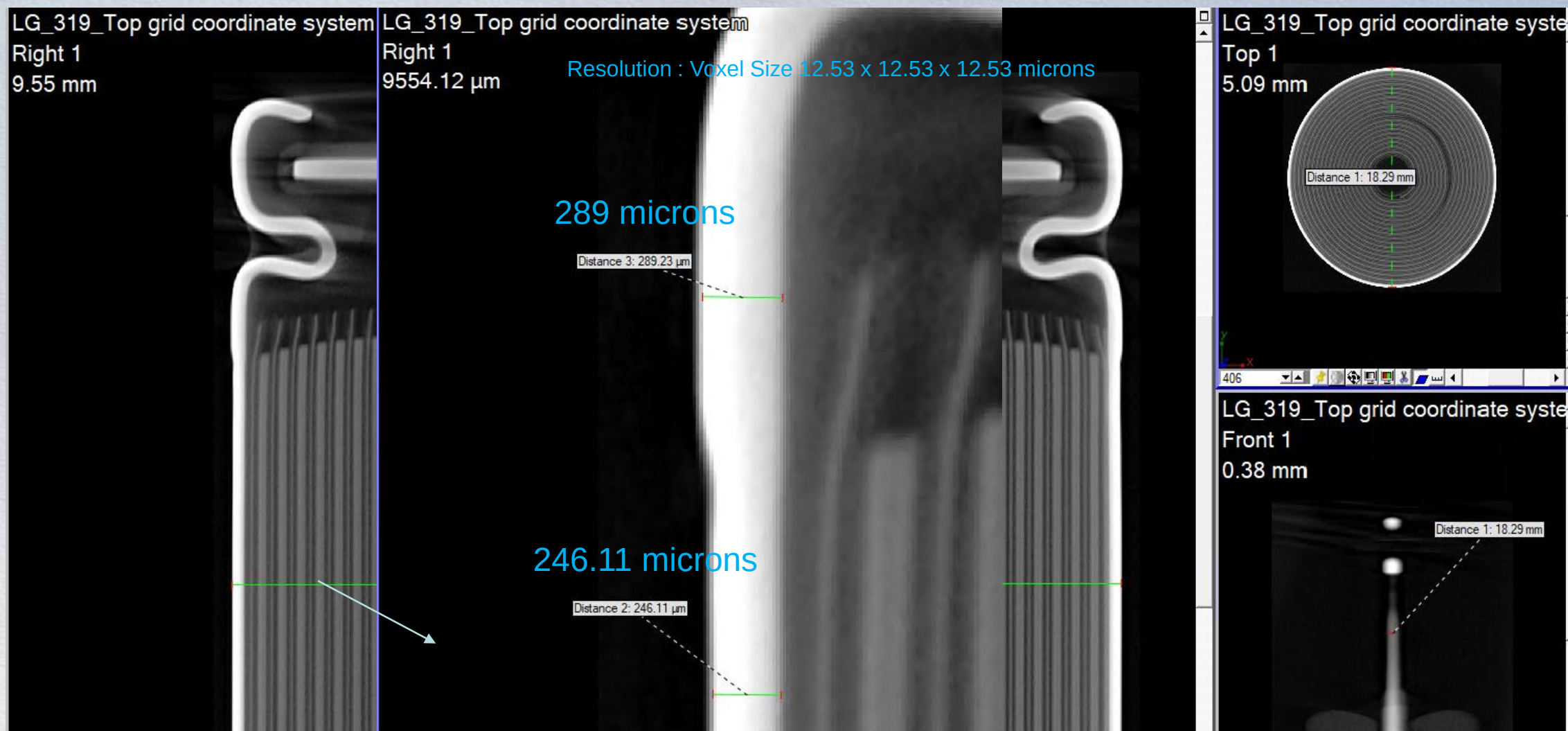
19 winds



Moli M35A

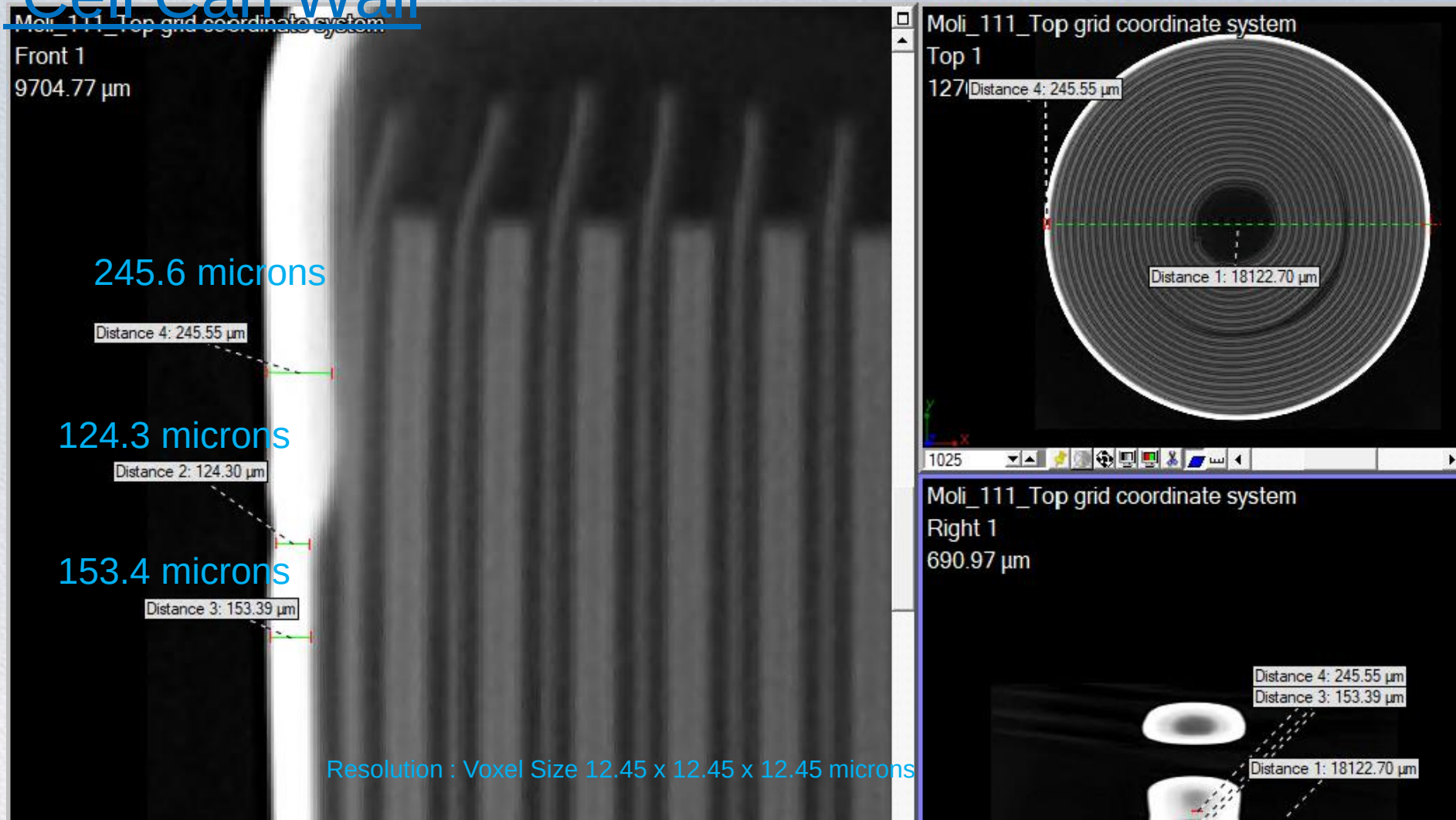
20 winds

LG INR18650-M36 - Cell Can Wall Thickness

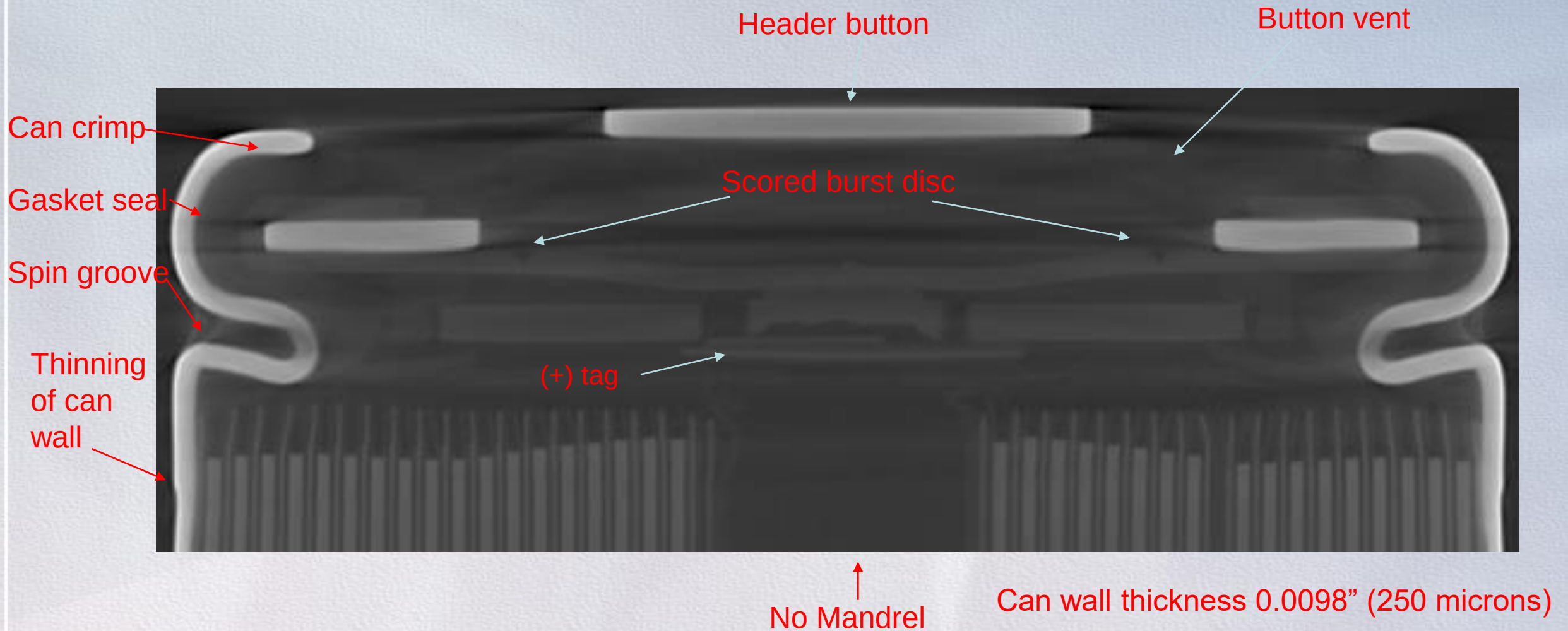


Molice! INR18650-M35A - Cell 1

- Cell Can Wall

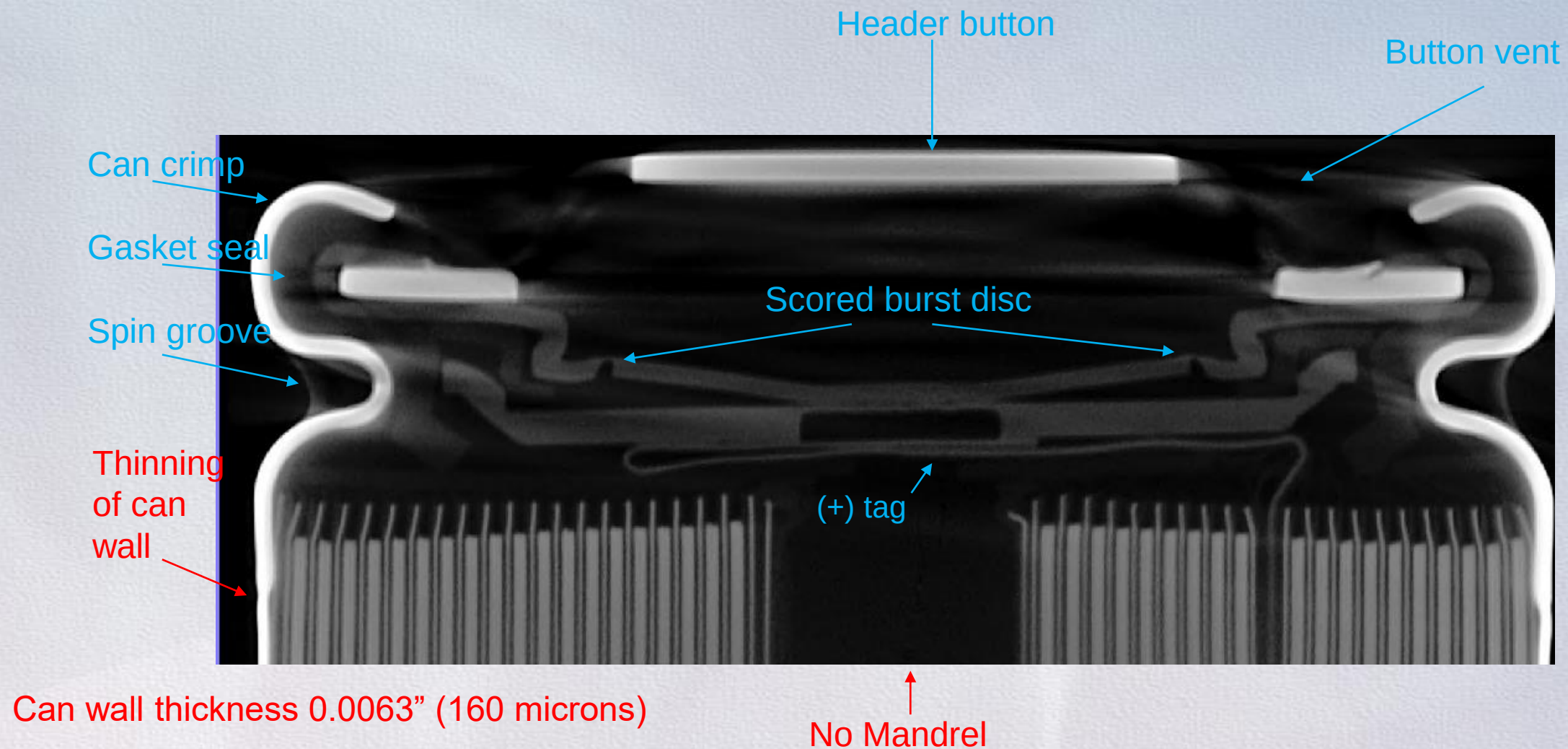


LG 18650 M36 - Axial View - Header - Cell



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

Molice! INR18650-M35A Axial View



Note the single crimped header design with burst pressure ~867 psia (~59 atm)

DPA – LG M36



Anode B

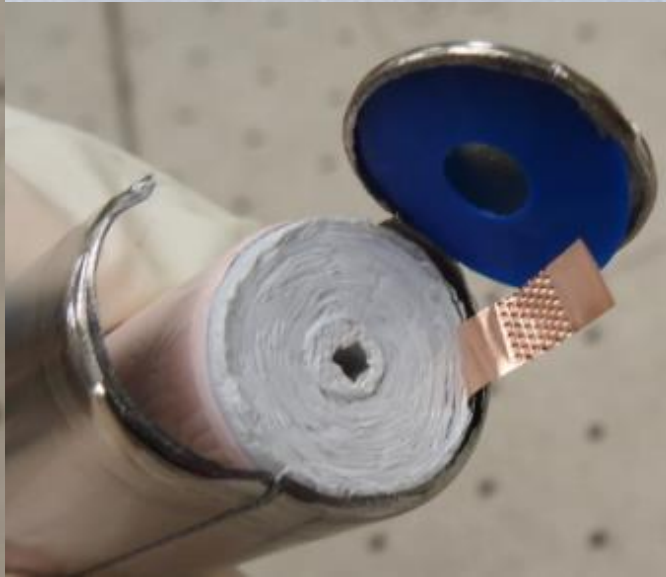


Cathode B



04.28.2021 10:14

DPA – Moli M35A



Separator 1B

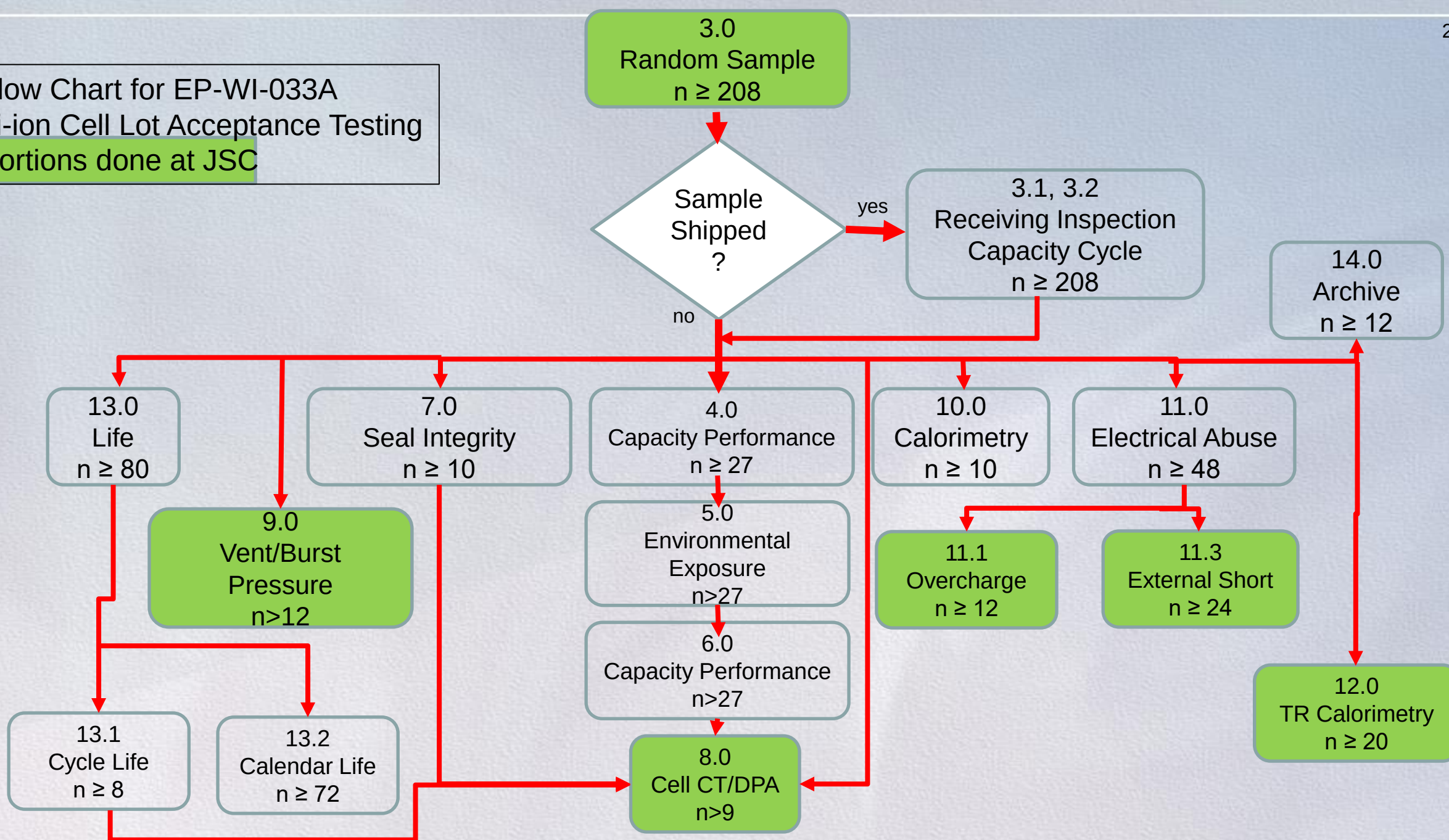
Anode A

Separator 2B

Cathode B



Flow Chart for EP-WI-033A
Li-ion Cell Lot Acceptance Testing
Portions done at JSC

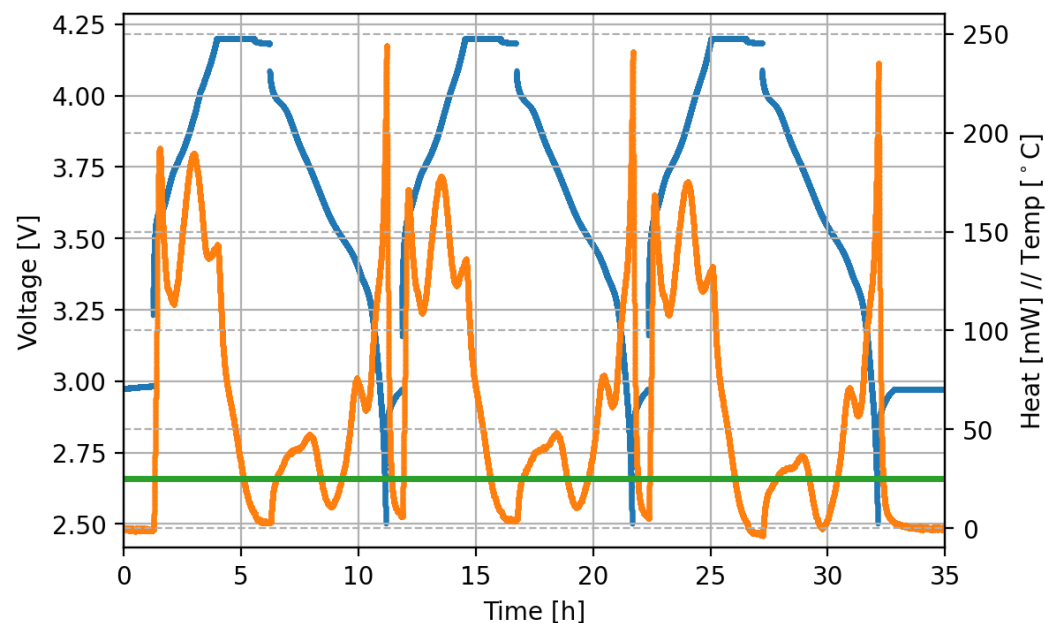


LG Chem M36 – Charge/Discharge Heat Conduction Calorimetry and Heat Capacity Measurements

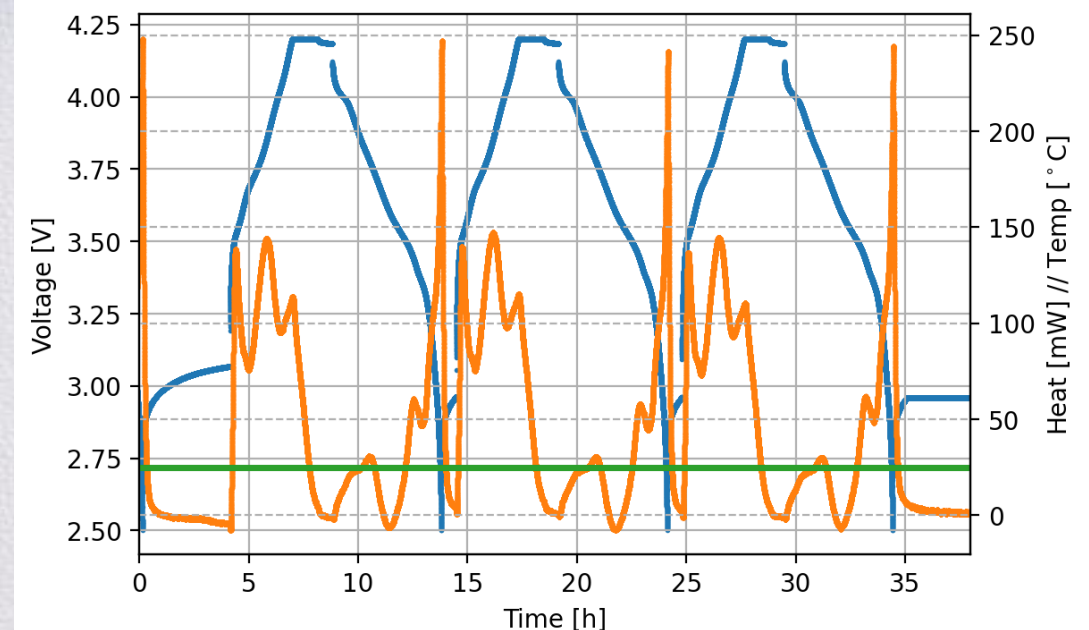
- Monitored heat flux during 3 “standard” cycles
 - 1 A (0.3C) charge to 4.2 V, 4.2 V hold until $I < C/67$ (0.05 A)
 - C/5 (0.67 A) discharge to 2.5 V
- Average heat generation
 - Charge at 1A estimated at 100 mW (or 2.7%)
 - Discharge at 0.67A estimated at 70 mW (or 2.8%)

Cell	Heat capacity [J/gK]		
	@ 0% SOC	@ 30% SOC	@ 100% SOC
26 (25 °C)	0.921	0.923	0.918
27 (25 °C)	0.910	0.909	0.908

Cell #26



Cell #27



OCV vs SOC for LG M36

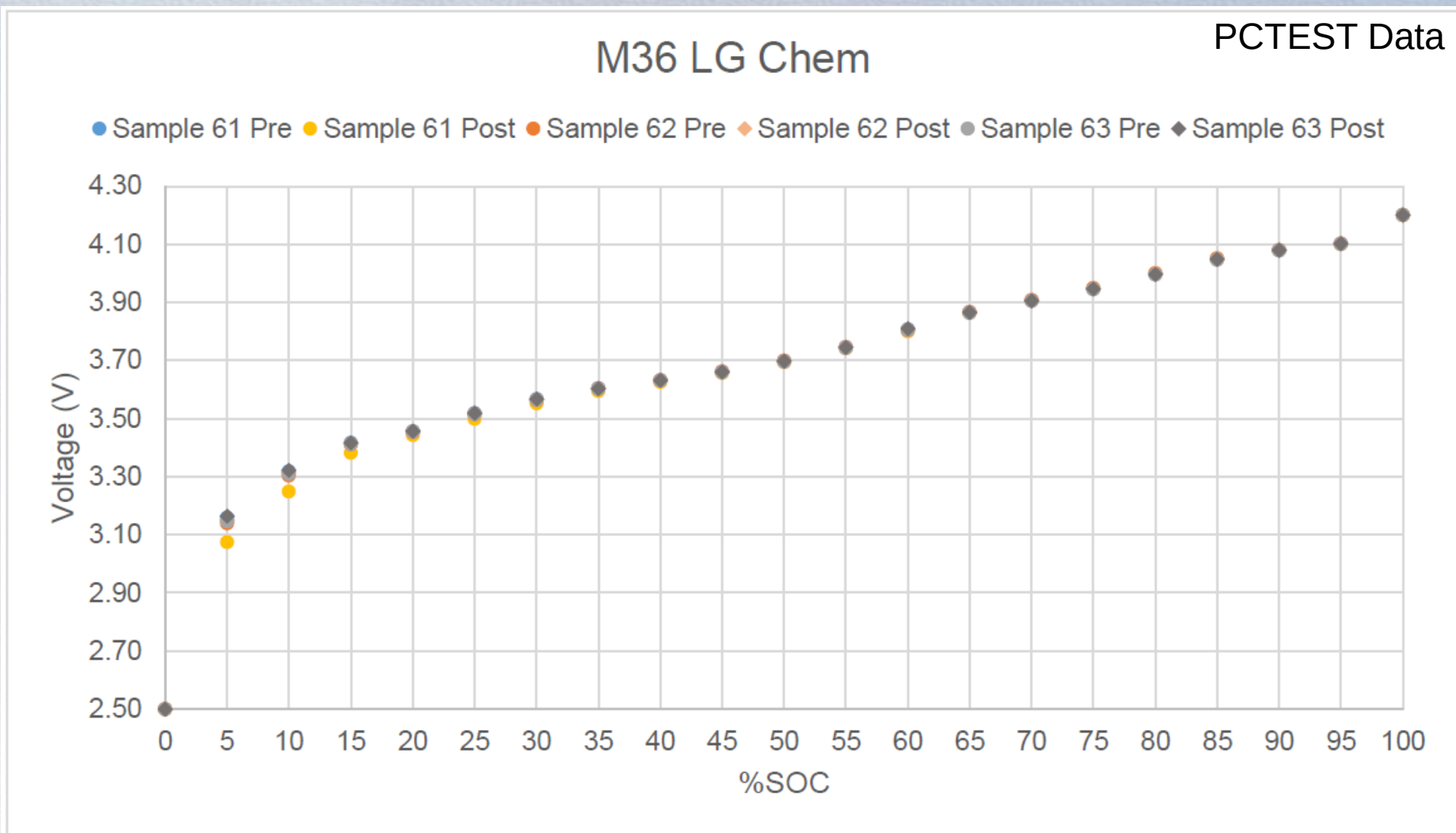


Figure 2.2.3.2 – Capacity vs Voltage at each 5% DoD.

OCV vs SOC for Moli M35A

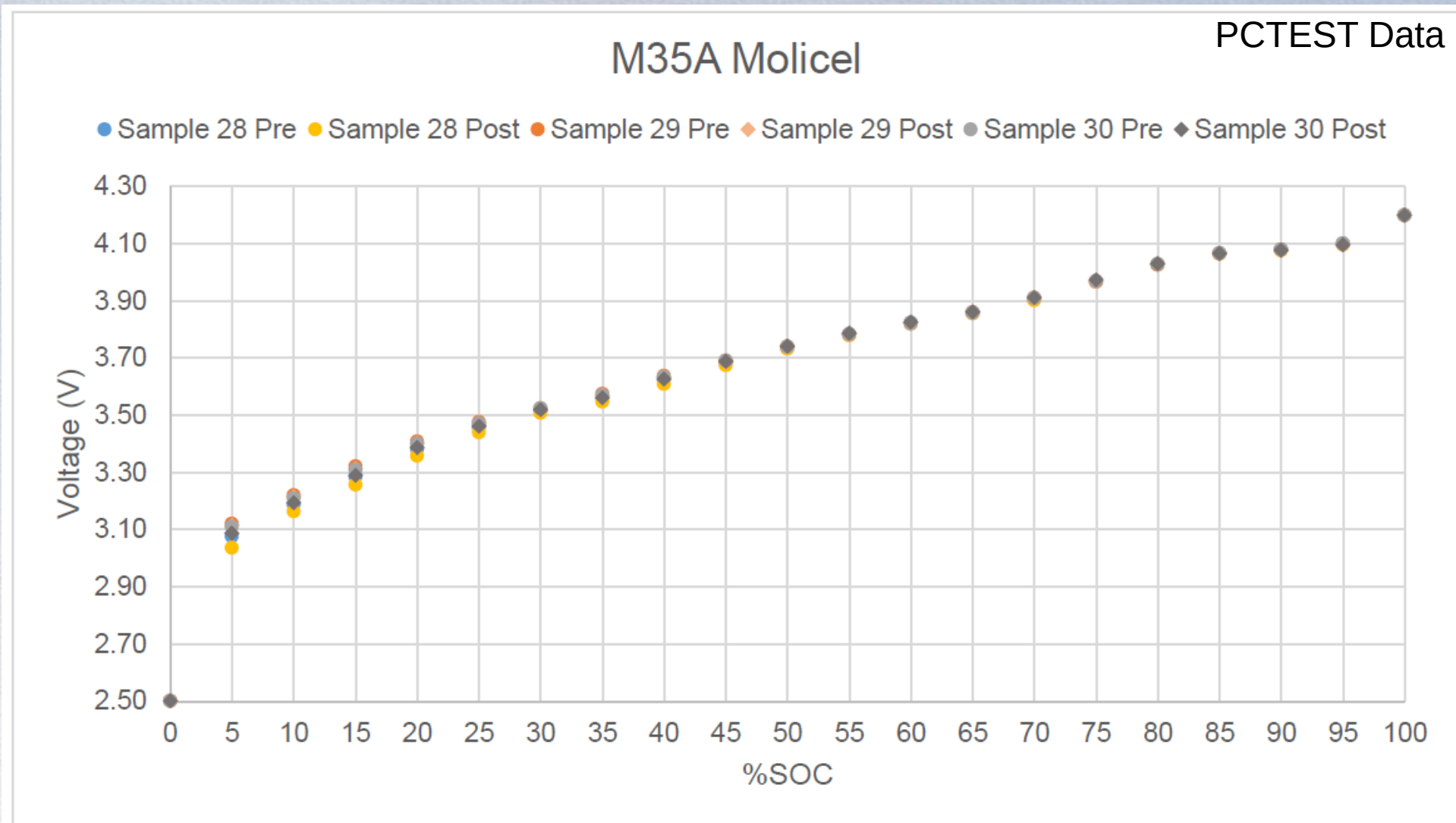
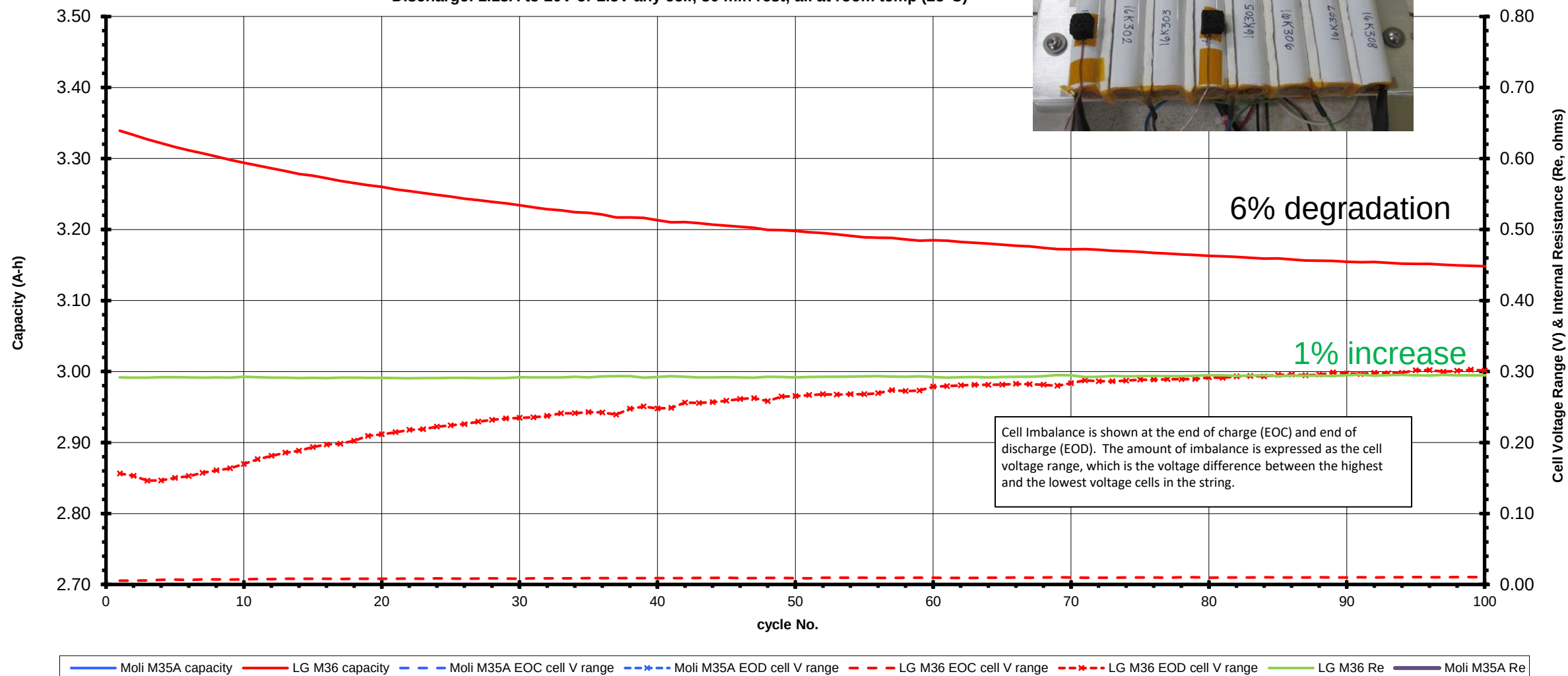


Figure 2.2.3.2 – Capacity vs Voltage at each 5% Depth of Discharge.

LG M36 Cycle Life

SRI Data

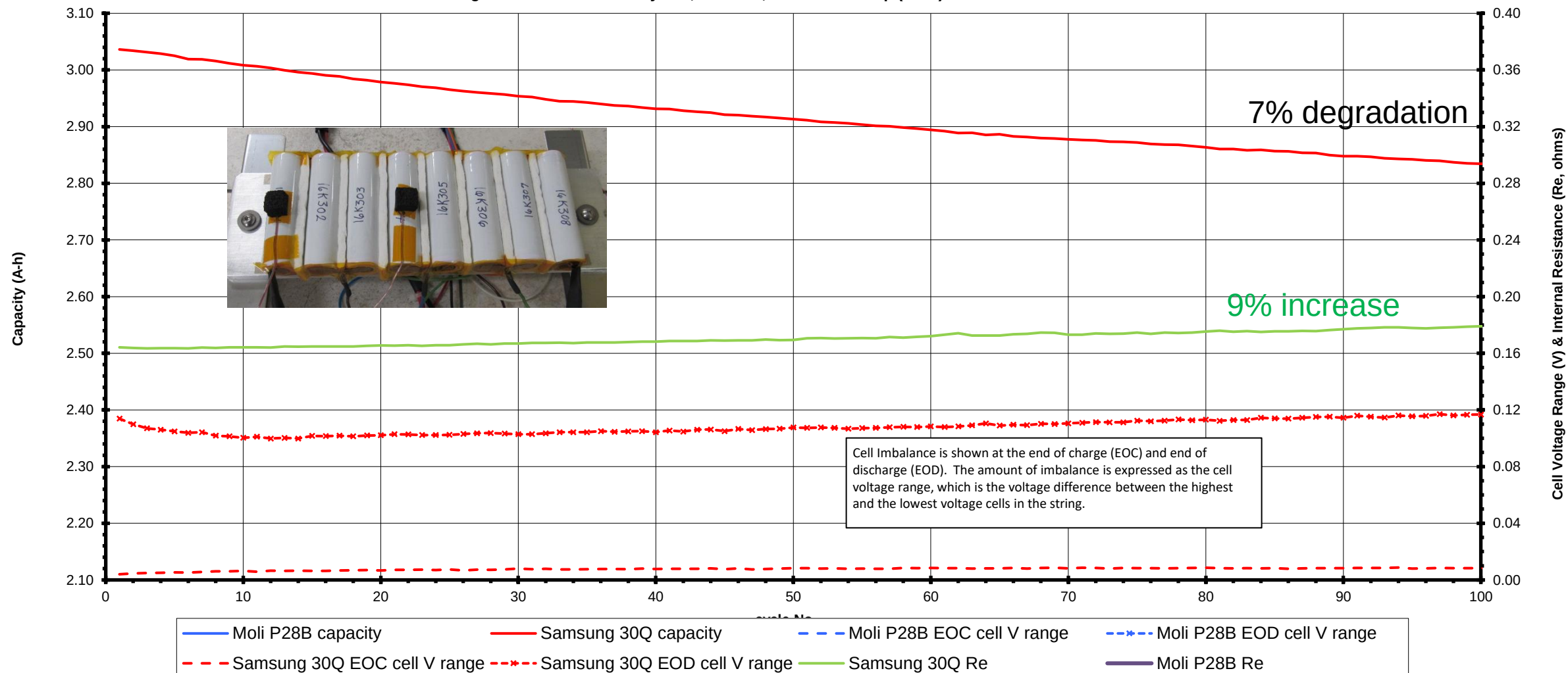
High Energy 18650 Li-Ion Cell Characterization Testing
Cycle Life, Discharge Capacity and Cell Imbalance Trends; 8S Strings
 Charge: 1.13A to 33.6V, 33.6V to 50mA; 10 min rest
 Discharge: 1.13A to 20V or 2.5V any cell; 30 min rest; all at room temp (25°C)



30Q Cycle Life

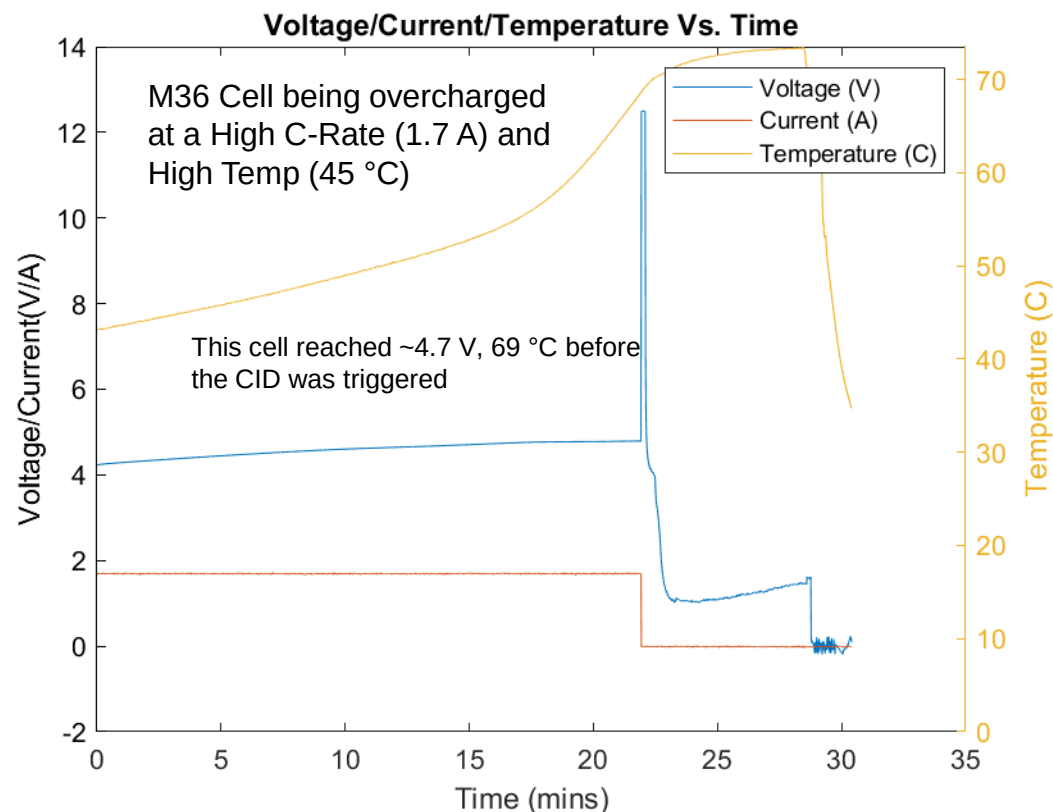
SRI Data

High Power 18650 Li-Ion Cell Characterization Testing
Cycle Life, Discharge Capacity and Cell Imbalance Trends; 8S Strings
 Charge: 1C to 33.6V, 33.6V to 50mA; 30 min rest
 Discharge: 1C to 20V or 2.5V any cell; 1 hr rest; all at room temp (25°C)



Overcharge

- Cells are overcharged in 4 different conditions based on temperature and C-Rate until CID activation, thermal runaway, or 100% overcharge capacity of nameplate capacity is achieved
- Pass/Fail criteria is that there is no flame, fire, explosion, or violent (releasing shrapnel) rupture

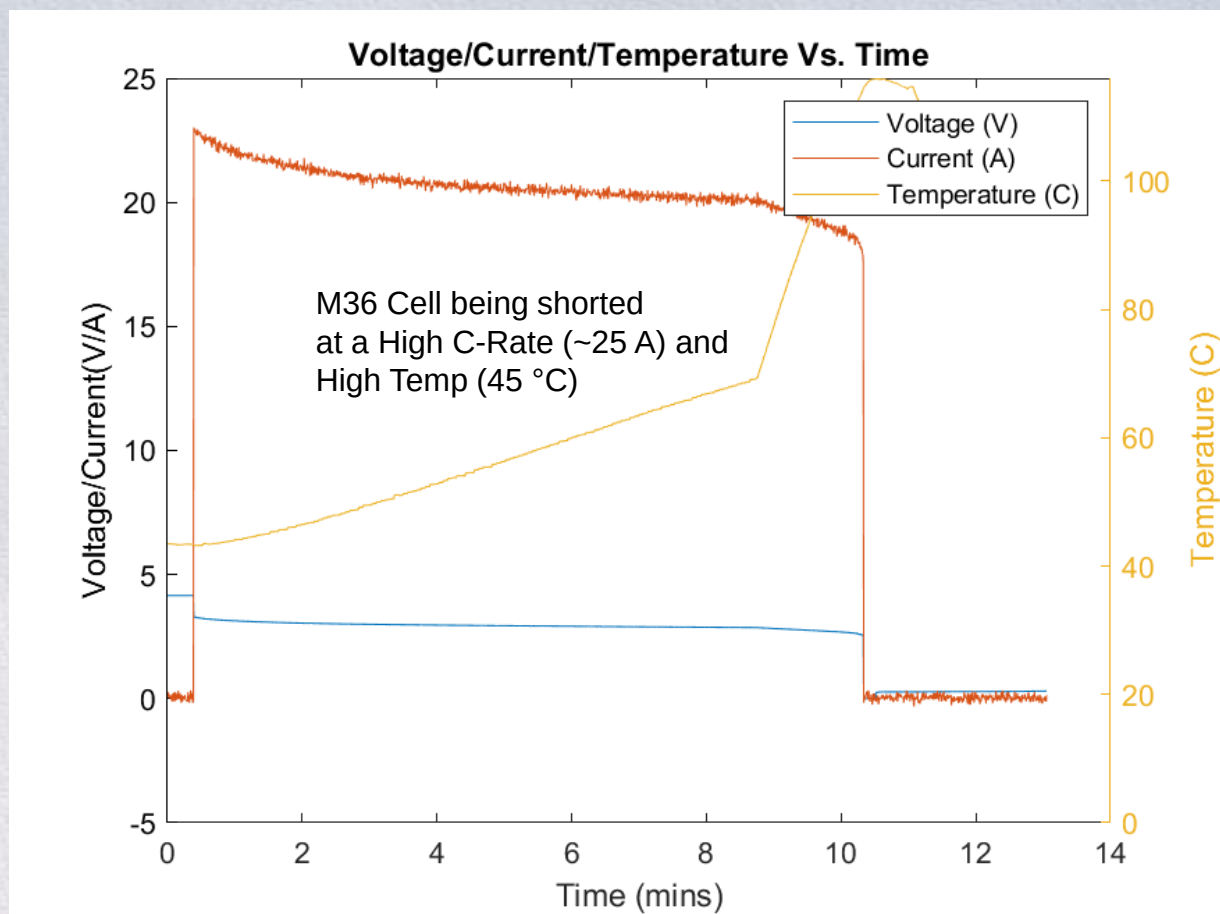
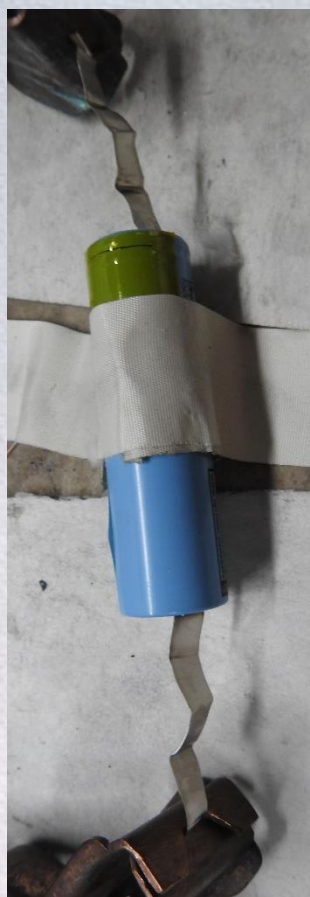


Cell	Low C-Rate (A)	High C-Rate (A)
M35A	C/7 (0.5)	C/2 (1.7)
M36	C/7 (0.5)	C/2 (1.7)
30Q	C/3 (1)	2C (6)
P28B	C/3 (1)	2C (6)

Cell	Low Temp (°C)	High Temp (°C)
M35A	0	45
M36	0	45
30Q	0	60
P28B	0	60

Short Circuit

- At worst case hot and cold temperatures, cells are loaded with an appropriately sized resistor to pull a low (3C), medium low (4C), medium (5C), and high (10C) current
- Pass/Fail criteria is that there is no flame, fire, explosion, or violent (releasing shrapnel) rupture



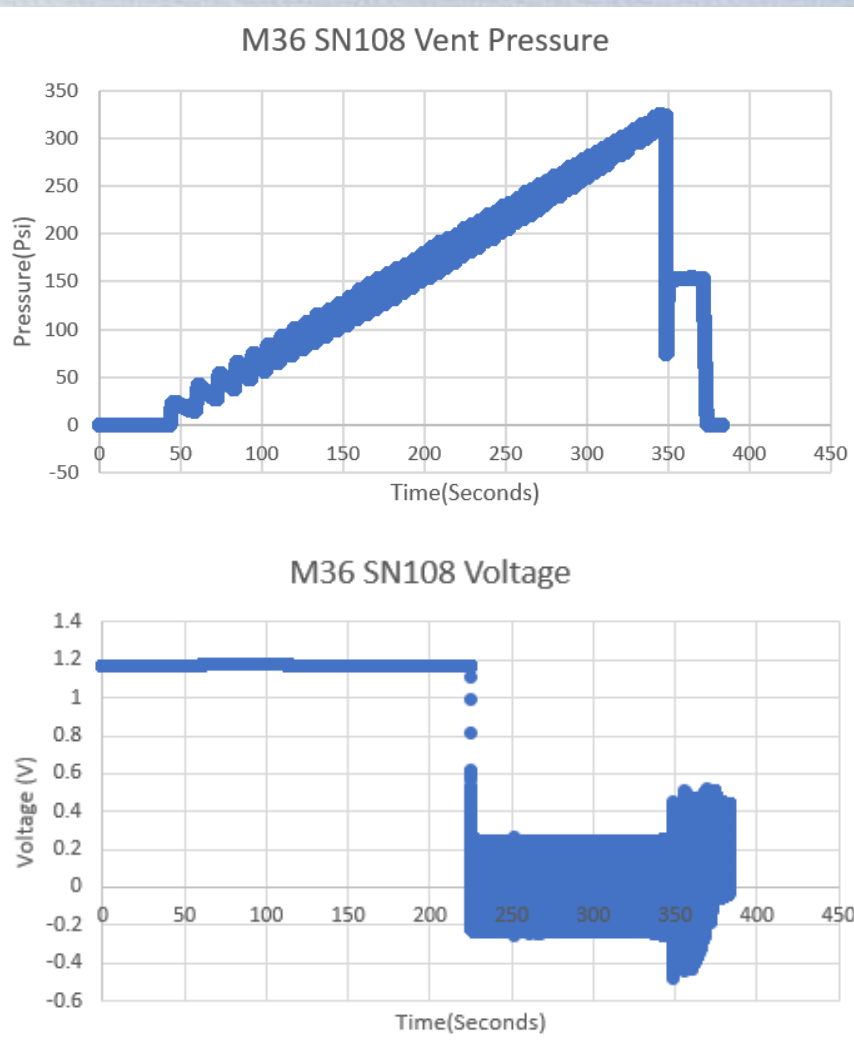
Cell	Low C-Rate (A)	Medium Low C-Rate (A)	Medium C-Rate (A)	High C-Rate (A)
	3C	4C	5C	10C
M35 A	9	12	15	25
M36	9	12	15	25
30Q	12	16	20	30
P28 B	12	16	20	30

Cell	Low Temp (°C)	High Temp (°C)
M35A	RT (25)	45
M36	RT (25)	45
30Q	RT (25)	60
P28B	RT (25)	60

Cell is
tabbed on
the positive
button and
can wall



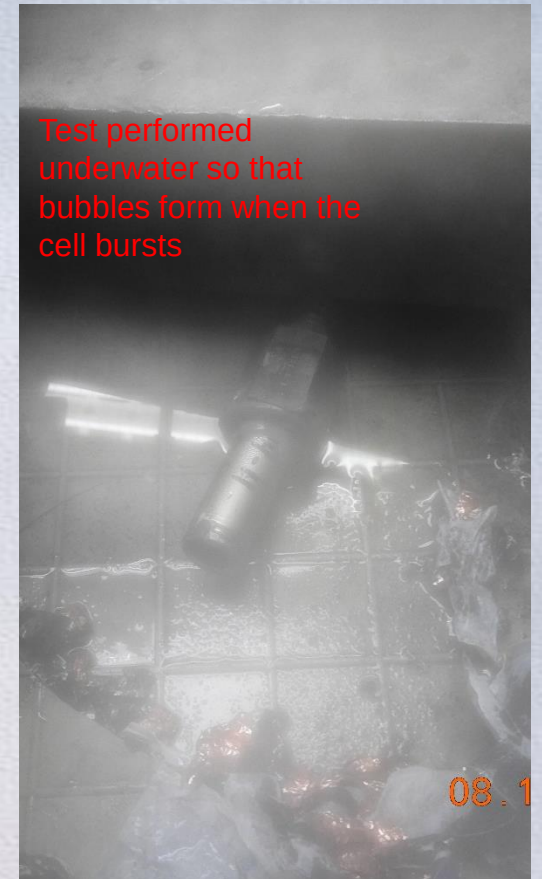
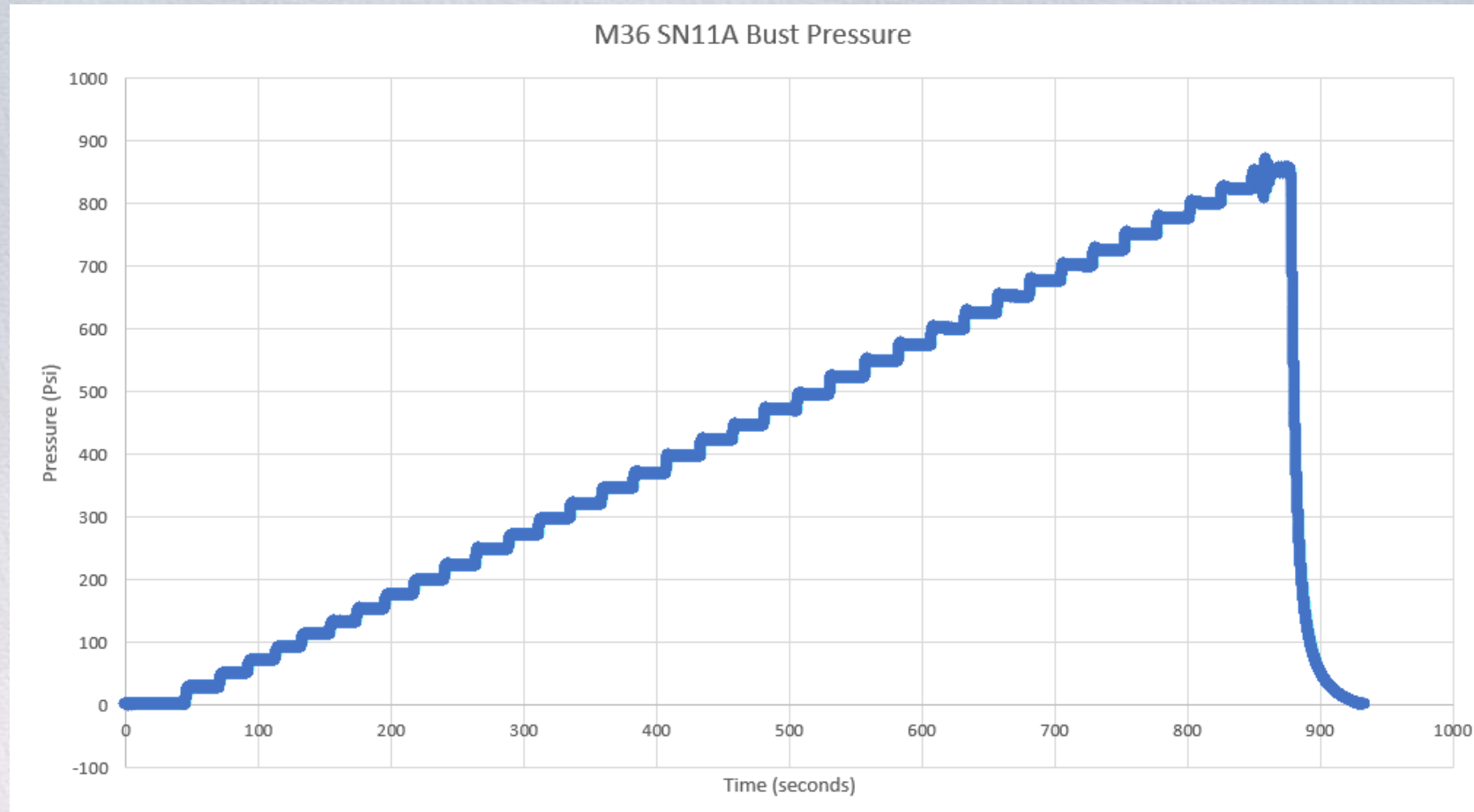
Cell Vent Pressure



- Cell is pressurized until it vents
- Pass/Fail criteria is for average vent pressure to average burst pressure ratio to be greater than 1:1.5

Cell Burst Pressure

- Cell vent is sealed shut using epoxy then the cell is pressurized until the crimp seal of the cell bursts
- Pass/Fail criteria is for average vent pressure to average burst pressure ratio to be greater than 1:1.5



Testing Status

TBD = To be done

Test	LG M36	Moli M35A	Samsung 30Q	Moli P28B
ILA				
• Uniformity	Done	Done	Done	On-going
• CT/DPA	Done	Done	On-going	On-going
LAT Performance				
• Cycle life	Done	On-going	Done	TBD
• Environmental	Done	Done	Done	TBD
• Seal integrity	TBD	TBD	TBD	TBD
• Heat conduction calorimetry	Done	Done	TBD	TBD
• Calendar life	On-going	On-going	Jun 2022	Jun 2022
LAT Abuse				
• Overcharge	Done	Done	On-going	TBD
• Short circuit	Done	Done	On-going	TBD
• Fractional TR calorimetry	Done	Done	On-going	TBD
• Vent & burst pressure	Done	Done	TBD	TBD
LAT CT/DPA	TBD	TBD	TBD	TBD
SWR	Done	Done	TBD	TBD

Looking to issue LAT reports for the 2 high energy cells by Christmas and 2 high power cells by Mar 2022

Reserve Team (so far)

- NAVSEA – Developing partner for all processes
- Buying cells
 - ADS, PCTEST, LG Chem
 - E-one Moli Energy
 - KULR, De-Leon Energy, SDI
- Buying ISC device implanted cells - KULR
- ILA – PCTEST, Ralph White & Associates, JSC
- LAT – PCTEST, SRI, NRL, JSC
- Storage - JSC
- Screening – Energy Assurance

Summary

- COTS Li-ion Cylindrical Cell Strategic Reserve Reduces Risks NASA & NAVSEA Projects
 - Four 18650 lots bought in large qty with chain of custody evidence to cell manufacturer
 - Two high energy designs
 - Two high power designs
 - Processed through standardized work instructions
 - Receiving inspection (EP-WI-035)
 - Initial Lot Assessments (EP-WI-36A)
 - Cell CT/DPA (EP-WI-034)
 - Side Wall Rupture Characterization (EP-WI-038)
 - Cell Lot Acceptance Testing (EP-WI-033A)
 - Cell Screening (EP-WI-037)
 - Provide projects with screened cells from certified lots
 - Address availability, quality, and safety risks that are currently exacerbated by world-wide cell shortages
 - Contact me at eric.c.darcy@nasa.gov

