GS Yuasa MA12x Modular Battery Platform & Qualification Test Results

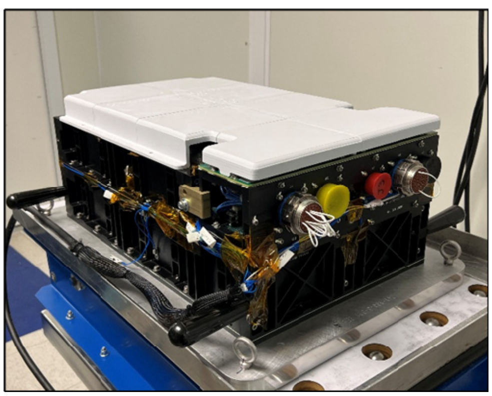
Executive Summary

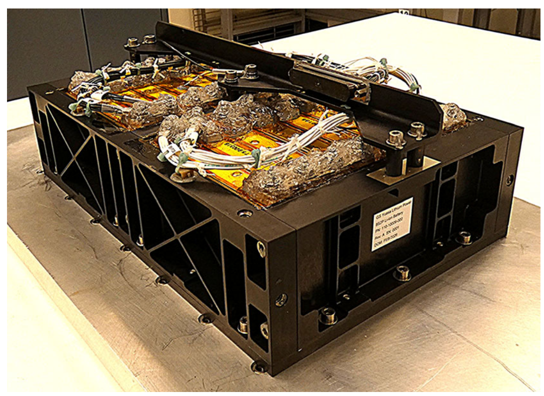
GS Yuasa Lithium Power (GYLP) has developed a scalable battery platform known as the MA12x battery. The battery can be configured to accommodate 16 to 96 of the GS Yuasa LSE12x Li-ion cells. Cells can then be connected to achieve the target voltage and capacity of the application. Using GS Yuasa's life and performance modeling, GYLP can right size the battery to best match the end users desired mission performance and life goals.

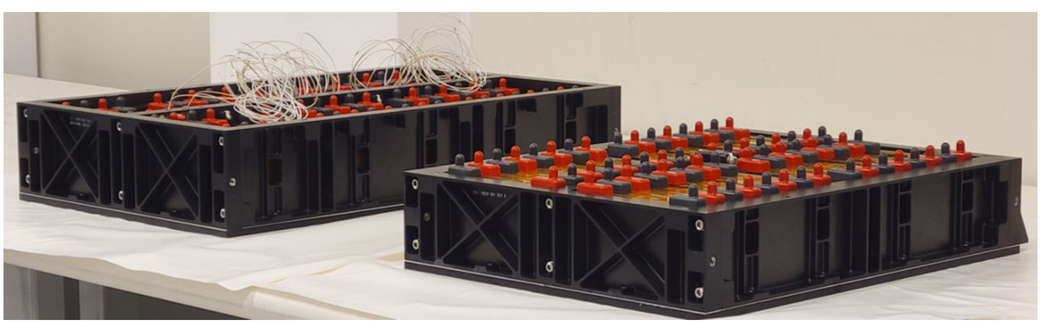
The MA12x battery platform completed qualification Q1 of 2025 and has an estimated rating of MRL 8 and TRL 7. The MA12x platform's initial qualification unit was a 72-cell battery electrically wired as an 8s9p (MA12x-0809). The qualification platform has successfully completed comprehensive environmental and performance qualification testing, demonstrating readiness for spaceflight applications.

The MA12x-0809 qualification battery demonstrates many common build and performance features used across the other configurations in the portfolio which enables consideration of qualification by similarity for the other configurations with targeted proto-qualification testing as needed. This strategy has been accepted by other end user's resulting in the proto-qualification of the 16-cell MA12x-0802 battery.

GYLP can offer a minimal NRE "off the shelf" configuration of the MA12x battery. This would represent our standard offering and test program. If a program has specific requirements different or in addition to this baseline, GYLP can tailor those aspects including electrical interface (number/type of connectors), telemetry, fault clearance approach, heaters, and test campaign for a nominal NRE.







1. Introduction

GS Yuasa is a world leader in high performance reliable energy storage solutions for the space market. The first qualified Li-ion cell design for space applications was released in 1998. The chemistry consisted of an LCO/Graphite system. Since its introduction there have been only 4 revisions, or generations, of this chemistry produced. The underlying LCO/Graphite foundation has not changed, but through improvements in raw material processing and manufacturing techniques, the chemistry has been refined to provide greater performance with respect to critical parameters such as energy density, DCR growth suppression, and capacity retention through life. These properties provide greater operational benefits such as higher discharging voltages under load and near 100% cell energy efficiency; ideal for a low earth orbit mission where time to charge is relatively short.

GS Yuasa's Li-ion cells are built exclusively by GS Yuasa Technology LTD (GYT) in Kyoto, Japan. GYT's quality system is certified to JISQ9100 (technically equivalent to AS9100). GYT has over 25 years of experience designing, manufacturing and qualifying cells for critical space applications.

GS Yuasa Lithium Power is the USA affiliate based in Roswell, GA and is tasked with designing and building batteries based on the GYT cells for North American satellite manufacturers. GYLP is also certified to the rigorous requirements of AS9100 and has successfully manufactured space qualified batteries totaling over 410kWh of Li-ion energy storage for spacecrafts.

2. GS Yuasa Spaceflight Heritage

GS Yuasa has an unparalleled track record in space Li-ion batteries:

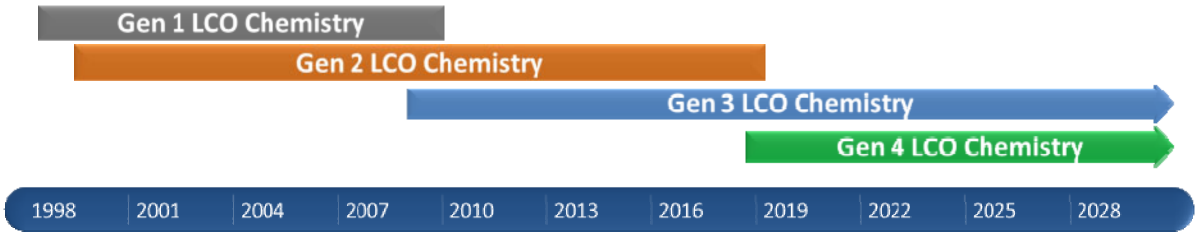
- 262+ satellites powered (91 LEO, 33 MEO, 135 GEO, 1+ interplanetary)
- First satellite on-orbit: Servis 1 (October 30, 2003)
- Longest on-orbit: >19 years (Thaicom 4)
- Total Li-ion energy in space: 5.19 MWh (surpassing 5.0 MWh milestone)
- Performance: Zero failures in flight

Notable Missions: Northrop Grumman's Cygnus spacecraft (LSE190 cells), NASA's Dragonfly Mission (Johns Hopkins APL, LSE134/147 cells), and the International Space Station (LSE134 cells).

Over 18,500 LSE cells manufactured for space applications, delivering 7.60 MWh of energy storage capacity. All cells share a common fundamental technology: wound-prismatic construction in aluminum cases and LCO chemistry, manufactured in Kyoto, Japan.

3. Approach to Li-ion Chemistries for Spacecraft

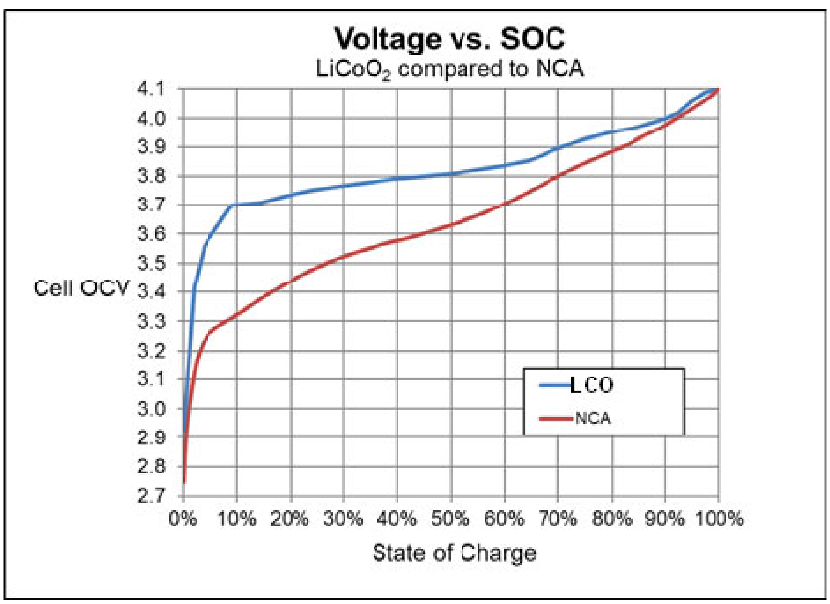
Once a cell chemistry is qualified there are no major changes permitted to the active material specifications. The formulation for that generation is "locked". The figure below illustrates when each LCO chemistry generation has been introduced and the duration a specific chemistry generation has been available to the market.



GS Yuasa has demonstrated the ability to maintain configuration and control over the cell active material sources for 15+ years. This is critical for establishing the reliability and performance of the cells lot to lot as well as providing users the confidence needed to invest in developing battery solutions based on the LSE cell technology. Additionally, GS Yuasa supports the previous generation for several years after the introduction of a new generation. Users do not need to worry about a sudden change if the existing generation still meets their needs.

3.1 Why LCO based chemistry?

From a performance and operational perspective, the LCO/Graphite chemistry system is especially attractive for spacecrafts that need high discharge power or have an unregulated or "battery on bus" architecture due to the high discharge voltage under load. The graph below compares the LCO chemistry voltage profile to another major cell manufacturer's Nickel Cobalt Aluminum (NCA) based chemistry:



Assuming both cells have the same Ah capacity, the higher voltage of the LCO means the Wh capacity will be greater. Alternatively, the LCO battery can have a smaller absolute capacity but have greater accessible Wh capacity (the capacity the spacecraft can actually employ on-orbit) due to the higher nominal voltage. This enables the spacecraft to discharge more deeply or at higher power while staying above the minimum operational voltage limit.

5. LSE12x Cell Design and Performance

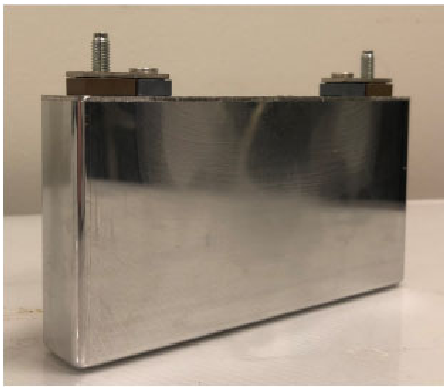
5.1 Design Features

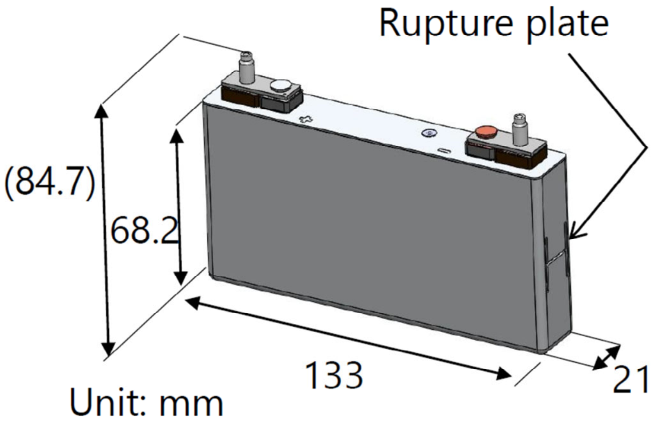
The LSE12x is a Generation 4 Lithium Cobalt Dioxide (LCO) cell inspired by mature commercial designs but enhanced for space environments. Key features include case-neutral design, radiation hardening, and hermetic sealing. It offers extremely low DC resistance, excellent cycle and calendar life, and high discharge voltage—ideal for unregulated bus applications across all space vehicle types.

Furthermore, the LSE12x is specifically designed for high power delivery. The electrode coatings are thinner compared to energy optimized cells. This effectively allows more windings (or length of electrode) to be inserted into the same case volume. As a result, for a slight reduction in absolute capacity, the current density is reduced across the entire electrode enabling greater power delivery and acceptance. This is evidenced by the lower DC resistance under load leading to higher average discharging voltages and reduced thermal dissipation.

5.2 LSE12x Key Specifications

Parameter	Value
BOL Capacity (2.75V-4.10V range)	13.6 Ah / 51.0 Wh
Nameplate Capacity	12 Ah / 45 Wh
Nominal Discharge Voltage	3.75 V
Continuous Discharge Rate	24 A
Pulse Discharge Rate	60+ A
Nominal BOL Cell Impedance	<6 mΩ
Nominal Mass	0.390 kg
Continuous Charge Rate	12A



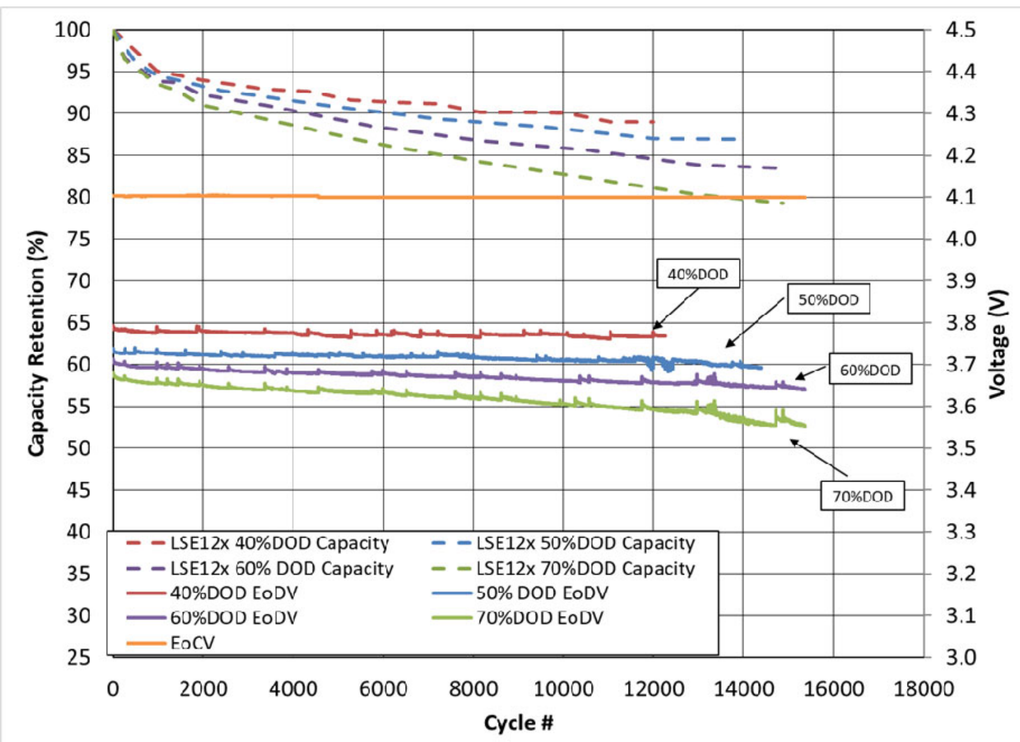


5.3 High DOD LEO Cycling Life Test (Updated April 2025)

Extensive cycle testing demonstrates robust performance under high Depth-of-Discharge (DOD) LEO conditions (5840 cycles ≈ 1 year LEO):

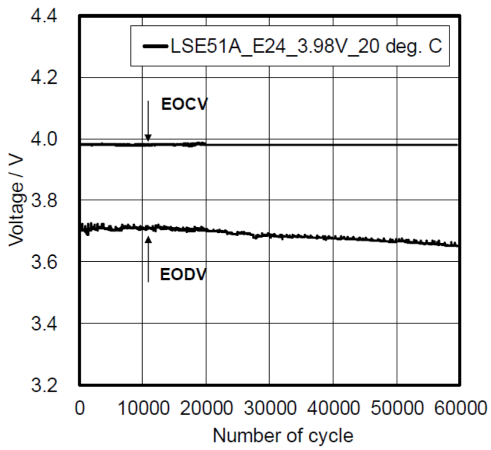
Test DOD	Last Cycle (#)	Cycle Time (yrs)	EoDV (V)	Real-time (Ah)	Status
40%	13,488	2.31	3.759	12.2	Ongoing
50%	18,112	3.10	3.673	11.5	Ongoing
60%	19,072	3.26	3.615	11.1	Ongoing
70%	15,474	2.65	3.548	10.8	DPA'd

Note: 70% test adjusted to 4.15V; completed 16,000 cycles before destructive physical analysis (DPA). 40-60% tests ongoing with excellent capacity retention.

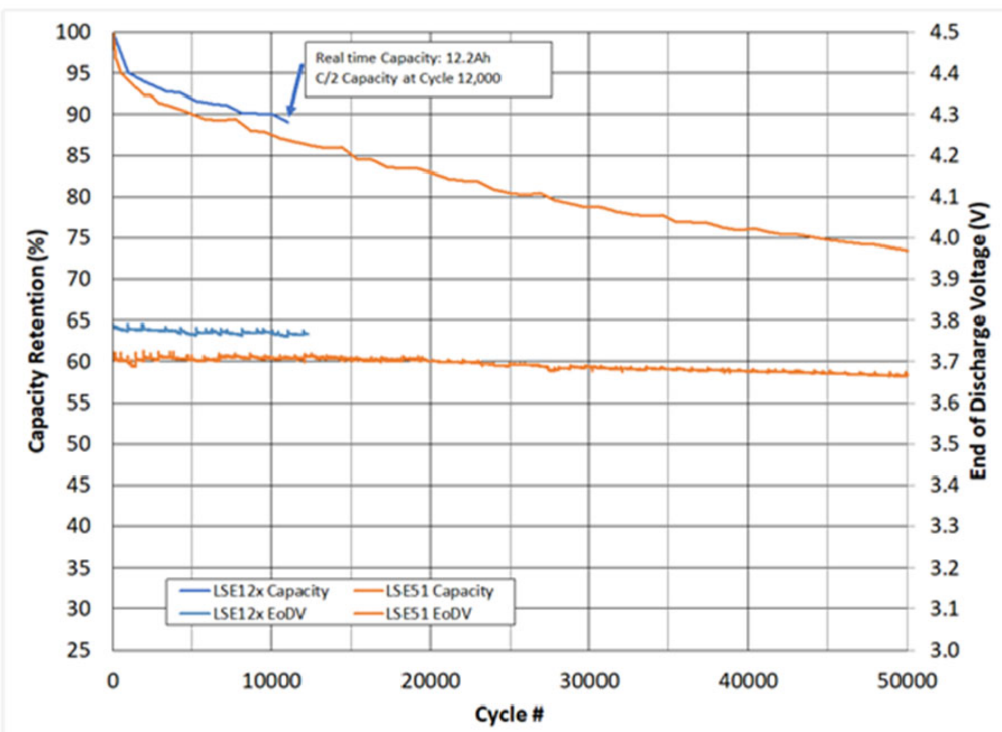


Cycle	Discharge	Charge
40%DOD	0.8C (9.6A) for 0.5hr	0.5C, 4.10V, CC/CV, 1hr
50%DOD	1.0C (12.0A) for 0.5hr	0.6C, 4.10V, CC/CV, 1hr
60%DOD	1.2C (14.4A) for 0.5hr	0.7C, 4.10V, CC/CV, 1hr
70%DOD	1.4C (16.8A) for 0.5hr	0.8C, 4.10V, CC/CV, 1hr

As mentioned earlier, the LSE12x is a generation 4 LCO/Graphite cell. We can compare this to the previous generation to gauge performance expectations. The LSE51 is a generation 3 power optimized LCO/Graphite cell and has surpassed of 60,000 LEO cycles in testing:



When compared with the LSE51 cell, the performance trend is similar, with the LSE12x demonstrating slightly higher performance retention:



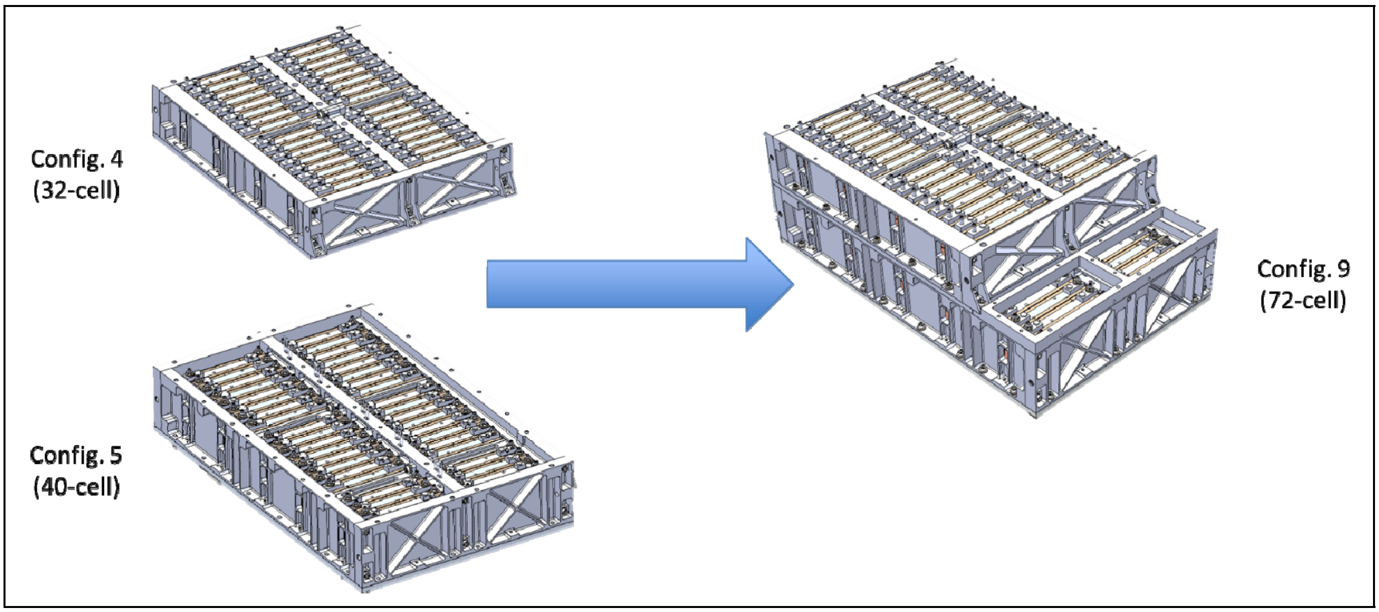
After 2 years of 40% DOD LEO cycling, the LSE12x cell is not yet under its rated nameplate capacity and EODV performance remains stable.

6. MA12x Modular Battery Platform Design

The MA12x is a modular battery platform designed for scalability and fault tolerance.

6.1 Scalability and Configurations

- Scalable from 720 Wh (16-cells) to 4,320 Wh (96-cells)
- Single-level deployment up to 48-cells; stackable configurations up to 96-cells to minimize footprint
- Baseline bussing approach for nominal 28V applications (8 cells in series).Each 8s group is then paralleled to achieve desired Ah capacity.
- Alternate bussing possible for higher voltage strings or virtual cells configurations.



Example of MA12x scalability and packing efficiency.

6.2 Key Design Features

- Neutral case design, radiation hardened, hermetically sealed cells
- No cell balancing functionality required; cells pre-balanced at 4.10V
- Fault tolerance ready: Capable of disconnecting a "sick" string in the event of a fault
- Passive propagation resistance materials and techniques deployed
- Compact footprint
- Tailorable connector interface

6.3 Small Battery Configuration and fault tolerance

For smaller batteries, it may not be feasible to deploy individual string disconnects efficiently. For those missions that can accept this risk, a more optimal battery size can be considered. Furthermore, GS Yuasa proposes a bussing architecture consisting of “virtual cells” (cells bussed in parallel first, then in series) to improve resilience against the most credible, though unlikely, failure mode: a sudden [latent] increase of a single cell's self-discharge rate that persists. Over time, this condition can cause a voltage imbalance across the battery pack, reducing performance. This anomaly is often called a "soft short." Typically, a latent increase in self-discharge rate is transitory and will return to nominal levels over time, slowing further imbalance. The virtual cell bussing counters the soft short's impact by expanding the capacity reservoir, mitigating the soft short's impact without introducing complex bypass or balancing systems. The extended timeline of the anomaly provides ample time to detect and address it before operational impact occurs. It should also be known that GS Yuasa has over 5MWh of energy storage that has operated in space with no such failures observed.

A sudden severe fault, such as a hard short, could potentially render the battery inoperable. However, the likelihood of such a fault originating within the battery and causing immediate failure is extremely low. No such event has ever been observed in GS Yuasa's 25+ years of supporting critical space missions.

6.4 Cell Balancing

As said in the previous section, the most credible failure mode is through the gradual imbalance of cells. This typically occurs due to:

1. Natural performance variability cell to cell or,
2. A latent defect that suddenly increases the self-discharge rate.

The primary way to mitigate cell to cell variability is through careful sorting and matching of cells based on their measured self-discharge characteristics. GS Yuasa monitors each cell's OCV periodically and cells with similar self-discharge rates and capacities will be designated to specific groups. In all but the rarest cases, after 90 days post initial electrical testing cell electrical characteristics are stable and allow for confident cell selection. Prior to final harness installation, cells are balanced at top of charge (4.1V).

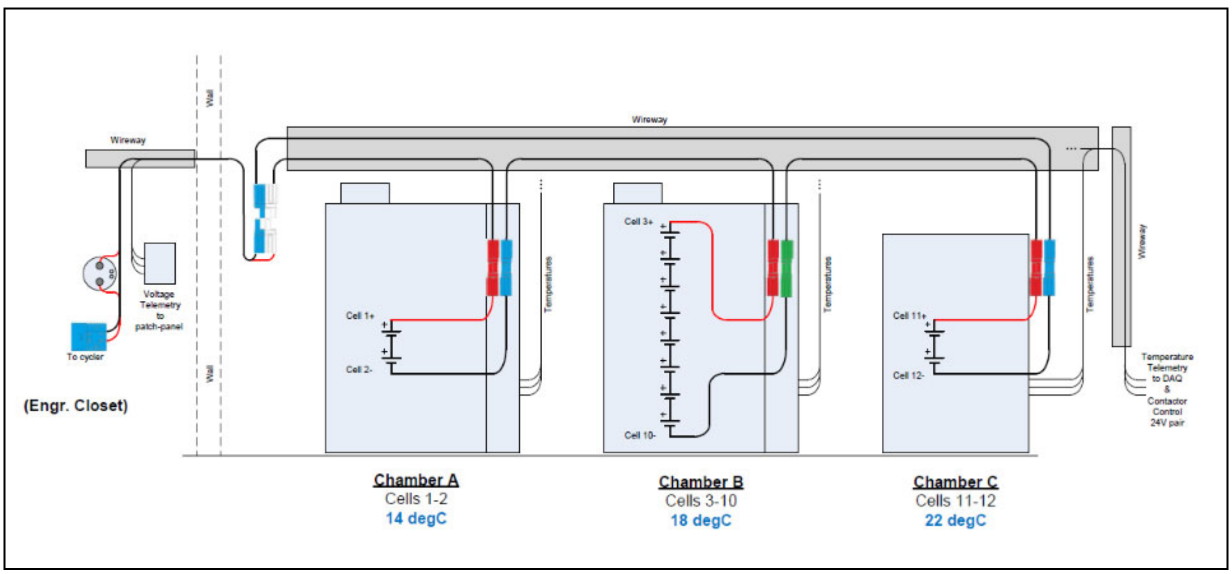
A cell balancing circuit is also a way to mitigate natural cell to cell self-discharge variability and overcome latent defects that result in an increase in a cell's self-discharge rate. This accessory typically works by selectively discharging cells in the string to effectively match the cell with the highest self-discharge rate. However, cells that are configuration controlled and matched well for electrical characteristics should have very similar self-discharge rates and remain this way through life. This makes a balancing circuit a potential liability due to their own reliability concerns and complexity added to the system. Also concerning, balancing circuits can induce variable parasitic loads on individual cells thus requiring balancing when it may not had been needed if absent. It is therefore advantageous to operate without a balancing circuit.

GS Yuasa is confident that operating the battery without balancing circuitry is reasonable based upon real on-orbit experience cited by our customers using the larger capacity LSE cells. Users have disclosed that in their applications balancing either has not been needed or the balancing circuit itself was found to have induced the imbalance due to variable parasitic loads.

Another point of consideration comes from the field experience of GS Yuasa's LVP10 aircraft batteries. The LVP10 is another GS Yuasa LCO/Graphite cell and is very similar in both electrochemistry and construction to the LSE12x. Since 2016 over 27,000 cells, equivalent to ~1.0MWh of Li-ion capacity, have been incorporated into 8-cell series batteries without balancing circuity. There have been zero imbalance failures observed over this period.

GS Yuasa also understands that anecdotal evidence alone may not be sufficient to support reliable conclusions. Therefore, GYLP is in the early stage of testing a 12-cell series string of LSE12x cells to understand how cell divergence in a 50% DOD LEO profile will trend through time and cycling. The 12s string is divided into three groups and operated at different ambient temperatures to force differences in their performance. Assuming cell to cell variability is low, cells at the same temperature should perform similarly and stay in balance with each other, but will diverge from the cells held in other temperature conditions. This test will help inform the level of imbalance a series string can tolerate before there is an impact on performance. Limits can then be established to aid in decision making for when to command a relay to open and isolate the string.

See SINV24-316R1 which provides a more detailed description of the referenced test above as well as preliminary results. The model includes basic ground test and storage experiences prior to the mission. This experience can be revised when the ground operation and storage conditions and time are better defined.

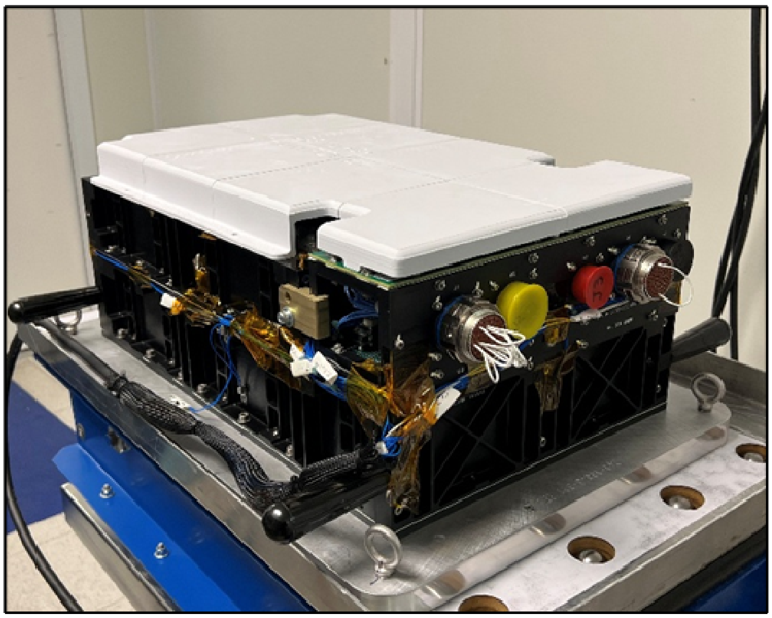


LSE12x Cell Imbalance Test Set-up

7. Qualification Test Program and Results

The MA12x-0809 qualification unit is a 72-cell double deck battery that underwent a comprehensive test flow in Q1 2025, including electrical characterization, mechanical environmental testing (shock and vibration),and thermal vacuum (TVAC) testing.

This unit was additionally configured to include complete cell voltage telemetry, heater circuits, and string disconnect features to envelop envelope a majority of requirements. We expect most end users will only require a subset of these capabilities as it relates to their mission requirements. The connector box consists of both flight and non-flight components and is included as a demonstration. The electrical interface is tailorable without affecting the qualification status of the overall MA12x platform.



7.1 Test Sequence

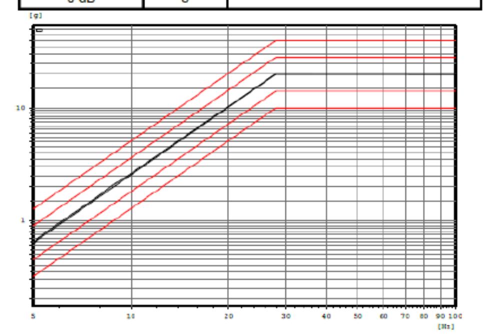
1. Mass Properties / Dimensions measurement
2. Initial Capacity & Pulse DCR Test
3. Shock Test (SRS shock, X/Y/Z axes)
4. Post-Shock Capacity Test
5. Connectivity & Isolation Test
6. Vibration (Sine Survey + Random at full level)
7. Post-Vibration Capacity Test
8. TVAC Test: Survival (-20°C/+45°C), Operation cycles (+10°C/+30°C), Heater test (+0°C), 8x 50% DOD LEO cycles (+15°C)
9. Post-TVAC Capacity Test
10. 50% DOD LEO Cycle Life Test
11. Final Return Testing (connectivity, mass, capacity, DCR)

7.2 Mechanical Test Results

Vibration and Shock: All tests passed with no significant changes (<10%) in primary mode frequencies.

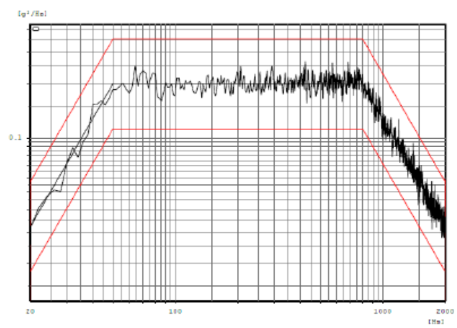
Sine Survey

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 $0.002 g^2/Hz$ for 30 Seconds	
-6 dB	1	2 Octaves/Minute	
-3 dB	1		
0 dB	3		



Random Vibration Levels

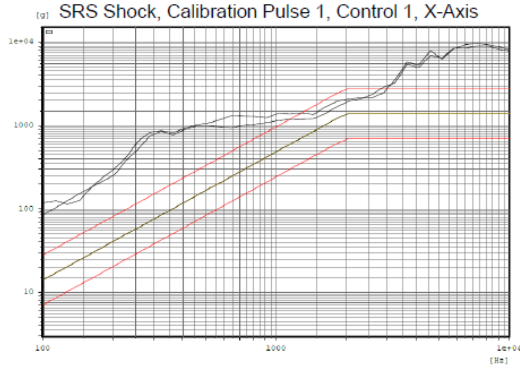
Frequency (Hz)	*Qualification Level*	*Units*
20	0.032	g^2/Hz
20-50	6	dB/oct
50-800	0.2	g^2/Hz
800-2000	-6	dB/oct
2000	0.032	g^2/Hz
Overall grms: 15.78		
Duration: 120-Seconds		



Shock Levels

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

SRS Shock, Calibration Pulse 1, Control 1, X-Axis

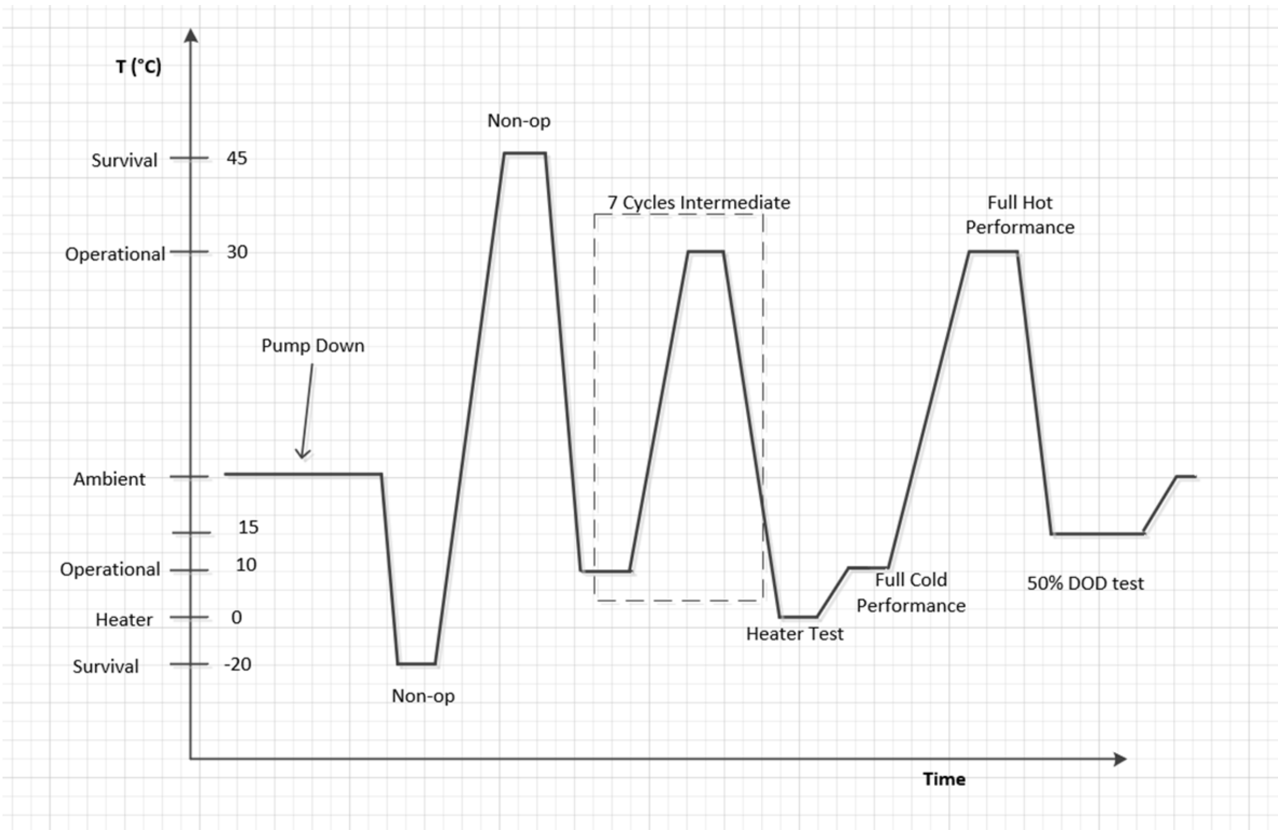


Results:

Axis	Sine Shift	Random Shift	Result
X	0.0%	0.0%	Pass
Y	4.1%	5.1%	Pass
Z	0.7%	0.7%	Pass

7.3 Thermal Vacuum (TVAC) Results

Thermal performance was nominal with no excessive temperature gradients (<5°C for isoline positions during cycling). Approximately 5°C rise observed during 50% DOD LEO discharge cycles. Voltage spread at end of discharge was ~5 mV. Pump-down achieved <1E-5 Torr. Heater function verified at +0°C.



7.4 Capacity Retention

Total capacity loss across the qualification campaign: 1.34 Ah (~1.1%). Measurements performed at consistent conditions (primarily 25°C ambient or chamber).

Date	Capacity (Ah)	Temp (°C	Notes
2/19/2025	120.34	25	Initial
2/24/2025	118.36	AMB	Post-shock
3/7/2025	118.16	AMB	Post-vibe
3/31/2025	119.00	25	Final

Note: Minor fluctuations attributable to measurement conditions; overall retention excellent.

8. Conclusions and Production Readiness

The MA12x Modular Battery Platform has successfully completed qualification testing as of Q1 2025. All environmental and performance requirements were met or exceeded, with minimal capacity degradation (~1.1%) and stable mechanical/thermal characteristics.

- Generation 4 LCO/Graphite chemistry: Increased energy density, superior capacity retention, decreased DCR
- Scalable battery platform: 720 Wh – 4,320 Wh configurations
- Production lead time target: 6 months from ARO for first delivered unit
    Current lead time is ~9-12 months ARO.

GS Yuasa continues to lead in space energy storage solutions, leveraging extensive heritage and rigorous qualification processes to deliver reliable, high-performance batteries for the most demanding missions.