Qualification and Performance of GS Yuasa's Generation 4 Lithium-ion Chemistry for Space Applications

2021 Space Power Workshop

April 21, 2021

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GS Yuasa Corporate Highlights & Global Network

Powering the Next Generation

GS Yuasa Corporation (2004)

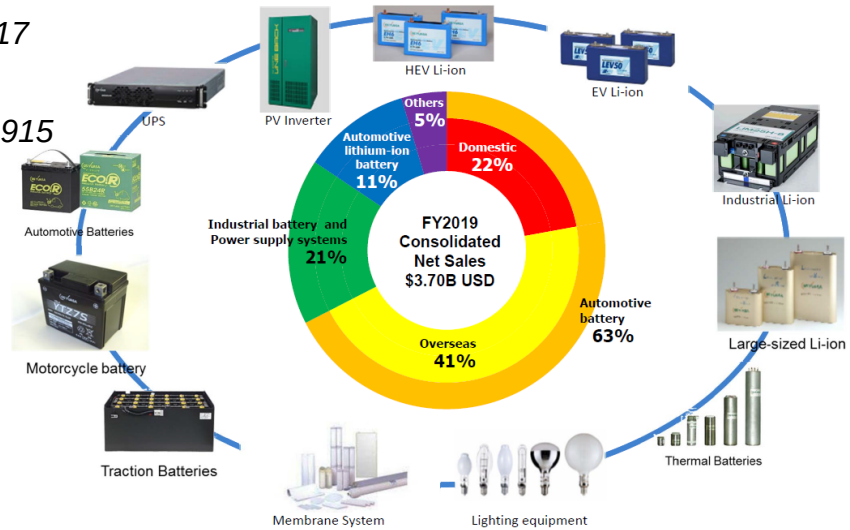
Develops management plan and strategy for GS group and administrate the group companies to enhance the total value of the group.

GS Japan Storage Battery Co., *Est. 1917*

YUASA Yuasa Battery Manufacturing, *Est. 1915*

GS Yuasa International

Manufacturing and sales of automotive & industrial batteries, power supply systems, switch gear, lighting & ultra violet systems, specialty equipment and other electrical equipment



37 Overseas affiliates
19 Countries

Lithium Energy Japan (JV) (2007)

Development, manufacturing and sales of large lithium-ion batteries for electric vehicles

Blue Energy Co., Ltd (JV) (2009)

Development, manufacturing and sales of lithium-ion batteries for hybrid electric vehicles

GS Yuasa Technology Ltd. "GYT"

Manufacturing and sales of specialty batteries

GS Yuasa Energy Solutions (2019)

Sales of automotive, industrial and power-sports batteries

GS Yuasa Lithium Power "GYLP" (2006)

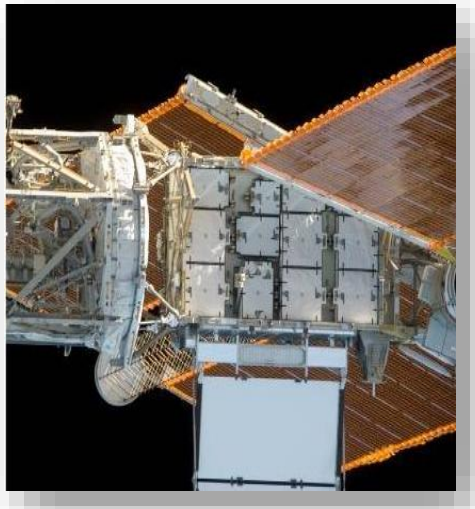
Li-ion battery manufacturing and sales
North American aerospace and defense applications

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……..…….. 212+
  - LEO/MEO……..….. 100+
  - GEO……..…… 112
- 1st satellite on-orbit……..… Servis 1 (30 Oct. 2003)
- Longest satellite on-orbit (yrs)…..... >15.5yr (IPSTAR, 11 Aug. 2005) still operational
- Watt hours on-orbit…….……..... >4.2 MWh (world leader)
- Space cell qualification programs……. >24
- Cell sizes (Ah) flown…..... 35; 50; 100; 102; 110; 134; 145; 175; 190; 200
- Performance to date……..... No failures
- Backlog (Wh)…….…… >1.59MWh



Launch vehicles & number of satellites

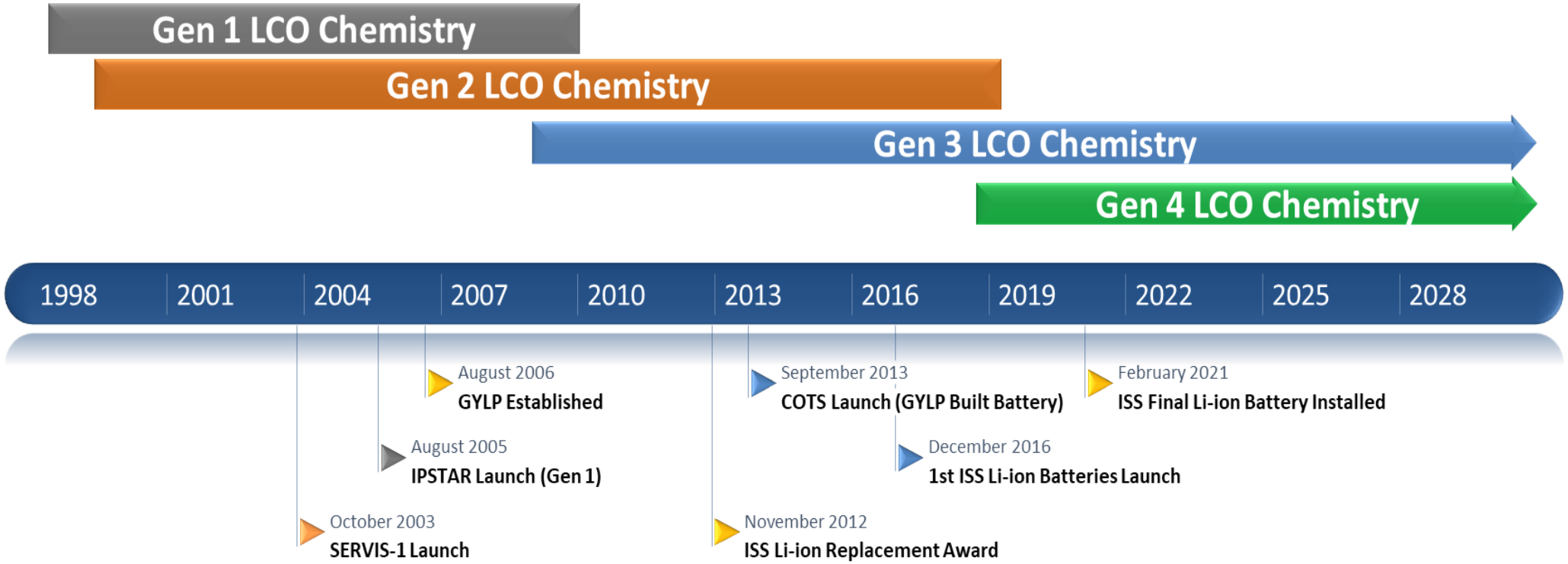
Ariane-5ECA	45	Falcon-9 v.1.2	13	Soyuz-2-1b Fregat	3	H-2A-2024	2	Atlas-5(421)	1
Soyuz-2-1 Fregat	24	Antares 230	9	Zenit-3SLB	3	H-2A-204	2	Delta II-7420	1
H-2B-304	22	Proton-M Briz-M (Ph.4)	6	Antares 120	2	H-IIA	3	Dnepr	1
H-2A-202	19	Atlas-5(401)	5	Ariane-5ECA+	2	Rokot-KM	2	Epsilon CLPS	1
Proton-M Briz-M (Ph.3)	18	Falcon-9 v.1.1	5	Atlas-5(431)	2	Zenit-3SL (2)	2	GSLV Mk.2	1
Soyuz-STB Fregat-MT	17	Proton-M Briz-M (Ph.2)	4	Epsilon	2	Ariane-5GS	1	Proton-M Briz-M (P1 M1)	1

Metrics updated March 2021

GS Yuasa Li-ion Space Chemistry Heritage and Approach

Heritage of GS Yuasa Space Chemistry

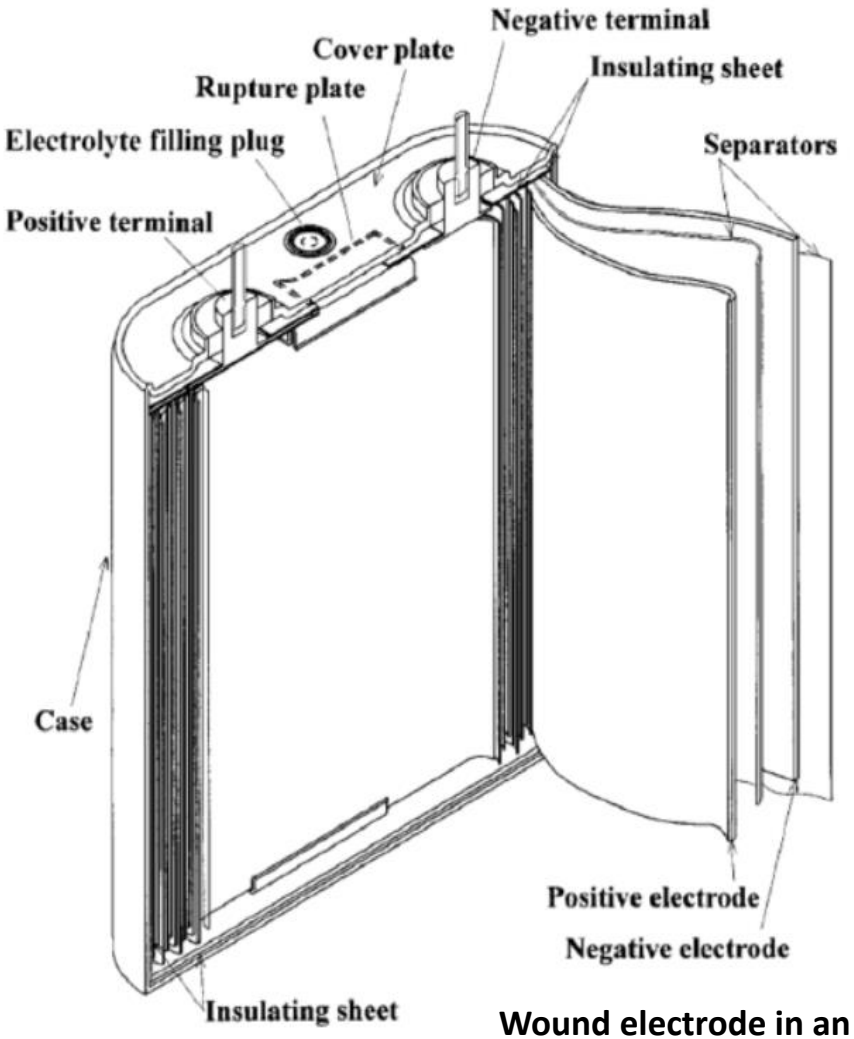
Powering the Next Generation



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.

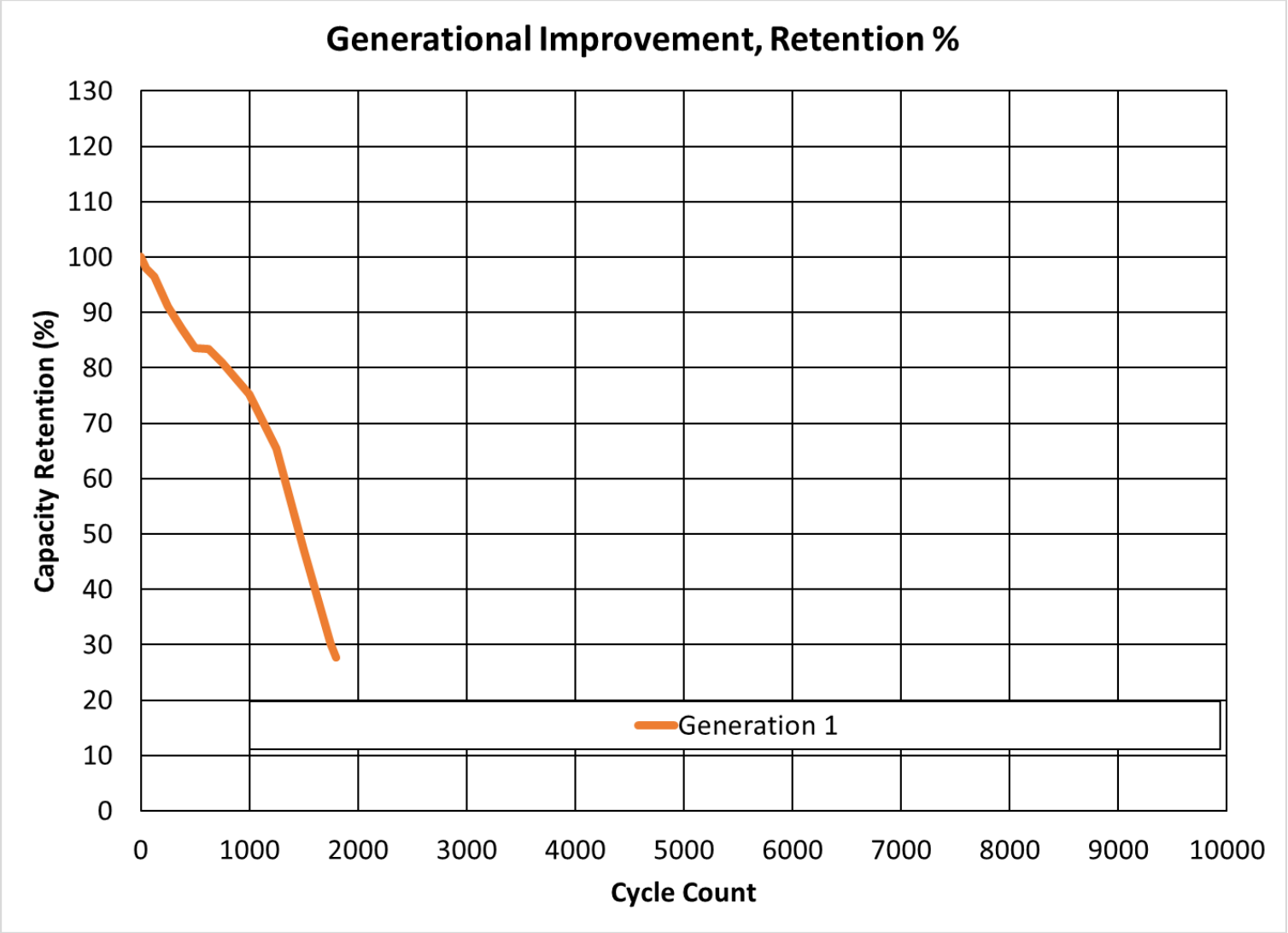
LSE Cell Basic Shape



Wound electrode in an elliptical cylindrical case

Evolution of GS Yuasa $LiCoO_2$, 100% DOD

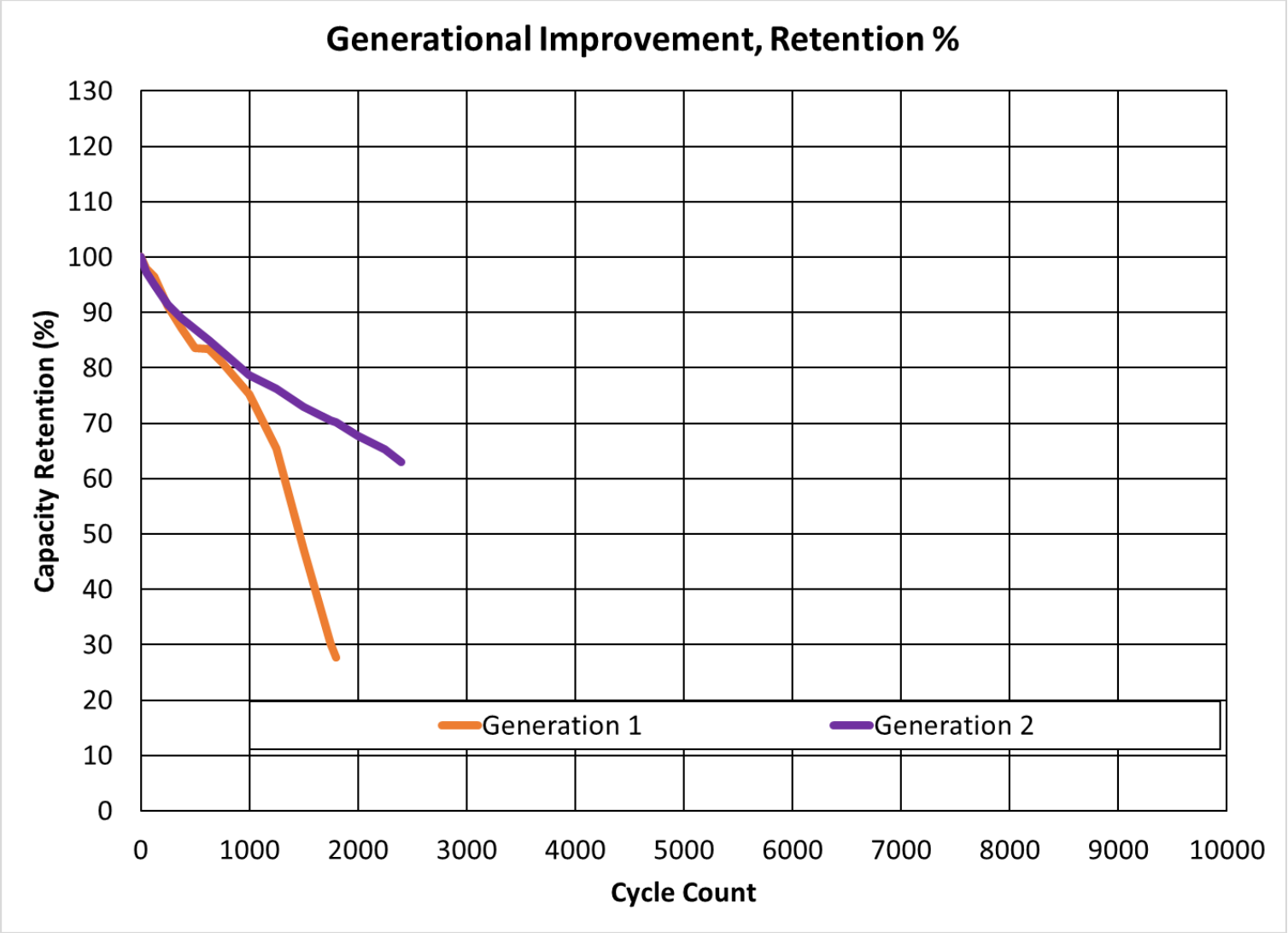
Powering the Next Generation



	Cell	Nominal BOL Ah Capacity	EoCV	BOL Wh/Kg
Gen1	LSE100	107	3.98	141

Width	Thick	Height*
130	50	208

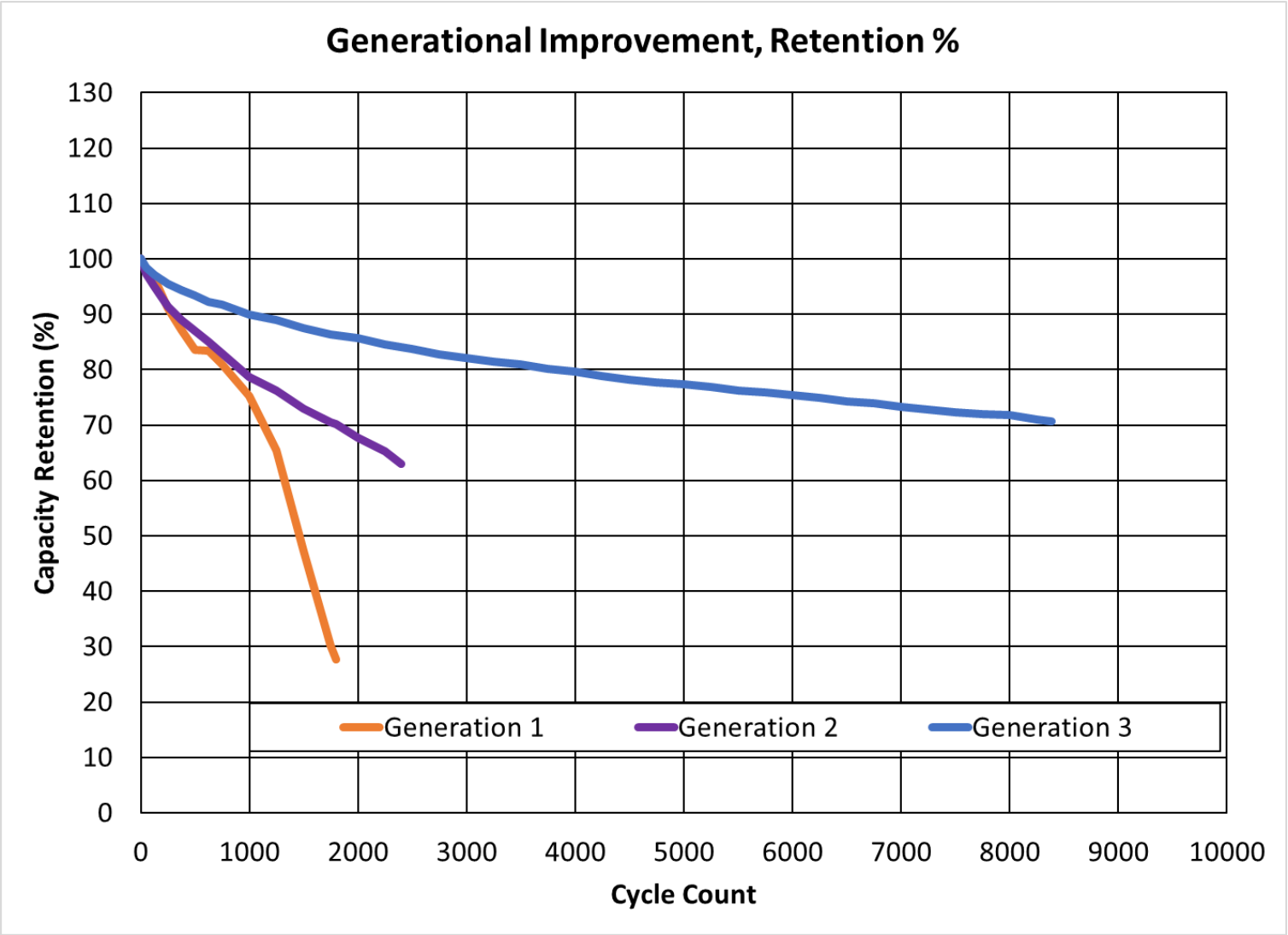
Evolution of GS Yuasa $LiCoO_2$, 100% DOD



	Cell	Nominal BOL Ah Capacity	EoCV	BOL Wh/Kg
Gen1	LSE100	107	3.98	141
Gen2	LSE100	109	3.98	144

Width	Thick	Height*
130	50	208

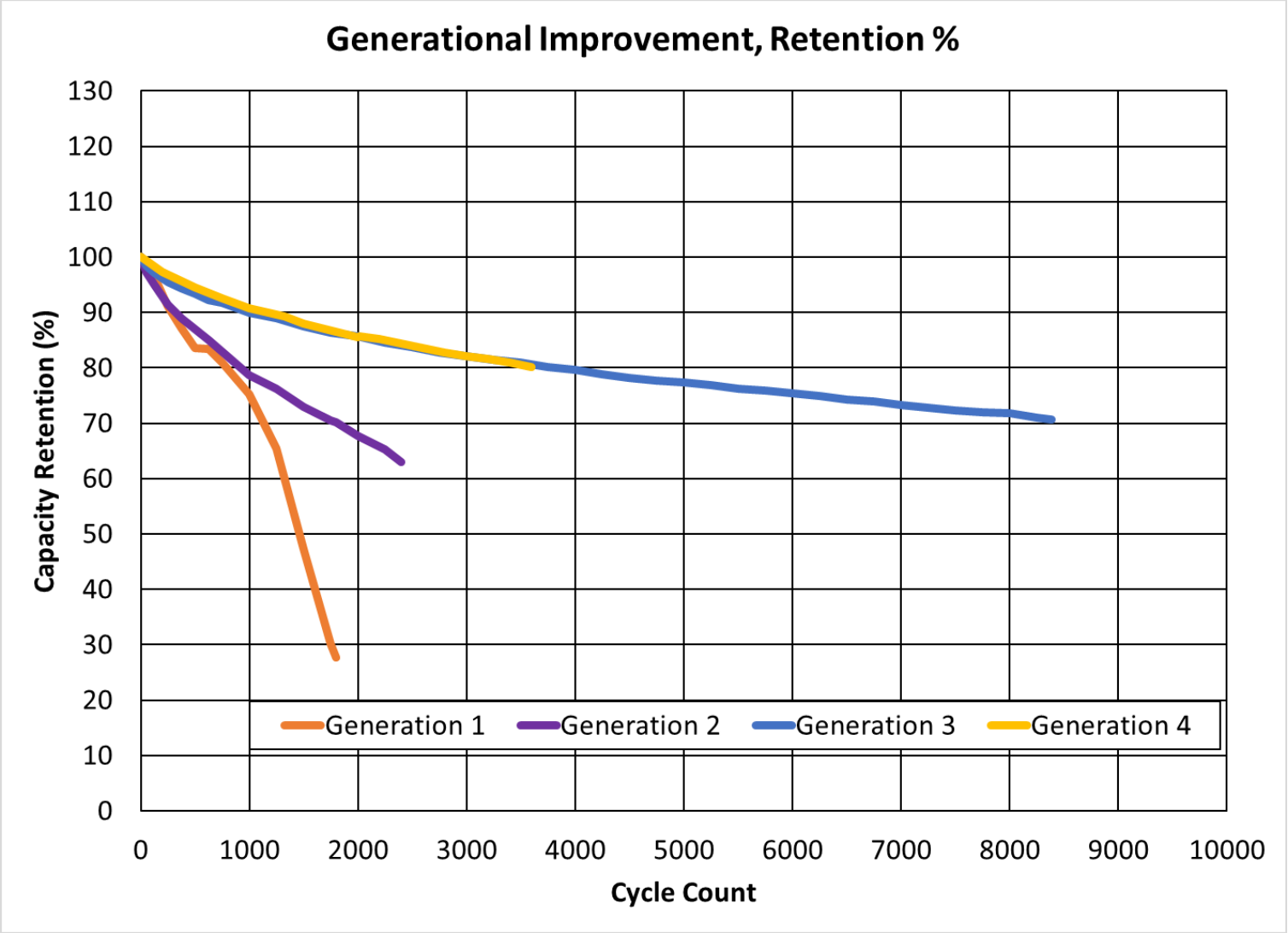
Evolution of GS Yuasa $LiCoO_2$, 100% DOD



	Cell	Nominal BOL Ah Capacity	EoCV	BOL Wh/Kg
Gen1	LSE100	107	3.98	141
Gen2	LSE100	109	3.98	144
Gen3	LSE110	122	4.1	165

Width	Thick	Height*
130	50	208

Evolution of GS Yuasa $LiCoO_2$, 100% DOD



	Cell	Nominal BOL Ah Capacity	EoCV	BOL Wh/Kg
Gen1	LSE100	107	3.98	141
Gen2	LSE100	109	3.98	144
Gen3	LSE110	122	4.1	165
Gen4	LSE120	132	4.1	175

Width	Thick	Height*
130	50	208

Generation 4 Chemistry Improvements, Qualification Status and Cycle Performance

Generation 4 Major Constituent Improvements

		Generation 3	Generation 4	Comments
Positive Electrode	LCO	Heritage LCO	Improved LCO	Increase in energy density
	Binder ratio	Standard	Reduced	Increase in energy density
	Porosity	Standard	Reduced	Increase in energy density, reduction of electrolyte decomposition
Negative Electrode	Binder and ratio	Standard	Improved and reduced	Increase energy density
Separator	Material	Polyolefin	Polyolefin with ceramic coating	Improved capacity retention in high voltage/temperature conditions
	Thickness	Standard	Thinner	Thick in comparison to typical commercial separators, improved high-rate performance and higher energy density
Electrolyte		Standard	Improved	Reduced SEI reaction rate, Maintain superior capacity retention

Generation 4 LCO/Graphite Space Cell

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

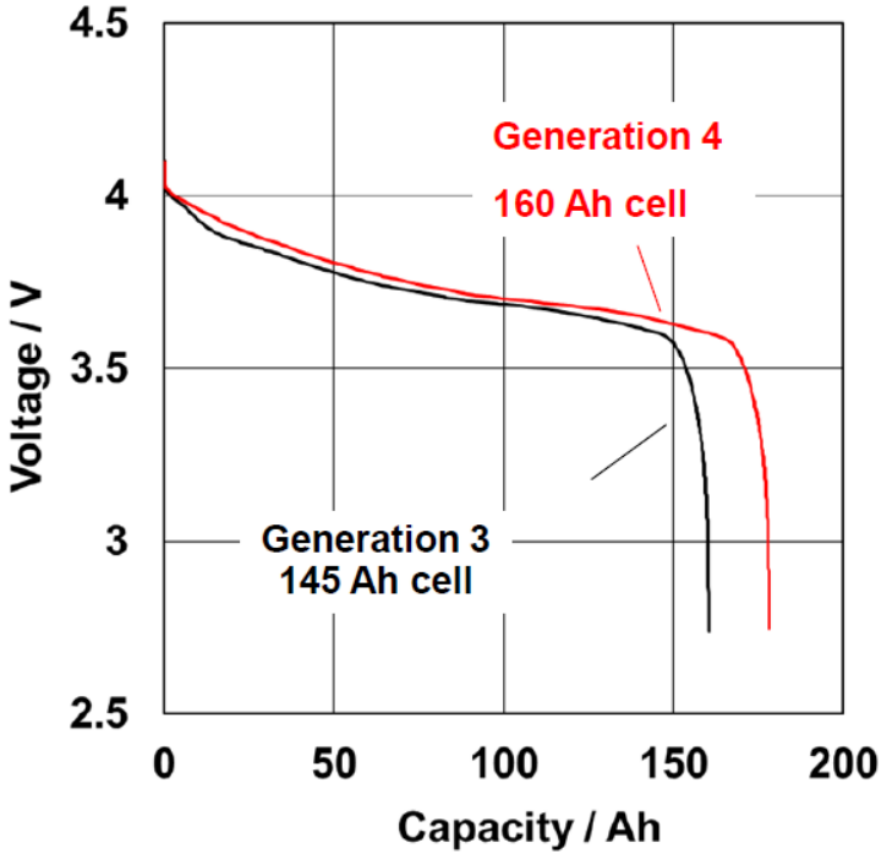
	160 Ah Generation 4	145 Ah Generation 3
Dimensions / mm	H 263* W 130 T 50	H 263* W 130 T 50
EoCV / V	4.10	4.10
Capacity / Ah (Rated) (Actual)	 160 178	 145 161
Discharge Voltage / V	3.72	3.70
Mass / kg	3.69	3.55
Specific energy / Wh/kg	180	168

*Excluding terminal studs

ETS-9 (JAXA)

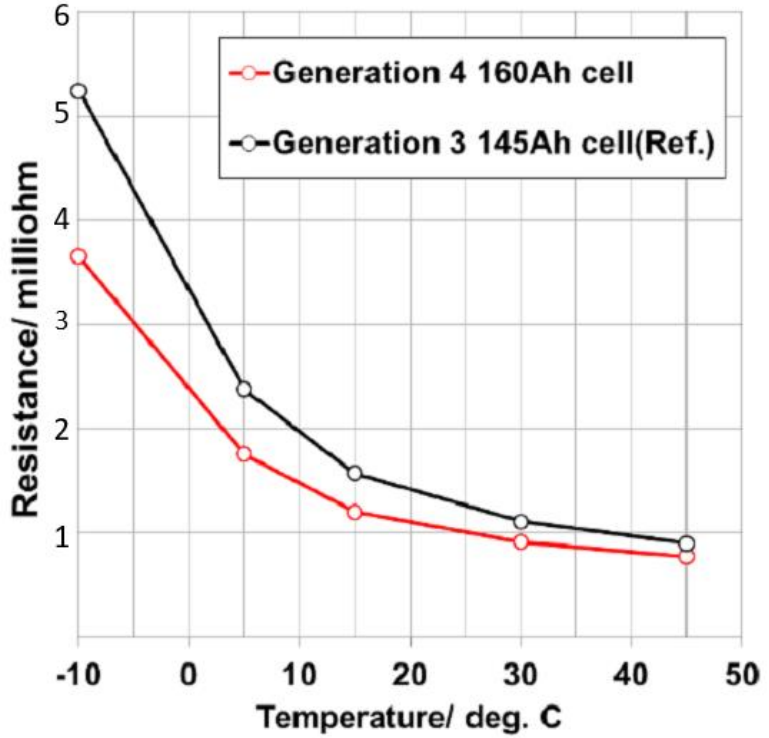
Minimum Design Changes Since 1999; Enhancements Only

Generation 4 Characteristic Improvements



Discharge performance of 160 Ah cells

Charge: 0.2 CA, 4.10 V, CC/CV, 8 h
Discharge: 0.5 CA to 2.75 V
Temperature: 15°C



(b) DC resistance

Gen IV LSE Cell Configurations & Qualification Status

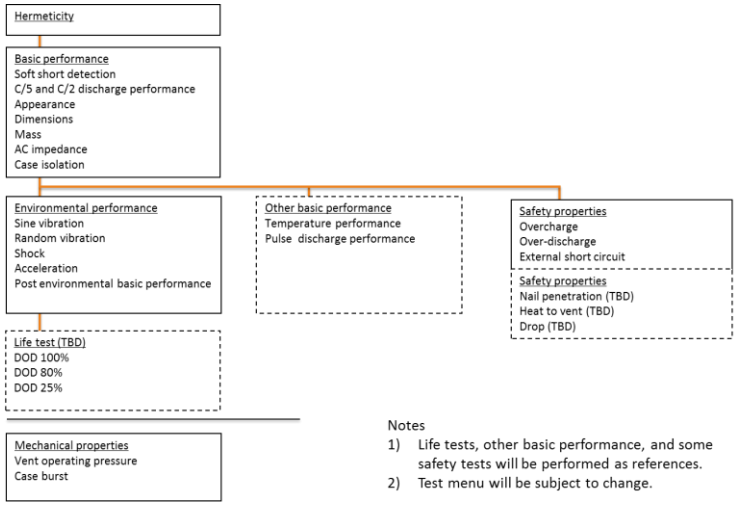
The available LSE cell form factors will remain constant with 5 cell sizes available. GS Yuasa has manufactured >16,000 "LSE" cells for space applications totaling more than >6.2MWh of energy storage for this design.

Naming Convention is the prefix "LSE" followed by the nameplate capacity. All C-rates are in reference to this nameplate capacity.

	Chemistry				Dimensions		
	Gen 3		Gen 4		Width	Thick	Height*
	Energy	Power	Energy	Power			
Cell Configuration	LSE42	LSE38	*TBD*	*TBD*	98	37	151
	LSE55	LSE51	LSE60	LSE56	130	50	123
	LSE110	LSE102	LSE120	LSE112	130	50	208
	LSE145	LSE134	LSE160	LSE147	130	50	263
	LSE190	--	LSE205	*TBD*	165	50	263

Gen IV LSE Cell Configurations & Qualification Status

- Configuration Qualified
- Configuration Qualified, QT data property of US Government
- Qualification by Similarity
- Engineering model cells on test



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

	Chemistry				Dimensions		
	Gen 3		Gen 4		Width	Thick	Height*
	Energy	Power	Energy	Power			
Cell Configuration	LSE42	LSE38	*TBD*	*TBD*	98	37	151
	LSE55	LSE51	LSE60	LSE56	130	50	123
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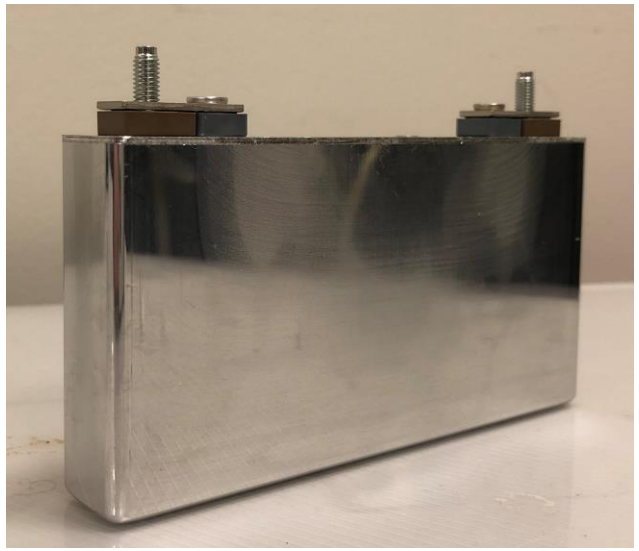
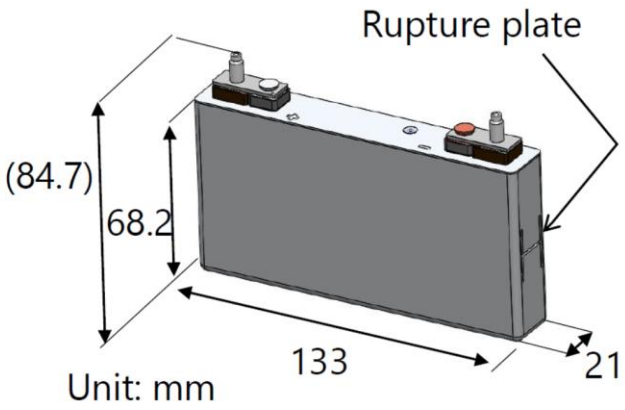
LSE12x -- New 12Ah Form Factor for Space Applications





ITEM	Spec
Chemistry	Gen. 4
Electrode	Power Type
BOL Capacity (Ah)	13.6
Nameplate Capacity (Ah)	12
Nominal Discharge Voltage (V)	3.75
Mass (Kg)	0.39
DCR (mOhm)	<8.0

- Cost competitive smaller form factor cells.
  - Mechanical components influenced by existing qualified commercial automotive and aviation cell designs.
- Utilizing GS Yuasa's Generation 4 Chemistry with 100% configuration management control and superior electrical performance of the traditional LSE cells.
- Targeting small LEO/GEO spacecraft, & human rated missions.
- Cell qualification testing to complete by Q4 2021

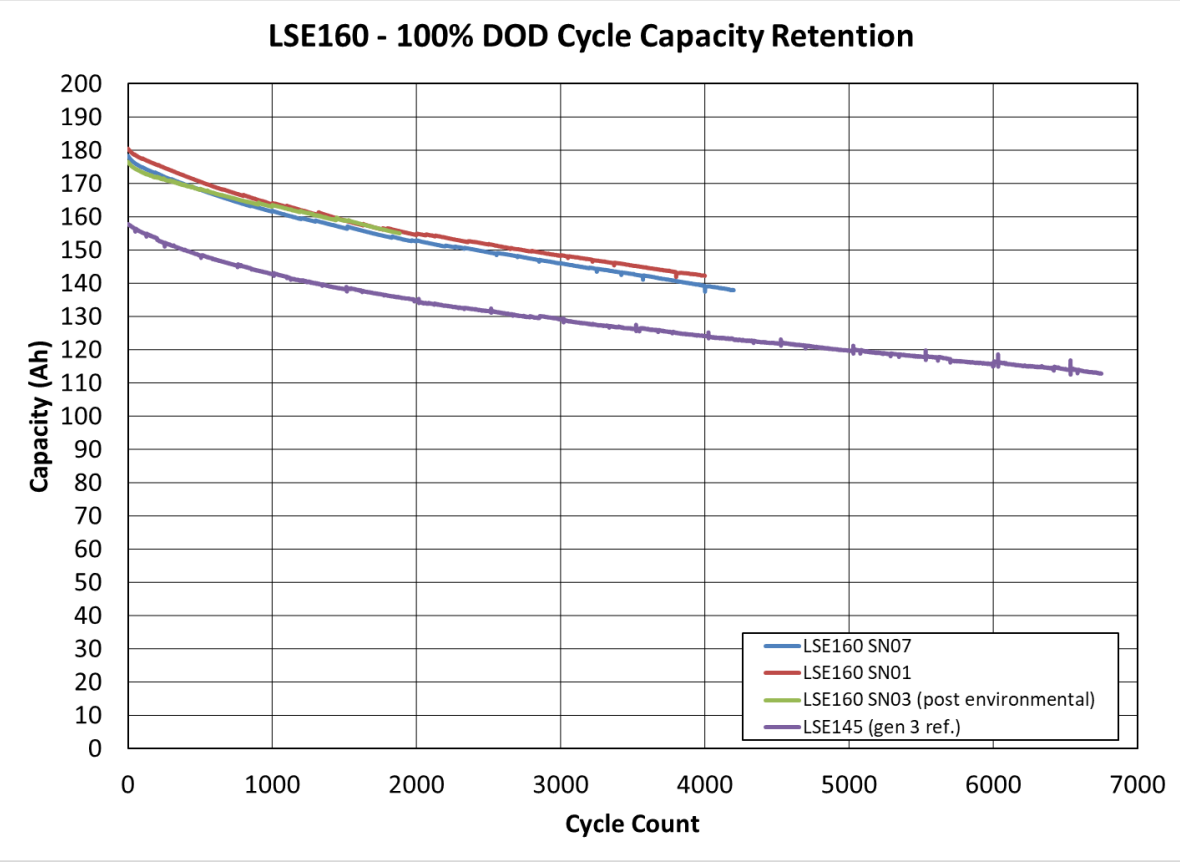
Generation 4 Life Testing

Test Name.	Cell Type	Test Conditions						Ambient Test Temp	Number of Cycles	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition					
		EoCV	Rate	Time	EoDV	Rate	Time			
Energy Cell Testing										
100% DoD Cycling	LSE160	4.10V	80A	4.0hr	2.75V	100A	N/A	25°C	4,200	
80% DOD GEO	LSE160	4.10V	32A	10.8hr	N/A	107A	1.2hr	15°C	1,900	Cont. Deep DoD GEO Cycle
60% DoD GEO	LSE160	4.10V	32A	10.8hr	N/A	80A	1.2hr	15°C	1,587	Nominal DoD GEO Cycle
40% DoD LEO	LSE160	4.10V	80A	1.0hr	N/A	120A	0.53Hr	15°C	12,264	Deep DOD LEO Cycle
25% DoD LEO	LSE160	4.10V	48A	1.0hr	N/A	80A	0.5Hr	15°C	12,275	Nominal DOD LEO Cycle
Power Cell Testing										
100% DoD Cycling	LSE112	4.10V	56A	4.0hr	2.75V	100A	N/A	25°C	2000+	
40% DoD LEO	LSE112	4.10V	56A	1.0hr	N/A	89.6A	0.5hr	20°C	8,250+	Deep LEO Cycle
60% and 70% DoD LEO	LSE12x	4.10V	Various	1.0Hr	N/A	Various	0.5hr	15°C	500+	Ultra Deep DOD LEO Cycling

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

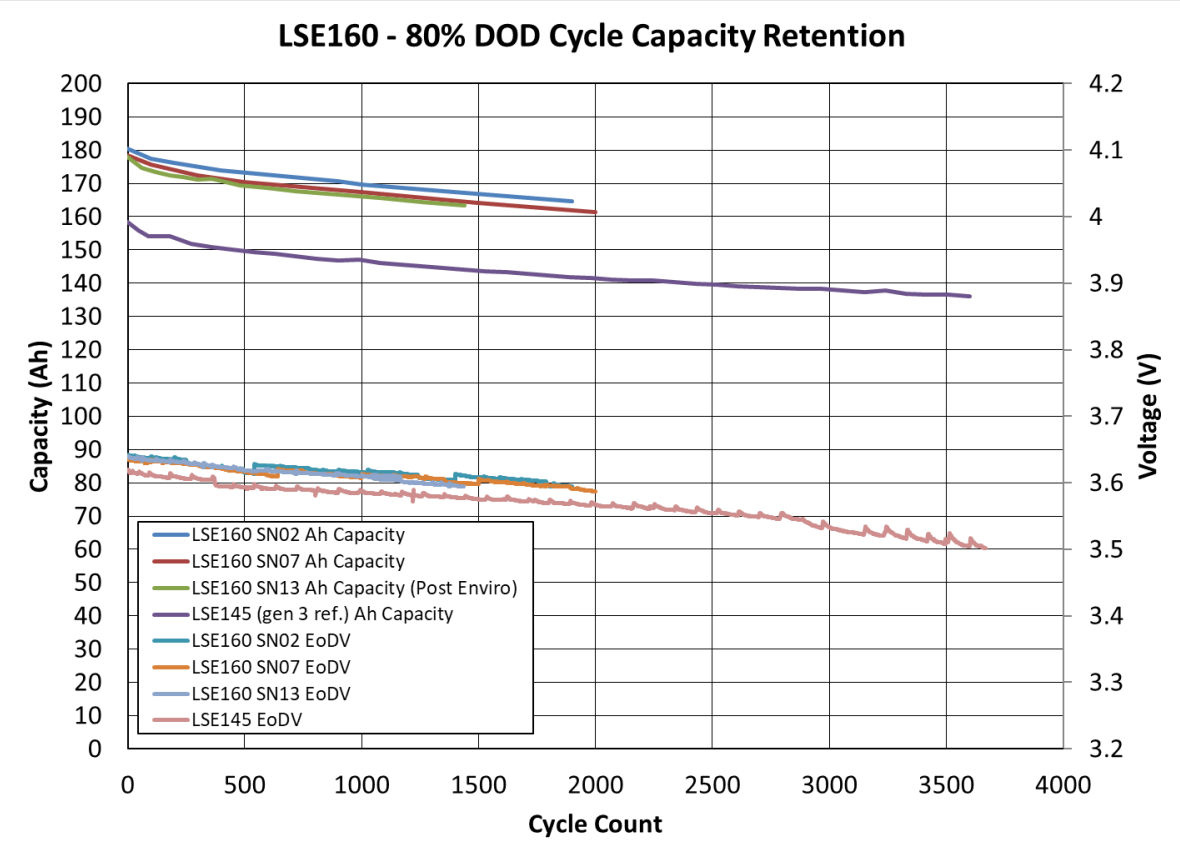
LSE160 – 100% DOD Cycle Life

Test Name	Cell Type	Test Conditions						Ambient Test Temp	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition				
		EoCV	Rate	Time	EoDV	Rate	Time		
100% DoD Cycling	LSE160	4.10V	80A (0.5C)	4hr	2.75V	100A	N/A	25°C	4000+ cycles complete



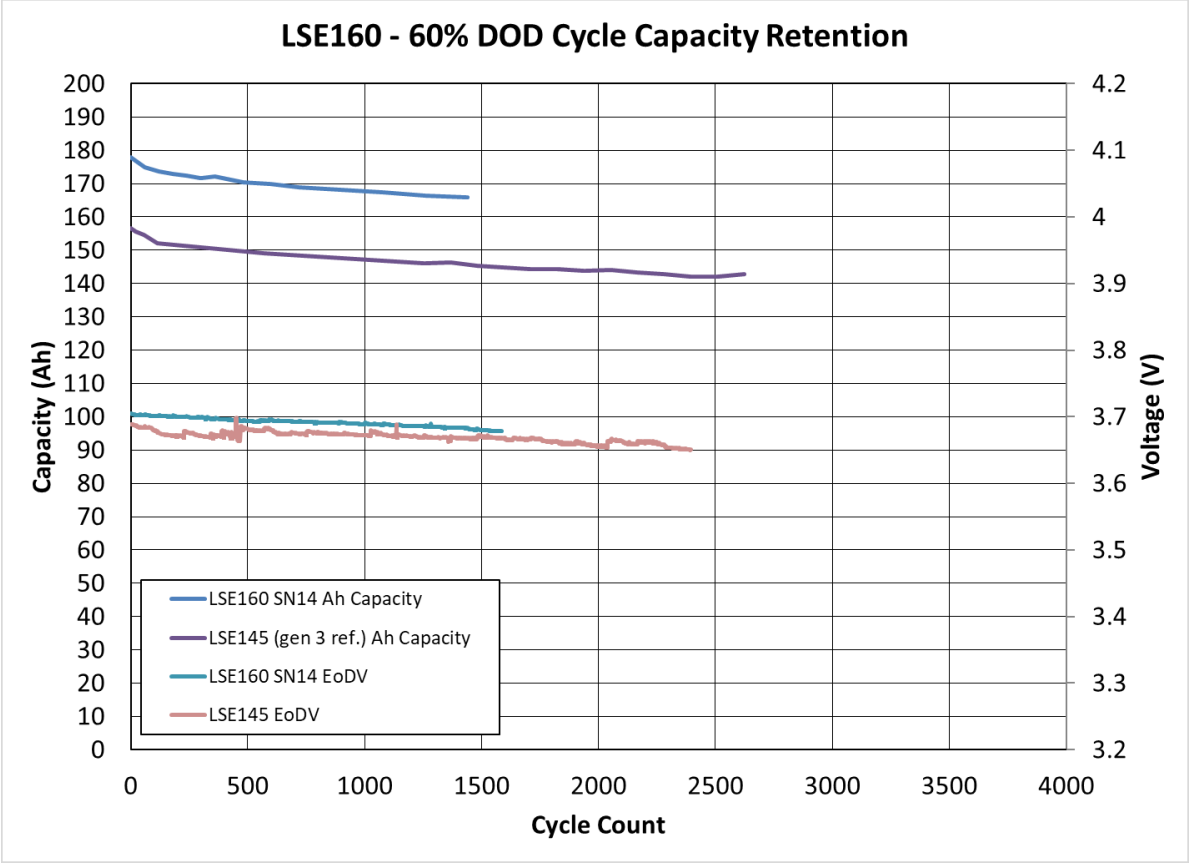
LSE160 – 80% DOD Cycle Life

Test Name	Cell Type	Test Conditions						Ambient Test Temp	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition				
		EoCV	Rate	Time	EoDV	Rate	Time		
80% DOD Cycling	LSE160	4.10V	32A (0.2C)	10.8hr	N/A	107A (0.67C)	1.2hr	15°C	1,900+ Cycles complete



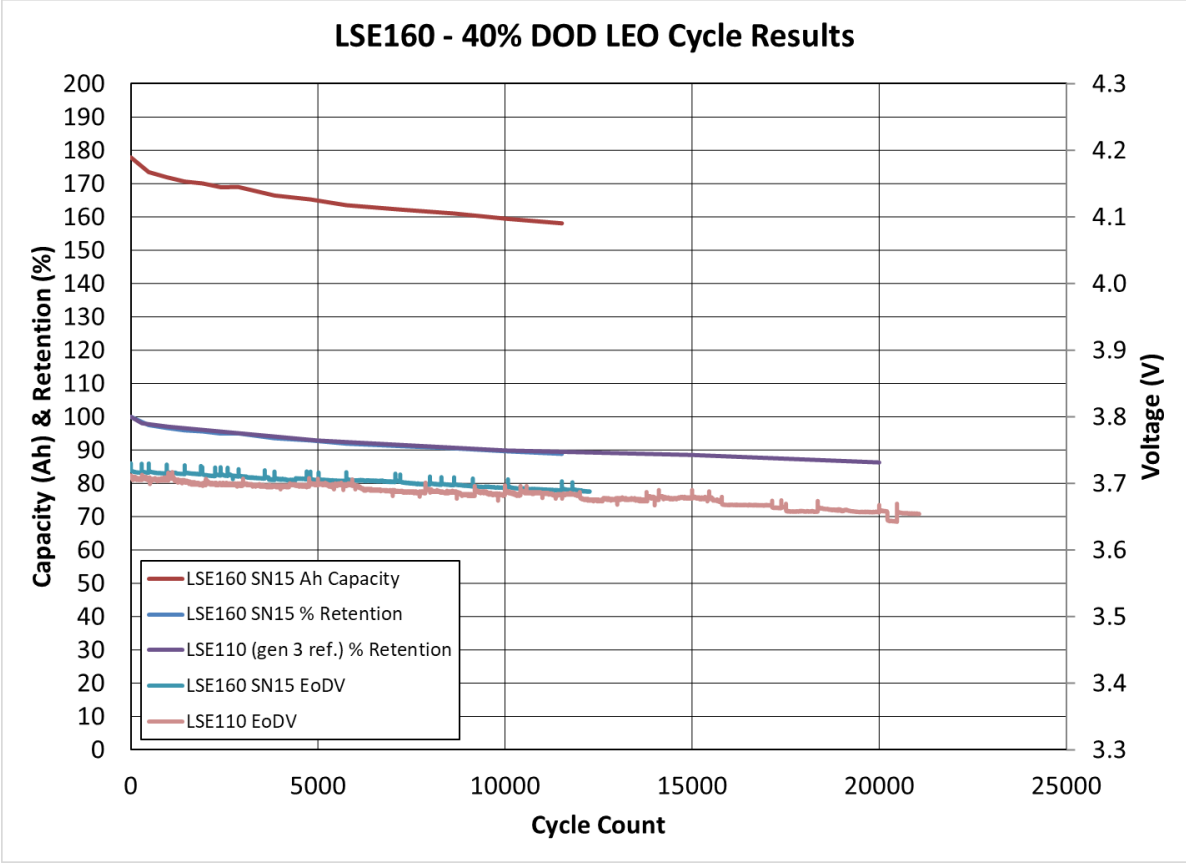
LSE160 – 60% DOD Cycle Life

Test Name	Cell Type	Test Conditions						Ambient Test Temp	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition				
		EoCV	Rate	Time	EoDV	Rate	Time		
60% DoD Cycling	LSE160	4.10V	32A (0.5C)	10.8hr	N/A	80A (0.5C)	1.2hr	15°C	1,587



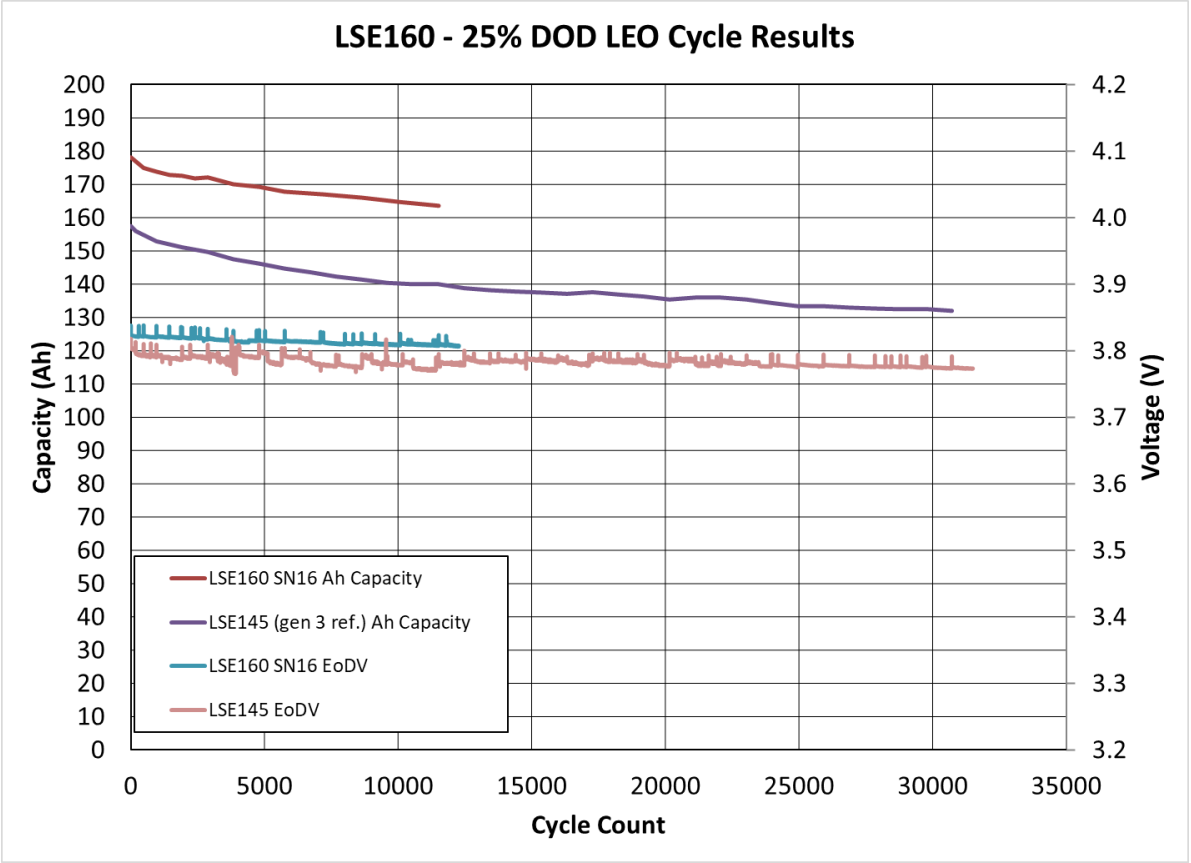
LSE160 – 40% DOD Cycle Life

Test Name	Cell Type	Test Conditions						Ambient Test Temp	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition				
		EoCV	Rate	Time	EoDV	Rate	Time		
40% DoD LEO	LSE160	4.10V	80A (0.5C)	1.0hr	N/A	120A (0.75C)	0.53Hr	15°C	12,264



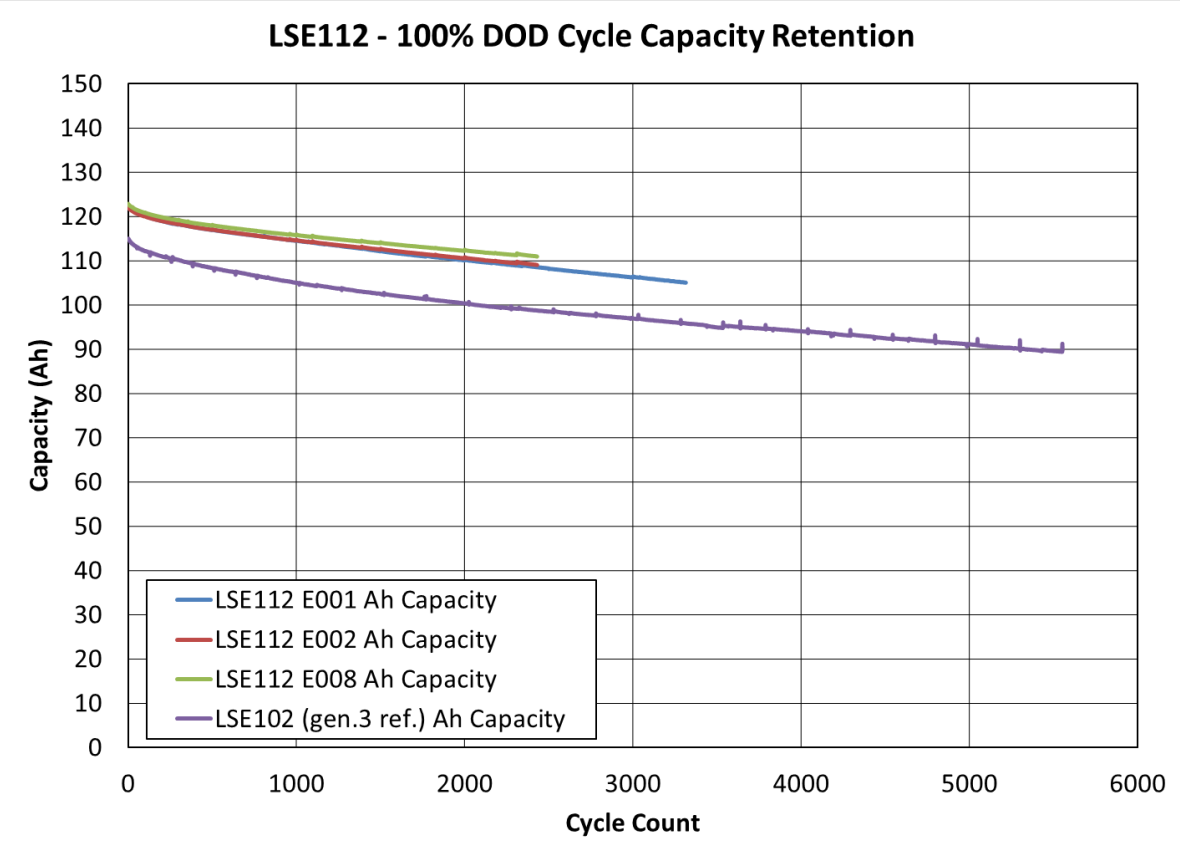
LSE160 – 25% DOD Cycle Life

Test Name	Cell Type	Test Conditions						Ambient Test Temp	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition				
		EoCV	Rate	Time	EoDV	Rate	Time		
25% DoD LEO	LSE160	4.10V	48A (0.3C)	1.0hr	N/A	80A (0.5C)	0.5Hr	15°C	12,275



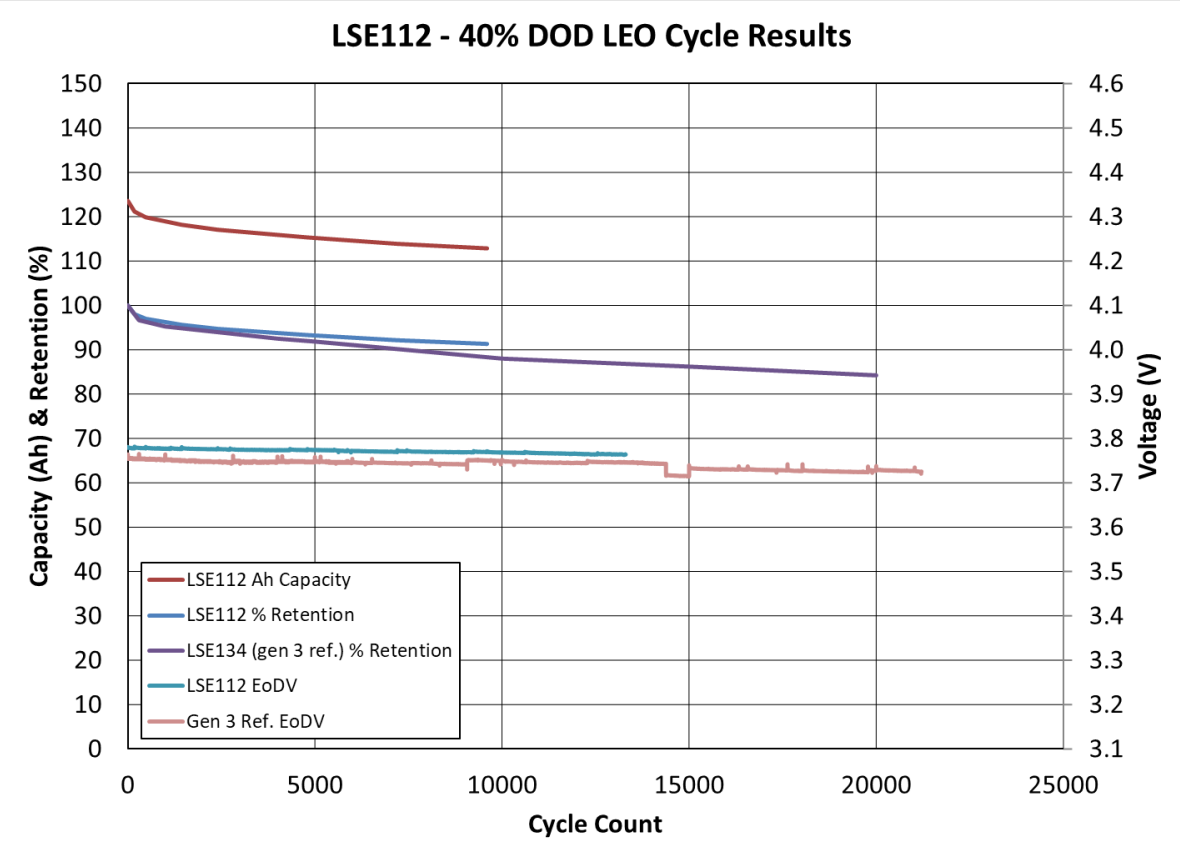
LSE112 – 100% DOD Cycle Life

Test Name	Cell Type	Test Conditions						Ambient Test Temp	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition				
		EoCV	Rate	Time	EoDV	Rate	Time		
100% DoD Cycling	LSE112	4.10V	56A (0.5C)	4.0hr	2.75V	100A	N/A	25°C	2000+



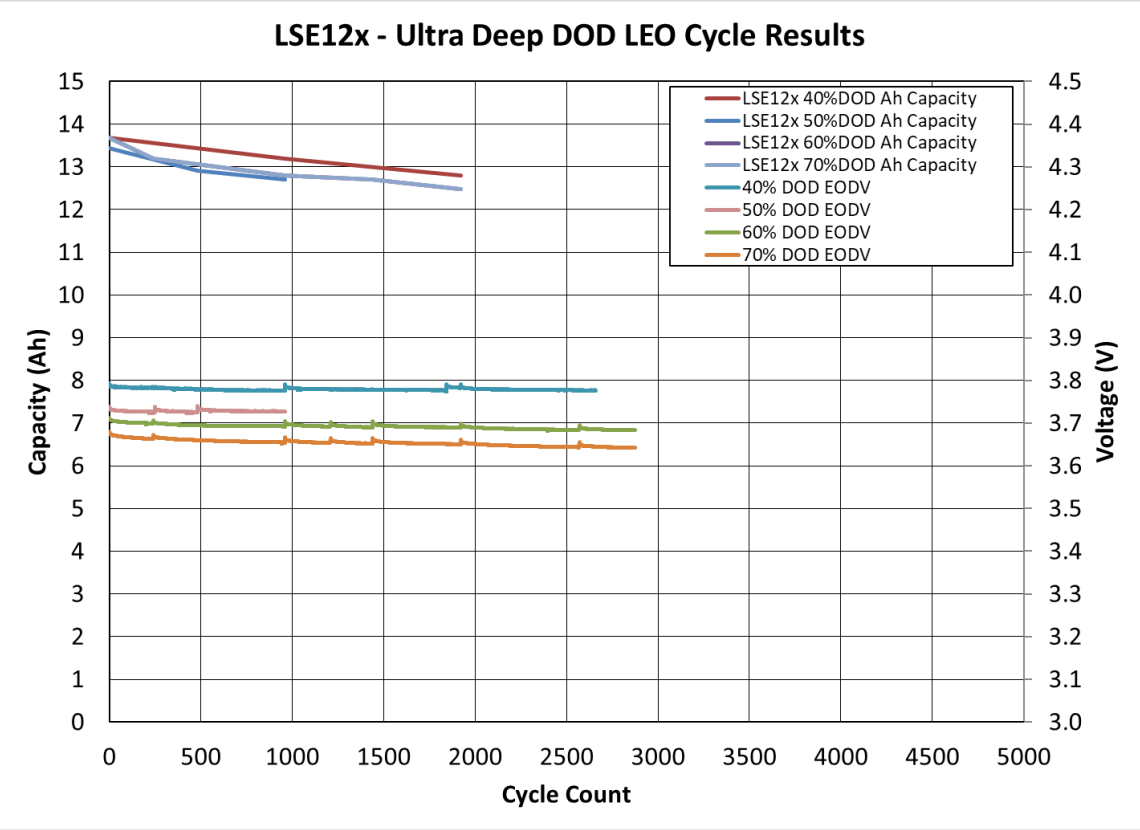
LSE112 – 40% DOD Cycle Life

Test Name	Cell Type	Test Conditions						Ambient Test Temp	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition				
		EoCV	Rate	Time	EoDV	Rate	Time		
40% DoD Cycling	LSE112	4.10V	56A (0.5C)	1.0hr	N/A	89.6A (0.8C)	0.5hr	20°C	8,250+



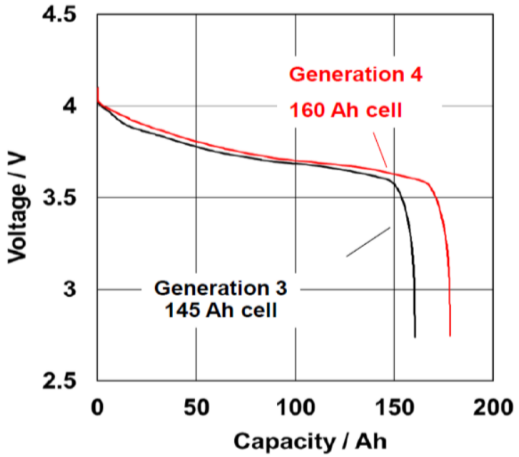
LSE12x – Ultra High DOD LEO Cycle Tests

Test Name	Cell Type	Test Conditions						Ambient Test Temp	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition				
		EoCV	Rate	Time	EoDV	Rate	Time		
40%, 50%, 60%, & 70% DoD LEO	LSE12x	4.1V	Various	1.0Hr	N/A	Various	0.5hr	15°C	Ultra high DOD LEO Cycle



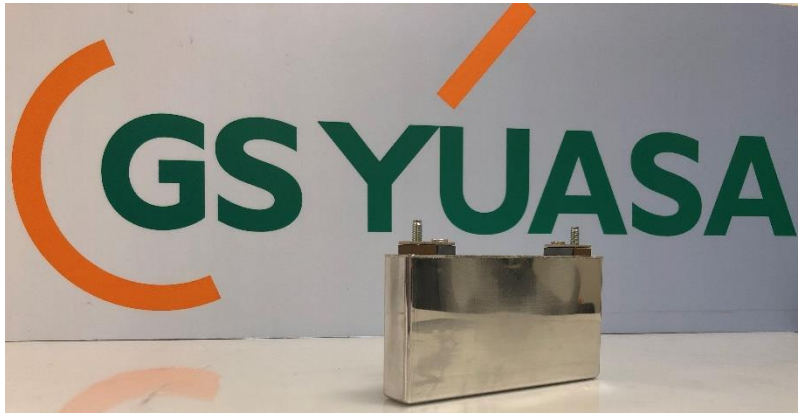
Cycle	Discharge	Charge
40%DOD	0.8C (9.6A) for 0.5hr	0.5C, 4.10V, CC/CV, 1hr
50%DOD	1.0C (12.0A) for 0.5hr	0.6C, 4.10V, CC/CV, 1hr
60%DOD	1.2C (14.4A) for 0.5hr	0.7C, 4.10V, CC/CV, 1hr
70%DOD	1.4C (16.8A) for 0.5hr	0.8C, 4.10V, CC/CV, 1hr

- GS Yuasa's Generation 4 LCO/Graphite chemistry for space completed qualification in 2018.
  - Increased Energy density (~10% from Gen.3 at same EOCV)
  - Decreased DCR
  - Excellent Capacity Retention under demanding cycle conditions



- Successful integration into LSE cell form factors complete
  - Energy and Power electrode optimizations available
  - LSE160 and LSE205 energy cells have completed formal qualification
  - LSE112 power cell ready for qualification (Pre-QT cells complete and under test)

- New 12Ah small form factor cell added to line-up
  - Cell qualification occurring now.
  - Scalable battery designed and built by GYLP in Roswell, Ga.



Thank You For Your Attention

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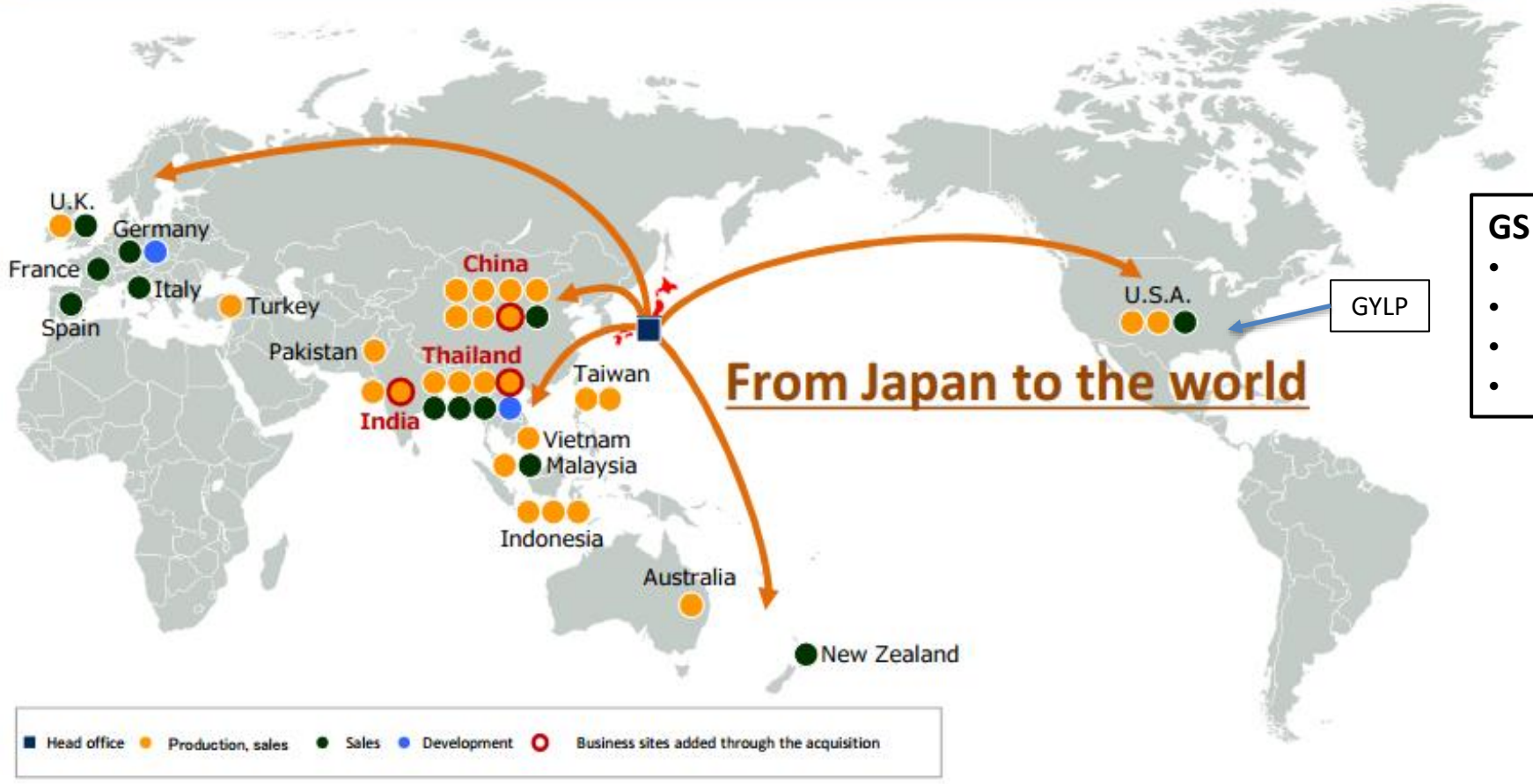
37 affiliates in 17 countries.



GS YUASA CORPORATE HIGHLIGHTS

- Celebrated 100th anniversary in 2017
- Consolidated FY2019 Net Sales: $3.7B
- 37 affiliates in 17 countries
- 14,585 employees worldwide