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Technical Consultation of the Hubble Space Telescope (HST) Nickel Hydrogen (NiH_2) Battery Charge Capacity Prediction

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September 2005

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Technical Consultation

of the

Hubble Space Telescope (HST)

Nickel Hydrogen (NiH_2) Battery Charge Capacity Prediction

June 17, 2004

Prepared by:
Steven J. Gentz
NESC Principle Engineer

Signature Page

NESC Independent Technical Evaluation Team
Original Signatures on file

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EXECUTIVE SUMMARY

A multi-Center and industry review team of knowledgeable Nickel Hydrogen (NiH_2) battery specialists was convened to assess the Goddard Space Flight Center (GSFC) position paper entitled, "The State of the HST Batteries as it Relates to HST Health, Safety, and Ability to Support an On-going Science Operation", dated May 21, 2004 (provided in Appendix D) [ref. 1]. This document was prepared by Dr. J. Keith Kalinowski, Deputy Manager, Hubble Space Telescope (HST) Operations Project, with planned approval by Preston M. Burch, Manager, HST Program Office. The document review was supplemented with extensive technical discussions with the position paper author, pertinent reports from literature, NASA-sponsored Aerospace Battery Workshops, and consultations with team peers.

In the course of the assessment, it was recognized that the HST battery thermal control system has an average heat dissipation limitation of 30 W per bay per orbit cycle. This thermal constraint will continue to govern options for battery capacity maintenance. In addition, the HST usage represents the longest exposure of NiH_2 batteries to Low Earth Orbit (LEO) at the current level of Depth of Discharge (DOD). Finally, the current battery life is at the limit predicted by the manufacturer, EaglePicher. Therefore, given these factors, the potential exists that the HST battery capacities could radically degrade at any point.

Given this caveat on any life extrapolations, the conservative model proposed in the GSFC position paper was viewed by the NASA Engineering and Safety Center (NESC) assessment teams as having several technical assumptions such as limited utilization of flight battery capacity data, the susceptibility of the proposed prediction method to large variations when supplemented with additional information, and the failure to qualitatively or quantitatively assess life prediction sensitivities. Additional life prediction models to those cited in the GSFC position paper were reviewed with the Hollandsworth/ Armantrout model being viewed as having the greatest likelihood of estimating future HST battery capacities.

It was also observed in the course of the assessment that the battery charge control strategy might not have been optimized to allow the batteries to reach their maximum charge state. Options appear to exist to improve or maintain overall battery capacity by maximizing the charge current and raising the temperature compensated voltage level (V/T) levels to improve the charge efficiency without exceeding the indicated thermal dissipation limit. Enhancements for decreasing cell divergences also appear possible by alterations to the capacity test procedures.

In summary, it is recommended the identified conservative assumptions of the GSFC proposed model be addressed and the Hollandsworth/Armantrout model be enhanced to augment the life predictions for the HST batteries. It is also recommended the current HST battery charge control management strategy be revised to maximize both the charge efficiency and the capacity test depth and rate of discharge.

NESC Position Paper

Request Number #: 04-050-E	
Requestor Name: William F. Townsend	**Requestor Contact Info:** William.F.Townsend@nasa.gov 301-286-5066
Short Title: HST NiH_2 Battery Charge Capacity Prediction	
Description: The paper examines the viability of the HST with respect to the NiH_2 continued battery charge capacity. It proposes a life prediction technique to determine critical HST milestone dates for continued science studies followed by the attachment of a re-entry module or a robotic servicing mission.	
Date Received: May 25, 2004	**Date Consultation Initiated:** May 25, 2004
Lead Assigned: Steven Gentz	**Lead Contact Info:** Steven.J.gentz@nasa.gov
Date Consultation Concluded: June 17, 2004	

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In addition to outstanding support provided by the assessment team and the technical exchange with Dr. Keith Kalinowski, the rapid response to this request could not have been accomplished without the exemplary services of the NESC Management and Technical Support Office (specifically Ms. Pam Fullen and Ms. Debby Lodding) and Mr. Hugh Baker, JSC Contracting Officer Technical Representative for Aerospace Corporation contract.

Consultation Approach

The purpose of the GSFC position paper is to identify critical HST milestone dates for continued science studies followed by the attachment of a re-entry module or a robotic servicing mission. The paper examines the viability of the HST with respect to the NiH_2 continued battery charge capacity.

The NESC conducted an independent evaluation of the supporting information and assumptions to generate the predictions for battery capacity loss and practicality of on-orbit battery conditioning. The following are the major activities of the NESC assessment:

Milestone	Date
Initial Teleconference	May 27, 2004
Review Team Identification	June 1, 2004
Position Paper and Support Documentation Review	June 4, 2004
Technical Interchange Meeting	June 6-7, 2004
Preliminary Findings Presentation to NESC Review Board (NRB)	June 10, 2004
Final Report Submission	June 17, 2004

Data Reviewed

Mr. William F. Townsend, GSFC Deputy Director, contacted Mr. Ralph Roe, NESC Director, concerning an independent assessment of a review copy entitled, "The State of the HST Batteries as it Relates to HST Health, Safety, and Ability to Support an On-going Science Operation", dated May 21, 2004. This document was prepared by Dr. J. Keith Kalinowski, Deputy Manager, HST Operations Project, with planned approval by Preston M. Burch, Manager, HST Program Office.

Findings/Observations/Recommendations

Following are three main areas pertaining to ***System Aspects, Life Prediction Methodology,*** and ***Battery Charge Control Management***. The information is intended to address potential system issues, the most accurate life prediction models, and methods to improve the capacity and life of the HST batteries. The recommendations are sequentially numbered to aid discussion. More detailed descriptions of the recommendations are provided in Appendix A. Note that these recommendations are suggested actions to the program and do not constitute NESC requirements.

1. SYSTEM ASPECTS

Observations/Findings

- Battery thermal control system has an orbital average heat dissipation limitation of 30 W per bay per orbit cycle.
- Structural integrity life prediction (cell pressure vessel) is not addressed.
- Voltage plateau depression is not addressed.

Recommendations

1.1. Assess energy storage system safe life analysis based on fracture mechanics.

1.2. Specify assumptions and limitations of analytical Minimum Reserve Margins:
- 14 Ah uncertainty with respect to observed strain gauge drift and cell-to-cell divergences

1.3. Clarify depressed voltage plateau and substantiate its retardation.

1.4. Develop a power management strategy to minimize orbital night load:
- Verify safe mode requirements being maintained
- Perform trade studies and determine strategy that minimizes instrument cycling stress and maximizes science
- Communicate strategy to the science community

2. LIFE PREDICTION METHODOLOGY

Observations/Findings

- Rationale for use of limited data sample (post Service Missions 3B) for projecting life of HST batteries is not properly provided.

- Proposed life prediction method is subject to large variations when supplemented with additional measurements.

- Additional NiH_2 battery life prediction models are available:
    - Meet indicated criteria
    - Hollandsworth/Armantrout, "Hubble Space Telescope Battery Capacity Trend Studies", 2003 NASA Aerospace Battery Workshop [ref. 2]

- Listed life prediction models are not properly referenced.

Recommendations

2.1. Select prediction method that includes a statistical determination of its probability that allows its inherent uncertainties to be evaluated.

2.2. Update Hollandsworth/Armantrout, "Hubble Space Telescope Battery Capacity Trend Studies", 2003 NASA Aerospace Battery Workshop prediction:
- Incorporate additional data (2004 data)
- Correct for 9 A discharge offset
- Apply statistical bounding analysis
- Supplement results into Table III, Total System Charge Capacity and Margins vs. Time, of the GSFC position paper

2.3. Determine if a proportional correlation exists between the voltages in the test battery discharge at the 9 Ah point and the measured capacity to 1.2 V for each cell (Figure 2.3-1).

2.4. Attempt to reproduce HST Battery 5 overcharge to the SBT batteries without exceeding thermal limitation to determine duration of improved capacity.

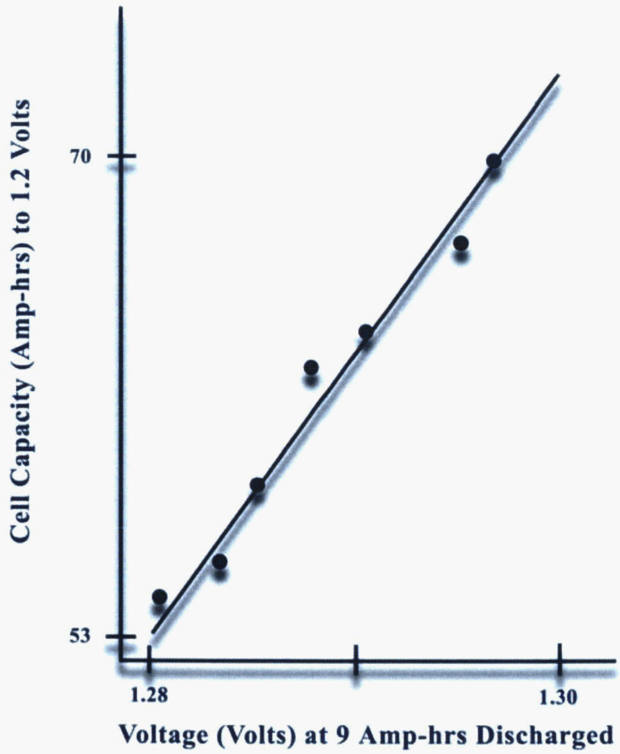

Figure 2.3-1. Typical Plot of Correlation between Battery Voltage (at 9 Ah load) and Cell Capacity at 1.2 V

3. BATTERY CHARGE CONTROL MANAGEMENT*

* Battery charge control consists of charge and discharge segments. Battery discharge occurs by "nominal" or "capacity testing". Nominal discharge is the capacity used during the night periods. Capacity testing occurs periodically where an artificial load is induced to partially deplete the battery. Charging following a capacity test involves an initial charge cycle at a lower current for the first cycle.

Observations/Findings

- Charge management strategy (thermal constraints plus operational cycling) might not have been optimized to allow the batteries to reach their maximum state of charge.

Recommendations

Charge

3.1. Maximize charge current and raise V/T levels to improve charge efficiency during cycling operations as heat rejection capabilities will allow.

3.2. Explore increased temperature implications (3 to 5°C) in conjunction with alterations to charge modifications.

3.3. Investigate ratchet charging:

After the first ratchet to the voltage cutoff, then trickle charge mode and wait for recovery (10 to 20 minutes) and ratchet again.

- On-orbital cycling operations (Figure 3.3-1)
- Ratchet charging following capacity check (Figure 3.3-2)

Discharge (Capacity Test)

3.4. Revert to heritage method of continuous discharge using 5.1 ohm load.

3.5. Investigate frequency of capacity testing.

- Lower discharge level to below 15 V (3 to 5 V)
- Substantiate the maximum duration (hours) of reversal allowed for individual cells

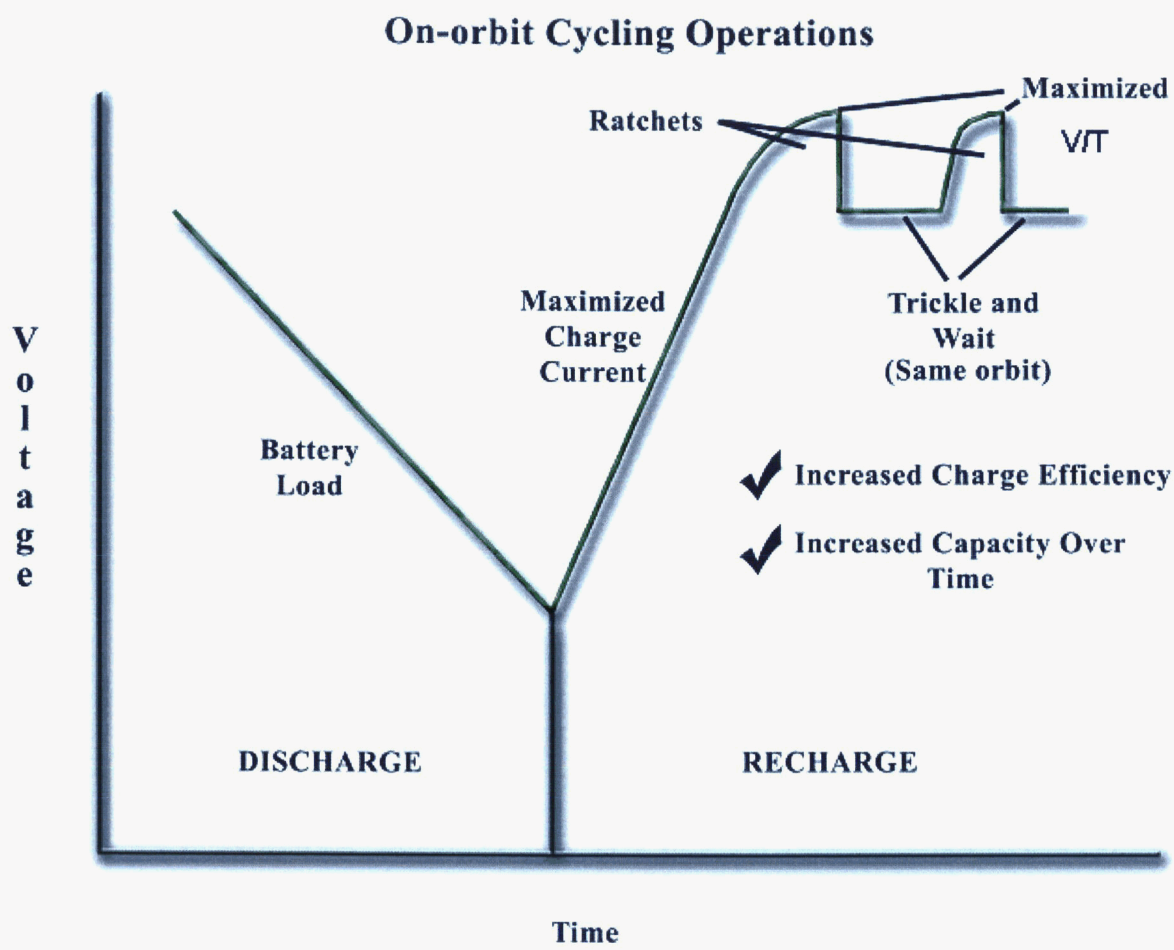

Figure 3.3-1. Ratchet Charging for Nominal On-orbit Cycling Operations

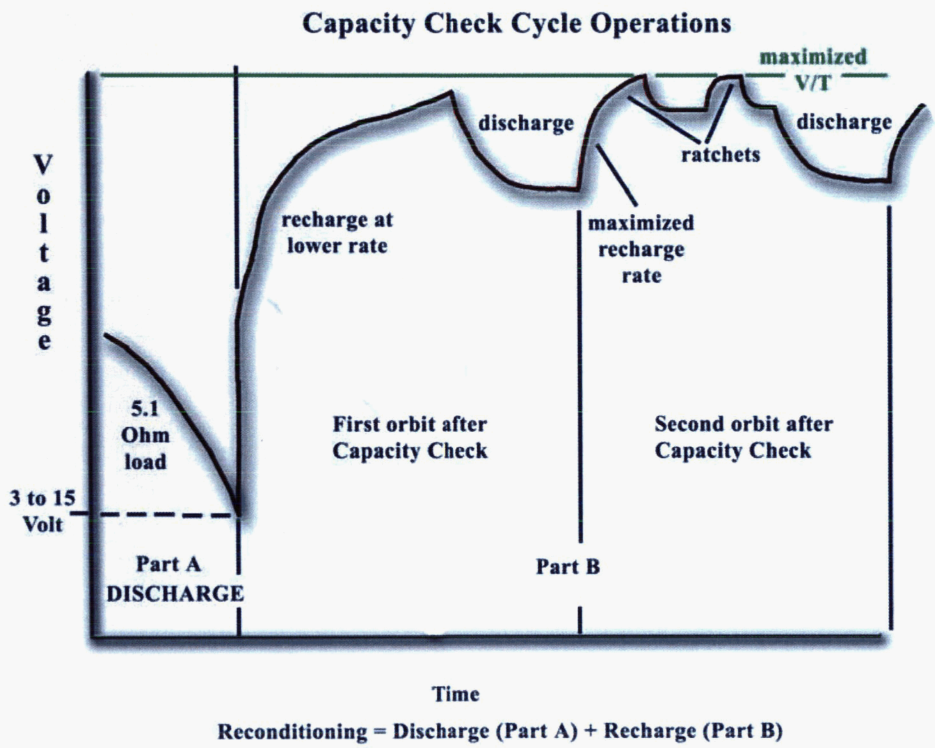

Figure 3.3-2. Ratchet Charging following Capacity Test

APPENDIX A

Detailed Findings/Observations/Recommendations

1. SYSTEM ASPECTS

Observations/Findings

- Battery thermal control system has an orbital average heat dissipation limitation of 30 W per bay per orbit cycle.
- Structural integrity life prediction (cell pressure vessel) is not addressed.
- Voltage plateau depression is not addressed.

Recommendations

1.1. Assess energy storage system safe life analysis based upon fracture mechanics.

The cells as well as other EPS components were designed with specific design life parameters. A reassessment needs to be performed in order to identify components (pressure vessels, cell internal components, wire insulation, etc.) which may have limited on-orbit life remaining. Failure of any of these items could result in loss of HST or its functions. A particular item of concern is the pressure vessels, which have associated with them a certain number of pressure cycles. An updated fracture/fatigue analysis should be objectively performed by structural analysis experts using the proper modeling analysis tools for the purpose of projecting when a failure of this type might occur. Limited life items such as switches, sensors, etc., should be reassessed in accordance with reliability predictions.

1.2. Specify assumptions and limitations of analytical Minimum Reserve Margins:

- 14 Ah uncertainty with respect to observed strain gauge drift and cell-to-cell divergences

Provide breakdown of various safe-mode Ah threshold requirements used in Table III of the GSFC position paper. Identify any margins included and assumptions made in arriving at those thresholds. For example, if the battery capacity measurements are discontinued, then it is necessary to depend on the battery-cell strain (pressure) gauge to assess capacity of the batteries at any time. However, there is some uncertainty with *respect to observed strain gauge drift and the actual measured capacity. There is also uncertainty in translating cell capacity to battery capacity as cells diverge with life and cell voltages are not monitored.*

Clarify if the strain gauge drift is a certain percentage of the total cell capacity at any time or is typically constant at ~ 2 Ah/battery irrespective of its capacity. Also, clarify how typical annual drift in total system capacity (based on the pressure readings) correlates with the allotted 14 Ah uncertainty.

1.3. Clarify depressed voltage plateau and substantiate its retardation.

A depression of the upper discharge plateau (~ 1.2 V per cell) during capacity testing was observed beginning in 2002. This depression was not present in 1998. The cause of the depression is not clear, although it does not appear to be progressively getting worse with time since it appeared in 2002. Without understanding the origin of this depression, there is little assurance that it will not continue to lower or suddenly step the voltage downwards further, or perhaps cause failure to support the 26.4 V requirement. At the relatively low capacity test discharge rates for the HST batteries, this depression is not a typical aging behavior of NiH_2 cells. It is possible that this is a new aging phenomenon related to the present ~ 15-year lifetime of the HST batteries.

However, a number of system changes occurred between 1998 and 2002 that should be explored as possible contributors. A new solar array and new instruments were installed, a new PCU was installed, loads and DOD were increased, and temperatures were changed slightly. These changes may have system-level implications that could influence the capacity test discharge plateau level. It is uncertain whether the same voltage depression is seen in the battery voltages during orbital cycling. It is recommended that these issues be explored to better understand the voltage depression, and to develop confidence that it will not suddenly increase further in the future to potentially limit the useful battery lifetime.

1.4. Develop a power management strategy to minimize orbital night load:

- Verify safe-mode requirements are being maintained
- Perform trade studies and determine strategy that minimizes instrument cycling stress and maximizes science
- Communicate strategy to science community

The science instruments are reported to be currently maintained in various levels of operate mode continuously regardless of orbital day or night. To reduce/minimize the orbital night load, consideration should be given to the following:

- *Turn off all or some of the science instruments during orbital night.*
- *Switch all or some of the science instruments into low power or standby mode during orbital night.*
- *Operate some of the science instruments continuously, for a week/month, and operate reminder of the science instruments the next week/month and cycle them back and forth.*

Although, it may be undesirable to duty cycle the science instruments in view of associated risks, various duty cycling options should be studied and presented to the science community. Trade studies should be performed to determine a strategy that minimizes cycling stress on the instruments while maximizing science productivity.

Also, consider shifting some of the HST spacecraft bus operations to orbital daytime without affecting the science operations, like vehicle slews, etc.

Tables I and III of the GSFC position paper present full science operations as a requirement. Tables I and III should be modified to include some of the options that might result from the power management strategy discussed above. Thus, the modified Table III entries might lead to several more options for extended HST viability. For example, per current Conclusion 2, halting the science program may not be required and can be modified to operate some of the science instruments as per power management strategy above. This option might be more favorable for the science community rather than halting the science program.

Further, consider providing a breakdown of various safe-mode Ah threshold requirements used in Table III and identify any margins included in arriving at those thresholds.

2. LIFE PREDICTION METHODOLOGY

Observations/Findings

- Rationale for use of limited data sample (post SM3B) for projecting life of HST batteries is not properly provided.

- Proposed life prediction method is subject to large variations when supplemented with additional measurements.

- Additional NiH_2 battery life prediction models are available.
  - Meet indicated criteria
  - Hollandsworth/Armantrout, "Hubble Space Telescope Battery Capacity Trend Studies", 2003 NASA Aerospace Battery Workshop

- Listed life prediction models are not properly referenced.

Recommendations

2.1. Select a prediction method that includes a statistical determination of its probability that allows its inherent uncertainties to be evaluated.

While it is recommended that an updated version of the Hollandsworth model be used to predict battery capacity and life, it is also recommended that an appropriate statistical analysis of the regression results be performed for whatever model is employed. The statistical analysis should use the data to provide the changes in degradation-line slopes for different probability levels. The results should be used to provide the probability of reaching each of the capacity benchmarks indicated on a time line such as that provided in Table III of the GSFC position paper. Alternatively, a time line could be developed at a given probability level (i.e., 90% might be a worst case while 50% would be a nominal case). This would allow HST Program plans to be developed both for well-defined worst case as well as for nominal battery lifetime scenarios. The Program would also see the years of extended battery operation that would accompany acceptance of additional risk (added probability of battery failure).

A more rigorous evaluation of models for predicting battery life is recommended and should include the appropriateness of each model with respect to the HST battery situation. The following models are known to be available, and their applicability should be addressed:

- *The assessment of the Hafen model seems appropriate in the GSFC position paper.*
- *A simple wear out model has been developed by Thaller et. al. (Lim and Thaller, Proceedings of the 22nd IECEC, Vol. 2, pp 751-757, 1987. Updated by Thaller in Proc. of the 1997 NASA Battery Workshop, pp. 411-427) [ref. 5]. This model predicts ~ 35 years of operation at 10% DOD for generic NiH_2 cell capability.*

Because the 10% DOD situation is an extrapolation from the DOD range covered by the data used in the model, this model may overestimate the battery life.

- *The wear model developed by Dr. Zimmerman [ref. 6] does specifically take the DOD, recharge conditions, temperature, and other environments to which the HST batteries have been exposed into account. The Zimmerman model predicts the most probable time of failure (50% probability) for the first battery to be about year 2011, and a 95% probability of battery failure at 10% DOD by about year 2015. However, it is also based on data obtained at higher DOD (30 to 60%), and thus assumes a specific dependence of wear rate on DOD that may not be accurate at 10% DOD. It furthermore predicts failure to be much more likely as a result of continued loss of usable capacity, rather than failure from a cell short circuit. It also predicts that at about 76,000 cycles the usable battery capacity will fall to 50% of nameplate (45 Ah) capacity. This is actually relatively close to the current measured capacity of about 50 Ah for the lowest batteries. This correlation is within the expected 10 to 20% accuracy expected from this model, and suggests that the HST batteries are actually degrading at rates and by processes that are fully consistent with industry NiH_2 battery life test experience.*
- *The Hollandsworth model appears to be the best for actual HST life predictions, since it is based on trend analysis of the measured HST battery capacity data. The Hollandsworth model does not allow for any type of accelerated battery capacity degradation later in life, at least in its present form. Accelerated or non-linear degradation late in the battery life is the only reason for excluding the early-life data from the Hollandsworth model trend analysis (except for several points that are influenced by known charge control changes, and which are statistically out of family by > 2 sigma). However, no evidence appears that such accelerated degradation is occurring in the most recent battery capacity measurement data.*

2.2. Update Hollandsworth/Armantrout, "Hubble Space Telescope Battery Capacity Trend Studies", 2003 NASA Aerospace Battery Workshop prediction:

- Incorporate additional data (2004 data)
- Correct for 9 A discharge offset
- Apply statistical bounding analysis
- Supplement results into Table III, Total System Charge Capacity and Margins vs. Time, of the GSFC position paper

Various models for predicting battery life were discussed in the GSFC position paper. Admittedly, time seems to have invalidated the prediction of the Hafen model that was cited. The Zimmerman model, which neither includes nor requires any a priori knowledge of the HST on-orbit battery trends, does make some interesting predictions of *life and reliability out to the 2011 to 2015 time frame. These predictions are based on generic experience with NiH_2 cells, and should be recalled when estimating life from HST battery trend data. The validity of the Zimmerman model will ultimately be determined by how well it agrees with the observed battery trends.*

As was noted, the Zimmerman model does make some assumptions. The issue of predicting capacity and life to a 1.0 V failure criterion rather than a 1.2 V criterion appears to be a limited issue, since there only appears to be a 2 Ah difference in cell capacity between these two voltage levels for the HST discharge conditions (see Figure 1 of GSFC position paper). In fact, all such models for predicting HST cell and battery life should attempt to predict the step change in voltage from 1.2 to 0.8 V, which tends to be centered in the 1.0 to 1.1 V range. It is this voltage step that will trigger a significant load off-share (and anomaly declaration) when it occurs in a cell within any of the HST batteries.

Probably the greatest limitation with the Zimmerman model is its uncertain applicability to the 9 to 10% DOD operation of the HST. The data on which the Zimmerman model is based and validated are in the 30 to 60% DOD range. Extrapolation to 10% DOD may result in some systematic errors in wear rates, which could decrease the accuracy of the model.

The best previous model for the HST battery life is the empirical trend analysis of the HST orbital data reported by Hollandsworth, et. al. (Hollandsworth model). This model does meet the criteria described as needed for an acceptable model (GSFC position paper, page 11, paragraph 2), but this work is neither cited nor used. The Hollandsworth model simply uses a linear regression analysis of the HST capacity test battery measurements as a function of time to predict when each battery will cross particular capacity thresholds of interest. The added data obtained since late 2003 do not appear to deviate significantly from the trend lines in the Hollandsworth model, and thus do not suggest the batteries are now dropping more rapidly, on average, than they have in the past. The model offered in the GSFC position paper is essentially the same as the Hollandsworth model, except that it does not include any of the battery data prior to 2002.

It is recommended that the Hollandsworth model be updated to include the most recent battery capacity measurements, and that the capacities in the Hollandsworth model be adjusted to reflect the expected actual battery discharge rate (4 Ah offset). The Hollandsworth model should be used to most accurately predict HST battery capacity and life, unless future data show statistically significant deviation from the historical downward trend. It is also recommended that the resultant timelines (such as those provided in Table III of the GSFC position paper) be updated to reflect the

Hollandsworth model predictions, and that the trends and predictions be periodically updated as significant new data becomes available. It is recognized that this approach will provide a nominal battery life that is much longer than that presented in the GSFC position paper (since the degradation slopes are 1/3 as great). However, the Hollandsworth model is believed to provide a prediction that is better supported by the data, assuming a worst case corresponding to 90+% battery reliability rather than simply the mean battery lifetime (~ 50% reliability).

2.3. Determine if a proportional correlation exists between the voltages in the test battery discharge at the 9 Ah point and the measured capacity to 1.2 V for each cell (Figure 2.3-1).

Correlations between NiH_2 cell or battery voltage and the amount of stored capacity have often been found to be confounded by all the other variables that influence voltage, but not capacity. Such variables include current, temperature, and the past history of charge, discharge, as well as the SOC.

Discussions concerning the FSB testing, where the voltages of all cells are measured, have sometimes equated cell voltage divergence during cycling to capacity divergence. Establishing a correlation between the amount of stored capacity and the cell voltage at the end of the 9 to 10% DOD orbital cycle would provide a simple, real-time diagnostic tool to monitor the evolution of cell imbalance during cycling. This correlation could be checked (or recalibrated) each time the test battery is subjected to a capacity test. Such a correlation would plot the voltage of each cell at the DOD corresponding to orbital cycling (~10% DOD) during the capacity discharge against the capacity measured for that cell to 1.2 V. If a good correlation is in fact found to exist, cell voltage dispersion at the end of each orbital cycle can be used to accurately indicate relative shifts in cell capacities, and thus capacity imbalance. If a good correlation is not established, cell voltage divergence should not necessarily be used as a meaningful measure of capacity imbalance.

For HST batteries, where individual cell voltages are not available, this tool may help quantify how shifts in battery voltage during eclipse operation or capacity testing could translate into capacity loss or capacity divergence.

2.4. Attempt to reproduce HST Battery 5 overcharge to the SBT batteries without exceeding thermal barrier to determine duration of improved capacity.

The GSFC position paper makes reference that Battery 5 was most affected by overcharge while the PCU bus impedance fault existed. However, no details of *overcharge were included. There was also no mention if the thermal limitation of 30 W was exceeded. Hence, first compile the conditions, like charge current, V/T level, charge duration, battery temperature, etc., under which the Battery 5 was inadvertently overcharged. Then, select two batteries from the SBT with approximately matched characteristics. Operate one battery (hereafter termed as Battery-A) similar to current flight batteries on-board HST and treat this battery as the control battery. Now operate the second battery (hereafter termed as Battery-B) with the conditions of overcharge that occurred on Battery 5 when the PCU bus impedance fault existed. Ensure that thermal barrier is not exceeded. Now continue to operate these two batteries and monitor them to observe how long the improved performance can be retained.*

If the improved performance can be retained for more than 4 months, then the same can be implemented to the batteries on-board HST.

3. BATTERY CHARGE CONTROL MANAGEMENT*

* Battery charge control consists of charge and discharge segments. Battery discharge occurs by "nominal" or "capacity testing". Nominal discharge is the capacity used during the night periods. Capacity testing occurs periodically where an artificial load is induced to partially deplete the battery. Charging following a capacity test involves an initial charge cycle at a lower current for the first cycle.

Observations/Findings

Charge management strategy (thermal constraints plus operational cycling) might not have been optimized to allow the batteries to reach their maximum state of charge.

Recommendations

Charge

3.1. Maximize charge current and raise V/T levels to improve charge efficiency during cycling operations as heat rejection capabilities will allow.

The data shows the HST batteries and, in particular, the cells within the batteries degrading with time. This in itself is not surprising considering the length of time and number of orbiting cycles. Fortunately, the depth of discharge is only 9 to 10% of the original 90 Ah and the temperature is being maintained near 0℃. This operational methodology is known to be consistent with long LEO operating cycle life. There is concern, however, that even with these optimum operating conditions, the capacities of the batteries as measured during the near annual capacity test process have dropped to 50.8 Ah on Battery 2 and 51.7 Ah on Battery 4. What is considered as important is the rate at which the measured capacity is decreasing (by 7 to 8 Ah/year) with a maximum of 16.6 Ah/year for Battery 5.

The complexities in the charge control system were known when the decision was made to use the 90 Ah NiH_2 batteries in place of the 55 Ah nickel cadmium batteries. The replacement proved to be fortuitous by providing significant margin for HST life in orbit. However, with 6 batteries, each charged from its dedicated 3 solar panels while at the same time tied in parallel to the power bus, required a complex method for controlling charge, minimizing overcharge, and assuring all 6 batteries were fully charged during the sunlight period without exceeding the thermal design of 30 W average. HST was therefore operated to limit the charge current and voltage to minimize heat and extend life. However, this method is counter to optimizing long-term cycling capacity.

To counteract the decrease in capacity with cycling, those on this review committee considered methods for increasing battery capacity. The preferred method is to charge the batteries more efficiently during the sunlight period, thus attaining a higher capacity level. The purpose is to restore some of the lost energy storage on the charge cycle, to increase discharge capacity, or as a minimum maintain the present capacity. If the batteries had higher available capacity, then potentially the degradation could be slowed.

One of the ways of increasing the Ah stored in the battery during charge is to use high rate (C/5 to C/2) as a minimum. Cells operated in this manner accept charge at high rates at nearly 100% efficiency before reaching an overcharge condition wherein heat is generated.

HST is one of the first LEO missions to use NiH_2 batteries. However, comparing HST with the Solar Max Mission, the charge current is presently only at 13.5 A (C/6.7). It is interesting to note that the lower charge rate is less efficient and generates more heat than the higher charge current. At high current, the charge efficiency is near 100%, which means there is no accompanying heating. This has been verified by numerous tests at Comsat and Crane as well as reported in the "NASA Handbook for NiH_2 Batteries" [ref. 3]. This implies that the effect on thermal limitation would be lowered.

Secondly, the present V/T level cutoff of 33 V (1.50 V / cell) is too low for a NiH_2 battery at 0^oC. The original V/T levels for the HST batteries are shown on page 3-45 in the "NASA Handbook for NiH_2 Batteries". At 0^oC, the K1-3 voltage initially used was 34.3V (1.56 V/cell). The chart shows that a V/T of 33V now in use is appropriate for 20^oC, clearly too low for 0^oC. The V/T values in report "On-Orbit Health Check of HST NiH_2 Batteries" by Rao, Wajsgras and Krol, presented November 15, 2002, shows a dark blue line on the V/T curve page at V/T of 33.2 V (1.51 V / Cell), which is also too low.

From the conversations with HST personnel and the data provided, it seems that to limit the orbital battery dissipation to about 30 W, the charge current was reduced from ~ 14 *to ~ 8 A after the first battery reached its software V/T limit (~ 32.3 V) and to trickle charge current of ~ 2 A when the first battery reached its hardware V/T limit (~ 33 V). Obviously, this scheme reduces the trickle charge duration and, in turn, reduces the battery dissipation during trickle charge period, but at the cost of lowering the charge efficiency as mentioned in the previous paragraphs. The lower charge efficiency results in a) increased battery heat dissipation during charging, and b) preventing battery from reaching a high state of charge.*

Therefore, the following are recommendations for the HST project consideration to enhance the capacity of the HST batteries in orbit.

a. *Increase the V/T level to appropriate levels to provide improved charge efficiency and energy. Raise the V/T level to a minimum of 34 V and allow the high rate charge to continue until 65 to 70% of the Ah, removed on the previous discharge, are returned when the V/T level is reached. Increasing the end of charge voltage is accomplished by raising to a higher V/T level consistent with operating at 0^oC.*

b. *Concurrently, with paragraph a. above, increase the charge current so that it is at the maximum when entering into the sun acquisition portion of the orbit. As a minimum, the high current can be implemented by leaving the solar panels connected to the battery at night so when the s/c comes into the sunlight and the solar panels are cold they can provide the maximum charge current. Additional current may be available if some of the loads are not operating at that time.*

c. *Develop a charge operation scenario in combination with paragraph a. above to utilize the lower current of trickle charge more advantageous by removal of solar panels or by ratchet charging described below in 3.3.*

d. *Enter into discussions with the experimenters on how to balance their needs with the importance of maintaining or increasing the charge state of the batteries fully in order to extend the mission.*

e. *Although the 30 W average heat load looms as a tall figure, it is not certain as to why this limit is so rigid. It is known that the long-term operation lower temperature affords longer cycle life, but can the present temperature limit be opened somewhat to accommodate more efficient charging associated with higher current and voltage operation?*

f. *Consider a method for interrupting charge with a trickle or lower level charge, then resuming the charge to increase the energy storage into the battery (see the discussion on ratchet charging below). When both the V/T level and charge current* *are increased, the trickle charge duration will be longer. Thus, a reduction of heat dissipation can occur if the trickle charge current can be reduced to below 2 A (perhaps to 1.5 or 1.0 A).*

It is understood the HST charge control system is complex and subject to limits and operations not fully understood by the committee members in the time allotted for the independent assessment. It is apparent that the members of the Project team have made a significant effort to continue the successful HST operation. The committee recommendations, made without the direct hands-on experience, are aimed at increasing the energy storage of the NiH_2 batteries to meet the present life requirements.

3.2. Explore increased temperature implications (3 to 5°C) in conjunction with alterations to charge modifications.

Cell performance is linked to environmental temperature. There is an optimum temperature range for the performance of older cells. Providing the cells with a colder environment can favorably affect cell performance to a certain point. However, more capacity may be gained by raising the temperature 3 to 5°C along with the proposed changes in charging procedures. Increasing the battery temperature by 3 to 5°C should be investigated and tested using ground-based testbed cells.

3.3. Investigate ratchet charging:

After the first ratchet to the voltage cutoff, then trickle charge mode and wait for recovery (10 to 20 minutes) and ratchet again.

- On-orbital cycling operations (Figure 3.3-1)
- Ratchet charging following capacity check (Figure 3.3-2)

Ratchet charging involves recharge to a V/T level or other charge cutoff criterion at a high charge rate, followed by a period of rest (typically trickle charge or open circuit), then a repeated recharge at the high rate to the same V/T cutoff level. If time permits, this high rate recharge and rest period can be repeated multiple times to ratchet the state of charge to higher levels (in LEO there may only be time for one ratchet). The overall RCF is intended to be similar to that with no ratchet recharge. However, three factors provide higher charge efficiency with the ratchet pulse-recharge sequence when the peak recharge rate is maximized. First, the lower recharge voltage that results from the rest period provides improved charge efficiency. Second, the trickle charge is more efficient when performed at a lower average state of charge. Third, charge efficiency always tends to be greater at higher recharge current.

This charge control method is particularly advantageous when recharge to the V/T cutoff at high rate occurs in a short period of time. Application of much of the trickle charge during the middle portion of the recharge period takes maximum advantage of the higher charge efficiency for trickle charge at lower SOC. The second high rate recharge pulse will provide an SOC boost due to the improved charge efficiency at the high recharge rate. Repeated recharge pulses with adequate rest between can ratchet the SOC up significantly.

This type of recharge profile should be evaluated to determine whether it is possible with the HST charge control hardware/software. This recharge method is expected to particularly benefit the recharge of a newly capacity tested battery, since it should allow a higher fraction of the returned charge to occur at the high rate. This charge method is not expected to have deleterious thermal effects if the total RCF is maintained to be similar to the RCF without ratchet charging. The average heat produced by the batteries can be limited to 30 W by appropriate adjustment of the software V/T levels for each battery.

Discharge (Capacity Test)

3.4. Revert to heritage method of continuous discharge using 5.1 ohm load.

The battery capacity test method used by HST up to 2002/2003 involved discharge through a 5-ohm load to a cutoff limit of 15 V. In 2003 this was changed to 5-ohm to a cutoff voltage just below 26.4, then 50-ohm to 15 V. This change in procedure, which was instituted to reduce the discharge current during the cell reversals, extended the capacity test timeline without improving the cell balancing effects.

It is recommended a return to the pre-2003 heritage capacity test procedure of applying a 5-ohm load until the battery reaches its cutoff level (whether this level remains at 15 V or is reduced to lower voltage levels in the future). The 5-ohm load will not allow reversal currents greater than 5 A, and the reversal current will be much less than 5 A for all reversals seen to date. The 5 A (~ C/18) is well below the acceptable gas evolution rate limit of C/10 (8.8 A) in the HST cells. Such reversals (~ 3 A rate) have been repeatedly demonstrated as not causing degradation every time the HST flight batteries have been capacity tested prior to 2003. Similarly, ground tests have not shown any evidence of degradation resulting from low rate (<C/10) reversals, where the duration of the reversal was limited to less than 48 hours.

The 5-ohm load during capacity testing will maximize the rebalancing benefit by driving the lowest capacity cells into depletion (reversal) sooner, particularly when combined with a lower cutoff voltage (i.e., ~ 3 V).

3.5. Investigate frequency and depth of capacity testing.

- Lower discharge level to below 15 V (3 to 5 V)
- Substantiate the maximum duration (hours) of reversal allowed for individual cells

In general, the capacity test has been found to serve several purposes for NiH_2 batteries:

- *Provides a check of the battery capacity to various voltage levels, as well as the correlation between the pressure monitor readings and the capacity level. This allows correction for slow pressure drift and maintains pressure as a good indication of the available capacity over the life of the batteries. The capacity test procedure also provides long-term trends of capacity degradation that can be used to predict battery life or the need to modify battery management methods.*
- *Provides rebalancing of the battery individual cell. If individual cells spread in capacity (which they typically do after significant cycling), they can all be brought back to a common, fully discharged state by the capacity test discharge. This rebalancing occurs as a result of the lowest capacity cells going into reversal when fully depleted, thus allowing the SOC of the higher cells to be brought down closer to the common zero-point capacity. The rebalancing from capacity test discharge only occurs during cell reversal, since this is the only time during discharge when no stored cell capacity is being depleted. The rebalancing can provide a significant improvement in the state of health of the overall battery by restoring cell capacity balance.*

There is very little evidence that capacity testing provides any long-term improvement of the health of individual cells (it does improve overall battery capacity by rebalancing cell capacities, thus allowing lower capacity cells to achieve a higher SOC). There is, however, a short-term improvement of the performance of individual cells. After capacity testing, each cell will have a higher discharge voltage and will produce less heat during discharge. Unfortunately, the cells also have a higher recharge voltage behavior, making them somewhat more difficult to pump up to high SOC following the capacity test discharge. The higher voltage behavior constitutes a short-term change in performance, typically lasting through several months of LEO cycling before the cells settle back to their pre-capacity test behavior.

Because cell rebalancing in a battery occurs when the lowest cells are in reversal, it is advantageous to maximize the reversal Ah to which these cells are exposed, within limits that are defined below. This will maximize the rebalancing effect. This can be accomplished by continuing the capacity test discharge to as low a battery voltage cutoff as possible. This allows even the highest capacity cells to be brought down to near-zero

SOC, and thus be capacity-matched to all the other cells in the battery. Capacity test cutoff voltage levels down to 2 to 3 V have been successfully used for 22-cell batteries to achieve satisfactory rebalancing even when cell voltage monitoring is unavailable.

It is recommended the voltage cutoff levels for the capacity test that are significantly lower than 15 V be explored as a method for the HST to achieve more complete cell balancing. This is likely to become more important late in life when cell imbalances tend to become greater.

Recharge following capacity testing is also a key portion of the conditioning exercise. More efficient methods are needed to restore full battery capacity in newly conditioned HST batteries. Tests are ongoing to evaluate several approaches and we recommend that the recharge methods described in Recommendations 1.1 and 1.2 be included in these evaluations.

Recommended Limits on Cell Reversal During Capacity Testing:

- *Cell reversal (in aged HST batteries) involves the evolution of hydrogen gas from the nickel electrodes and the recombination of this gas at the hydrogen electrode at -0.01 to -0.05 V, a process that involves no stored cell capacity and limited heat generation. Excessive rates of gas evolution are to be avoided during reversal, since the gas evolution pressure differentials can mechanically degrade the nickel electrode during reversal much as it does during overcharge (without the deleterious thermal effects of overcharge). Long-term overcharge at rates as high as C/10 are commonly applied to NiH_2 cells during acceptance testing and capacity verification tests. This same limitation should apply to the maximum acceptable reversal rate, which is 8.8 A (C/10) for the HST batteries.*
- *Cell reversal involves holding the nickel electrode at the highly reducing chemical potential of hydrogen gas (below zero cell voltage with hydrogen present). This voltage level initiates slow reactions that chemically reduce the active material in the nickel electrode. If allowed to proceed for a long period of time, these reactions can degrade electrode performance significantly. Controlling the duration of the low voltage exposure is thus paramount. Cell and battery testing (acceptance tests, capacity tests, and integration & test tests) typically put a limit of 16 hours on the duration of letdown periods to a low voltage. No performance degradation has been documented as occurring from up to 16 hours of low-voltage exposure. Low voltage cell storage tests with hydrogen gas present in the cells have indicated signs of undesirable degradation after 2 weeks of low voltage exposure. Thus, between 16 hours and 2 weeks there is a range of low voltage exposure time that can cause detectable nickel electrode degradation. Typically, a 48-hour limitation on low voltage (or reversal) exposure with hydrogen gas present has been recommended as a reasonable and safe threshold between 16 hours and 2 weeks. Many*

satellite programs have used the 48-hour limit over the past 10 to 12 years without experiencing deleterious effects on cell performance.

APPENDIX B

List of Acronyms

Ah	Amp Hour
DOD	Depth of Discharge
EPS	Electrical Power System
FSB	Flight Spare Battery
GSFC	Goddard Space Flight Center
HST	Hubble Space Telescope
JSC	Johnson Space Center
LEO	Low Earth Orbit
NiH_2	Nickel Hydrogen
NRB	NESC Review Board
PCU	Power Control Unit
RCF	Recharge Fraction
S&MA	Safety and Mission Assurance
SBT	Six Battery Testbed
SOC	State of Charge
V	Volt
V/T	Temperature Compensated Voltage Level
W	Watt

APPENDIX C

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APPENDIX D

Review Copy

The State of the HST Batteries

As it

Relates to HST

Health, Safety

and Ability to Support an On-going Science Operation

May 21, 2004

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____

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Important Note

This, the review copy of this paper, incorporates comments received on two previous drafts and is now submitted for review by GSFC's Applied Engineering and Technology Directorate.

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Executive Summary

Forecasts of HST viability vs. time based on battery charge capacity trends and extrapolations are context dependent. Battery capacity requirements for an on-going science operation are significantly higher than those for spacecraft maintenance in a sun-point safemode. At the present rate of capacity loss (~38 ampere-hours/year at the system-level), a hiatus in HST science operations will more likely be caused by loss of gyros. In a relatively low-electrical-load safemode, HST will need less capacity margin to ensure mission health and safety than it requires for science operations. If HST is being maintained in safemode it is reasonable to assume that it can, if necessary, remain viable while awaiting a re-entry module attachment or a robotic servicing mission that reaches the spacecraft as by the middle of calendar year 2009. However, HST *will have to be placed* into safemode sometime in 2008 if the present capacity trend continues.

The *viability at risk* "milestone" moves about a year earlier (into 2008) and the *safemode required* "milestone" moves into 2007 if the present system-level trend worsens by about one-third. Both milestones move over two years later if the present trend is reduced by a similar amount.

At present, it is not possible to predict a significant change in the system-level battery capacity loss rate. For now, prudence appears to dictate that a re-entry module attachment or a robotic servicing mission to HST is best scheduled for 2008, and, if delayed, should occur before the fall of 2009.

*Near-term, projections will be affected by the results of battery capacity measurements scheduled from now through October 2004. The Battery 5 results available at the end of June will be of particular interest. They will indicate whether Battery 5 has continued to lose capacity at a much higher rate than the other five batteries, or is now aging similarly to them. Available data indicate that the latter is more likely true.

Battery and Electrical Power Subsystem Overview

The three primary elements of the HST Electrical Power System (EPS) are the solar array (SA3), the Power Control Unit Replacement (PCU-R) and the six Nickel-Hydrogen (NiH2) batteries. All the electrical energy used by HST is either provided or distributed by these elements. Neither the SA3 nor PCU-R (nor for that matter, any downstream EPS element) is presently subject to any liens that preclude continuation of the HST operation well beyond 2010. Among the three subsystems, only the batteries are original equipment.

Each of the six batteries contains 22 individual cells connected in series. The nameplate (i.e., when new) capacity of each of the batteries is 88 Ampere-Hours (AHr) when discharged by a 15-ampere load. Prior to launch in 1990, however, the batteries were "super-charged" so that each had over 90 AHr of initial capacity. More specifically, the nameplate capacity originally defined the number of AHr the battery was required to provide to a 15-ampere load before the voltage at the battery terminals dropped below 26.4 volts (V). The voltage requirement itself relates to the minimum spacecraft bus voltage that, after diode drops and harness losses, is needed to keep each HST subsystem powered and reliably functional. Put differently, individual battery cells, on average, had to provide ~88 AHr between their fully charged voltage of ~1.5 V, and an average discharged cell voltage of (26.4/22 =) 1.2 V. At launch there was very little dispersion in cell capacity or performance. The present-day safemode load corresponds to approximately 9 amperes per battery. At this discharge rate, each battery's usable charge capacity is about 4 AHr smaller, to 26.4 V, than the value measured under the ~5 amp load through the on-board 5.1 ohm discharge resistor. The make-up of an HST battery and battery cell is further described in the Appendix.

The batteries themselves are connected in parallel to the main spacecraft bus. Each orbit day the SA3 powers the spacecraft and provides the energy to re-charge the batteries. Each orbit night, the batteries power the spacecraft and are discharged *approximately* equally by HST's activity- and configuration-dependent electrical load. The duration of orbit night ranges from ~27 to ~36 minutes (biased to the longer time), and the operational load is presently ~80-90 amperes (13-15 amperes per battery). For the longer nights as many as ~54 AHr are removed from the battery system total (above 26.4 V) of ~312 AHr (for a 9-ampere per battery load).* At the end of orbit night, the system depth-of-discharge (DOD) (relative to nameplate capacity) is about 9-10%. The DOD is ~16-17% of the present total system charge capacity. Fundamentally, the system charge capacity remaining at the end of orbit night must support a worst-case safemode entry from the spacecraft configuration and spacecraft attitude existing at the end of orbit night.

*For simplicity, usable battery capacity is not debited for the higher load of science operations, since remaining capacity under a 9-amp load is the relevant measure of survivability after safemode entry. At present, the margin in HST's battery capacity safemode triggers is more than adequate to compensate for the difference. If these margins are scrubbed in the future, the operational rate of capacity use will have to be accounted for.

The EPS system design assured HST survival following total failure of one battery. Prior to SM3A's installation of PCU-R, the possibility of simultaneous loss of two batteries (caused by an open circuit in the PCU) was examined and found to be survivable with the then-available capacities of the remaining batteries. Future survivability if total loss of a battery occurs will depend on the charge capacity of the remaining five batteries. Fortunately, the probability of NiH2 battery failure due to an open circuit within the battery is universally considered to be extremely low. Short circuits within cells are far more likely (to occur eventually). These lower, but do not zero-out available battery capacity. The probability of battery cell short-circuits will be discussed later.

Spacecraft Electrical Load and Orbit Night Battery Depletion vs. Spacecraft Configuration

Table I. enumerates the spacecraft load and battery capacity utilization of various HST configurations. It gives values for the present science operation, for Software Sun-Point (SWSP), Zero-Gyro Sun-Point (ZGSP), Spin-Stabilized Sun-Point (SSSP), and Hardware Sun-Point (HWSP) Safemodes, and for Gravity-Gradient Mode (GGM).

The table illustrates that forecasts of HST viability vs. time based on battery charge capacity trends and extrapolations are context dependent. In two significant respects battery capacity requirements for an on-going science operation are significantly higher than those for spacecraft maintenance in a sun-point safemode. First, the load requirements of the modes differ, and deplete the batteries differently each orbit night. Second, the margin needed to assure safemode survival in a safemode cascade is different from the margin required for assured safemode entry from the science operation. Primarily this difference arises because the safemodes are already sun-pointed or near-sun-pointed and because the battery capacity margin need not protect for a failed initial entry into a software safemode that must be followed by a successful hardware safemode entry from an arbitrary attitude. Later, this difference will be illustrated by comparing mission need dates for which the batteries 1) are assumed to support continued science operations until the mission, and 2) support HST maintenance in ZGSP until the mission.

Battery Testbeds and Flight Battery Diagnostics

The HST Program resources available for diagnosis and evaluation of battery-related anomalies, EPS operational and hardware configuration changes, battery degradation and performance maintenance/enhancement options reside at the Marshall Space Flight Center and have been in continuous use since approximately 1989. These resources are the Six-Battery Testbed (SBT) and the Flight Spare Battery (FSB). For the majority of the HST mission, the SBT and FSB have been cycled to mirror the cycling of the fight batteries under similar conditions. (For example, the pre-SM3B PCU bus fault was simulated in the SBT so as to expose its Batteries 5 and 6 to the anomalous overcharging and underutilization of on-orbit Batteries 5 and 6.) Additional SBT and FSB descriptions are provided in the Appendix.

Table I. Electrical Power Needs and Battery Usage of Various HST Configurations

HST Configuration	Nominal Power Required (watts)	Minus a load equivalent to NICMOS & NCS (watts) [As *one* example of a load reduction]	Max AHr used during orbit night (Nominal)/(sans NICMOS & NCS equivalent)
Present Science Operations Configuration	~2400	~1900	~54/~42
SWSP/ZGSP w/payload load shed (and FGE on)	~1780	~1680	~40/~37
SSSP (with FGE on and OTA heaters enabled)	~1450	~1350	~32/~30
HWSP (with comm.)	~1440	~1340	~32/~30
GGM *	< 18 hr ~ 840 > 18 hr ~ 1000	< 18 hr ~ 740 > 18 hr ~900	~19/~16 ~22/~20
GGM (with SI C&DH, ACS, STIS, FGEs) * *ACS (safe) ~ 62w* *SI C&DH (safe) ~25w* *STIS (safe) ~ 95w* *FGEs ~ 200w*	> 18hr ~ 1600	> 18hr ~1500	~36/~33

* GGM still under assessment, capability in standard configuration is questionable.

Recently, these test articles have begun to be used to explore approaches for improving the condition and performance of the flight batteries. Figures 1 and 2 document a recent deep discharge of SBT battery 6. Typical features of battery aging and degradation are readily seen. First, originally similar battery cells now have markedly different characters. This is seen (Figure 1) in the way successive cells stop supporting voltages above 1.2 V at different times; in the way their voltages decline differently to "second plateau" voltages around 1.0 V; and by where, exhausted of stored charge, each drops to a reversed voltage condition. Figure 2 shows the wide variance in the charge capacity available above 1.2 V, from 1.2 V to 1.0 V, and from 1.0 to 0.5 V. While many of the cells still store a large fraction charge they could originally store, much of this charge is no longer available above 1.2 V. In addition, individual cells charge to slightly different peak voltages and discharge to slightly different minimum voltages during the testbed equivalent of orbit night. Note also (Figure 2) that the capacity (above 1.2 V) of the battery as a whole, 53 AHr, is only 4 AHr greater than the capacity of the weakest battery cell (49 AHr). This battery's ability to provide >26.4 V was lost once four of its 22 cells dropped below 1.2 V. The present challenges include reducing the divergence in capacity (charge balance) among cells, and either stemming continued loss of capacity or increasing the percentage of cell capacity above 1.2 V.

Figure 1. Dependence of Useful Battery Capacity on the Weakest Cells Falling to 2nd Plateau Voltages
HST Six Battery Test - Battery 6
March 12, 2004

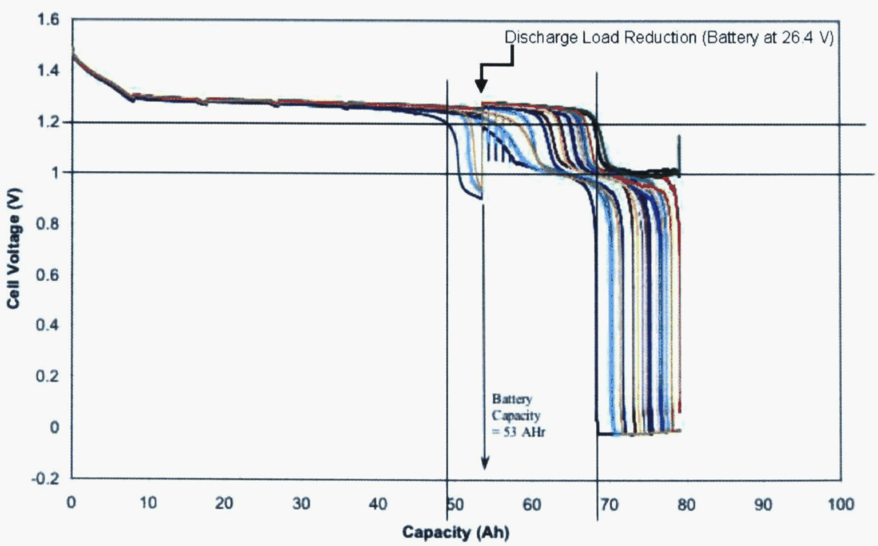
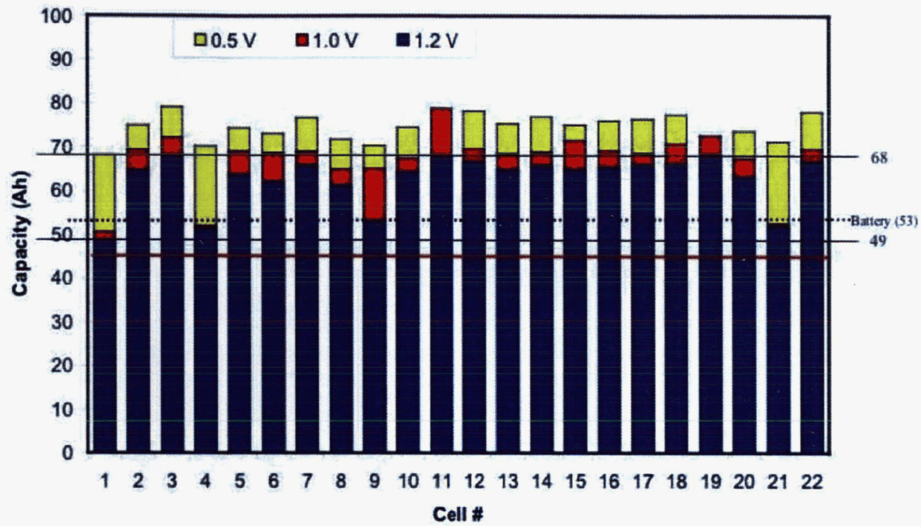


Fig. 1. Monitoring of individual cell voltages during discharge reveals a wide range of usable cell capacity. Once its voltage drops below 1.2 V, each cell provides some capacity on a "2nd voltage plateau" of ~1 V before the voltage plummets and the cell goes into reversal. When 4 cells have dropped to their 2nd plateaus the battery voltage drops below 26.4 V. Cell voltages then rebound as the test's 5.1-ohm discharge resistor is exchanged for a 51-ohm resistor. The substitution prevents the test from subjecting cells to larger, undesirable reversal currents after they "drop out" (i.e., go into reversal). The 10x-smaller discharge current markedly extends test duration.

Monitoring of SBT Battery 6 since the March test has revealed that post-test battery performance improvements persisted only temporarily. The initial conclusion drawn from this is that HST battery degradation rates will be halted, and improved performance sustained, only if a more effective technique for recharging the batteries after discharge is found. It appears to be very important that all of a battery's cells be initially recharged above the usual on-orbit charge cut-off voltage.

Figure 2
TM2 - Battery 6
March 12, 2004



Using the FSB, attention is now being focused on how to optimize recharge. The subsequent, and more difficult question will be how to transfer this process to the batteries in the flight system so as to restore charge balance among their cells and maintain that balance for usefully longs periods of time. The challenge exists because the six flight batteries (three batteries in each of two modules, with one module in each of two adjacent battery bays) are electrically in parallel (and non-isolatable), and because the bay design limits the tolerable thermal dissipation of the batteries.

The voltage of every cell in the SBT and FSB can be individually monitored. On orbit, each flight battery's aggregate terminal voltage can be monitored, but individual cell voltages are not telemetered. Moreover, each battery contains only two cells whose pressures can be measured by strain gauges mounted on them, and only one of these is visible on the HST's "active-side." (Switching to redundant-electronics for the additional measurements has its own risks and is highly undesirable.)

Nonetheless, when a flight battery is discharged to 15 V during a periodic reconditioning exercise, the aggregate battery voltage vs. AHrs out signature permits determination of the useful battery capacity and also yields indicators of individual cell performance.

Results from the March 29, 2004 discharge of flight battery 2 are shown in Figure 3. This test found the Battery 2 charge capacity above 26.4 V to be 50.8 AHr for a 9-amp load. It also provides indications that the battery voltage fell below 26.4 V after five cells dropped to a second plateau of ~1 V, and shows the dropout (reversal) of six cells before the battery voltage reached the test cutoff value of 15 V.

Figure 3

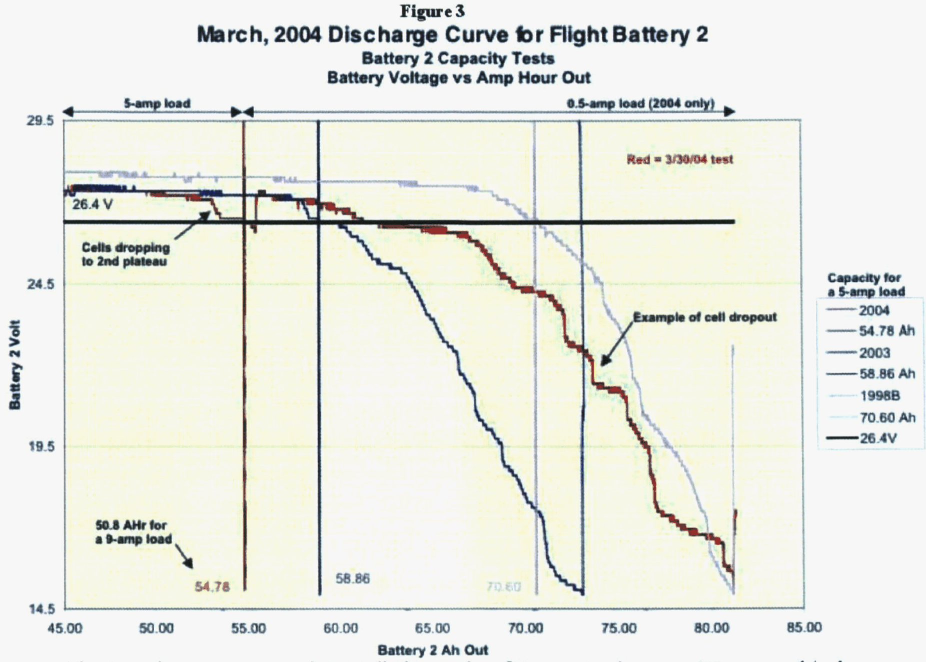


Fig. 3. In the aggregate March 2004 discharge plot of Battery 2 voltage vs. AHr removed (red line), the signatures of cells falling ~0.2 V to their 2nd plateaus, discharge resistor substitution, and cell dropout (0.8-1V decreases) are analogous to the cell-level signatures seen in Figure 1.

As is to be expected, the HST flight batteries and the test assets at MSFC exhibit similar characteristics. All of the flight batteries are losing useful charge capacity, and experiencing increasing cell divergence with time. Because cell divergence is increasing, the battery capacity reading derived from the pressure of the single, actively monitored cell in each battery is less reliable as an overall capacity indicator than it once was.

Cell Failures Mechanisms and Results from Destructive Physical Analysis of Flight Spare Battery Cells

Cell failures within NiH2 batteries are usually attributed to two principle mechanisms: gradual loss of capacity resulting in inability to maintain a required voltage for a required time while supporting a required load, and cell loss caused by an internal "hard" short circuit. Although different shorting paths can develop, the usual mechanism within an HST-type NiH2 cell is the development of a conductive path through the insulation separating successive plates. In HST's NiH2 cells, the insulation is provided by a double-layer Zircar separator.

Over the years, various models have been used to predict the probability of experiencing a failure in one or more of HST's battery cells. The definition of failure used in these models is inclusive of hard short circuits within cells, but much more broadly *and predominantly* encompasses all other changes that deprive a cell of the capacity above some minimum voltage that is required by the load the cell must support. The models produce failure probabilities as a function of battery DOD and cumulative discharge cycles. The model published by D. Hafen in 1998 predicted the likelihood of one HST cell failure after 13-14 years of operation. A different model, by A. Zimmerman in 2004, predicts that HST is less likely to have a cell failure before 2011 than it is to have one. Both assessments, however, define failure as the inability of a cell to provide a certain capacity down to 1 V. In Zimmerman's model, a cell is failed when it doesn't remain above 1 V down to a DOD of 10% (about 9 AHr).

For three reasons, the above-mentioned models cannot be used to directly answer questions about HST's future viability on-orbit. First, neither model directly addresses cell performance (or total battery capacity) down to 1.2 V; nor do the databases used to develop the models contain specific information on discharge cycle life to 1.2 V. Second, as is illustrated above, a significant portion of HST battery capacity is no longer available above 1.2 V. Third, as is seen in Figures 1, 2 and 3, a battery voltage above 26.4 V is no longer sustained, when as few as four cells (for now at least) fall to "second plateau" discharge voltages of ~1 V. *Cells do not need to fail per the encompassing definition of cell failure for a battery to lack adequate capacity above 1.2V – a small number of them only need to drop to their 2nd plateau voltage.*

In anticipation of this paper's Table III, another illustration of this point (with a simple one of many potentials examples) is useful: If each battery is to provide an equal share of the 110 AHr total useful capacity needed to comply with the criterion in the table's last row, then, per Figures 1 and 3, no more than four or five of its 22 cells can fall to their 2nd plateaus before the battery has provided ~18 AHr of charge. Neither presently observed HST cell trends nor available models can predict the success or failure of a battery to meet this criterion.

Returning to the topic of cell short circuits, Zimmerman's model also predicts that the probability of a hard cell short is *four orders of magnitude* smaller for the HST operating condition than the probability of failure within his broader definition. There are, at present, no reported instances of a hard short in any NiH2 cell possessing double-layer Zircar separators and cycled per HST operating conditions.

At different times over the last several years, four cells have been removed from the original 22-cell FSB and subjected to Destructive Physical Analysis (DPA). DPA results, including thorough chemical and physical analyses, have been documented elsewhere, and will not be overviewed herein. The single point to be made herein concerns the absence of evidence of incipient cell failure resulting from migration/penetration of conductive material through the dual Zircar separators in the cells. In fact, no penetrations spanning more than the first Zircar layer were observed. If all the flight cells are behaving similarly to this small sample from the flight spare battery, it may be some time before any of them experience a hard short. On balance, no firm conclusion can be drawn. On the one hand it seems very reasonable to assume the absence of a hard cell short in the HST flight batteries during the next five or six years. On the other hand, the DPA sample is small, and the batteries met their lifetime requirement long ago. The occurrence of a cell short would hardly be termed anomalous.

Loss of charge capacity, however, is clearly a phenomenon occurring in the HST batteries. The key question is whether the total system's recent capacity loss rate will persist, increase, lessen, or even be reversed by improvements that might be made to the manner in which the batteries are discharged during reconditioning and subsequently recharged. The answers to these questions await further testbed experimentation and additional tests of the on-orbit batteries.

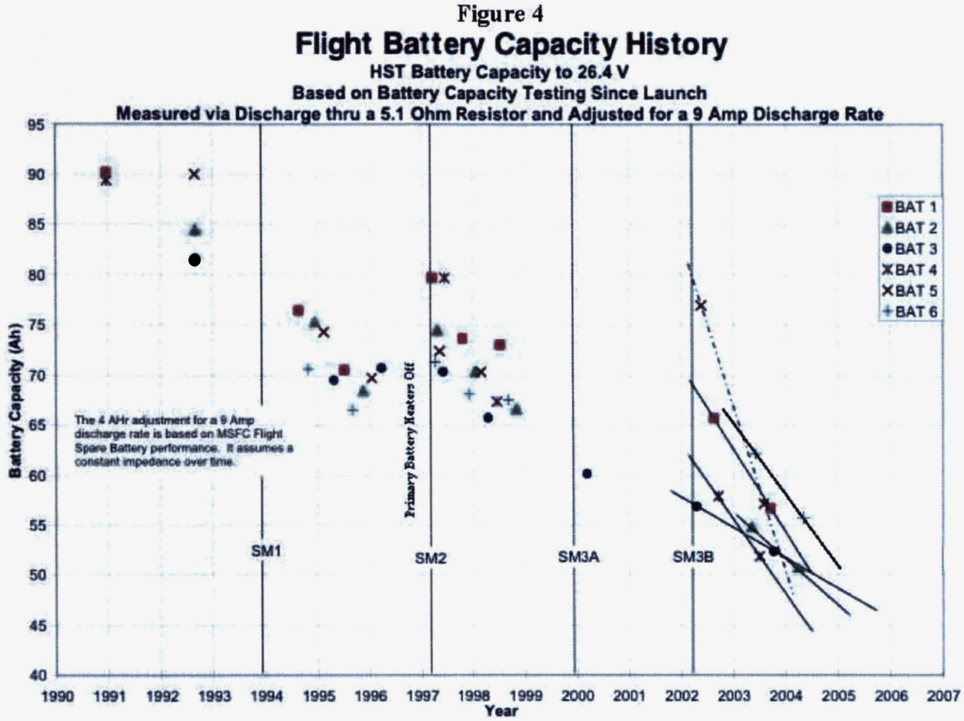
Battery Charge Capacity History and Trends

Primarily since 1994, periodic discharge-based measurements of the capacity of each battery have been made – partly to update the calibration of the strain gauges on the pressure-monitored cells to correct for anticipated beginning-of-life drift, and partly to obtain direct measurements of the total battery capacity. Over the last few years, gauge drift has become negligible, and the inaccuracy of capacity estimates from single-cell measurements has become a function of the increasing voltage and capacity divergence of each battery's 22 cells. Figure 4 shows the historical record of capacity measurements.

By 1996 decreasing battery capacity had become enough of a concern that a decision was made to turn off the primary battery heaters and allow the batteries to drop several degrees C in temperature. As expected, this change increased the capacity of the batteries and succeeded in maintaining the 1995 total system capacity through the end of 1997. There were no measurements in 1999 as SM3A approached, and only a single measurement (for Battery 3) in 2000. Following the appearance of the impedance fault in PCU Bus C, the next battery reconditioning was halted when it resulted in instability of the fault impedance. This phenomenon caused a hiatus in capacity measurements until PCU-R installation in March 2002. Measurements resumed in 2002 and yielded a modest loss of battery capacity between 1998 and 2002. The annual average capacity loss was – 2.0 AHr/battery/year across this time interval.

As shown in Table II, concerns about battery longevity arose during the reconditioning "season" in 2003. Second-epoch measurements of three batteries yielded a much steeper annualized average capacity decline over the preceding year: -6.3 AHr/battery/year, or triple the average over the preceding 4 years. This average excluded the result for Battery 5 (-16.6 AHr/year), which was most affected by overcharge while the PCU bus

Figure 4



impedance fault existed. A key question to be answered in June 2004 is whether Battery 5 continues to lose capacity rapidly, or is now following the trend of the other batteries. With the April 2004 second-epoch measurement for Battery 6 now included, the annualized capacity loss rate calculated from five batteries remains –6.3 AHr/battery/year.

Forecasts Based on Charge Capacity Trends

Absent the answer to the previously posed question about future charge capacity trends, forecasts of future HST mission capability will now be made using the currently available data. It is assumed below that the annual capacity decline in Battery 5 is now equal to the average decline of the other five batteries with two capacity measurements since SM3B. This key assumption will be confirmed or refuted in late June 2004. For now, it appears reasonable because the Battery 5 capacity presently derived from its strain gauge reading is little different from the elapsed-time-adjusted July 2003 discharge-derived capacity. With this assumption, the annual system-level capacity loss rate (rounded up) is presently –38 AHr/year.

Table II.

HST NiH_2 Battery Capacity Measurements Through April 27, 2004

Battery	Last Recon Pre-SM3B Date	Last Recon Pre-SM3B Cap*	1st Post-SM3B recon Date	1st Post-SM3B recon Cap*	2nd Post-SM3B recon Date	2nd Post-SM3B recon Cap*	3rd Post-SM3B recon Date	3rd Post-SM3B recon Cap*	AHr loss/yr Pre-SM3B to 1st Post-SM3B	AHr loss/yr 1st Post-SM3B to 2nd Post-SM3B	AHr loss/yr 2nd Post-SM3B to 3rd Post-SM3B
1	15-Jul-98	73.1	20-Aug-02	65.7	16-Sep-03	56.7	Jul 04		-1.8	-8.4	
2	5-Nov-98	66.6	7-May-03	54.9	30-Mar-04	50.8	TBD		-2.6	-4.6	
3	22-Apr-98	65.8	18-Apr-02	56.9	10-Oct-03	52.4	Aug 04		-2.2	-3.0	
4	23-Jun-98	67.4	16-Sep-02	57.9	1-Jul-03	51.9	early Jun 04		-2.2	-7.6	
5	4-Mar-98	70.3	21-May-02	77	31-Jul-03	57.2	late Jun 04		1.6	-16.6	
6	9-Sep-98	67.6	3-Jun-03	62.2	27-Apr-04	55.3	TBD		-1.1	-7.7	

*All capacities adjusted for 9 Amp discharge

Avg. ΔAHr/year= -2.0 Ahr*   Avg. ΔAHr/year= -6.3 Ahr**

*Batteries 1-4 & 6   **Batteries 1, 3, 4 2 and 6

The elapsed-time-adjusted Full State-of-Charge Capacity of the 6 batteries at 4/1/04, applying an average decrease of 5.9 Ahr/battery/year to the most recent measurement for each, was ~312 Ahr. The pressure-based Full-SOC Capacity prior to Battery 2 Discharge was ~325 Ahr*

*Pressure-based estimates are derived from telemetry of a single-cell per battery, using the charge capacity vs. pressure calibration determined during the most recent, prior reconditioning of that battery. The measurement cannot be adjusted for divergent cell performance within a battery. However, the pre-discharge prediction for Battery 2 was only 2.1 AHr higher than the value measured on 3/30/04. The difference between the time-adjusted system total and the pressure-based estimate also averages about 2 Ahr/battery.

Loss rates for Battery 5 are unlike those of the other batteries, and are likely an artifact of the Pre-SM3B Power Control Unit's condition. However, the measured capacity of Battery 5 on 7/31/03 was much more like the capacities of the other batteries.

With just a few measurements so far, each additional datum can affect the average significantly. The present spread in recent measurements suggests that it's not yet meaningful to talk of statistical significance. Moreover, as the batteries age further, the trend line slope may become shallower (especially if testbed experimentation identifies useful capacity preservation techniques); or it may become steeper, or even non-linear. With these possibilities in mind, the present forecast reduces the last-determined capacity of each battery by the adopted average annual loss rate times the elapsed year fraction since the measurement. The start-of-April 2004 system total is thus estimated to be 312 AHr. Linear extrapolation into the future follows and permits construction of Table III. Actual system performance may be better or worse, and move the negative-margin predictions for each row of the table backward or forward in time.

Table III's entries lead to several conclusions (in reverse chronological order of occurrence):

1. Through mid-2009, HST will most likely survive continued battery capacity loss at the assumed, constant rate if it is being maintained in a low-load Sun-Point Safemode controlled by the HST486 computer. After that time the risk of mission failure if HWSP entry occurs will grow.
2. Sometime in 2008, power limitations may require halting the science program and placing HST into, and maintaining it in safemode.
3. In 2006, infrared science with NICMOS/NCS may have to be terminated, or a mix of other load reductions imposed. Alternatively, the HST Program may have to significantly lower the SOC safemode triggers now in use and, earlier than otherwise, move decisively toward adoption of the "Minimum Reserve Capacity for Science Operations" defined in Row 3 of Table III.
4. Some downward adjustments to the current EPS SOC safemode triggers will be needed in 2005.

Table III.
Total System Charge Capacity and Margins vs. Time

Date	April '04	April '05	April '06	April '07	April '08	April '09	April '10
Total Battery Capacity at end-of-orbit-day (AHr)	312	274	236	198	160	122	84
Margin at end-of-orbit-night to the 235 AHr First State-of-Charge (SOC) SWSP Safemode Trigger now used in Science Operations	23	-15/-3*	-41*				
Science Operations end-of-orbit-night margin to the 180 AHr Second-SOC (HWSP) Safemode Trigger now in use	78	40/52*	2/14*	-24*			
Margin to the Minimum Reserve Capacity for Science Operations (115 AHr) if an allowance for successful SWSP entry is also being maintained	143	105/117*	67/79*	29/41*	3*	-35*	
Margin at end-of-orbit-night to the Minimum Reserve Capacity for HWSP Safemode (70 AHr**) if HST is being maintained in ZGSP	202	164	126	88	50	12	-26*

*Minus a load equivalent to turning NICMOS/NCS Off
**Suitability of a 70 AHr reserve capacity if entering HWSP from ZGSP is subject to verification in near-term simulations. Based on present knowledge it includes 14 AHr uncertainty in the system-level capacity derived solely from pressure readings of 1 cell/battery.

= Minimum Reserve Capacities no longer ensure survival if certain additional failures occur concurrently with safemode entry (e.g., failure of the active side of the Hardware Safemode computer).

Relationship of Pointing Performance to Battery Capacity Requirements in Safemode

Conclusions 1 and 2 of the previous section point to the eventual need to maintain HST in a low-load Sun-Point Safemode controlled by the HST486 computer. Whether or not a One-Gyro Science Mode is found feasible, HST will likely be in, or have to be put into ZGSP in 2008. The Program's experience with ZGSP (in late 1999 and since) is generally positive – especially since the introduction of several software fixes in 2000. Nevertheless, a known characteristic of the current ZGSP implementation is that the HST will occasionally drift considerably off its required orientation during orbit night. The 70 AHr minimum reserve is believed to be adequate for both a large-angle sun-point recovery and HWSP entry should it be required. To verify this, computer runs simulating numerous starting conditions will be conducted, and will include the additional assumption that HST has only three working Reaction Wheel Assemblies (RWAs).

Meanwhile, the Program's Two-Gyro Science Mode development experience suggests that a replacement ZGSP that provides good attitude stability regardless of orbit phase might be possible. This option will be carefully assessed in due course.

The On-going Battery Test Program

An experienced team of HST contractor and GSFC civil servant EPS and battery engineers are actively engaged in defining, executing and interpreting results from a continuing series of SBT and FSB tests. In parallel, the 2004 series of on-orbit battery reconditioning tests is underway. MSFC tests are focusing on three objectives: reducing the degree of voltage, impendence, and capacity divergence that has developed within the cells of HST's NiH2 batteries; finding a flight-viable technique for improved battery charging that stems cell divergence and increases the charge capacity available to support the minimum necessary bus voltage; and demonstrating that candidate techniques can be successfully applied to the on-orbit batteries. These efforts will continue through 2005. On-orbit tests of the best approach will likely begin during Spring 2005, if not before.

Summary

The principle concern regarding useful HST battery life and mission survivability is the rate of loss of total system charge capacity identified in 2003. While hard shorts in battery cells may occur eventually, there is no present evidence that they will occur soon enough to be relevant. Assuming the observed capacity loss rate remains constant over the next five years, the HST science program will have to be halted, and the spacecraft will have to be placed in safemode in 2008. However, in safemode HST should survive on-orbit into the second half of 2009. Prior to 2008, new operational constraints will be required and the use of smaller, less robust EPS safemode margins will have to be accepted. Efforts are underway to identify battery reconditioning and recharge techniques that will stem the rate of capacity loss, improve cell charge balance, and prolong mission viability. Relevant tests using the MSFC battery testbeds have begun.

Appendix

Flight and Testbed Battery Descriptions

HUBBLE SPACE TELESCOPE PROJECT

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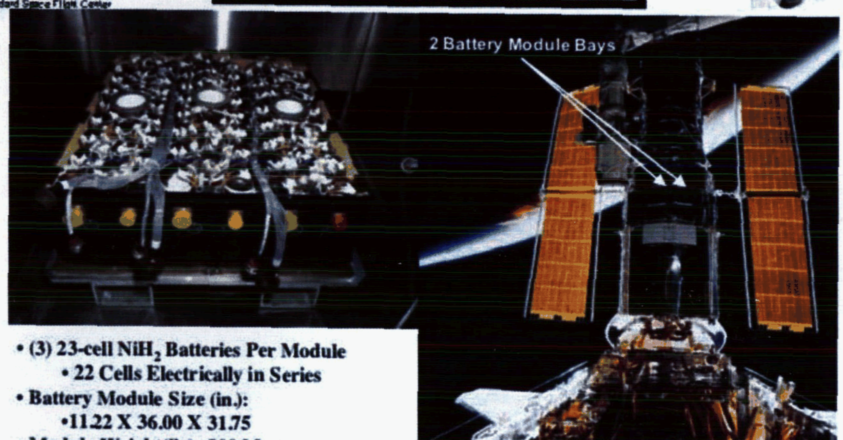
HST Nickel Hydrogen (NiH_2) Cell Design Description

- 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

Goddard Space Flight Center

HUBBLE SPACE TELESCOPE PROJECT

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 (AHr)
  - 15 A Discharge to 26.4 V at 10 °C
- Launch: April 24, 1990 (14 Years)
- Part No:4177755

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HUBBLE SPACE TELESCOPE PROJECT

Goddard Space Flight Center

HST Resources

- On-Orbit HST Batteries
  - Flight Module 2 (FM2) & Flight Spare Module (FSM)
  - Six 23-Cell Batteries (Launched 4/1990)
  - 73.5K Cycles (13+ Years) [76K cycles as of May, 2004]
- Marshall Space Flight Center (MSFC) HST Flight Spare Battery (FSB)
  - 23-Cell Battery (Cycled Started 6/1989) [4 cells since removed for DPA]
  - 78 K Cycles (14+ Years)
  - Individual Cell Voltage Monitor
- MSFC Six Battery System Test - Test Module 1 (TM1) & TM2
  - Six 23-Cell Batteries (Cycled Started 5/1989)
  - 78K Cycles (14+ Years)
  - Individual Cell Voltage Monitor
- Flight Module #1 (FM1) Re-designated as "Flight Spare"
  - Three 23-Cell Batteries
  - Cold Stored @ EPT
  - Currently at Goddard Space Flight Center (GSFC)
    - Used for Test Equipment Checkout & Fit Checks

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14. ABSTRACT
The purpose of the GSFC position paper is to identify critical HST milestone dates for continued science studies followed by the attachment of a re-entry module or a robotic servicing mission. The paper examines the viability of the HST with respect to the NiH2 continued battery charge capacity. In the course of the assessment, it was recognized that the HST battery thermal control system has an average heat dissipation limitation of 30 W per bay per orbit cycle. This thermal constraint will continue to govern options for battery capacity maintenance. In addition, the HST usage represents the longest exposure of NiH2 batteries to Low Earth Orbit (LEO) at the current level of Depth of Discharge (DOD). Finally, the current battery life is at the limit predicted by the manufacturer, EaglePicher. Therefore, given these factors, the potential exists that the HST battery capacities could radically degrade at any point. Given this caveat on any life extrapolations, the conservative model proposed in the GSFC position paper was viewed by the NESC as having several technical assumptions such as limited utilization of flight battery capacity data, the susceptibility of the proposed prediction method to large variations when supplemented with additional information, and the failure to qualitatively or quantitatively assess life prediction sensitivities. The NESC conducted an independent evaluation of the supporting information and assumptions to generate the predictions for battery capacity loss and practicality of on-orbit battery conditioning.

15. SUBJECT TERMS
Battery charge control management; Hubble; NiH2; System aspects; V/T; Battery; Life prediction Methodology; Peak rates; Ratchet; Voltage

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