GS Yuasa LSE12x Cell and Battery Update

Prepared for
NASA Battery Workshop 2023

November 14-16, 2023

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Go Honda, Hiroki Fuse, Masazumi Segawa - GYT

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
- MA12x battery and manufacturing capability at GYLP (Roswell, Ga, USA)

GS Yuasa Company Overview

GS YUASA

GS Yuasa Aerospace and Specialty Battery Groups

GS YUASA

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

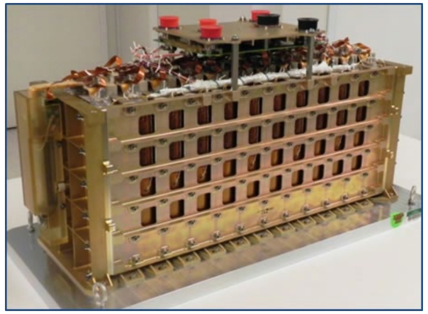
GS Yuasa Lithium Power, Inc. "GYLP"

- 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

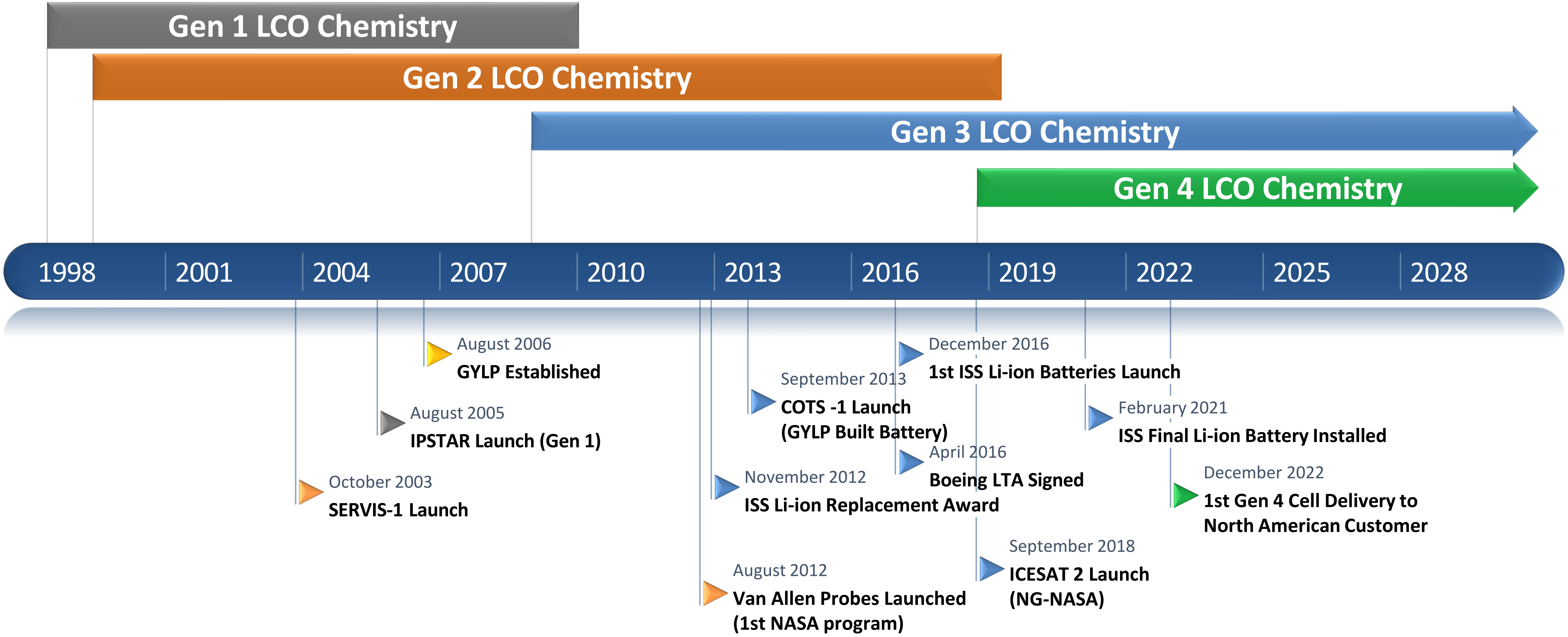
DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

RECIPROCAL DEFENSE PROCUREMENT MOU

June 2016, extended through June 2031

LSE Cell Heritage and Program Experience

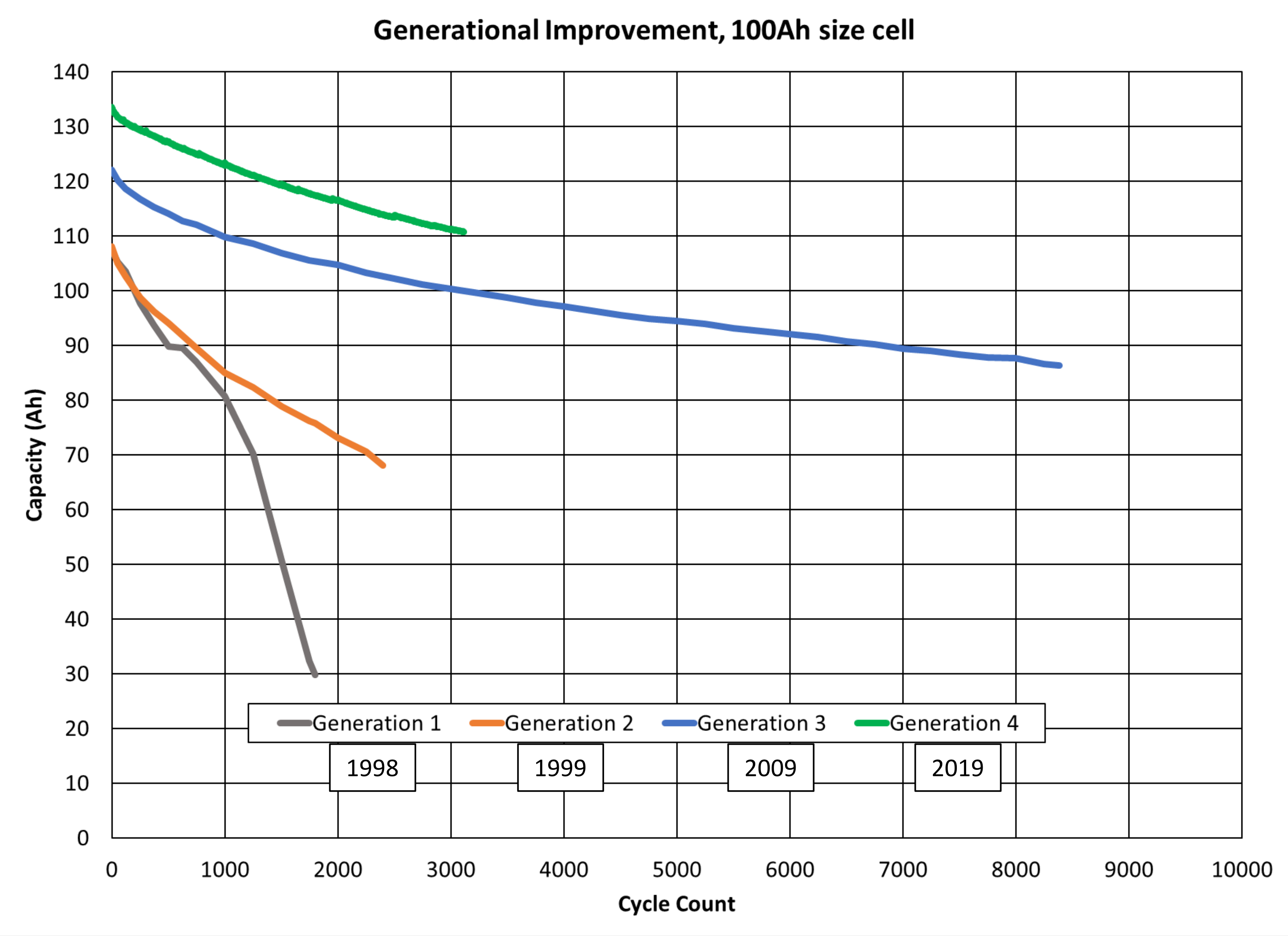
Timeline of GS Yuasa Space Chemistry



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

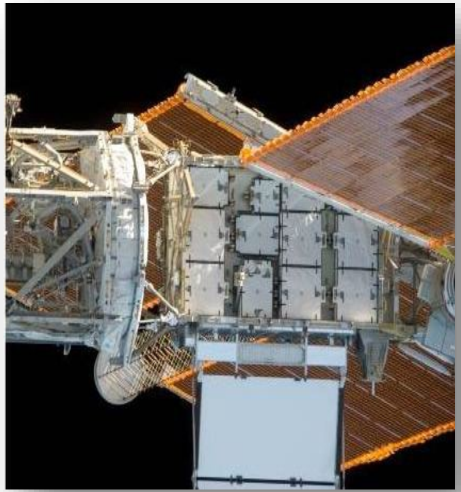
100Ah Class Cell, Energy Type



	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…………..…… 245+
- LEO/MEO……………….. 112+
- GEO……………………… 132
- Interplanetary…………… 1+

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.…..... >4.96 MWh (world leader)
Cell-hours flown in space………….. >619 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)……………………………. >1.04 MWh

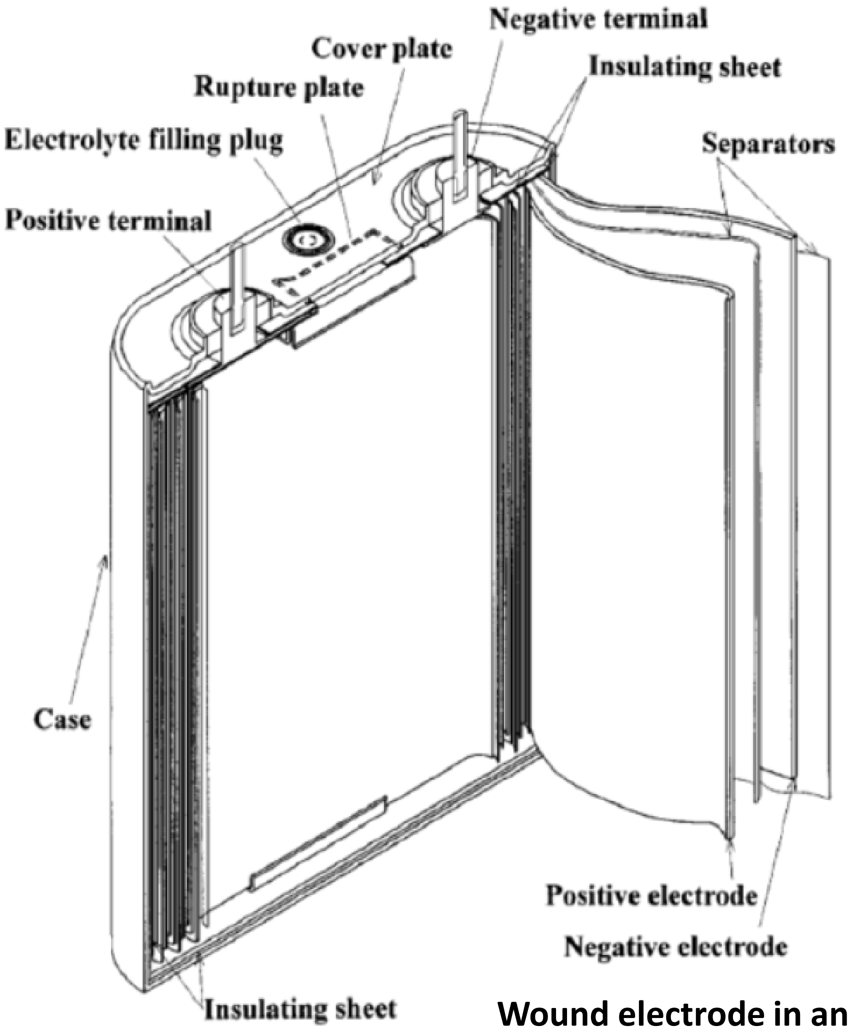
Launch vehicles & number of satellites

Ariane-5ECA	51	Soyuz-STB Fregat-MT	17	Epsilon	6
Falcon 9	28	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 November 2023

LSE Cell Basic Shape

Over 25 years of outstanding performance

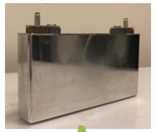


Wound electrode in an elliptical cylindrical case

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.

LSE Cell Configurations & Qualification Status

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



	Chemistry				Dimensions		
	Gen 3		Gen 4				
	Energy	Power	Energy	Power	Width	Thick	Height*
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

 NASA Battery Workshop 2023

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

LSE12x Design Objectives

Goal: Design and qualify a cost competitive small form factor cell that aligns with the market's expansion toward smaller and high power spacecraft.

Cell should achieve the following objectives:

- →Continue LSE cell reputation for ultra high reliability
  - Leverage heritage mechanical piece parts and processes to reduce risk
  - GS Yuasa's Generation 4 LCO-Graphite Space chemistry
- →Minimize user's program risk through complete configuration control and material traceability
- →Design for manufacturability and cost competitiveness

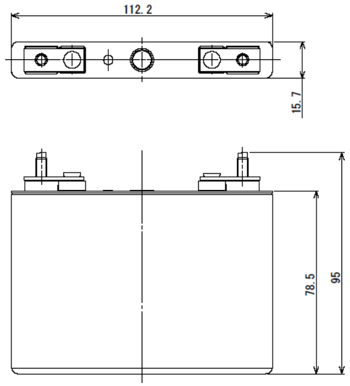
LSE12x Case Design

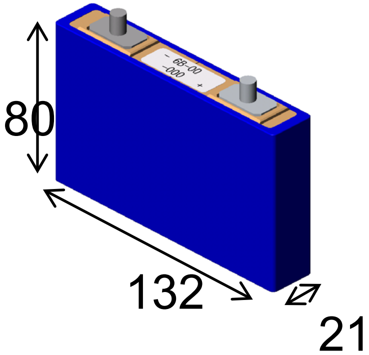
Fusion of Aviation and Automotive Cells

GS YUASA

Blue Energy

- EH5 Ultra high power cell for Honda/Acura hybrids





- LVP10 Cell for Aviation Applications

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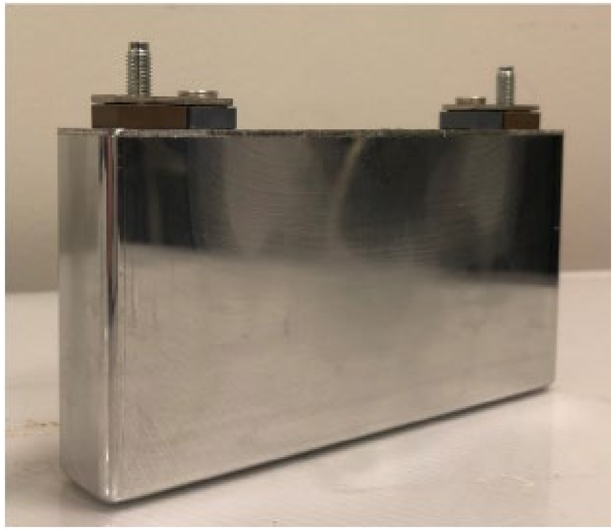
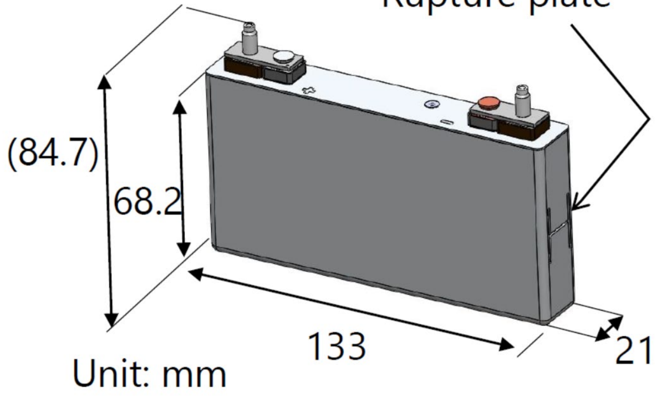
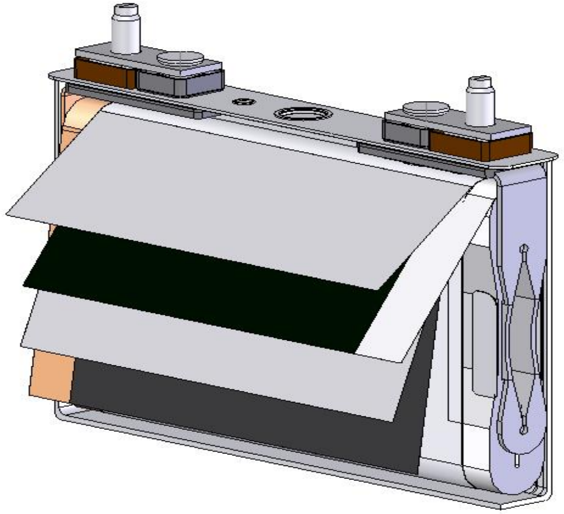
GS Yuasa Technology Ltd.



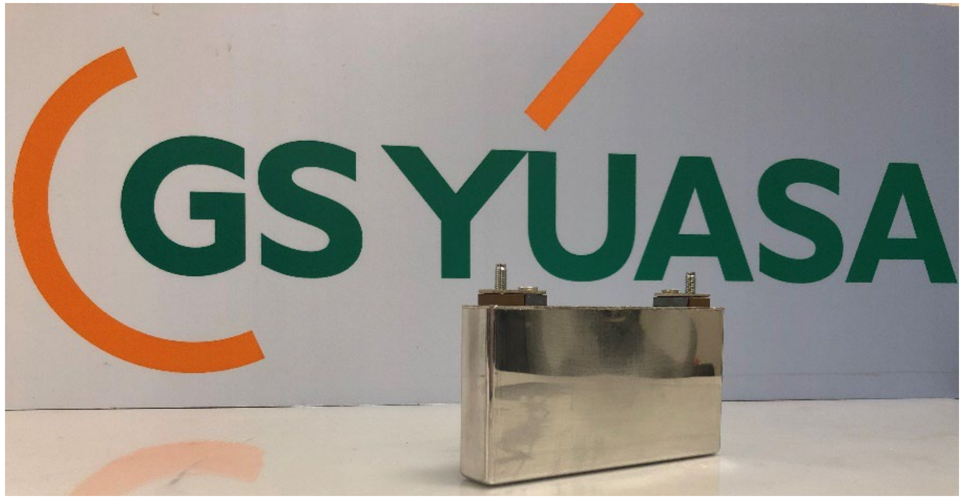




- Wound Element
- Aluminum Case
- Case Neutral Design
- Hermetically Sealed
- Ruggedized Current Collectors

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

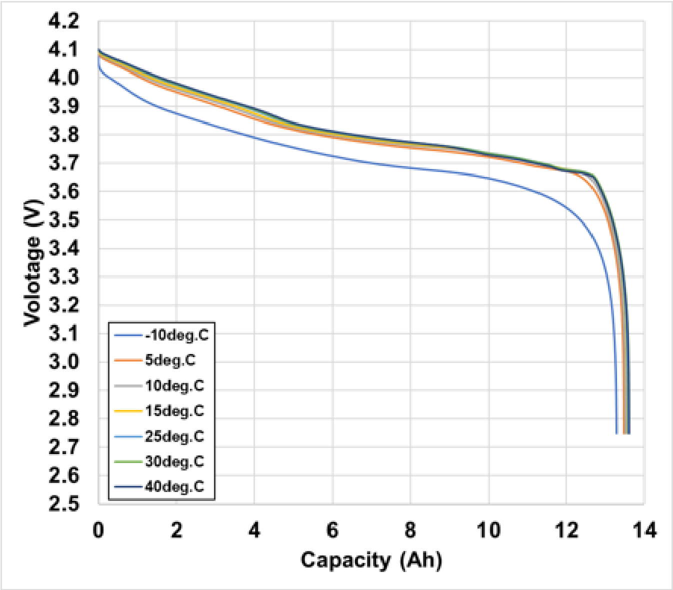
BOL Capacity	4.1V-2.75V	13.6 Ah, 51.0Wh
	*4.2V-2.75V	15.0 Ah, 56.3Wh
Nameplate Capacity		12 Ah, 45Wh
Nominal Discharge Voltage		3.75 V
Continuous Charge Rate, 15°C		6A
Continuous Discharge Rate		24A
Pulse Discharge Rate		60+A
DCR @ 50% SOC, 15°C		<6 mΩ
Nominal Cell Impedance		1.1mΩ
Mass		0.390 kg

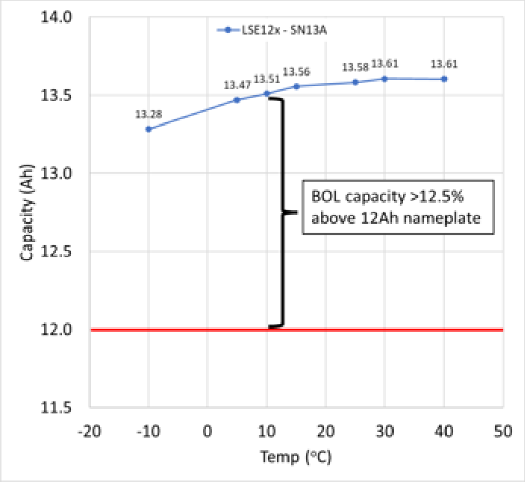
GS Yuasa validated Life and Performance model capability to allow for "right sizing" of a battery solution.

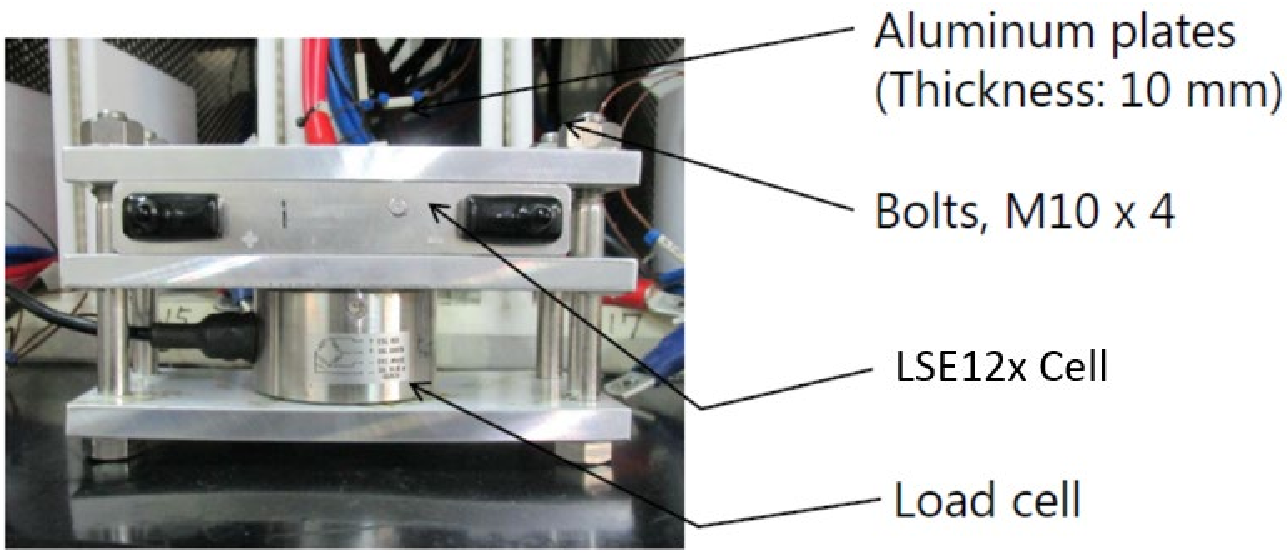
LSE12x Qualification

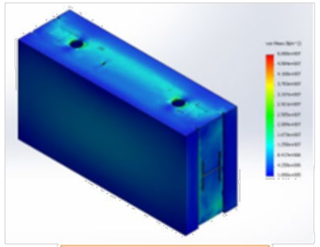
Aerospace Space Power Workshop 2022

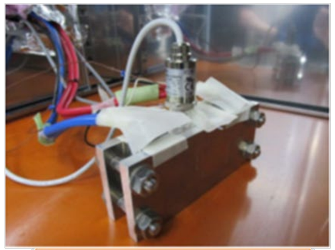
Cell completed qualification in December 2021. Results presented at Space Power Workshop 2022: https://gsyuasa-lp.com/news/gylp-presents-at-the-2022-aerospace-space-power-workshop/



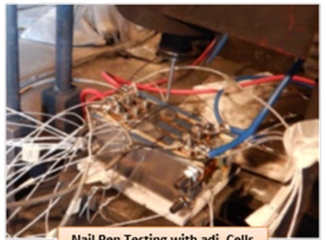





EOL Mechanical FEA

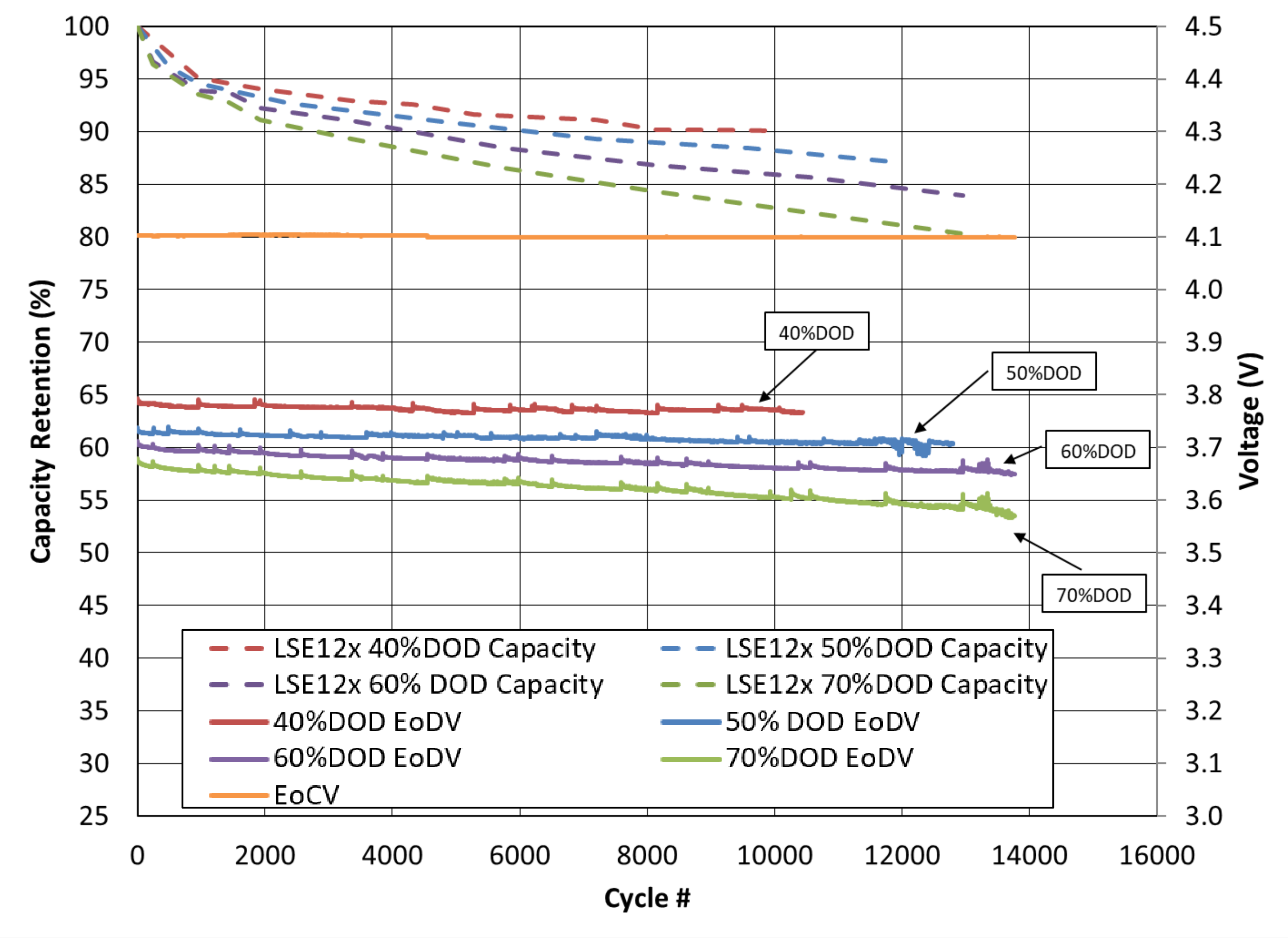

Cycle Internal Pressure Change Evaluation

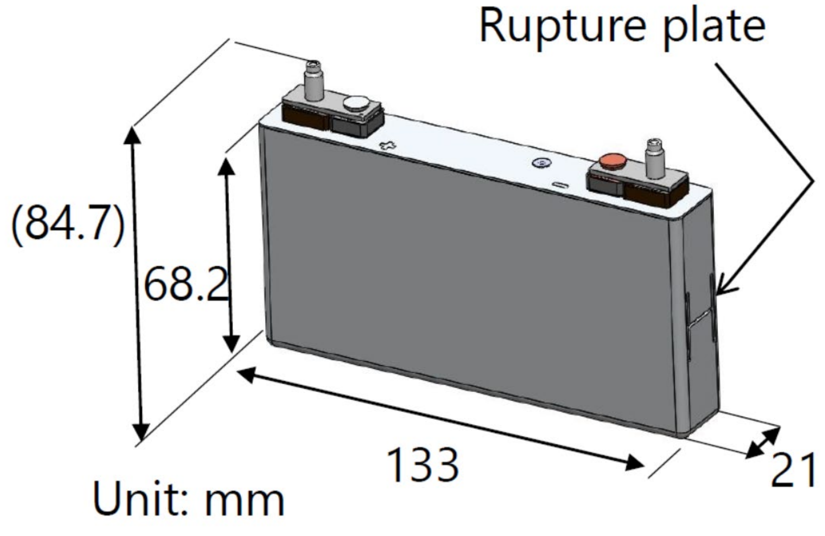

Case Bust Test


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

LSE12x Generation 4 LCO-Graphite Chemistry

High DOD LEO Cycling Life Test



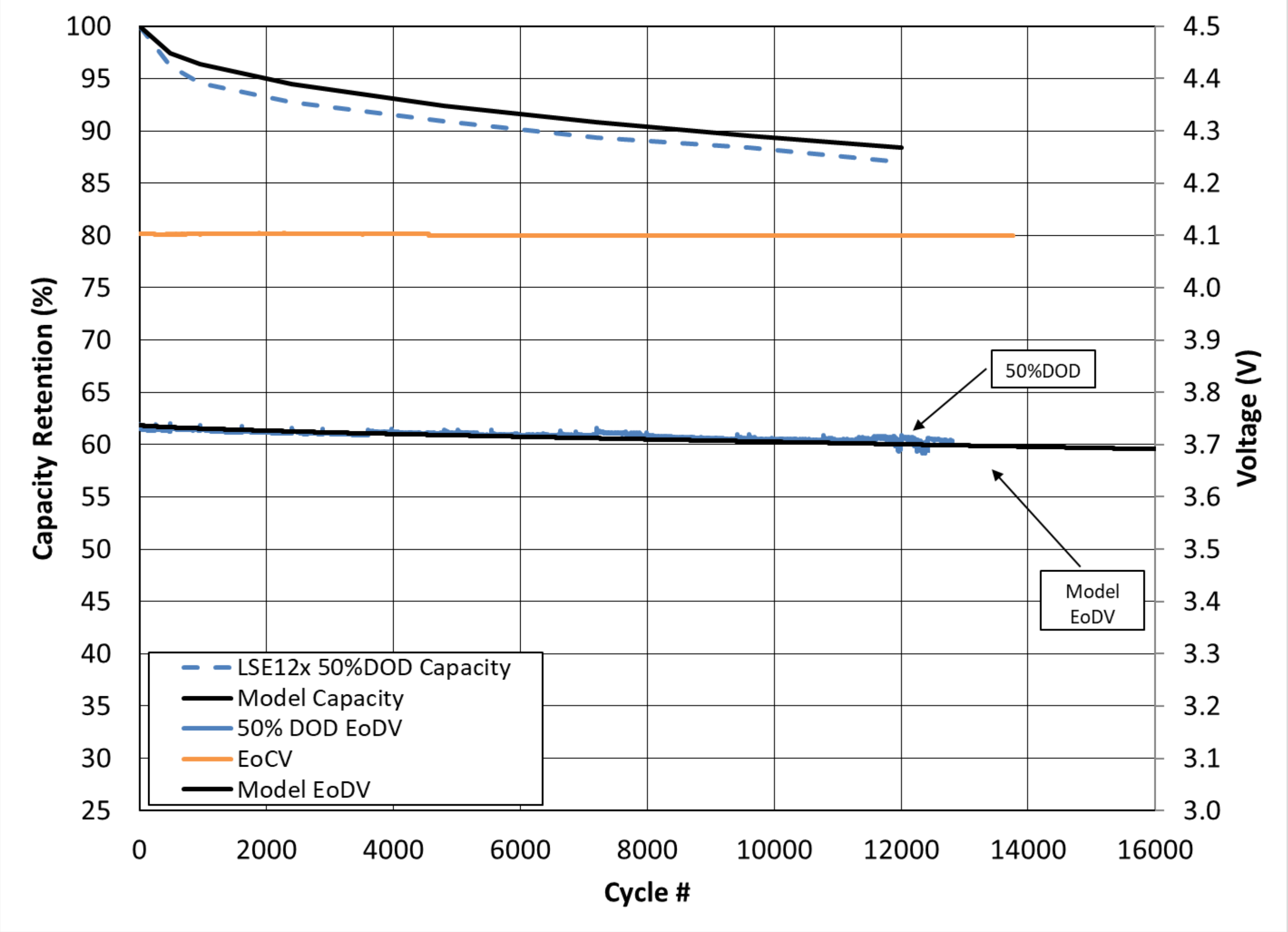


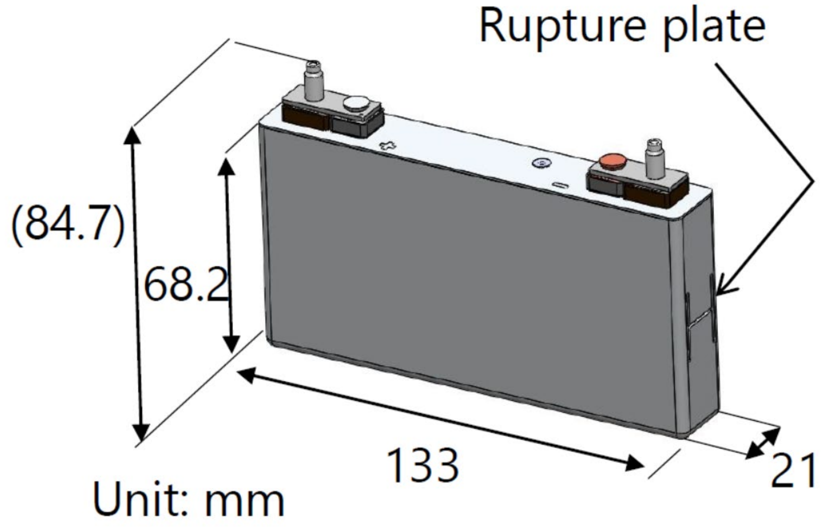
Cycle	Discharge	Charge
40%DOD	0.8C (9.6A) for 0.5hr	0.5C, 4.10V, CC/CV, 1hr
50%DOD	1.0C (12.0A) for 0.5hr	0.6C, 4.10V, CC/CV, 1hr
60%DOD	1.2C (14.4A) for 0.5hr	0.7C, 4.10V, CC/CV, 1hr
70%DOD	1.4C (16.8A) for 0.5hr	0.8C, 4.10V, CC/CV, 1hr

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 Generation 4 LCO-Graphite Chemistry

Life and Performance Model





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LSE12x Generation 4 LCO-Graphite Chemistry

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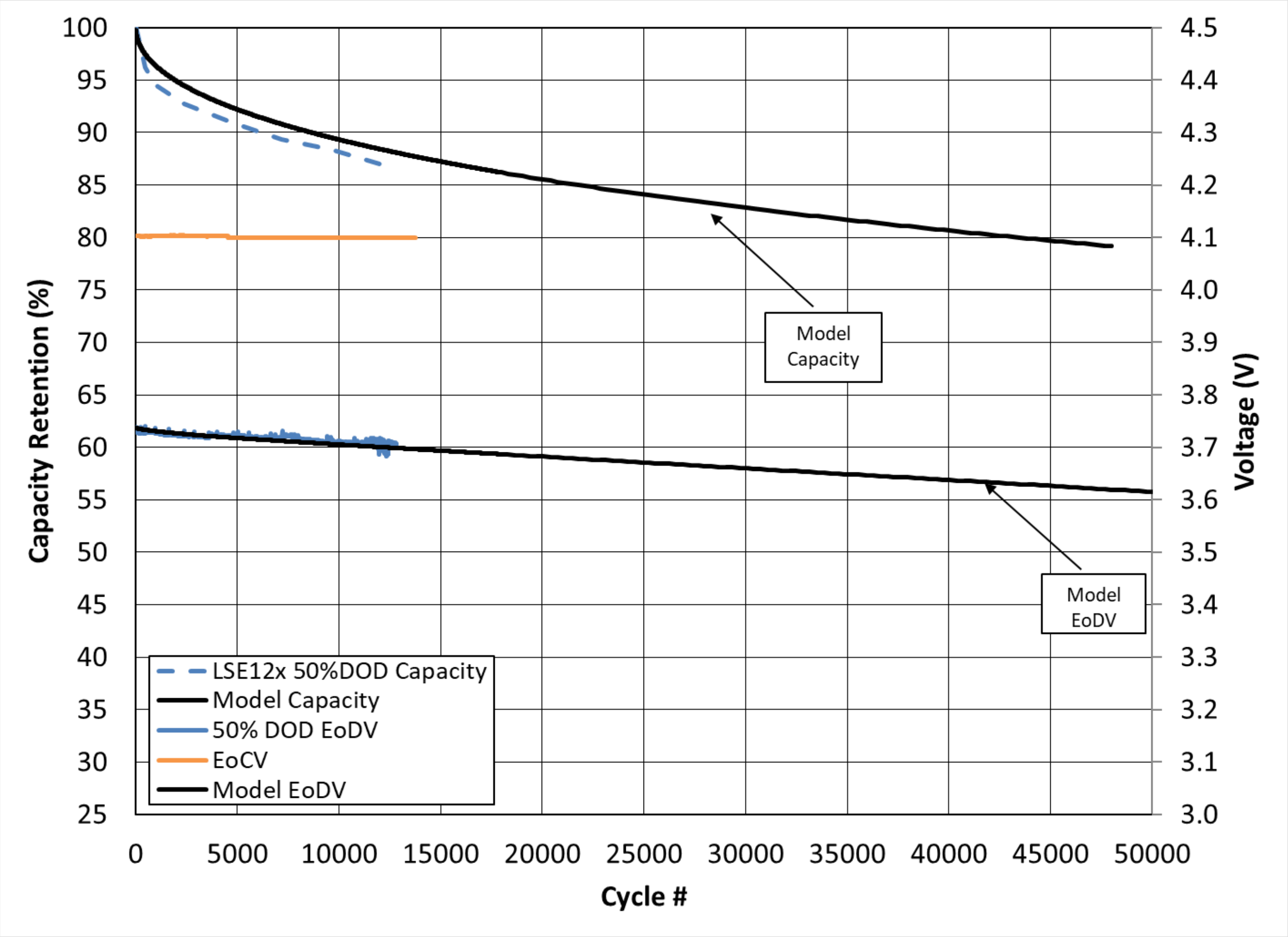

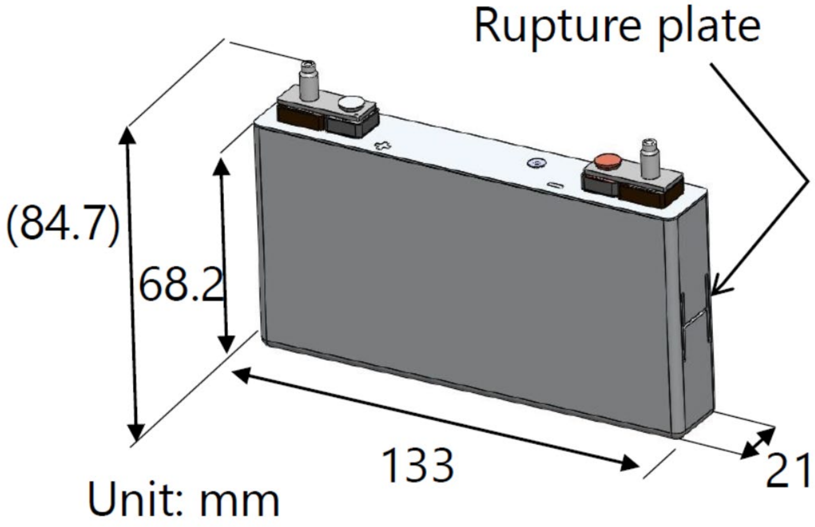

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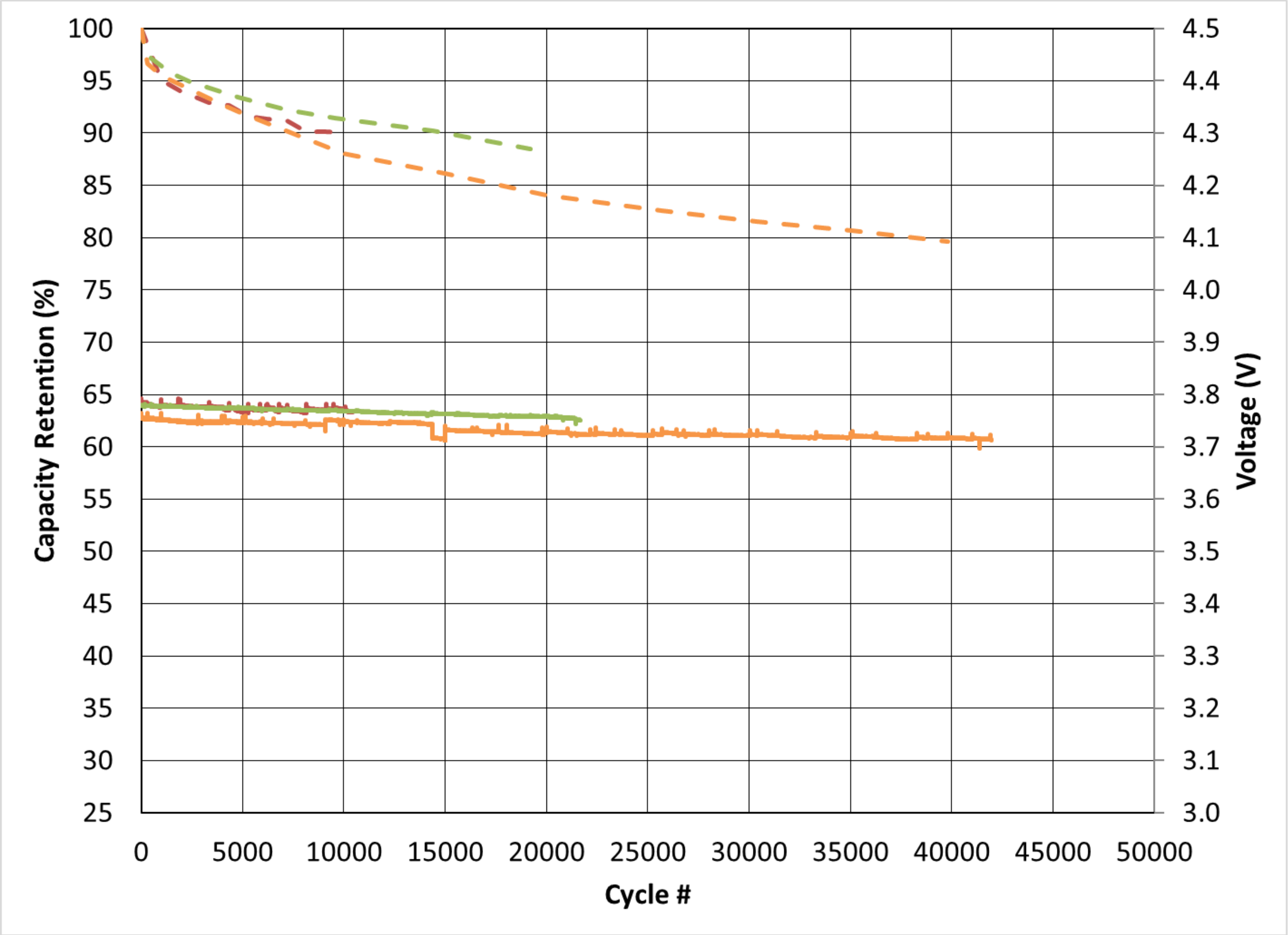
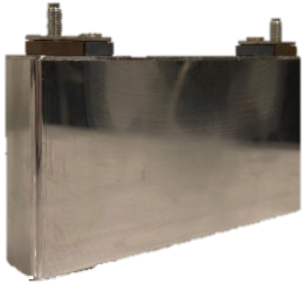
LSE12x Lithium-ion Cell for Space Performance Compared to COTS 18650 cells

LSE12x Compared to GS Yuasa Large Format Cells

40% DOD LEO Cycle Life



GS Yuasa LSE12x

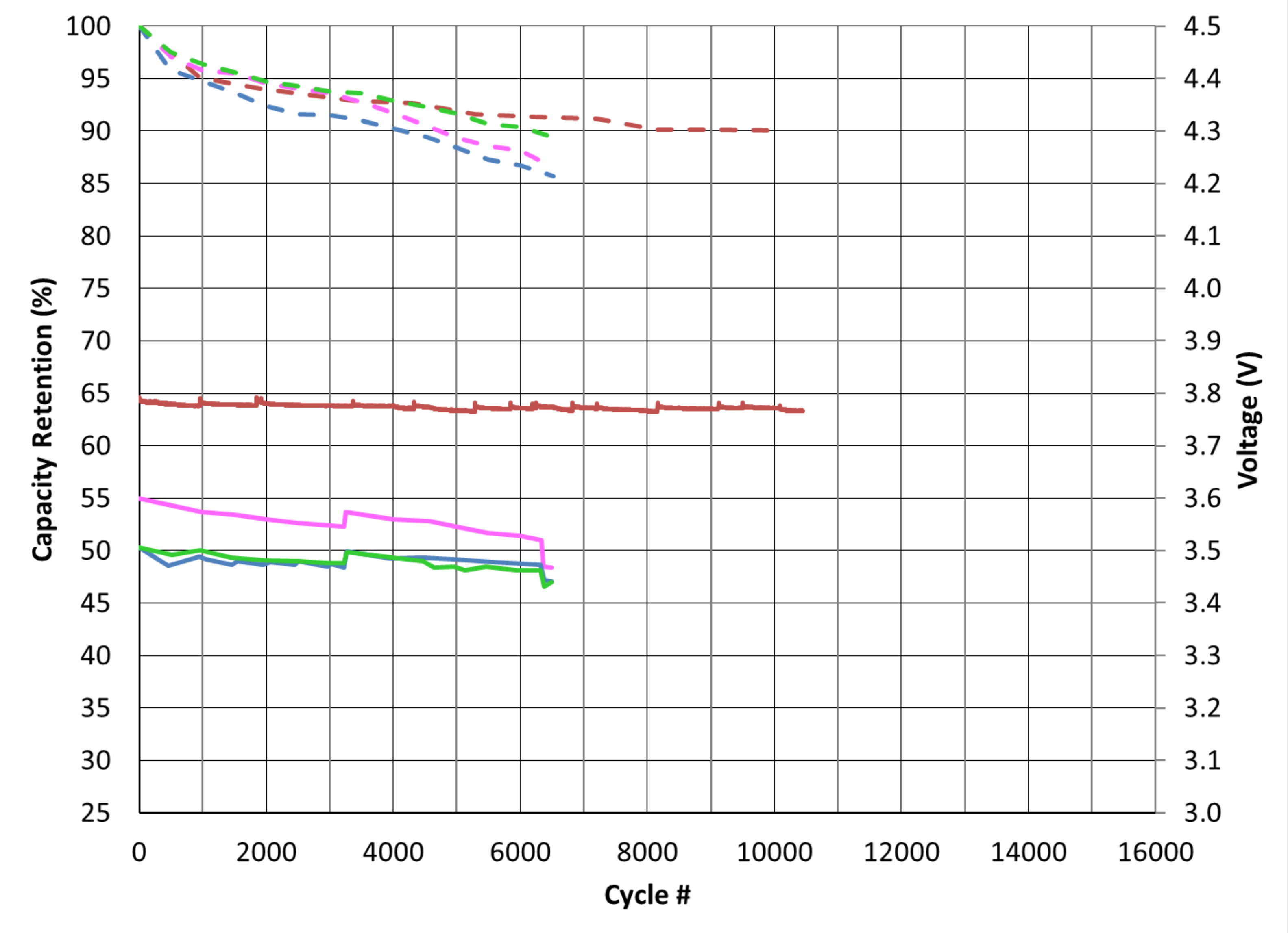


(Not to scale)

LSE134 & LSE112

LSE12x Compared to COTS 18650

40% DOD LEO Cycle Life



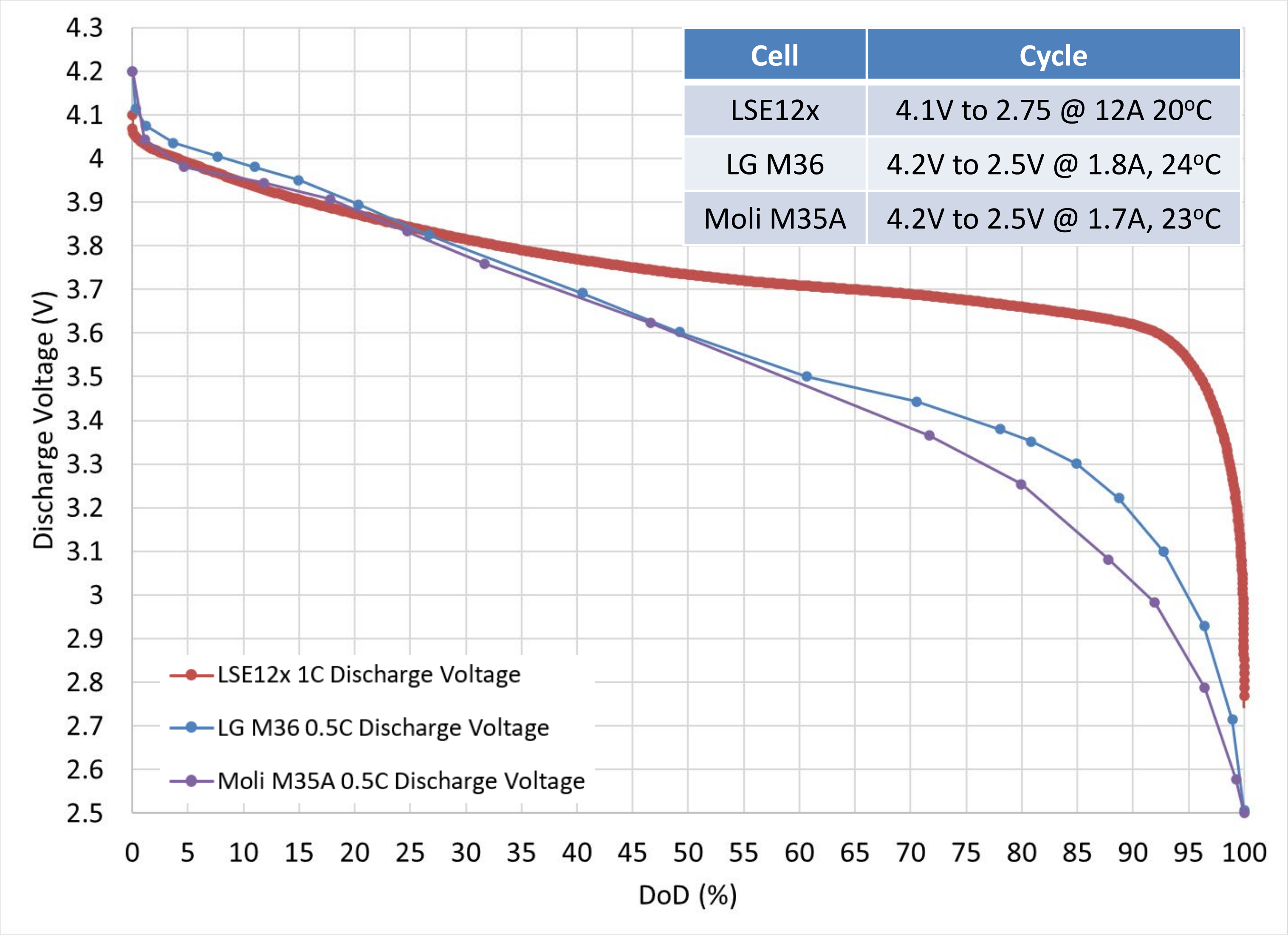
GS Yuasa LSE12x | LG M36 | LG MJ1 | Samsung Q30

(Not to scale)

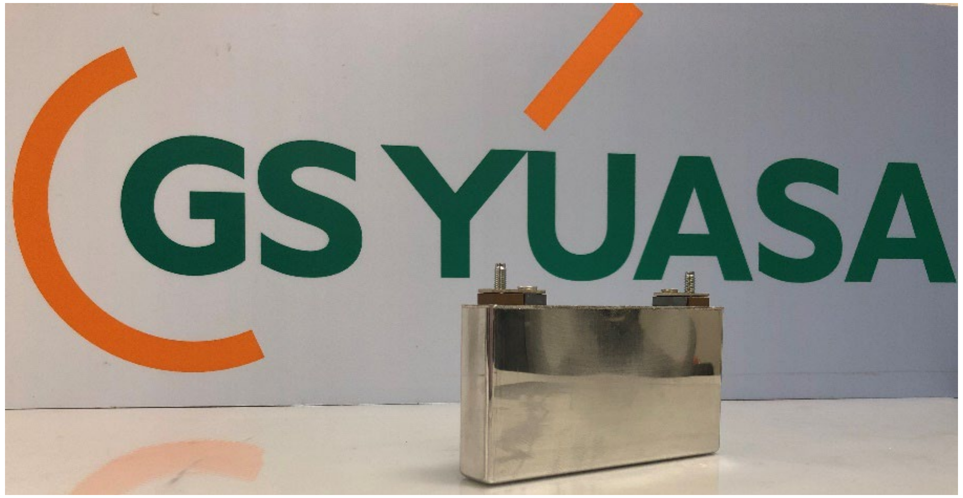
COTS 18650 data reference:
F. C. Krause et al 2021 J. Electrochem. Soc. 168 040504

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

 NASA Battery Workshop 2023

LSE12x Generation 4 LCO-Graphite Chemistry

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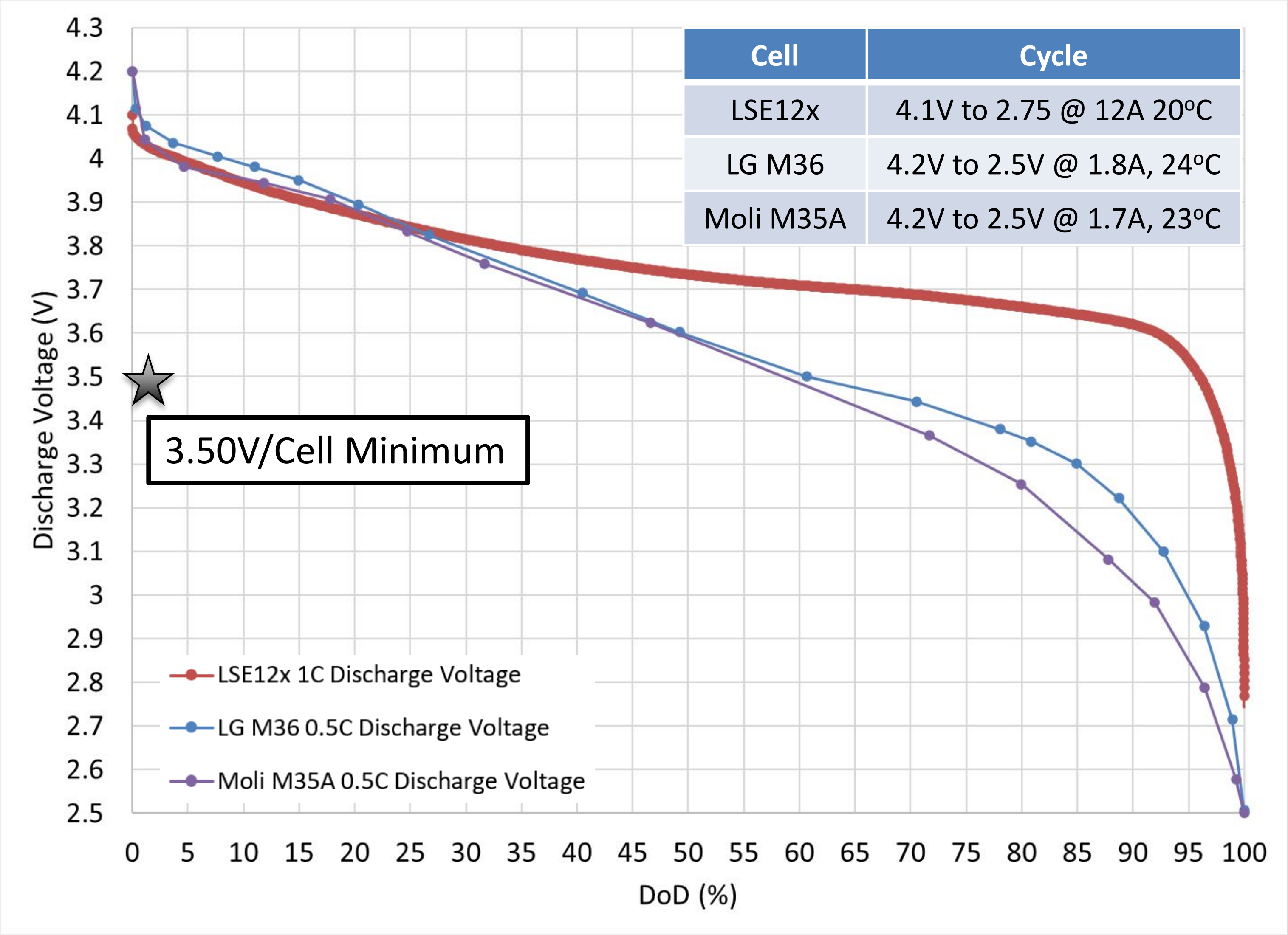

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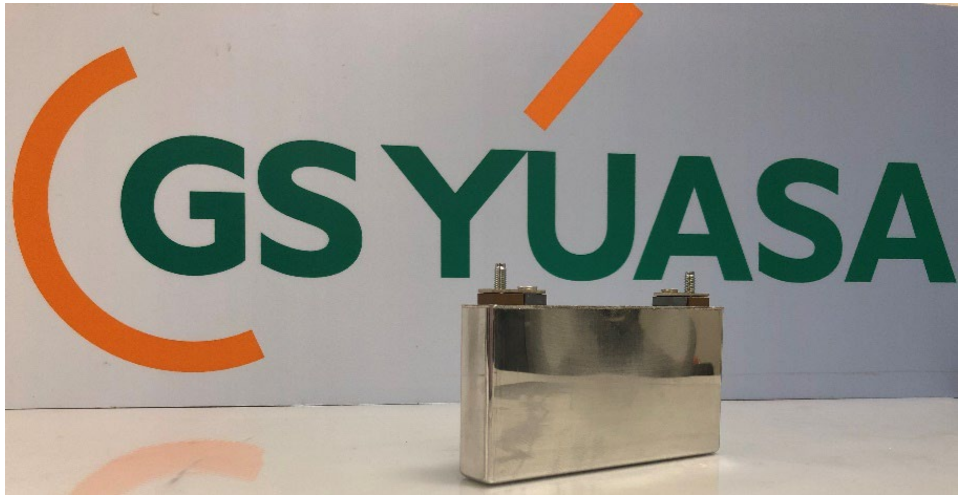

LG M36 Moli M35A

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

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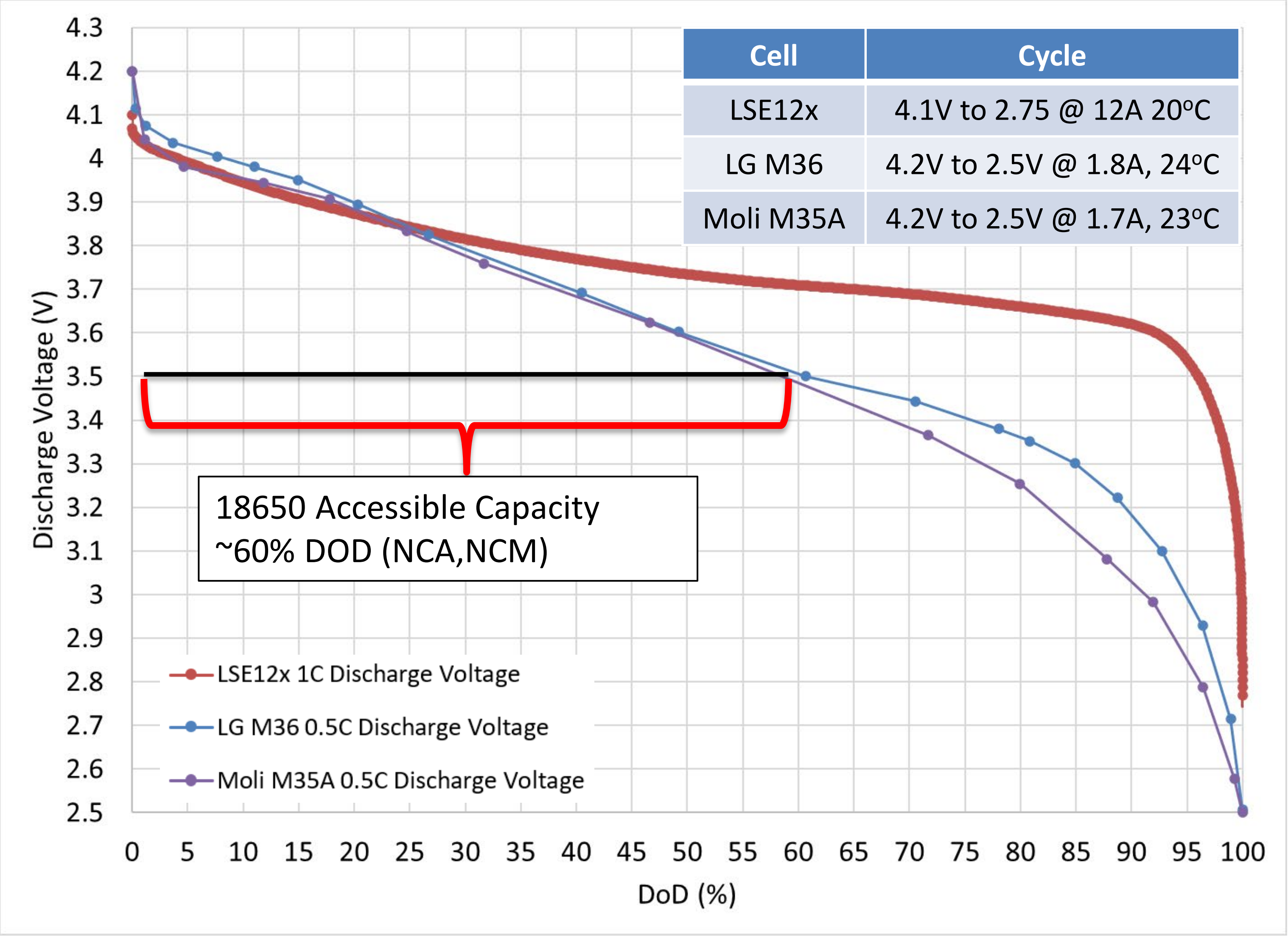

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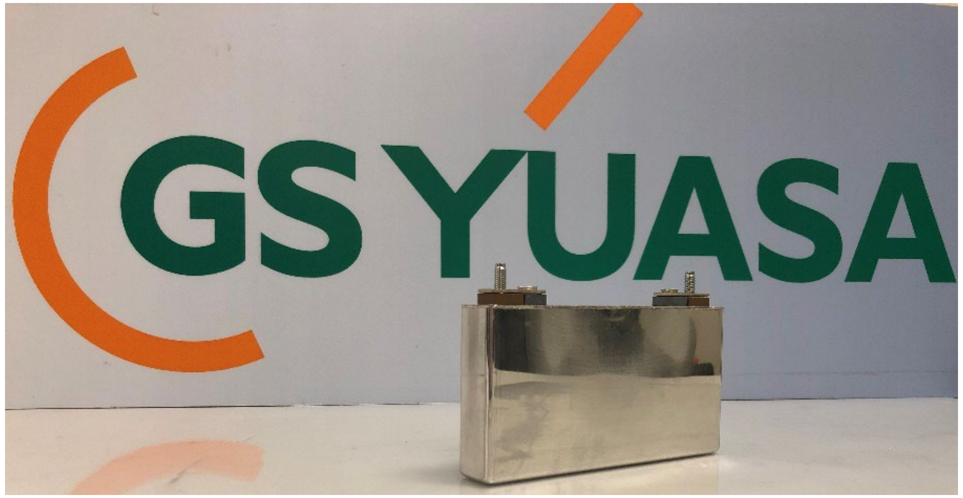
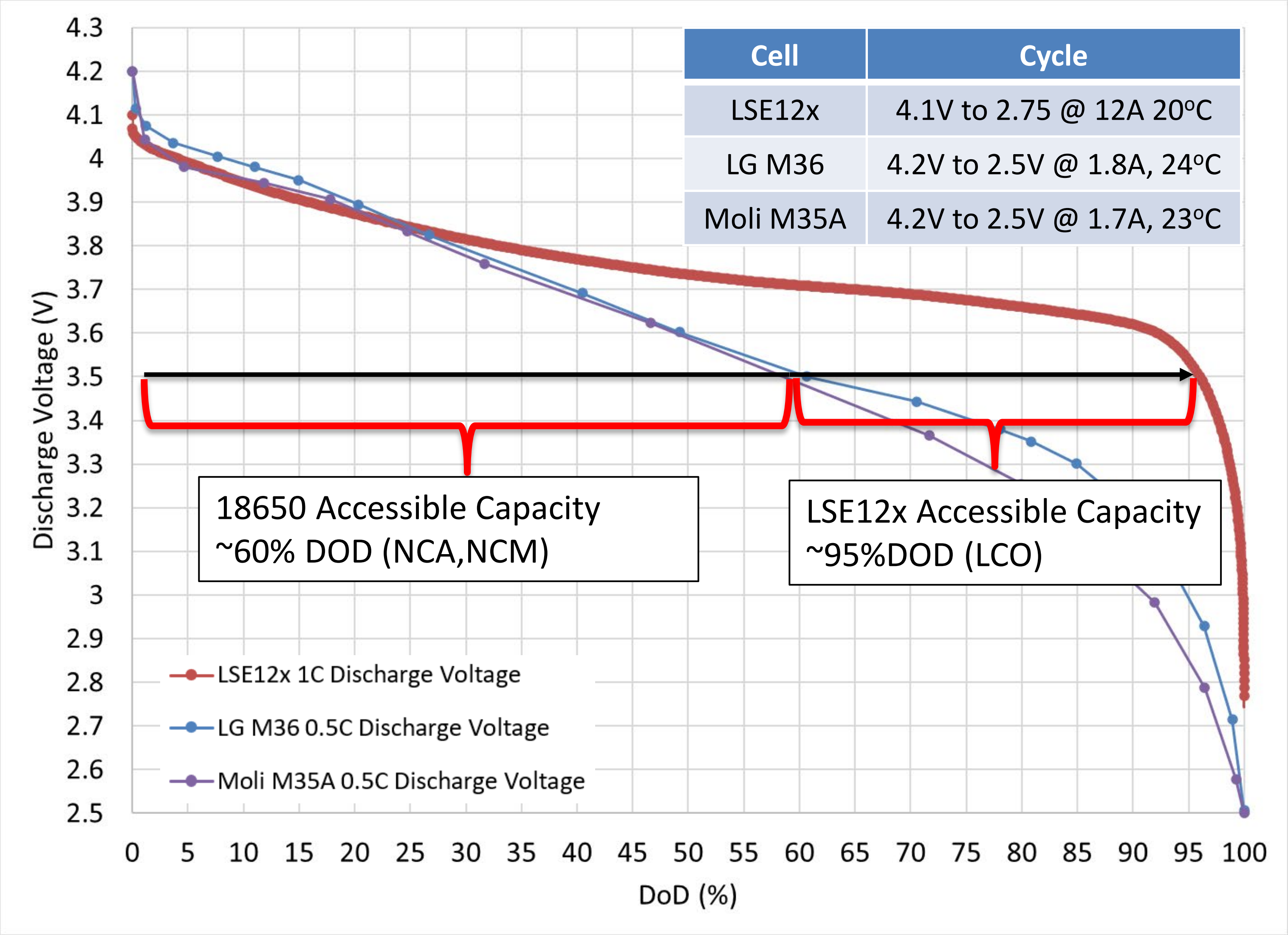


LG M36 | Moli M35A

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



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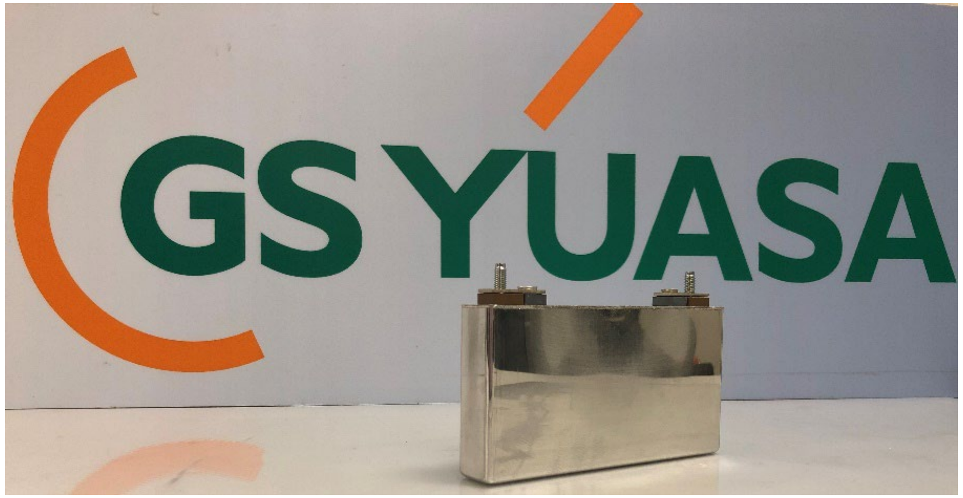


LG
M36

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)

GS Yuasa Lithium Power
MA12x Modular Battery

Challenge and Design Approach

GS YUASA

- **Challenge:**
  → Design a modular battery capable of being combined and / or stacked to meet customer voltage and capacity needs for use in the space industry.

- **Design Approach:**
  → Develop a low impedance, 12-14 Ahr, Li-Ion Cell utilizing GYT space cell expertise and high reliability manufacturing.
    - *Complete: LSE12x developed, qualified, and available to the market*

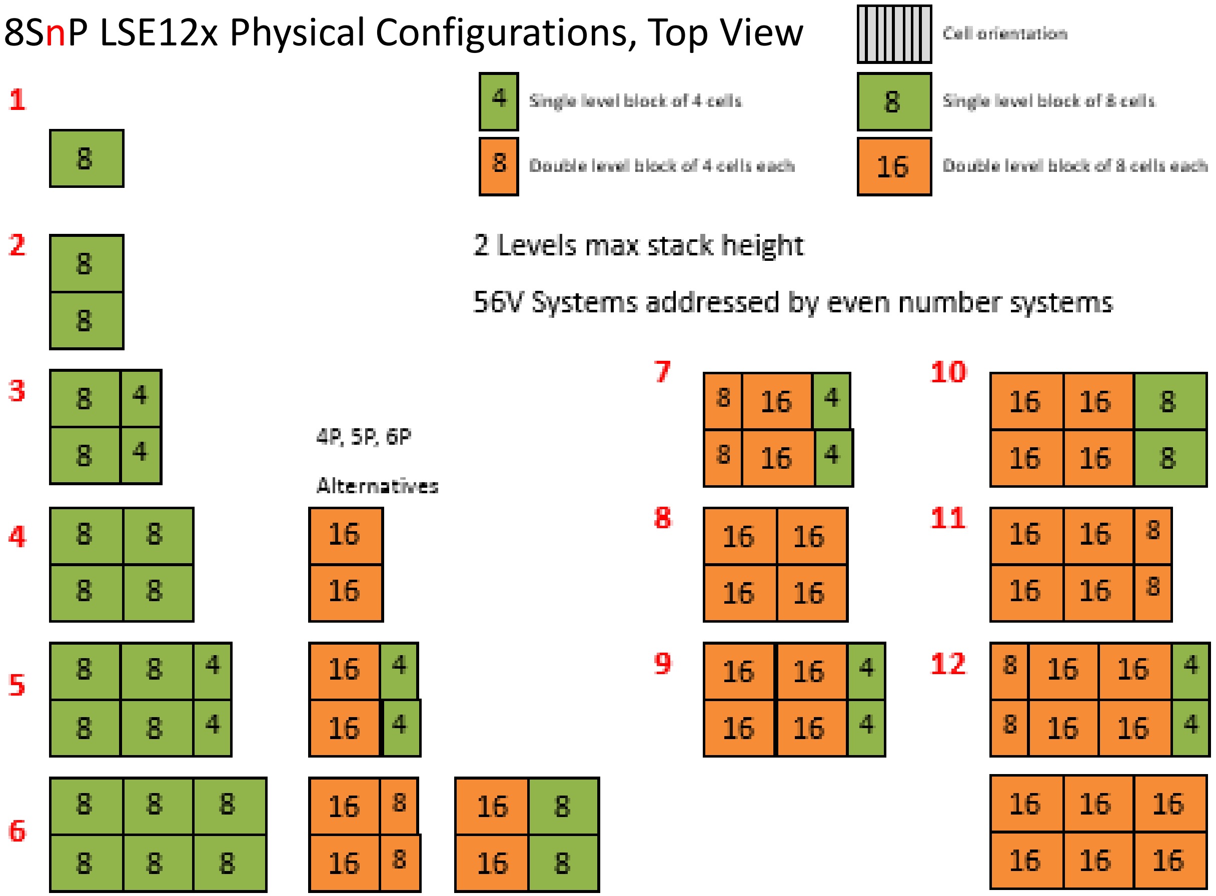
  → Utilize this smaller cell in an 8S (series combination) to generate the voltage commonly used in space applications (24V - 33V).

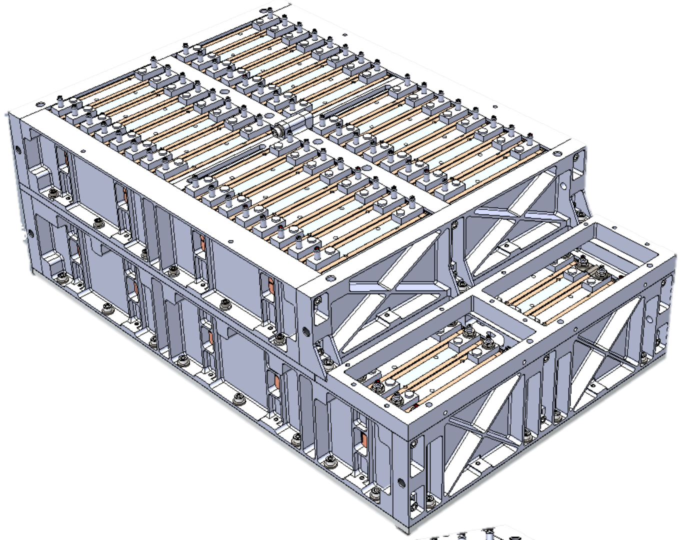
  → Develop a mechanical structural strategy to accommodate various number of 8S units connected in parallel to provide the overall capacity required by the customer.
    - 8SnP Capacity = 12Ahr*n units in parallel

Modular Structure Strategy

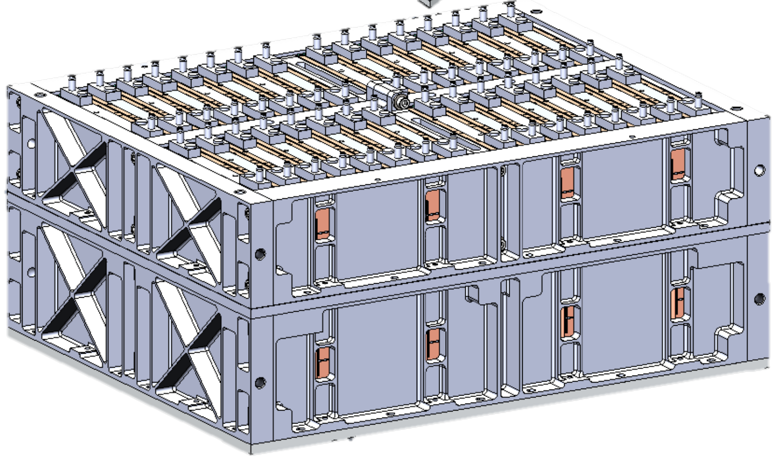
GS YUASA

- 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.



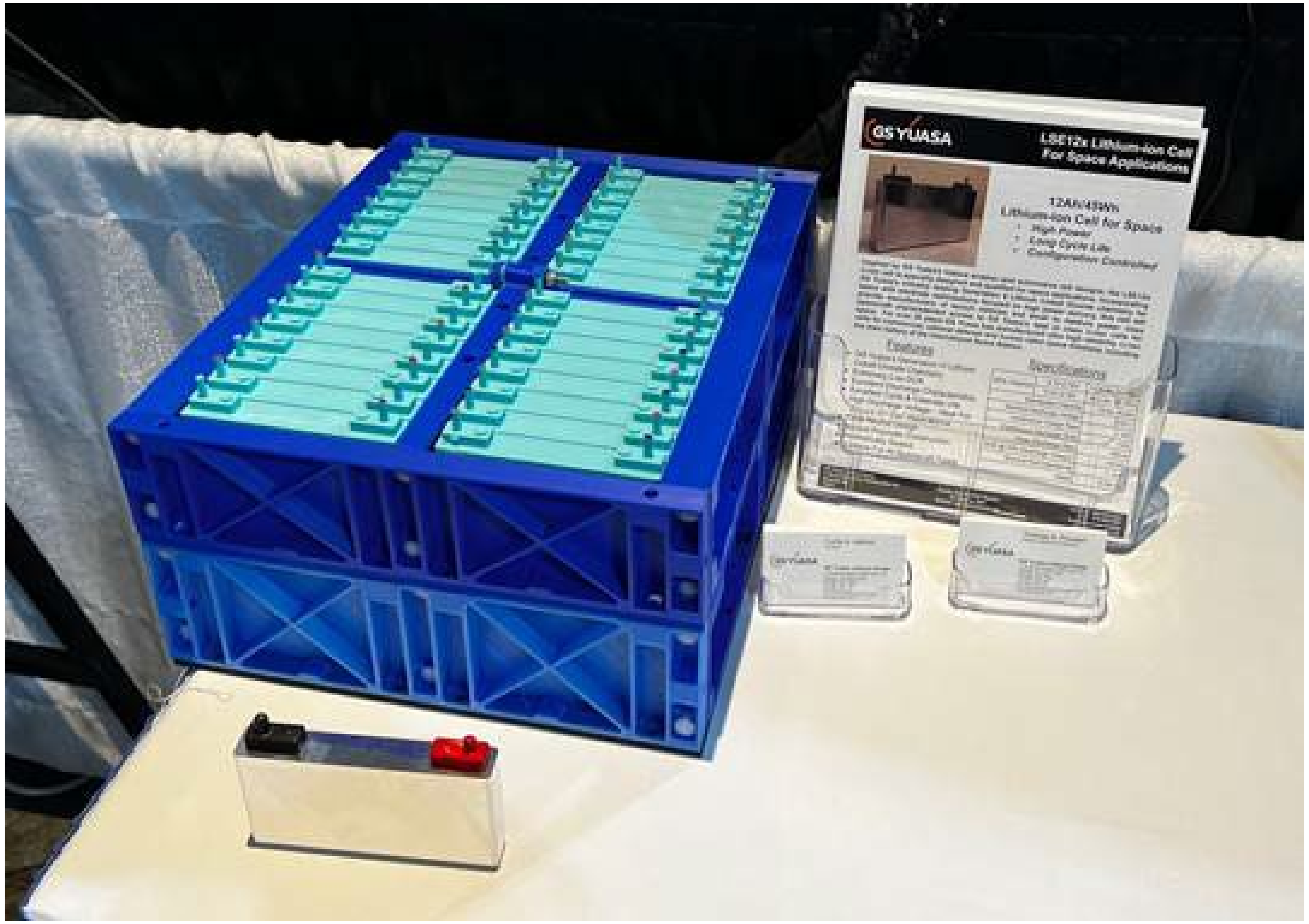


Config. 9
(72-cell)
Qual Unit



Config 8
(64-cell)

MA12x-0808



"MA12x-0808" (8s8p)

3D printed scale model of 64-cell ~2.9kWh Pack

Thermal Management

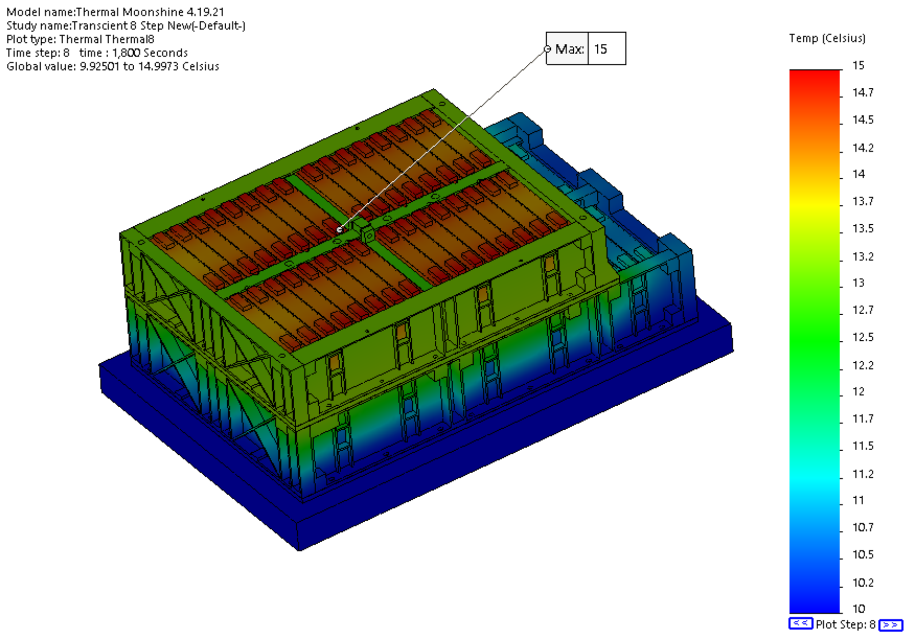
- **Thermal Management Goal**
  →Minimize thermal gradient to a difference of < 5°C
  - From cell to cell in an 8S string
  - From 8S string to 8S string
  - From top assembly to bottom assembly

- **GYLP's Design Approach**
  →Isolate the cells from each other (JSC 20793 Rev. D in mind…)
  →Create a thermal path that conducts heat to the spacecraft baseplate interface.

Thermal Analysis Summary

- Thermal model shows positive results with meeting the goal of a < 5°C thermal gradient in the battery elements.
- Cell to Cell and 8S block to 8S block show thermal uniformity with no major thermal concerns for top or bottom assemblies under these conditions.

BOTTOM LAYER TEMP MEASUREMENTS IN MODEL	CELL TOP ° C	CELL BTM °C	Cell Average from TOP and Btm ° C	TOP LAYER TEMP MEASUREMENT S IN MODEL	CELL TOP ° C	CELL BTM °C	Cell Average from TOP and Btm ° C
BL1-1	11.52	10.32	10.92	TL1-1	14.20	13.50	13.85
BL1-2	11.37	10.29	10.83	TL1-2	14.27	13.52	13.90
BL1-3	11.33	10.29	10.81	TL1-3	14.39	13.57	13.98
BL1-4	11.41	10.32	10.87	TL1-4	14.44	13.63	14.04
BL1-5	11.41	10.31	10.86	TL1-5	14.46	13.63	14.05
BL1-6	11.36	10.30	10.83	TL1-6	14.46	13.60	14.03
BL1-7	11.42	10.30	10.86	TL1-7	14.46	13.64	14.05
BL1-8	11.46	10.34	10.90	TL1-8	14.45	13.61	14.03
BL2-1	11.46	10.34	10.90	TL2-1	14.49	13.63	14.06
BL2-2	11.44	10.33	10.89	TL2-2	14.48	13.62	14.05
BL2-3	11.35	10.31	10.83	TL2-3	14.47	13.61	14.04
BL2-4	11.43	10.33	10.88	TL2-4	14.48	13.65	14.07
BL2-5	11.39	10.30	10.85	TL2-5	14.46	13.64	14.05
BL2-6	11.32	10.29	10.81	TL2-6	14.42	13.60	14.01
BL2-7	11.31	10.27	10.79	TL2-7	14.34	13.55	13.95
BL2-8	11.36	10.29	10.83	TL2-8	14.25	13.52	13.89
BL3-1	11.41	10.31	10.86				
BL3-2	11.21	10.28	10.75				
BL3-3	11.07	10.25	10.66				
BL3-4	10.93	10.23	10.58				
Cell Group	Max Temp °C	Min Temp °C	Delta T in group ° C	Cell Group	Max Temp °C	Min Temp °C	Delta T in group ° C
BL1	11.52	10.29	1.23	TL1	14.46	13.50	0.96
BL2	11.46	10.27	1.19	TL2	14.49	13.52	0.97
BL3	11.41	10.23	1.18				
Battery Estimated Delta T °C	4.23						

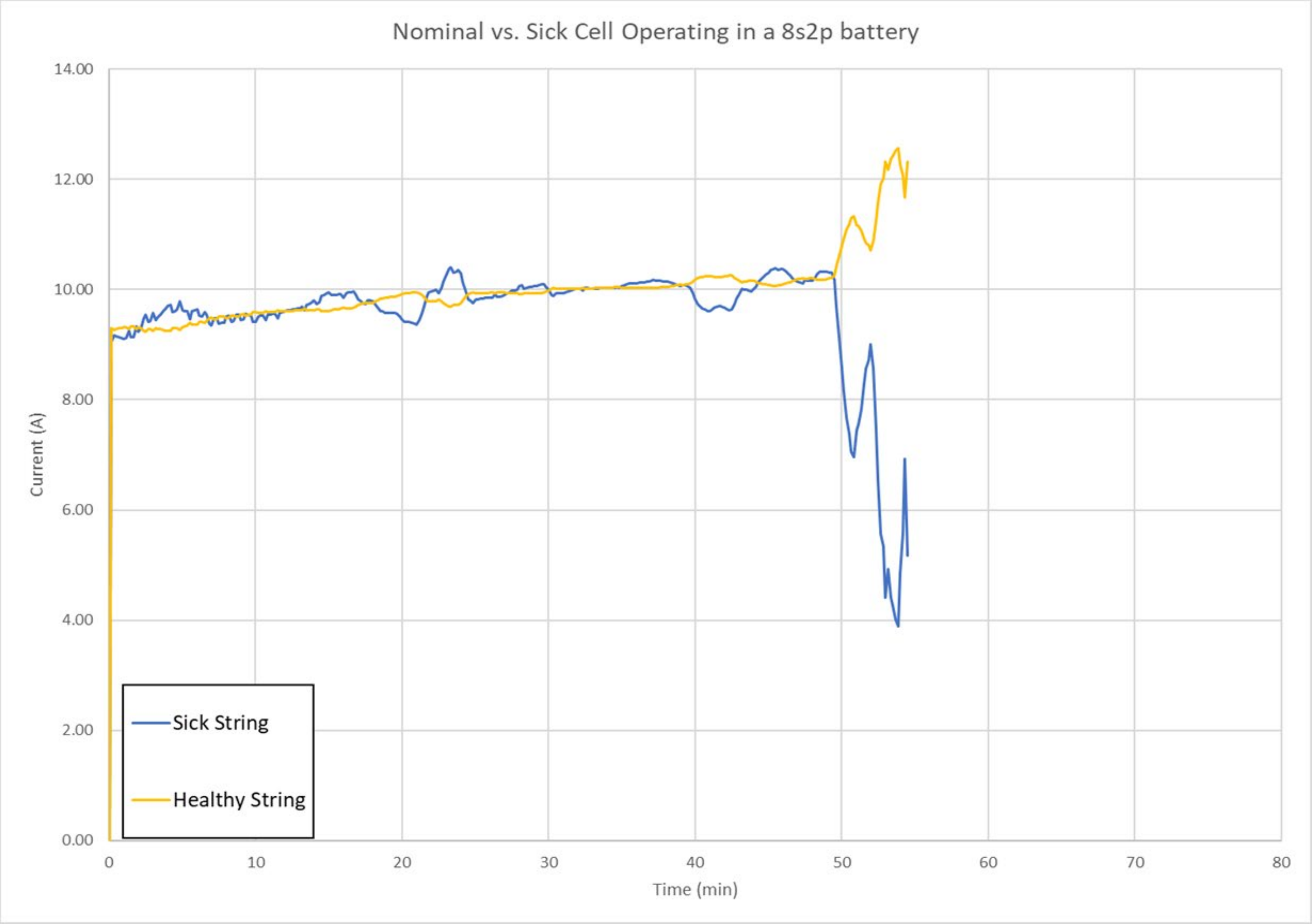


Detection and Isolation of "Sick" Strings

- GYLP has developed mathematical models to analyze the performance of healthy and sick strings in an MA12x pack
- This manifests as unequal current sharing between the sick and healthy stings.

→ Example: Sick string 10% SOC divergence, 0.8C discharge rate

- Fault tolerance and anomaly mitigation has also been carefully considered. In the event of a cell fault, each series string can be isolated in the battery through a commandable normally closed latching relay. The net result will be a loss of Wh battery capacity equivalent to the single isolated string (360Wh).



GYLP Production Readiness

MA12x battery design and qualification:

- PDR: Complete
- CDR: Schedule for December 2023, MA12-0809 (8s9p)
- Qual Battery MRR/TRR: February 2024
- Qualification Complete: Q3/Q4 2024
- Production: Q1 2025

  → Target continuous manufacturing capability is one 8s8p battery per week (2.9kWh/week)

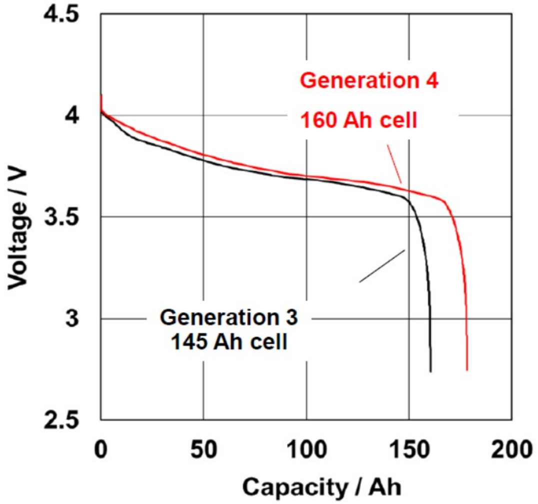
  → Less than 6-month lead time ARO for first unit to support constellation opportunities.

  → 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.

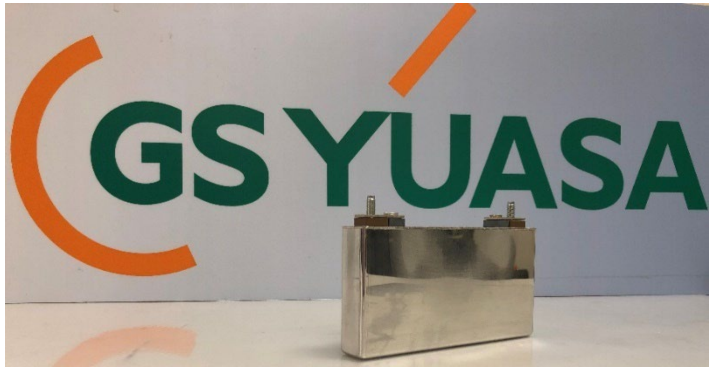
Summary

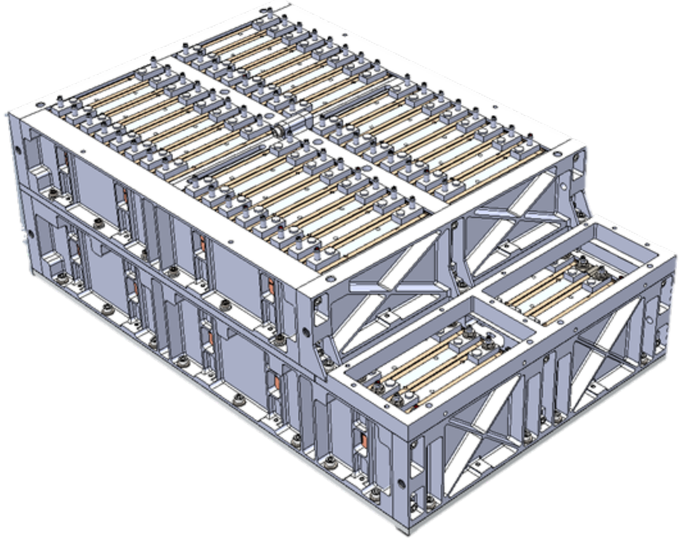
- GS Yuasa's Generation 4 LCO/Graphite chemistry provides meaningful performance increases from Generation 3 including:
  - Increased Energy Density
  - Excellent Capacity Retention under demanding cycle conditions
  - Decreased DCR for enhanced voltage performance under load



- 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

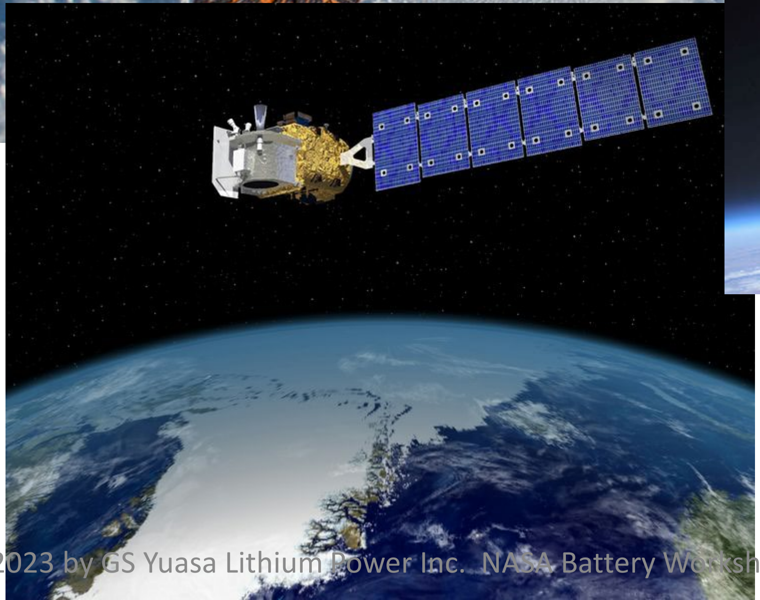


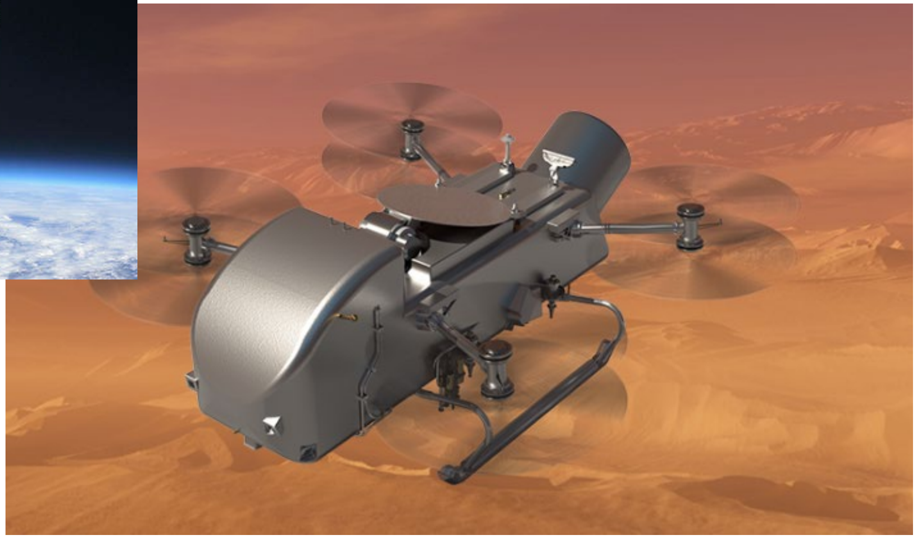


Energy storage design test and manufacturing expertise

Industry leading spaceflight heritage

Validated and reliable performance modelling





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