GS Yuasa MA12x Modular Battery Platform Qualification Test Results

Prepared for Space Power Workshop 2025

April 29, 2025

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Topics

- GS Yuasa Spaceflight Heritage Update
- Generation 4 “LSE” Li-ion Space Cell Qualification Status
- Small Format LSE12x Cell Performance Update
- MA12x-0809 Battery Qualification Results

Northrop Grumman's Cygnus Spacecraft
Powered by GS Yuasa LSE190

GS Yuasa
Spaceflight Heritage

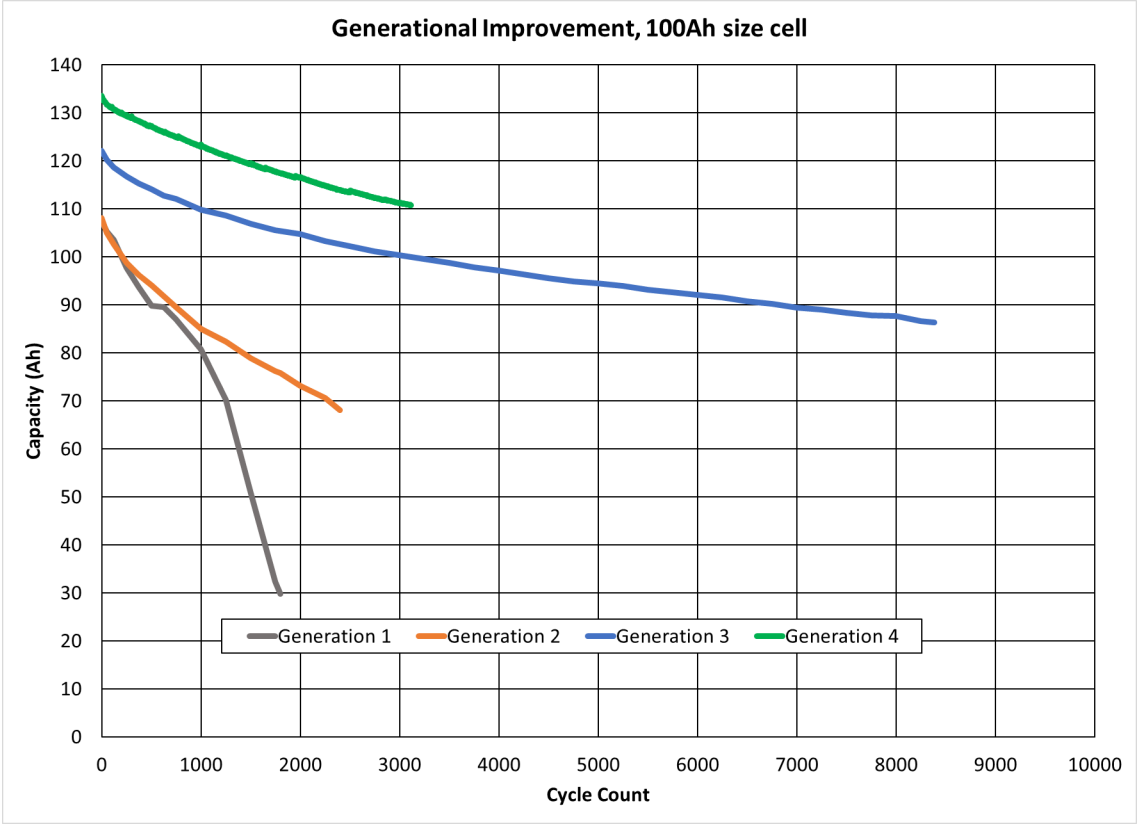
Approach to Li-ion Chemistries for Spacecraft

- Critical space applications depend on demonstrated reliability, consistent performance and minimal changes once qualified.

- Only after exhaustive qualification process will a new “chemistry” be applied to the space cell portfolio.
  - → Typically changes can be considered simply as incremental improvements to the underlying materials

- Once qualified the chemistry configuration is “locked”
  - → Enables investment in long term cycle and stress tests, calibration of empirical models and right sizing of solutions targeting end of mission performance.
  - → Demonstrated the ability to maintain a single production configuration for more than 15 years.

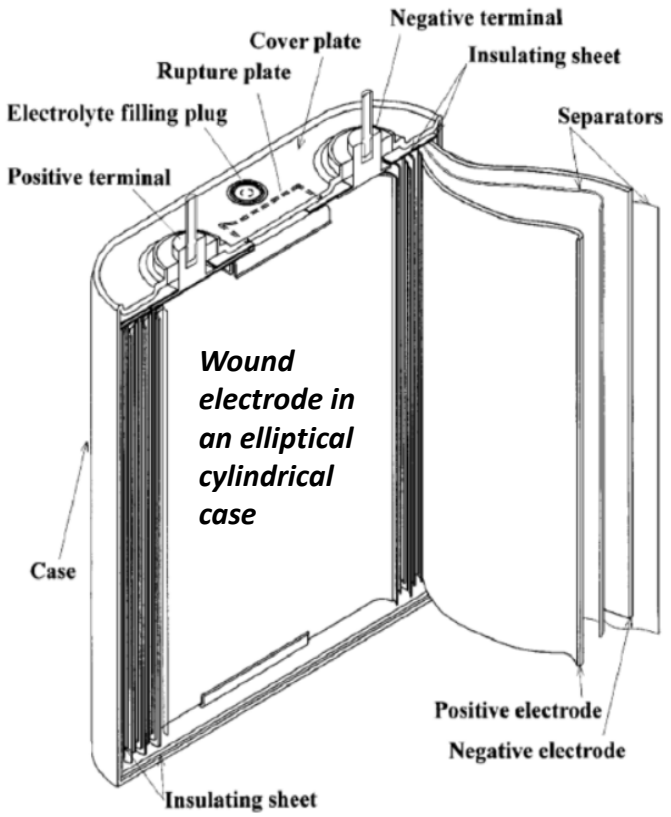
- All GS Yuasa space cells in production to date are based on the LCO/Graphite Li-ion chemistry.
  - → Demonstrated heritage and chemical stability in space application
  - → LCO/Graphite voltage performance advantageous for long duration space applications



100% DOD Cycle Life Performance

LSE Cell Basic Shape

Over 25 years of outstanding performance



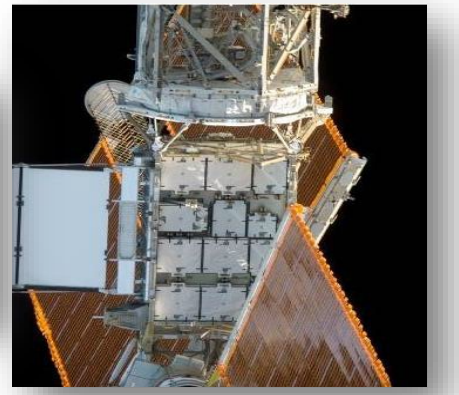
GS Yuasa has manufactured >18,500 “LSE” cells for space applications accounting for more than 7.60MWh of energy storage for this design.

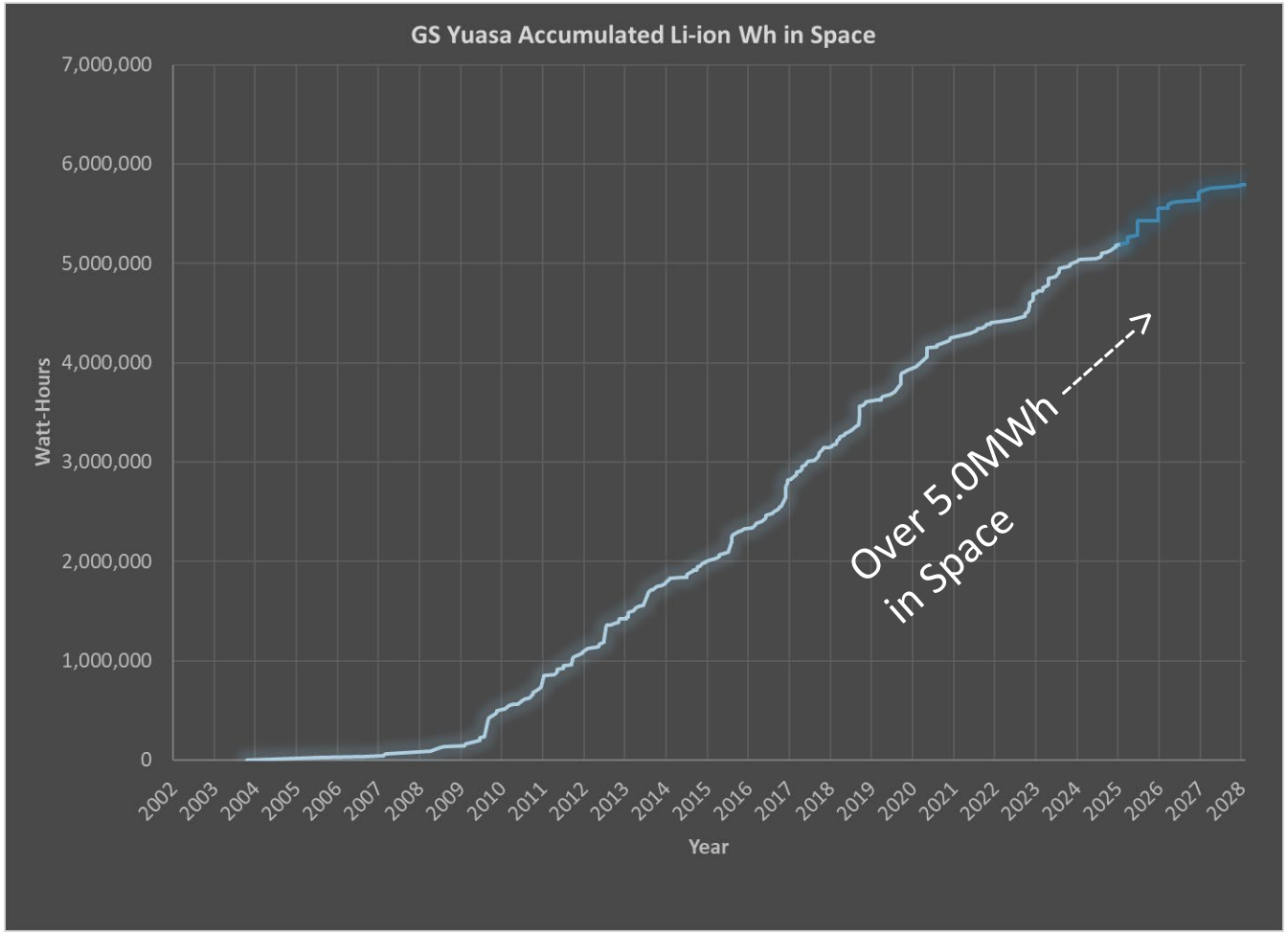
All cells share the same primary features: Al-case, wound-prismatic construction, ceramic terminals, LCO chemistry. All are manufactured in Kyoto, Japan on the same equipment and using the same basic processes. The portfolio can be viewed as a single fundamental cell technology, configurable in height,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

GS Yuasa Space Flight Heritage Update

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

Number of satellites……	262+
− LEO……..	91
− MEO……..	33
− GEO……	135
− Interplanetary……	1+
1st satellite on-orbit……	Servis 1 (30 Oct. 2003)
Longest satellite on-orbit (yrs)….....	>19yrs (Thaicom 4)
Li-ion Watt-hours used in space……....	5.19 MWh
Performance to date…….....	No failures
Backlog (Wh)……	>0.79 MWh





[GS Yuasa Surpasses 5.0MWh in Space]

Metrics updated April 2025

LSE Cell
Qualification Status

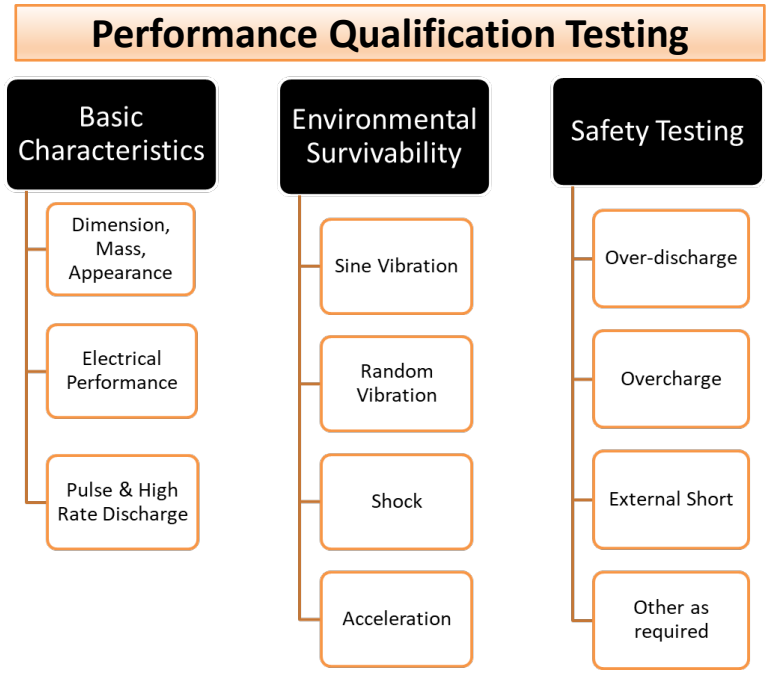
NASA’s Dragonfly Mission
Developed by Johns Hopkins Applied Physics Laboratory
Powered by GS Yuasa LSE134/147

LSE Cell Configurations & Qualification Status

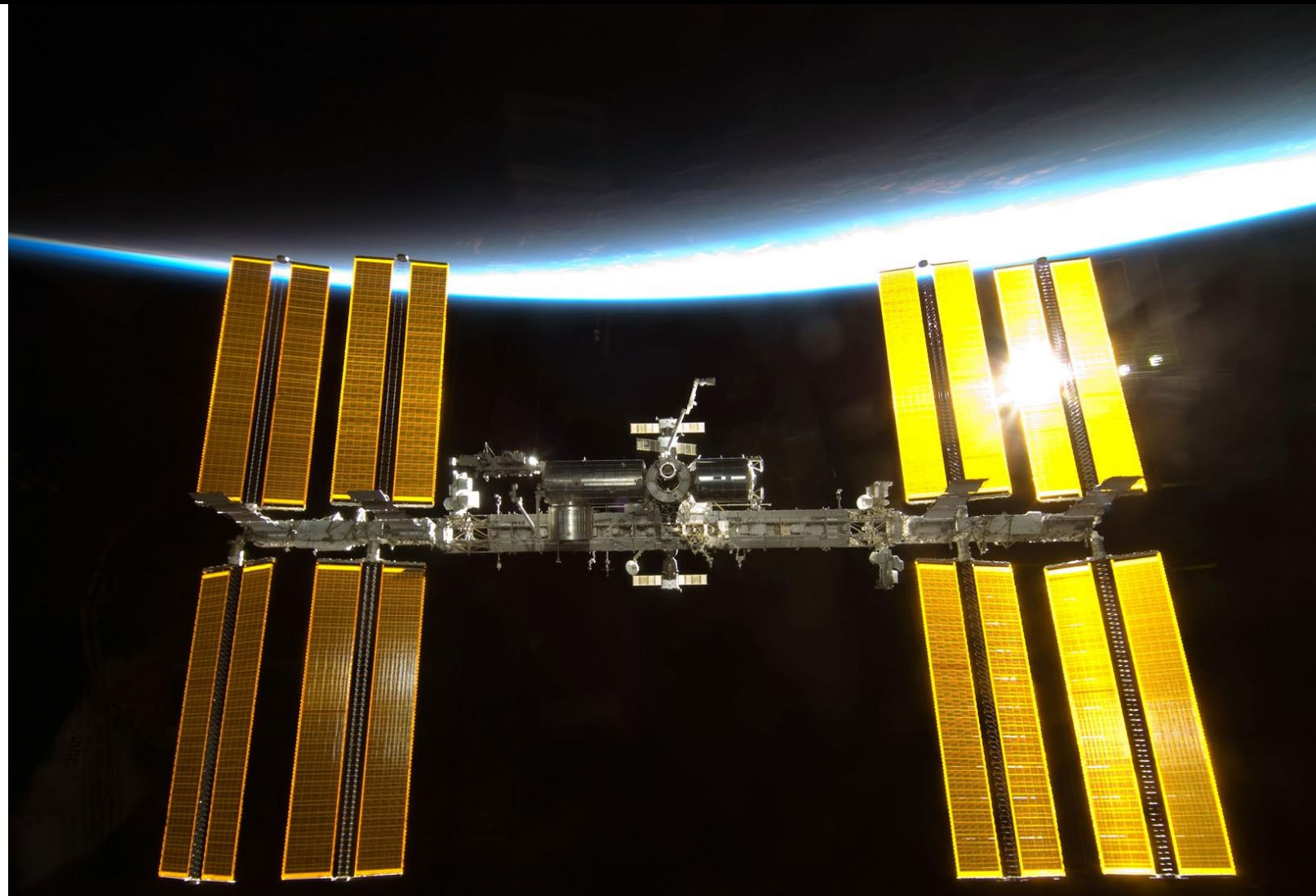
	Electrode Type	Cell Model	Designed / EM Cells	Qualified	Delivered	Flown
Gen 3	Energy	LSE42	X	X	X	X
		LSE55	X	X	X	X
		LSE110	X	X	X	X
		LSE145	X	X	X	X
		LSE190	X	X	X	X
	Power	LSE38	X			
		LSE51	X			
		LSE102	X	X	X	X
		LSE134	X	X	X	X
Gen 4	Energy	LSE60	X	*Prelim*	X (*EM*)	
		LSE122	X			
		LSE160	X	X	X	
		LSE205	X	X	X	
	Power	LSE12x	X	X	X	
		LSE56				
		LSE112	X	X	X	
		LSE147	X	X	X	

A range of cell sizes have been qualified to GS Yuasa's criteria, developed to envelope a majority of encountered industry requirements and mission types.

Cell naming convention is the prefix "LSE" followed by the nameplate Ah capacity. All C-rates are in reference to this nameplate capacity.



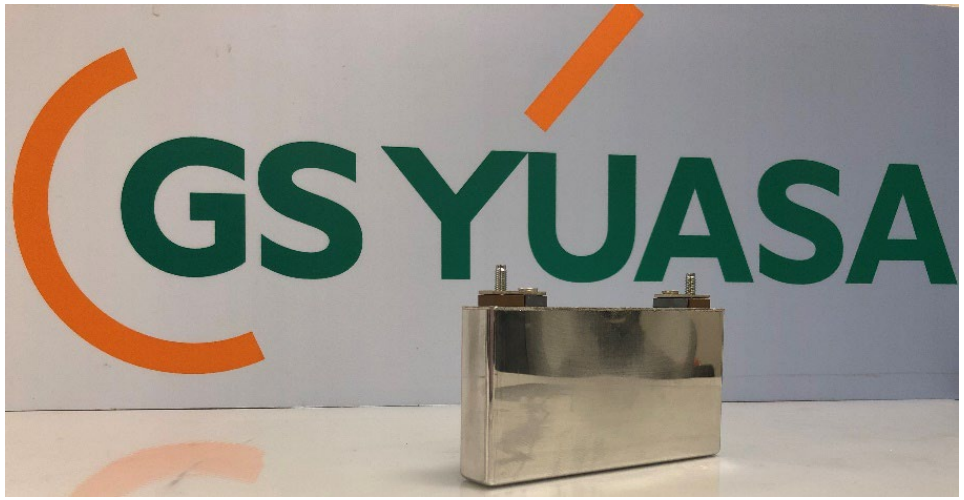
LSE12x
“Small” Format
Li-ion Cell for Space



International Space Station
Powered by GS Yuasa LSE134

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

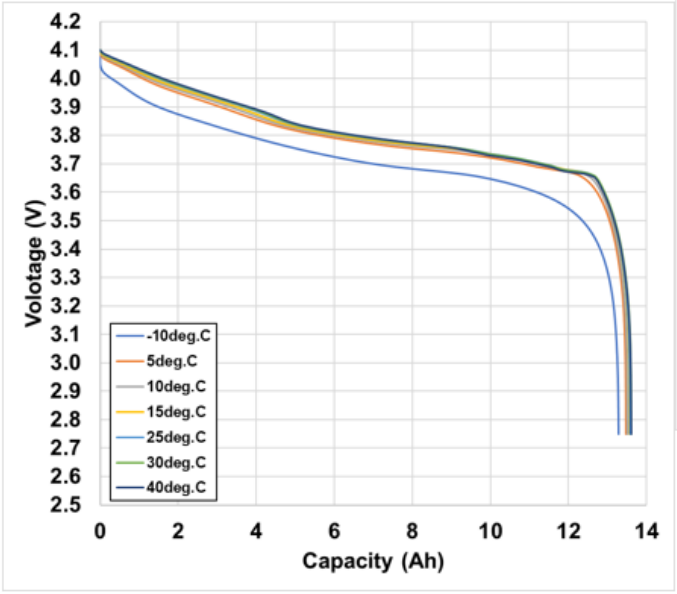
BOL Capacity, 4.1V-2.75V	13.6 Ah, 51.0Wh
Nameplate Capacity	12 Ah, 45Wh
Nominal Discharge Voltage	3.75 V
Continuous Charge Rate, 15°C	12A
Continuous Discharge Rate	24+A
Pulse Discharge Rate	60+A
DCR @ 50% SOC, 15°C	<6 mΩ
Nominal Cell Impedance	1.1mΩ
Mass	0.390 kg

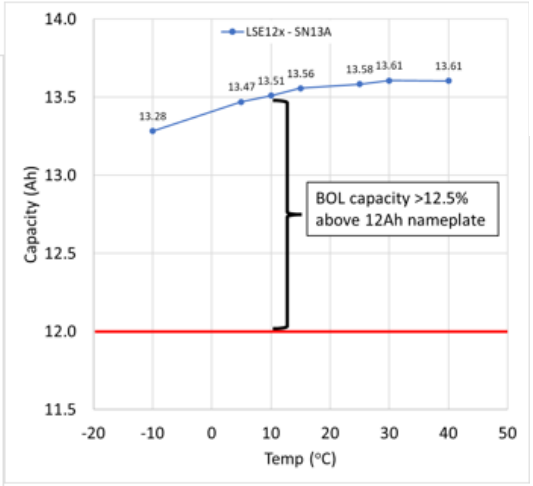
GS Yuasa validated Life and Performance model capability to allow for "right sizing" of a battery solution.

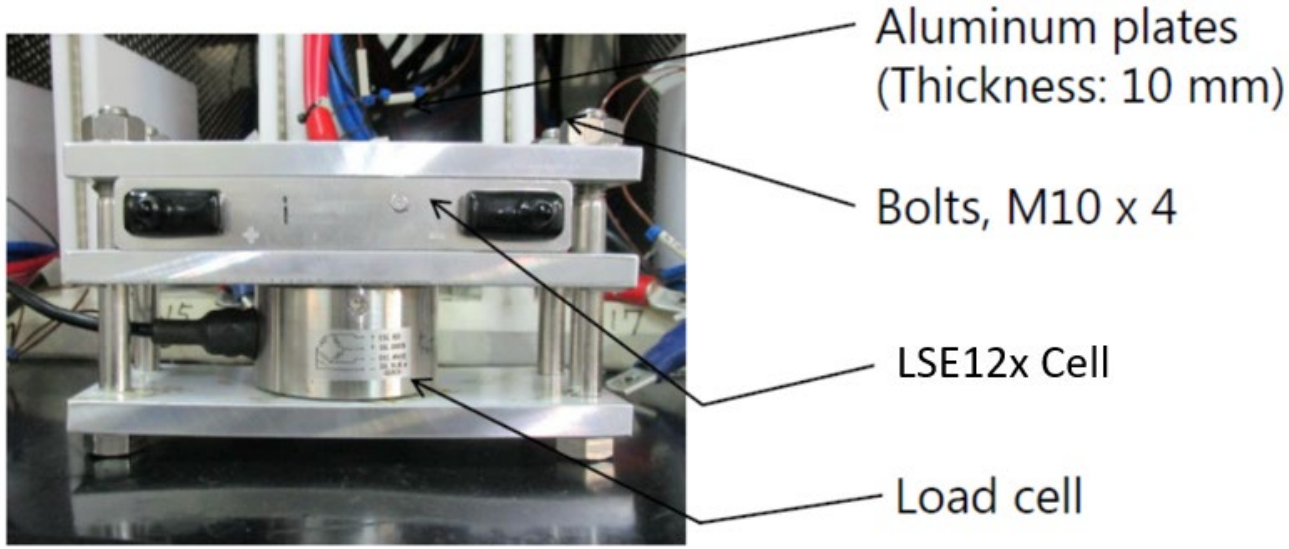
LSE12x Qualification

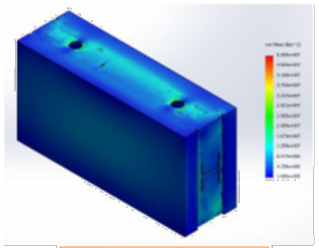
Aerospace Space Power Workshop 2022

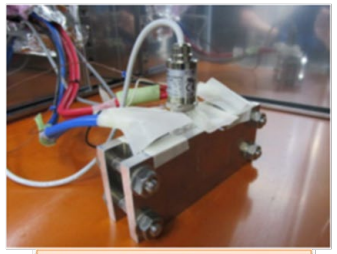
Cell completed qualification in December 2021. Results presented at Space Power Workshop 2022: https://gsyuasa-lp.com/news/gylp-presents-at-the-2022-aerospace-space-power-workshop/








EOL Mechanical FEA

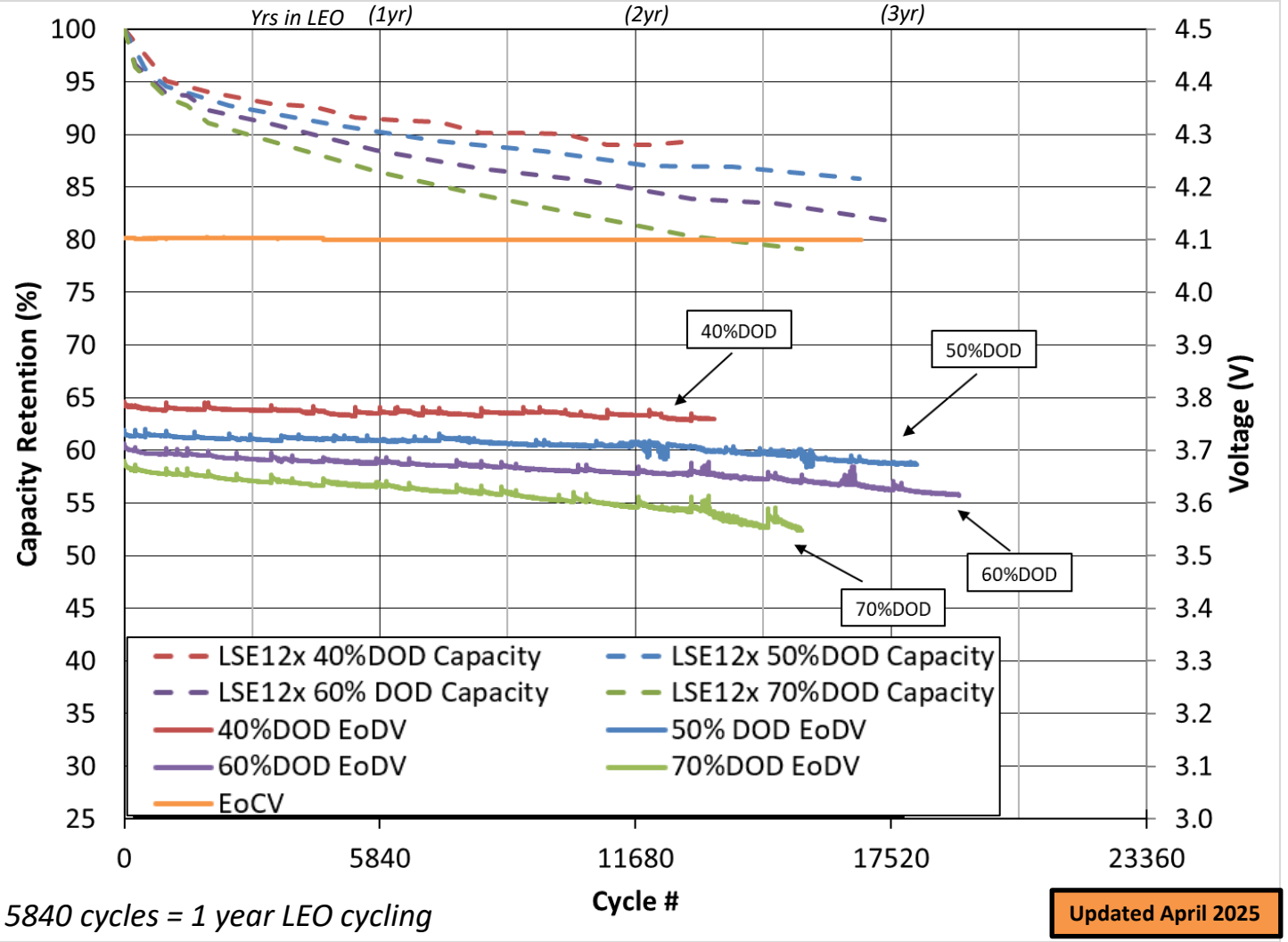

Cycle Internal Pressure Change Evaluation


Case Bust Test


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

LSE12x Generation 4 LCO-Graphite Chemistry

High DOD LEO Cycling Life Test



5840 cycles = 1 year LEO cycling

Updated April 2025

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

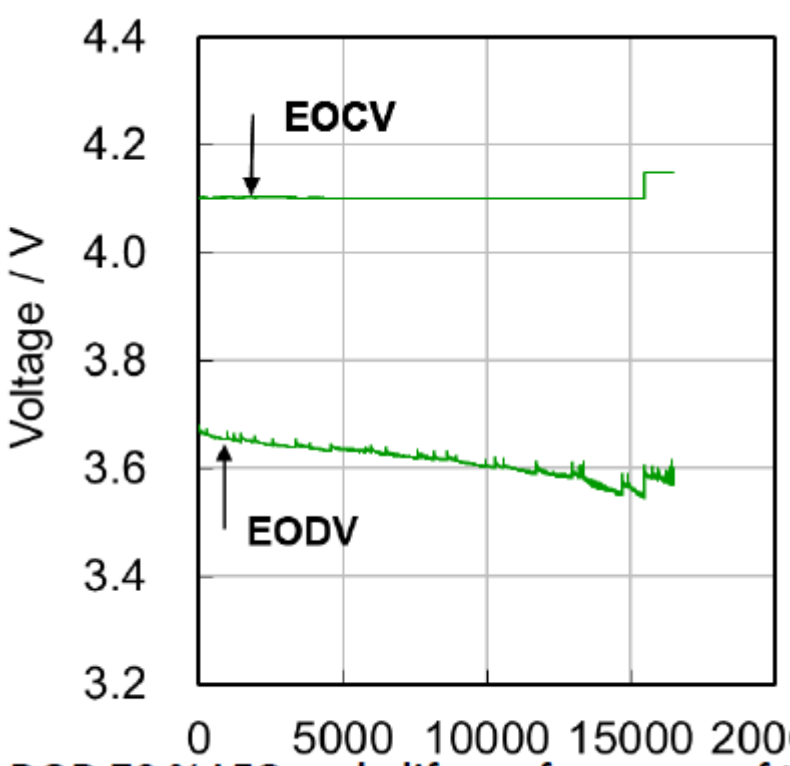
Test	Last Cycle (#)	Cycle Time (yrs)	EoDV (V)	Real-time Capacity (Ah)
40%	13,488	2.31	3.759	12.2
50%	18,112	3.10	3.673	11.5
60%	19,072	3.26	3.615	11.1
70%	15,474	2.65	3.548	10.8

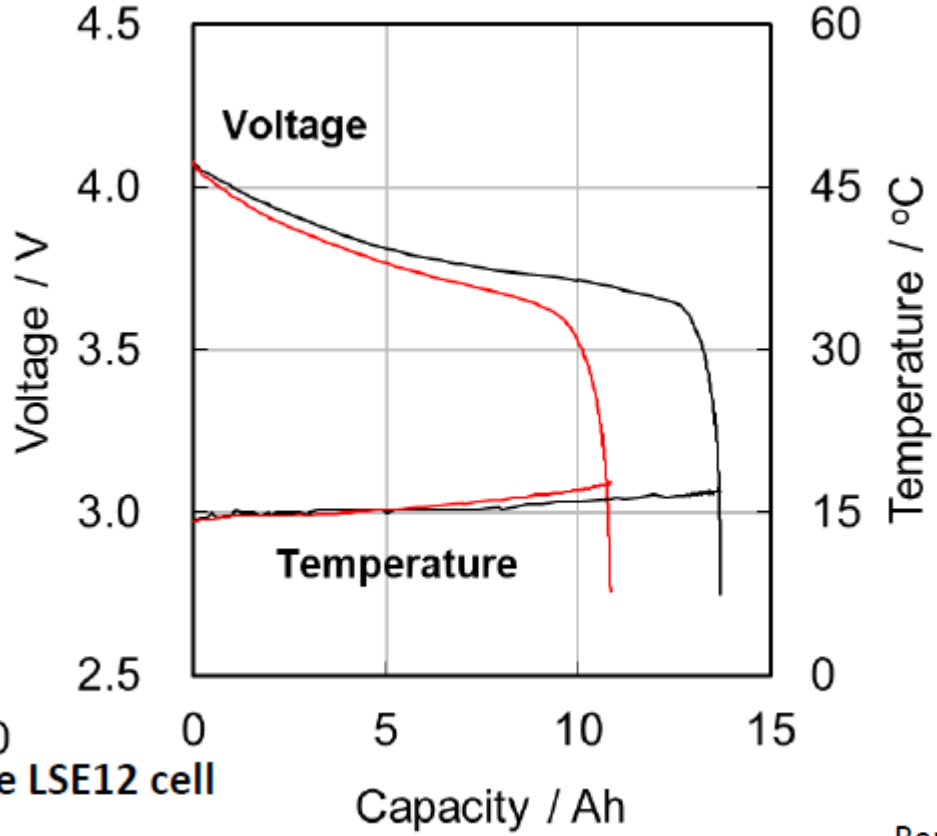
- 40%, 50%, 60% cycle testing continues
- 70% cycle test at 4.1V adjusted to 4.15V EoCV, completed 16,000 cycles and was DPA'd.

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 70% DOD LEO Cycle DPA

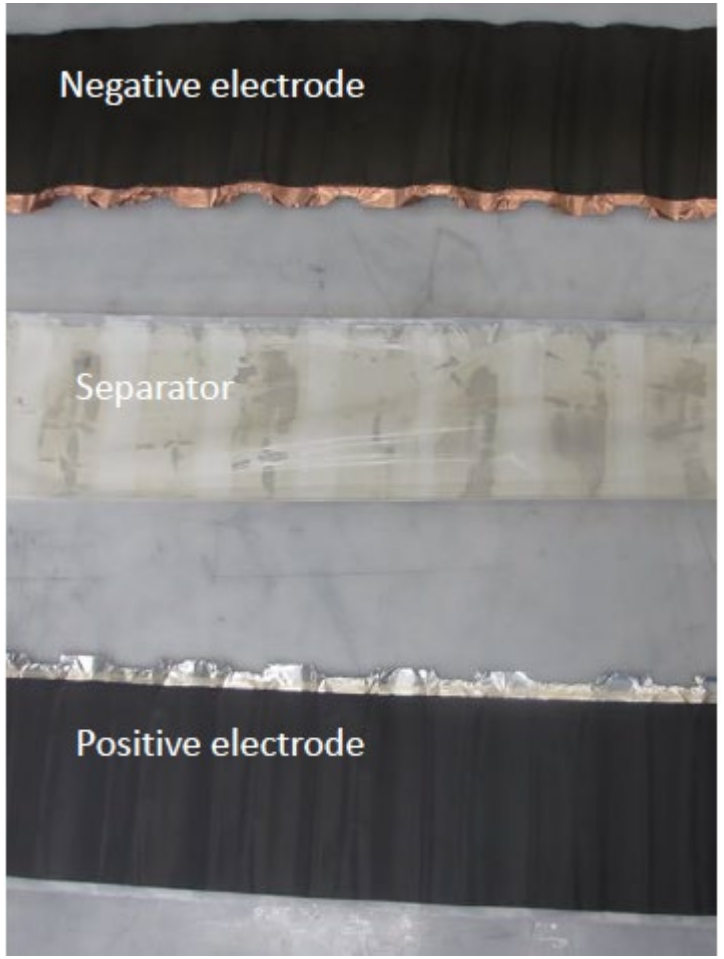
- Over 16,000 70% DOD LEO Cycles
- Cell performance remained nominal, capacity retention >75%
- DPA revealed no anomalies or areas of concern.





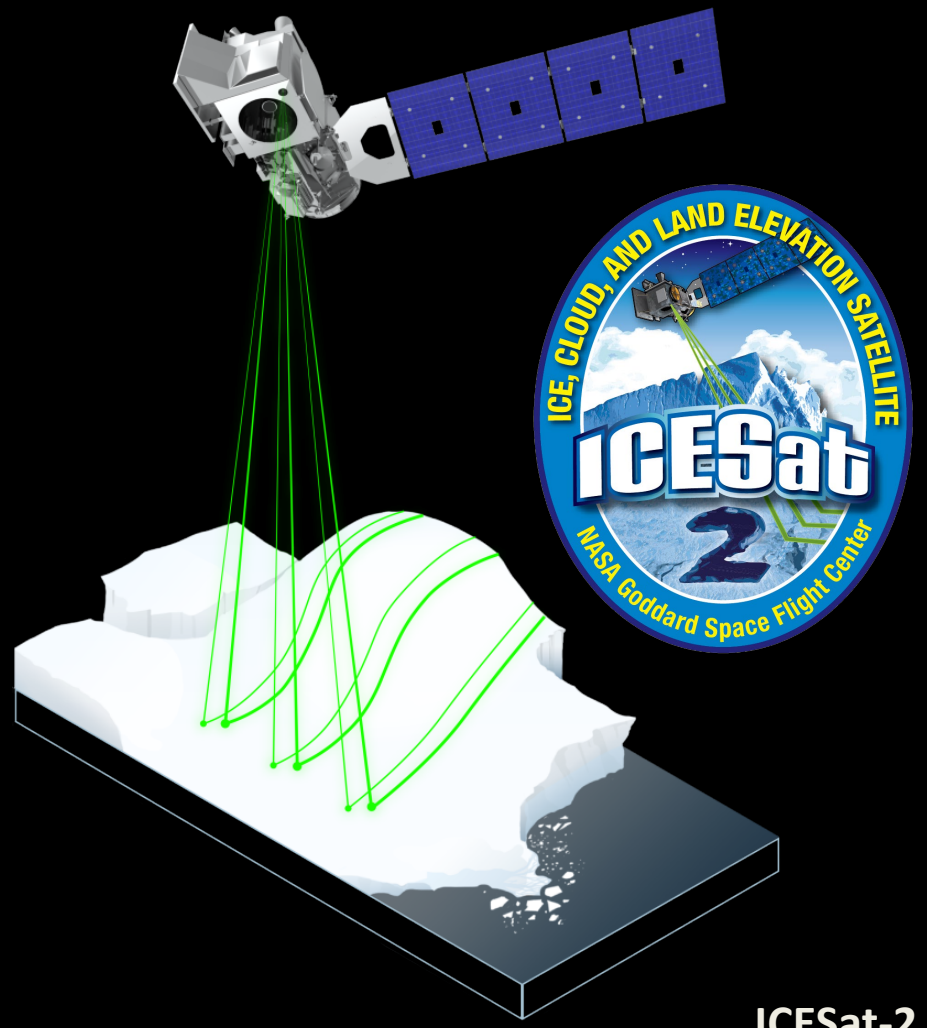
DOD 70 % LEO cycle life performance of the LSE12 cell

Charge: 4C/5, 4.10 V, CC/CV, 1 h, 15°C
Discharge: 1.4 C for 0.5 h, 15°C



Representative appearance of positive and negative electrodes, and separator after cycling test

MA12x
Modular Battery



ICESat-2
Manufactured by Northrop Grumman
Powered by GS Yuasa LSE134

Challenge and Design Approach

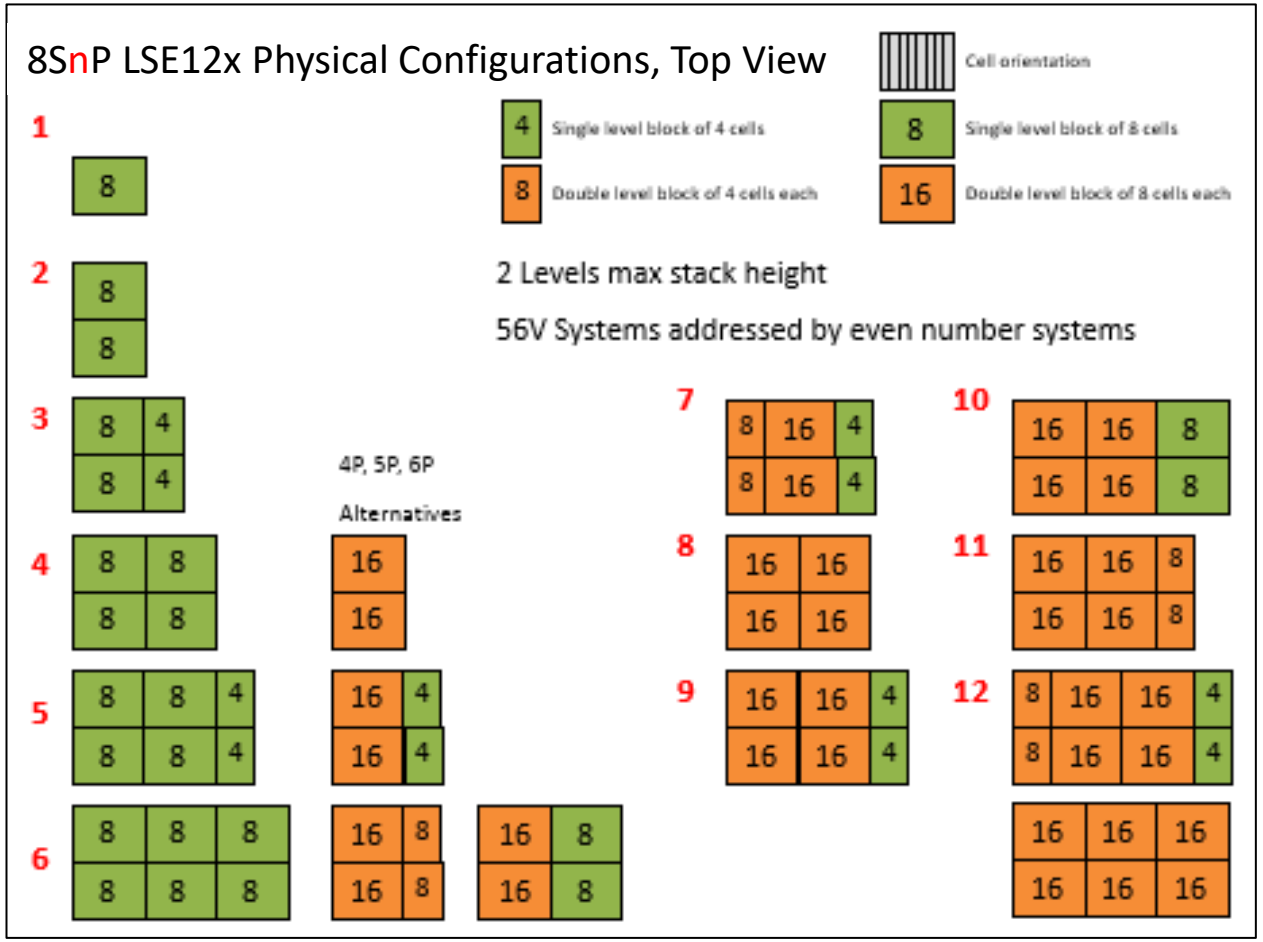
- **Challenge:**
  - → Design a modular battery capable of being combined and / or stacked to meet customer voltage and capacity needs for use in the space industry using the LSE12x cell.

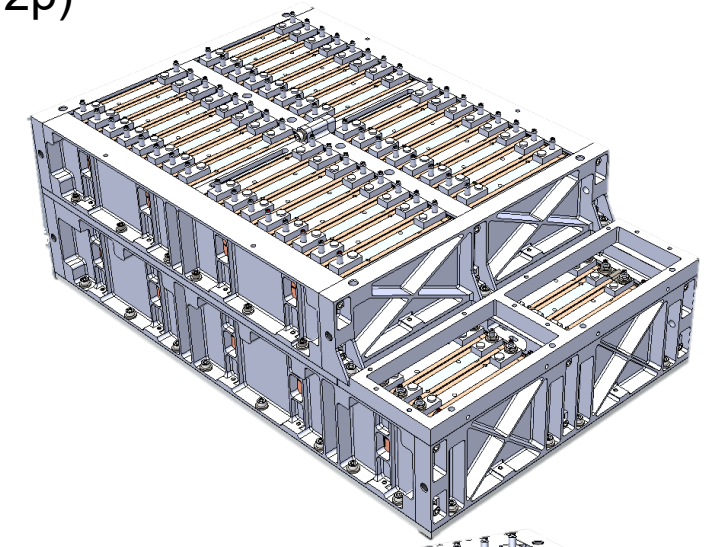
- **Design Approach:**
  - → Deploy the LSE12x in an 8S (series combination) to generate the voltage commonly used in space applications (24V - 33V).
    - Bonus: Consider layouts that allow enable higher voltage applications
  - → Develop a mechanical structural strategy to accommodate various number of 8S units connected in parallel to provide the overall capacity required by the customer.
  - → In the event of a fault, the Battery must be able to disconnect a “sick” string in the battery.
    - Fault tolerant design
  - → Consider materials which could enable passive propagation resistance.

MA12x Modular Battery Approach

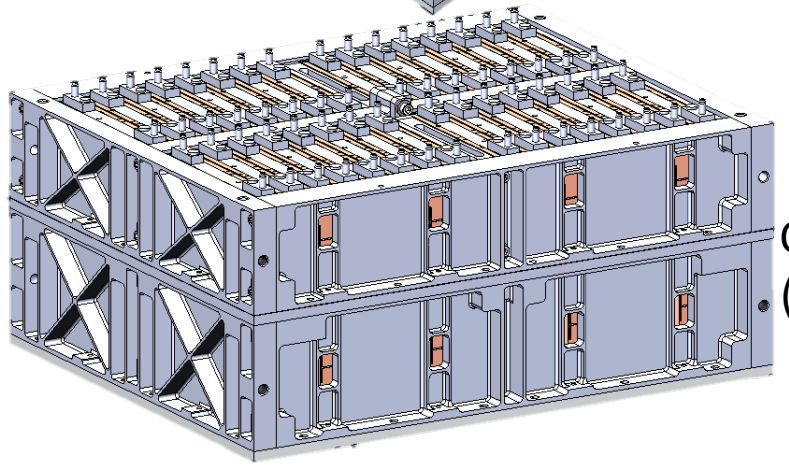
Battery Configuration Matrix

- Modular concepts were developed using this design approach and several options were captured that could be qualified depending on customer needs.
- Architecture can be scaled from 720Wh (8s2p) up to 4320Wh (8s12p)





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

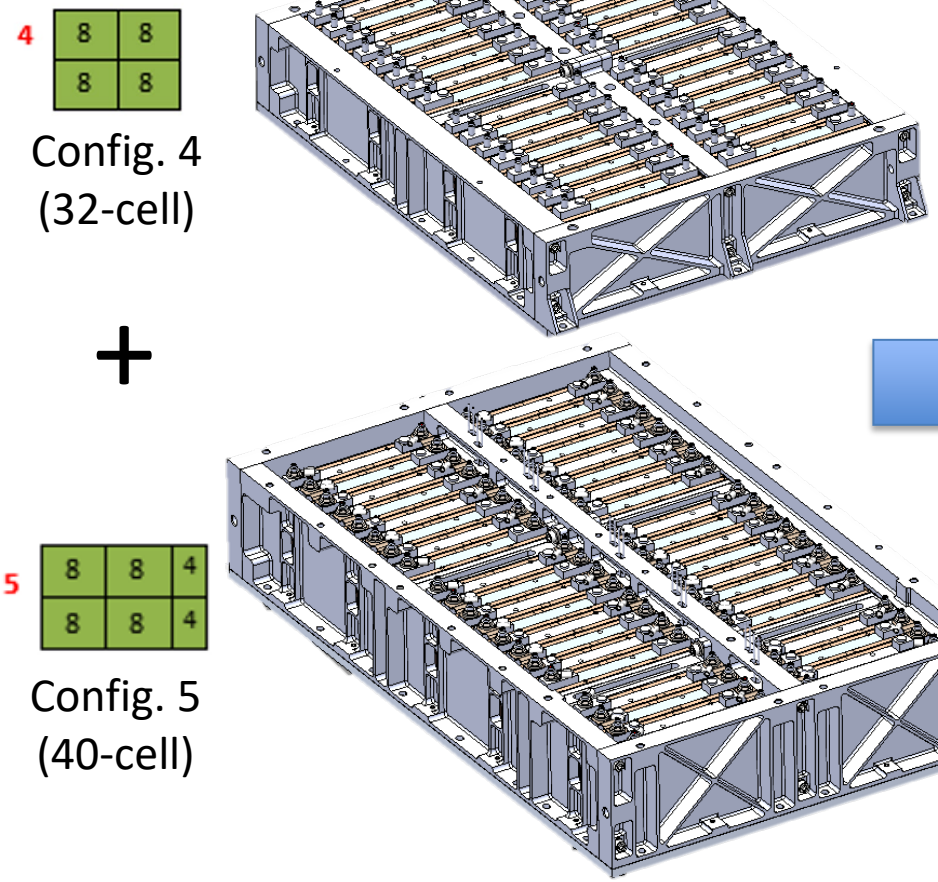


Config 8 (64-cell)

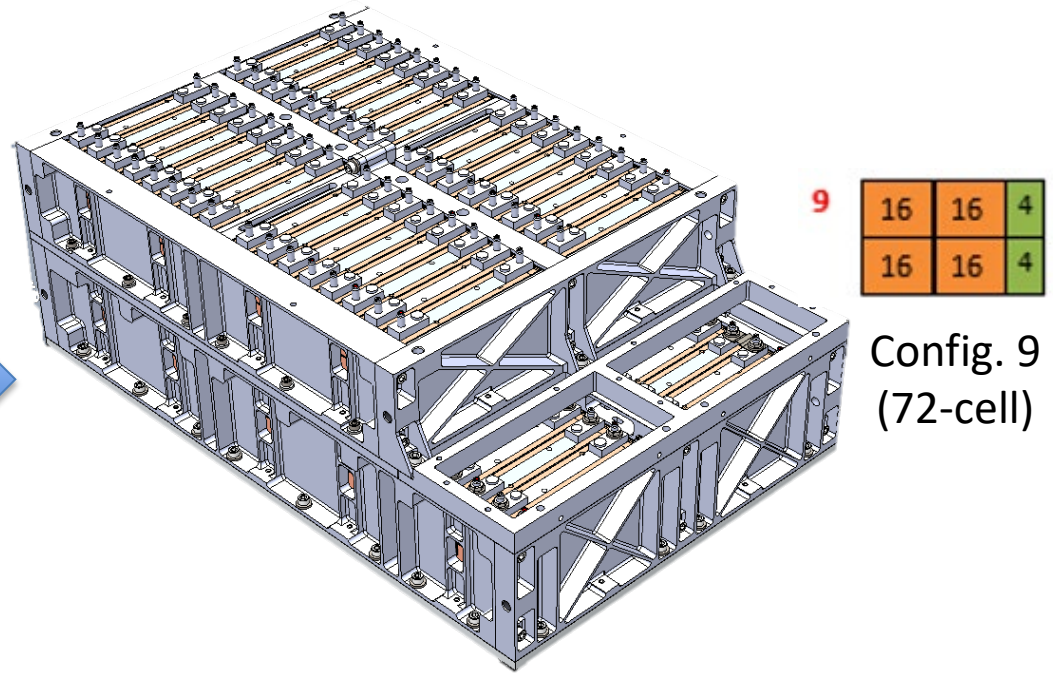
MA12x Modular Battery Approach

Single and Dual Level Packs

- The configurations can be deployed as a single level up to 8s6p configuration



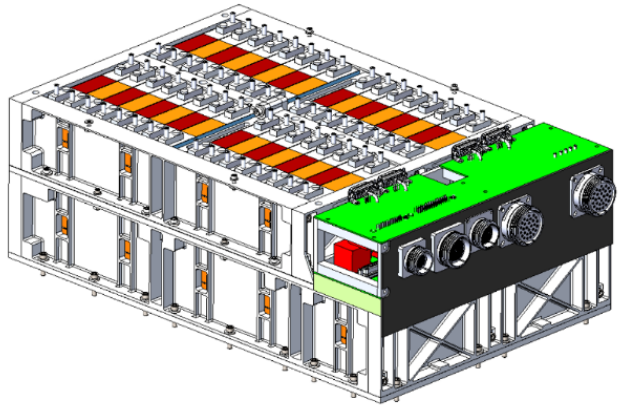
- Two modules can be “stacked” to minimize footprint and/or size up to larger batteries:

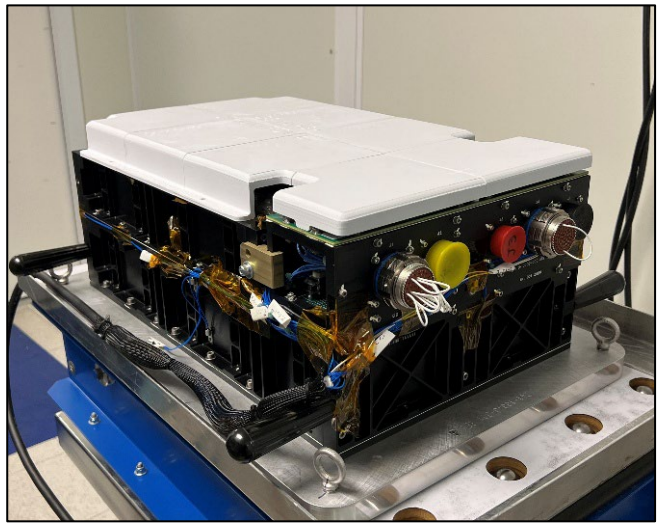


MA12x Modular Battery Platform

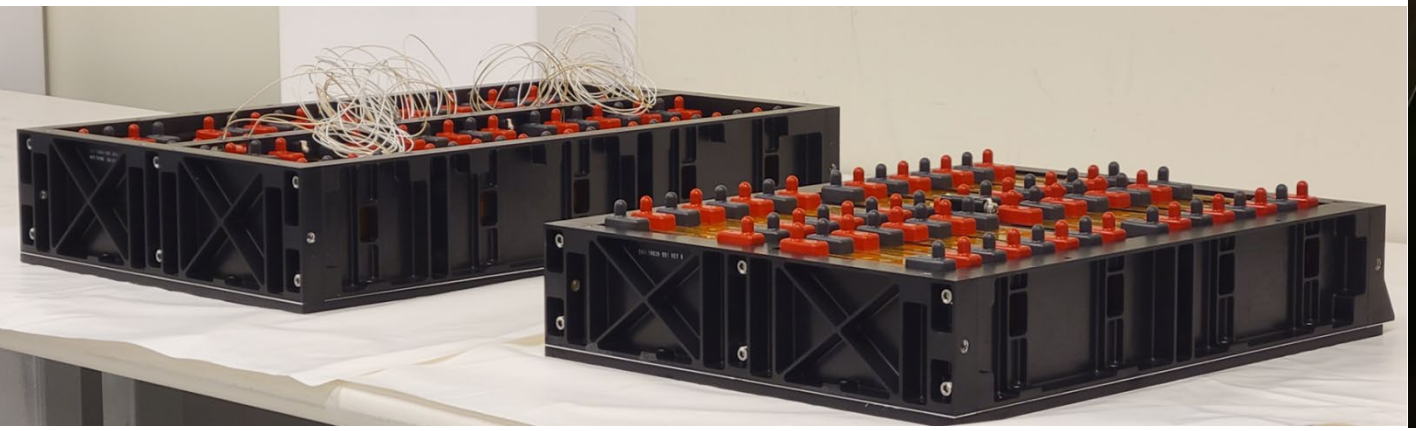
Designed and Manufactured by GS Yuasa Lithium Power, Inc.

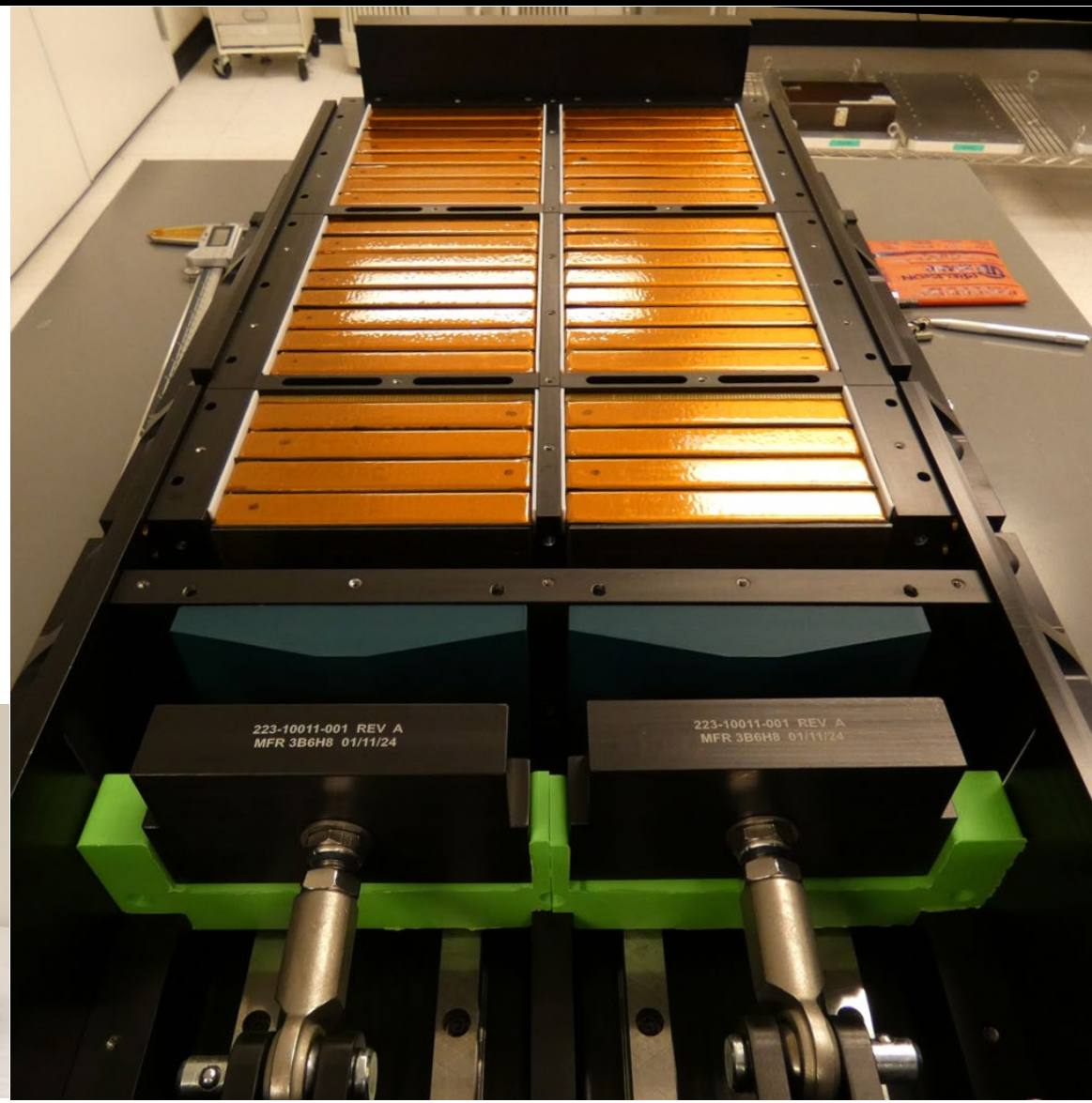
- GYLP has built and qualified the 8s9p configuration
- Qualification testing to complete Q1 2025





3,240Wh 8s9p (72-cell) *Qual Unit*





MA12x-0809 Qualification Unit

Wiring Configuration:

→ 8s9p – 72 total cells

Non-flight connector box

→ Interface is typically driven by spacecraft requirements and designed as part of program.

→ Demonstrate power and telemetry approaches with mix of space-rated and “off the shelf” non-space rated components.

Qual Configuration Telemetry

→ Individual cell voltage sense

- Flight configuration will reduce.

→ Mid-stack and full stack voltage taps per 8s group

→ 1 Thermistor per 8s group

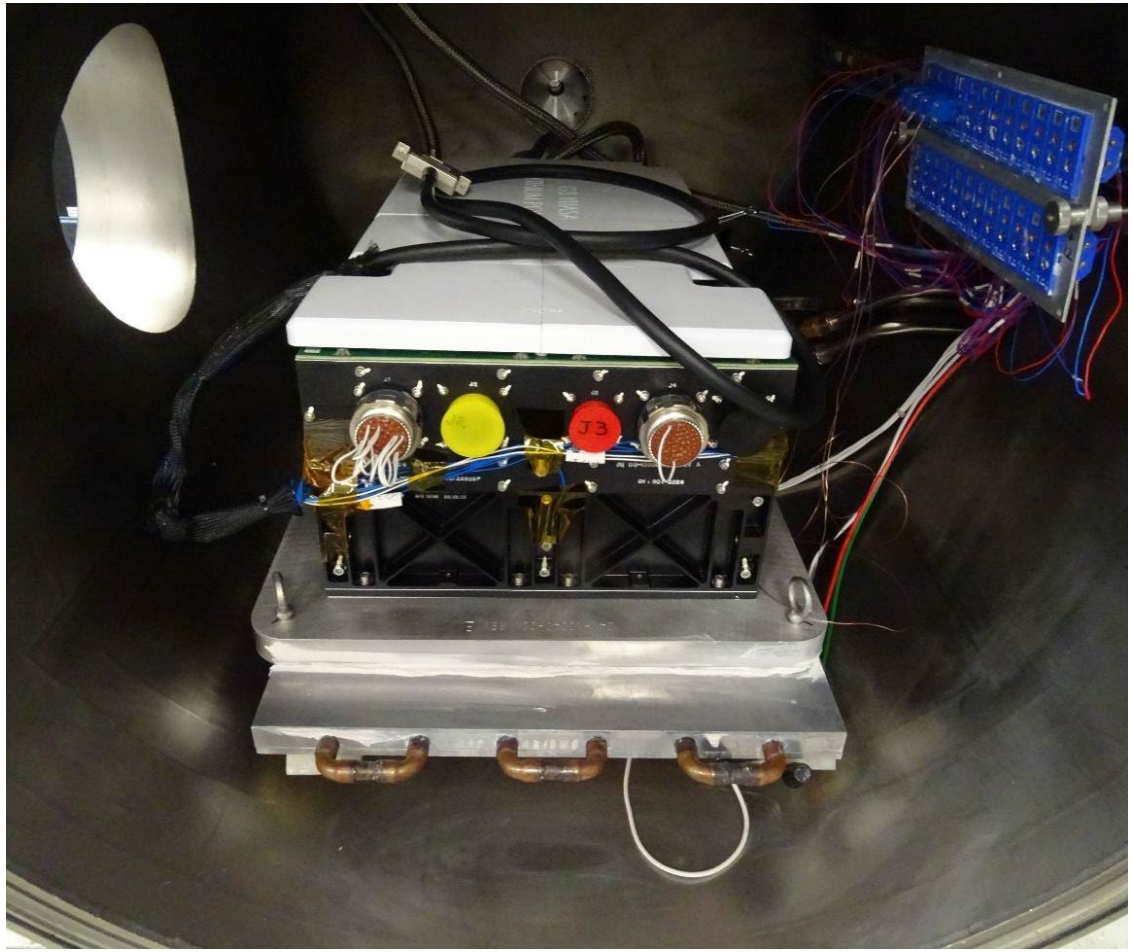
Fault tolerance

→ Commandable relays can disconnect individual strings from the power path in event of a fault.

No Cell Balancing

→ Cells are balanced before integration at 4.1V/cell

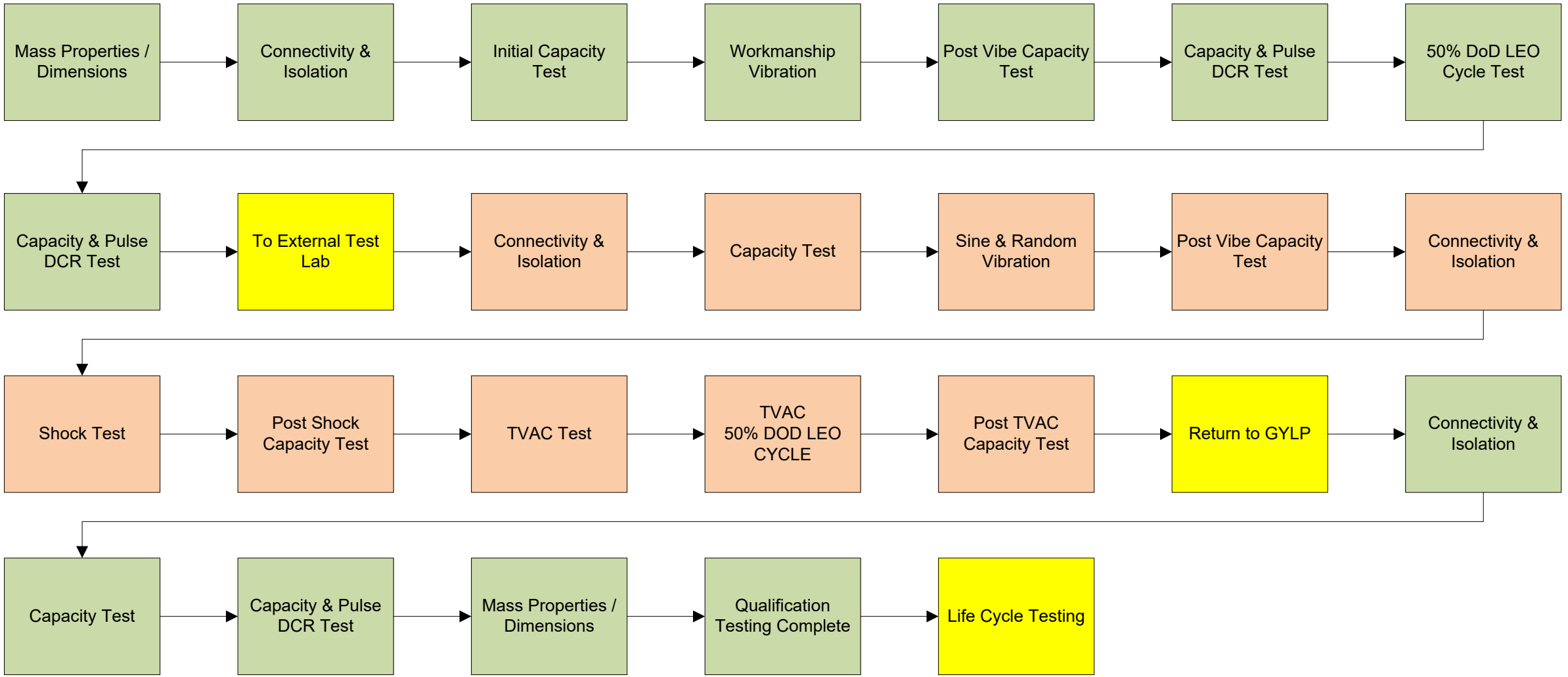
Primary and redundant heaters present



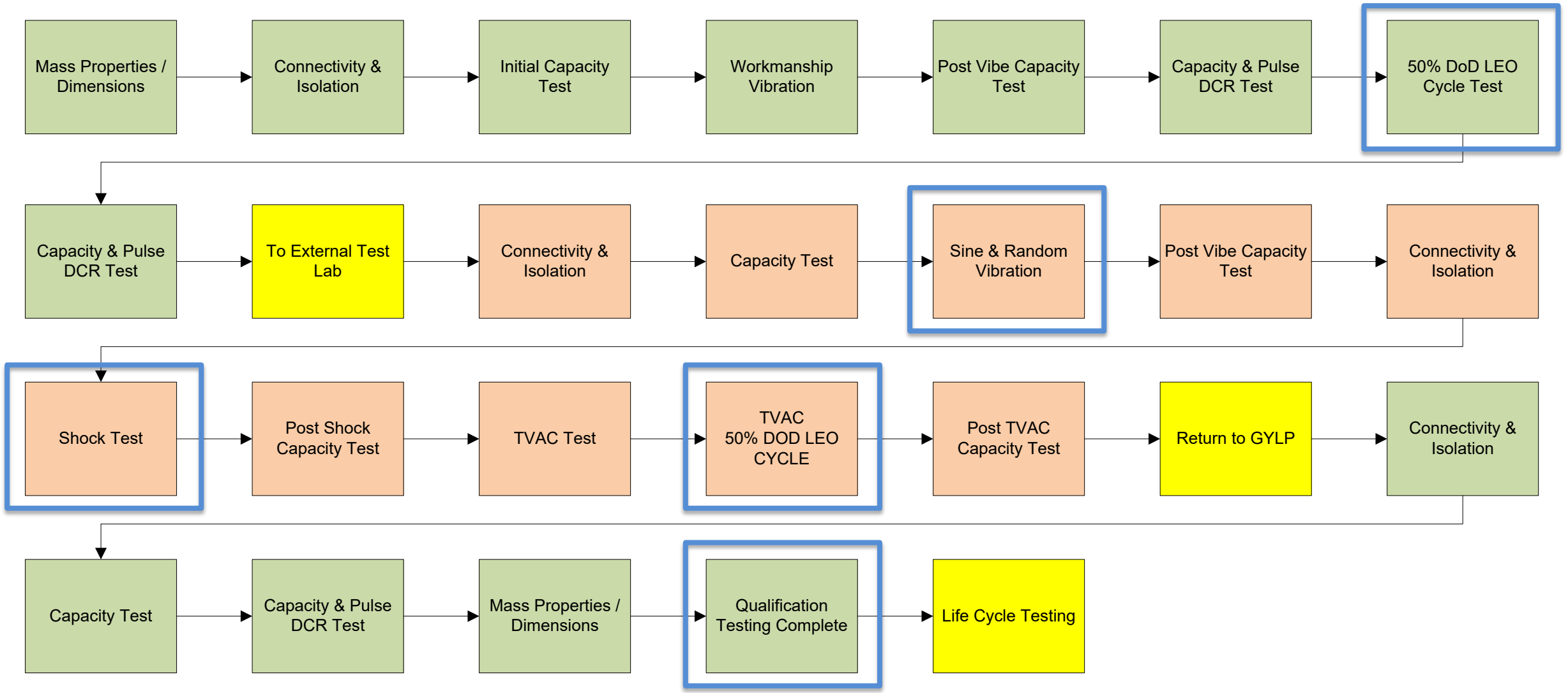
SES's O3b mPOWER
Boeing 702x Satellites
Powered by GS Yuasa LSE190

MA12x Qualification Testing & Results

Qualification Test Flow



Qualification Test Flow



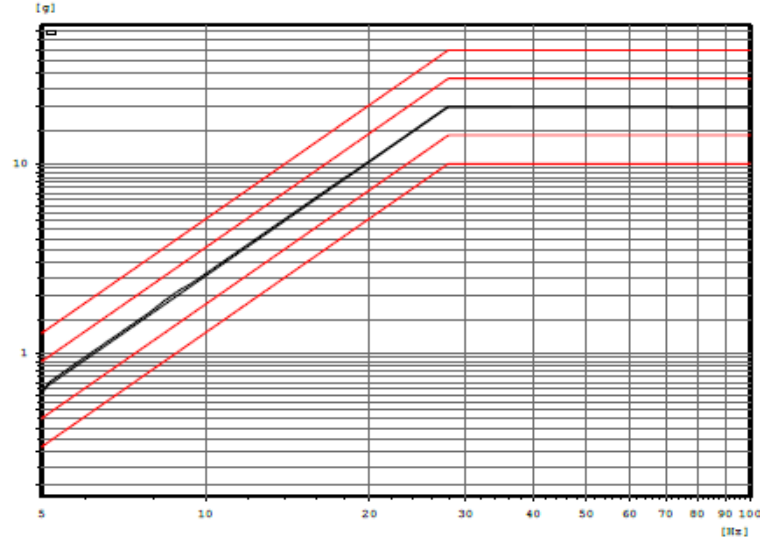
MA12x-0809 Environmental Qualification

Sine Vibration, Random Vibration, Shock Levels

Sine Survey

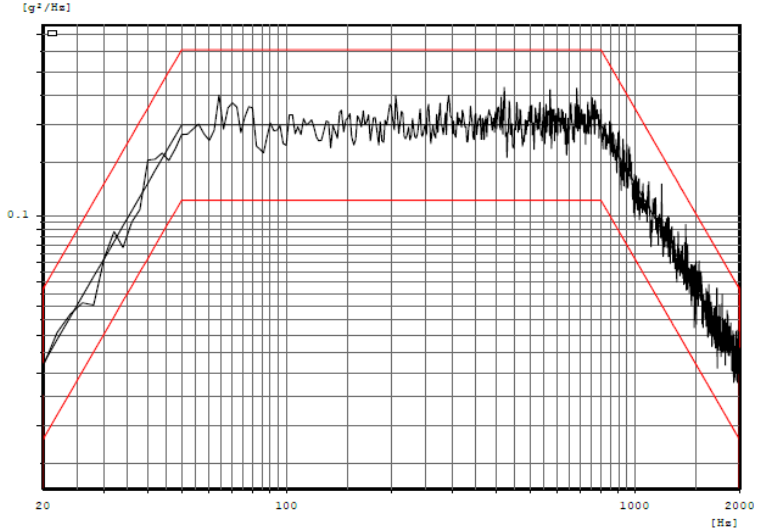
Axis	Frequency (Hz)	Acceleration (g)	Displacement
3 Orthogonal Axes	5	0.639	0.5
	27.9	20	0.5
	100	20	0.039
Sweep Rate:		2 Octaves/Minute	

Level	# of Sweeps	Rate/Level
Sine Pre-Random	N/A	Random Vibration Profile at $0.002g^2/Hz$ for 30 Seconds
-6 dB	1	2 Octaves/Minute
-3 dB	1	
0 dB	3	



Random Vibration Levels

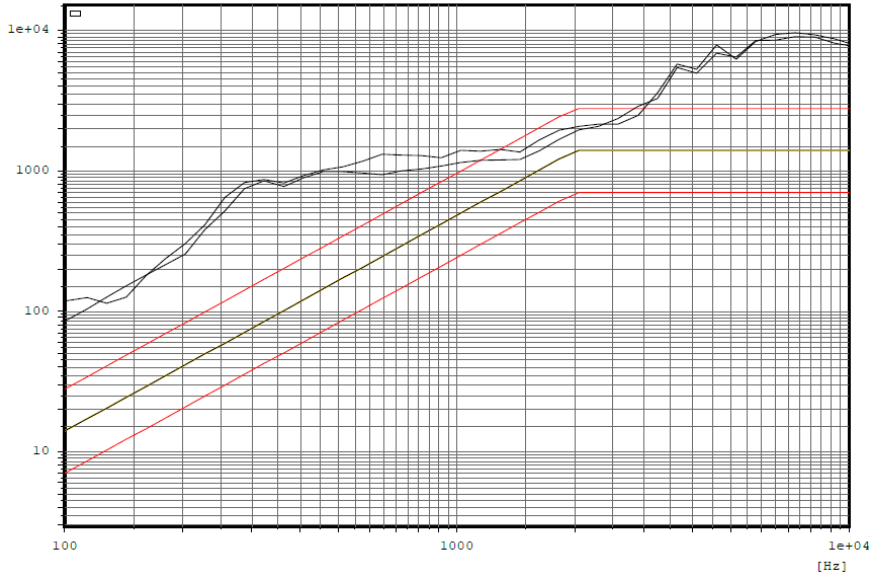
Frequency (Hz)	Qualification Level	Units
20	0.032	g^2/Hz
20-50	6	dB/oct
50-800	0.2	g^2/Hz
800-2000	-6	dB/oct
2000	0.032	g^2/Hz
Overall grms: 15.78		
Duration: 120-Seconds		



Shock Levels

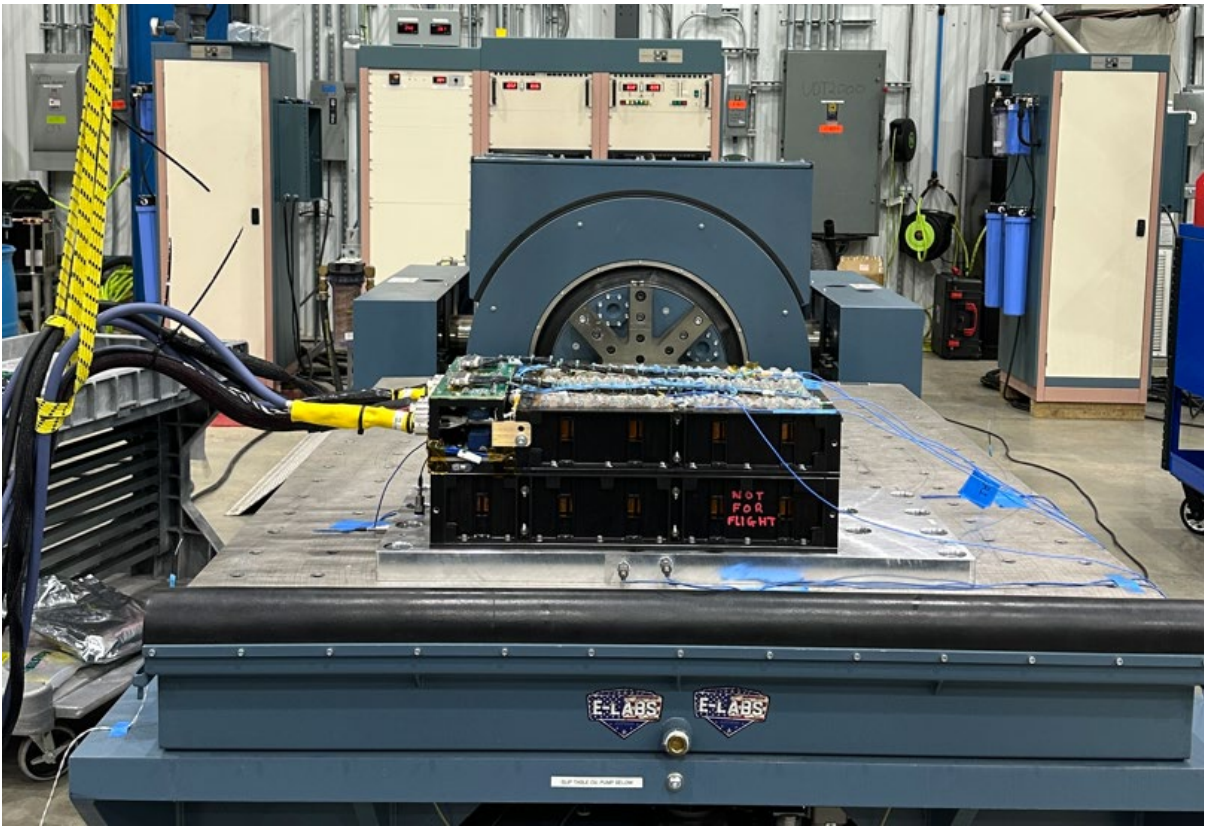
Frequency (Hz)	Shock Level (g)	Number of Shocks
100	14	3
2000	1400	
10000	1400	

[g] SRS Shock, Calibration Pulse 1, Control 1, X-Axis

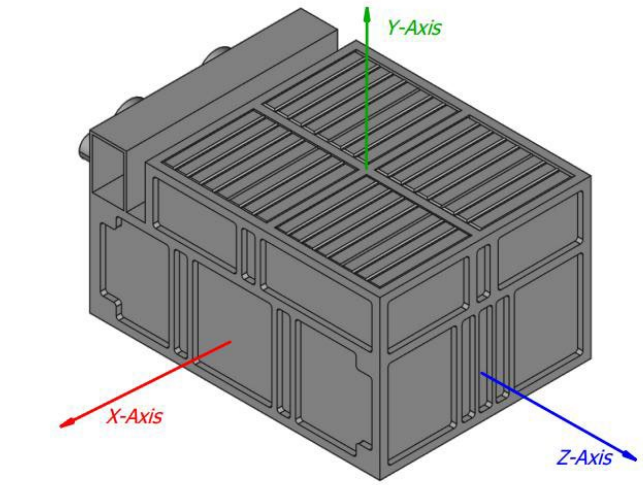


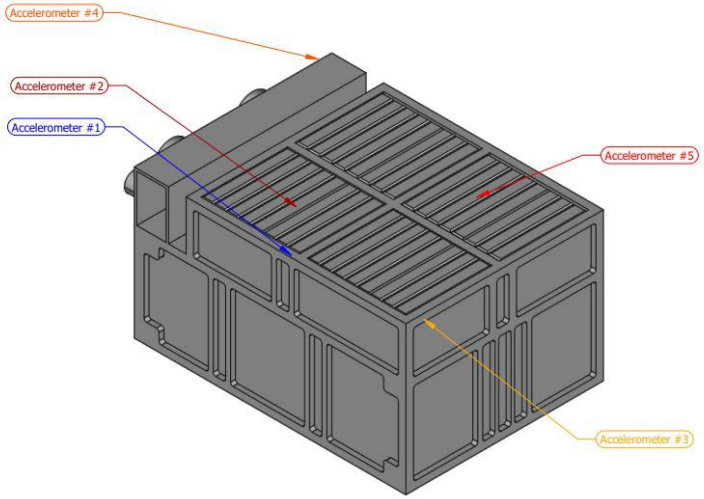
MA12x-0809 Environmental Qualification

March 2025



Sine / Random Vibration





Shock

MA12x-0809 Environmental Qualification

Sine Vibration Results

Pre/Post Sine Survey No Significant change (<10%)

Primary Mode Shift

→ X: 0.0%

→ Y: 4.1%

→ Z: 0.7%

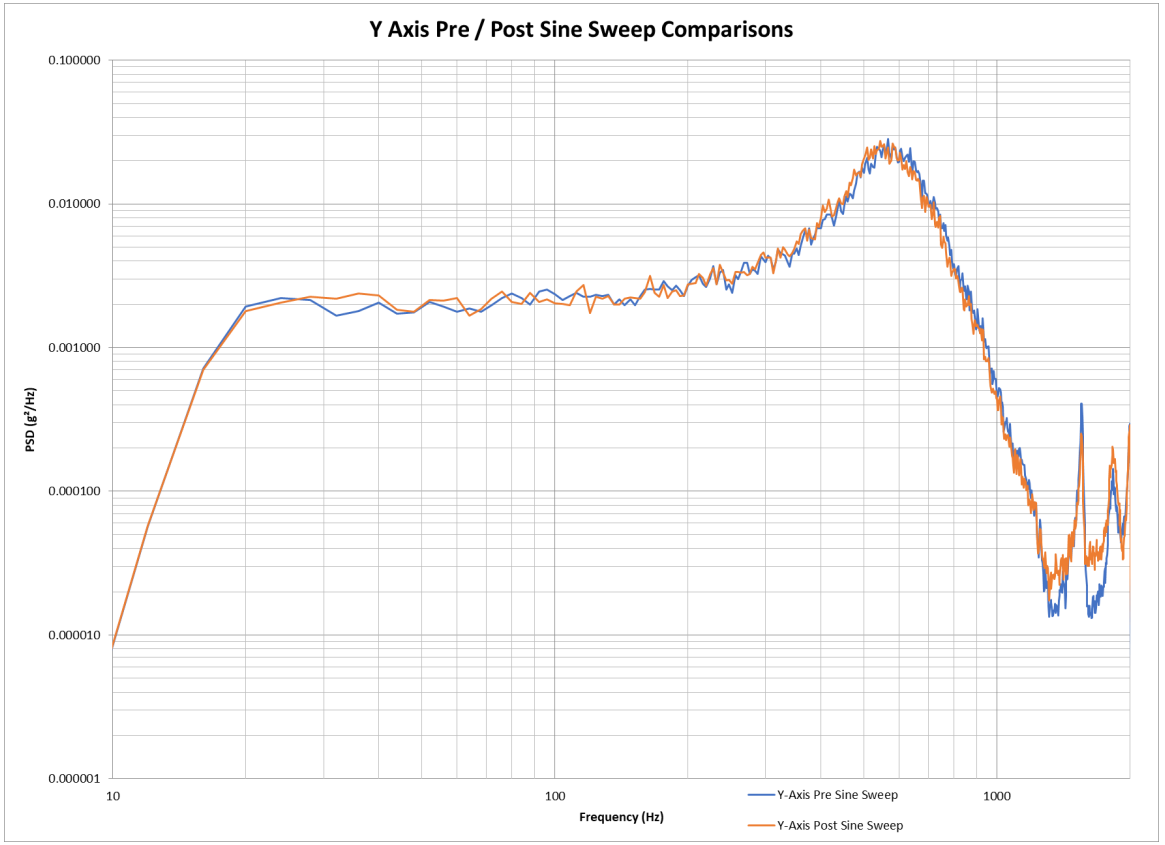
Sine Vibration

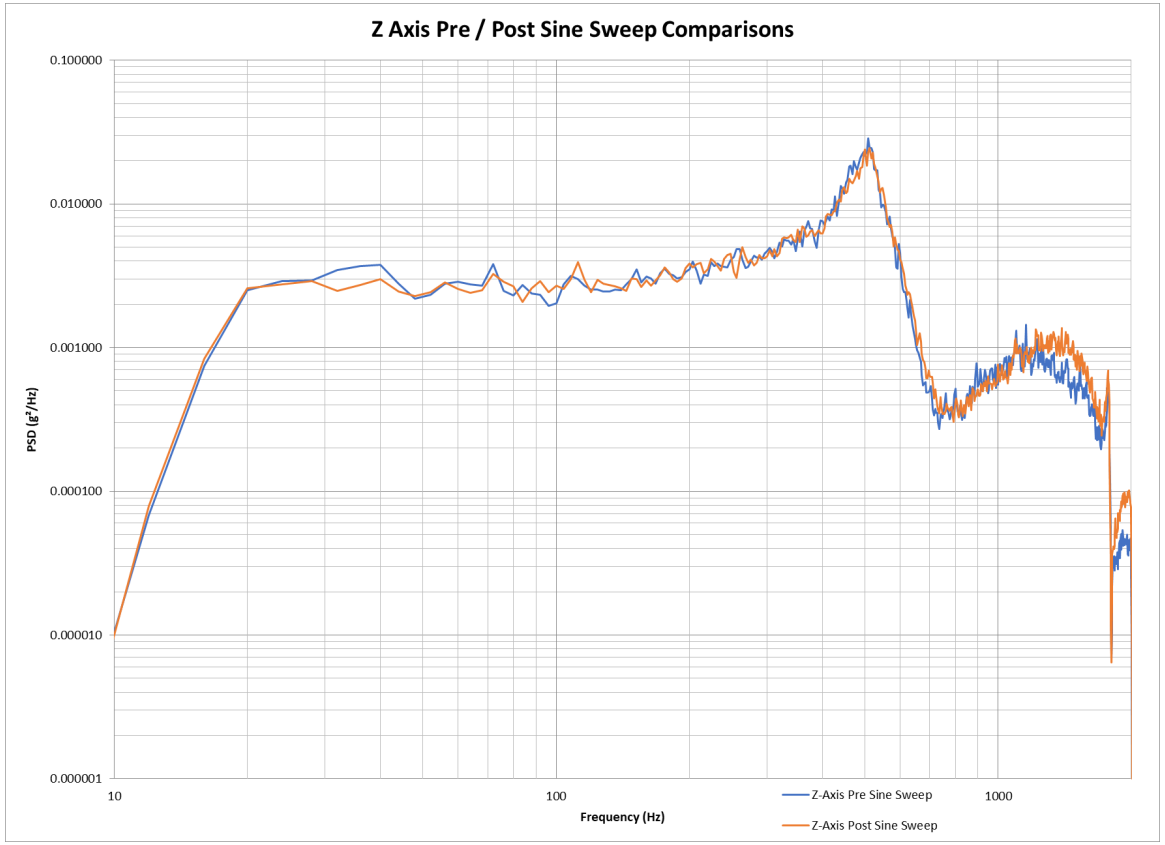
Primary Modal response

→ X: 464Hz

→ Y: 548Hz

→ Z: 512Hz

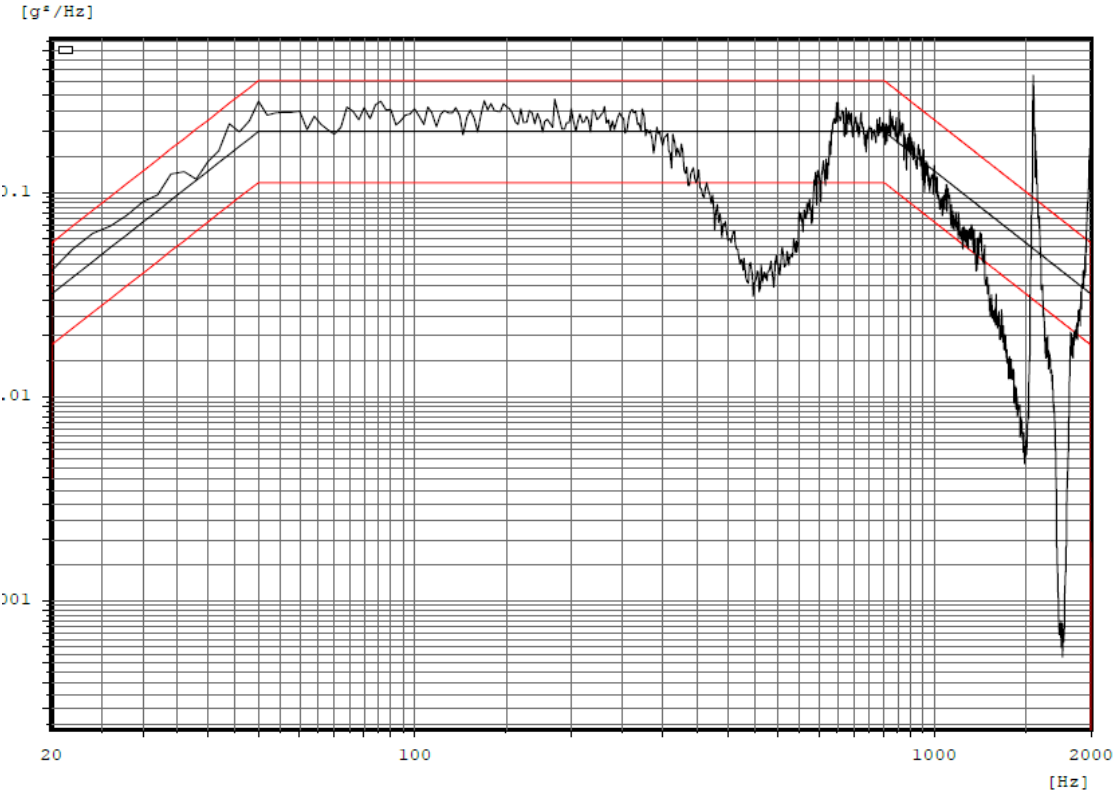




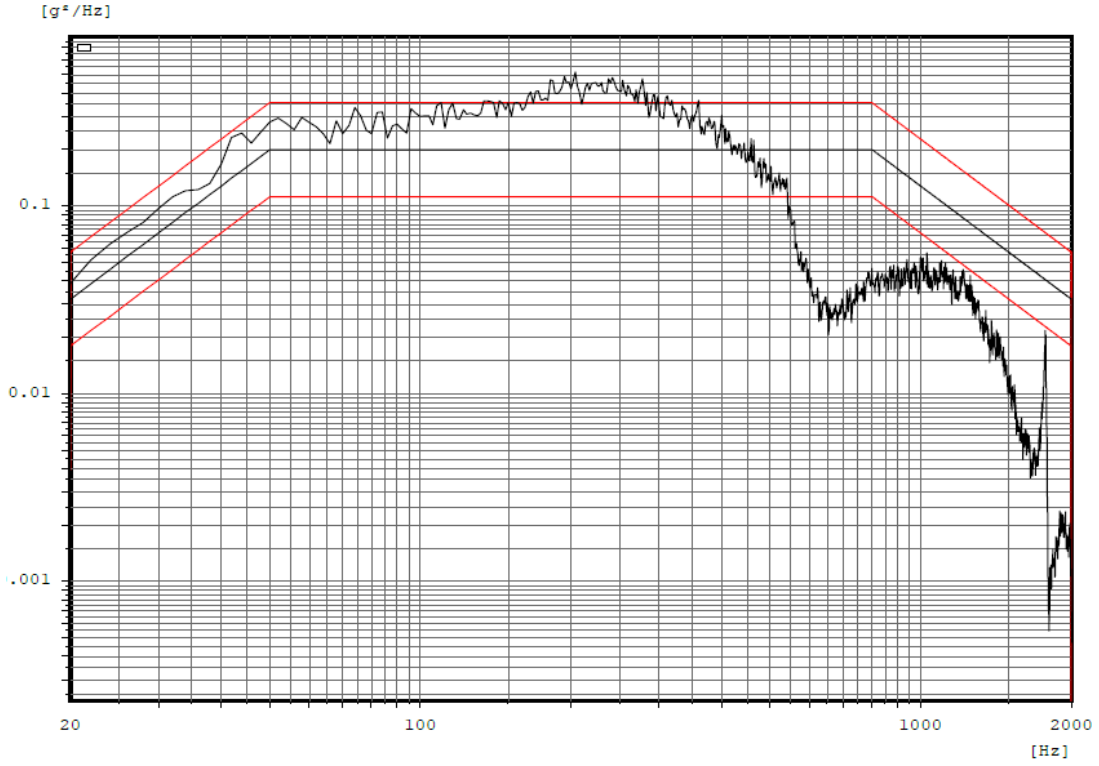
Random Vibration - Full Level

Accel 2 - Cell Case Lid

Y-Axis



Z-Axis



MA12x-0809 Environmental Qualification

Random Vibration Results

Pre/Post Sine Survey No Significant change (<10%)

Primary Mode Shift

→ X: 0.0%

→ Y: 5.1%

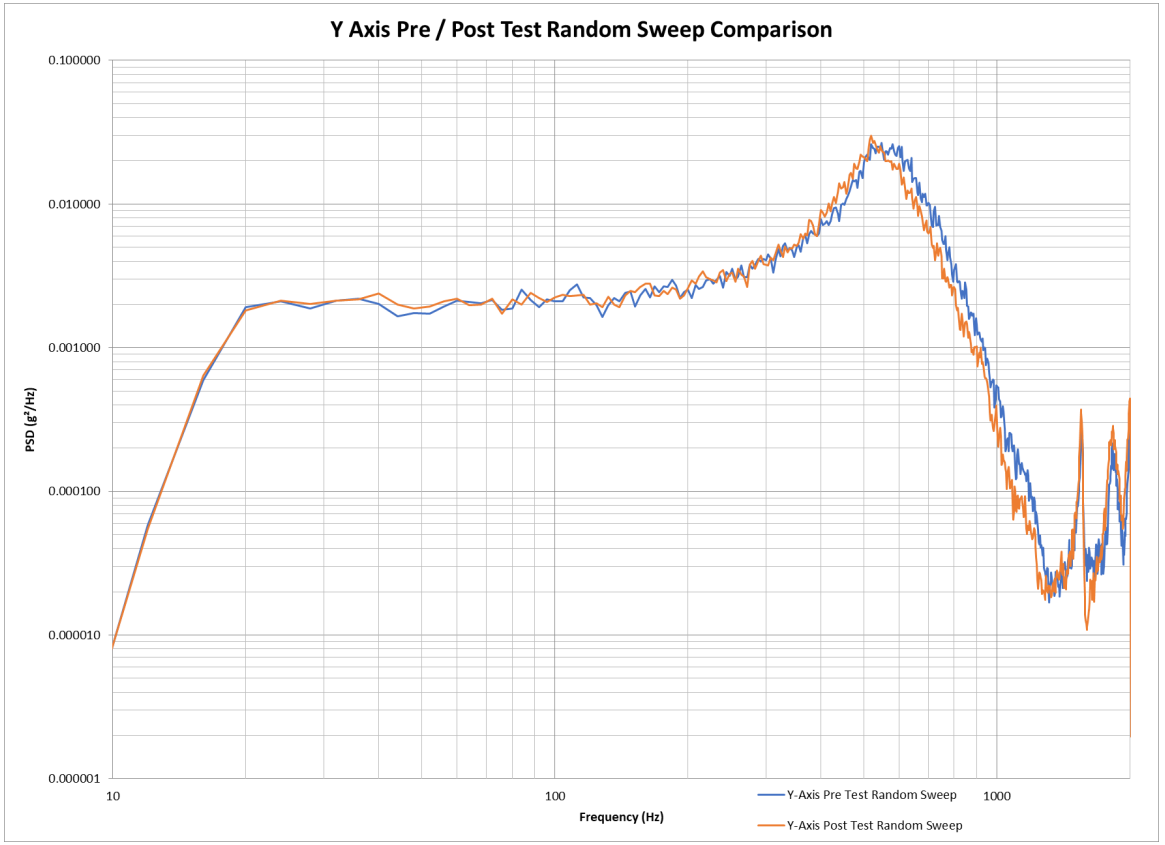
→ Z: 0.7%

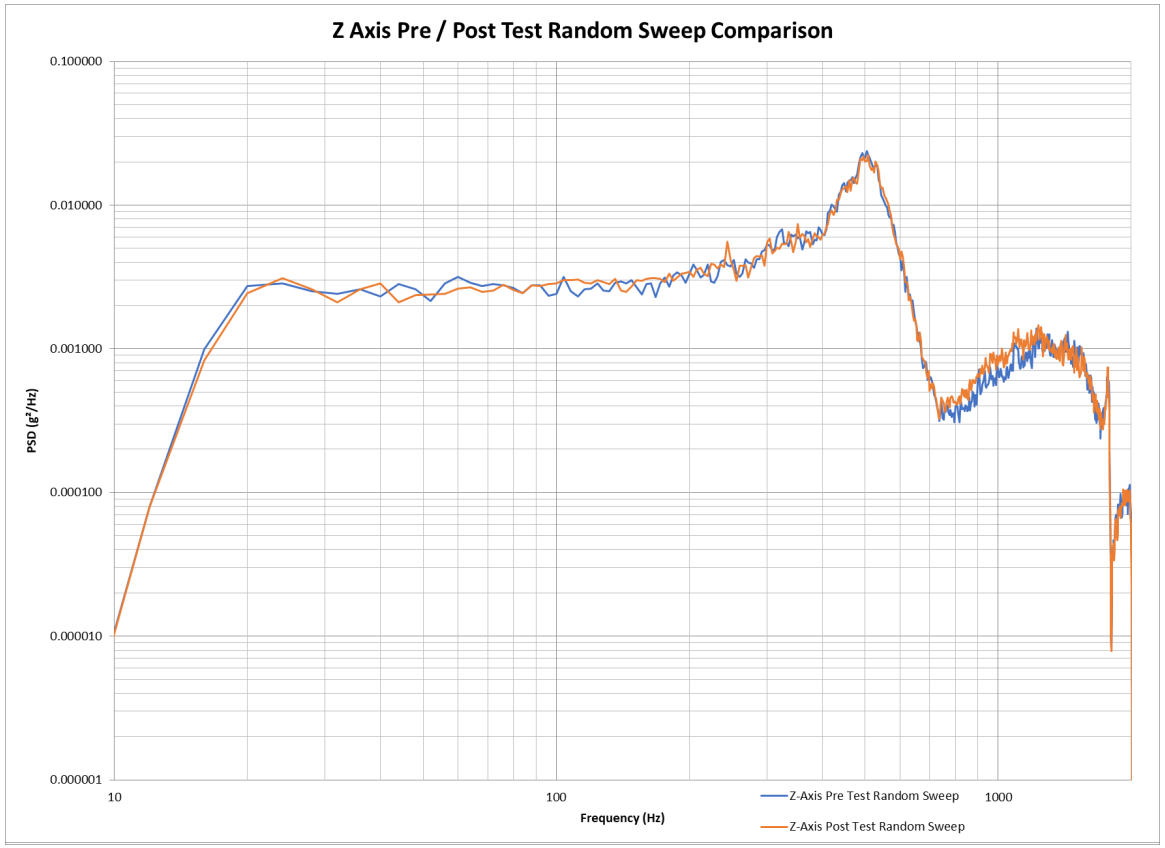
Primary Modal response

→ X: 464Hz

→ Y: 520Hz

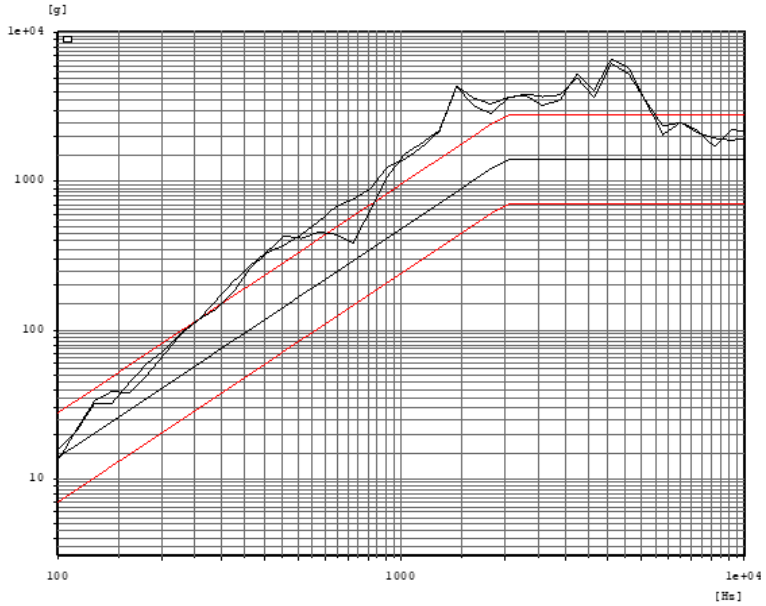
→ Z: 508Hz





MA12x-0809 Environmental Qualification

Shock Results

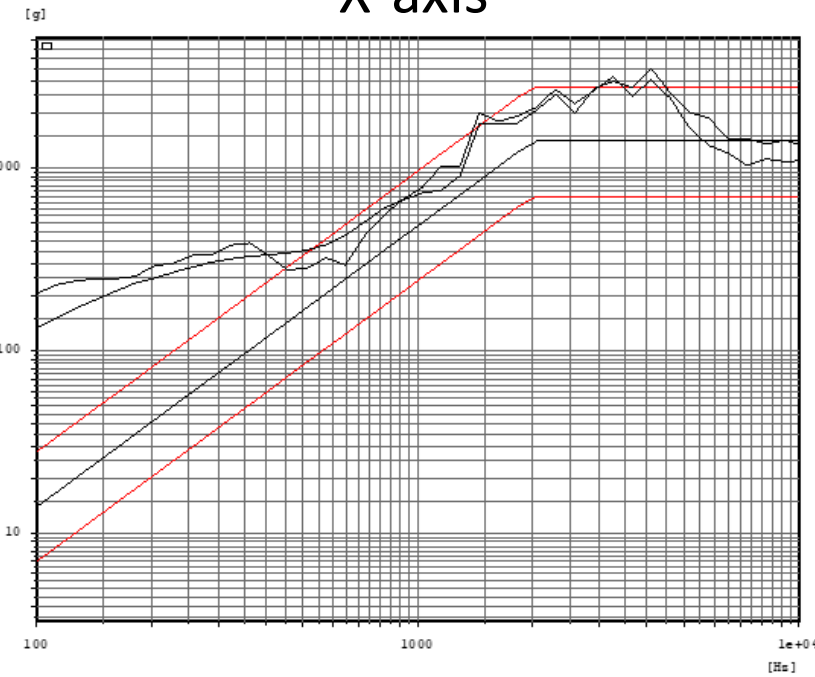


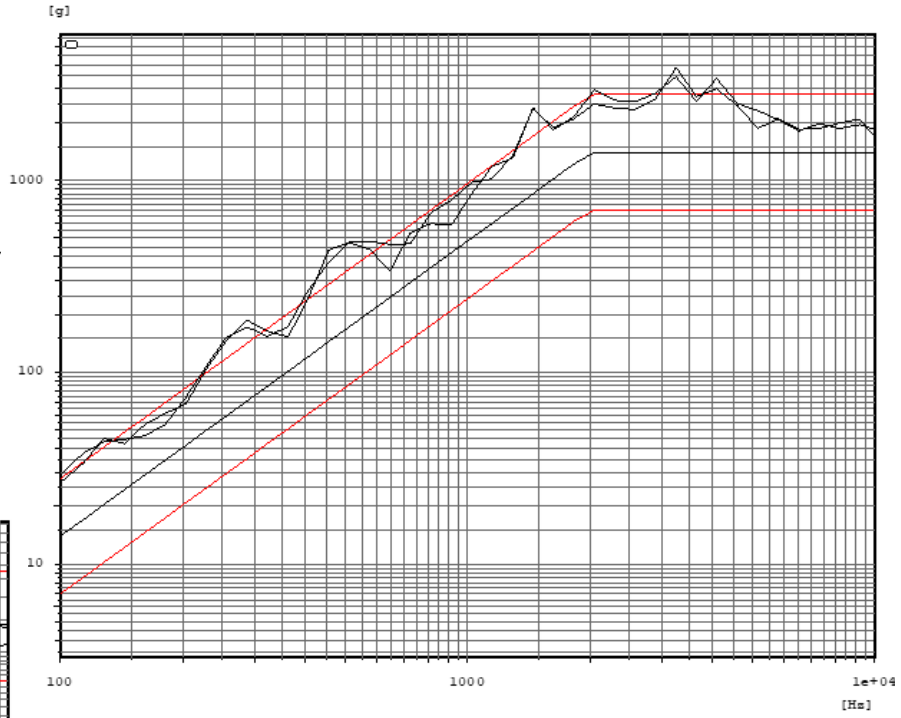
Y-axis

Minimum 3 passing shocks per axis

Battery performed nominally post exposure

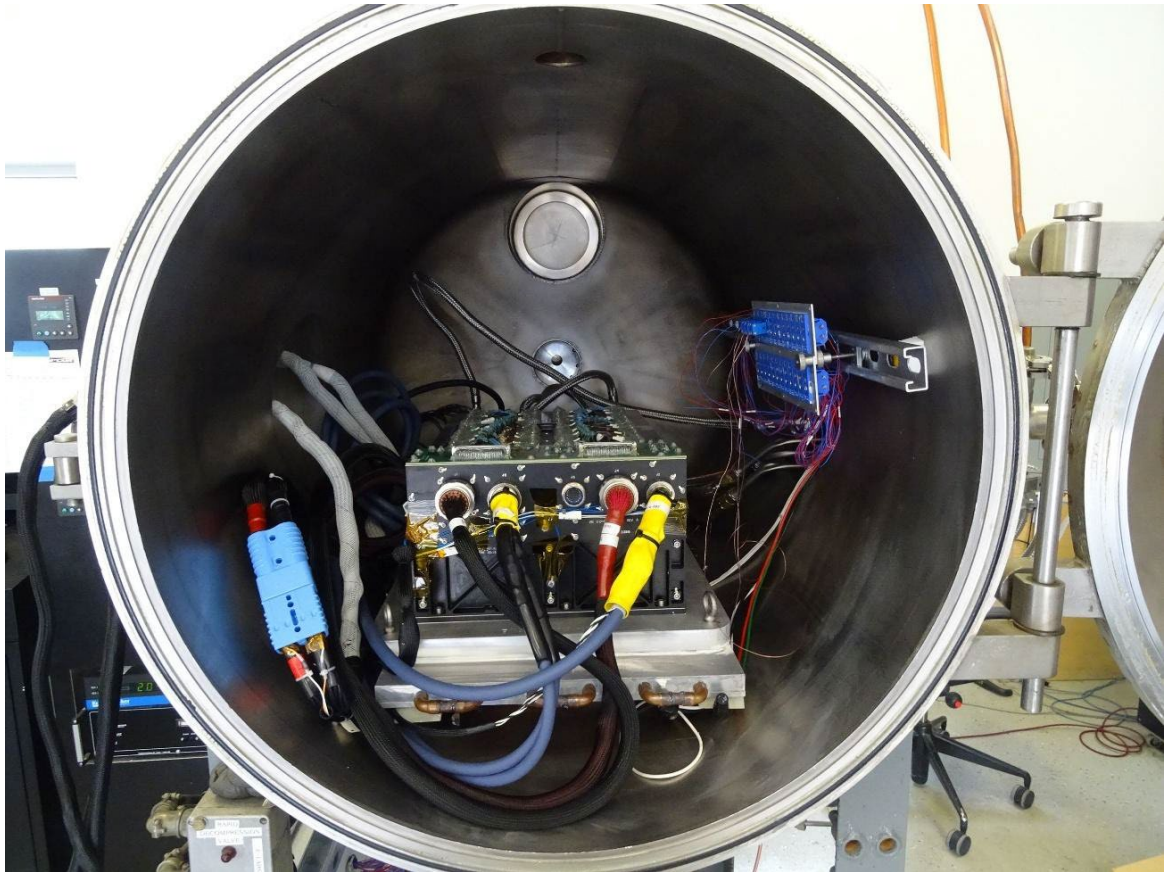
X-axis

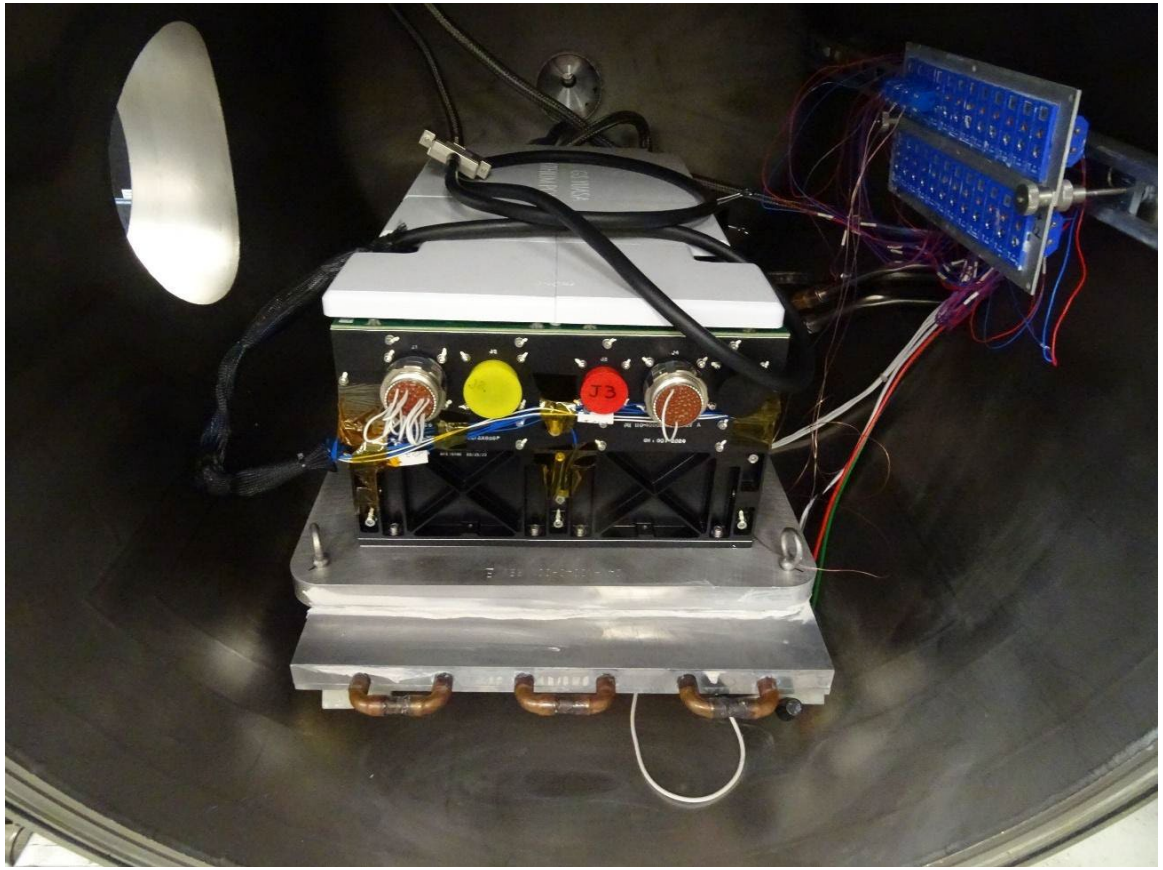




Z-axis

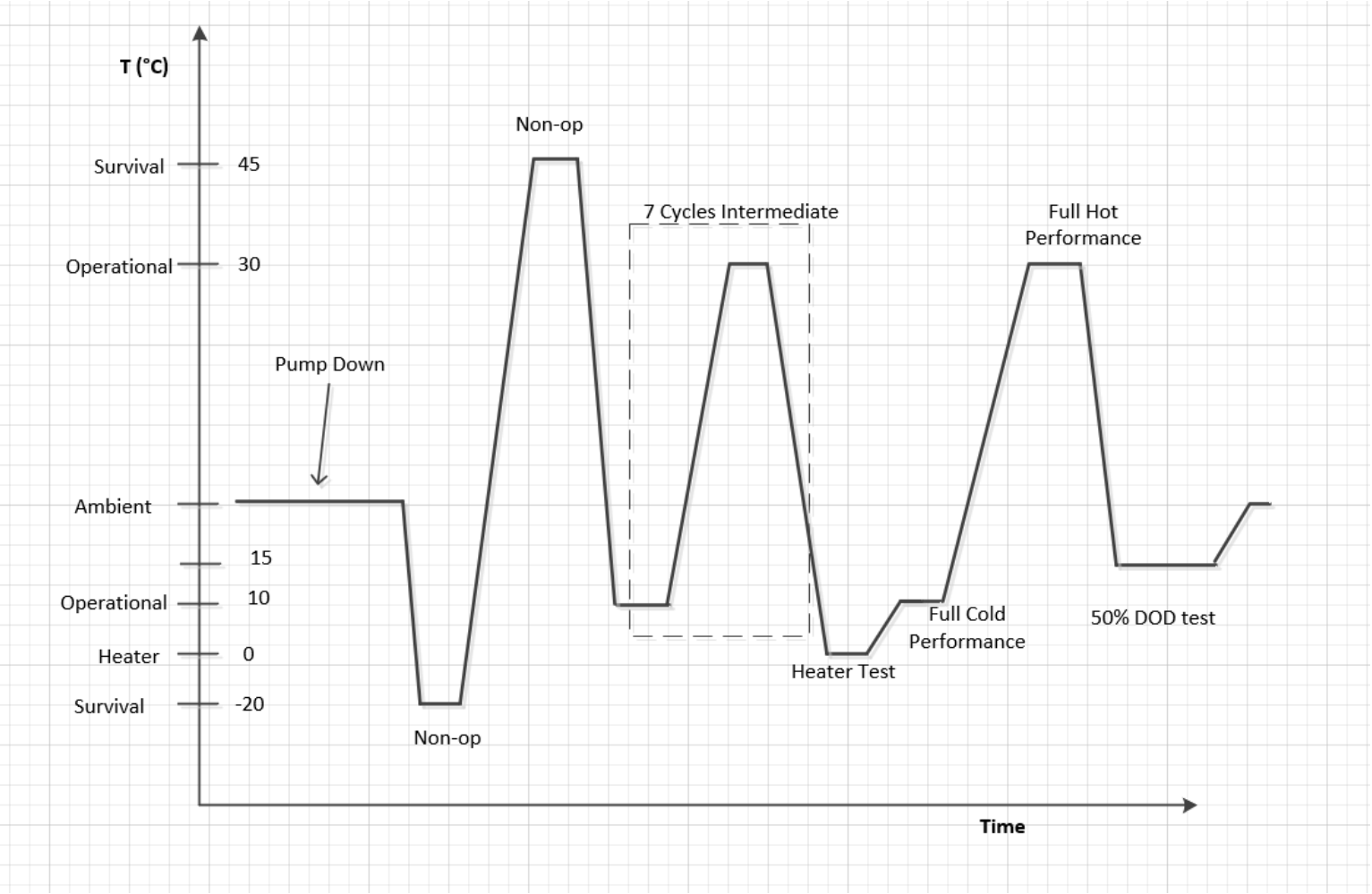
Thermal Vacuum Test





Thermal Vacuum Test

Profile



Thermal Vacuum profile to demonstrate performance across the range of temperatures.

- Pump down to 1E-5 Torr or less
- Survival at -20°C and +45°C
- 7 Operation cycles at +10°C and +30°C
  - 108A discharge for 6min
  - 54A charge for 12 min
- Heater function test at +0°C
- Full discharge at +10°C.
- Full discharge at +30°C
- 8 total 50% DOD LEO Cycles at +15°C
- Return to ambient temperature and pressure

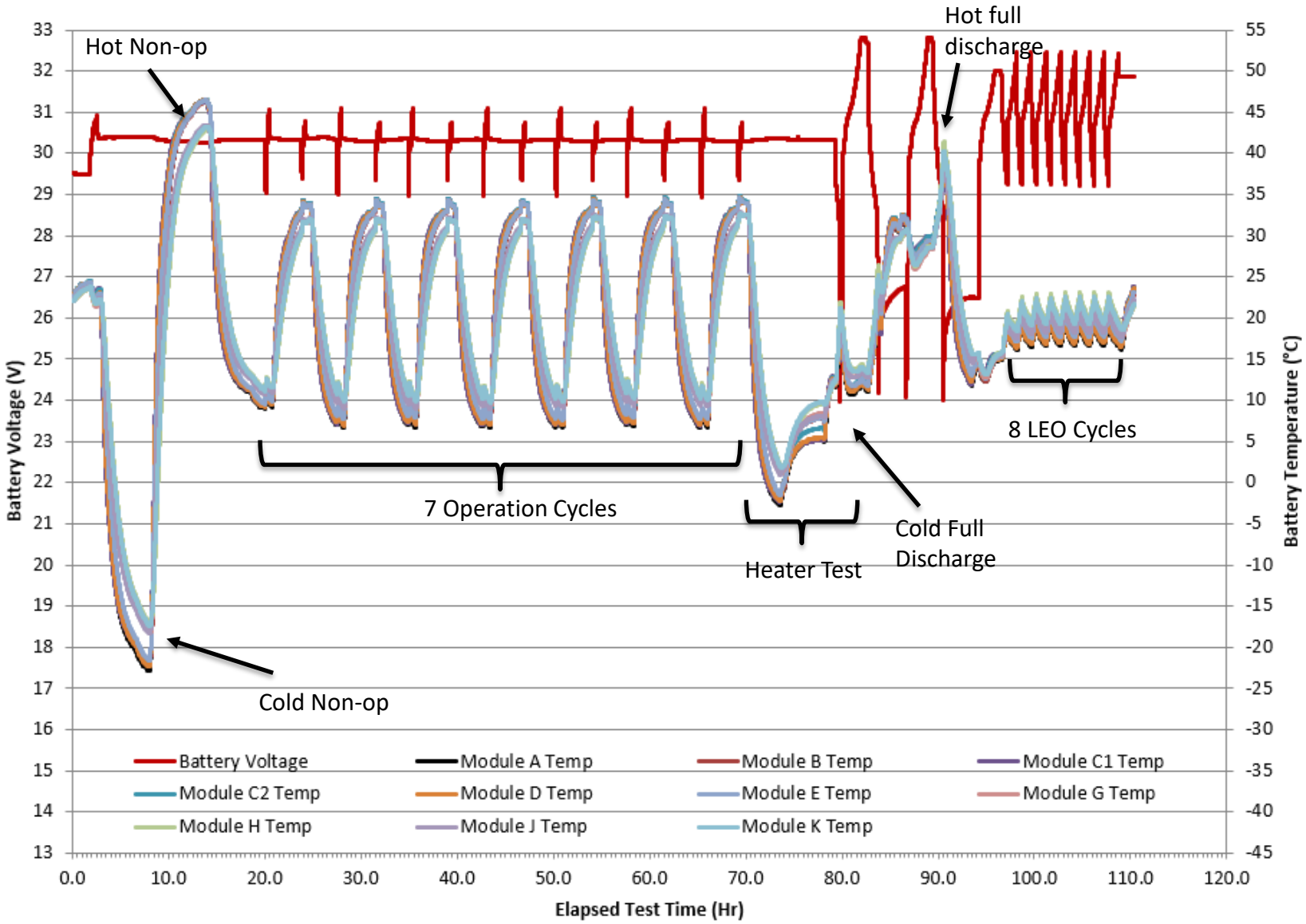
T-Vac Performance

Test Results

Thermal performance in vacuum is nominal with no excessive temperature gradients observed during battery use.

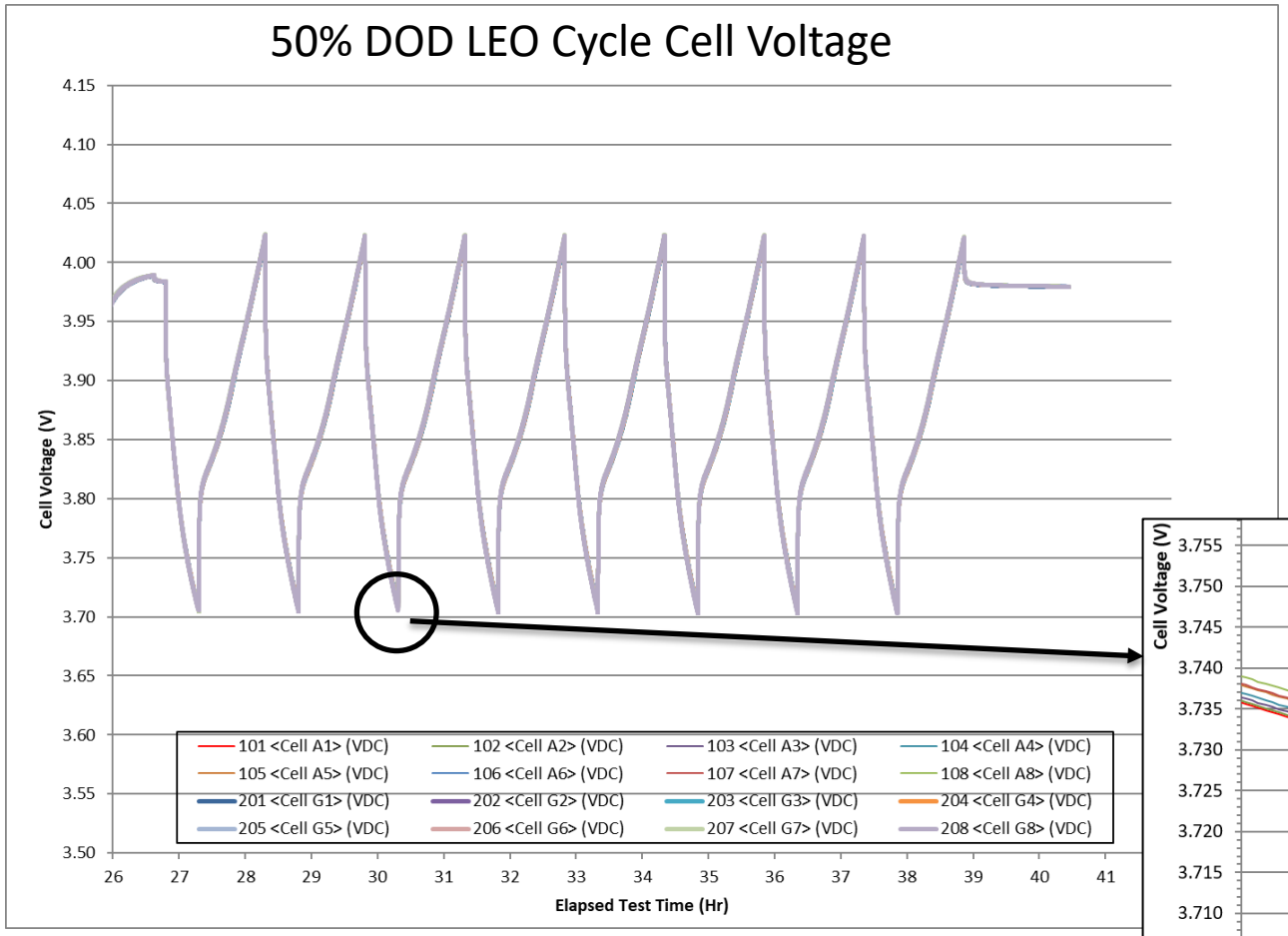
<5deg.C gradients for isoline positions when cycling.

~5deg.C rise during 50% DOD LEO Discharge Cycle

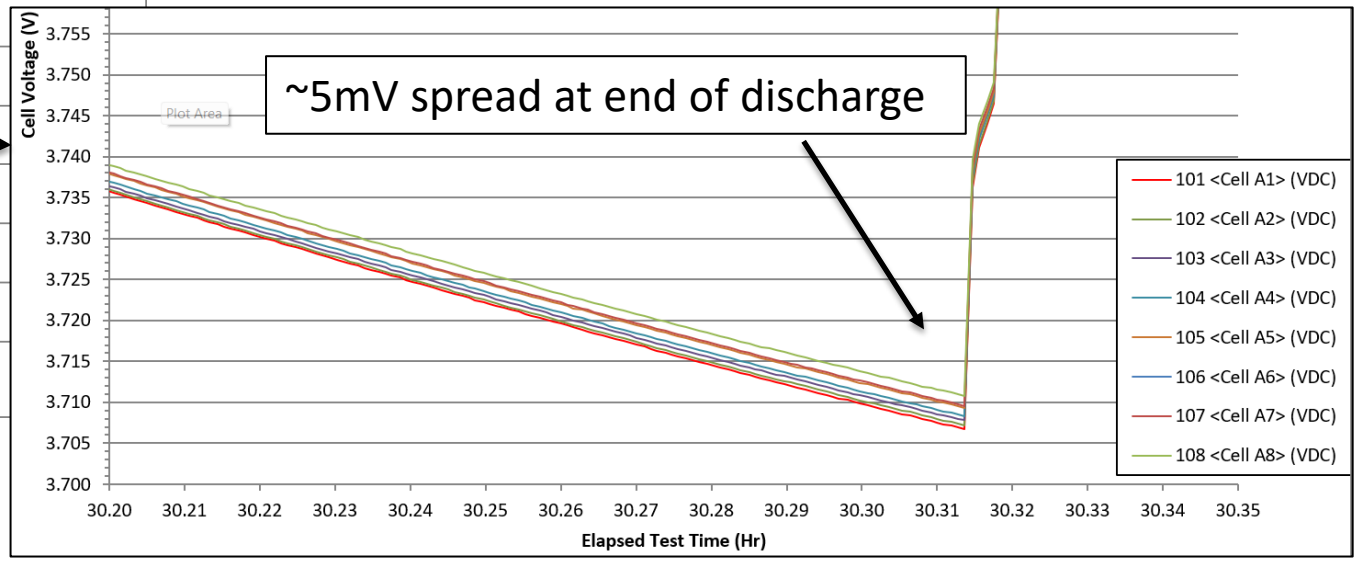


T-Vac

50% LEO Cycling



The qualification battery has no cell balancing functionality.
Cells were balanced at 4.10V prior to installation in November of 2024.

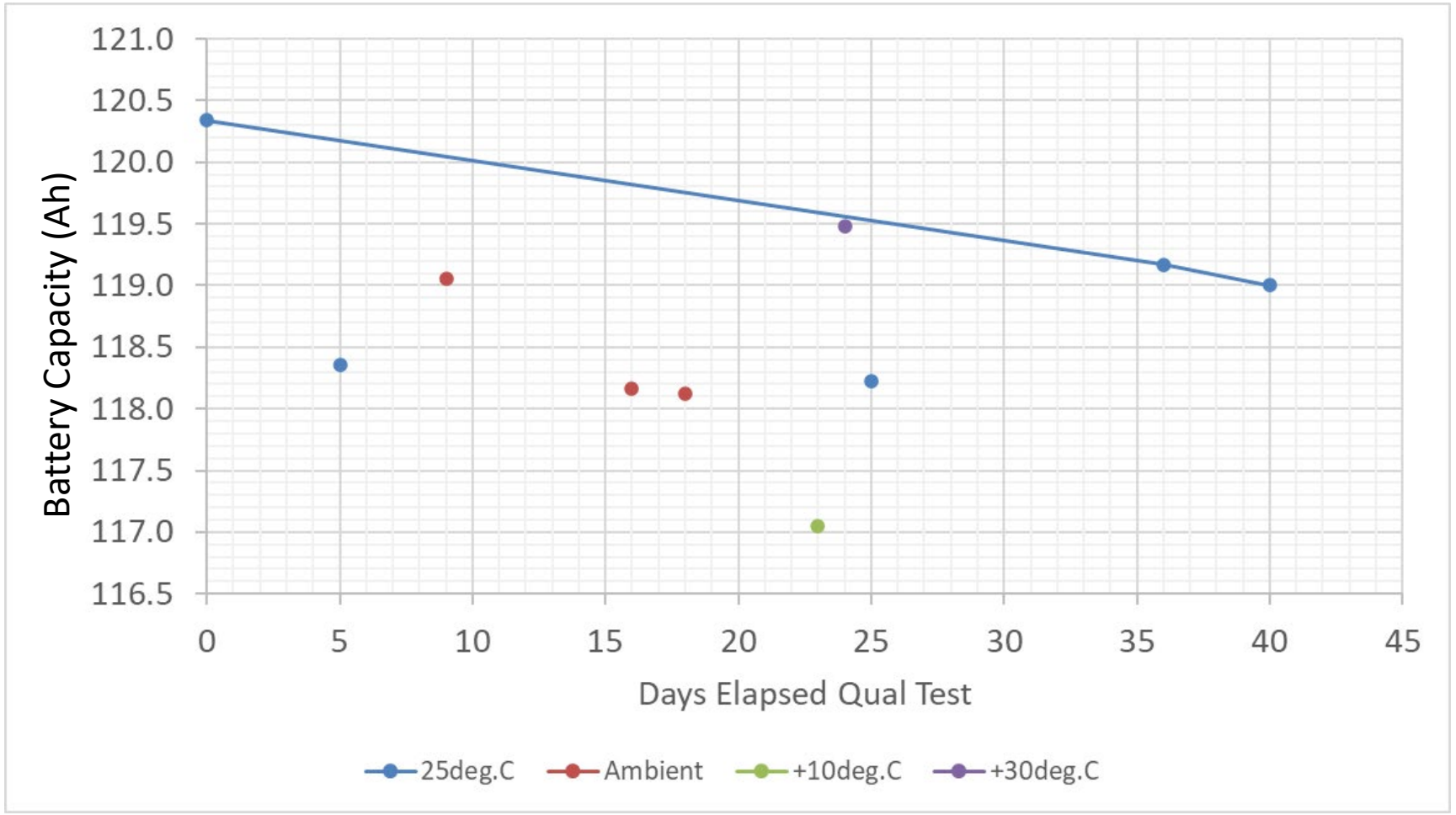


Capacity Retention through Qual

1C Discharge Capacity Test

Date	Capacity (Ah)	Temp
2/19/2025	120.34	25ºC
2/24/2025	118.36	25ºC
2/27/2025	119.05	AMB
3/7/25	118.16	AMB
3/9/25	118.12	AMB
3/14/25	117.05	10ºC
3/15/25	119.48	30ºC
3/16/25	118.22	25ºC
3/27/25	119.17	25ºC
3/31/2025	119.00	25ºC

Total capacity loss of 1.34Ah (~1.1%)
When measured on same channel/chamber



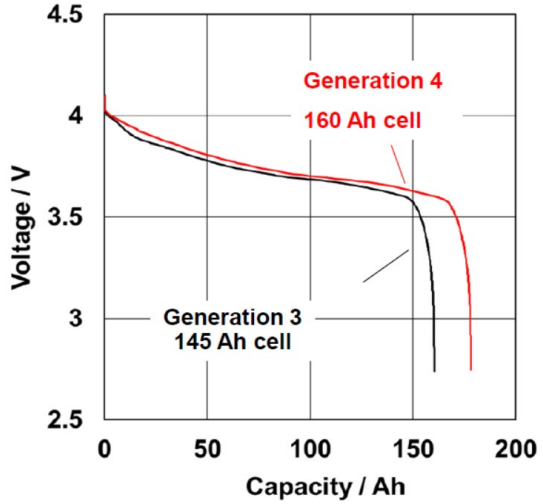
GYLP Production Readiness

MA12x battery design and qualification:

- PDR: Complete
- CDR: Complete
- MA12x-0908 Qual Battery MRR/TRR: Complete
- Qualification: Complete (Q1 2025)
- Production Targets: 6-month lead time from ARO for first delivered unit.

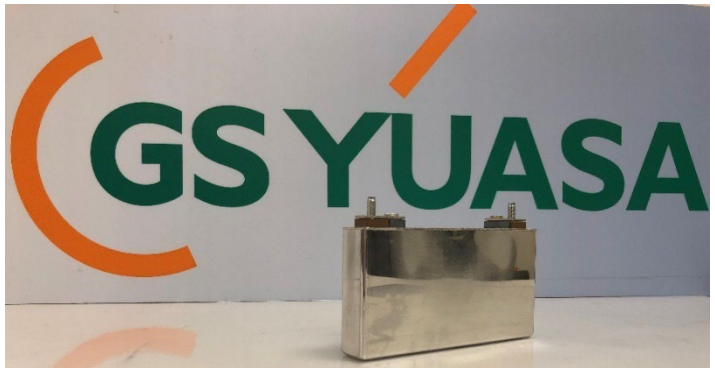
Summary

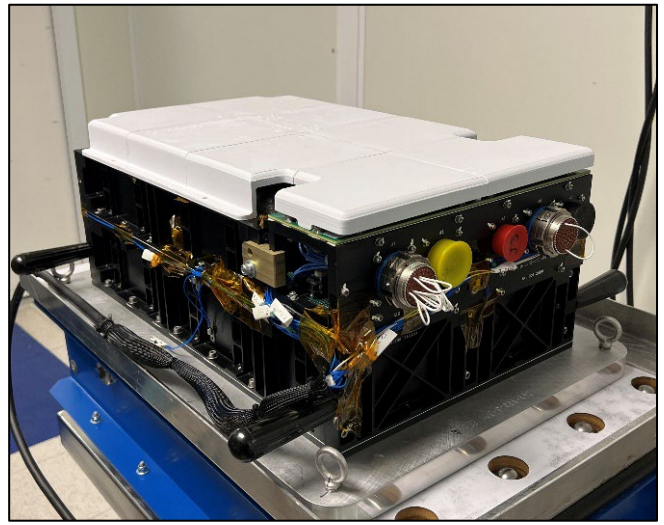
- GS Yuasa's Generation 4 LCO/Graphite chemistry provides meaningful performance increases from Generation 3 including:
  - Increased Energy Density
  - Excellent Capacity Retention under demanding cycle conditions
  - Decreased DCR for enhanced voltage performance under load



- Gen. 4 cells available from 12Ah to 205Ah in a single cell
  - LSE12x, LSE112, LSE147, 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

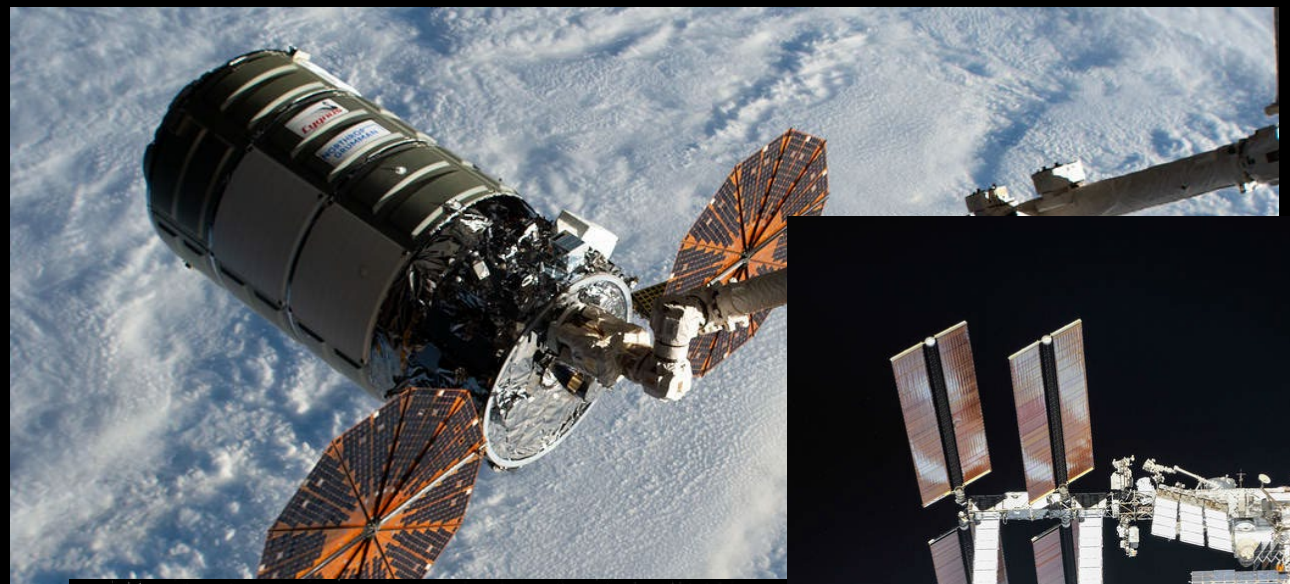


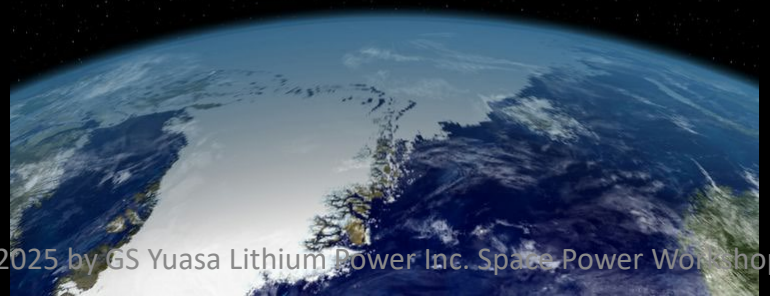


Energy storage design test and manufacturing expertise

Industry leading spaceflight heritage

Validated performance modelling





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