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.
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 \( \text{NiH}_2 \) 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 \( \text{NiH}_2 \) cell design.

The HST replacement batteries for Service Mission 4, originally scheduled for Spring 2005, are currently in cold storage at NASA Goddard Space Flight Center (GSFC). The SM4 battery cells utilize slurry process electrodes having 80% porosity.
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”.
16 NiH2 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.
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, 2nd 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.
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.
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. Second plateau is one limiting mechanism, with a second 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
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 activities (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.
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.
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.
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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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.
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.
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. The following charts will provide an explanation for this phenomenon.
When the capacity check curves shown in the last chart are re-plotted based 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 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, similar to ATP Levels at BOL.
Voltage as Function of State of Charge
Battery 2 – Inverted SOC

Voltage (V)

Amp-Hours (SOC)

1992 Volts
1994 Volts
1995 Volts
1998 Volts
2003 Volts
2004 Volts
Voltage as Function of State of Charge
Battery 3 – Inverted SOC

Voltage (V)

Amp-Hours

12 14 16 18 20 22 24 26 28 30 32 34

0 10 20 30 40 50 60 70 80 90 100

1992 Volts
1995 Volts
1996 Volts
1998 Volts
2000 Volts
2002 Volts
2003 Volts
2004 Volts

HUBBLE SPACE TELESCOPE PROJECT
Voltage as Function of State of Charge
Battery 4 – Invert SOC

2nd Plateau
Voltage as Function of State of Charge
Battery 5 – Inverted SOC

- 1992 Volts
- 1995 Volts
- 1996 Volts
- 1997 Volts
- 1998 Volts
- 2002 Volts
- 2003 Volts
- 2004 Volts
Voltage as Function of State of Charge
Battery 6 – Inverted SOC

- 1992 Volts
- 1994 Volts
- 1995 Volts
- 1997A Volts
- 1997B Volts
- 2003 Volts
- 2004 Volts
The capacity of batteries in orbit is based upon the pressure reading from one of 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.
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 plateaus at around 150 psi and the cell voltage is at around –0.04 V.
HSJ Six Battery Test - Battery 1
July 30, 2004

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

Cell Voltage (V) vs. Capacity (Ah)

Pressure (psi) vs. Capacity (Ah)

Cell 1  Cell 22
Prs_A  Prs_B
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 will depend upon which cell is being monitoring – weak, average, strong, etc.
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.
This chart shows a typical drift of the strain gauge pressure to higher pressures with time in 1998 and 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.
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.
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.
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.
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.
This is the 2004 capacity check plot for 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 the coarse telemetry data, with different data rates for voltage and current.

Fitting the 1996 S/N 204 data yields the power formula (insert).
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 shown above. 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 parallel 6-battery 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 V the battery voltage approaches, during the 18 A/battery discharge curve 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, on a per battery basis. This represents the margin currently available for extreme reaction wheel slew loads of 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; the defined Science Minimum Capacity was 26 Ah. If the vehicle slews can be modified to reduce the reaction wheel current loads to below 13 A, then science operations could possibly be extended another 3-4 years. When reconditioning is performed the battery voltage will be several hundred millivolts greater.
Battery capacity fade, corrected for 9 A 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 A load.
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 A 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.
- Cycle Life Projection Based Upon Minimum Capacity Requirement of 20 Ah/Battery [9 Amp Rate]

<table>
<thead>
<tr>
<th>From Launch (4/30/1990)</th>
<th>System</th>
<th>Bat 1</th>
<th>Bat 2</th>
<th>Bat 3</th>
<th>Bat 4</th>
<th>Bat 5</th>
<th>Bat 6</th>
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<tbody>
<tr>
<td>Projected Life (Yrs)</td>
<td>26.8</td>
<td>20.3</td>
<td>26.7</td>
<td>26.9</td>
<td>25.5</td>
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<tr>
<td>R2</td>
<td>0.811</td>
<td>0.955</td>
<td>0.928</td>
<td>0.970</td>
<td>0.941</td>
<td>0.915</td>
<td>0.778</td>
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<tr>
<td>Capacity Fade (AH/Yr)</td>
<td>2.40</td>
<td>2.37</td>
<td>2.62</td>
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<td>2.93</td>
<td>2.74</td>
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<table>
<thead>
<tr>
<th>From 60+ Months (1997 -)</th>
<th>System</th>
<th>Bat 1</th>
<th>Bat 2</th>
<th>Bat 3</th>
<th>Bat 4</th>
<th>Bat 5</th>
<th>Bat 6</th>
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<tbody>
<tr>
<td>Projected Life (Yrs)</td>
<td>27.8</td>
<td>25.6</td>
<td>24.4</td>
<td>25.8</td>
<td>23.0</td>
<td>26.3</td>
<td>35.8</td>
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<td>R2</td>
<td>0.766</td>
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<td>0.946</td>
<td>0.981</td>
<td>0.921</td>
<td>0.975</td>
<td>0.900</td>
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<tr>
<td>Capacity Fade (AH/Yr)</td>
<td>2.77</td>
<td>3.17</td>
<td>3.114</td>
<td>2.69</td>
<td>3.19</td>
<td>2.80</td>
<td>1.79</td>
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<table>
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<tr>
<th>Since SM3B (4/2002 -)</th>
<th>System</th>
<th>Bat 1</th>
<th>Bat 2</th>
<th>Bat 3</th>
<th>Bat 4</th>
<th>Bat 5</th>
<th>Bat 6</th>
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<tbody>
<tr>
<td>Projected Life (Yrs)</td>
<td>19.7</td>
<td>18.9</td>
<td>21.2</td>
<td>23.4</td>
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<td>R2</td>
<td>0.892</td>
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<td>0.992</td>
<td>0.735</td>
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<tr>
<td>Capacity Fade (AH/Yr)</td>
<td>4.55</td>
<td>7.22</td>
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<td>7.18</td>
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<th>Last Recondition</th>
<th>System</th>
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<th>Bat 2</th>
<th>Bat 3</th>
<th>Bat 4</th>
<th>Bat 5</th>
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<tbody>
<tr>
<td>Capacity (Ah)</td>
<td>52.38</td>
<td>52.30</td>
<td>51.77</td>
<td>49.71</td>
<td>52.70</td>
<td>51.68</td>
<td>56.3</td>
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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.
LMSSC Astronautics in Denver was recently awarded a Contract to design and build the HST Robotic Servicing Module. This contract is very time dependent and is using only flight qualified hardware to reduce time and cost. The schedule calls for a late-2007 launch with the on-orbit servicing lasting about a year. Due to on-orbit HST battery and gyro aging the timeline is critical.
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  • Directed LMSSC to Design, Develop and Deliver Nickel-hydrogen Battery Modules
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  • HST Program Office for Orbital Data
  • NASA/MSFC for Ground Test Data.
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