

Lot-to-Lot Performance Review of GS Yuasa Li-Ion Space Cells

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- GS Yuasa Technology (GYT) Lithium-ion Space Flight Heritage Update
- Current Cell Line up and Qualification Status
- Configuration Management's role on Manufacturing Consistency and Quality
- Lot to Lot Performance review of the LSE134-101 and LSE190-101.
 - Method of cell data analysis
 - Typical statistical methods (assumes normal distribution)
 - Nonparametric methods (assumes no underlying distribution)

GS Yuasa Lithium-ion Space Heritage



Powering the Next Generation

GS Yuasa is a world leader in Li-ion energy storage for orbital vehicles

- Number of satellites..... 135+
 - LEO/MEO..... 56
 - GEO..... 80
- 1st satellite on-orbit..... Servis 1 (30 Oct. 2003)
- Longest satellite on-orbit (yrs)..... >10 (IPSTAR, 11 Aug. 2005) still operational
- Watt hours on-orbit..... >2.85 million
- Space cell qualification programs..... >21
- Cell sizes (Ah) flown..... 35; 50; 100; **134**; 175; 190; 200
- Performance to date..... No failures
- Backlog (Wh)..... ~1.6 million



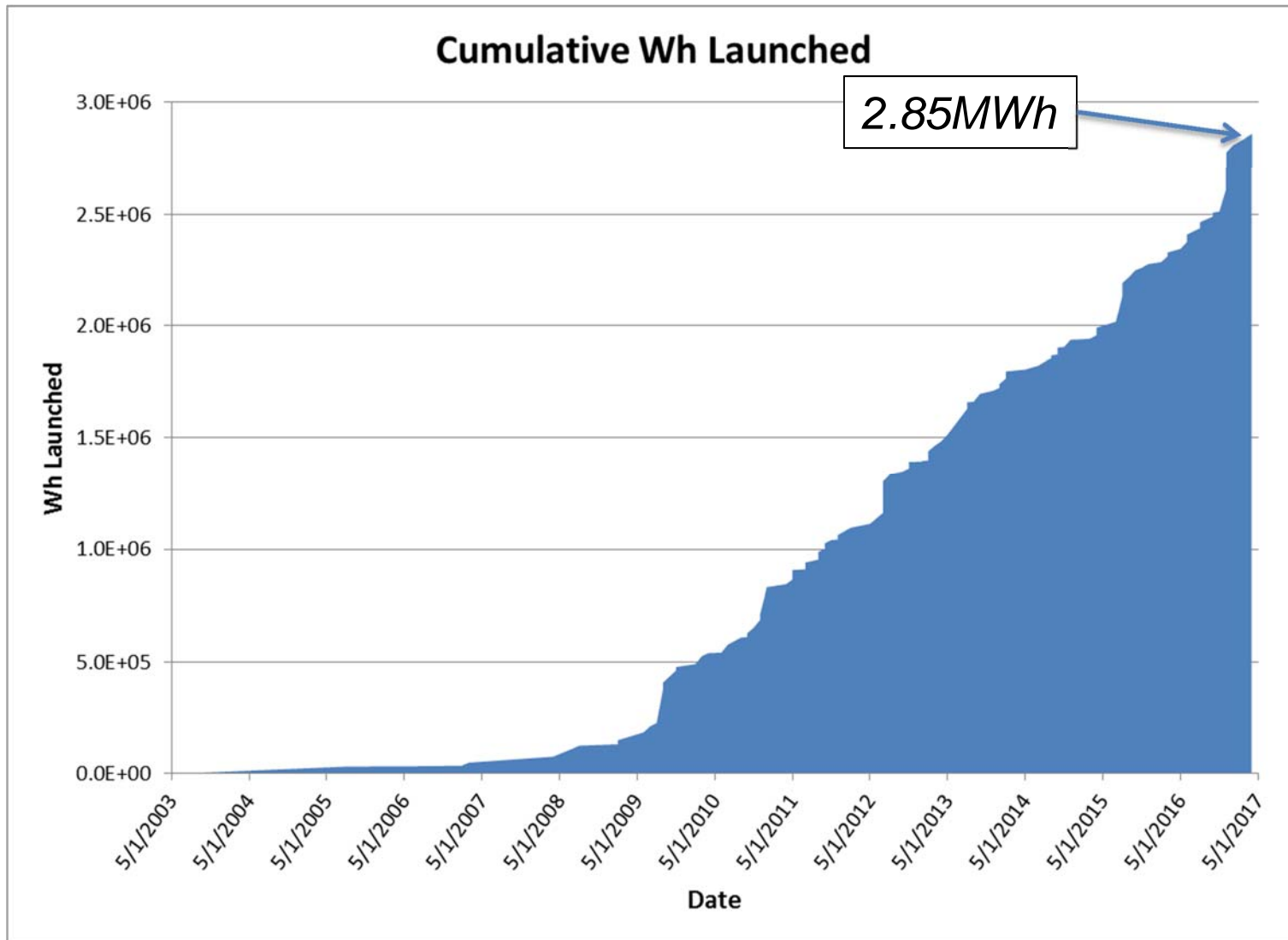
Launch vehicles & number of satellites

Ariane-5	33	H-2B	5	Falcon-9 v.1.2	3	Atlas-5(431)	1
Soyuz-2-1 Fregat	24	Antares	4	Proton-M Briz-M (Ph.4)	2	Dnepr	1
Proton-M Briz-M (Ph-3)	18	Atlas-5(401)	5	Rokot-KM	2	Epsilon	1
H-2A	15	Proton-M Briz-M (Ph.2)	4	Zenit-3SL (2)	2	GSLV Mk.2	1
Falcon-9 v.1.1	5	Zenit-3SLB	3	Atlas-5(421)	1	Proton-M Briz-M (P1m1)	1

GS Yuasa Lithium-ion Cells, MWh Launched



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GS Yuasa Space Li-Ion Cell Configurations



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Cell Configuration	Chemistry		Dimensions (mm)			
	Generation II	Generation III		Width	Height*	Thk.
	Standard	Energy Type	Power Type			
	LSE35	LSE42	LSE38	98	151	37
	LSE50	LSE55	LSE51	130	123	50
	LSE100	LSE110†	LSE102†	130	208	50
		LSE145†	LSE134	130	263	50
	LSE175	LSE190	LSE176	165	263	50

* Not including terminal

† Revised positive terminal

GS Yuasa Space Li-Ion Cell Configurations



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- Configuration qualified
- Configuration qualified, QT data property of US Government
- Qualification pending
- Engineering model cells on test
- Equivalent configuration qualified and flown, Japanese program

Cell Configuration	Chemistry			Dimensions (mm)		
	Generation II	Generation III		Width	Height*	Thk.
	Standard	Energy Type	Power Type			
	LSE35	LSE42	LSE38	98	151	37
	LSE50	LSE55	LSE51	130	123	50
	LSE100	LSE110 [†]	LSE102 [†]	130	208	50
		LSE145 [†]	LSE134	130	263	50
	LSE175	LSE190	LSE176	165	263	50

* Not including terminal

† Revised positive terminal

GS Yuasa Lithium-ion Cells for Space



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		GEN II			GEN III					
		Heritage			Power			Energy		
Model		LSE50	LSE100	LSE175	LSE51	LSE102	LSE134	LSE110	LSE145	LSE190
Cathode		LiCoO2			LiCoO2			LiCoO2		
Anode		Graphite			Graphite			Graphite		
Cell Capacity										
Nominal Capacity	Ah	50	100	175	51	102	134	110	145	190
Nominal Energy	Wh	185	370	648	189	377	496	407	536.5	703
Specific Energy (Nominal)	Wh/kg	123	133	139	124	136	140	147	151	153
Cell Electrical Specifications										
Nominal Voltage	V	3.7			3.7			3.7		
End of Charge	V	3.98			4.1			4.1		
End of Discharge	V	2.75			2.75			2.75		
Max Continuous Charge Current	A	25	50	87	25	50	67	55	72.5	95
Continuous Discharge Current	A	50	100	175	76.5	150	134	110	145	190
Maximum Discharge Current	A	150	300	525	153	300	402	330	435	570
Environmental Operation Ranges										
Temperature range (°C)	Charge	10 ~ 30			10 ~ 30			10 ~ 30		
	Discharge	-10 ~ 30			-10 ~ 30			-10 ~ 30		
	Storage	-10 ~ 10			-10 ~ 10			-10 ~ 10		

* Charge/discharge currents limited by temperature.

- Large format Lithium-ion cells are built to order and while the factory is always in production, several months can go by between production runs of a particular cell design.
 - How do I know if any changes have been made since the last build or order?
 - Have the materials changed or come from different sources?
 - Is it a risk that the cell design hasn't been manufactured for several months?

Robust Configuration Management Systems and Supplier Control Regulation is the answer.

A strong configuration management system covering procurement through final test will mitigate the above concerns.

Supplier management is critical to the performance consistency of the LSE cell.

- GS Yuasa maintains strong relationships with suppliers of LSE components.
 - GS Yuasa is a major purchaser of Li-ion materials (for both space and terrestrial applications) and has significant leverage in the marketplace.
 - Key supplier relationships date back several decades.

- GYT conducts regular audits of supplier's facilities.
 - Suppliers who provide critical components (terminals, cell cases, active material) are audited more frequently.

- GYT holds a Supplier Conference in Kyoto every year.
 - 60+ suppliers attend.
 - GYT reports on the quality ratings of those suppliers and collaborate on ways to improve quality systems.

- How can we measure the effectiveness?
 - Internal and External Audits of the quality system and cell design documentation.
 - Audits should reveal no unauthorized changes to the documentation
 - Organizations are welcomed to visit the factory in Kyoto to review the quality system, production documentation and tour the manufacturing and test areas.
 - » Aerojet Rocketdyne, Aerospace Corp, Boeing, JHUAPL, Lockheed, NASA, Orbital, USG, etc...
 - Review Cell Test Data
 - The ability to demonstrate lot to lot consistency is critical and can be used as an indirect measure of the organizations quality system. However this requires a large amount of manufactured cells for effective analysis.

Production Data Review



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Study Population 1:

Cell Design: LSE134-101

Unique Production Lots: 12

Serialized Cell Quantity: 1247

Activation Date ranges: Q4 2011 through Q2 2016

(Not continuous production. Typical for other cell designs to be manufactured in between LSE134-101 lots)

Study Population 2:

Cell Design: LSE190-101

Unique Production Lots: 11

Serialized Cell Quantity: 514

Activation Date ranges: Q4 2009 through Q4 2016

(Not continuous production. Typical for other cell designs to be manufactured in between LSE190-101 lots)

Note on Manufacturing:

- Cell Manufacturing consists of several batch processes.
 - Mixing, Coating, Winding, Electrolyte Filling / Activation, Testing
- Critical that processes be repeatable.
 - Inconsistency can create variation in the cell characteristics.
- Continuous improvement activities incorporated over time

LSE134-101 & LSE190-101 Production Quantities



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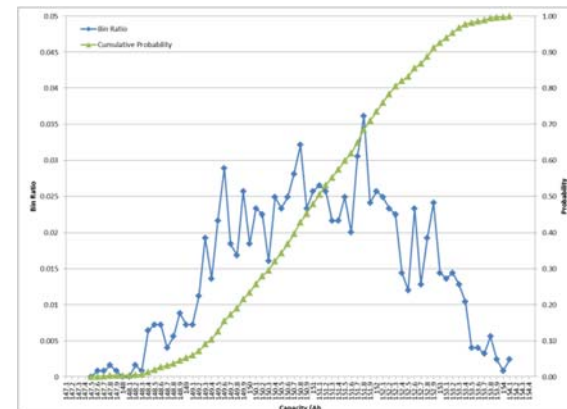
Lot Number	Activation Date	Serialized cell qty
001	09/2011	111
002	04/2012	67
003	01/2013	68
004	09/2013	110
005	01/2014	111
006	09/2014	113
007	12/2014	107
008	06/2015	115
009	07/2015	110
010	10/2015	112
011	04/2016	110
012	06/2016	113
	Total	1247

Lot Number	Activation Date	Serialized cell qty
001	11/2009	77
002	09/2010	27
003	11/2010	27
004	02/2012	55
005	07/2012	28
006	09/2012	27
007	01/2013	25
008	05/2013	29
009	10/2015	11
010	12/2015	118
011	12/2016	90
	Total	514

- Typical Statistical Methods
 - Population Average
 - Population Standard Deviation (σ)
 - Average $\pm 3\sigma$
 - Check for possible out of family data or test anomalies

Assumes the data is normal which is not always a good assumption!

- Nonparametric statistical methods
 - Population Median
 - Population fourths (pseudo quartiles)
 - Define outlier tolerance
 - Check for out of family data. Can be made more or less sensitive depending on the criticality.



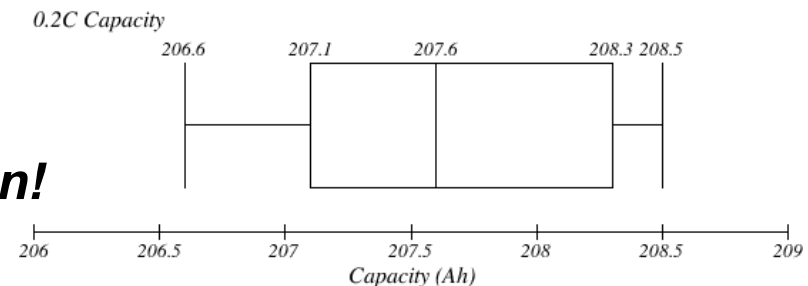
Nonparametric Data Examination Techniques

- Method of Fourths, Data review process
 - Sort values according in ascending order and assign Ranks (1,2,...,n)
 - Find rank that corresponds to Median value ($n_{Median} = \frac{n+1}{2}$)
 - Establish Fourth Rank boundaries and their corresponding values
 - Lower Fourth Rank: $F_L = \frac{n_{Median}+1}{2}$
 - Upper Fourth Rank: $F_U = n + 1 - F_L$
 - Establish Fences
 - Spread: $d_f = \text{Value}_{F_U} - \text{Value}_{F_L}$
 - Lower Fence, $L_{fence} = \text{first data point} > \text{Value}_{F_L} - 1.5 * d_f$
 - Upper Fence: $U_{fence} = \text{first data point} < \text{Value}_{F_U} + 1.5 * d_f$
 - If data is a normal distribution data between the fences is $\text{Average} \pm 2.7\sigma$
 - Use a Box Plot for quick visual identification
 - Easily shows potential outside values, but may not necessarily be outliers

Rank	Value
1	206.6
2	206.7
3	206.8
4	207.4
5	207.5
6	207.6
7	207.9
8	208.3
9	208.4
10	208.4
11	208.5

Lfence		205.3
FL	3.5	207.1
median	6	207.6
Fu	8.5	208.3
Ufence		210.2
df		1.23

Does not assume an underlying distribution!



- Cell initial characteristics are inspected for prior to serialization. This suite of tests is standard for space cells GS Yuasa manufactures:
 - Soft Short Test
 - **0.2C Discharge Capacity**
 - 0.5C Discharge Capacity
 - DC Resistance (calculated)
 - AC Impedance
 - Dimensions
 - Appearance

Initial Characteristics Inspection

C/5 and C/2 Standard GYT Capacity Test



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0.2CA discharge capacity is measured with the procedure shown below:

LSE134-101 C/5 Capacity Test						
Step	Operation	Type	Current / A	Voltage / V	Time	Temp.
1	Rest	–	–	–	4 hours or more	20 deg.C
2	Charge	CC/CV	26.8	4.10	8 hours	
3	Rest	–	–	–	+30/-0 minutes	
4	Discharge	CC	26.8	2.75	–	
5	Rest	–	–	–	10 min or more	

Requirement: Discharge capacity shall be >140 Ah as measured in step 4

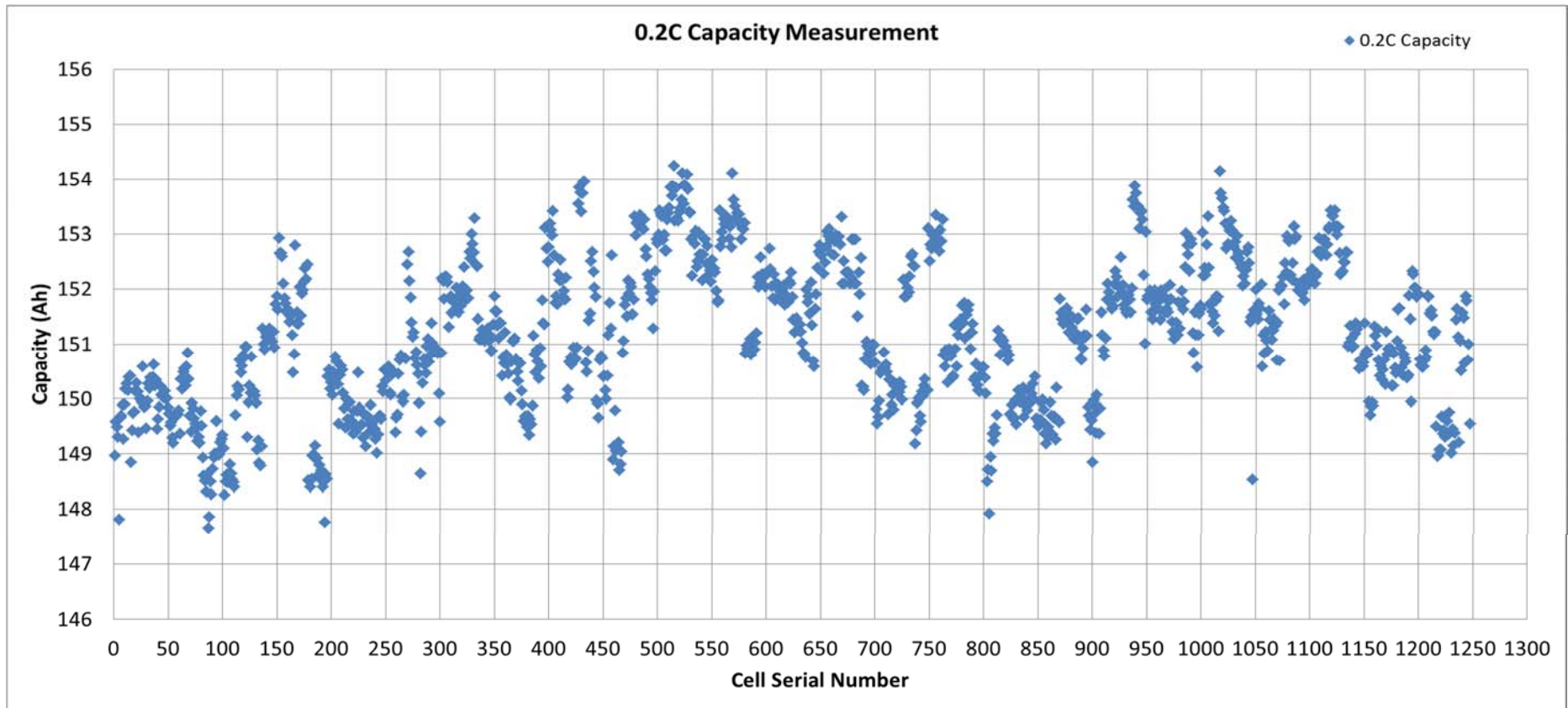
LSE190-101 C/5 Capacity Test						
Step	Operation	Type	Current / A	Voltage / V	Time	Temp.
1	Rest	–	–	–	4 hours or more	15 deg.C
2	Charge	CC/CV	38	4.10	8 hours	
3	Rest	–	–	–	+30/-0 minutes	
4	Discharge	CC	38	2.75	–	
5	Rest	–	–	–	10 min or more	

Requirement: Discharge capacity shall be >198 Ah as measured in step 4

LSE134-101 0.2C Capacity



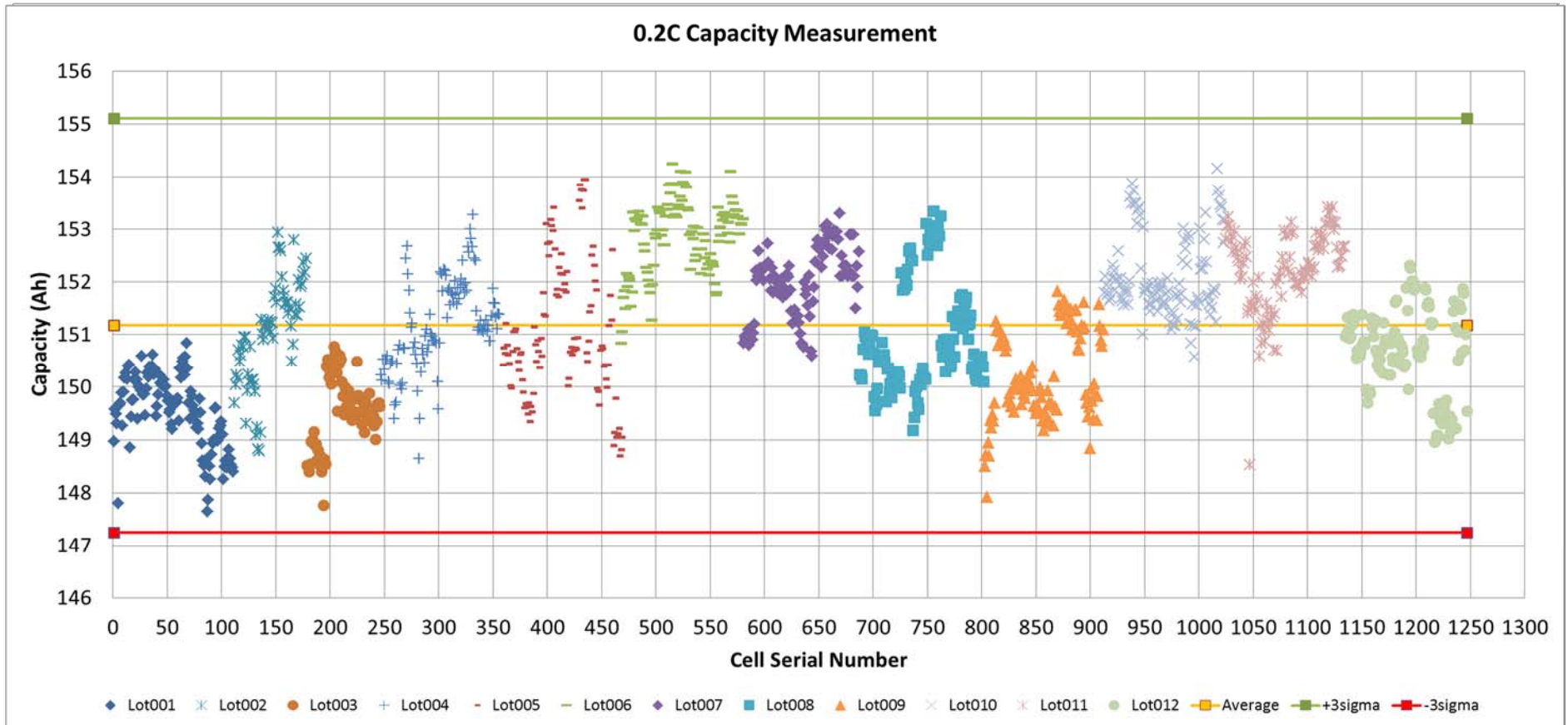
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LSE134-101 0.2C Capacity



Powering the Next Generation



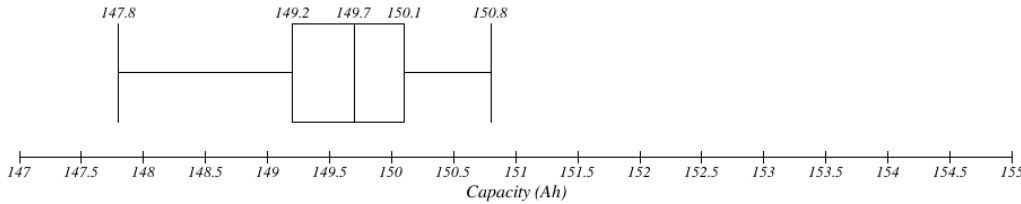
Lot	Average	Std Deviation	$\pm 3\sigma$	Min-Max
All	151.18	1.31	147.25-155.11	147.65-154.25

Nonparametric LSE134-101 Lot to Lot Comparison



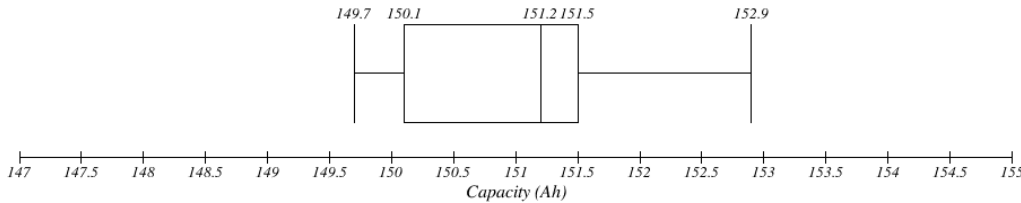
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Lot001



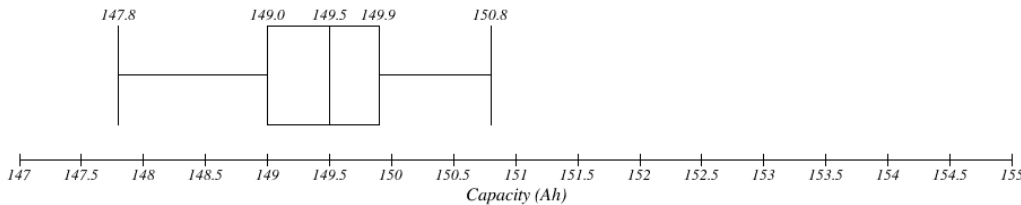
Lot	Median	F _L	F _U	Fence _L	Fence _U
001	149.7	149.2	150.1	147.8	150.8

Lot002



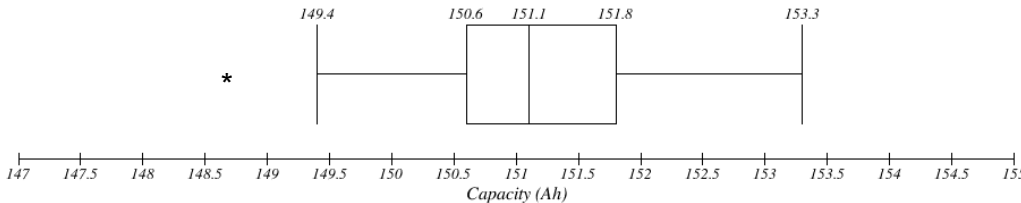
Lot	Median	F _L	F _U	Fence _L	Fence _U
002	151.16	150.36	151.67	148.79	152.93

Lot003



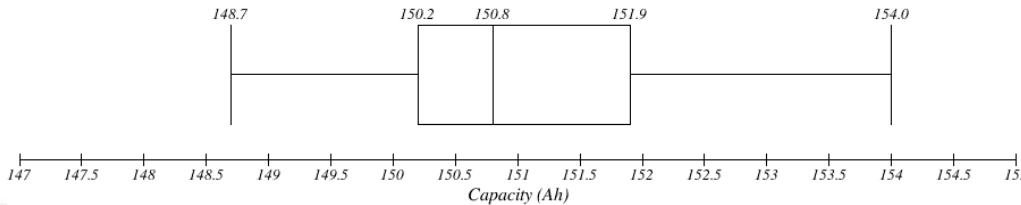
Lot	Median	F _L	F _U	Fence _L	Fence _U
003	149.53	149.00	149.91	147.76	150.77

Lot004



Lot	Median	F _L	F _U	Fence _L	Fence _U
004	151.11	150.61	151.83	149.39	153.28

Lot005



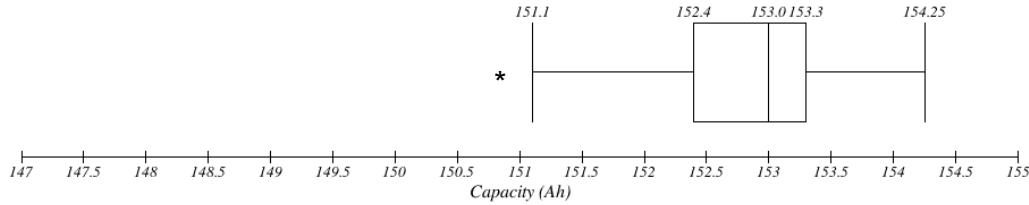
Lot	Median	F _L	F _U	Fence _L	Fence _U
005	150.75	150.16	151.86	148.70	153.95

Nonparametric LSE134-101 Lot to Lot Comparison



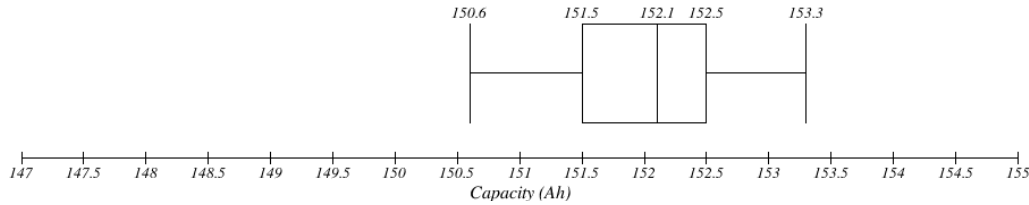
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Lot006



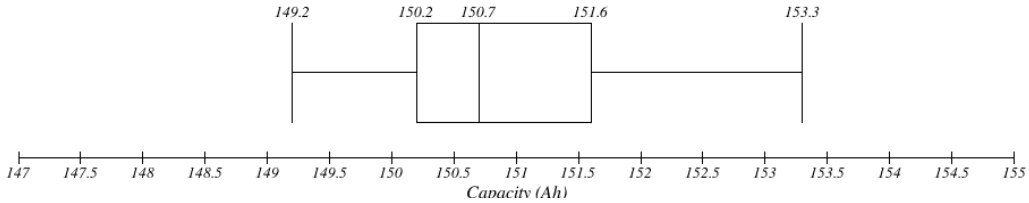
Lot	Median	F _L	F _U	Fence _L	Fence _U
006	152.99	152.37	153.31	151.1	154.25

Lot007



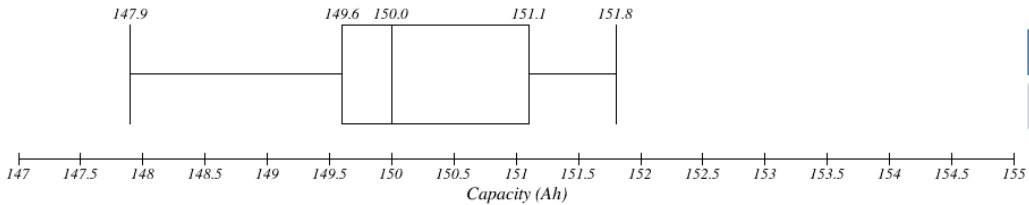
Lot	Median	F _L	F _U	Fence _L	Fence _U
007	152.10	151.53	152.49	150.59	153.30

Lot008



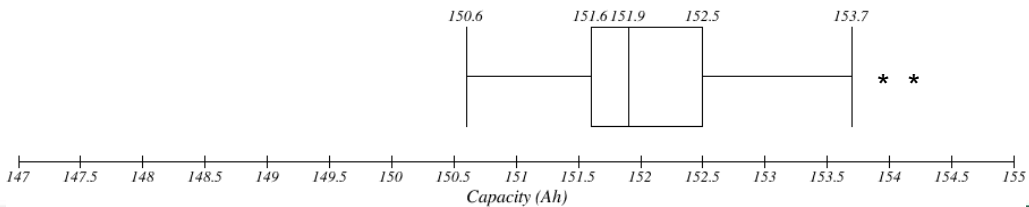
Lot	Median	F _L	F _U	Fence _L	Fence _U
008	150.66	150.24	151.57	149.18	153.34

Lot009



Lot	Median	F _L	F _U	Fence _L	Fence _U
009	114.98	147.46	151.08	147.92	151.82

Lot010



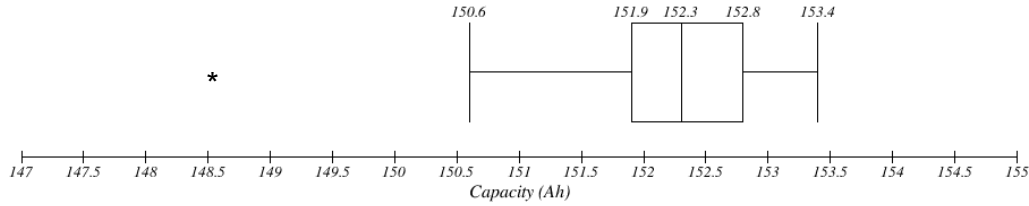
Lot	Median	F _L	F _U	Fence _L	Fence _U
010	151.86	151.63	152.49	150.57	153.74

Nonparametric LSE134-101 Lot to Lot comparison



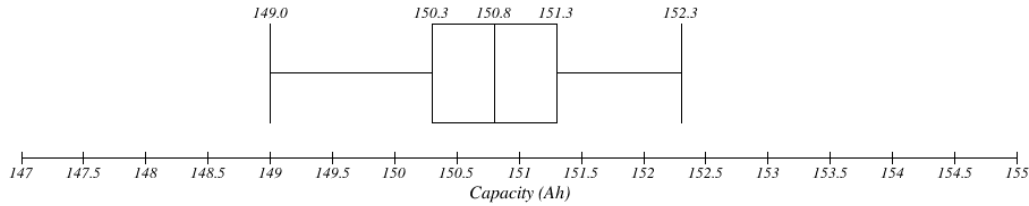
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Lot011



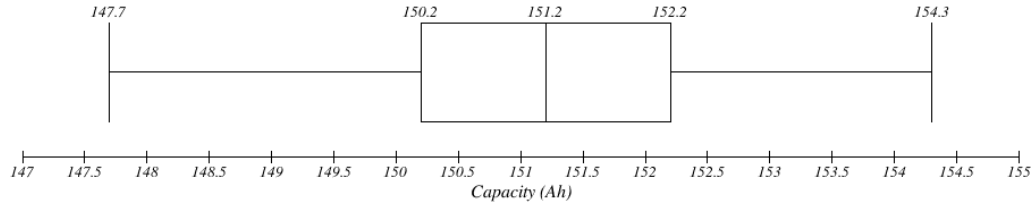
Lot	Median	F _L	F _U	Fence _L	Fence _U
011	152.29	151.91	152.81	150.59	153.42

Lot012



Lot	Median	F _L	F _U	Fence _L	Fence _U
012	150.76	150.26	151.27	148.95	152.32

All Lots



Lot	Median	F _L	F _U	Fence _L	Fence _U
All	151.17	150.15	152.16	147.65	154.25

Consistency Comparison



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- Relative Standard Deviation (RSD):
 - $RSD\% = \text{Stdev} / \text{abs}(\text{Mean}) * 100$
 - Expressed as a percent, this equation describes the data variation relative to the mean of the study population.
 - The lower the value the less variation there is around the mean.

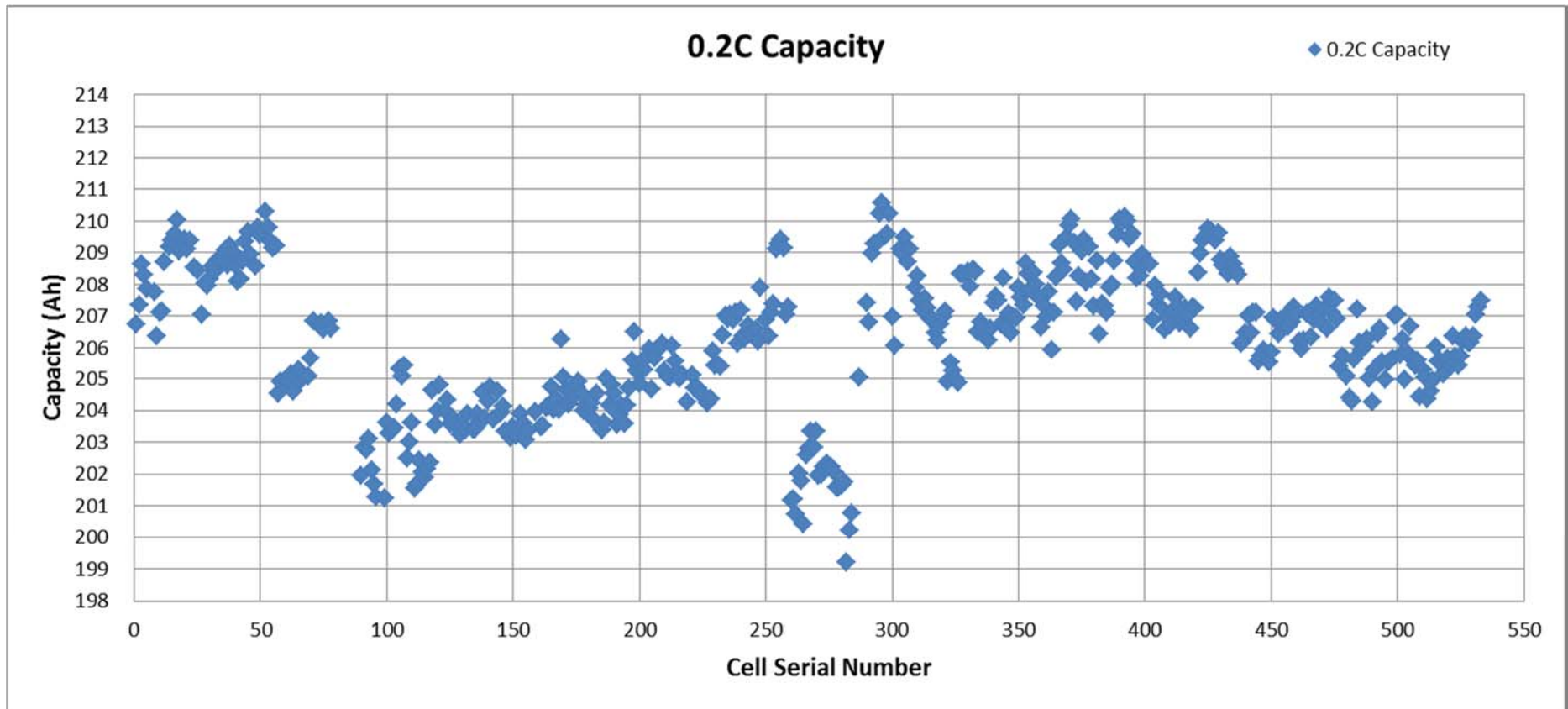
Across 12 unique manufacturing lots consisting of 1247 serialized cell there is <1% RSD, with an intra-lot <1%RSD. Manufacturing process is very consistent!

Lot #	Stdev	Mean	RSD%
1	0.69	149.54	0.69
2	0.99	154.05	0.66
3	0.67	149.50	0.45
4	0.86	151.18	0.57
5	1.28	151.06	0.85
6	0.69	152.9	0.45
7	0.66	152.01	0.44
8	1.01	150.98	0.67
9	0.85	150.24	0.57
10	0.76	152.11	0.50
11	0.75	152.23	0.50
12	0.82	150.70	0.55
All Lots (1247 cells)	1.31	151.18	0.87

LSE190-101 0.2C Capacity



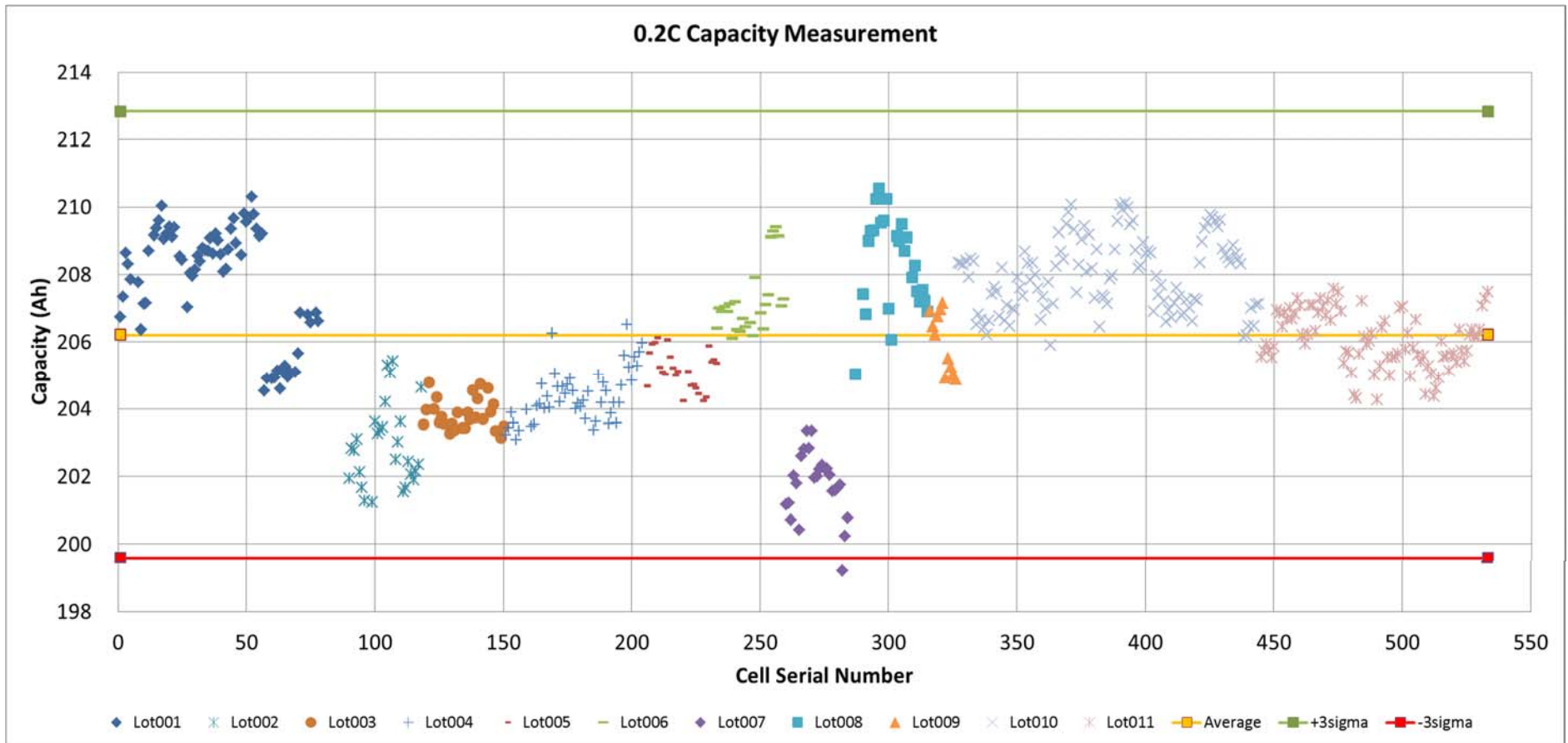
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LSE190-101 0.2C Capacity



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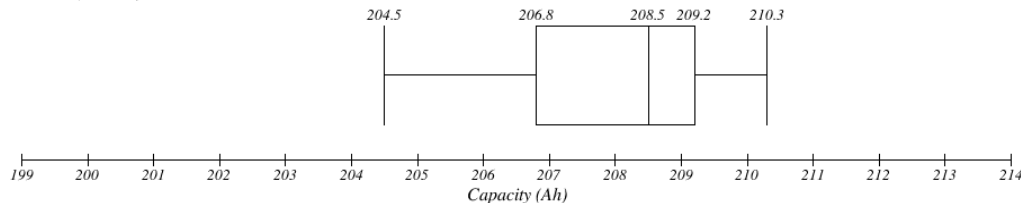
Lot	Average	Std Deviation	$\pm 3\sigma$	Min-Max
All	206.2	2.2	199.59-212.84	199.59-210.56

Nonparametric LSE190-101 Lot to Lot Comparison



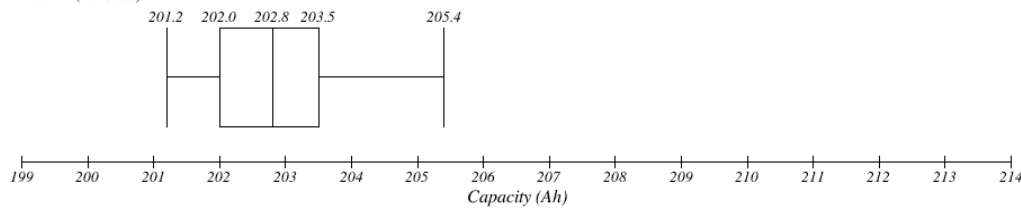
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Lot001 (67 cells)



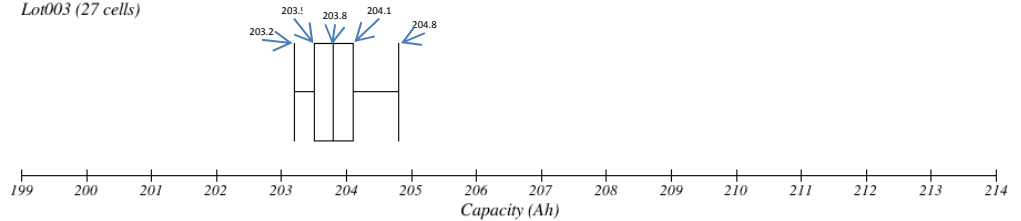
Lot	Median	F _L	F _U	Fence _L	Fence _U
001	208.54	206.82	209.16	204.54	210.31

Lot002 (27 cells)



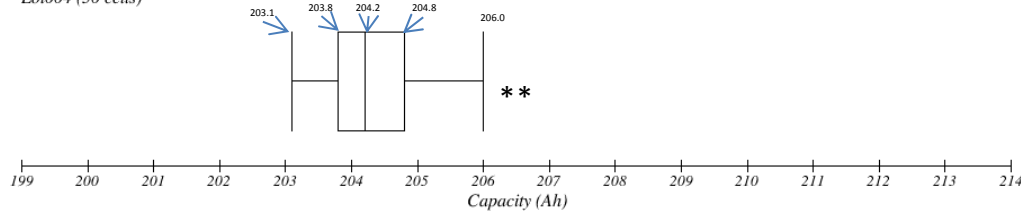
Lot	Median	F _L	F _U	Fence _L	Fence _U
002	202.76	202.00	203.54	201.24	205.42

Lot003 (27 cells)



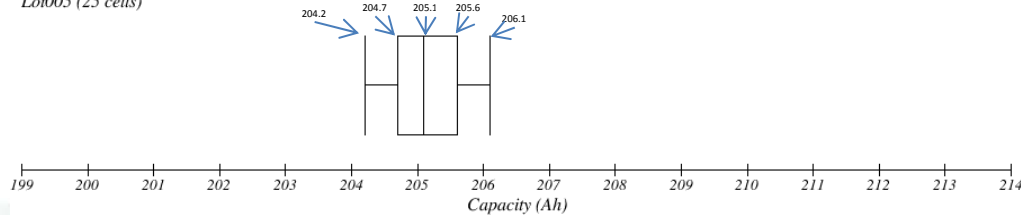
Lot	Median	F _L	F _U	Fence _L	Fence _U
003	203.75	203.51	204.07	203.15	204.79

Lot004 (50 cells)



Lot	Median	F _L	F _U	Fence _L	Fence _U
004	204.19	203.79	204.77	203.08	205.97

Lot005 (25 cells)



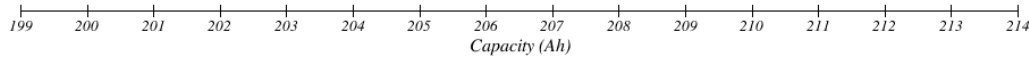
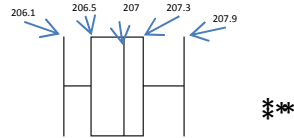
Lot	Median	F _L	F _U	Fence _L	Fence _U
005	205.12	204.7	205.56	206.13	204.24

Nonparametric LSE190-101 Lot to Lot Comparison



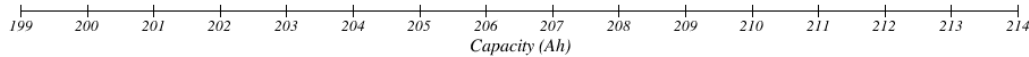
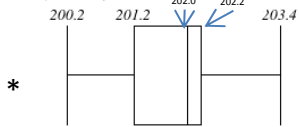
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Lot006 (25 cells)



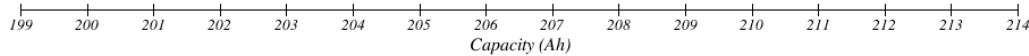
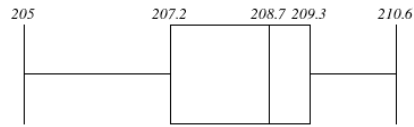
Lot	Median	F _L	F _U	Fence _L	Fence _U
006	207.00	206.45	207.27	206.12	207.91

Lot007 (25 cells)



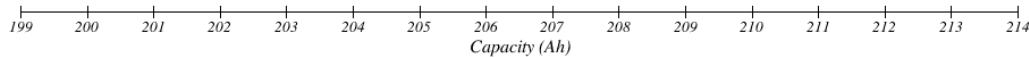
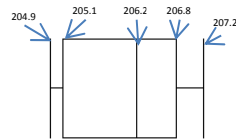
Lot	Median	F _L	F _U	Fence _L	Fence _U
007	201.95	201.22	202.23	200.24	203.36

Lot008 (25 cells)



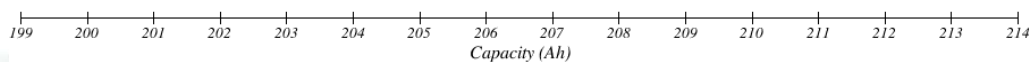
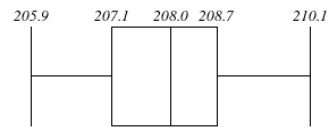
Lot	Median	F _L	F _U	Fence _L	Fence _U
008	208.7	207.24	209.31	205.04	210.56

Lot009 (11 cells)



Lot	Median	F _L	F _U	Fence _L	Fence _U
009	206.22	205.13	206.84	204.88	207.15

Lot010 (118 Cells)



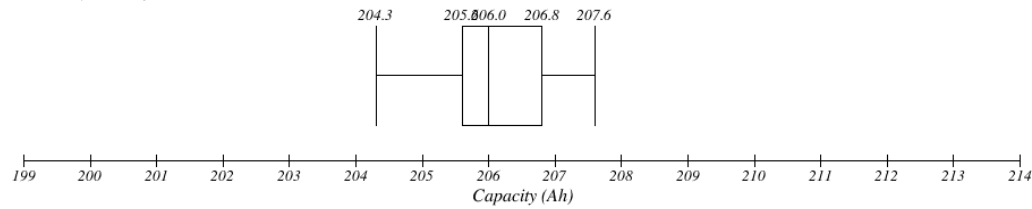
Lot	Median	F _L	F _U	Fence _L	Fence _U
010	207.97	207.09	208.70	205.91	210.12

Nonparametric LSE190-101 Lot to Lot Comparison



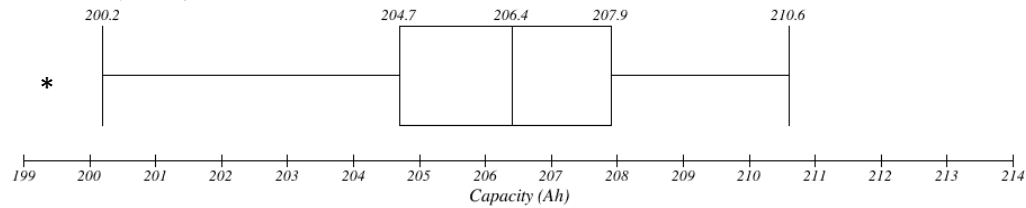
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Lot011 (89 Cells)



Lot	Median	F _L	F _U	Fence _L	Fence _U
011	206.02	205.55	206.82	204.27	207.59

LSE190-101 (All Cells)



Lot	Median	F _L	F _U	Fence _L	Fence _U
All	206.44	204.70	207.91	200.24	210.56

Consistency Comparison



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- Relative Standard Deviation (RSD):
 - $RSD\% = \text{Stdev} / \text{abs}(\text{Mean}) * 100$
 - Expressed as a percent, this equation describes the data variation relative to the mean of the study population.
 - The lower the value the less variation there is around the mean.

Across 11 unique manufacturing lots consisting of 514 serialized cell there is <1.5% RSD with an intra-lot <1% RSD. Manufacturing process is very consistent!

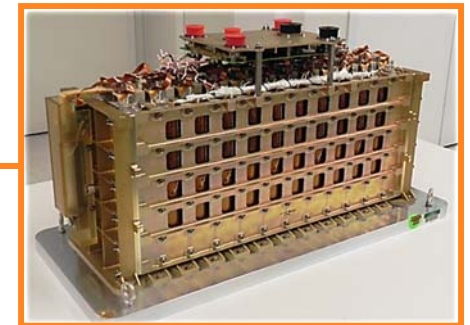
Lot #	Stdev	Mean	RSD%
1	1.62	207.9	0.78
2	1.19	202.9	0.59
3	0.45	203.8	0.22
4	0.78	204.4	0.38
5	0.57	205.2	0.28
6	0.98	207.2	0.47
7	0.95	201.8	0.47
8	1.38	208.3	0.66
9	0.86	206.0	0.42
10	1.07	208.0	0.52
11	0.83	206.1	0.20
All Lots (514 cells)	2.21	206.2	1.07

Conclusions



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- Rigorous systems in place for the control of materials, manufacturing, and test processes for GS Yuasa's LSE cells result in excellent consistency between manufacturing lots.
- Initial Characteristics reviewed for over 1200 manufactured LSE134-101 cells and 500 manufactured LSE190-101 cells and show excellent consistency for key parameters.
- When reviewing data for a single lot or several batch lots, assuming a normal population may not be a good assumption.
 - When writing specs be careful if you define statistical requirements for out of family determination.
 - Nonparametric methods can be used for verifying performance consistency as well as identifying which cells should be considered "best" for down selecting for delivery to a customer.



EPT part no.: SAR-10199
electrical config.: 1P9S
spaceflight heritage: 7 yrs



EPT part no.: SAR-10197
electrical config.: 2P9S
spaceflight heritage: 8 years



EPT part no.: SAR-10213
electrical config.: 2P9S
2018 launch



EPT part no.: SAR-10209
electrical config.: 1P8S
2017 launch

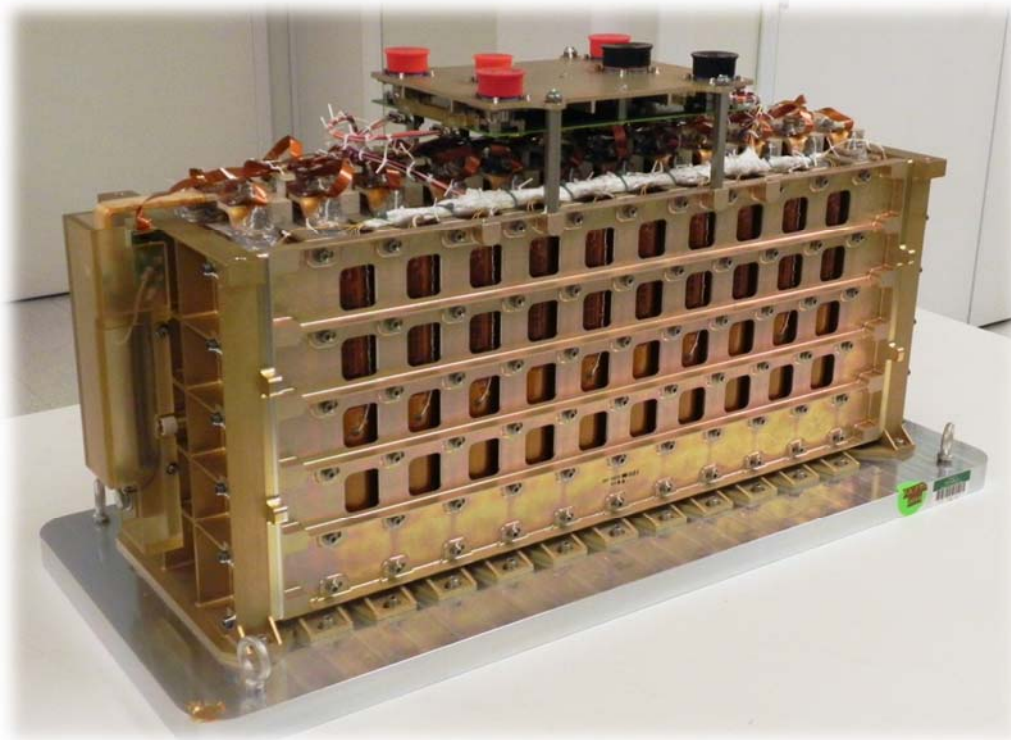
EPT Spaceflight Heritage with GS Yuasa cells: 26 batteries

Designs may be modified to meet customer specific requirements without invalidating qualification history.

LSE190 Modular Battery System Introduction



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GYLP has manufactured a 12 cell pack Qualification Battery

In application, a battery system may be comprised of multiple packs in series

**Cell level testing completed:
Environmental Tests (JSC 20793)**

- Vibration (sine & random)
- Shock
- Acceleration

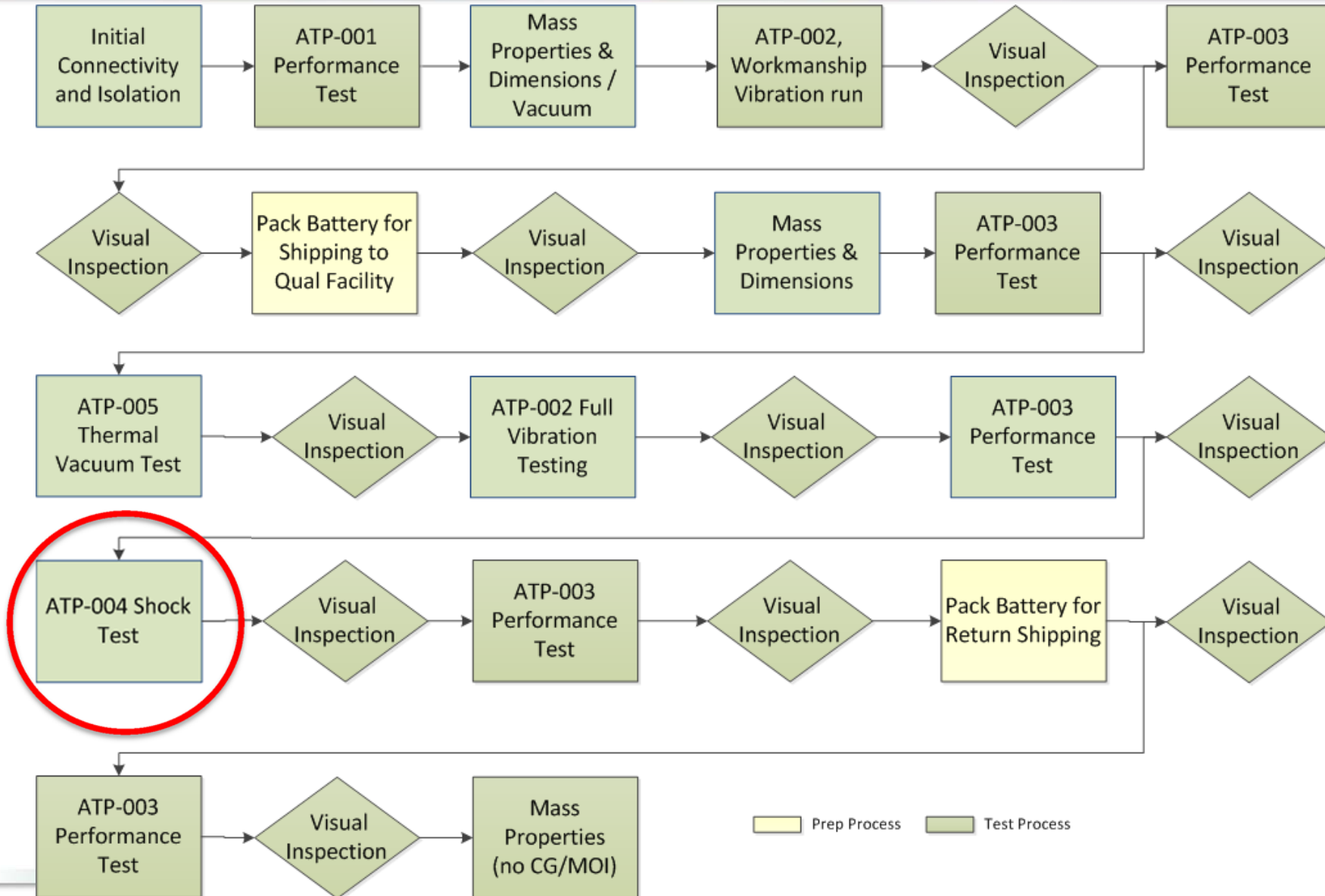
Cell Safety Tests

- Over-charge
- Over-discharge (forced reversal)
- External short circuit (2 & 5 milliohm)
- Crush (induced internal short circuit, fresh & seasoned specimen)
- Heat to vent
- Drop
- Vent pressure, Burst pressure

Battery Qualification Test Flow



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Battery Module Building Blocks



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Module	Configuration	Watt-hours ₁	GEO power (W) ₂	EOCV ₃	EODV ₄	Mass (lbm) ₅	Length (in.)	Width (in.)	Height (in.)
A	1p6s	4286.4	2610	25.2	20.1	86.1	15.16	9.17	13.17
B	1p7s	5000.8	3045	29.4	23.4	97.2	17.19	9.17	13.17
C	1p8s	5715.2	3480	33.6	26.7	108.4	19.22	9.17	13.17
D	1p9s	6429.6	3915	37.8	30.1	119.6	21.25	9.17	13.17
E	1p10s	7144	4350	42.0	33.4	130.7	23.28	9.17	13.17
F	1p11s	7858.4	4785	46.2	36.8	141.9	25.32	9.17	13.17
G	1p12s	8572.8	5220	50.4	40.1	153.1	27.35	9.17	13.17
H	2p3s	4286.4	2610	25.2	20.1	84.1	15.16	9.17	13.17
I	2p4s	5715.2	3480	33.6	26.7	105.8	19.22	9.17	13.17
J	2p5s	7144	4350	42.0	33.4	127.4	23.28	9.17	13.17
K	2p6s	8572.8	5220	50.4	40.1	149.1	27.35	9.17	13.17

¹BOL, C/2 discharge, 4.10V to 2.75V

²15 year GEO mission, 80% actual DOD max, no bypassed cells

³based on 4.20V per cell EOM condition

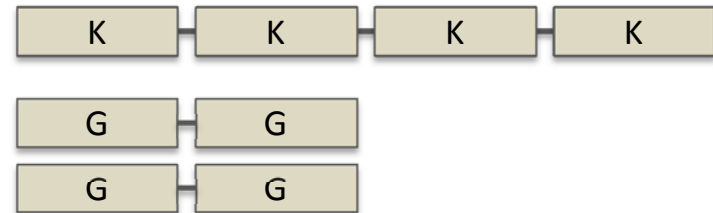
⁴EOM, based on 20 year GEO mission at rated power

⁵includes cell pack, bus bars, bypass switches, wire harness, heaters, FITs and flexes

Battery Configuration: 17.8kW GEO example

High voltage

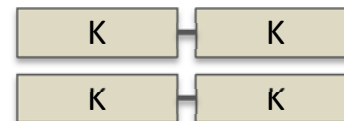
1 battery, 2p modules
[(K+K+K+K)*1]



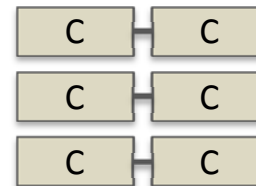
2 batteries, 1p module
[(G+G)*2]

Medium voltage

2 batteries, 2p modules
[(K+K)*2]



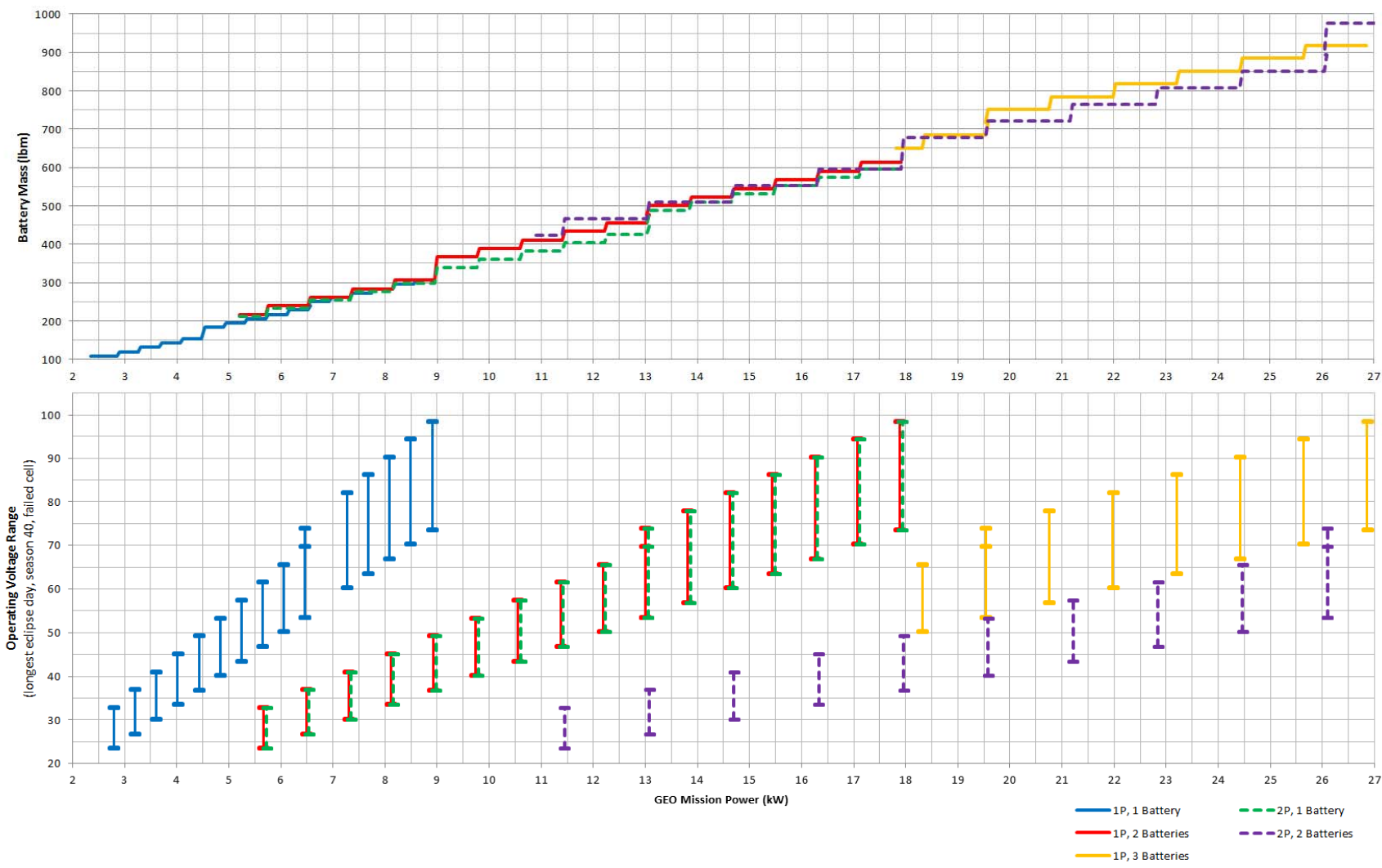
3 batteries, 1p module
[(C+C)*3]



Operating Voltage Range & Mass vs Power



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