The primary objective of the Six-Battery Nickel-Cadmium Mission Simulation Test in operation at the National Aeronautics and Space Administration's (NASA) Marshall Space Flight Center (MSFC) is to determine battery life and electrical power system (EPS) performance characteristics for the Hubble Space Telescope (HST) program. The basic HST power system requirements are to provide power generation, energy storage, and EPS control and distribution for 2.5 years with the nickel-cadmium (NiCd) batteries at an end of life solar array of 2 years. Mission simulation life testing began in April of 1986 and the batteries have completed their 2.5 year mission requirement. Conditions as close as practical to the actual predicted mission profiles were followed. These included solar array degradation, load variations, beta angle changes, temperature changes (with excursions to 10 °C), battery reconditioning, safemode simulations, and off-normal roll activities. As a result, these mission simulation tests gave NASA valuable information to aid in determining EPS operations in order to maximize battery life and capacity. This paper presents some of these results.

ABSTRACT

The primary objective of the Six-Battery Nickel-Cadmium Mission Simulation Test in operation at the National Aeronautics and Space Administration’s (NASA) Marshall Space Flight Center (MSFC) is to determine battery life and electrical power system (EPS) performance characteristics for the Hubble Space Telescope (HST) program. The basic HST power system requirements are to provide power generation, energy storage, and EPS control and distribution for 2.5 years with the nickel-cadmium (NiCd) batteries at an end of life solar array of 2 years. Mission simulation life testing began in April of 1986 and the batteries have completed their 2.5 year mission requirement. Conditions as close as practical to the actual predicted mission profiles were followed. These included solar array degradation, load variations, beta angle changes, temperature changes (with excursions to 10 °C), battery reconditioning, safemode simulations, and off-normal roll activities. As a result, these mission simulation tests gave NASA valuable information to aid in determining EPS operations in order to maximize battery life and capacity. This paper presents some of these results.

BACKGROUND

NASA’s HST is the largest single scientific instrument built to date. It is a cooperative project between NASA and the European Space Agency (ESA). MSFC is responsible for the overall development of the HST while ESA developed the solar arrays which supply electrical power to the telescope. Lockheed Missiles and Space Company, Inc. (LMSC) is responsible for the HST Support Systems Module (SSM) and for the spacecraft integration, while Perkin-Elmer is responsible for the Optical Telescope Assembly (OTA). The Electrical Power Branch at MSFC implemented and tests the HST EPS breadboard.

The components of the EPS breadboard are as follows: (1) 13 independently controlled power supplies which simulate the 20 Solar Panel Assemblies (SPAs) of the HST solar arrays; (2) 3 independently programmable load banks which simulate the HST loads; and (3) 6 flight type Charge Current Controllers (CCCs) which provide multilevel, temperature compensated charge cutoff control of the 6 batteries. All of the above are interconnected by a distribution network that includes protective devices as well as various switching capabilities to simulate the actual EPS elements. For instance, SPAs can be switched to different diode busses during reconditioning in order to retain use of their power output. The entire EPS breadboard is monitored by a Digital Data Acquisition System (DDAS) and is controlled by a microprocessor-based control computer (CC). The DDAS monitors 138 cell voltages, and 138 cell pressures, 6 Battery Protection and Reconditioning Circuits (BPRCs), the Solar Array Simulators (SASs), the battery load currents, load voltages, and 36 (6 per battery) temperatures. Complete battery isolation occurs when a fault is detected by the DDAS, and fuses are also installed to protect other equipment as well as the batteries. The CC autonomously controls the 13 SASs (power supplies), the three load banks (regulating constant power or constant current), the temperature of two aluminum plates (see below), and the trickle charge level (see Figure 1). A simplified block diagram of the HST EPS is shown in Figure 3. The SPA configuration is simulated by two constant current power supplies; one power supply simulates one SPA and another power supply simulates two SPAs. The charge voltage cutoff settings for the CCC are shown in Figure 4. [1]

THE BATTERIES

The six Eagle-Picher, Type 44, 23-cell nickel-cadmium batteries in the breadboard were fabricated using the same manufacturing processes as the flight batteries. These batteries provide power during the eclipse period of the HST orbit. The batteries are installed in one temperature-controlled chamber, but are mounted three each on two aluminum plates which simulate the two bays on the HST where the batteries are located (see Figure 2). Independent temperature control of the two aluminum plates provides up to a 10 °C difference between the two plates for test purposes. Housed in a cast aluminum battery case, each battery weighs approximately 135 pounds and contains 23 RSN-55-15 NiCd cells connected in series. Each cell is independently fitted with a pressure transducer. Under normal operating conditions, internal cell pressure should not exceed 30 psi. The batteries are designed to operate for 2.5 years with a maximum depth of discharge (DOD) equivalent to 16 percent of the nameplate capacity of 55 ampere-hours (Ah). [1]

TESTING AND RESULTS

Prior to the actual “mission simulation test,” several system simulation tests, or parametric tests, were performed on the HST EPS breadboard. These included changes in charge levels
and charge control schemes, changes in beta angle, failed cells, failed batteries, failed SPAs, beginning of life (BOL) and end of life (EOL) SPAs, and temperature variations [1]. These were executed to observe system performance under special conditions. The "mission simulation test" completed the level one requirement for life in operation after 30 months or approximately 14,100 orbits. The mission simulation tests are performed by simulating the predicted flight conditions of the HST EPS. Seasonal load and solar array variations along with beta angle variations of 52 degrees (maximum) and 0 degree (minimum) (i.e., sun/eclipse ranges from 69/27 minutes for maximum sun beta angle, to 61/35 minutes for minimum sun beta angle) are simulated. The batteries were cycled at a step-to-trickle charge mode and special test conditions such as vehicle attitude rolls and certain contingency conditions (safemode) were also performed. Battery temperature was maintained at 0 °C except during an annual "hot" condition (10 °C for one month). These test conditions were simulated in an effort to provide a realistic test of the power system.

Battery Cycling

The HST is scheduled to launch in early 1990. The telescope will be initially launched into a low Earth orbit of approximately 593 km. This altitude sets the orbit cycle time at approximately 96 minutes. The breadboard at MSFC simulates the predicted time of launch and inclination of the orbit by controlling the beta angle (day/night ratio) as seen in Figure 5. The batteries’ charge and discharge profiles are determined from the predicted solar array aging characteristics and the predicted load power profile provided by ESA and MSFC.

Battery voltage during normal operation ranges between 28 and 34 volts depending on load, battery state-of-charge, the number of batteries on-line and the time elapsed since the last reconditioning was performed. During testing, MSFC found that battery voltage varied significantly depending upon life and operating conditions.

Trickle Charge

The batteries were initially cycled at a one step-to-trickle charge from the voltage cutoff level K2 level 1 (K2-1) (see Figure 4). After several orbital cycles, the batteries were adjusted to cycle at K1-2 in direct response to revised voltage limitations set forth by LMSC and MSFC. To allow for adequate charging during reconditioning, the batteries were set to cycle at a two step-to-trickle charge. However, following a scheduled battery reconditioning, when recharging that tested battery, all batteries were left cycling at two step-to-trickle in order to allow that battery and any other newly reconditioned battery to receive additional high rate charge. This, in turn, would assist them in returning to full charge. As a result, a recommendation for cycling at all times at a two step-to-trickle charge voltage level of K1-2 was implemented for the flight

Figure 1. HST EPS Breadboard Test Panel.

Figure 2. The Six, Type 44, NiCd Batteries in the Chamber.

Figure 3. Simplified Block Diagram of HST EPS.
vehicle. On the HST EPS this desired step-to-trickle charge mode was accomplished by the CC (or in flight, the DF224 flight computer) by monitoring the CCC operation, and when a specified number of CCC relays opened, the CC commanded the SASs to simulate trim relay openings which resulted in the predetermined trickle charge level. This level was at a 2 to 3 amperes rate.

Earlier testing had indicated a need for a minimum of 20 minutes of trickle charge time for normal EPS operations to maximize battery life and capacity. However, at high beta angles (52 degrees maximum) a significantly longer trickle charge time occurs. This causes increases in battery temperature and recharge ratio (RR), and decreases in efficiency if excessive coulombs of trickle charge are allowed. This may lead to unnecessary stress on the batteries. As a result a recommended envelope of trickle charge time as a function of trickle charge current was developed and is shown in Figure 6. This current/time relationship is controlled by adjusting the average current (by controlling the number of SPAs on line) during trickle charge.

Trickle charge times of less than 5 minutes must be limited to 10 orbits or less per the requirement for off-normal rolls. If this envelope is followed, the profile of predicted trickle charge time expected during the mission based on predicted solar array power and predicted loads is not expected to adversely affect the life of the batteries within the 30 month life requirement. By maintaining this envelope, battery rundown with greater than 5 minutes of trickle charge has not been experienced in any of the HST battery tests, and is not expected to be a problem.

**Vehicle Attitude Rolls**

A slew or off-normal roll will occur when certain HST operations require the vehicle to be in an attitude that inhibits the solar arrays from being within 5 degrees perpendicular to the sun. Off-normal roll orientations of up to ±30 degrees for no more than four consecutive orbit revolutions are simulated on the HST breadboard. It was found that rolls of less than 27 degrees had insignificant effect on the trickle charge time. The effect on the SPAs is simulated by manually adjusting the 13 SASs (power supplies) to account for the reduced current and shadowing.

All rolls, except those scheduled consecutively on the same day, were initiated not less than two days apart. After a 30-degree roll maneuver, all batteries returned to near full charge by the next orbit. In addition, a 30-degree roll maneuver not followed by a safemode produced a battery DOD of less than the predicted 25 percent. The batteries returned to normal cycling by the first orbit following all other rolls.

**Safemode**

The HST flight vehicle safing system utilizes system level monitors which take autonomous corrective actions to ensure survival upon detection of certain system abnormalities. Sunpoint orientations and load shedding are examples of mode changes for corrective actions such that a power positive condition is maintained.

The EPS monitor for safemode is simulated on the MSFC’s CC by manually changing the load to cause the load shedding effect.

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Figure 4. CCC Settings.

Figure 5. Beta Angle Variations at 0 °C.

Figure 6. Type 44 NiCd Trickle Charge Operating Range.
MSFC observes system performance by emphasizing those roll conditions which create a maximum DOD. This includes activities with or without a safemode condition. A cumulative discharge of approximately 80 Ah is achieved per safemode. Eight safemode procedures were performed over the 2.5 year period. Some of the eight followed off-normal roll conditions of 27 and 30 degrees. Following a 30-degree roll maneuver, a maximum (as high as 44 percent) DOD was reached. This is well above the allocated predicted battery DOD of 25 percent. However, in this case, the batteries reached full charge by the sixth orbit of normal cycling.

For a very short period of time, the RR increased slightly while battery efficiency, cell voltage charge and discharge divergence decreased. No adverse effects occurred on the system when these rolls and/or safemode conditions were performed. However, a maximum DOD of approximately 21 percent occurred when a 30-degree roll was performed during a capacity test. For all other 30-degree roll maneuvers, the DOD fell within a range of 12 to 15 percent.

**Capacity/Reconditioning**

The “memory effect” in NiCd cells occurs when the cells cycle at a constant DOD and is characterized by progressive decreases in discharge voltage with increasing cycles. This phenomenon can be observed when NiCd batteries are fully discharged after having been cycled for several orbits at a constant DOD, and the decreases or depression in discharge voltage are seen shortly after the previous DOD cycle point. [2] In the HST EPS breadboard, the DOD is initially at 7/55 Ah or approximately 13 percent. Reconditioning the batteries allows a large part of the “memorized” cells' original capacity to be somewhat restored. This is accomplished by fully discharging the cells and forcing the batteries to a low voltage (less than 0.8 volt/cell) for a predetermined period of time (in this case, approximately 30 hours).

Each battery is equipped with a BPRC that prevents cell reversal during failure and/or reconditioning. Each BPRC consists of a dc-to-dc converter with a separate low voltage, full wave rectified output for each cell. This allows the batteries to discharge rapidly during the reconditioning process with no danger of cell reversal. During normal operation, the BPRC is isolated from the cells by reverse biased diodes. During reconditioning, the diodes in the BPRC for those cells with lower state of charge (SOC) become forward biased and the BPRC prevents cell reversal. As a result, these cells are maintained at approximately 0.5 volt. In the case of a failed cell, the BPRC prevents cell reversal by providing the discharge current for the weak cell. That battery can thus still provide a share of the vehicle load even with a failed cell. [3]

The battery capacity results are shown in Figure 7. In a capacity test, each battery is discharged through a 5.1 ohm resistor until a battery voltage of 26.45 volts is reached. This is the minimum allowable battery voltage for normal operation. For reconditioning, the battery remained on the 5.1 ohm resistor for approximately 30 hours. Only one battery at a time was off-line for reconditioning. Alternating between battery bays to minimize thermal effects is the suggested procedure when more than one battery is being reconditioned. The accumulative capacity averages during the mission simulation test for all six batteries are shown in Figure 8. Each battery was reconditioned every third month per the flight operation requirements.

**Figure 7. Individual Battery Capacity Tests.**

**Figure 8. Type 44 Battery Capacity Average over a 2.5 Year Period.**
At the completion of their 2.5 year (30 month) level 1 mission cycling requirement, the batteries’ total capacity at 14,100 orbits was approximately 242 Ah which met the 162 Ah safemode requirement for the system. However, the effect of battery cell aging led to degradation of several cells in the six batteries, so that the capacities of two of these batteries did not meet their 1/5 share of the 162 Ah requirement for safemode (see Figure 7).

While system cycling progressed, battery 4’s (B4) recharge ratio average (10 orbit average) exceeded the 105 percent requirement. In attempts to correct this high RR, several procedures were undertaken to try and maintain RR below 105 percent. Following a second reconditioning, the battery was adjusted to a lower voltage cutoff level. The lower cells became more stable and battery efficiency improved. To date this battery is still cycling at the lower voltage level. It continues to deliver within 5 percent of the other batteries during normal cycling and its capacity, in this mode of operation, at 2.5 years was 33.7 Ah.

CONCLUSIONS

Discounting system cycling interruptions caused by hardware, software, human error, and periodic updates and revisions, the HST EPS breadboard hardware operated continuously for 30 months and demonstrated the power system ability to meet the HST requirement. In fact, no adverse effects occurred on the system even during the 10 °C tests. During this time, all other activities such as rolls and beta angle variations continued.

Battery capacity actually increased (see Figures 7 and 8), and battery efficiency decreased while recharge ratio climbed linearly.

Current plans are to continue flight scenario system cycling beyond the 30 month requirement. At launch, the system may be adjusted to follow the actual flight data of the HST, if the vehicle is still equipped with NiCd batteries (these may be replaced with Nickel-Hydrogen batteries prior to launch). Any flight anomaly could be duplicated on the breadboard, which could lead to early resolution and correction of a problem. Otherwise, the breadboard can be left operating indefinitely in order to gain continued life test information on these batteries. Nonscheduled reconditionings and other actions would be performed in attempts to correct or control abnormal conditions such as excessive recharge ratio and cell failures.

References

