State of GS Yuasa Lithium-ion Space Products and Introduction to Life and Thermal Modeling Capabilities

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Agenda

Powering the Next Generation

- GS Yuasa Company Overview
  - → Corporate Background
  - → GS Yuasa Lithium Power Inc.
  - → Products/Manufacturing Capabilities
- Review of GS Yuasa Satellite cell technology
  - → Space Cells
  - → Qualification Status
- GS Yuasa LSE Life Model and Validation to Cell Data
  - → Life cycle testing performed/on-going
  - → Validation cases
    - – 100% DoD cycling
    - – 40% DoD LEO type cycling
    - – Max 70% DOD Accelerated GEO cycling
    - – *Van Allen Probes On-orbit Model Validation*
- GS Yuasa Thermal Modeling Capabilities
  - → Creation
  - → Testing
  - → Validation

Background

GS YUASA

Est. 2004

GS Yuasa Corporation

GS *Est. 1917*

Japan Storage Battery Co., Ltd

YUASA *Est. 1915*

Yuasa Battery Manufacturing

- Li-ion battery development began in 1985
- Production of commercial Prismatic lithium-ion batteries begins in1993
- GS Yuasa Lithium Power, Inc. (Roswell, GA, USA) established 2006
- Lithium Energy Japan established 2007
- Blue Energy Co., Ltd. established 2009
- Consolidated 2013 Net Sales: USD 2.8 billion
- Li-Ion sales USD 178.4 million in 2013


Stationary Batteries


Traction Batteries


Thermal Batteries


Ni-MH


Large Format Li-ion


Automotive Batteries


Motorcycle Batteries

USA Production Capabilities:
GS Yuasa Lithium Power, Inc. (GYLP)

Powering the Next Generation

Element	Production Capabilities U.S.A.	Comments
Battery Assembly & Test	Clean Room, FOD practices, ESD, NASA crimp/conformal coat certified operators	GYLP manufactures and ships human-rated batteries to OSC for Cygnus
Cell / Battery Qualification Testing	Shock, Vibration, Thermal Cycle, Vacuum	Full flight testing completed on Cygnus batteries
Life Testing	Cell and battery level testing, thermal chambers, redundant safety backup system.	Multiple test channels available in U.S.A. and Japan

GYLP functional roles

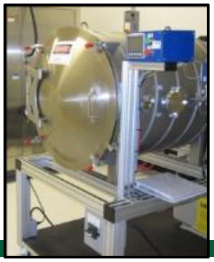
- Engineering
- Business development
- Technical support
- Program management
- Export/Technology Control
- Cell/battery testing
- Environmental testing
- Battery assembly
- ISO9001 AS9100
- Supported 17 space programs


DET NORSKE VERITAS

MANAGEMENT SYSTEM CERTIFICATE

GS Yuasa Lithium Power




GS Yuasa
Li-Ion Chemistries Produced

Li-Ion Chemistry	TRL	Wh / kg Wh / liter	Status and Safety Characteristics
Lithium Cobalt Oxide (LCO) (Space Cell)	9	160 – 190 375 – 430	▪ >15 years heritage in portable applications and >8 years on-orbit heritage in satellite applications ▪ Boeing 787: World's first commercial aviation application of Li-ion ▪ Passed UN Transportation test criteria
Lithium Manganese Mixed Metal (LMO)	9	110 220	▪ Started mass-production of EV battery in 2009 ▪ Supply 50Ah EV battery for Mitsubishi i-MiEV ▪ Production of EV battery started with 1,900 EV cars/year in 2009 and increase to 50,000 cars/year by 2012 ▪ Safety: Compliant with Mitsubishi regulations and trouble-free use ▪ Lowest practical material cost for cathode materials ▪ Abundant natural resources
Lithium Mixed Metal (NMC) (Cobalt / Nickel / Manganese)	9	65~120 130~250	▪ Started mass-production of 4Ah HEV battery in 2011 ▪ Honda Motors launched new Civic HEV in U.S. in April 2011 ▪ Safety: compliant with SAE J2464
Lithium Iron Phosphate (LFP)	6-7	80 180	▪ GS-Yuasa developed 25Ah PHEV battery in 2010 ▪ Mass-production will start in 2014 ▪ Intrinsically longer life than other layered oxide type cathode materials ▪ Passed -18°C APU start test with LVP60B, low DCR at low temp
Lithium Manganese Phosphate ($LiMnPO_4$)	4	95 215	▪ Under cell level evaluation (20Ah class) ▪ Safety: same level as LFP
Lithium Vanadium Phosphate ($Li_3V_2(PO_4)_3$)	4	70 160	▪ Under cell level evaluation (5Ah class) ▪ Lower specific energy, but 25% higher specific power than LFP cell ▪ Safety: same level as LFP
Lithium rich type NMC ($Li_{1+x}(Ni,Mn,Co)_{1-x}O_2$)	4	170 340	▪ Under cell-level evaluation (800mAh class) ▪ Extremely high energy density ▪ Safety: same level as mass-produced NMC

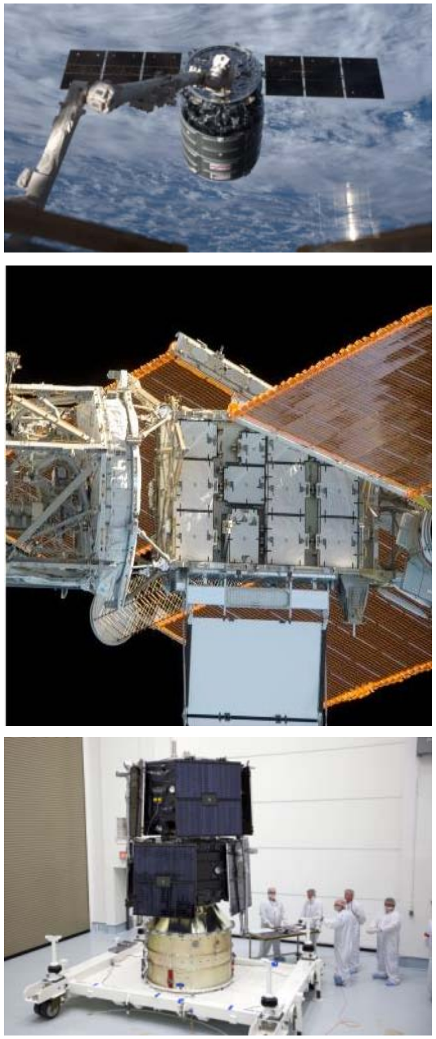
GS Yuasa
On-Orbit LEO / GEO Li-ion Heritage

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

- Number of satellites…………..…………….. **86+**
  - LEO*/MEO……………………………..…… 33+ (26+ active)
  - GEO……………………………..………… 51 (51 active)

  *1 of 4 LEO missions, 77% of Li-ion in LEO on Wh basis
- Li-Ion Chemistry…………………………… $LiCoO_2$
- Watt hours……………………..…………….. **~1.76 million**
- 1st satellite on-orbit……………………….. Servis 1 (10/30/2003)
- Space cell qualification programs……….. >21
- Cell sizes (Ah) flown…............................ 35; 50; 100; 175; 190; 200
- Longest satellite on-orbit (yrs)….............. >8 (IPSTAR) still operational
- Performance to date………….................. No anomalies
- Backlog (Wh)……………………………….. **~1.4 million**
- Launch vehicles & number of satellites:

Antares 110	1	Atlas-5 (401)	2	Falcon-9 v.1.1	2	Rokot-KM	2
Antares 120	1	Atlas-5 (421)	1	H-2A-202	1	Soyuz-2-1a Fregat	24
Ariane-5ECA	18	Atlas-5 (431)	1	H-2B-304	4	Zenit-3SL (2)	2
Ariane-5GS	1	Epsilon	1	Proton-M Briz-M (Ph. 1-3)	22	Zenit-3SLB	3



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
	[redacted]	LSE145	LSE134	130	263	50
	LSE175	LSE190	LSE176	165	263	50

* Not including terminal

"Heritage"

"Next Generation"

GS Yuasa
Space Li-Ion Cell Configurations

- 🟩 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.
	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

"Heritage" (Generation II)

"Next Generation" (Generation III)

GS Yuasa
Notable NASA Space Programs

Powering the Next Generation

OSC's CRS Cygnus vehicle

- GSY cell: LSE190-101 (Gen. III Energy Type)
- Cell qualification testing (JSC20793) completed (GYT)
- Battery qualification successfully completed (GYLP)
- Flight batteries manufactured and delivered (GYLP)

Van Allen Probes (Radiation Belt Storm Probes)

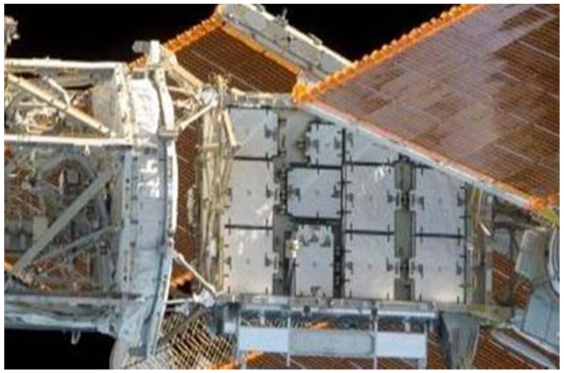
- GSY cell: LSE50-002 (Gen. II)
- Cell qualification testing completed (GYT)
- Successful launch of RBSP satellites on August 30, 2012
- Cells functioning as intended

International Space Station

- GSY cell: LSE134-101 (Gen. III Power Type)
- Cell qualification completed (GYT)
- Evaluation and battery EM cells delivered (Phase I)
- Awarded Phase II contract to deliver 957 cells (2013-2018)
  - → 67 delivered, 100 to be delivered by June 2014

ICESat-2

- GSY cell: LSE134-102 (Gen. III Power Type)



GS Yuasa Space Li-Ion Cells
GEN 3 – Power Cell Cycle Test Summary

Test Description	Cell Type	Conditions						Cells	Temp (°C)	Started
		Charge			Discharge					
		EoCV	Rate	Time	EoDV	Rate	Time			
LSE51_100% DOD cycling	LSE51	4.1	0.5C	4 hr	2.75	1C	--	2	25	9/25/2009
LSE51_100% DOD cycling	LSE51	3.98	0.5C	4 hr	2.75	1C	--	1	25	9/25/2009
LSE51_40% DOD cycling	LSE51	3.98	0.5C	1 hr	>3.4	0.8C	0.5 hr	1	20	9/28/2009
LSE51_25% DOD cycling	LSE51	4.1	0.3C	1 hr	>3.4	0.5C	0.5 hr	1	20	9/28/2009
LSE51_25% DOD cycling	LSE51	3.98	0.3C	1 hr	>3.4	0.5C	0.5 hr	1	20	9/28/2009
LSE102_100% DOD cycling	LSE102	4.1	0.5C	4 hr	2.75	1C	--	1	25	10/30/2010
LSE102_86% DOD cycling	LSE102	4.1	0.33C	11.4 hr	>2.75	0.74C	1.2 hr	1	15	10/30/2010
LSE102_27% DOD cycling	LSE102	4.1	0.55C	1 hr	>3.4	0.33C	0.5 hr	1	15	10/30/2010
LSE134_40% DOD cycling	LSE134	4.1 & 3.98	0.5C	1 hr	>3.4	0.8C	0.5 hr	2	20	5/2012
LSE134_40% DOD cycling w/ induced thermal gradient	LSE134	4.1 & 3.98	0.5C	1 hr	>3.4	0.8C	0.5 hr	2	20	6/2012

GS Yuasa Space Li-Ion Cells
GEN 3 – Energy Cell Cycle Test Summary

Powering the Next Generation

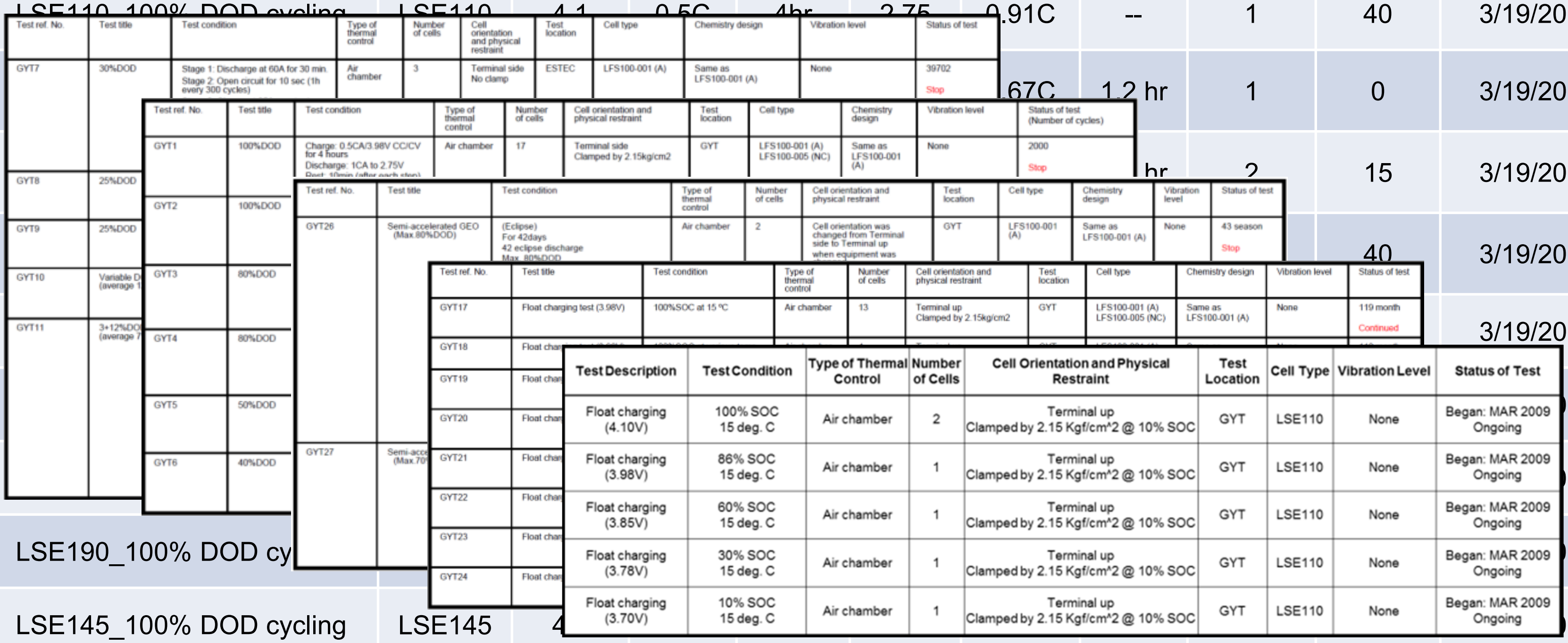
Test Description	Cell Type	Conditions						Cells	Temp (°C)	Started
		Charge			Discharge					
		EoCV	Rate	Time	EoDV	Rate	Time			
LSE110_100% DOD cycling	LSE110	4.1	0.5C	4 hr	2.75	0.91C	--	1	25	3/19/2009
LSE110_100% DOD cycling	LSE110	4.1	0.5C	4hr	2.75	0.91C	--	1	40	3/19/2009
LSE110_80% DOD cycling	LSE110	4.1	0.2C	11.4 hr	>2.75	0.67C	1.2 hr	1	0	3/19/2009
LSE110_80% DOD cycling	LSE110	4.1	0.2C	11.4 hr	>2.75	0.67C	1.2 hr	2	15	3/19/2009
LSE110_80% DOD cycling	LSE110	4.1	0.2C	11.4 hr	>2.75	0.67C	1.2 hr	1	40	3/19/2009
LSE110_25% DOD cycling	LSE110	4.1	0.3C	1 hr	>3.4	0.5C	0.5 hr	1	0	3/19/2009
LSE110_25% DOD cycling	LSE110	4.1	0.3C	1 hr	>3.4	0.5C	0.5 hr	1	15	3/19/2009
LSE110_25% DOD cycling	LSE110	4.1	0.3C	1 hr	>3.4	0.5C	0.5 hr	1	40	3/19/2009
LSE190_100% DOD cycling	LSE190	4.1	0.5C	4 hr	2.75	0.5C	--	4	25	10/8/2009
LSE145_100% DOD cycling	LSE145	4.1	0.5C	4 hr	2.75	0.69C	--	2	25	7/29/2010

GS Yuasa Space Li-Ion Cells
GEN 3 – Energy Cell Cycle Test Summary

GS YUASA
Powering the Next Generation

In addition to Gen III testing, > 750 cell years of Gen II life cycle/calendar testing have been completed to date.

Test Description	Cell Type	Conditions						Cells	Temp (°C)	Started
		Charge			Discharge					
LSE110_100% DOD cycling	LSE110	4.1	0.5C	4hr	2.75	0.91C	--	1	40	3/19/2009
						.67C	1.2 hr	1	0	3/19/2009
							hr	2	15	3/19/2009
									40	3/19/2009
										3/19/2009
										09
										09
LSE190_100% DOD cy										09
LSE145_100% DOD cycling	LSE145	4								10



Test ref. No.	Test title	Test condition	Type of thermal control	Number of cells	Cell orientation and physical restraint	Test location	Cell type	Chemistry design	Vibration level	Status of test
GYT7	30%DOD	Stage 1: Discharge at 60A for 30 min. Stage 2: Open circuit for 10 sec (1h every 300 cycles)	Air chamber	3	Terminal side No clamp	ESTEC	LFS100-001 (A)	Same as LFS100-001 (A)	None	39702 Stop
GYT8	25%DOD									
GYT9	25%DOD									
GYT10	Variable D (average 1									
GYT11	3+12%DO (average 7									

Test ref. No.	Test title	Test condition	Type of thermal control	Number of cells	Cell orientation and physical restraint	Test location	Cell type	Chemistry design	Vibration level	Status of test (Number of cycles)
GYT1	100%DOD	Charge: 0.5CA/3.98V CC/CV for 4 hours Discharge: 1CA to 2.75V	Air chamber	17	Terminal side Clamped by 2.15kg/cm2	GYT	LFS100-001 (A) LFS100-005 (NC)	Same as LFS100-001 (A)	None	2000 Stop
GYT2	100%DOD									
GYT3	80%DOD									
GYT4	80%DOD									
GYT5	50%DOD									
GYT6	40%DOD									

Test ref. No.	Test title	Test condition	Type of thermal control	Number of cells	Cell orientation and physical restraint	Test location	Cell type	Chemistry design	Vibration level	Status of test
GYT26	Semi-accelerated GEO (Max.80%DOD)	(Eclipse) For 42days 42 eclipse discharge Max. 80%DOD	Air chamber	2	Cell orientation was changed from Terminal side to Terminal up when equipment was	GYT	LFS100-001 (A)	Same as LFS100-001 (A)	None	43 season Stop
GYT27	Semi-acce (Max.70									

Test ref. No.	Test title	Test condition	Type of thermal control	Number of cells	Cell orientation and physical restraint	Test location	Cell type	Chemistry design	Vibration level	Status of test
GYT17	Float charging test (3.98V)	100%SOC at 15 ℃	Air chamber	13	Terminal up Clamped by 2.15kg/cm2	GYT	LFS100-001 (A) LFS100-005 (NC)	Same as LFS100-001 (A)	None	119 month Continued
GYT18	Float char									
GYT19	Float char									
GYT20	Float char									
GYT21	Float char									
GYT22	Float char									
GYT23	Float char									
GYT24	Float char									

Test Description	Test Condition	Type of Thermal Control	Number of Cells	Cell Orientation and Physical Restraint	Test Location	Cell Type	Vibration Level	Status of Test
Float charging (4.10V)	100% SOC 15 deg. C	Air chamber	2	Terminal up Clamped by 2.15 Kgf/cm^2 @ 10% SOC	GYT	LSE110	None	Began: MAR 2009 Ongoing
Float charging (3.98V)	86% SOC 15 deg. C	Air chamber	1	Terminal up Clamped by 2.15 Kgf/cm^2 @ 10% SOC	GYT	LSE110	None	Began: MAR 2009 Ongoing
Float charging (3.85V)	60% SOC 15 deg. C	Air chamber	1	Terminal up Clamped by 2.15 Kgf/cm^2 @ 10% SOC	GYT	LSE110	None	Began: MAR 2009 Ongoing
Float charging (3.78V)	30% SOC 15 deg. C	Air chamber	1	Terminal up Clamped by 2.15 Kgf/cm^2 @ 10% SOC	GYT	LSE110	None	Began: MAR 2009 Ongoing
Float charging (3.70V)	10% SOC 15 deg. C	Air chamber	1	Terminal up Clamped by 2.15 Kgf/cm^2 @ 10% SOC	GYT	LSE110	None	Began: MAR 2009 Ongoing

GS Yuasa Lithium Power Cell Modeling Capabilities

Powering the Next Generation

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

Cell Life Test Data and Model Validation

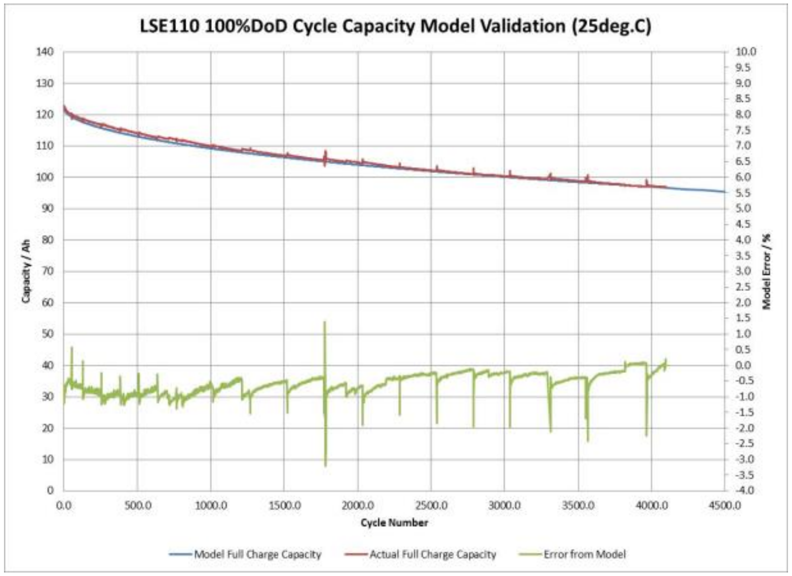
Powering the Next Generation

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

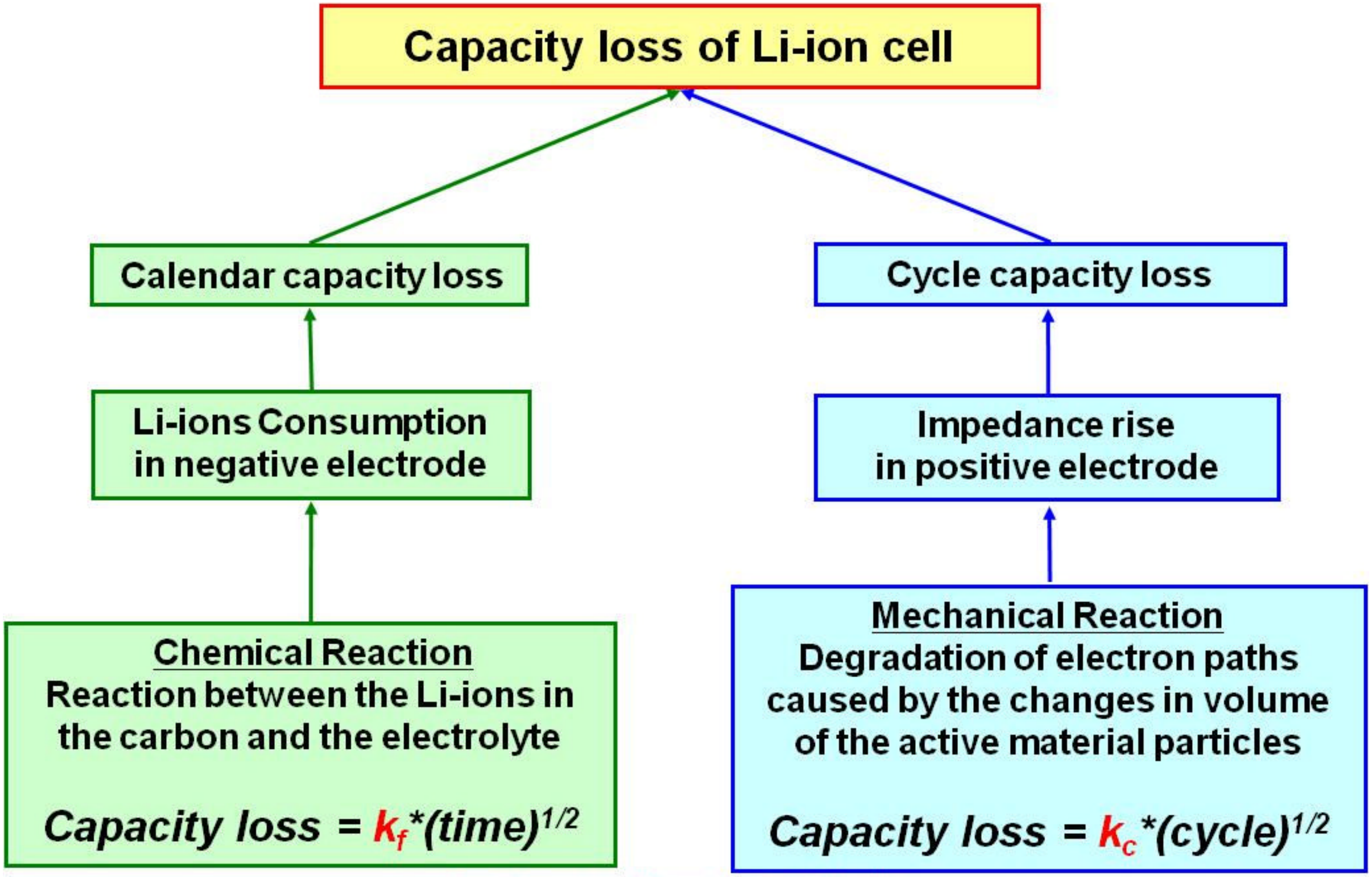


Basic Li-ion Capacity Degradation

Capacity degradation is primarily due to two factors

→ Calendar effects (Chemical degradation)

→ Cycling effects (Mechanical degradation)



Capacity loss of Li-ion cell

Calendar capacity loss

Li-ions Consumption in negative electrode

Chemical Reaction
Reaction between the Li-ions in the carbon and the electrolyte

$$\text{Capacity loss} = k_f*(\text{time})^{1/2}$$

Cycle capacity loss

Impedance rise in positive electrode

Mechanical Reaction
Degradation of electron paths caused by the changes in volume of the active material particles

$$\text{Capacity loss} = k_c*(\text{cycle})^{1/2}$$

Parameters That Impact Capacity Retention

Powering the Next Generation

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*

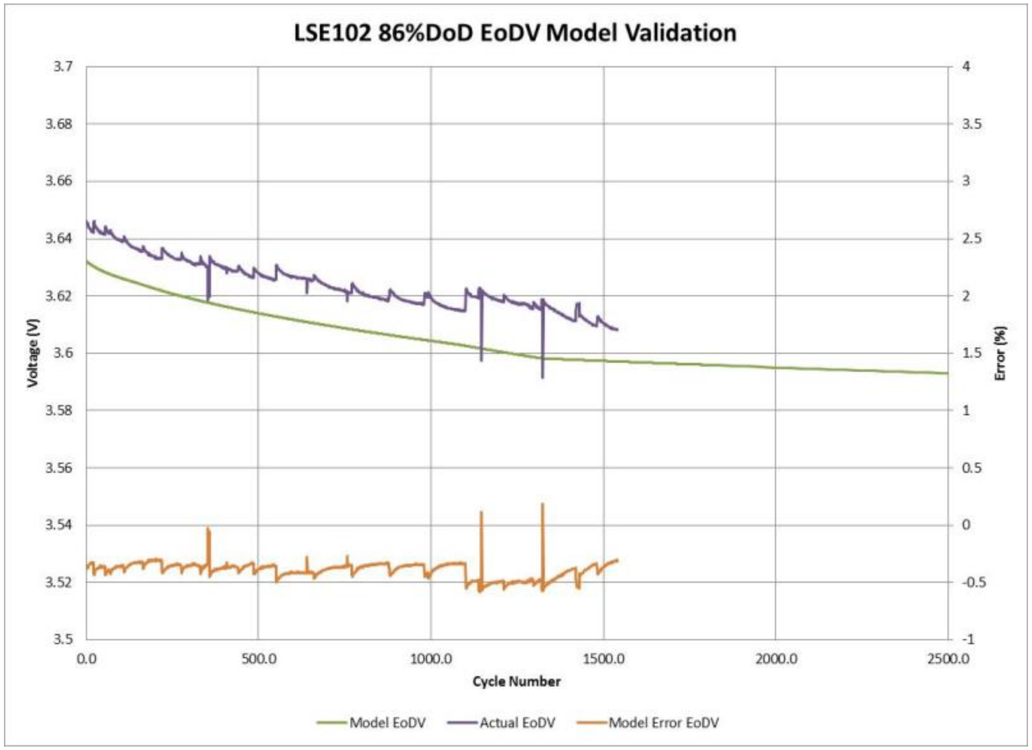
Cycle Retention -- Occurs only when cell is actively being used

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

Voltage Retention Prediction Capability

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.



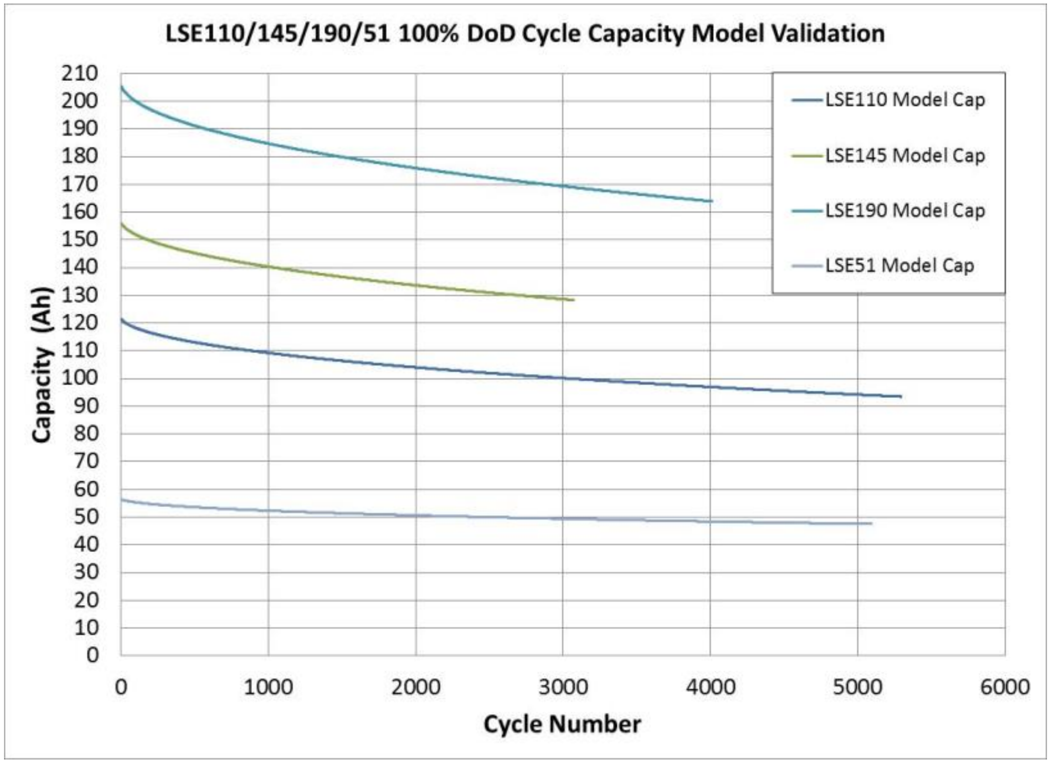
Ground Life Cycle Data and Life Model Validation Cases

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			
Energy Cell Testing and Validation										
100% DoD Cycling	LSE110 LSE145 LSE190	4.10V	0.5C	4hr	2.75V	100A 95A 100A	N/A	25°C	3/19/2009 10/8/2009 7/29/2010	
25% DoD Cycling	LSE110	4.10V	33A	1hr	(3.40V)	55A	0.5hr	15°C	3/19/2009	Standard LEO Orbit Cycle
Semi-Accelerated GEO Cycle	LSE145	4.00V	14.5A	22.83hr	(3.40V)	86.3A	Varies	10°C	10/2009	60 day solstice season 25°C 45day eclipse season
Power Cell Testing and Validation										
100% DoD Cycling	LSE51	4.10V	0.5C	4hr	2.75V	50A	N/A	25°C	9/25/2009	
40% DoD Cycling	LSE51	3.98V	25.5A	1hr	(3.40V)	40.8A	0.5hr	20°C	9/28/2009	Deep DoD LEO Cycle
27% DoD Cycling	LSE102	4.10V	33A	1hr	(3.40V)	55A	0.5hr	15°C	10/30/2010	Analog of 25%DoD LSE110 Cycling

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

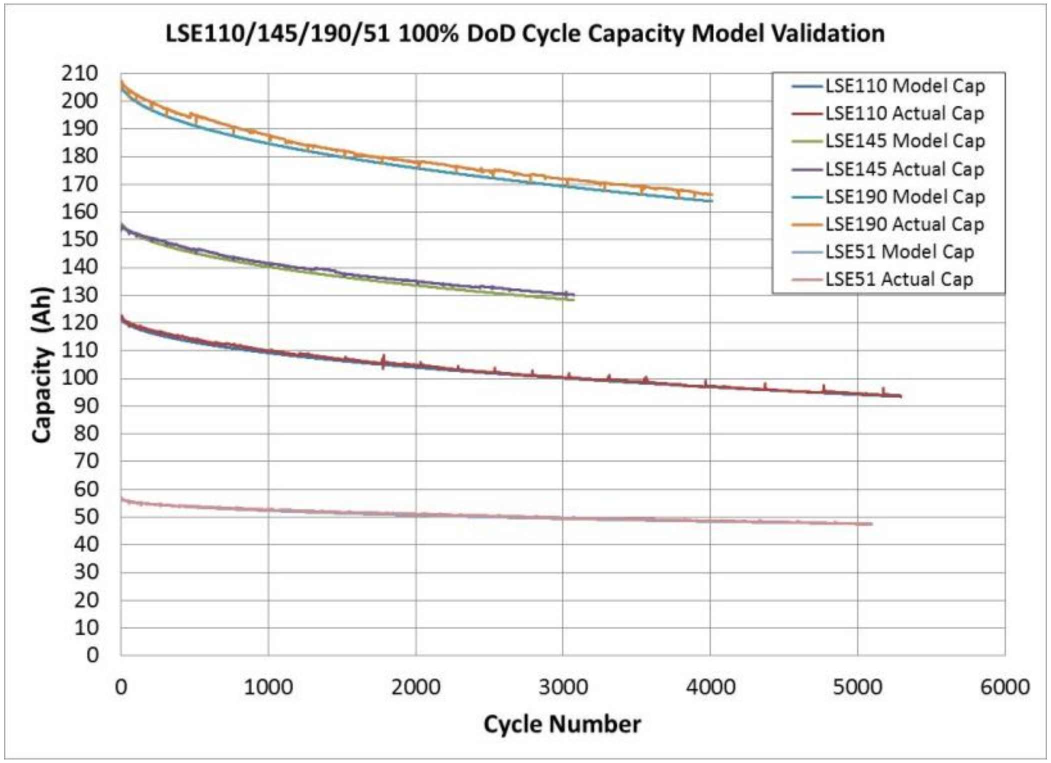
100%DoD Full Capacity Cycle Validation

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 LSE145 LSE190	4.10V	0.5C	4hr	2.75V	100A 95A 100A	N/A	25°C	3/19/2009 10/8/2009 7/29/2010	Energy Cells
100% DoD Cycling	LSE51	4.10V	0.5C	4hr	2.75V	50A	N/A	25°C	9/25/2009	Power Cell



100%DoD Cycle Validation

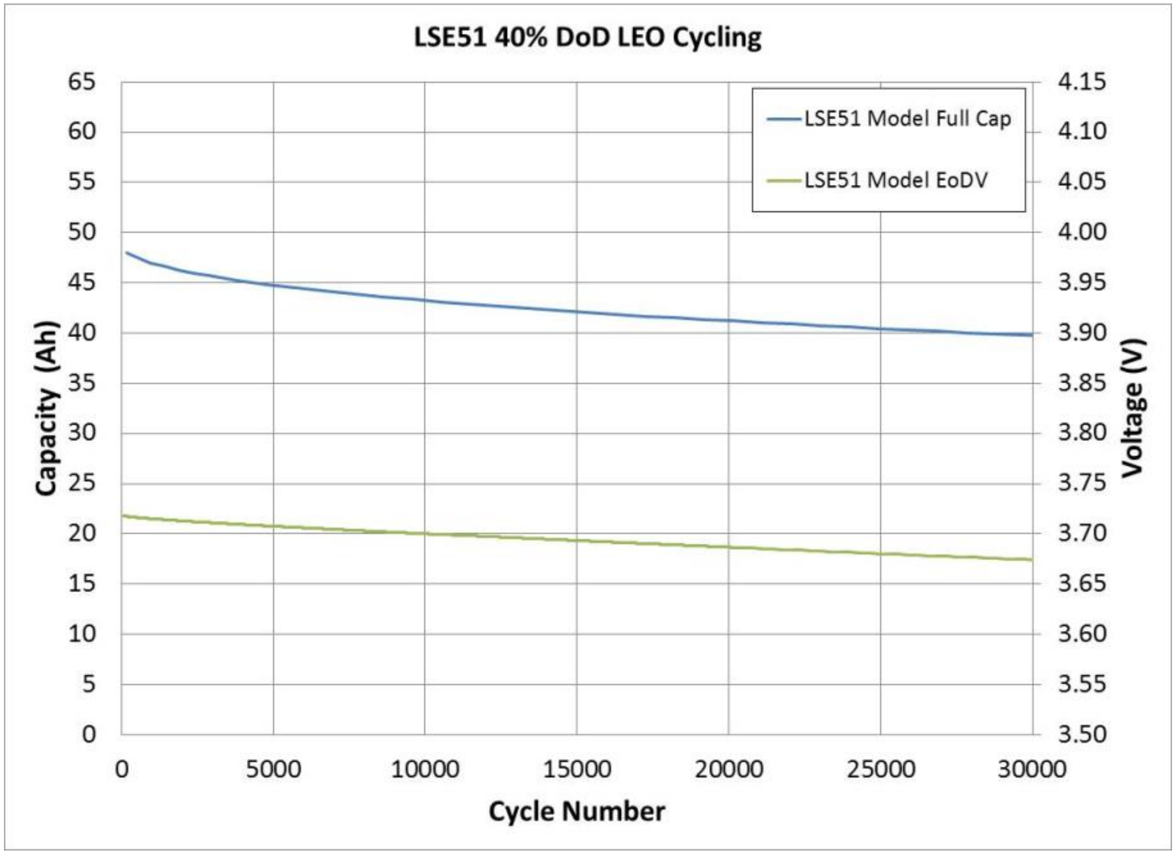
Test Name	Cell Type	Test Conditions						Ambient Test Temp	Start Date	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition					
		EoCV	Rate	Time	EoDV	Rate	Time			
100% DoD Cycling	LSE110 LSE145 LSE190	4.10V	0.5C	4hr	2.75V	100A 95A 100A	N/A	25°C	3/19/2009 10/8/2009 7/29/2010	Energy Cells
100% DoD Cycling	LSE51	4.10V	0.5C	4hr	2.75V	50A	N/A	25°C	9/25/2009	Power Cell



40%DoD LEO Cycle Validation

Powering the Next Generation

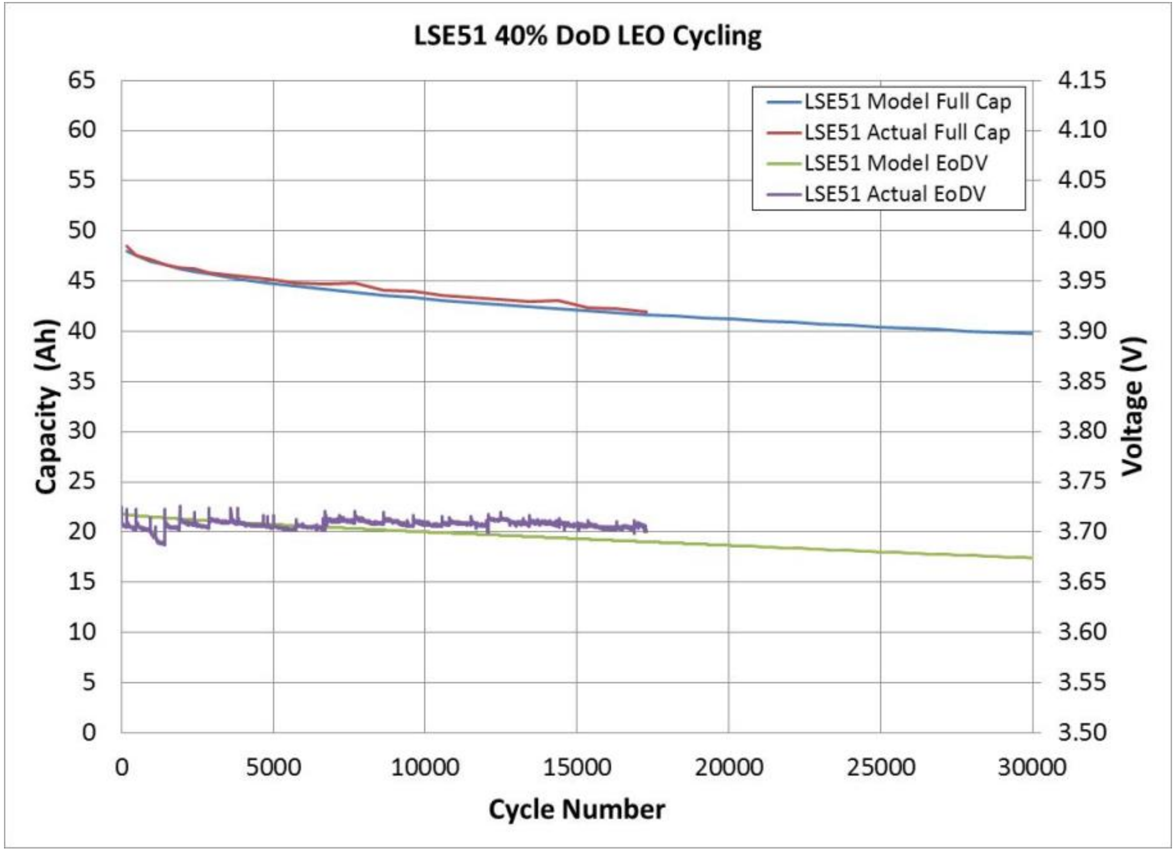
Test Name	Cell Type	Test Conditions						Ambient Test Temp	Start Date	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition					
		EoCV	Rate	Time	EoDV	Rate	Time			
40%DoD Cycling	**LSE51**	**3.98V**	**25.5A**	**1hr**	**(3.40V)**	**40.8**	**0.5hr**	**20°C**	**9/28/2009**	**Deep DoD LEO Cycle**



40%DoD LEO Cycle Validation

Powering the Next Generation

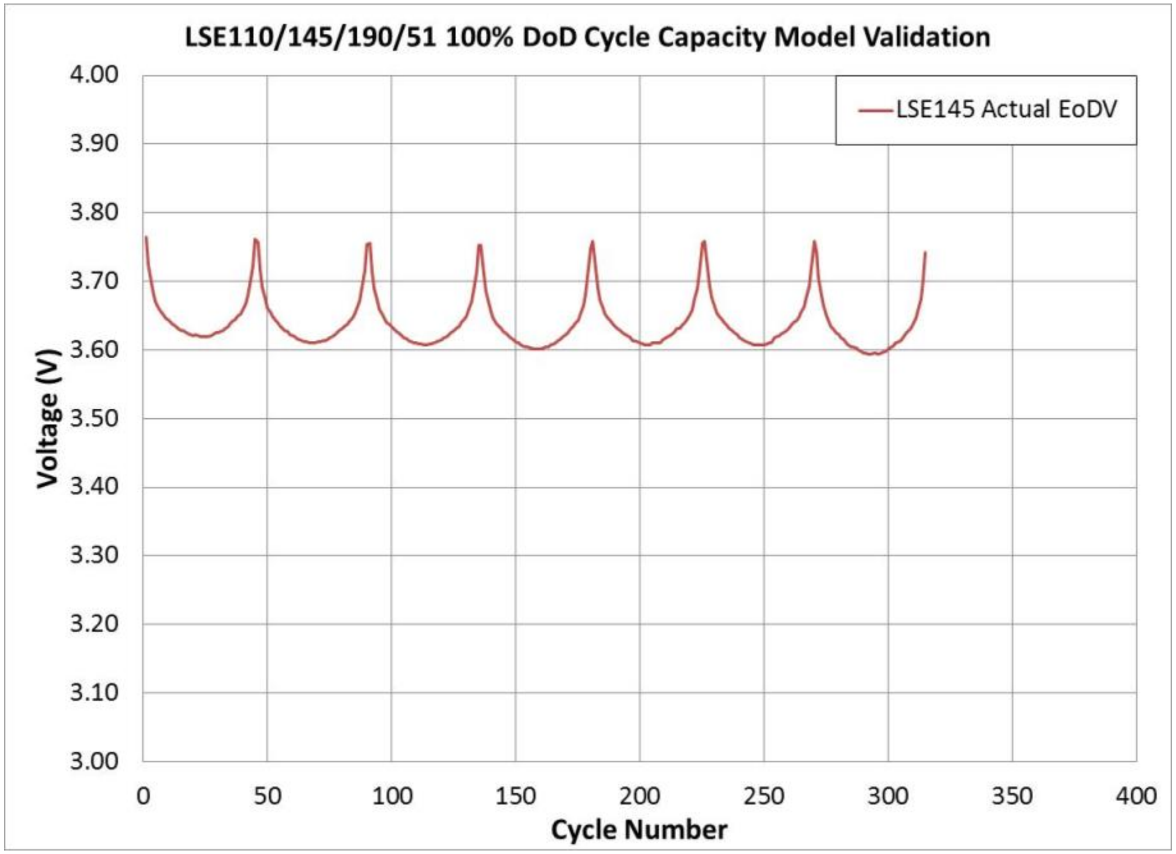
Test Name	Cell Type	Test Conditions						Ambient Test Temp	Start Date	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition					
		EoCV	Rate	Time	EoDV	Rate	Time			
40%DoD Cycling	**LSE51**	**3.98V**	**25.5A**	**1hr**	**(3.40V)**	**40.8**	**0.5hr**	**20°C**	**9/28/2009**	**Deep DoD LEO Cycle**



Semi-Accelerated 70% Max DoD GEO Cycle Validation

Powering the Next Generation

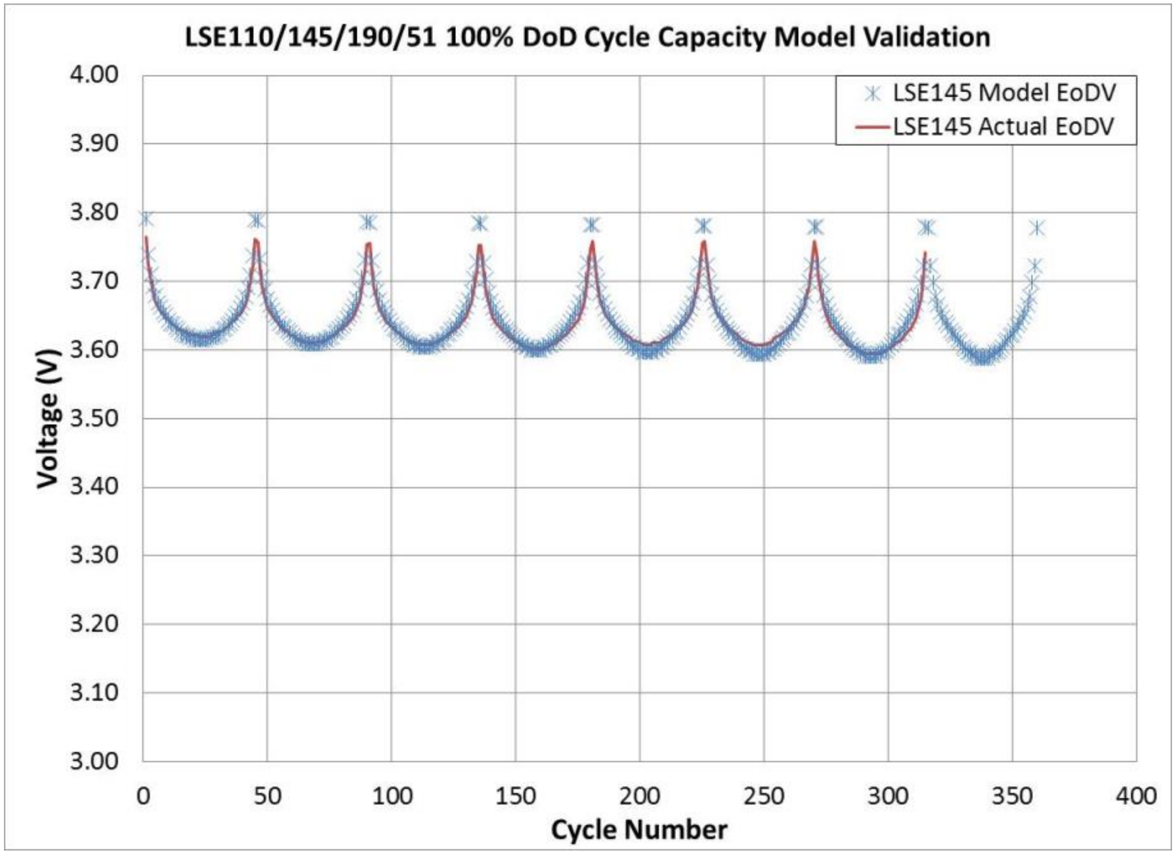
Test Name	Cell Type	Test Conditions						Ambient Test Temp	Start Date	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition					
		EoCV	Rate	Time	EoDV	Rate	Time			
Semi-Accelerated GEO Cycle	LSE145	4.00V	14.5A	22.83hr	(3.40V)	86.3A	Varies	10°C	10/2009	60 day solstice season 25°C 45day eclipse season



Semi-Accelerated 70% Max DoD GEO Cycle Validation

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			
Semi-Accelerated GEO Cycle	LSE145	4.00V	14.5A	22.83hr	(3.40V)	86.3A	Varies	10°C	10/2009	60 day solstice season 25°C 45day eclipse season

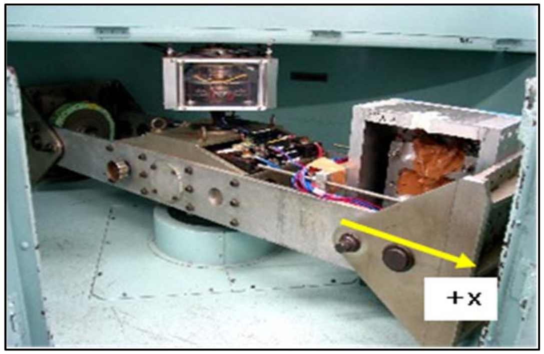


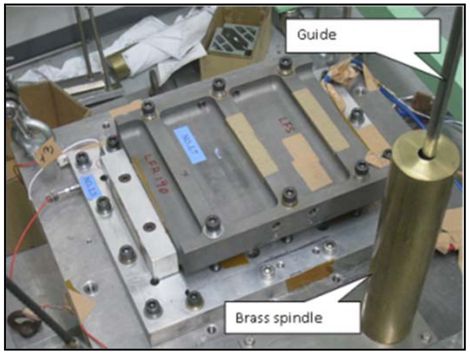
Life Model Validation to Actual On-Orbit Data

Powering the Next Generation

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.





Life Model Validation to Actual On-Orbit Data

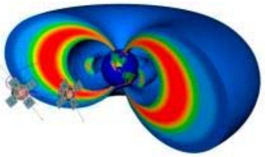
John Hopkins University Applied Physics Laboratory (JHU/APL) has shared on-orbit battery performance data collected from their twin Van Allen Probe spacecraft.

→ 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

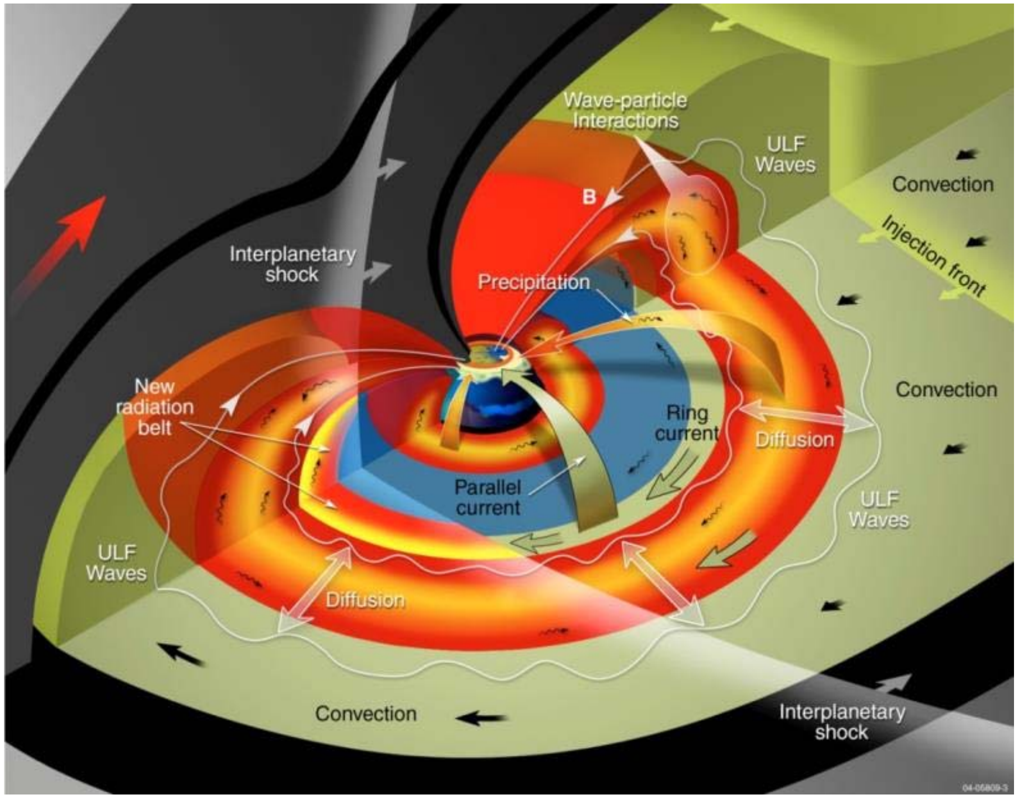


- Objective:

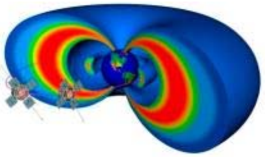
  Provide understanding, ideally to the point of predictability, of how populations of relativistic electrons and penetrating ions in space form or change in response to variable inputs of energy from the sun.

- 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



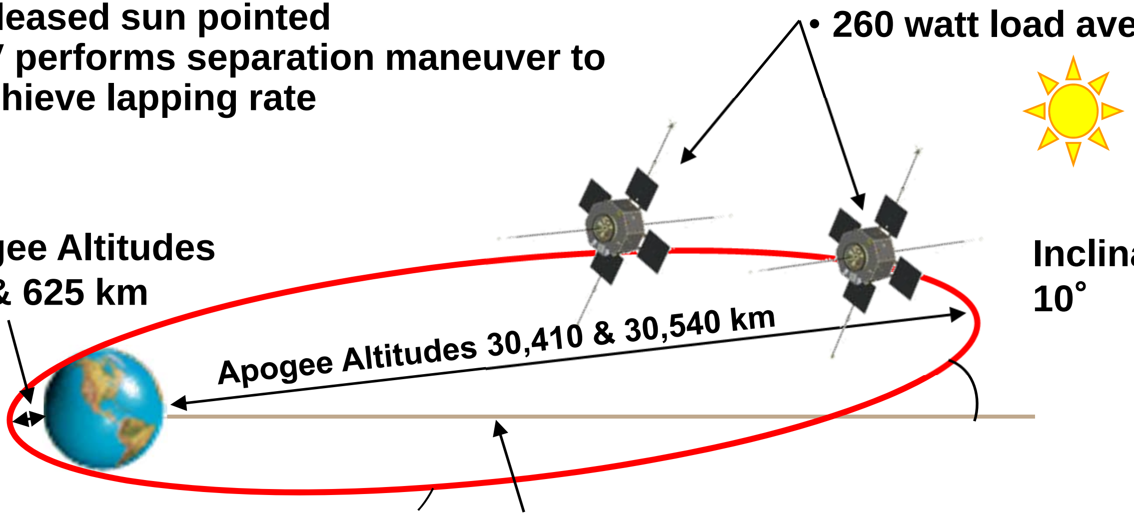
- The Van Allen Probes mission objectives:
  - Discover which processes accelerate and transport electrons and ions.
  - Quantify the loss of electrons and determine balance between loss and acceleration.
  - Understand how the belts change during geomagnetic storms.

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



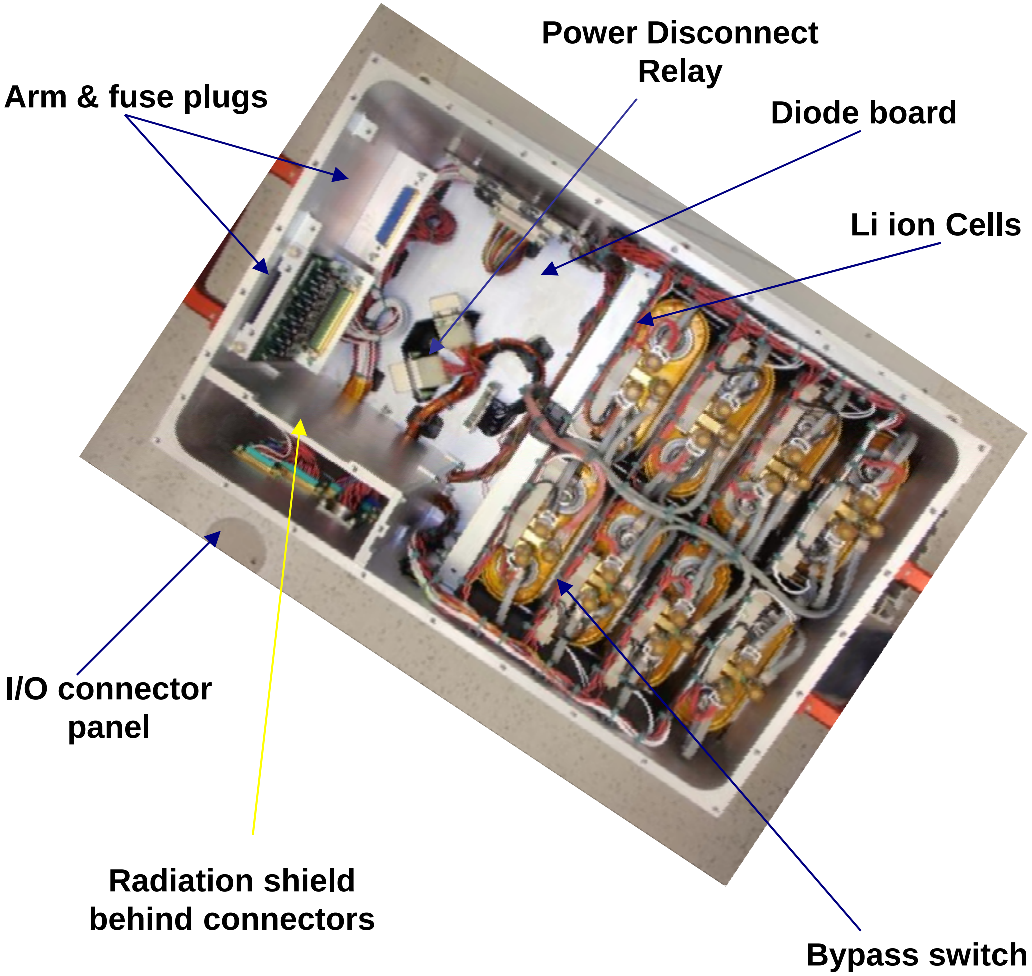
Perigee Altitudes
605 & 625 km

Apogee Altitudes 30,410 & 30,540 km

Inclination
10°

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**

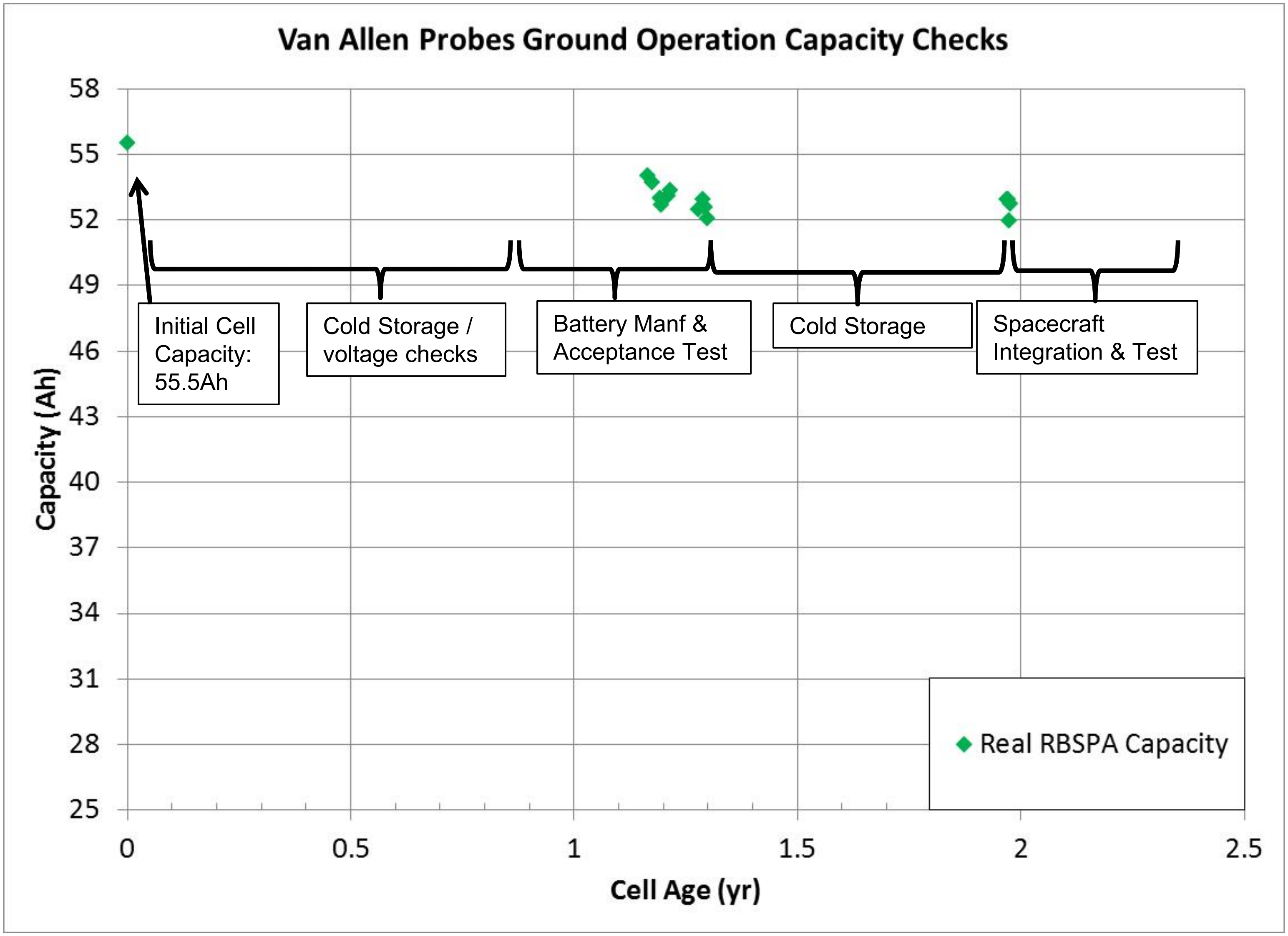
Terrestrial Service Timeline for Cells in Spacecraft A

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

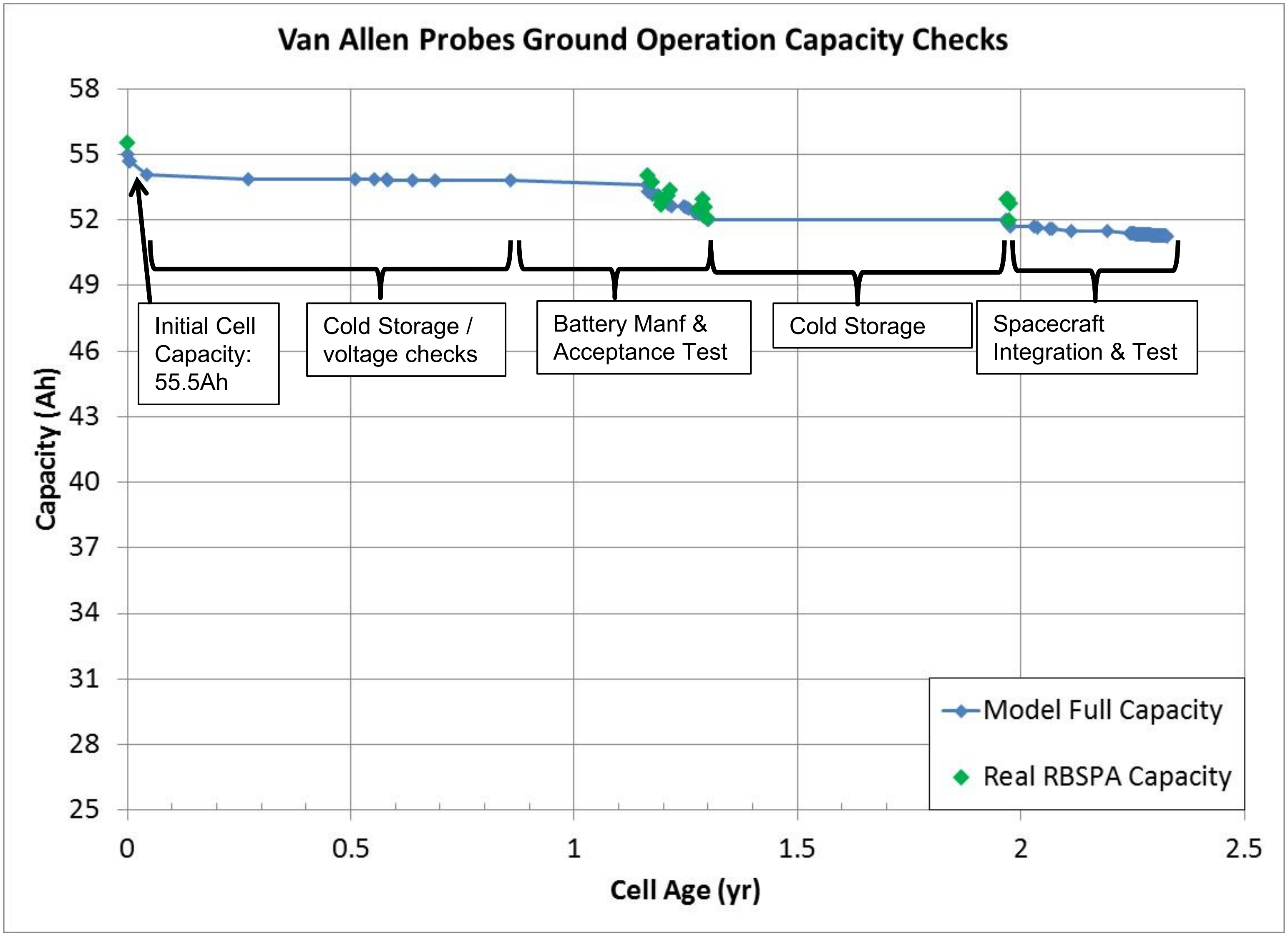


Points represent at what time in the cell's life a full capacity check cycle was completed (100% Depth of Discharge).

These points should correspond to the model Full Capacity Prediction.

Actual vs. Life Model Capacity Data for Ground Operations

Powering the Next Generation

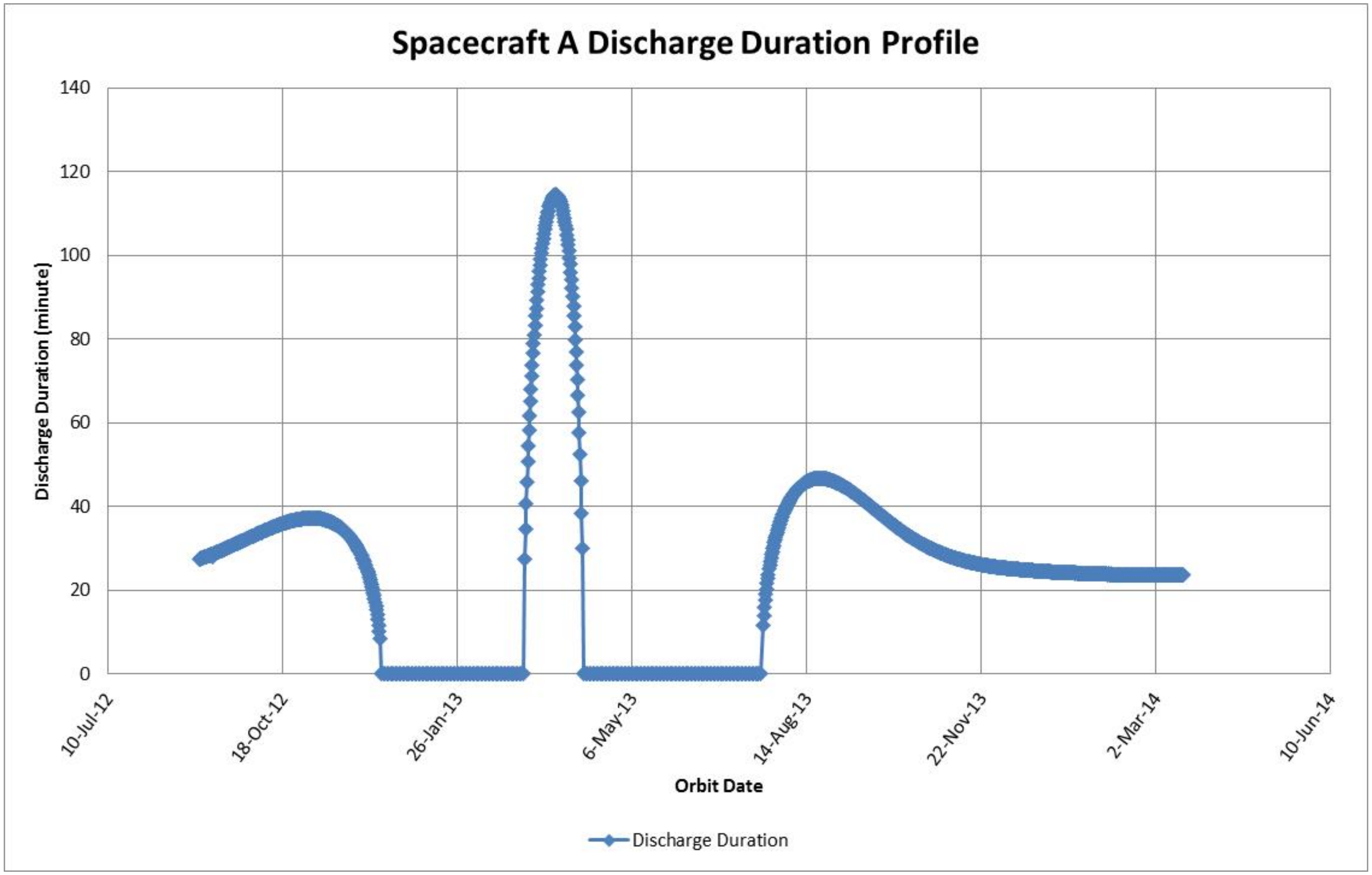


Model matches well with ground operation data collected over 2 year period up to launch.

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

Discharge Duration Profile of Spacecraft A

Powering the Next Generation

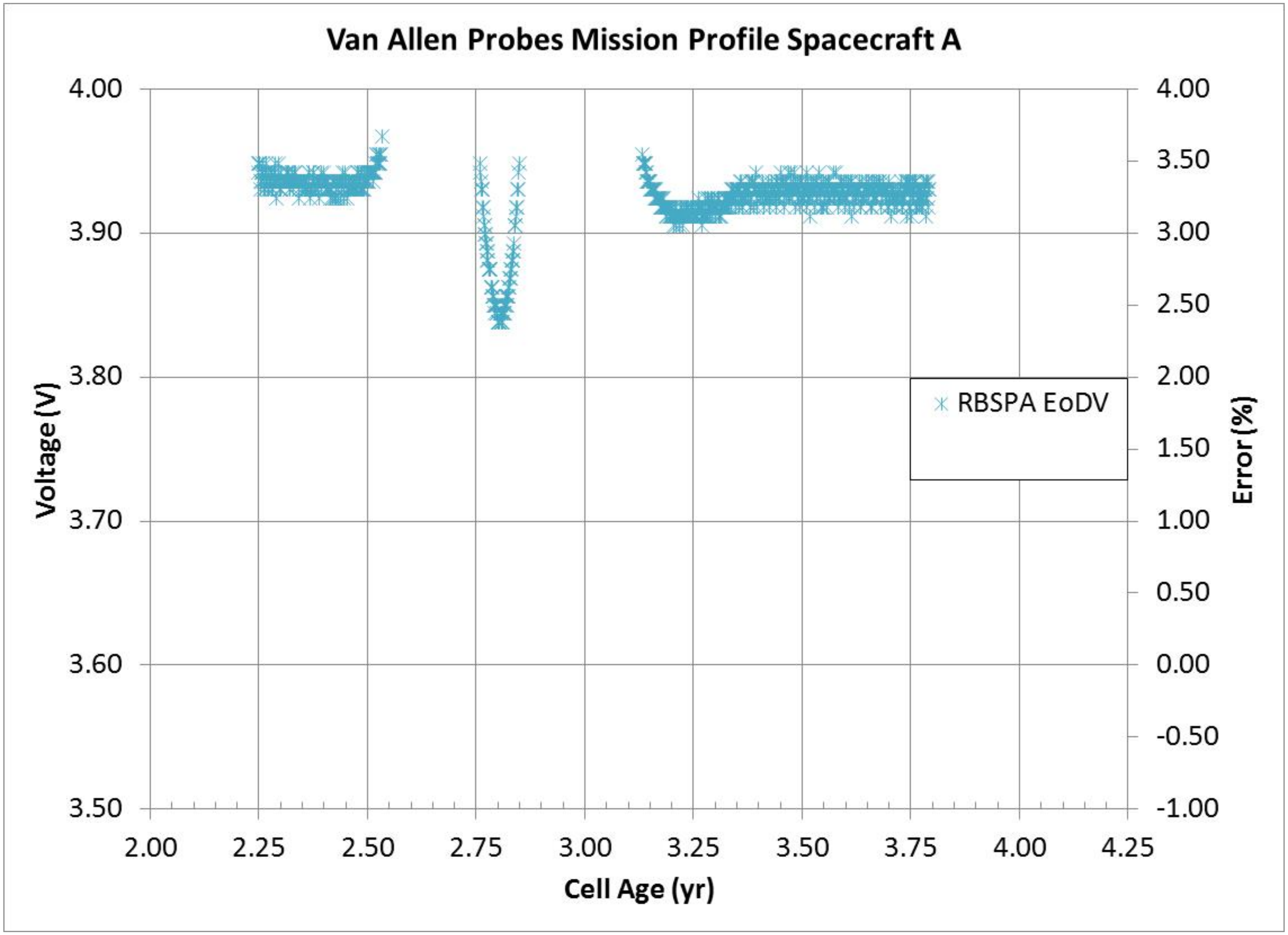


Discharge duration is highly variable and includes periods with no discharge.

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

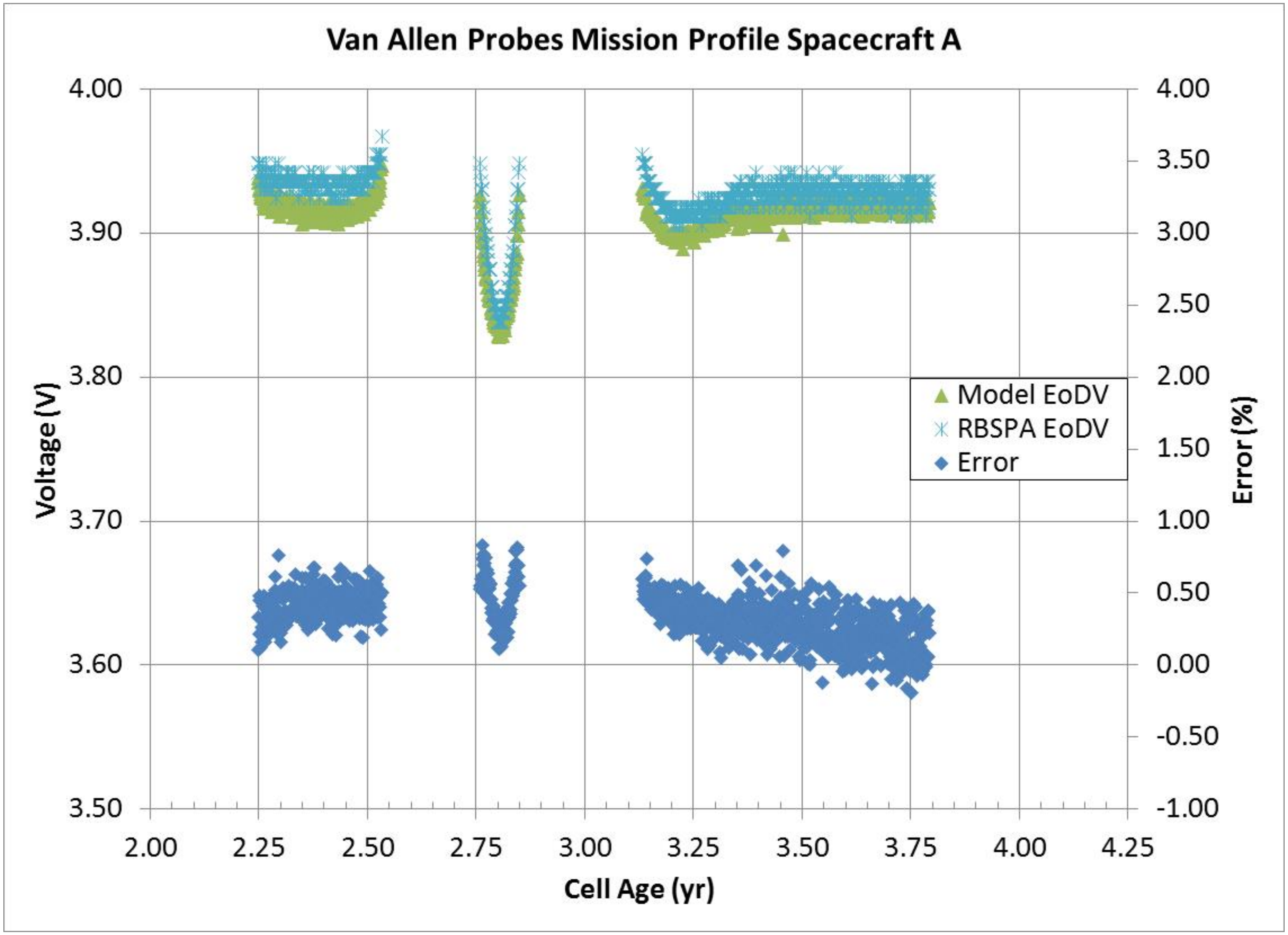


Average Cell EoDV of Spacecraft A.

Data collected from 8/2012 through 3/2014.

On-Orbit EoDV Comparison, Actual vs. Life Model

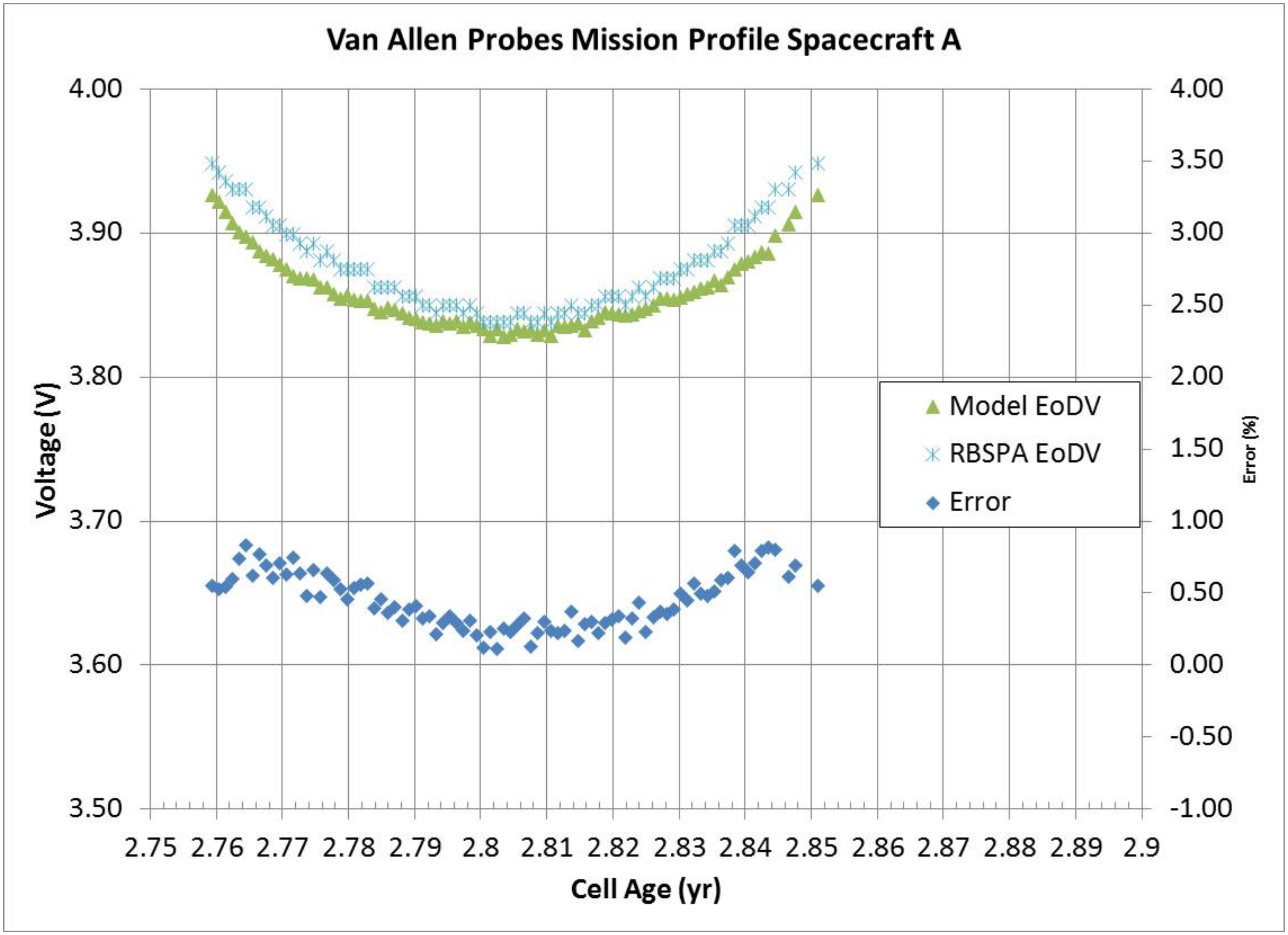
Powering the Next Generation



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

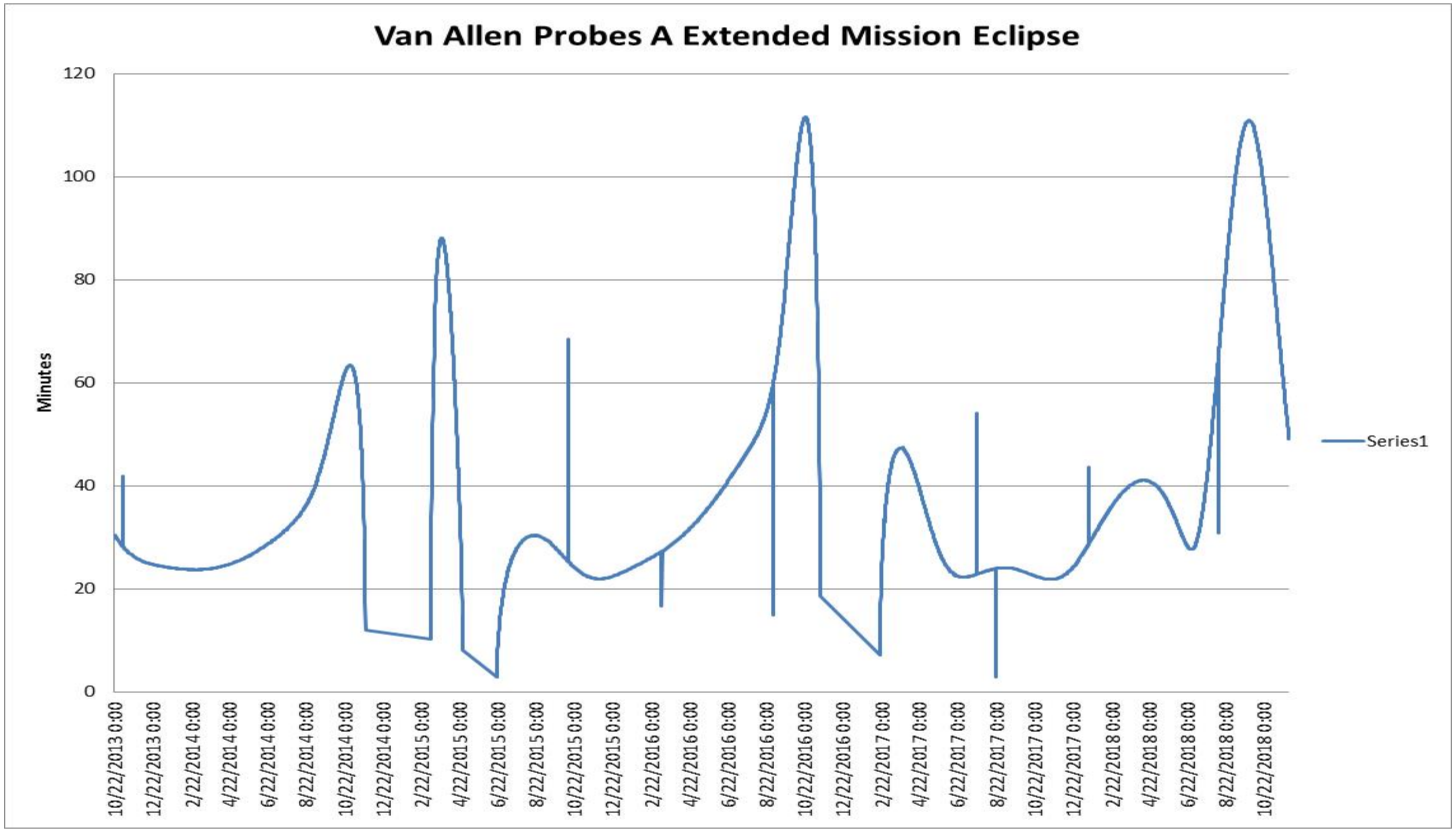
Powering the Next Generation

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.



Other Uses of the Life Model

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

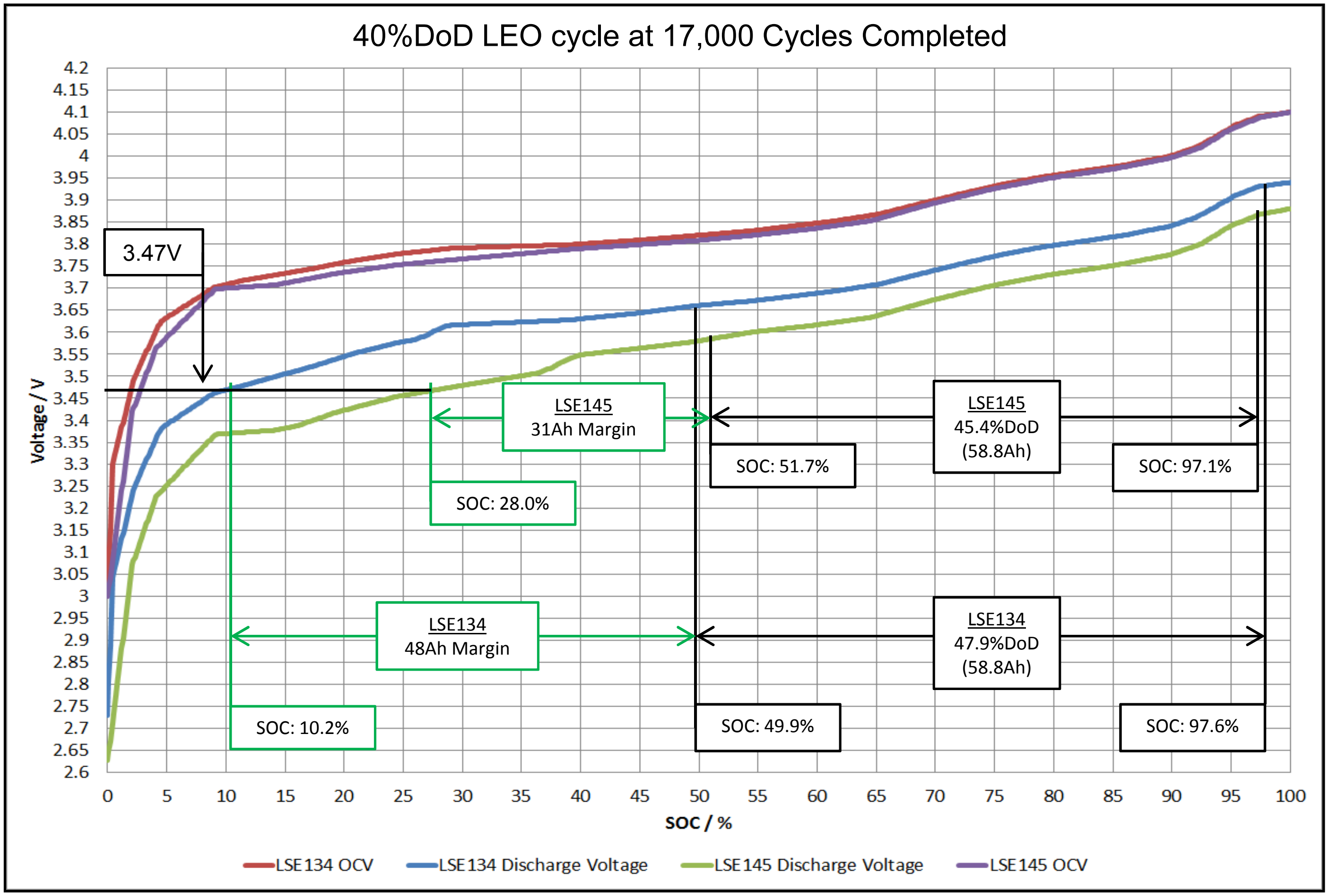
Lower voltage limit: 3.47V per cell.

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

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

GS YUASA

Powering the Next Generation



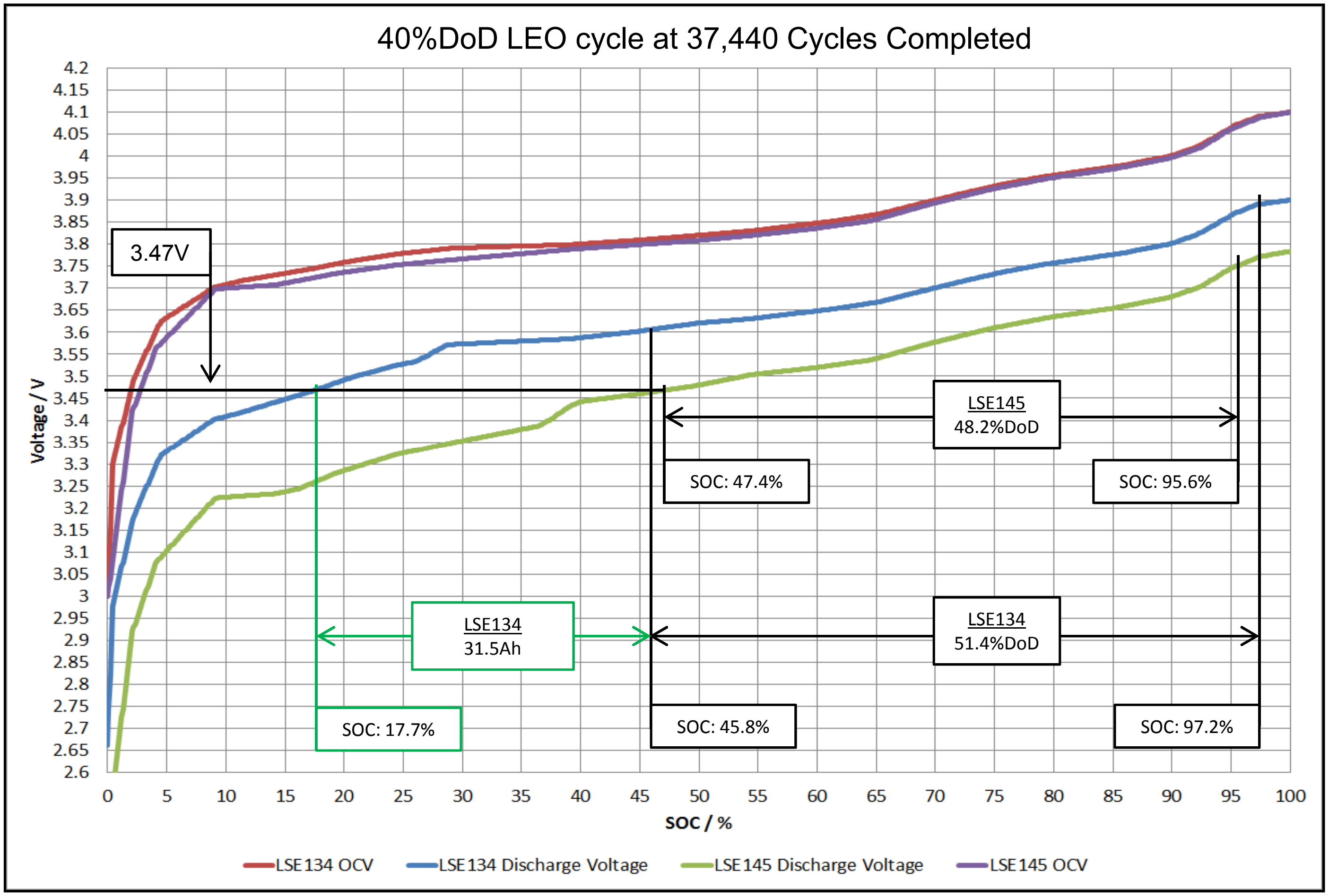
	LSE134	LSE145
Full Capacity	122.8	129.5
Orbit Capacity	119.8	125.8
% of Full	97.6%	97.1%

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%

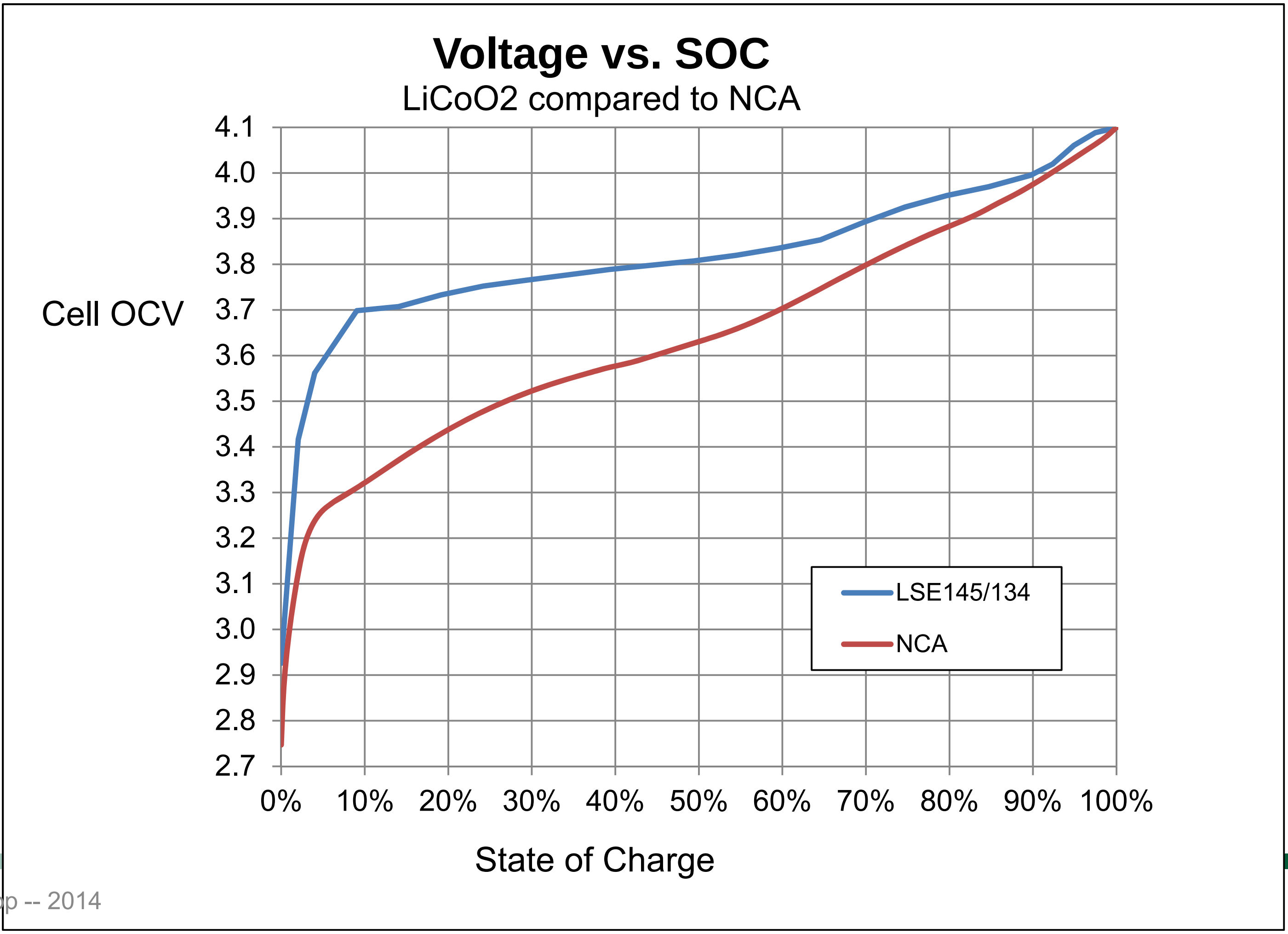
The chart above shows the predicted discharge curve and expected DoD at 37,440 cycles (~6.5years) which shows the LSE145 will fall below 3.47V/cell. Due to the suppressed DCR growth of the Power type cell, there is still significant margin available to continue the mission.

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

Final Thoughts on Retention Model and Cell Selection

Powering the Next Generation

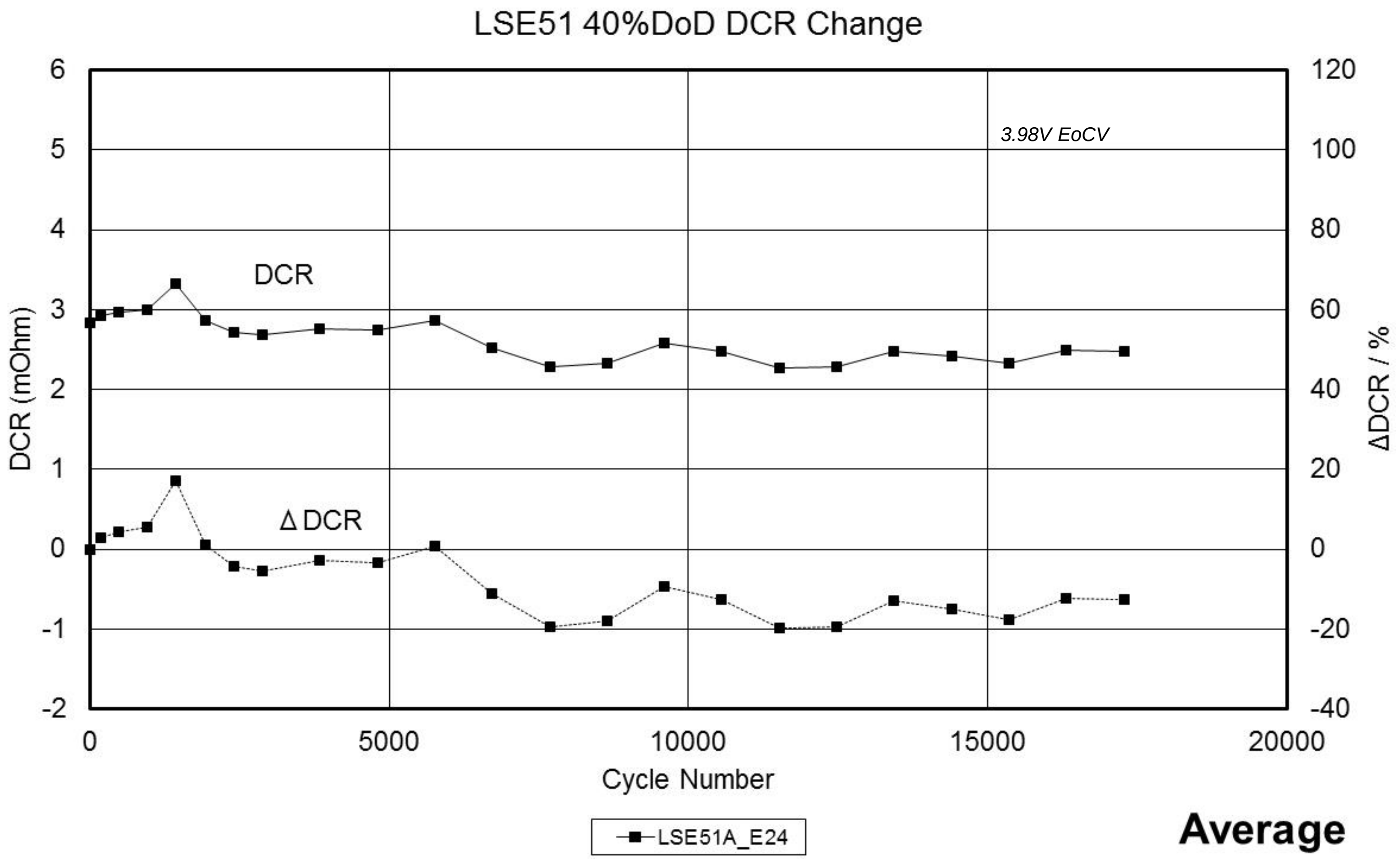
End of Mission performance is ultimately defined by how much energy/power the cell can deliver while remaining above spacecraft lower voltage limits. Defining batteries in terms of “Max Allowable DoD” or arbitrary “EOM Capacity” has the potential to result in inefficient solutions.   “Accessible Watt-hour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



Final Thoughts on Retention Model and Cell Selection

Powering the Next Generation

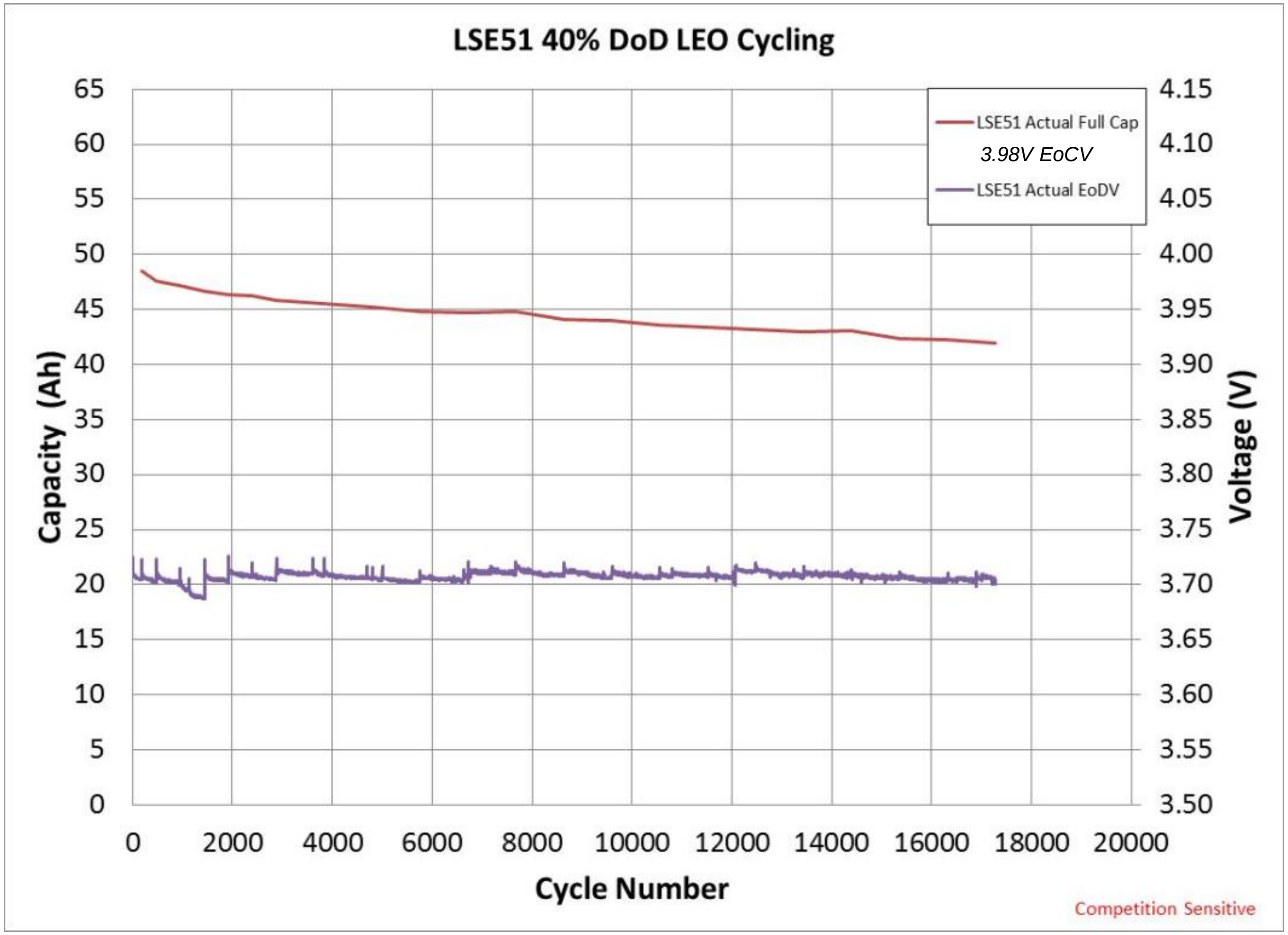
Higher average operating voltage of $LiCoO_2$ coupled with suppression of DCR growth achieved by the Generation 3 chemistry results in exceptional Watt-Hr retention



Average

Final Thoughts on Retention Model and Cell Selection

Higher average operating voltage of $LiCoO_2$ coupled with suppression of DCR growth achieved by the Generation 3 chemistry results in exceptional Watt-Hr retention

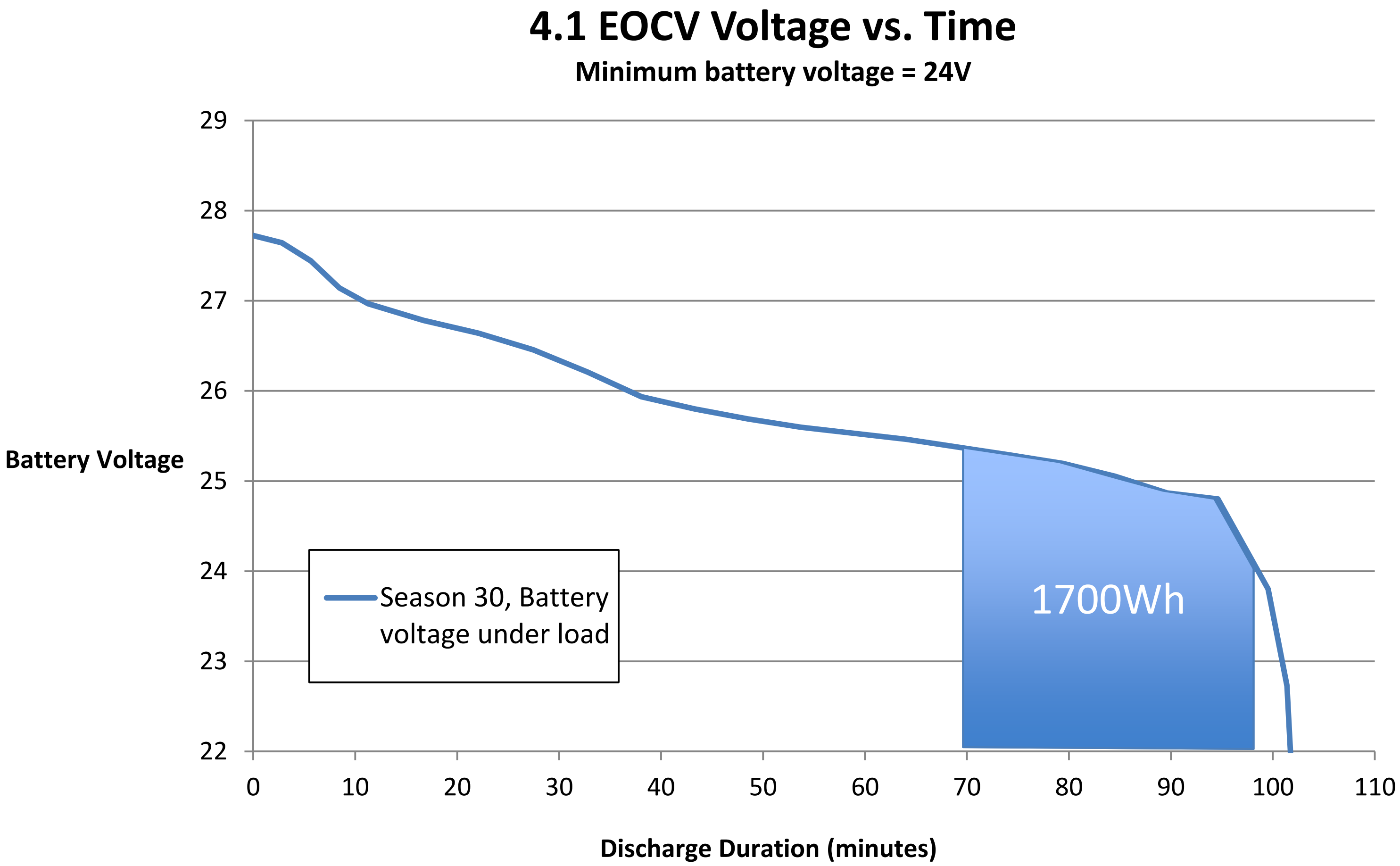


Final Thoughts on Retention Model and Cell Selection

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



Thermal Modeling Capabilities

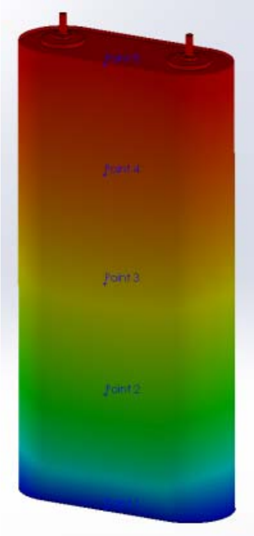
Powering the Next Generation

GYLP, with cooperation from GYT, JAXA, and National Renewable Energy Laboratory, has calculated and validated thermal modeling parameters for the LSE cell.

This information can be utilized to optimize overall battery thermal design.

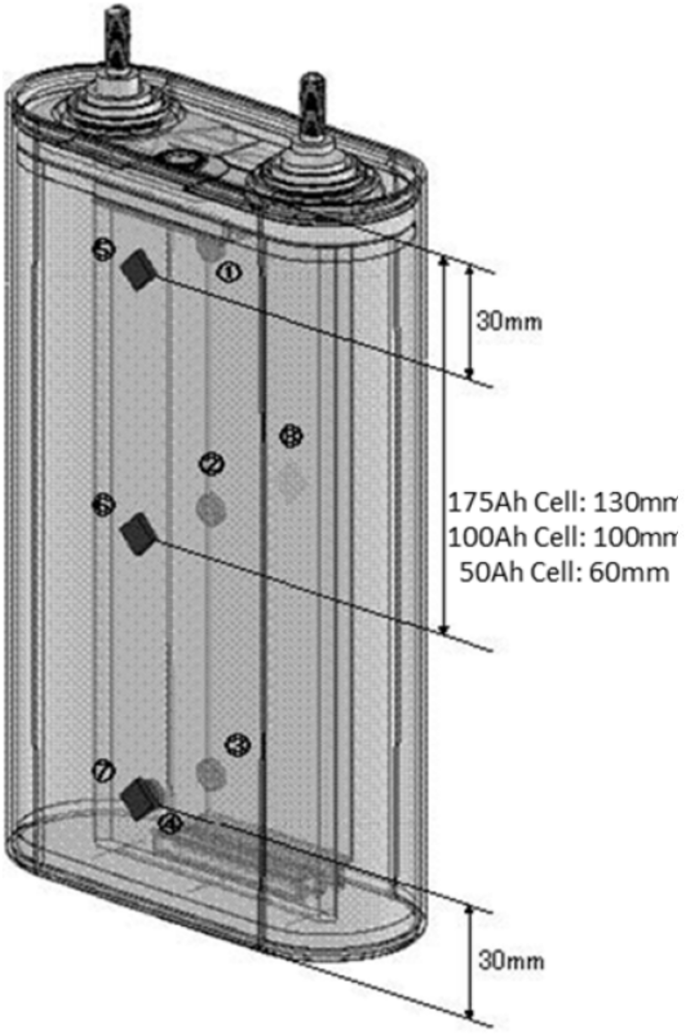
The following slides summarize:

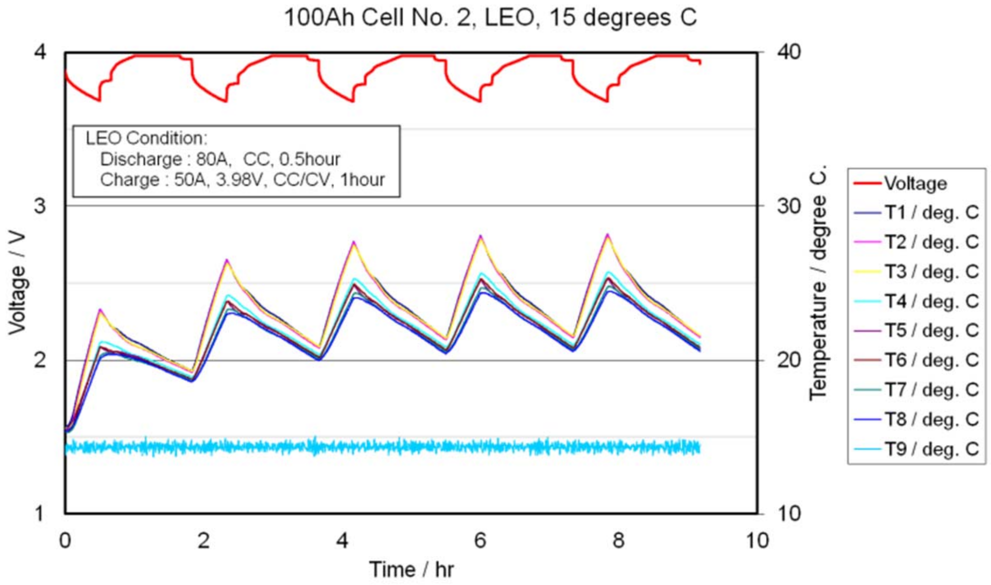
1. Calculation of thermal properties from existing cell data
2. Creation of the LSE Thermal Finite Element Model (FEM)
3. Experiment performed to validate the calculated properties and Thermal FEM

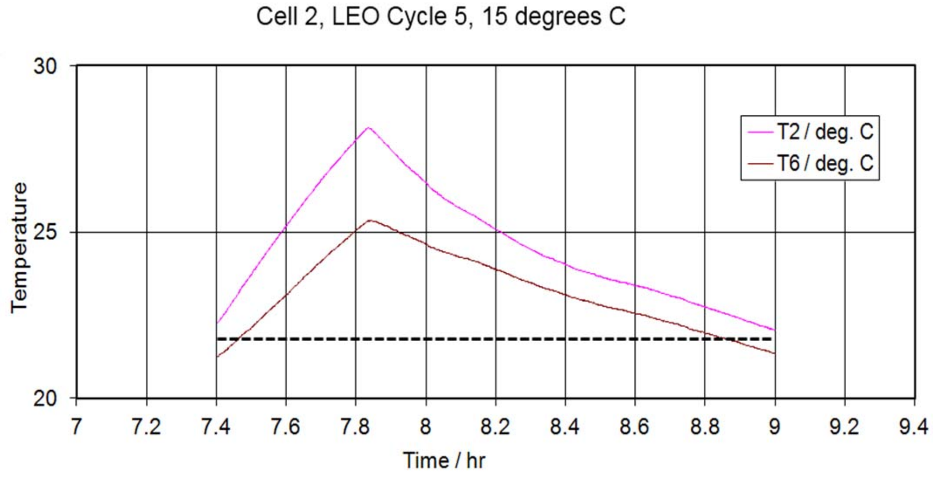


Existing Cell Thermal Data

Powering the Next Generation



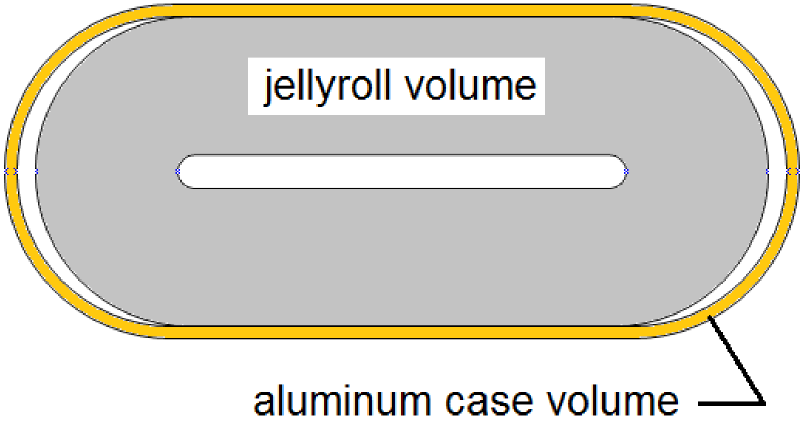




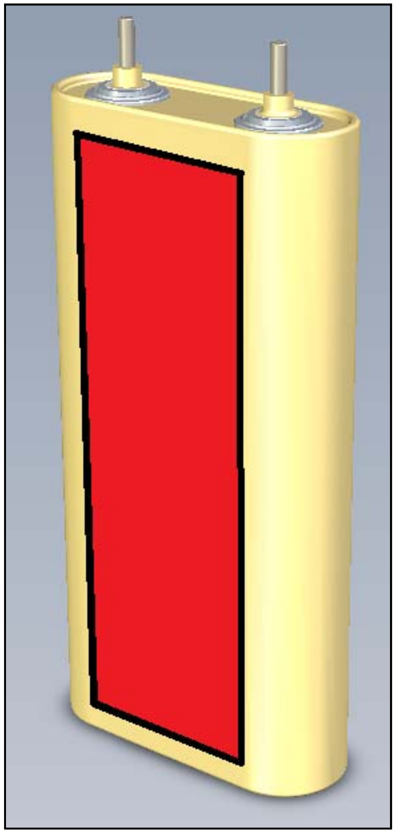
LSE Cell Geometry and Heat Paths

Powering the Next Generation

Cell can be thought of as two regions (1) the jellyroll and (2) the aluminum case. The jellyroll is assumed to make contact with the case only at the flat walls and does contact the case at the curved surfaces (see graphic).



Above: LSE cell cross-section showing the jellyroll and case volumes
Right: Region of contact between jellyroll and case volumes



LSE134 Cell Thermal FEM Parameters and Inputs

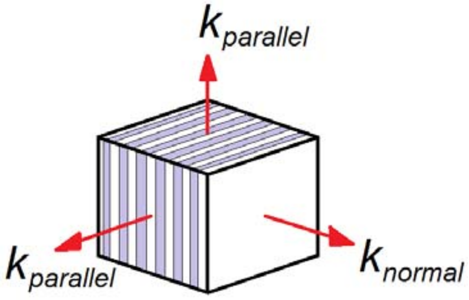
Powering the Next Generation

The jellyroll consists of wound layers of metallic foil, binders, metallic oxides, graphites, polyolefin and organic solvent. It is a classic example of a composite and it can be expected to have a highly directional thermal conductivity.

Key Parameters:

- Geometry of jelly roll and case
- Heat paths
- Directional Thermal Conductivity
- Cell Heat Capacity

LSE134 Thermal Parameters (Calculated)	
$K_{Parallel}$	$46.5\ \frac{W}{m*K}$
K_{Normal}	$1.02\ \frac{W}{m*K}$
Heat Capacity of Jellyroll	$3535.2\ \frac{J}{K}$
Heat Capacity of Al Case	$291.1\ \frac{J}{K}$

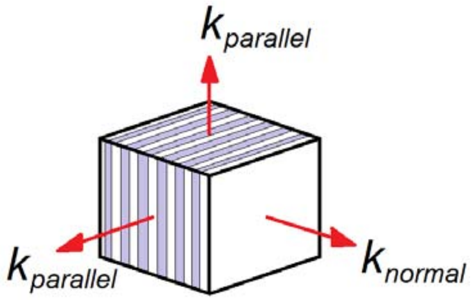


Test to Validate Calculated Thermal Parameters

GYLP needed to devise a test which would validate the calculated directional thermal conductivity parameters. After several iteration a relatively simple test was planned to accomplish the following:

1. Cycle the cell in such a way that the heat generation rate on discharge is equal to the heat generation rate on charge.
2. Create an adiabatic environment which forces the heat generated to flow only through the bottom surface of the cell.
3. Allow the cell to cycle until cell temperature stabilizes creating a pseudo steady-state which allows the heat capacity to be ignored.

LSE134 Thermal Parameters (Calculated)	
$K_{Parallel}$	$46.5 \frac{W}{m*K}$
K_{Normal}	$1.02 \frac{W}{m*K}$



Test Requirement 1: Steady State Heat Generation

To effectively validate the model it is convenient to define a cycle regime where the average heat generation from discharge is equal to the average heat generation on charge. This will allow the cell temperature to reach a pseudo steady state

The heat generation (or absorption) by the cell is defined by two simultaneous mechanisms:

1. Resistive heating: $P_R = I^2 * R$
2. Electrochemical heating: $P_E = I * T\left(\frac{dEemf}{dT}\right)$

I= Current (A) (positive on charge, negative on discharge)
R= DC Resistance (Ohm)
T= Temperature (K)
$\frac{dEemf}{dT}$=Entropy (V/K)

The DC resistance and Entropy are a function of SOC. Furthermore, DC resistance is also a function of Temperature. Using high resolution DCR map and entropy versus SOC data it was possible to define a cycle which generated the equivalent amount of heat on both charge and discharge.

Test Requirement 1: Steady State Heat Generation

SOC Region: 50%-60%	-- This region was selected because the DCR is relatively constant with respect to SOC.
Charge Rate: 67A	-- Quick charge rate (C/2) to reduce cycle time

Using the basic equations on the previous chart it was found that over this region the average heat generation (H_{cavg}) is approximately ***5.26J/s***.

Next we solve for the proper discharge current to generate the equivalent amount of heat:

$$H_D = \sum_{n=1}^{n=22} \left(\frac{(t_{n-1} - t_n) * \left(\left[I^2 * R + I * T \left(\frac{dEemf}{dT} \right) \right]_{n-1} + \left[I^2 * R + I * T \left(\frac{dEemf}{dT} \right) \right]_{n} \right)}{2} \right)$$

$$H_{Davg} = \frac{H_D}{t_{22} - t_0}$$

H_D=total discharge heat generation (Joules)

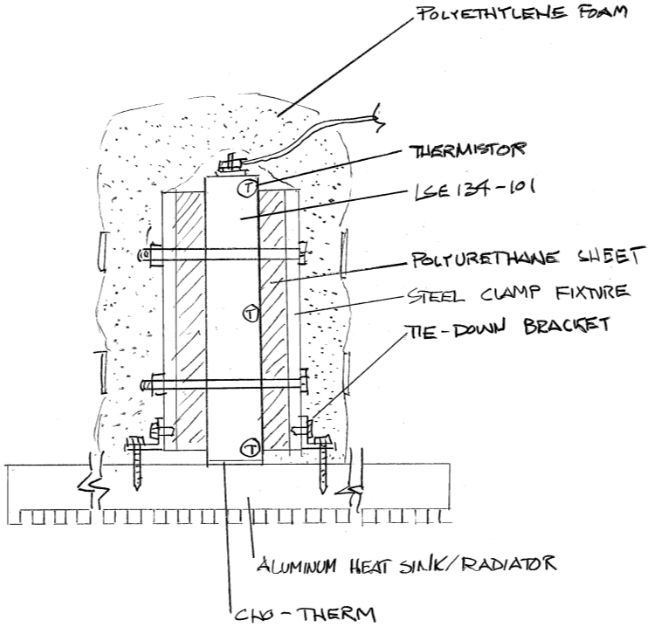
Discharge current is adjusted until convergence is achieved, such that:

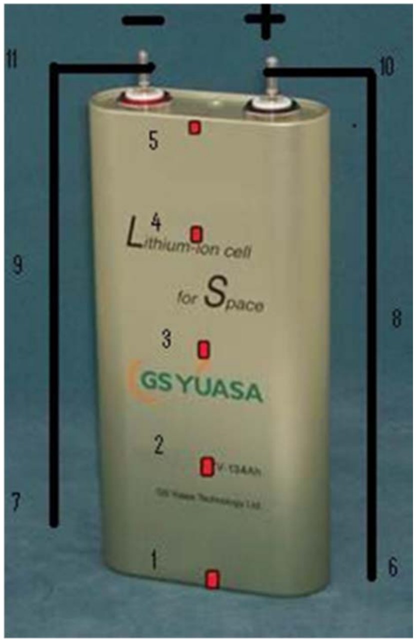
$$H_{Cavg} = H_{Davg} = 5.26\ J/s$$

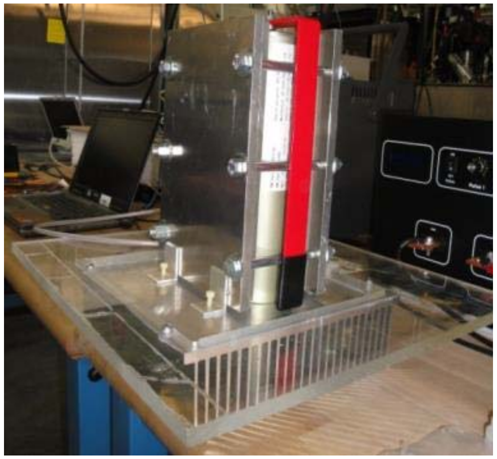
Solution: Discharge Current= -56.19Amps

Test Requirement 2: Adiabatic Cycling Fixture
NREL Thermal Testing Set-up

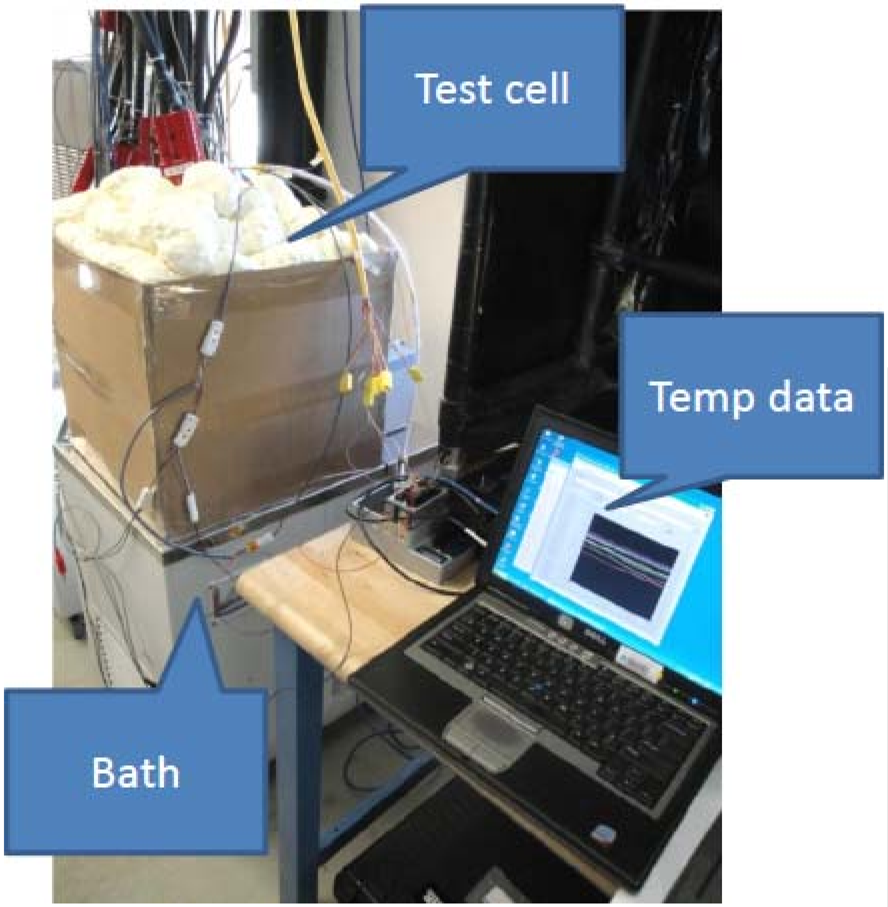
Powering the Next Generation



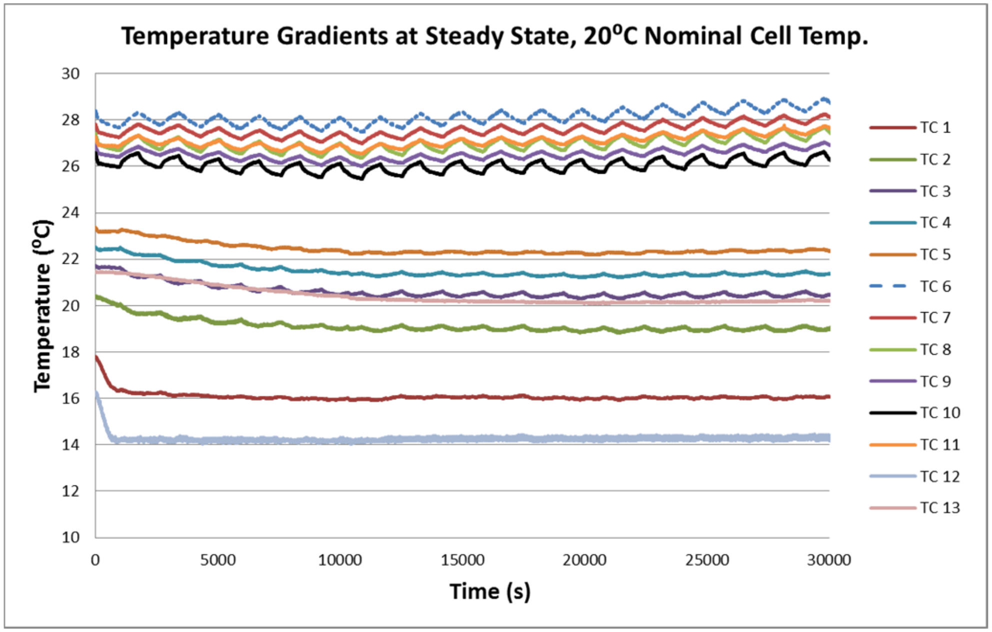




Test Requirement 3: Achieve Pseudo Steady State



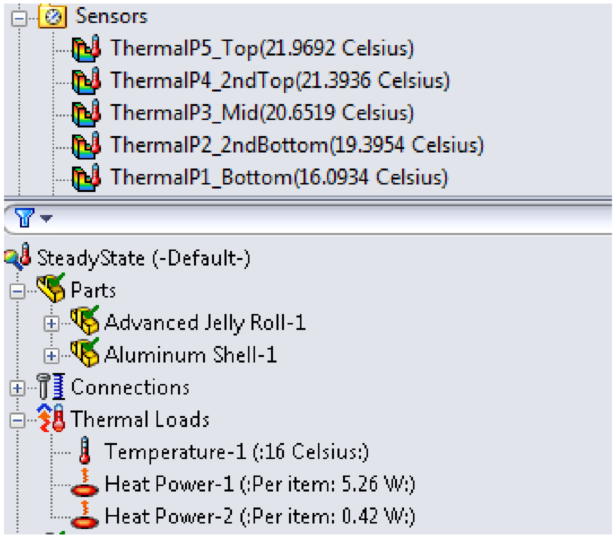
Fins of the fixture shown on the previous slides were submerged in a temperature controlled water bath. Bath temperature was controlled such that the temperature at the cell to baseplate interface was held at 16deg.C Cell was cycled according to the profile calculated previously. After several cycles the cell temperatures effectively stabilized to 20deg.C indicated that the cell had reached pseudo steady state.



LSE Cell Preliminary FEM Validation (LSE134)

Powering the Next Generation

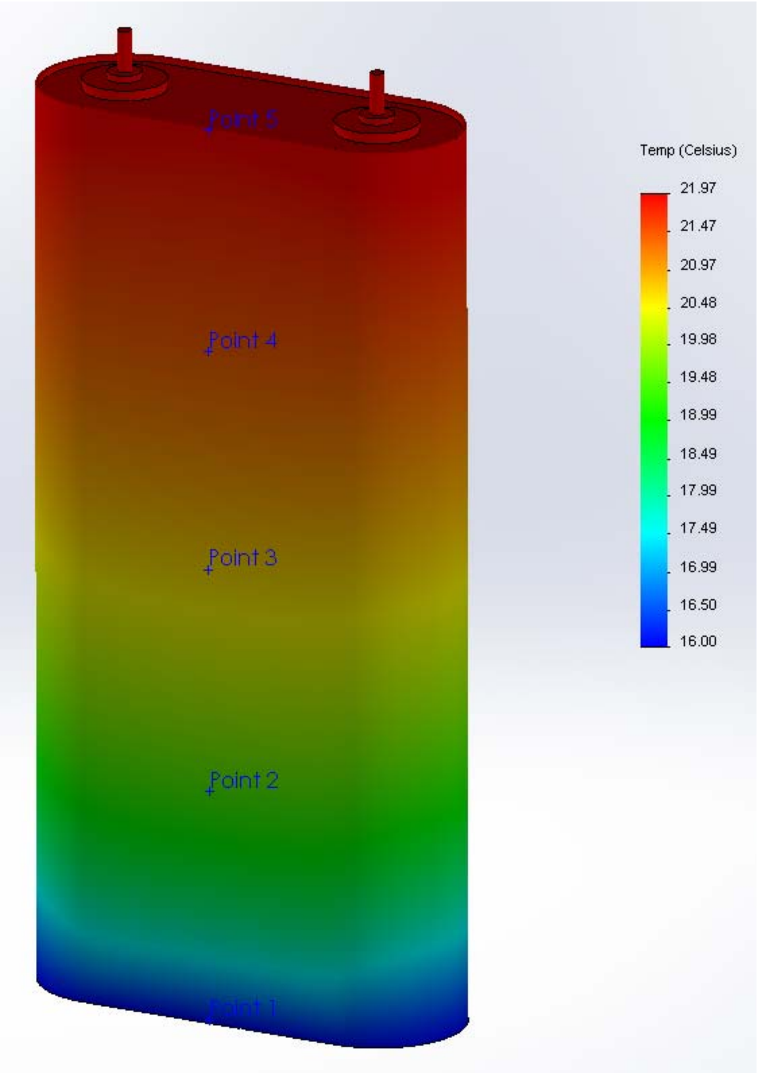
Model was compared to the results obtained from the NREL test and excellent agreement was achieved and thermal conductivities validated.


Sensors
ThermalP5_Top(21.9692 Celsius)
ThermalP4_2ndTop(21.3936 Celsius)
ThermalP3_Mid(20.6519 Celsius)
ThermalP2_2ndBottom(19.3954 Celsius)
ThermalP1_Bottom(16.0934 Celsius)

SteadyState (-Default-)
Parts
Advanced Jelly Roll-1
Aluminum Shell-1
Connections
Thermal Loads
Temperature-1 (:16 Celsius:)
Heat Power-1 (:Per item: 5.26 W:)
Heat Power-2 (:Per item: 0.42 W:)

Location	Temperature (^oC)		Model performance	
	FEA	NREL test	Divergence (^oC)	Error*
5	21.97	22.31	-0.34	-5.4%
4	21.39	21.33	0.06	1.0%
3	20.65	20.44	0.21	3.3%
2	19.40	18.98	0.42	6.7%
1	16.09	16.03	0.06	1.0%

** error expressed as % of NREL test ΔT top to bottom (TC5-TC1)*



Thermal FEM Results

- Data collected from NREL testing supports the calculated values of the directional thermal conductivity.
  - → Model predicts within 0.5°C to the measured data at each thermometry point in the steady-state condition.
- Model is therefore validated under these conditions and can be used with confidence in nominal operating temperature range of 10-35deg.C
- Using the heat capacity and directional thermal conductivities it is possible to define a model which predicts both temperature and heat flow gradients in a battery.

Other Considerations

- Determine if thermal conductivity is significantly affected by temperature. Unknown if K_{normal} or $K_{parallel}$ depend strongly on Temperature
  - → Temperatures in excess of nominal range may introduce other mechanisms that increase or decrease the thermal conductivities.
- Validate temperature gradient present in the normal direction of the jelly roll.
  - → Analytical approach using the model to recreate test data already collected by GYT.

Final Summary

Powering the Next Generation

- GS Yuasa has accumulated an extensive database of cell storage and cycling data.
  - → Includes test at various SOC, DOD, temperatures, etc.…
- GS Yuasa utilizes this empirical data to create and calibrate performance models
  - → Capacity, Voltage, Thermal
- Models have been validated by ground and on-orbit data.
  - → High confidence in validity of model with proper inputs
  - → Properly captures dynamic events and storage

Using these models it is possible to predict with a high level of accuracy the performance of the LSE cells in a variety of usage profiles.

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