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

2023 Space Power Workshop

April 25-27, 2023

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GS Yuasa Company Overview

GS YUASA

GS (Japan Storage Battery)

Inventor's spirit
contribute to society by developing high quality products

Founder of Japan Storage Battery Co., Ltd.
Genzo Shimadzu

Contributing to the steady supply of electric power and the development of public infrastructure

1900s
Manufacture of large-capacity storage batteries for auxiliary power

YUASA (Yuasa Corporation)

Challenging spirit
develop new businesses ahead of time

Founder of Yuasa Storage Battery Co., Ltd.
Shichizaemon Yuasa

Contributing to the development of the automotive industry

1910s
Manufacture of automotive lead-acid batteries

2004 Corporate Merger

Ushering in a new EV era

2000s
Supply of lithium-ion batteries for the i-MiEV, the world's first mass-produced EV

2010s
Supply of lithium-ion batteries for PHEVs to Mitsubishi Motors Corporation

Mitsubishi Motors "Eclipse Cross PHEV"

Honda "FIT HYBRID"

Contributing to electrification of Japanese automakers

2010s
Supply of lithium-ion batteries for HEVs to Honda Motor Co.,Ltd.

TOYOTA "Harrier"

2020s
Supply of lithium-ion batteries for HEVs to Toyota Motor Corporation

Contributing to the promotion of clean energy

2000s
Development of renewable energy storage systems

Contributing to the realization of decarbonized society

2020s
Delivery of a world-class storage battery facility for wind power generation

Supporting the development of aircrafts

2000s
Receiving orders of lithium-ion battery system for Boeing 787 in the U.S.

Support safety from deep sea to outer space under harsh conditions

2010s
Installation of lithium-ion batteries on the International Space Station

2010s
Mass production of Japan's first lithium-ion batteries for submarines

For the next 100 years

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GS Yuasa Aerospace and Specialty Battery Groups

GS Yuasa Technology Ltd. “GYT”

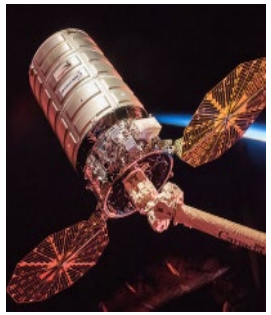
- Research, development, manufacturing, test, and sales of specialty cells and batteries for:
  - Aerospace
  - Undersea
  - Defense and Security
- ISO9001 & JISQ9100 certified
- Headquarters and located in Kyoto, Japan

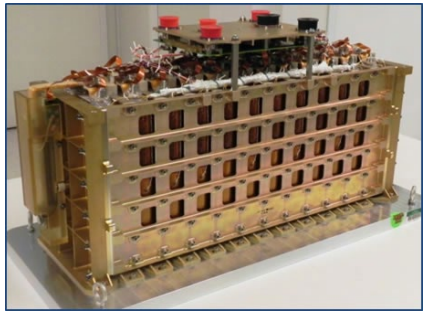
GS Yuasa Lithium Power, Inc. “GYLP”

- Primary channel for GS Yuasa Li-ion energy storage technologies and solutions for North American aerospace and defense applications.
- Engineering, sales, service, manufacturing, program management, logistics and export compliance
- ISO9001 & AS9100 certified
- Incorporated in the state of Georgia, US Company










防衛省 MINISTRY OF DEFENSE

RECIPROCAL DEFENSE PROCUREMENT MOU

June 2016, extended through June 2031

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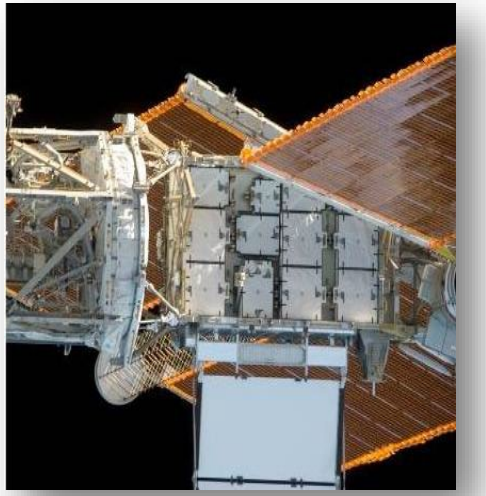
GS Yuasa LSE Li-ion Cell for Space
Overview

GS Yuasa Space Flight Heritage Update

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



Number of satellites…….……	234+
– LEO/MEO……..	108+
– GEO……	124
– Interplanetary……	2+
1st satellite on-orbit……..…	Servis 1 (30 Oct. 2003)
Longest satellite on-orbit (yrs)….....	>18yr (IPSTAR, 11 Aug. 2005) still operational
Li-ion Watt-hours flown in space….....	>4.69 MWh (world leader)
Cell-hours flown in space……..	>573 million hours
Space cell qualification programs…….	>27
Cell sizes (Ah) flown….....	35; 50; 55; 100; 102; 110; 134; 145; 175; 190; 200
Performance to date…….....	No failures
Backlog (Wh)……..……	>1.20 MWh

Launch vehicles & number of satellites

Ariane-5ECA	51	Soyuz-STB Fregat-MT	17	Epsilon	6
Falcon 9	27	Antares 120, 230, 230+	15	Zenit-3	5
H-2A-20x	28	H-2B-304	13	Others	10
Proton-M Briz-M	29	Atlas 5 (401)	7		
Soyuz	27	Atlas 5 (421,431,551)	6		

Metrics updated February 2023

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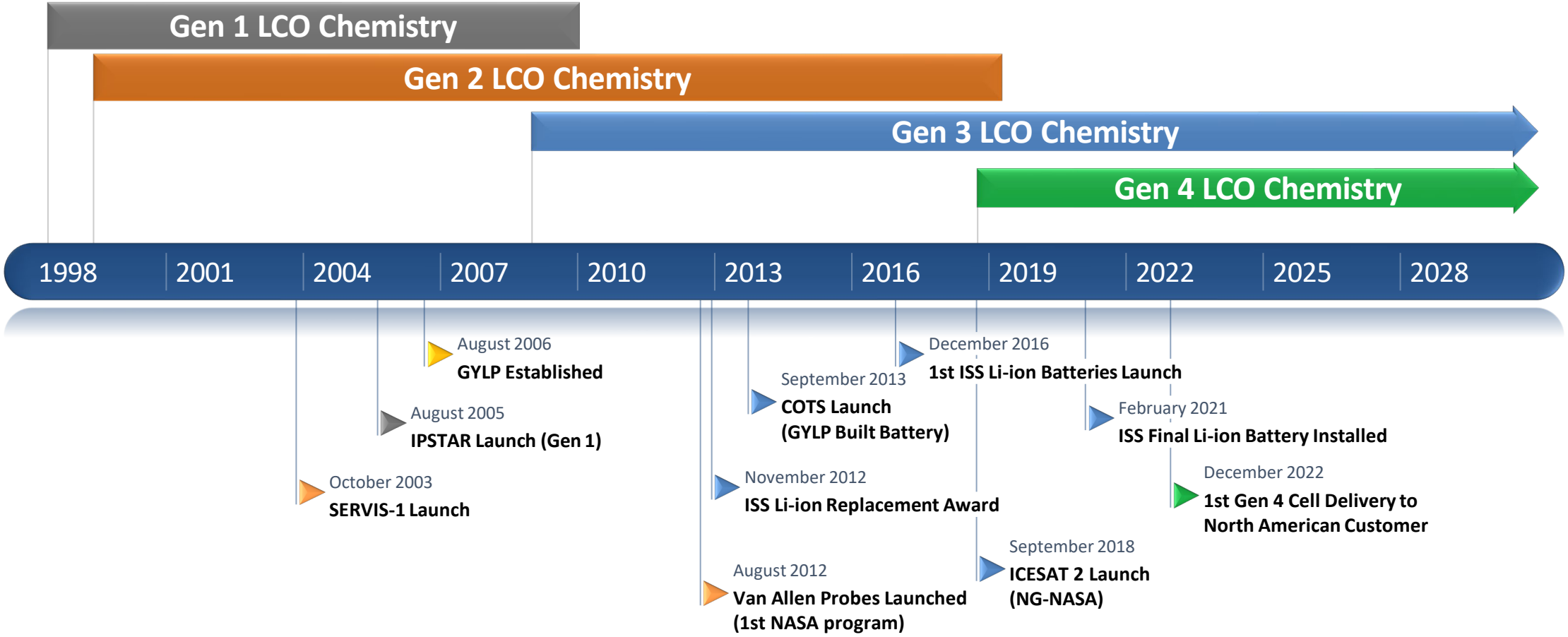
Timeline of GS Yuasa Space Chemistry



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.

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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

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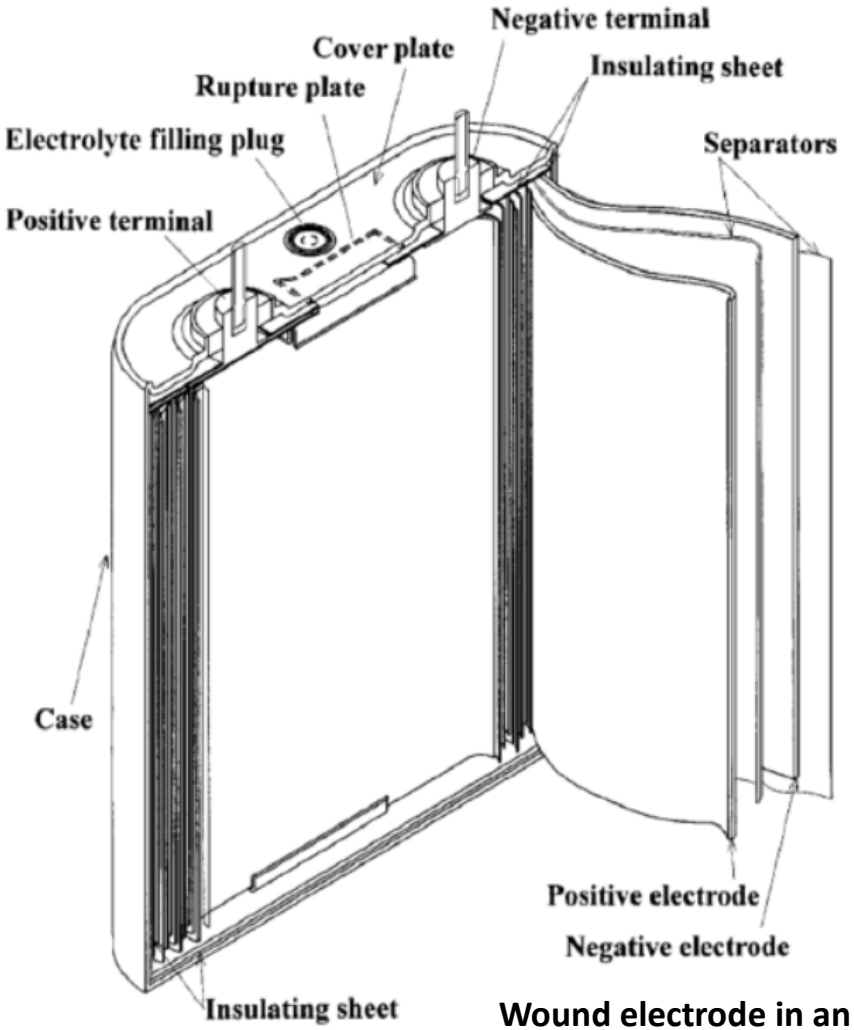
LSE Cell Basic Shape

Over 25 years of outstanding performance



Wound electrode in an elliptical cylindrical case

The LSE cell portfolio consists of various sizes of Li-ion cells.
All cells share the same primary features: Al-case, wound-prismatic construction, ceramic terminals, LCO chemistry. All are manufactured in Kyoto, Japan on the same equipment and using the same basic processes. The portfolio can be viewed as a single fundamental cell technology, configurable in height, width and thickness.

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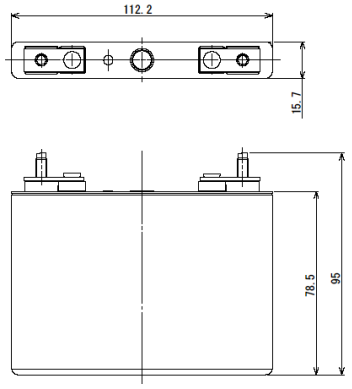
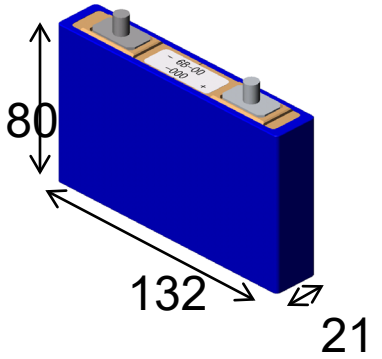
LSE12x Cell Case

Fusion of Aviation and Automotive Cells

Blue Energy

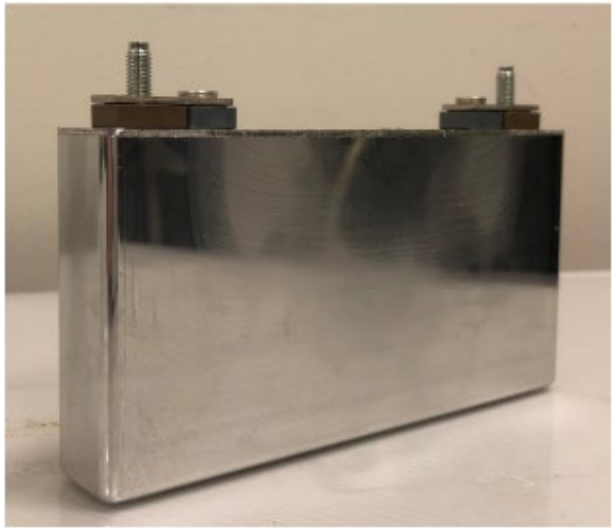
- EH5 Ultra high power cell for Honda/Acura hybrids

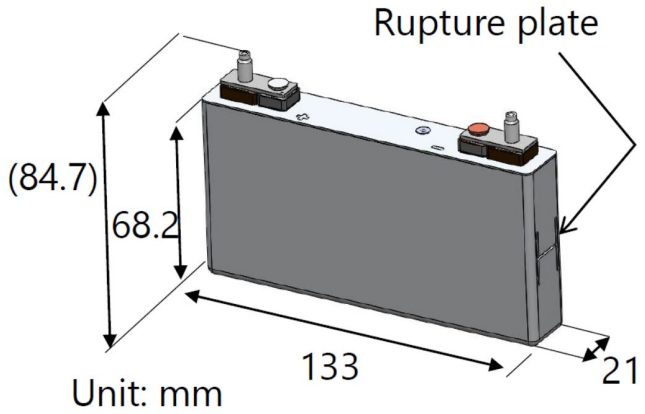




- LVP10 Cell for Aviation Applications

株式会社 ジーエス・ユアサ テクノロジー
GS Yuasa Technology Ltd.





- Inspired by mature commercial cell designs; Enhanced for space
  - Case neutral design
  - Radiation hardened
  - Hermetically sealed
- Power optimized Gen 4 chemistry suitable for all space vehicles

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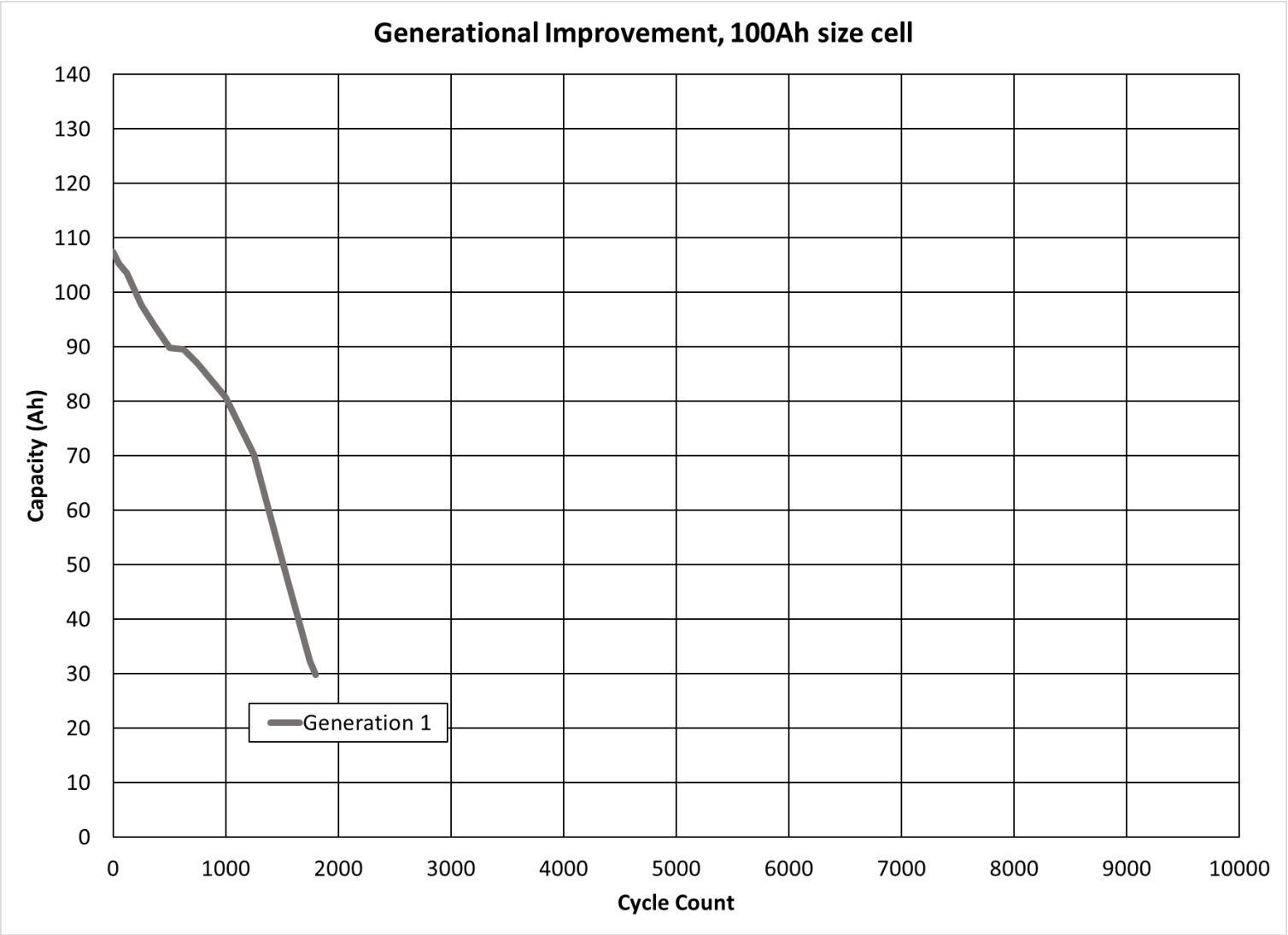
Evolution of GS Yuasa $LiCoO_2$, 100% DOD

100Ah Class Cell, Energy Type



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

Width	Thick	Height*
130	50	208

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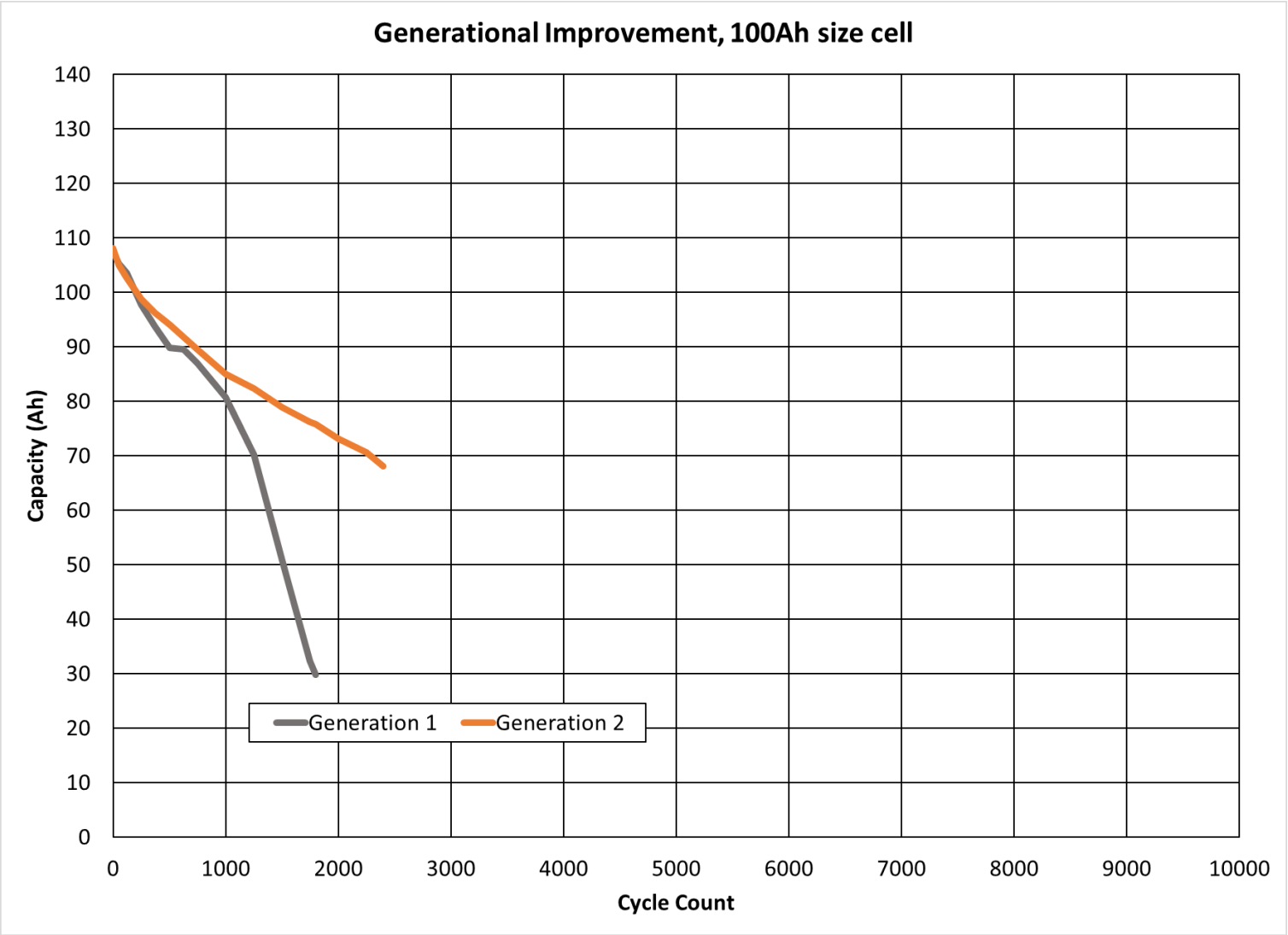
Evolution of GS Yuasa $LiCoO_2$, 100% DOD

100Ah Class Cell, Energy Type



	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

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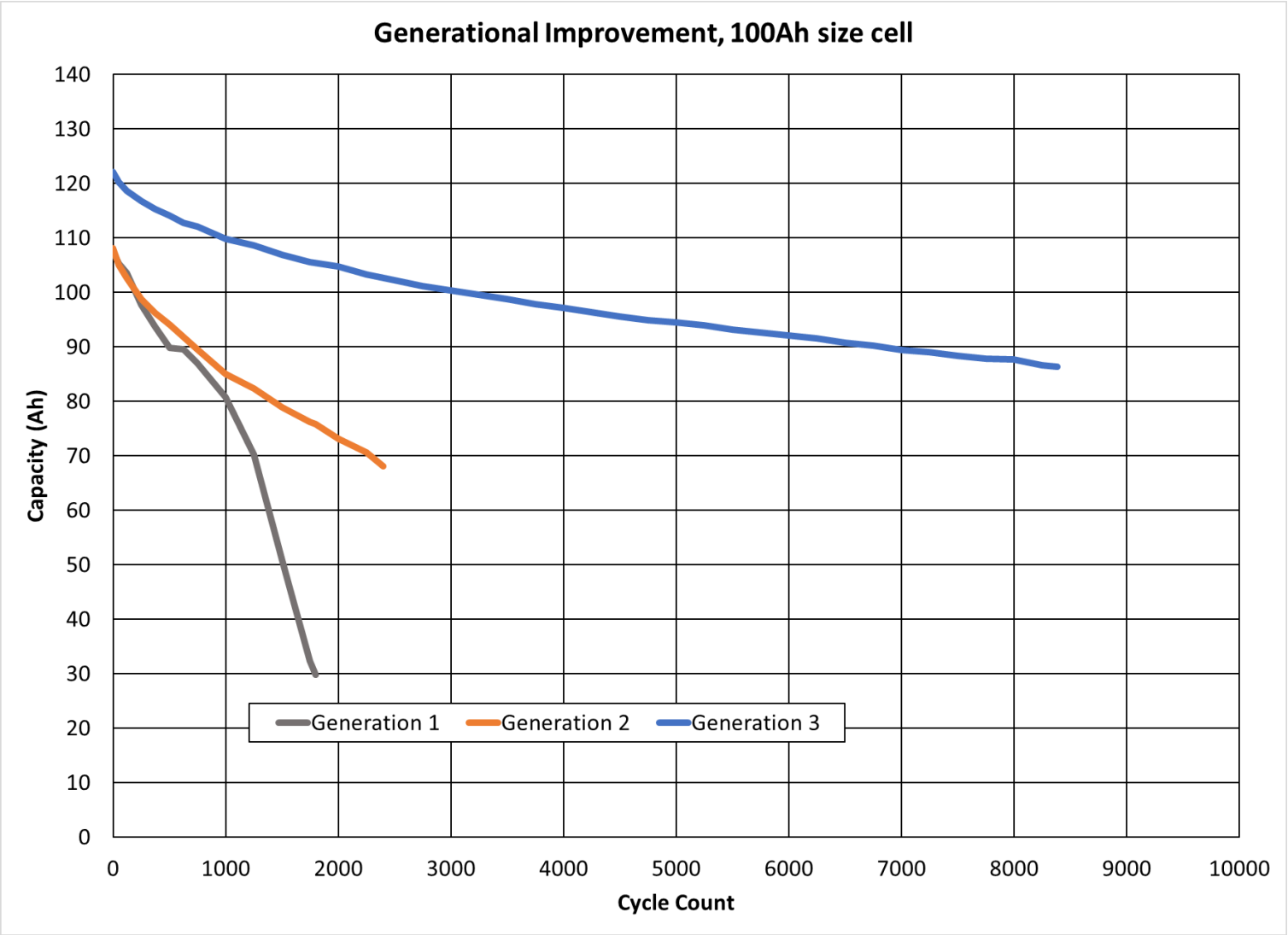
Evolution of GS Yuasa $LiCoO_2$, 100% DOD

100Ah Class Cell, Energy Type



	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*
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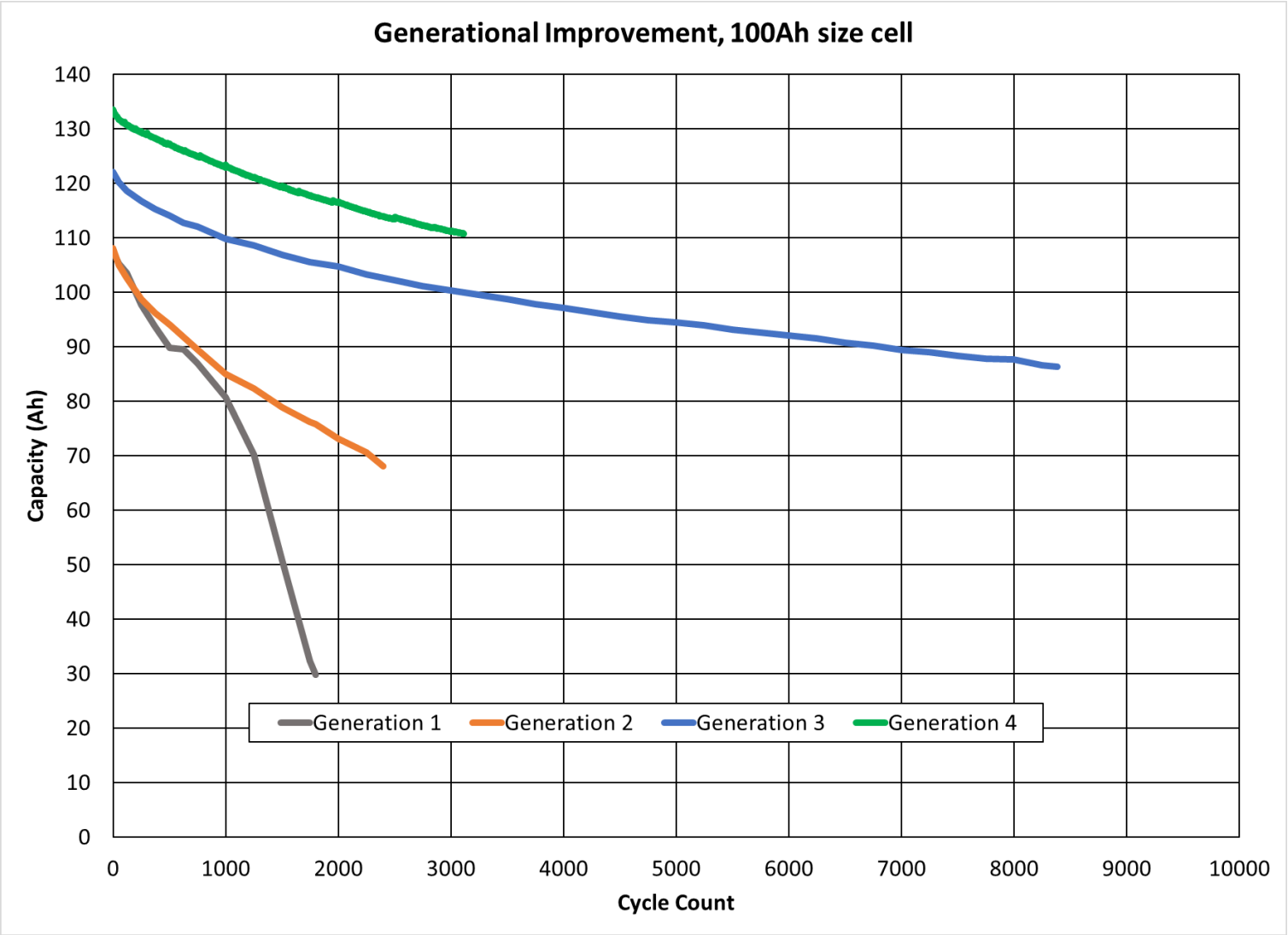
Evolution of GS Yuasa $LiCoO_2$, 100% DOD

100Ah Class Cell, Energy Type



	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	LSE122	132	4.1	175

Width	Thick	Height*
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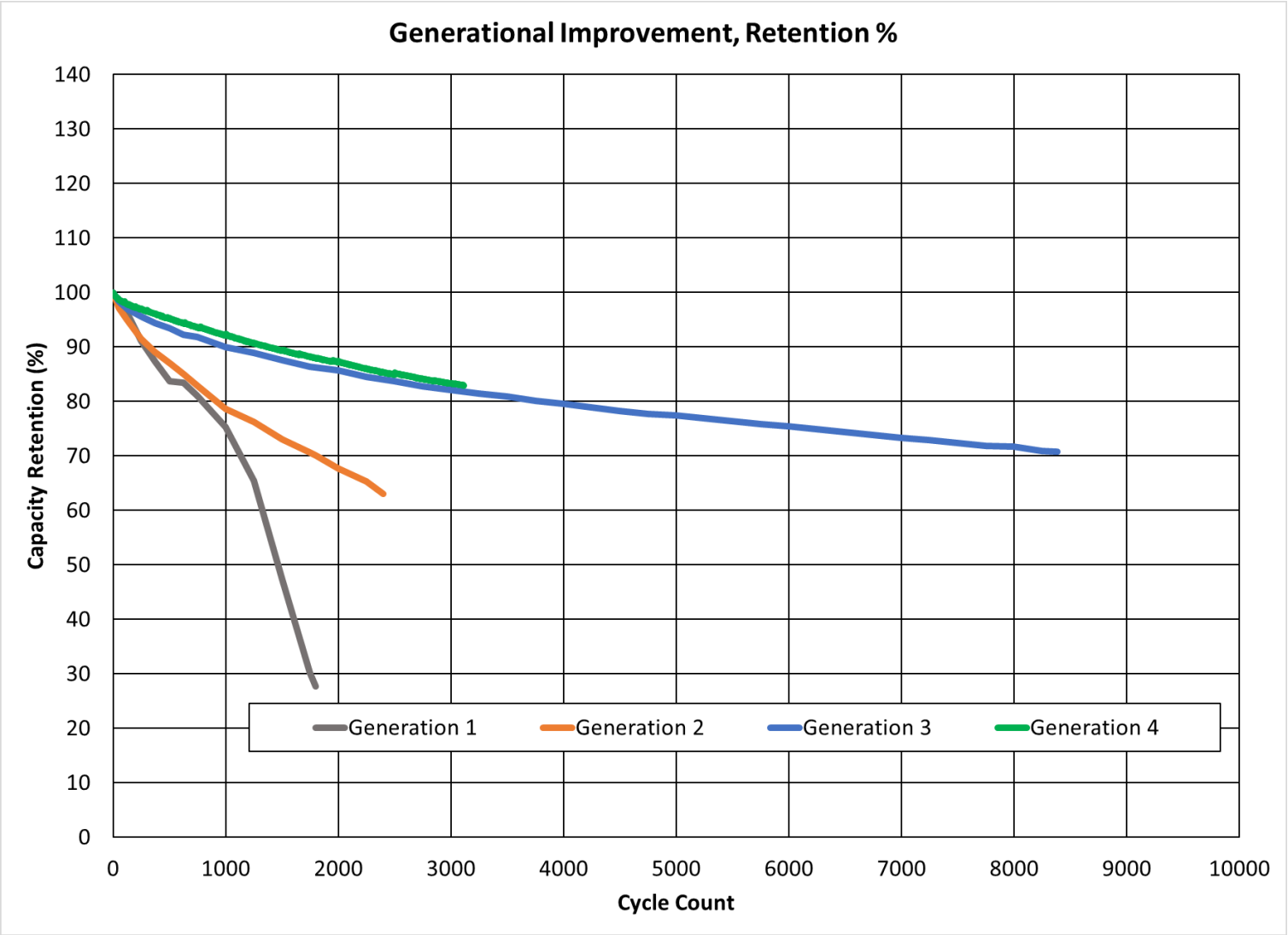
Evolution of GS Yuasa $LiCoO_2$, 100% DOD

100Ah Class Cell, Energy Type



	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	LSE122	132	4.1	175

Width	Thick	Height*
130	50	208

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Generation 4
Qualification Status and Life Performance

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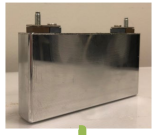
Gen IV LSE Cell Configurations & Qualification Status

The available LSE cell form factors will remain constant with 5 cell sizes available. GS Yuasa has manufactured >17,000 “LSE” cells for space applications totaling more than >6.85MWh 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				LSE12x	133	21	68.2
	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

*not including terminal posts

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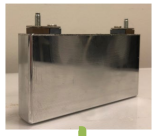
Gen IV LSE Cell Configurations & Qualification Status

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



Cell Configuration	Chemistry				Dimensions		
	Gen 3		Gen 4		Width	Thick	Height*
	Energy	Power	Energy	Power			
				LSE12x	133	21	68.2
	LSE42	LSE38	*TBD*	*TBD*	98	37	151
	LSE55	LSE51	LSE60	LSE56	130	50	123
	LSE110	LSE102	LSE122	LSE112	130	50	208
	LSE145	LSE134	LSE160	LSE147	130	50	263
	LSE190	--	LSE205	*TBD*	165	50	263

*not including terminal posts

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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	4,500	
80% DOD GEO	LSE160	4.10V	32A	10.8hr	N/A	107A	1.2hr	15°C	2,500	Cont. Deep DoD GEO Cycle
60% DoD GEO	LSE160	4.10V	32A	10.8hr	N/A	80A	1.2hr	15°C	2,100	Nominal DoD GEO Cycle
40% DoD LEO	LSE160	4.10V	80A	1.0hr	N/A	120A	0.53Hr	15°C	16,000	Deep DOD LEO Cycle
25% DoD LEO	LSE160	4.10V	48A	1.0hr	N/A	80A	0.5Hr	15°C	16,000	Nominal DOD LEO Cycle
Power Cell Testing										
100% DoD Cycling	LSE112	4.10V	56A	4.0hr	2.75V	100A	N/A	25°C	4,500	
40% DoD LEO	LSE112	4.10V	56A	1.0hr	N/A	89.6A	0.5hr	20°C	19,500	Deep LEO Cycle
25% DoD LEO	LSE112	4.10V	56A	1.0hr	N/A	89.6A	0.5hr	20°C	19,500	Deep LEO Cycle
40%,50% ,60% and 70% DoD LEO	LSE12x	4.10V	Various	1.0Hr	N/A	Various	0.5hr	15°C	15000+	Ultra Deep DOD LEO Cycling

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

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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	4,500	
80% DOD GEO	LSE160	4.10V	32A	10.8hr	N/A	107A	1.2hr	15°C	2,500	Cont. Deep DoD GEO Cycle
60% DoD GEO	LSE160	4.10V	32A	10.8hr	N/A	80A	1.2hr	15°C	2,100	Nominal DoD GEO Cycle
40% DoD LEO	LSE160	4.10V	80A	1.0hr	N/A	120A	0.53Hr	15°C	16,000	Deep DOD LEO Cycle
25% DoD LEO	LSE160	4.10V	48A	1.0hr	N/A	80A	0.5Hr	15°C	16,000	Nominal DOD LEO Cycle
Power Cell Testing										
100% DoD Cycling	LSE112	4.10V	56A	4.0hr	2.75V	100A	N/A	25°C	4,500	
40% DoD LEO	LSE112	4.10V	56A	1.0hr	N/A	89.6A	0.5hr	20°C	19,500	Deep LEO Cycle
25% DoD LEO	LSE112	4.10V	56A	1.0hr	N/A	89.6A	0.5hr	20°C	19,500	Deep LEO Cycle
40%,50% ,60% and 70% DoD LEO	LSE12x	4.10V	Various	1.0Hr	N/A	Various	0.5hr	15°C	15000+	Ultra Deep DOD LEO Cycling

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

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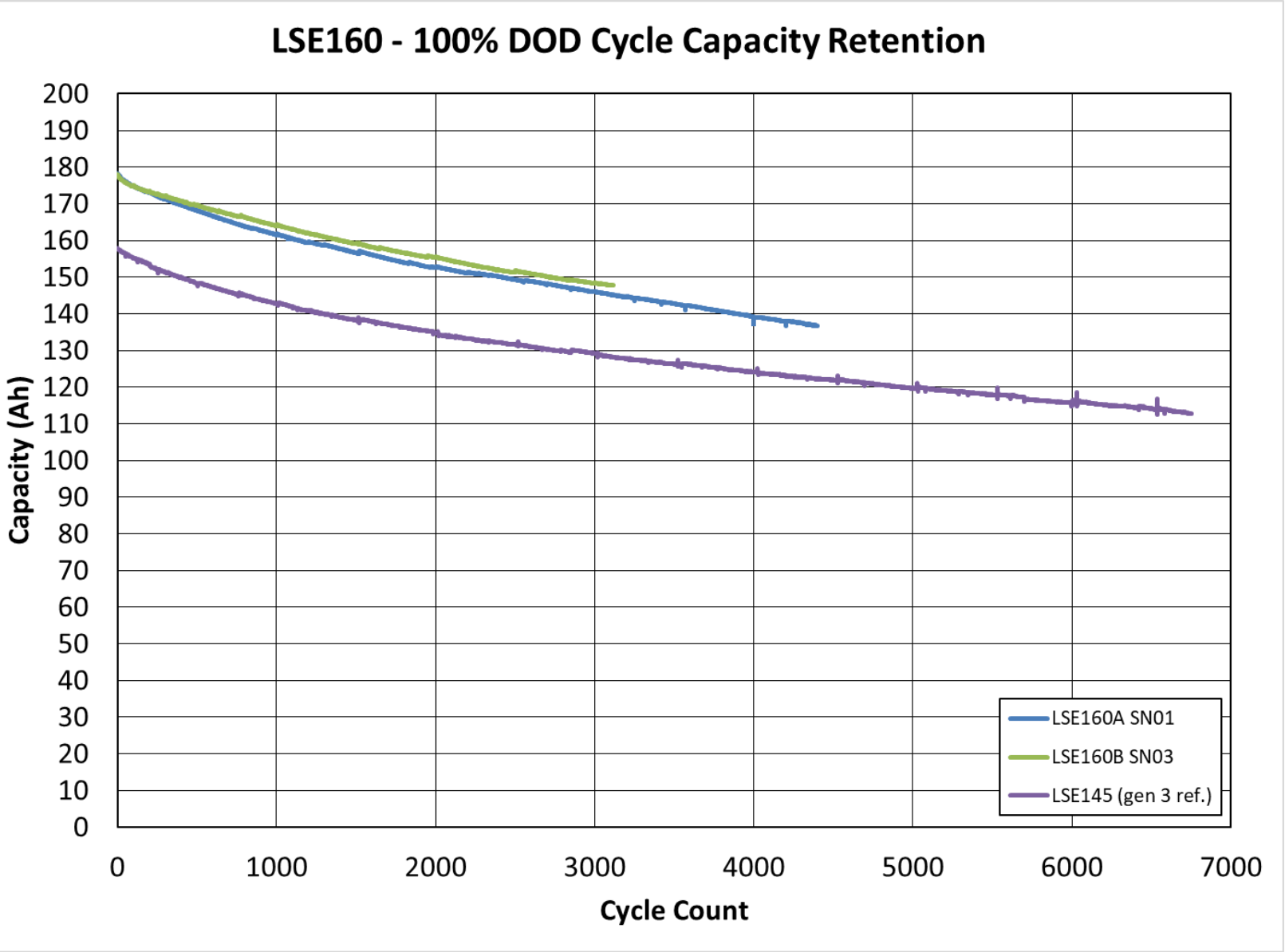
LSE160 – 100% DOD Cycle Life

Generation 4 Energy Type

Test Conditions						Ambient Test Temp
Charge Condition (CCCV unless noted)			Discharge Condition			
EoCV	Rate	Time	EoDV	Rate	Time	
4.10V	80A (0.5C)	4hr	2.75V	100A	N/A	25°C

Generation 4 provides ~10% Ah increase from Generation 3 with similar retention characteristics



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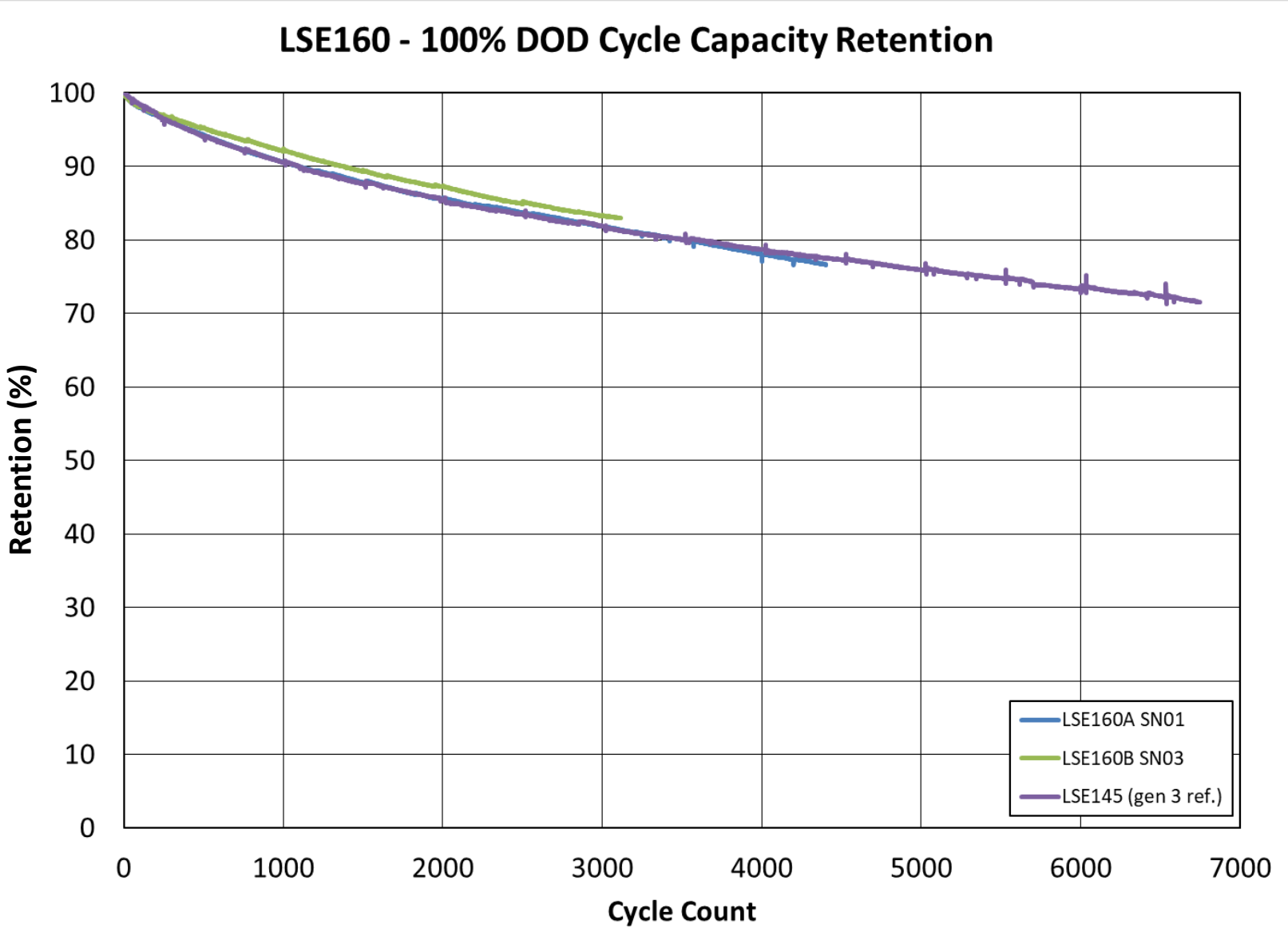
LSE160 – 100% DOD Cycle Life

Generation 4 Energy Type

Test Conditions						Ambient Test Temp
Charge Condition (CCCV unless noted)			Discharge Condition			
EoCV	Rate	Time	EoDV	Rate	Time	
4.10V	80A (0.5C)	4hr	2.75V	100A	N/A	25°C

Generation 4 provides ~10% Ah increase from Generation 3 with similar retention characteristics



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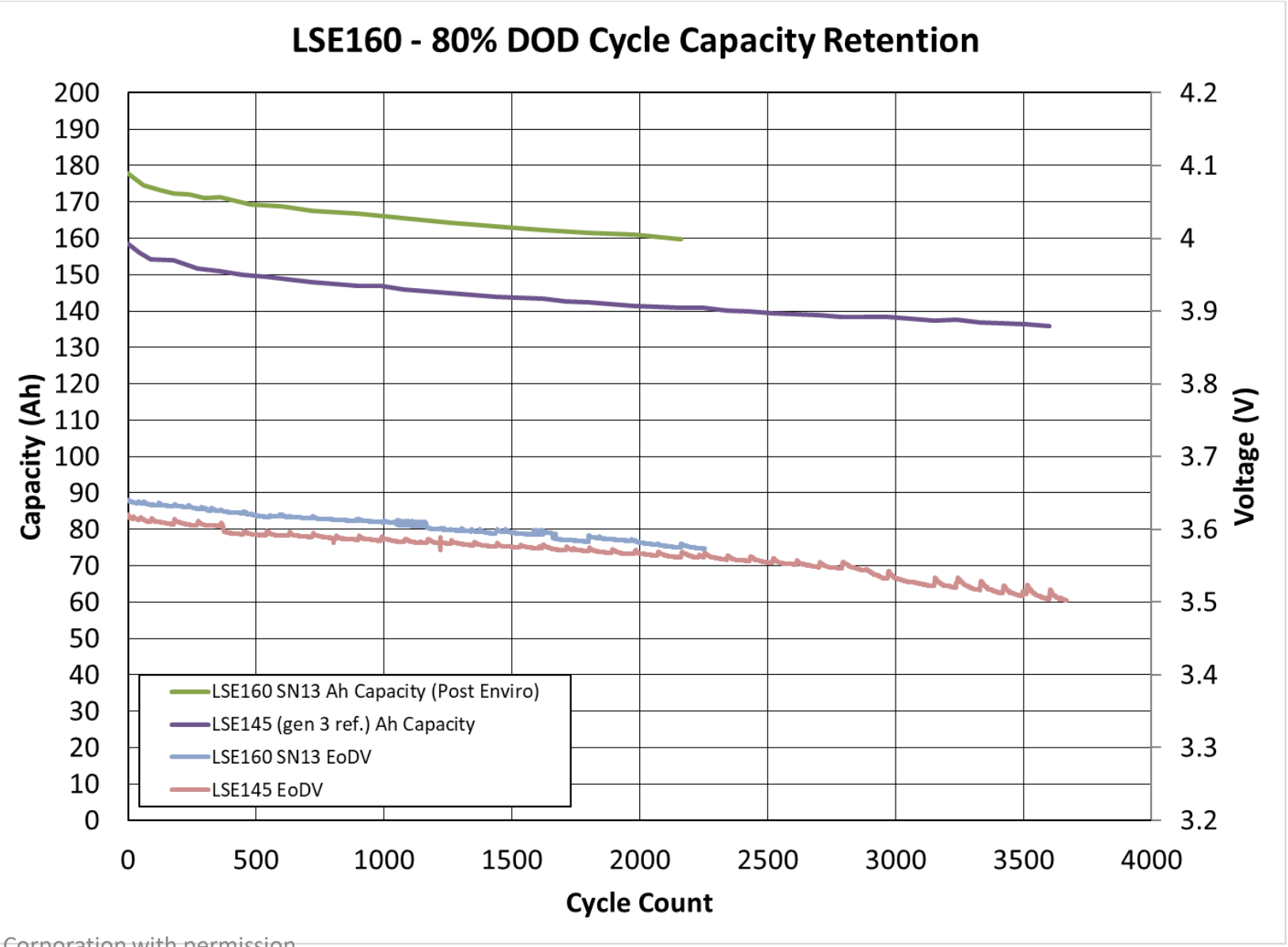
LSE160 – 80% DOD Cycle Life (GEO)

Generation 4 Energy Type

Test Conditions						Ambient Test Temp
Charge Condition (CCCV unless noted)			Discharge Condition			
EoCV	Rate	Time	EoDV	Rate	Time	
4.10V	32A (0.2C)	10.8hr	N/A	107A (0.67C)	1.2hr	15°C

Accelerated 80% DOD GEO cycling profile.
2 cycles per day with no solstice periods.

Cycle count already exceeds typical 15 year GEO profile



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LSE160 – 80% DOD Cycle Life (GEO)

Generation 4 Energy Type

Test Conditions						Ambient Test Temp
Charge Condition (CCCV unless noted)			Discharge Condition			
EoCV	Rate	Time	EoDV	Rate	Time	
4.10V	32A (0.2C)	10.8hr	N/A	107A (0.67C)	1.2hr	15°C

Accelerated 80% DOD GEO Cycle profile.
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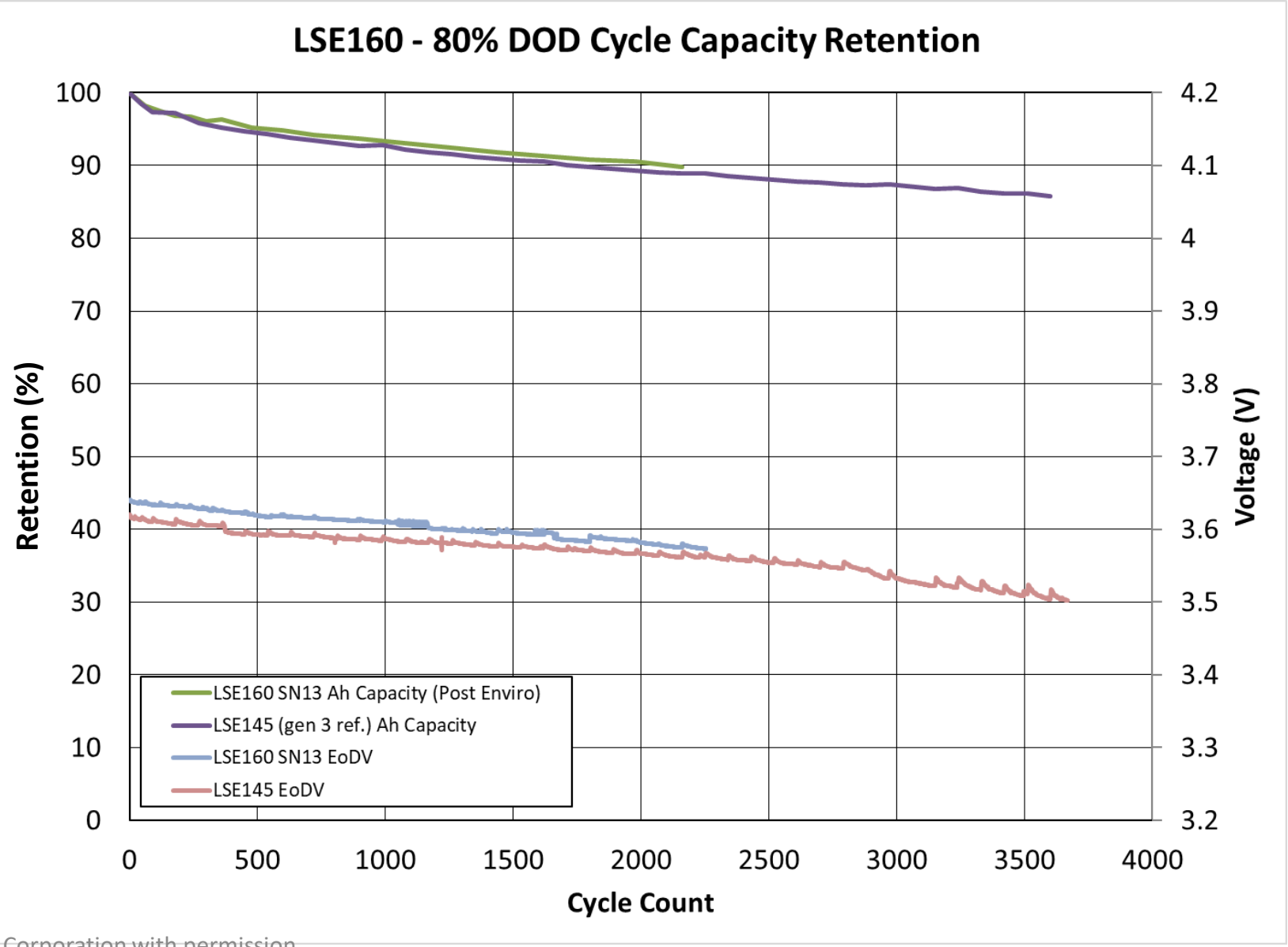
Cycle count already exceeds typical 15 year GEO profile



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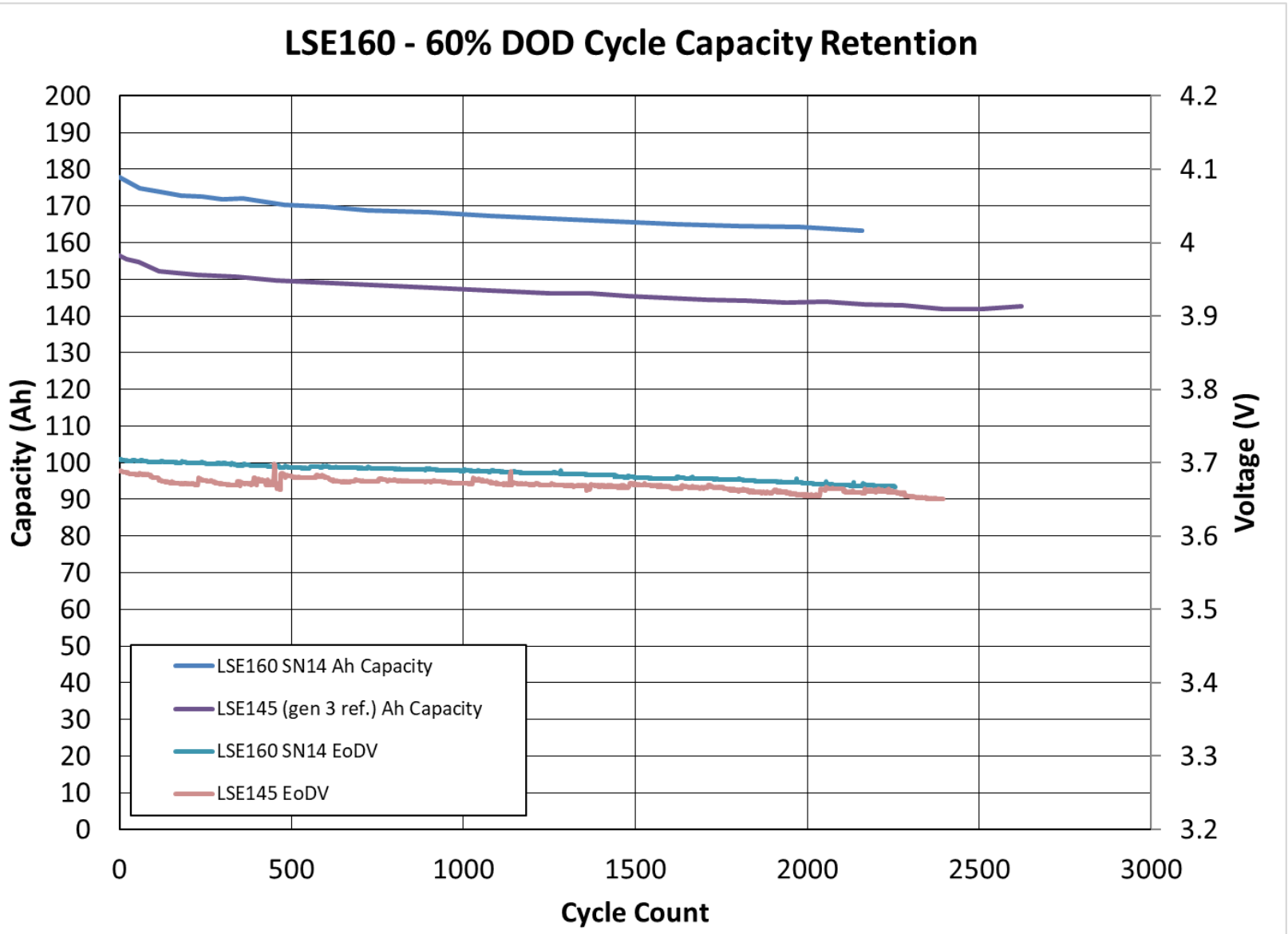
LSE160 – 60% DOD Cycle Life (GEO)

Generation 4 Energy Type

Test Conditions						Ambient Test Temp
Charge Condition (CCCV unless noted)			Discharge Condition			
EoCV	Rate	Time	EoDV	Rate	Time	
4.10V	32A (0.5C)	10.8hr	N/A	80A (0.5C)	1.2hr	15°C

Accelerated 60% DOD GEO Cycle profile.
2 cycles per day with no solstice periods.

Cycle count already exceeds typical 15 year GEO profile



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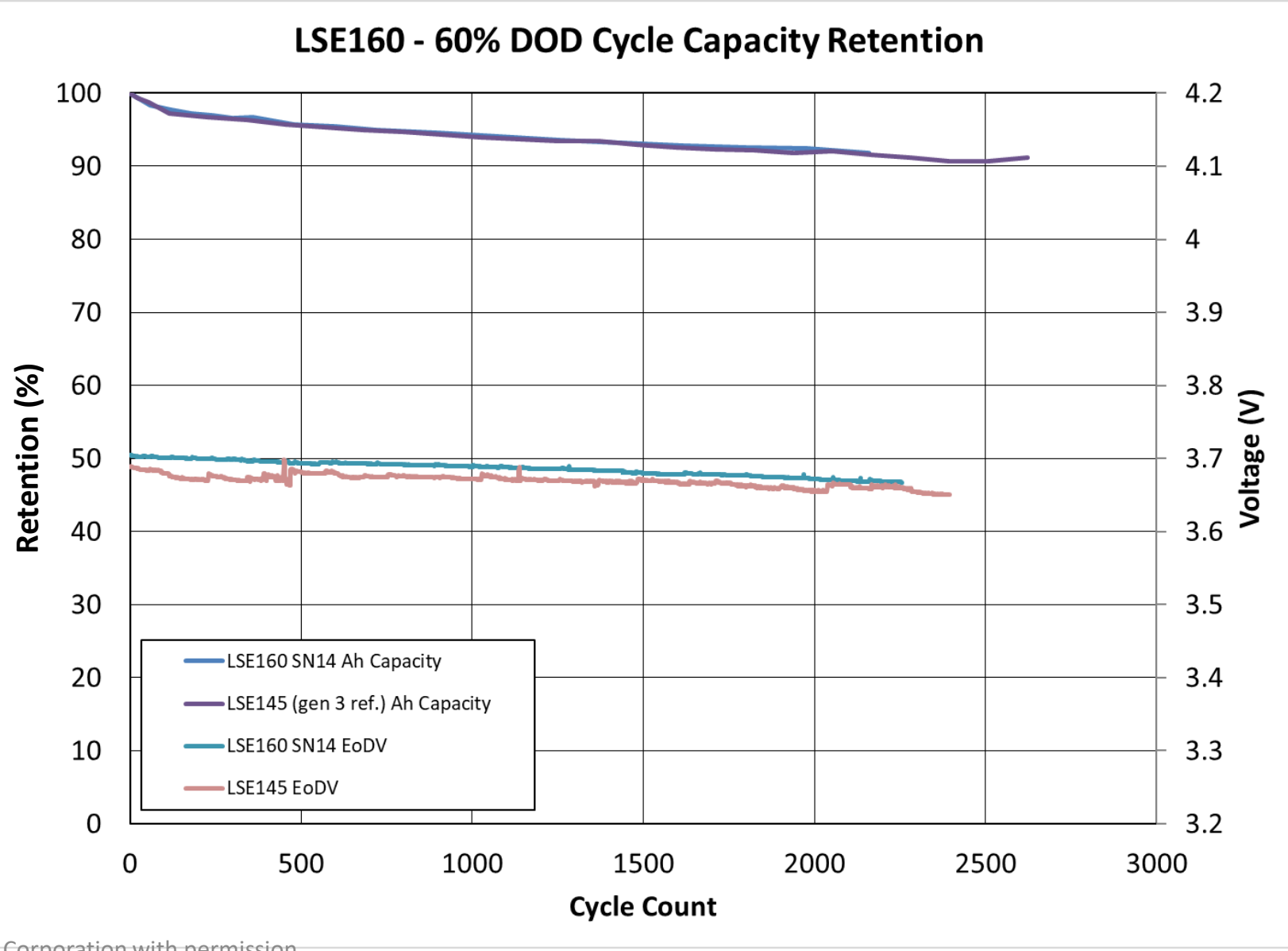
LSE160 – 60% DOD Cycle Life (GEO)

Generation 4 Energy Type

Test Conditions						Ambient Test Temp
Charge Condition (CCCV unless noted)			Discharge Condition			
EoCV	Rate	Time	EoDV	Rate	Time	
4.10V	32A (0.5C)	10.8hr	N/A	80A (0.5C)	1.2hr	15°C

Continuous cycling between 60% and 80% DOD show no adverse effects on Gen 4 performance.



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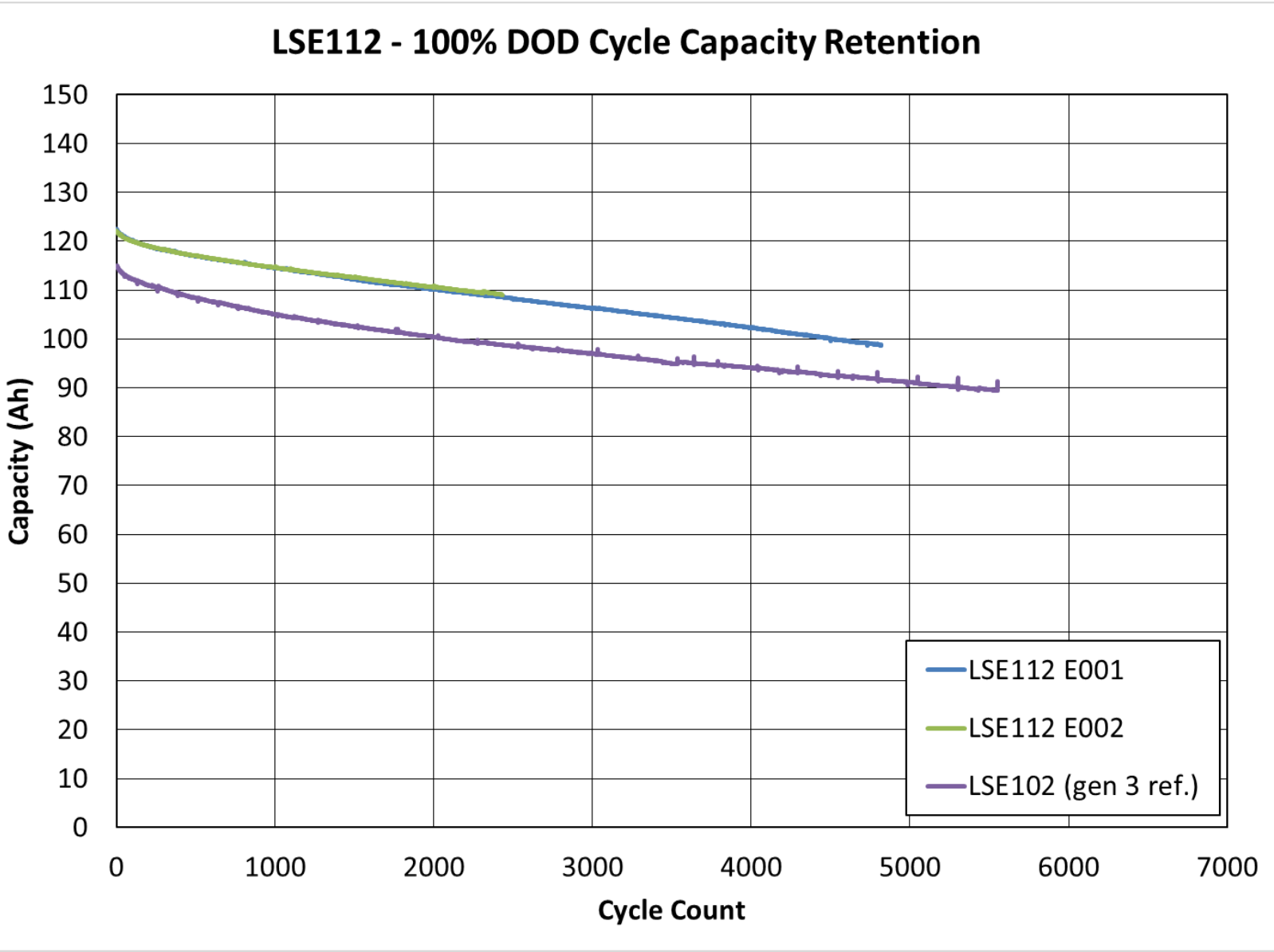
LSE112 – 100% DOD Cycle Life

Generation 4 Power Type

Test Conditions						Ambient Test Temp
Charge Condition (CCCV unless noted)			Discharge Condition			
EoCV	Rate	Time	EoDV	Rate	Time	
4.10V	56A (0.5C)	4.0hr	2.75V	100A	N/A	25°C

Generation 4 provides ~10% Ah increase from Generation 3 with similar retention characteristics



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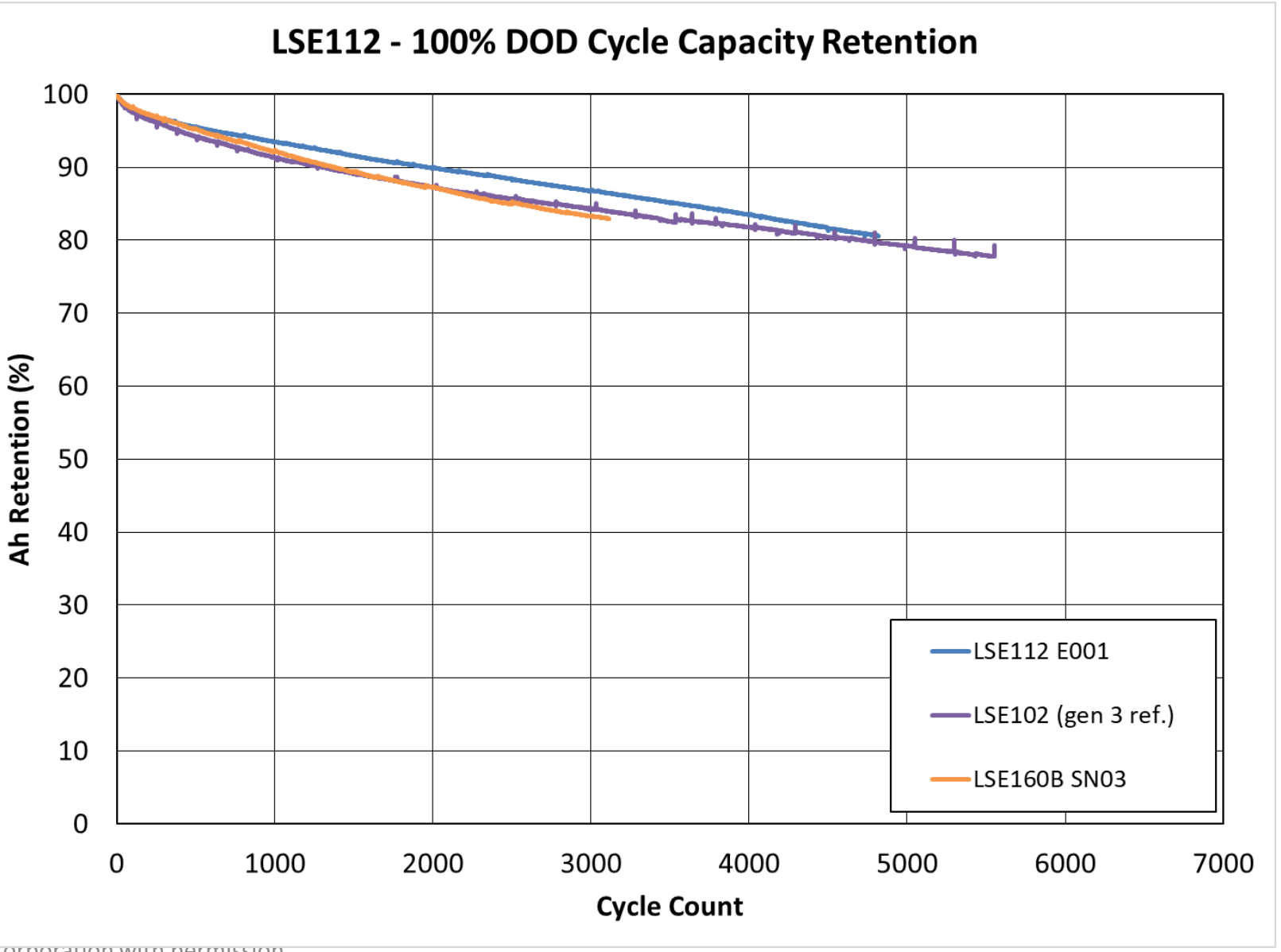
LSE112 – 100% DOD Cycle Life

Generation 4 Power Type

Test Conditions						Ambient Test Temp
Charge Condition (CCCV unless noted)			Discharge Condition			
EoCV	Rate	Time	EoDV	Rate	Time	
4.10V	56A (0.5C)	4.0hr	2.75V	100A	N/A	25°C

Gen 4 Power type Ah retention similar to Gen 3. Power type cells



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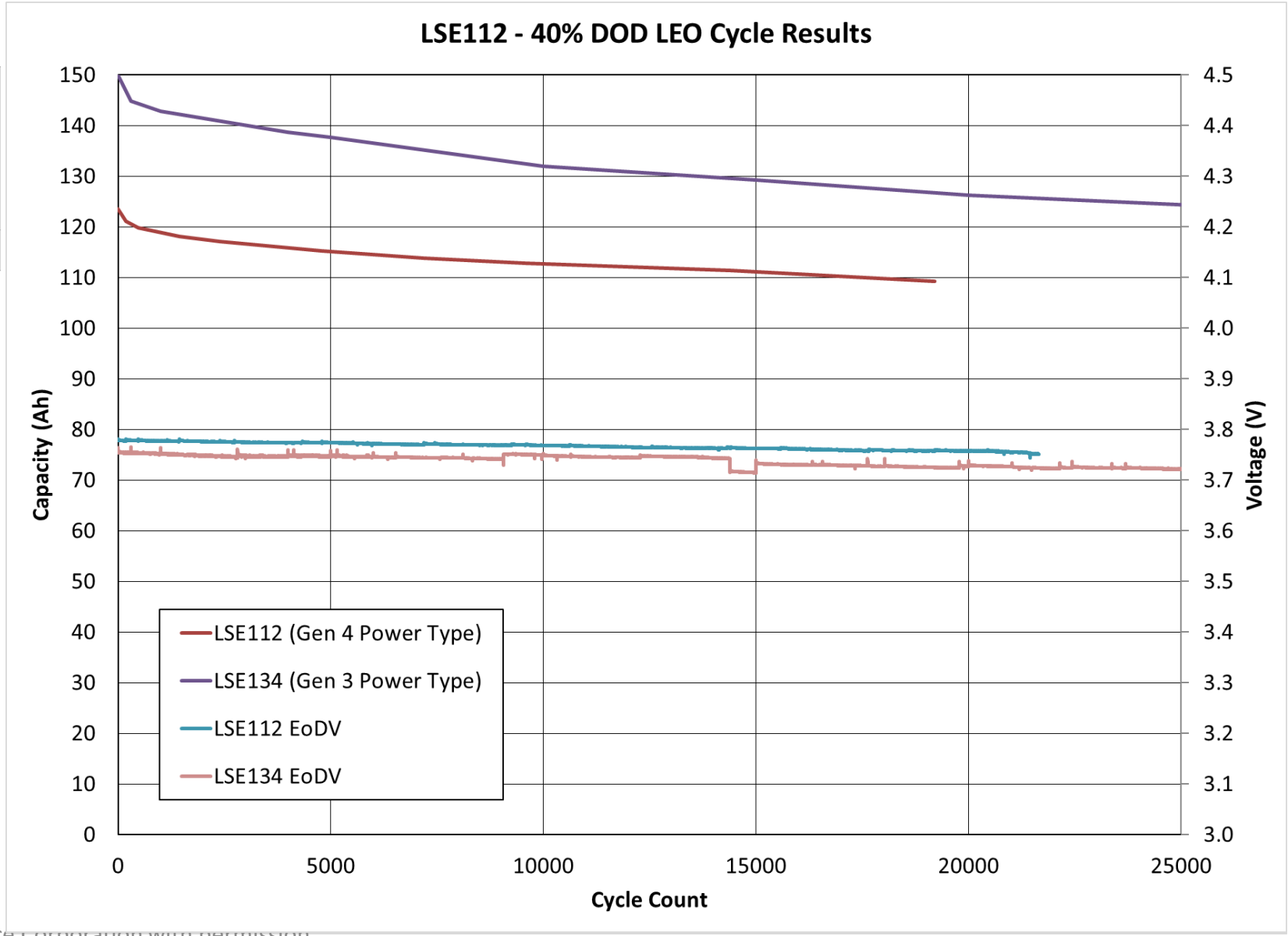
LSE112 – 40% DOD Cycle Life (LEO)

Generation 4 Power Type

Test Conditions						Ambient Test Temp
Charge Condition (CCCV unless noted)			Discharge Condition			
EoCV	Rate	Time	EoDV	Rate	Time	
4.10V	56A	1.0hr	N/A	89.6A	0.5hr	20°C

40% Deep DoD LEO cycling presents no issues for Gen 3 or Gen 4 chemistries.



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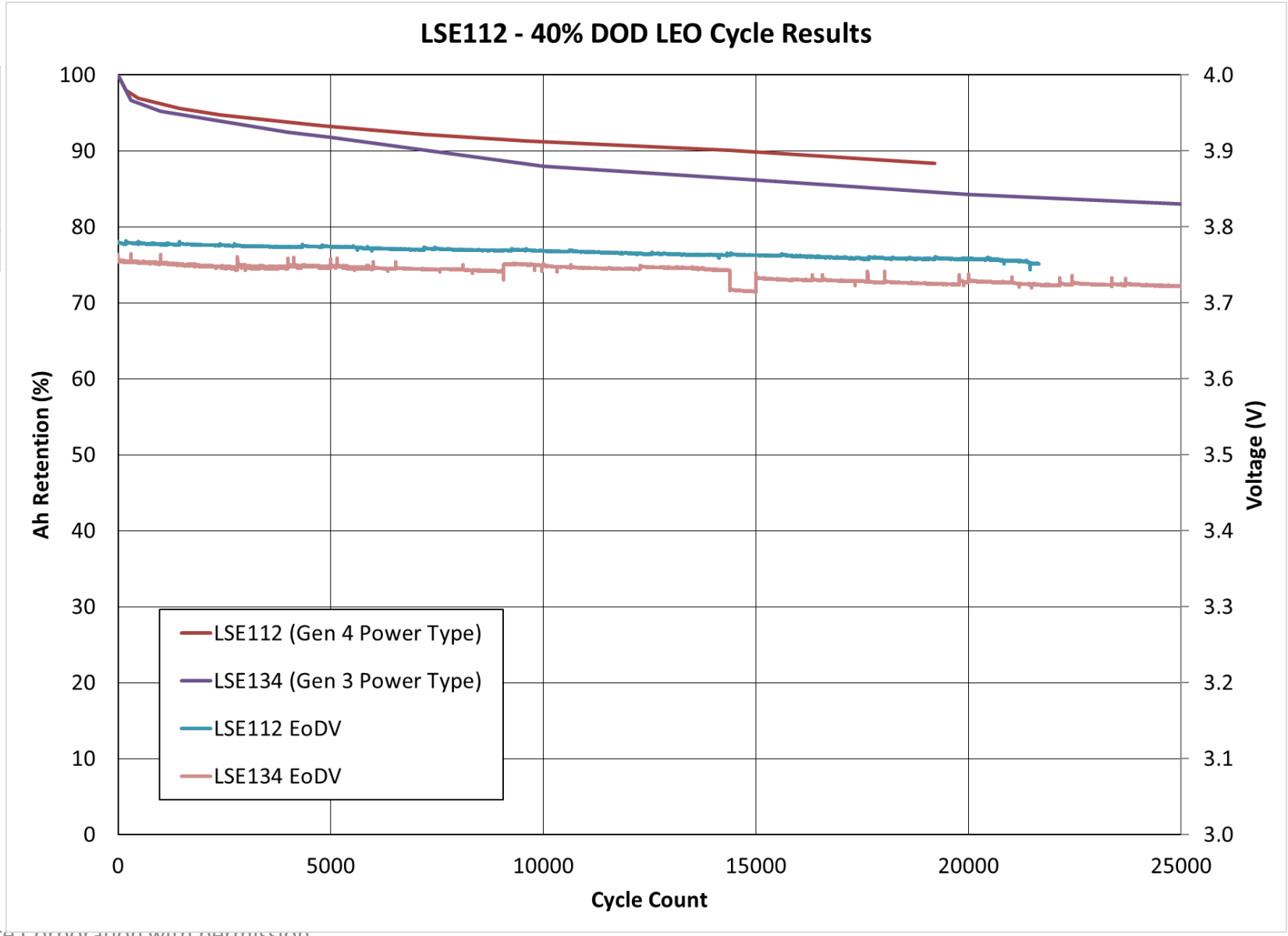
LSE112 – 40% DOD Cycle Life (LEO)

Generation 4 Power Type

Test Conditions						Ambient Test Temp
Charge Condition (CCCV unless noted)			Discharge Condition			
EoCV	Rate	Time	EoDV	Rate	Time	
4.10V	56A	1.0hr	N/A	89.6A	0.5hr	20°C

Gen. 4 Ah retention exhibits marginal improvement to Gen. 3



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LSE12x – Ultra High DOD LEO Cycle Tests

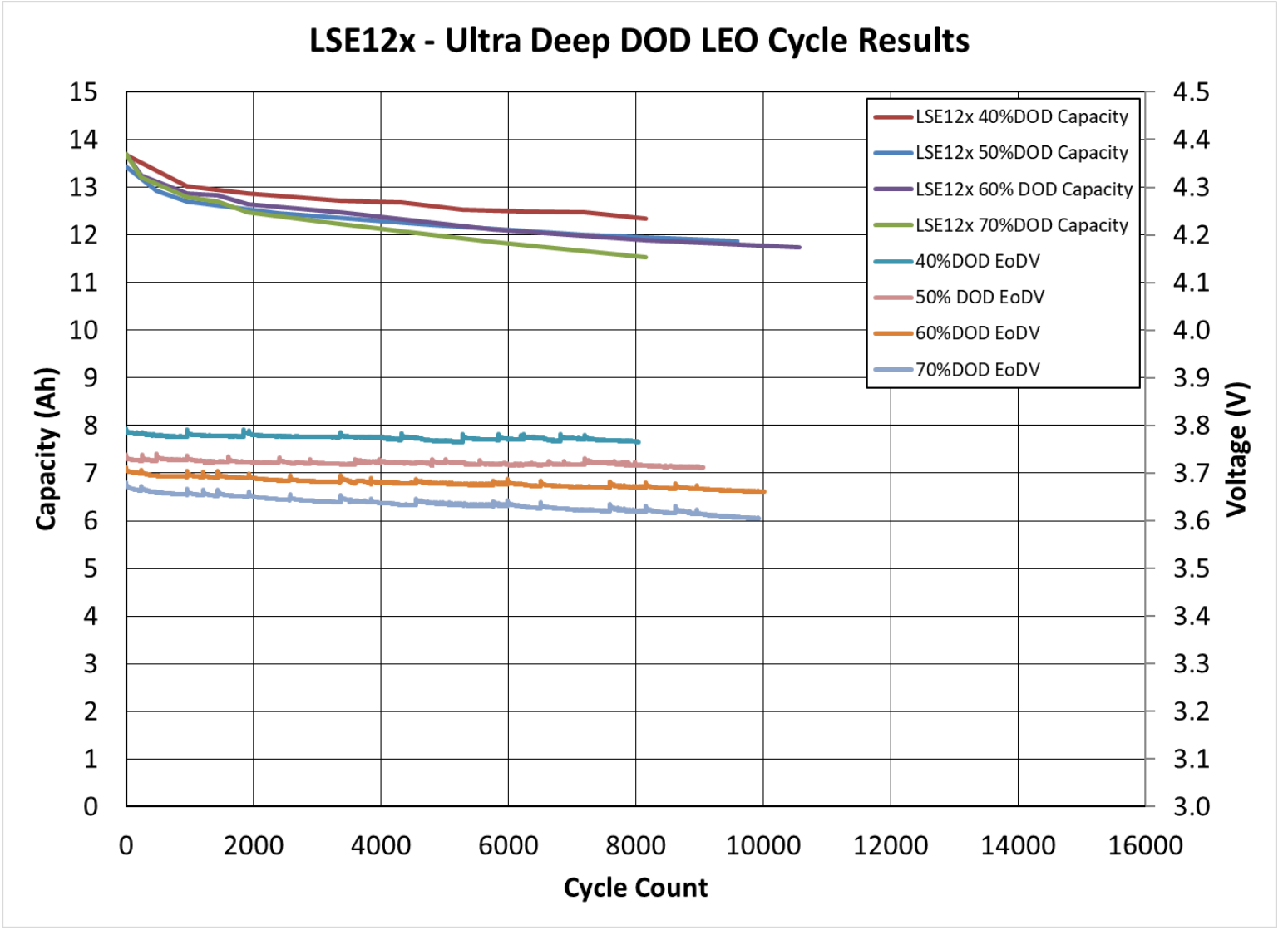
New cell size, ultra high performance, Gen 4 Power Type

Test Conditions						Ambient Test Temp
Charge Condition (CCCV unless noted)			Discharge Condition			
EoCV	Rate	Time	EoDV	Rate	Time	
4.1V	Various	1.0Hr	N/A	Various	0.5hr	15°C

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

LSE12X Performance Specification

BOL Capacity	4.1V-2.75V	13.6 Ah, 51.0Wh
	*4.2V-2.75V	15.0 Ah, 56.3Wh
Nameplate Capacity		12 Ah, 45Wh
Nominal Discharge Voltage		3.75 V
Continuous Charge Rate, 15°C		6A
Continuous Discharge Rate		24A
Pulse Discharge Rate		60+A
DCR @ 50% SOC, 15°C		<6 mΩ
Nominal Cell Impedance		1.1mΩ
Mass		0.390 kg



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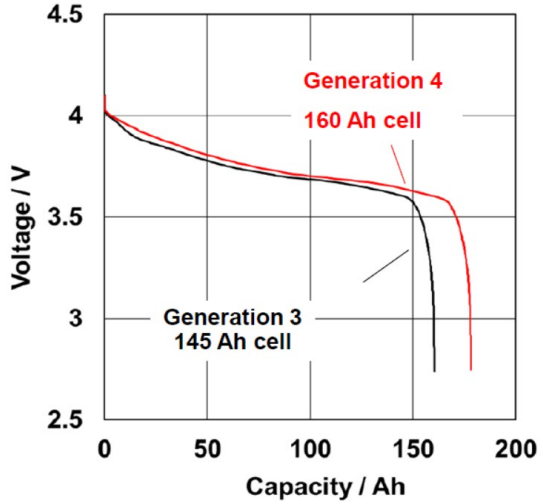
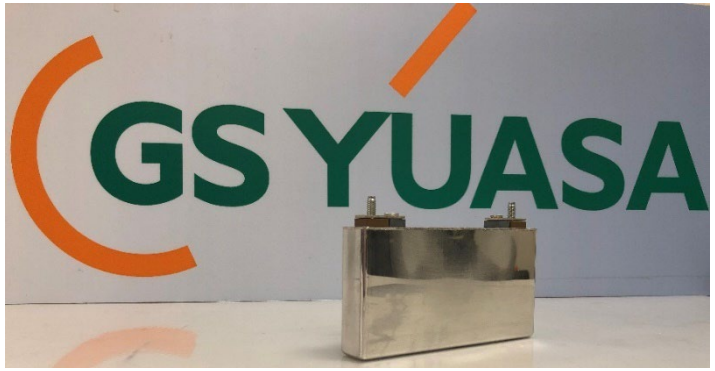
Summary

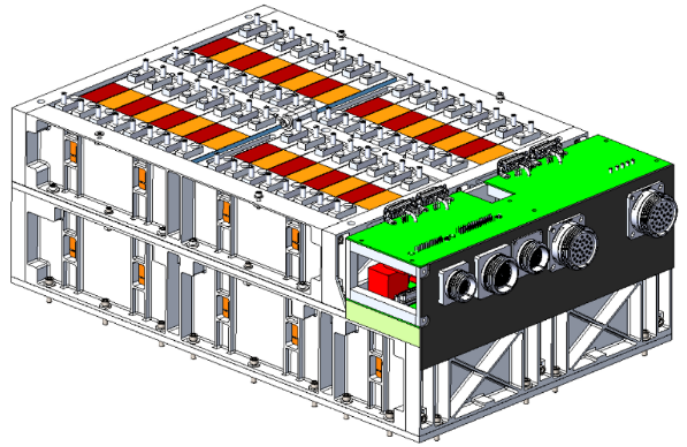
- GS Yuasa's Generation 4 LCO/Graphite chemistry provides meaningful performance increases from Generation 3 including:
  - Increased Energy Density
  - Excellent Capacity Retention under demanding cycle conditions
  - Decreased DCR for enhanced voltage performance under load



- Gen. 4 cells available from 12Ah to 205Ah in a single cell
  - LSE12x, LSE60, LSE112, LSE160, LSE205 Qualified
  - Energy and Power electrode optimizations

- LSE12x - New 12Ah small form factor cell added to the portfolio
  - Enabling smaller spacecraft access to industry leading performance
  - Scalable battery designed and built by GYLP in Roswell, Ga.
    - Configurations ranging from 720Wh to 4,320Wh





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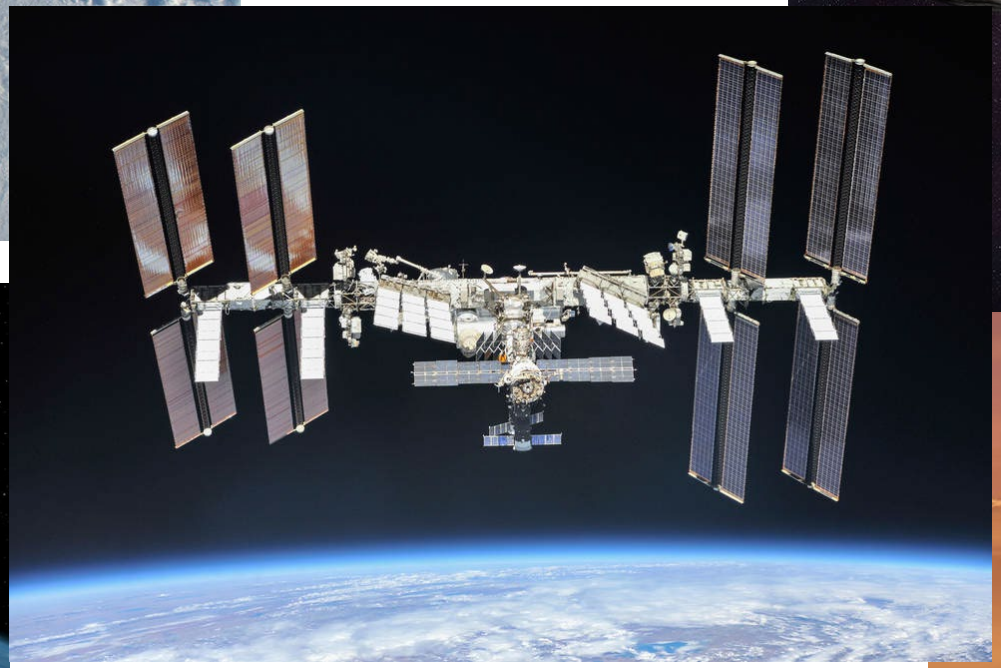
Energy storage design test and manufacturing expertise

Industry leading spaceflight heritage

Validated and reliable performance modelling



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