HUBBLE SPACE TELESCOPE PROJECT

Goddard Space Flight Center

Hubble Space Telescope

2004 Battery Update

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Battery cell wear out mechanisms and signatures are examined and compared to orbital data from the six on-orbit Hubble Space Telescope (HST) batteries, and the Flight Spare Battery (FSB) Test Bed at Marshall Space Flight Center (MSFC), which is instrumented with individual cell voltage monitoring.

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HST Nickel Hydrogen (NiH_2) Cell Design Description

- Eagle Picher Technologies (EPT) RNH 90-3
- Air Force MANTECH Design
- Rabbit Ear Terminals
  - Graduated Leads
- Double Layer Zircar Separator
- Back-to-Back Electrode Configuration, 48 Plates
  - Zirconia Wall Wick
- Dry Sinter Nickel Plaque (84% Porosity)
  - EPT-Colorado Springs Plaque
  - Electrochemical Impregnation
  - EPT-Joplin Impregnation & Assembly
- 27% KOH (At Discharged)
- Slight H_2 Pre-Charge

The on-orbit HST batteries were manufactured on an expedited basis after the Challenger Shuttle Disaster in 1986. The original design called for the HST to be powered by six 50 Ah Nickel Cadmium batteries, which would have required a shuttle mission every 5 years for battery replacement. The decision to use NiH_2 instead has resulted in a longer life battery set which was launched with HST in April 1990, with a design life of 7 years that has now exceeded 14+ years of orbital cycling. This chart details the specifics of the original HST NiH_2 cell design.

The HST replacement batteries for Service Mission 4, originally scheduled for Spring 2005, are currently in cold storage at Goddard Space Flight Center (GSFC). The SM4 battery cells utilize slurry process electrodes having 80% porosity.

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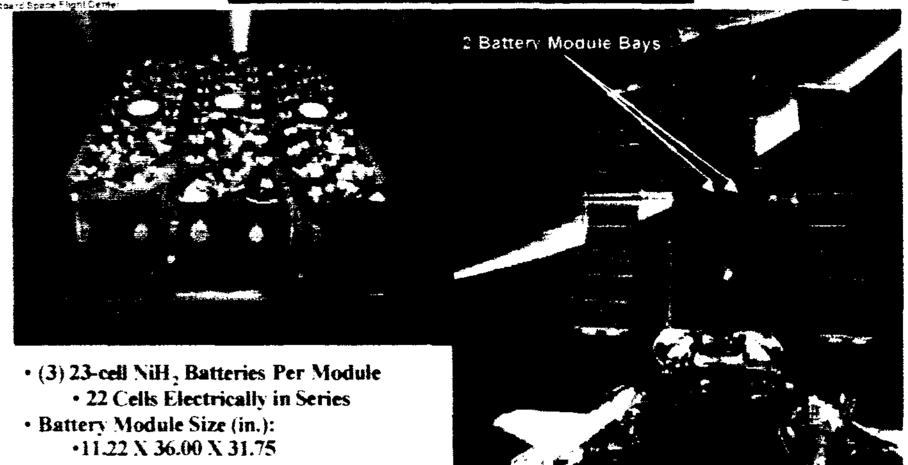
HST Flight Batteries



- (3) 23-cell NiH_2 Batteries Per Module
  - 22 Cells Electrically in Series
- Battery Module Size (in.):
  - 11.22 X 36.00 X 31.75
- Module Weight(lb.): 500 Max
- Battery Capacity: 88 Amp-hr (Ah)
  - 15 A Discharge to 26.4 V at 10°C
- Launch: April 24, 1990 (13+ Years)
- Part No:4177755

A total of 16 batteries were manufactured for the HST Program - 3 Flight Modules, 2 Test Modules, and a Flight Spare Battery. The 23-cell batteries only used 22 cells connected electrically in series. The 23rd cell was determined as driving the system voltage outside the voltage limits of some electronic boxes. The six on-orbit batteries are enclosed in 2 modules, like the one shown on the left here, each module has 3 batteries. Flight Module 2 (FM2) is mounted inside Equipment Bay Door #3, and the Flight Spare Module (FSM) is mounted inside Equipment Bay Door #2. Flight Module 1 (FM1) was re-designated as the "spare".

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HST Resources

- On-Orbit HST Batteries
  - Flight Module 2 (FM2) & Flight Spare Module (FSM)
  - Six 23-Cell Batteries (Launched 4/1990)
  - 75.5K Cycles (14+ Years)
- Marshall Space Flight Center (MSFC) HST Flight Spare Battery (FSB)
  - 23-Cell Battery (Cycles Started 6/1989)
  - 80 K Cycles (15+ Years)
  - Individual Cell Voltage Monitor
- MSFC Six Battery System Test - Test Module 1 (TM1) & TM2
  - Six 23-Cell Batteries (Cycles Started 5/1989)
  - 80K Cycles (15+ Years)
  - Individual Cell Voltage Monitor
- Flight Module #1 (FM1) Re-designated as "Flight Spare"
  - Three 23-Cell Batteries
  - Cold Storage @ EPT
  - Currently at Goddard Space Flight Center (GSFC)
    - Used for Test Equipment Checkout & Fit Checks

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16 NiH_2 batteries were manufactured for HST, most of which are the resources used in this analysis. Six batteries have been deployed since 1990 on HST and 7 batteries are being life cycled, since 1989, at MSFC on two test beds. The test beds are utilized to evaluate system and battery control issues. These assets have slightly more cycles than the orbital batteries. The remaining 3 batteries are in FM1 which was designated the flight spare, just prior to the launch in 1990.

The Flight Spare Battery (FSB) and the Six Battery System Test Modules (TM1 & TM2) used for ground studies at MSFC are unique, in that they have individual cell monitoring, which provides very useful insight into individual cell ageing processes.

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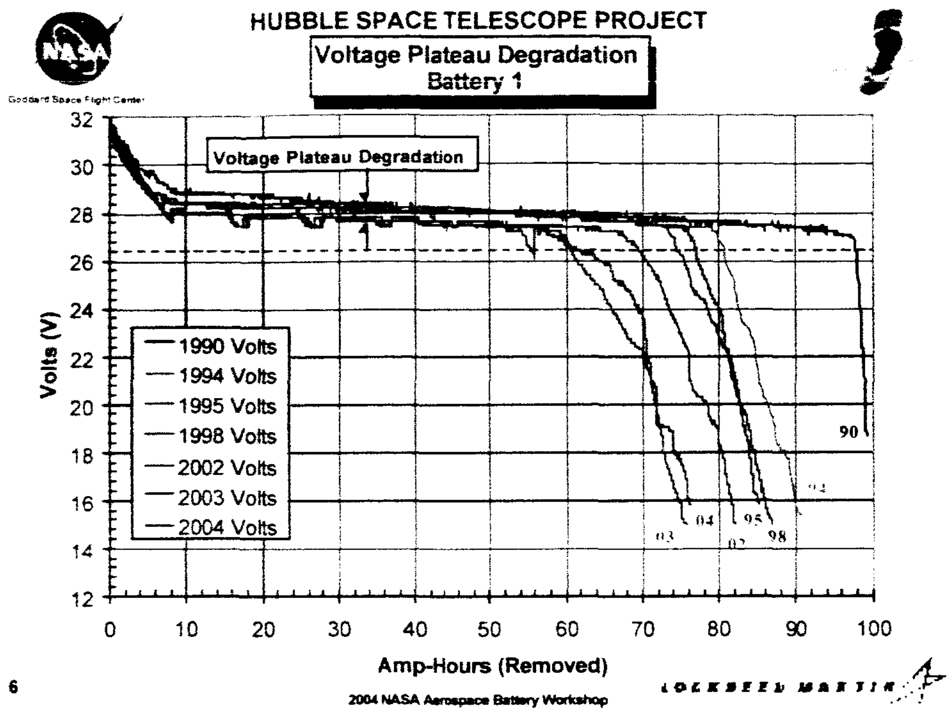
HST Flight Batteries
Ageing Signatures

- **Voltage Curves From Orbital Capacity Checks Exhibit**
  - **Voltage Plateau Degradation on All Batteries**
    - **Shown herein to be Artifact of State-of-Charge**
  - **Capacity Fade on All Batteries**
  - **Impedance Growth on All Batteries**
  - **Cell Drop Outs *(Reversal)* on All Batteries**
    - *Signature is sudden >0.8 V Drop in Battery Voltage*
  - **Second Plateau Formation on All Batteries**
    - *Second Plateau Signature <0.5 V*

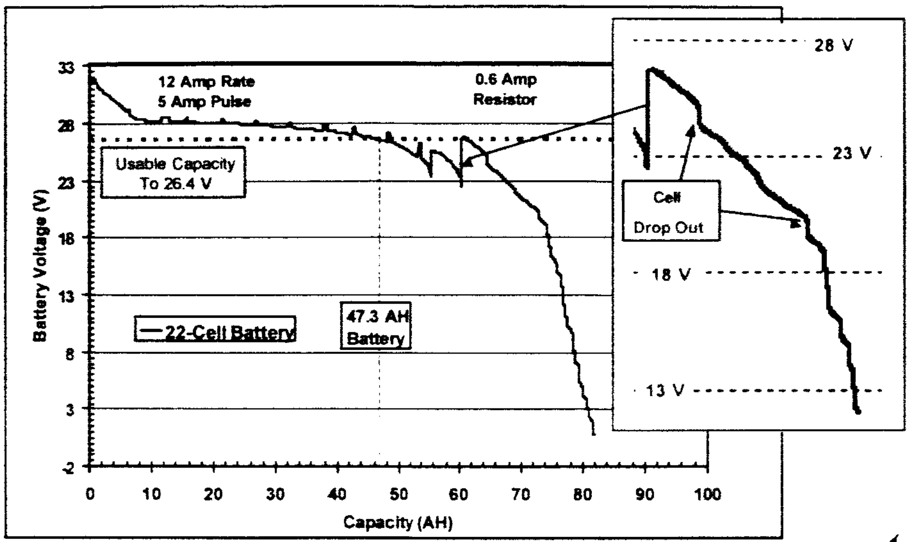
Capacity Check using 5.1 ohm Resistor across the Battery to 15 V

The on-orbit HST batteries, while having no individual cell monitor sensors, do exhibit similar voltage discharge signatures during capacity checks. Observed from these discharge curves are capacity fade, voltage plateau depression, impedance growth, 2^{nd} plateau, and cell drop out. The voltage plateau depression will be shown to be an artifact of beginning State of Charge (SOC), for the capacity check, and not real.



HST has experienced a depressed voltage plateau which was first observed after the SM3B servicing mission. This chart shows the capacity checks performed on HST Orbital Battery 1 since launch, as plotted versus the amp-hours removed from the battery. The depressed voltage at the midpoint of the discharge curve, as indicated, is of some concern, and the mechanism is being questioned.

Cell Wear Out Signatures - FSB



This is the battery voltage profile during a capacity discharge test conducted upon the Flight Spare Battery at MSFC. A 12 Amp discharge was modified to include 5 Amp pulses at 15 minute intervals, which provides dual discharge curves, which are then used for cell modeling of impedance and Electromotive Force (EMF) as a function of State of Charge (SOC).

Note that this battery exhibits a usable capacity (to 26.4 V) of 47.3 Ah. Additionally there are several sharp deflections in the discharge curve beyond 64 AH with delta-V in excess of 0.5 V, which have previously been identified as being individual cell reversals. With HST hydrogen pre-charge cells, this cell reversal voltage is around 0 to -0.100 V depending upon the current.

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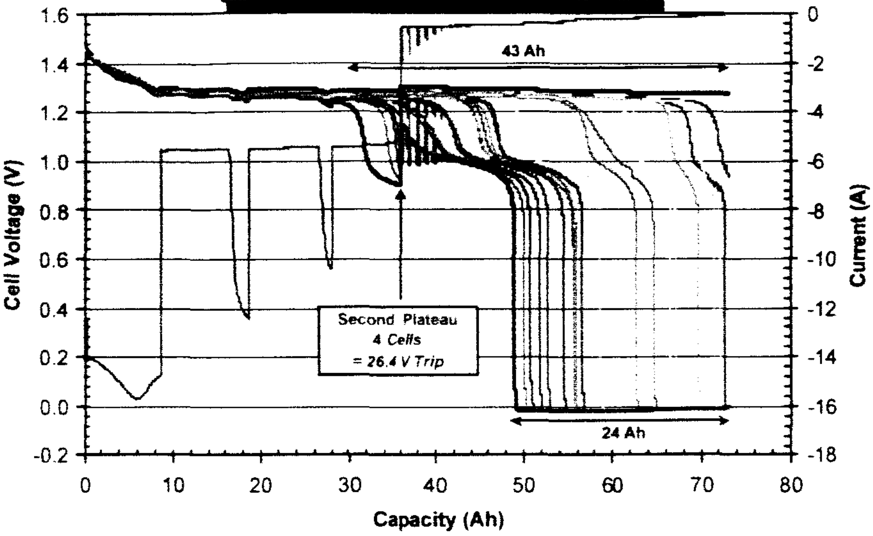
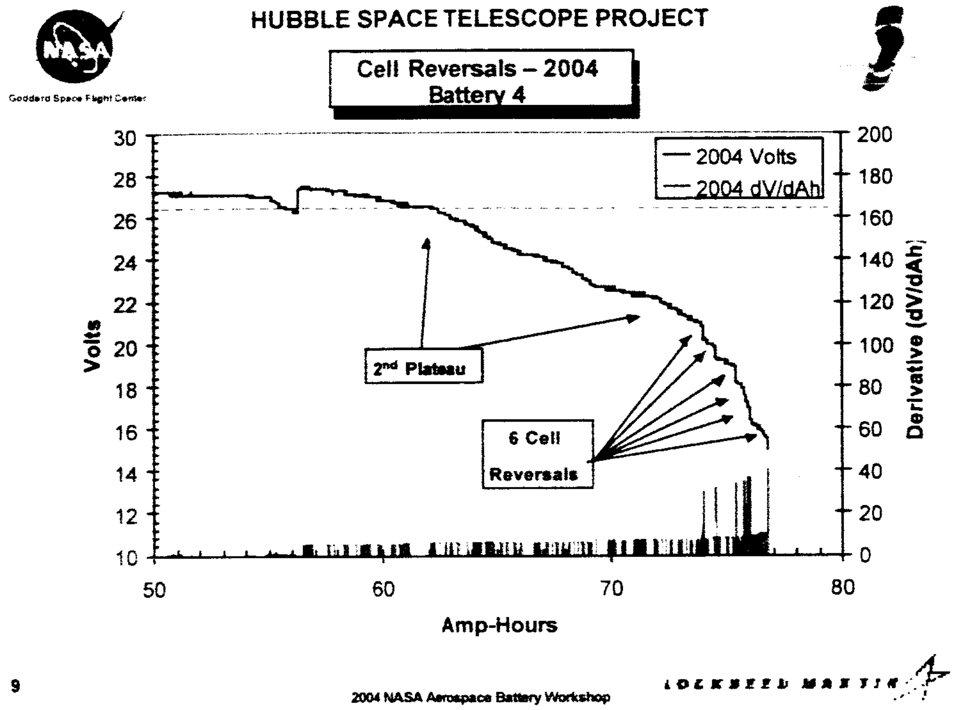
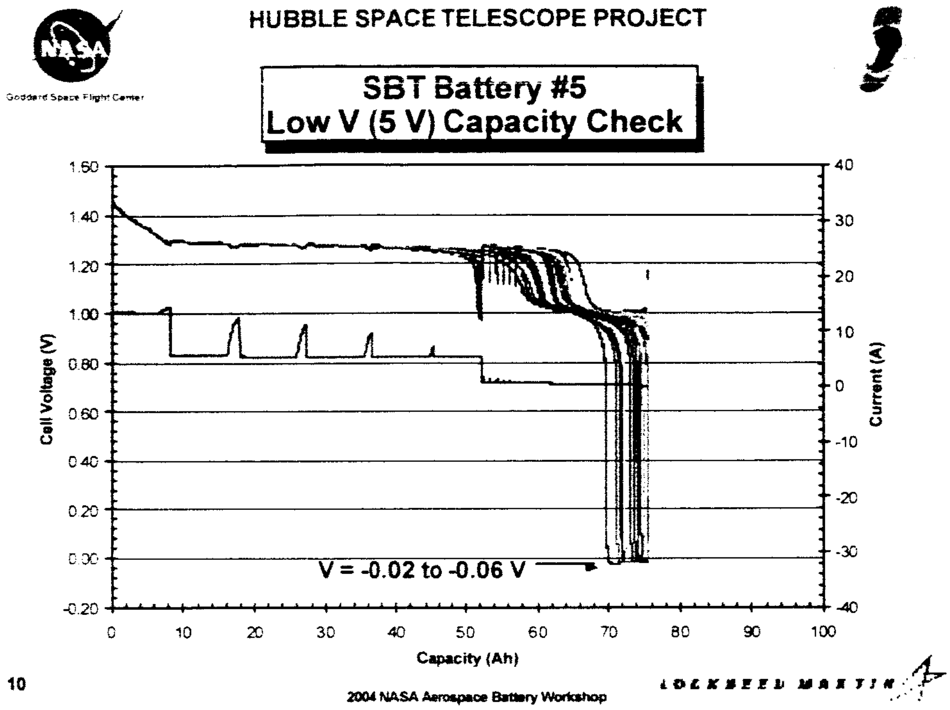
SBT Battery #1
Low V (2 V) Capacity Check



Battery cell wear out mechanisms and signatures are shown here for Battery 1 of the Six Battery Test Bed. Note that when the battery voltage declines to less than the 26.4 V battery minimum at about 36 Ah the individual cell monitoring indicates that only 4 cells have dropped down to the second discharge plateau. This is one limiting mechanism with a second mechanism being cell reversal. Note also that there is a capacity imbalance of 43 Ah between when the first cell goes down to the second plateau and when the test is terminated with one cell still above 1.3 V. Similarly the cell imbalance, between when the first cell goes into reversal and when the test is terminated with 2 cells not in reversal, is 24 Ah.



This chart details the voltage telemetry from the 2004 HST Orbital battery capacity check, plotted against the integrated Ah capacity. When the derivative of the Voltage/Ah capacity data is examined, as shown by the bottom trace here, it becomes apparent that 6 cells drop out, or go into reversal, between 74 Ah and 77 Ah. The slow decline in the battery voltage, starting at 60 Ah, is indicative of cells experiencing second plateau formation.



The individual cell voltages during a capacity check performed on Battery #5 of the Six Battery Test Bed shows significant second plateau formation, followed by cell reversals to voltages around –0.04 V. This reversal voltage is at the low rate resistor (50 ohm) discharge rate and the voltage is a function of the current. Other cell reversals on the Flight Spare Battery, with currents of 15 A, have shown reversal voltages of –0.08 V. The observed reversal voltage is a function of the electrochemical reactions occurring within the cell and this can help define the capacity fade mechanism.

Electrochemical Reactions

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NiH2 Electrochemistry
Normal Charge/Discharge

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Positive - Nickel Electrode

$$\beta - NiOOH \underset{charge}{\overset{discharge}{\rightleftarrows}} \beta - Ni(OH)_2$$

$$NiOOH + H_2O + e^- \underset{charge}{\overset{discharge}{\rightleftarrows}} Ni(OH)_2 + OH^-$$

E° = +0.5183 V

Negative - Hydrogen Electrode

$$\frac{1}{2}H_2 + OH^- \underset{charge}{\overset{discharge}{\rightleftarrows}} H_2O + e^-$$

E° = +0.8280 V

Net Reaction (Cell Voltage)

$$H_2 + NiOOH \underset{charge}{\overset{discharge}{\rightleftarrows}} Ni(OH)_2 + OH^-$$

E° = +1.3183 V

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The reactions occurring during discharge are shown here with the half-cell reactions on the individual electrodes shown by the first two equations. The sum of these equations is shown next, with the sum of the electrochemical voltages being 1.318 V, which equates to the cell standard potential. The actual observed voltage is this standard potential plus a correction for the reactant/product concentrations and the temperature (Nernst Equation).

The second set of reactions define the cell reversal when there is still hydrogen present, and nickel is depleted, I.e., nickel limited. The reactions occurring here are reversible on both electrodes and represent no net change of reactants, and a potential close to 0 V.

This is the case for the HST capacity fade mechanism, namely loss of electrochemically active nickel oxyhydroxide (NiOOH) due to charge limitations.

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NiH2 Electrochemistry
Second Plateau Discharge

$$\beta - NiOOH \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftarrows}} \beta - Ni(OH)_2$$

- Nickel Discharge Product
  - P-Type Semiconductor
  - Between Current Collector and Bulk Active Material
  - Film Thickness Builds With Cycling
  - Acts Like Schottky Diode
    - Requires ~ 0.3-0.4 V Drop to Conduct Current
    - Voltage Impact Lessened by +0.2-0.3 V (H2 Pressure Dependent)
      - Protons formed catalytically from Hydrogen
        - Injected at Current Collector

Albert Zimmerman of Aerospace Corporation has suggested that the second plateau observed during cycling is *possibly* due to the nickel hydroxide discharge product being a p-type semiconductor and builds up film thickness between the nickel electrode current collector and the bulk active material, undischarged nickel oxyhydroxide. This p-type interface film acts as a schottky diode, which requires a voltage drop (~0.3-0.4V) across the film to conduct current. This drop is lessened by the presence of hydrogen gas injecting protons at the current collector.

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NiH2 Electrochemistry
Cell Reversal – Hydrogen Pre-Charge (HST)

Positive - Nickel Electrode

$$H_2O + e^- \rightarrow \tfrac{1}{2}H_2 + OH^- \qquad E^\circ = -0.828\ V$$

Negative - Hydrogen Electrode

$$\tfrac{1}{2}H_2 + OH^- \rightarrow H_2O + e^- \qquad E^\circ = +0.828\ V$$

Net Reaction (Cell Voltage)

No Net Reactant Change $E^\circ = +0.000$

- *No Net Change in Reactant or Products*
- *No Pressure Change*
- *Current Must Be Low to Restrict Heat From Catalytic Recombination*

Cell reversal due to loss of active nickel oxyhydroxide reactant occurs with hydrogen pre-charge cells, with excess hydrogen gas, via the chemical reactions shown above, which define the cell voltage observed during cell reversal. Note that there is no net reactant change with no pressure changes. The current during cell reversal *must* be kept low to limit the heat due to catalytic recombination and thus possible cell electrode popping.

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NiH2 Electrochemistry
Cell Reversal – Nickel Pre-Charge

Positive - Nickel Electrode

$2\ NiOOH + 2\ H_2O + 2\ e^- \rightarrow 2\ Ni(OH)_2 + 2(OH)^-$ $E^o = +0.490\ V$

Negative - Hydrogen Electrode

$2(OH)^- \rightarrow H_2O + \frac{1}{2}O_2 + 2\ e^-$ $E^o = -0.401\ V$

Net Reaction (Cell Voltage)

$2\ NiOOH + H_2O \rightarrow 2\ Ni(OH)_2 + \frac{1}{2}O_2$ $E^o = -0.891$

$\frac{1}{2}O_2 + H_2 \rightarrow H_2O + HEAT$

- Nickel Oxide Discharge
- Increasing Oxygen Pressure
- Voltage Recovery Lags Due to Excess Oxygen
    - Loss Of Hydrogen Capacity Due to O_2-H_2 Recombination
- Oxygen Can Readily Dissolve Platinum (H_2 Catalyst)

Cell reversal due to loss of active hydrogen gas occurs with nickel pre-charge cells, with excess nickel oxyhydroxide, via the chemical reactions shown above, which define the cell voltage observed during cell reversal. The current during cell reversal *must* be kept low to limit the heat due to catalytic recombination and thus possible cell electrode popping.

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HST Cell Ageing Mechanism

- Charge is Limited to Low Recharge Ratios Due to Thermal Design
  - Thermal Design Limits Dissipation to 30 Watts
  - Batteries Enclosed in Two Compartments
  - Limited Trickle Charge Period for Charge Top-Off

- P-Type Semi-conductor β-$Ni(OH)_2$ Discharge Product
  - Film Thickness Increases with Cycles
  - Results in Second Plateau (0.2 – 0.3 Voltage Drop Below 1.3 V)
  - 4 Cells in Second Plateau Limits Battery Capacity at 26.4 V

- Solution to Second Plateau Formation
  - Long Period in Trickle Charge
  - Higher Recharge Ratio (> 1.2)

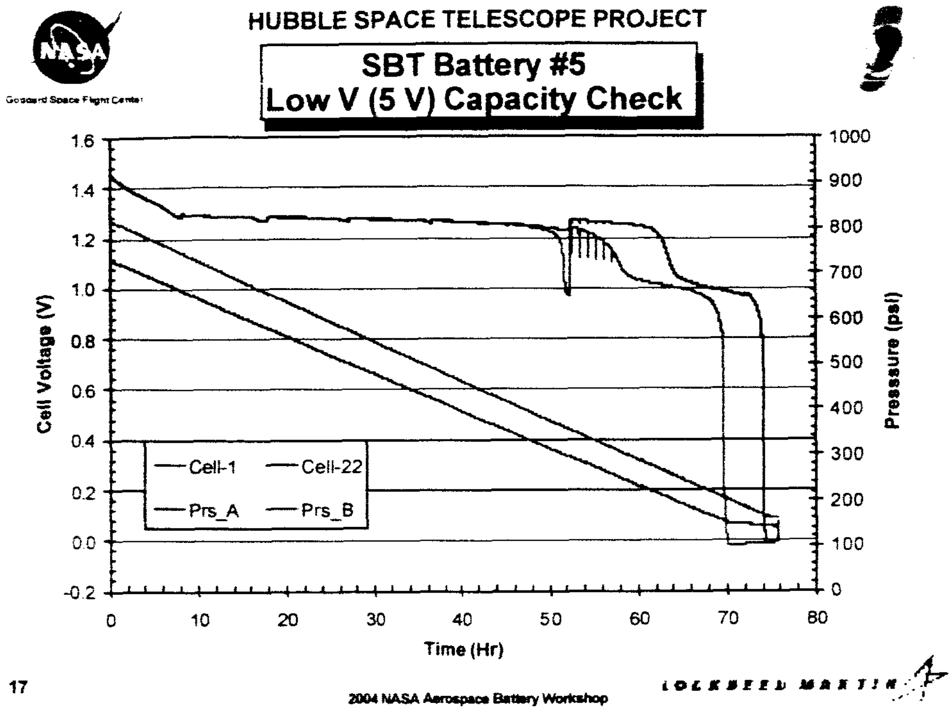
Two important facts should be mentioned here.

1) The battery age, with the thermal design, met the design criteria of 7 years, by 2X.

2) The Recharge Ratio, and thus the thermal dissipation design must be raised to insure longer battery life.

Similar battery ageing characteristics has been observed on a number of other LEO applications.

MEO and GEO applications tend to have enough trickle charge time to eliminate this ageing mechanism.



Battery cell wear out mechanisms and signatures are examined and compared to orbital data from the six on-orbit Hubble Space Telescope (HST) batteries, and the Flight Spare Battery (FSB) Test Bed at Marshall Space Flight Center (MSFC), which is instrumented with individual cell voltage monitoring.

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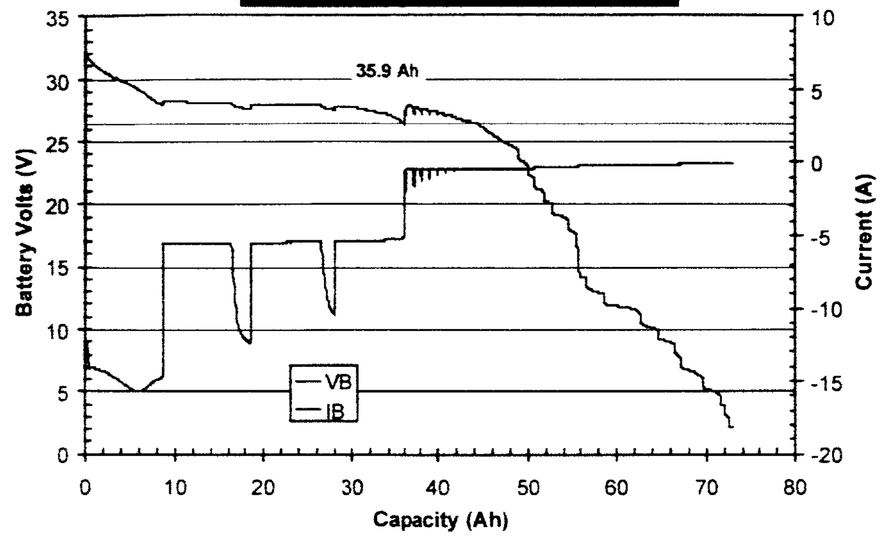
SBT Battery #1
Low V (2 V) Capacity Check



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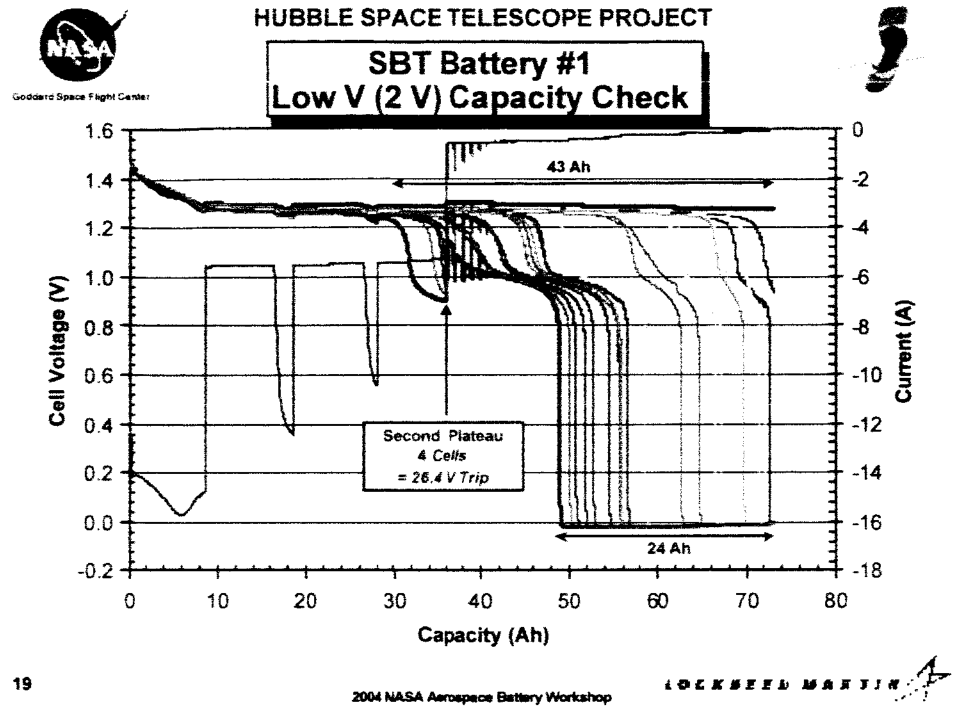

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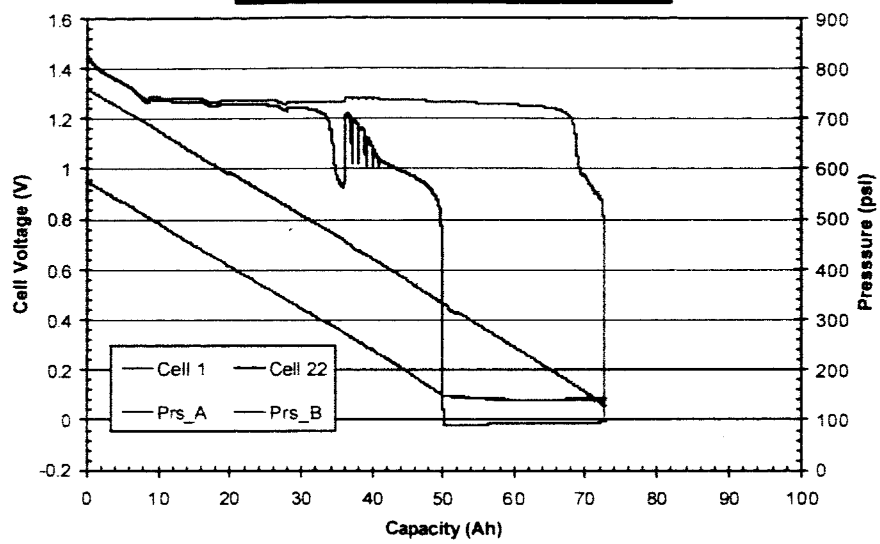

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Battery cell wear out mechanisms and signatures are examined and compared to orbital data from the six on-orbit Hubble Space Telescope (HST) batteries, and the Flight Spare Battery (FSB) Test Bed at Marshall Space Flight Center (MSFC), which is instrumented with individual cell voltage monitoring.

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Voltage Plateau Degradation Analysis

HST has observed a depressed voltage plateau which was first observed after the 2002 SM3B servicing mission. The following charts provide an analysis of this phenomenon and show that it is not a new wear out mechanism.

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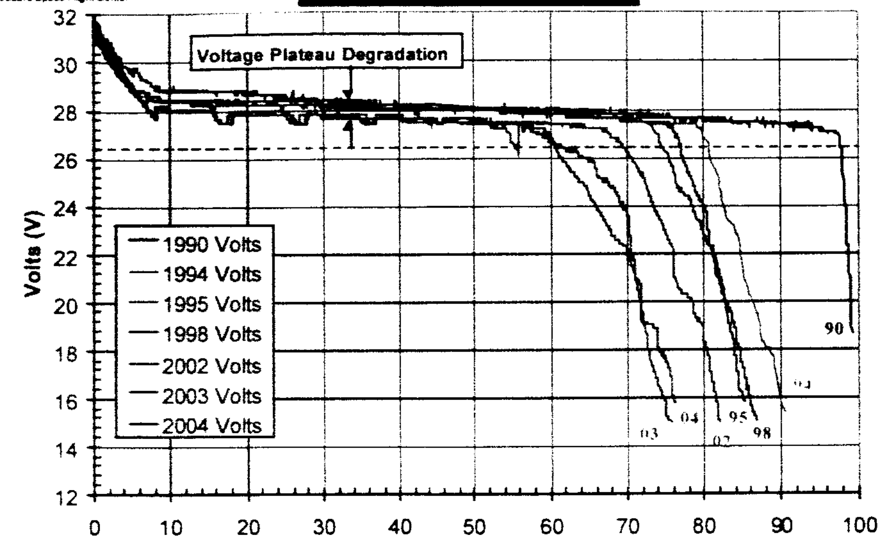
Voltage Plateau Degradation
Battery 1



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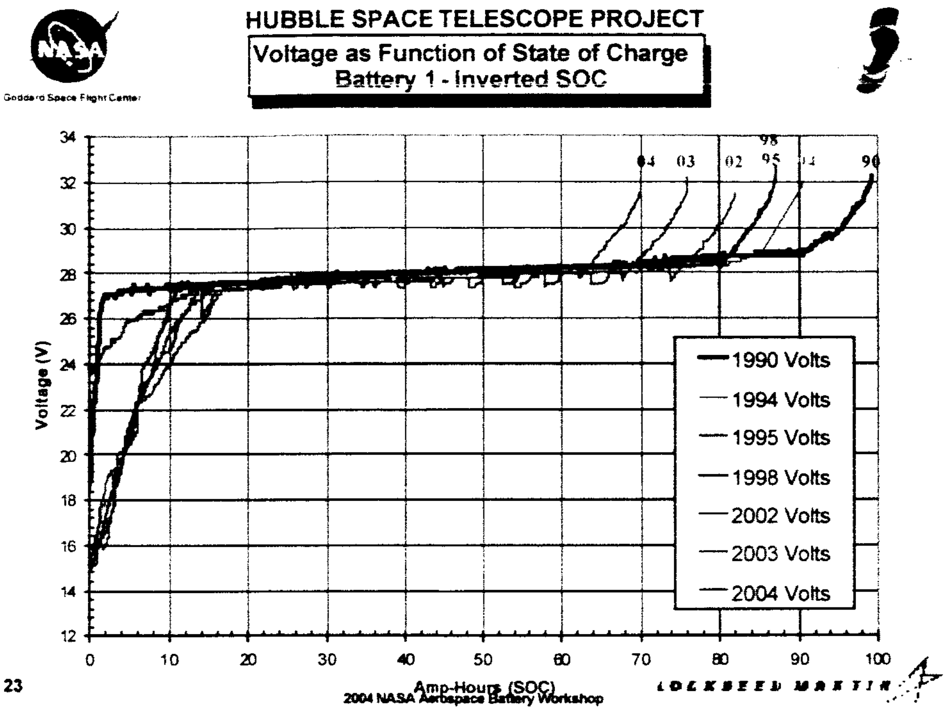
This chart shows the capacity checks performed on HST Orbital Battery 1 since launch, as plotted versus the amp-hours removed from the battery. The depressed voltage at the midpoint of the discharge curve, as indicated, is of some concern, and the mechanism is being questioned. The following charts will provide an explanation for this phenomenon.



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When the capacity check curves shown in the last chart are re-plotted based loosely upon State-of-Charge (SOC), with all the End-of-Discharge-Voltages (EODV) referenced as the starting point, then it becomes clear that the voltage plateau is really a function of the initial SOC, when the capacity check began rather than a new ageing signature. This chart suggests that the capacity decline observed with HST is a function of the system undercharge of the batteries. This also suggests that getting more charge into the battery would raise the available capacity. This chart also explains why Hari Vaidyanathan reports high (ATP BOL Level) capacity numbers on 13 & 14 year old Flight Spare Battery cycled cells during electrical testing in the DPA process, when he submited them to recharge ratios of 1.5, which charges the cells to full capacity.

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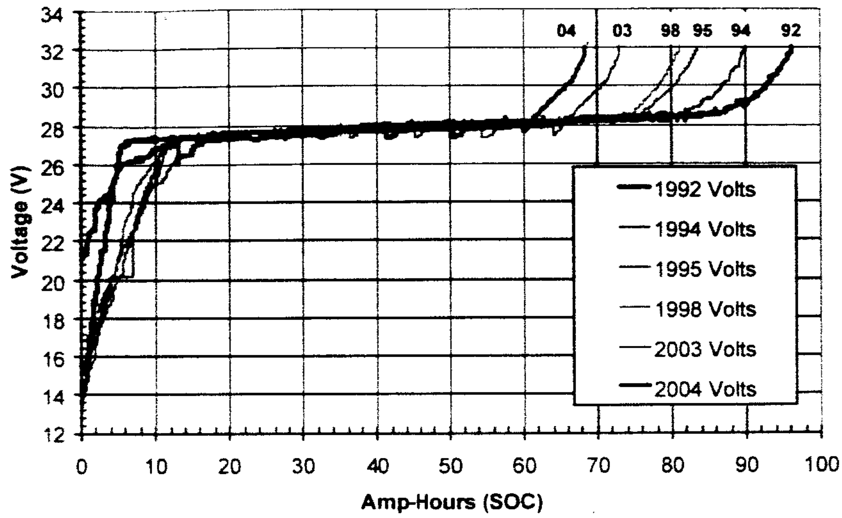
Voltage as Function of State of Charge
Battery 2 - Inverted SOC



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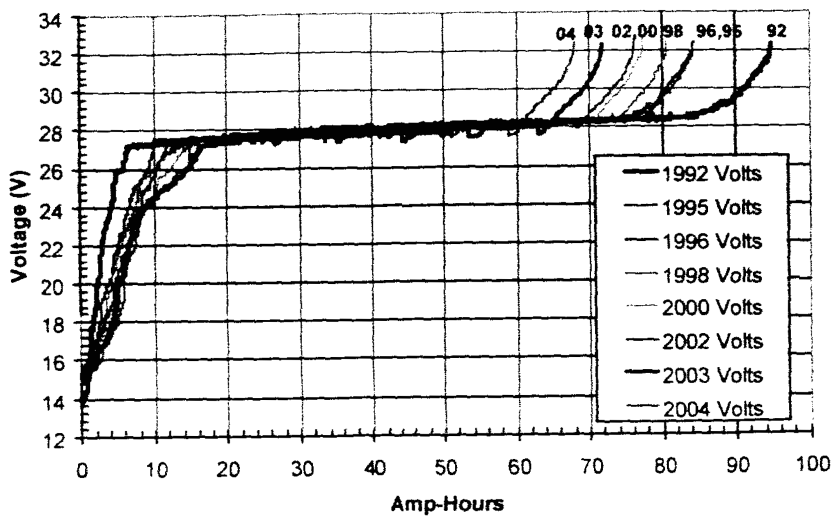
Voltage as Function of State of Charge
Battery 3 – inverted SOC



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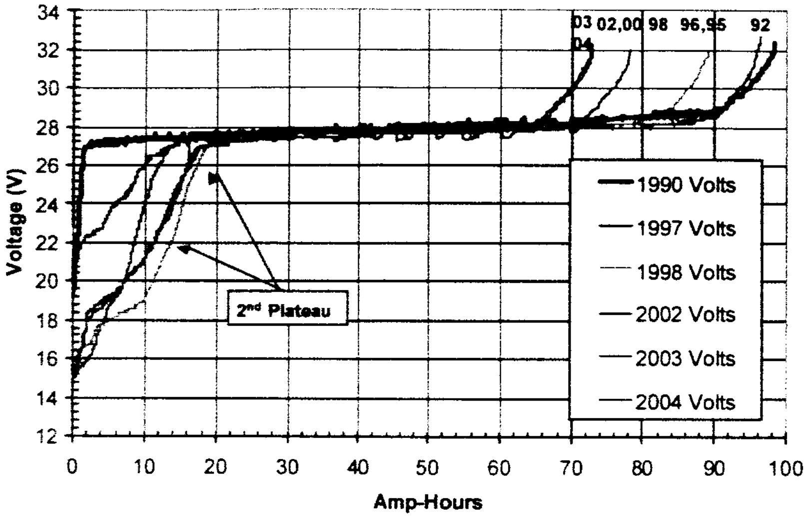
Voltage as Function of State of Charge Battery 4 – invert SOC



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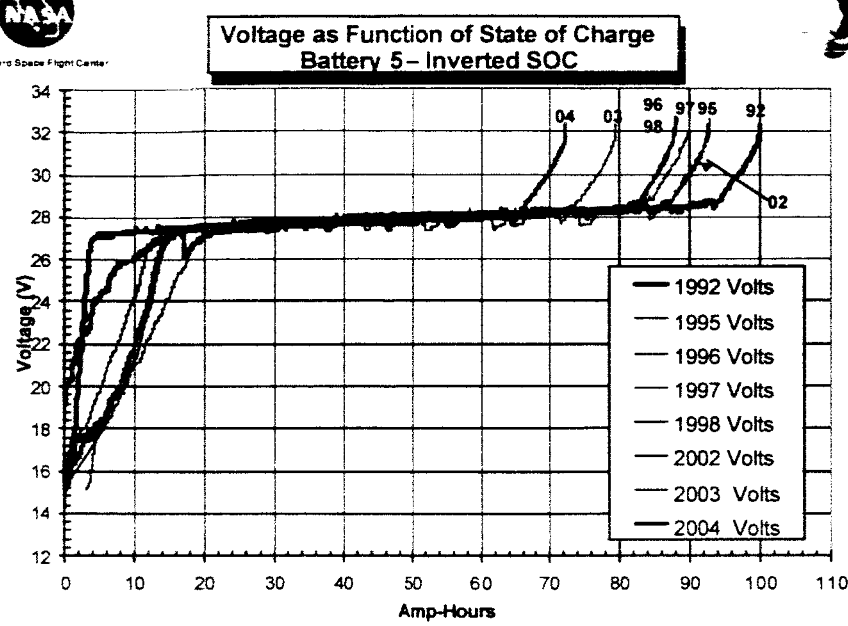

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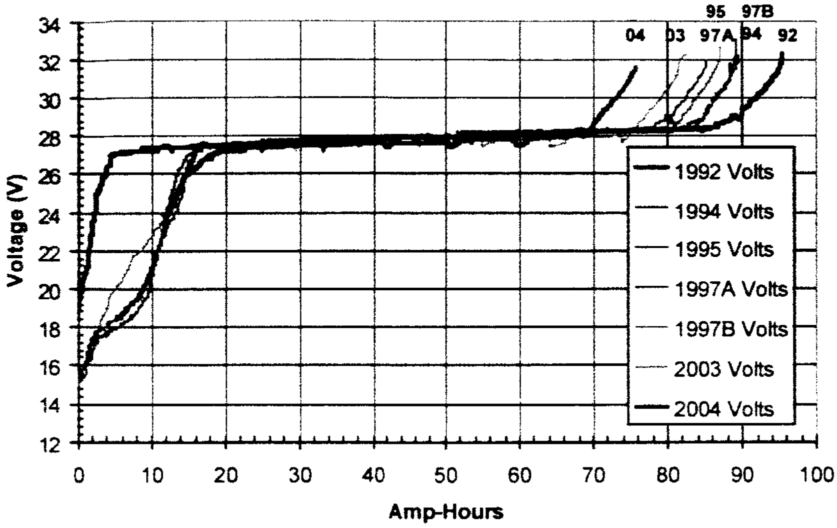
Voltage as Function of State of Charge Battery 6 – Inverted SOC



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Orbital Strain Gauge Drift Analysis

The capacity of batteries in orbit is based upon the pressure reading from one or two strain gauges per battery. The question of strain gauge drift has been raised and the following charts provide an analysis of the orbital pressure readings and their relation to actual battery capacity.

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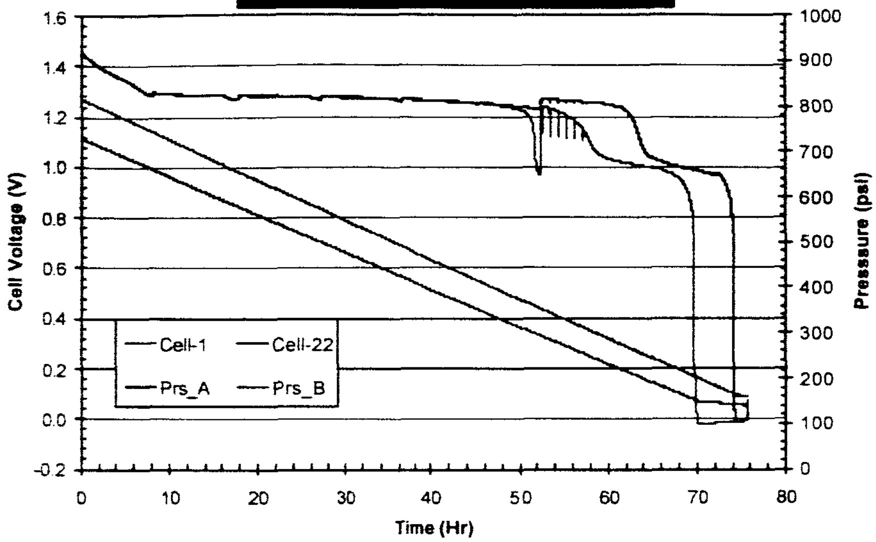
SBT Battery #5
Low V (5 V) Capacity Check



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The ground test results from the Six Battery Test-Bed and the Flight Spare Battery show in every case that when the strain gauge pressure flat-lines during a capacity check, it indicates that the strain gauge cell becomes nickel limited and the cell is in reversal. The pressure flat-lines at around 150 psi and the cell voltage is at around –0.04 V.

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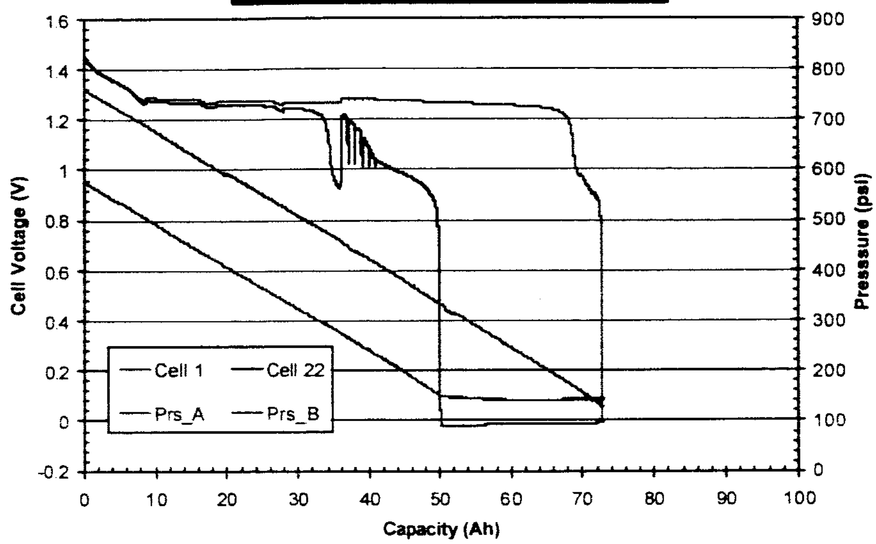
SBT Battery #1
Low V (2 V) Capacity Check



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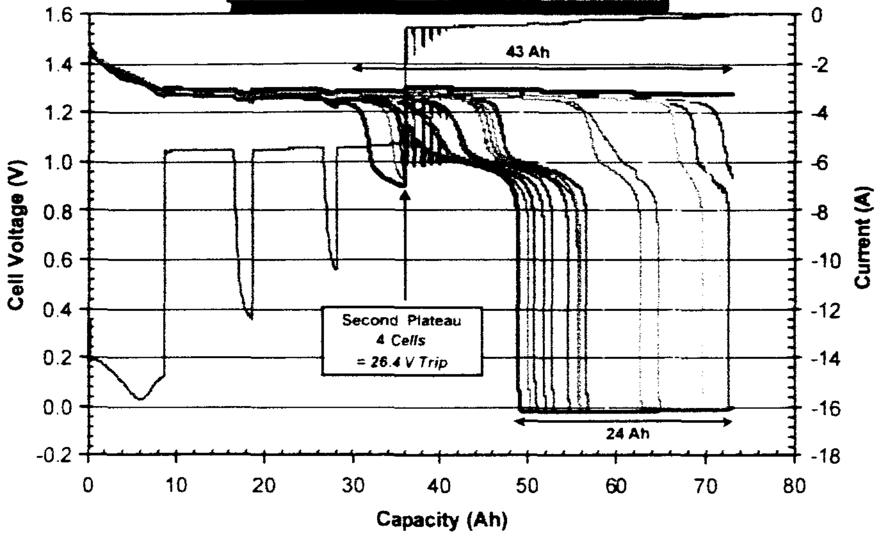
SBT Battery #1
Low V (2 V) Capacity Check



Strain Gauge Drift is indicative of the capacity imbalance between cells, as shown by this chart where the difference in second plateau capacity is at least 43 Ah, while the cell reversal capacity is at least 24 Ah. The strain gauge pressure indicated would depend upon which cell is was monitoring – weak, average, strong, etc.

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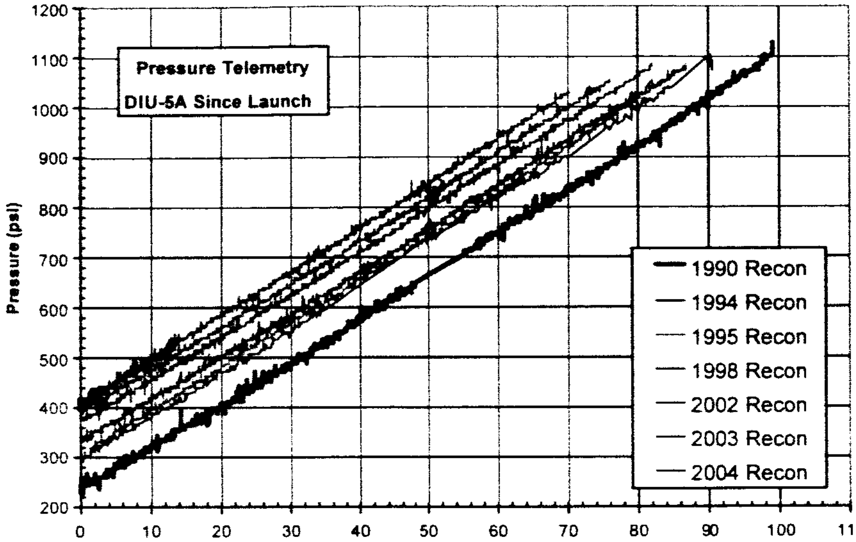
Strain Gauge Drift
Battery 1



The orbital pressure telemetry only monitors either the A-side or B-Side pressure, which means only one of 22 cells is monitored. This chart shows a typical drift of the strain gauge pressure to higher pressures with time. This could be due to either nickel corrosion producing more hydrogen, or it could indicate that the strain gauge cell is a stronger cell within the battery. The stronger cells would have higher states of charge and thus capacity.

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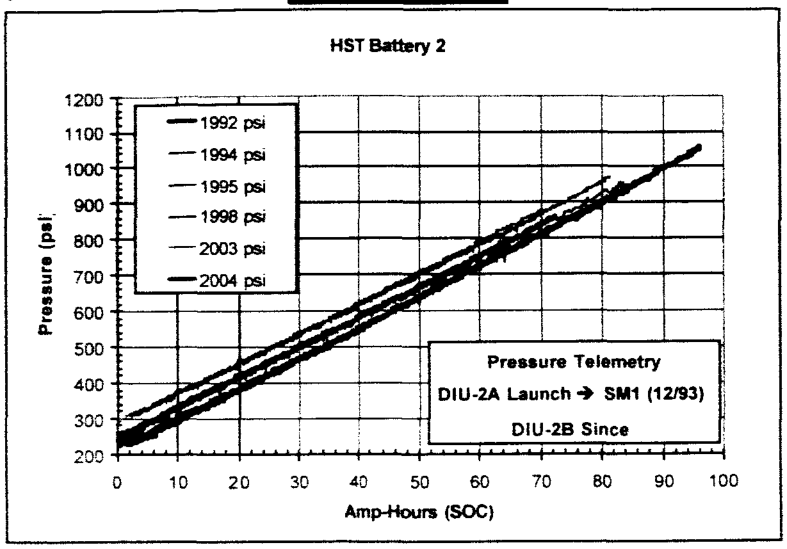
Strain Gauge Drift Battery 2



This chart shows a typical drift of the strain gauge pressure to higher pressures with time in 1998 ands 2003. This could be due to either nickel corrosion producing more hydrogen, or it could indicate that the strain gauge cell is a stronger cell within the battery. The strain gauge pressure then drops in 2004 indicating the strain gauge cell is a weaker than average cell.

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Strain Gauge Drift
Battery 3

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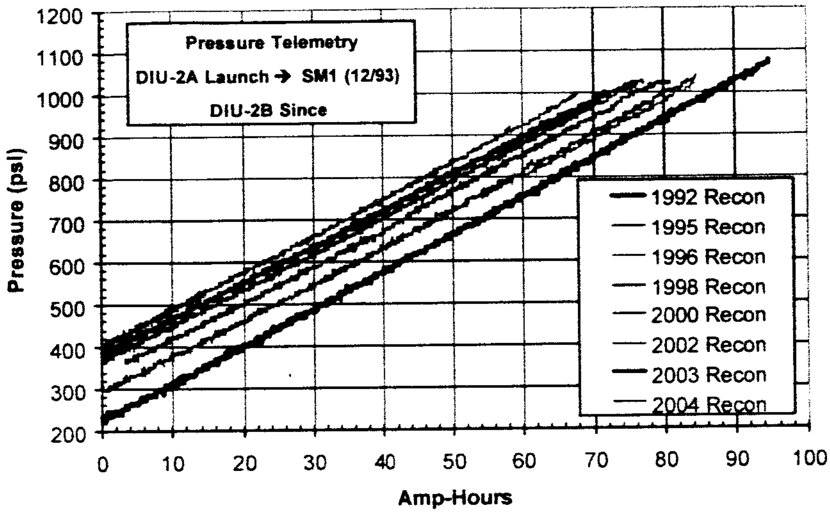

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This chart shows a typical drift of the strain gauge pressure to higher pressures with time. This could be due to either nickel corrosion producing more hydrogen, or it could indicate that the strain gauge cell is a stronger cell within the battery. The stronger cells would have higher states of charge and thus capacity.

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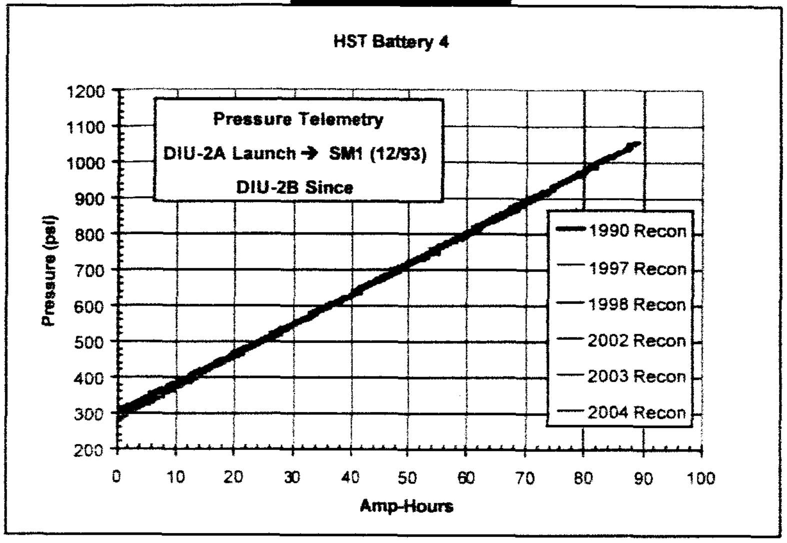
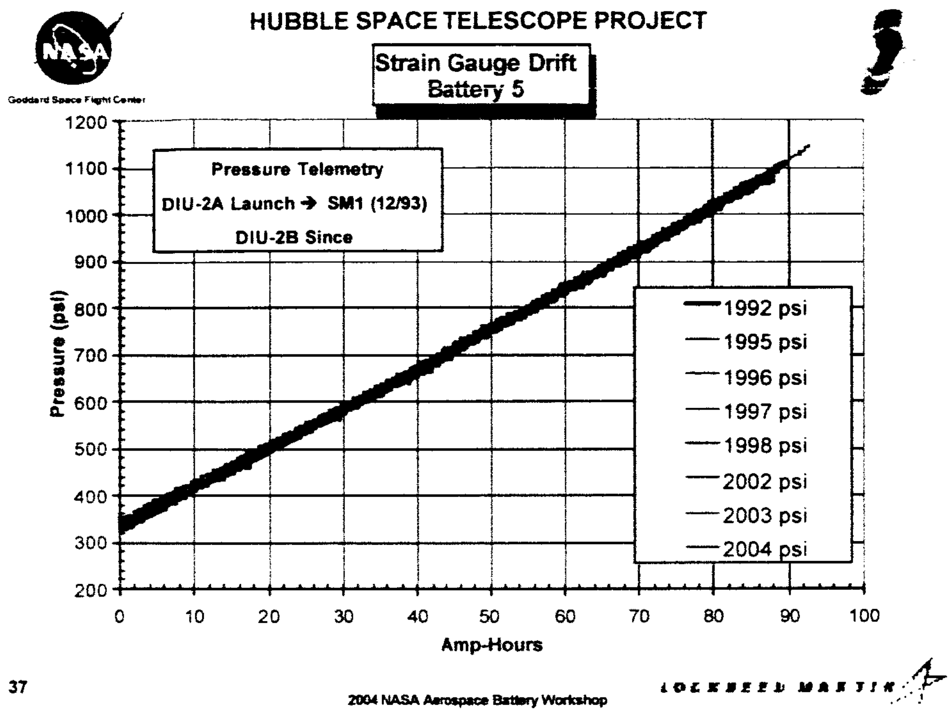
Strain Gauge Drift
Battery 4



This chart shows no change of the strain gauge response with time which suggests no nickel corrosion. The stable operation also suggests no physical or electronic issues. The strain gauge cell probably is a very average cell within the battery, with an average capacity.



This chart shows a slight drift of the strain gauge pressure to higher pressures with time. This could be due to either nickel corrosion producing more hydrogen, or it could indicate that the strain gauge cell is a stronger cell within the battery. The stronger cells would have higher states of charge and thus capacity.

HUBBLE SPACE TELESCOPE PROJECT

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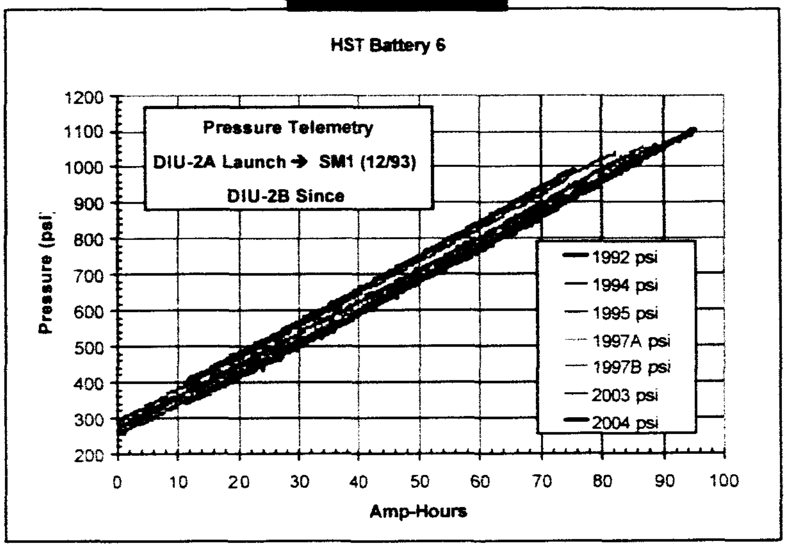
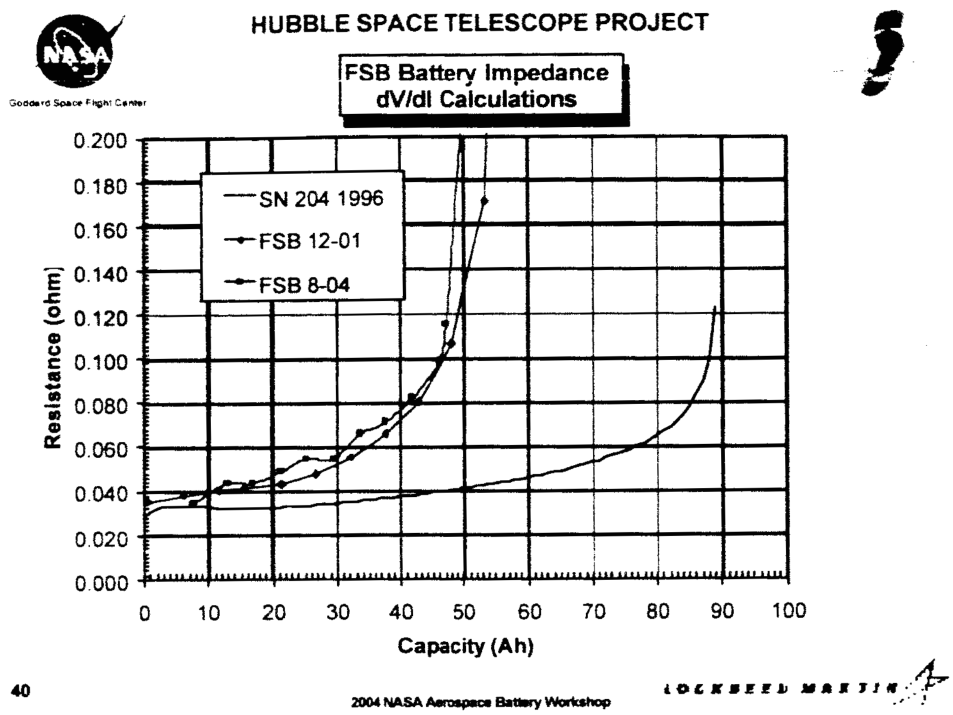
Strain Gauge Drift
Battery 6



This chart shows a slight drift of the strain gauge pressure to higher pressures with time. This could be due to either nickel corrosion producing more hydrogen, or it could indicate that the strain gauge cell is a stronger cell within the battery. The stronger cells would have higher states of charge and thus capacity.

Hubble Space Telescope

Impedance & Safe Mode Margins Analysis



This details the impedance of the HST cells at various points in age. The S/N 204 impedance data is from the modeling of separate 40 A and a 18/9 A discharges conducted in 1996 as part of the HST Mini-Characterization Studies conducted at MSFC and Eagle Picher. This study compared the HST dry sinter cells with the SM4 wet slurry cells. The Flight Spare Battery (FSB) impedance data is from pulse discharge studies conducted at MSFC in 2001 and 2004. All this data is plotted versus the capacity delivered by the battery.

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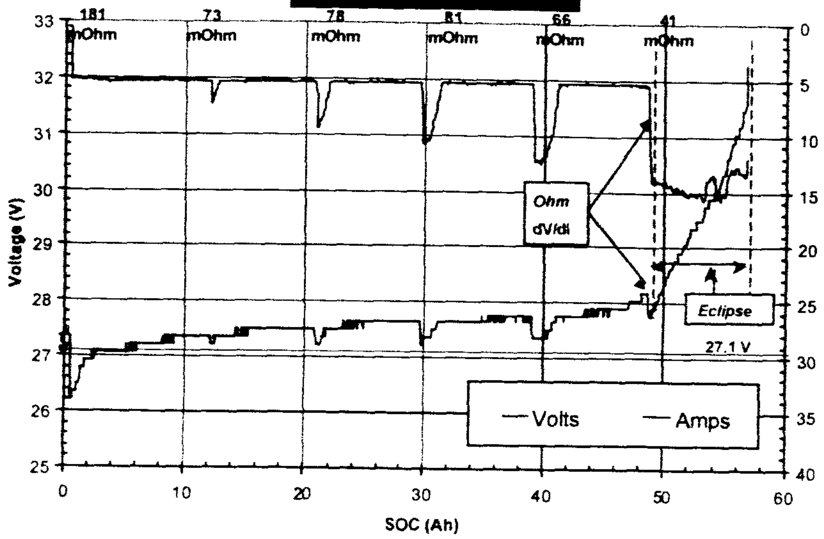
Orbital Battery 4
2004 Capacity Check



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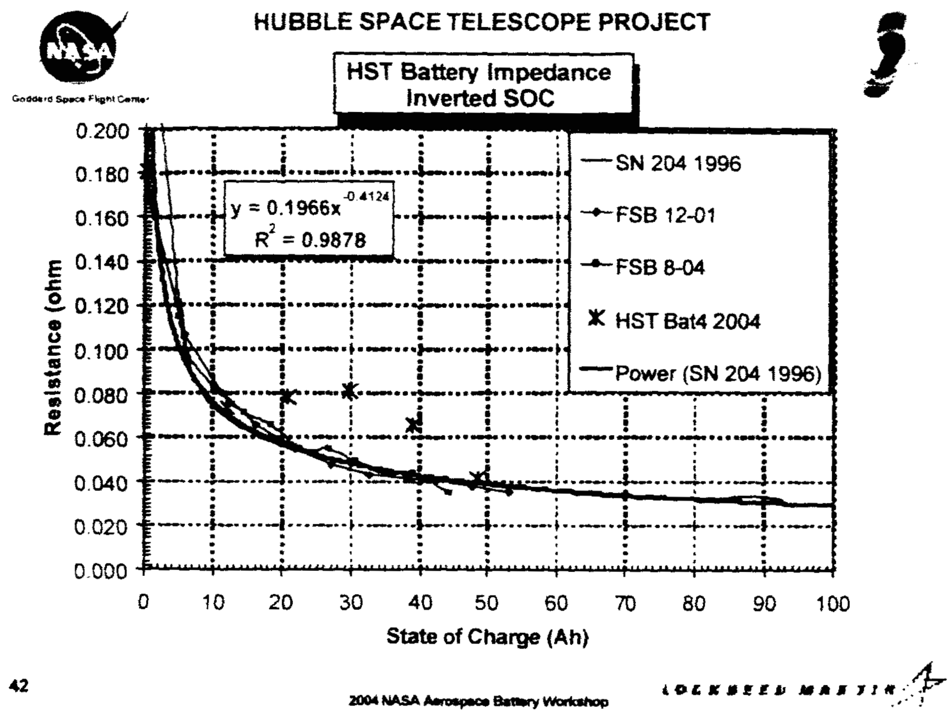
2004 NASA Aerospace Battery Workshop

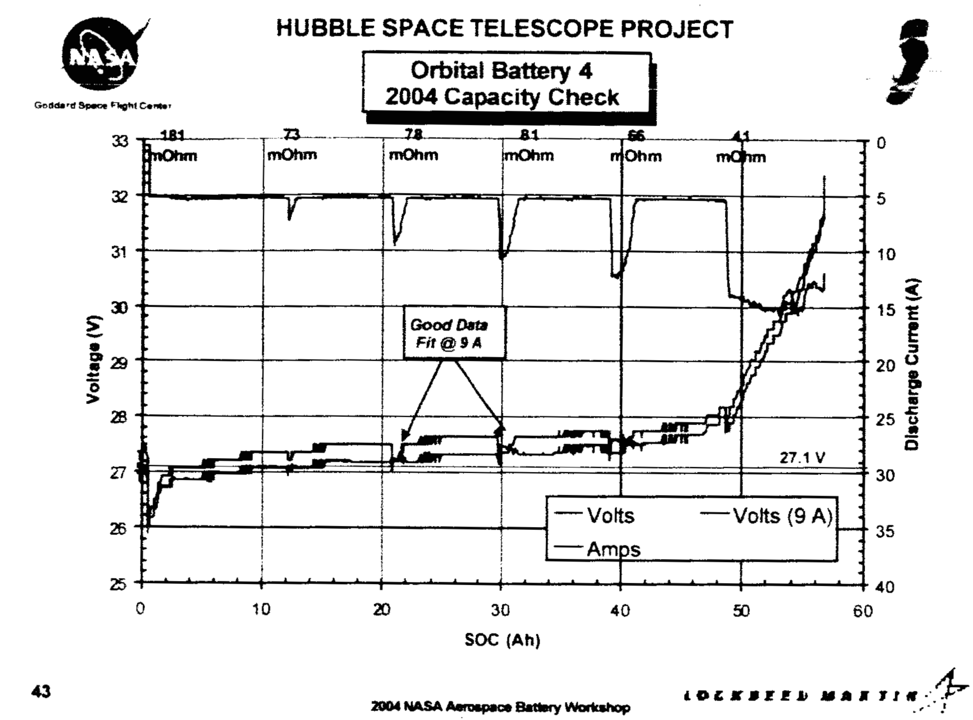
LOCKHEED MARTIN

This is telemetry from the 2004 capacity check performed on Battery #4, which had periods of load share with the other five orbital batteries, as shown by periods of current in excess of 5 A. The transition from load share to high rate resistor (5 A) can be used to calculate a battery impedance as a function of state of charge.

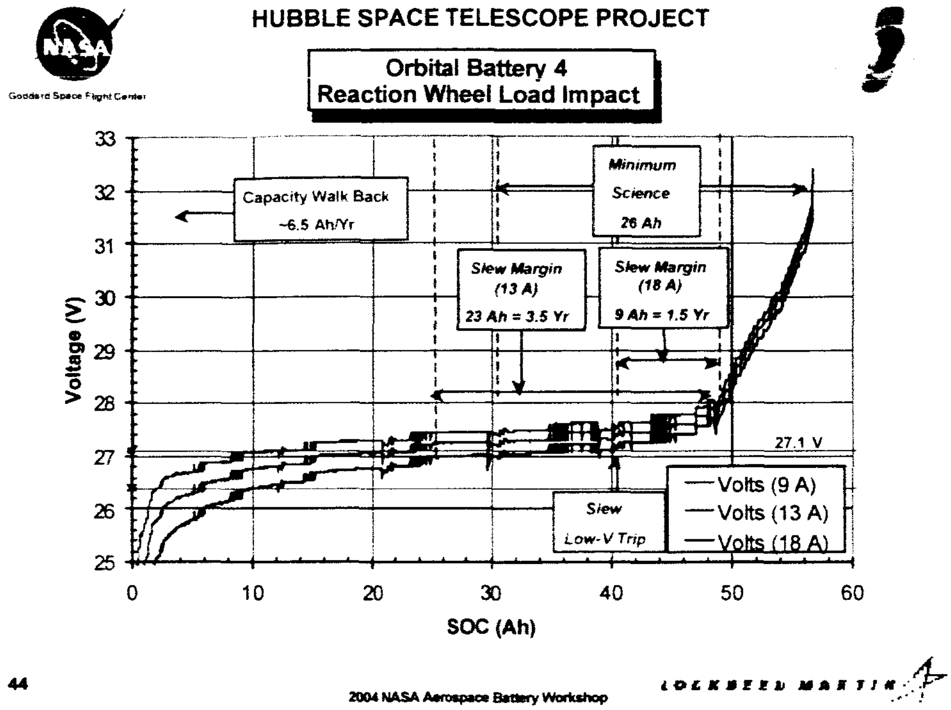


Standardizing this data to a common point, namely a discharged battery or cell, where all cells are at a similar State-of-Charge (SOC), is shown. Here it can be seen that the impedance versus SOC curves for the above ground testing, and the impedance data derived from the Orbital Battery #4 (Slide 4), are very similar. The outliers of the Battery 4 data can be explained by the nature of telemetry data, with different data rates for voltage and current.

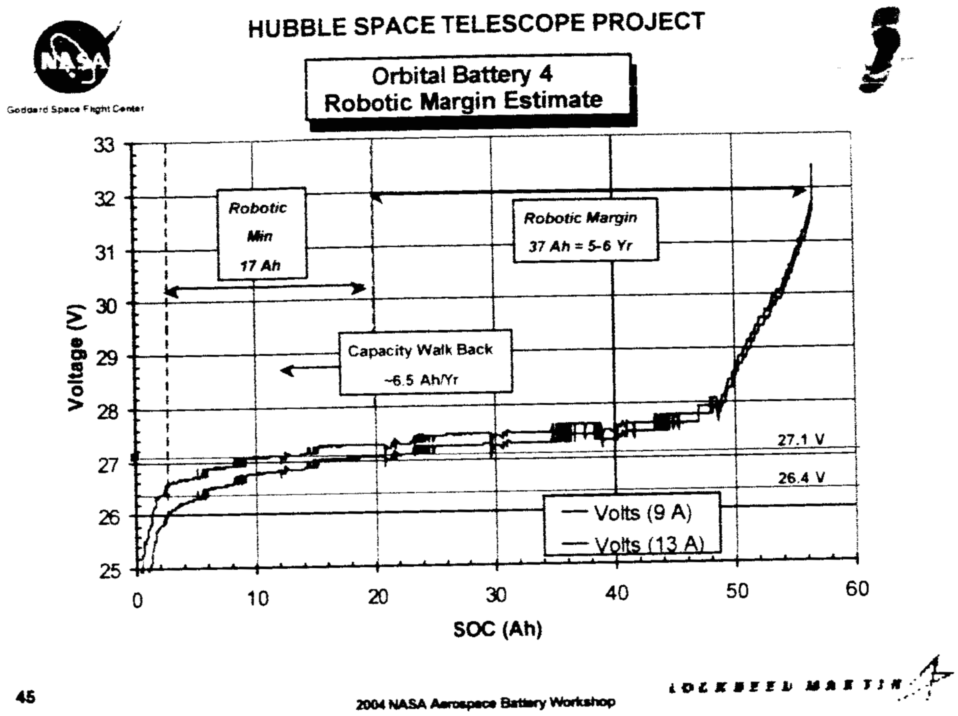
Fitting the 1996 S/N 204 data yields the power formula shown.



This equation was then used to calculate a battery impedance as a function of the SOC, and that impedance applied to the Battery 4 voltage/current data to project what a 9 A discharge would look like, as show. Note that when the orbital data is load sharing with currents close to 9 A (22 & 30 Ah) that the 9 A projected curve is a close approximation of the voltage actually observed during those periods. This is a strong validation of this technique. **It should be noted that the battery voltage shown here during the load share periods is representative of all 6 batteries because HST has a battery clamped bus.**



This slide shows the projected 9 A, 13 A, and 18 A discharge curves, as applied to the Battery 4 2004 Capacity Check. This slide enables one to examine how close to the minimum science voltage of 27.1 the battery voltage approaches, during the 18 A/battery expected due to reaction wheel, used for HST pointing, spin up. ***The projected discharge curve for 18 A shows that the 27.1 V minimum science voltage would be encountered within 9 Ah of the exit of the current eclipse period. This represents the margin currently available for extrme reaction wheel slew loads ot 18 A, during eclipse periods. With a capacity fade rate of 6.55 Ah/year/battery, this minimum will be encountered within 1-2 years, with the defined Science Minimum Capacity of 26 Ah already being violated.*** If the vehicle slews can be modified to reduce the reaction wheel current loads to below 13 A, then science ops can possibly be extend out 3-4 years. The battery voltages shown on this slide represents a deconditioned battery. When reconditioning occurs the battery voltage will be raised by several hundred millivolts, giving the science community an additional time margin before losing science capabilities. This is an argument for continued reconditioning of the HST batteries.



This slide addresses when control of the HST vehicle will be lost due to insufficient capacity required to maintain control the vehicle attitude during a robotic docking mission. As shown there is currently a margin of 37 Ah, which with the capacity fade rate, projects a 5-6 year window of opportunity, before control of the vehicle becomes unstable

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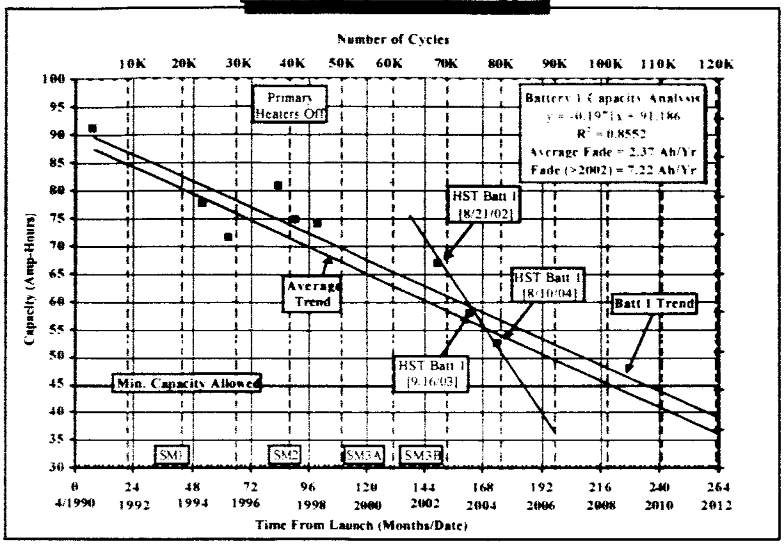
HUBBLE SPACE TELESCOPE PROJECT

Orbital Trending
Battery 1 (9 A Capacity)



R^2 = Fit Coefficient (1.0 = Best)

LOCKHEED MARTIN

Battery capacity fade, corrected for 9 Amp capacity, trend suggests a Battery 1 replacement in 2009 (assuming 45 Ah/battery) if the general trend (with a R^2 fit coefficient of 0.86) is used or 2005 if the trend from the last two reconditioning cycles were to continue. With the increased DOD since SM3B, it is anticipated that the capacity degradation will be slightly higher to that prior to SM3B.

The capacities shown here have been corrected to reflect a 9 amp load.

HUBBLE SPACE TELESCOPE PROJECT

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HST Orbital Data
Cycle Life Projections (45 Ah)

- Cycle Life Projection Based Upon Minimum Capacity Requirement of 45 Ah/Battery [9 Amp Rate]

From Launch (4/30/1990)	System	Bat 1	Bat 2	Bat 3	Bat 4	Bat 5	Bat 6
Projected Life (Yrs)	18.4	19.5	17.2	16.8	17.0	17.2	21.5
Date (System Min = 45 Ah)	Sep-2008	Nov-2009	Jun-2007	Feb-2007	Apr-2007	Jun-2007	Oct-2011
R2	0.811	0.855	0.928	0.970	0.943	0.915	0.776
Capacity Fade (AH/Yr)	2.40	2.37	2.62	2.49	2.93	2.74	1.78

From 80+ Months (1997 -)	System	Bat 1	Bat 2	Bat 3	Bat 4	Bat 5	Bat 6
Projected Life (Yrs)	18.8	17.7	16.41	16.5	16.1	17.4	21.8
Date (System Min = 45 Ah)	Feb-2009	Jan-2008	Sep-2006	Nov-2006	May-2006	Sep-2007	Feb-2012
R2	0.766	0.926	0.986	0.981	0.973	0.975	0.900
Capacity Fade (AH/Yr)	2.77	3.17	3.114	2.69	3.59	2.80	1.79

Since SM3B (4/2002 -)	System	Bat 1	Bat 2	Bat 3	Bat 4	Bat 5	Bat 6
Projected Life (Yrs)	15.8	15.4	15.6	16.0	16.2	15.3	15.7
Date (System Min = 45 Ah)	Feb-2006	Oct-2005	Dec-2005	Apr-2006	Jul-2006	Aug-2005	Jan-2006
R2	0.692	0.992	1.000	0.992	0.735	1.000	1.000
Capacity Fade (AH/Yr)	6.55	7.22	4.49	3.38	3.49	7.18	7.50

Last Recondition	System	Bat 1	Bat 2	Bat 3	Bat 4	Bat 5	Bat 6
Capacity (Ah)	52.38	52.30	51.77	49.71	52.70	51.48	56.3
Date	8/23/04	8/10/04	3/29/04	8/23/04	6/3/04	6/29/04	4/27/04

Table summarizes the system and individual battery capacity fade rates and projects a date for replacement, assuming a minimum system capacity of 270 Ah (45 Ah per battery). The capacity trending shown here has been corrected to reflect a 9 amp load.

The top table summarizes the data since launch.

The second data set provides a projection since the primary heaters were disabled.

The third set examines the trend since the Power Conditioning Unit was replaced in 2002 during SM3B. Since that time, all of batteries have undergone 2 capacity checks, and 2 batteries each having undergone 3 capacity checks, with trends reported herein. Near-term battery replacement is required if these trends were to continue.

The last data set lists the date and capacity of the last capacity check for each battery.

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HST Orbital Data
Cycle Life Projections (20 Ah)

- Cycle Life Projection Based Upon Minimum Capacity Requirement of 20 Ah/Battery [9 Amp Rate]

From Launch (4/30/1990)	System	Bat 1	Bat 2	Bat 3	Bat 4	Bat 5	Bat 6
Projected Life (Yrs)	28.8	30.1	26.7	26.9	25.5	26.3	35.5
Date (System Min = 20 Ah/Bat)	Feb-2019	May-2020	Jan-2017	Mar-2017	Nov-2015	Aug-2016	Oct-2025
R2	0.811	0.855	0.928	0.970	0.943	0.915	0.778
Capacity Fade (AH/Yr)	2.40	2.37	2.62	2.49	2.93	2.74	1.78

From 80+ Months (1997 -)	System	Bat 1	Bat 2	Bat 3	Bat 4	Bat 5	Bat 6
Projected Life (Yrs)	27.8	25.6	24.44	25.8	23.0	26.3	35.8
Date (System Min = 20 Ah/Bat)	Feb-2018	Nov-2015	Oct-2014	Feb-2016	May-2013	Aug-2016	Feb-2026
R2	0.766	0.926	0.986	0.981	0.923	0.975	0.900
Capacity Fade (AH/Yr)	2.77	3.17	3.114	2.69	3.59	2.80	1.79

Since SM3B (4/2002 -)	System	Bat 1	Bat 2	Bat 3	Bat 4	Bat 5	Bat 6
Projected Life (Yrs)	19.7	18.9	21.2	23.4	23.4	18.8	19.0
Date (System Min = 20 Ah/Bat)	Dec-2009	Mar-2009	Jul-2011	Sep-2013	Sep-2013	Jan-2009	May-2009
R2	0.692	0.992	1.000	0.992	0.735	1.000	1.000
Capacity Fade (AH/Yr)	6.55	7.22	4.49	3.38	3.49	7.18	7.50

Last Recondition	System	Bat 1	Bat 2	Bat 3	Bat 4	Bat 5	Bat 6
Capacity (Ah)	52.38	52.30	51.77	49.71	52.70	51.48	56.3
Date	8/23/04	8/10/04	3/29/04	8/23/04	6/3/04	6/29/04	4/27/04

Table summarizes the system and individual battery capacity fade rates and projects a date for replacement, assuming a minimum system capacity of 120 Ah (20 Ah per battery). The top table summarizes the data since launch.

The second data set provides a projection since the primary heaters were disabled.

The third set examines the trend since the Power Conditioning Unit was replaced in 2002 during SM3B. Since that time, all of batteries have undergone 2 capacity checks, and 2 batteries each having undergone 3 capacity checks, with trends reported herein. Near-term battery replacement is required if these trends were to continue.

The last data set lists the date and capacity of the last capacity check for each battery.