



GOES-R Lithium-Ion Battery Life Test & Workhorse Battery Performance

NASA Aerospace Battery Workshop

2018 November 27-29, Huntsville AL

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Huntsville, AL
Nov. 27-29, 2018*

Outline

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- Life Test Capacity Results
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- Workhorse Battery Performance Summary
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- Conclusions

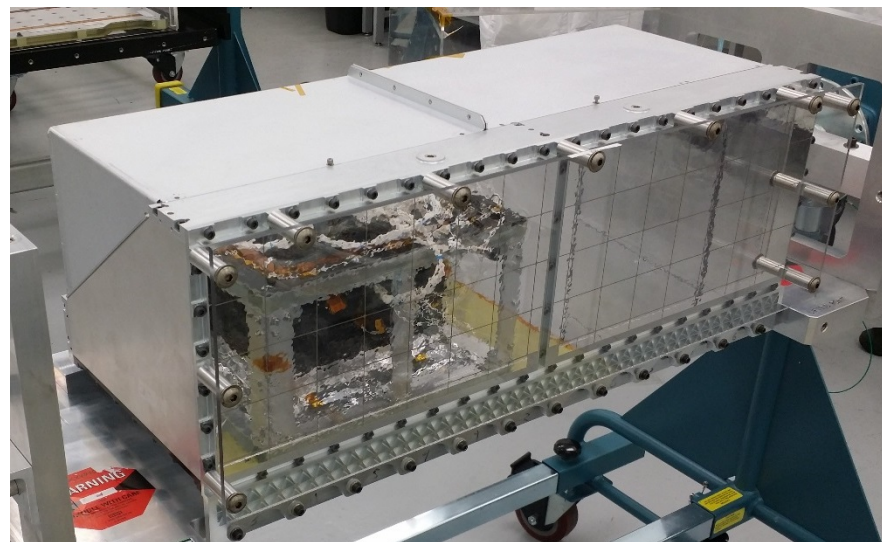
Overview



- Lockheed Martin is under contract to NASA Goddard to design and build four GOES-R series satellites to be operated by NOAA.
 - GOES-R is the next-generation geostationary NOAA weather satellite
 - <https://www.goes-r.gov/>
- Saft's Space & Defense Division provides the VL48E cells and the GOES-R series lithium-ion batteries to Lockheed Martin.
- GOES-R series battery life testing is in process at Lockheed Martin.
- 20 accelerated GEO seasons have been completed.
 - 20 seasons represents 10 years of on-orbit operation.
- A GOES-R series qualification & I&T workhorse battery were built and supported spacecraft-level testing since 2014.
- The GOES-R series life test battery and workhorse batteries' performance will be presented.

Life Test Battery Characteristics

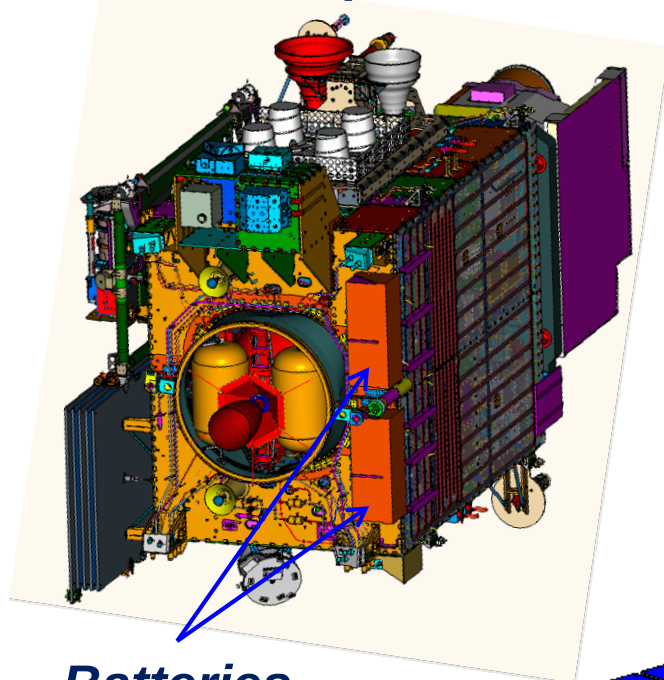
- Battery designed and manufactured by Saft in Cockeysville, Maryland.
- Life test battery built to flight drawings and processes.
 - Battery acceptance test performed 2014 Feb - Jun
- VL48E cells
 - Rated capacity (C_r) = 45.4 Ah at 20° C
 - C_r = required BOL capacity from 4.1 V to 3.0 V at $C_n/2hr$
 - Cells formed in 2011 Mar
- Electrical Configuration
 - 3 cells in parallel to form a cell bank
 - 12 cell banks in series to form a battery
 - Balancing circuits under FSW control apply current as needed to individual cell banks
 - Nameplate capacity (C_{bn}) = 113.5 Ah
 - Rated capacity (C_{br}) = 136.2 Ah at 20° C
- Mechanical configuration
 - 3 cells in a module; 12 modules in a battery
 - Thermistors, heaters, and radiator for thermal control
 - Isolated aluminum housing to protect against shorts and to enclose possible cell failures



Fully Assembled Battery
(with non-flight radiator shield attached)

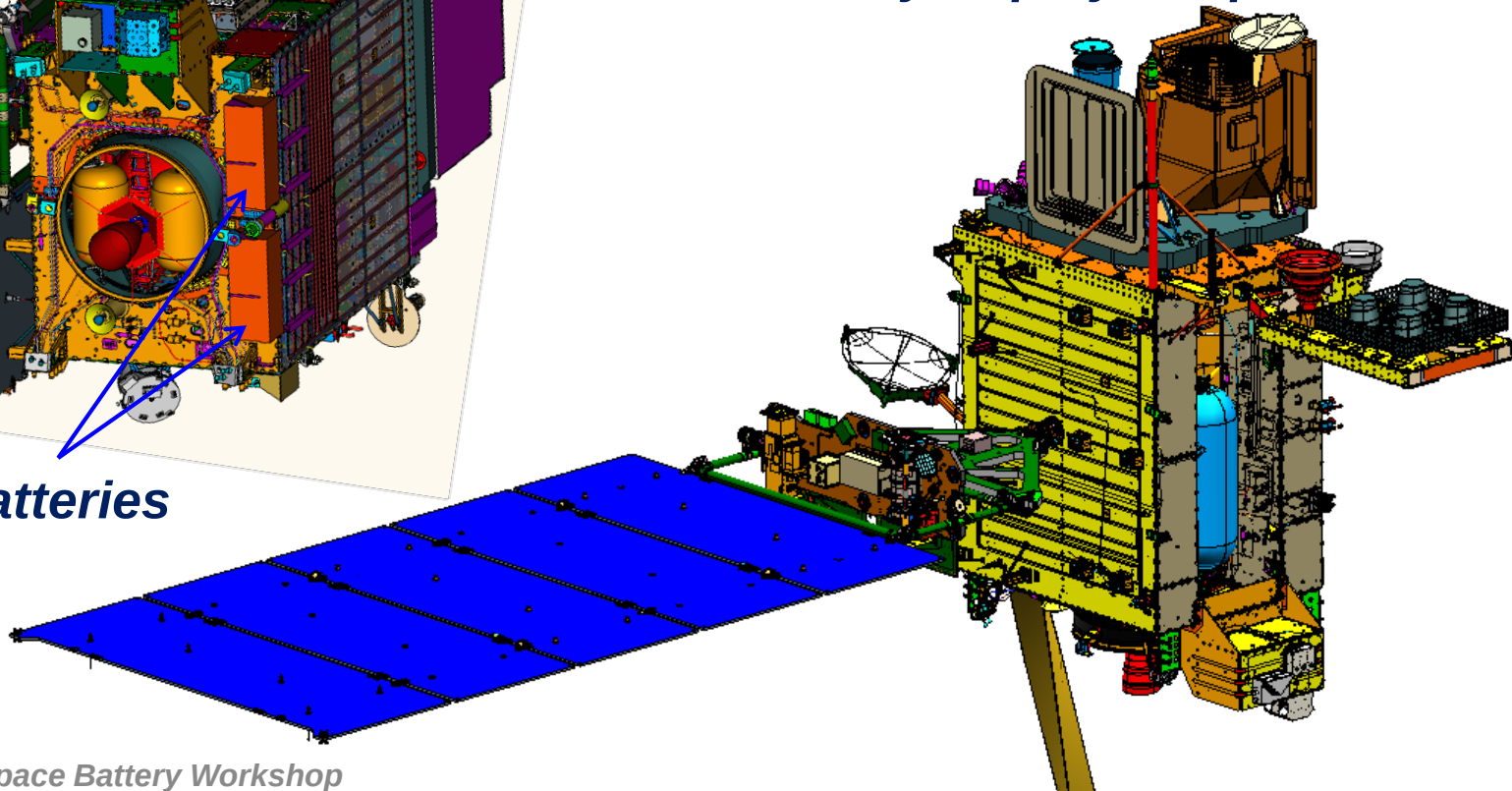
Battery Locations

Stowed Spacecraft

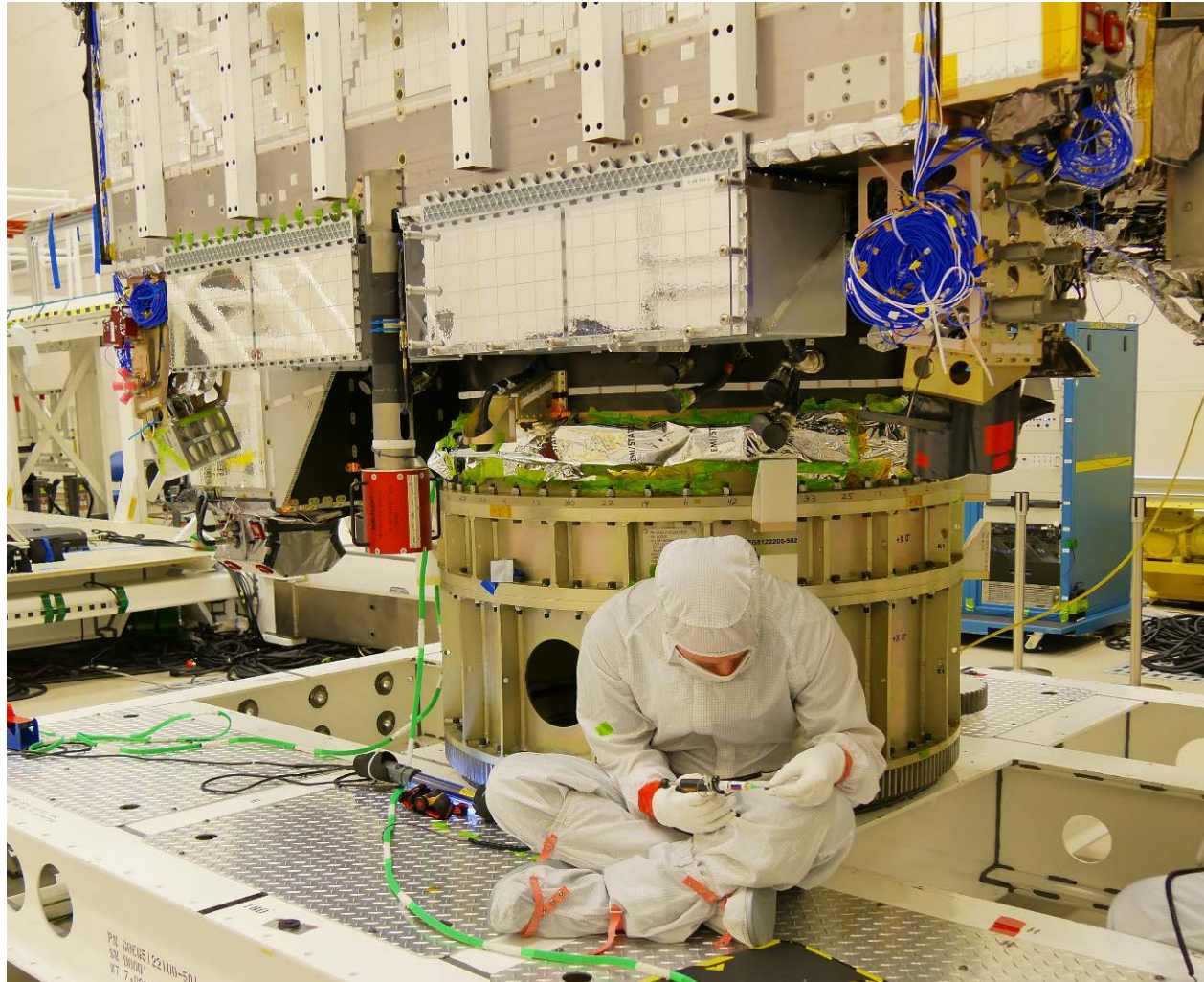


Batteries

Fully Deployed Spacecraft

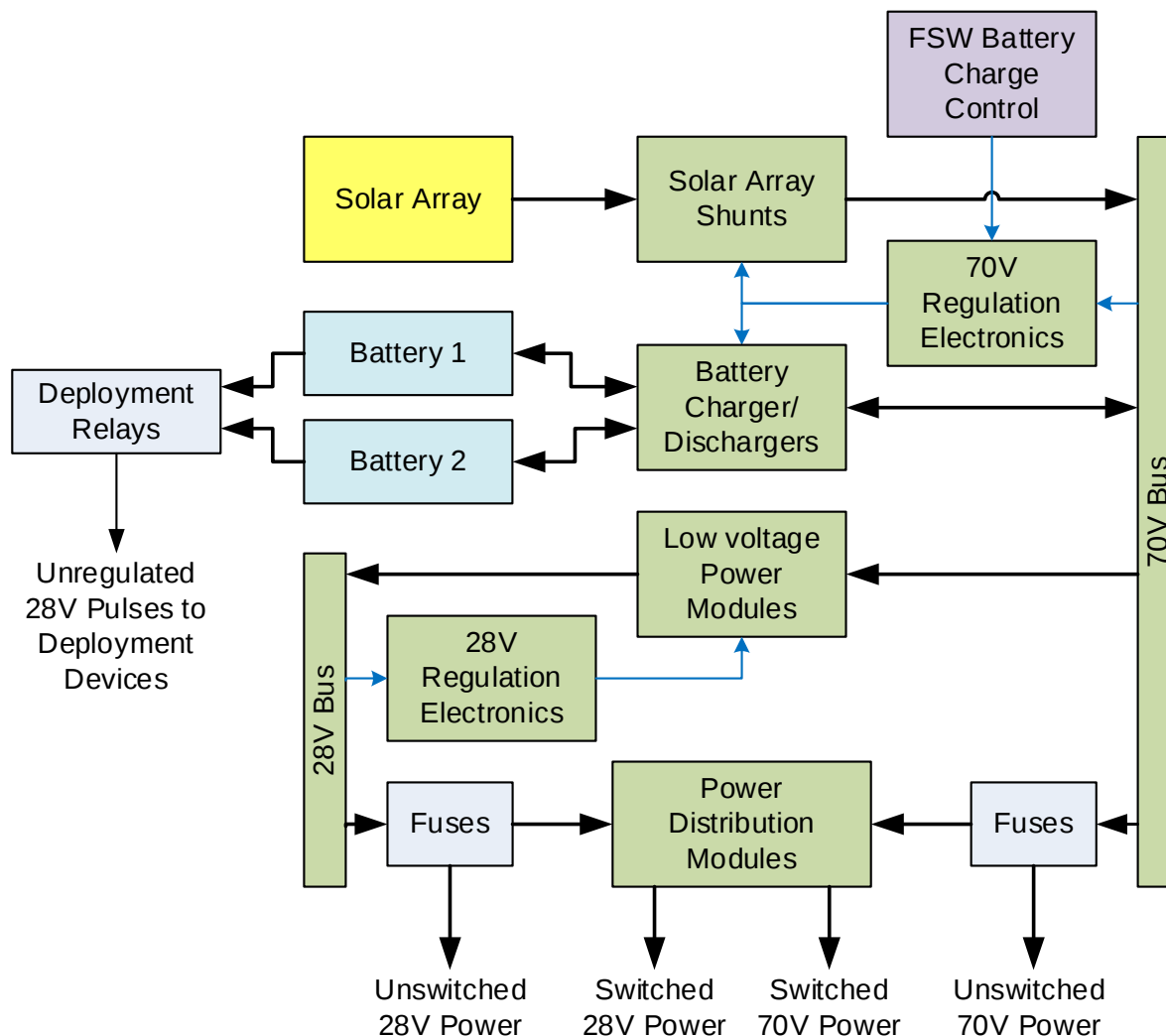


Battery Installed on Spacecraft



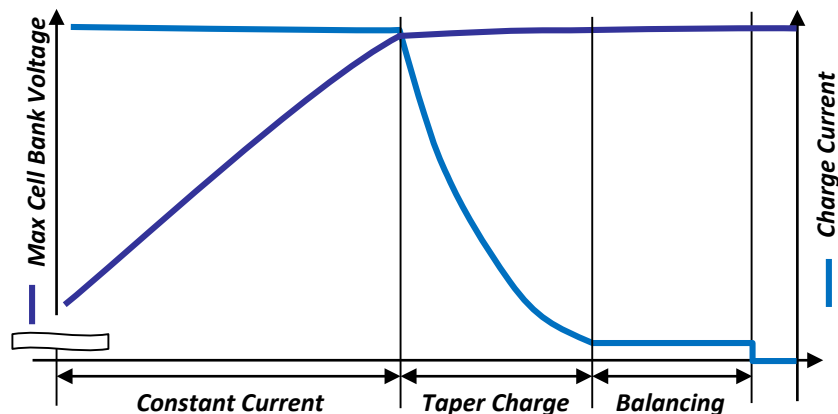
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Electrical Power Subsystem Diagram



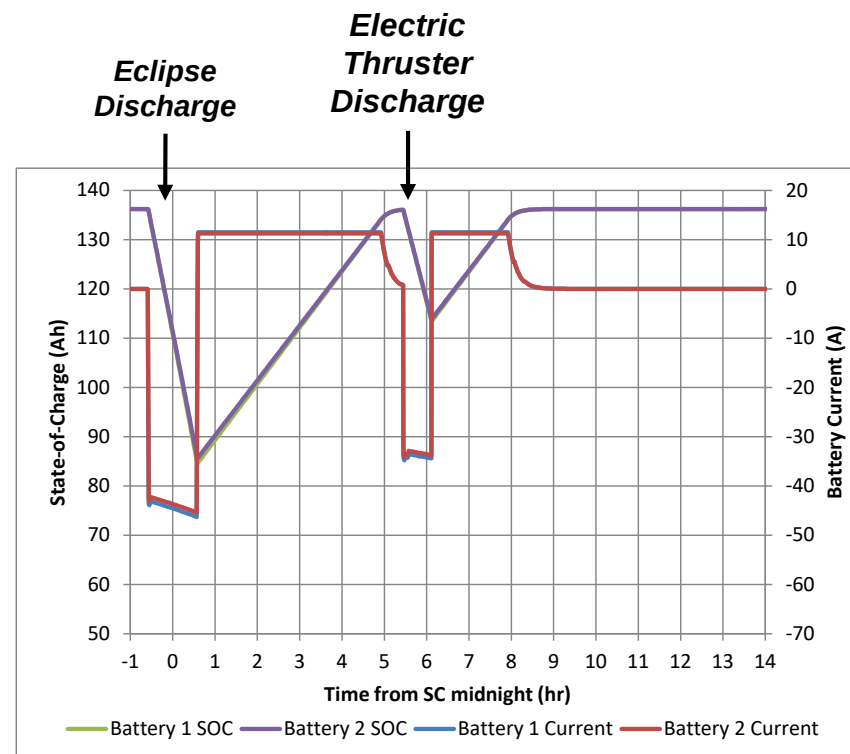
Battery Charge Control and SOC Profile

Charge Control



- **Charge control uses a constant current/constant voltage approach**
 - Constant current at $C_{br}/13hr$ until cell voltage reaches end-of-charge set point
 - Constant voltage (taper charge) until current drops to approx. $C_{br}/210hr$
- **Balancing performed at end of recharge; current = $C_{br}/210hr$**

State-of-Charge Profile



Life Test Description

- **Flight-like charge control and balancing**
- **Real-time eclipse season cycling**
 - Eclipse season is 44 days; Eclipse discharge once per day
 - Eclipse duration varies over the season from a few minutes to 70 minutes
 - Average eclipse discharge current for longest eclipse = 73 A
 - Max eclipse discharge = 75% C_{bn} (85 Ah out)
 - Electric thruster discharge once every four days, DOD = 36% C_{bn} (41 Ah out)
 - Average electric thruster discharge current = 28 A
- **Accelerated solstice season cycling**
 - Accelerated solstice season is 11 to 17 days
 - Two electric thruster discharges per day, DOD = 36% C_{bn} (41 Ah out)
 - Average electric thruster discharge current = 28 A
- **End-of-charge voltage (EOCV) increased over life**
 - BOL is 3.95 V/cell bank, EOL is 4.05 V/cell bank
- **Battery environment held at 15°C throughout test**

Life Test Capacity and Impedance Results

Test Condition*	Capacity (Ah) †	Cell Impedance (mΩ) ‡
Final acceptance test at Saft	136.22	3.25
Baseline just before life test cycling began	139.87	3.13
After 4 eclipse/solstice seasons	138.96	3.29
After 10 eclipse/solstice seasons	140.31	3.58
After 20 eclipse/solstice seasons	141.80	3.89

* Capacity tests at LM used same special test equipment that is used for life test

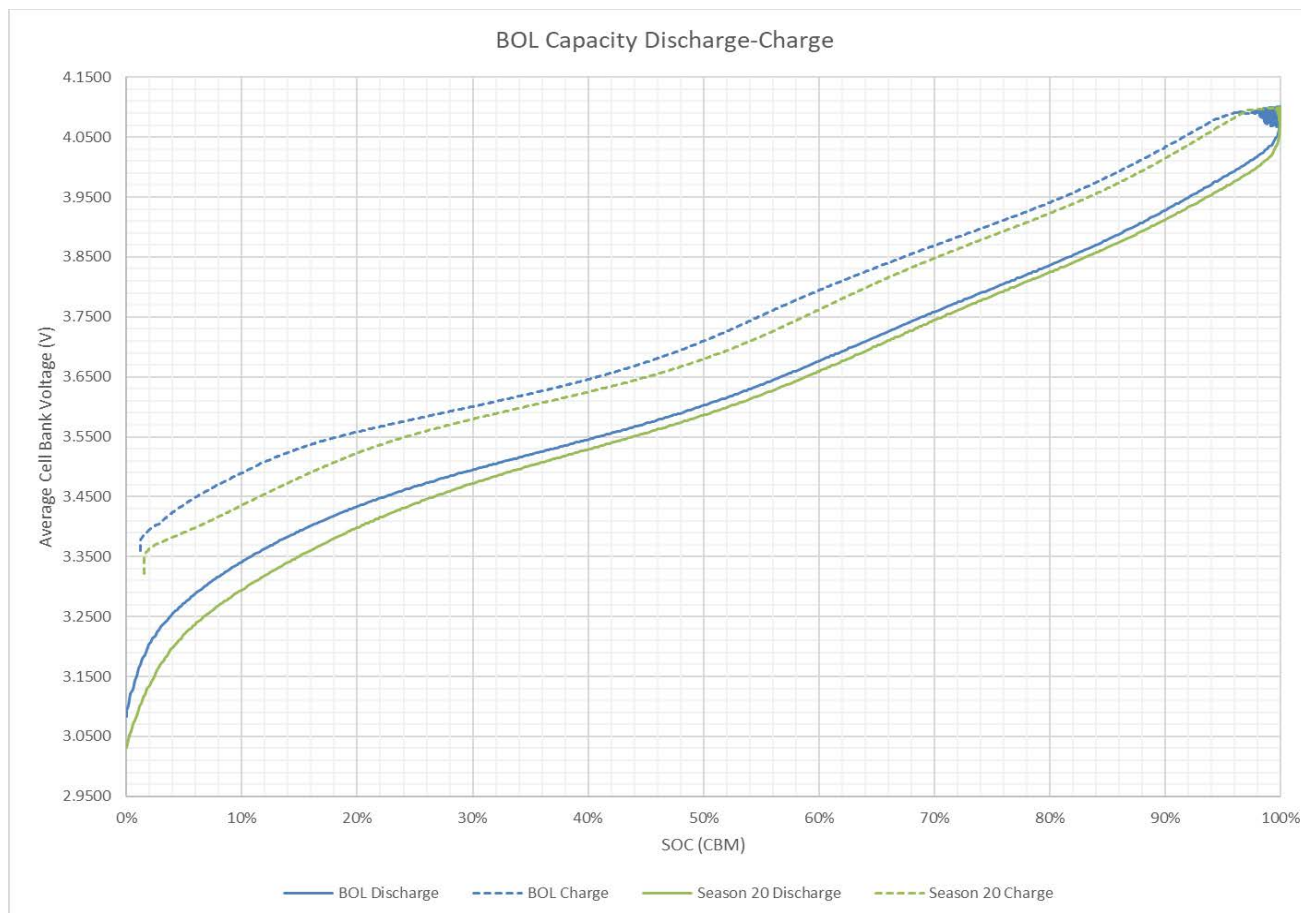
† Measured from 4.1 V to 3.0 V at $C_{bn}/2hr$

Increased capacity likely due to test equipment/measurement variations

‡ Average cell impedance (ohmic and polarized) at start of capacity discharge

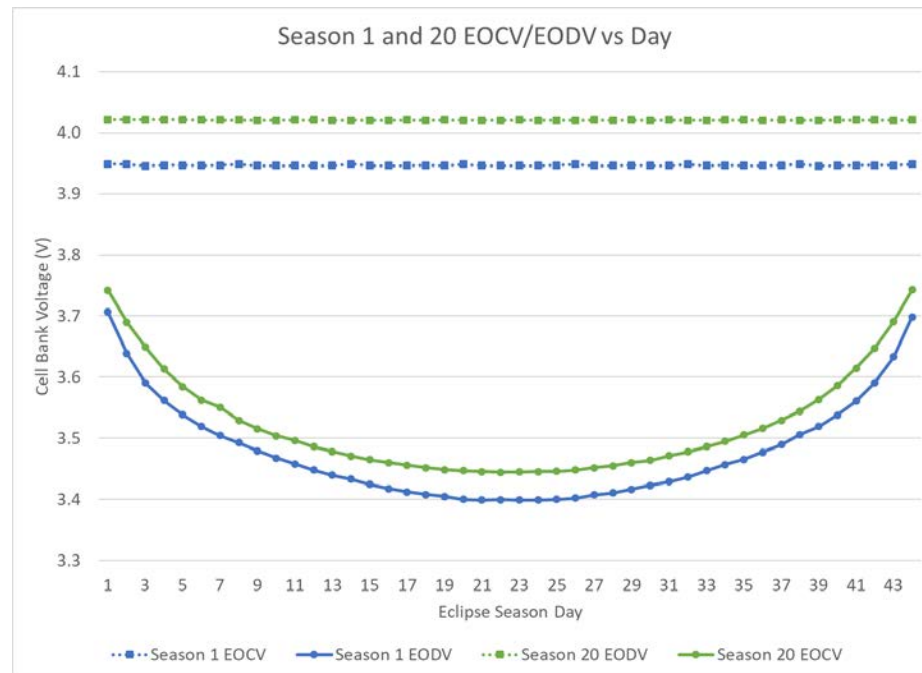
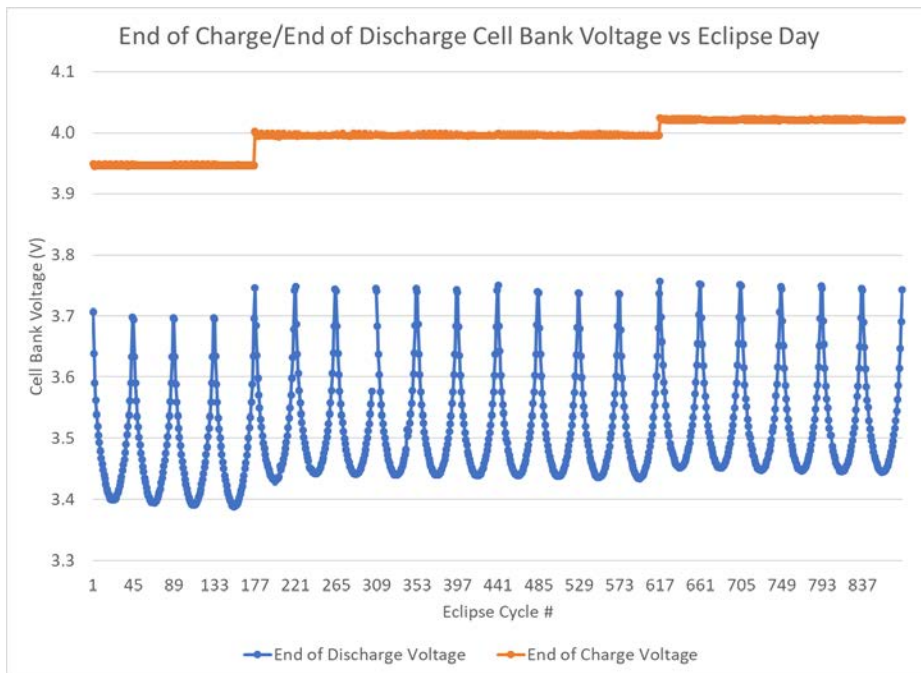
No Discernable Change in Capacity After 20 Seasons

Charge/Discharge Voltage



Voltage fade due to impedance increase

Max/Min Cell Bank Voltage



EOCV increases negate voltage fade

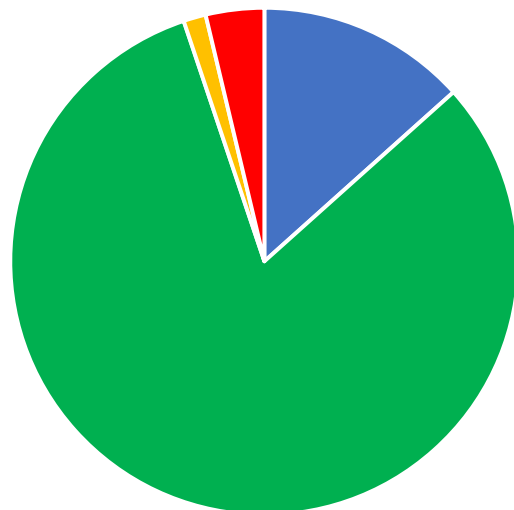
Workhorse Battery Characteristics

- **Used in spacecraft testing from 2014 April to present.**
 - Flight batteries installed shortly before spacecraft ships to launch site
- **Cells formed in 2011 March, same lot as life test battery.**
- **One battery was exposed to proto-flight testing.**
 - Higher vibration level and more extreme thermal cycling than acceptance
 - Testing perform from 2013 November to 2014 April
- **Other battery was exposed to qualification testing.**
 - Higher vibration level and more extreme thermal cycling than proto-flight
 - Testing perform from 2013 August to 2014 January
- **Capacity test performed in 2018 February, 7 years after cell formation.**

Workhorse Battery Utilization and Capacity

Workhorse Battery Utilization

Fraction of time at various cell voltages and temperatures



■ 3.65 V, 0 C ■ 3.65 V, 20 C
■ 3.95 V, 20 C ■ 4.05 V, 15 C

Work-Horse Battery Performance

- Workhorse cells formed in March 2011.
- Average cell acceptance 20 °C Capacity: 45.64 Ah
 - Cell acceptance testing 6-2011 – 12-2011
- Qual Battery 20 °C Capacity:
 - Expected after cell testing: 137.2 Ah
 - January 2014: 138.2 Ah
 - February 2018: 140.3 Ah
- I&T Battery 20 °C Capacity
 - Expected after cell testing: 136.7 Ah
 - March 2014: 136.5 Ah
 - February 2018: 138.2 Ah

No capacity loss after 6.5 years

VL48E Cell Chemistry Performance

- **Capacity increase expected during early seasons.**
 - Due to soaking of electrolyte into electrode, and repartition of binder on positive electrode.
- **Capacity is expected to fade by season 20 – observed increase likely due to measurement accuracy.**
 - 15-year capacity fade should be less than 1%.
- **Discharge voltage is decreasing as expected due to impedance increase over life.**
- **Expected energy decay is 5% to 6% after 15-year mission.**
 - Depends on battery storage voltage & charge voltage at solstice/eclipse.
 - Anode/electrolyte designed for negligible SEI decay during 15-year GEO mission.
 - Cathode formulized to minimize the cathode capacity fade, by providing a good electric conduction network and protected NCA particle surface.

Conclusions

- **GOES-R Series Lithium-Ion Life Test Battery Results**

- Accelerated GEO testing: 20 seasons of 30 complete
 - Real-time eclipse seasons of 44 days each.
 - Maximum eclipses at 75% DOD of C_{bn} (113.5 Ah).
 - Accelerated solstice seasons of 11-17 days.
- No degradation in 20 °C capacity after 20 seasons of accelerated GEO
 - BOL 20 °C Capacity: 139.9 Ah
 - 20-season accelerated GEO 20 °C capacity: 141.8 Ah
 - 1.36% delta due to test equipment accuracy and temperature control.

- **GOES-R Series Work-Horse Battery Performance**

- No degradation in 20 °C capacity 6.5 years after cell acceptance testing.
 - Four years of ground operations at ambient.
 - Majority of time (~80%) at 3.60 V – 3.65 V and 20 °C.
 - Remaining time at 3.65 V and 0 °C or 3.95 V – 4.05 V and 15 °C – 20 °C.

- **Batteries/Cells Are Performing as Expected – No Concerns with Meeting 15-year Mission Life**

Appendix: Acronym List

- C_{bn} :** Battery nameplate capacity. The battery nameplate capacity, C_{bn} , is 5/6 of the battery rated capacity, C_{br} . The battery nameplate capacity, C_{bn} , is the minimum capacity at 20 °C when the battery cells are charged to 4.1 V and discharged with a $C_{bn}/2$ discharge rate to 3.0 V which the battery manufacturer guarantees for the mission life. The term, C_{bn} , is, also, a current which is numerically equivalent to the nameplate capacity, Ah, and is used to define the charge current or discharge current during capacity measurements. Therefore, a battery nameplate capacity, C_{bn} , at 120 Ah with a discharge rate of $C_{bn}/2$ would be discharged at 120 A/2 or 60 A during the capacity measurement. For GOES R, the battery nameplate capacity, C_{bn} , is 113.5 Ah.
- C_{br} :** Battery rated capacity. The battery rated capacity, C_{br} , is the battery capacity requirement which the spacecraft manufacturer agrees to meet prior to build. The battery rated capacity, C_{br} , is the beginning-of-life (BOL) capacity at 20 °C when the battery cells are charged to 4.1 V and discharged with a $C_{bn}/2$ discharge rate until the 1st battery cell end-of-discharge voltage is 3.0 V. For GOES R, the battery rated capacity, C_{br} , is 136.2 Ah.

Appendix: Acronym List

- C_n :** Battery cell nameplate capacity. The battery cell nameplate capacity, C_n , is 5/6 of the battery cell rated capacity, C_r . The battery cell nameplate capacity, C_n , is the minimum capacity at 20 °C when the cell is charged to 4.1 V and discharged with a $C_n/2$ discharge rate to 3.0 V which the cell manufacturer guarantees for the mission life. The term, C_n , is, also, a current which is numerically equivalent to the nameplate capacity, Ah, and is used to define the charge current or discharge current during capacity measurements. Therefore, a battery cell nameplate capacity, C_n , at 40 Ah with a discharge rate of $C_n/2$ would be discharged at 40 A/2 or 20 A during the capacity measurement. For GOES R, the C_n was 37.83 Ah.
- C_r :** Battery cell rated capacity. The battery cell rated capacity is the battery cell capacity requirement which the cell manufacturer agrees to meet prior to build. The battery cell's rated capacity, C_r , is the beginning-of-life (BOL) capacity at 20 °C when the cell is charged to 4.1 V and discharged with a $C_n/2$ discharge rate to 3.0 V. For GOES R, the VL48E battery cell rated capacity was 45.4 Ah.

Appendix: Acronym List

GOES:	Geostationary Operational Environmental Satellite
NASA:	National Aeronautics and Space Administration
NCA:	Lithium nickel cobalt aluminum oxide (LiNiCoAlO₂)
NOAA:	National Oceanic and Atmospheric Administration