

# Performance Review of GS Yuasa Generation 3 Space Cells and Introduction of Generation 4

2019 Space Power Workshop

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Curtis Aldrich, George Bergmark, Tom Pusateri - GYLP  
Go Honda, Yuta Kagami, Masazumi Segawa - GYT

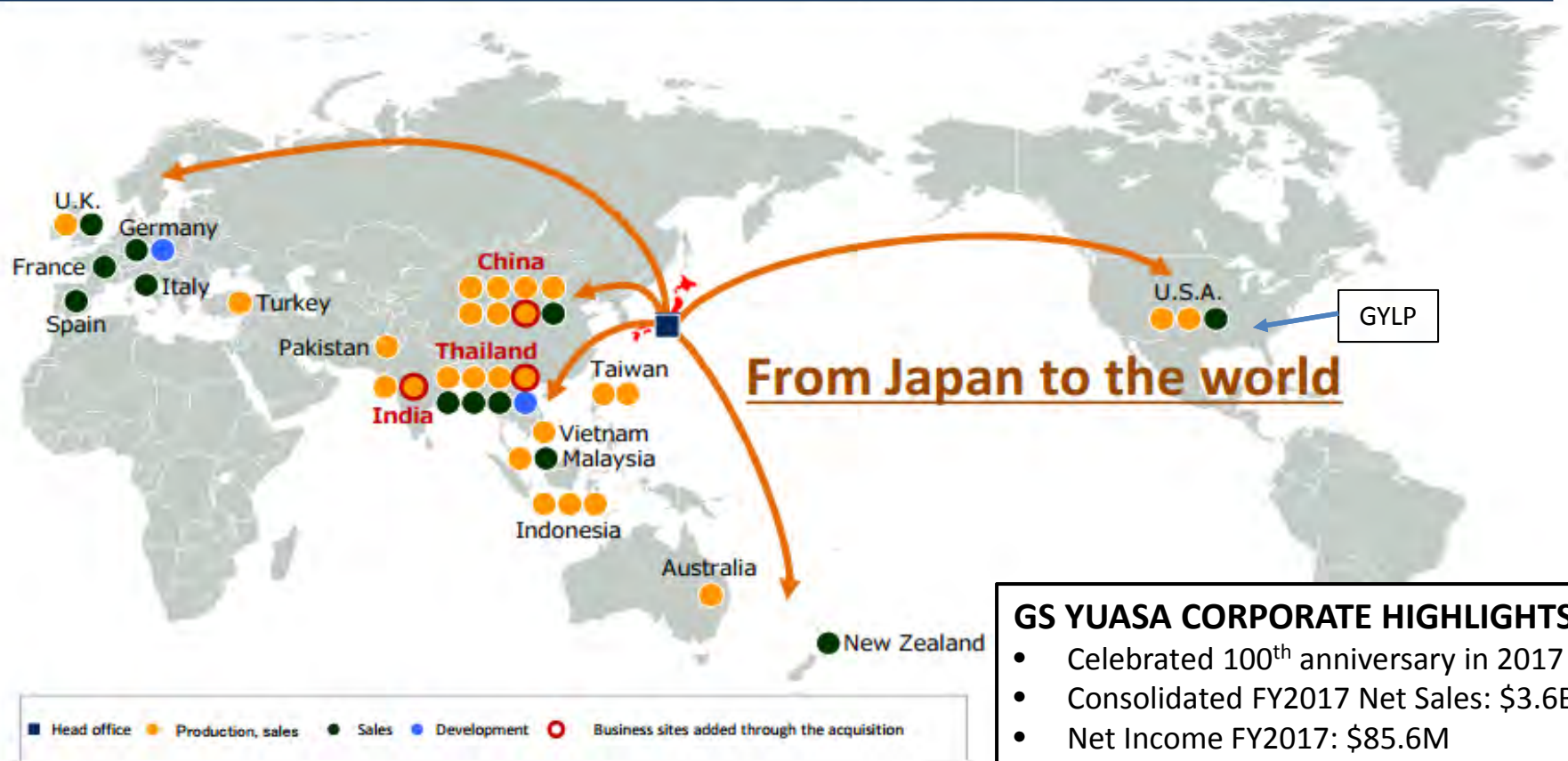
# Agenda



*Powering the Next Generation*

- Update of Space Li-ion Activity
- Evolution of GS Yuasa Chemistry
- Performance of Generation 3 in 10 Year Life Tests
- Generation 4 Introduction

**37 affiliates in 17 countries.**



- GS YUASA CORPORATE HIGHLIGHTS**
- Celebrated 100<sup>th</sup> anniversary in 2017
  - Consolidated FY2017 Net Sales: \$3.6B
  - Net Income FY2017: \$85.6M
  - 37 affiliates in 17 countries
  - 14,585 employees worldwide

# 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..... 190+
  - LEO/MEO..... 87+
  - GEO..... 103
- 1<sup>st</sup> satellite on-orbit..... Servis 1 (30 Oct. 2003)
- Longest satellite on-orbit (yrs)..... >13 (IPSTAR, 11 Aug. 2005) still operational
- Watt hours on-orbit..... >3.7 million
- Space cell qualification programs..... >21
- Cell sizes (Ah) flown..... 35; 50; 100; 134; 175; 190; 200
- Performance to date..... No failures
- Backlog (Wh)..... >2MWh



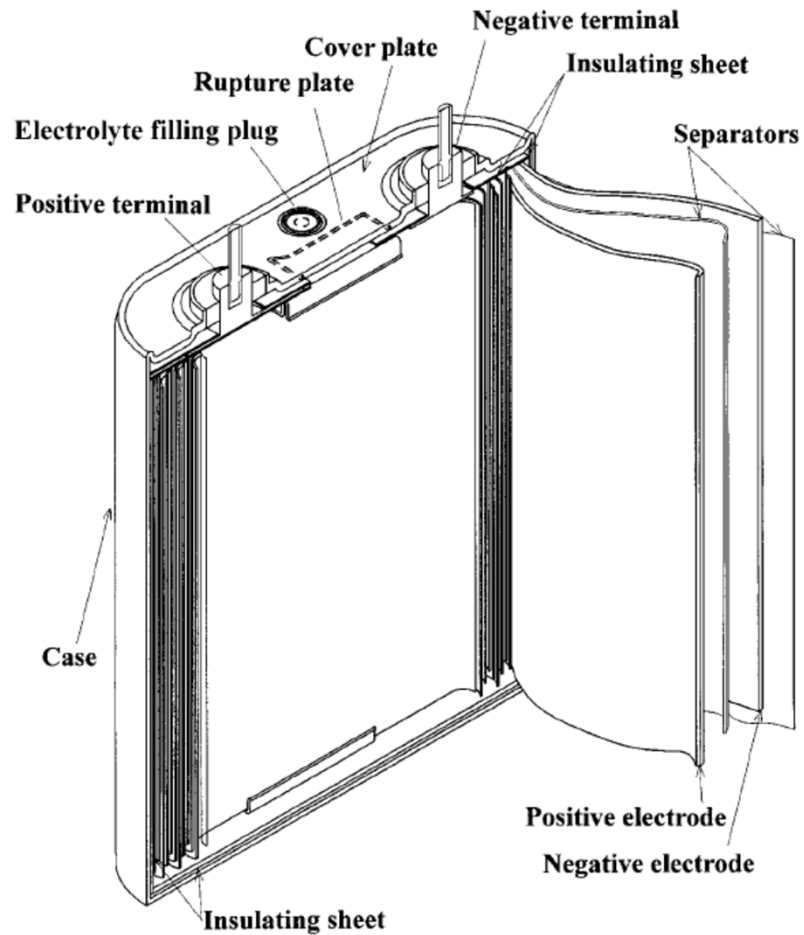
## Launch vehicles & number of satellites

Ariane-5ECA	42	Falcon-9 V.1.2	12	Proton-M Briz-M (Ph.2)	4	H-2A-2024	2	Atlas-5(421)	1
Soyuz-2-1 Fregat	24	Atlas-5(401)	5	Soyuz-2-1b Fregat	3	H-2A-204	2	Delta II-7420	1
Proton-M Briz-M (Ph.3)	18	Falcon-9 V.1.1	5	Zenit-3SLB	3	Rokot-KM	2	Dnepr	1
H-2A-202	17	Proton-M Briz-M (Ph.4)	5	Antares 120	2	Zenit-3SL (2)	2	Epsilon CLPS	1
H-2B-304	16	Antares 230	4	Atlas-5(431)	2	Antares 130*	1	GSLV Mk.2	1
Soyuz-STB Fregat-MT	13	H-2A	4	Epsilon	2	Ariane-5GS	1	Proton-M Briz-M (Ph.1 M1)	1

Metrics updated March 2019

# **GS Yuasa Space Li-ion Cell Overview**

# LSE Cell Basic Shape



**Wound electrode in an elliptical cylindrical case**

# LSE Cell Chemistry Evolution

- Generation 1 Cell (1998) – Initial Lithium Cobalt Dioxide / Graphite system developed by GS Yuasa.
  - 100Ah Nameplate cell design
    - 100Ah Gen 1 cell has been operating IPSTAR-1 since 2005, exceeding 12yr satellite design life.



Gen. 1 100Ah Cell  
(GS Yuasa)



IPSTAR-1  
(MELCO-SS/L)

- Generation 2 Cell (1999) – Lithium Cobalt Dioxide / Graphite system with enhanced specifications for critical performance impacting parameters.
  - 35Ah, 50Ah, 100Ah, 175Ah Nameplate cell designs.
  - Suppressed DCR growth and improved capacity retention over Gen 1.
  - 2019 will be the final manufacturing year for Generation 2 cells.
    - Manufactured the same active material configuration for 20 years.
  - Broad adoption for numerous GEO and LEO mission profiles.
    - JAXA, JHU/APL, MELCO, NASA, NGIS (formerly OSC), SSL and others



AMC-21  
(OSC)  
Gen 2 100Ah

*Minimum Design Changes Since 1999; Enhancements Only*

# LSE Cell Chemistry Evolution

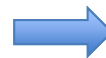
- Generation 3 Cell (2009) – LCO-Graphite design utilizes improved raw materials (positive and negative active materials, electrolyte).
  - Two electrode “types” created to optimize for Energy or Power applications. Positive / negative active materials and electrolyte are the same for both Energy and Power types. Only variable is electrode thickness
- Energy Type – electrode design optimized to maximize capacity (same design as Gen. 2)
  - Higher Energy Density
  - Low Initial DCR and Suppressed DCR growth
  - Target applications: MEO, GEO and long duration missions
  - 42Ah, 55Ah, 110Ah, 145Ah, 190Ah Nameplate Capacities
- Power Type – electrode design optimized to minimize DCR
  - Superior discharge and charge rate capability
  - Lower initial DCR and negligible DCR growth
  - Higher average discharge voltages and Wh retention
  - Target applications: High DOD LEO and special high charge / discharge rate missions
  - 38Ah, 51Ah, 102Ah, 134Ah, 176Ah Nameplate Capacities



LSE134 Cell  
(GS Yuasa)



Battery  
(Aerojet Rocketdyne)



HTV delivery  
(JAXA-MHI)



International Space Station  
(Numerous)

*Minimum Design Changes Since 1999; Enhancements Only*

# LSE Cell Chemistry Evolution

- Generation 4 Cells (2019) - Improvements to Generation 3 LCO/Graphite chemistry resulting in increased energy density while maintaining superb capacity retention and suppression of DCR growth.
  - Energy and Power optimized electrode optimizations will be available.



	160 Ah Generation 4	145 Ah Generation 3
<b>Dimensions / mm</b>	H 263* W 130 T 50	H 263* W 130 T 50
<b>EoCV / V</b>	4.10	4.10
<b>Capacity / Ah</b>		
(Rated)	160	145
(Actual)	178	161
<b>Discharge Voltage / V</b>	3.72	3.70
<b>Mass / kg</b>	3.69	3.55
<b>Specific energy / Wh/kg</b>	180	168

\*Excluding terminal studs

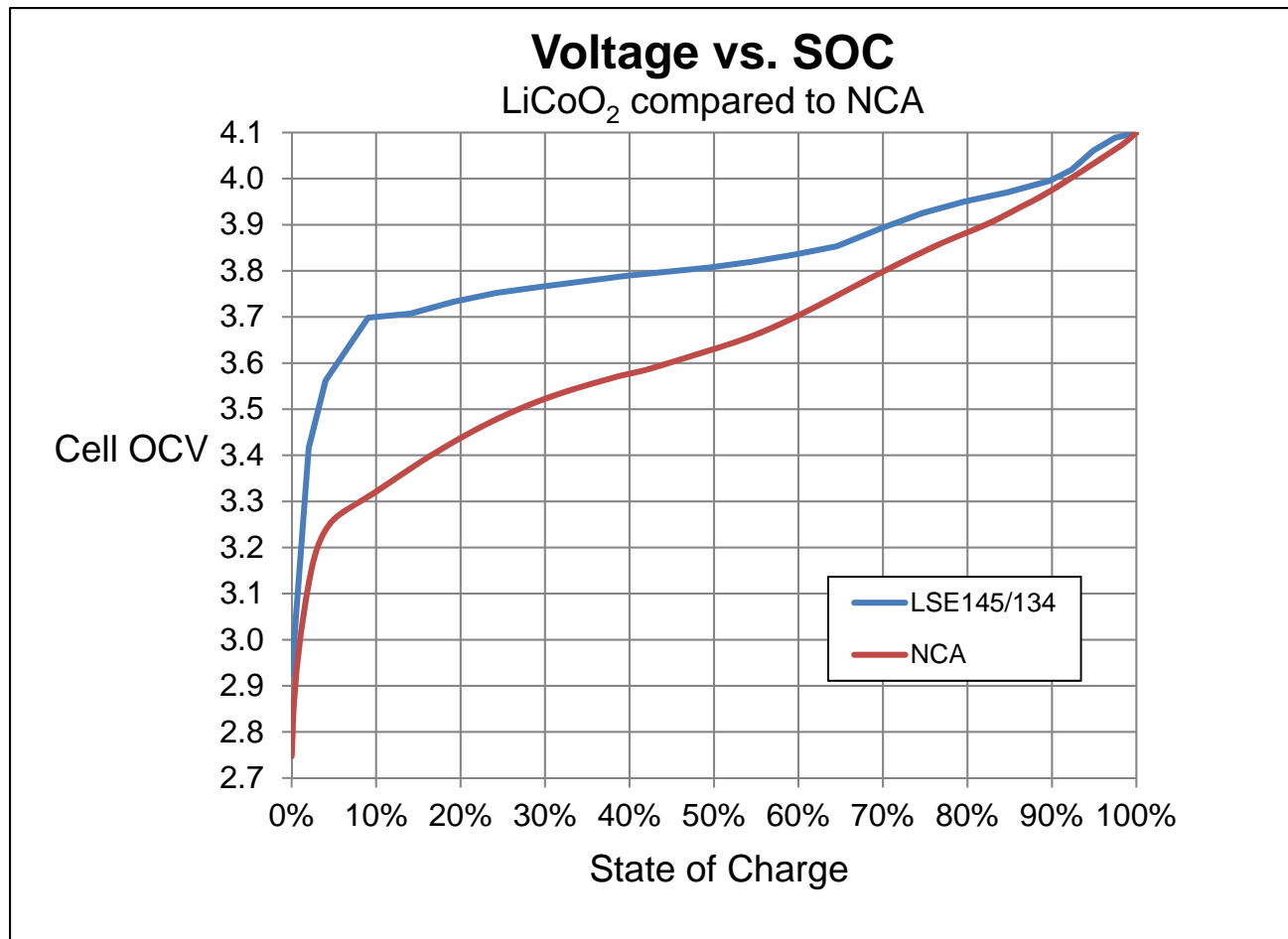
Minimum Design Changes Since 1999; Enhancements Only

# LSE Cell Basic Chemistry



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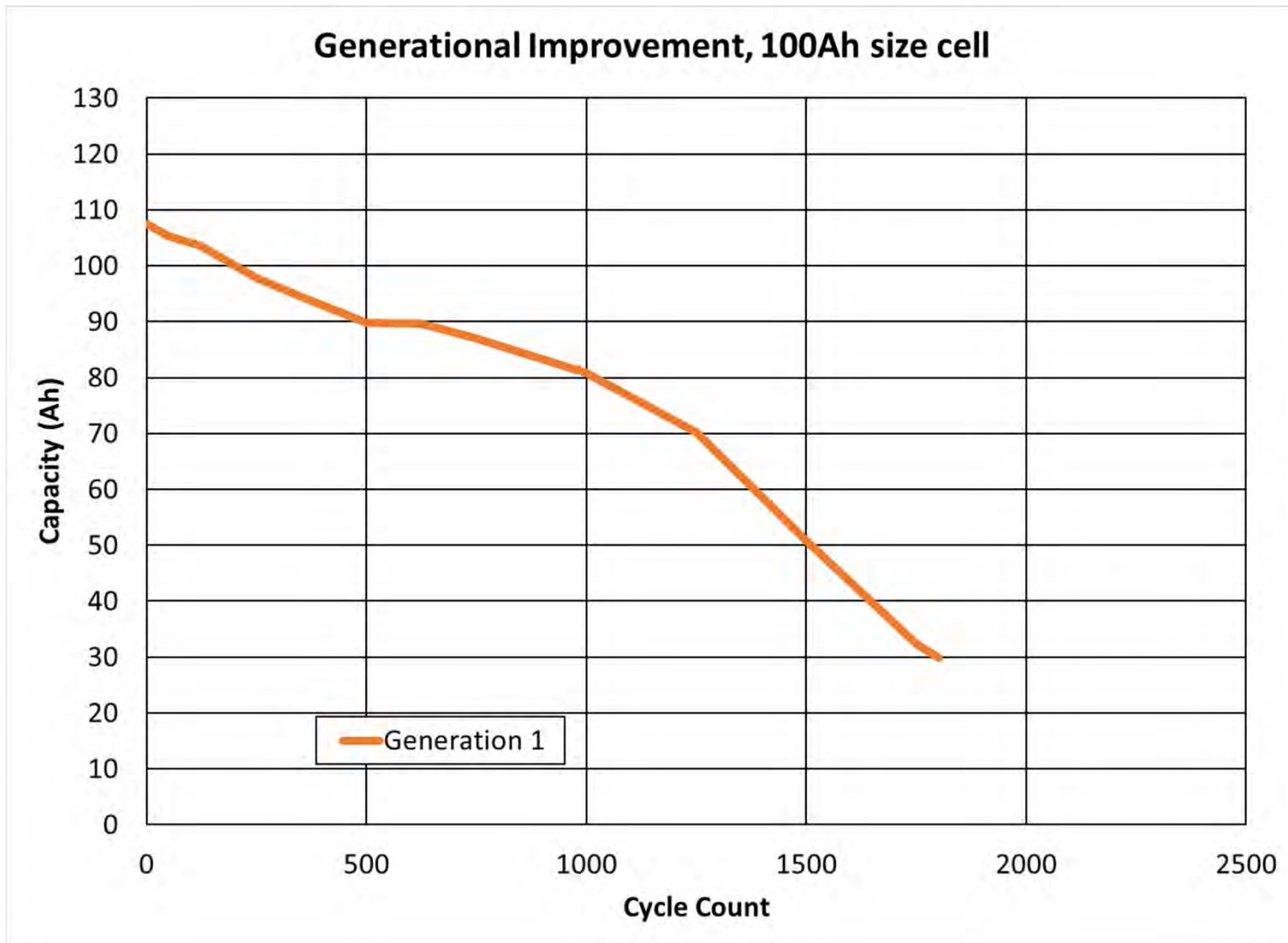
GS Yuasa has preferred the LCO chemistry for space applications due to its higher average voltage during discharge. This is especially beneficial for batteries installed on an unregulated bus. Accessible Watt-hour capacity through life is maximized with this chemistry.



# Evolution of GS Yuasa LiCoO<sub>2</sub>, 100% DOD



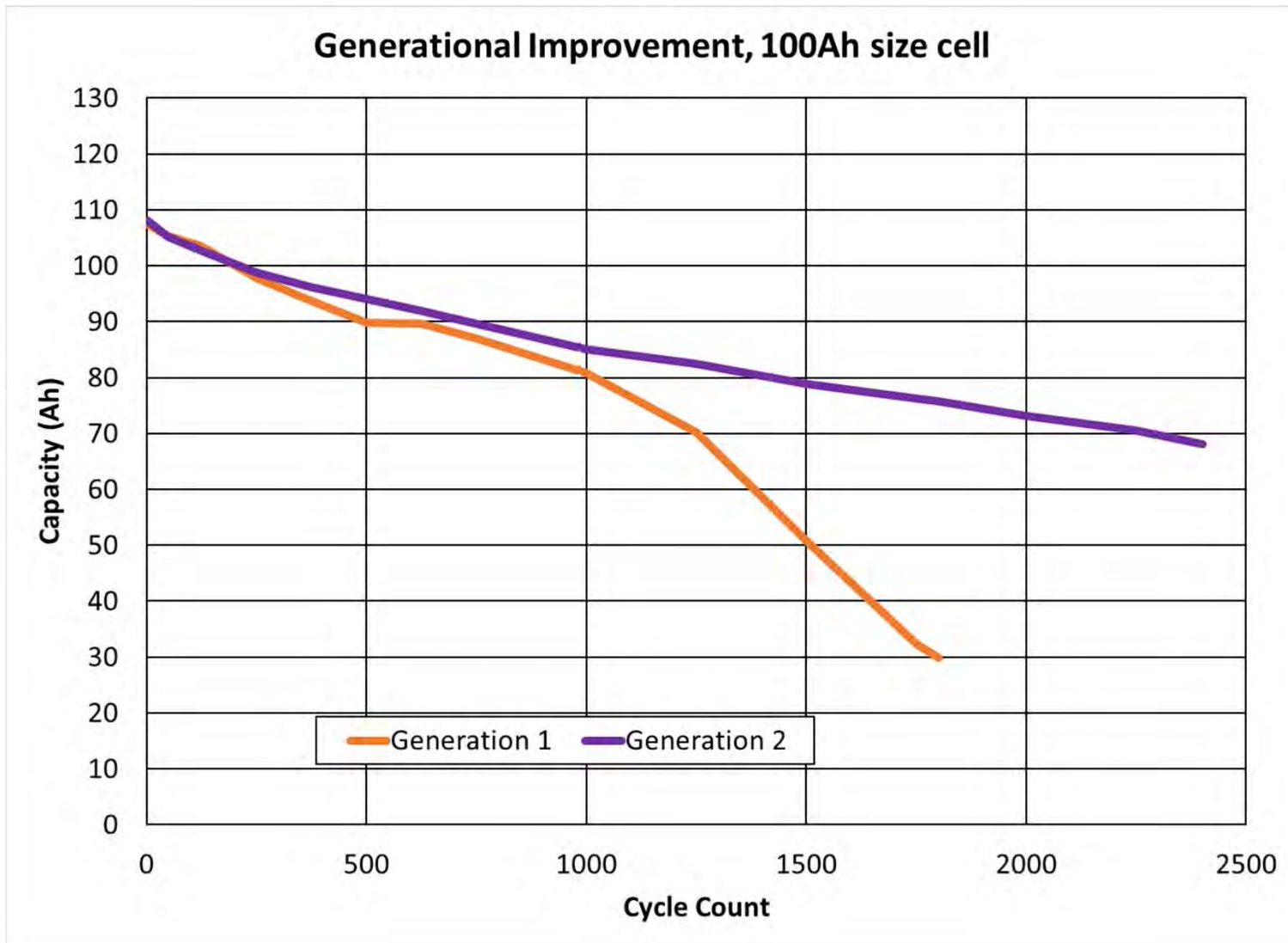
Powering the Next Generation



# Evolution of GS Yuasa LiCoO<sub>2</sub>, 100% DOD



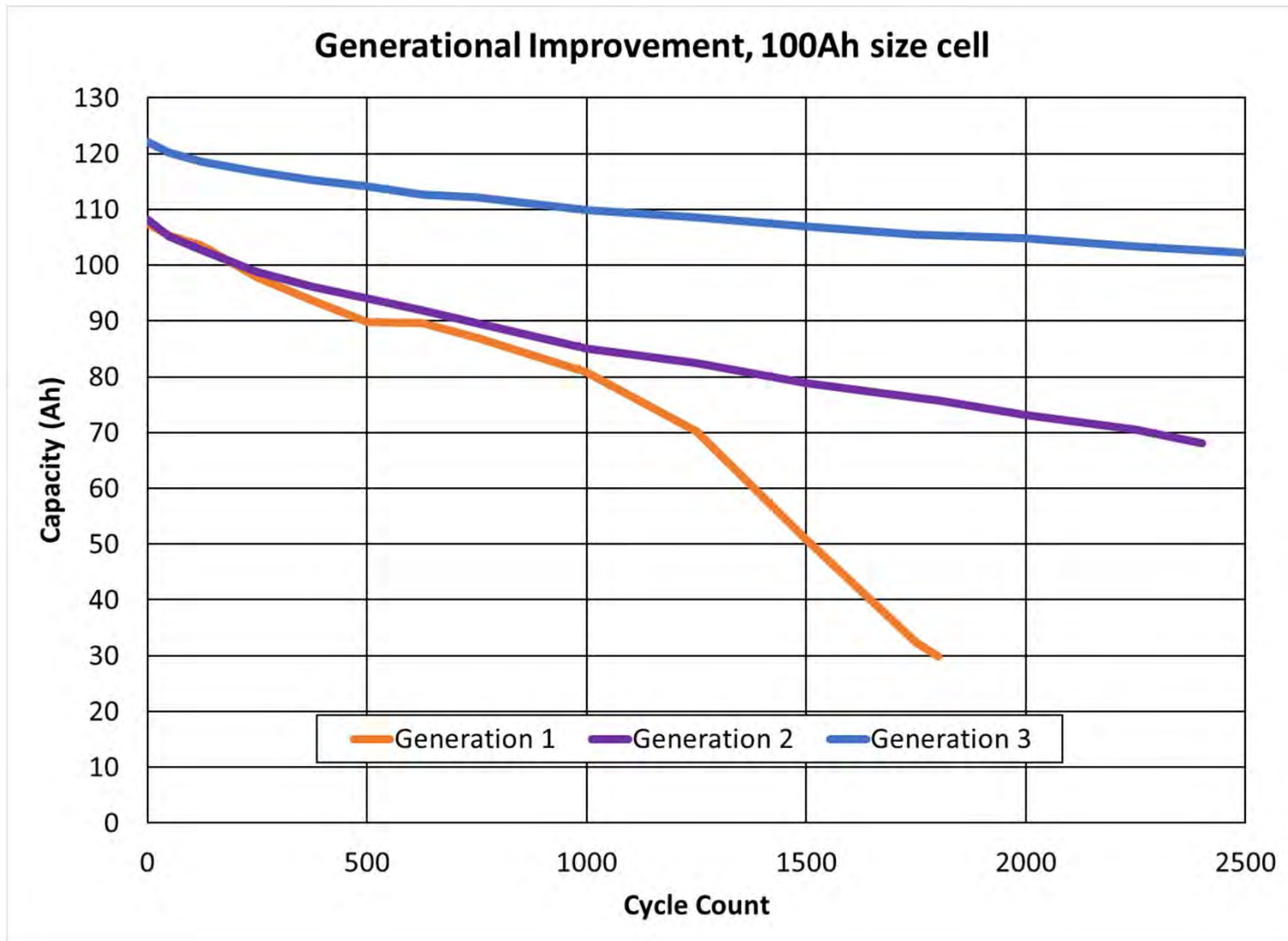
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# Evolution of GS Yuasa LiCoO<sub>2</sub>, 100% DOD



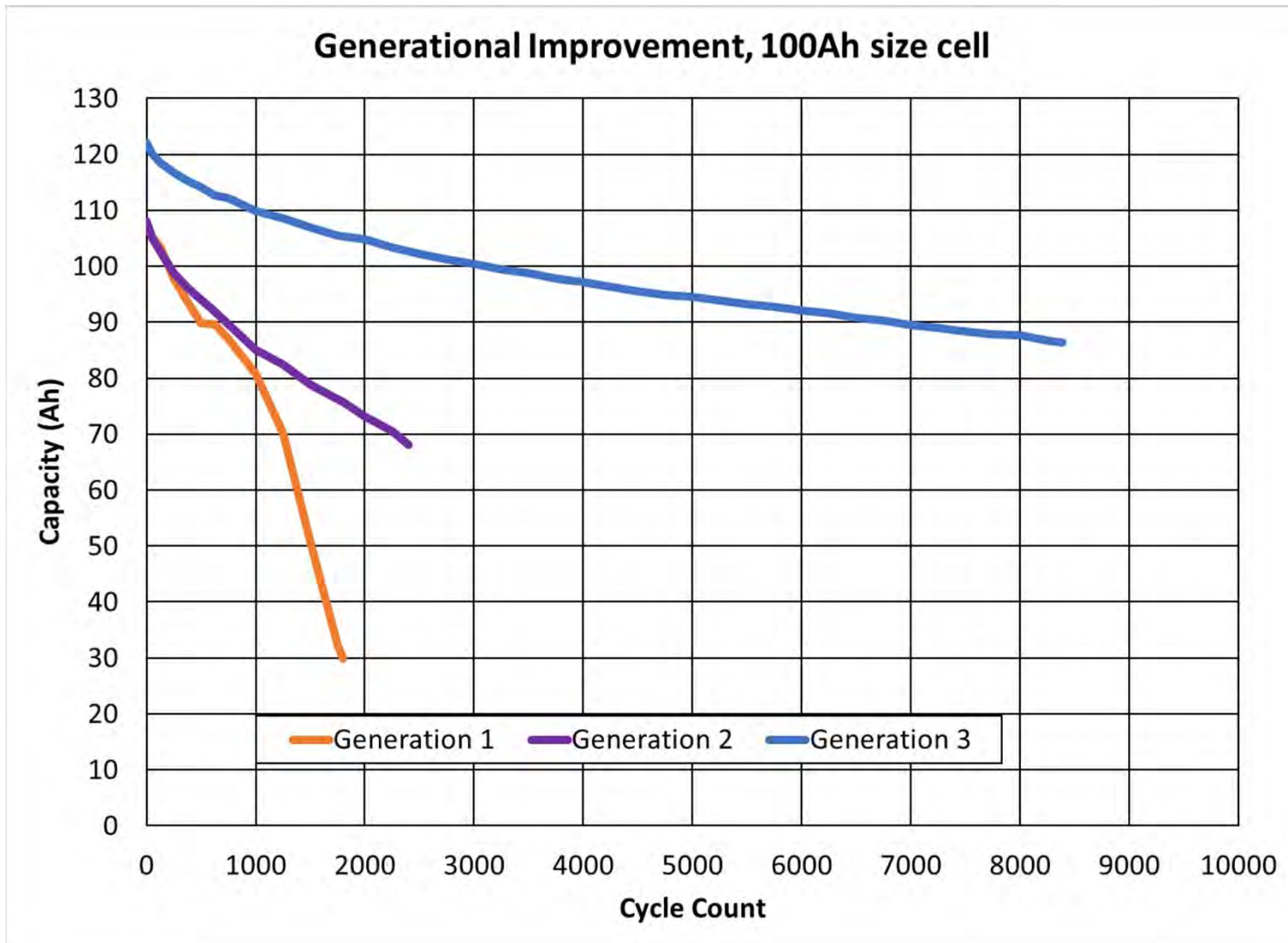
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# Evolution of GS Yuasa LiCoO<sub>2</sub>, 100% DOD



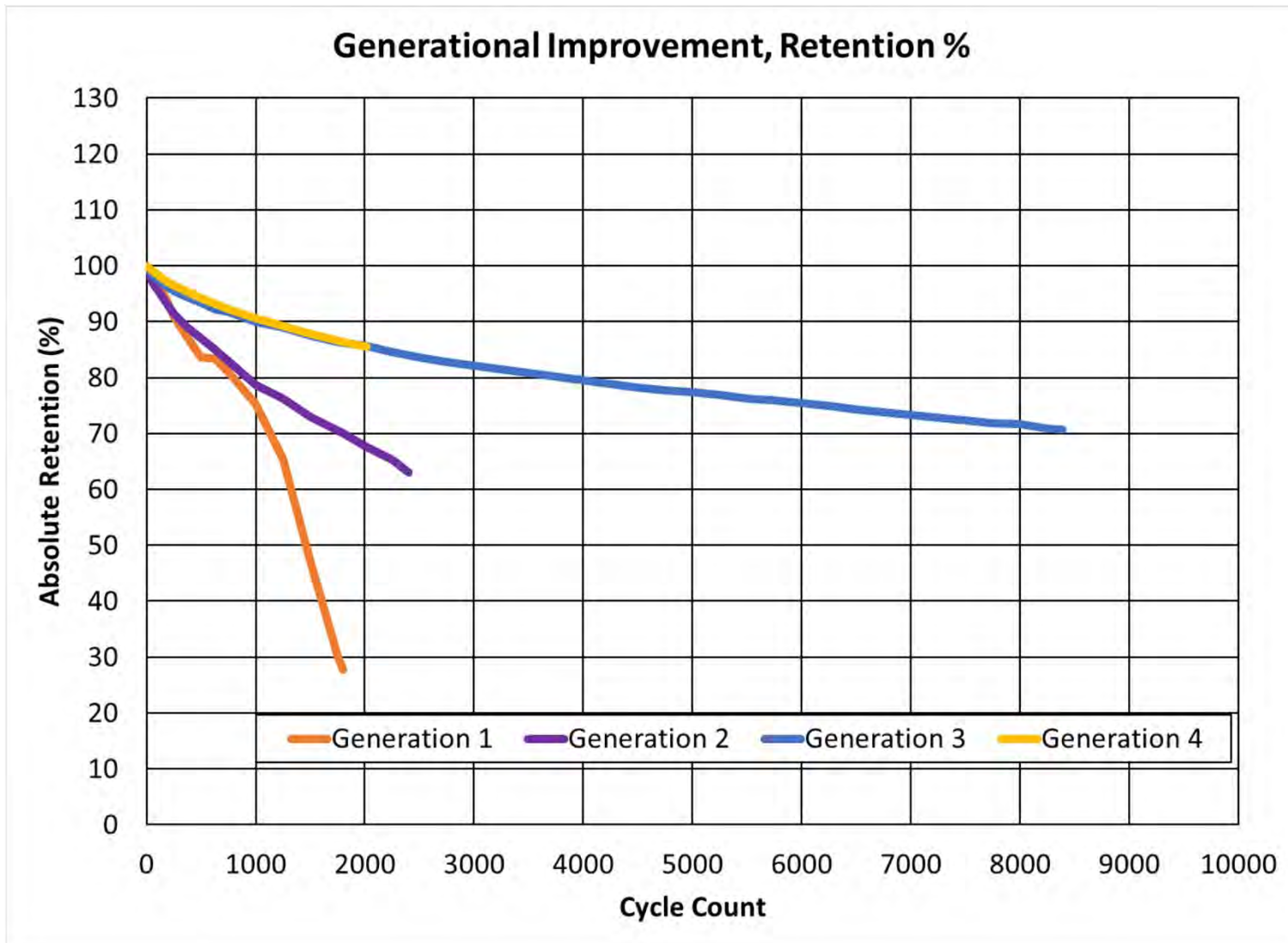
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# Evolution of GS Yuasa LiCoO<sub>2</sub>, 100% DOD



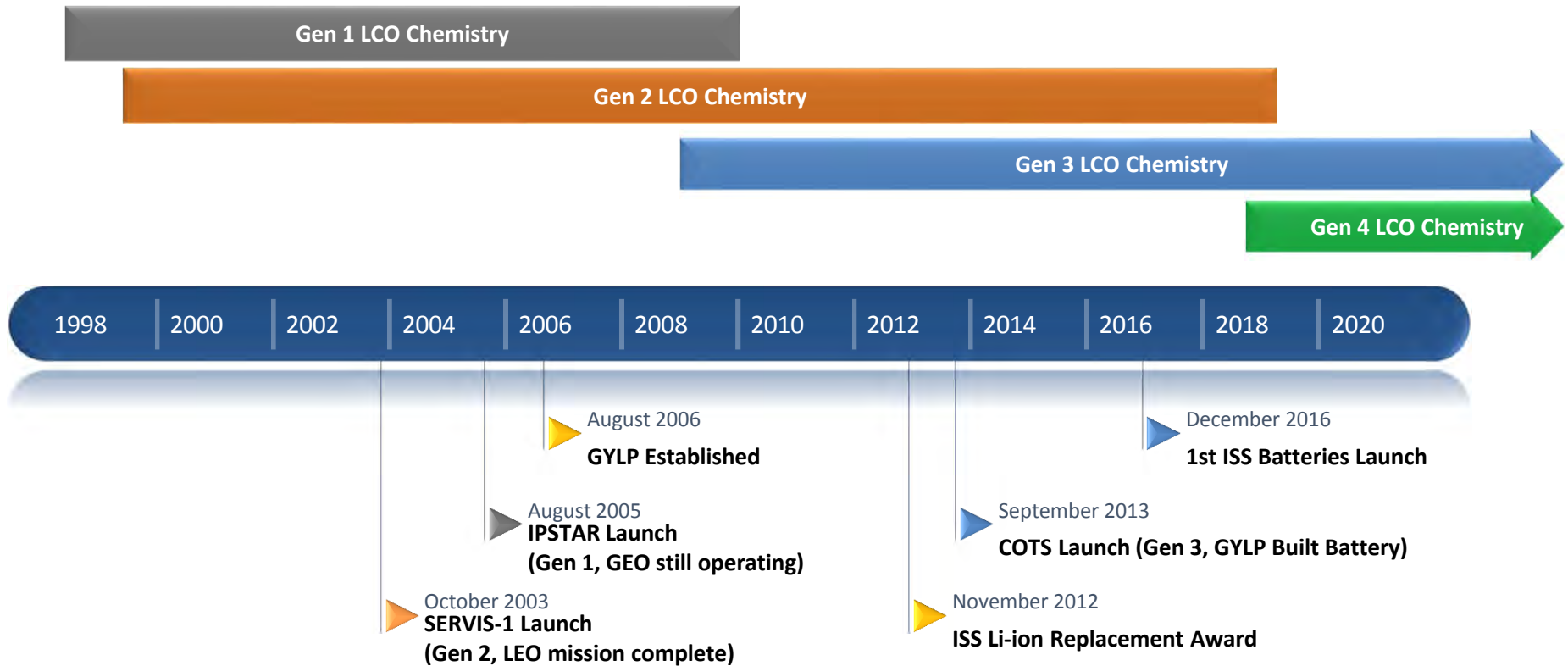
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# Production Timeline of GS Yuasa Space Chemistry



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**GS Yuasa has demonstrated the ability to maintain configuration and control over the material sources for 15+ years thanks to strong relationship with the suppliers of the materials.**

Once a chemistry is qualified there are no major changes to the active material specifications. Generation 3 will be available for several years as Generation 4 is introduced.

# Life Test Performance of Generation 3 Cells

# Longest Running Gen 3 Cycle Life Tests



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Test Name	Cell Type	Test Conditions						Ambient Test Temp	Start Date	Number of Cycles	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition						
		EoCV	Rate	Time	EoDV	Rate	Time				
<i>Energy Cell Testing</i>											
100% DoD Cycling	LSE110	4.10V	0.5C	4hr	2.75V	100A	N/A	25°C	3/19/2009	8,385	Test Finished (9/2016)
80% DOD Cycling	LSE110	4.10V	0.2C	11.4hr	(2.75V)	74A	1.2hr	15°C	3/19/2009	4,503+	Deep DoD GEO Cycle
25% DoD Cycling	LSE110	4.10V	33A	1hr	(3.40V)	55A	0.5hr	15°C	3/19/2009	38,384+	Standard LEO Orbit Cycle
70% Max DoD GEO	LSE145	4.00V	14.5A	22.8hr (min)	(2.75V)	86.3A	1.17hr (Max)	10°C	9/3/2011	861+	19 complete seasons
<i>Power Cell Testing</i>											
100% DoD Cycling	LSE51	4.10V 3.98V	0.5C	4hr	2.75V	50A	N/A	25°C	9/25/2009	9,500+	Still Running
40% DoD Cycling	LSE51	3.98V	25.5A	1hr	(3.40V)	40.8A	0.5hr	20°C	9/28/2009	36,480+	Deep DoD LEO Cycle
25% DoD Cycling	LSE51	4.10V 3.98V	15.3A	1hr	(3.40V)	25A	0.5hr	20°C	10/30/2010	36,480+	Standard LEO Orbit Cycle

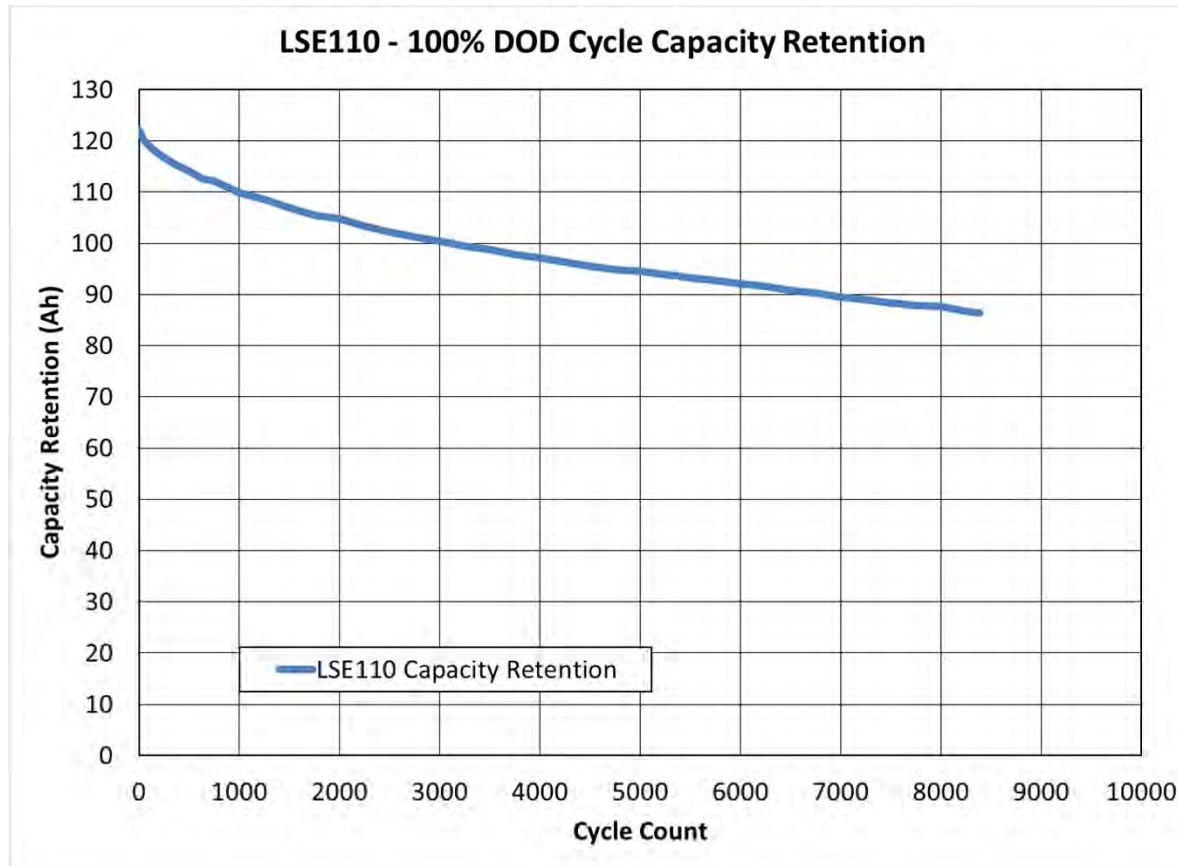
*Above table is not a comprehensive list of all life cycle testing available. Please contact GYLP to request.*

# LSE110 – 100% DOD Cycle Life



Powering the Next Generation

Test Name	Cell Type	Test Conditions						Ambient Test Temp	Start Date	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition					
		EoCV	Rate	Time	EoDV	Rate	Time			
100% DoD Cycling	LSE110	4.10V	0.5C	4hr	2.75V	100A	N/A	25°C	3/19/2009	8,385 cycles Complete 2016

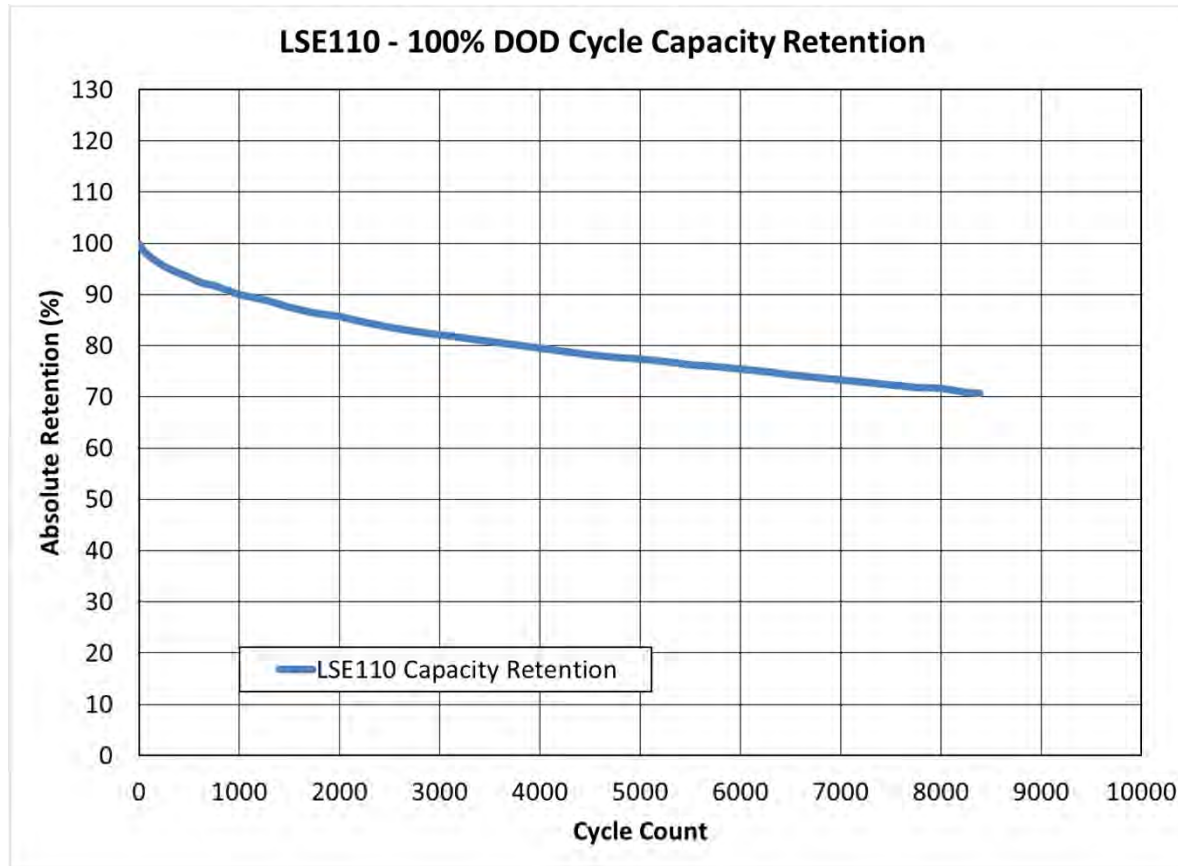


# LSE110 – 100% DOD Cycle Life



Powering the Next Generation

Test Name	Cell Type	Test Conditions						Ambient Test Temp	Start Date	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition					
		EoCV	Rate	Time	EoDV	Rate	Time			
100% DoD Cycling	LSE110	4.10V	0.5C	4hr	2.75V	100A	N/A	25°C	3/19/2009	8,385 cycles Complete 2016

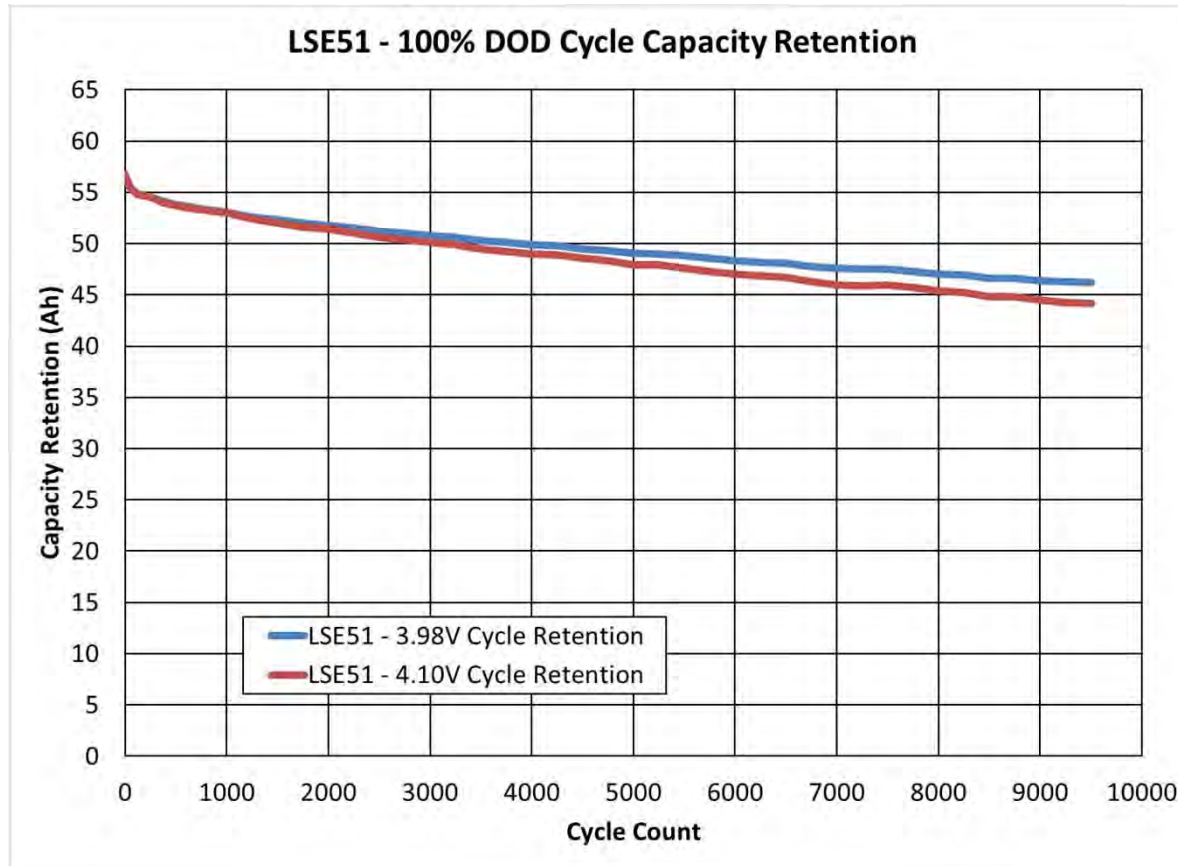


# LSE51 – 100% DOD Cycle Life



Powering the Next Generation

Test Name	Cell Type	Test Conditions						Ambient Test Temp	Start Date	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition					
		EoCV	Rate	Time	EoDV	Rate	Time			
100% DoD Cycling	LSE51	4.10V 3.98V	0.5C	4hr	2.75V	50A	N/A	25°C	9/25/2009	9,500 cycles (ongoing)

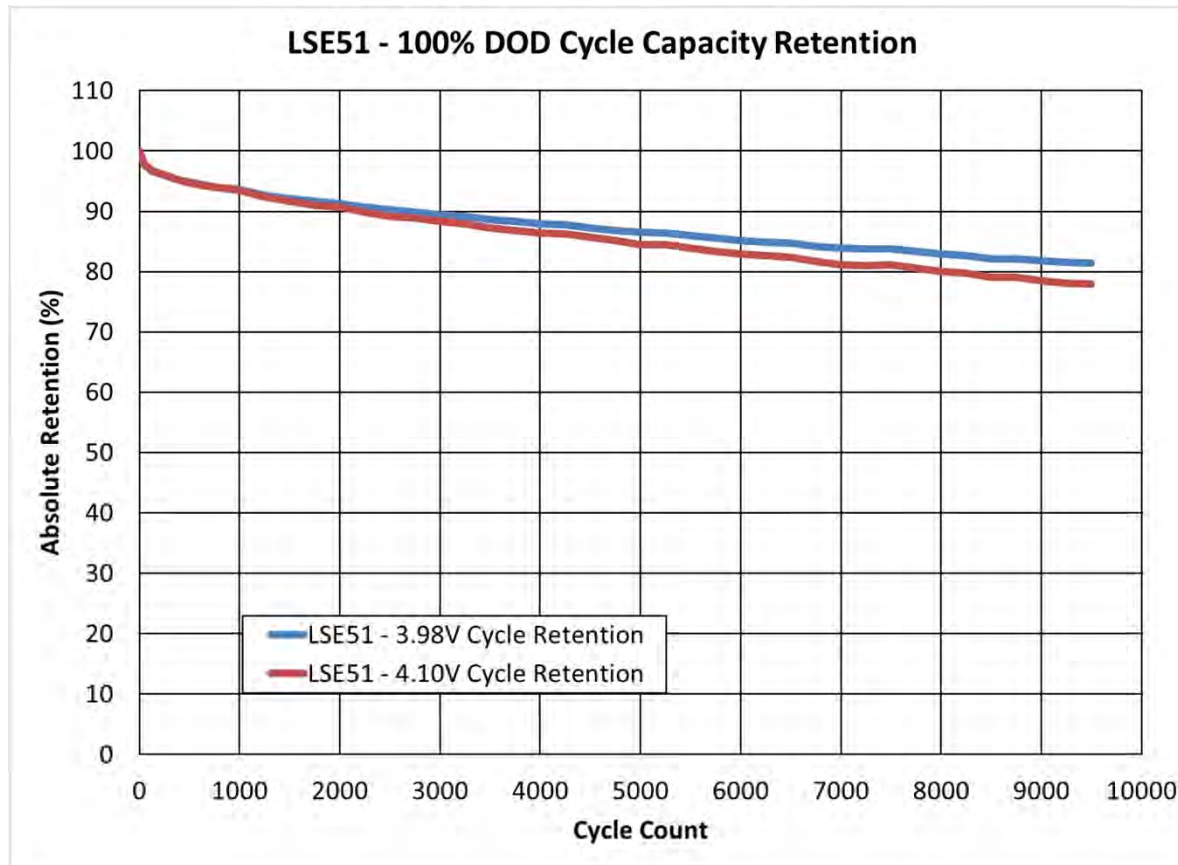


# LSE51 – 100% DOD Cycle Life



Powering the Next Generation

Test Name	Cell Type	Test Conditions						Ambient Test Temp	Start Date	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition					
		EoCV	Rate	Time	EoDV	Rate	Time			
100% DoD Cycling	LSE51	4.10V 3.98V	0.5C	4hr	2.75V	50A	N/A	25°C	9/25/2009	9,500 cycles (ongoing)

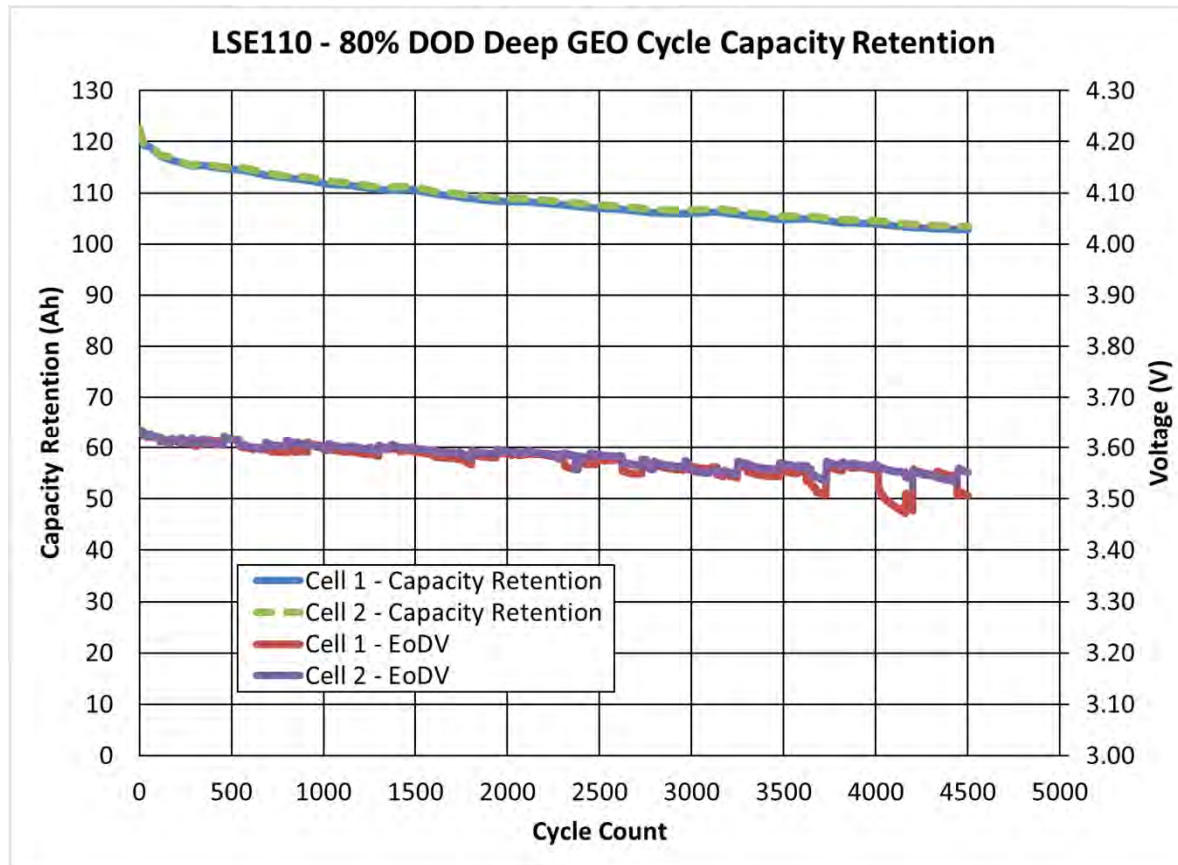


# LSE110 -- 80% DOD Deep GEO Cycle Life



Powering the Next Generation

Test Name	Cell Type	Test Conditions						Ambient Test Temp	Start Date	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition					
		EoCV	Rate	Time	EoDV	Rate	Time			
80% DOD Cycling	LSE110	4.10V	0.2C	11.4hr	(2.75V)	74A	1.2hr	15°C	3/19/2009	4,503 Cycles (2) Cells on Test

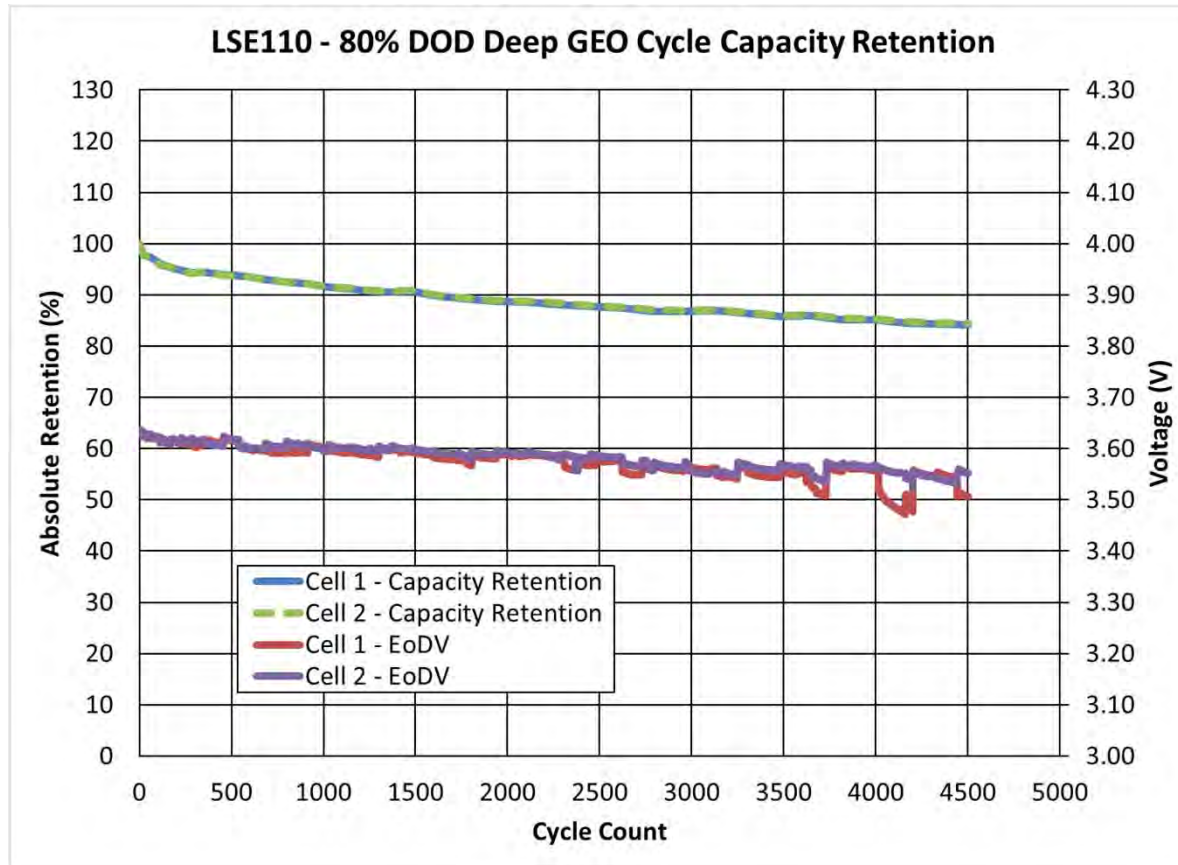


# LSE110 -- 80% DOD Deep GEO Cycle Life



Powering the Next Generation

Test Name	Cell Type	Test Conditions						Ambient Test Temp	Start Date	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition					
		EoCV	Rate	Time	EoDV	Rate	Time			
80% DOD Cycling	LSE110	4.10V	0.2C	11.4hr	(2.75V)	74A	1.2hr	15°C	3/19/2009	4,503 Cycles (2) Cells on Test

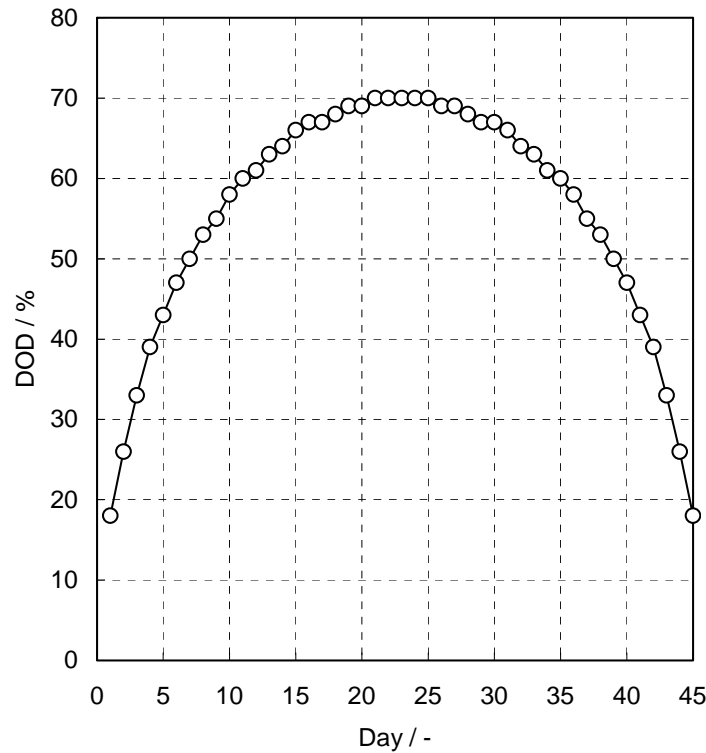


# Semi-accelerated GEO Life Cycle Test



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Cell	Solstice Season	Eclipse Season
<b>LSE145</b> <b>Energy Type</b> <b>Gen. 3 cell</b>	<b>SOC: ~90% (4.0V EOCV)</b> <b>Temperature: 25°C</b> <b>Duration 69days</b>	<b>1 cycle per day for 45 days</b> <b>Charge: 0.1C(14.5A),</b> <b>Duration: 24h-discharge time</b> <b>Discharge: 0.595C (86.3A)</b> <b>Min duration: 18.15min, Max Duration: 70.5m (see chart)</b> <b>Temperature: 10°C</b>

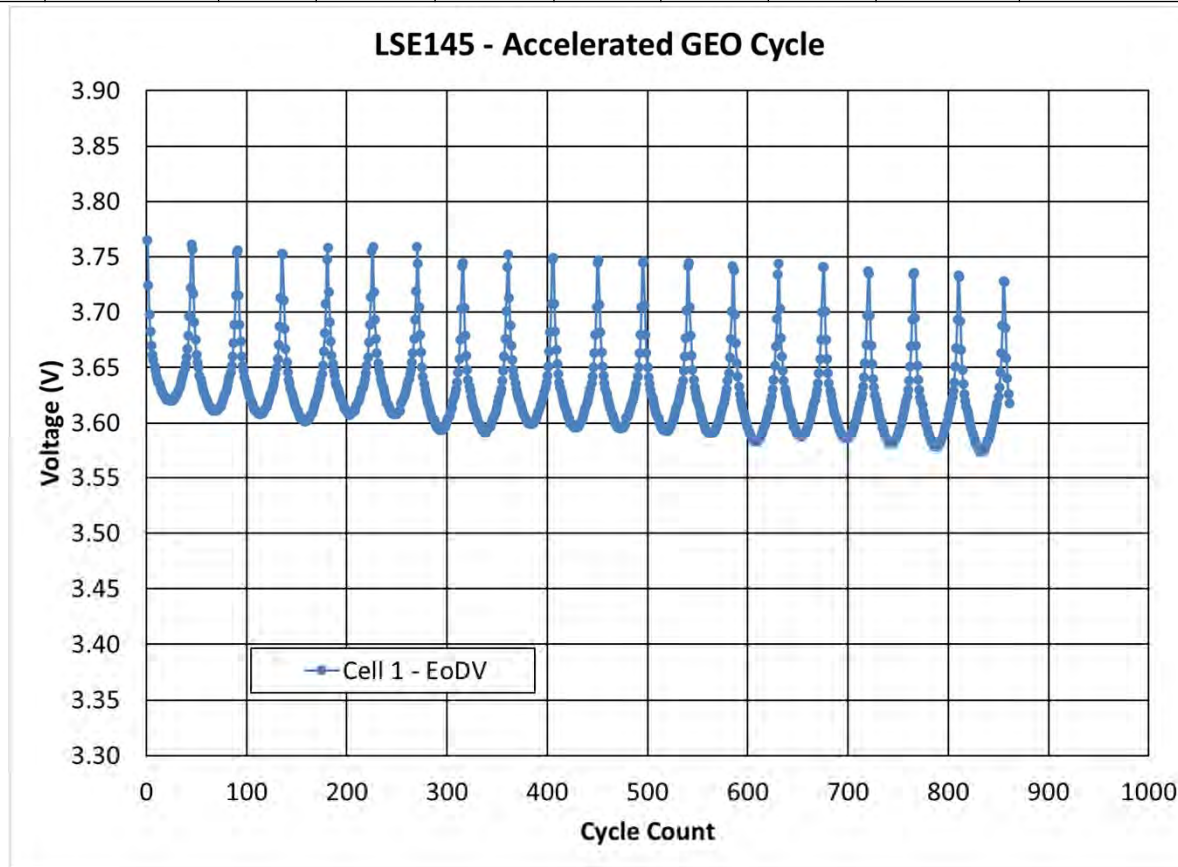


# Semi-accelerated GEO Life Cycle Test



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Test Name	Cell Type	Test Conditions						Ambient Test Temp	Start Date	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition					
		EoCV	Rate	Time	EoDV	Rate	Time			
Semi-Accelerated GEO Cycle	LSE145	4.00V	14.5A	22.83hr	(3.40V)	86.3A	Varies	10°C	9/3/2011	69 day solstice season 25°C 45day eclipse season

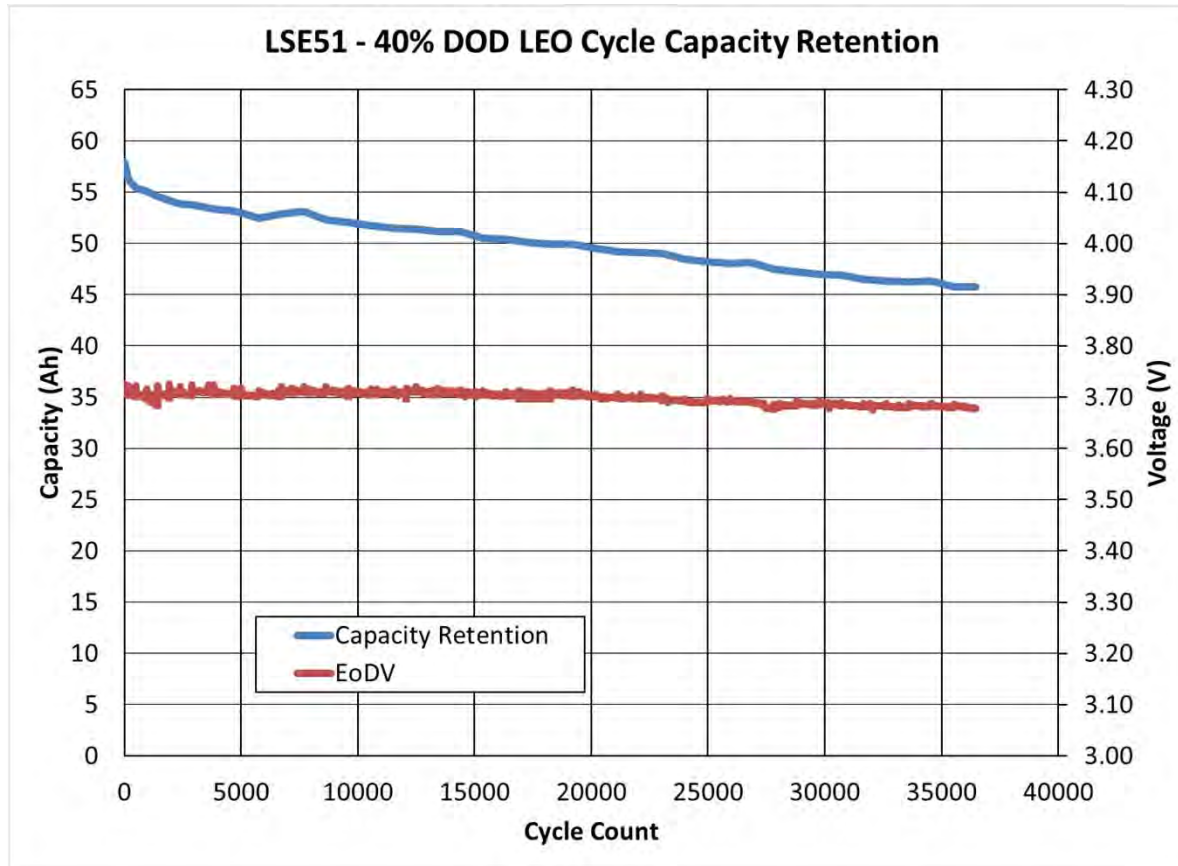


# LSE51 -- 40% DOD LEO Cycle Life



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Test Name	Cell Type	Test Conditions						Ambient Test Temp	Start Date	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition					
		EoCV	Rate	Time	EoDV	Rate	Time			
40% DoD Cycling	LSE51	3.98V	25.5A	1hr	(3.40V)	40.8A (0.8C)	0.5hr	20°C	9/28/2009	36,480 Cycle (ongoing)

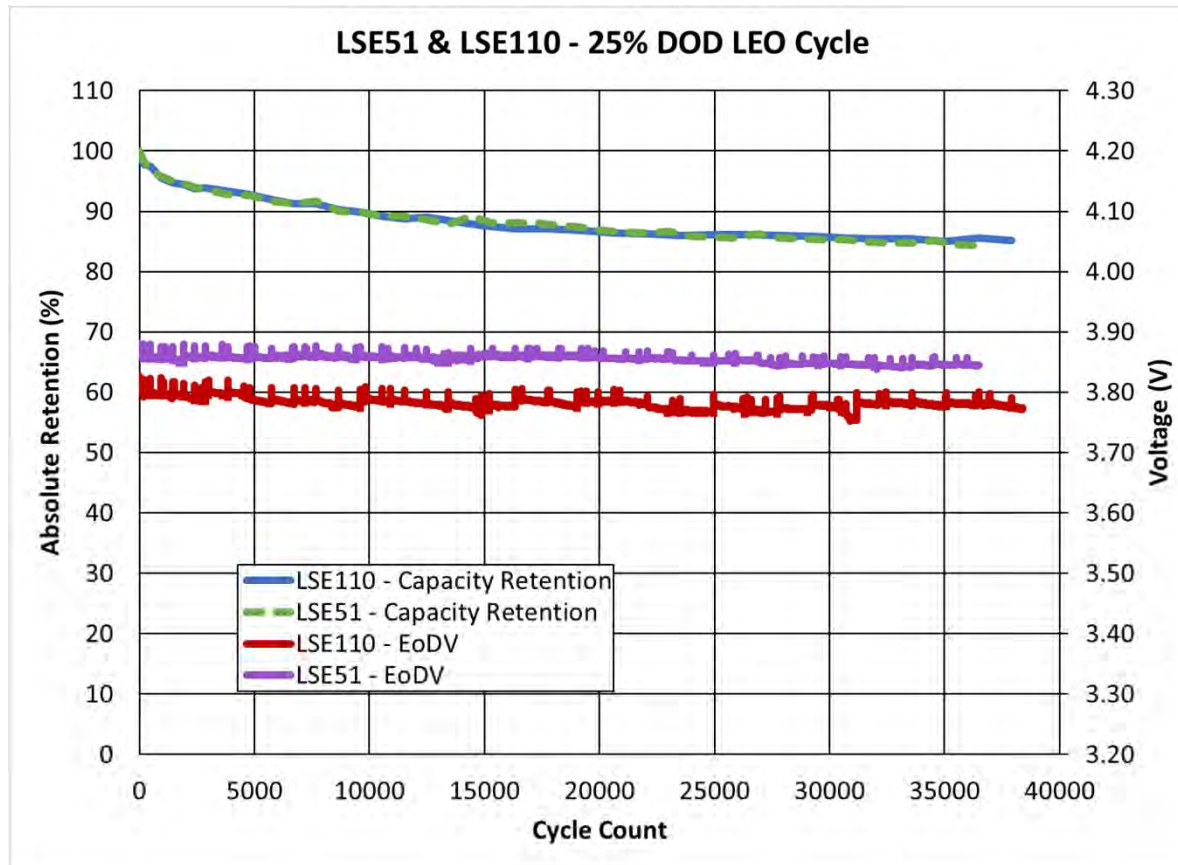


# LSE51 & LSE110 -- 25% DOD LEO Cycle Life



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Test Name	Cell Type	Test Conditions						Ambient Test Temp	Start Date	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition					
		EoCV	Rate	Time	EoDV	Rate	Time			
25% DoD Cycling	LSE110	4.10V	33A	1hr	(3.40V)	55A	0.5hr	15°C	3/19/2009	38,384 cycles
	LSE51		15.3A			25A		20°C	10/30/2010	36,480 cycles

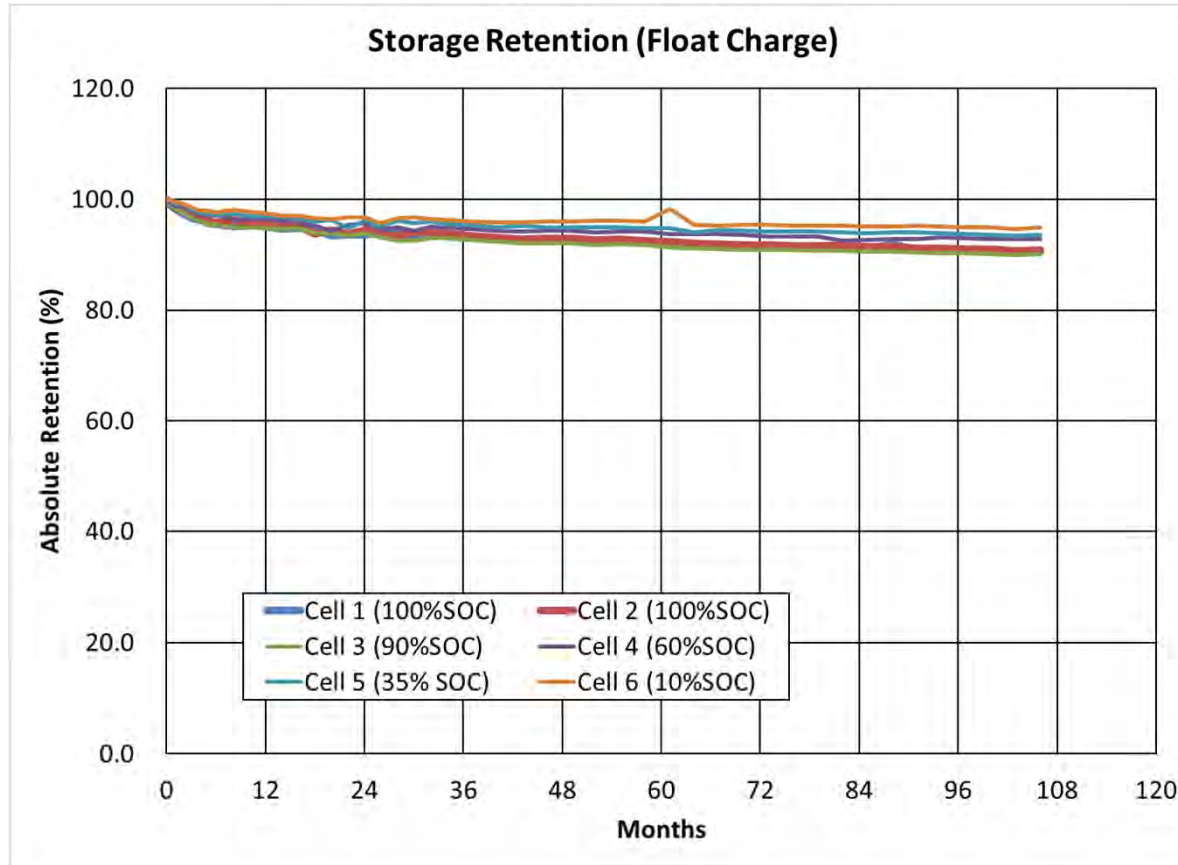


# Storage Retention Test



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Test Name	Cell Type	Test Conditions						Ambient Test Temp	Start Date	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition					
		EoCV	Rate	Time	EoDV	Rate	Time			
Storage Retention	LSE110	Various	N/A	∞	N/A	N/A	N/A	15°C	4/1/2009	Float charge storage (ongoing)

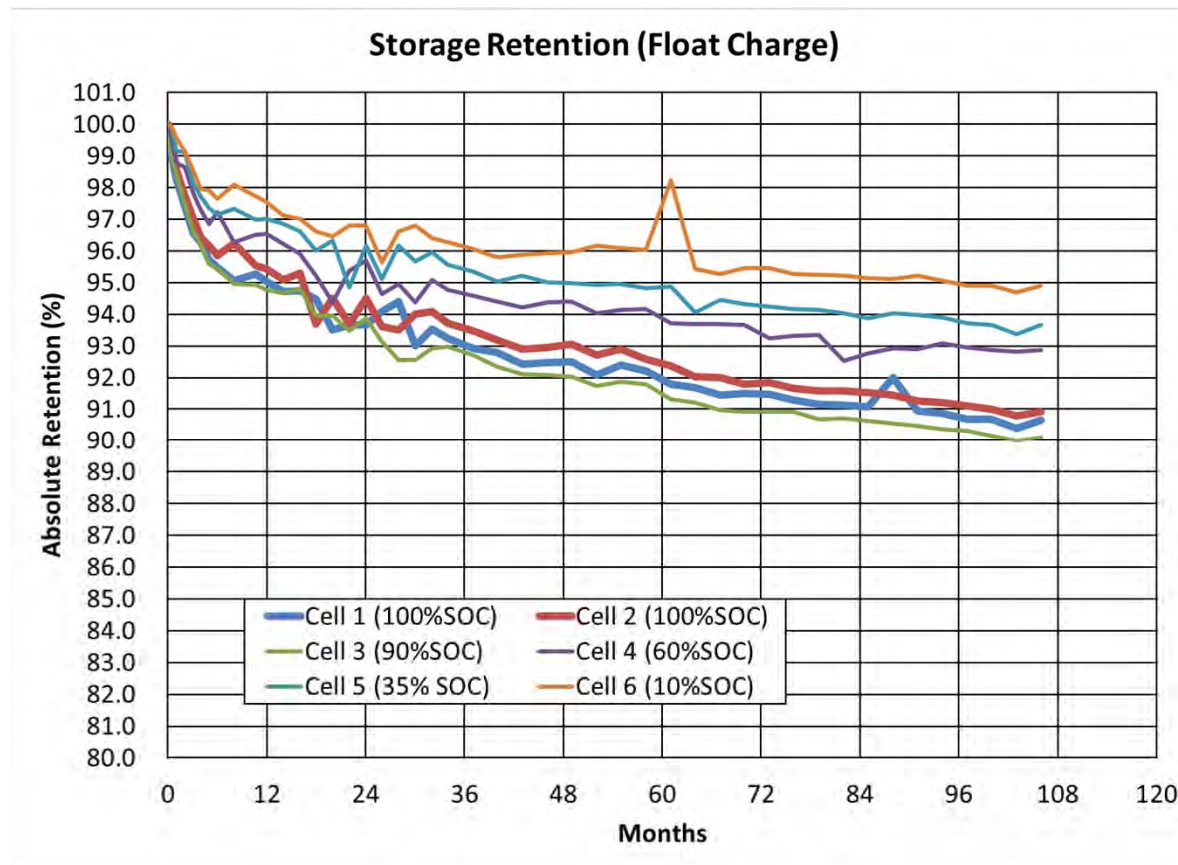


# Storage Retention Test



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Test Name	Cell Type	Test Conditions						Ambient Test Temp	Start Date	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition					
		EoCV	Rate	Time	EoDV	Rate	Time			
Storage Retention	LSE110	Various	N/A	∞	N/A	N/A	N/A	15°C	4/1/2009	Float charge storage (ongoing)



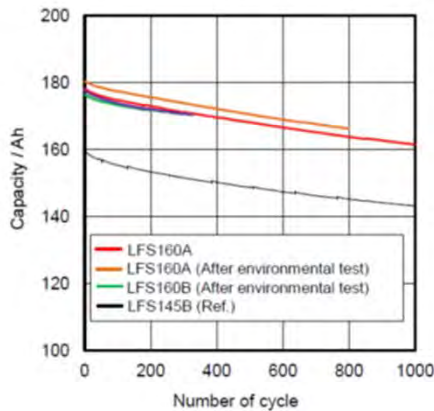
# Gen IV Qualification Status



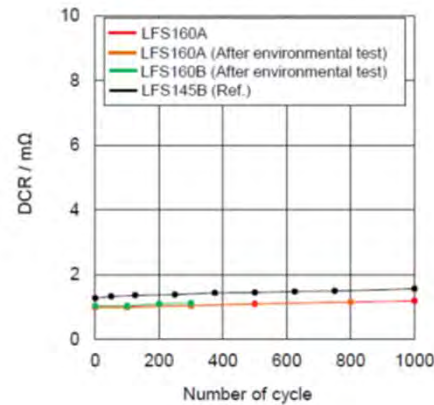
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- LSE160 has completed qualification successfully → JAXA Engineering Satellite ETS-9
- Gen IV continues the improvement of LCO chemistry for space applications

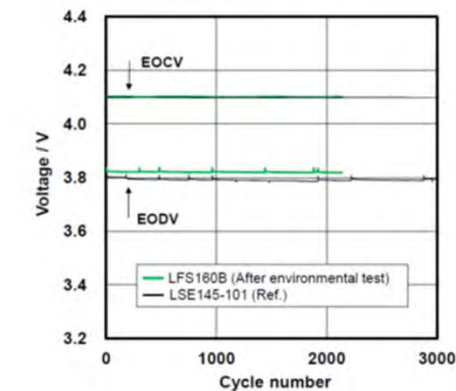
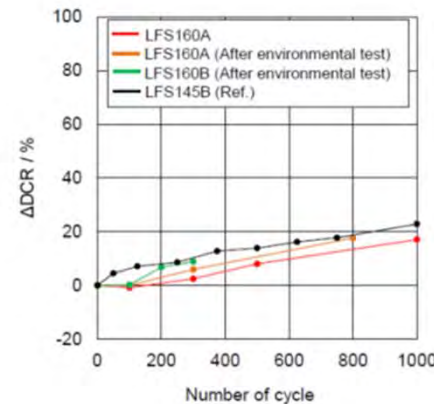
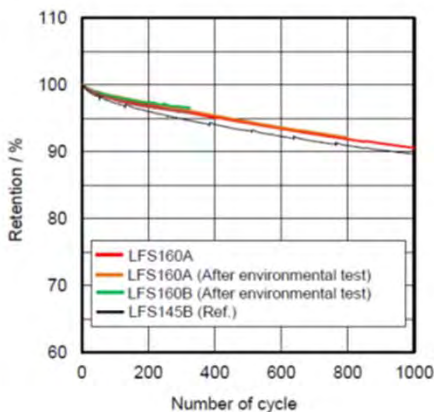
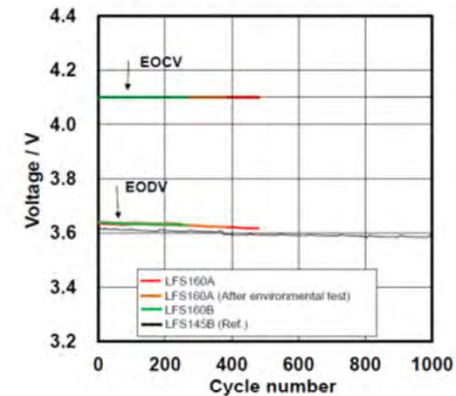
Improved initial capacity and capacity retention



Reduced DCR and improved growth suppression



Higher nominal discharge voltage and EODV



# LSE205 Qualification Status



Generation	III	IV
Part name	LSE190	"LSE205"
Chemistry	LCO/Graphite	←
EoCV	4.10	←
Rated capacity (Ah)	190	205
Nominal capacity (Ah)	205	225
Nominal discharge voltage	3.74	3.76
Nominal capacity (Wh)	766	846
Relative Wh capacity	100%	110%
Mass (kg)	4.59	4.78
Nominal specific energy (Wh/kg)	166	176

Hermeticity

Basic performance  
 Soft short detection  
 C/5 and C/2 discharge performance  
 Appearance  
 Dimensions  
 Mass  
 AC impedance  
 Case isolation

Environmental performance  
 Sine vibration  
 Random vibration  
 Shock  
 Acceleration  
 Post environmental basic performance

Life test (TBD)  
 DOD 100%  
 DOD 80%  
 DOD 25%

Mechanical properties  
 Vent operating pressure  
 Case burst

Other basic performance  
 Temperature performance  
 Pulse discharge performance

Safety properties  
 Overcharge  
 Over-discharge  
 External short circuit  
Safety properties  
 Nail penetration (TBD)  
 Heat to vent (TBD)  
 Drop (TBD)

Manufacturing of qualification cells expected to begin May 2019. Qualification expected in 2020.

**Notes**

- 1) Life tests, other basic performance, and some safety tests will be performed as references.
- 2) Test menu will be subject to change.

The **absence** of significant configuration changes to the Li-ion chemistry and the **abundance** of empirical test data allows for the development of reliable cell models. Specifically GS Yuasa has the in-house capability to model:

1. Full Capacity Retention
2. Maximum Available On-Orbit Capacity
3. On-Orbit Voltage Retention (End of Discharge Voltage)
4. Cell Heat Generation
5. Thermal Finite Element Modeling

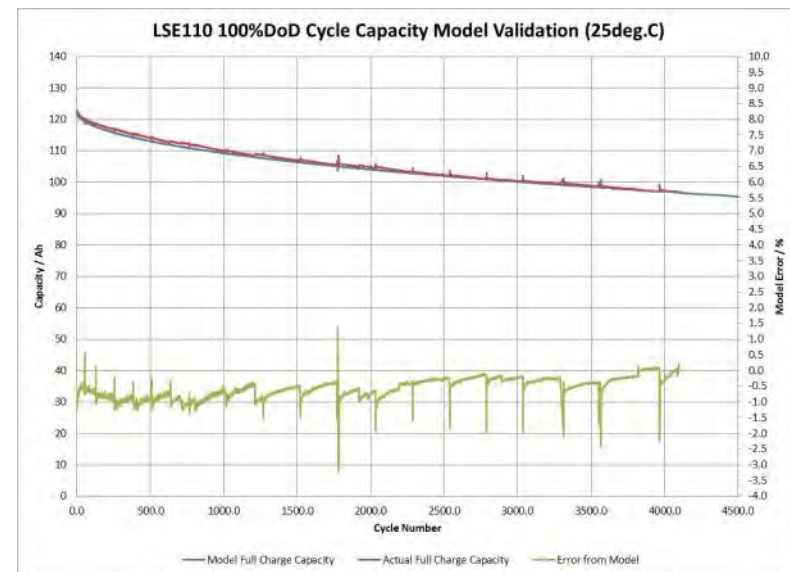


The GS Yuasa Capacity and Voltage Retention Model is an internally developed tool for predicting cell performance in a variety of ground and dynamic on-orbit usage profiles.

The model is based on the empirical life testing data accumulated by GS Yuasa over the past 15 years.

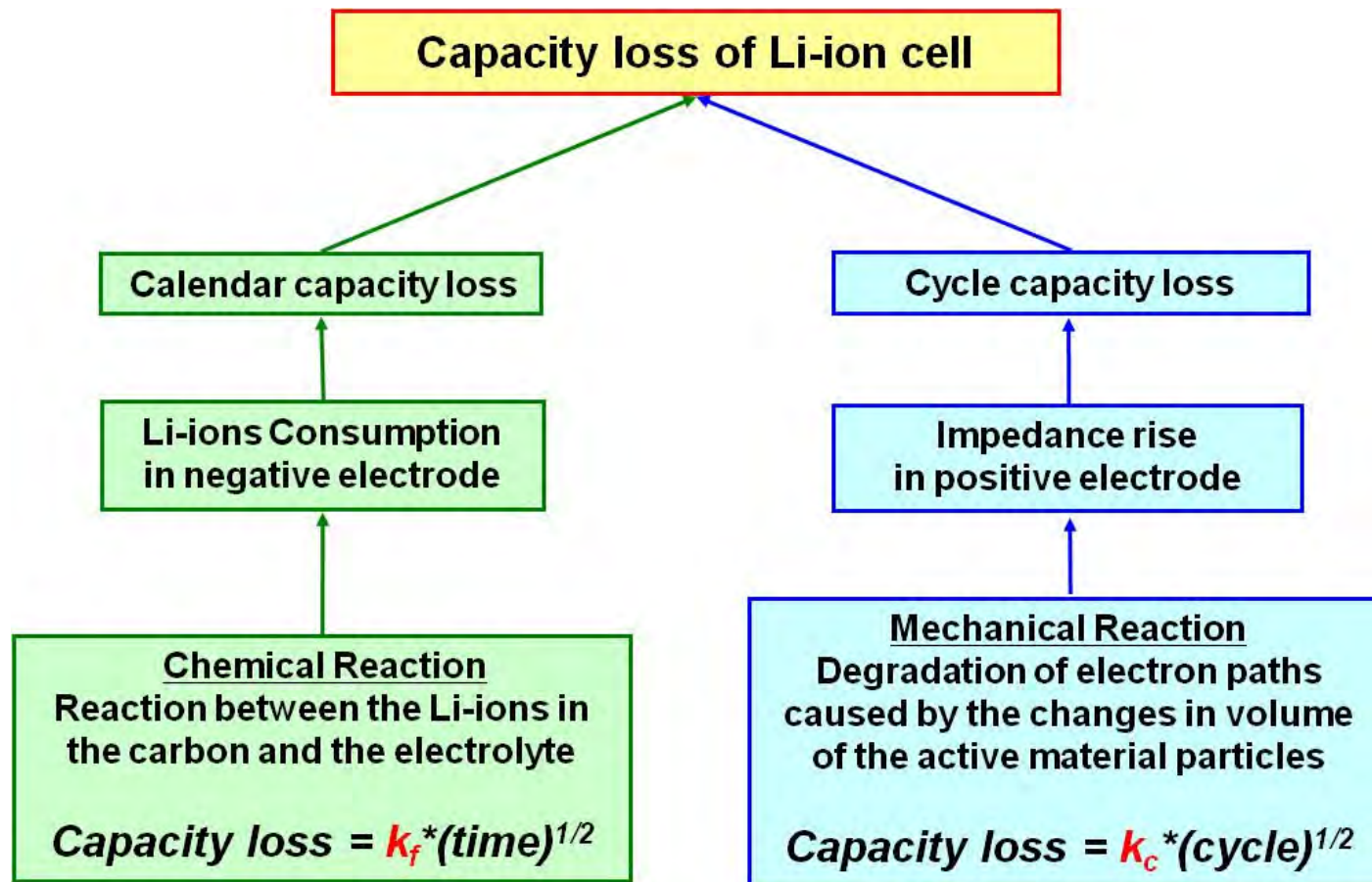
Model will accurately predict 3 key metrics for determining a cell's useful life:

- Full Charge Capacity
- On-Orbit Capacity
- End of Discharge Voltage



Capacity degradation is primarily due to two factors

- Calendar effects (Chemical degradation)
- Cycling effects (Mechanical degradation)



# Parameters That Impact Capacity Retention



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Following cell usage parameters have been shown to significantly impact cell capacity retention:

Calendar Capacity Retention -- Occurs continuously after cell activation.

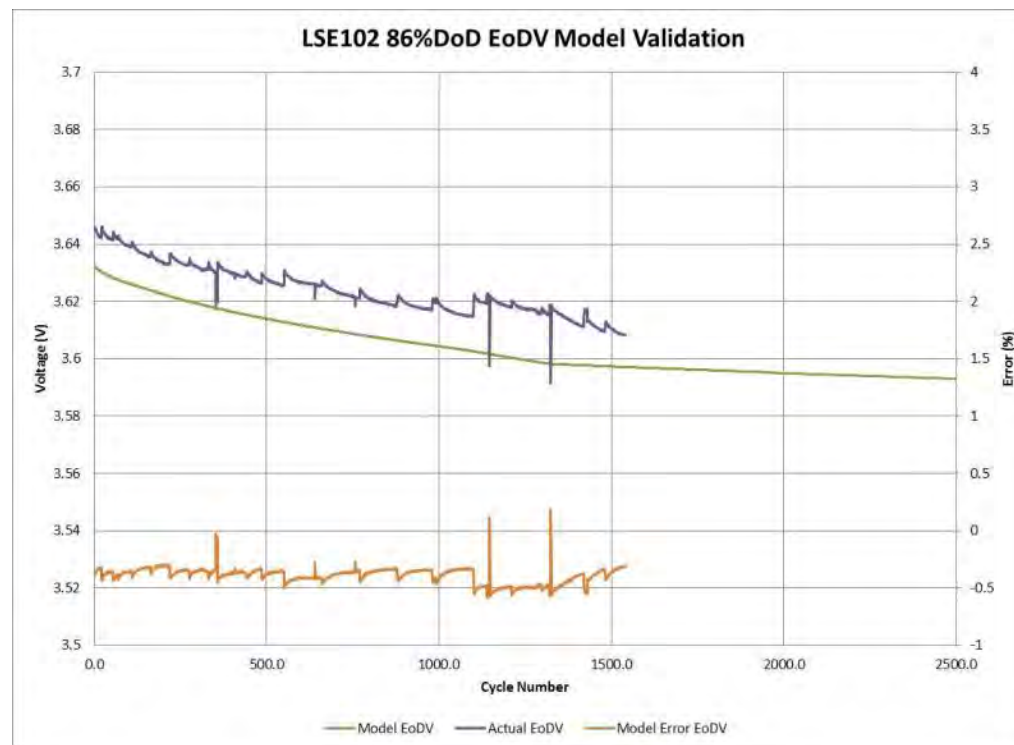
Variable	Effect on Irreversible Capacity Fade
State of Charge	As state of charge increases capacity fade increases
Temperature	As temperature increases capacity fade increases
Cell Age	As cell age increases capacity fade decreases*

Cycle Retention -- Occurs only when cell is actively being used

Variable	Effect on Irreversible Capacity Fade
Cycle Depth of Discharge	As cycle DoD increases capacity fade increases

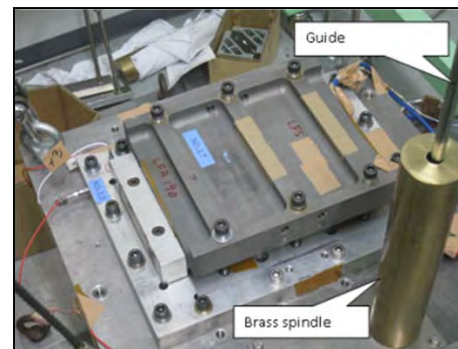
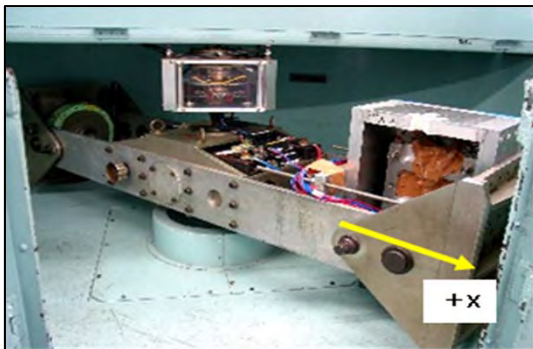
The GS Yuasa Life model also predicts End of Discharge Voltage (EoDV) performance for a given discharge load for a specified amount of time.

Major parameters which impact the EoDV include Remaining Capacity and cell DCR. Remaining capacity is calculated by the methods described previously. DCR and DCR rate of change is a function of temperature, cycle number, and cell age.



Life Model shows excellent agreement with the life cycling tests performed on the ground... But what good is the tool if it can only predict ground tests?

Real applications have ground operations, storage, varying temperatures, off nominal excursions, contingency planning, etc... all of which can occur in non-uniform ways.



John Hopkins University Applied Physics Laboratory (JHU/APL) has shared on-orbit battery performance data collected from their twin Van Allen Probe spacecraft.

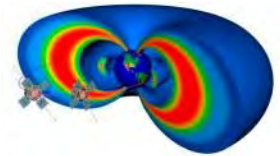
- Powered by GS Yuasa Generation 2 LSE50 (50Ah, 3.7V) cells
- Satellites launched August 30, 2012

Using the ground experience and orbit profile GYLP will model the mission and verify the End of Discharge Voltage results to those collected on-orbit.





# The Van Allen Probes Mission Objective

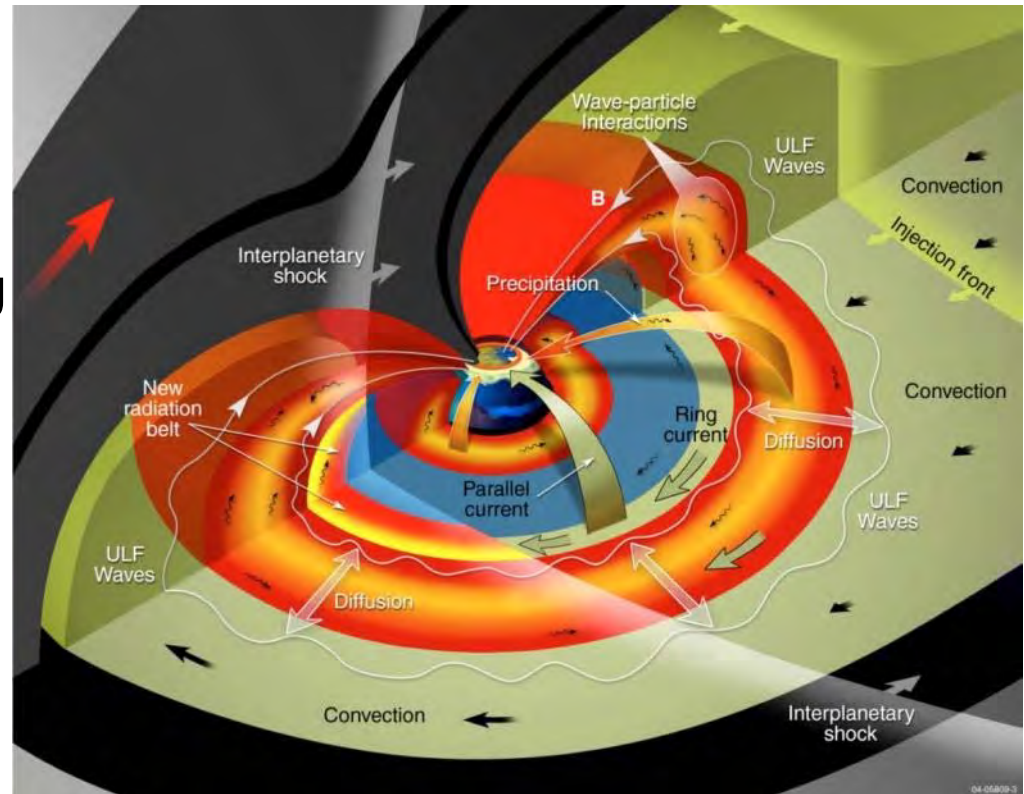


- Objective:

Provide understanding, ideally to the point of predictability, of how populations of **relativistic electrons and penetrating ions** in space form or change in response to variable inputs of energy from the sun.

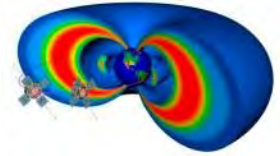
- Impacts:

1. Understand fundamental radiation processes operating throughout the universe.
2. Understand earth's radiation belts and related regions that pose hazards to human and robotic explorers.





# Van Allen Probes Mission Description



- The Van Allen Probes mission objectives:
  - Discover which processes accelerate and transport electrons and ions.
  - Quantify the loss of electrons and determine balance between loss and acceleration.
  - Understand how the belts change during geomagnetic storms.

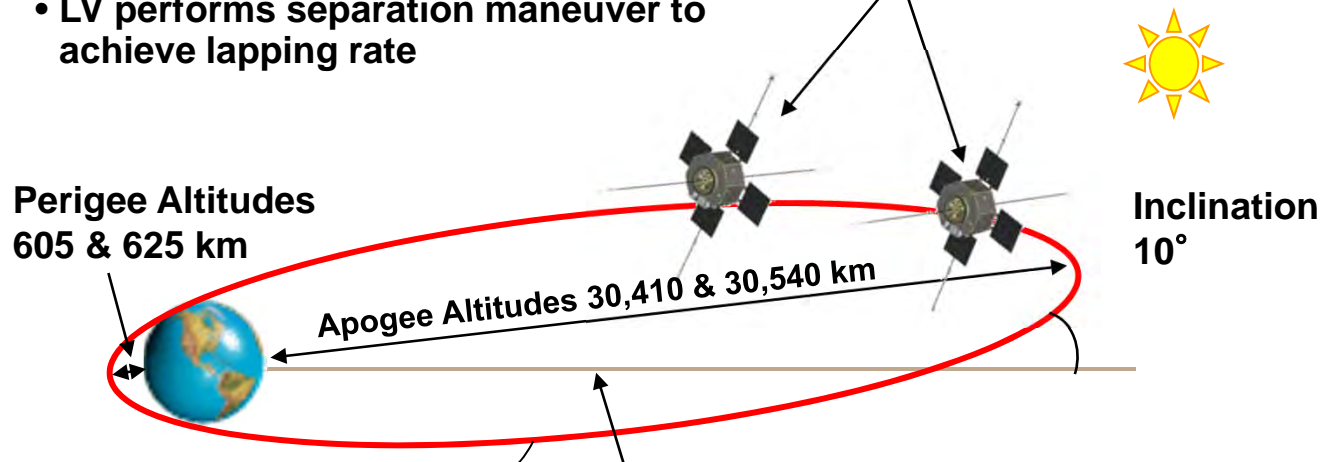
## Launch and Orbit Insertion



- Single Atlas V 401 (observatories stacked)
- Launch from KSC
- Each observatory independently released sun pointed
- LV performs separation maneuver to achieve lapping rate

## 2 Observatories

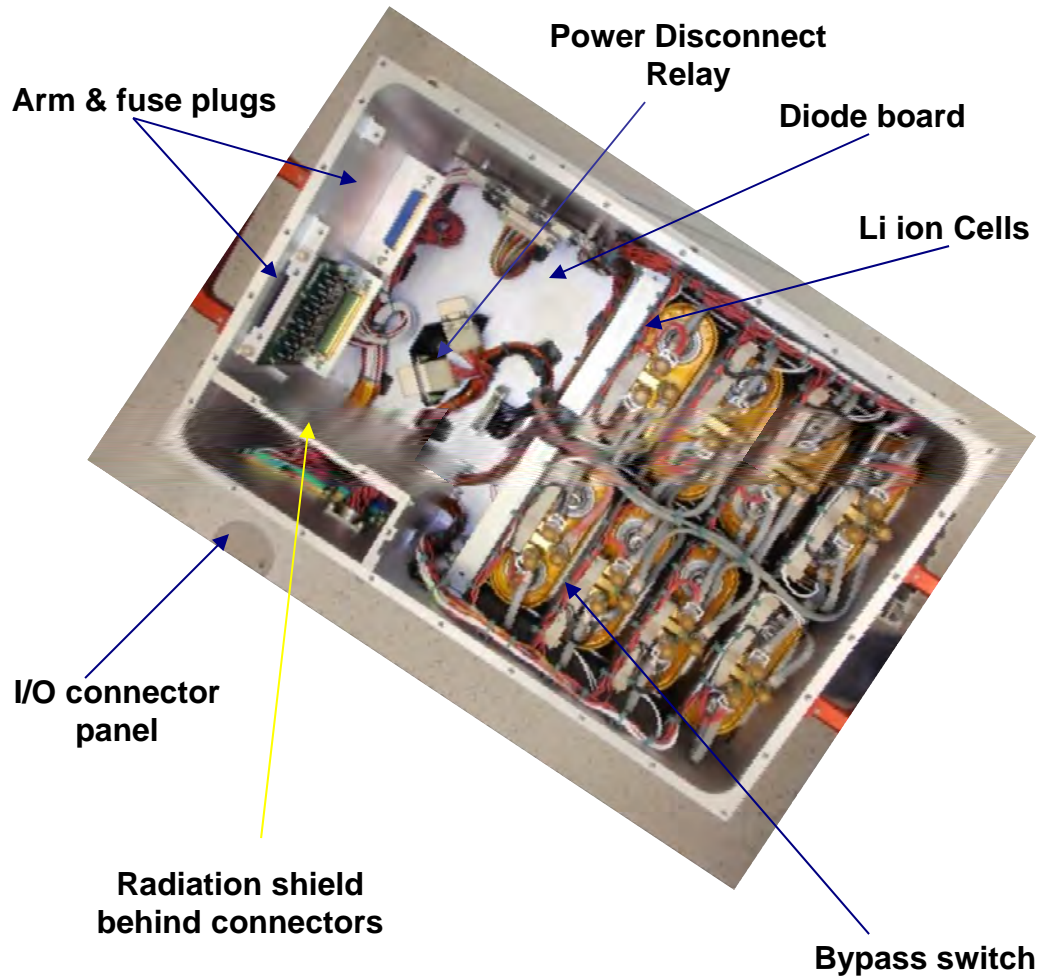
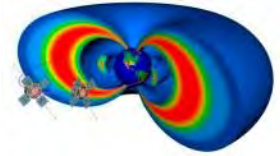
- Spin stabilized ~5 RPM
- Spin-axis 15° -27° off Sun
- Attitude maneuvers every 21 days
- Operational design life of 2 years
- 260 watt load average, Design 350W



Differing apogees allow for simultaneous measurements to be taken over the full range of observatory separation distances several times over the course of the mission. This design allows one observatory to lap the other every 75 days.



# Van Allen Probes 50AH Battery



- **Main charge/discharge path wired in figure 8 pattern to minimize magnetic field**
- **Removable fuse plug**
  - Fuses can be replaced without effecting the flight acceptance status of the battery
- **350 mil walls to protect electronics from total dose**
  - Selected areas thinned for weight reduction
- **Deep dielectric discharge protection on all interfaces**
  - Shunt capacitors
- **Bleed resistors for open circuit interfaces in flight**
- **Radiator integrated into housing baseplate**
- **Thermostats mounted inside battery chassis**
- **Heaters mounted to external surface of radiator**

# Terrestrial Service Timeline for Cells in Spacecraft A



Powering the Next Generation

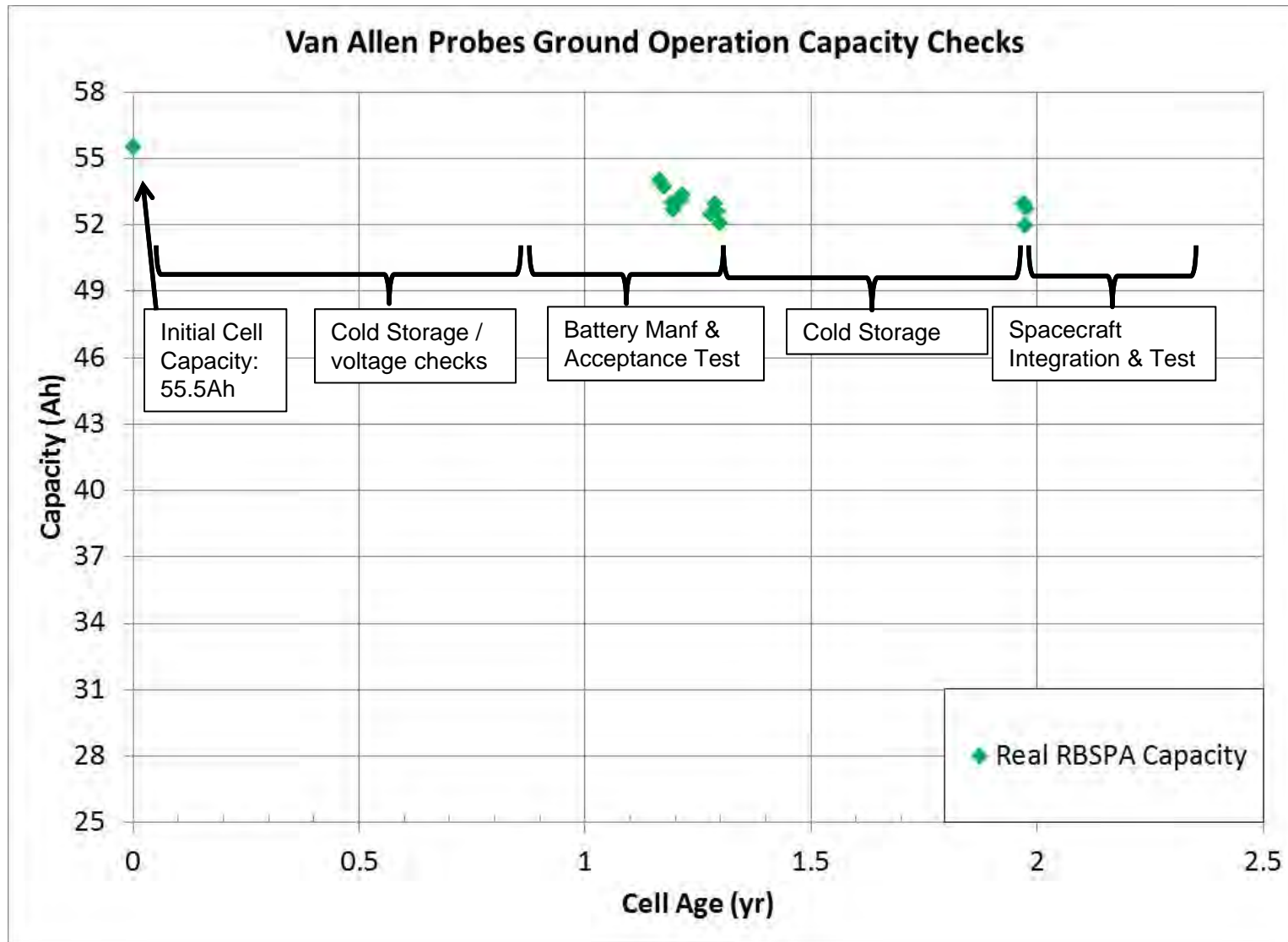
Event	Approximate Dates	Approximate Duration
Cell Activation at Acceptance Testing	4/2010 -- 5/2010	1month
Cold Storage	5/2010 -- 8/2010	3month
Delivery to JHU/APL	8/2010	0.5months
Cold Storage	8/2010 -- 3/2011	7months
Battery Manufacturing	3/2011 -- 7/2011	4months
Battery Acceptance Testing	7/2011 -- 9/2011	2months
Cold Storage	9/2011 -- 5/2012	8months
Spacecraft Integration & Test	5/2012 -- 8/2012	3months
Launch	8/30/2012	
First on-orbit cycle	8/30/2012 6:14:02PM	

*~28months from Cell activation to on-orbit operations*

# Actual vs. Life Model Capacity Data for Ground Operations



Powering the Next Generation



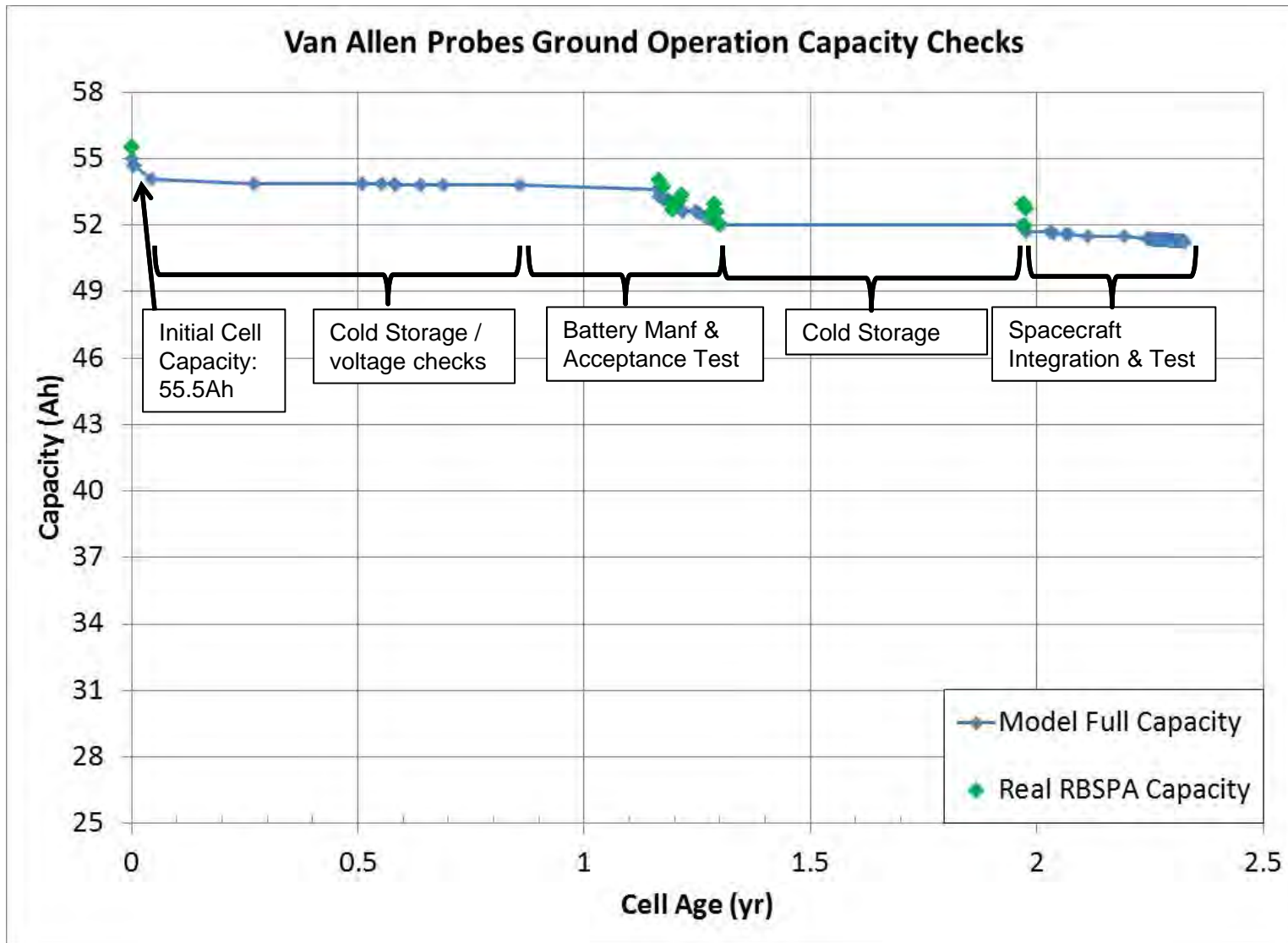
Points represent at what time in the cell's life a full capacity check cycle was completed (100% Depth of Discharge).

These points should correspond to the model Full Capacity Prediction.

# Actual vs. Life Model Capacity Data for Ground Operations



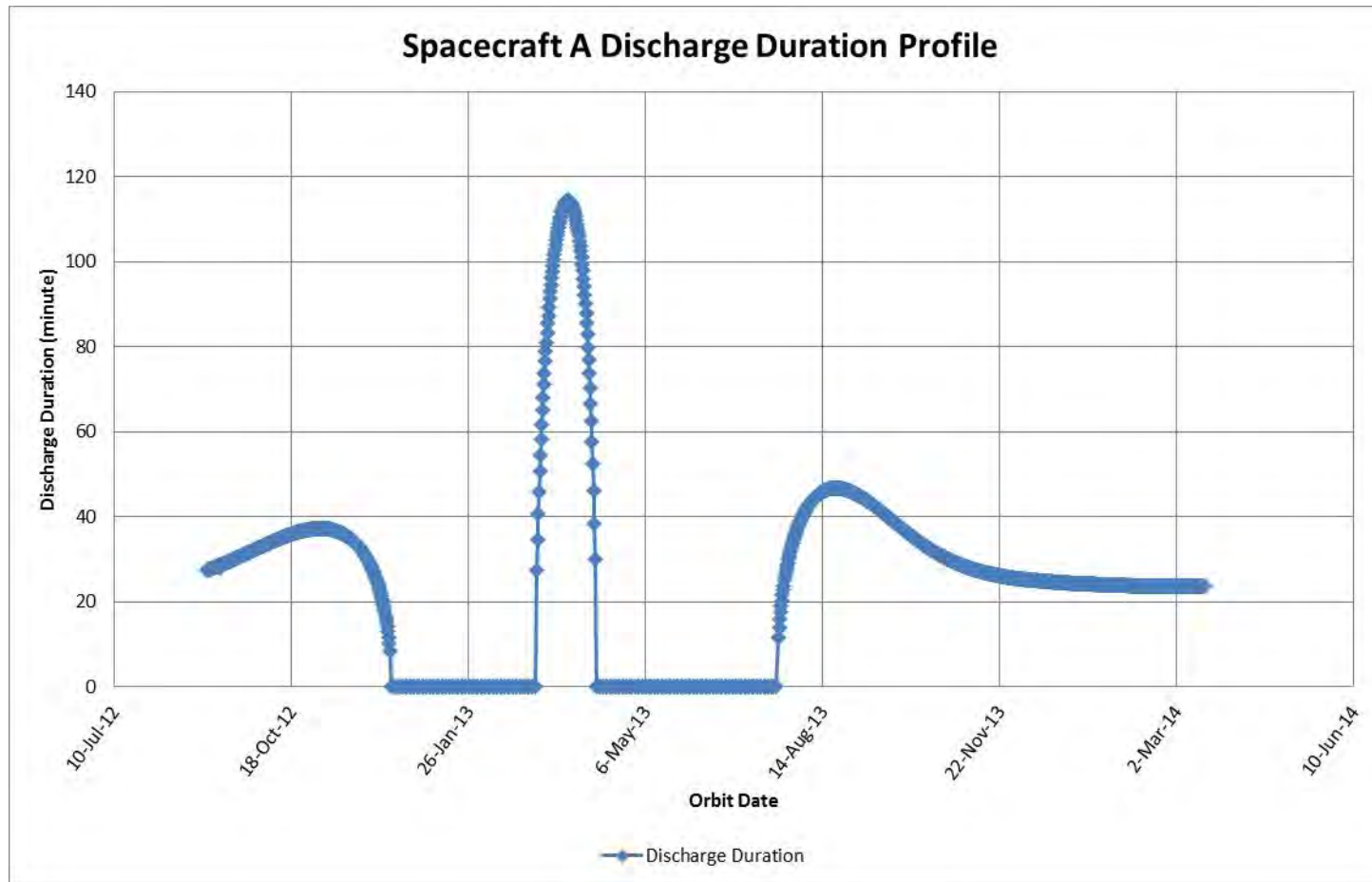
Powering the Next Generation



Model matches well with ground operation data collected over 2 year period up to launch.

This period includes storage, vibe, thermal, and mission cycling at various DoD.

# Discharge Duration Profile of Spacecraft A



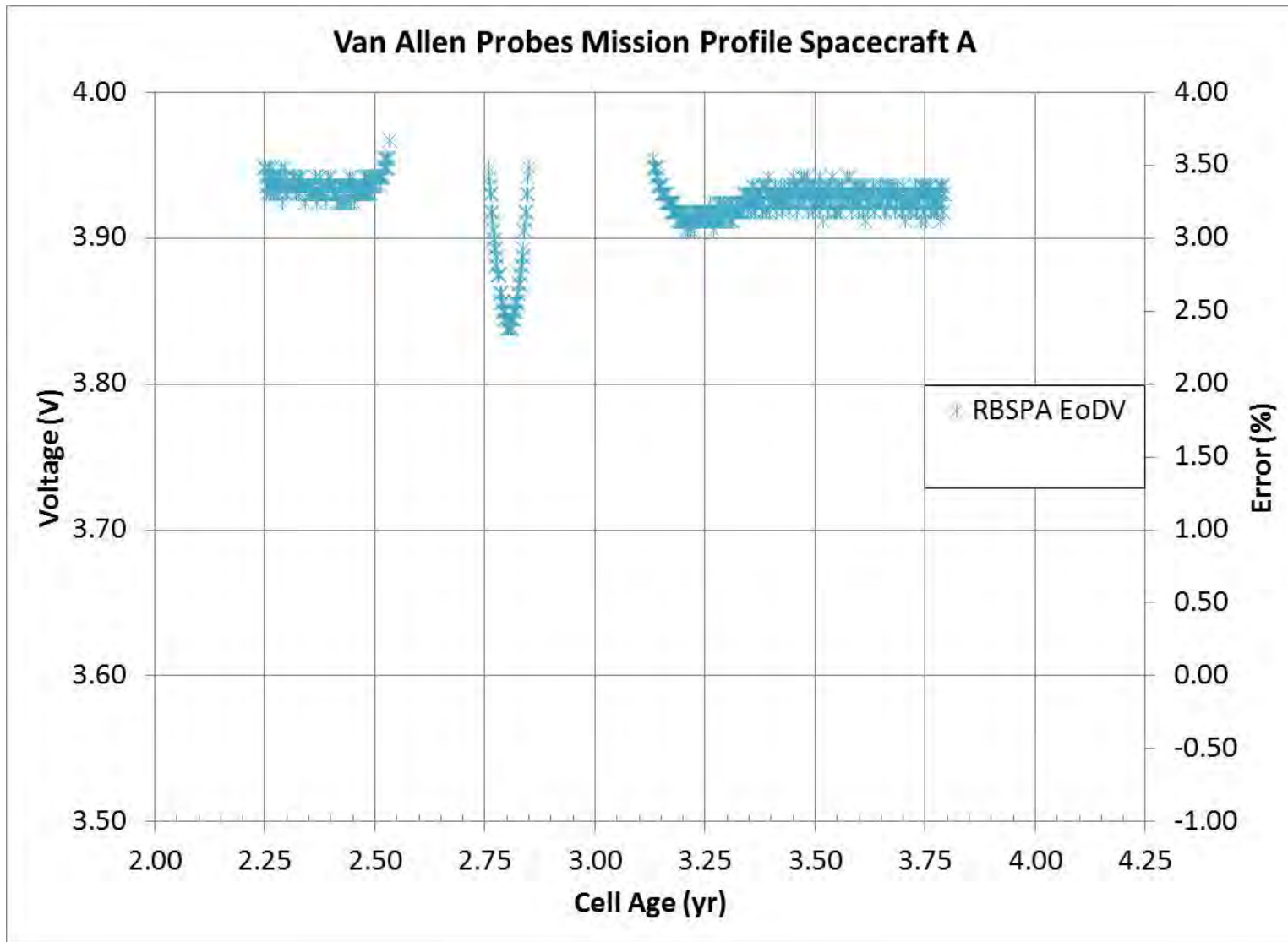
Discharge duration is highly variable and includes periods with no discharge.

Will the model be able to accommodate this condition and accurately predict the End of Discharge Voltage (EoDV)?

# On-Orbit EoDV Comparison, Actual vs. Life Model



Powering the Next Generation



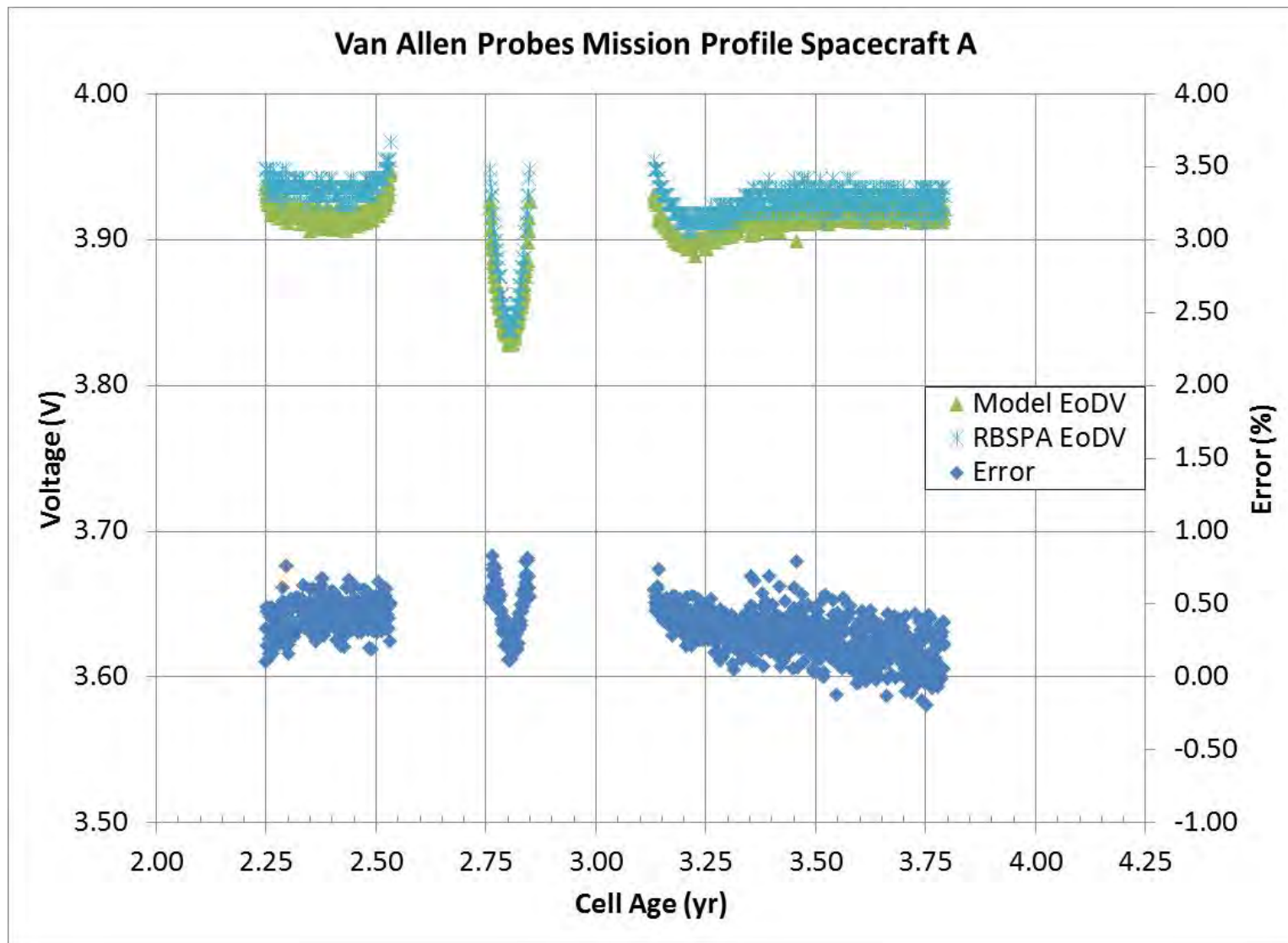
Average Cell EoDV of Spacecraft A.

Data collected from 8/2012 through 3/2014.

# On-Orbit EoDV Comparison, Actual vs. Life Model



Powering the Next Generation

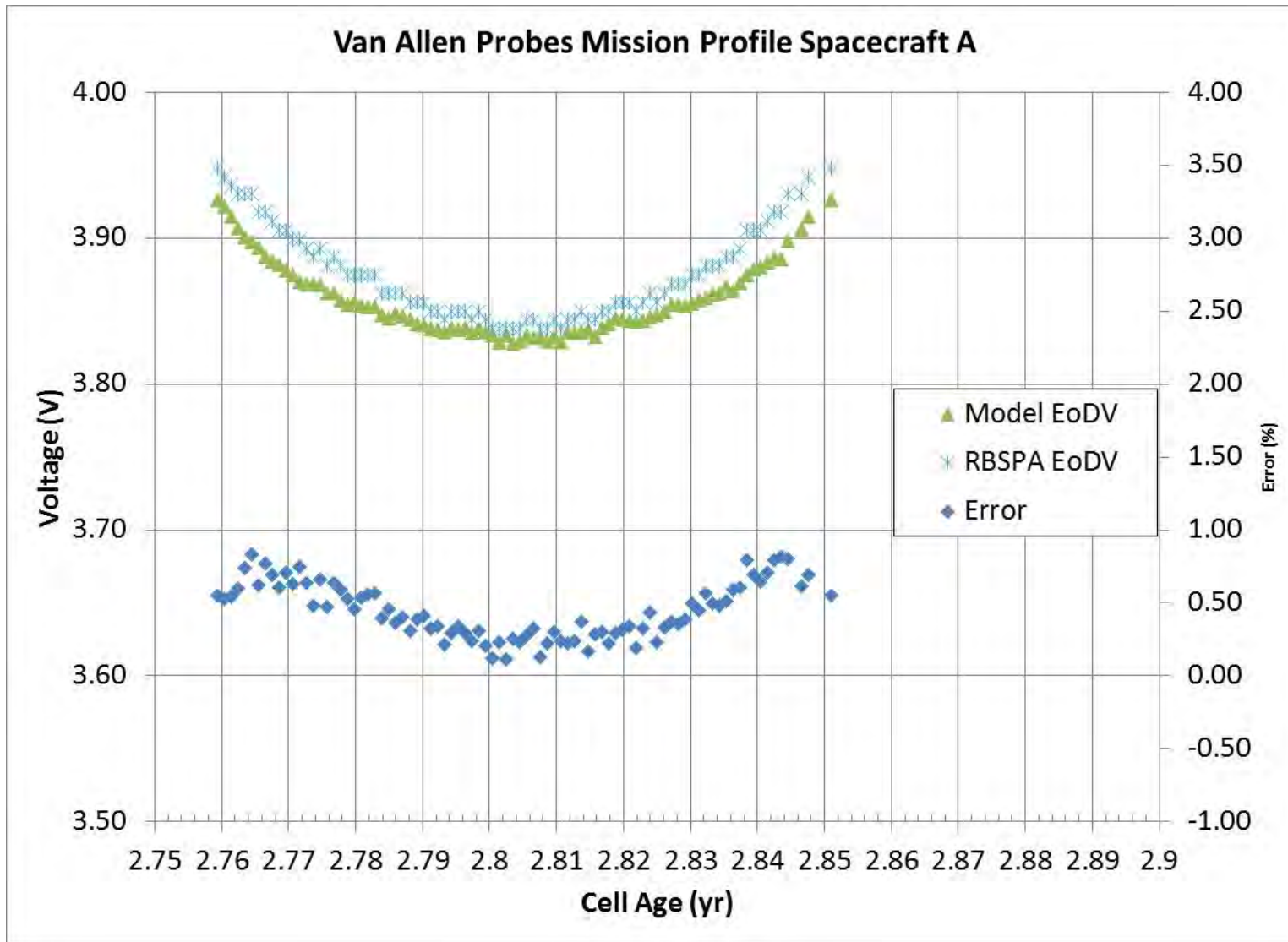


Using JHU/APL provided orbit inputs, the model matches the data to within 1% of actual.

# On-Orbit EoDV Comparison, Actual vs. Life Model



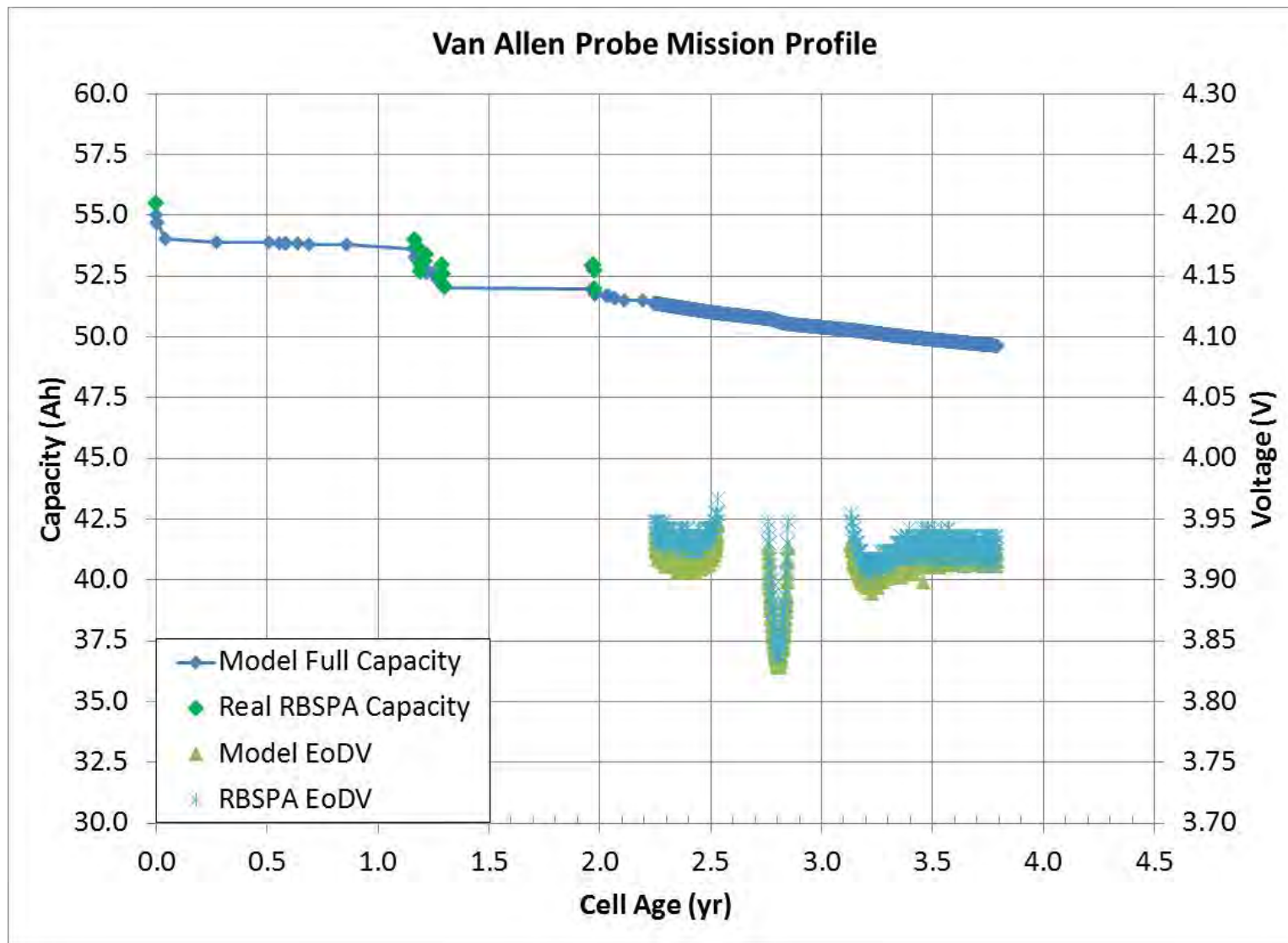
Powering the Next Generation



Expanded detail of deep discharge orbits

(Max DoD of ~31.5% of nameplate)

# Spacecraft A Full Profile to Date



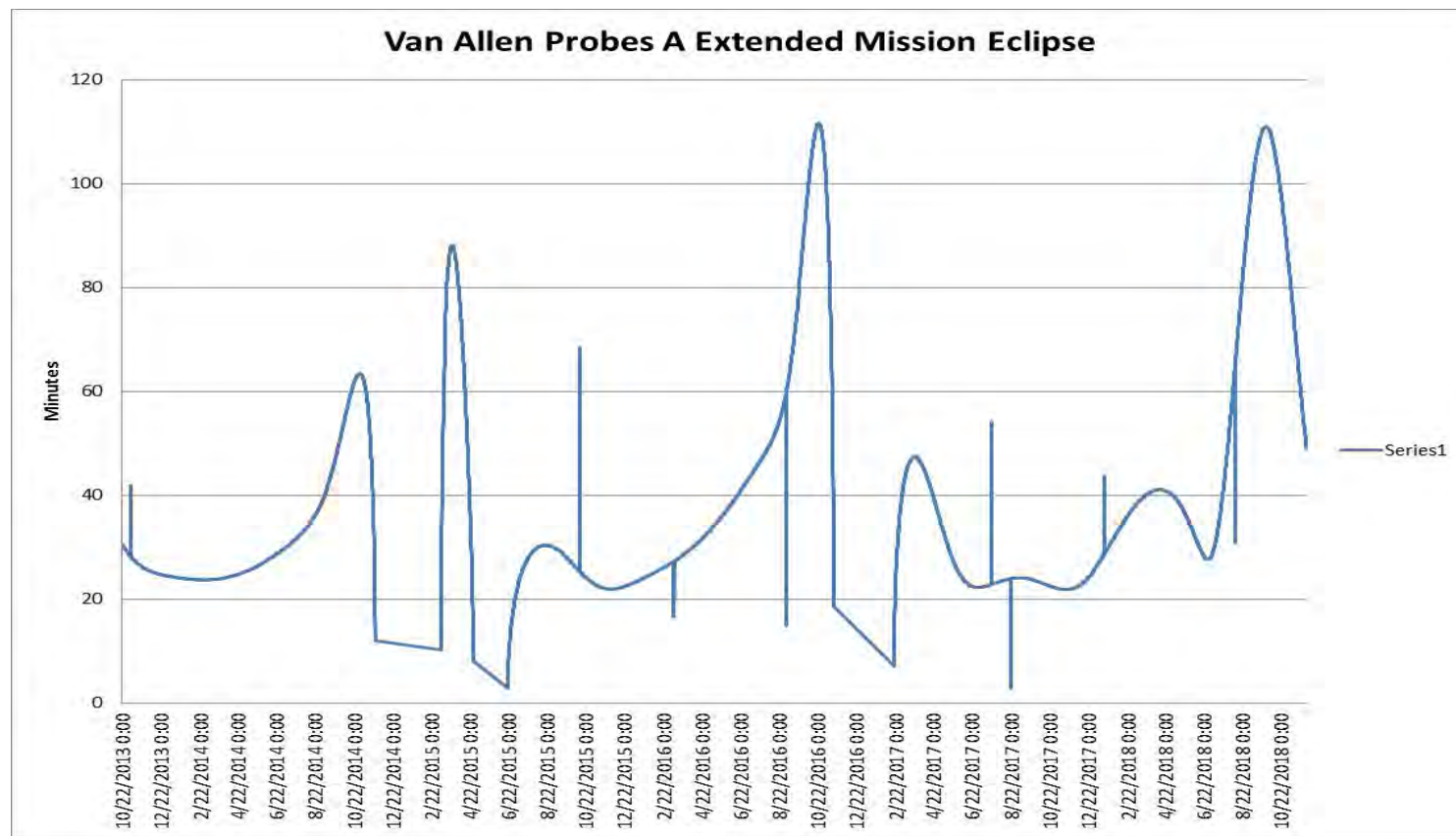
Very high confidence in the ability to predict cell (and battery) performance with appropriate simple usage information.

# Next Steps for GYLP and JHU/APL



Powering the Next Generation

- Van Allen Probes achieved mission success March 2014.
- Project will be proposing for an extended mission with a possible duration through 2018.
- GS Yuasa will use the life model to predict performance of the batteries through 2018 and determine capability of LSE50 cells to continue the mission.



The cell model not only provides a macro view of cell capacity and voltage retention. It also has the functionality to analyze specific cycles in the cell's life. This is extremely useful when determining which cell is appropriate for an application and predicting end of mission margin.

### For example

Orbit type: LEO Cycle (60min charge, 30min discharge)

Service life: >6 years on-orbit

Discharge energy required: ~58Ah

- 40.0% DoD of LSE145 nameplate

- 43.3% DoD of LSE134 nameplate

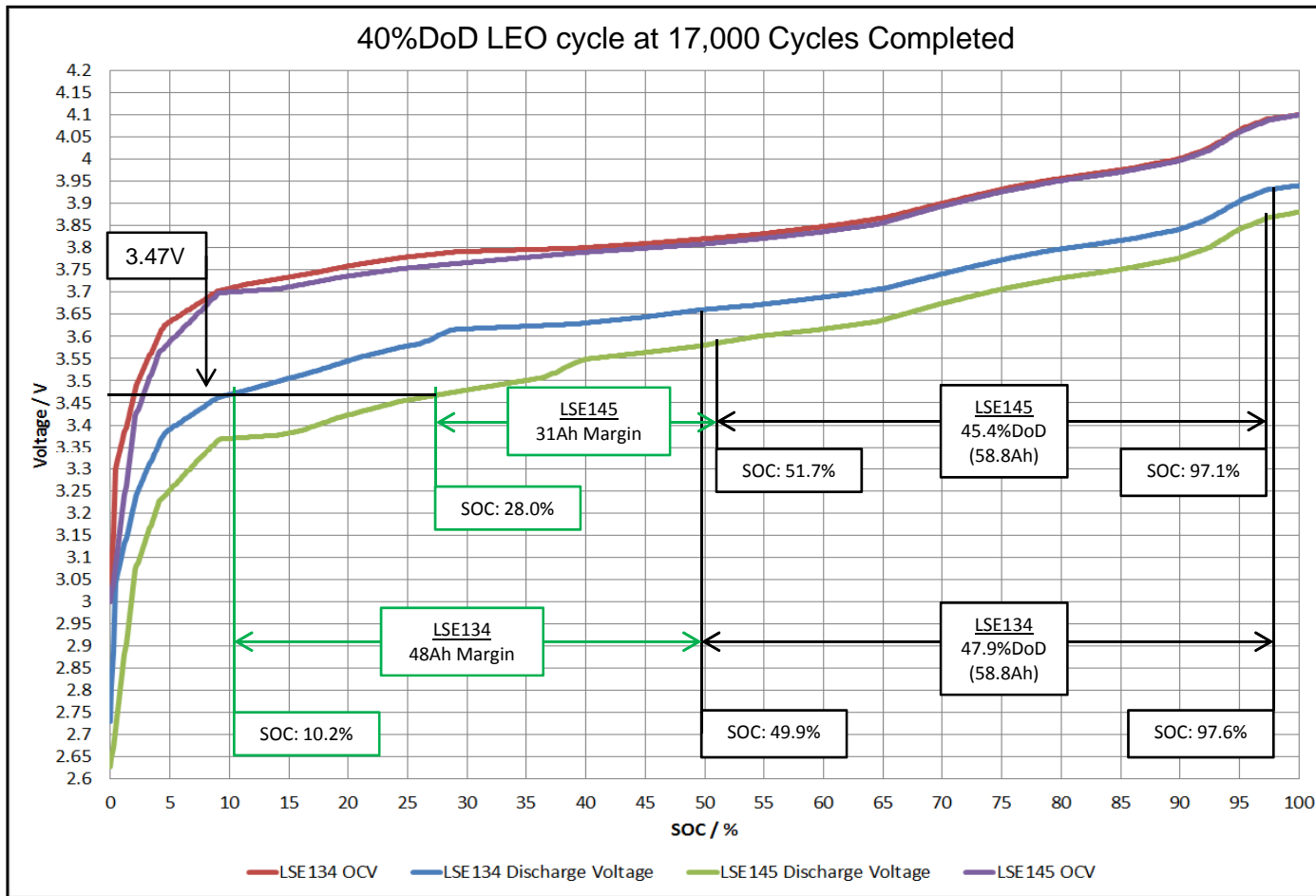
Lower voltage limit: 3.47V per cell.

Which cell will close the mission and provide maximum margin to the program?

# Discharge Voltage Profile at 17,000 cycles (~3years on-orbit)



Powering the Next Generation



	LSE134	LSE145
Full Capacity	122.8	129.5
Orbit Capacity	119.8	125.8
% of Full	97.6%	97.1%

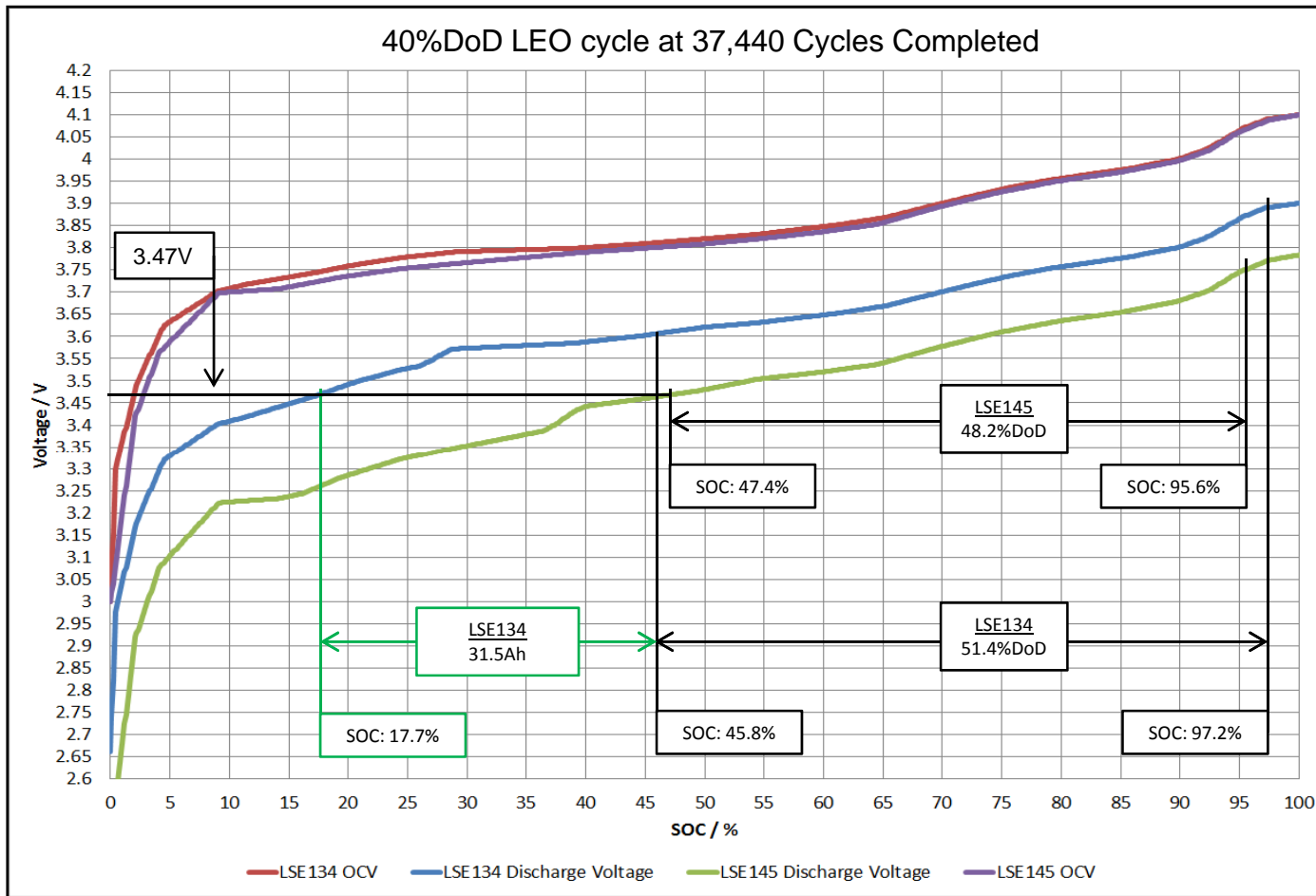
Discharge: >100A  
Duration: 0.5hr

The chart above shows the predicted discharge curve and expected DoD at 17,000 cycles (~3years) on mission. Both cell can continue the mission with substantial margin. The Power cell (LSE134) allows access to more capacity and higher operational voltage. *NOTE: 100%SOC = full charge capacity of cell at cycle 17,000*

# Discharge Voltage Profile at 37,400 cycles (~6.5yr on-orbit)



Powering the Next Generation

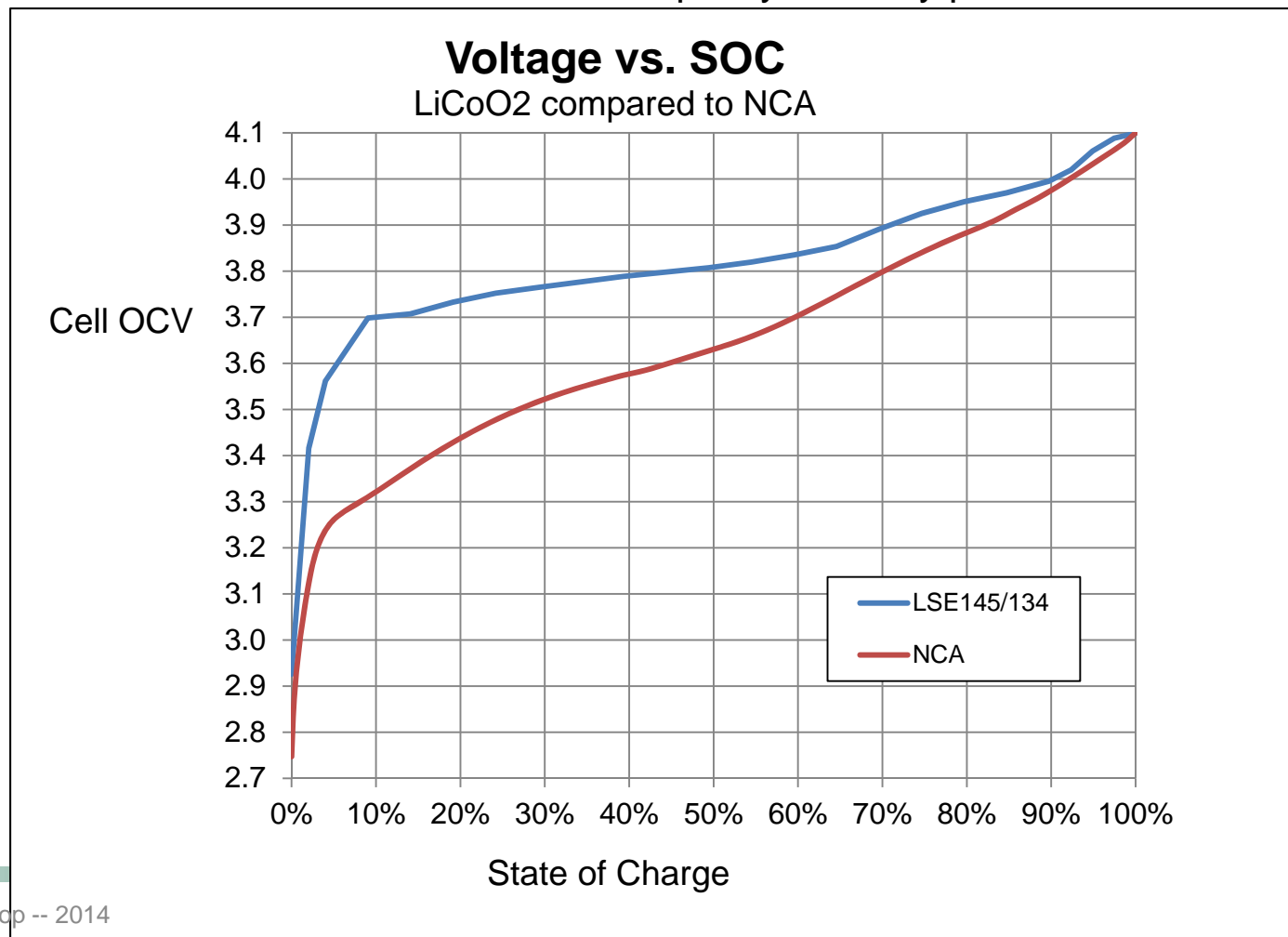


	LSE134	LSE145
Full Capacity	112.2	118.1
Orbit Capacity	109.1	112.9
% of Full	97.2%	95.6%

The chart above shows the predicted discharge curve and expected DoD at 37,440 cycles (~6.5years) which shows the LSE145 will fall below 3.47V/cell. Due to the suppressed DCR growth of the Power type cell, there is still significant margin available to continue the mission.

NOTE: 100%SOC = full charge capacity of cell at cycle 37,440

End of Mission performance is ultimately defined by how much energy/power the cell can deliver while remaining above spacecraft lower voltage limits. Defining batteries in terms of “Max Allowable DoD” or arbitrary “EOM Capacity” has the potential to result in inefficient solutions. “Accessible Watt-hour Capacity” is a key parameter.

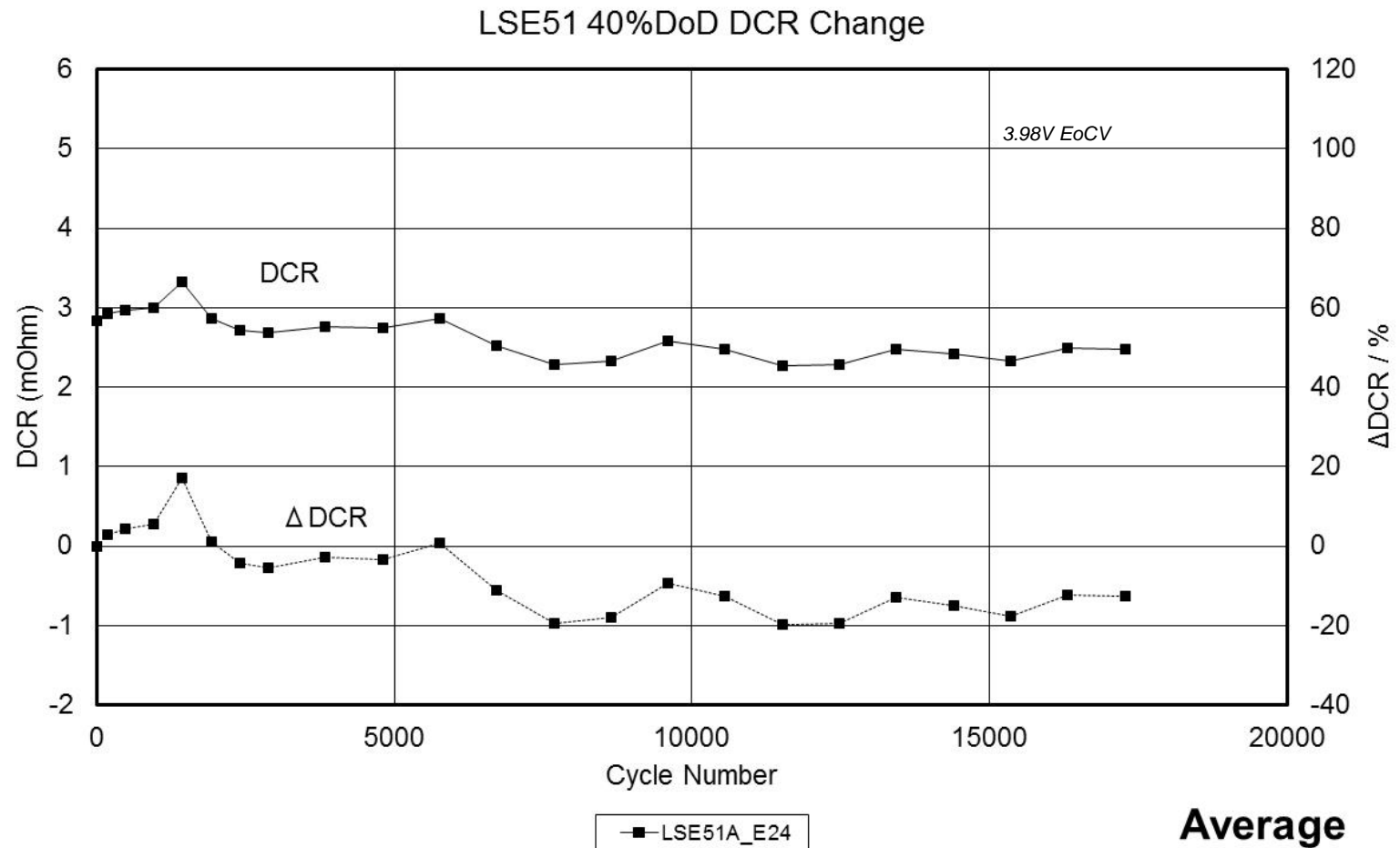


# Final Thoughts on Retention Model and Cell Selection



Powering the Next Generation

Higher average operating voltage of  $\text{LiCoO}_2$  coupled with suppression of DCR growth achieved by the Generation 3 chemistry results in exceptional Watt-Hr retention

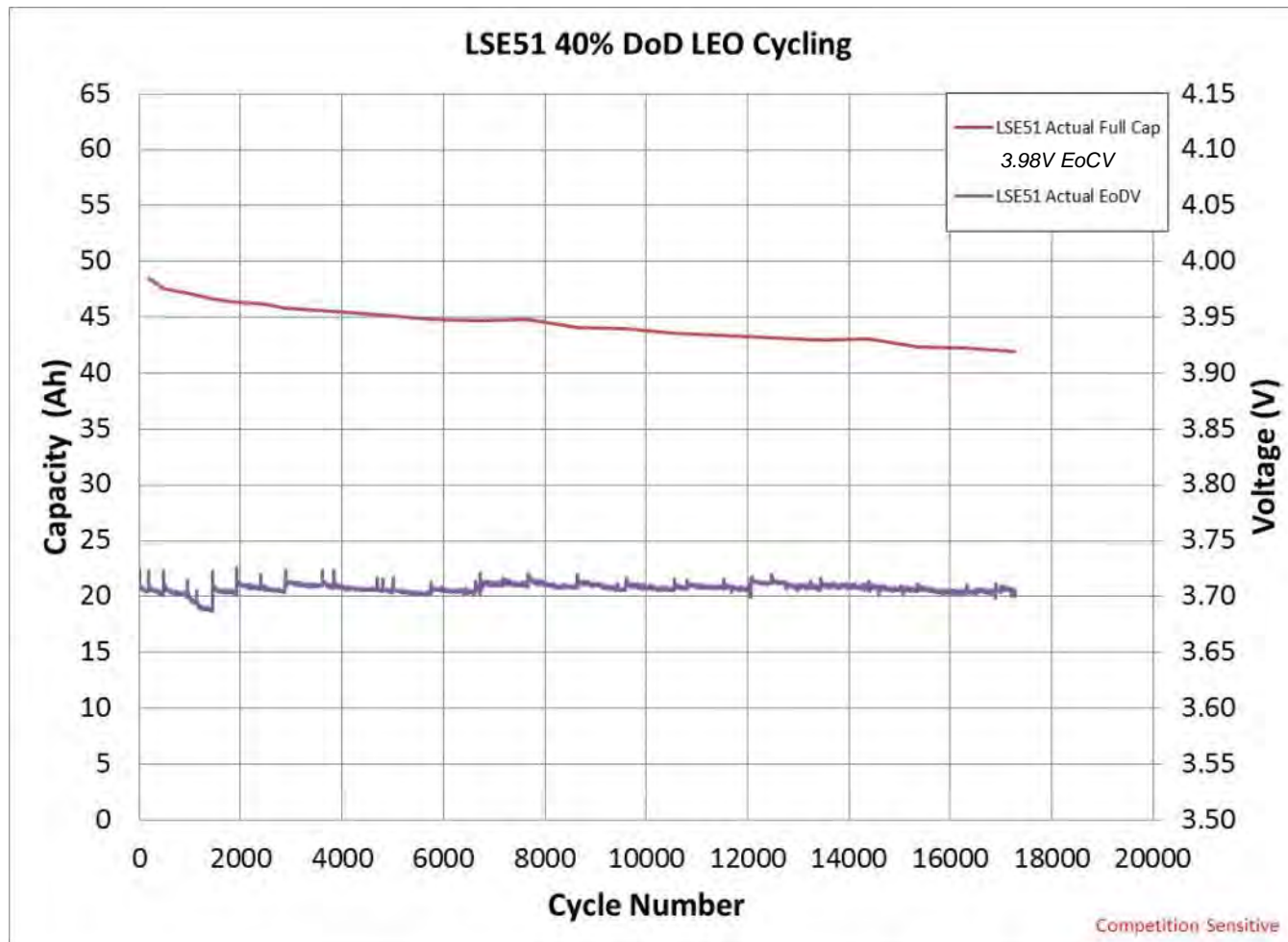


# Final Thoughts on Retention Model and Cell Selection



Powering the Next Generation

Higher average operating voltage of  $\text{LiCoO}_2$  coupled with suppression of DCR growth achieved by the Generation 3 chemistry results in exceptional Watt-Hr retention



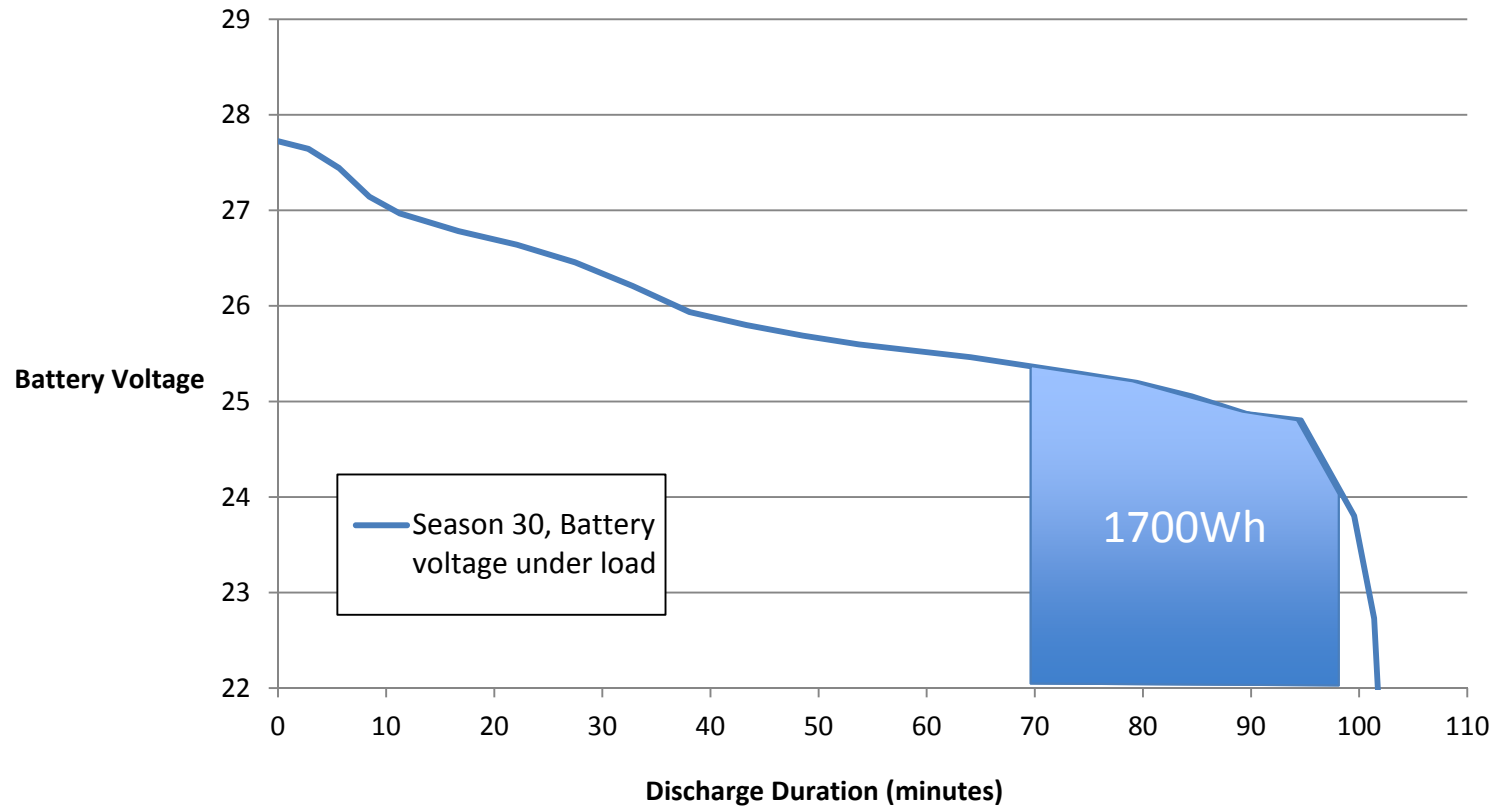
GEO mission: ~3800W Constant power discharge.

Max eclipse duration: 70minutes

Using the model it is possible to determine how much additional run time (Margin) is available to the spacecraft

## 4.1 EOCV Voltage vs. Time

Minimum battery voltage = 24V





Industry leading spaceflight heritage  
Qualified, high value MA190 battery  
Validated and reliable performance modelling

