GS Yuasa Modular Battery Qualification Update and Cell Performance Model Validation

2018 Space Power Workshop
April 26, 2018

Thomas Pusateri, Curtis Aldrich, George Bergmark, Masazumi Segawa

- GS Yuasa corporate introduction
- Update of space Li-ion activity
- Introduction of the space-qualified MA190 modular space battery
- LSE cell Life and Performance model validation
- Debut of cell and battery Life and Performance model for GYLP customers

GS Yuasa Corporate Introduction

Powering the Next Generation

GS Est. 1895 — Japan Storage Battery Co., Ltd

YUASA Est. 1913 — Yuasa Battery Manufacturing

2004

GS YUASA

100 Years of History, 200 Years of Expertise
100 ANNIVERSARY

- **Consolidated FY2016 Net Sales: $3.2B**
- **Li-Ion sales $350.9M in FY2016**
- **37 affiliates in 17 countries**
- **14,710 employees worldwide**
- **GS Yuasa Lithium Power, Inc.**
  - **established 2006 (USA)**

GS Yuasa Corporation

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 Yuasa Battery Ltd.
Sales of aftermarket automotive batteries & automobile-related products.

GS Yuasa Technology Ltd.
Manufacturing and sales of specialty batteries.

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.

Lithium Energy and Power (JV) (2013)
Development and sales of lithium-ion batteries for electric and hybrid electric vehicles.

GYLP and Other Affiliates

GS Yuasa Lithium Power (GYLP)

Powering the Next Generation

- Established: 2006
- Mandate: Sales channel for GS Yuasa's li-ion energy storage technologies and solutions in North America
- Mission: Deliver best-in-class solutions for North American clients within the Aerospace, Military, and Specialty industries
- Focus: Quality, Service, Value
- Functions: Sales, service, engineering, manufacturing program management, logistics and export compliance
- Size: 26 employees and contractors

  17 with B.S. or advanced engineering/technical degrees

  NASA-certified Level B Trainers

- Certifications: ISO 9001 and EN/JISQ/AS9100

Incorporated in Georgia, US company, ITAR compliant, DDTC registered

GS Yuasa Lithium-ion Space Heritage

Powering the Next Generation

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

- Number of satellites…….…….. 174+
  - LEO/MEO……..…….. 79+
  - GEO……..…… 95
- 1st satellite on-orbit…… Servis 1 (30 Oct. 2003)
- Longest satellite on-orbit (yrs)…..... >12 (IPSTAR, 11 Aug. 2005) still operational
- Watt hours on-orbit……..... >3.25 million
- Space cell qualification programs……. >21
- Cell sizes (Ah) flown…..... 35; 50; 100; 175; 190; 200
- Performance to date……..... No failures
- Backlog (Wh)…… >1MWh

Launch vehicles & number of satellites

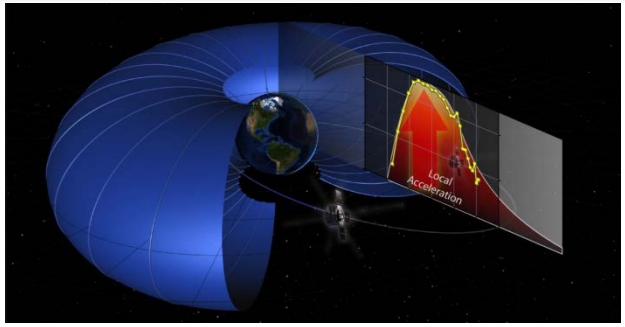
Ariane-5ECA	39	Atlas-5 (401)	5	Soyuz-2-1b Fregat	3	H-2A-2024	2	Atlas-5 (421)	1
Soyuz-2-1 Fregat	24	Falcon-9 v.1.1	5	Zenit-3SLB	3	H-2A-204	2	Dnepr	1
Proton-M Briz-M (Ph.3)	18	Proton-M Briz-M (Ph.4)	5	Antares 120	2	Rokot-KM	2	Epsilon CLPS	1
H-2A-202	14	Falcon-9 v.1.2	4	Antares 230	2	Zenit-3SL	2	Falcon-9 v.1.2 (refly)	1
H-2B-304	13	H-2A	4	Atlas-5 (431)	2	Antares 130	1	GSLV Mk.2	1
Soyuz-STB Fregat-MT	9	Proton-M Briz-M (Ph.2)	4	Epsilon	2	Ariane-5GS	1	Proton-M Briz-M (Ph.1 M1)	1

Updated FEB 2018

GYLP Space Programs

JHU/APL

- LSE50, LSE55
- Critical space science missions
- Van Allen Probes (RBSP), Double Asteroid Redirection Test (DART)



OrbitalATK

- LSE100, LSE110, LSE134, LSE145, LSE190
- Several platforms supported. Batteries built by EPT and GYLP
- CRS Cygnus Vehicle, >39 fight batteries manf. and delivered by GYLP
- GEOStar-2, GEOStar-3, LEOStar-3, MEV

International Space Station

- Won highly competitive down-select process
- >5 year period of performance, >1000 LSE134 cells
- 6 of 24 ORU batteries have been installed (channels 3A and 1A)

Boeing LTA

- LSE42, LSE102, LSE190
- >$3.5 Million awarded
- ViaSat-3 Americas & EMEA, GiSat

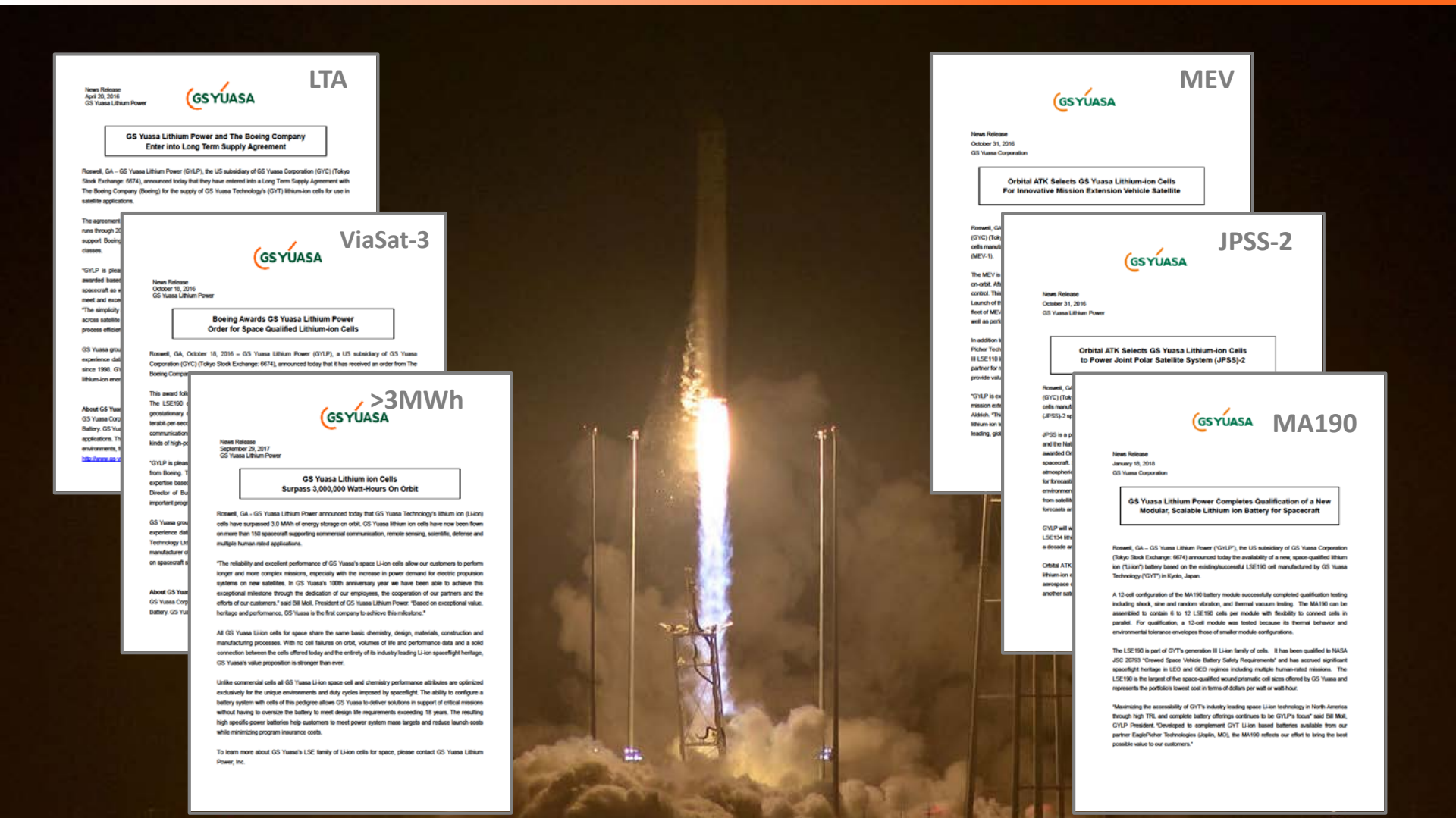
Other Govt. Programs

- LSE Gen. III cells selected for flight vehicles
- $7 Million in contracts awarded

GYLP In The News

http://www.gsyuasa-lp.com/

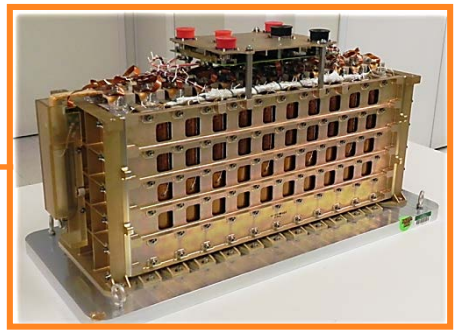
Powering the Next Generation



GS Yuasa Modular Space Battery Overview and Qualification Test Summary

EaglePicher™ Technologies, LLC
A VECTRA Company

GS YUASA



EPT part no.: SAR-10199
electrical config.: 1P9S
spaceflight heritage: 7 yrs

EPT part no.: SAR-10197
electrical config.: 2P9S
spaceflight heritage: 8 years

EPT part no.: SAR-10213
electrical config.: 2P9S
2018 launch

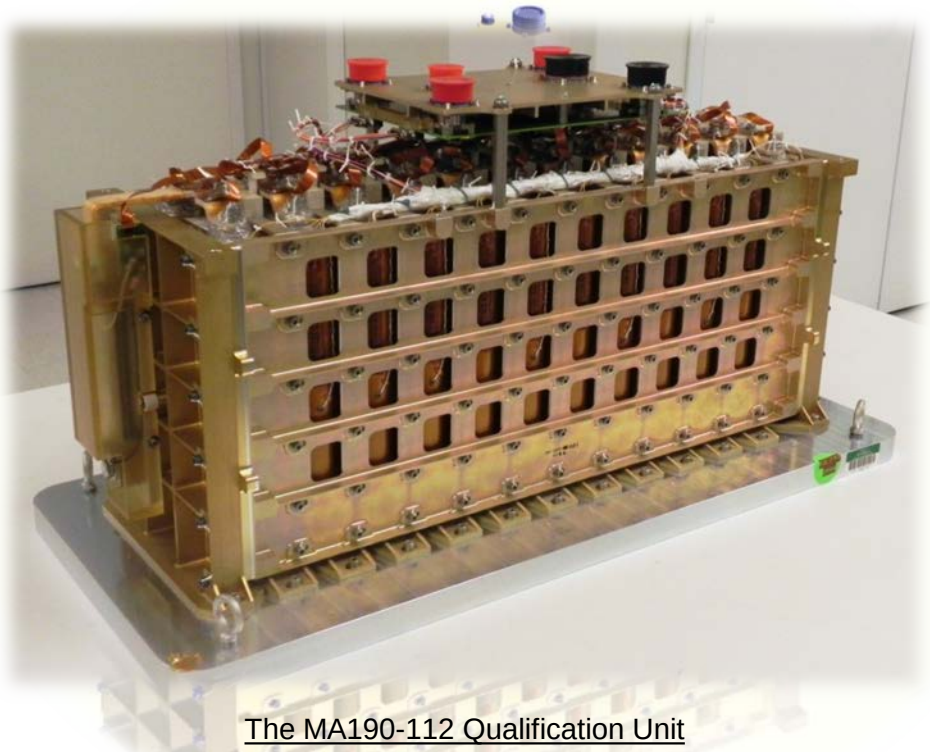
EPT part no.: SAR-10209
electrical config.: 1P8S
2017 launch

EPT Spaceflight Heritage with GS Yuasa cells: 26 batteries

Designs may be modified to meet customer specific requirements without invalidating qualification history.

MA190 Modular Battery

- The MA190 module is a scalable and configurable cell pack based on GS Yuasa's LSE190 Li-ion cell
- Modules may each contain between 6 and 12 LSE190 cells
- Cells may be electrically connected in series (1P), 2P or 3P yielding 190, 380 and 570Ah respectively
- A 12 cell, 1P battery module completed qualification testing in 2017



The MA190-112 Qualification Unit

MA190 Module Configuration Numbering

Modular Aerospace Battery

MA 190 - 1 12

LSE190 Li-ion cell: 1

Cells in parallel: 2, 3

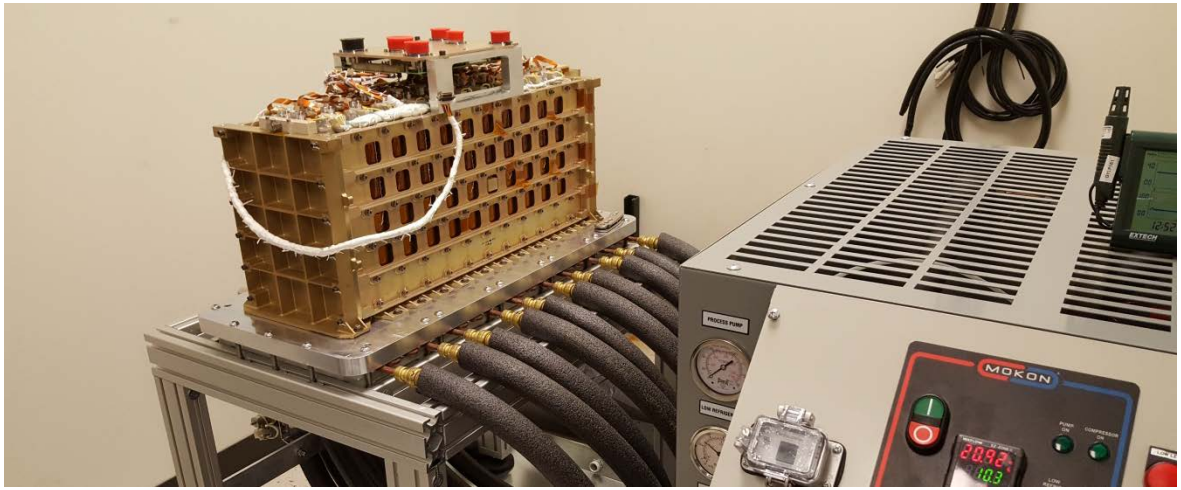
Cells per module: 6, 7, 8, 9, 10, 11, 12

Available Configurations

-106
-107
-108
-109
-110
-111
-112
-206
-208
-210
-212
-306
-309
-312

MA190-112 Qualification Unit

- Qualification Unit
  - → 1P12S Configuration
    - Largest modular configuration
    - Most complex wiring
    - Largest connector interface
      - o Connector Plate placed in worst case location for dynamic testing
  - → 12 cells selected from multiple production lots
    - All flight qualified production units
  - → Successfully completed environmental qualification
  - → Plan to start long-term cycling test on cold plate Q2 2018



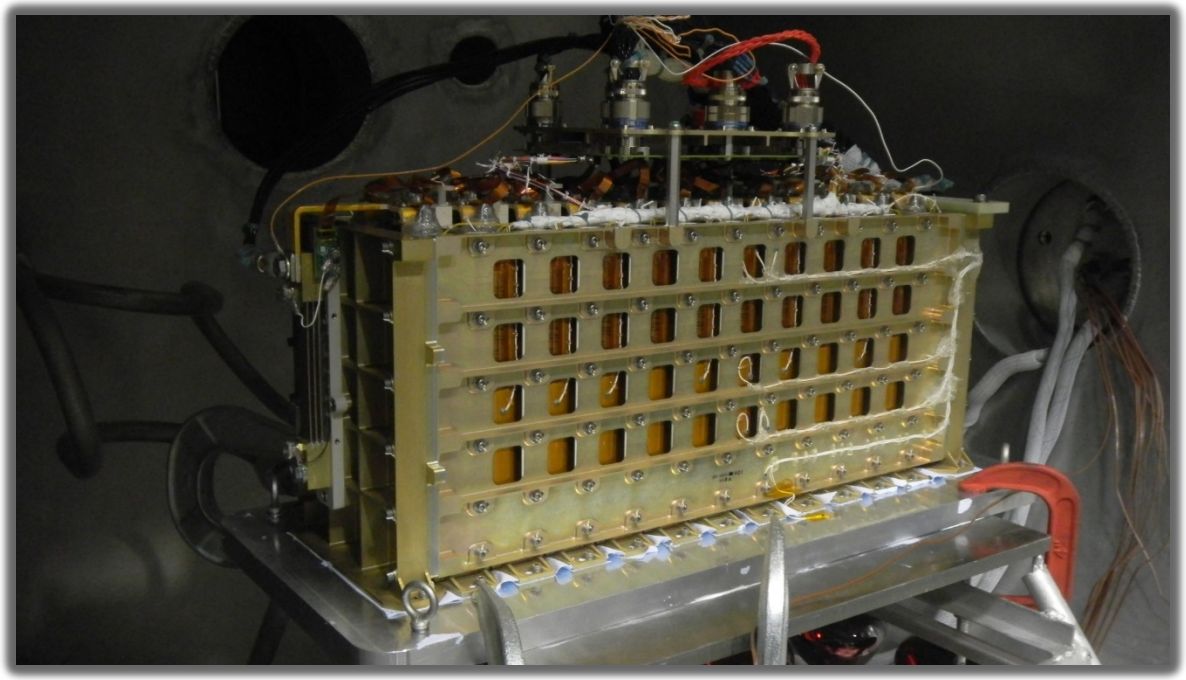
MA190-112 Qualification Unit

The qualification model built from spare flight cells.

- 4 different lots
- activation dates ranging from 07/2012 to 10/2015

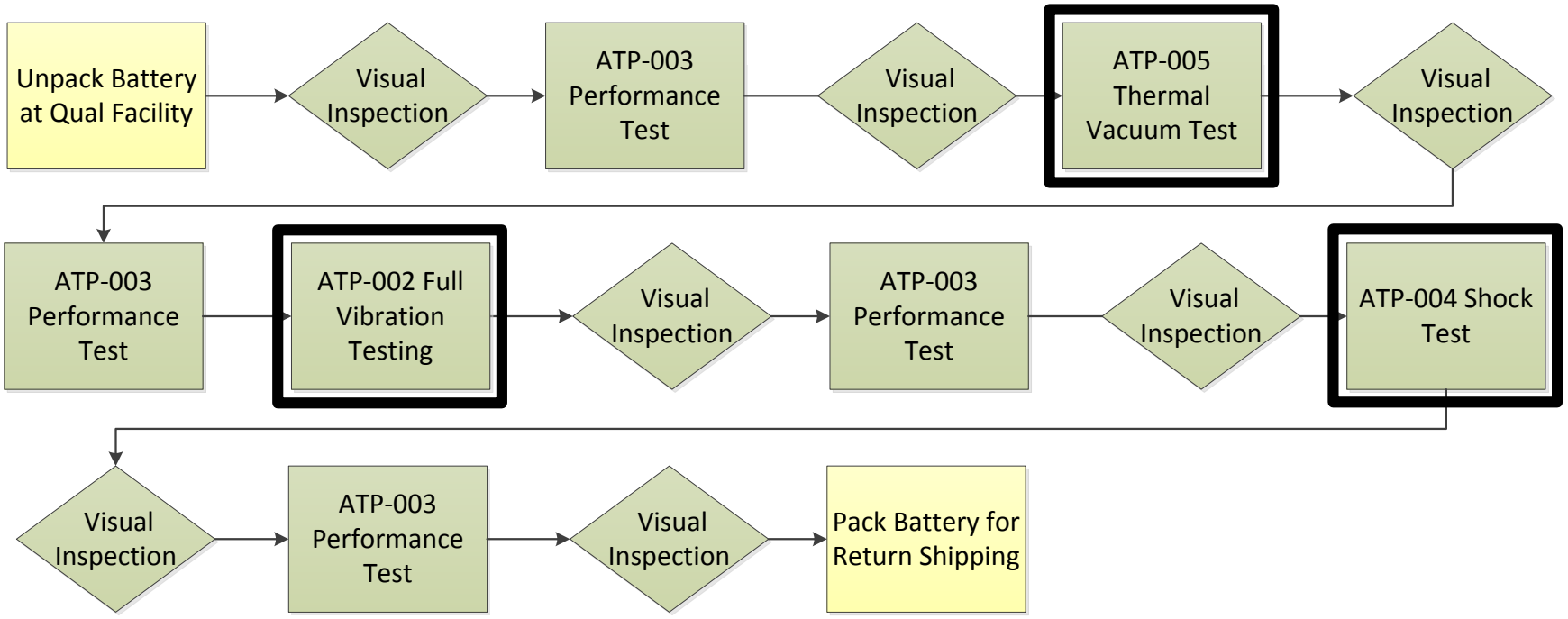
Cell Position #	Cell SN	Lot#	Cell Activation Date
1	323	Lot009	10.2015
2	317	Lot009	10.2015
3	318	Lot009	10.2015
4	308	Lot008	05.2013
5	249	Lot006	09.2012
6	218	Lot005	07.2012
7	245	Lot006	09.2012
8	286	Lot008	05.2013
9	319	Lot009	10.2015
10	316	Lot009	10.2015
11	320	Lot009	10.2015
12	321	Lot009	10.2015

MA190-112 1P12S Environmental Test Summary



MA190-112 QUALIFICATION UNIT

Battery Environmental Qualification Test Flow

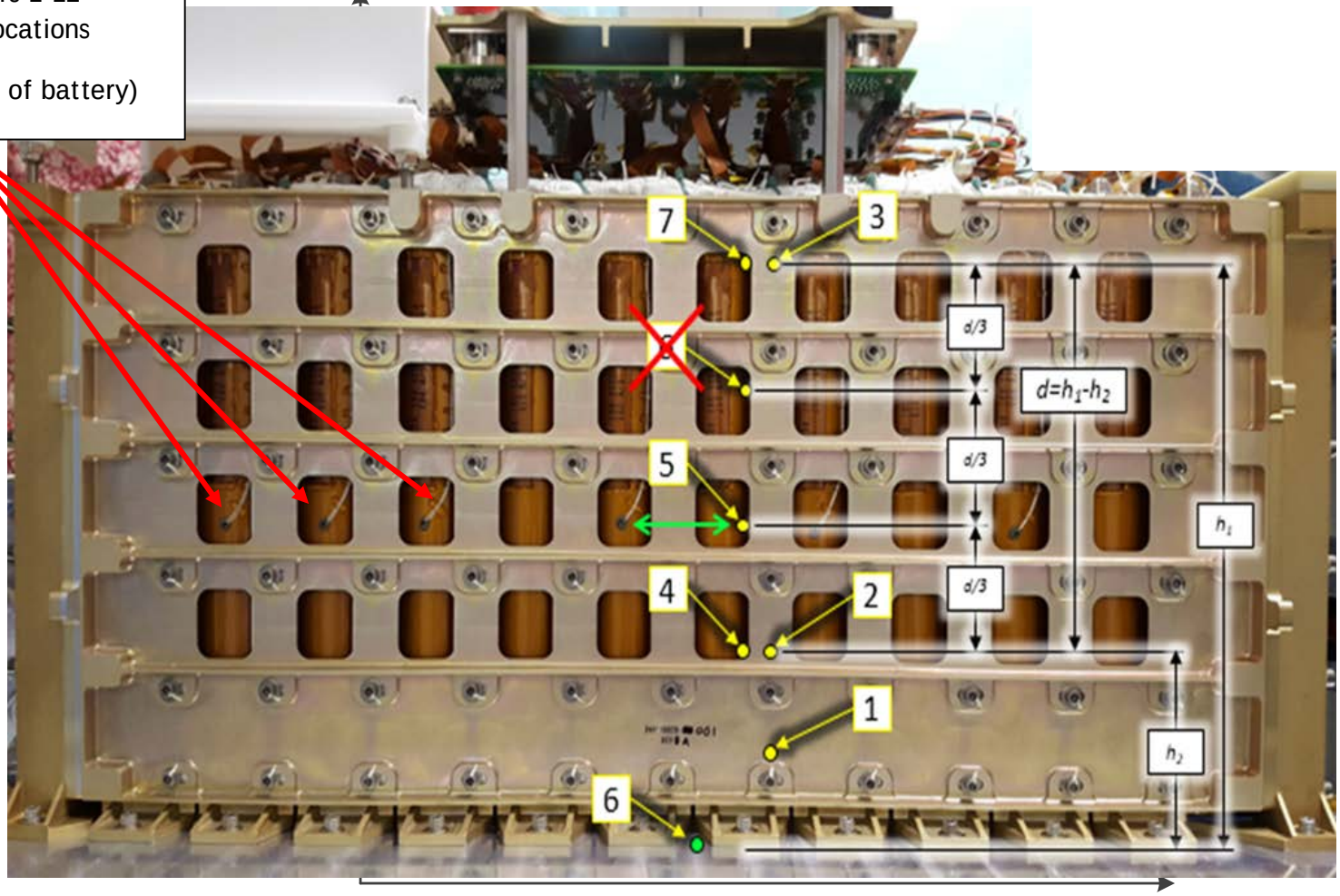


Battery Qualification: Thermal Vacuum Test

Full Hot Performance Test: 30°C environment, 126A (2/3C) discharge, 100%DOD

Cell Thermistors 1-12
approximate locations

(on both sides of battery)

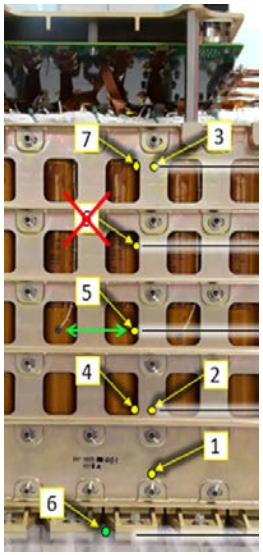


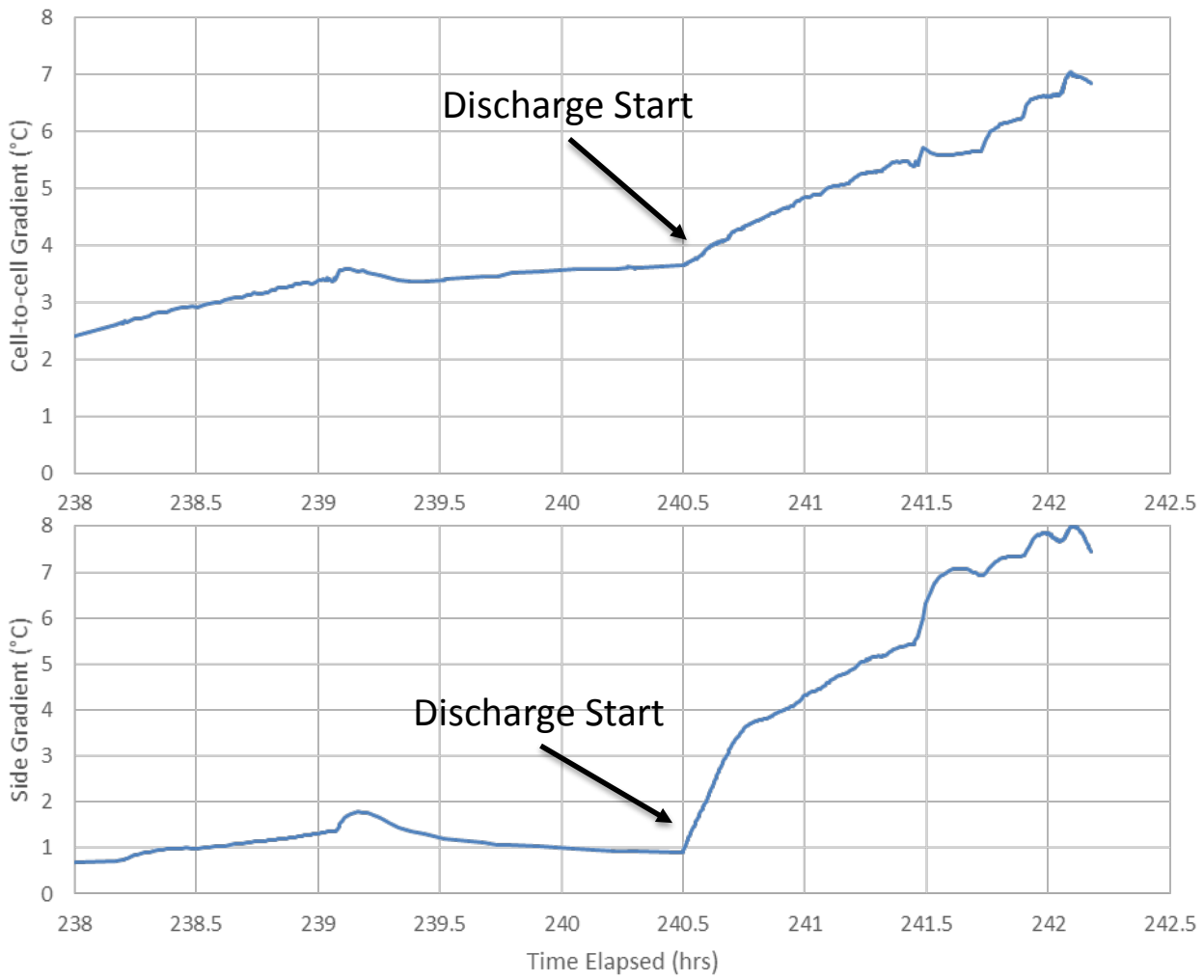
Battery Qualification: Thermal Vacuum Test

Full Hot Performance Test: 30°C environment, 126A discharge 100%DOD

Requirement: cell temperature gradients may not exceed 10 °C

Cell-to-Cell Gradient	7.0 °C
Top-to-bottom Cell Gradient	8.0 °C





Environmental Test Summary

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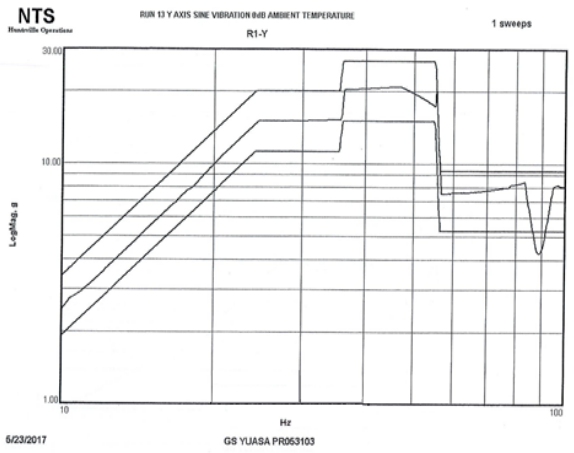
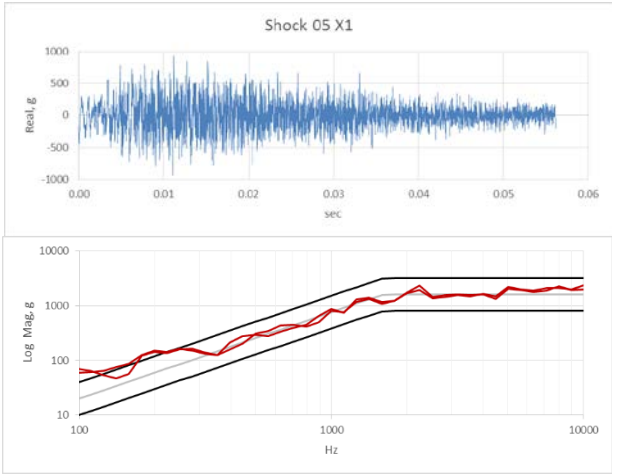
Sine Vibe

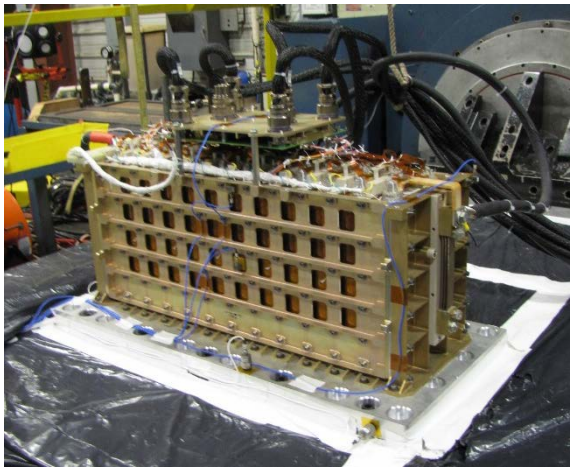


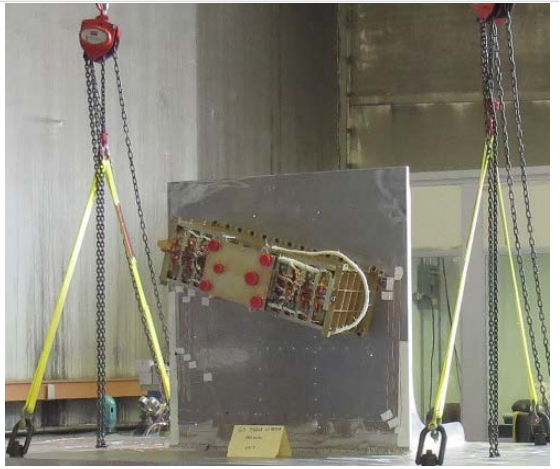
Random Vibe

- Primary modal response of the battery:
  X: 550 Hz
  Y: 242 Hz
  Z: 212 Hz

Shock







Capacity Retention Summary

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Date	Step	Capacity (Ah)	AC Impedance (mOhm)	Temperature
01/31/2017	Battery pre-ship to NTS	**200.83**	10.920	+15 °C
02/23/2017	Battery as received at NTS	201.39	11.216	Ambient
03/08/2017	full performance, cold	189.395	n/a	-5 °C
03/09/2017	full performance, model validation	197.663	n/a	+10 °C
03/09/2017	full performance, hot	201.093	n/a	+30 °C
03/09/2017	post t-vac	200.69	11.356	Ambient
03/31/2017	post vibe	200.07	12.805	Ambient
04/26/2017	post shock	199.89	12.153	Ambient
05/24/2017	final (post sine retest)	**198.1**2	13.896	Ambient

Cell Life Cycle Testing and Performance Modeling

The GS Yuasa Capacity and Voltage Retention Model is an internally developed tool for predicting cell performance in a variety of ground and dynamic on-orbit usage profiles.

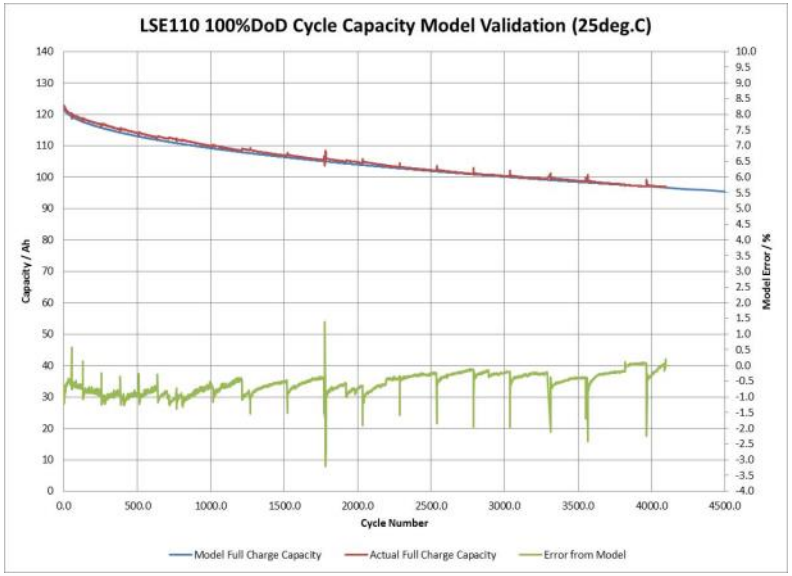
The model is based on the empirical life testing data accumulated by GS Yuasa over the past 15 years.

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

→ Full Charge Capacity

→ On-Orbit Capacity

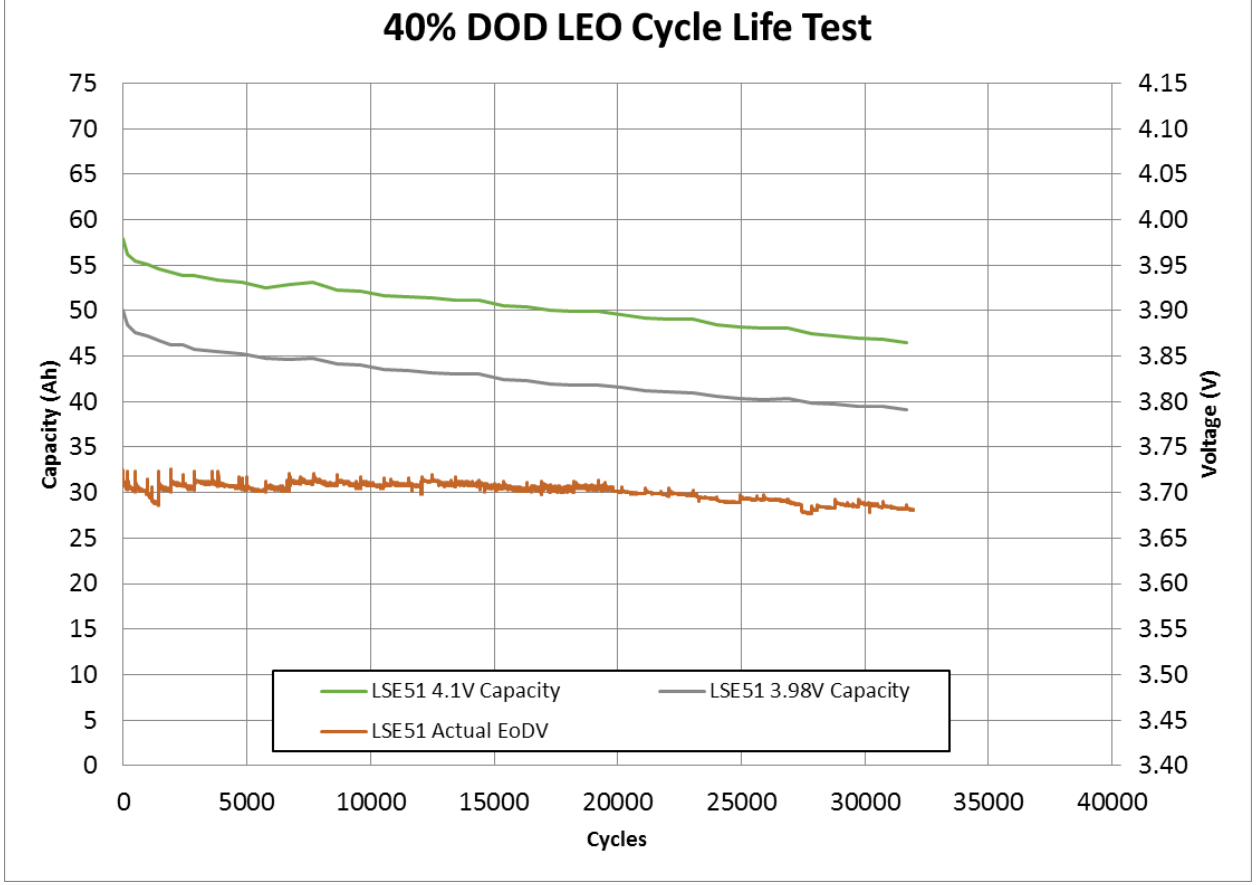
→ End of Discharge Voltage



See Reference:
2014 Space Power Workshop

40% DOD LEO Cycle

Test Name	Cell Type	Test Conditions						Ambient Test Temp	Start Date	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition					
		EoCV	Rate	Time	EoDV	Rate	Time			
40%DoD Cycling	LSE51	3.98V	25.5A	1hr	(3.40V)	40.8	0.5hr	20°C	9/28/2009	Deep DoD LEO Cycle



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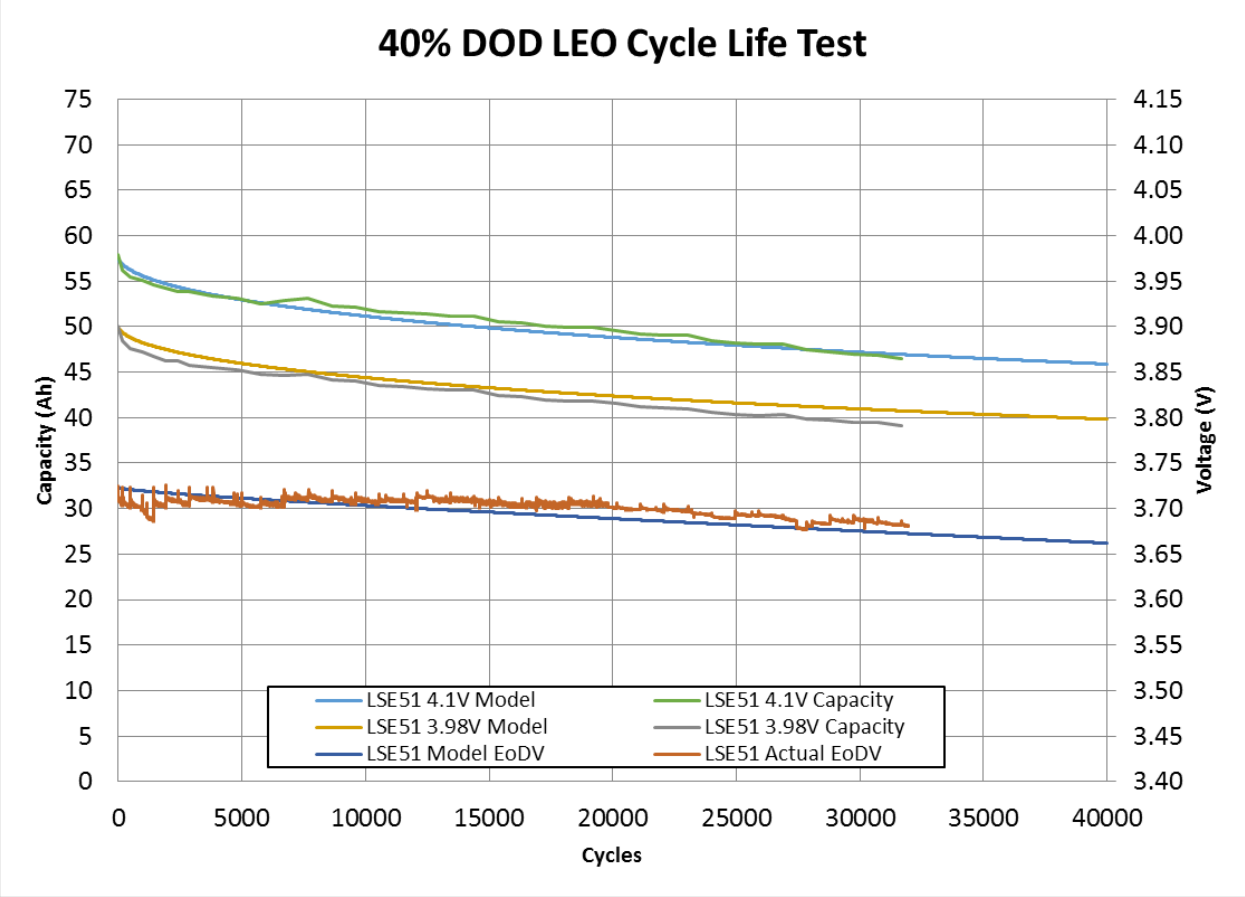
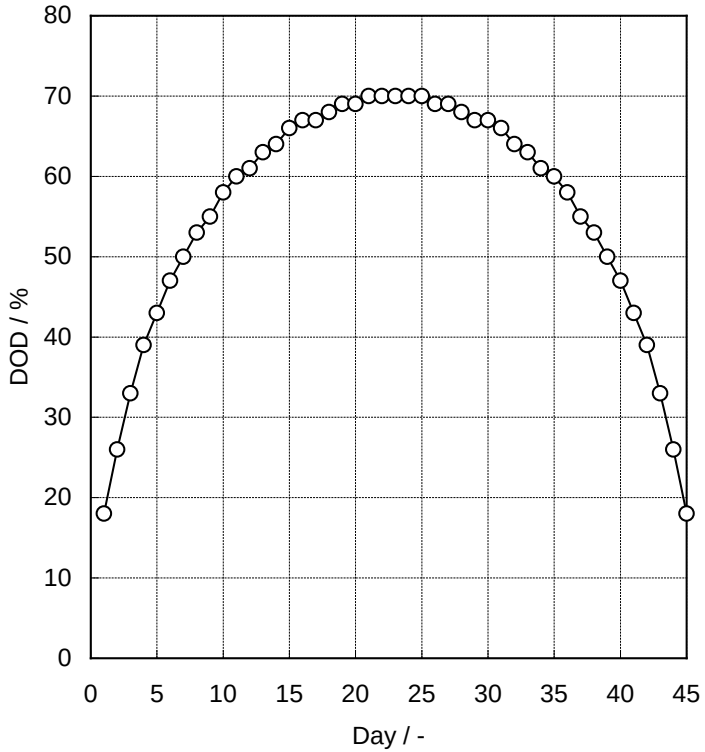


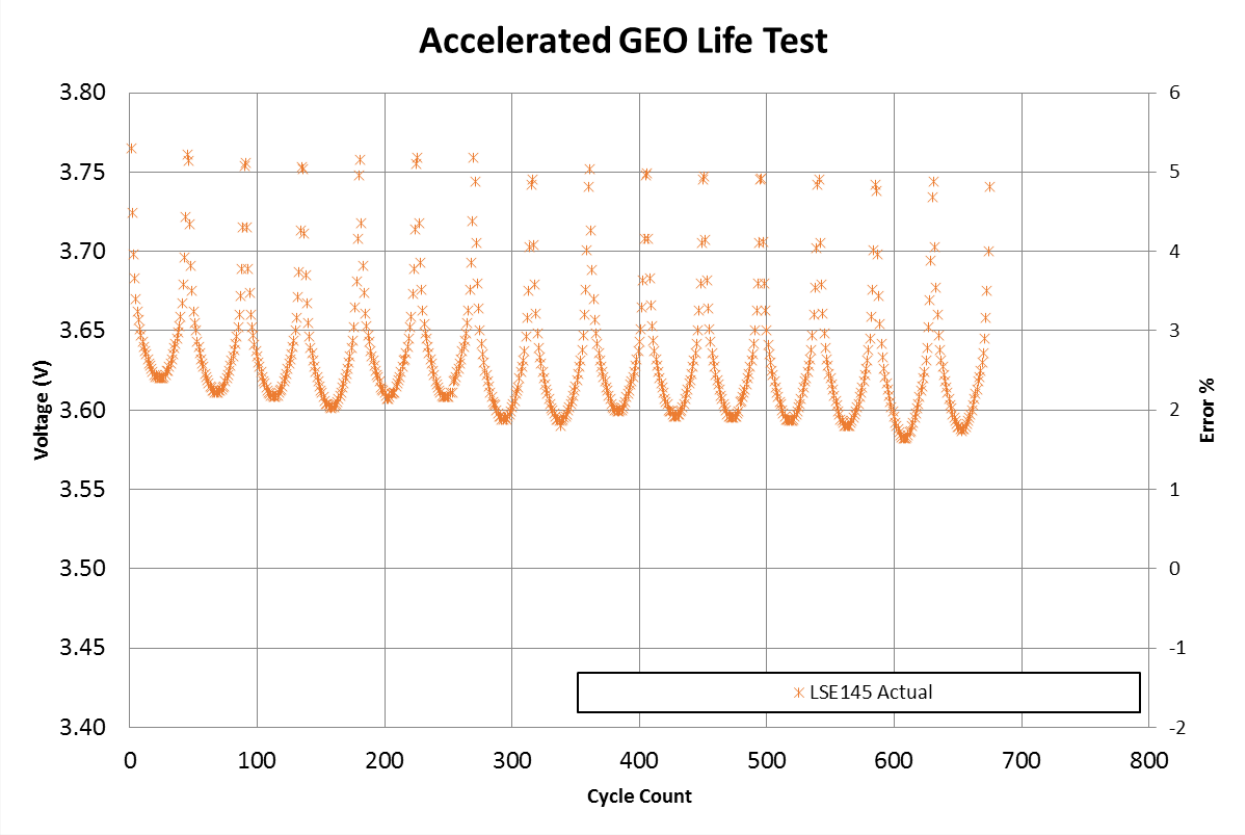
Semi-accelerated GEO Life Cycle Test

Cell	Solstice Season	Eclipse Season
LSE145 **Energy Type** **Gen. 3 cell**	**SOC: ~90% (4.0VEOCV)** **Temperature: 25°C** **Duration 69days**	**1 cycle per day for 45 days** **Charge: 0.1C(14.5A),** **Duration: 24h-discharge time** **Discharge: 0.595C (86.3A)** **Min duration: 18.15min, Max Duration: 70.5m (see chart)** **Temperature: 10°C**



Semi-accelerated GEO Life Cycle Test

Test Name	Cell Type	Test Conditions						Ambient Test Temp	Start Date	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition					
		EoCV	Rate	Time	EoDV	Rate	Time			
Semi-Accelerated GEO Cycle	LSE145	4.00V	14.5A	22.83hr	(3.40V)	86.3A	Varies	10°C	10/2009	60 day solstice season 25°C 45day eclipse season



Semi-accelerated GEO Life Cycle Test

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Test Name	Cell Type	Test Conditions						Ambient Test Temp	Start Date	Remark
		Charge Condition (CCCV unless noted)			Discharge Condition					
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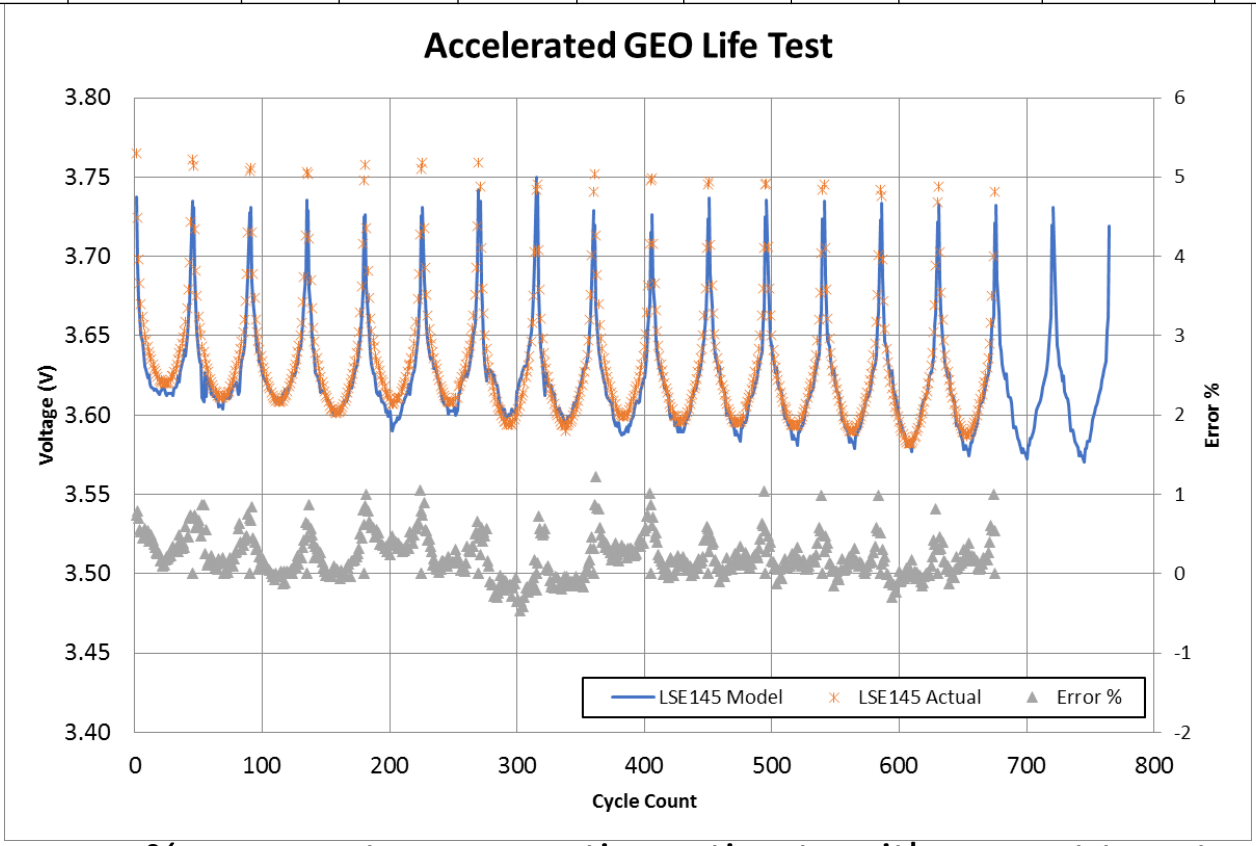


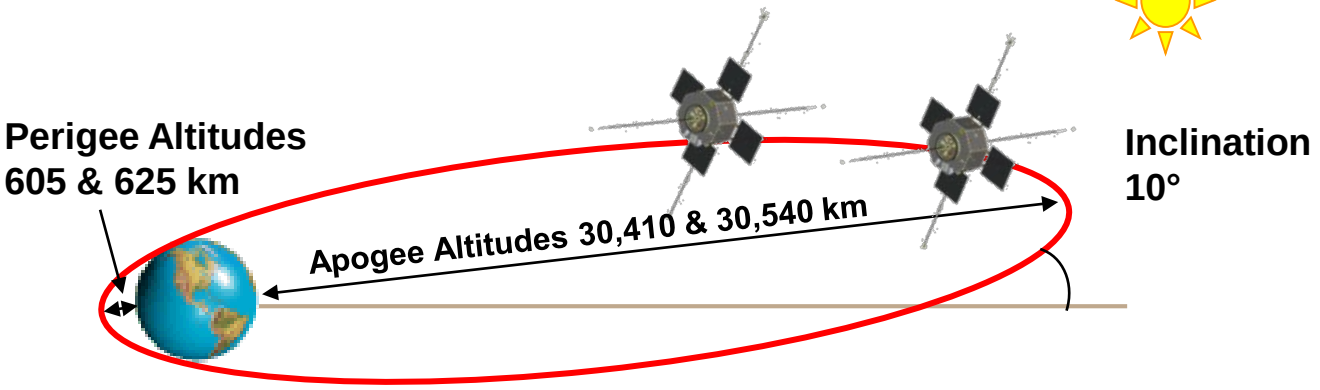
Positive error % represents conservative estimate with respect to actual data

John Hopkins University Applied Physics Laboratory (JHU/APL) has shared on-orbit battery performance data collected from their twin Van Allen Probe spacecraft.

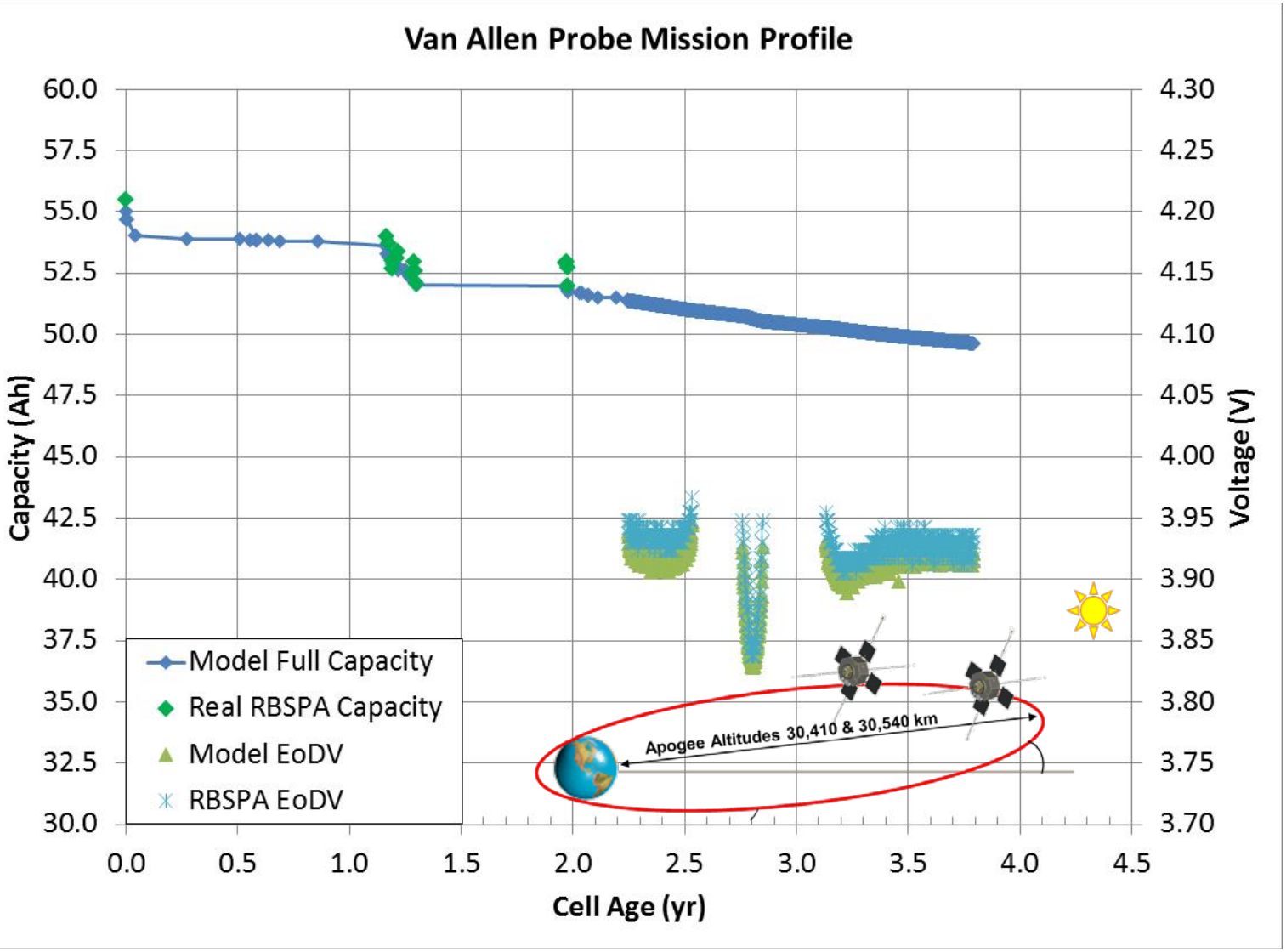
→ Powered by GS Yuasa Generation 2 LSE50 (50Ah, 3.7V) cells

→ Satellites launched August 30, 2012

Using the ground experience and orbit profile GYLP will model the mission and verify the End of Discharge Voltage results to those collected on-orbit.



Spacecraft A Full Profile to Date



Very high confidence in the ability to predict cell (and battery) performance when provided the relevant use case inputs.

38

- For a given set of mission parameters, what is the maximum continuous power an LSE cell can provide for an entire mission?

Mission Duration	4.1V/cell Power (W)
15year	???
18year	???
20year	???

→ Using the GS Yuasa Life and Performance model in an iterative fashion, this can be estimated!

- Additional mission assumptions:
  - BOL capacity 198Ah (minimum guaranteed activated capacity, 205Ah nominal)
  - Maximum EOCV 4.1V/cell
  - EoDV >3.6V/cell
  - Eclipse cycle discharge Ah cannot exceed 80% of cell's actual remaining capacity

- All that's needed is a set of mission parameters

Notional 18year On-orbit GEO Mission

What is the maximum power an LSE190 can provide in a GEO application for 18 years:

- Battery manf. & ground activity

  → ~5.6yr duration

  - Duration and usage assumptions leading to higher capacity losses

- LSE190 Energy Type Cell

  → 18 year on-orbit (36 seasons)

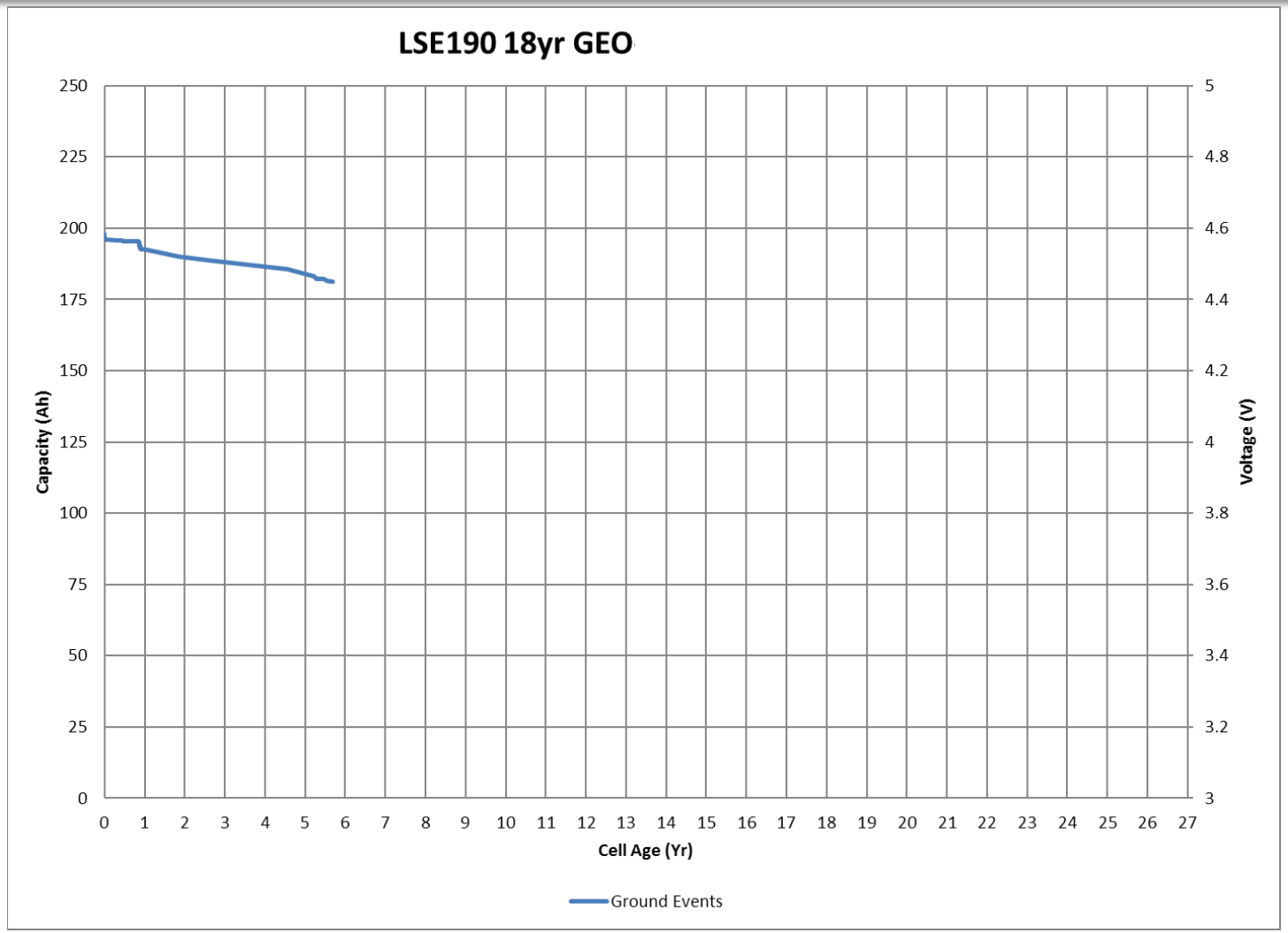
  → Eclipse conditions:

  - 45 day period with max duration of 70min.
  - Temperature: 10°C

  → Solstice conditions: 60%SOC @10°C

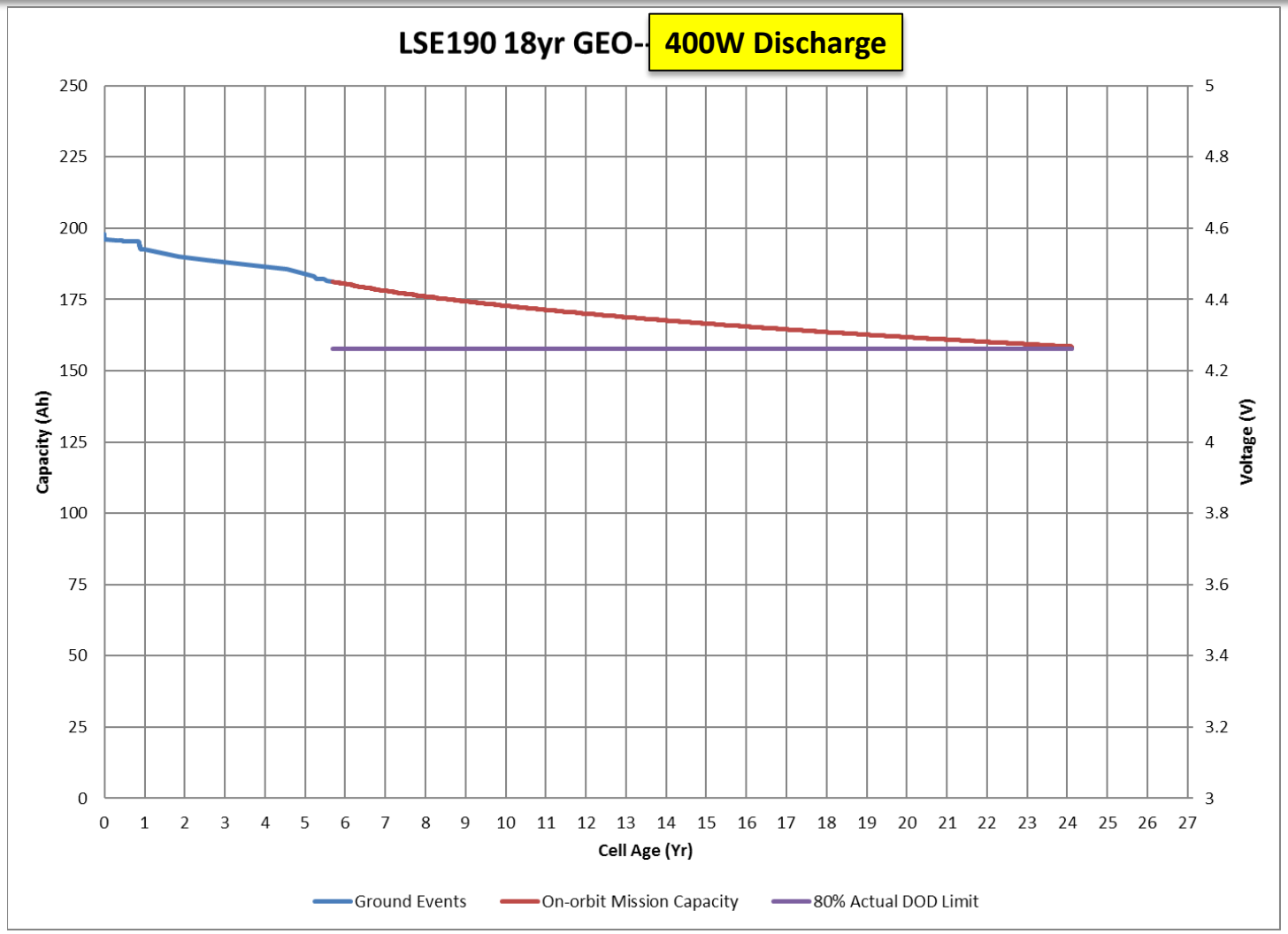
  → NSSK cycles: 60 min discharge at TBD spacecraft power level 5 times per week.

18year GEO mission, maximum power



Event	Capacity (Ah)
Activation	198
Ground Events (5.6yr)	181.3
End of mission	TBD Ah

18year GEO mission, maximum power



Event	Capacity (Ah)
Activation	198
Ground Events (5.6yr)	181.3
End of mission	158.5 Ah

At 400W/cell (~108A) spacecraft power, Capacity retention approaches the 80% max DOD after 18years on orbit

108A*70/60=126Ah

126/158.5=79.4%DOD

18year GEO mission, maximum power

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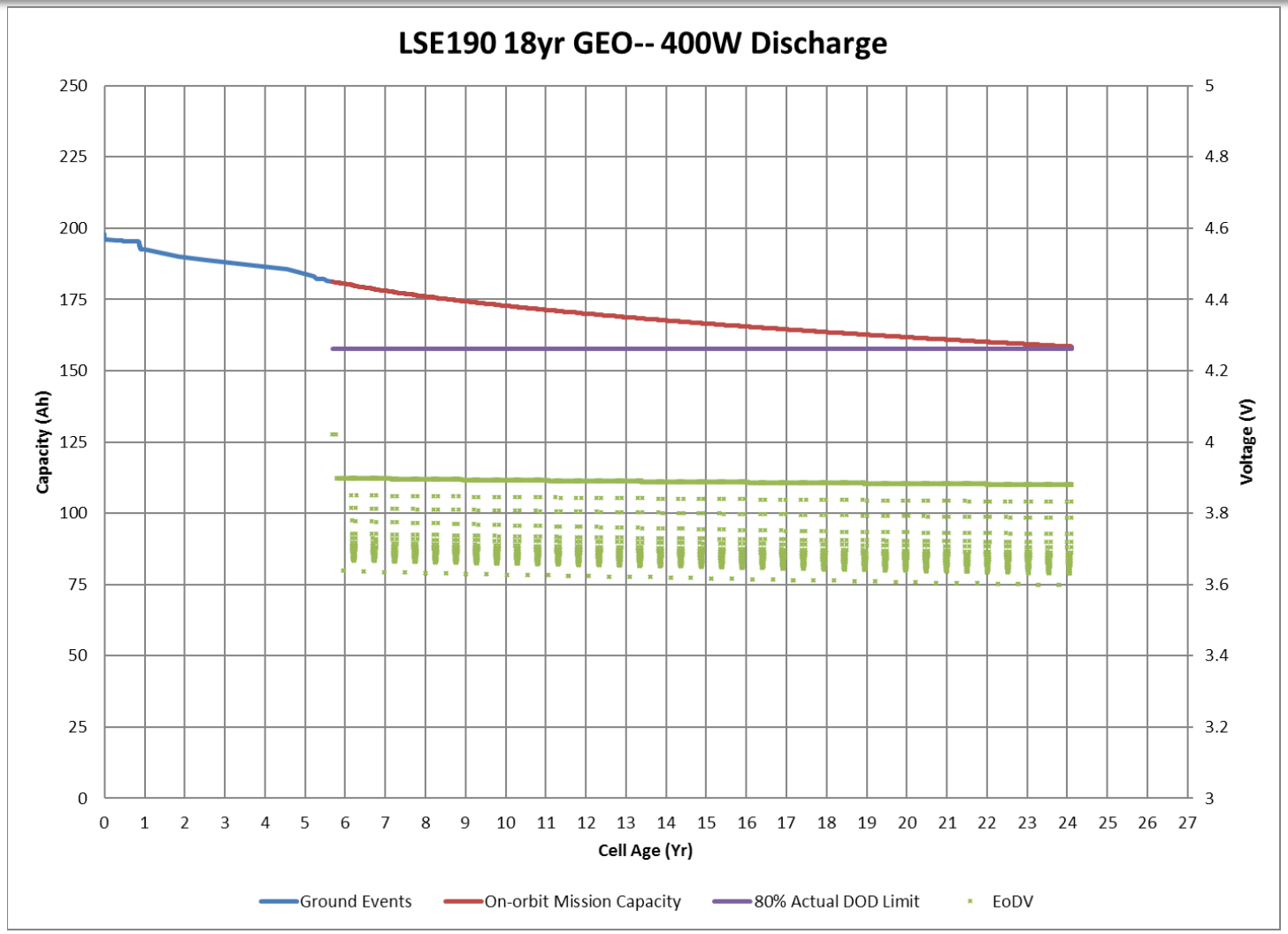

Event	Capacity (Ah)
Activation	198
Ground Events (5.6yr)	181.3
End of mission	158.5 Ah

EoDV does not violate the 3.6V/cell minimum for the life of the mission

3.63V @season 36

NSSK DOD=20.5% of nameplate @400W.

LSE190 GEO Mission Power Support Capability

The powers below represent the GEO eclipse power that yields a maximum real DoD of 80% at the final season max eclipse day

Mission Duration	4.1V/cell EoCV Power/cell (W)	4.2V/cell EoCV** Power/cell (W)
15year	407	435
18year	400	429
20year	395	425

**Cell begins mission at 4.10V and rises to 4.15V and 4.20V when capacity or voltage limit is exceeded

The EoDV below represents the EoDV of the maximum eclipse day in season 30, season 36, and season 40.

Max EoCV	Power (W)	EoDV		
		Season 30	Season 36	Season 40
4.1	395	3.64	3.63	3.63
4.1	400	3.64	3.63	N/A
4.1	407	3.63	N/A	N/A
4.2	425	3.63*	3.64	3.63
4.2	429	3.63*	3.63	N/A
4.2	435	3.64	N/A	N/A

*EoCV of 4.15V

Notional MA19

Battery system ma

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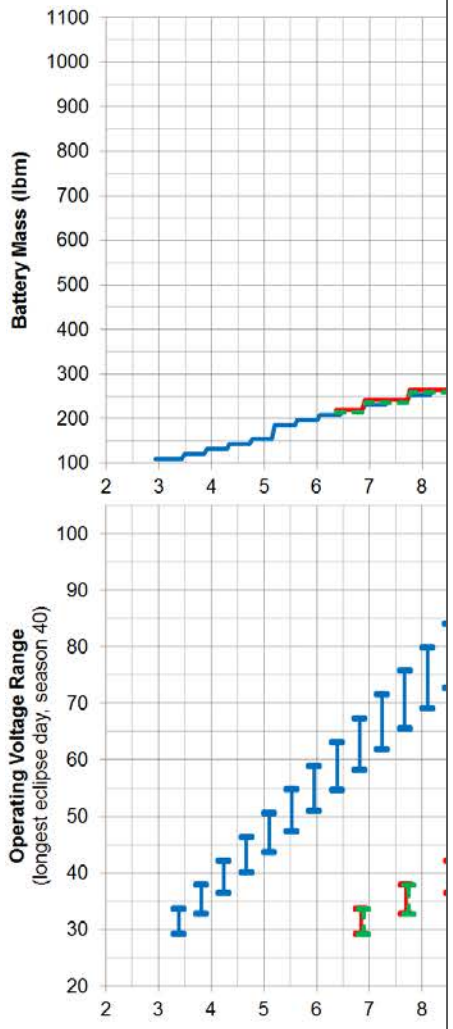
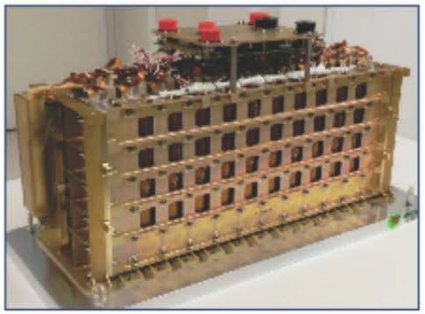


MA190 Modular Lithium Ion Battery For Satellites

The MA190 module is a scalable and configurable cell pack based on GS Yuasa's LSE190 Generation III lithium ion cell.
With a nameplate capacity of 190Ah, the LSE190 cell has significant spaceflight heritage supporting both human rated LEO missions as well as commercial GEO satellites.

MA190 modules may each contain between 6 and 12 LSE190 cells. The cells in a module may be electrically connected in a simple series arrangement, yielding a module rated for 190Ah. Alternatively, two or three cells may be connected first in parallel and then in series yielding 380Ah or 570Ah modules.

The GS Yuasa LSE190 Li-ion Cell



MA190-112 Qualification Model

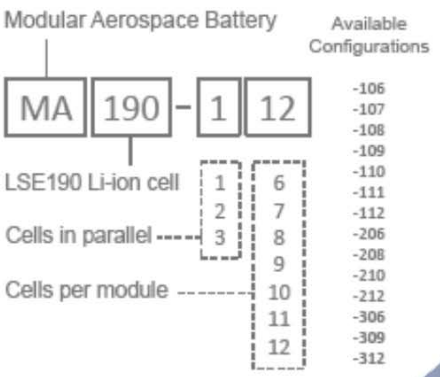
LSE190 Cell Safety Tests (JSC 20793)

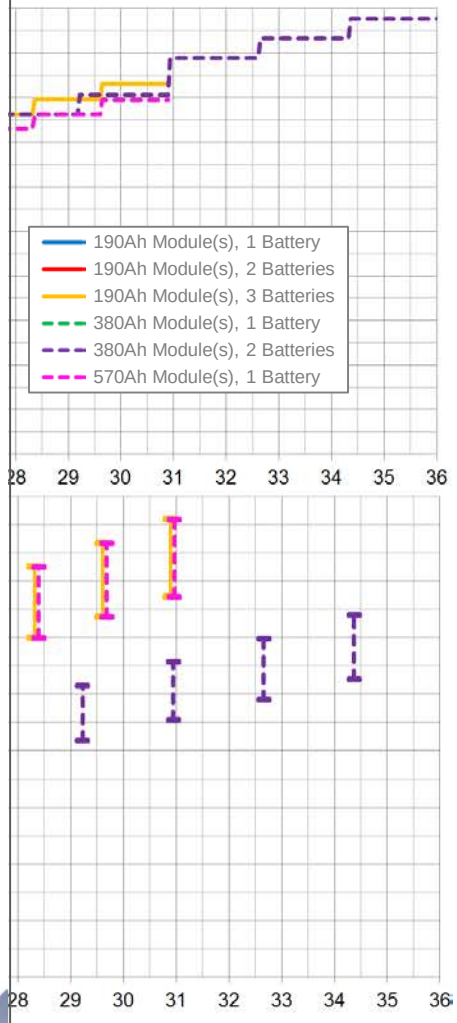
- Over-charge
- Over-discharge (forced reversal)
- External short circuit (2 & 5 milliohm)
- Crush (fresh & seasoned cells)
- Heat to vent
- Three orientation drop
- Vent and burst pressure

MA190 Module Qualification Tests

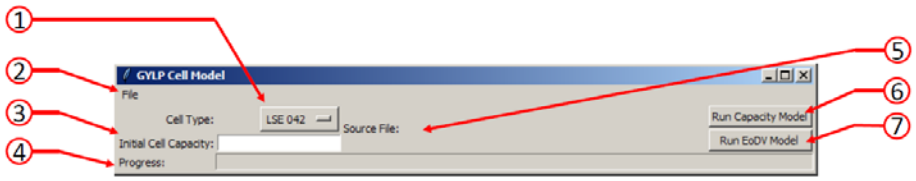
- Sine vibration
- Random Vibration
- Shock
- Thermal vacuum

MA190 Module Configuration Numbering





- GYLP has emulated the GYT model and it can now be provided to users of the LSE Generation 3 Cells.
- Model has been simplified to improve the user experience and consists of the following parts:
  - → Cell Model Input Sheet – An external spreadsheet for describing the steps of the mission. Contains several useful tools to help determine the proper inputs based on your mission criteria.
  - → Cell Capacity and EoDV Retention model.exe – Executable containing the model presented to the user as a GUI.
    - Executable works on Windows OS machines.

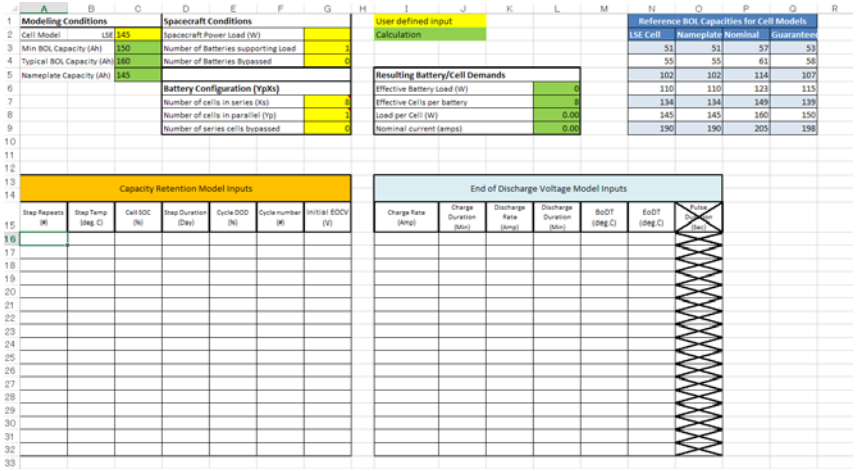


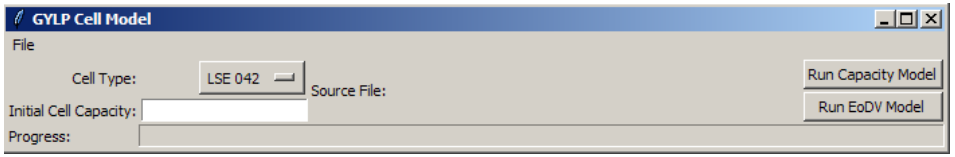
1. Cell Type Dropdown (nameplate capacity)
2. File Selection Dialog
3. Cell Capacity at activation
4. Cell model progress bar
5. Name and location of selected file
6. Capacity retention start button
7. EoDV model start button

After either model is complete, a file explorer window opens allowing the user to save the results in a folder of their choosing.

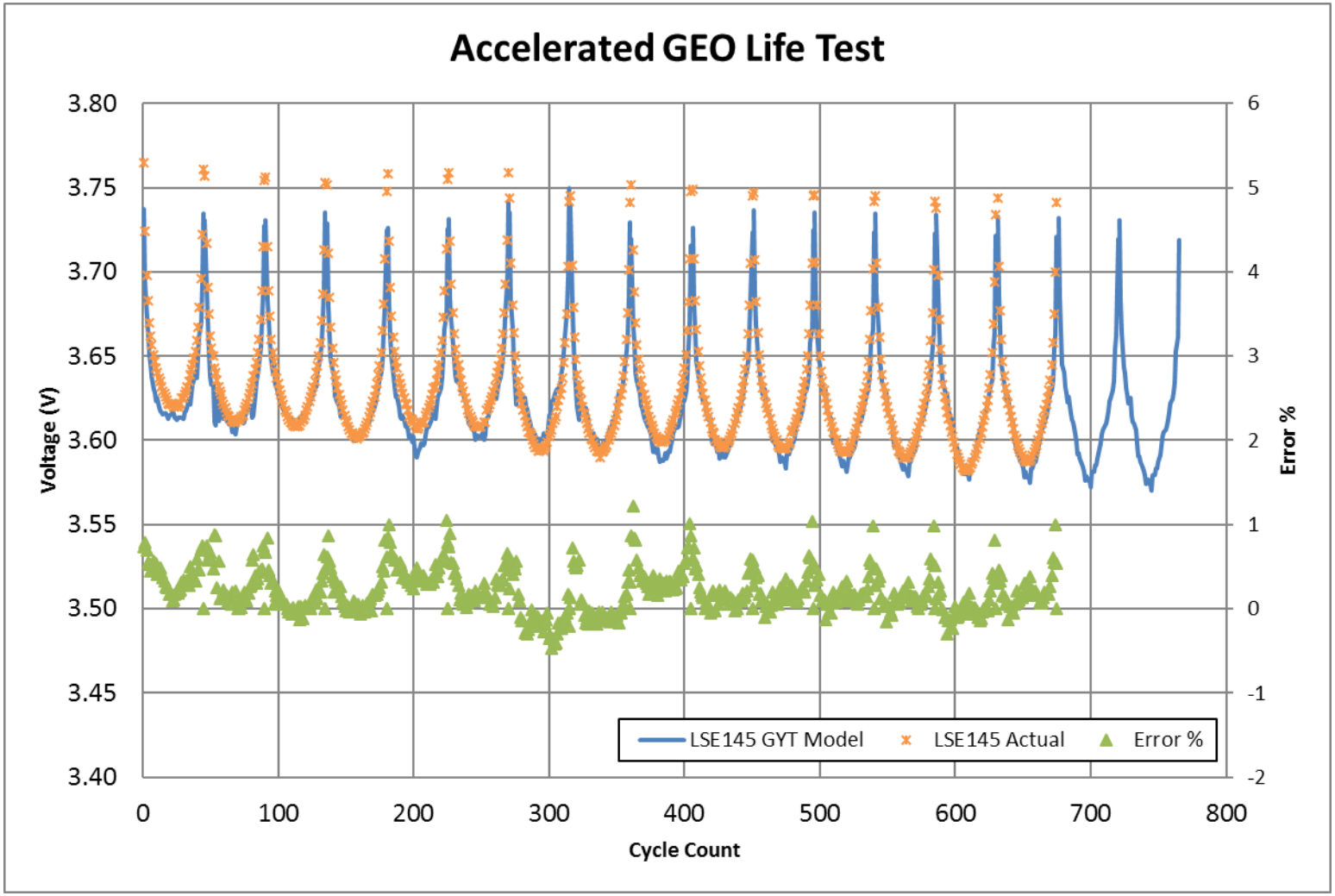
The model is split into two parts: an excel spreadsheet input sheet and a user interface for running the model.

- Mission profile information is entered into the input sheet
- The model interface reads the input sheet and outputs the capacity retention and EoDV information
- The capacity retention model and the end of discharge voltage model are separated to allow workflow flexibility





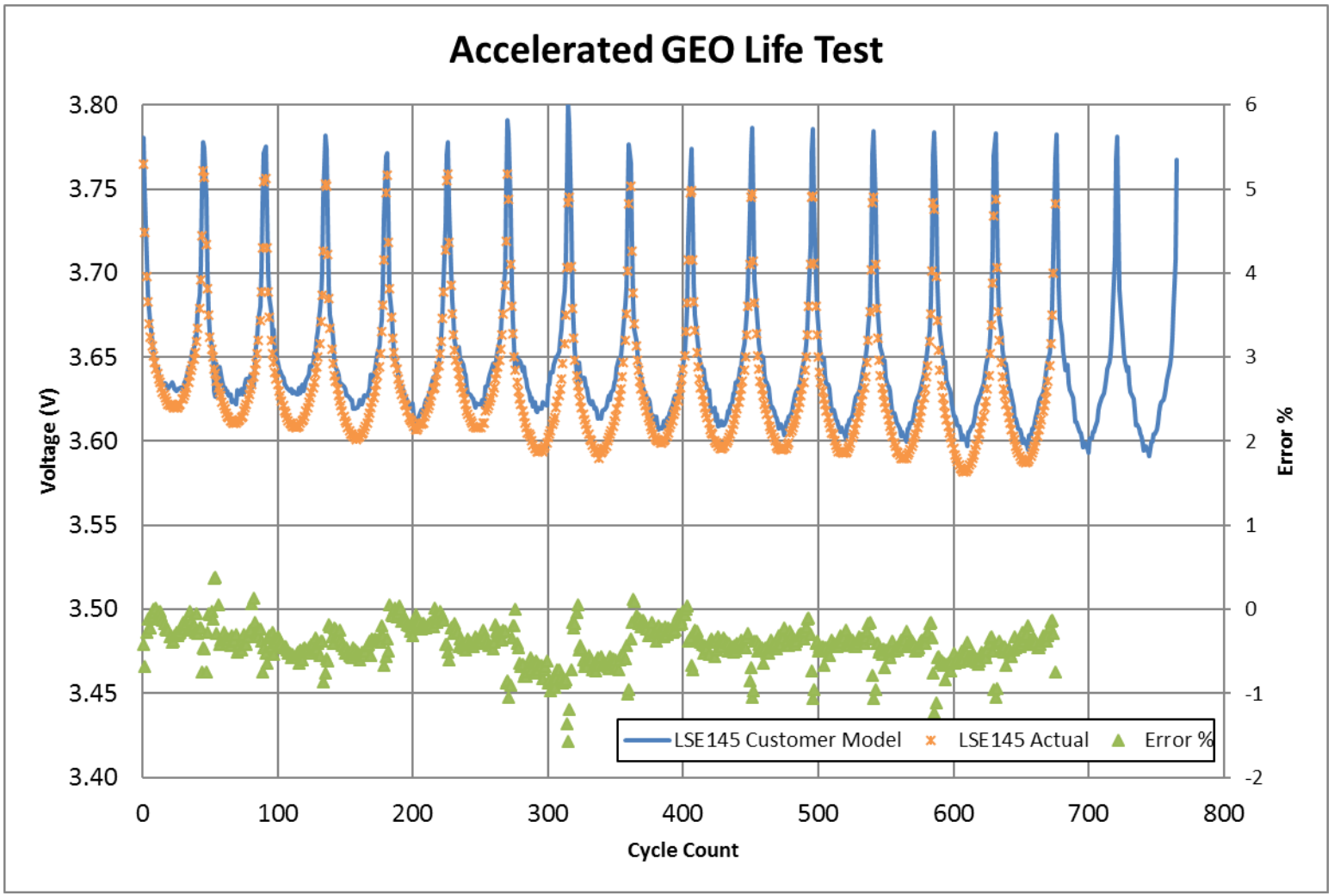
LSE145 Accelerated GEO, GYT Model

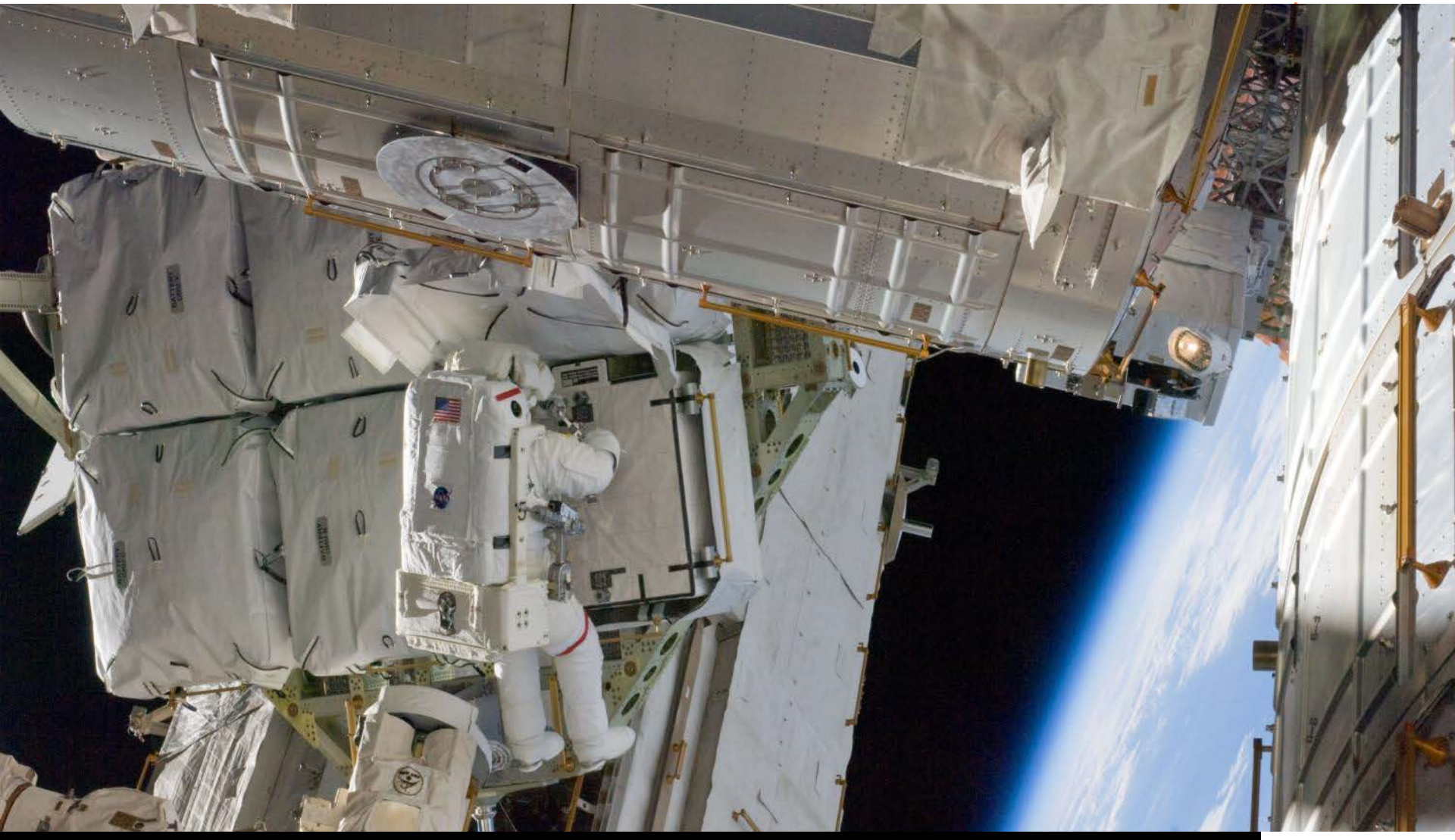


LSE145 Accelerated GEO GYLP Model (Version 1.0)

GS YUASA

Powering the Next Generation





GS YUASA

Industry leading spaceflight heritage
Qualified, high value MA190 battery
Validated and reliable performance modelling
Will support launch vehicle applications