GS Yuasa LSE12x Cell Performance and Life Modeling

Prepared for
Space Power Workshop 2024

April 23-25, 2024

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Topics

- GS Yuasa corporate introduction & experience supporting critical space applications
- Gen 4 Space Cell Li-ion design and qualification status
- LSE12x cell introduction
- LSE12x performance compared to COTS 18650 cells
- Life and Performance Modeling of prospective missions

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

GS Yuasa Aerospace and Specialty Battery Groups

GS Yuasa Technology Ltd. “GYT”

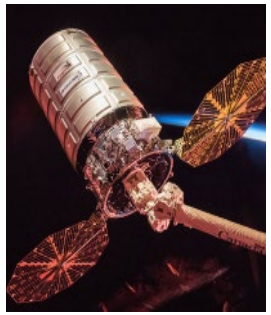
- Research, development, manufacturing, test, and sales of specialty cells and batteries for:
  - Aerospace
  - Undersea
  - Defense and Security
- ISO9001 & JISQ9100 certified
- Headquarters located in Kyoto, Japan

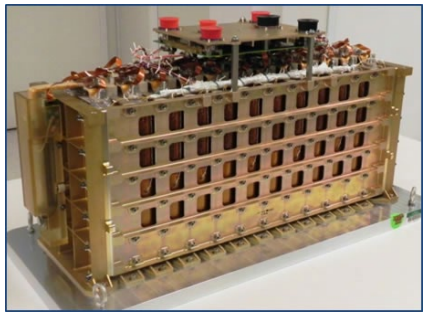
GS Yuasa Lithium Power, Inc. “GYLP”

- 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

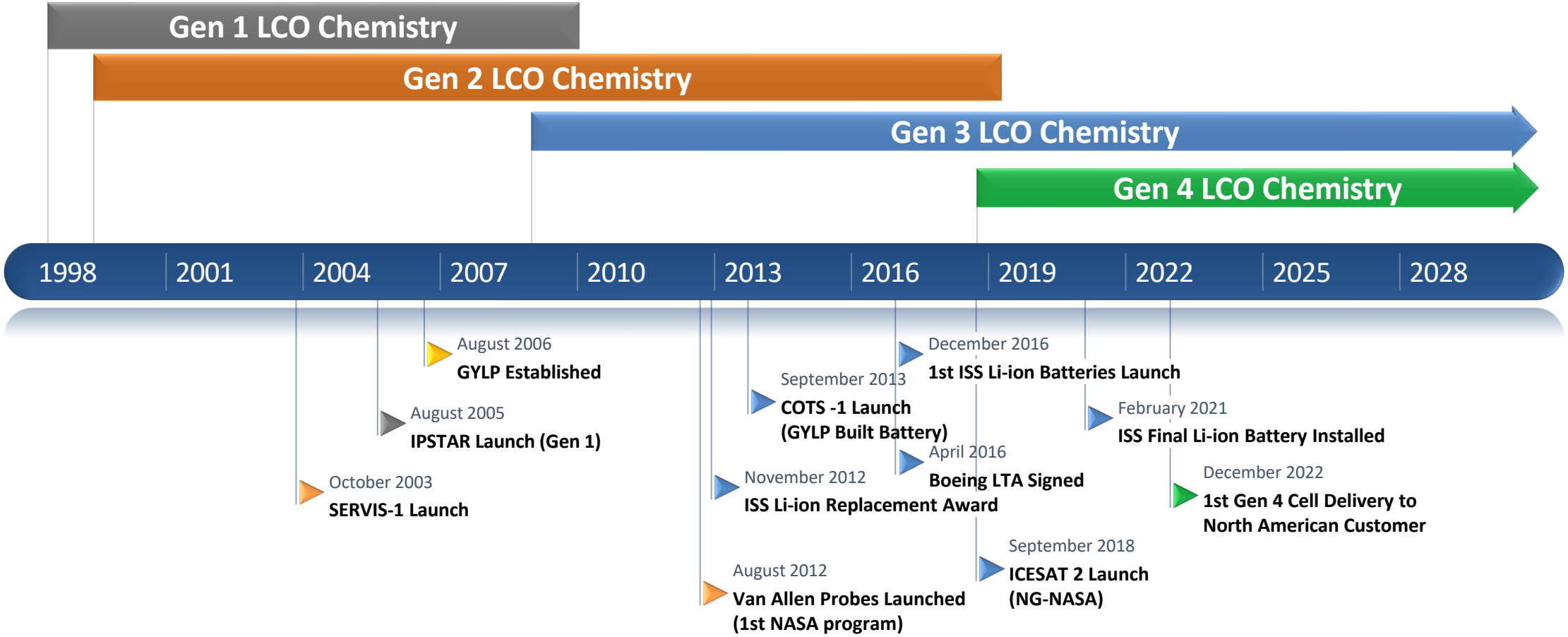
DEPARTMENT OF DEFENSE · UNITED STATES OF AMERICA

RECIPROCAL DEFENSE PROCUREMENT MOU

June 2016, extended through June 2031

LSE Cell Heritage and Program Experience

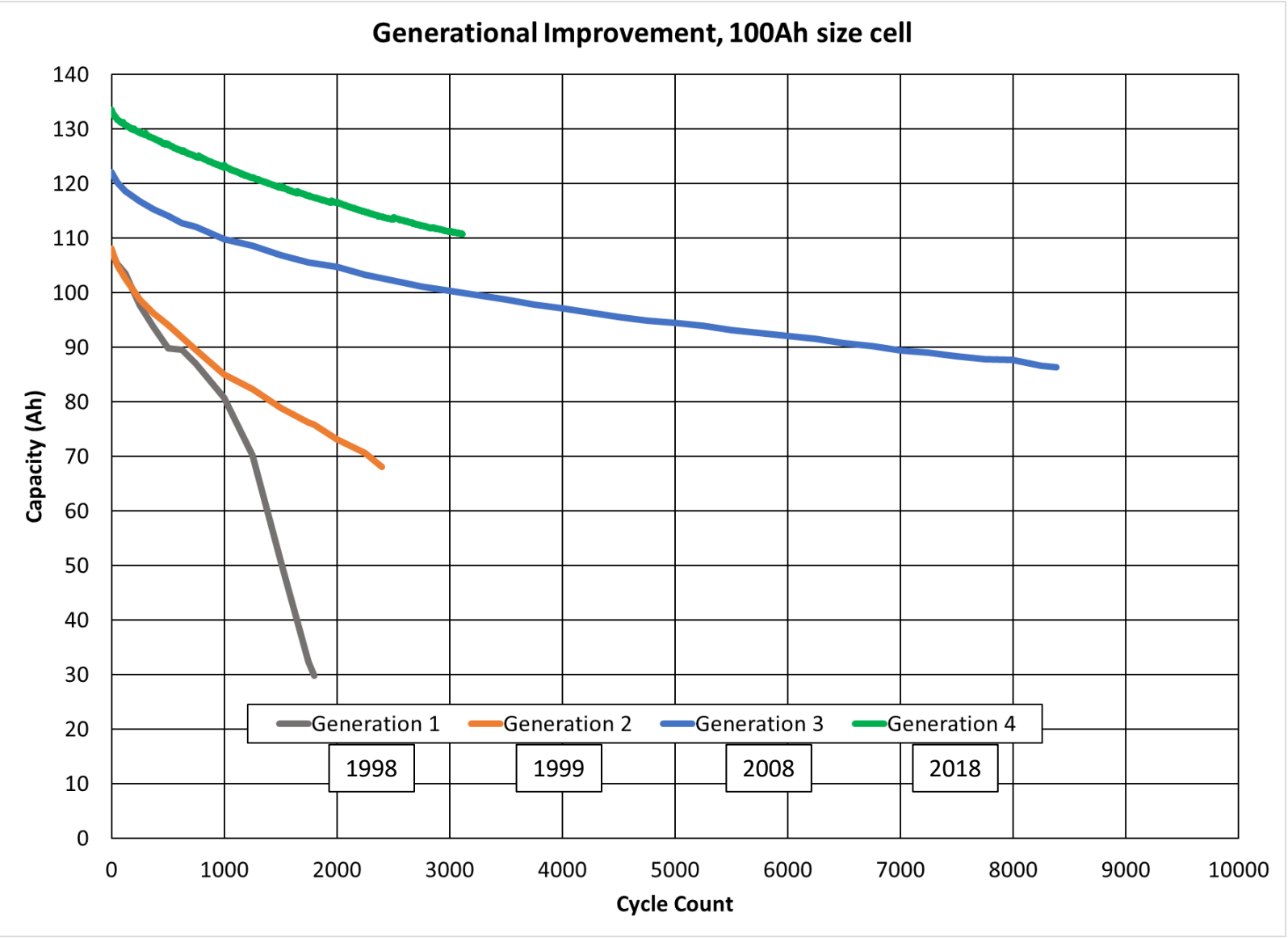
Timeline of GS Yuasa Space Chemistry



Since inception in 1998, GS Yuasa has demonstrated the ability to maintain configuration and control over material sources for 15+ years thanks to strong relationship with the suppliers.

Evolution of GS Yuasa $LiCoO_2$, 100% DOD

100Ah Class Cell, Energy Type



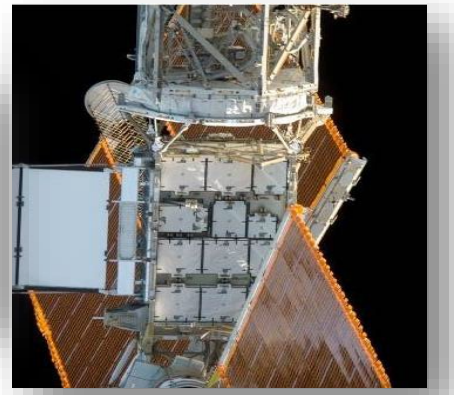
	Cell	Nominal BOL Ah Capacity	EoCV	BOL Wh/Kg
Gen1	LSE100	107	3.98	141
Gen2	LSE100	109	3.98	144
Gen3	LSE110	122	4.1	165
Gen4	LSE122	132	4.1	175

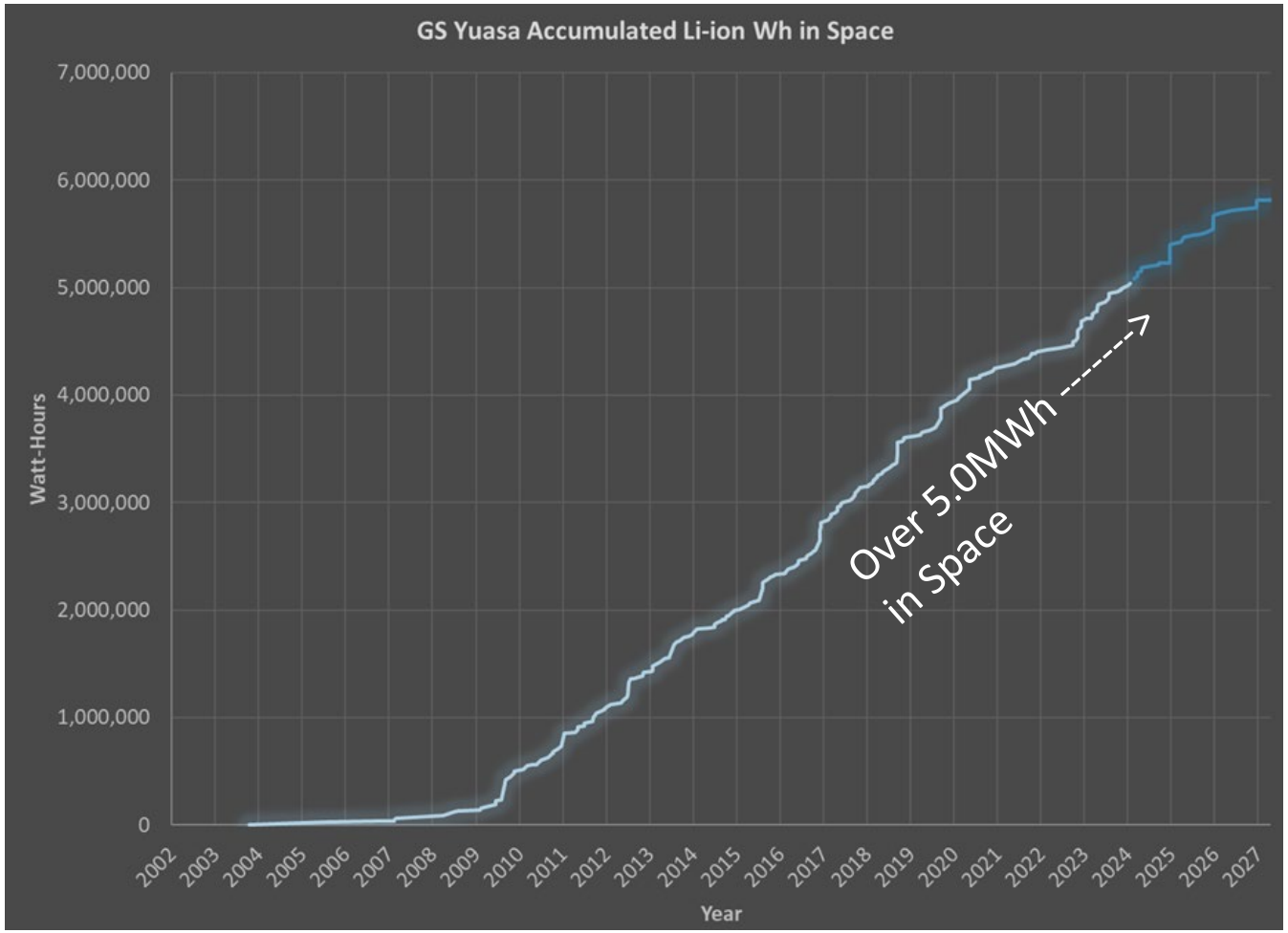
Width	Thick	Height*
130	50	208

GS Yuasa Space Flight Heritage Update

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

Number of satellites……	246+
− LEO/MEO……..	113+
− GEO……	132
− Interplanetary……	1+
1st satellite on-orbit……	Servis 1 (30 Oct. 2003)
Longest satellite on-orbit (yrs)….....	>18yr
Li-ion Watt-hours used in space……....	5.08 MWh
Performance to date…….....	No failures
Backlog (Wh)……	>1.04 MWh



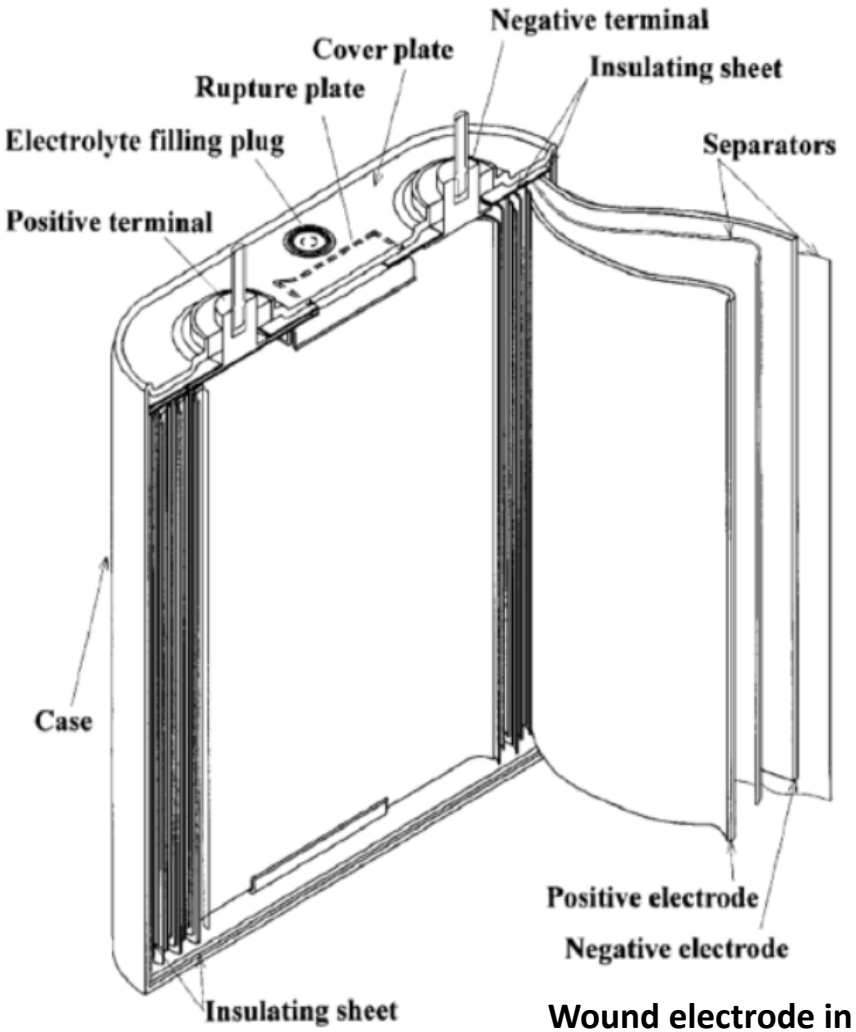


[GS Yuasa Surpasses 5.0MWh in Space]

Metrics updated March 2024

LSE Cell Basic Shape

Over 25 years of outstanding performance



Wound electrode in an elliptical cylindrical case

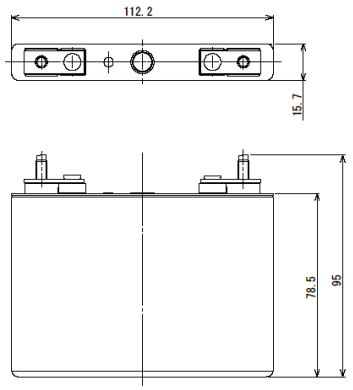
The LSE cell portfolio consists of various sizes of Li-ion cells.
All cells share the same primary features: Al-case, wound-prismatic construction, ceramic terminals, LCO chemistry. All are manufactured in Kyoto, Japan on the same equipment and using the same basic processes. The portfolio can be viewed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

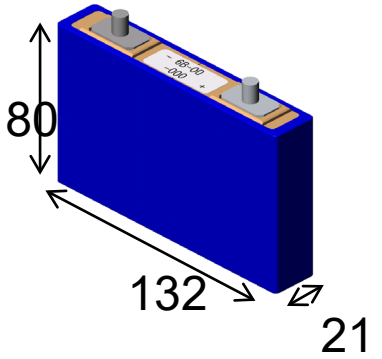
LSE12x Case Design

Fusion of Aviation and Automotive Cells

Blue Energy

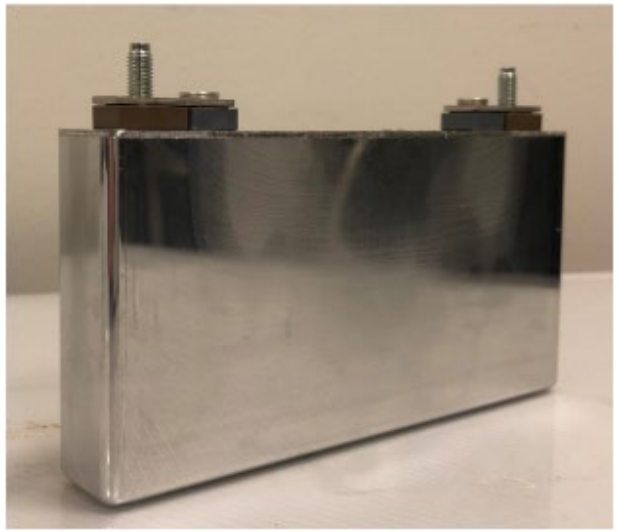
- EH5 Ultra high power cell for Honda/Acura hybrids

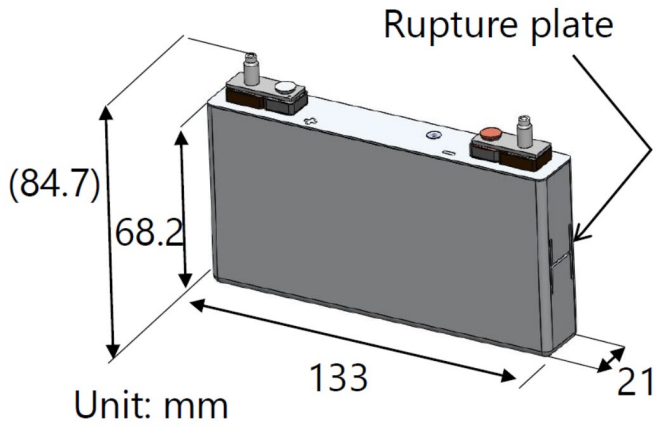


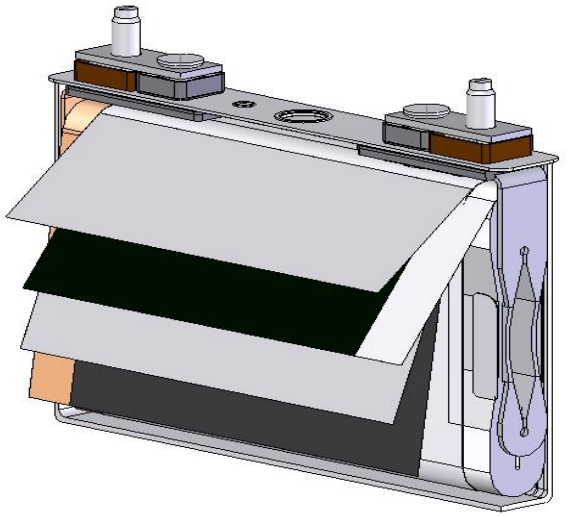


- LVP10 Cell for Aviation Applications

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





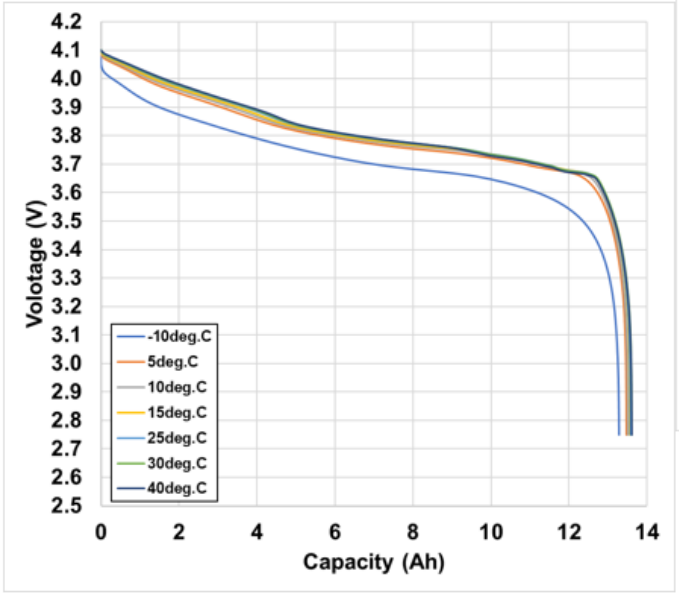


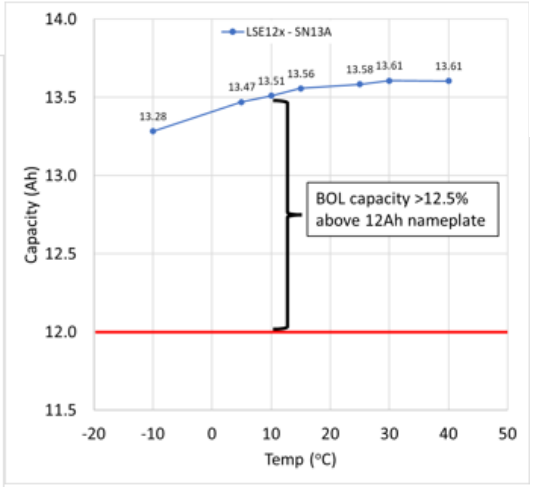
- Wound Element
- Aluminum Case
- Case Neutral Design
- Hermetically Sealed
- Ruggedized Current Collectors

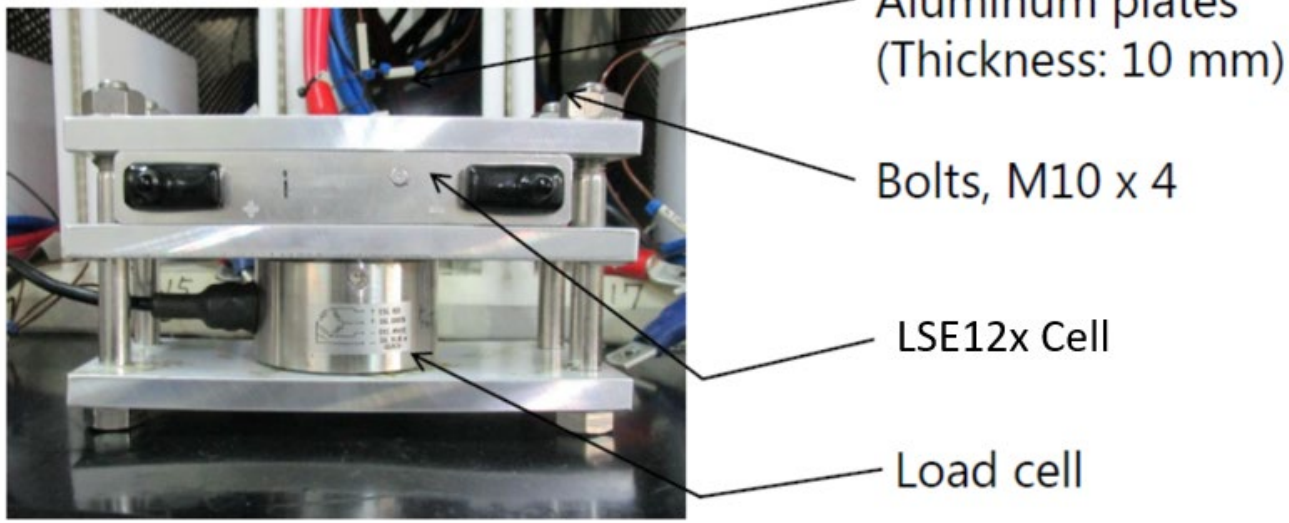
LSE12x Qualification

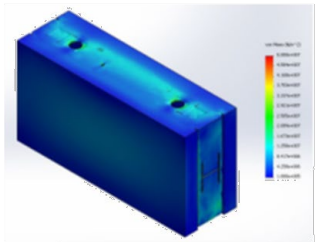
Aerospace Space Power Workshop 2022

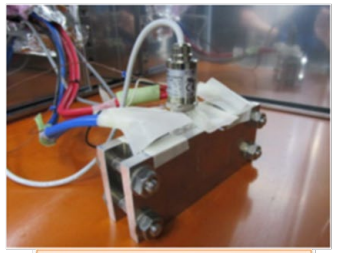
Cell completed qualification in December 2021. Results presented at Space Power Workshop 2022: https://gsyuasa-lp.com/news/gylp-presents-at-the-2022-aerospace-space-power-workshop/








EOL Mechanical FEA

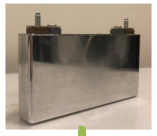

Cycle Internal Pressure Change Evaluation


Case Bust Test


Nail Pen Testing with adj. Cells (P20L-9567-2B)

LSE Cell Configurations & Qualification Status

- Configuration Qualified (10)
- Configuration Qualified, QT data property of US Government (1)
- Qualification by Similarity (1)
- Engineering model cells on test (1)
- Qualification Pending (1)



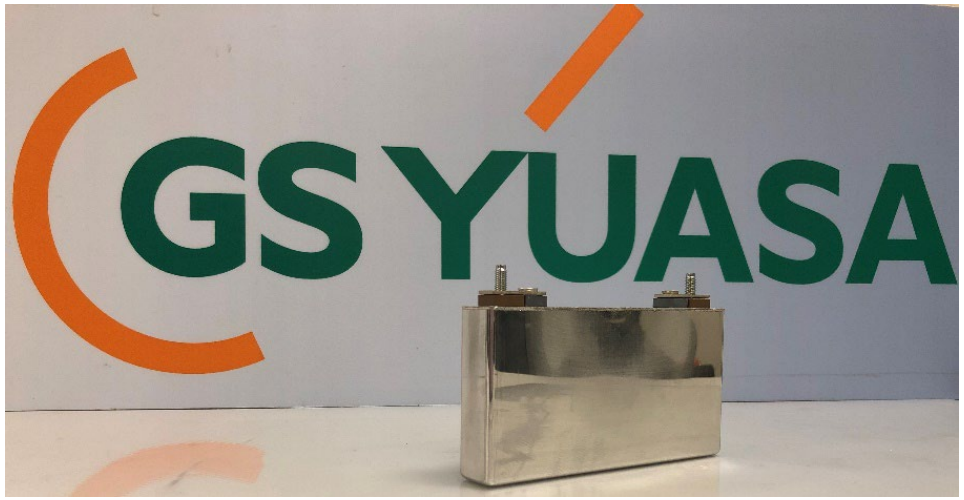
	Chemistry				Dimensions		
	Gen 3		Gen 4		Width	Thick	Height*
	Energy	Power	Energy	Power			
Cell Configuration				LSE12x	133	21	68.2
	LSE42	LSE38	*TBD*	*TBD*	98	37	151
	LSE55	LSE51	LSE60	LSE56	130	50	123
	LSE110	LSE102	LSE122	LSE112	130	50	208
	LSE145	LSE134	LSE160	LSE147	130	50	263
	LSE190	--	LSE205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

*not including terminal posts

LSE12x Lithium-ion Cell for Space
“Small” format cell

LSE12x Cell Design

Features and Specifications Summary



- Inspired by mature commercial cell designs; Enhanced for space
  - Case neutral design
  - Radiation hardened
  - Hermetically sealed
- GS Yuasa's Generation IV Lithium Cobalt Dioxide Chemistry
  - Extremely low DCR
  - Excellent cycle & calendar life
  - High discharge voltage
    - ✓ Ideal for unregulated bus applications
- Suitable for all space vehicles

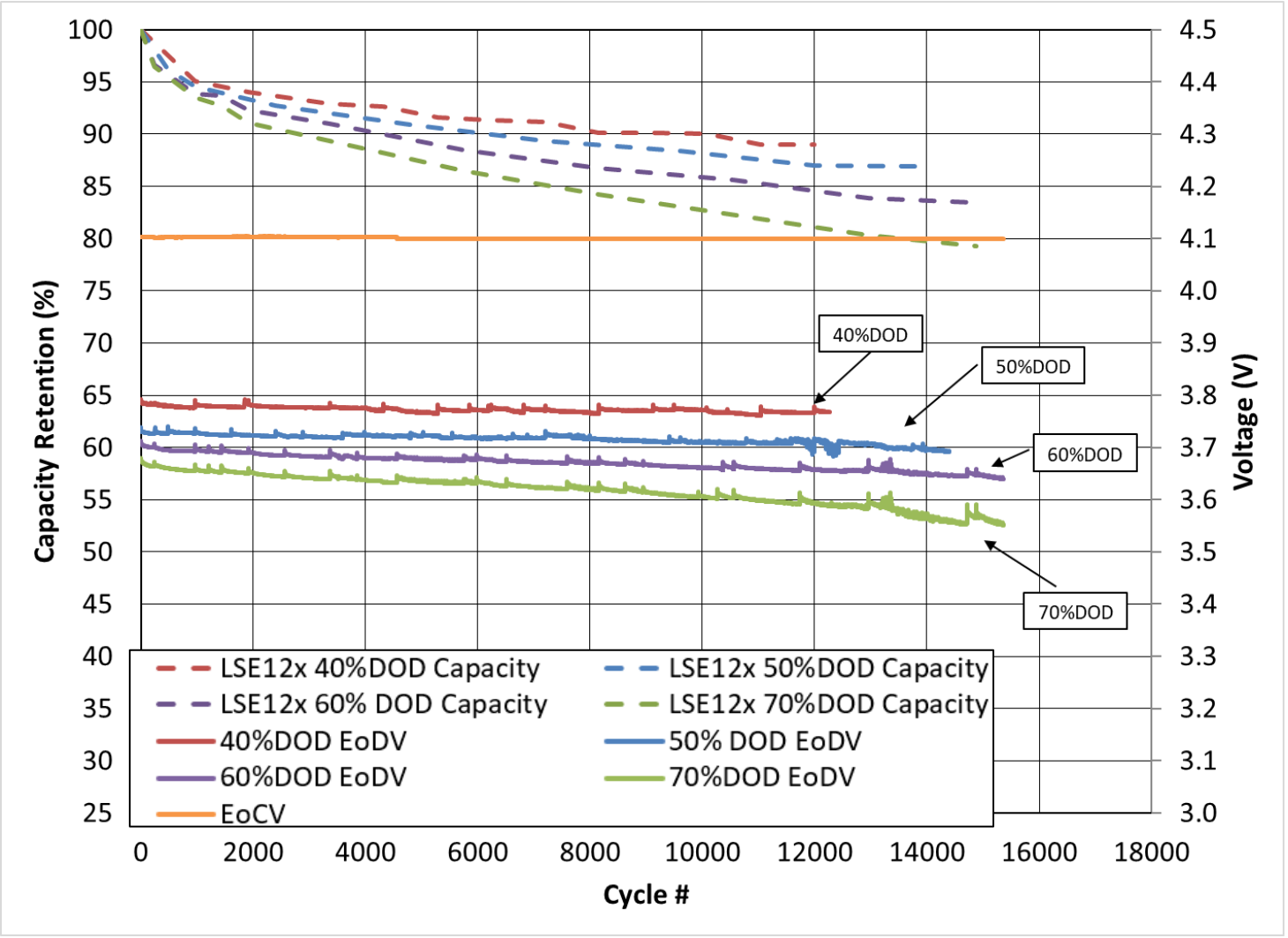
LSE12X Performance Specification

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

GS Yuasa validated Life and Performance model capability to allow for "right sizing" of a battery solution.

LSE12x Generation 4 LCO-Graphite Chemistry

High DOD LEO Cycling Life Test



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

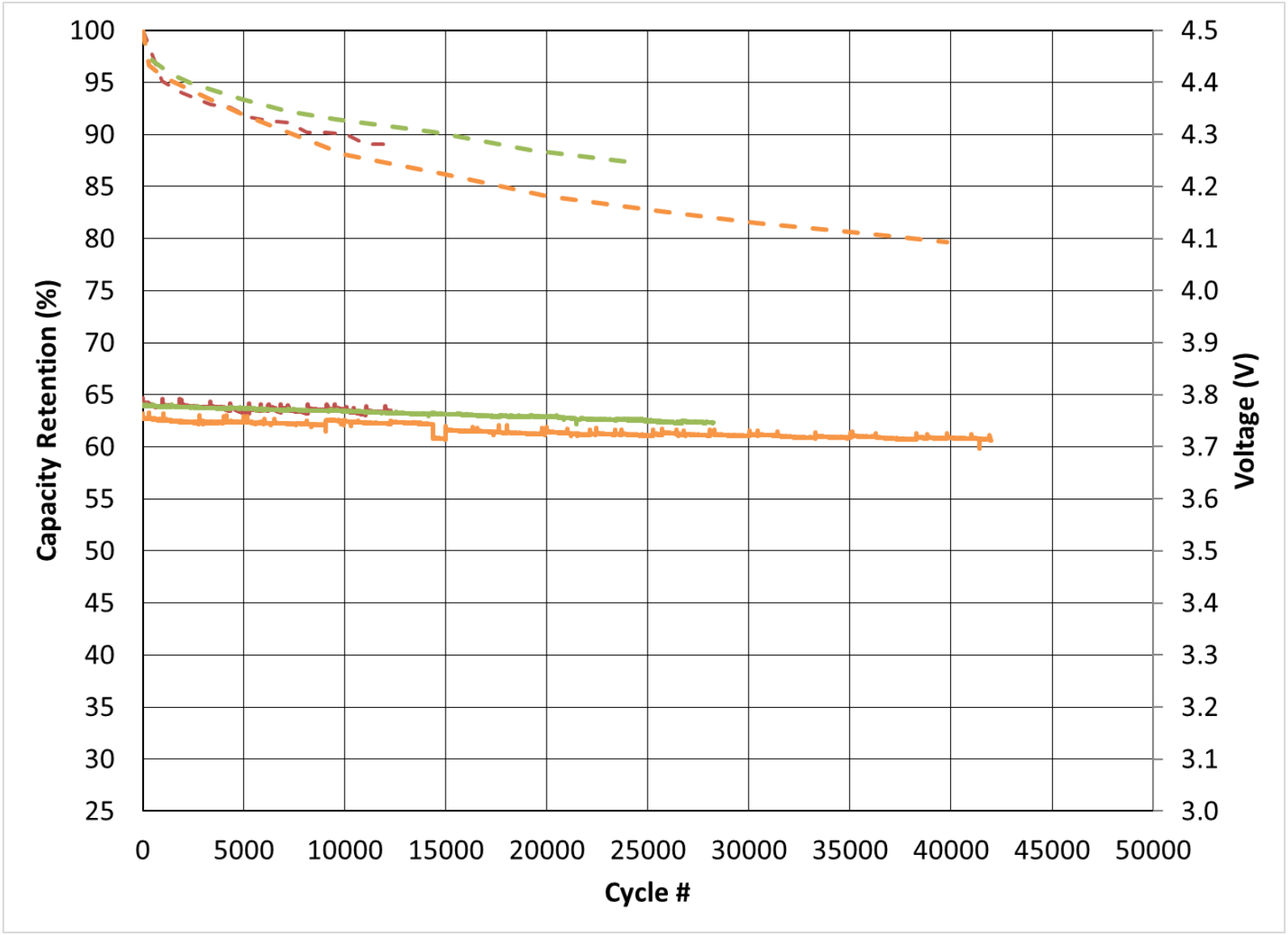
Approaching 3 years of LEO cycling at DOD ≥50% DOD.

See GS Yuasa's SPW2023 Presentation for more Gen 4 Cycle Life Performance: https://gsyuasa-lp.com/news/gs-yuasa-lithium-power-presents-at-the-2023-aerospace-space-power-workshop/

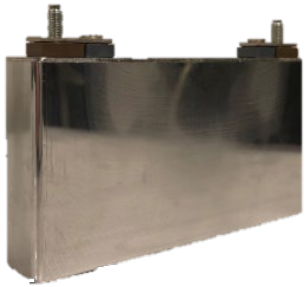
LSE12x Lithium-ion Cell for Space
Performance Compared to COTS 18650 cells

LSE12x Compared to GS Yuasa Large Format Cells

40% DOD LEO Cycle Life



GS Yuasa
LSE12x



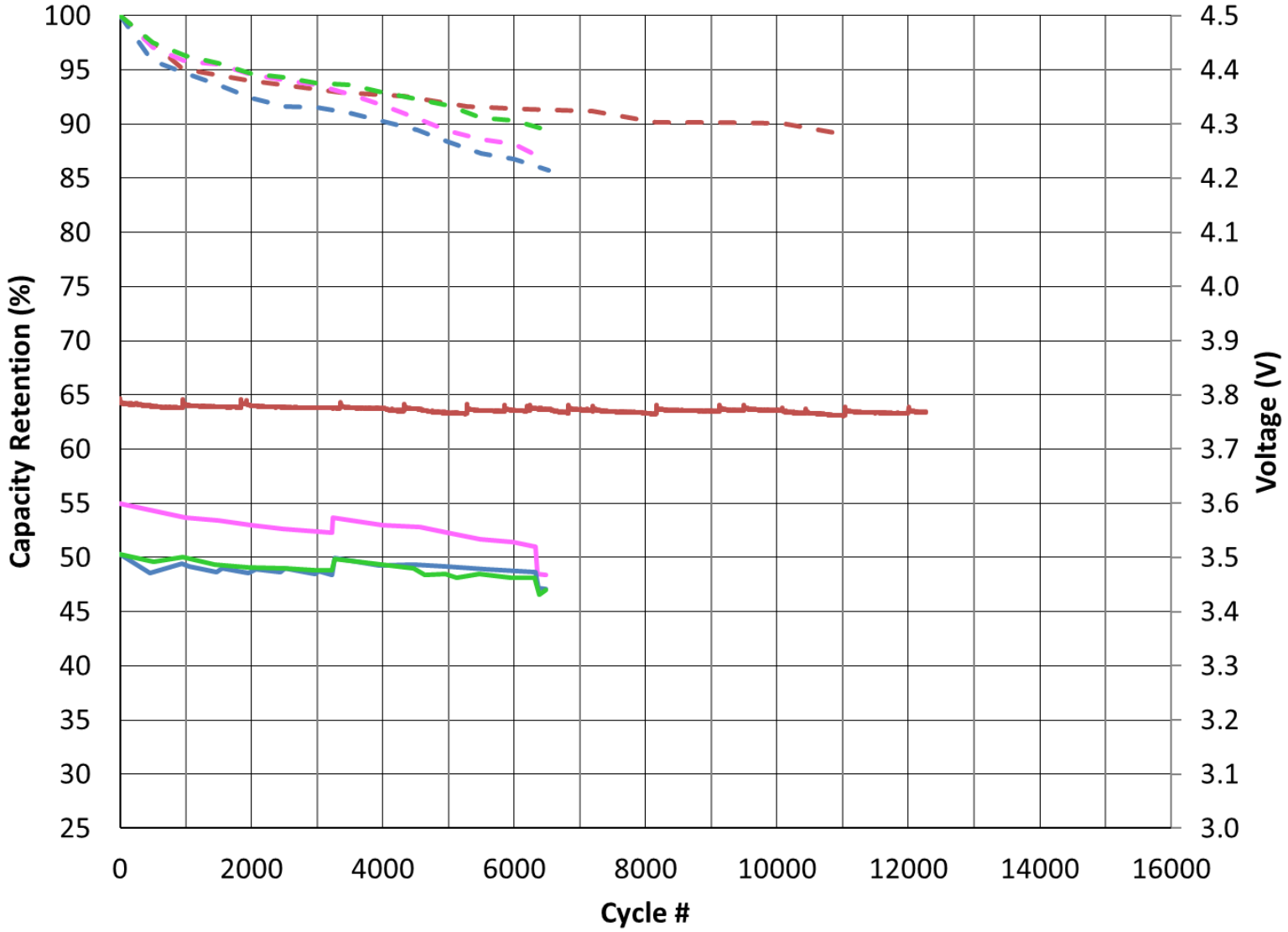
(Not to scale)

LSE134 & LSE112

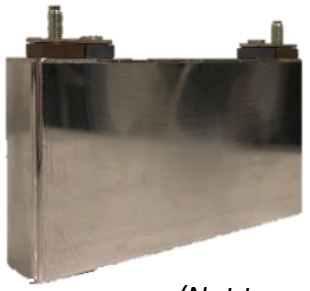
- - LSE12x 40%DOD Capacity
- - LSE112 (Large Format Gen 4 LSE Cell)
- - LSE134 (Gen 3 Ref)
— LSE12x EoDV
— LSE112 EODV (Large Format Gen 4 LSE Cell)
— LSE134 EoDV (Gen 3 ref)

LSE12x Compared to COTS 18650

40% DOD LEO Cycle Life



GS Yuasa LSE12x | LG M36 | LG MJ1 | Samsung Q30



(Not to scale)

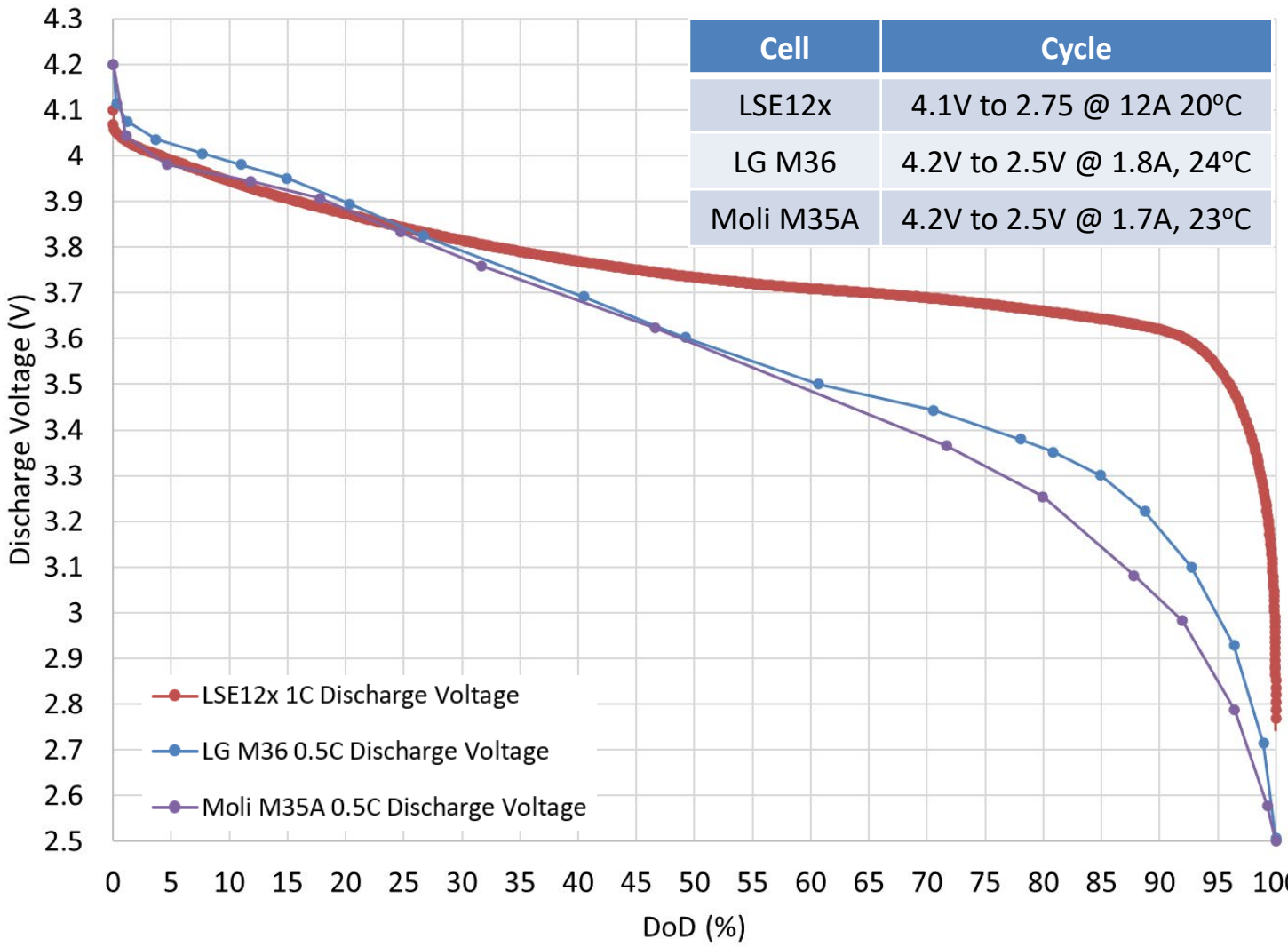
- LSE12x 40%DOD Capacity (4.1V EoCV)
- Samsung Q30 (4.1V EoCV)
- LG M36 Capacity (4.1V EoCV)
- LG MJ1 Capacity (4.1V EoCV)
- LSE12x EoDV
- Samsung Q30 EoDV
- LG MJ36 EoDV
- LG MJ1 EoDV

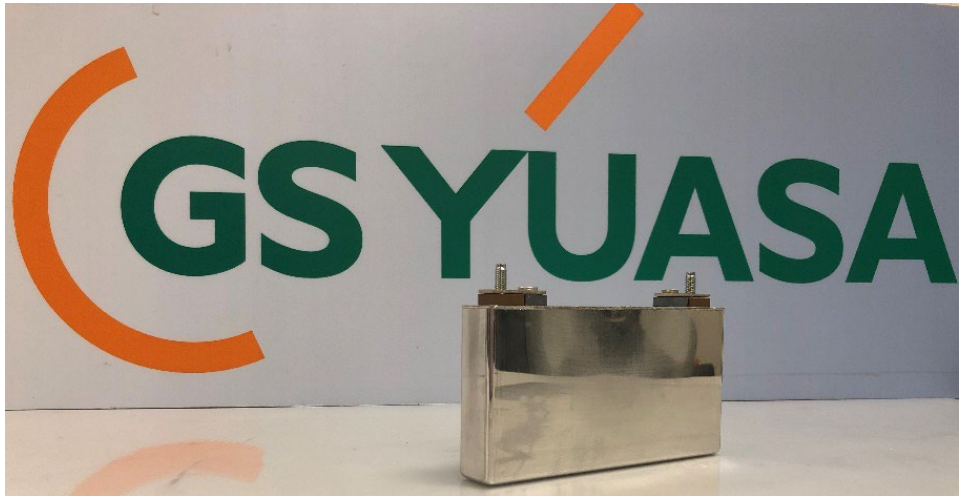
COTS 18650 data reference:
F. C. Krause et al 2021 J. Electrochem. Soc. 168 040504

LSE12x Generation 4 LCO-Graphite Chemistry

Voltage Performance vs. LG and Moli 18650 Cells

Cell	Cycle
LSE12x	4.1V to 2.75 @ 12A 20°C
LG M36	4.2V to 2.5V @ 1.8A, 24°C
Moli M35A	4.2V to 2.5V @ 1.7A, 23°C





LG M36

Moli M35A

LSE12x discharging at 1.0C rate has superior voltage performance compared to COTS cells discharging at 0.5C rate

LSE12x Generation 4 LCO-Graphite Chemistry

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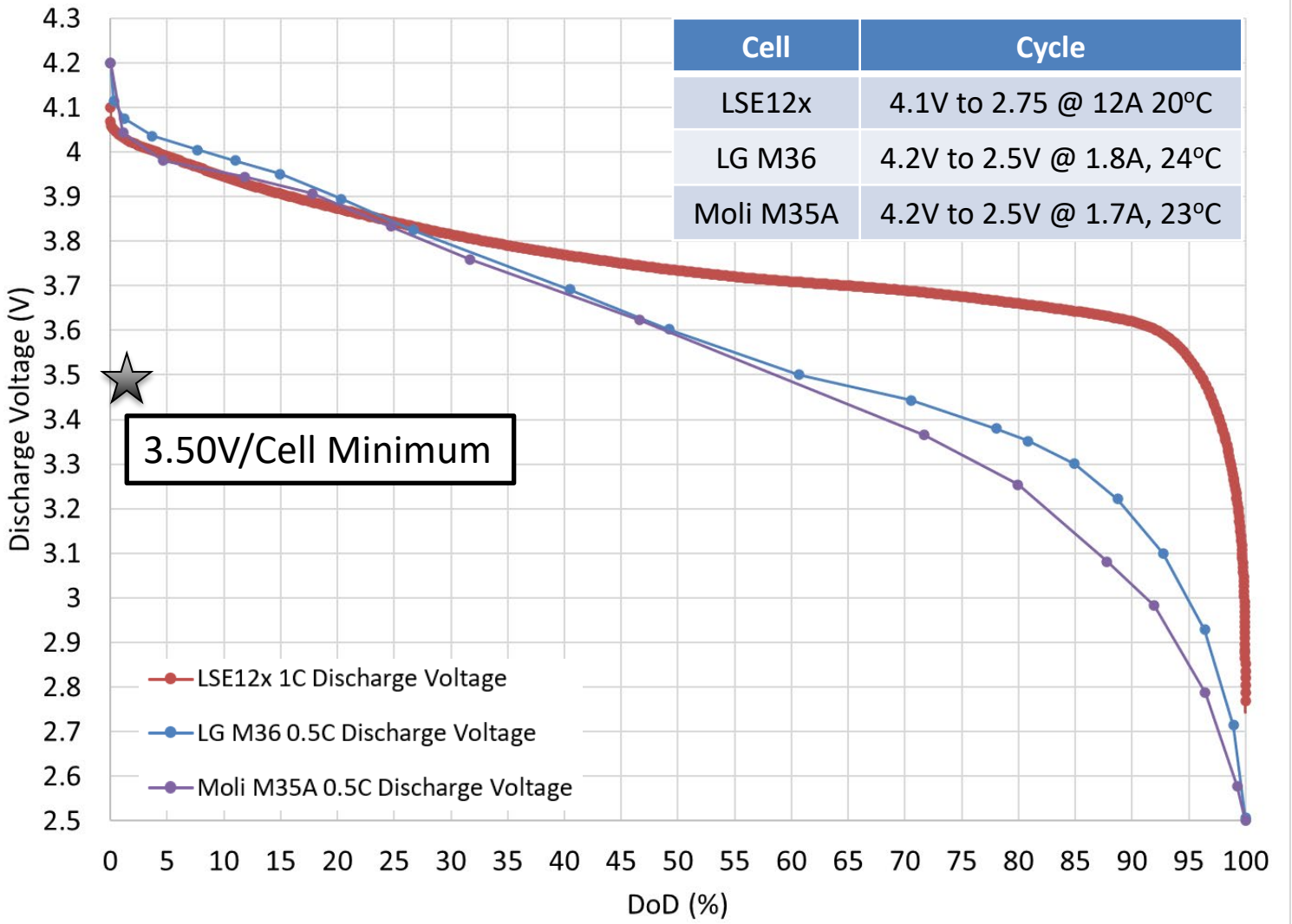

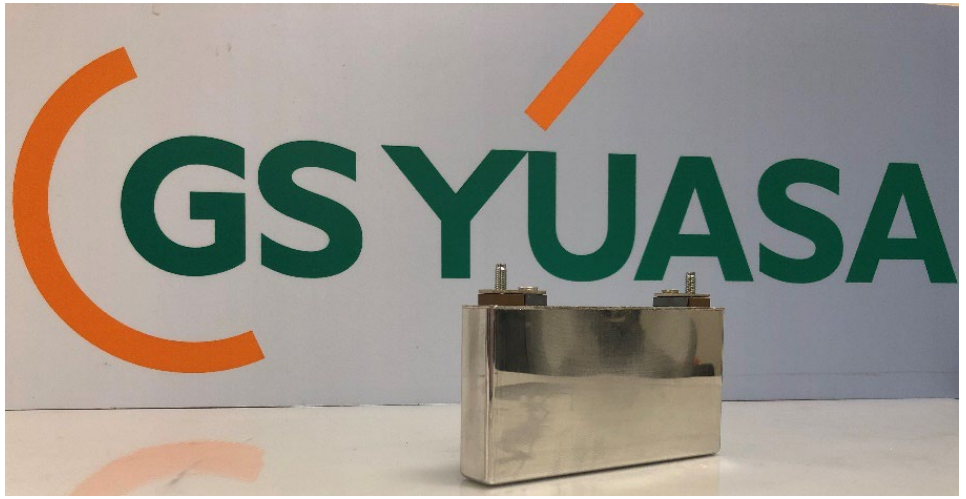

LG M36

Moli M35A

In the case of an unregulated bus architecture, a critical voltage lower bound is present, e.g. 3.50V/cell

LSE12x Generation 4 LCO-Graphite Chemistry

Voltage Performance vs. LG and Moli 18650 Cells

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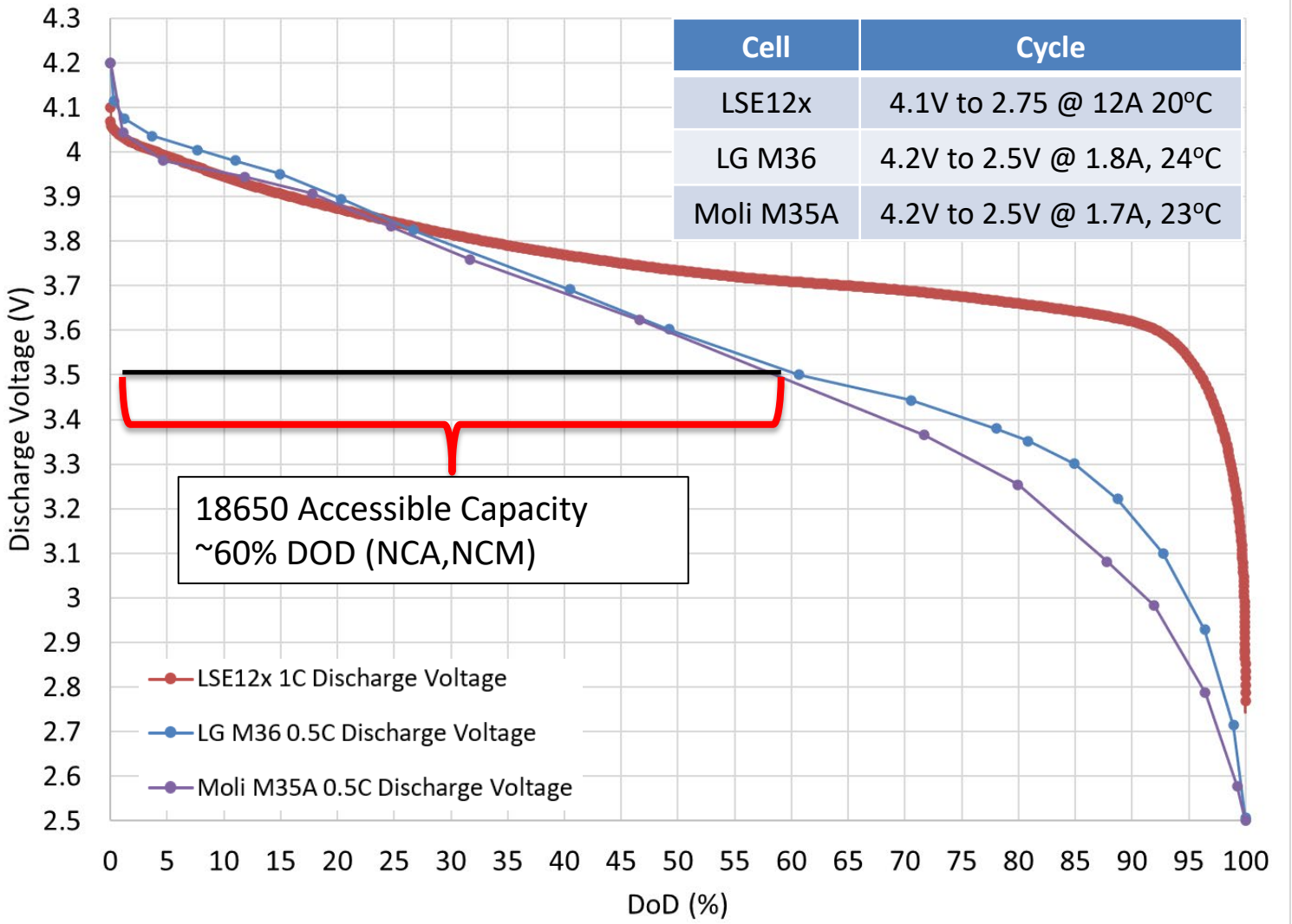

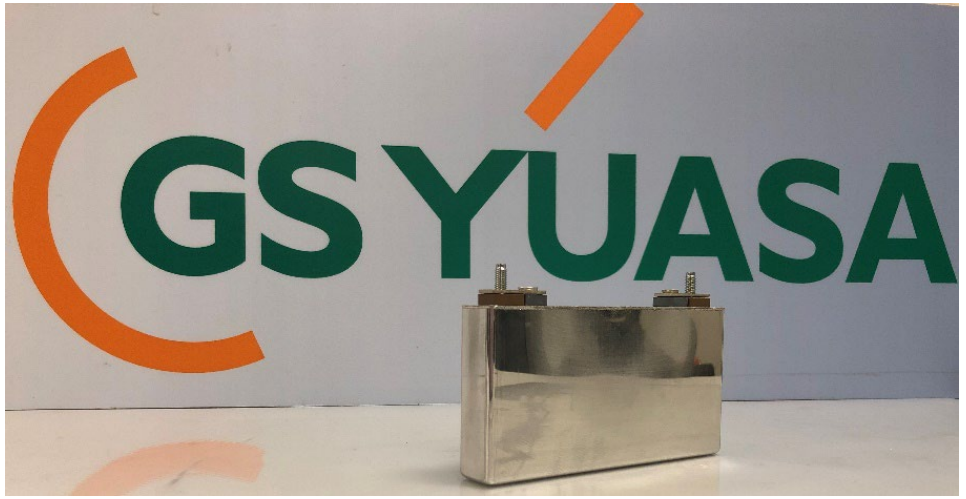

LG M36

Moli M35A

COTS 18650 cells can access only 60% of available capacity at 0.5C discharge rate. 3.45Ah cell is ~2.07Ah effectively (BOL)

LSE12x Generation 4 LCO-Graphite Chemistry

Voltage Performance vs. LG and Moli 18650 Cells

Cell	Cycle
LSE12x	4.1V to 2.75 @ 12A 20°C
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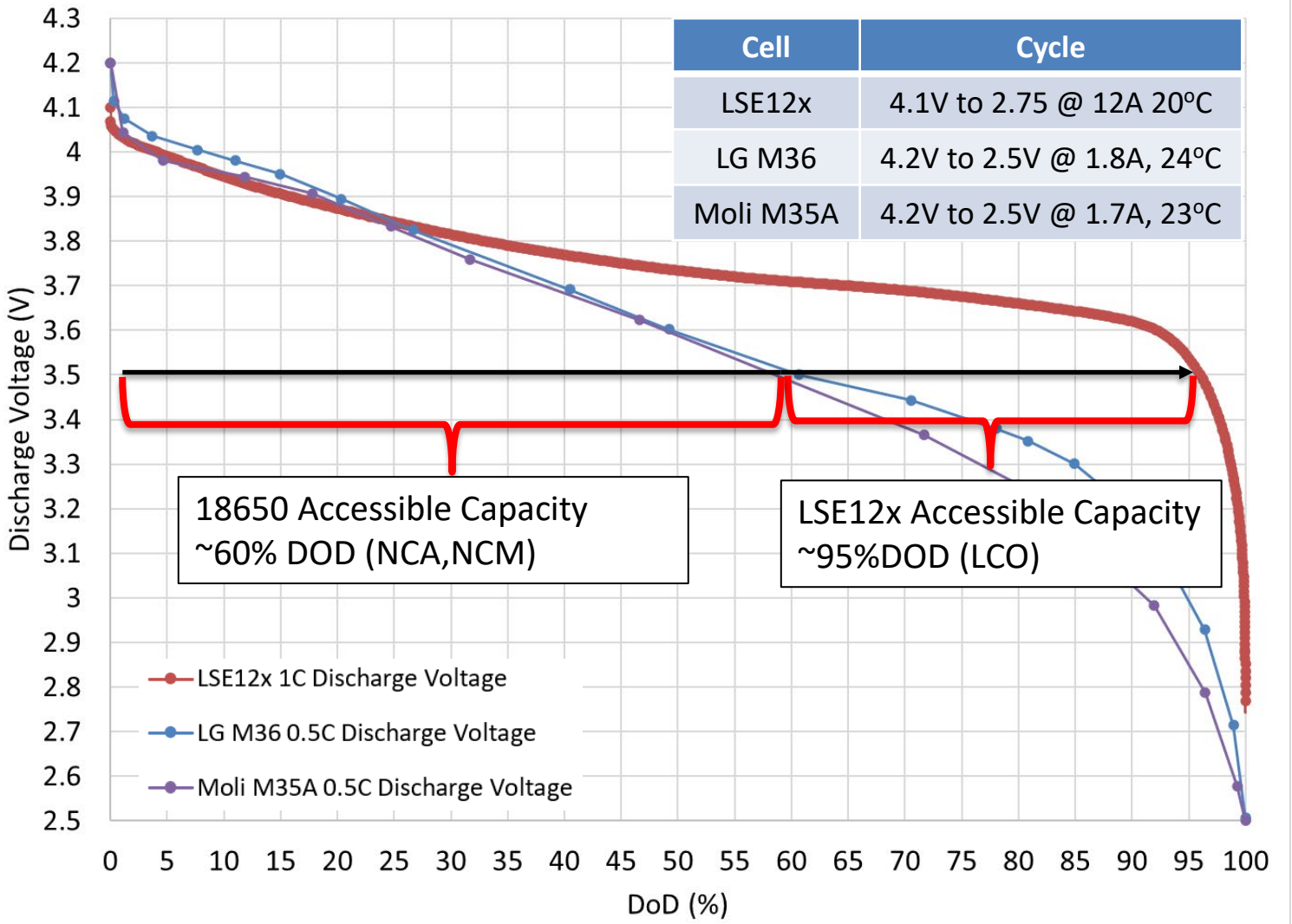
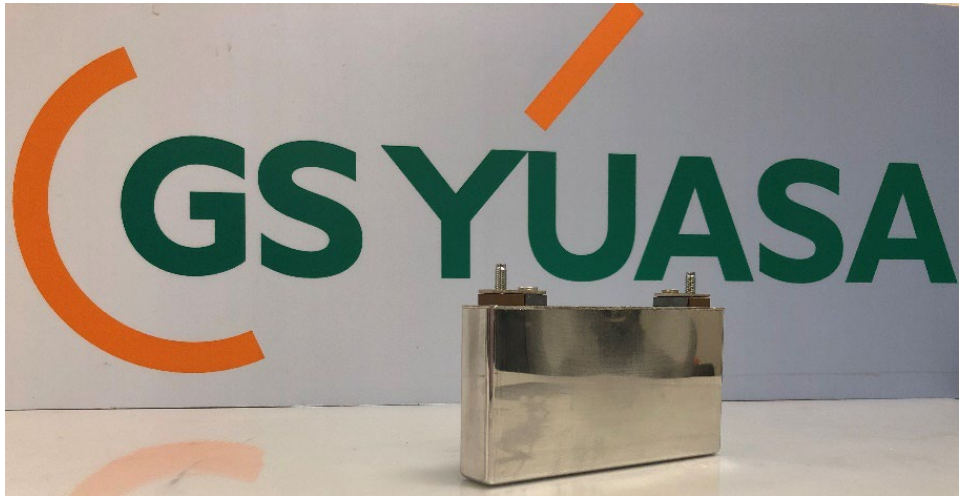




LG M36

Moli M35A

LSE12x Gen 4 cell has access to ~95% of available capacity at a 1C discharge rate. 13.54Ah cell can access 12.86 Ah (BOL)

Life and Performance Mission Modeling

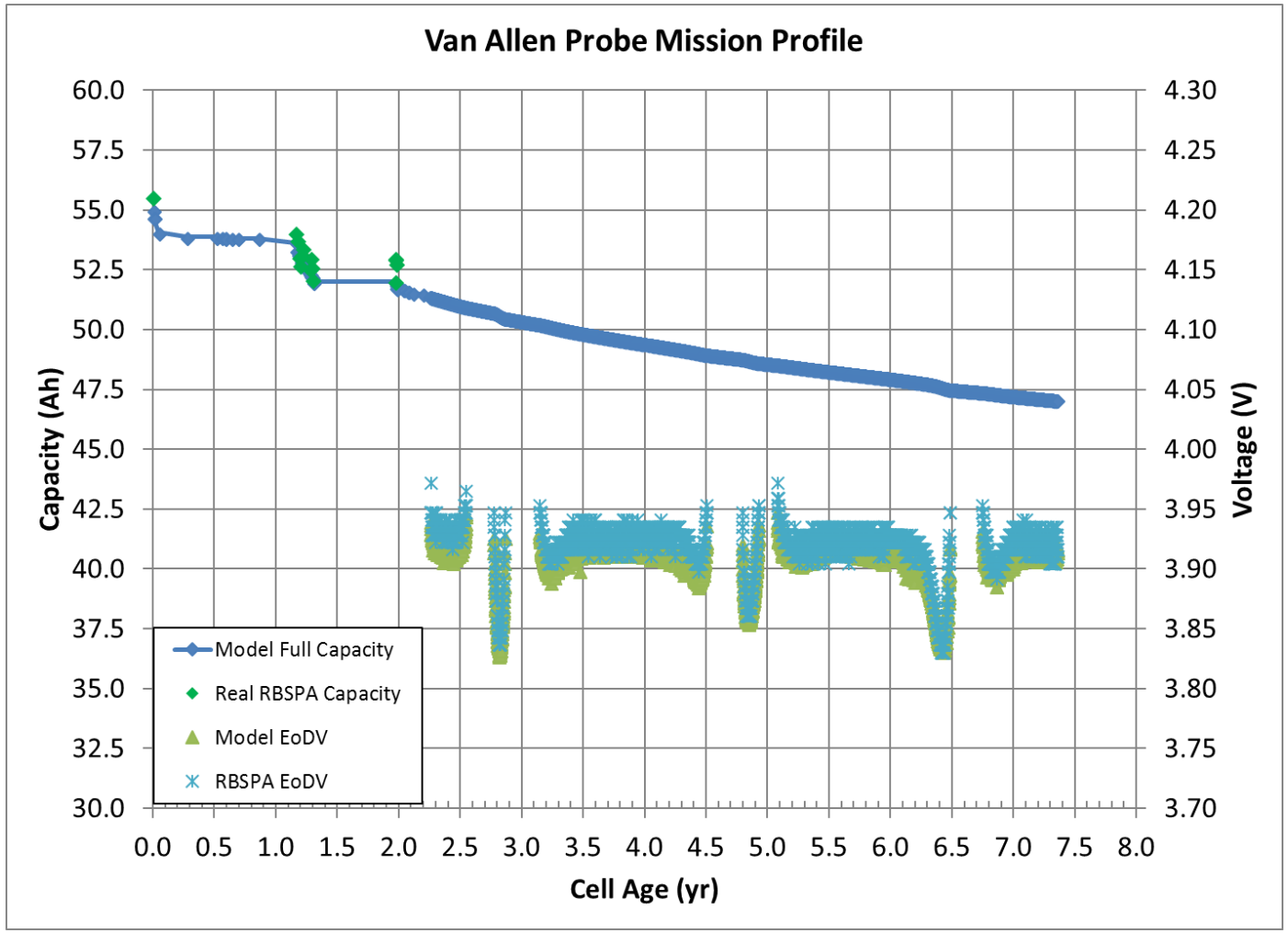
Cell Life Test Data and Model Validation

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 20+ years. Validated against real on-orbit data.

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

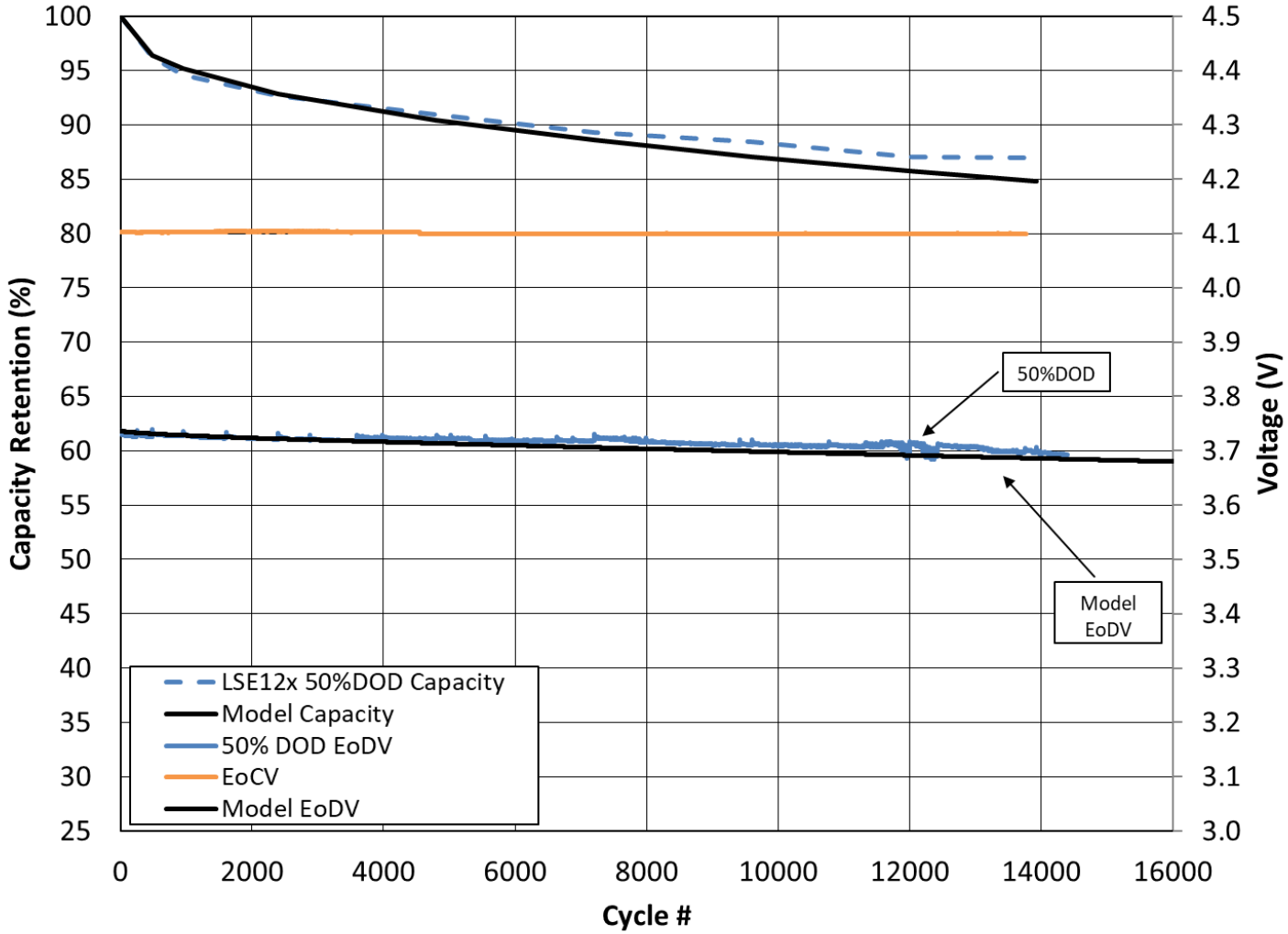
→ Full Charge Capacity
→ On-Orbit Capacity
→ End of Discharge Voltage

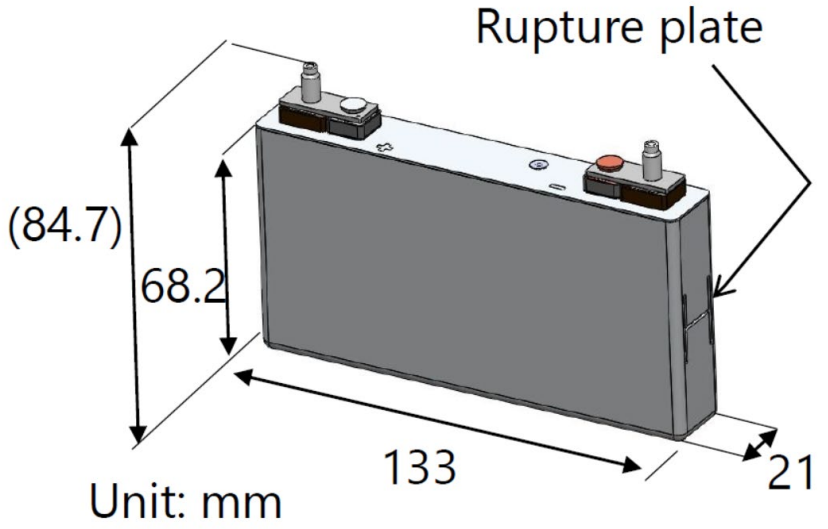


See GS Yuasa's SPW2014 Presentation for Modeling Capabilities and Validation

LSE12x Generation 4 LCO-Graphite Chemistry

Life and Performance Model





Cycle	Discharge	Charge
50%DOD	1.0C (12.0A) for 0.5hr	0.6C, 4.10V, CC/CV, 1hr

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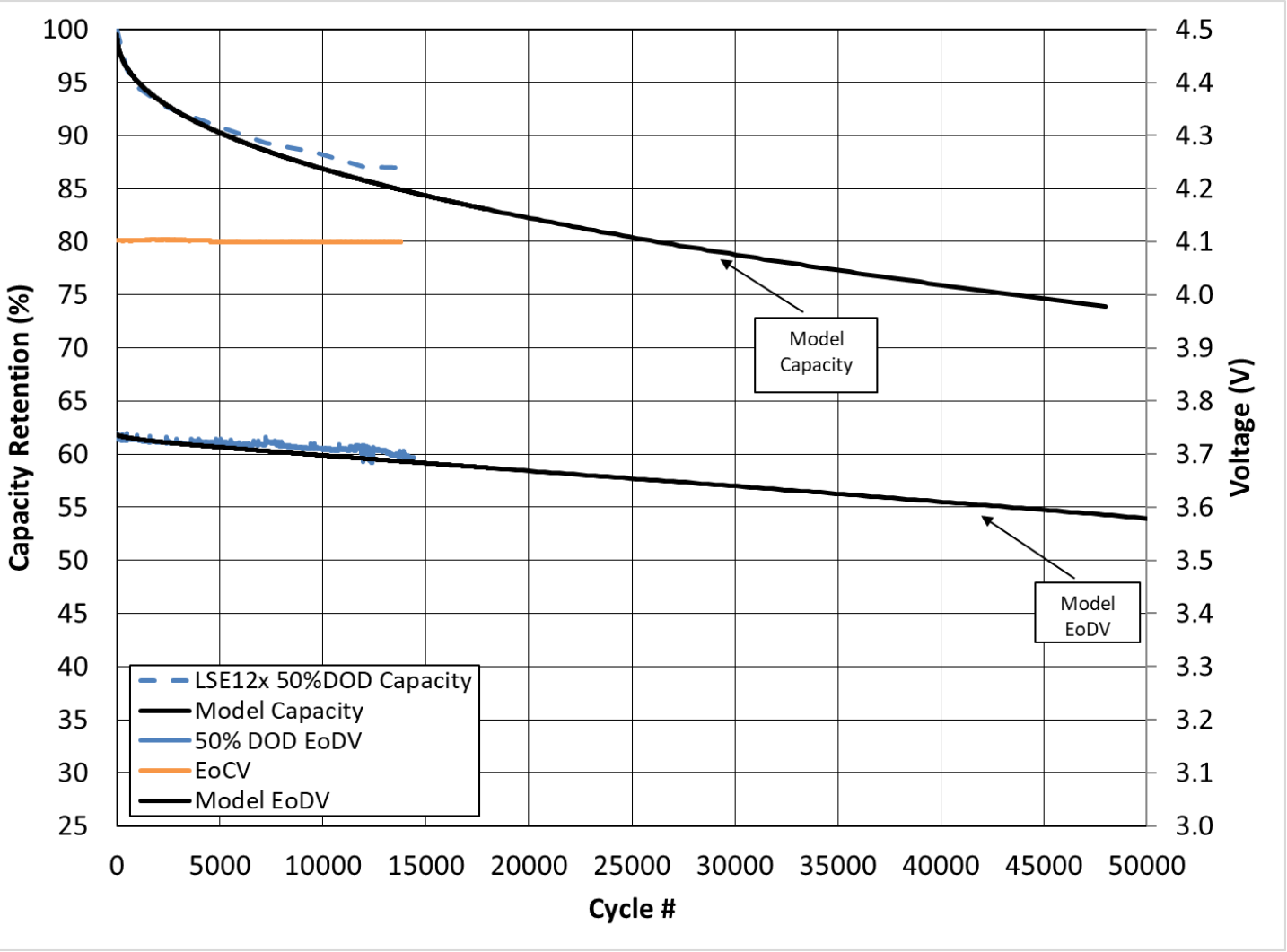
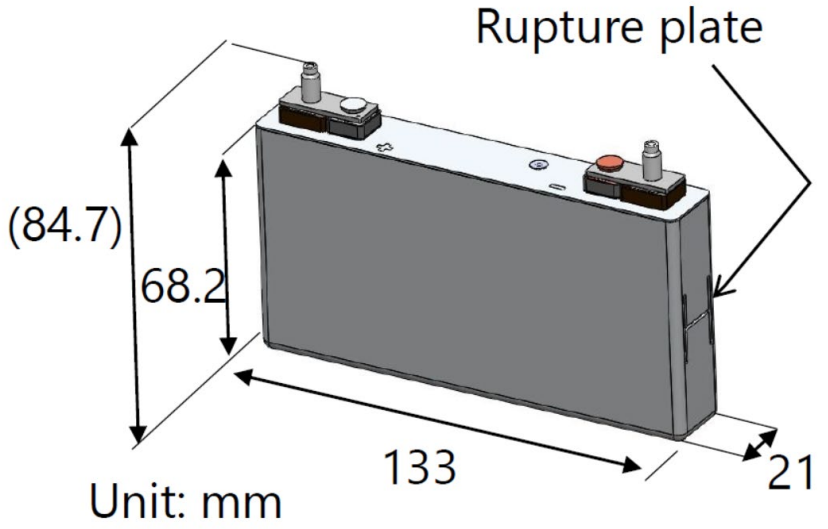
LSE12x Generation 4 LCO-Graphite Chemistry

Life and Performance Model





Cycle	Discharge	Charge
50%DOD	1.0C (12.0A) for 0.5hr	0.6C, 4.10V, CC/CV, 1hr

See GS Yuasa's SPW2023 Presentation for more Gen 4 Cycle Life Performance : https://gsyuasa-lp.com/news/gs-yuasa-lithium-power-presents-at-the-2023-aerospace-space-power-workshop/

ESPAStar-HP Mission Model

ESPAStar-HP™

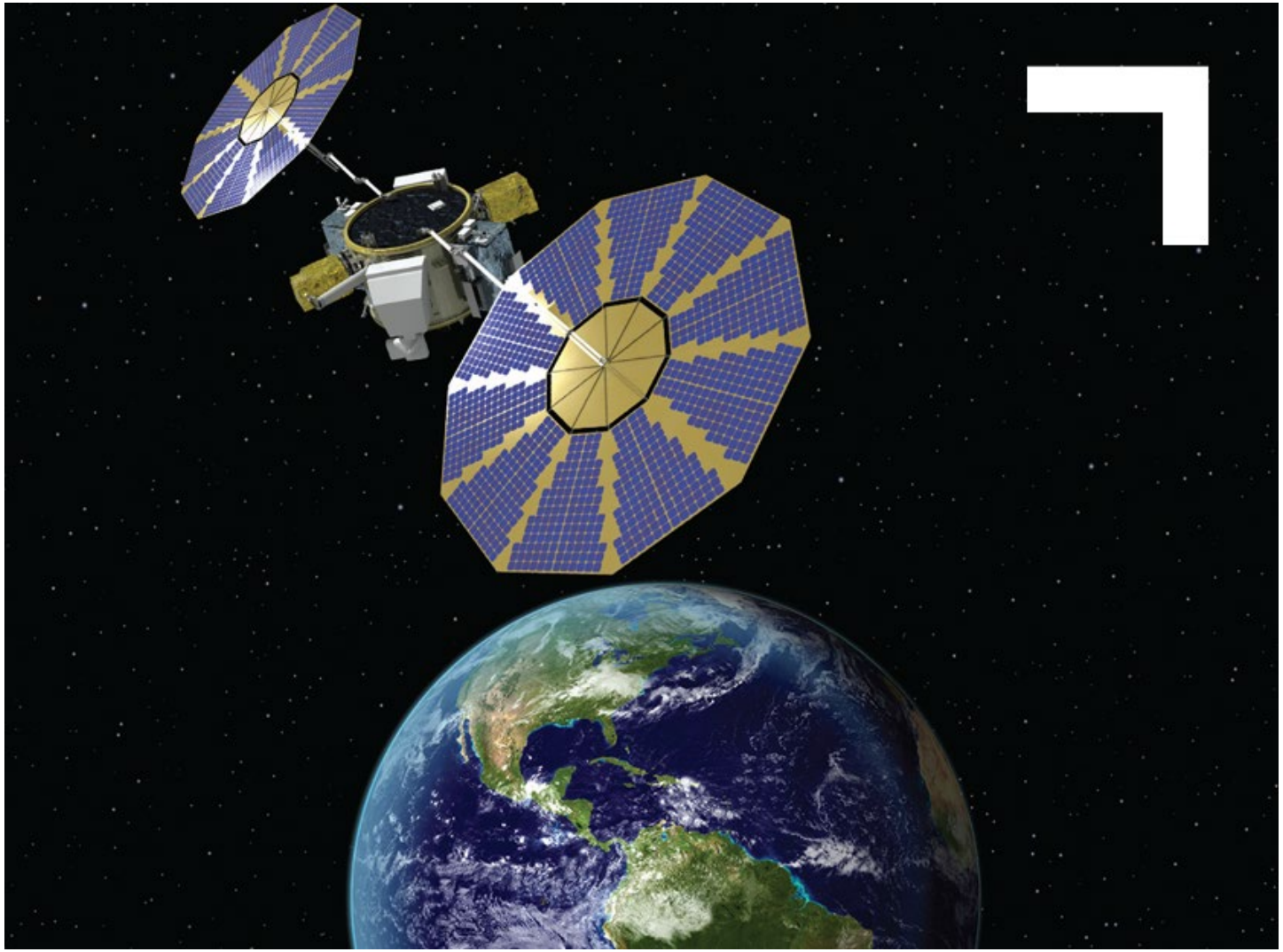
High Reliability Operational Access to Space

SPECIFICATIONS

SPACECRAFT

Orbit:	Optimized for GEO, adaptable for LEO and MEO missions
Targeted Mission Durations:	Five to seven years
Payload Power (OAP/PK):	3 kW (base), optionally up to 4 kW
Battery:	450 A-hr Li-ion

Source: https://www.northropgrumman.com/space/espastar



ESPAStar-HP Mission Model

7 Year GEO mission

Using the available literature from Northrup Grumman on the ESPAStar-HP platform, GYLP has prepared an example mission profile.

Durations	Event	Calendar Time (Days)	Storage SOC (%)	Number of Cycles	Maximum DoD or Power	Temperature	Remark
GYLP Activation, Testing and Storage	Supplier Testing and Storage*	414	10%	0	N/A	0°C	Cell aging phase (made to stock)
	Battery Build at GYLP	87	10%, 100%	6	N/A	0°C ,20°C	Manf/test
Ground storage	Battery delivery and storage	200	10	0		0°C	
Integration	Spacecraft: I&T Storage and Operation	90	50%	N/A	N/A	+20°C	
		20	100%	5	75	+20°C	
GEO Mission	Solstice	185.5	50	0		15	14 seasons (7 years)
	Eclipse	45	100	45	3.5kW (DOD variable)	15	

ESPAStar-HP™

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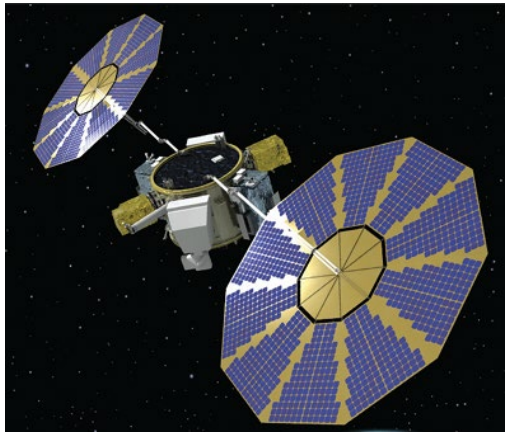
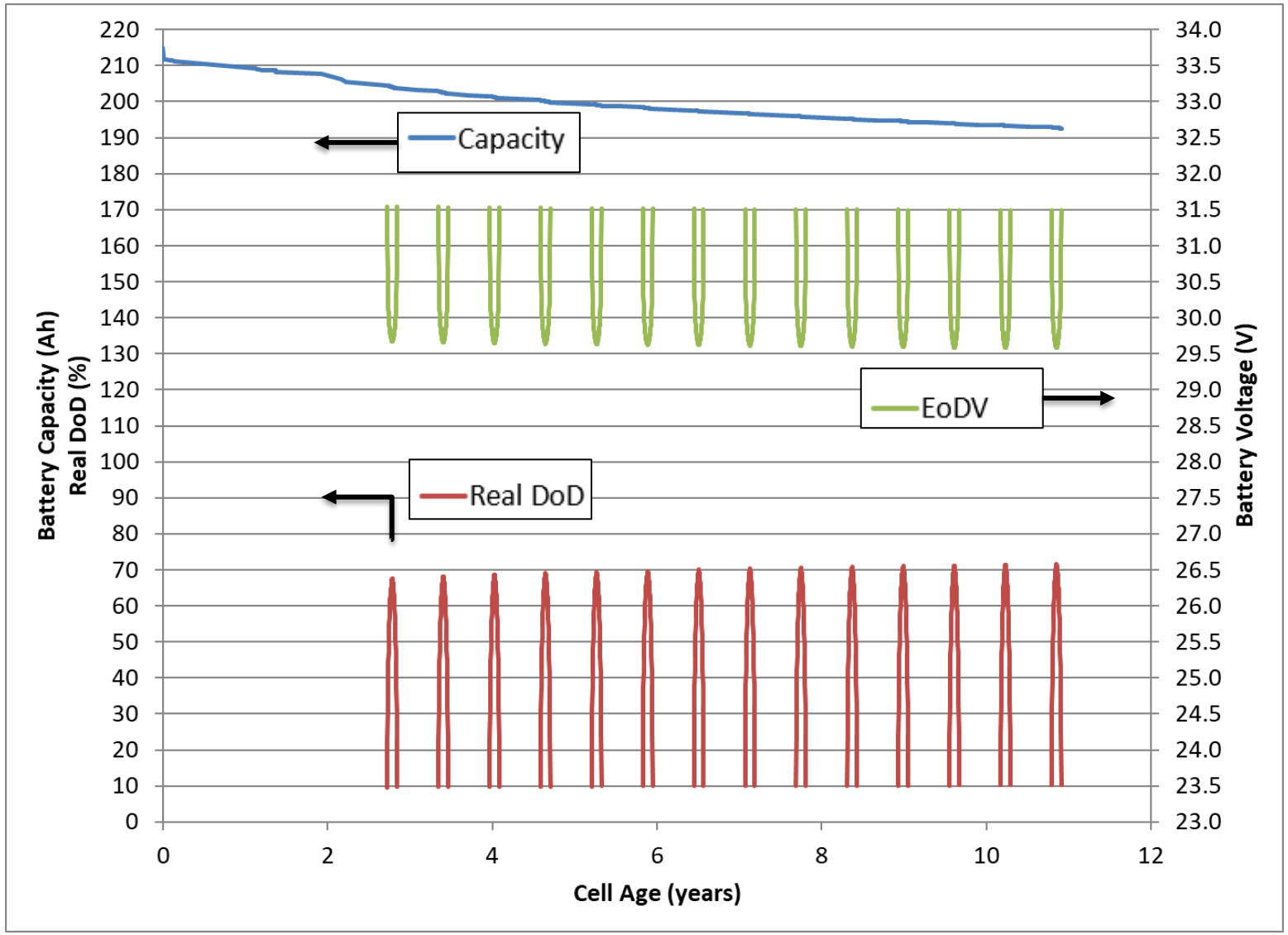


Source: https://www.northropgrumman.com/space/espastar

Using GS Yuasa's Life and Performance model it is possible to optimize an LSE12x battery to this particular use case!

ESPAStar-HP Example

7 Year GEO Mission



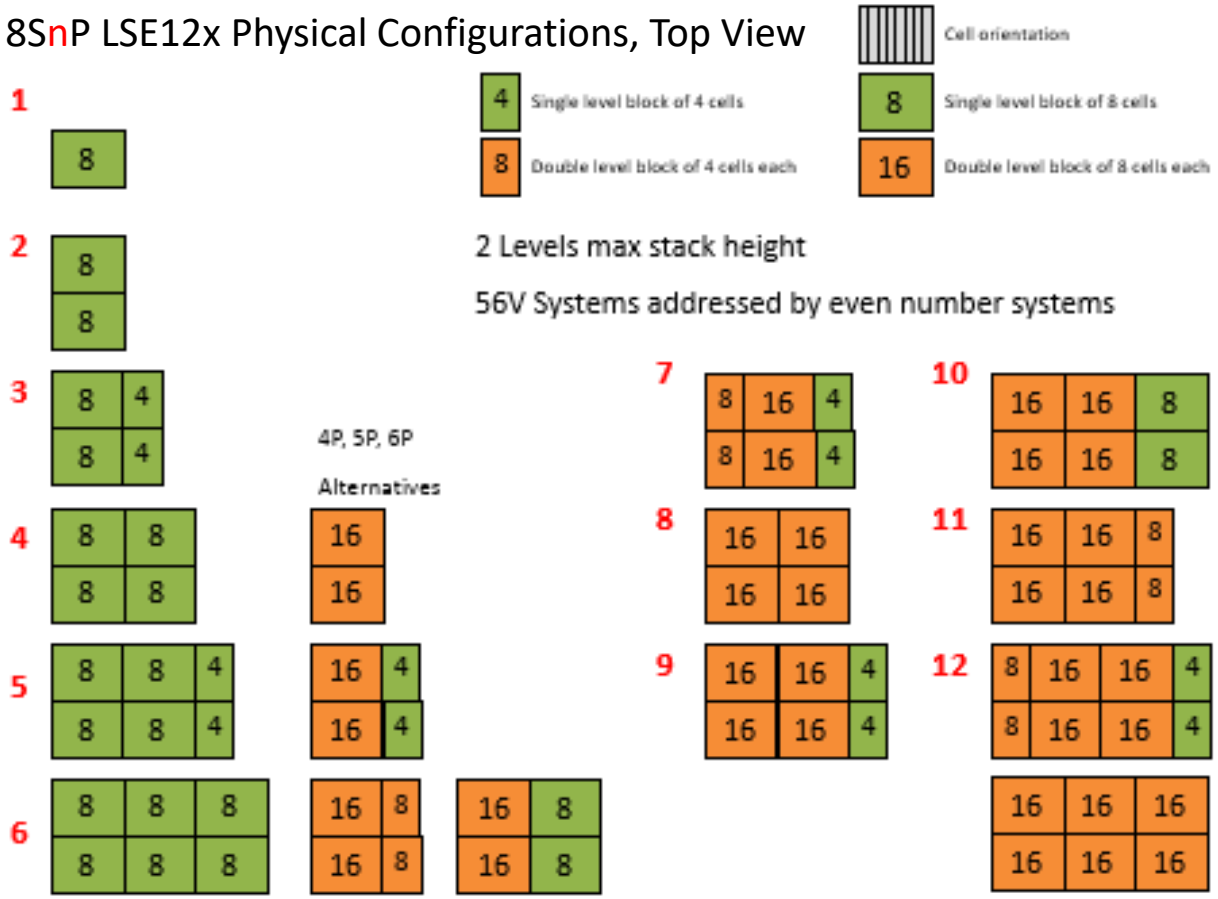
According to data sheet this spacecraft is equipped with a 450Ah battery.

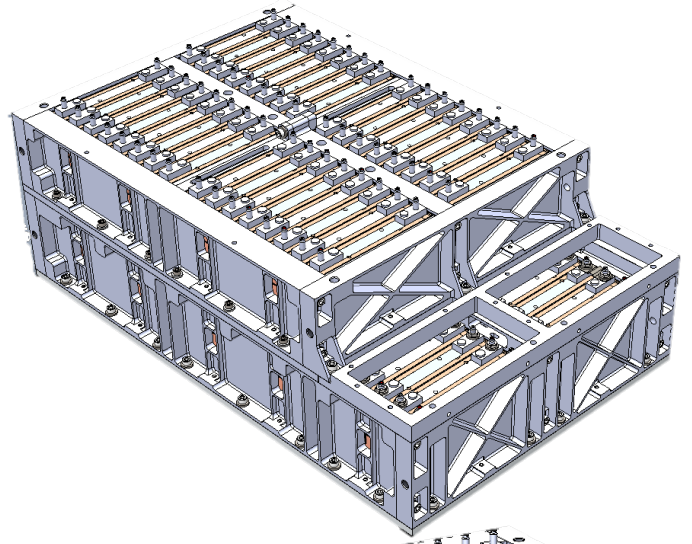
Assuming a 3.5kW payload in GEO. A 192Ah LSE12x battery (nameplate) can complete the mission. (16p8s configuration)

GS Yuasa Battery:
Last Season max EODV: 29.57V
Last Season max DOD: 71.66%

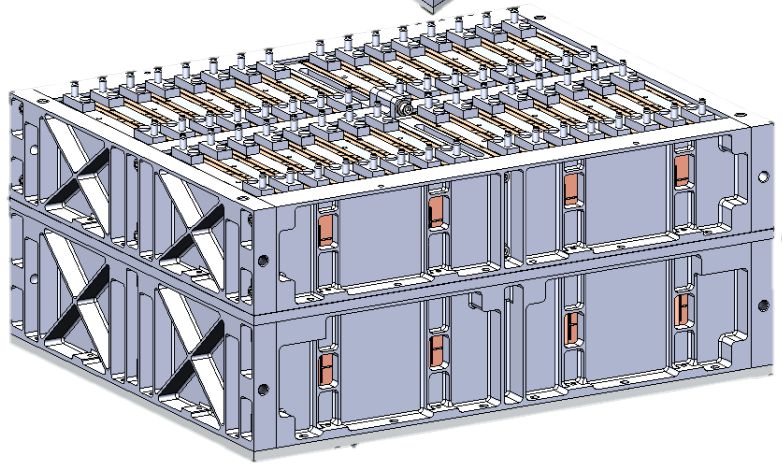
LSE12x Modular Battery Approach

- Modular concepts were developed using this design approach and several options were captured that could be qualified depending on customer needs.
- GYLP has decided to build and qualify an 9P8S configuration for the qualification unit since it has one of the larger bottom assemblies and is a two stack module.



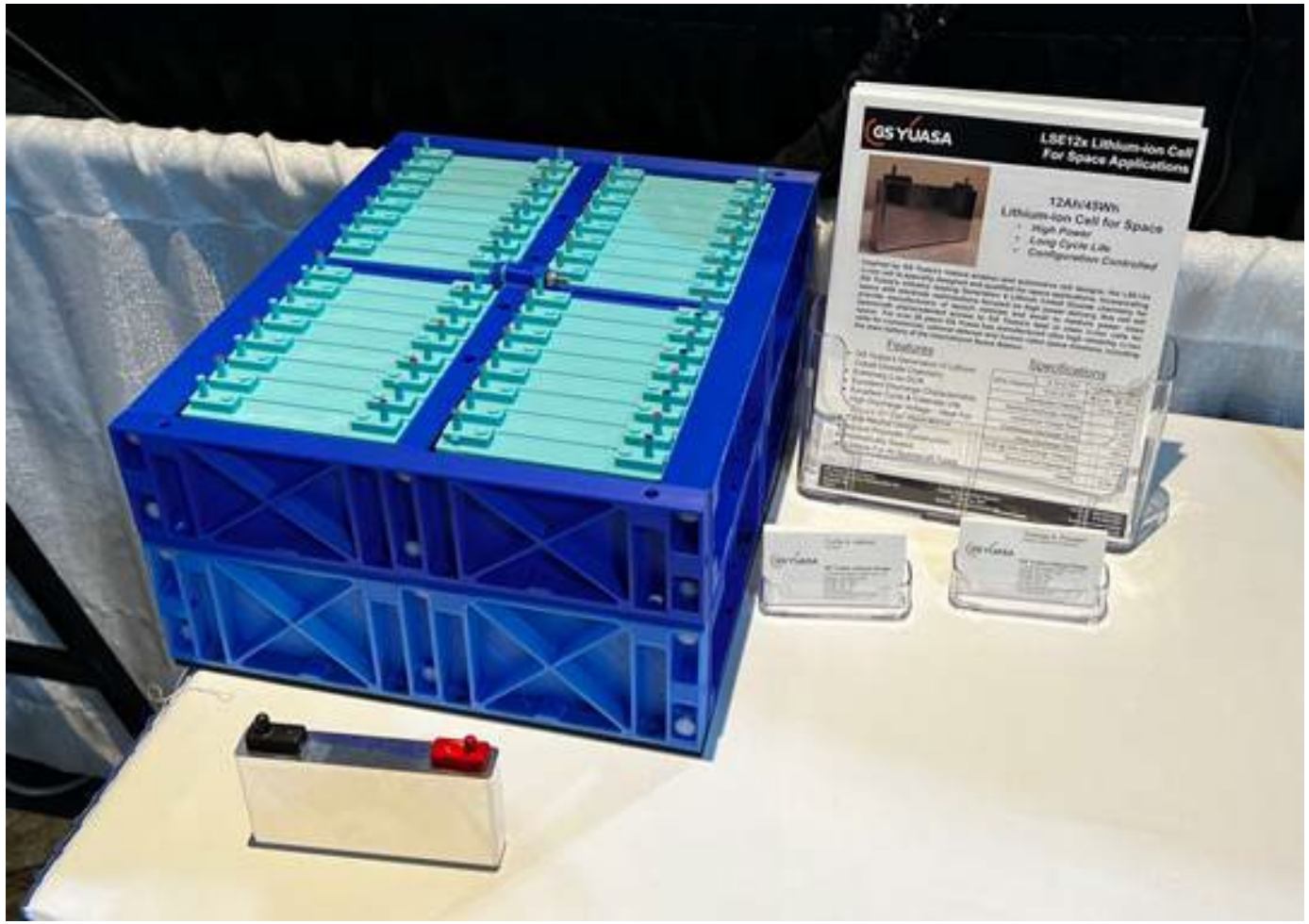


Config. 9 (72-cell) *Qual Unit*



Config 8 (64-cell)

MA12x-0808



"MA12x-0808" (8s8p)
3D printed scale model of 64-cell ~2.9kWh Pack

GYLP Production Readiness

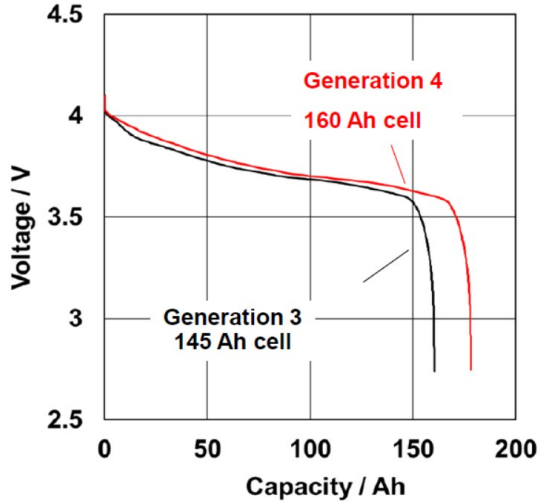
MA12x battery design and qualification:

- PDR: Complete
- CDR: Complete, MA12-0809 (8s9p)
- Qual Battery MRR/TRR: May 2024
- Qualification Complete: Q3/Q4 2024
- Production: Q1 2025
  - → Target continuous manufacturing capability is one 8s8p battery per week (2.9kWh/week)
  - → Less than 6-month lead time ARO for first unit to support constellation opportunities.
  - → GYLP is pursuing facility upgrades to our Roswell, Ga facility to enable this production rate.

GYLP is internally funding all design and qualification efforts for the MA12x portfolio of batteries. This schedule could be impacted by existing and new business. Schedule could be accelerated with help from an anchor tenant for the MA12x battery.

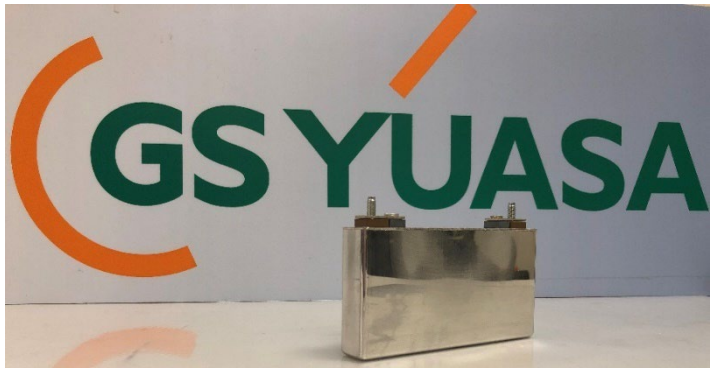
Summary

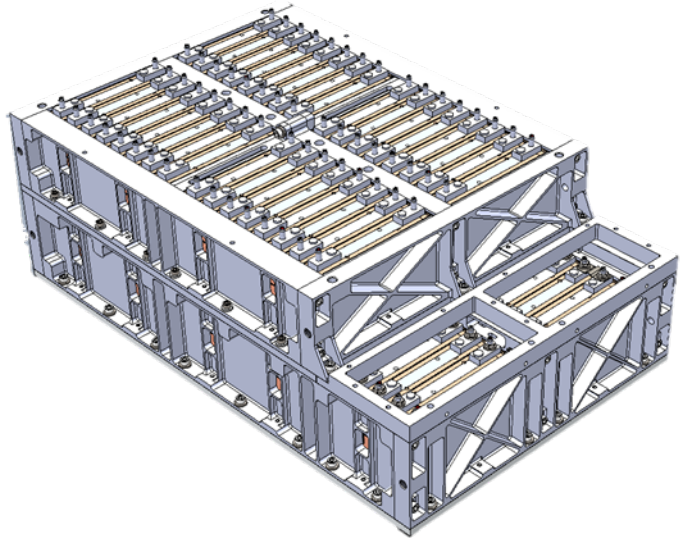
- GS Yuasa's Generation 4 LCO/Graphite chemistry provides meaningful performance increases from Generation 3 including:
  - Increased Energy Density
  - Excellent Capacity Retention under demanding cycle conditions
  - Decreased DCR for enhanced voltage performance under load



- 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

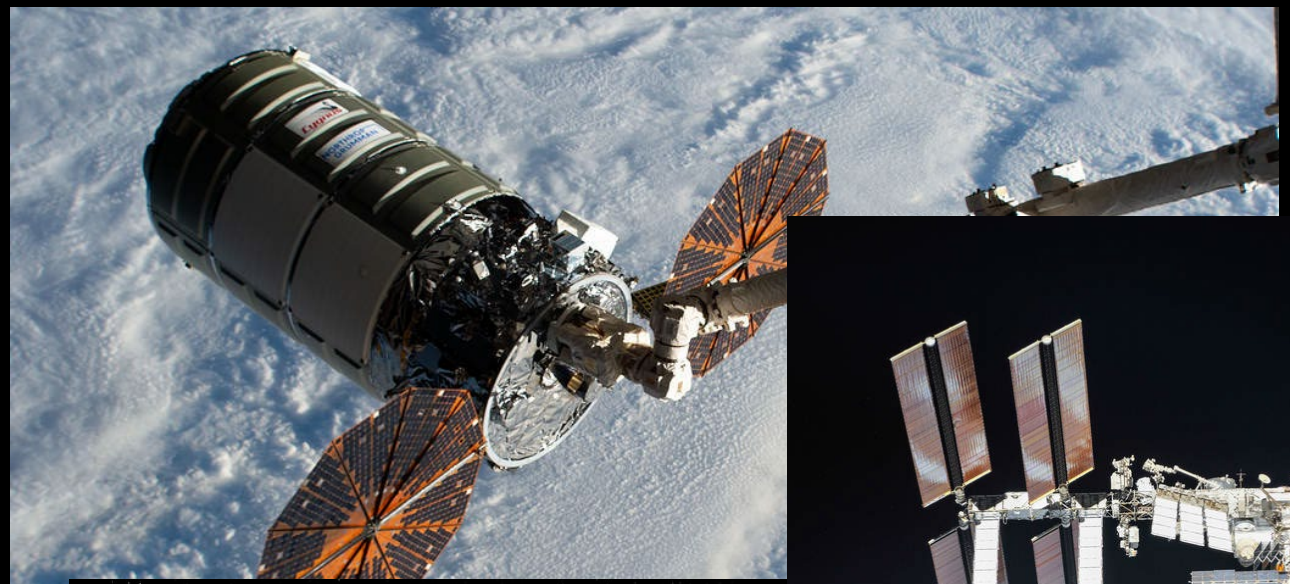


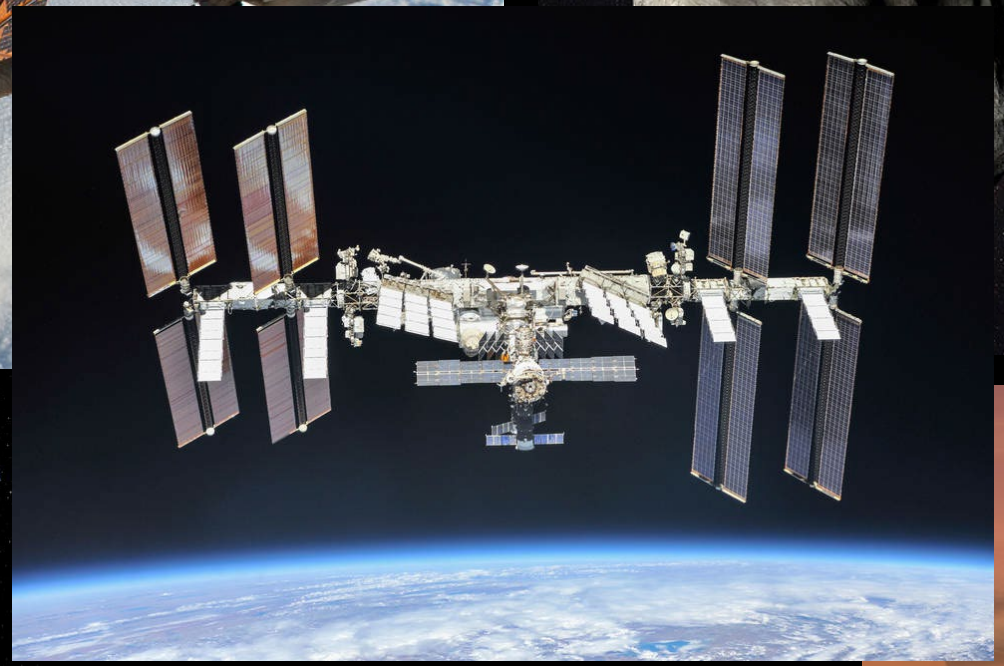


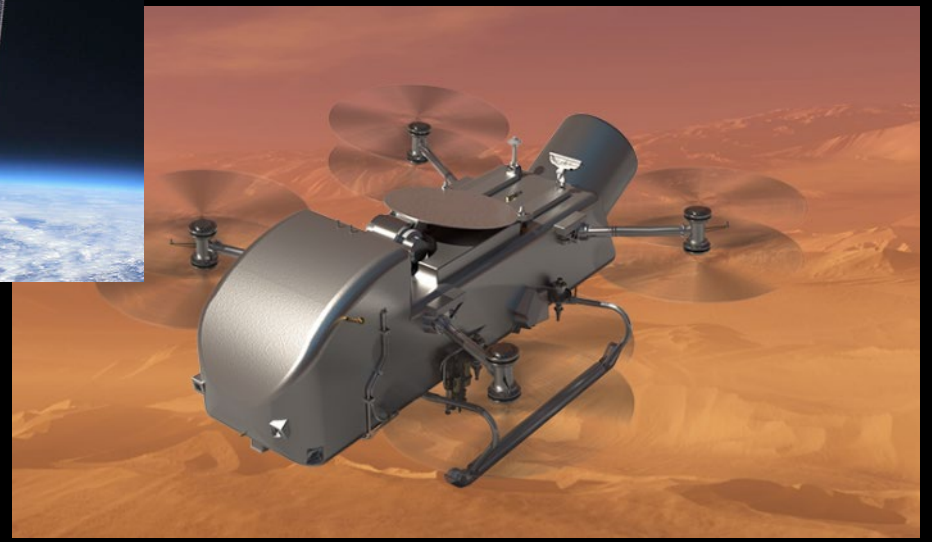
Energy storage design test and manufacturing expertise

Industry leading spaceflight heritage

Validated and reliable performance modelling







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