Powering the Next Generation

Lot-to-Lot Performance Review of GS Yuasa Li-Ion Space Cells & the Role of Configuration Management

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Overview

- GS Yuasa Technology (GYT) Lithium-ion Space Flight Heritage Update
- Current Cell Line up and Qualification Status
- GS Yuasa's Approach to Configuration and Supplier Management
- Method of cell data analysis
  → Typical sigma method (assumes normal distribution)
  → Method of fourths (assumes no underlying distribution)
- 12 production lots Performance review of the LSE134-101.
  → Initial Capacity, AC Impedance, Mass

GS Yuasa Lithium-ion Space Heritage

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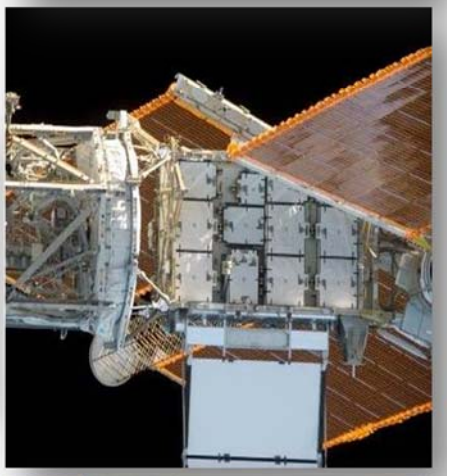
GS Yuasa is a world leader in Li-ion energy storage for orbital vehicles

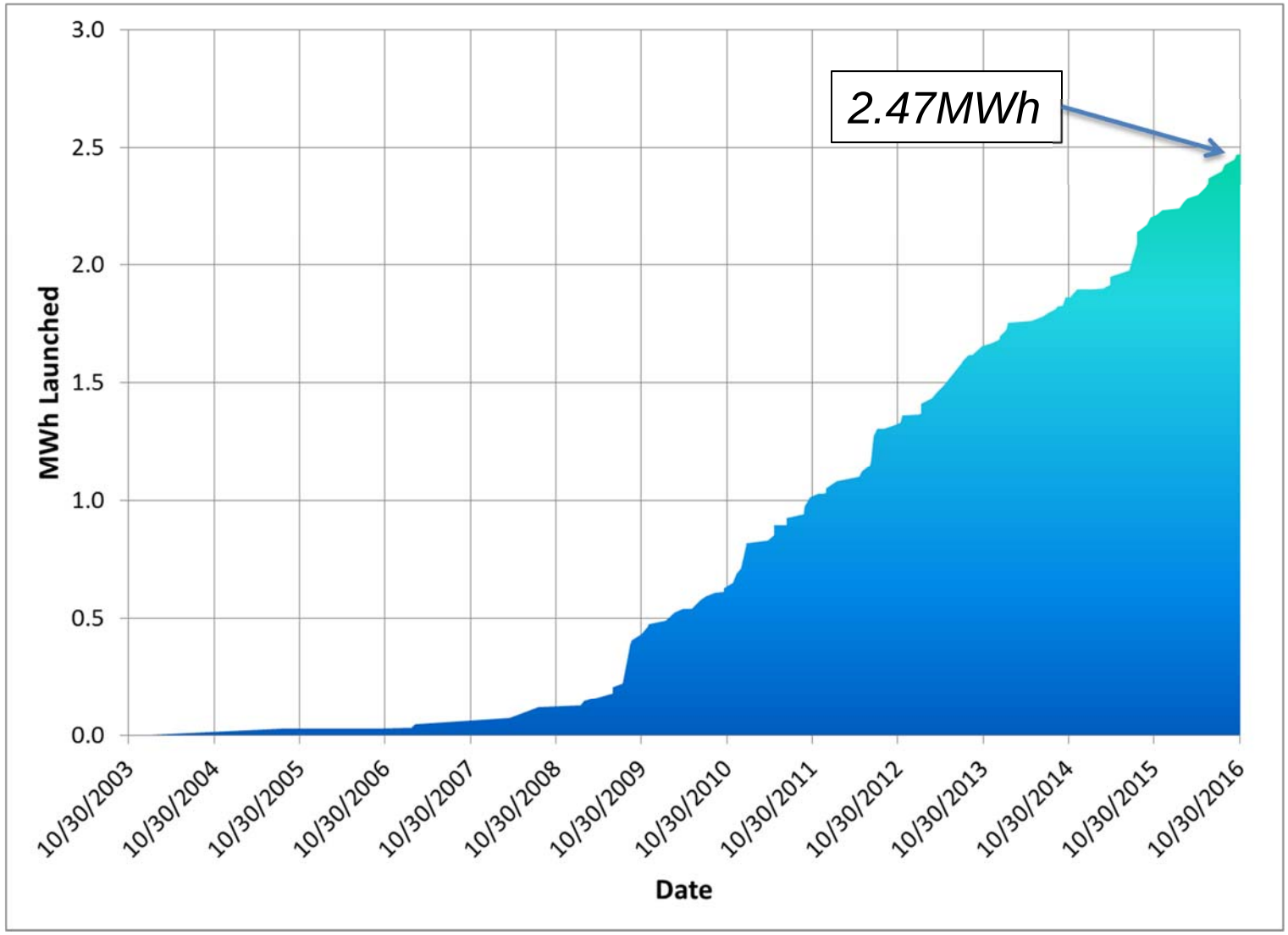
- Number of satellites…….…….. 129+
  - LEO/MEO……..….. 53
  - GEO……..…… 76
- 1st satellite on-orbit……..…. Servis 1 (30 Oct. 2003)
- Longest satellite on-orbit (yrs)…..... >10 (IPSTAR, 11 Aug. 2005) still operational
- Watt hours on-orbit…….…….... >2.47 million
- Space cell qualification programs……. >21
- Cell sizes (Ah) flown…..... 35; 50; 100; 175; 190; 200
- Performance to date……..... No failures
- Backlog (Wh)…….…… ~2 million



Launch vehicles & number of satellites

Ariane-5	33	H-2B	5	Falcon-9 v.1.2	2	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)	4	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



Notable NASA Space Programs

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OSC's CRS Cygnus vehicle

- LSE190 (Gen. III Energy Type Cell)
- Cell qualification testing (JSC20793) completed (GYT)
- Battery qualification successfully completed (GYLP)
- Flight batteries manufactured and delivered (GYLP)

Van Allen Probes (Radiation Belt Storm Probes)

- LSE50 (Gen. II Cell)
- Cell qualification testing completed (GYT)
- Successful launch of RBSP satellites on August 30, 2012
- Successfully completed primary mission

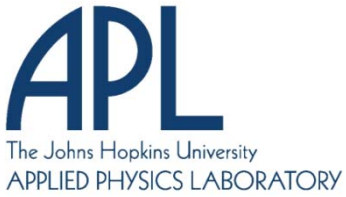
International Space Station

- LSE134 (Gen. III Power Type Cell)
- Cell qualification completed (GYT)
- Awarded contracts to deliver >1,000 cells (2012-2017)

ICESat-2

- LSE134 (Gen. III Power Type)

GS Yuasa Partners and Customers



GS Yuasa Space Li-Ion Cell Configurations

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	Chemistry			Dimensions (mm)		
	Generation II	Generation III		Width	Height*	Thk.
	Standard	Energy Type	Power Type			
Cell Configuration	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

"Heritage"

"Next Generation"

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

	Chemistry			Dimensions (mm)		
	Generation II	Generation III		Width	Height*	Thk.
Cell Configuration	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

"Heritage"

"Next Generation"

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	4.1			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 (^{0}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. While the factory is always in production, several months can go by between production runs of a particular cell design.

- This reality may raise a few questions:
  - → 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 significant 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.

- Configuration management refers to the specific quality processes which mandate how an organization will create, organize, manage and control the identification and physical/functional attributes of the product.
  → The configuration management quality regulation is developed by the organization with specific employees responsible for the training, execution, and oversight of the regulation's execution.

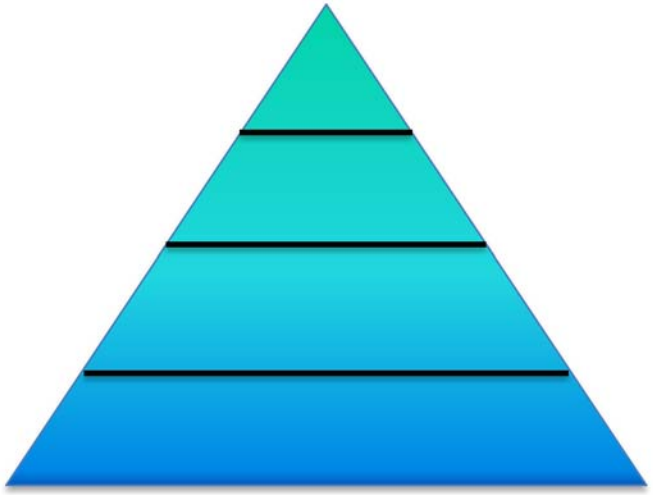
- Document Control: A systematic approach to the organization and release of official product documentation
- Change Control: Methods to allow changes of configuration controlled documents
  - Continuous improvement (Clarification, Improvements, etc…)
  - Correction of errors (incorrect information, typos, etc…)
  - Change to manufacturing (process/materials) or test

- Quality Assurance and Engineering groups work closely to execute, maintain and audit this system.
  → System is subjected to internal audits twice per year.

GS Yuasa Approach to Document Control

GS Yuasa defines 4 major levels of documentation, Starting with the most general and building to specific.

- Level 1: Quality Manual
- Level 2: Quality Regulations
- Level 3: Standards and Procedures
- Level 4: Forms and Records



The Quality Manual and various Quality Regulations describe how GS Yuasa will implement and control the quality of GS Yuasa Products. Level 3 and Level 4 documents define and control specific products and parts manufactured at GS Yuasa.

Level 3 and 4 documents are typically the focus of product audits.

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.
  - → Preservation of the qualified formulation.

- 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
      - o 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

Study Population

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)

Note on Manufacturing:

- Cell Manufacturing consists of several batch processes.
  → Mixing, Coating, Winding. Electrolyte Filling / Activation, Testing
- Critical that processes be repeatable.
  → If not a large variation in the cell characteristics should result.

LSE134-101 Production Quantities

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Lot Number	Activation Date	Delivery Target qty	Serialized cell qty
001	**09/2011**	100	111
002	04/2012	66	67
003	01/2013	66	68
004	09/2013	100	110
005	01/2014	100	111
006	09/2014	100	113
007	12/2014	100	107
008	06/2015	100	115
009	07/2015	100	110
010	10/2015	100	112
011	04/2016	100	110
012	06/2016	100	113
Totals		**1132**	**1247**

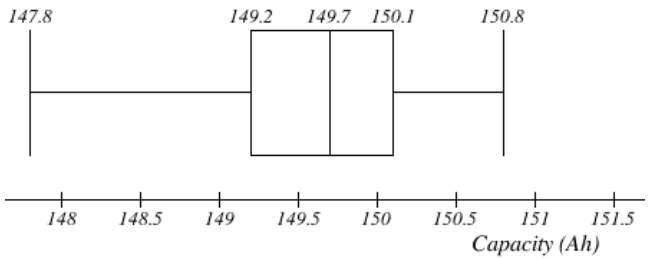
GS Yuasa typically manufactures 10%-15% more elements than required for delivery to account for typical process attrition.

Serialization occurs after the element has passed all internal GYT quality inspections

- Typical Statistical Methods
  - → Average
  - → Population Standard Deviation (σ)
  - → Average±3σ
    - Check for outliers as possible out of family data or test anomalies

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

- Method of Fourths, Alternate 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: $F_L = \frac{n_{Median}+1}{2}$
    - Upper Fourth: $F_U = n + 1 - F_L$
    - Fourth Spread: $d_f = F_u - F_L$



  - → Establish Fences
    - Lower Fence, L_{fence} = first data point > $F_L - 1.5*d_f$
    - Upper Fence: U_{fence} = first data point < $F_U + 1.5*d_f$
      - o If data is normal distribution data between the fences is Average±2.7σ
  - → Use a Box Plot for quick visual identification
    - Easily shows potential outside values, but may not necessarily be outliers

Does not assume an underlying distribution!

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:

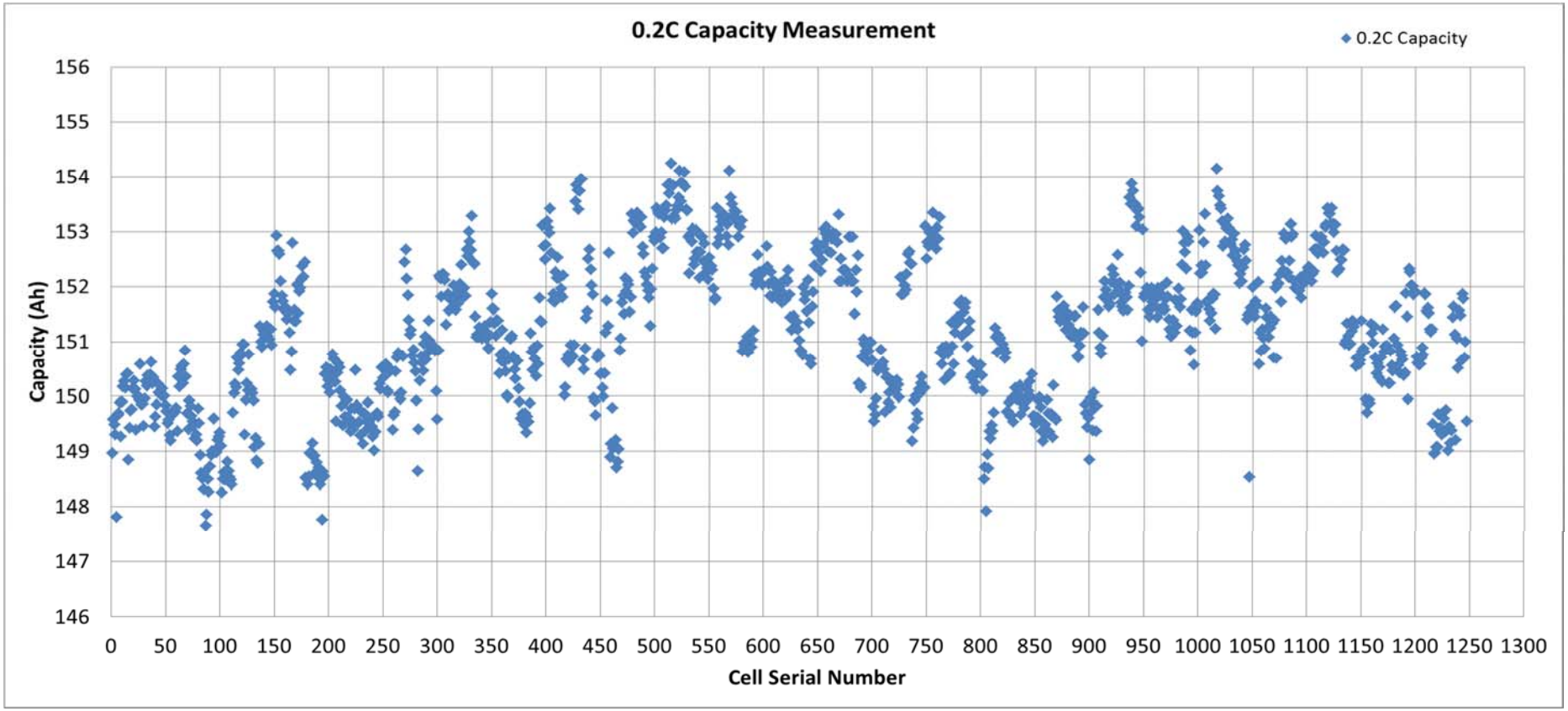
Step	Operation	Type	Current / A	Voltage / V	Time	Temp.
1	Rest	–	–	–	4 hours or more	20 deg.C
2	Charge	CC/CV	26.8	4.10	8 hours	
3	Rest	–	–	–	+30/-0 minutes	
4	Discharge	CC	26.8	2.75	–	
5	Rest	–	–	–	10 min or more	

0.5CA discharge capacity is measured with the procedure shown in below:

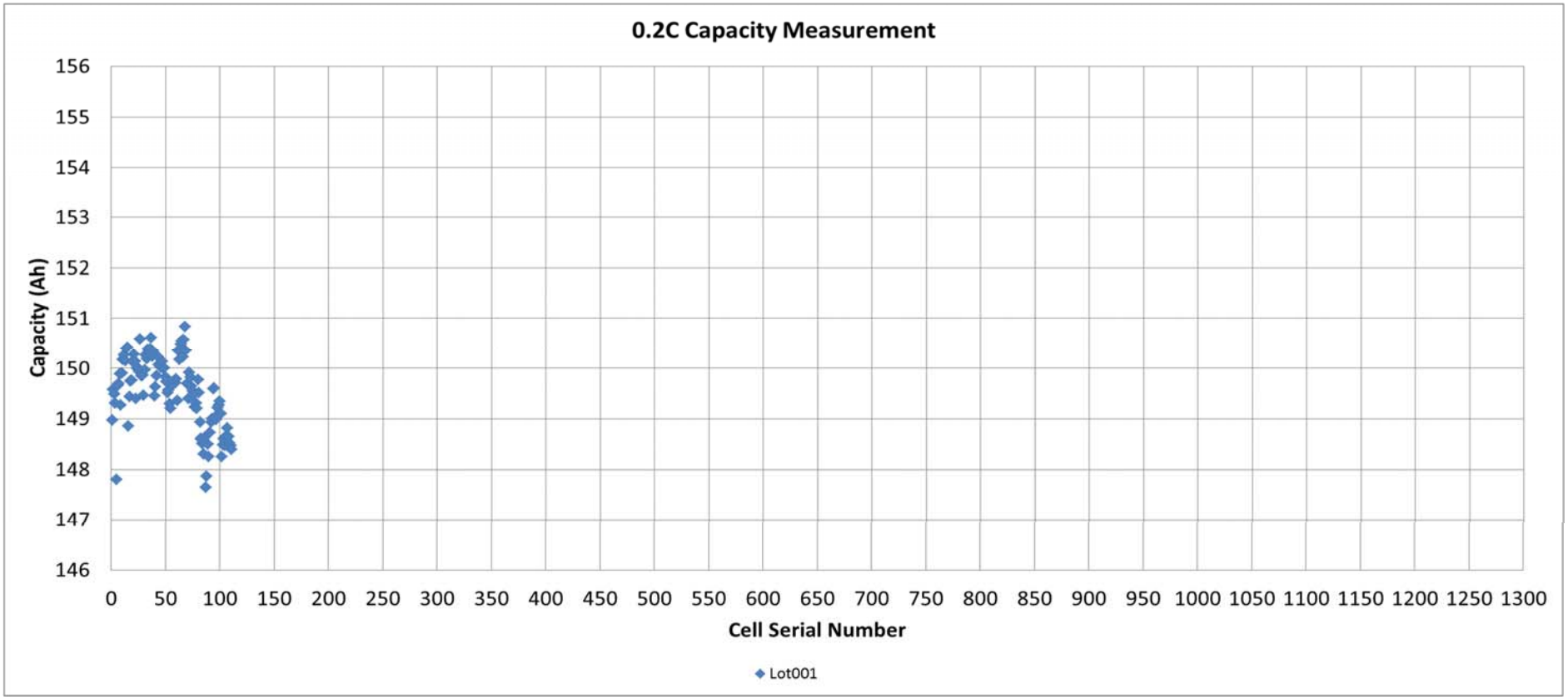
Step	Operation	Type	Current / A	Voltage / V	Time	Temp.
1	Rest	–	–	–	4 hours or more	20 deg.C
2	Charge	CC/CV	26.8	4.10	8 hours	
3	Rest	–	–	–	+30/-0 minutes	
4	Discharge	CC	67	2.75	–	
5	Rest	–	–	–	10 min or more	

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

0.2C Capacity

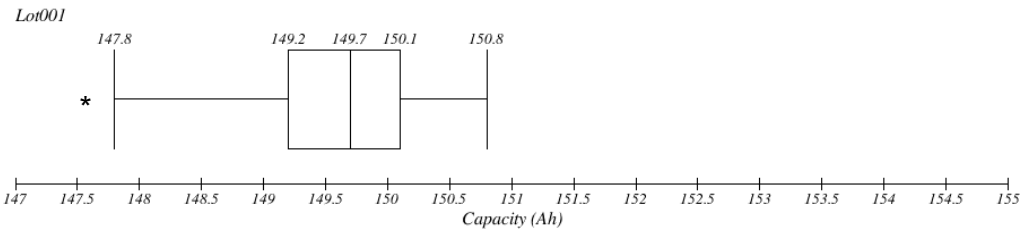


0.2C Capacity

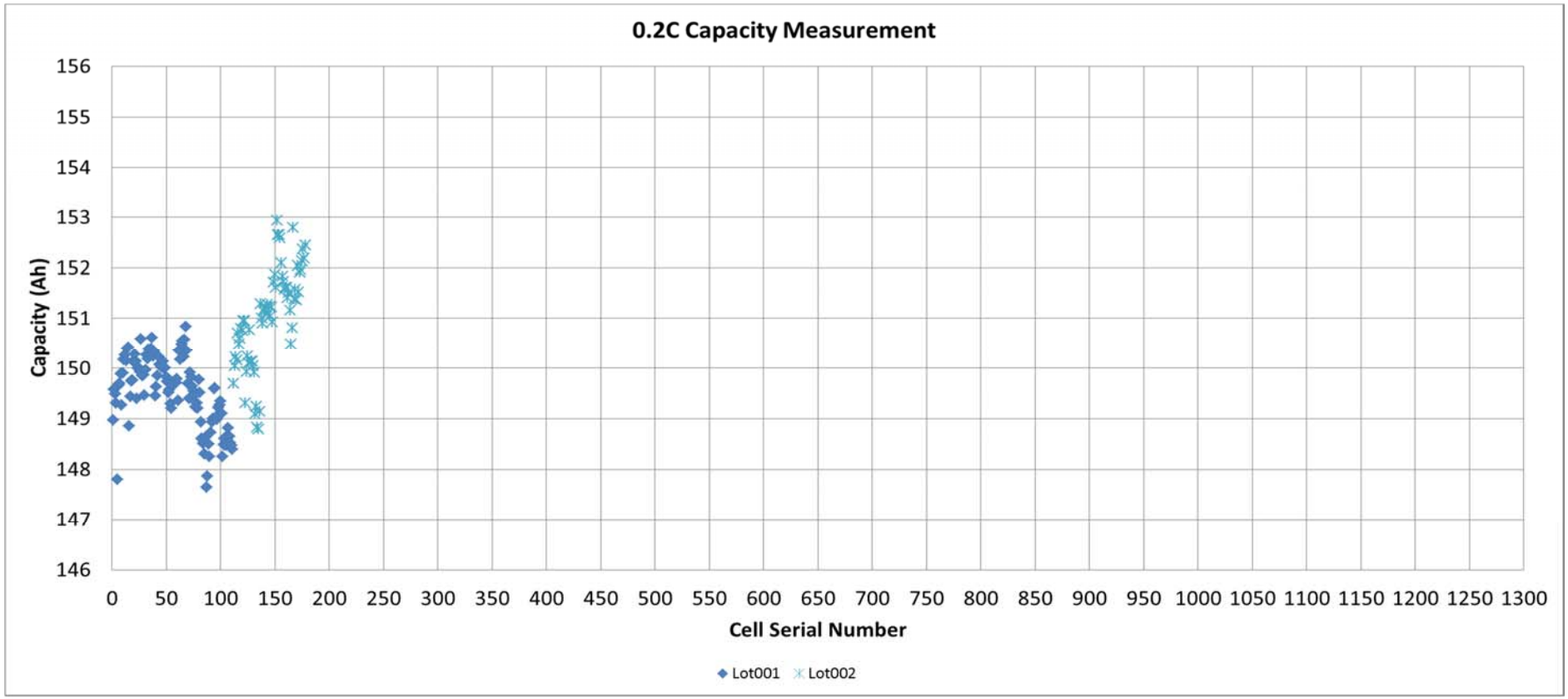


Lot	Average	Std Deviation	±3sigma	Min-Max
001	149.54	0.69	147.47-151.61	147.65-150.84

Lot	Median	F_L	F_U	$Fence_L$	$Fence_U$
001	149.7	149.2	150.1	147.8	150.8

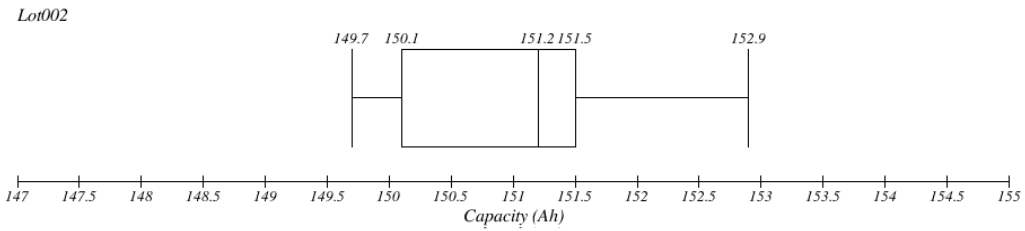


0.2C Capacity

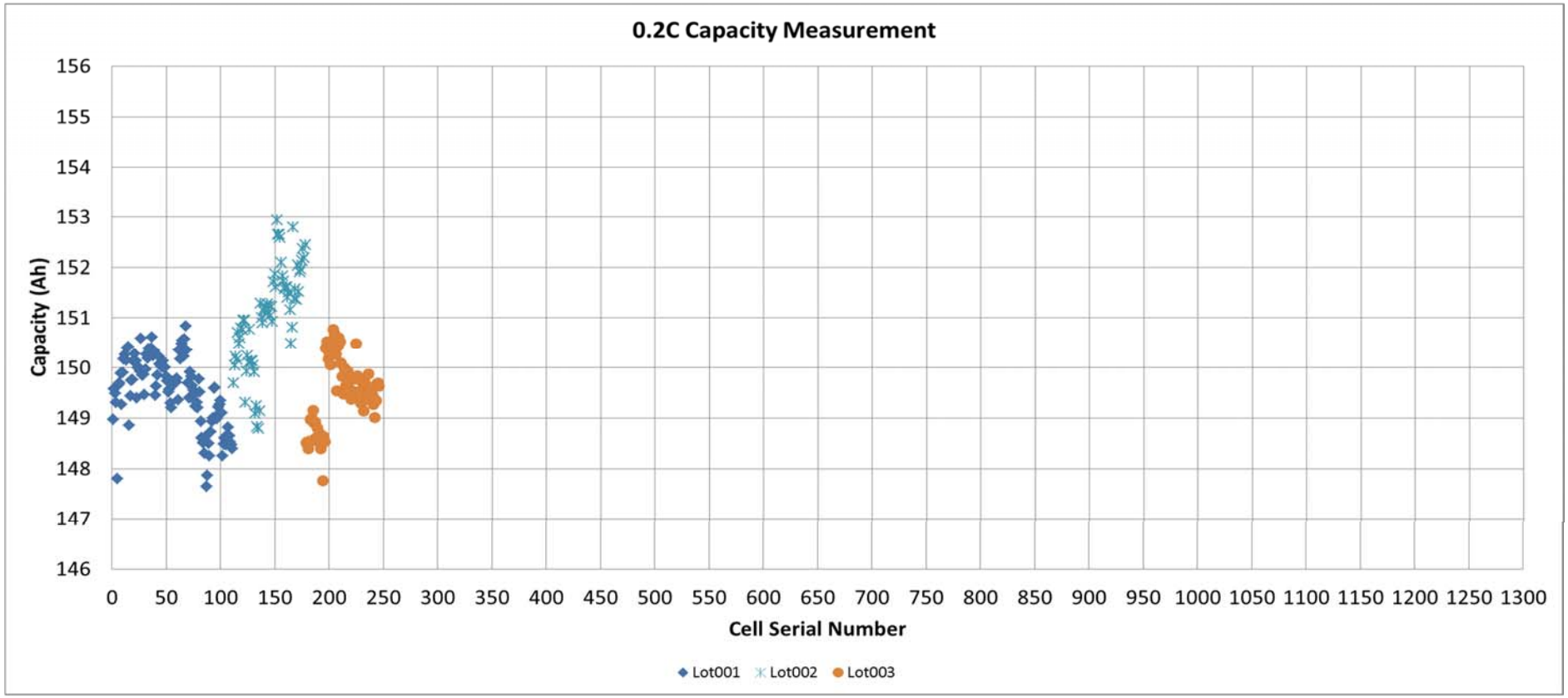


Lot	Average	Std Deviation	±3sigma	Min-Max
002	151.05	0.99	148.07-154.02	148.66-152.93

Lot	Median	F_L	F_U	$Fence_L$	$Fence_U$
002	151.16	150.36	151.67	148.79	152.93

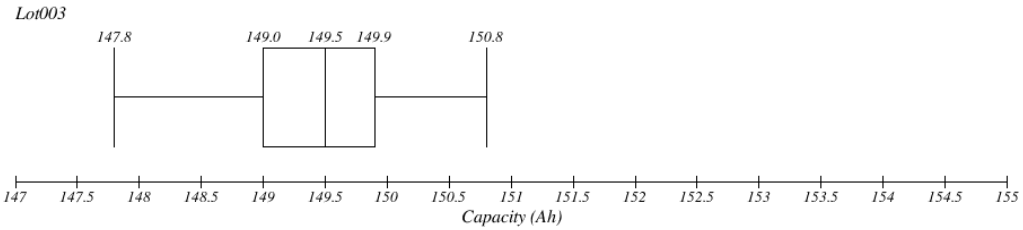


0.2C Capacity



Lot	Average	Std Deviation	±3sigma	Min-Max
003	149.50	0.67	147.49-151.51	147.76-150.77

Lot	Median	F_L	F_U	$Fence_L$	$Fence_U$
003	149.53	149.00	149.91	147.76	150.77



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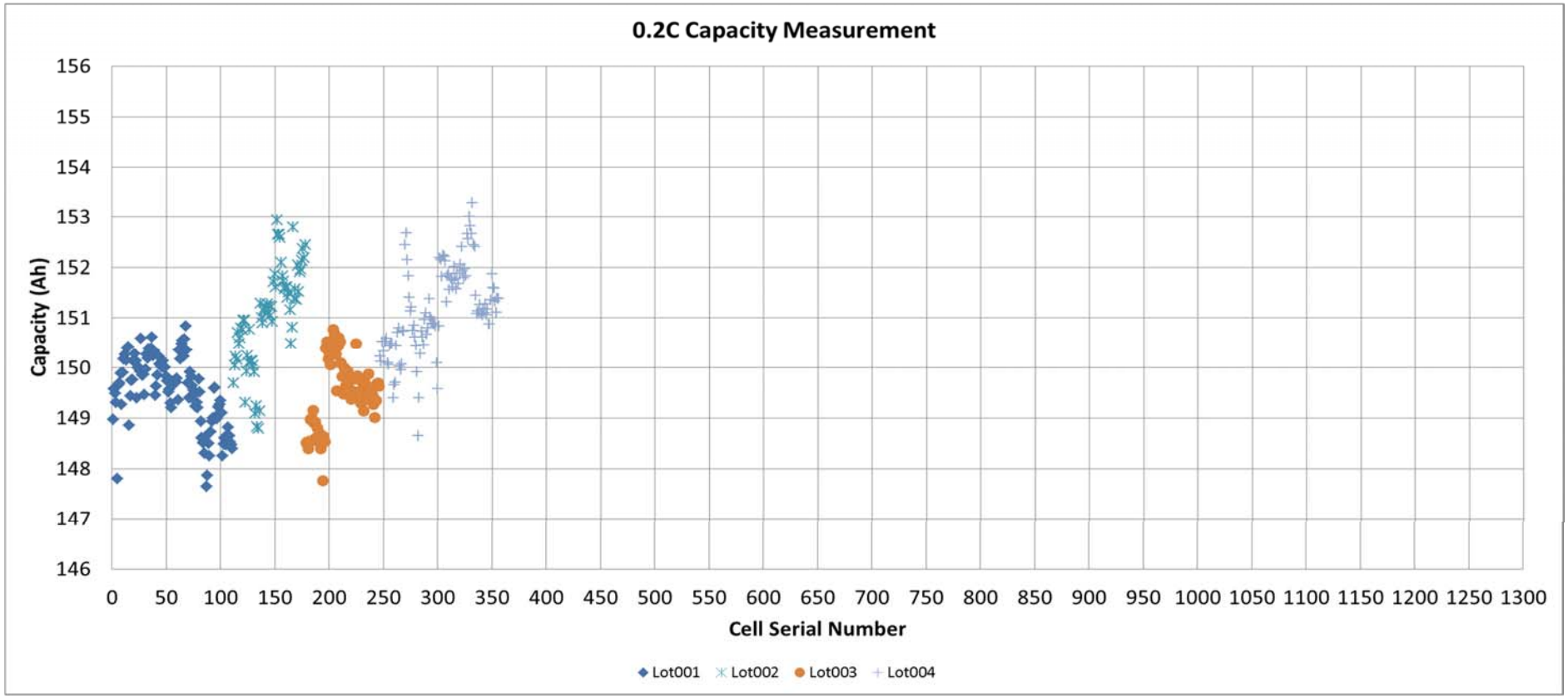
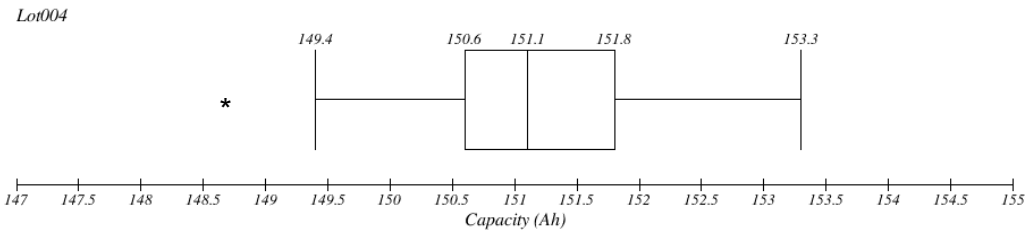


Lot	Average	Std Deviation	±3sigma	Min-Max
004	151.18	0.86	148.59-153.76	148.64-153.28

Lot	Median	F_L	F_U	$Fence_L$	$Fence_U$
004	151.11	150.61	151.83	149.39	153.28



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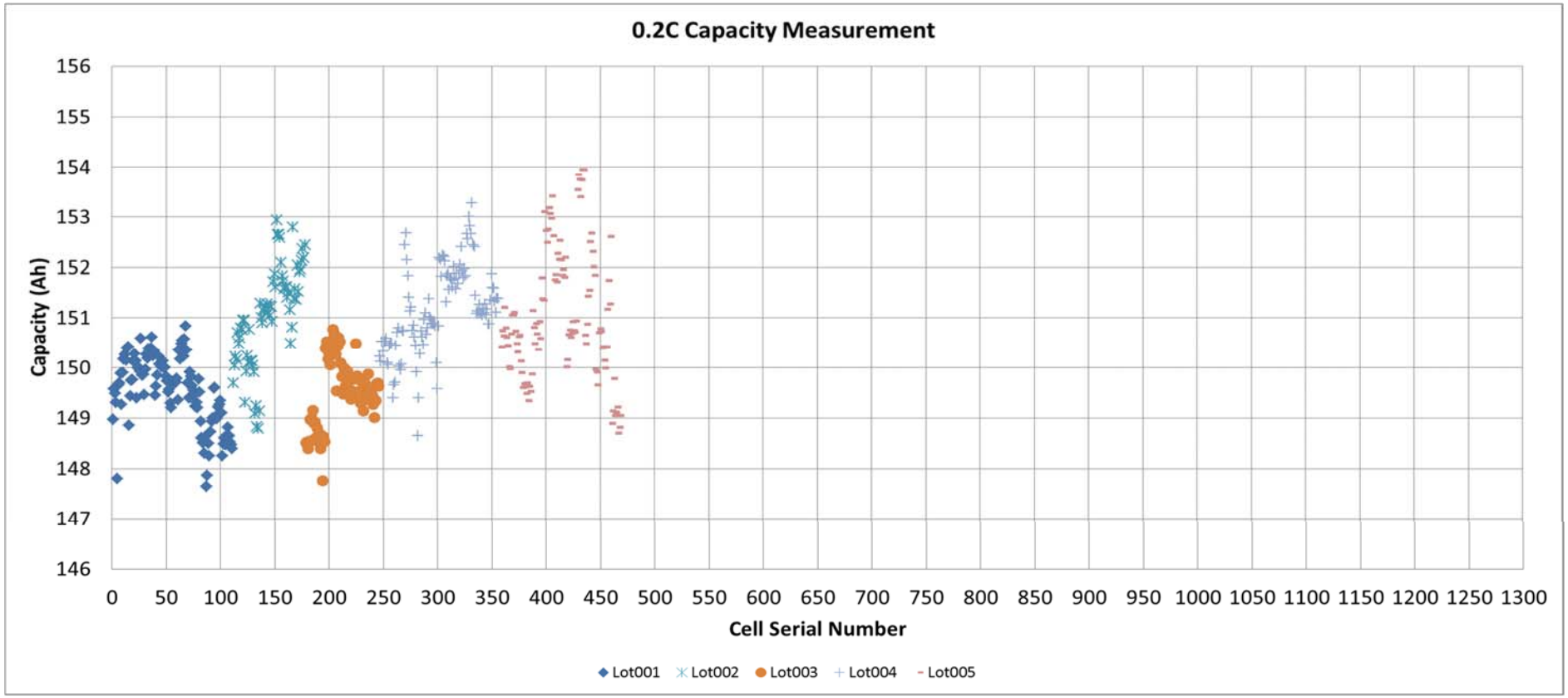
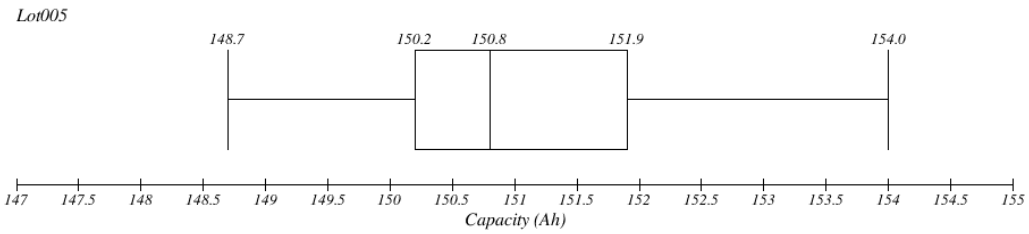


Lot	Average	Std Deviation	±3sigma	Min-Max
005	151.06	1.28	147.22-154.90	148.70-153.95

Lot	Median	F_L	F_U	$Fence_L$	$Fence_U$
005	150.75	150.16	151.86	148.70	153.95



0.2C Capacity

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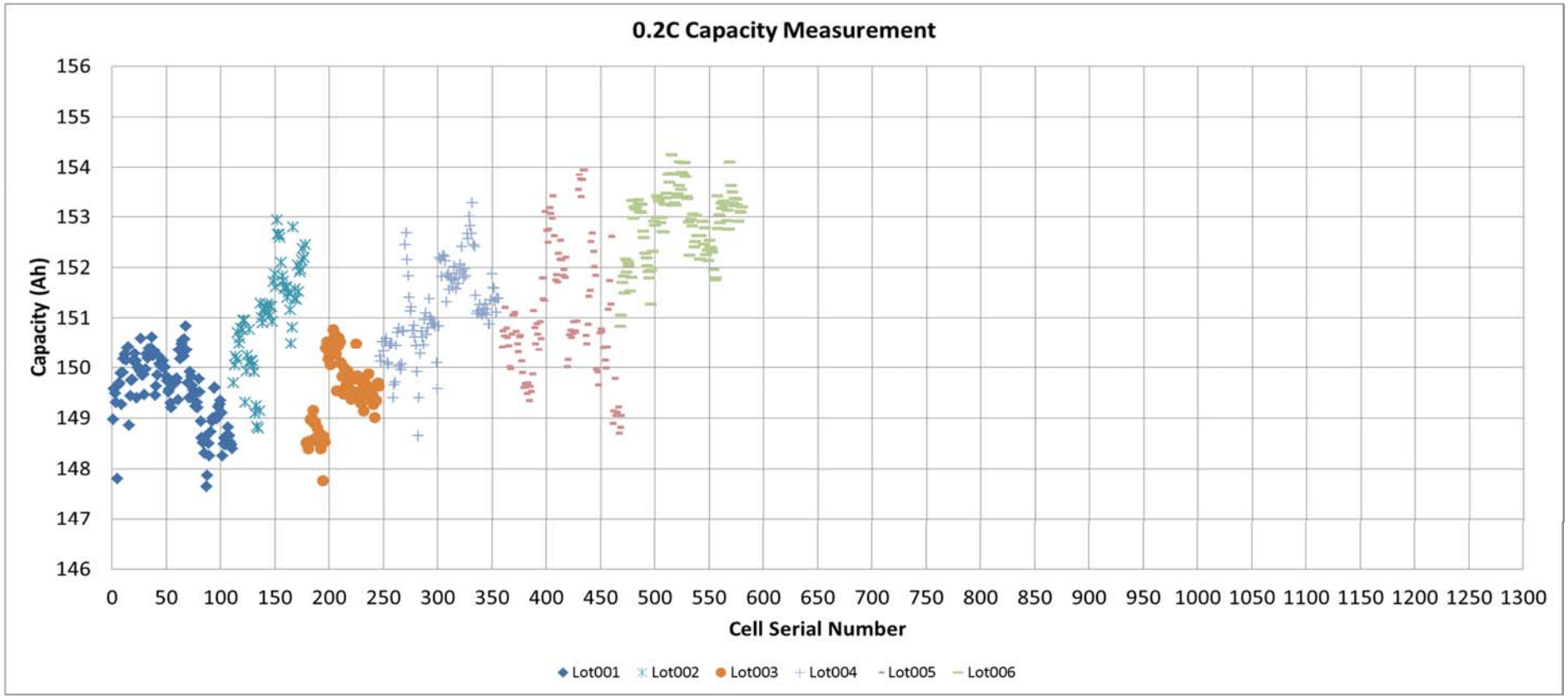
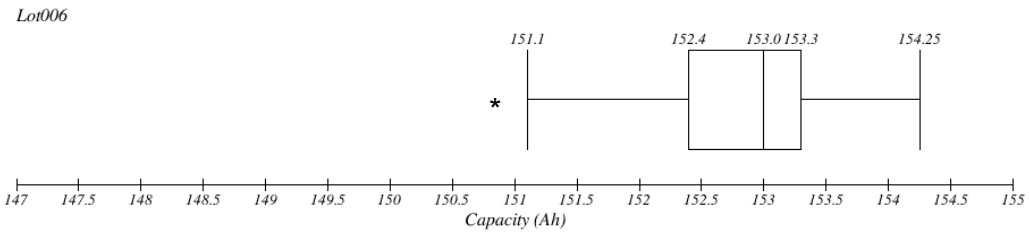


Lot	Average	Std Deviation	±3sigma	Min-Max
006	152.9	0.7	150.79-154.9	150.84-154.25

Lot	Median	F_L	F_U	$Fence_L$	$Fence_U$
006	152.99	152.37	153.31	151.1	154.25



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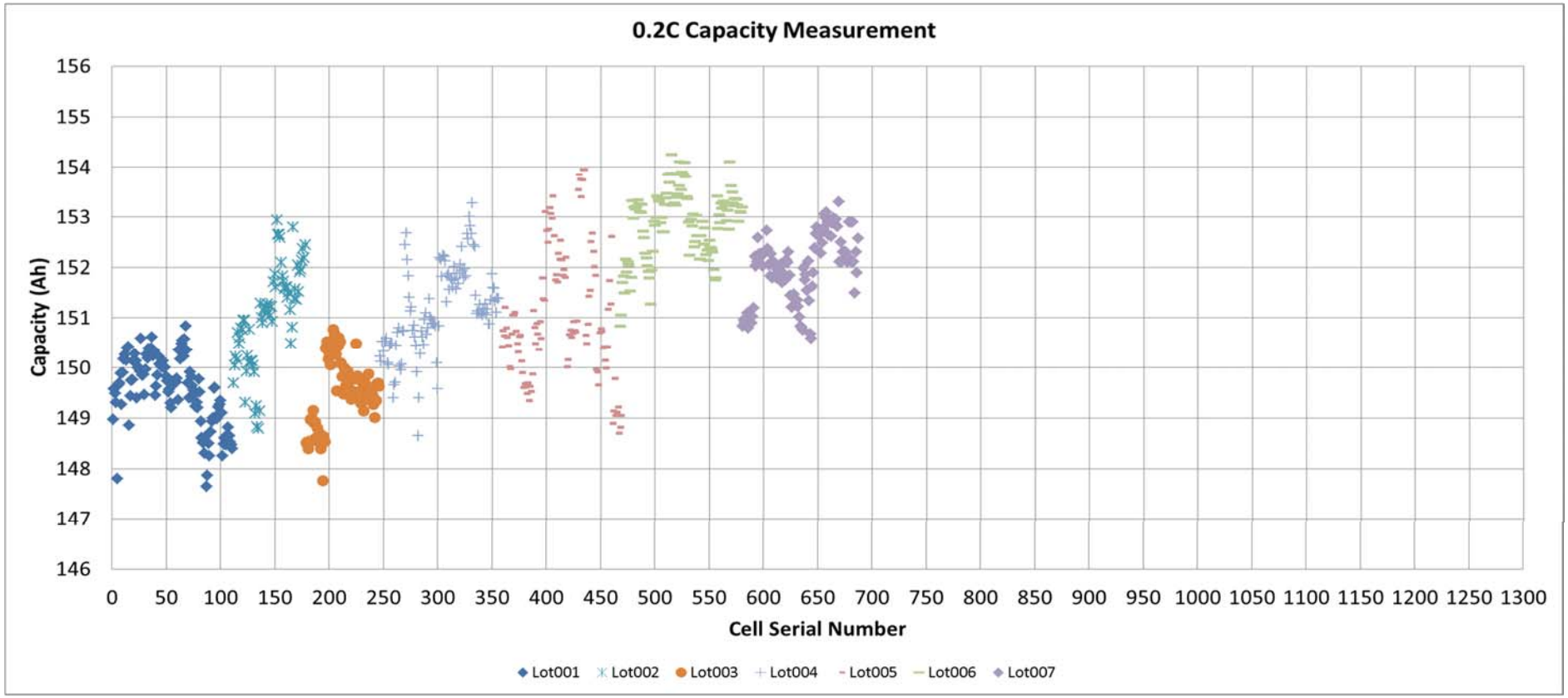
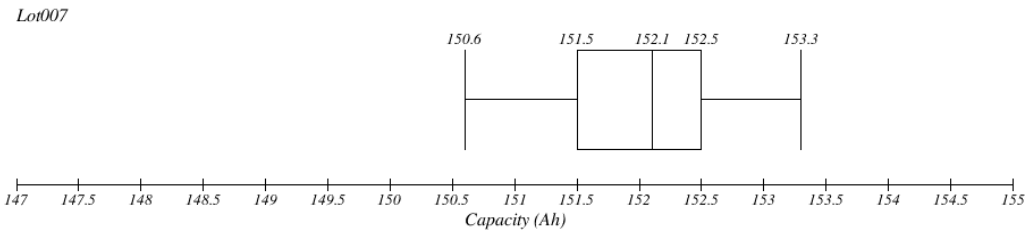


Lot	Average	Std Deviation	±3sigma	Min-Max
007	152.01	0.66	150.02-154.00	150.59-153.30

Lot	Median	F_L	F_U	$Fence_L$	$Fence_U$
007	152.10	151.53	152.49	150.59	153.30



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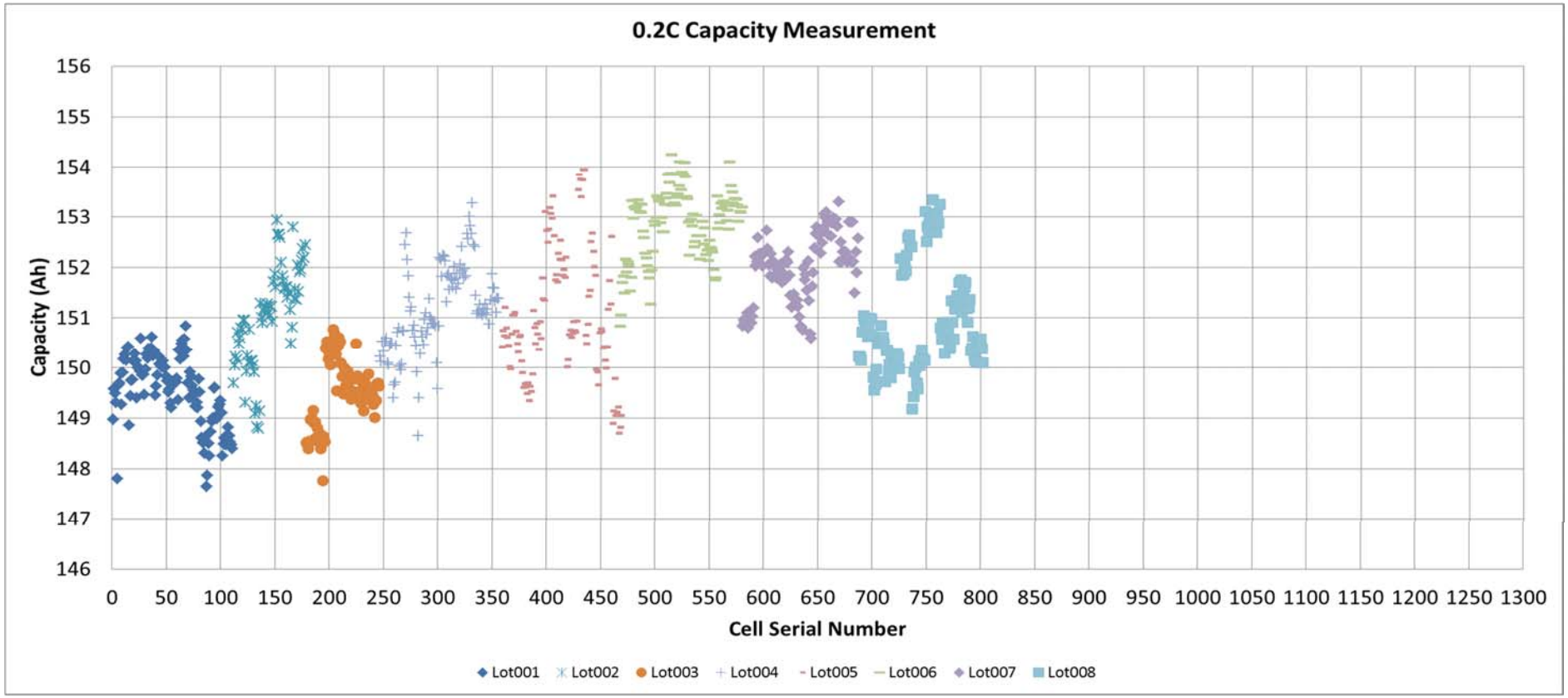
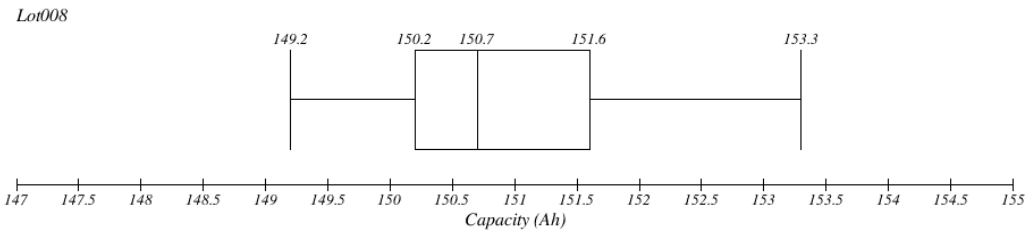


Lot	Average	Std Deviation	±3sigma	Min-Max
008	150.98	1.01	147.94-154.02	149.18-153.34

Lot	Median	F_L	F_U	$Fence_L$	$Fence_U$
008	150.66	150.24	151.57	149.18	153.34



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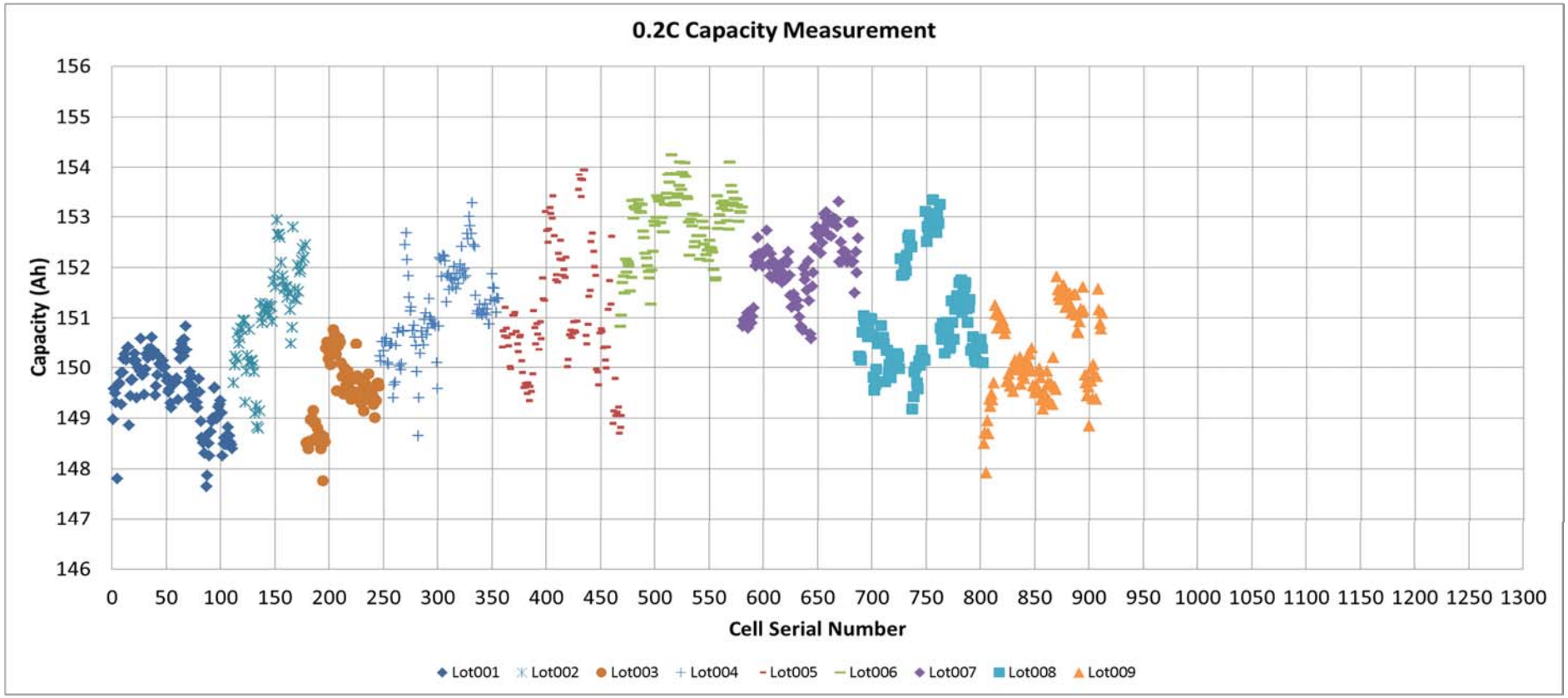
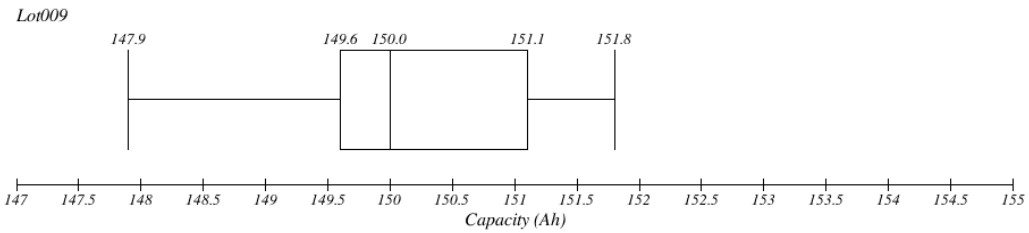


Lot	Average	Std Deviation	±3sigma	Min-Max
009	150.2	0.85	147.68-152.80	147.92-151.82

Lot	Median	F_L	F_U	$Fence_L$	$Fence_U$
009	114.98	147.46	151.08	147.92	151.82



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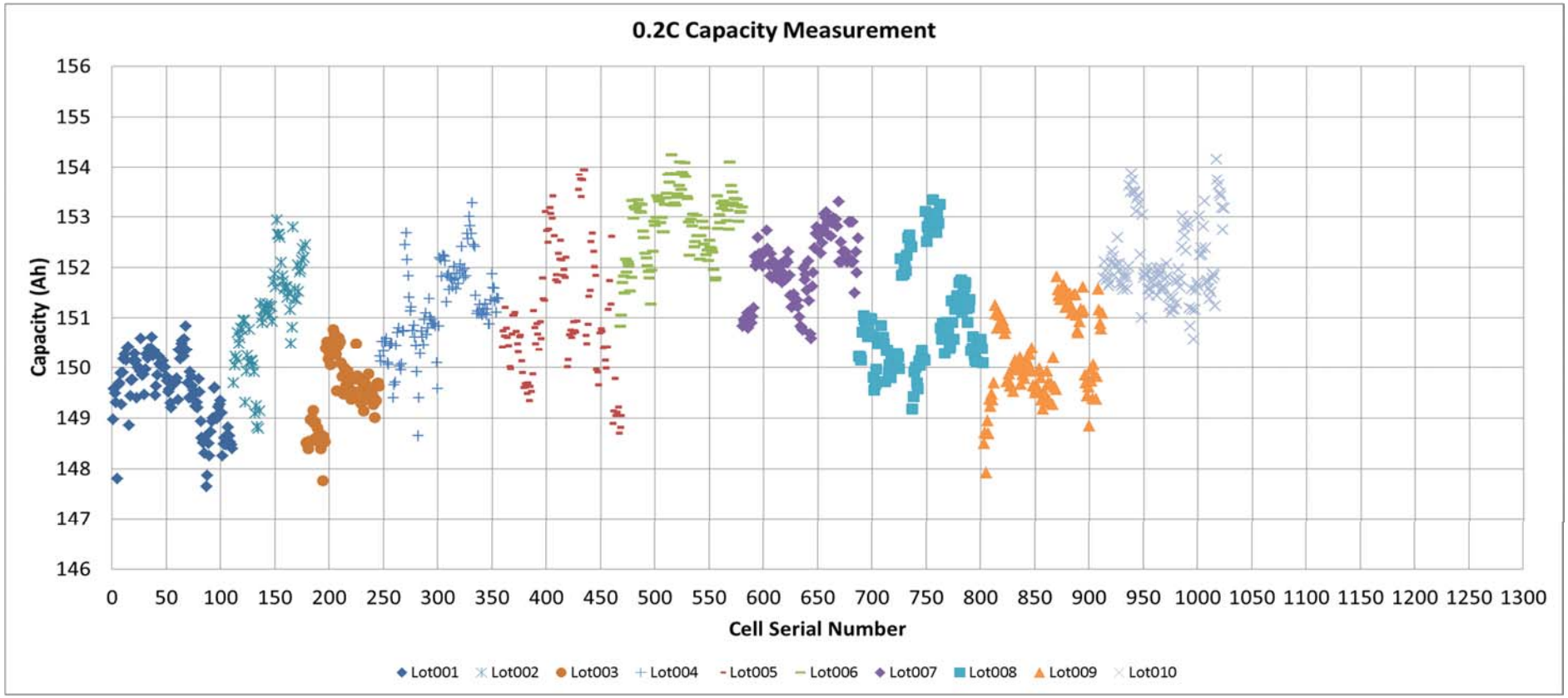
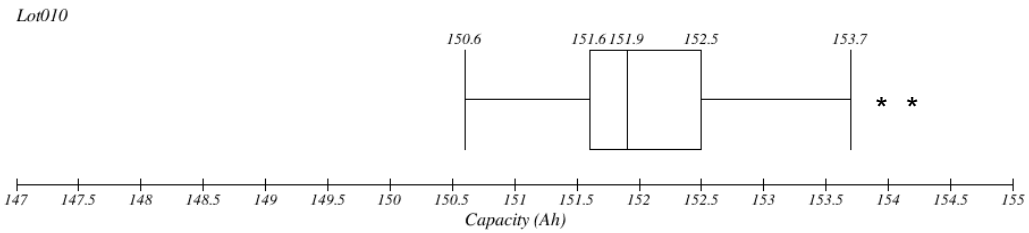
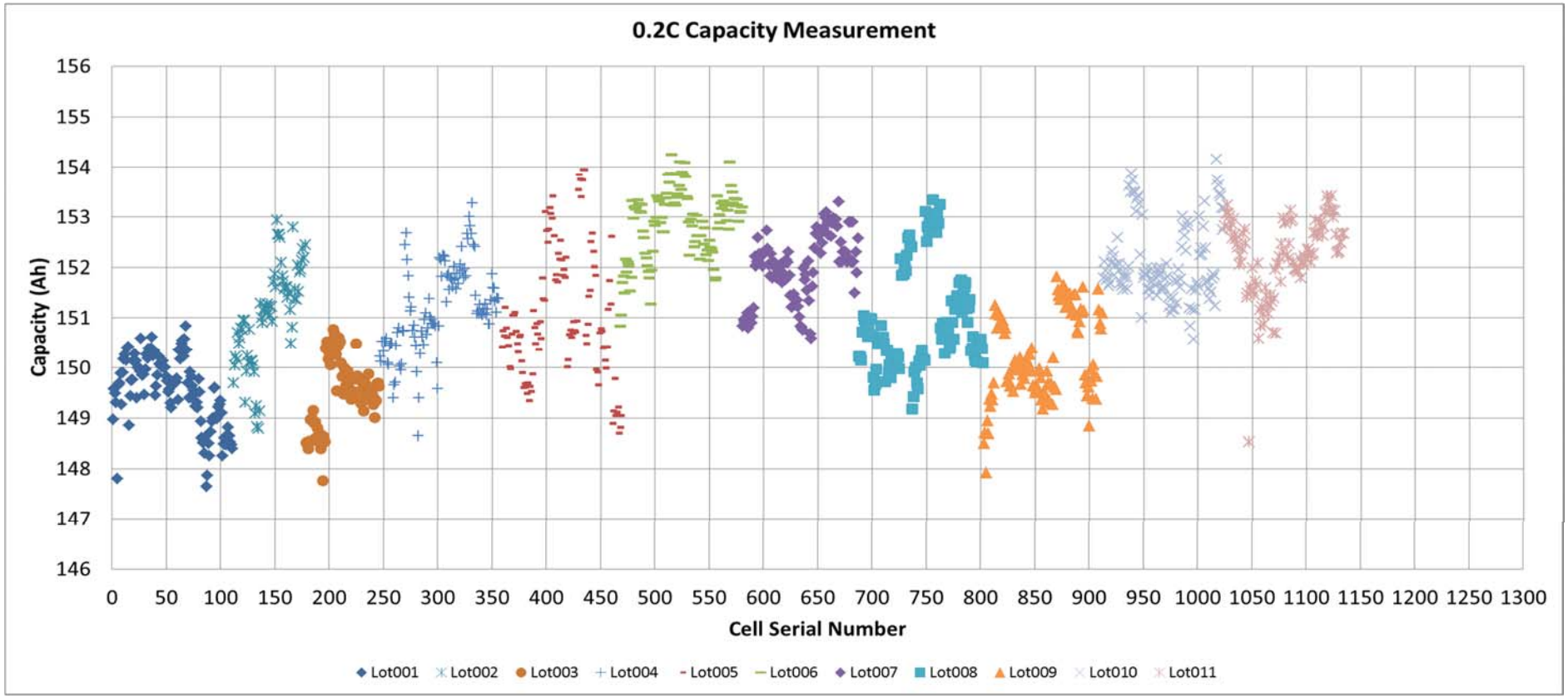


Lot	Average	Std Deviation	±3sigma	Min-Max
010	152.1	0.76	149.82-154.39	150.57-154.15

Lot	Median	F_L	F_U	$Fence_L$	$Fence_U$
010	151.86	151.63	152.49	150.57	153.74

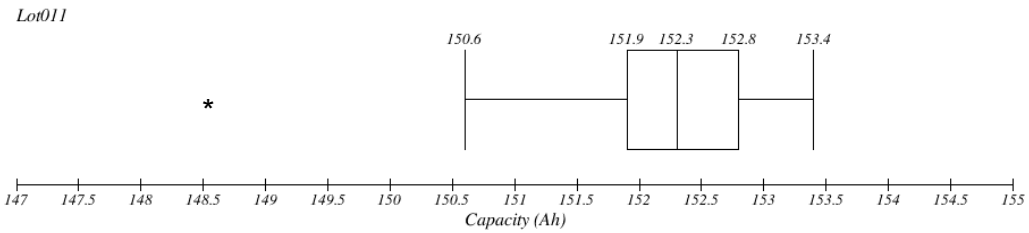


0.2C Capacity

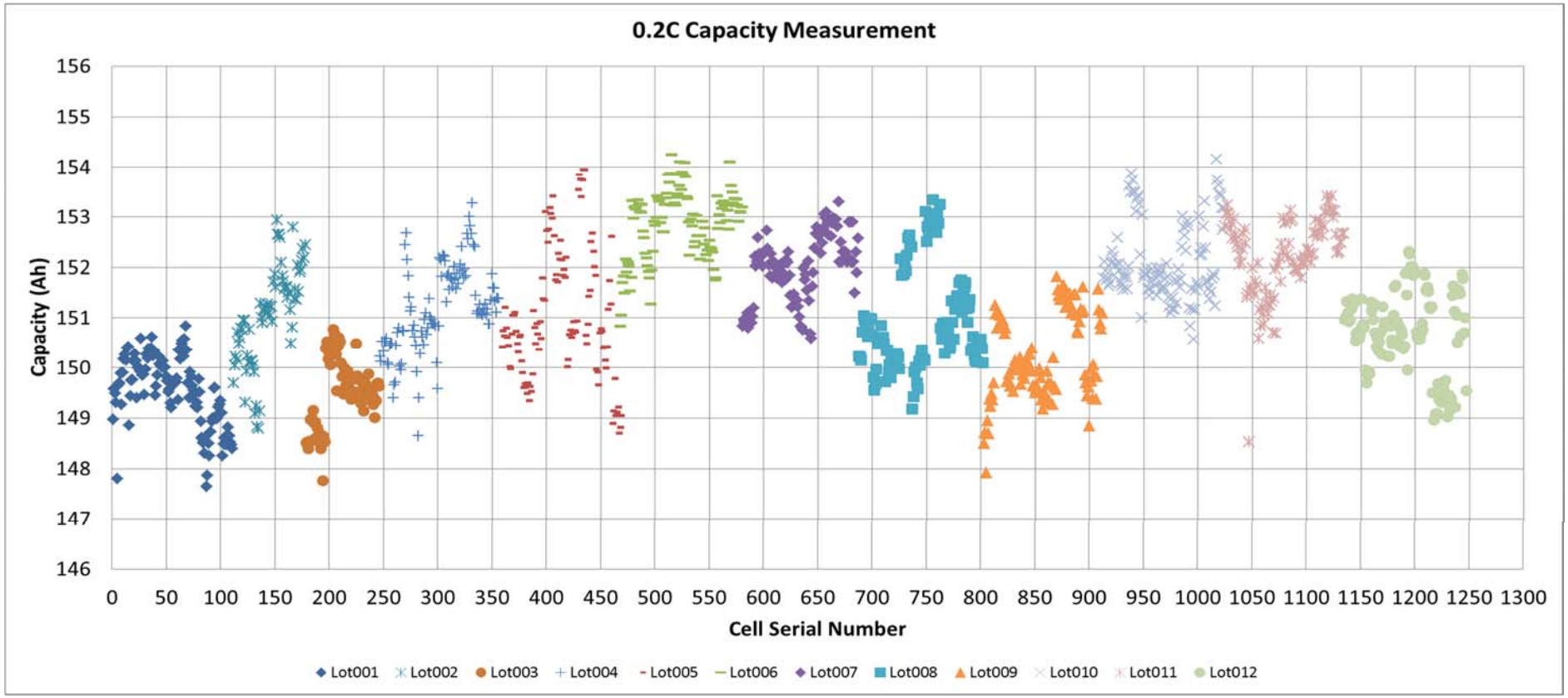


Lot	Average	Std Deviation	±3sigma	Min-Max
011	152.23	0.75	149.80-154.49	**148.53**-153.42

Lot	Median	F_L	F_U	$Fence_L$	$Fence_U$
011	152.29	151.91	152.81	150.59	153.42

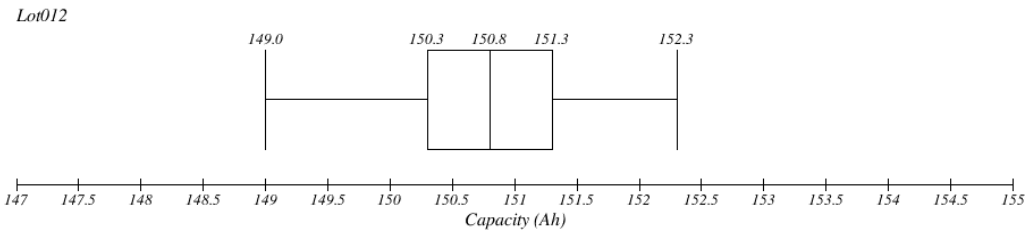


0.2C Capacity

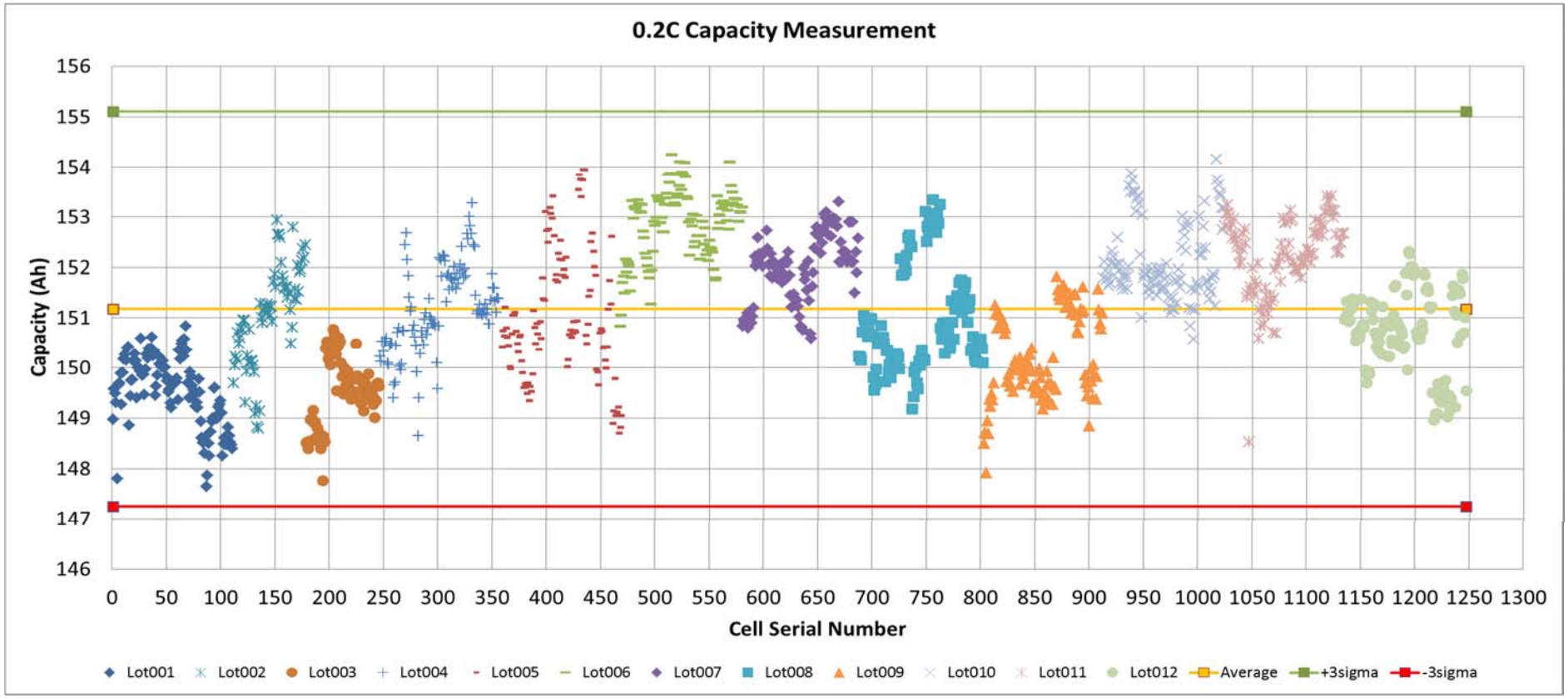


Lot	Average	Std Deviation	±3sigma	Min-Max
012	152.70	0.82	148.23-153.16	148.95-152.32

Lot	Median	F_L	F_U	$Fence_L$	$Fence_U$
012	150.76	150.26	151.27	148.95	152.32

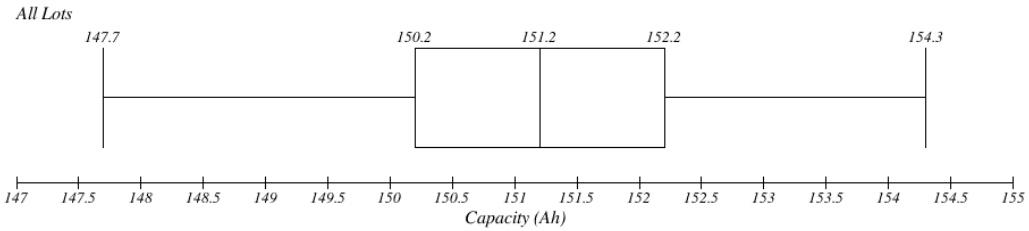


0.2C Capacity

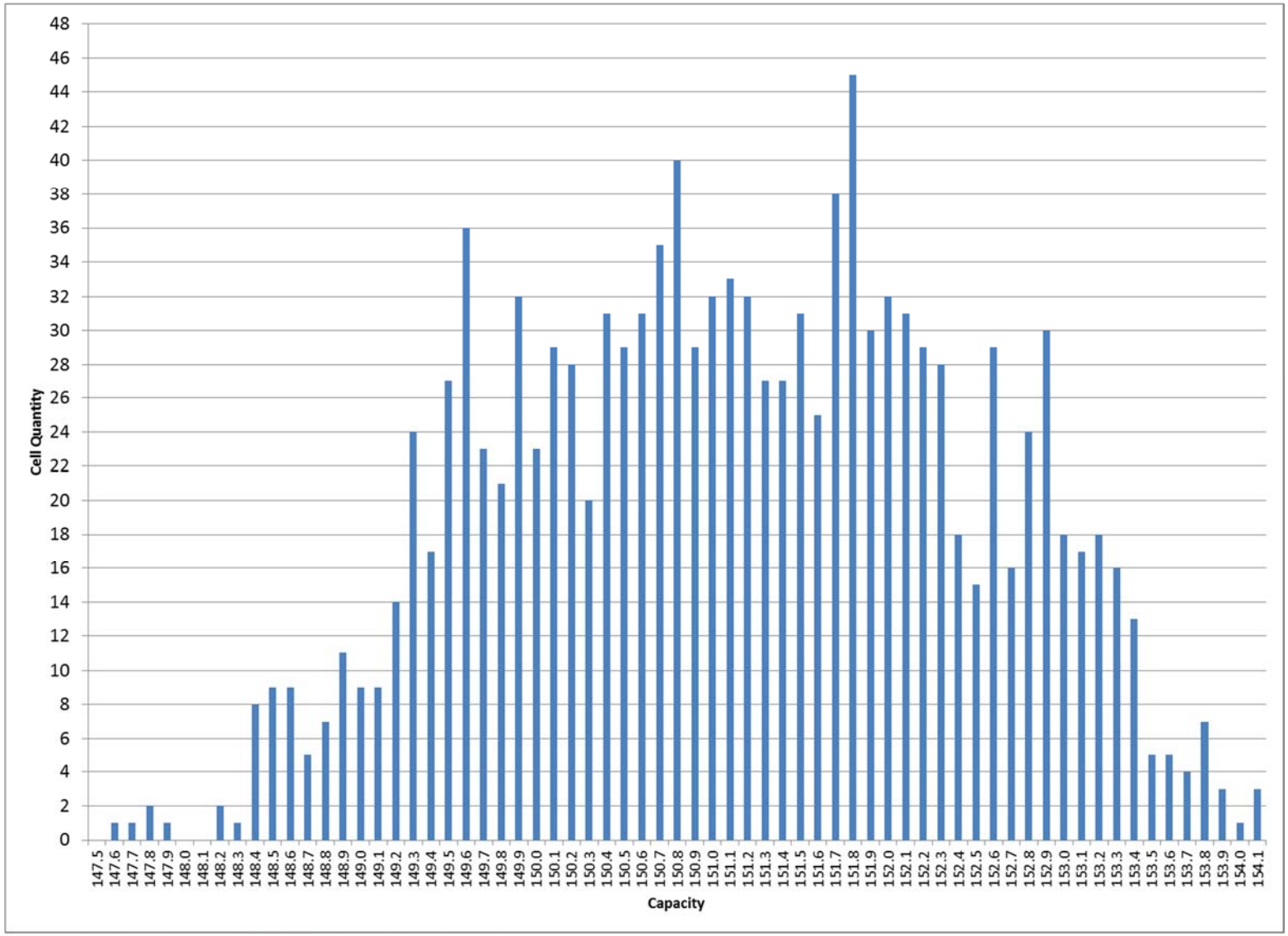


Lot	Average	Std Deviation	±3sigma	Min-Max
All	151.18	1.31	147.25-155.11	147.65-154.25

Lot	Median	F_L	F_U	$Fence_L$	$Fence_U$
All	151.17	150.15	152.16	147.65	154.25



0.2C Capacity Histogram



0.2C Capacity Final Thoughts

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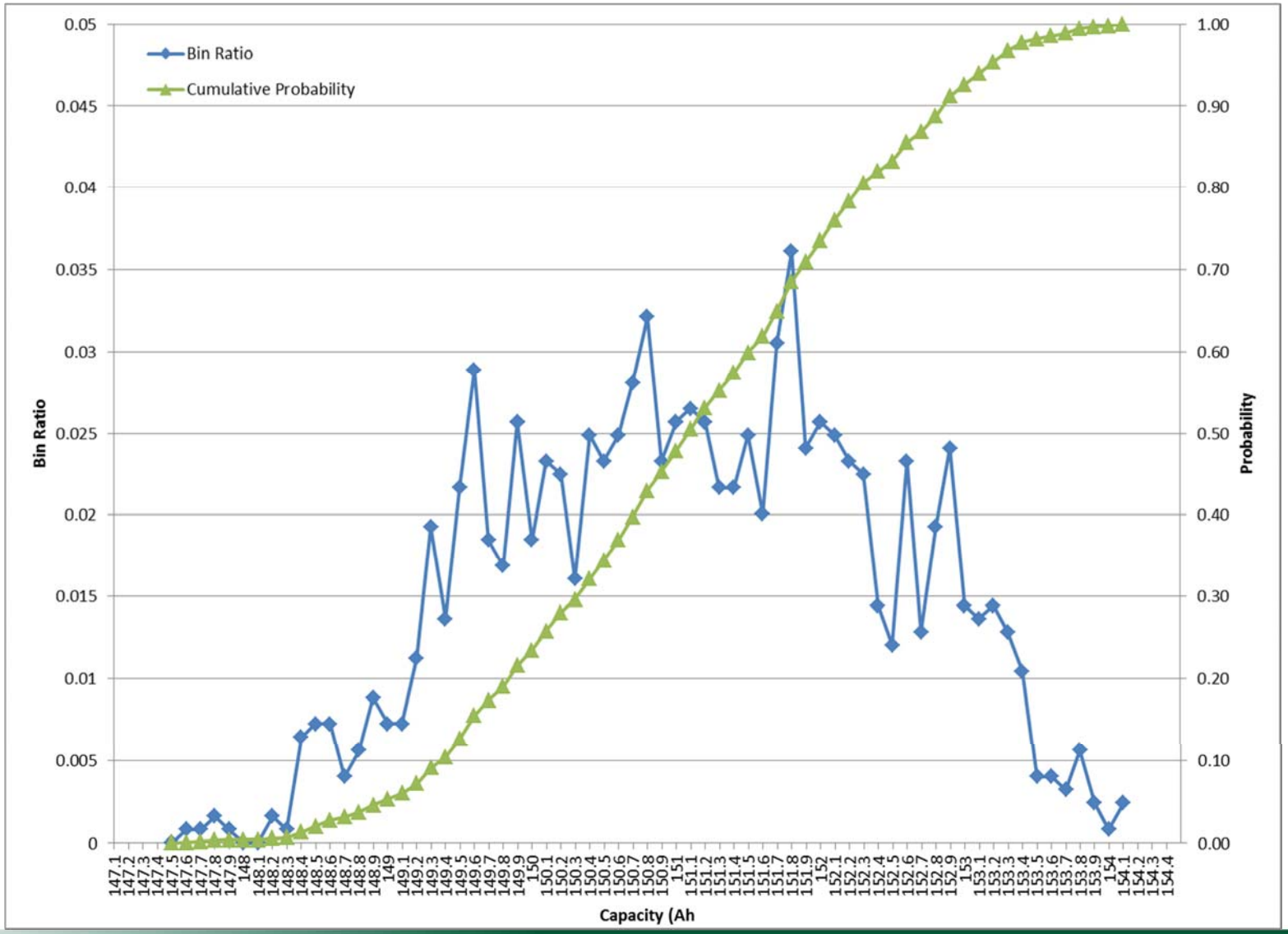
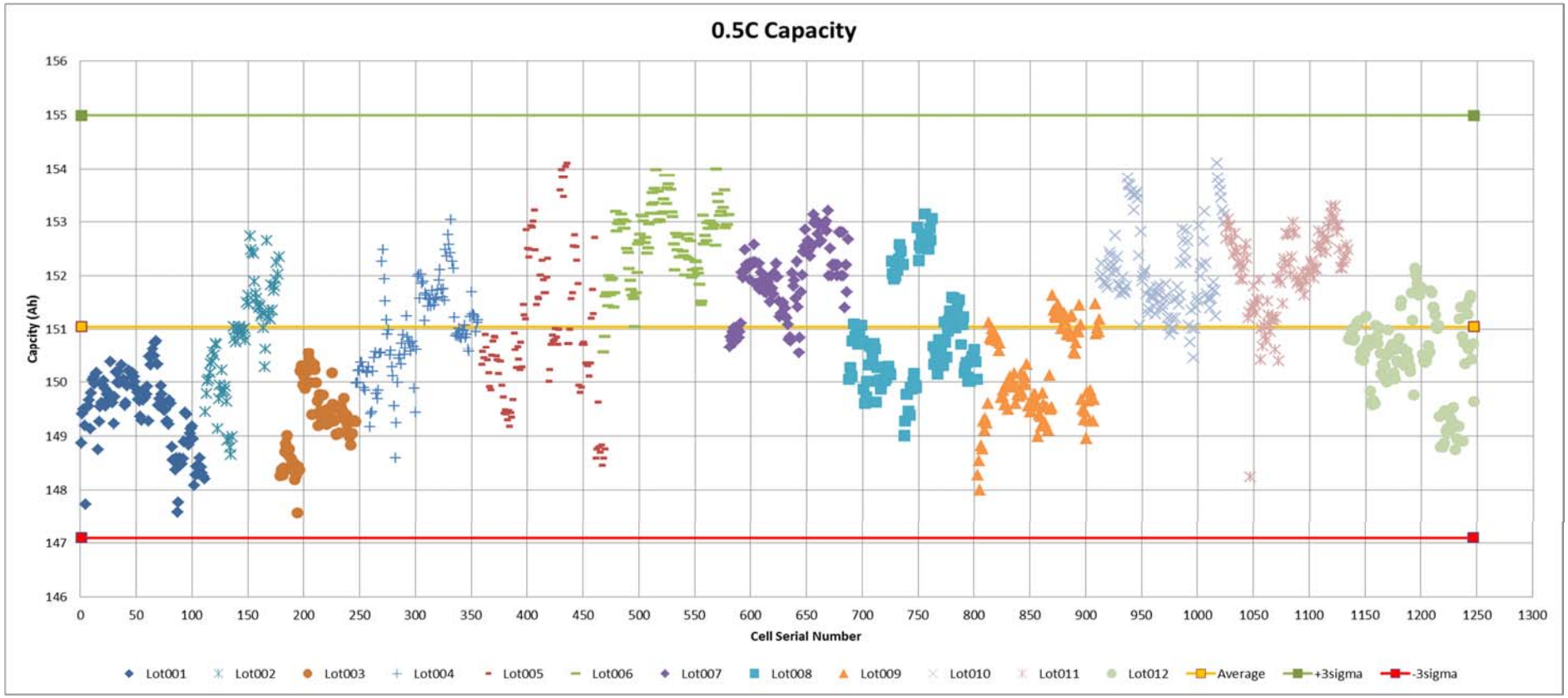
Powering the Next Generation

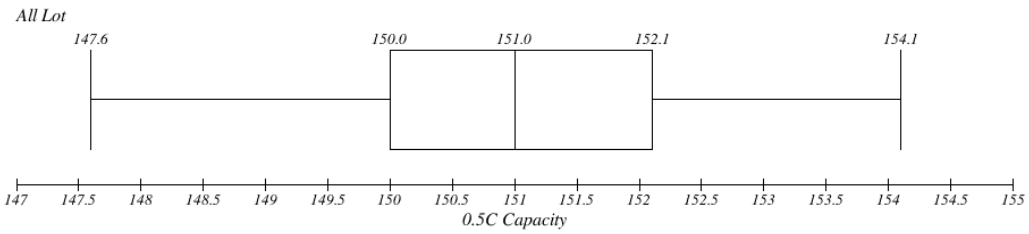


0.5C Capacity



Lot	Average	Std Deviation	±3sigma	Min-Max
All	151.05	1.32	147.10-155.00	147.57-154.10

Lot	Median	F_L	F_U	$Fence_L$	$Fence_U$
All	151.02	150.03	152.06	147.57	154.10



AC Impedance

Requirement: Each cell shall be tested for AC Impedance less than 0.65 milliohms at frequency of 1kHz at 13.4Ah charged state.

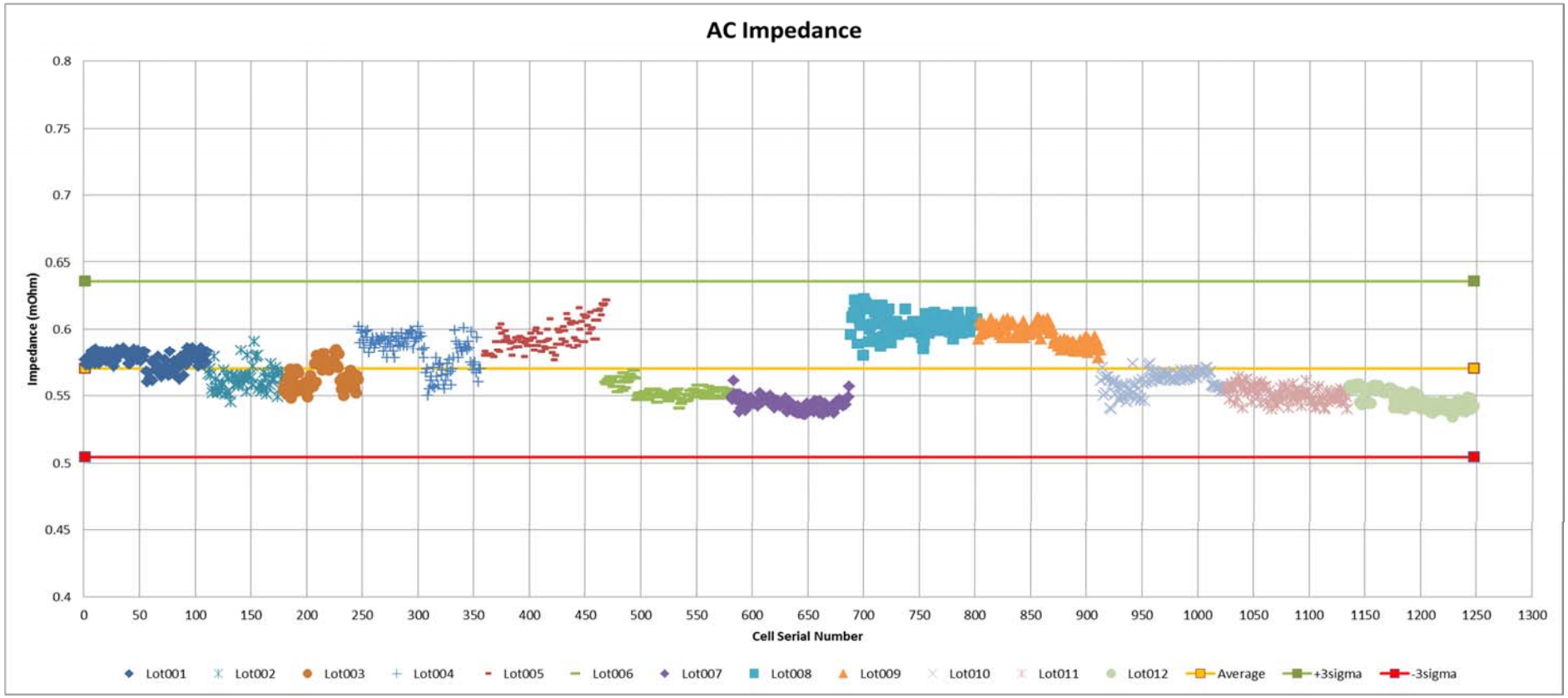
Major Test Equipment:

Item	Manufacturer	Range	Accuracy
Impedance Meter	HIOKI 3560	AC 1kHz	+/- 0.5% of rdg +/- 5dig

Prior to the measurement, SOC shall be adjusted as follows (if needed):

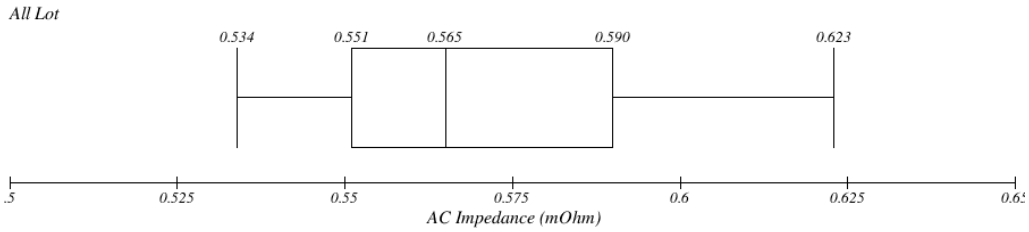
- Discharge the cell at C/5 to 2.75V at room temperature
- Charge the cell at C/5 for 30min. at room temperature (10%SOC)
- Perform AC impedance check

AC Impedance



Lot	Average	Std Deviation	±3sigma	Min-Max
All	0.570	0.022	0.505-0.636	0.534-0.623

Lot	Median	F_L	F_U	$Fence_L$	$Fence_U$
All	0.565	0.551	0.590	0.534	0.623

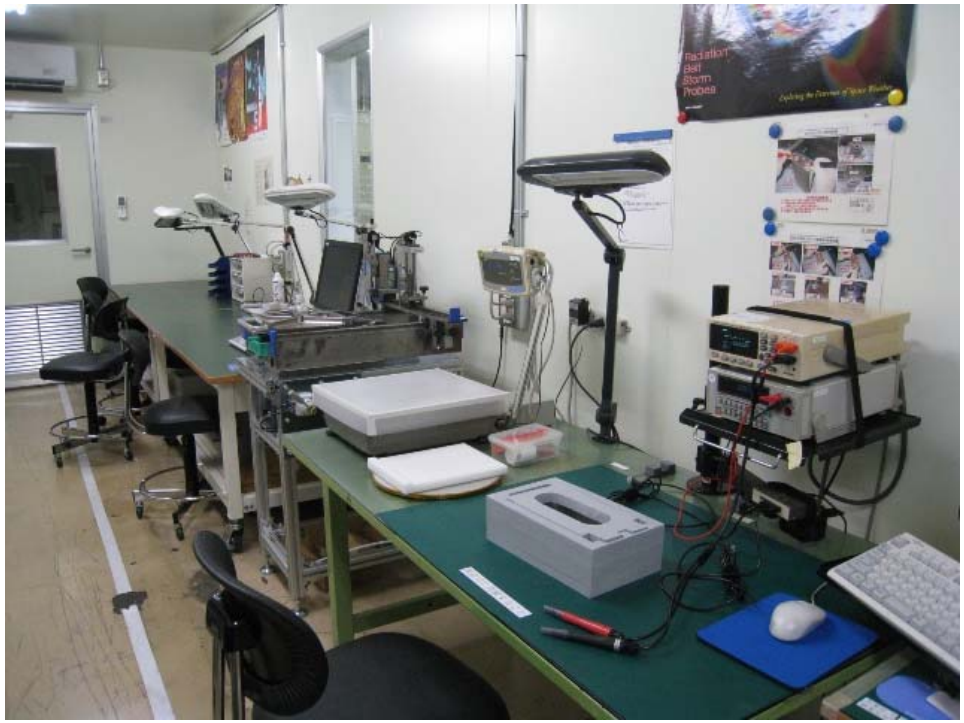


Mass

Requirement: Cell mass shall be 3530g±100g when measured with electronic balance

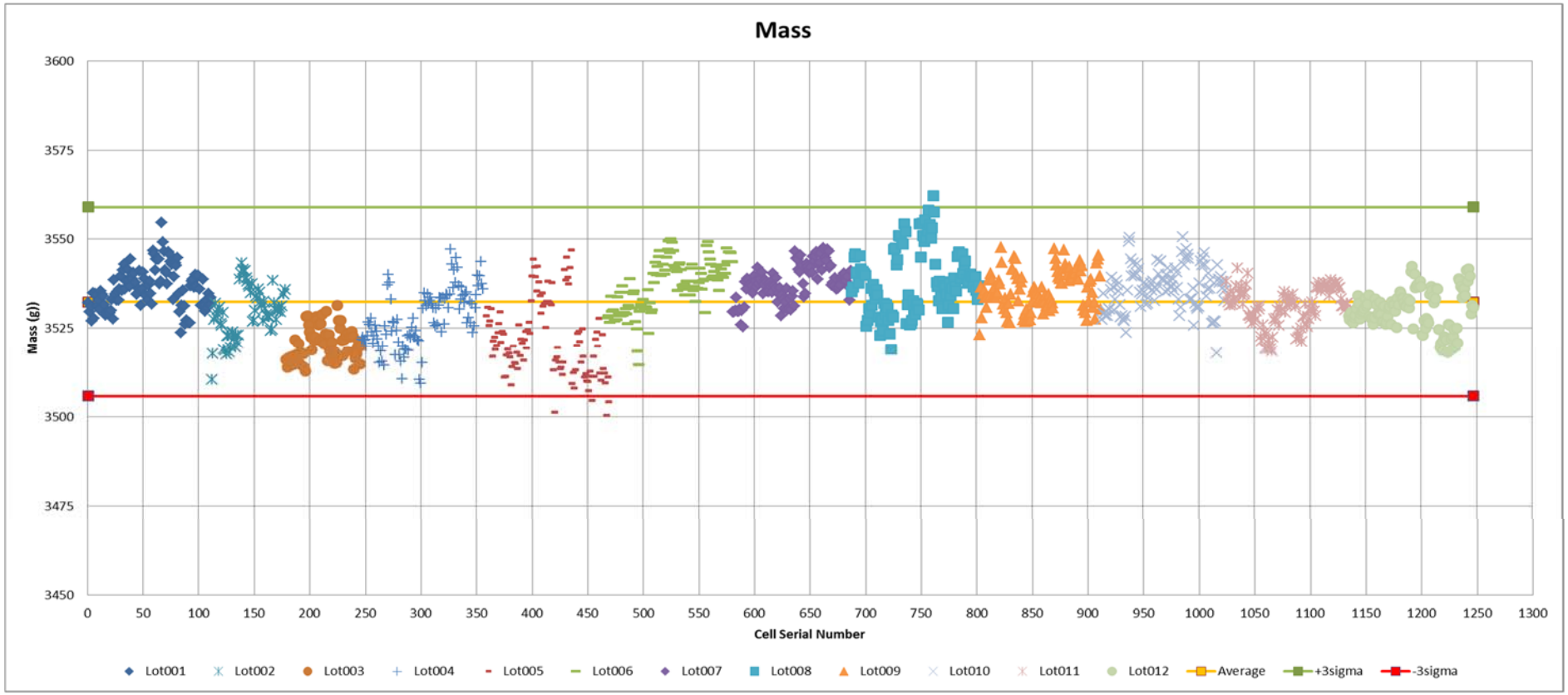
Major Test Equipment:

Item	Manufacturer	Range
Electronic Balance	METTLER PE-11	0-11kg



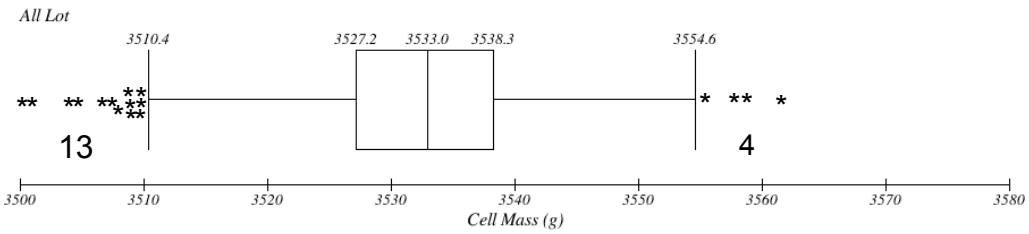
Cell Inspection Area

Cell Mass



Lot	Average	Std Deviation	±3sigma	Min-Max
All	3532.4	8.8	3505.8-3558.9	3500.4-3562.0

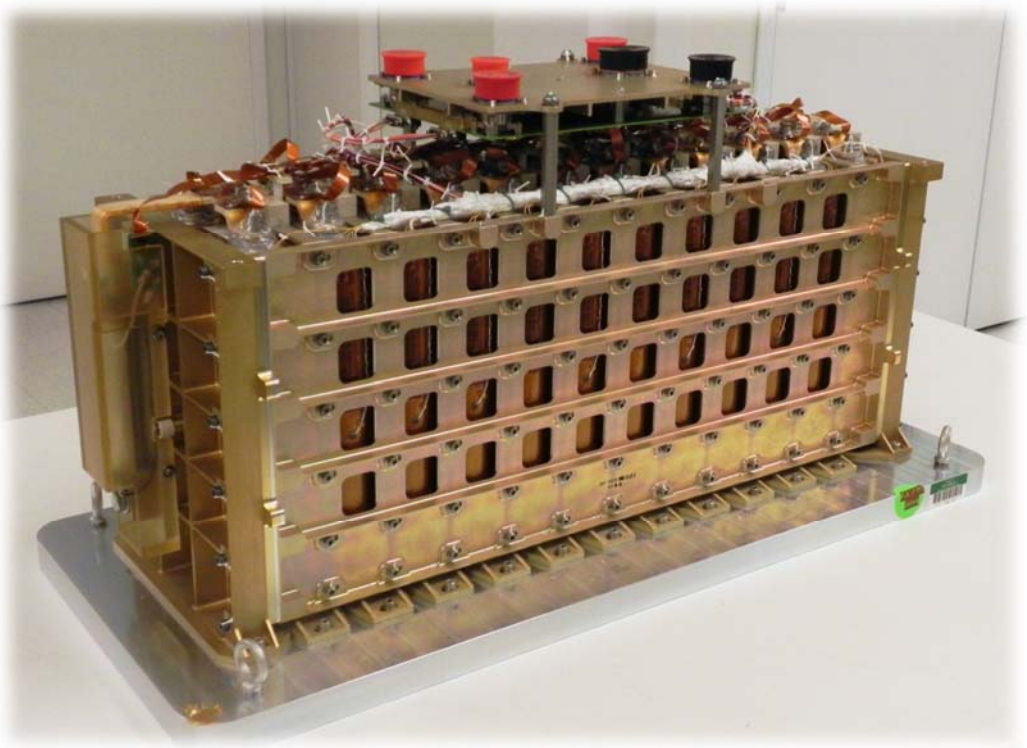
Lot	Median	F_L	F_U	$Fence_L$	$Fence_U$
All	3533.0	3527.2	3538.3	3510.4	3554.6



Conclusions

- By utilizing rigorous systems for the control of manufacturing and test processes, GS Yuasa's LSE cells show excellent consistency between manufacturing lots.
- Initial Characteristics reviewed for over 1200 manufactured LSE134-101 Cells shows excellent consistency for key parameters.
- Somewhat expectedly, Capacity data for all manufacturing lots are not normally distributed but skewed towards higher capacities from the mean.
- When reviewing single lots with a limited populations, 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!

One more thing…



LSE190 Modular battery system introduction

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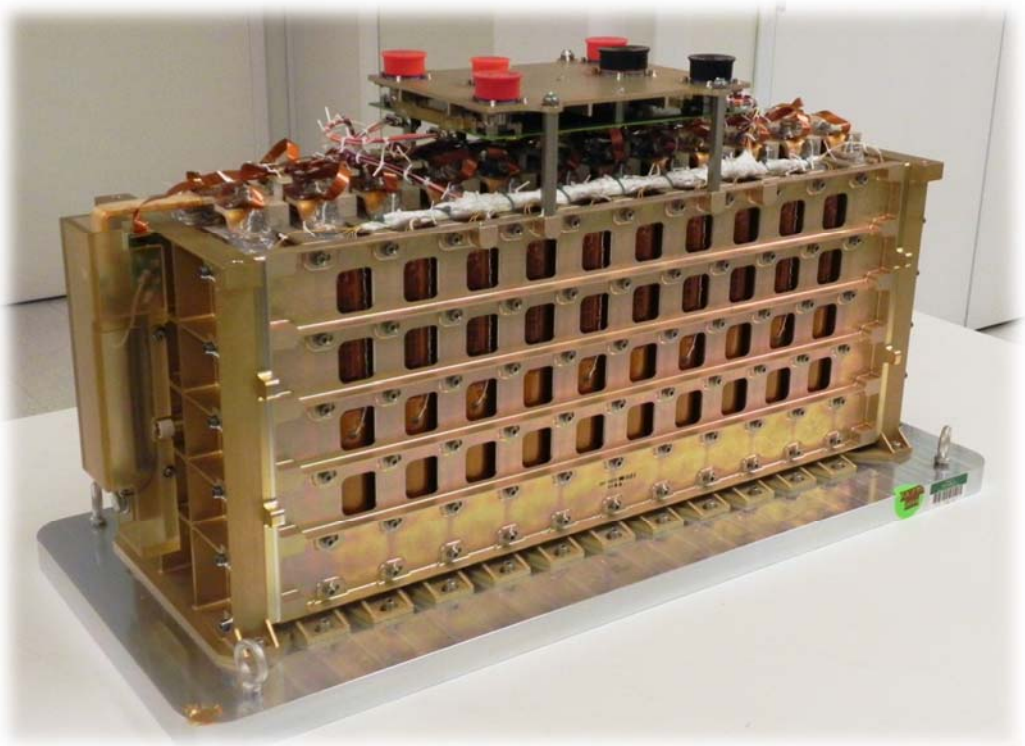
Powering the Next Generation



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 Module Building Blocks

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Powering the Next Generation

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

[1]BOL, C/2 discharge, 4.10V to 2.75V

[2]15 year GEO mission, 80% actual DOD max, no bypassed cells

[3]based on 4.20V per cell EOM condition

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

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

Module Stack-up Examples

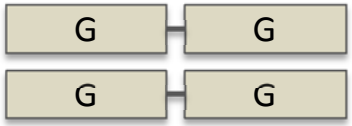
Powering the Next Generation

Battery Configuration: 17.8kW GEO example

High voltage

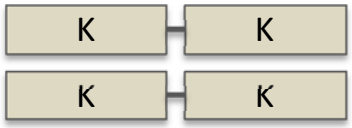
1 battery, 2p modules
[(K+K+K+K)*1]

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

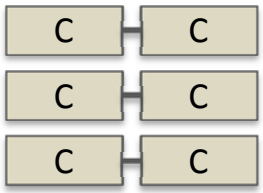


Medium voltage

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



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



Power vs. Mass and Expected Voltage Range.