Qualification Results of the LSE12x Cell New 12Ah Size Cell from GS Yuasa

2022 Space Power Workshop

April 28, 2022

Curtis Aldrich, George Bergmark, Tom Pusateri – GYLP
Go Honda, Munehiro Kusunoki, Masazumi Segawa – GYT

Agenda

- Space Flight Heritage Update
- LSE12x Cell Design Overview
- Qualification Results Summary
  - →Electrical Performance
  - →Environmental Performance
  - →Cycle Life Performance

GS Yuasa Corporate Highlights and Global Network

GS Yuasa Corporation (2004)

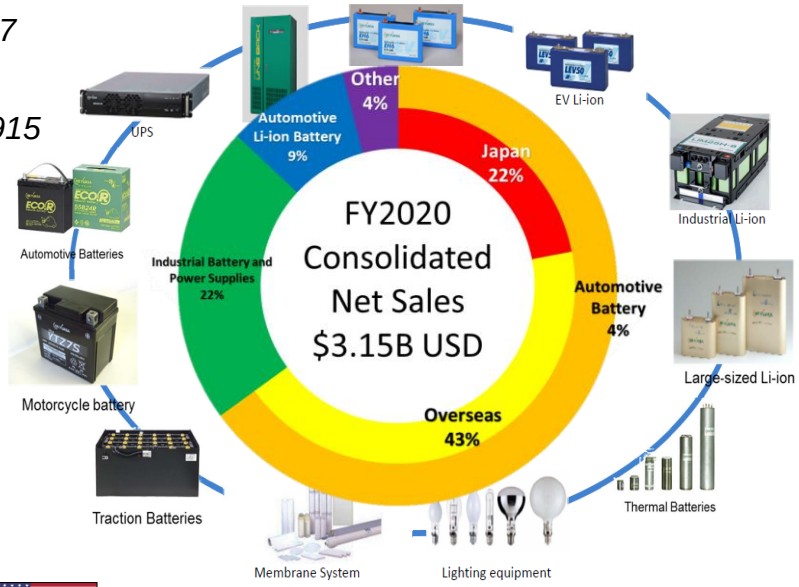
Develops management plan and strategy for GS group and administrate the group companies to enhance the total value of the group.

GS Yuasa International

Manufacturing and sales of automotive & industrial batteries, power supply systems, switch gear, lighting & ultra violet systems, specialty equipment and other electrical equipment

GS Japan Storage Battery Co., *Est. 1917*

YUASA Yuasa Battery Manufacturing, *Est. 1915*



37 Overseas affiliates
19 Countries

Lithium Energy Japan (JV) (2007)

Development, manufacturing and sales of large lithium-ion batteries for electric vehicles

Blue Energy Co., Ltd (JV) (2009)

Development, manufacturing and sales of lithium-ion batteries for hybrid electric vehicles

GS Yuasa Technology Ltd. "GYT"

Manufacturing and sales of specialty batteries

GS Yuasa Energy Solutions (2019)

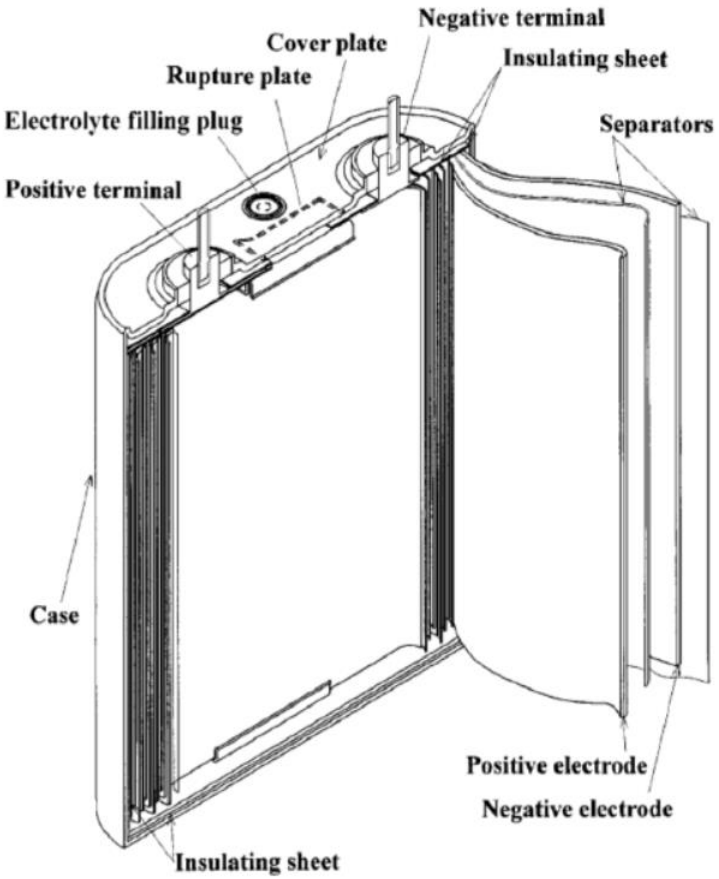
Sales of automotive, industrial and power-sports batteries

GS Yuasa Lithium Power "GYLP" (2006)

Li-ion battery manufacturing and sales
North American aerospace and defense applications

LSE Cell Heritage

Two Decades of Trusted Performance



Wound electrode in an elliptical cylindrical case

The LSE Li-ion cell portfolio consists of various sizes that share analogous design and manufacturing characteristics.

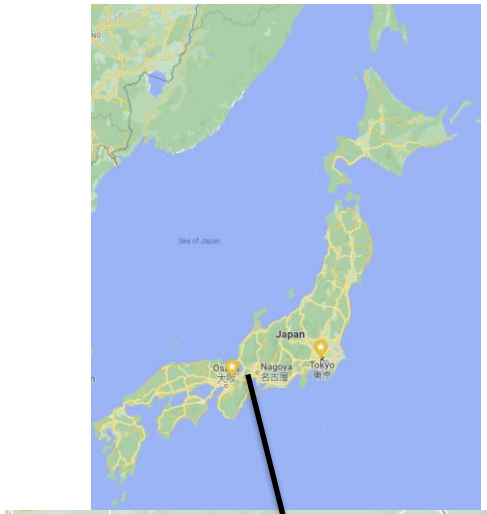
Approximate Nameplate Cell Capacities (left to right)
Gen 3: 35Ah, 55Ah, 190Ah, 145Ah, 110Ah
Gen 4: 40Ah, 60Ah, 205Ah, 160Ah, 120Ah

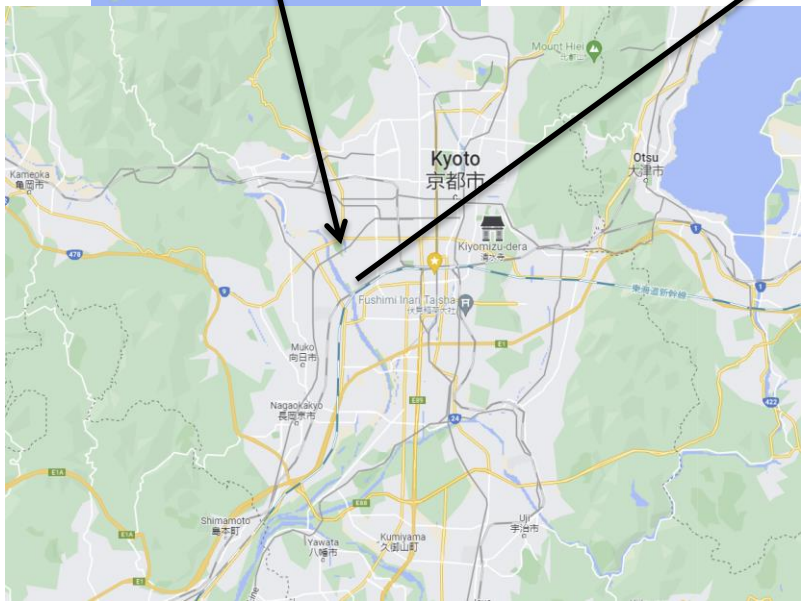
All cells share the same primary features:

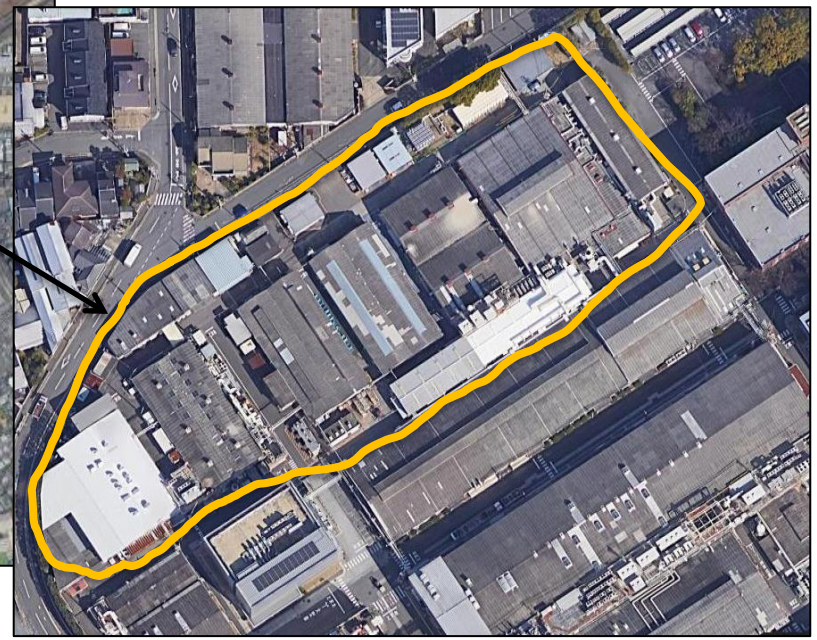
- Al-case
- Wound prismatic construction
- Ceramic terminals
- Case neutral
- LCO chemistry

LSE Cell Manufacturing Location

GS Yuasa Technology LTD. Kyoto, Japan







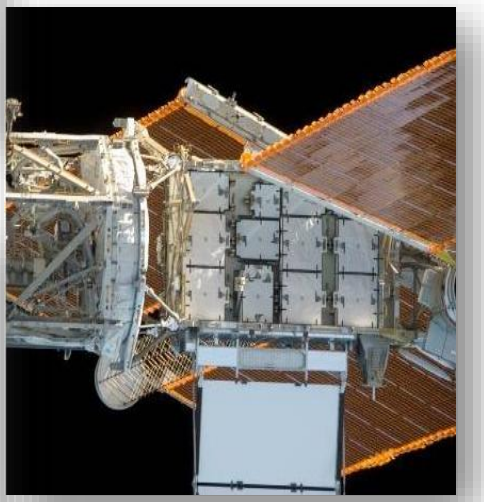
Green: GS Yuasa Main Campus – Engineering, Manufacturing, R&D, Sales

Orange: LSE Cell Manufacturing and Testing

GS Yuasa Space Flight Heritage Update

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

Number of satellites…….……	220+
– LEO/MEO……..	102+
– GEO……	117
1st satellite on-orbit……..…	Servis 1 (30 Oct. 2003)
Longest satellite on-orbit (yrs)….....	>16yr (IPSTAR, 11 Aug. 2005) still operational
Li-ion Watt-hours flown in space….....	>4.4 MWh (world leader)
Cell-hours flown in space……..	>510 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)…….……	>1.5 MWh



Launch vehicles & number of satellites

Ariane-5ECA	47	Falcon-9 v.1.2	14	Soyuz-2-1b Fregat	3	H-2A-2024	2	Atlas-5(421)	1
Soyuz-2-1 Fregat	24	Antares 230	10	Zenit-3SLB	3	H-2A-204	2	Delta II-7420	1
H-2B-304	13	Proton-M Briz-M (Ph.4)	6	Antares 120	2	H-IIA	2	Dnepr	1
H-2A-202	20	Atlas-5(401)	5	Ariane-5ECA+	2	Rokot-KM	2	Epsilon CLPS	1
Proton-M Briz-M (Ph.3)	18	Falcon-9 v.1.1	5	Atlas-5(431)	2	Zenit-3SL (2)	2	GSLV Mk.2	1
Soyuz-STB Fregat-MT	17	Proton-M Briz-M (Ph.2)	4	Epsilon	2	Ariane-5GS	1	Proton-M Briz-M (P1 M1)	1

Metrics updated February 2022

LSE12x Lithium-ion Cell for Space
Design Overview

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:

→Maintain 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

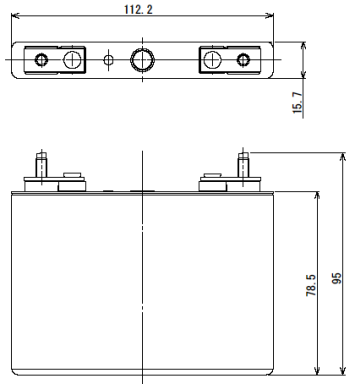
→Design for manufacturability and cost competitiveness

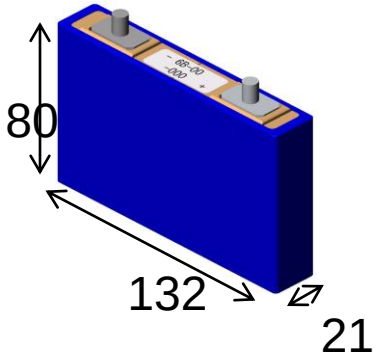
LSE12x Case Design

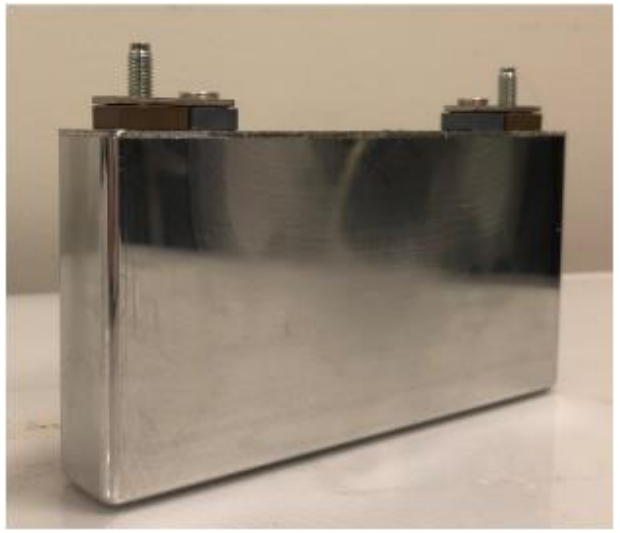
Fusion of Aviation and Automotive Cells

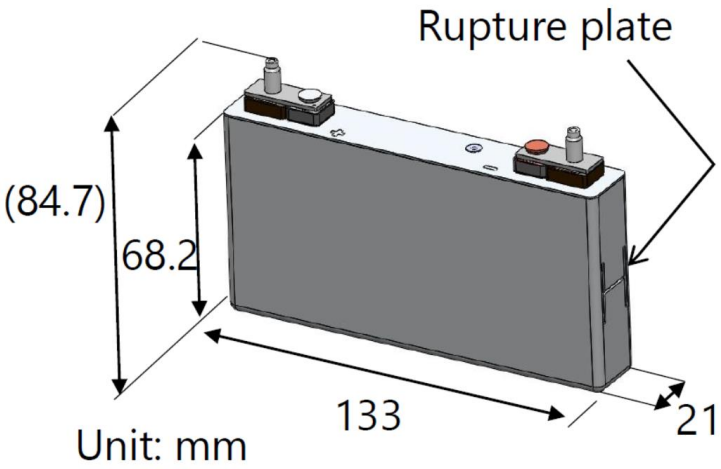
Blue Energy

- EH5 Ultra high power cell for Honda/Acura hybrids









- LVP10 Cell for Aviation Applications

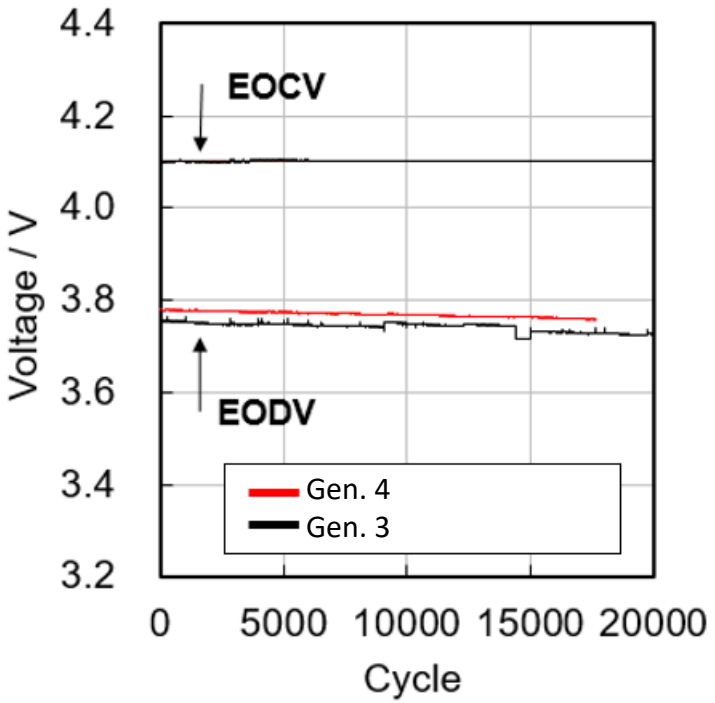
- Aluminum Case
- Case Neutral Design
- Hermetically Sealed
- Ruggedized Current Collectors

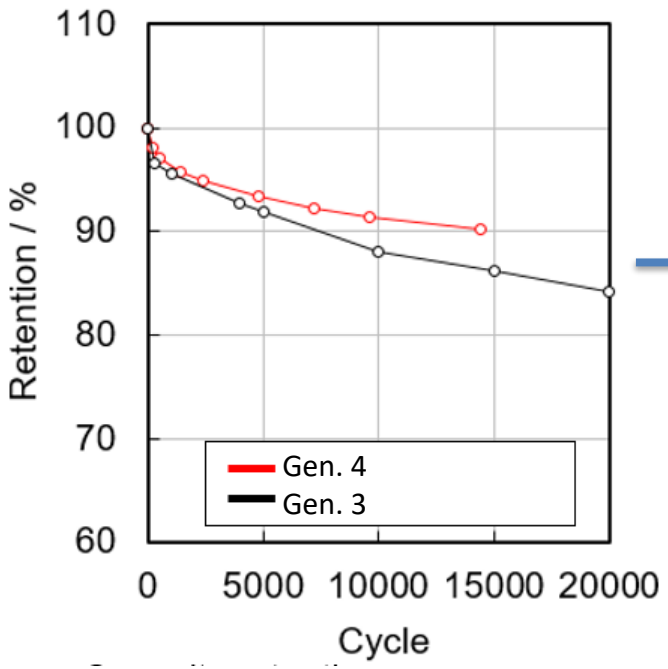
株式会社 ジーエス・ユアサ テクノロジー
GS Yuasa Technology Ltd.

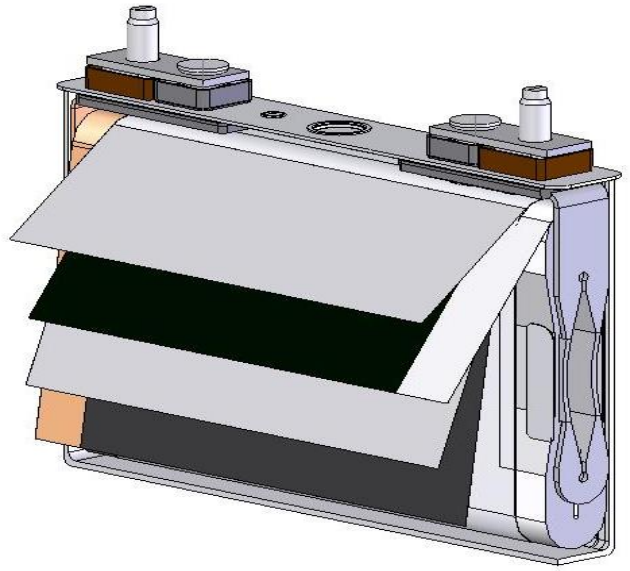
LSE12x Generation 4 LCO-Graphite Chemistry

Improved Cycle Life and Voltage Performance

40% DOD Cycle Life Test







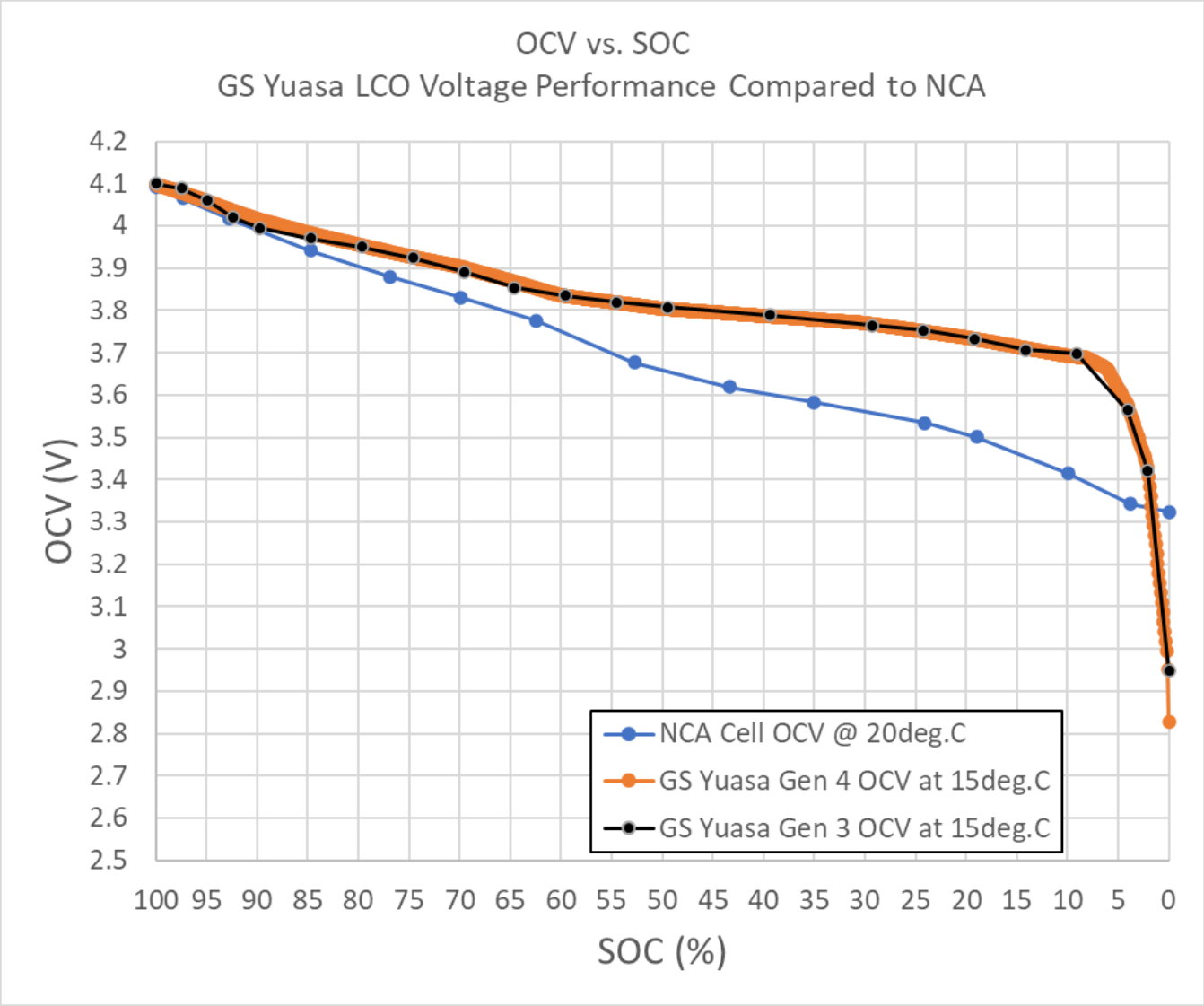
<u>40% DOD LEO Cycle Profile</u>
Charge: 0.5 CA, 4.1V, CC/CV, 1 h
Discharge: 0.8 CA, 0.5 h
Temperature: 20 deg. C

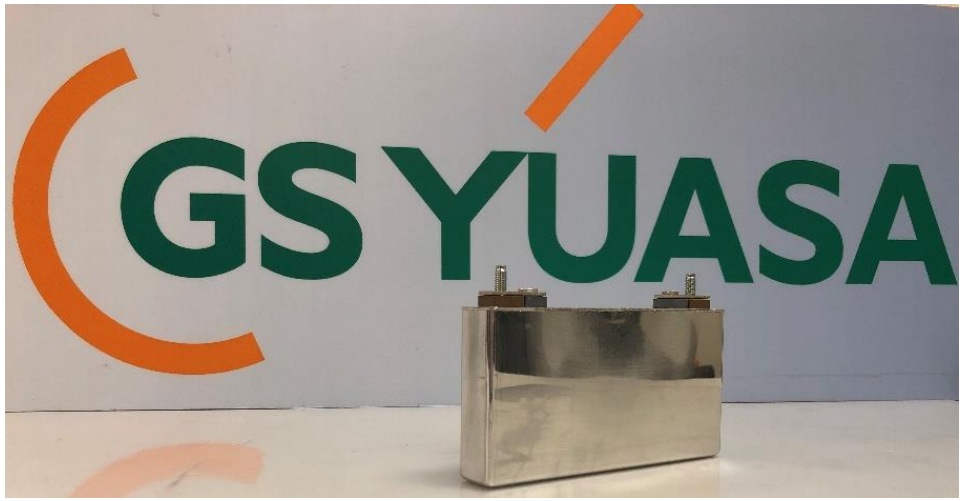
<u>Periodic capacity check</u>
Charge: 0.2 CA, 4.1V, CC/CV, 8 h
Discharge: 0.5 CA to 2.75V
Temperature: 15 deg. C

See GS Yuasa's SPW2021 Presentation for more Gen 4 Cycle Life Performance

LSE12x Generation 4 LCO-Graphite Chemistry

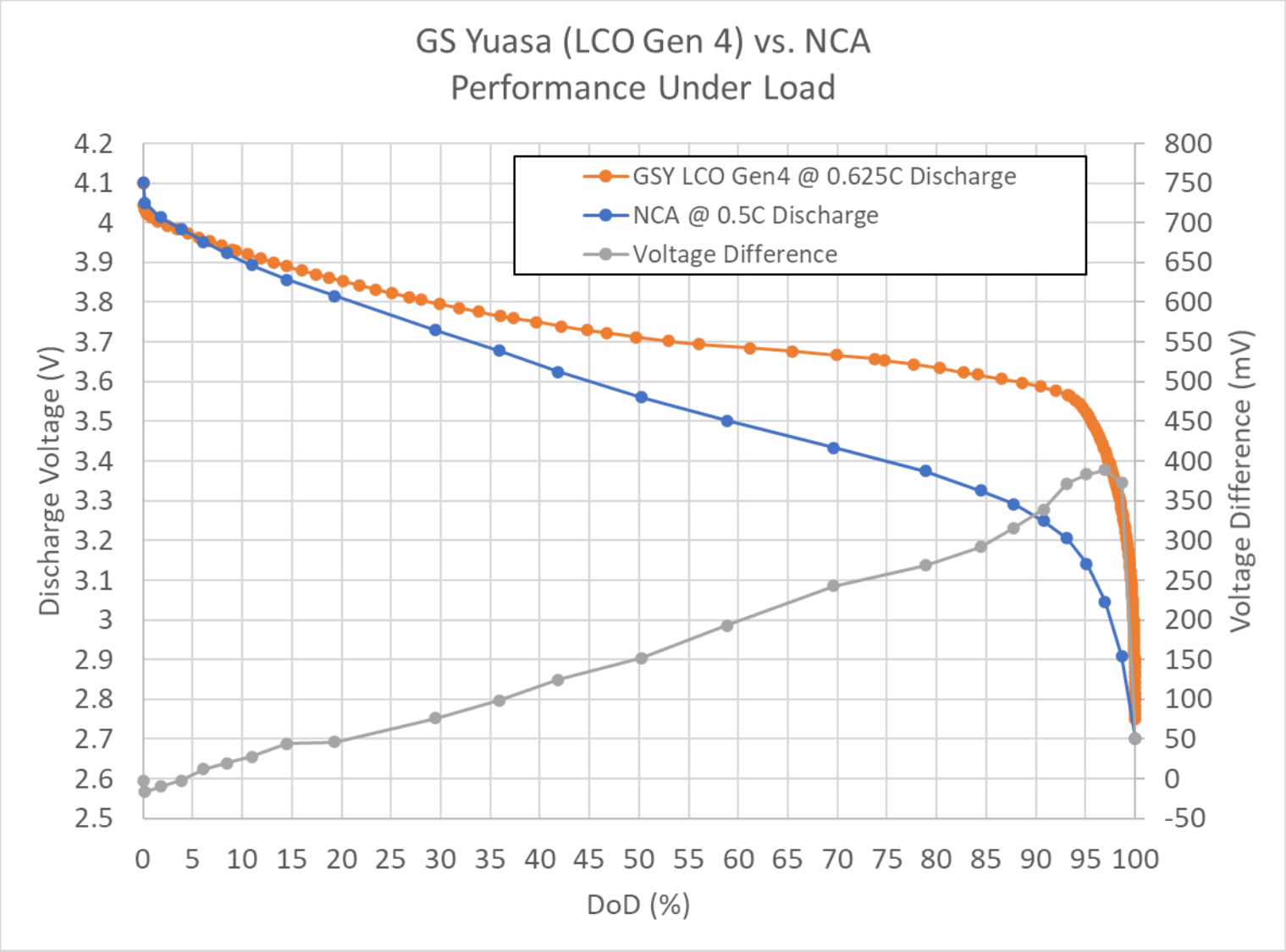
Voltage Performance vs. NCA

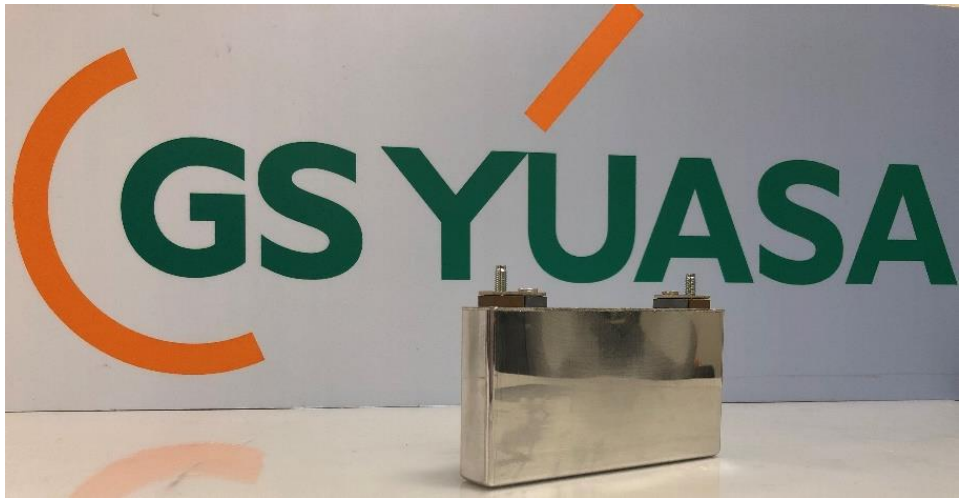




LSE12x Generation 4 LCO-Graphite Chemistry

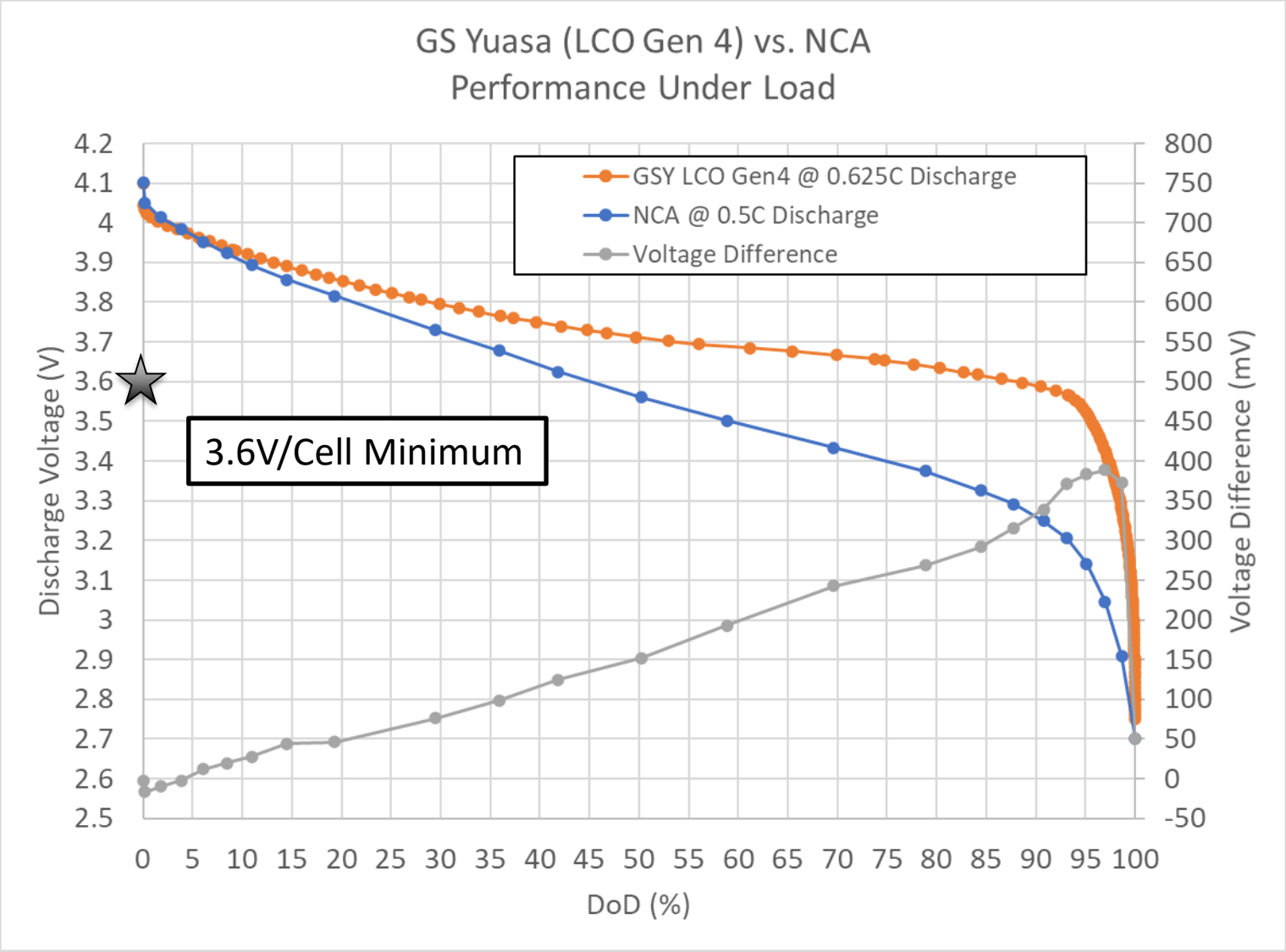
Voltage Performance vs. NCA

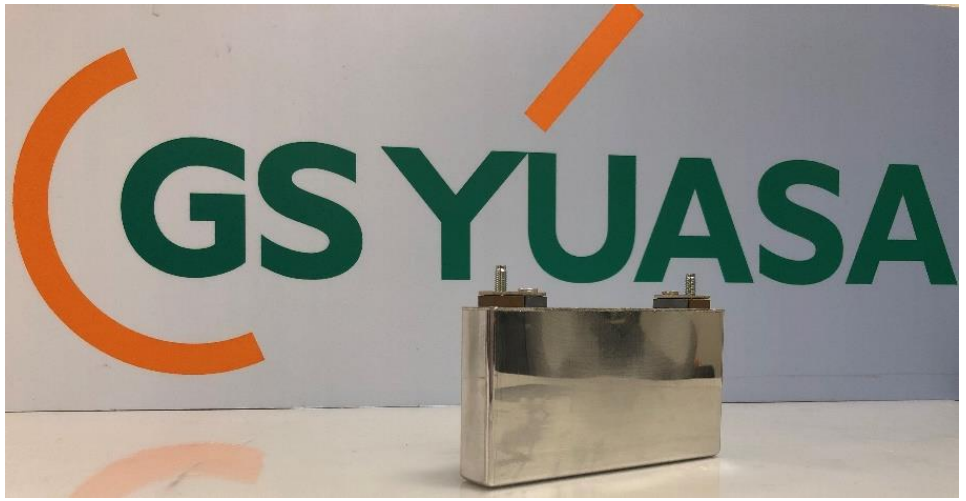




LSE12x Generation 4 LCO-Graphite Chemistry

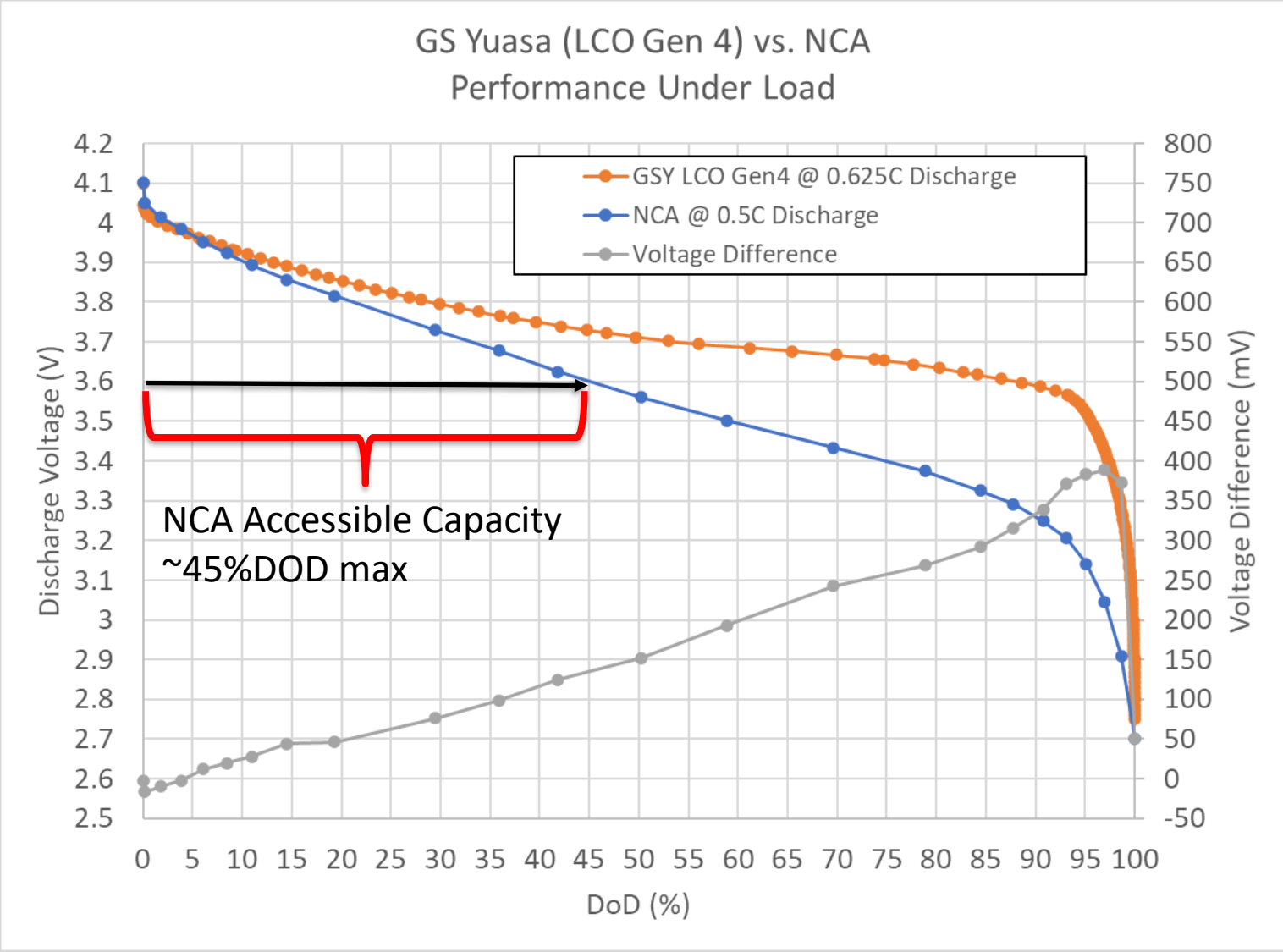
Voltage Performance vs. NCA

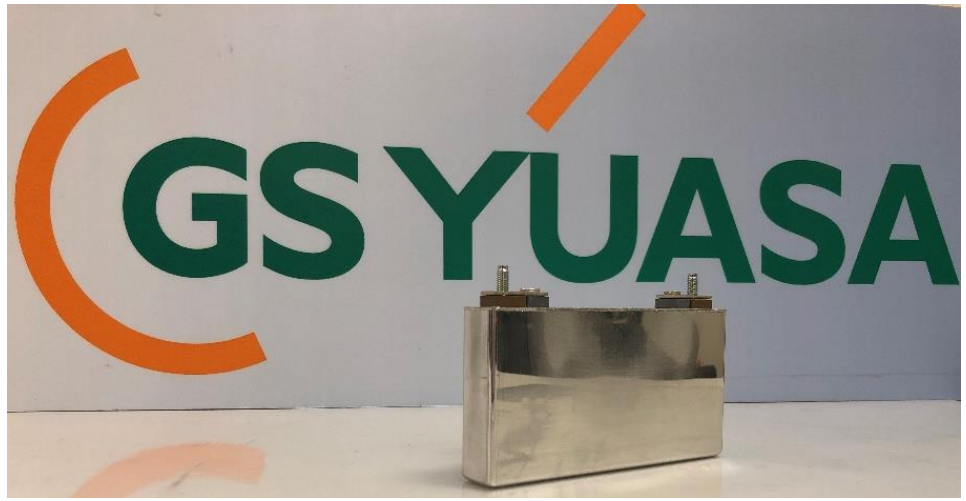




LSE12x Generation 4 LCO-Graphite Chemistry

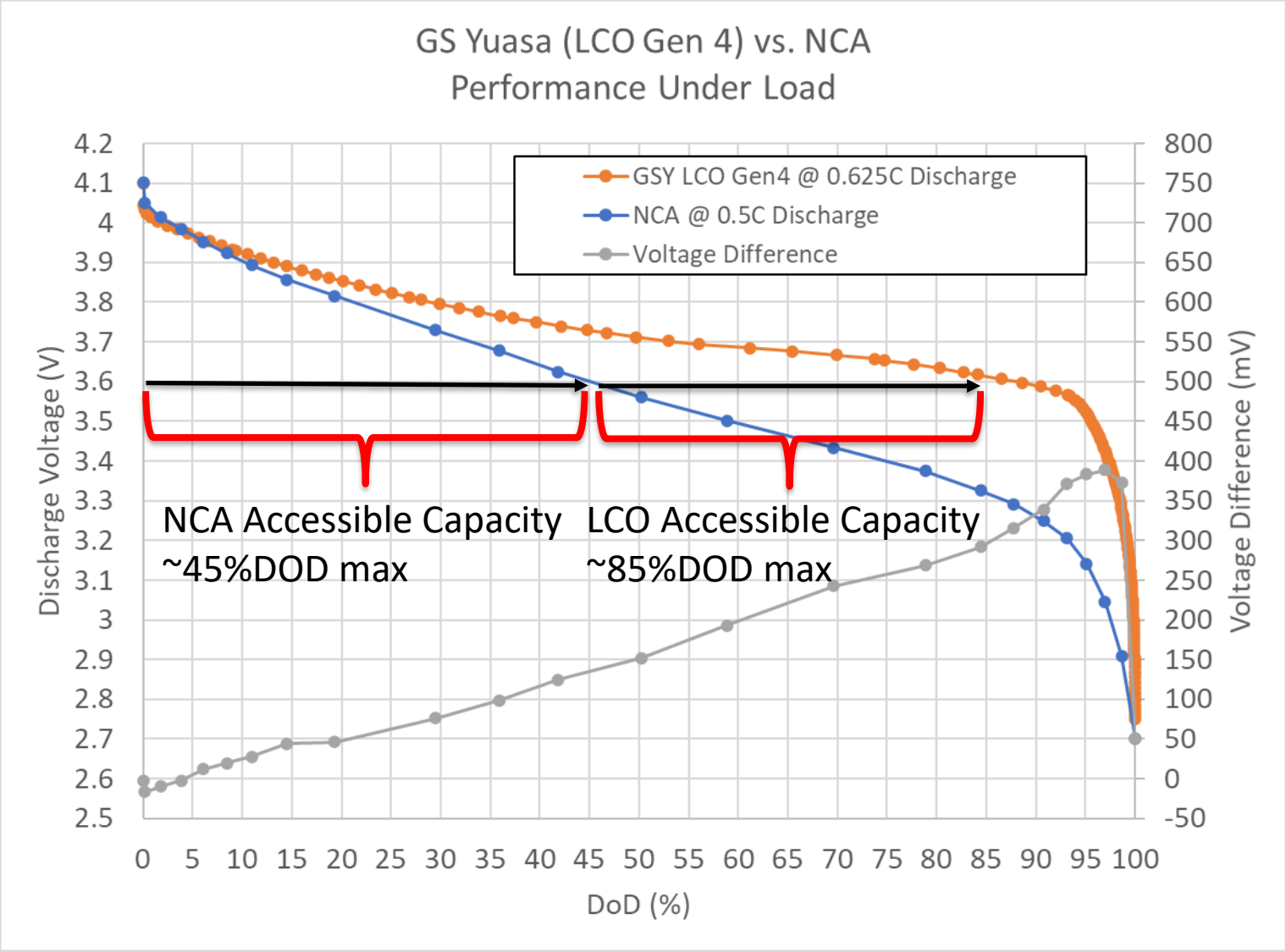
Voltage Performance vs. NCA

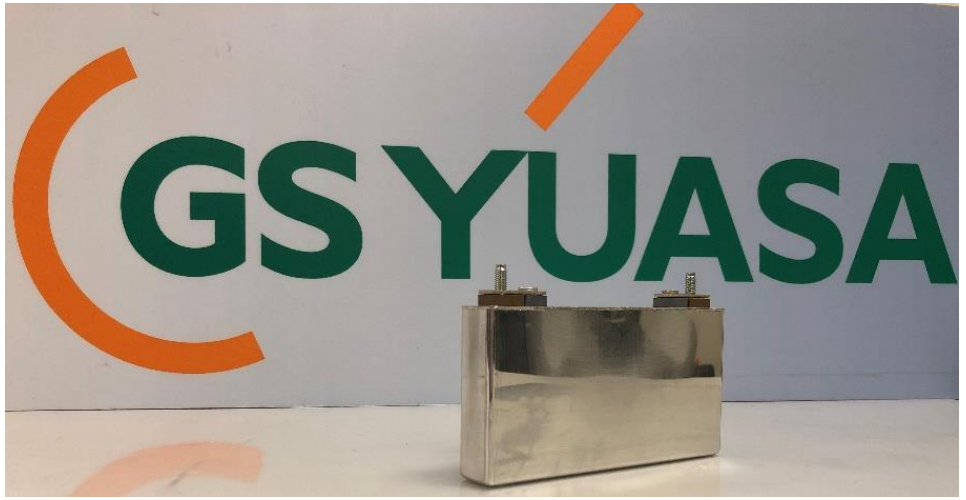




LSE12x Generation 4 LCO-Graphite Chemistry

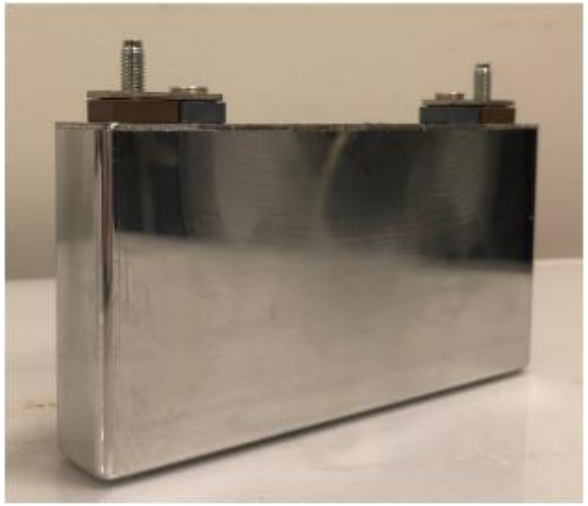
Voltage Performance vs. NCA





LSE12x Cell Design

Features and Specifications Summary

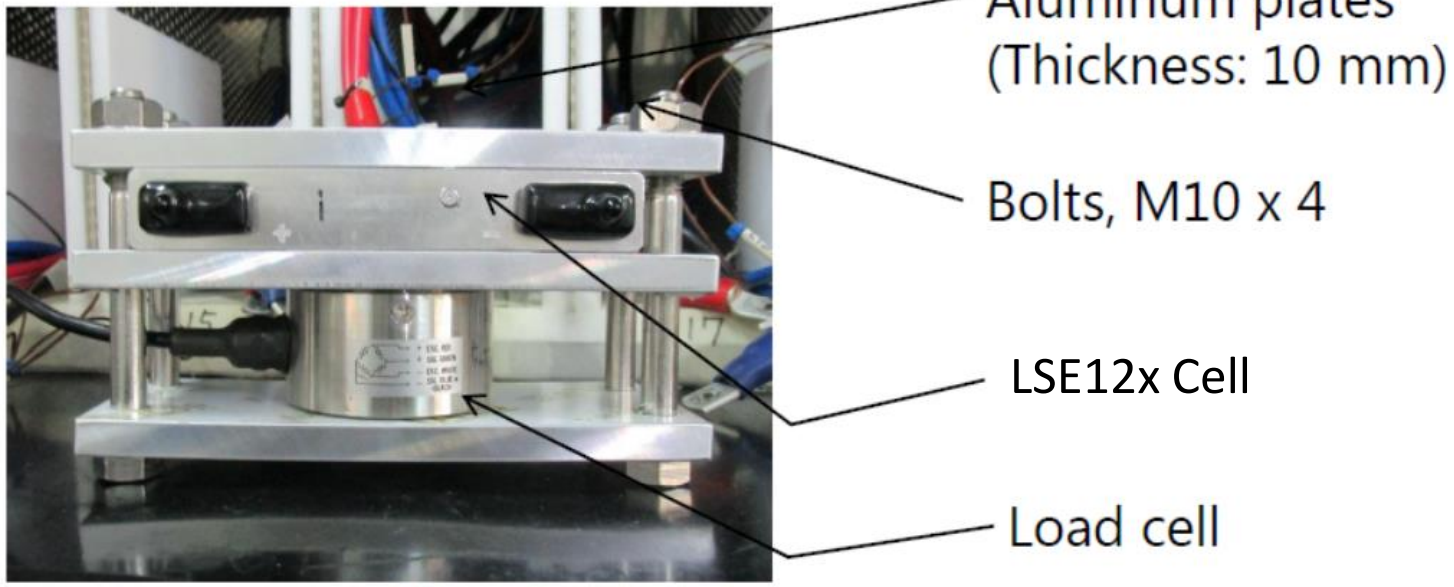


- Inspired by mature commercial cell designs; Enhanced for space
  - Case neutral design
  - Radiation hardened
  - Hermetically sealed
- GS Yuasa's Generation IV Lithium Cobalt Dioxide Chemistry
  - Extremely low DCR
  - Excellent cycle & calendar life
  - High discharge voltage
    - ✓ Ideal for unregulated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

LSE12X Performance Specification

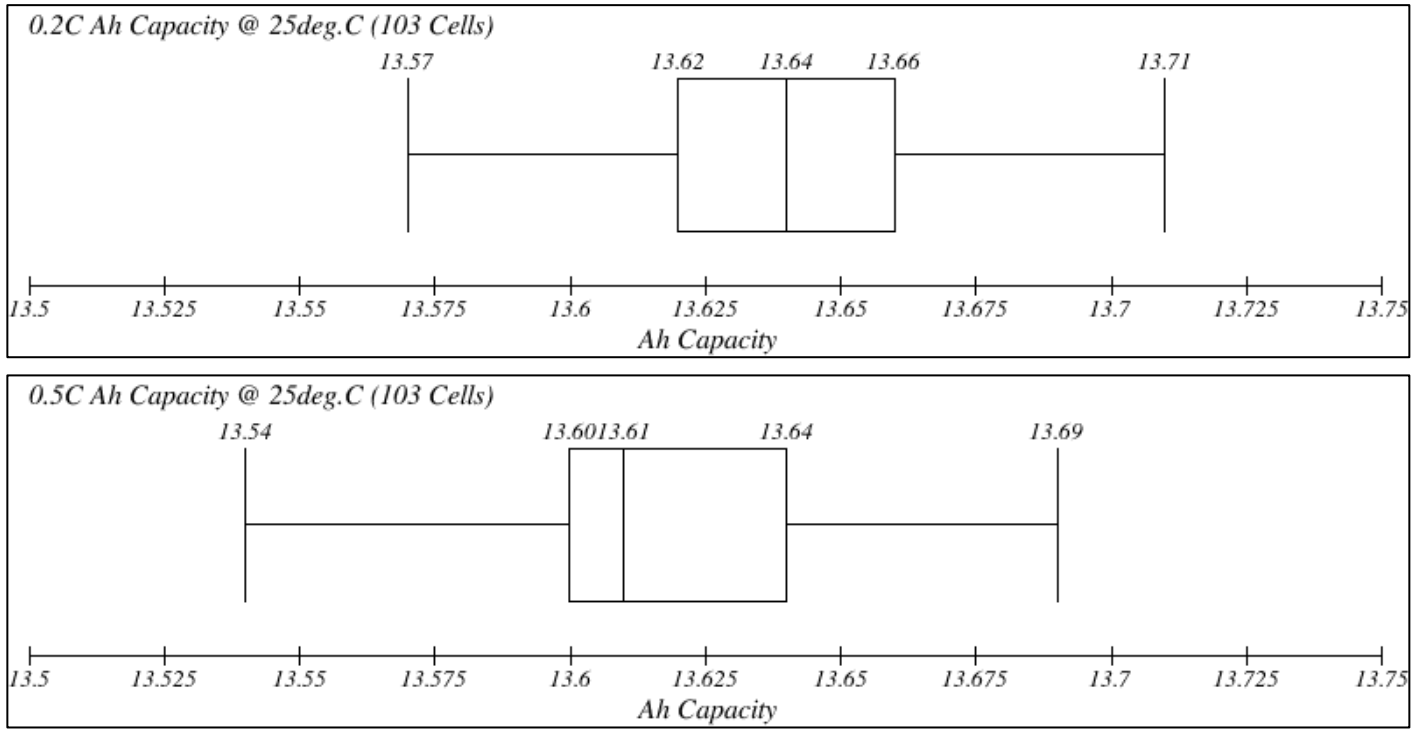
BOL Capacity	4.1V-2.75V	13.6 Ah, 51.0Wh
	*4.2V-2.75V	15.0 Ah, 56.3Wh
Nameplate Capacity		12 Ah, 45Wh
Nominal Discharge Voltage		3.75 V
Continuous Charge Rate, 15°C		6A
Continuous Discharge Rate		24A
Pulse Discharge Rate		60+A
DCR @ 50% SOC, 15°C		<6 mΩ
Nominal Cell Impedance		1.1mΩ
Mass		0.390 kg

LSE12x Lithium-ion Cell for Space Qualification Results



LSE12x Qualification Lot

Lot Number	Activation Date	Lot Size
001 (QM cell lot)	4/2021	103



103 Cells manufactured in QM cell lot

- 12 Cells selected for primary qualification test program
- Remaining cells used for:
  - → Life testing
  - → Special supplemental qual tests
  - → Battery development activities
- Configuration control and full traceability allows qualification data to remain applicable to future Flight production lots.
  - → Minimizes costly recertification testing.

Cell Qualification Test Areas

GS Yuasa Typical In-house Space Cell Qualification Program

Performance Qualification of Li-ion cells consist of four major testing areas

Basic Characteristics
Qty: 12

- Dimension, Mass, Appearance
- Electrical Performance
- Pulse & High Rate Discharge

Environmental Survivability
QTY: 6

- Sine Vibration
- Random Vibration
- Shock
- Acceleration

Safety Testing
QTY: 3

- Over-discharge (1)
- Overcharge (1)
- External Short (1)
- Other as required

Lot Testing

- Vent Opening Pressure
- Case Burst Pressure
- Self-discharge (12)
- Cycle life

Additional

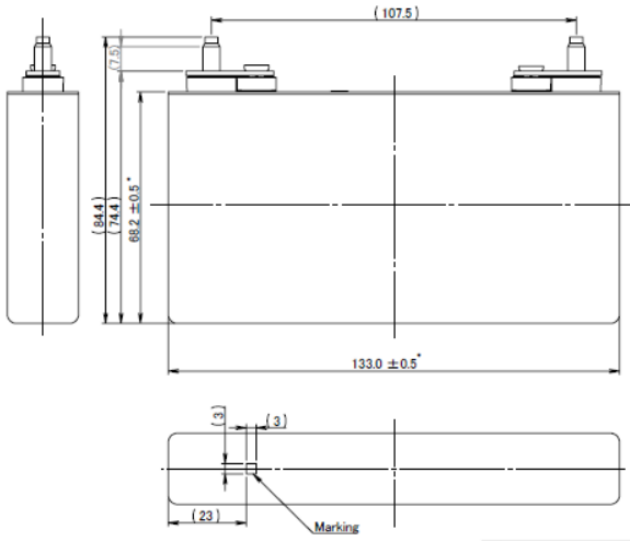
- Radiation Exposure
- Enhanced Dimensional Analysis
- High rate Charge & Discharge
- Others

LSE12x Basic Characteristics

Dimensions/Mass/Appearance

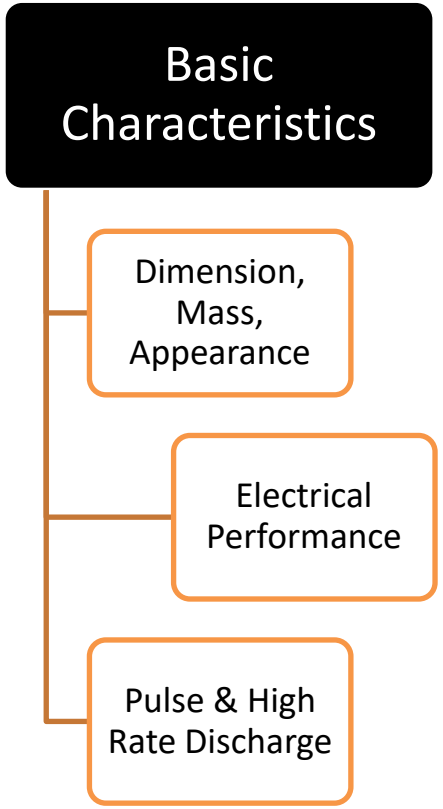
- Basic Characteristics
  - Dimension, Mass, Appearance
  - Electrical Performance
  - Pulse & High Rate Discharge

	Criteria	Average	Min/Max
Length	21.0 +1.5/-0.5mm	21.29mm	21.22/21.50mm
Width	133±0.5mm	133mm	132.95/133.05mm
Height	68.2±0.5mm	68.19mm	68.16/68.22mm
Mass	386±13	386.5	386.1/386.9g
ACz	<1.7mΩ	1.08mΩ	1.07/1.09mΩ
Appearance	Conformed to drawing. No appearance anomalies.		



LSE12x Basic Characteristics

Electrical Performance at Various Temperatures



Step	Operation	Type	Current / A	Voltage / V	Time	Temp.
1	Charge	CC/CV	1.2A @-10°C 2.4 A @>+5°C	4.10	6 hours @ -10°C 4 hours @ >+5°C	-10°C +5°C 15°C 25°C 30°C 40°C (One cycle at each temp)
2	Rest	–	–	–	10 min or more	
3	0.2C Discharge	CC	2.4A	2.75	–	
4	Rest	–	–	–	10 min or more	
5	Charge	CC/CV	1.2A @-10°C 2.4 A @>+5°C	4.10	6 hours @-10°C 4 hours @ >+5°C	
6	Rest	-	-	-	10 min or more	
7	0.5C Discharge	CC	6.0A	2.75	-	

Using the discharge voltage and current measurements from the 0.5C and 0.2C capacity test calculate the DCR by dV/dI of the cell at 20% 50% and 80% discharged states.

- DCR (mOhm) = $(V_{0.2C}-V_{0.5C}) / (I_{0.5C}-I_{0.2C})*1000$

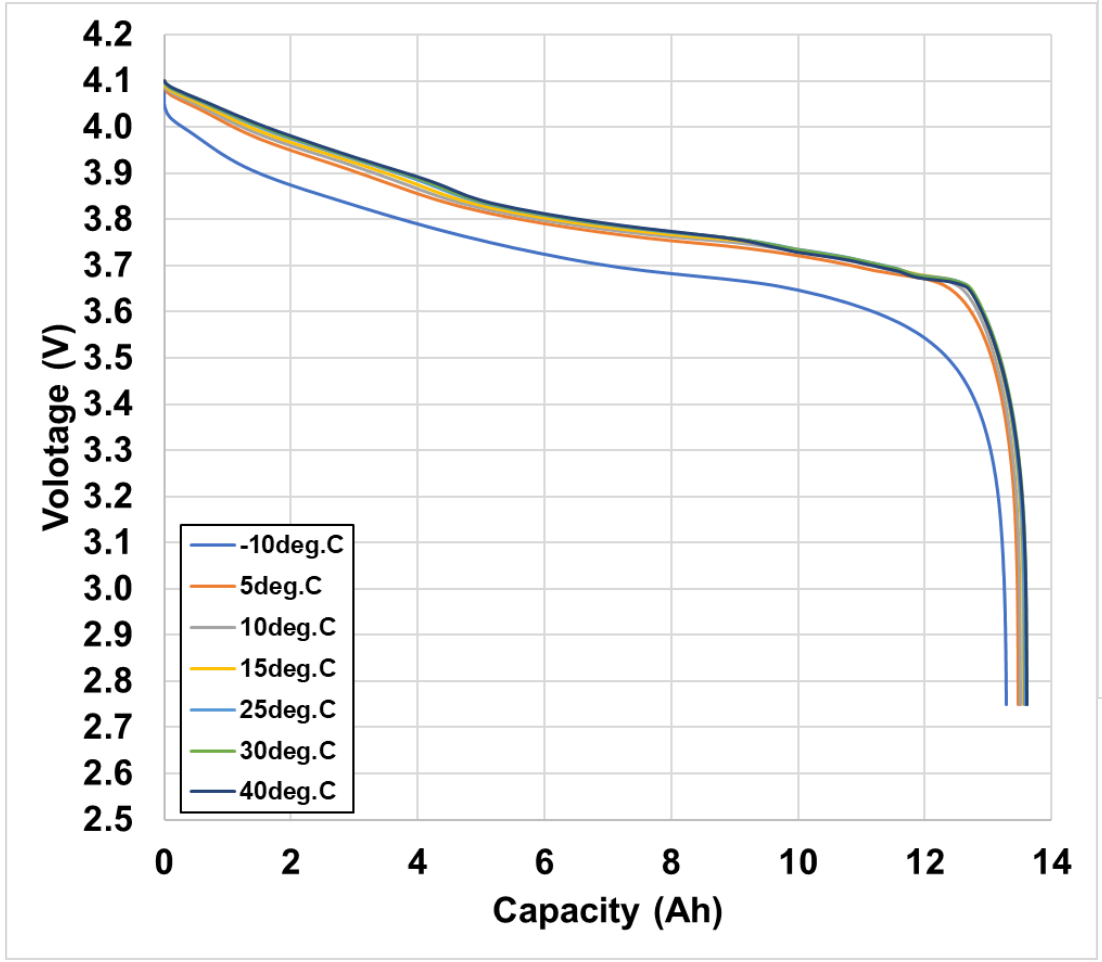
Report Ah Capacity and DCR

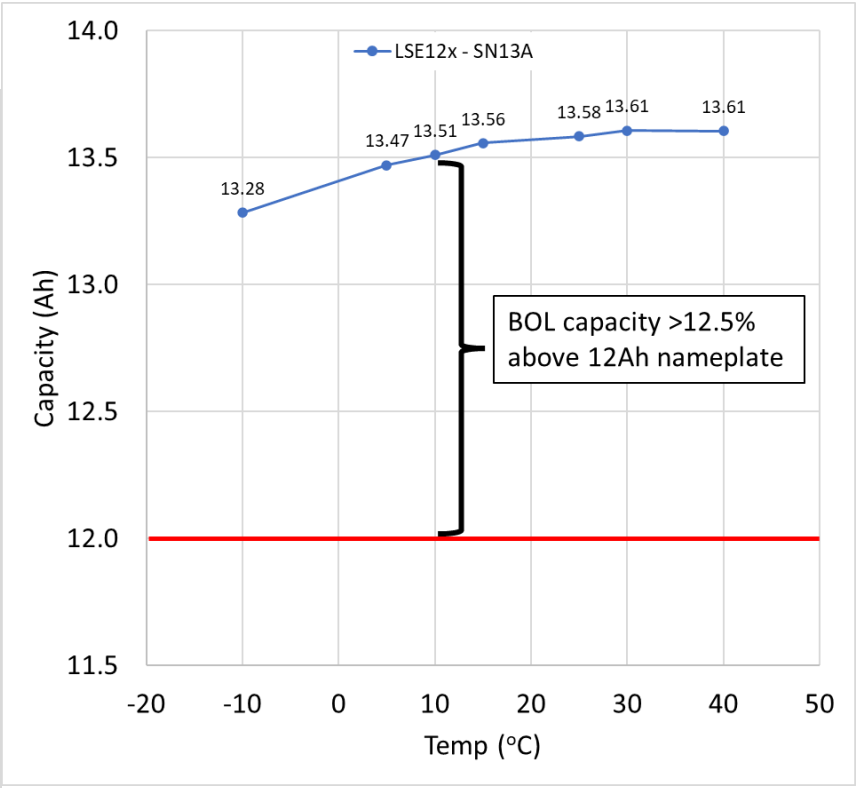
LSE12x Basic Characteristics

Electrical Performance at Various Temperatures

Basic Characteristics

- Dimension, Mass, Appearance
- Electrical Performance
- Pulse & High Rate Discharge





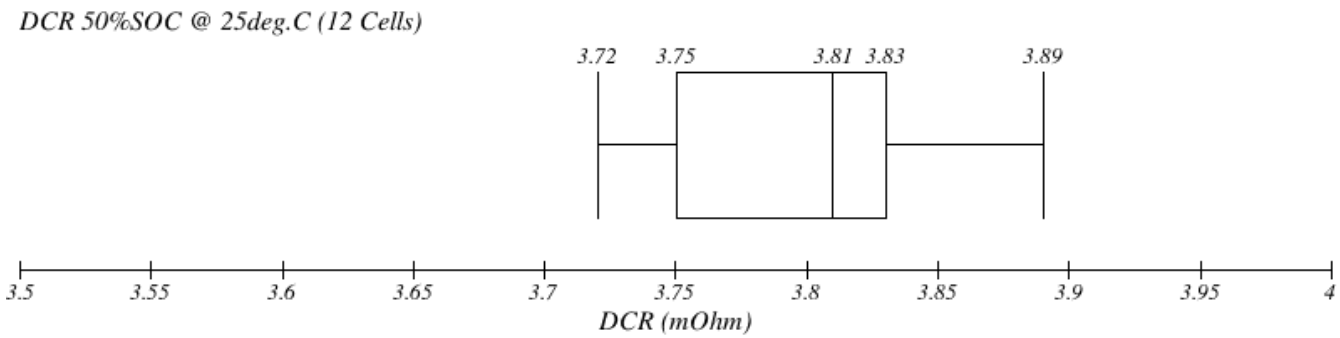
LSE12x Basic Characteristics

Electrical Performance at Various Temperatures

- Basic Characteristics
  - Dimension, Mass, Appearance
  - Electrical Performance
  - Pulse & High Rate Discharge

0.5C Capacity	-10°C	5°C	10°C	15°C	25°C	30°C	40°C
Average (Ah)	13.23	13.43	13.48	13.52	13.55	13.57	13.56
Max (Ah)	13.26	13.46	13.51	13.55	13.57	13.59	13.59
Min (Ah)	13.16	13.37	13.41	13.46	13.49	13.51	13.51
Criteria (Ah)	>10.6	>12.0	>12.0	>12.6	>12.6	>12.6	>12.6

DCR 50% SOC	-10°C	5°C	10°C	15°C	25°C	30°C	40°C
Average (mΩ)	19.56	9.62	7.07	5.51	**3.80**	3.24	2.54
Max (mΩ)	19.97	9.78	7.22	5.64	**3.89**	3.33	2.61
Min (mΩ)	19.19	9.39	6.92	5.36	**3.72**	3.17	2.58
Criteria (mΩ)	Ref	Ref	Ref	<8.0	**<8.0**	<8.0	<8.0

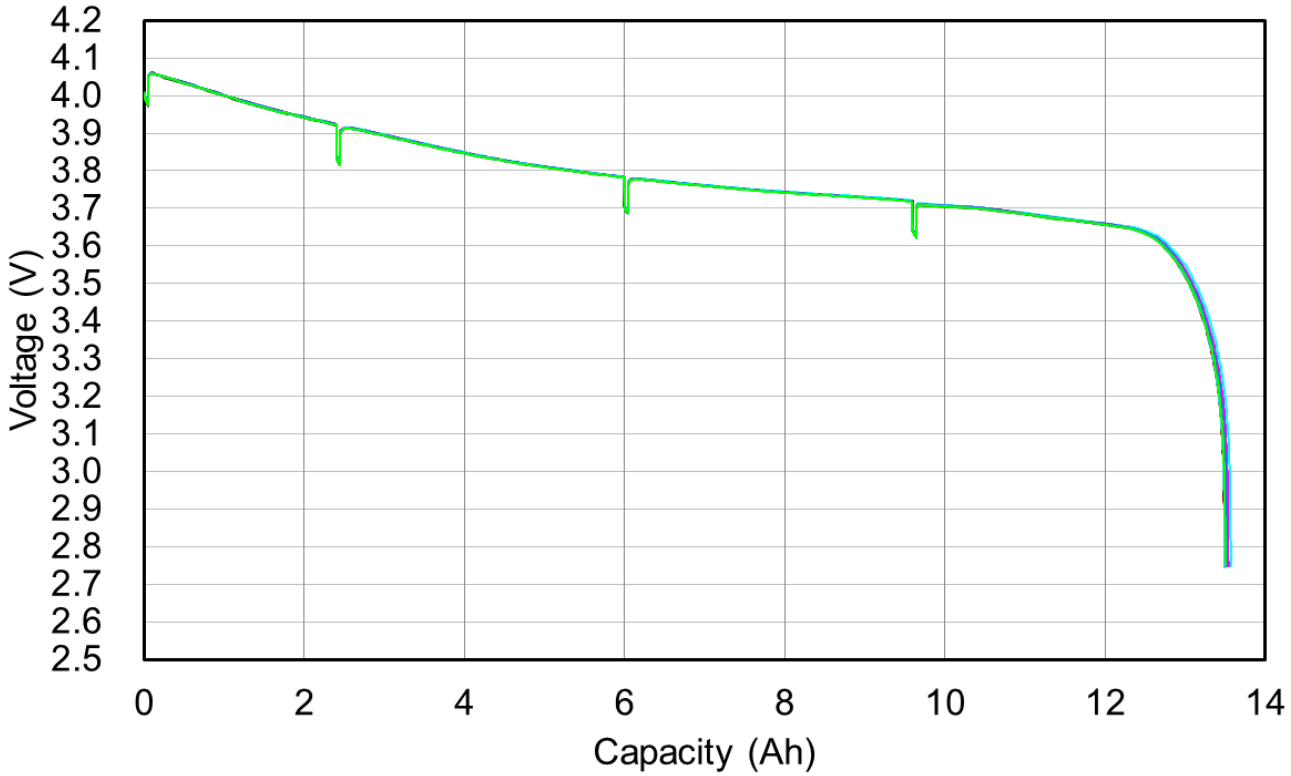


LSE12x Basic Characteristics

Pulse & High Rate Discharge Performance

- Basic Characteristics
  - Dimension, Mass, Appearance
  - Electrical Performance
  - Pulse & High Rate Discharge

Step	Operation	Type	Current / A	Voltage / V	Time	Temp.
1	Charge	CC/CV	6.0A	4.10	4 hours	+15°C
2	Rest	–	–	–	10 min or more	
3	3.0C Discharge	CC	18A	--	5 sec @ DOD 0%, 20%, 50%, 80%.	
4	0.5C Discharge	–	6A	2.75	Between pulses	



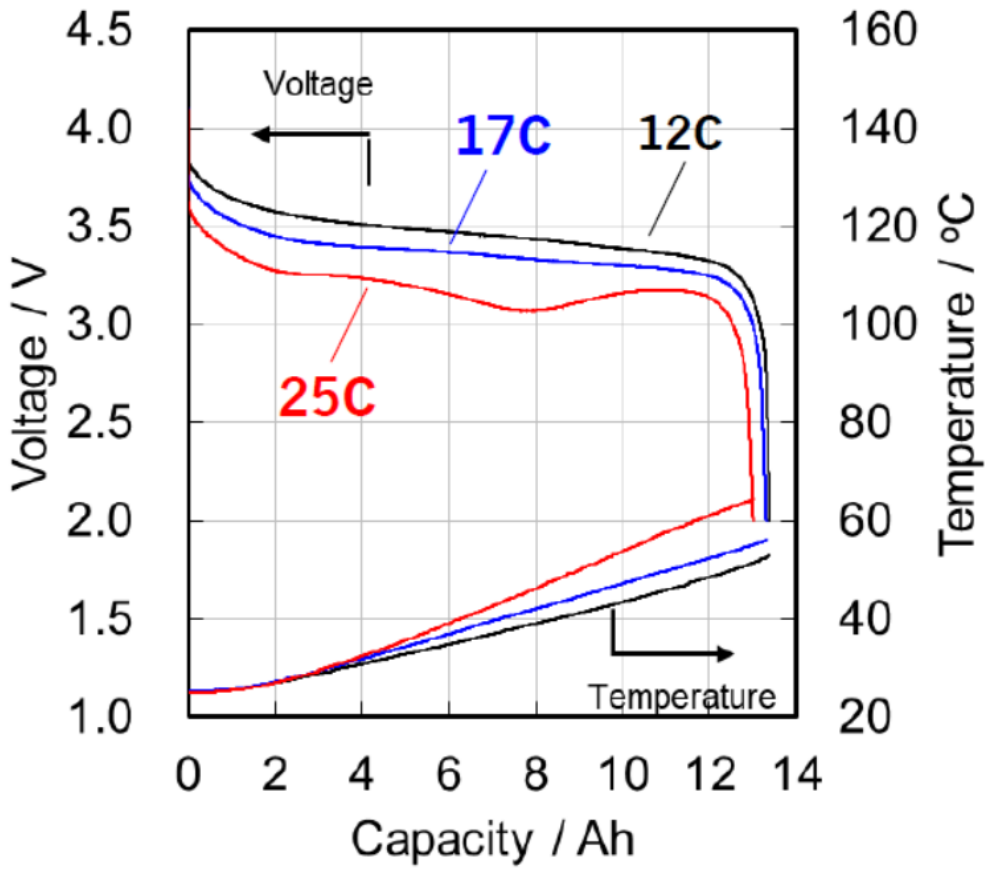
BOL Cell is capable of 3C pulses at 80% DOD while remaining above 3.6V

LSE12x Basic Characteristics

Pulse & High Rate Discharge Performance

Step	Operation	Type	Current / A	Voltage / V	Time	Temp.
1	Charge	CC/CV	6.0A	4.10	4 hours	+25°C
2	Rest	–	–	–	10 min or more	
3	Discharge	CC	144A, 204A, or 300A	2.75	--	

- Basic Characteristics
  - Dimension, Mass, Appearance
  - Electrical Performance
  - Pulse & High Rate Discharge

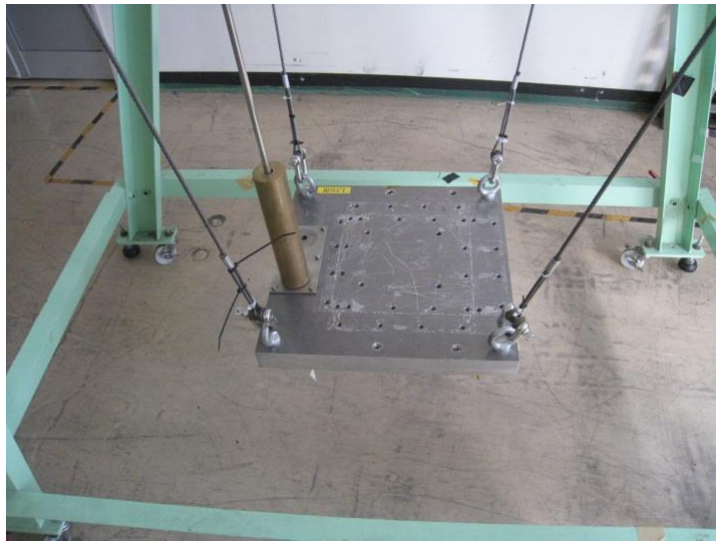


- LSE12x is capable of sustained ultra high rate discharge.
- Pulse discharge at these rates is possible.
- Continuous cycling has not yet been evaluated.

LSE12x Environmental Testing

Major Equipment Overview & Capabilities

- Vibration Test:
  - Sine: 0.1-20kHz
  - Random: Max 20kHz
- Shock Test:
  - Accel: 29-166713m/s^2
  - Time: 0.1-60ms
- Acceleration:
  - Accel: 2.4-240G
  - Max Weight: 30kg



LSE12x Environmental Testing

Prior to dynamic exposure cell basic electrical characteristics are confirmed again (Capacity, DCR, ACz, self discharge)

Cells are compressed and charged to 4.10V during exposure to each of the below environments.

Cell electrical performance is again confirmed after environmental exposure and compared to prior measurements.

Sine Vibration

Frequency / Hz	Level
5 to 27.9	6.4 mm (Single amplitude)
27.9 to 100	196 m/s^2 (20g)

Sweep rate: 2 oct/min

Random Vibration

Frequency / Hz	Level	Grms
20 to 58	+6 dB/oct	23.63
58 to 700	48.02 $(m^2/s^4)/Hz$ (0.5 g^2/Hz)	(231.57 m/s^2rms)
700 to 2000	-6 dB/oct	

Period: 3 minutes

Shock (Impact)

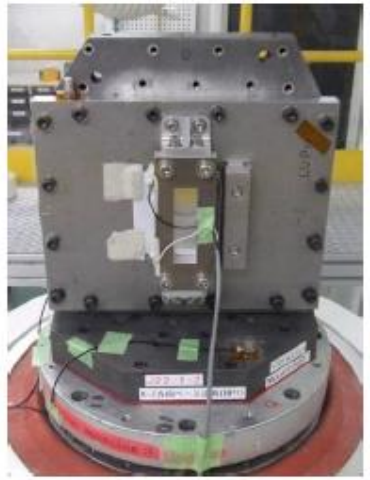
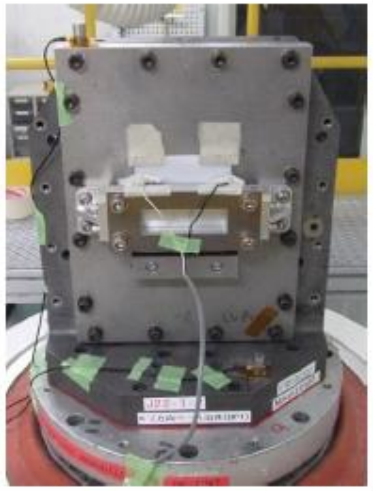
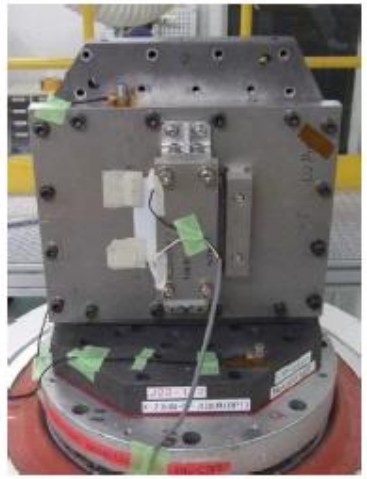
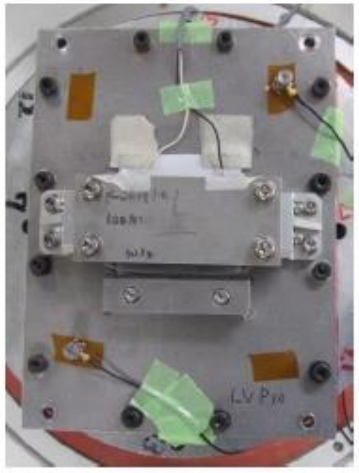
Frequency / Hz	Level
200	392 m/s^2 (40 g)
200 to 2000	+9.296 dB/octave
2000 to 7000	13,720 m/s^2 (1400 g)

Acceleration

Direction	Level
±X, ±Y, ±Z	30G for 5 Min

LSE12x Environmental Testing

Sine and Random Vibration Test Set-up

Configuration	X-axis	Y-axis	Z-axis
1			
2			

Sine Vibration

Frequency / Hz	Level
5 to 27.9	6.4 mm (Single amplitude)
27.9 to 100	196 m/s^2 (20g)

Sweep rate: 2 oct/min

Random Vibration

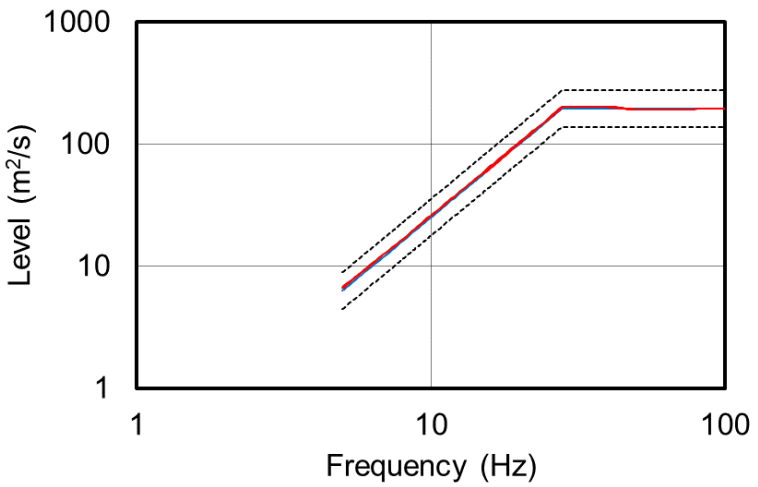
Frequency / Hz	Level	Grms
20 to 58	+6 dB/oct	23.63
58 to 700	48.02 $(m^2/s^4)/Hz$ (0.5 g^2/Hz)	(231.57 m/s^2rms)
700 to 2000	-6 dB/oct	

Period: 3 minutes

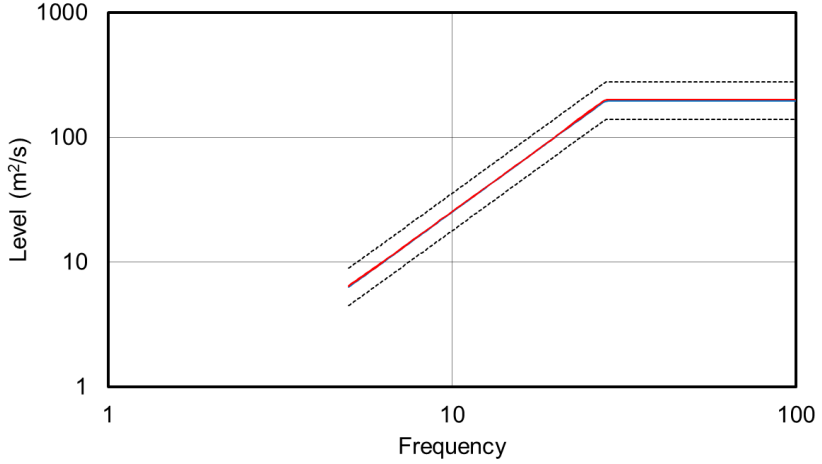
LSE12x Environmental Testing

Sine Vibration

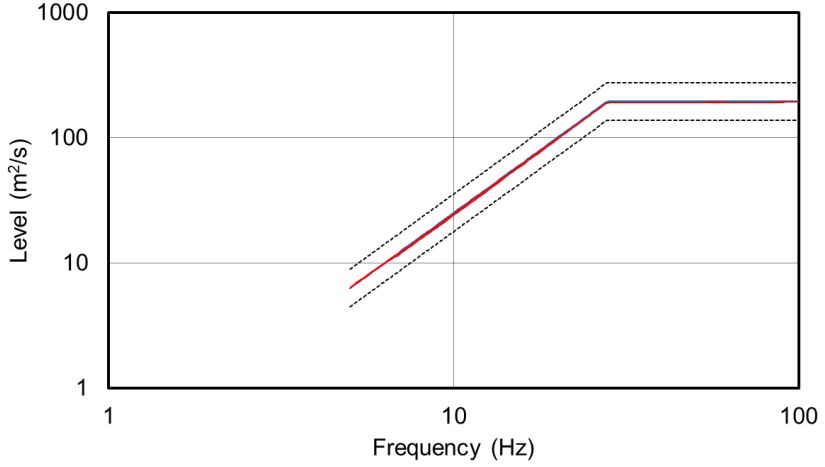
Response of cell x-axis random vibration

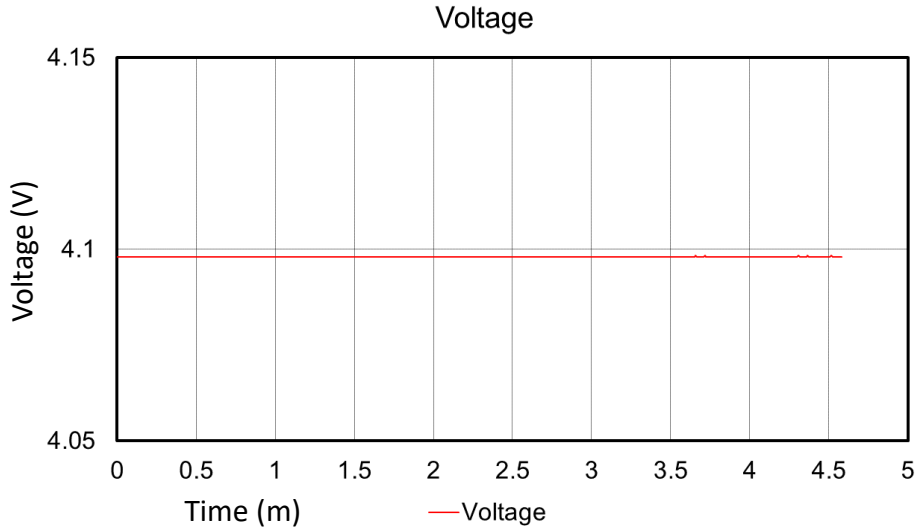


Response of cell y-axis random vibration



Response of cell z-axis random vibration



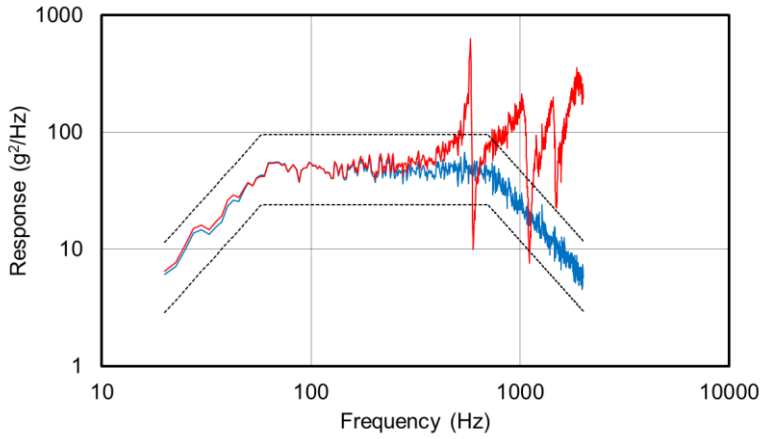


Voltage profile shows no abnormal activity while exposed to the Sine Vibration environment.

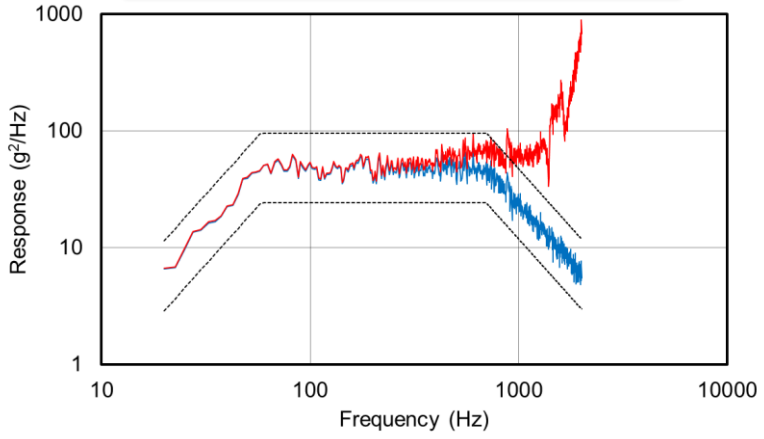
LSE12x Environmental Testing

Random Vibration

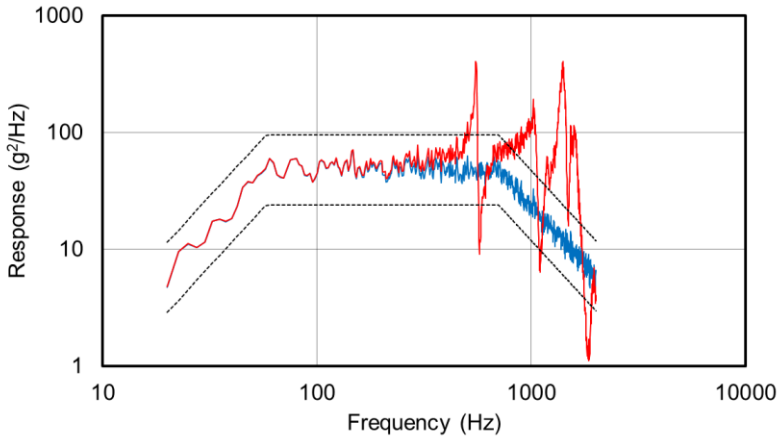
Response of cell x-axis random vibration

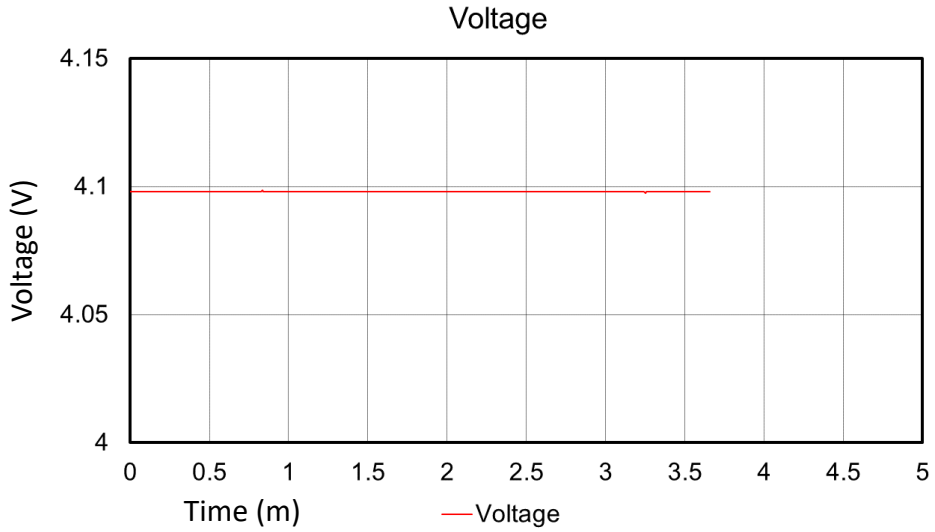


Response of cell y-axis random vibration



Response of cell z-axis random vibration

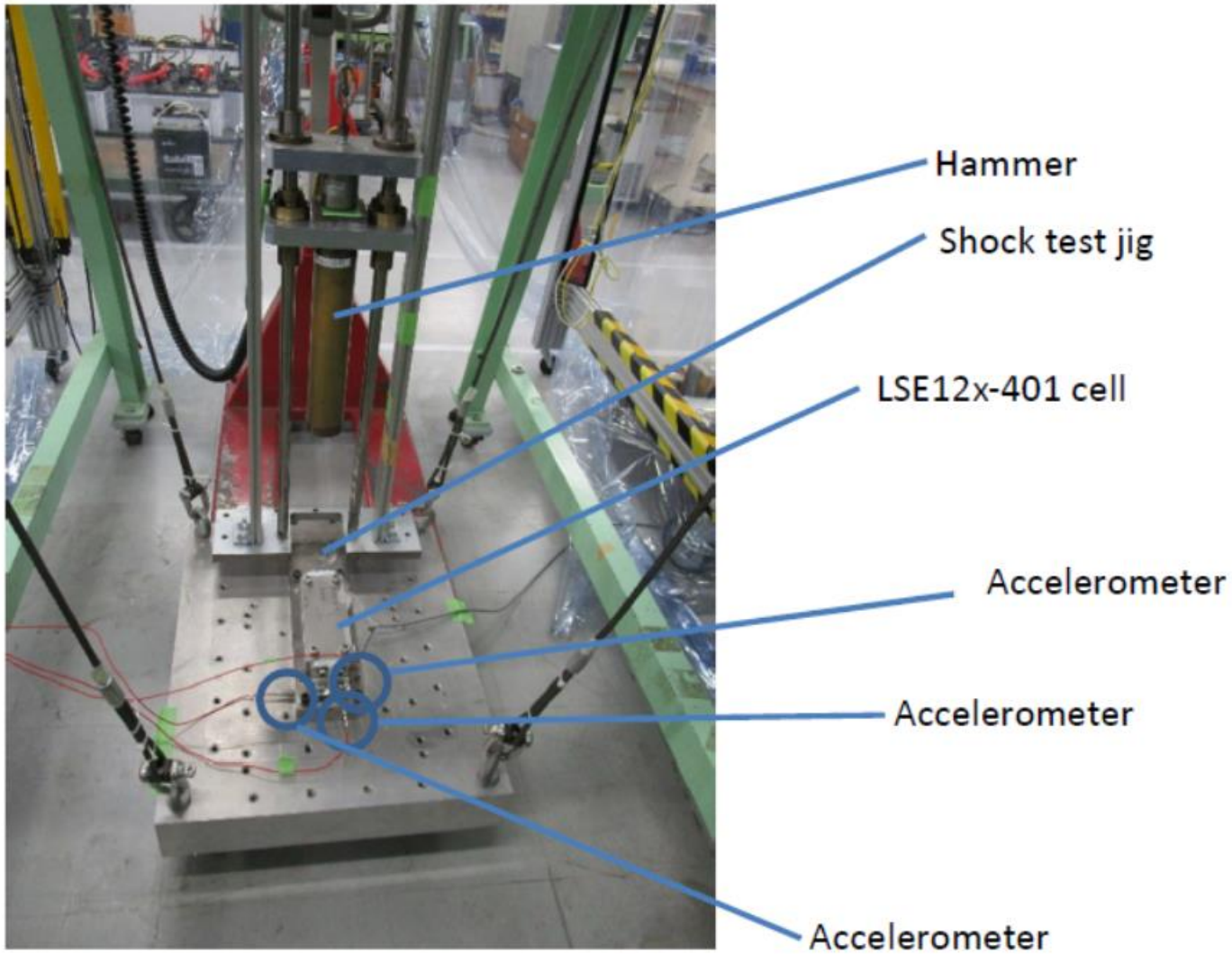




Voltage profile shows no abnormal activity while exposed to the Random Vibration environment.

LSE12x Environmental Testing

Shock Test Set-up



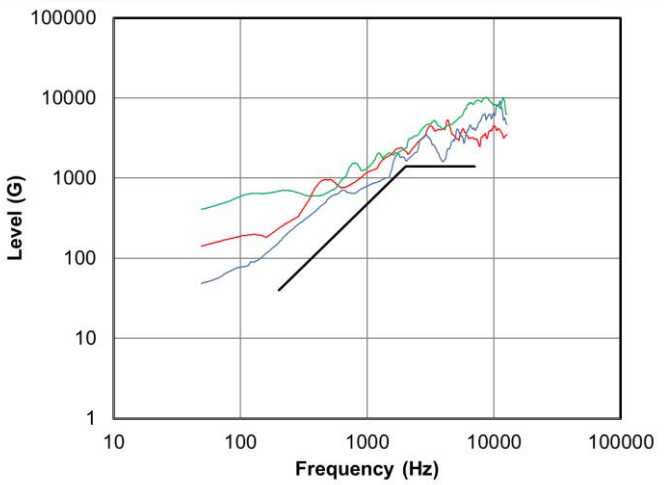
Shock Profile

Frequency / Hz	Level
200	392 m/s^2 (40 g)
200 to 2000	+9.296 dB/octave
2000 to 7000	13,720 m/s^2 (1400 g)

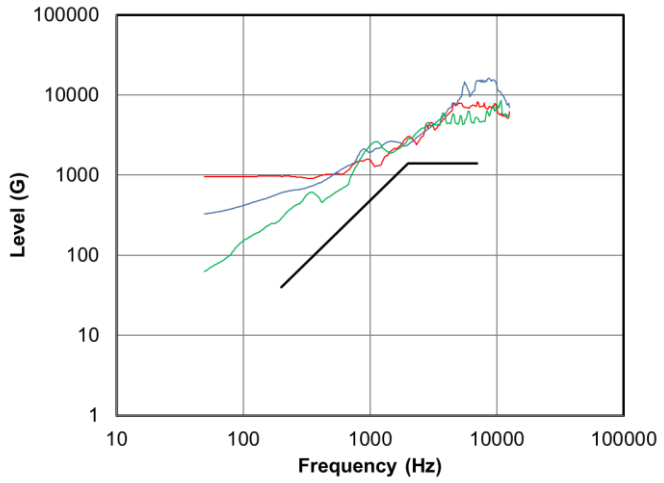
LSE12x Environmental Testing

Shock Response

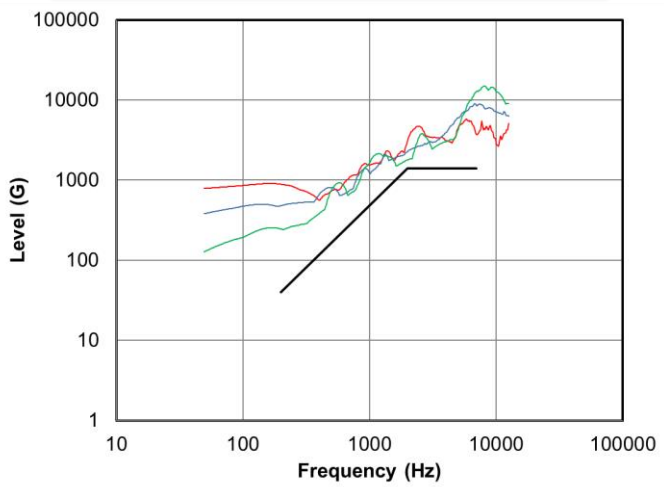
Response of cell x-axis random vibration

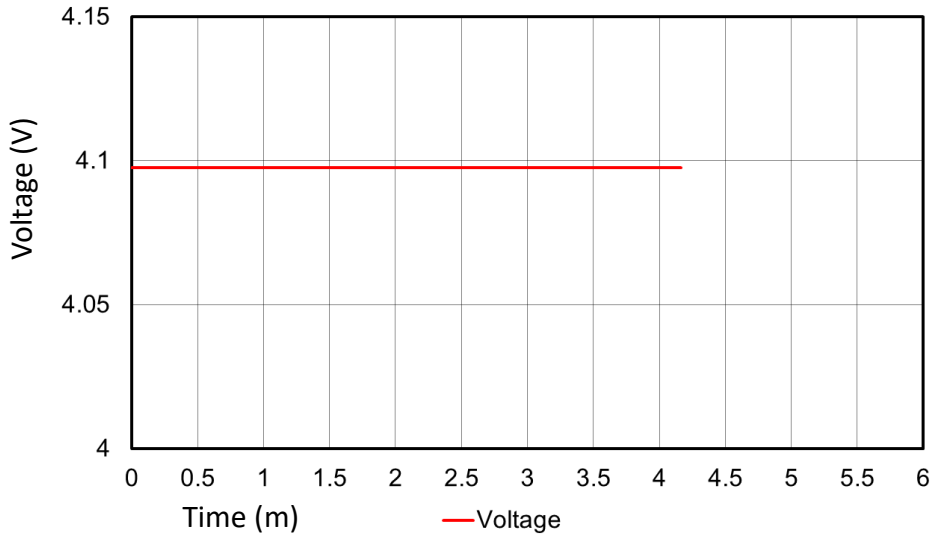


Response of cell y-axis random vibration



Response of cell z-axis random vibration

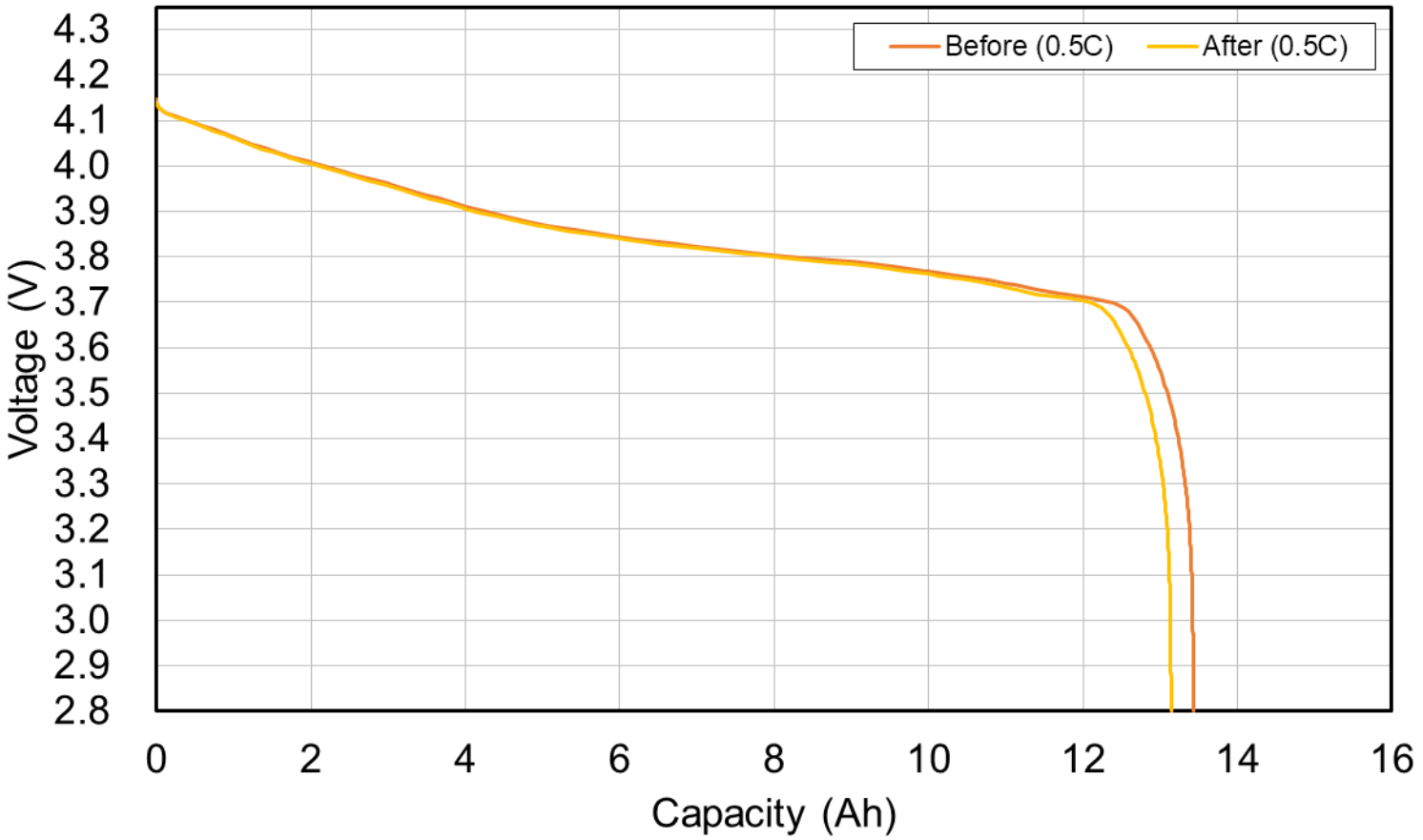




Voltage profile shows no abnormal activity while exposed to the Shock.

LSE12x Environmental Testing

Effect of Environmental Exposure

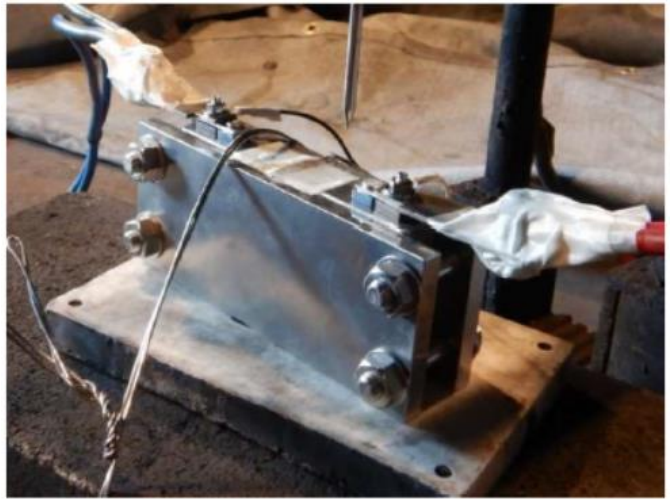


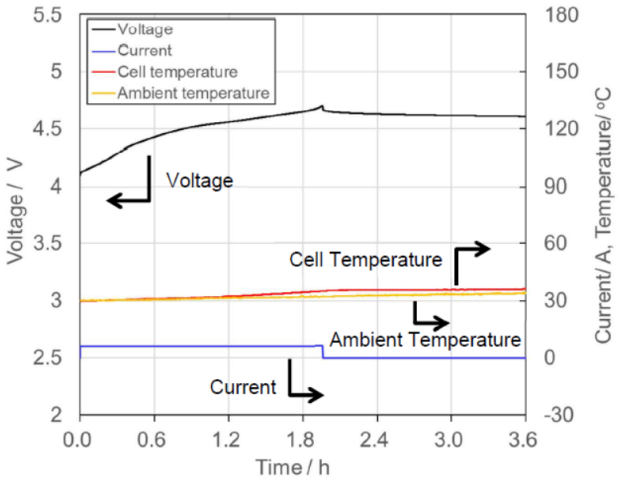
LSE12x Qty:6	0.5C Capacity (Ah)		DCR @ 50% (mΩ)		ACz (mΩ)	
	Before	After	Before	After	Before	After
Average	13.43	13.14	3.78	4.02	1.10	1.14
Max	13.46	13.23	3.91	4.15	1.11	1.15
Min	13.38	13.25	3.68	3.87	1.10	1.14

Slight change due to nominal aging effects accumulated over the test period. No attributable differences caused by environmental exposure.

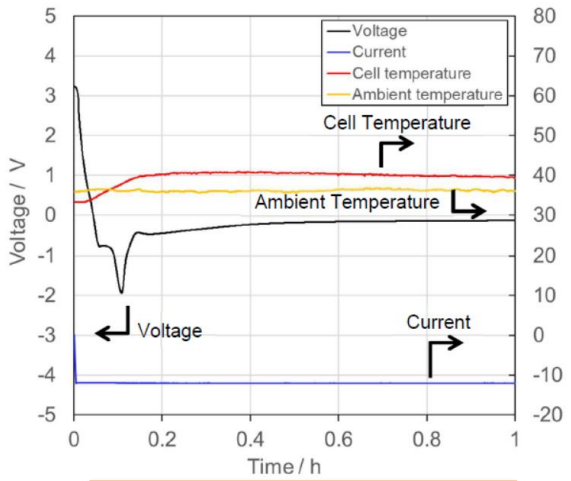
LSE12x Safety Testing

Cell Safety Qualification Tests (ERW 127-1)	Overcharge		Cell did not vent. Cell voltage reached 4.7 volts after ~+12 Ah charge above 100% SOC. No significant temperature increase was observed during overcharge.
	Over-discharge (Forced Discharge)		Cell did not vent. Cell acts as a resistor due to short circuit caused by copper dissolution and plating.
	External short	1.25 milliohm	Cell did not vent. Cell completely discharged in ~1minute. Peak current of 1700A.

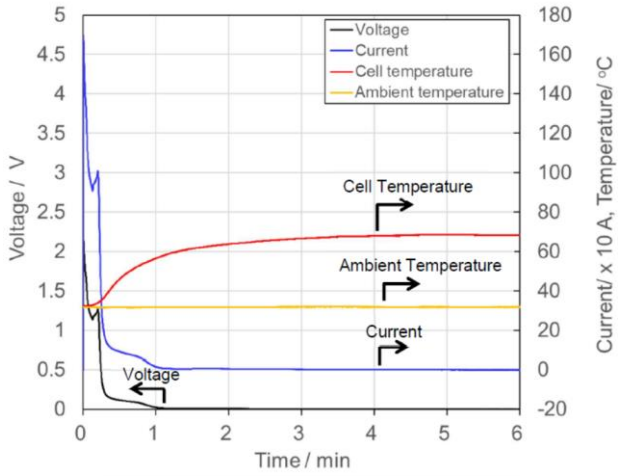




Overcharge to 4.7V



Forced Discharge

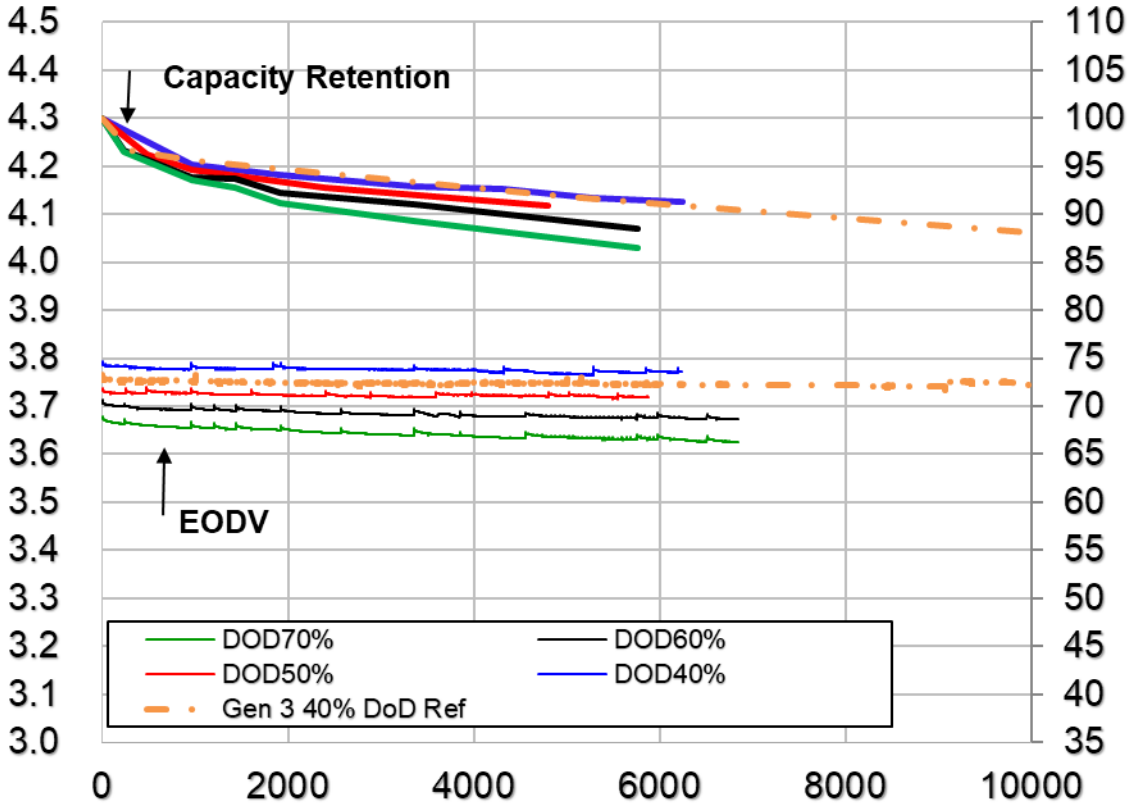


External Short

LSE12x Cycle Life

Ultra high DOD Cycle Life

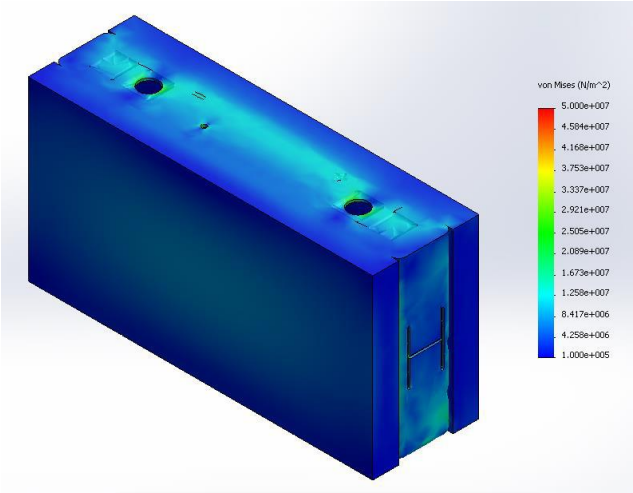
Test Name	Cell Type	Test Conditions						Ambient Test Temp	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition				
		EoCV	Rate	Time	EoDV	Rate	Time		
40%, 50%, 60%, & 70% DoD LEO	LSE12x	4.1V	Various	1.0Hr	N/A	Various	0.5hr	15°C	Ultra high DOD LEO Cycle



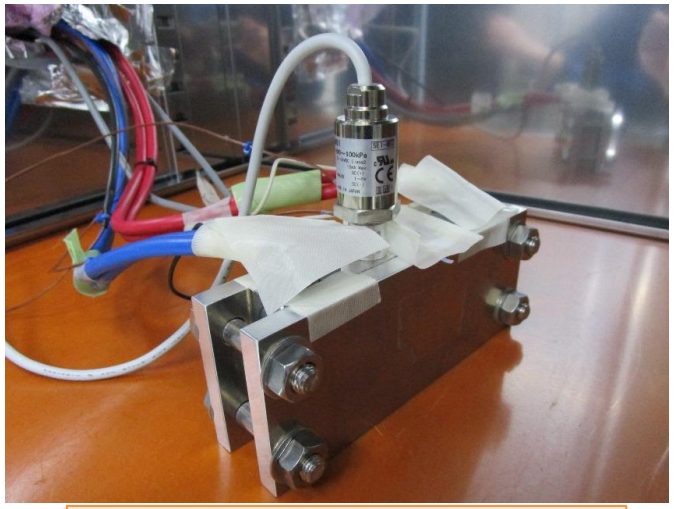
Cycle	Discharge	Charge
40%DOD	0.8C (9.6A) for 0.5hr	0.5C, 4.10V, CC/CV, 1hr
50%DOD	1.0C (12.0A) for 0.5hr	0.6C, 4.10V, CC/CV, 1hr
60%DOD	1.2C (14.4A) for 0.5hr	0.7C, 4.10V, CC/CV, 1hr
70%DOD	1.4C (16.8A) for 0.5hr	0.8C, 4.10V, CC/CV, 1hr

Ultra high DOD cycling supports LSE12x use in high power missions or to support off-nominal operations.

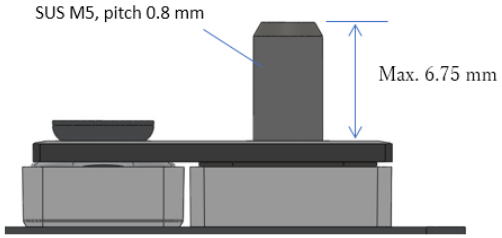
LSE12x Additional Qualification Tests



EOL Mechanical FEA



Cycle Internal Pressure Change Evaluation

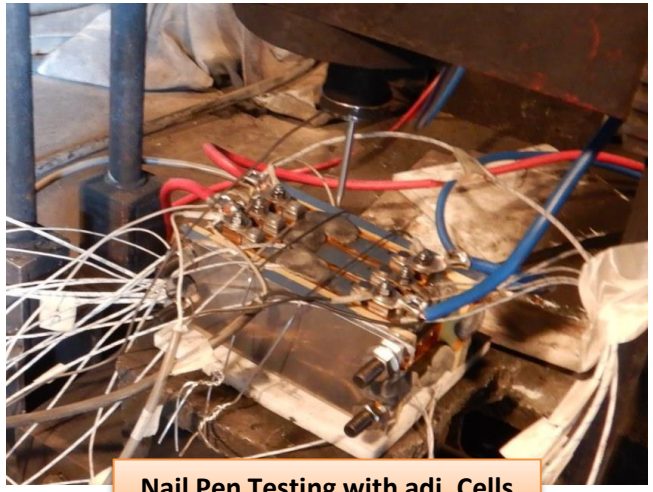


He-leak tests pre- and post- Irradiation (2Mrad, Co-60 source)

	Before	After
0001	8.59×10^{-10} Pa*m³/sec	7.44×10^{-10} Pa*m³/sec
0002	9.90×10^{-10} Pa*m³/sec	6.40×10^{-10} Pa*m³/sec
0003	8.82×10^{-10} Pa*m³/sec	7.70×10^{-11} Pa*m³/sec

Radiation Tolerance

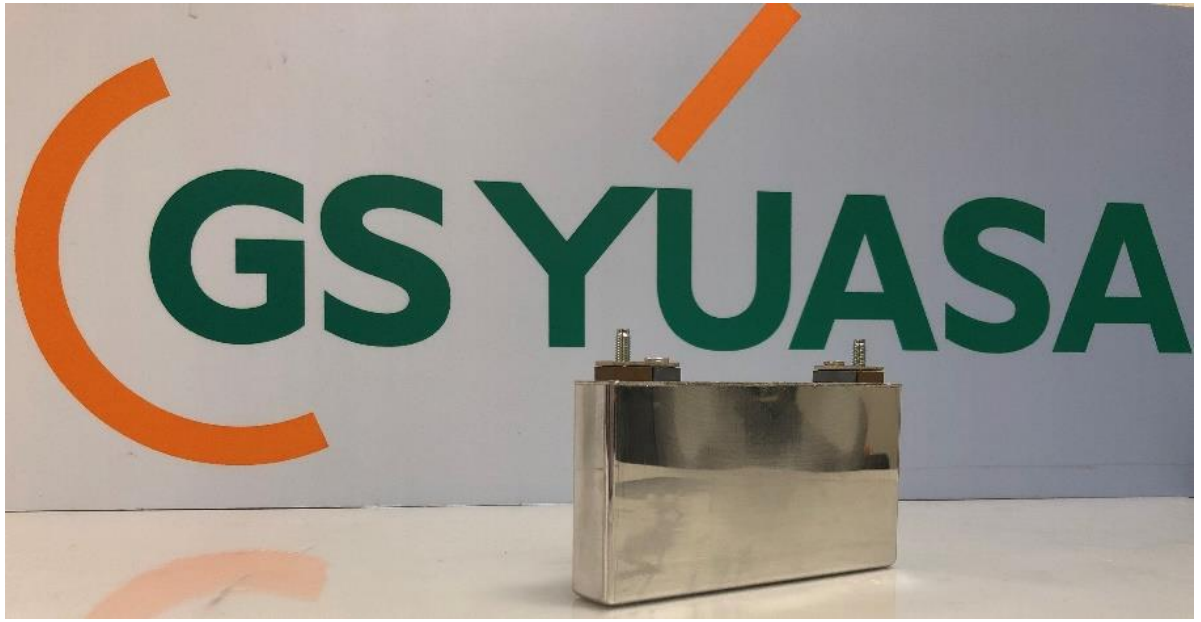
Case Bust Test



Nail Pen Testing with adj. Cells

LSE12x Qualified!

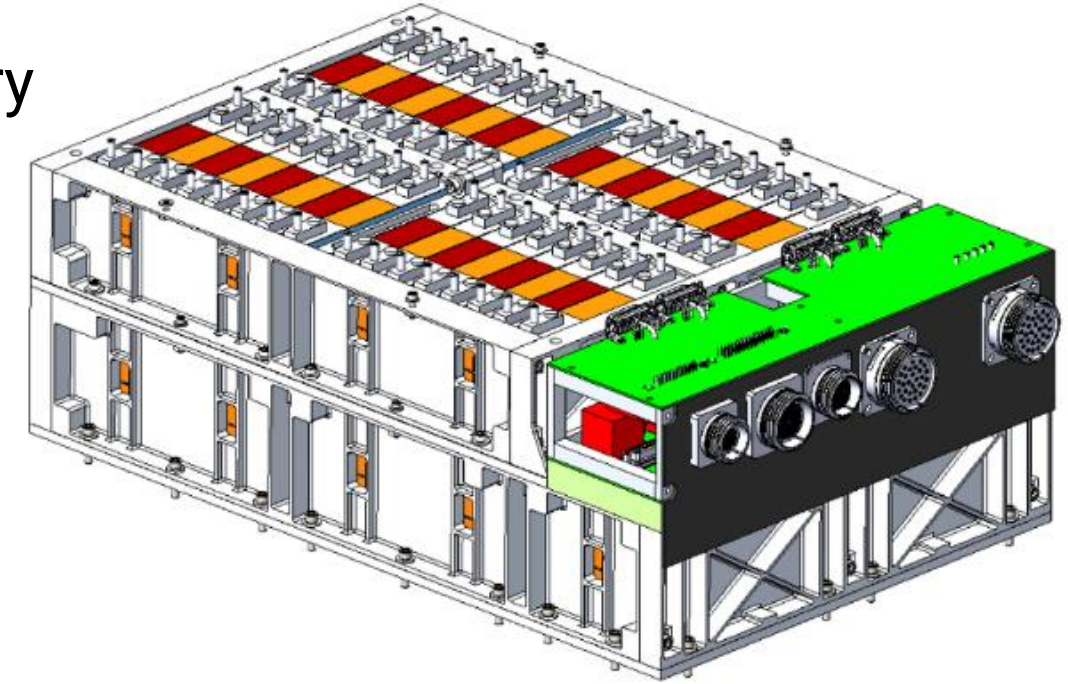
- The LSE12x cell has successfully completed all qualification testing and specification objectives have been achieved.
- Ready for production
- What next???



LSE12x Scalable Battery

Designed by GS Yuasa Lithium Power

- GYLP is currently designing a scalable battery based on the LSE12x cell building block.
- Battery configurations will offer capacities ranging from 360Wh to 4320Wh.
- Electrical configurations to support both low and high voltage applications.
- The design has completed internal Preliminary Design Review (PDR)
- GYLP is preparing for Critical Design Review (CDR) of a 72-cell variant, 8s9p.
- Full battery qualification is anticipated to be complete by Q2 2023.



Qualification unit with connector box
(cover and inter-cell connects not shown)

Energy storage design test and manufacturing expertise

Industry leading spaceflight heritage

Validated and reliable performance modelling

Visit www.GSYUASA-LP.com for more information

Thank you!