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NiH_2 Reliability Impact Upon Hubble Space Telescope Battery Replacement

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ABSTRACT

The NASA Hubble Space Telescope (HST) was designed to be deployed and later serviced for maintenance and upgrades, as required, by the space shuttle fleet, with a 5-year mission life for the batteries. HST was deployed 380 miles above the Earth, from Space Shuttle Discovery, on April 25, 1990. Four servicing missions, (SM1, SM2, SM3A, AND SM3B) have been performed. Astronauts have replaced or modified optics, solar arrays, a power control unit, and various science packages. A fifth Servicing Mission, SM4 scheduled for early 2004, is planned to replace the batteries for the first time.

The HST is powered by solar array wings and nickel hydrogen (NiH_2) 22-cell batteries, which are grouped into two parallel battery modules of three parallel batteries each. With a design life of 7 years at launch, these batteries have surpassed 12 years in orbit, which gives HST the highest number of charge/discharge cycles of any NiH_2 battery currently in low earth orbit (LEO) application. Being in a LEO orbit, HST has a 45-minute umbra period, during which spacecraft power requirements normally force the batteries into discharge, and a 60-minute sun period, which is available for battery recharge.

The intent of this paper is to address the issue of NiH_2 battery reliability and how battery capacity degradation can impact scheduling of a Servicing Mission to bring replacement batteries to HST, and extend mission life till deployment of Next Generation Space Telescope (NGST), planned for 2008 at the earliest.

INTRODUCTION

HST uses a battery dominated spacecraft bus, which means that the batteries dictate the bus voltage. If the bus voltage drops below a value of 26.4V, then the spacecraft goes either into load shedding mode, turning off science instruments, or the vehicle is placed into "safe mode" till the battery voltage can be restored. The batteries are charged by closing relays, which bring current from selected solar array panels, with the charge current controlled by the number of panels connected. The batteries are charged to a hardware and/or software defined temperature-compensated voltage (VT), or a software controlled constant current. The state-of-charge (SOC) of the HST batteries is monitored by strain gage bridges on two cells in each battery as described by Anderson et al (2000).

The reliability of NiH_2 battery cells, based upon published cycle life data on NiH_2 cells undergoing ground testing, has been analyzed and reported by Thaller (1987), Hafen (1998) and Silvester (1998). These analyses used a Hazard Analysis, applied to the raw cycle life data, and then Weibull Cumulative Distributions were used to determine the probability of one cell of the 132 battery cells failing, as a function of depth of discharge (DOD). The published data used for this analysis is grouped at 40, 60, and 80 % DOD, with only limited data between 20-40 % DOD, and no data below 20 %. Figure 1 shows the test data distribution with failed and/or terminated cells indicated by solid circles, and continuing tests indicated by open squares.

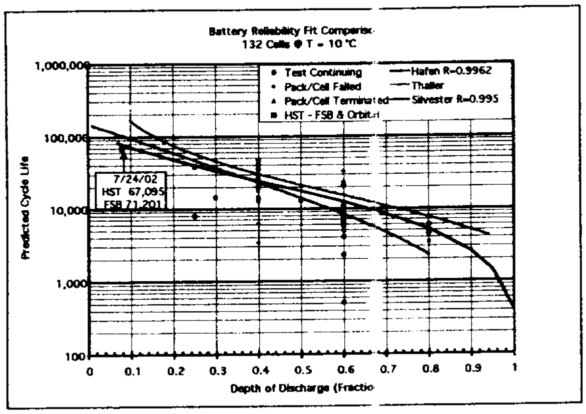

FIG.1 NIH2 RELIABILITY PROJECTION VS DOD

The HST battery operates between 8 to 12 % DOD, which, from Fig. 1, suggests that the reliable cycle life for the HST batteries is about 80,000 cycles, or 14.5 years.

The minimum battery capacity, defined by mission requirements at battery servicing, is 45 Ah delivered to a minimum bus voltage of 26.4 V. Since launch, the flight and ground batteries have been subjected to a periodic reconditioning procedure, the benefits of which was summarized by Armantrout et al (1996), which discharges the battery down to a voltage of 15 V on a selected battery, and then recharged. This was repeated at various intervals, till April 2000, when a bus bar fault in the charge controller unit was discovered. This fault meant that there was a probable single point failure mechanism, which might occur during battery reconditioning. The defective power control unit (PCU) was replaced during SM3B in Feb. 2002, and the batteries are now being reconditioned at the rate of one battery every 4-6 weeks.

Figure 2 details the load share among the six flight batteries, as a percentage of total current, prior to, and subsequent to SM3B, through Battery 3 and 5 reconditioning. Note that prior to SM3B, Batteries 5 and 6 were sharing less of the load, due to the bus bar fault problem, which limited the charge control VT levels for those batteries. The load share divergence prior to SM3B has been corrected after the new PCU was installed, as seen prior to the Battery 3 reconditioning. Battery 3 is handling a higher percentage of the load subsequent to it's reconditioning.

Battery 3 was reconditioned in April 2002 with an measured capacity of 60.0 Ah, as shown in Fig. 3. The decline, with cycle number, in usable capacity, above 26.4 V, is typical of NiH_2 satellite batteries operating in a LEO regime, as expected. Note several voltage inflections in the discharge slope below 26.4 V, which will be discussed later.

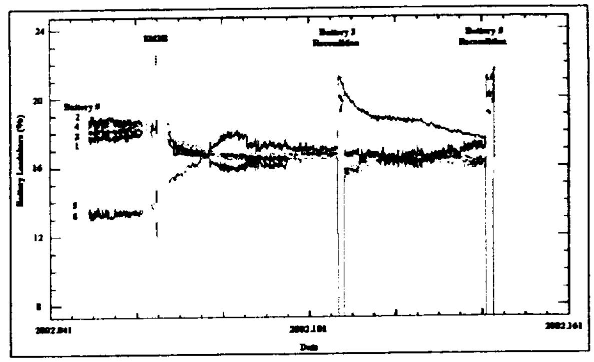

FIG 2. HST BATTERY 2002 LOAD SHARE HISTORY

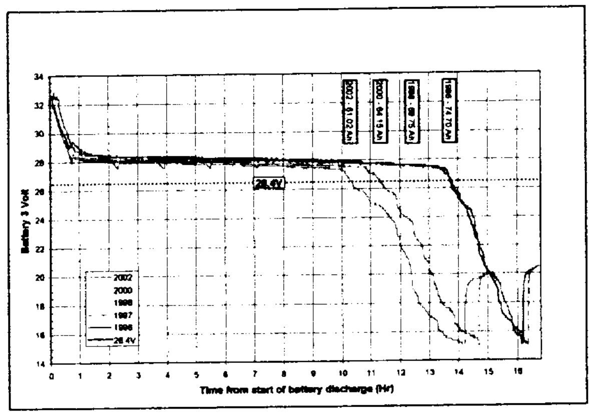

FIG 3. HST BATTERY 3 ORBITAL CAPACITY

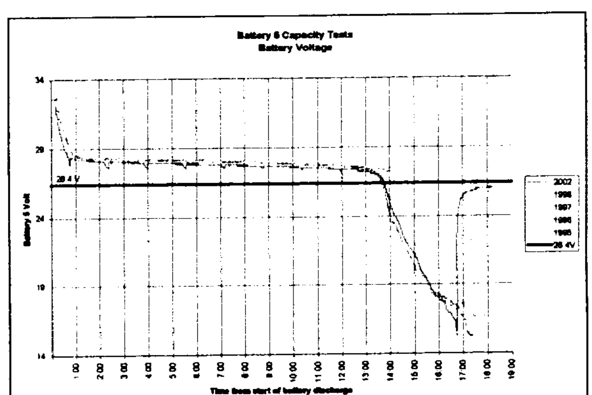

FIG 4. HST BATTERY 5 ORBITAL CAPACITY

Battery 5, reconditioned in May 2002 with a capacity of 81.03 Ah, also exhibited several voltage inflections, as shown in Fig. 4. Previous orbital reconditioning for this battery, in the period of 1995 to 1998, were 78 to 74 Ah respectively. The high capacity, for this latest reconditioning, may be due to the new PCU; reconditioning of the remaining four batteries will be needed to confirm the observed capacity recovery after the recent PCU refurbishment.

Orbital Reconditioning Trend Projection

The capacity data obtained from orbital reconditioning is averaged to project trend lines as shown in Fig.5. Since the PCU replacement, only Batteries 3 and 5 have been reconditioned, and moreover, Battery 1 is scheduled for reconditioning in June 2002. With the current data available, the required mission minimum capacity of 45 Ah/battery is projected until 2008. The reconditioning data points for the remaining four onboard batteries must be obtained in order to gain confidence in projecting the date of minimum capacity. This data together with other extended LEO cycling and destructive physical analysis of the extensively cycled cells data may influence the decision on SM4 replacement of the orbital batteries.

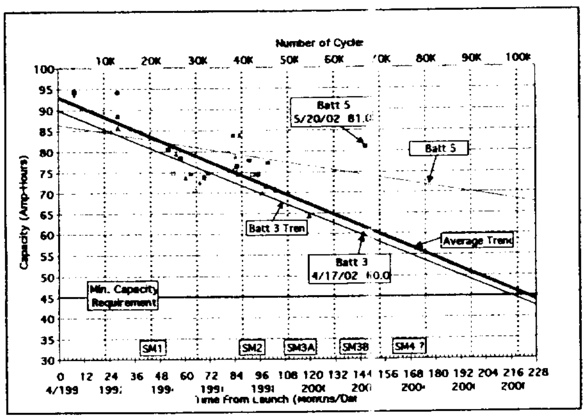

FIG 5. HST ON ORBIT CAPACITY DECLINE TREND

Ground Test Data

In addition to the orbital flight batteries, ground reconditioning trend data, shown in Fig. 6, for six batteries of the two Test Modules (TM1 and TM2), as well as the Flight Spare Battery (FSB), is available for analysis. TM1 and TM2 are cycled, Whitt and Brewer (1994), at the NASA Marshall Space Flight Center (MSFC) HST spacecraft Electrical Power System (EPS) breadboard, under operational conditions planned for the orbital batteries, to study "what if" scenarios, and to predict future on-orbit battery performance. The reconditioning degradation trend data from the 6-battery average of the TM data suggests that the orbital replacement is required in the 2006 timeframe at the earliest. While FSB, which is cycled also at MSFC under a typical HST profile, suggests that orbital replacement is required in the 2009 timeframe. The data scatter for all these projection yields a high error margin in these predictions.

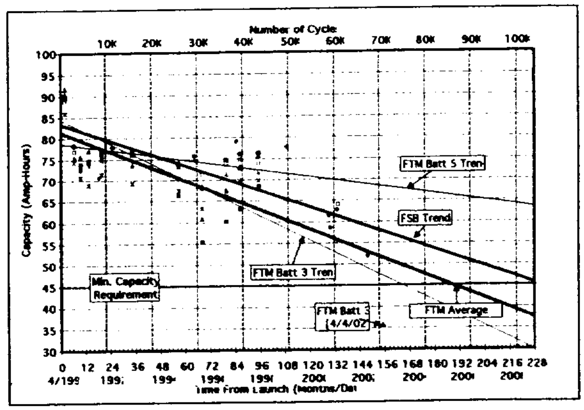

FIG 6. HST GROUND CAPACITY DECLINE TREND

Capacity Degradation

Cycle life studies, performed at Eagle Picher Technologies (EPT), on the Mantech cell design, with various pedigrees of slurry and dry sinter processed electrodes, provides information for evaluating capacity fade (degradation) mechanisms, and their impact upon battery cycle life, as was reported by Armantrout and Gordon (2000).

A typical second discharge plateau signature for a cell is shown in Fig. 7. With the second plateau, on discharge the cell capacity is still available, but at a lower voltage of 0.8 V. Several such plateaus could occur in a battery or a cell pack, where more than five cells are connected in series, at different discharge time periods depending on the extent of cell degradation. Then, the battery discharge voltage curve could exhibit several inflections (Fig. 3 and Fig. 4) that correspond to the second plateaus for each degraded cells. Because on board HST batteries do not have individual cell voltage monitoring telemetry, the verification to this explanation comes from the EPT tests data and from the ground FSB capacity test data, where individual cell potentials are recorded.

Therefore, it is proposed that when one cell exhibits a second plateau during discharge, that the battery voltage will display a voltage inflection, as noted during orbital reconditioning (Figs 3 and Fig. 4). Consequently, HST spacecraft will be switched into "safe mode" when the bus voltage drops below 26.4 V per battery, which means that the lower inflections' (cell plateaus') capacity is unavailable to the satellite for use.

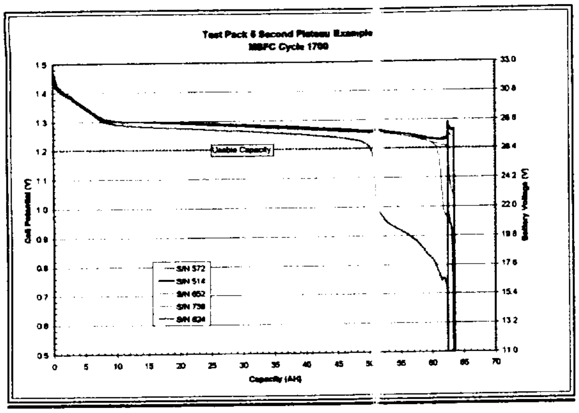

FIG 7. NIH2 CELL SECOND PLATEAU EXAMPLE

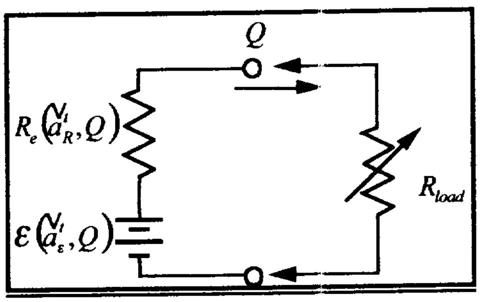

FIG. 8 BATTERY/CELL PERFORMANCE MODEL

Cell Performance Model

To enable operators to predict the performance of a battery or a cell during operation, a performance model, defined by Fig. 8, was developed by Clarke (2001), which uses polarization data from two discharges at two different currents, on a given battery or cell. This data is used to model the electromotive force, ε° in the Nernst Equation, and impedance components of the cell discharge voltage-DOD signature. The load on the battery is defined as a function of the battery resistance, R, and the battery electromotive force (EMF), ε, as a function of the state of charge, Q, and a series of empirically derived constants, a.

EPT cycle life studies, as well as MSFC tests with the FSB and other pack testing to compare dry sinter versus slurry electrodes, are used to model beginning, and end of life cell impedance. These studies show that cell impedance increases with cycle number and depth of discharge, as expected. Both contribute to capacity degradation results.

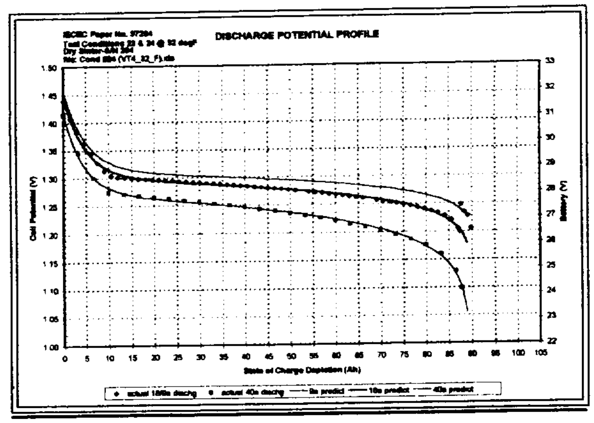

FIG. 9 RAW DATA VERSUS MODEL

Figure 9 compares the model predictions versus actual discharge data for 40, 18, and 9 amp discharges for a dry sinter electrode. Figure 10 shows the model predictions of EMF for two cells comparing the EMF of dry sinter and slurry. Note that, as expected, the EMF of the two cells is very similar. The cell impedance increases drastically when 50% capacity is withdrawn from the cell, as shown in Fig. 11. The model also shows that a slurry cell exhibits slightly higher cell impedance than a dry sinter cell.

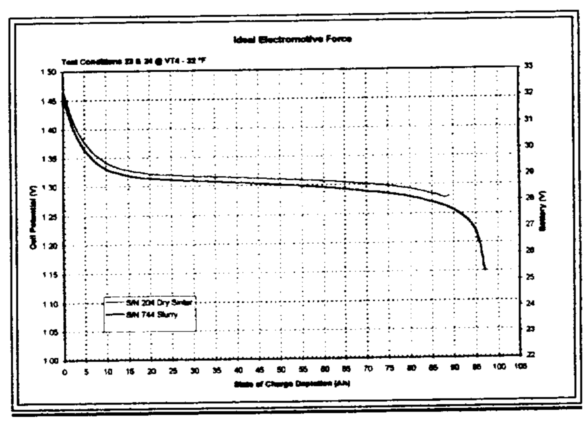

FIG.10 EMF DERIVED FROM MODEL

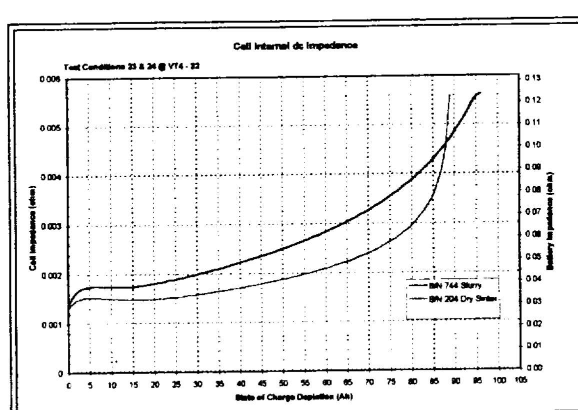

FIG. 11 IMPEDANCE DERIVED FROM MODEL

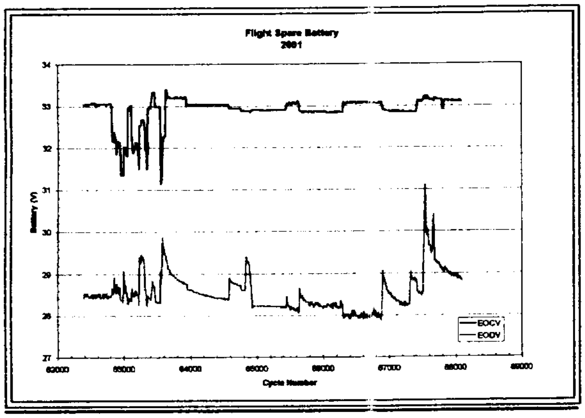

FIG. 12 FSB 2001 HISTORY

The Flight Spare Battery was subjected in 2001, to various mission profile cycling to evaluate various power issues, which resulted in the upper and lower voltage limits as shown in Fig. 12. At the end of this testing, the battery was discharged at 15 amps until a battery voltage of 26.4 V, and then discharged at 5 amps to a battery voltage of 15.0 V.

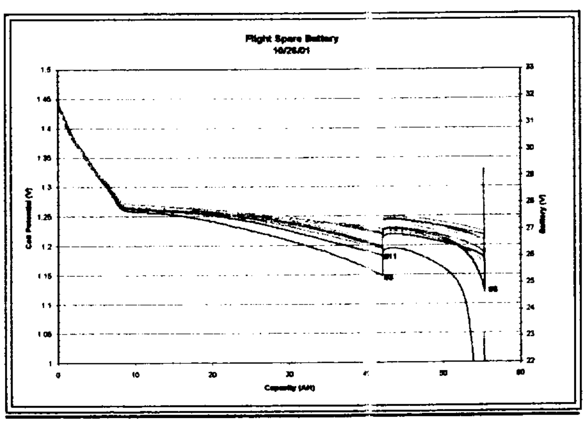

FIG. 13 FSB DISCHARGE CELL POTENTIALS

The FSB has individual cell monitoring, not available on-orbit, which shows in Fig. 13, that several cells have reduced capacity above 1.2 V. Based upon the decreased capacity performance shown in Fig. 13, MSFC was directed to perform a special discharge test upon the FSB, which involved a 12 amps discharge with a 5 amps discharge pulse, as shown in Fig. 14. The voltage of the 22-cell battery displays several voltage inflections above 65 Ah capacity, which has also been observed during orbital reconditioning. Individual cell monitoring of the 22 cells, all exhibited the characteristic second plateau signature, with cells 1-7 being shown in Fig. 15. Note that one cell, #3, drops below 1.2 V with a capacity of 38 Ah, while the other cells have capacities ranging from 42 to 52 Ah, above 1.2 V. Below 1.2 V till 0.8 V, the cells all have at least 20 Ah of unusable capacity.

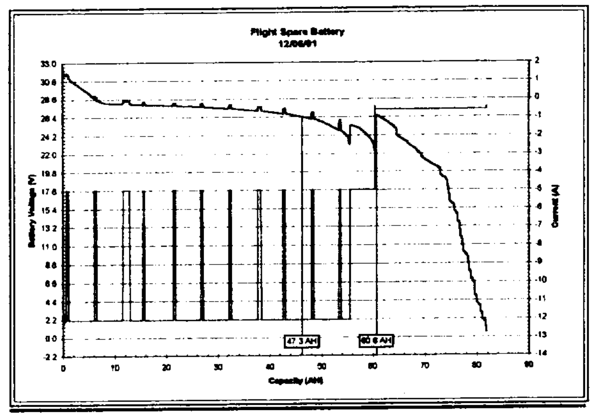

FIG. 14 SPECIAL DISCHARGE OF FSB

Using the discharge curves shown in Fig 15, one can project two separate discharge curves for the two discharge rates, which the cell performance model can be used to model cell impedances, determined for the individual cell discharges. Figure 16 details the cell impedance for Cells #3 and 7, which represent the worst cells, Cell # 2 which represents an average, and Cell #12 which was the best cell.

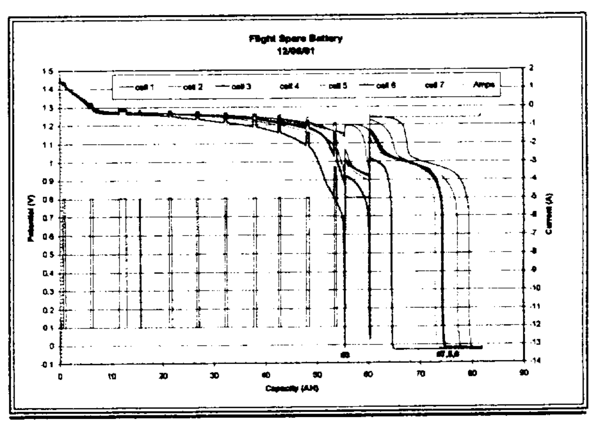

FIG. 15 SPECIAL DISCHARGE – CELL POTENTIAL

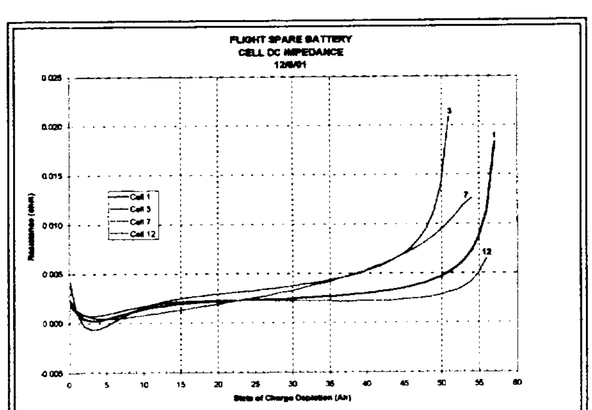

FIG. 16 FSB - CELL IMPEDANCE

SUMMARY

Periodic reconditioning, performed on the HST flight and test batteries, as summarized herein, provides usable capacity data for performance evaluation and trend analysis. Characterization and life test capacity measurements can provide a historical database to determine the need for reconditioning to improve voltage performance to a specified voltage level. Cycle life projections summarized herein indicates that the HST flight batteries can meet minimum specified mission eclipse load requirements at least through 2004. A decision to replace the batteries during SM4 in 2004 will be made after additional HST orbital capacity measurements have been made in 2002, and the data has been analyzed together with other extended LEO cycling and destructive physical analysis of the extensively cycled cells data.

ACKNOWLEDGEMENTS

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