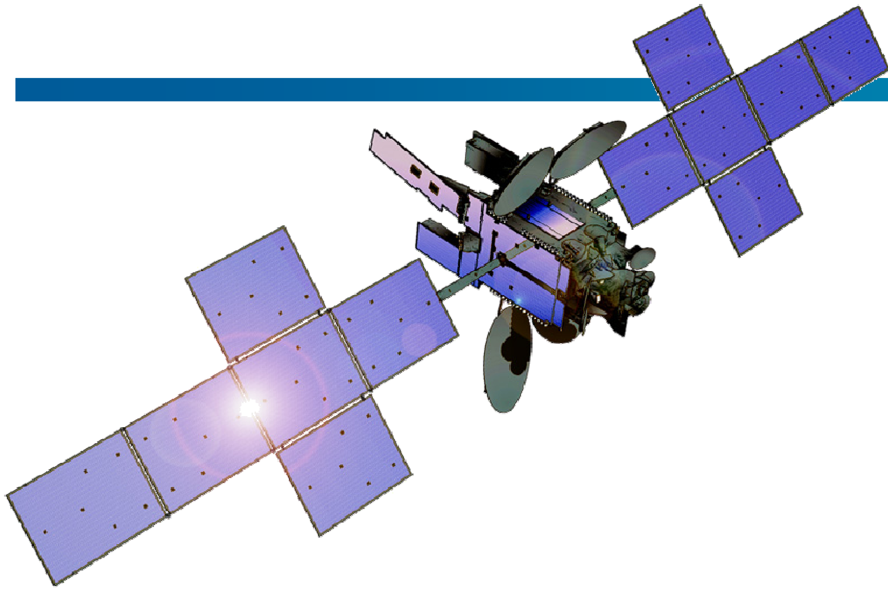


On-Orbit Experience, Life Testing, & Lessons Learned with Li-ION batteries

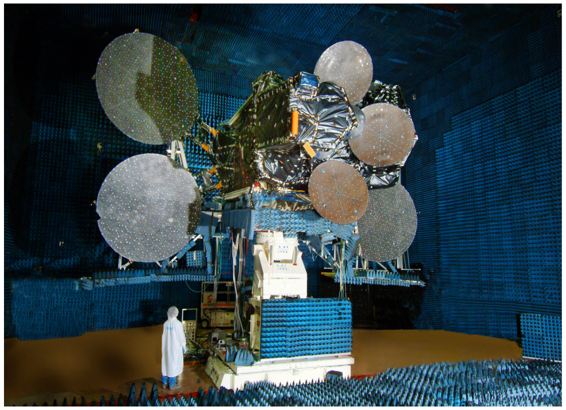
Dan DeBiccari & Anthony Applewhite

NASA Aerospace Battery Workshop

November 17, 2010

SPACE SYSTEMS LORAL

The World's Leading Provider of Commercial Satellites



- Greater than 40% share of high power commercial market since 2005
- Provider of hosted payloads for best value government mission solutions
- Broad base of blue-chip customers worldwide

- Over 230 satellites built
- 22 satellites in current backlog
- $1.9 billion backlog as of June 30, 2010

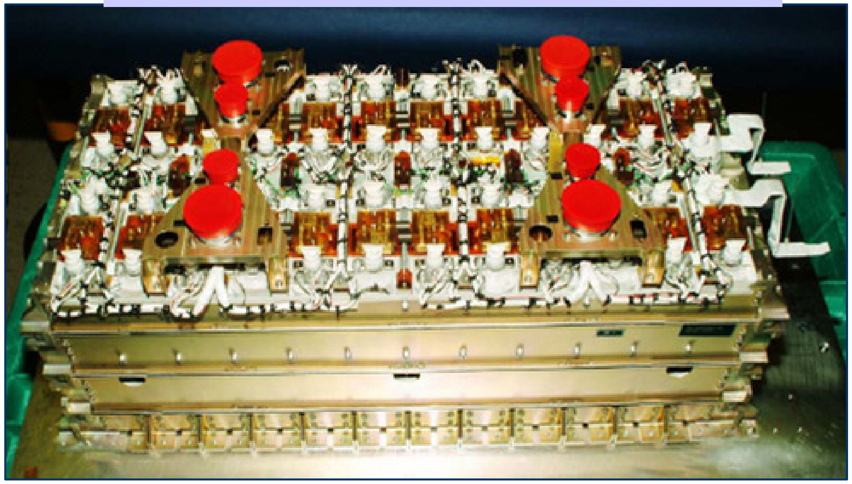
- 63 GEO satellites currently on-orbit
- More than 1700 on-orbit years experience
- Workforce of 2,900+

- Facility of 1.2M sq. ft. spanning 30 buildings and 72 acres
- 50+ years heritage of performance and reliability
- 13 awards and 10 launches since January 2009

Background

- Space Systems/Loral has extensive experience with GEO spacecraft with Li-Ion powered electrical power subsystems (EPS)
  - Development, qualification, & life testing initiated in late 1990's
    - SAFT, Varta, Sony/ComDev/AEA, JSB (GS Yuasa)
  - First launch in 2005
  - Presently 13 spacecraft in-orbit with Li-Ion
    - 42 batteries, 990 cells
    - Eclipse capability from ~7 kW to ~18 kW per S/C
  - Current backlog is 22 spacecraft
    - 71 batteries, ~1540 cells
      - 48–96 cells/spacecraft
    - Eclipse capability from ~9 kW to ~21 kW

24 cell SS/L battery with GS Yuasa 102 Ahr cells



- Adoption of Li-Ion technology was more rapid than SS/L had anticipated
  - SS/L has had no active GEO programs using Ni-H2 technology since our first Li-Ion launch in 2005

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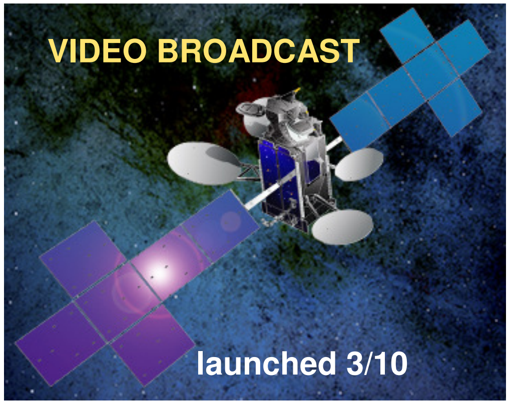
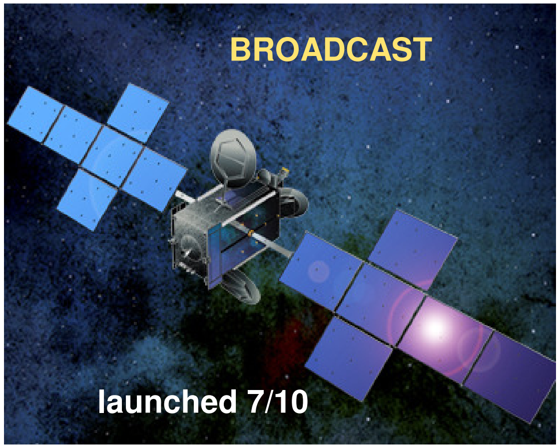
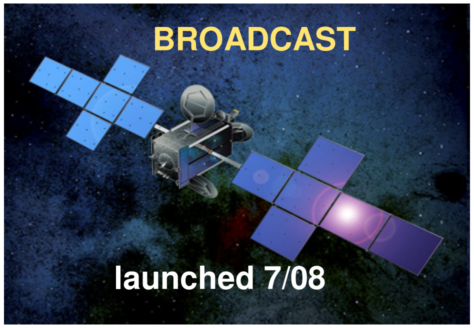
20kW Platform Satellite Experience





To date, SS/L has successfully launched 5 20kW-Class satellites



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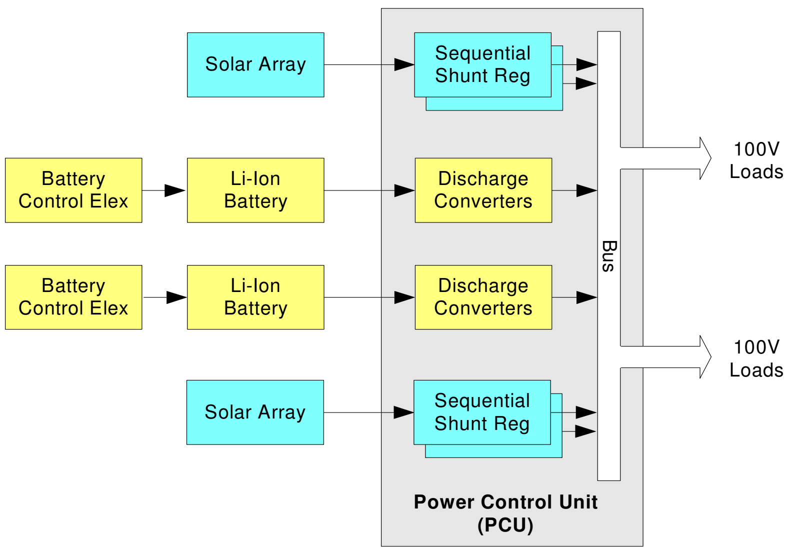
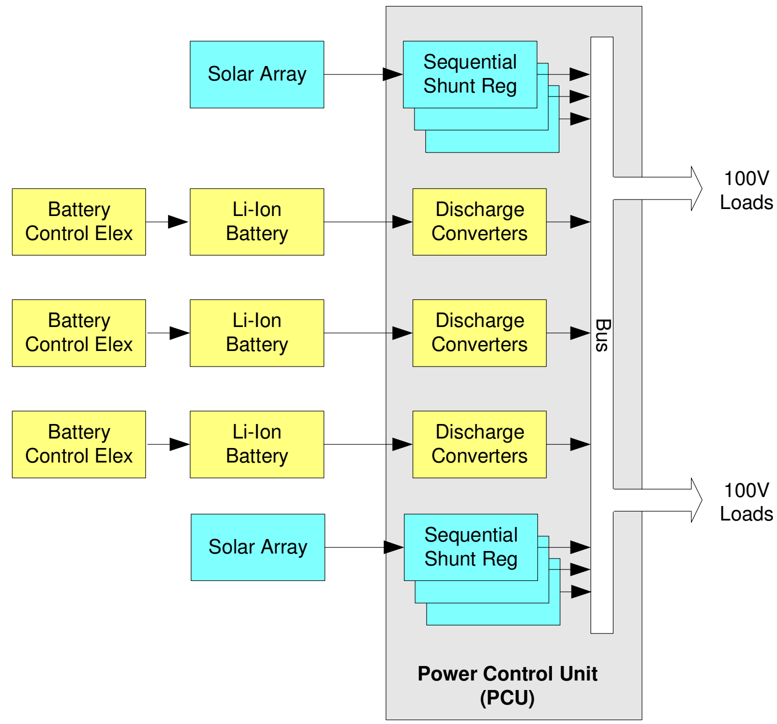
SS/L 10-kW and 15-kW Class EPS Architectures





- **10-kW Class Power Subsystem**
- **2 Batteries**

- **15-kW Class Power Subsystem**
- **3 Batteries**

Modular EPS Architecture

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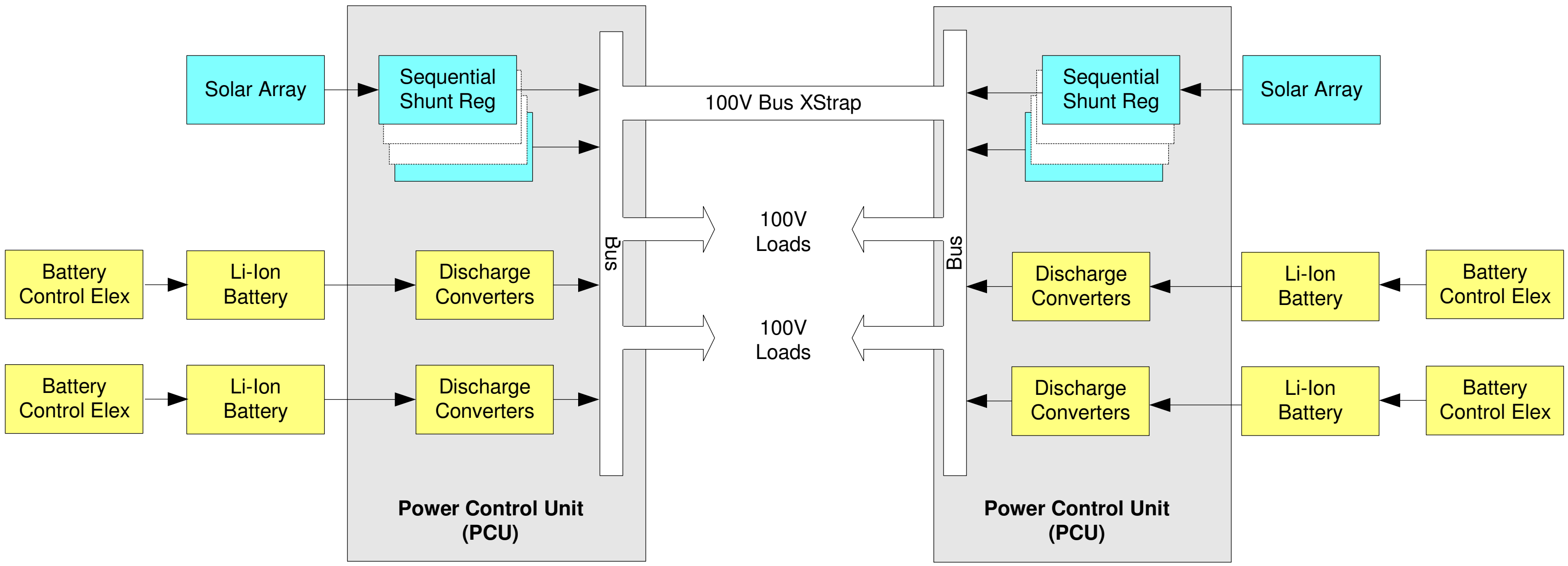
SS/L 20-kW and 25-kW EPS Architectures



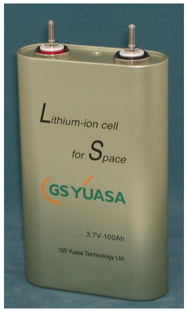
- 20-kW or 25kW Class Power Subsystem
- 4 Batteries

◆ 25 kW EPS Capabilities

- ➢ Batteries: High capacity Li-Ion batteries
- ➢ Solar Array: 8 panels with high efficiency solar cells

Li-ion Battery Capabilities

- State of Practice: 102-Ah Li-ion Cell Technology
- 2 Battery System
  - Spacecraft power ranges from 8.0 to 11kW
- 3 Battery System
  - Spacecraft power ranges from 12 to 18 kW
- 4 Battery System
  - Spacecraft power ranges from 20 to 24 kW
- Currently, SS/L is using GS Yuasa 102 Ahr cells for all spacecraft using Li-Ion
  - Evolution from ‘heritage’ cell to ‘standard’ cell

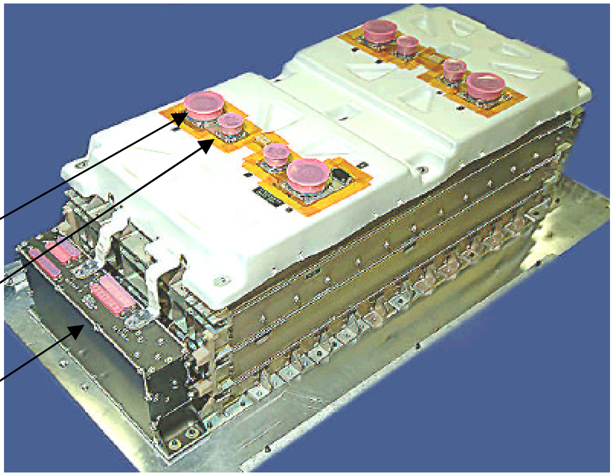


GYT 102 Ah Nameplate Li-ion Battery Cell

Charge Connector – each cell individually charged

Telemetry Connector

Battery Switch Tray



Battery pack scalable from 18 to 24 cells for flexible power capabilities

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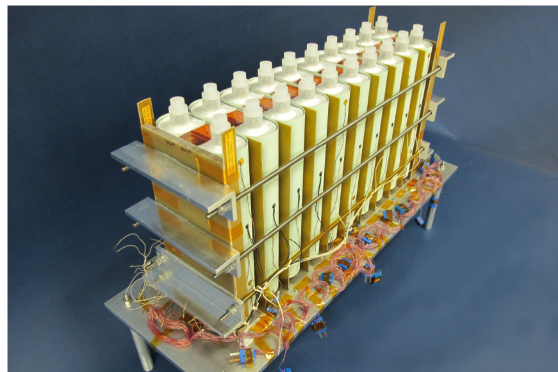
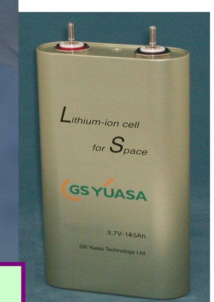
1300 PRODUCT EVOLUTION TO THE 25kW PLATFORM

- **SAFT 180 Whr battery cells provide increased capability**
  - Technology for 25 kW is flight proven and available
  - Improved energy density results in 20% less mass
  - Packaging fits within SS/L's existing allocated S/C battery volume
  - Works with SS/L's existing power electronics
  - Real time GEO life testing at SS/L initiated in late 2009 on 2P x 24S battery w/ Aeroflex balancing circuitry

SAFT 180 Whr cells – 2Px24S config.
Life Test Battery Assembly in test at SS/L

- **GYT battery 145 Ahr**
  - 20% improvement in Ahrs/Kg compared to 102 Ahr cell
  - Test cells delivered to SS/L in mid 2010
  - Testing will start by end 2010





GYT 145 Ahr 10 cell
Life Test Battery Assembly at SS/L

Qualifying larger capacity Li-ion cells with "next generation" technologies for lower mass and higher power capabilities

Lessons Learned

- High voltage of “discharged” Li-Ion cells & batteries is problematic during battery assembly, test, handling, & integration
  - “Hot mates” should be avoided to the greatest extent possible
  - Documented & verified procedures, when ‘hot mates’ cannot be avoided

- Spacecraft Thermal Vacuum testing is NOT the place to wring out a new Li-Ion EPS
  - Too late in the program to discover a problem
  - Schedule pressure limits thoroughness of testing
  - Orientation of spacecraft (relative to heat pipe operation) limits testing
  - Better to perform……

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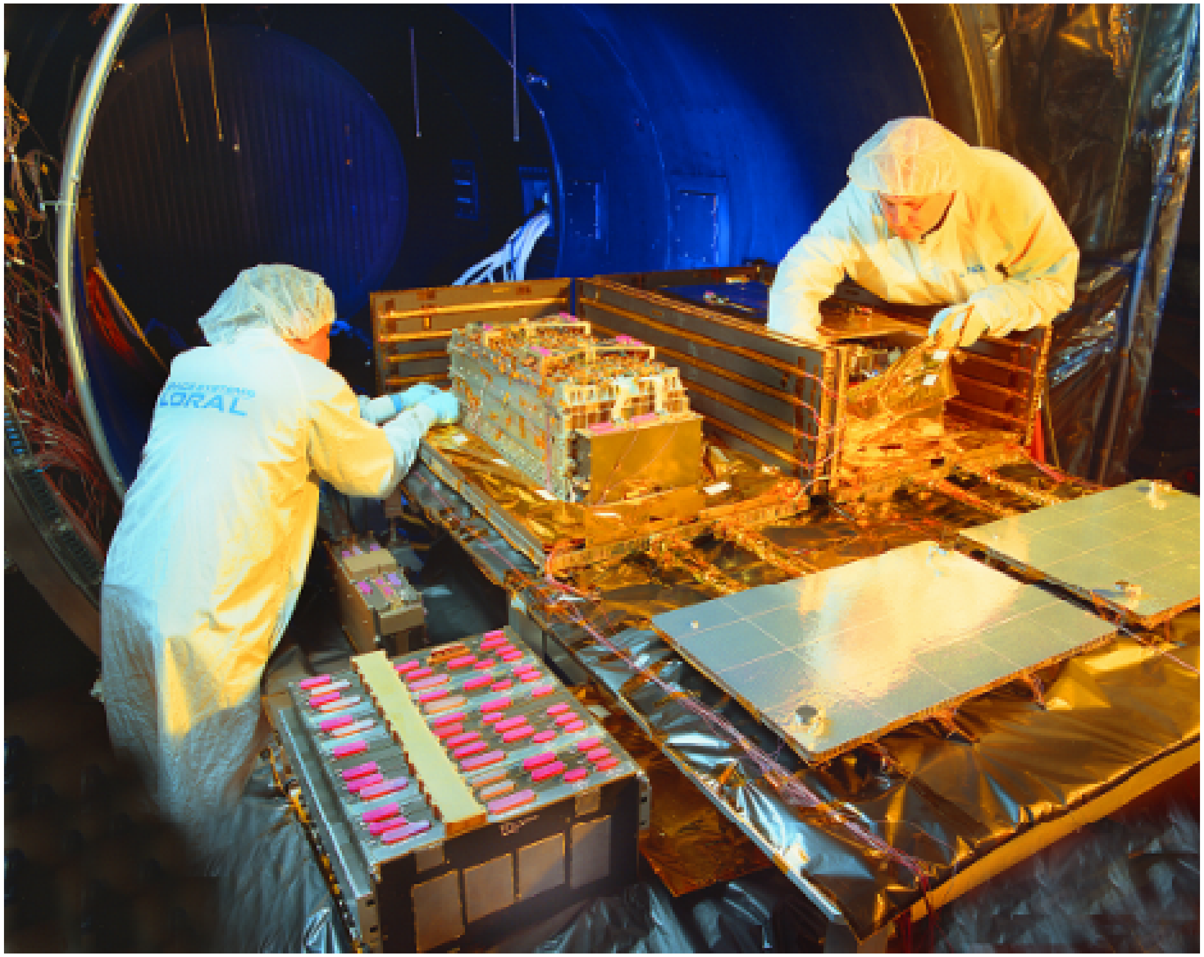
EPS “End to End” Test

- **Extensive test duration (> 3 months, most in hard vacuum) allows for all “normal” and "off normal" conditions to be actually tested**
  - **Use of battery simulator allows variety of failure conditions to be verified**



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EPS "End to End" Test was invaluable

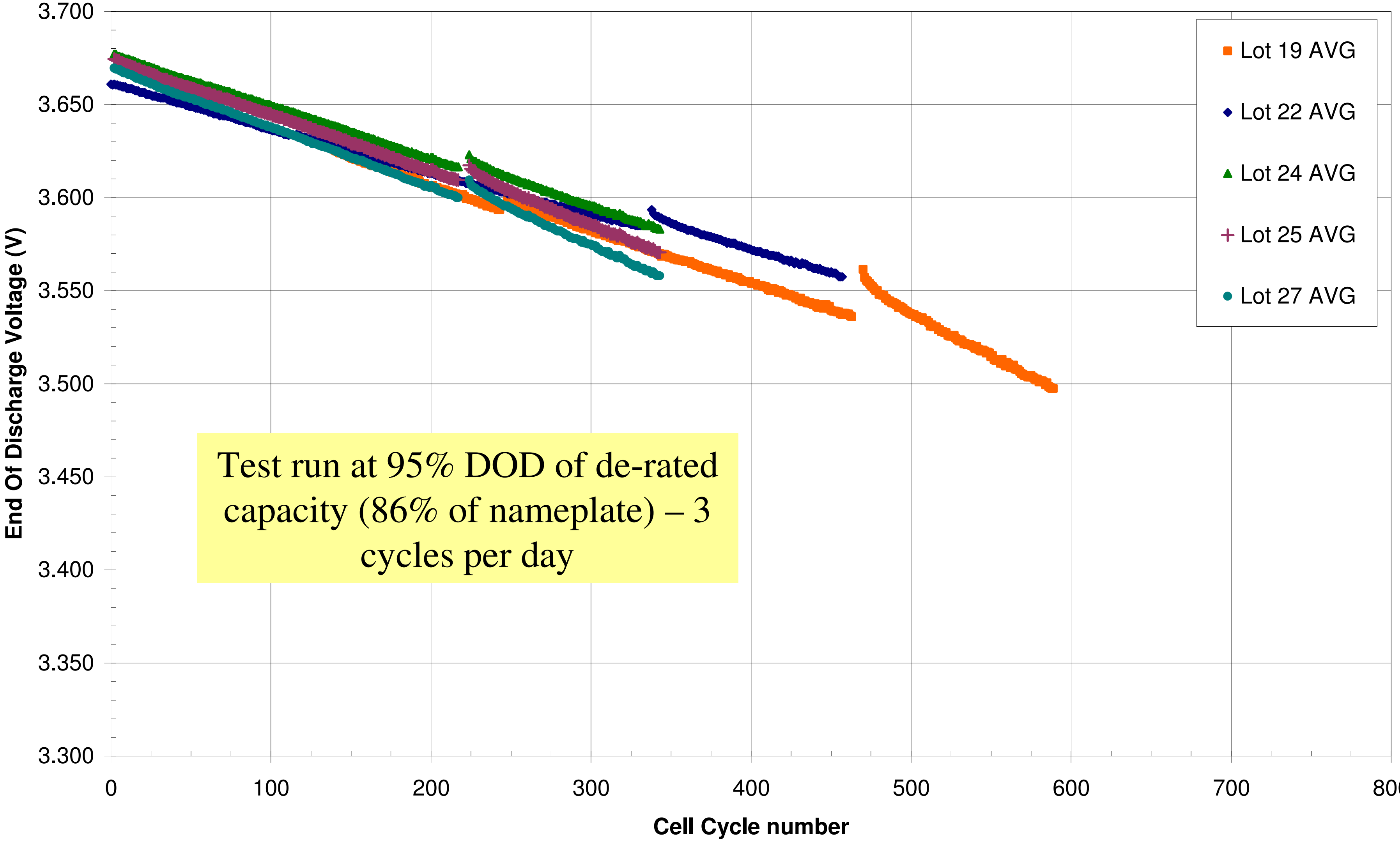
- EPS equivalent of an ADCS "3-axis test" performed immediately after unit level qualification testing and well in advance of spacecraft thermal vacuum testing
  - Similar to a qual test, done on a non-recurring basis for new EPS design
  - Included ALL critical elements of EPS (except Solar Array) as well as flight thermal control, flight software, and flight Data Handling Equipment
  - Vacuum sensitive units tested in common thermal vacuum chamber
  - Testing augmented with Battery Simulator and Solar Array Simulator

- Major test goals included
  - Verify / validate battery thermal control scheme (radiator performance, gradients throughout battery and structure, etc.)
  - Stability and bus regulation performance
  - Battery management software code validation and compatibility with Li-Ion cells (including database, code, FDIR, etc.)
  - Interface and functionality verification of EPS hardware (battery, battery charge electronics, dischargers, etc.)

Life Testing

- Two best reasons to perform life testing (in order of importance)
  - Increases customer confidence when introducing new technology
  - Allows life model to be validated
- On-going SS/L life testing:
  - Wear Out Testing – 2 cells per flight lot - 3 cycles per day
  - 80 Ah real time GEO life test - 10 cells, 12 years in test, 20 seasons
  - 92 Ah Real time GEO life test - 10 cells, 3 years in test, 7th season in process
    - Full simulation of prelaunch, 2.7 years of storage prior to test at both 10 & 20 deg C (20 deg C simulates battery assembly) at 10% SOC, including 8 weeks of launch base storage at 60% SOC
  - SAFT VES180 Real Time GEO life test – 2P x 24S
    - 2P x 24S cells, 3 different cell lots in battery, 1 year in test, 2 seasons
    - bulk charging with Aeroflex BEU for cell balancing
  - GYT 145 Ah Real Time GEO Life test – 10 cells, test scheduled to start 12/10
  - Other tests to validate long term storage & new cell materials also in progress

Performance of 'Standard' Electrolyte cells in Wear Out Test



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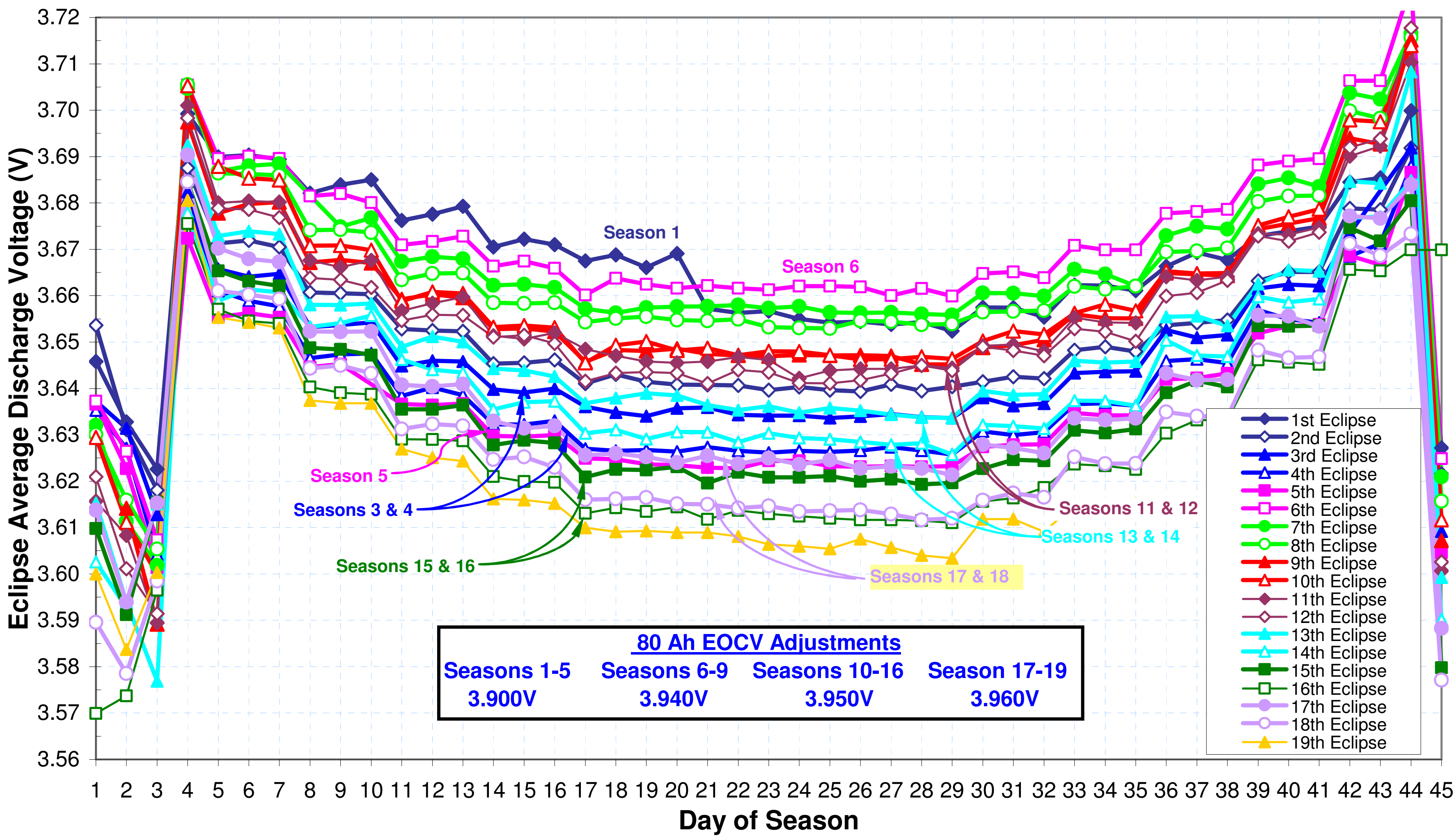
GEO Real Time Life Test Performance – Heritage Electrolyte Cells

- On-orbit battery management philosophy of periodically adjusting charge voltage to assure proper performance and adequate margins over mission life has been validated
- Real time performance is excellent and correlates well with expectations and Life test model predictions



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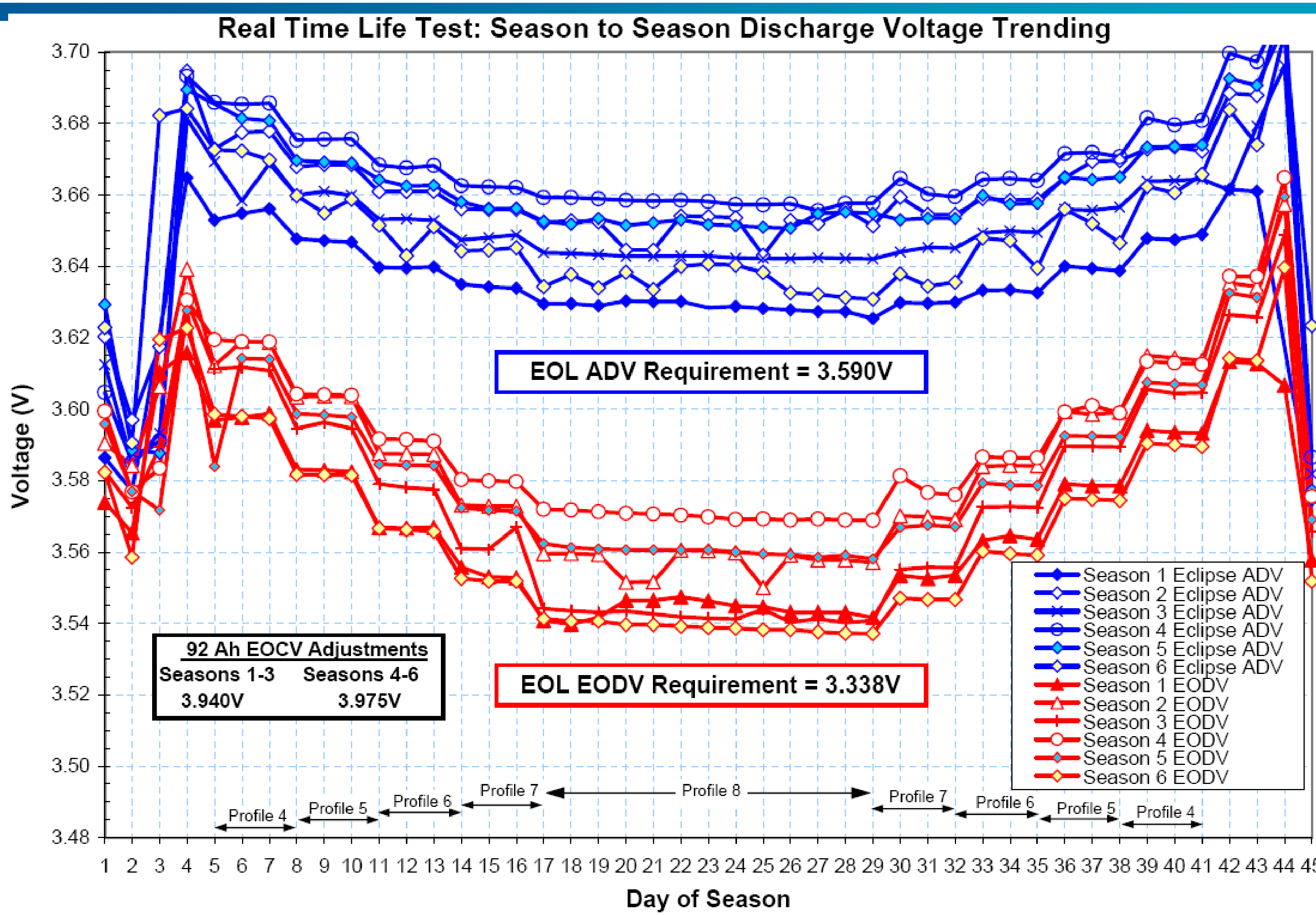
GEO Real Time Life Test Performance – Standard Electrolyte Cells



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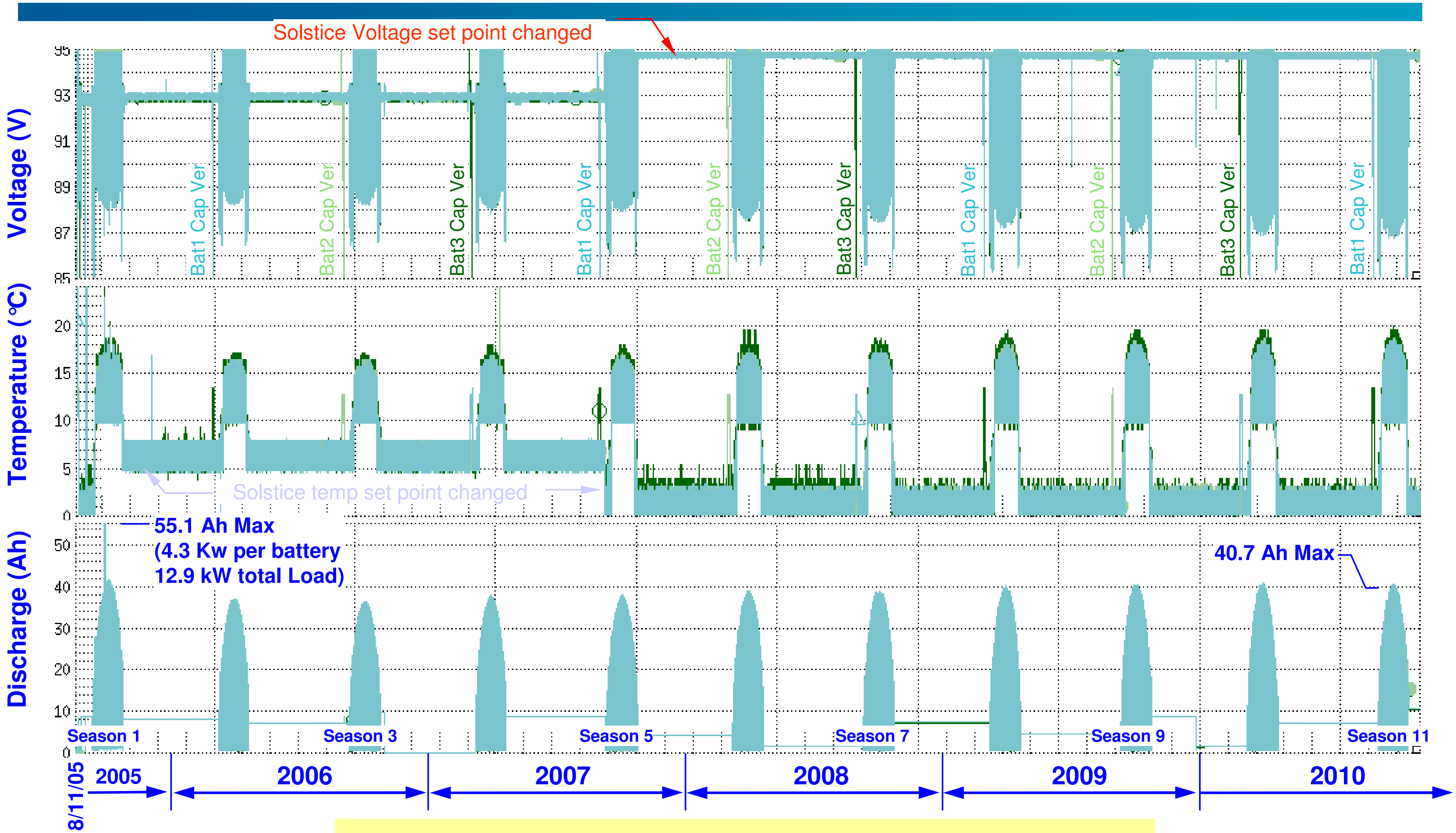
On Orbit Battery Data - Launch through Present



Stable Performance, very little operator intervention required

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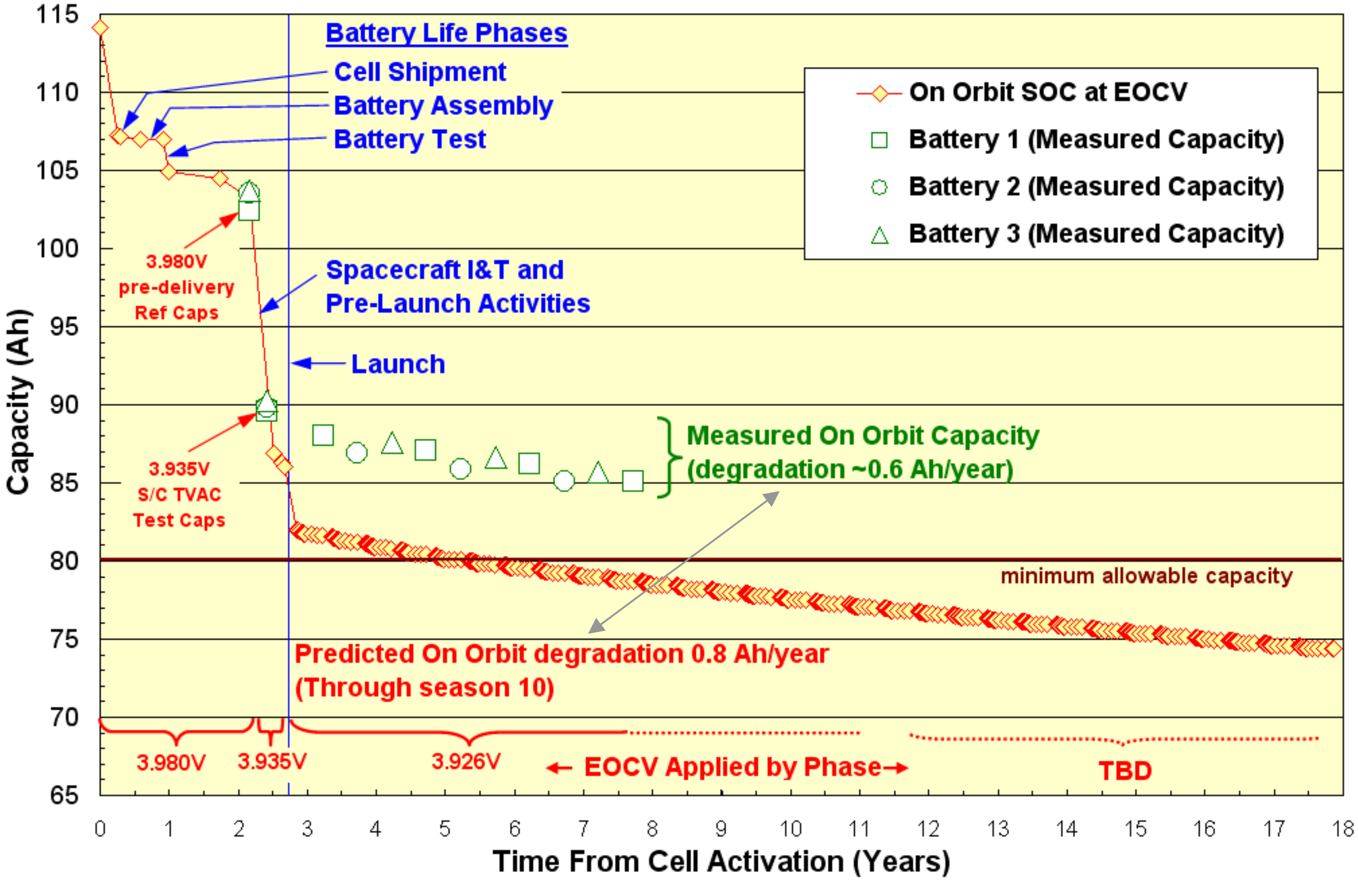
On-orbit capacity verification

- Capacity of one battery is verified prior to each eclipse season.
  - It takes 3 seasons to cycle through all three batteries



On-Orbit capacity exceeds model expectations, first Equinox EOCV adjustment predicted after mission life is complete. Actual Vset adjustments are dependent on future SC loading & cell voltage performance.

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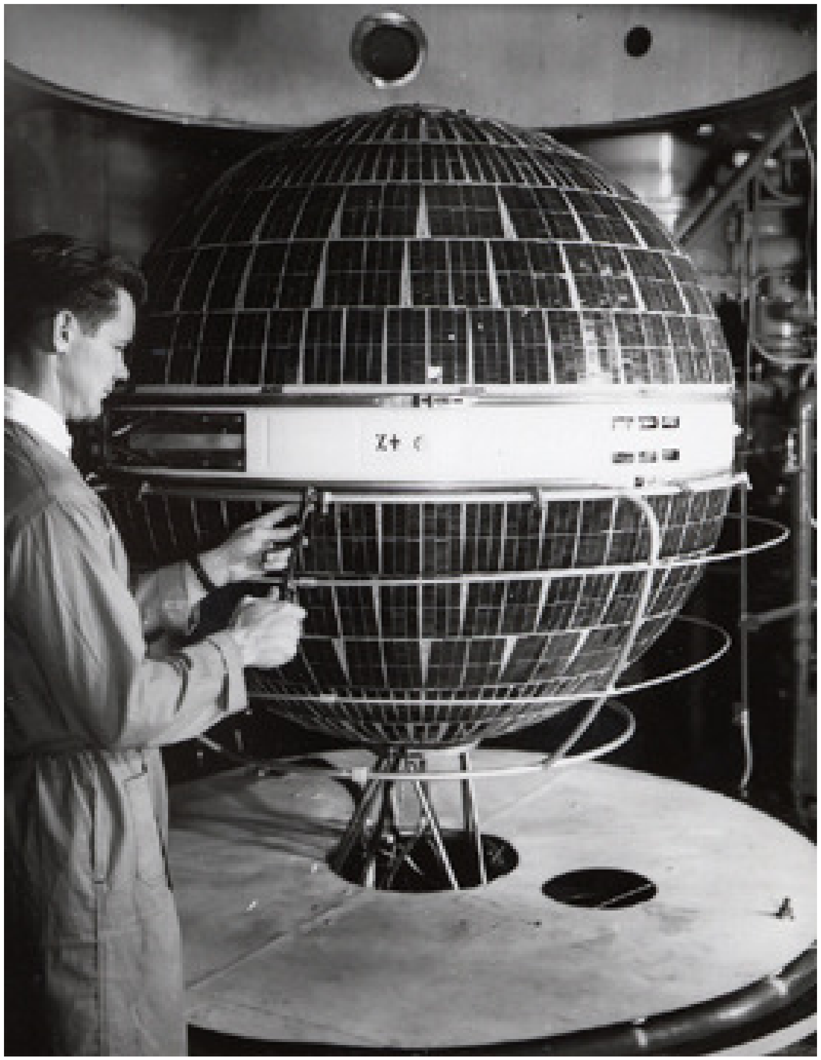
Wrap Up

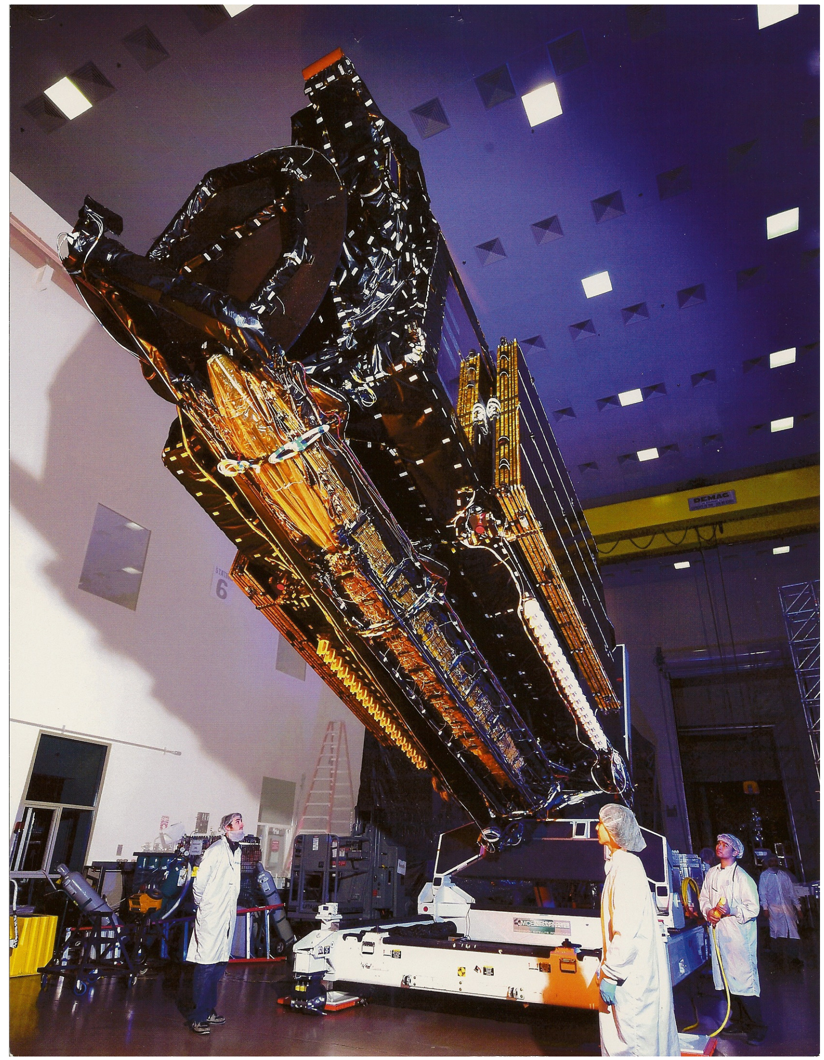
- Superb Li-ion self-discharge behavior and excellent room temperature performance allow dramatically easier launch base operations vs Ni-H2
  - No issue achieving desired state of charge for launch
  - No need to use umbilical or GSE to charge and maintain batteries
    - Flight battery charging hardware/software is already dual fault tolerant and extensively tested and verified
- Capacity verification trending has been great to have
  - Essentially a reconditioning style discharge that allows us to collect capacity data over the life of the cells
  - Not necessary for battery health, but provides data for SS/L & customers to confirm 'within predicted' performance
    - Will be a great database as more S/C are launched and multiple seasons are accumulated
- SS/L architecture with individual chargers for each cell was a good choice
  - Best way to assure that all cells are charged to the same cutoff voltage
    - No other system existed to provide balancing of cells at the time, but…
    - A charger failure results in the inability to charge the cell associated with that charger and ultimately the cell will be completely discharged and reversed
    - To date we have had a single charger failure (1 of 990)
    - This caused the cell to be driven into reverse voltage during subsequent discharge, causing autonomous actuation of the CSD (Cell Shorting Device). This places a 60 micro-ohm current path in parallel with the cell
    - Device is fused to provide fault clearing in the event of an unintended actuation of the device
    - Cell quantity per spacecraft is based on assumption that a charger failure = a cell failure

THEN & NOW

Courier – 1960, 500 lbs, 60 watts



Mobile Services Sat – 2009, 12,000 lbs, 20,000 watts



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