N94- 28120

Nickel Cadmium Battery Operations On-Orbit: Trials, Tribulations and Success on the Upper Atmosphere Research Satellite

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Abstract

The Upper Atmosphere Research Satellite (UARS), designed, built, integrated, tested and operated by NASA and Martin Marietta is a low-Earth orbiting, Earth-observing spacecraft which was launched via Space Shuttle Discovery on September 12, 1991 and deployed three days later. The Modular Power Subsystem (MPS) on-board the satellite is equipped with three NASA Standard 50 Ampere-hour (Ah) nickel-cadmium (NiCd) batteries. McDonnell Douglas Electronics Systems Company fabricated the MPS, and batteries from Gates Aerospace Batteries cells.

Nominal battery performance was achieved for the first four months of spacecraft operation. First evidence of anomalous battery performance was observed in January 1992, after the first maximum beta angle (low Depth of Discharge) period. Since then, the Flight Operations Team (FOT), under the direction of Goddard Space Flight Center's UARS Project and Space Power Application Branch, has monitored and managed battery performance by adjusting solar array offset angle, conducting periodic deep discharge, and controlling battery recharge ratio. This paper covers a brief overview of the UARS, its MPS, the FOT's operational battery management, and the observed spacecraft battery performance.

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Introduction

Spacecraft Systems Overview

The Upper Atmosphere Research Satellite (UARS) is NASA's first spacecraft (S/C) in its Mission to Planet Earth. The study of environmental change affecting the entire Earth as a self-contained system via space observations is the mission's goal. Nine instruments (plus one sensor of opportunity) simultaneously and comprehensively study global stratospheric energy input, winds, and chemical composition, in addition to those changes associated with human activities which lead to ozone depletion.

The UARS design is a three axis stabilized spacecraft which combines a Multimission Spacecraft (MMS) bus designed and manufactured by Fairchild Space Company with an Instrument Module (IM) designed, fabricated, integrated and tested by Martin Marietta (formerly General Electric) AstroSpace, East Windsor, New Jersey. This work was completed for NASA/ Goddard Space Flight Center's (GSFC's) Earth Science Mission Operations (ESMO) Project.

UARS achieved orbit through Space Shuttle Discovery launch on September 12, 1991 and was deployed three days later, September 15. Mission Operations have since been carried out by Martin Marietta for NASA's ESMO Project. The mission orbit is a 96 minute, circular orbit inclined 57 degrees to the Equator with a 585 Km height. This allows stratospheric sensors to observe up to 80 degrees in latitude (North and South) and provides near total global coverage. The full range of local times at all geographic locations is viewed every 36 days.

The UARS was designed for a nominal mission life of 18 months covering 2 Northern Hemisphere winters - the design life of the CLAES cryogenic instrument, with a minimum of an additional 18 months planned and a goal of 5 years. The S/C power system was designed for a maximum 1600 Watts (orbital average), 786 Watts of which was reserved for the instrument load. The S/C maximum load has been about 1350 Watts with instrument loads of approximately 450 Watts. S/C weight upon mission orbit insertion was 6800 kg. The FOT utilizes NASA's Space Network and the Tracking and Data Relay Satellite System (TDRSS) to provide routine command uplinks and science and telemetry data downlinks.

The IM is a truss-type torque-box constructed of graphite-epoxy tubes with titanium end fittings and supports all ten instruments. The plus Y side of the S/C, where the limb-looking and cryogenic instruments reside, must be kept in shadow at all times. To satisfy both the shadowing and full globe coverage requirements, a "Yaw-Around" maneuver is performed every 36 to 42 days. This entails turning the S/C around 180 degrees and allows, alternately, Northern (backwards flight) and Southern (forward flight) Hemisphere Limb viewing.

The MMS bus includes the Modular Attitude Control Subsystem (MACS), the Propulsion Module (PM), the Command and Data Handling Subsystem (C&DH) which incorporates the On-Board Computer (OBC), the Earth Sensor Assembly Module, the Signal Conditioning and Control Unit, and the Modular Power Subsystem (MPS) which houses the three NASA Standard 50 Ah NiCd batteries and power control/distribution circuitry.

The UARS Power Subsystem comprises all power control, power distribution and, all other related hardware. It contains the McDonnell Douglas Electronics Systems Company (MDESC) supplied MPS, main and auxilliary Solar Arrays and related equipment. Figure 1 relates how these components are connected and interact.

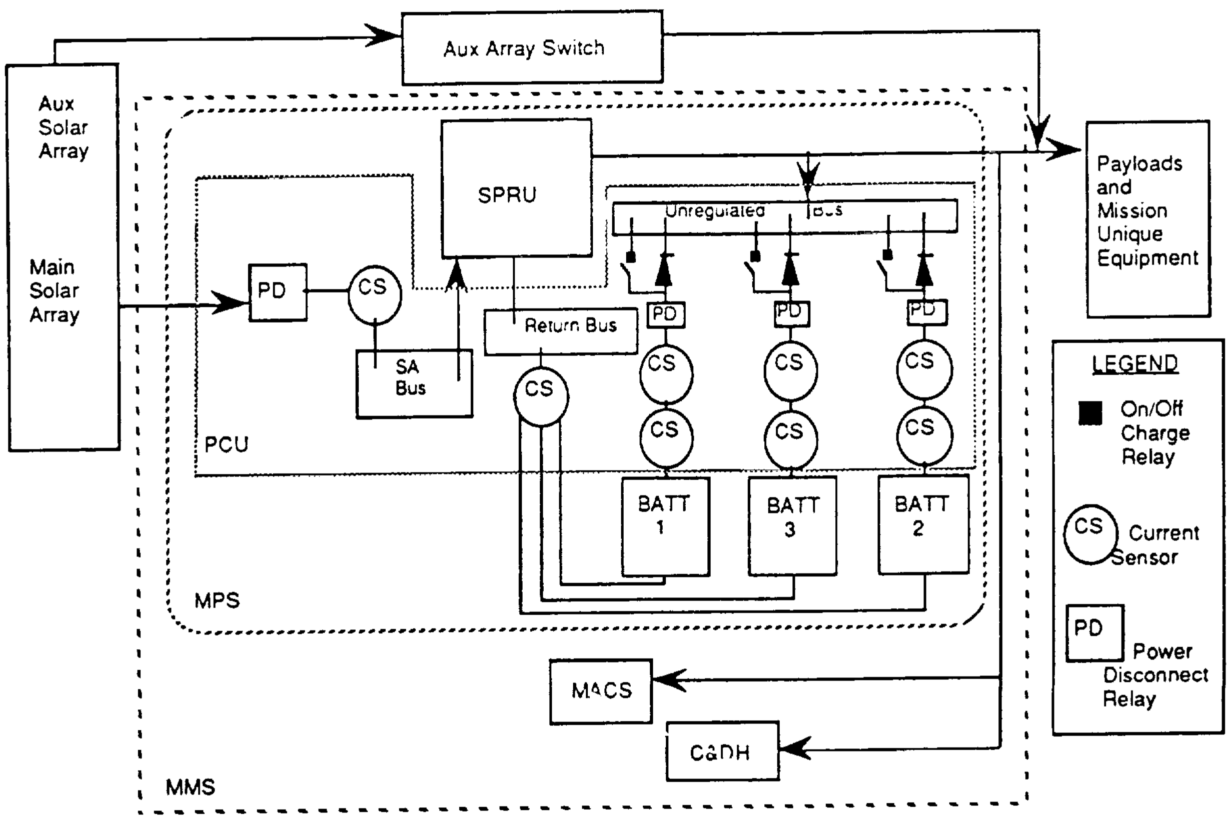

Figure 1. UARS Power Subsystem Block Diagram

Table 1 lists the major Power Subsystem components and their functions.

TABLE 1. UARS Power Subsystem Components and Their Functions

Power Subsystem Component	Function
Standard Power Regulation Unit (SPRU)	Battery charge control.
Signal Conditioning Assembly (SCA)	Command and telemetry conditioning.
Bus Protection Assembly (BPA)	Fusing of internal MPS loads.
50 Ah Batteries	Energy storage.
Power Control Unit (PCU)	Power distribution and system configuration.
Remote Interface Units (RIUs)	C&DH Interfaces.
Main Array	Energy conversion - provides 1200 Watts power for instrument loads and battery charging.
Aux Array	Energy conversion - provides additional 400 Watts power for instrument loads only.
Auxiliary Array Switch	Controls Aux Array power as a function of Instrument load current.
Solar Array Drive and Deployment Electronics (SADDE)	Provides drive and rate control to rotate SA at 1 revolution per orbit, tracking the Sun.
Solar Array Drive (SAD)	Maintains SA Sun-pointing while the S/C is in an Earth-viewing orientation. Can rotate the SA in either direction for both forward and backward S/C flight.

Mission & Power Subsystem Operations

Total S/C operations are provided by Martin Marietta under the direction of the ESMO/UARS Project staff. The power and battery operations are managed in concert with the Space Power Applications Branch.

The Power Subsystem was designed to provide 1600 Watts orbital average by using the MPS in conjunction with an auxilliary Solar Array and auxilliary array switch, since the MPS capability is limited to 1200 Watts. Power is distributed to the MMS and IM modules at 28 +/-7 Volts D.C. The MPS was constructed by MDESC according to the NASA/GSFC Specification for Multimission Modular Spacecraft (MMS) Modular Power Subsystem(1). According to the UARS General Instrument Interface Specification(2), the MPS output voltage range should be between 22 and 35 V.

The MPS receives commands from the OBC for enabling the battery control mode in the SPRU and for setting the operating limits for battery voltage and battery current. The various MPS operation modes are summarized in Table 2.

Table 2. MPS Charge Modes and Their Operations

MPS Battery Charge Mode	Operation
Standby	When no SA power is available and the batteries are supplying the S/C power, the SPRU retains its last commanded state in memory and can receive additional commands.
Peak Power Tracking (PPT)	The SPRU will always operate at the SA maximum power output point in order to transfer all available power to the load and to charge the batteries until the voltage-temperature set point (V/T mode) is reached, or until the battery current reaches the current set point if Constant Current Mode (CCM) is enabled.
Battery Voltage Limited (V/T)	The SPRU will operate on the voltage side of the SA I-V curve in order to control the battery voltage to one of the eight selected voltage-temperature set points, and will allow the battery to charge at a current determined by the battery characteristics.
Constant Current Limited (CCM)	When enabled, the SPRU will operate on voltage side of the SA I-V curve in order to control the battery current to one of three selected levels (0.75, 1.5, 3.0 A), and will allow the batteries to charge at a voltage determined by the battery characteristics up to the selected V/T limit.
Safehold	When an OBC fault is detected, the SPRU will receive a command to disable CCM (if enabled) and to set the V/T set point to a preselected V/T level. This remains in effect until reset by an external command.

MPS telemetry data is reported by the C&DH module and is plotted by the UARS Generalized Plotting Software/Level Zero (UGPL) off-line . Table 3 lists the MPS Telemetry Points that the UARS FOT uses for trend analysis.

Table 3. MPS Telemetry Points

Battery Terminal Voltage (Volts)
Load Bus Voltage (Volts: EOD,EON Instantaneous)
Battery Current (Amperes: High & Low Sensors)
Total S/C Current (Amperes)
IM Current (Amperes)
Half-Battery Differential Voltage (mV)
Battery Temperatures (C)
MPS Temperatures (C)
Total Discharge (Amp-min)
Net Charge (Amp-min)
C/D Ratios
State Of Charge (%)
Depth Of Discharge (%)
Main SA Power (Watts)
Aux SA Power (Watts)
Solar Array Temperatures (C)
Solar Array Output Power (Watts)

Batteries

The three NASA Standard 50 Ah NiCd Batteries on-board UARS, which were fabricated by MDESC using GAB cells (50AB35, LOT 2), are on a parallel bus and charged to NASA Standard V/T curves using the MPS and NASA Standard Power Regulator Unit (SPRU). The battery cells were constructed according to the NASA/GSFC Specification for the Manufacture of Aerospace Nickel-Cadmium Storage Cells[3 & 4], while the Batteries were manufactured according to NASA/GSFC Specification for the Standard Nickel-Cadmium Spacecraft Batteries[5].

The batteries were specified to a name plate capacity of 50 Ah and to operate in low-Earth orbit up to 20% Depth of Discharge (DOD), and 28+/-7 Volts for a nominal 36-month mission[3 & 4]. Thermal vacuum testing revealed that with a full-up UARS at 24% DOD, the lowest EON Voltage at the beginning of the mission should have been close to 27.0 V[2]. Thermal vacuum testing also revealed nominal performance within specifications on ground tests prior to launch.

Beta Angle

Beta angle is defined as the angle between the orbital plane and the Earth-to-Sun line. Variation of this parameter affects the Solar Array (SA) energy conversion, the S/C loading, and the Battery Charge and Discharge profiles. The cyclical variation of the orbit Beta angle (ß) is caused by the 57 degree orbital inclination and orbital geometry. Figure 2 shows the cyclical Beta angle and Night Length variations since launch. The Beta angle variation changes SA Night periods (in addition to the normal seasonal changes) from a maximum eclipse of 36 minutes at zero degree Beta, to a minimum of zero minutes at Beta angles above 66 degrees. Figure 3 is a plot of the Total S/C Current over the mission to date.

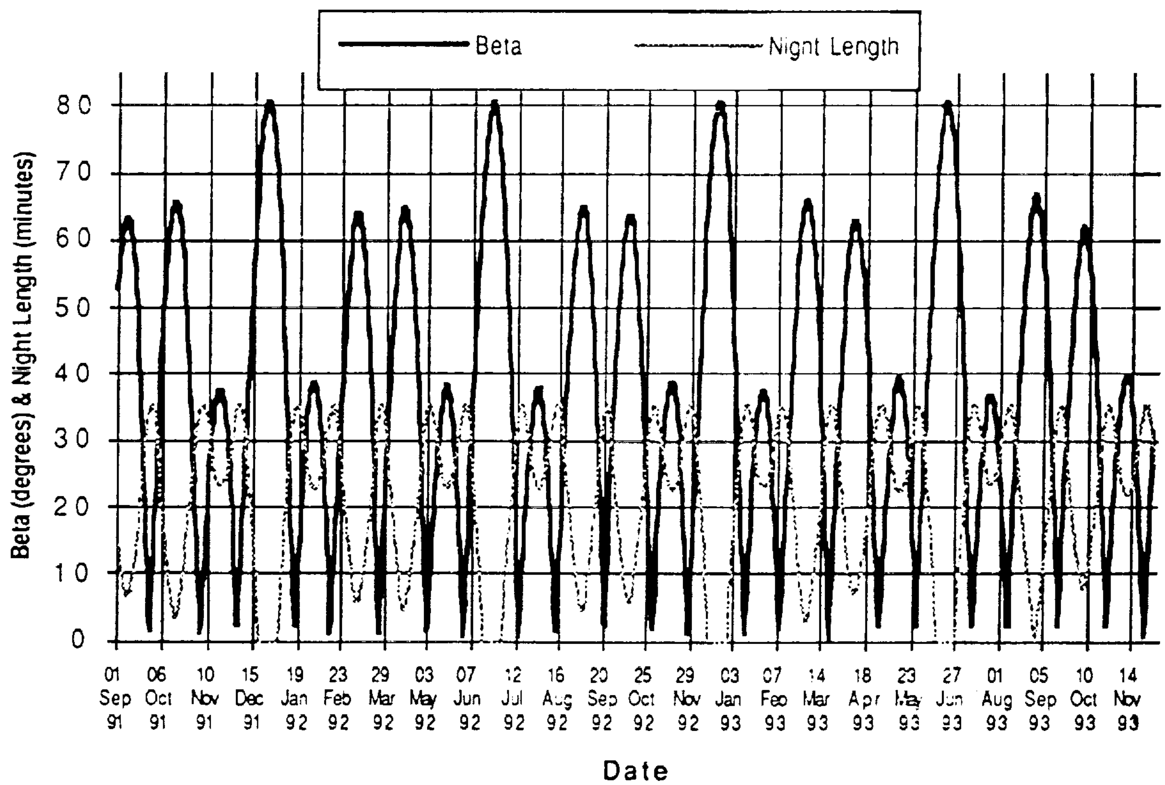

Figure 2. Beta Angle & Night Length vs. Date

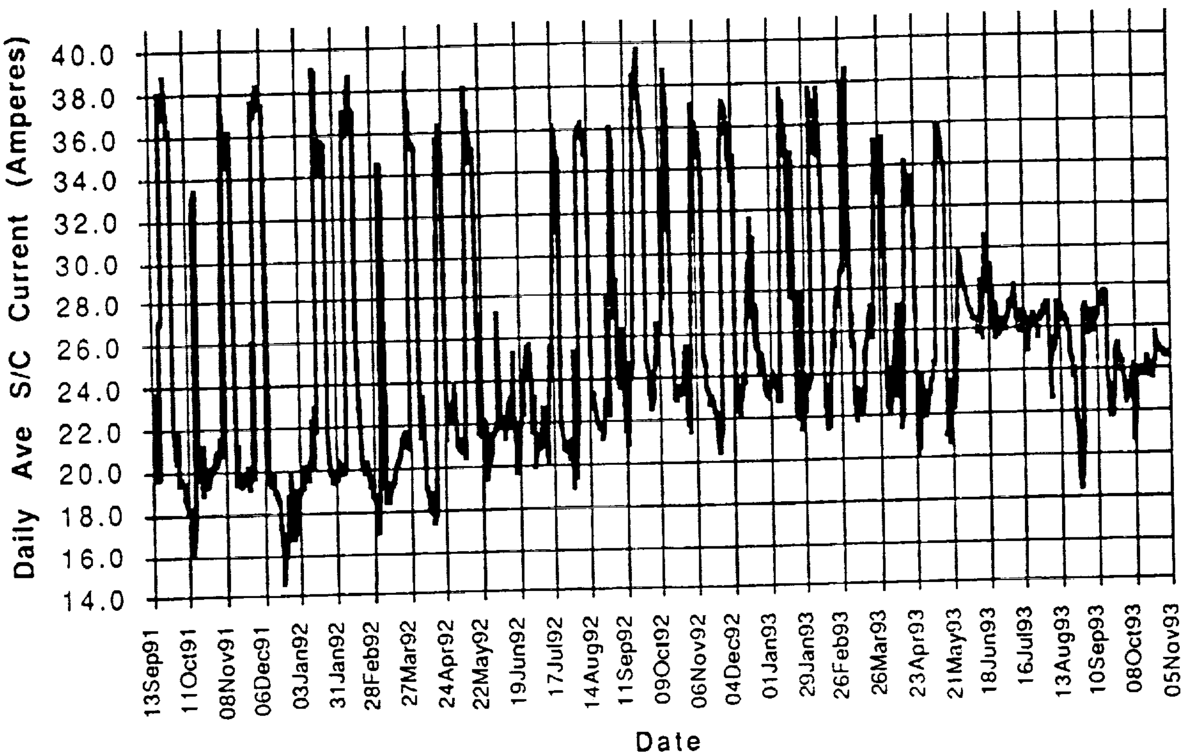

Figure 3. Total S/C Load

Battery/MPS Management

This section highlights UARS MPS and battery management from deployment to 26 October 1993. Table format is used to aid both clarity and brevity. The heading lists the covered periods and orbit beta angles, the battery performance and characteristic parameters are presented in each Table.

The FOT, Project Office and Space Power Applications Branch have managed the MPS and Batteries by monitoring the Half Battery Differential Voltage (Differential Voltage), End Of Night (EON) Voltage, and Battery Charge and Discharge current sharing, and by controlling battery overcharge, recharge ratio, battery temperature, the difference between battery temperature (delta temperature), and DOD. This strategy has continuously been updated and changed to fit the battery performance and characteristics that were of greatest concern at that particular time. The end result is a plan that started with a basic premise that operations would be normal and not intensive.

I. Early Orbit (9/15/91-12/91)

Beta : 27, 0 (Yaw Forward to Backward {F>B}), 65 , 0 (Backward to Forward {B>F}), 37 - 0 (F>B), 80 (Full Sun when Beta >66)

MPS mode(s)	**Operations Comments**
Switch V/T 6 to V/T 5 by OBC when System C/D = 1.00	Early-orbit/Instrument activation and calibration were priorities. Power Subsystem set-up for 1600 Watt load, actual S/C load ~1350 Watts. No SA offset. High Peak charge current and battery overcharge. NOMINAL PERFORMANCE

II. Post Max Beta #1 (1/92-4/92)

Beta: 80, 0 (B>F), 39, 0(F>B), 63, 0 (B>F),

MPS mode(s)	**Operations Comments**
V/T 6 to V/T 5 by OBC when System C/D = 1.00	After return to S/C eclipses, onset of Differential Voltage observed, 10-20 mV on all 3 Batteries (Figure 4). Onset of ANOMALOUS PERFORMANCE
Switch to straight V/T charging: V/T6 V/T5, finally V/T4	Began increased battery performance monitoring and investigations. Battery temperature rose and delta temperature increased in V/T6 (Figure 5). Switched to V/T5 until Beta >60 degrees, then switched to V/T4 to decrease both battery temperatures and delta temperature, and reduce overcharge during low DOD period.

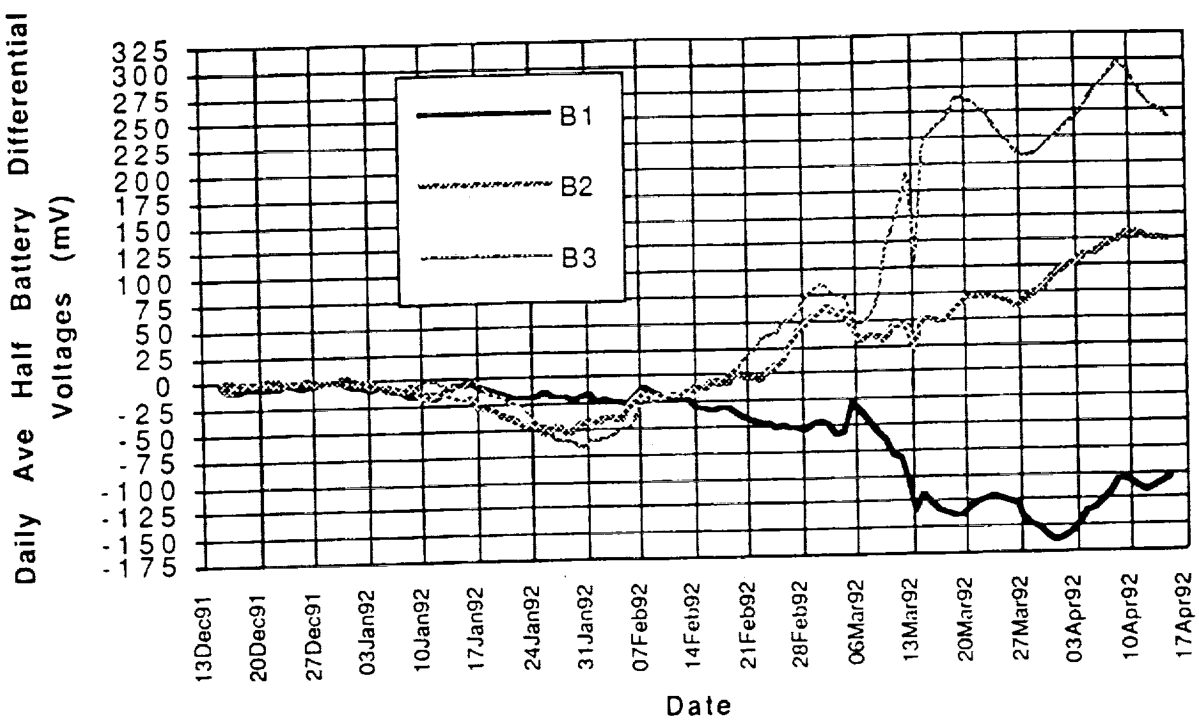

Figure 4. Half Battery Differential Voltage: 15 December 91 - 15 April 92

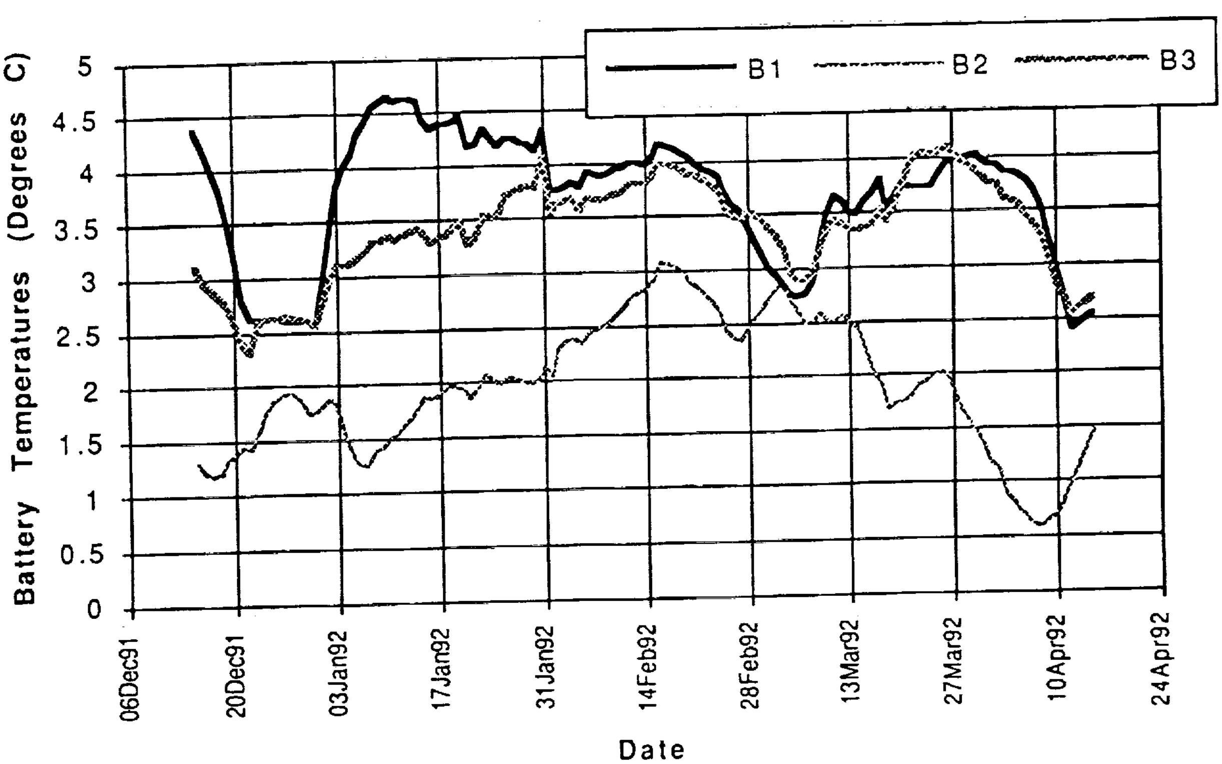

Figure 5. Battery Temperatures :15 December 91 - 15 April 92

III. *Through next relative max Beta, low DOD (4/92-5/92)*
Beta: , ~65, 0 (F>B), 37,

MPS mode(s)	Operations Comments
V/T4, V/T5, and then back to V/T4	V/T4 at higher Beta angles, switched to V/T5 after increasing the load, but battery temperature rose and delta temperature diverged dramatically, switched back to V/T4 and battery temperature and delta temperature decreased, however still operating with higher delta temperature. Began TMON control of MPS heater thermostat with little to no effect on delta temperature.
V/T4	After next relative max Beta (37 deg), began SA Offset ~35 deg ahead, controlled manually. Reduced peak charge current per battery from 33 A to ~20-25 A. Still no effect on differential voltage, battery temperature or delta temperature.

IV. *SA Drive Anomaly (6/92-7/92)*
Beta: , 0 (B>F), 80, 0 (F>B),

MPS mode(s)	Operations Comments
V/T4	SA "parked" at S/C Noon. Minimum S/C Load (2 of 10 instruments on) -- max DOD 18-20%. S/C nights vary from 54 min to 10 min over Beta cycle with the SA stopped.
V/T4	Reduced charge capability during full sun reduces overcharge during Max Beta. Higher effective load and decreased charge rates. Observed first beneficial battery operations and improved performance during this period. Differential Voltages, delta temperatures and C/Ds decrease.

V. SA Restarted, next Relative max Beta (7/92-8/92)

Beta:, 38, 0 (B>F), 65,

MPS mode(s)	Operations Comments
V/T4	SA rotation restarted with 45 degree offset ahead of Sun. Attempted to maintain improved characteristics. Changed TMON set points for MPS heater activation to maintain low delta temperature. Differential Voltages and delta temperatures increased.

VI. Next Rel Max Beta (9/92-10/92)

Beta:, 0 (F>B), 64, 0 (B>F),

MPS mode(s)	Operations Comments
V/T4	SA offset increased to further limit peak charge current and to decrease heat generation on charge. Decreased time in taper. No effect on delta temperatures. EON Voltage reached new low (26.4V). Consequently, achieved a Power negative condition during relative maximum Beta. Increased DOD, "exercised" batteries during normally low DOD period. Reduced overcharge and delta temperature. As Beta angle decreased and load increased, low EON LBV (<26 V) and increased delta temperature became major concerns. Decreasing SA Offset resulted in poor current sharing. Could not switch to V/T5 due to high delta temperature experienced at V/T5 in 4/92.

VII. EON LBV continues to decrease (11/92)
Beta:, 39, 0 (F>B),

MPS mode(s)	Operations Comments
V/T4	Differential Voltage curves change character, considered a change but not certain if this indicates improvement or further degradation. By Inhibiting the warmest/weakest battery (#1) from controlling the V/T feedback loop, EON voltage was raised. Battery 3 (next warmest battery) controls/delays V/T switch to taper (effective V/T=4.2+), increased charge without increasing peak charge current. Consequently, battery temperatures rose.
V/T4	At maximum S/C loading, could not provide required EON Voltages. Used other than normal MPS configuration to maitain EON LBV above 26.8V when DOD>18%. Load sharing improved slightly with inhibited Battery 1 V/T feedback loop (Figure 6).

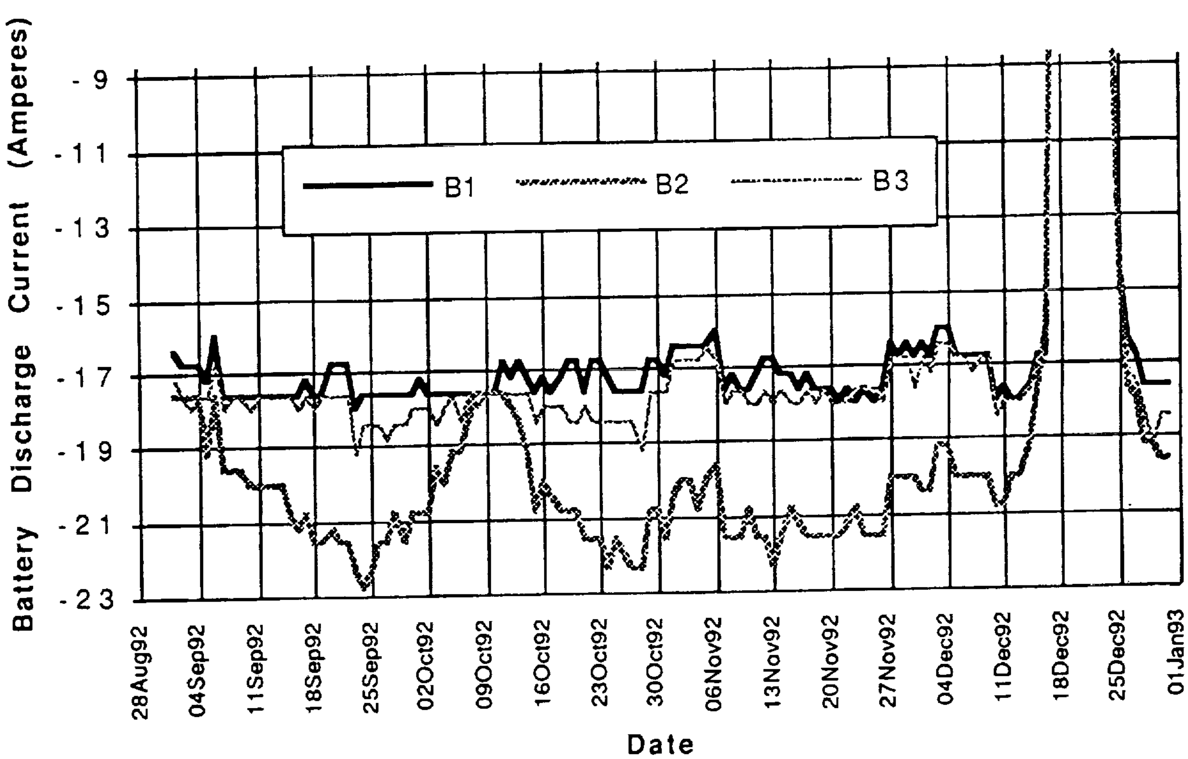

Figure 6. Battery Load Sharing: September - December 92

VIII. *Max Beta #3, Deep DOD Conditioning #1 (12/92)*
Beta:, 80,

MPS mode(s)	Operations Comments
V/T4, then V/T3 when DOD<10%	Battery 1 differential voltage range surpassed battery 3's. Decreased battery overcharge and increased DOD during low load period.
V/T3/CCM 0.75A	Performed first low earth orbit battery conditioning to boost EON Voltage - Deep DOD (target 35%) conditioning without reconditioning circuitry. Used Full-Sun period 12/12-12/25 when recharge opportunities are the greatest. Increased S/C load to maximum (slow discharge rates ~5-9 Amps), increased SA Offset to achieve a negative energy balance, and took the best performer (battery 2) off the charge bus to force it to discharge through the diode which allowed batteries 1 & 3 to get deeper DODs. Also used Constant Current Mode of 0.75 A to limit charge during Albedo Charge periods.
V/T3	When battery 2 reached 32% DOD; began Peak Power Tracking and decreased SA offset to allow system to be power positive. Put battery 2 back on charge bus when all three battery voltages were approximately the same. Maximum DODs were: Battery 3=34.0%, Battery 1=31.5%, and Battery 2=32%. Voltages increased approximately 1.5 volts per battery (see Figure 7), however, battery discharge sharing remained unchanged (Figure 8).
V/T3	Exercised the batteries when normal DOD<10%. Increased SA Offset to make subsystem power negative and achieve a DOD between 12-18% at least once every other day.
V/T4	When DOD>10%, resumed normal operations. Loaded New PMON Software to autonomously control SA Offset. Three SA Control modes: (1). Select Offset Angle and PMON maintains it, (2). Select Desired Total Peak Charge Current and PMON calculates and commands required SA Offset once per orbit, and (3). Retain Manual Control by rate variation (same as before).

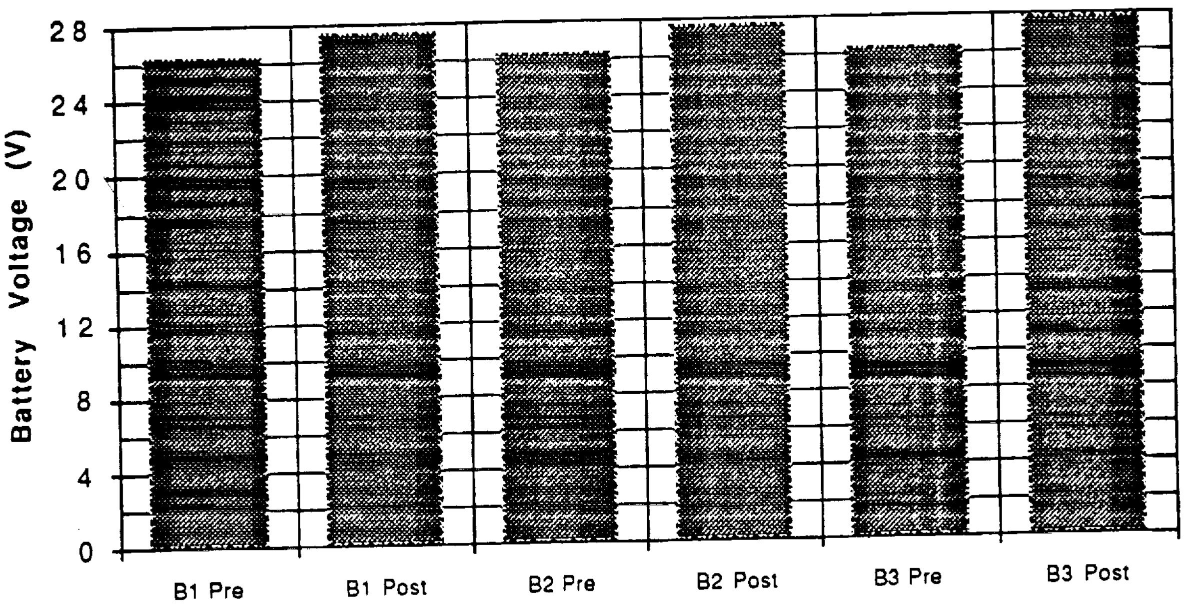

Figure 7. Battery Voltages Pre and Post Conditioning (December 92)

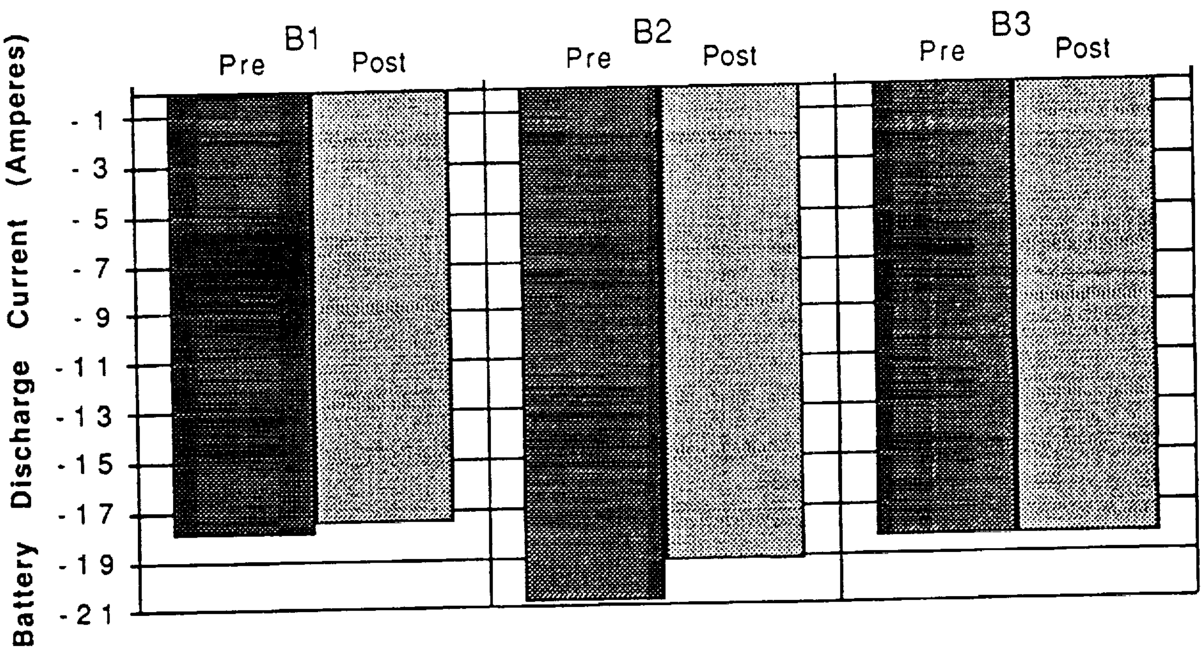

Figure 8. Battery Discharge Currents Pre and Post Conditioning (December 92)

IX. Post Max Beta #3, and next Zero Beta (1/93-2/93)

Beta:, 0 (B>F), 38, 0 (F>B),

MPS mode(s)	Operations Comments
V/T4 & V/T4.2+	Battery delta temperatures and current sharing diverged. Inhibited battery 1 from V/T feedback to increase charge without increasing peak charge currents and boost EON Voltages. Used V/T4 when delta temperatures increase. Also decreased MPS heaters on period with TMONs. Battery temperatures and delta temperature remained unchanged.
V/T4 & V/T4.2+	At Zero Beta (Maximum load) turned off redundant S/C equipment (1 Transponder and 1 Star Tracker) and damaged instruments to reduce load and maintain EON LBV above 24.8V. Further evidence of weak battery performance.

X. Next 2 Relative max Betas (3/93-4/93)

Beta:, 64, 0 (B>F), 64, 0 (F>B),

MPS mode(s)	Operations Comments
V/T4 & V/T4.2+	Battery temperatures and charge/discharge current sharing continued to diverge. MPS battery heaters on at S/C sunrise by stored commands to better control peak charge heating, and also decreased peak charge current and decreased overcharge, but no real effect on temperatures and current sharing.
V/T3	At relative maximum Beta angles, when DOD<10%, cycled SA Offset to achieve 12-18% DOD at least once every other day and exercised batteries. Tested New PMON software allowing a switch from V/T control to CCM based on a selected battery 1 C/D goal. <u>Achieved greater control of battery overcharge.</u> Also utilized SA Offset control to select peak charge current.

XI. Relative Max Beta (5/93)
Beta:, 39, 0 (B>F),

MPS mode(s)	Operations Comments
V/T4	Load decreased due to ISAMS decreased operation, 7 of 10 instruments fully operational. Still observing significant delta temperatures and poor charge/discharge current sharing.
V/T4 to CCM (0.75 A) at selected Battery 1 C/D goal.	Results of decreased overcharge lead to implementation of V/T control to CCM switching upon reaching Battery 1 C/D goal as the operational mode. <u>Continued improvement in charge acceptance, load sharing (Figure 9), and battery delta temperatures (Figure 10).</u>

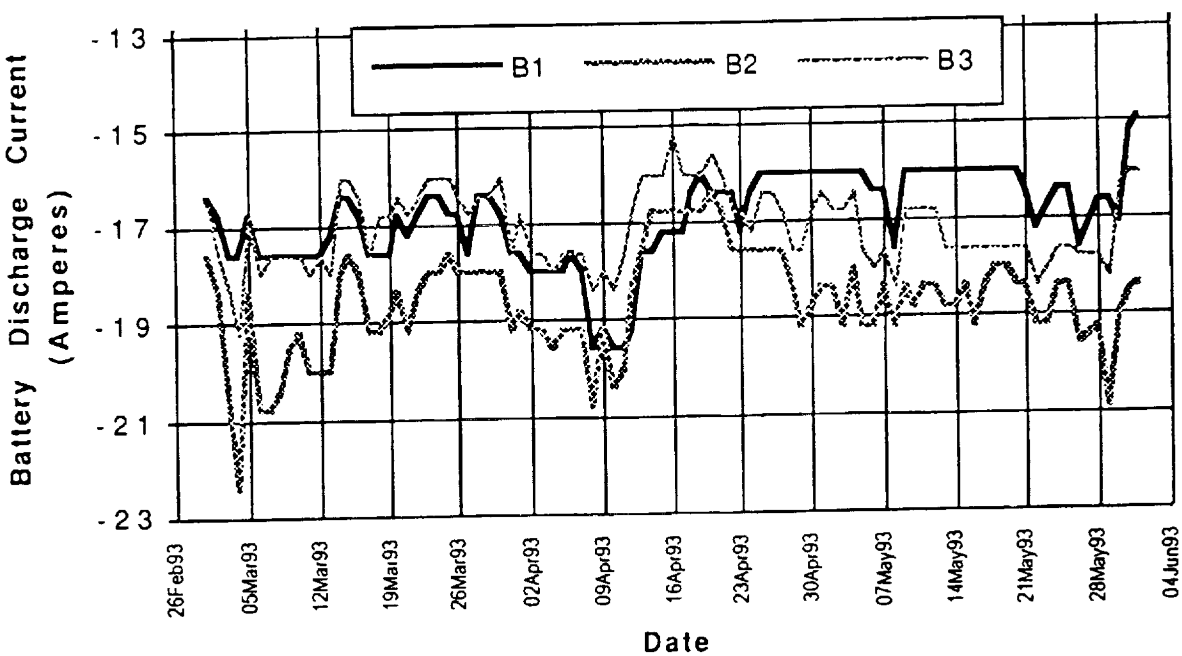

Figure 9. Battery Load Sharing from March - May 93

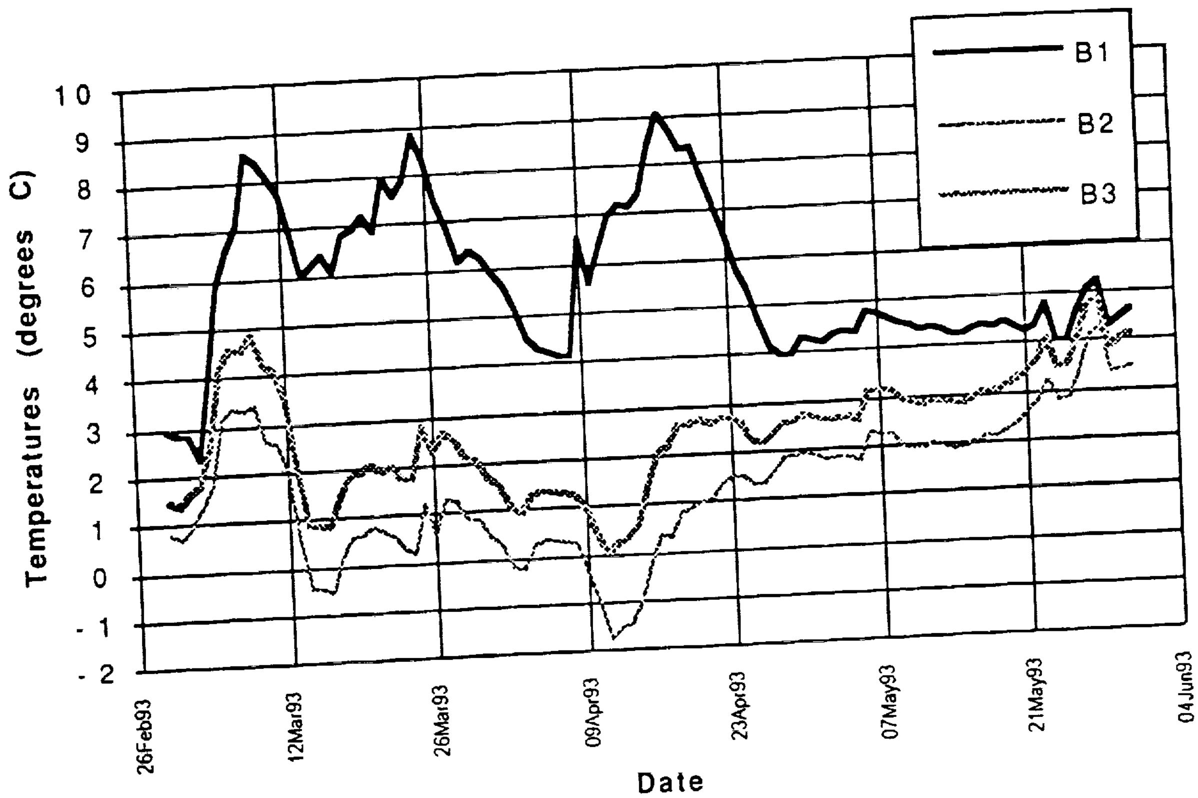

Figure 10. Battery Temperatures from March - May 93

XII. *Max Beta #4, Deep, Discharge Conditioning #2 (6/93)*
Beta:, 80 (Full Sun, Min DOD, 6/15-6/18),

MPS mode(s)	Operations Comments
V/T3	When DOD<10%, exercised batteries, by cycling SA Offset to achieve 12-18% DOD at least once per day. Decreased overcharge and increased load during low DOD/load period.
V/T3 & CCM 0.75A & V/T1 & CCM 1.5A & V/T3	Deep DOD Conditioning #2: Performed 2 conditioning discharges - one each on consecutive Full-sun days, to achieve the full benefit of the deep discharges based on the ground test results of Zimmerman and Effa(6). **DAY ONE** - Deep Discharge (40% target, discharge rates ~5-9 amps) and Slow Recharge (Increased SA Offset), Battery 2 off the charge bus, and extra heater loads to decrease Albedo charging. When Battery 3=36% DOD (B1=33%, B2=31.5%), decreased SA Offset, Commanded V/T1 at CCM 1.5 A until all 3 battery voltages were same, then put Battery 2 back on the charge bus and switched to straight V/T3 recharge back to 100% SOC. **DAY TWO** - Repeated Day One with all three batteries on charge bus. When Battery 2=40% DOD (B3=38.5%, B1=34.5%) decreased SA Offset, commanded straight V/T3 recharge to 100%. No net EON Voltage gain (Figure 11), however, battery discharge sharing improved (see Figure 12 below).
V/T3 & V/T4	Continued to limit overcharge and to exercise batteries until DOD>10% by cycling SA Offset to achieve 12-18% DOD at least once every other day. Switched to V/T4 when DOD>10%, SA Cycling ceased

C-6

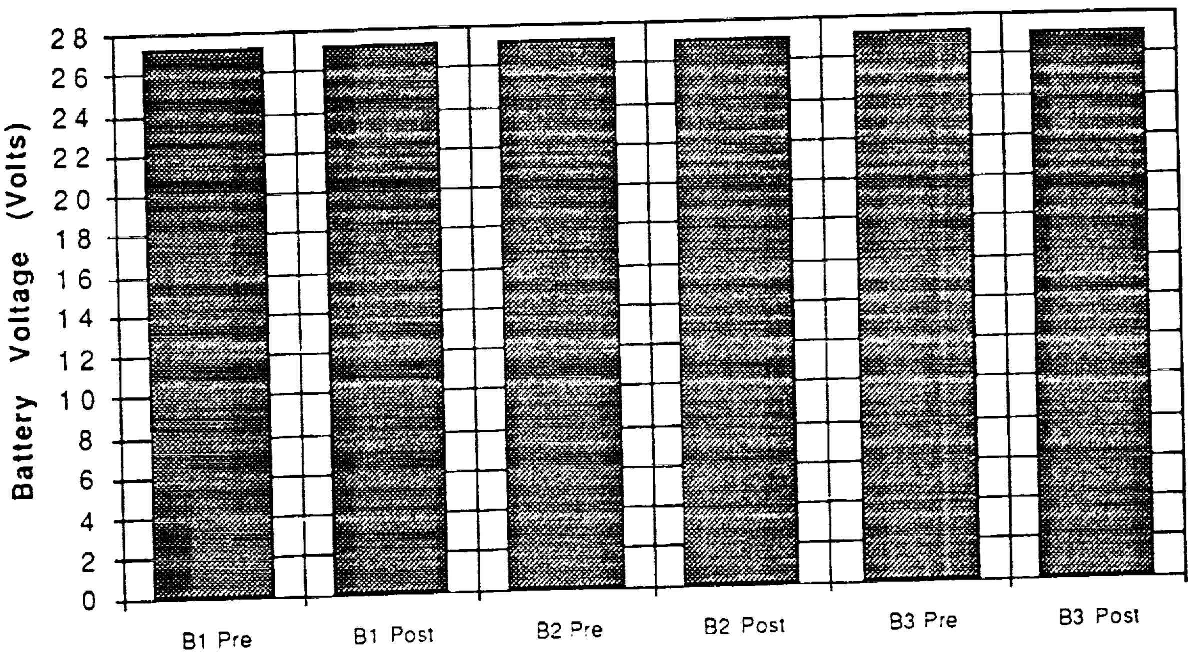

Figure 11. Battery Voltages Pre and Post June 93 Conditioning

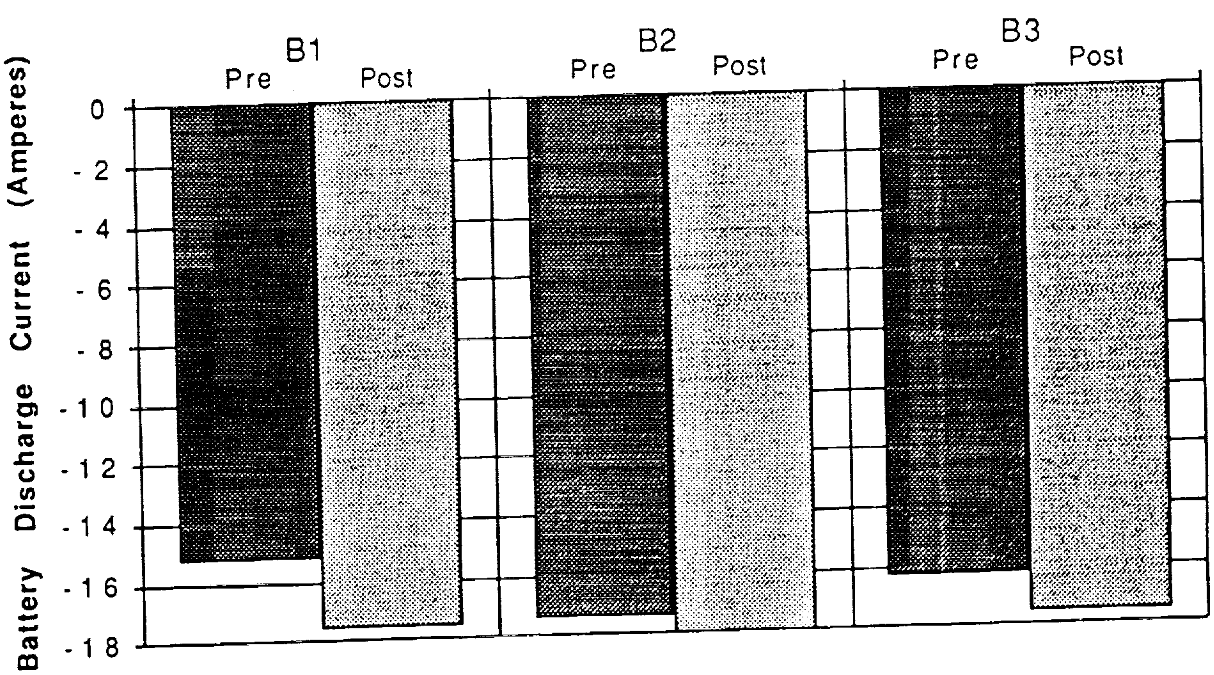

Figure 12. Battery Discharge Current Pre and Post Conditioning June 93

XIII. Post Max Beta #4, Next 2 relative Max Betas (7/93-8/93)
Beta: 0 (F>B), 37, 0 (B>F), 66

MPS mode(s)	Operations Comments
V/T4 and CCM (0.75A)	Battery charge and discharge current sharing continued to improve. Battery delta temperatures decreased. Battery performance improved. Continued to utilize switching from V/T4 to CCM based on selected C/D of battery 1 (maintained Battery 1 C/D between 1.04 and 1.05).
V/T4 and CCM (0.75A)	SA Anomaly - SA parked at S/C Noon from 4 to 8 August led to minimum Instrument Load (2 of 10 on) and a change in battery charge regime due to fixed SA.
V/T4 and CCM (0.75A)	SA restarted with Offset after Yaw around, utilized SA Offset to control peak charge currents. No change in battery performance.

XIV. Next Relative Max Beta: September 93 SA Anomaly to Present (9/93-Present)
Beta: 0 (F>B), 62, 0 (B>F)

MPS mode(s)	Operations Comments
V/T4 and CCM (0.75A)	SA Anomaly - SA parked at S/C noon 9/17-9/21, leads to minimum Instrument Load (4 of 10 on). SA-control TMONS developed and loaded to S/C. SA restarted with SA Offset 9/21. Little change to battery performance.
V/T4 and CCM (0.75A), Straight V/T4, V/T5 & V/T5 and CCM (0.75A)	SA stopped to investigate "jumping ahead" SA motion 10/2-10/25. However, now kept 5 of 10 instruments on with parked SA due to improved battery performance and S/C load management. Switched to V/T5 as load increased and Beta decreased without battery thermal runaway. Differential Voltage pegged (>+728mV) during SA testing (>65 min SA night, EON LBV=24.2V @ 28% DOD).
V/T5 and CCM (0.75A)	SA restarted with Offset after Yaw around. Battery performance continues to improve.

Figure 13 shows the EON LBV from December 1992 (the first deep discharge attempt) though October 26, 1993. It is annotated with significant events effecting the EON LBV and all YAW maneuvers. Yaw maneuvers usually represent the highest DOD for any particular Beta cycle. Figure 14 is a plot of the Minimum EON Voltage for the mission to date. C/D ratios, and Half Battery Differential Voltages over the mission are represented in Figures 15, and 16 respectively. Battery load sharing and Battery Temperatures since launch are presented in Figures 17 and 18.

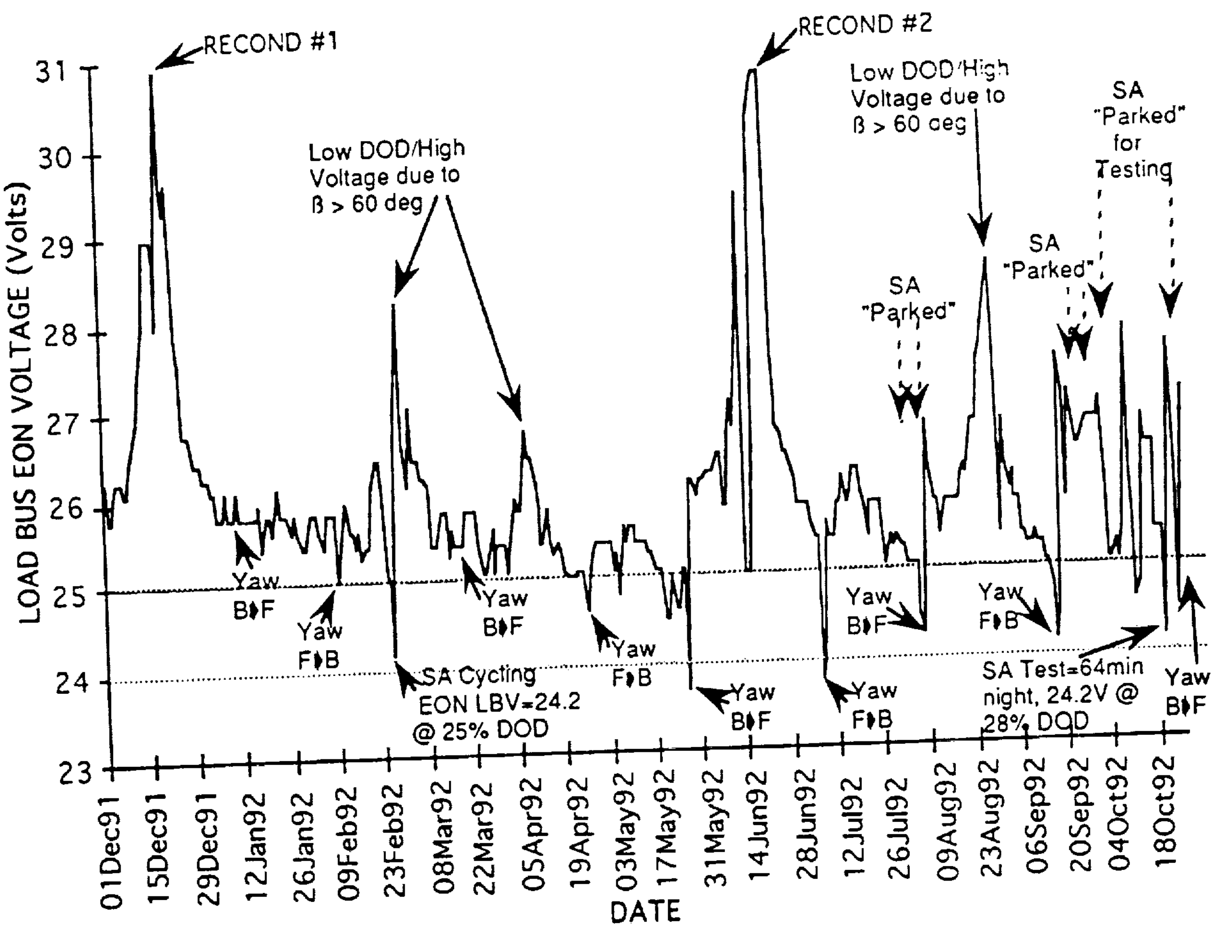

Figure 13. Daily Minimum EON LBV, 1 Dec 92 - 26 Oct 93

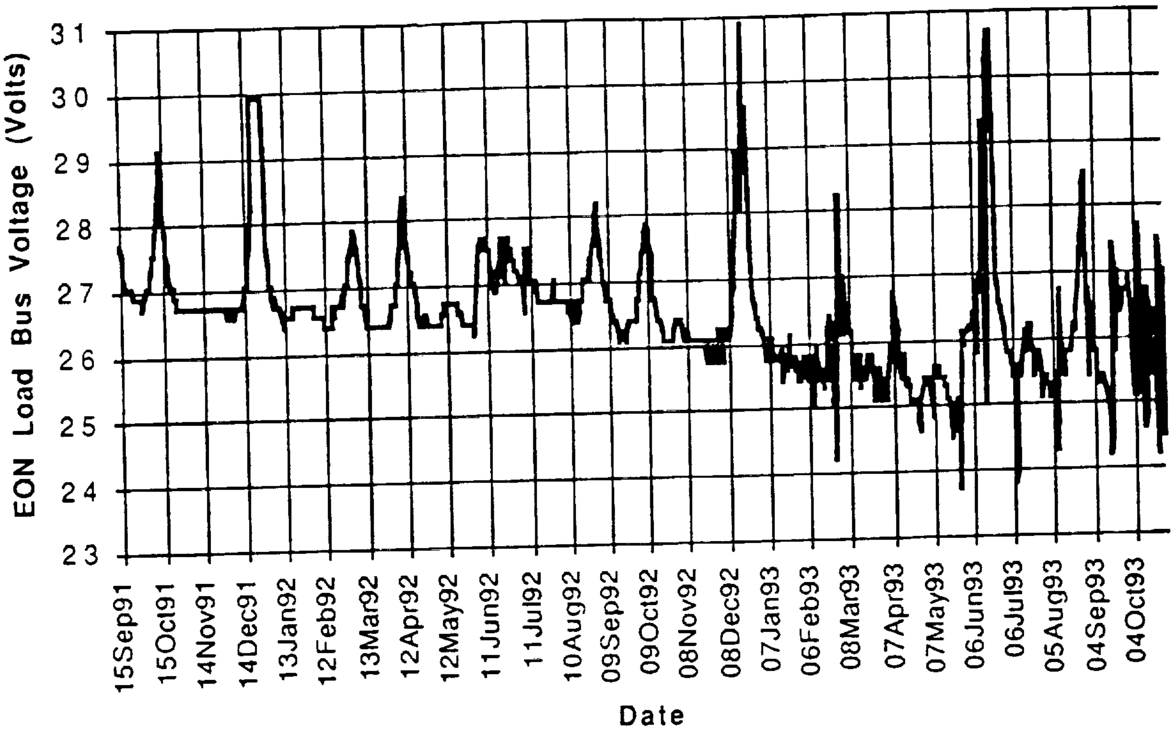

Figure 14. EON Load Bus Voltage

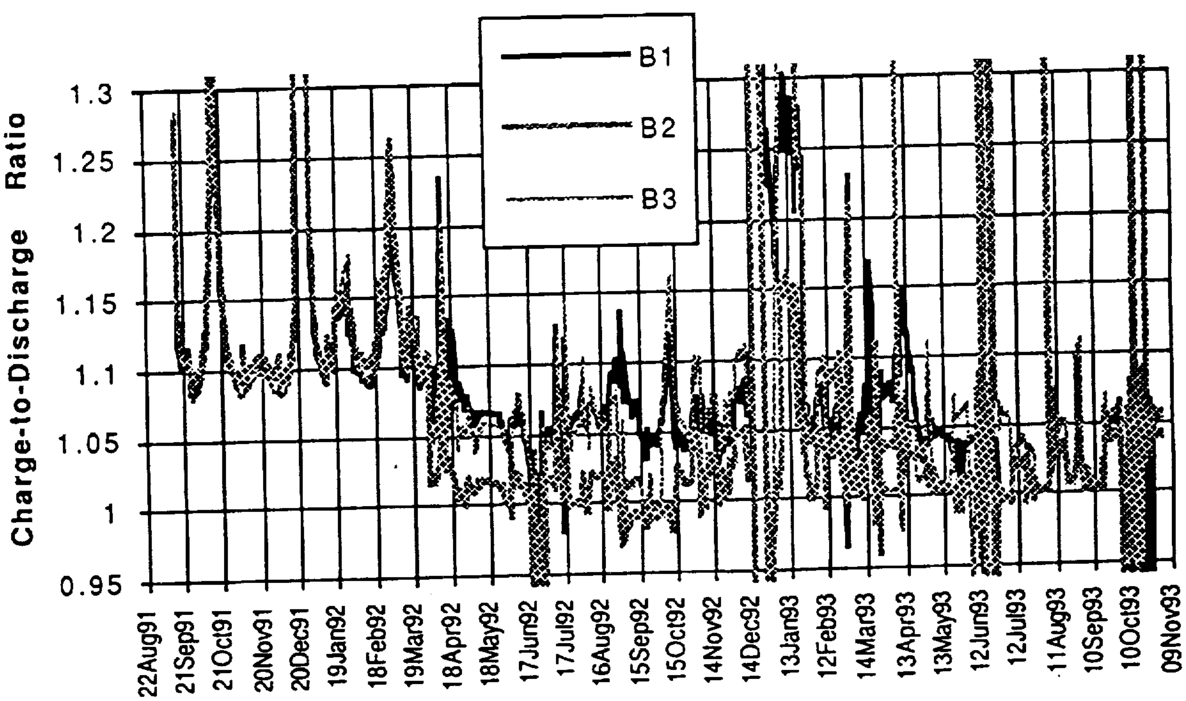

Figure 15. Battery C/D Ratio

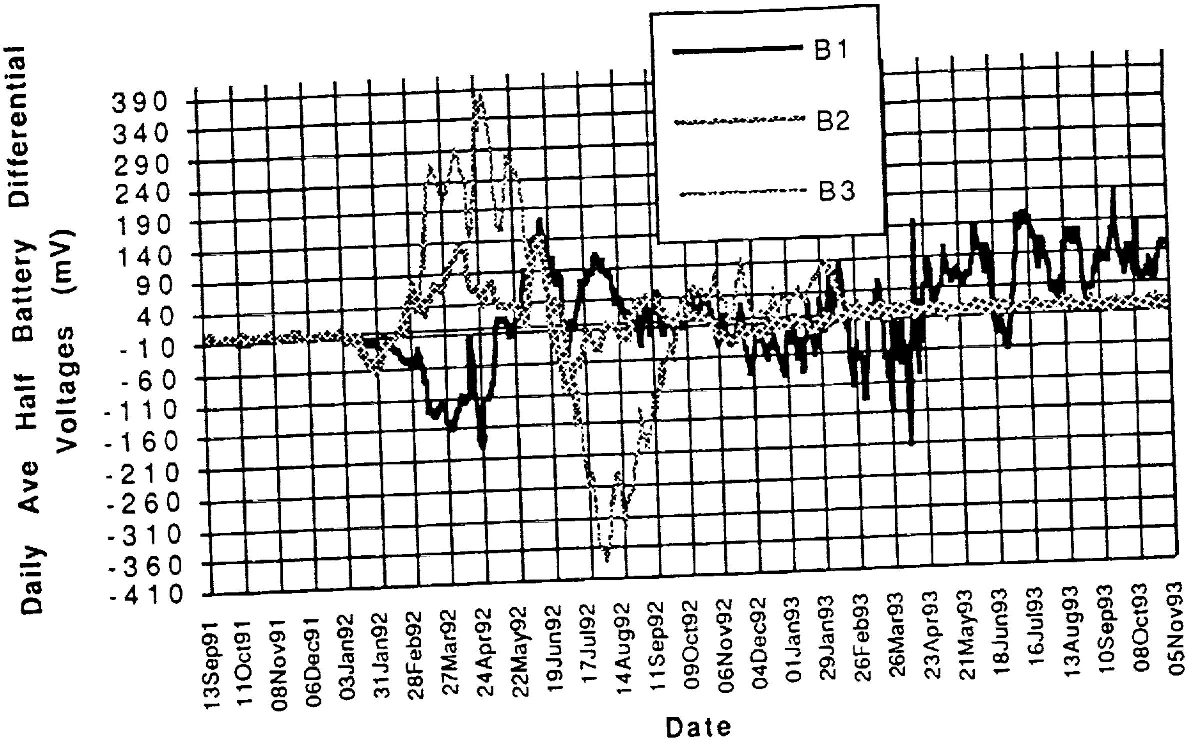

Figure 16. Average Half Battery Differential Voltage

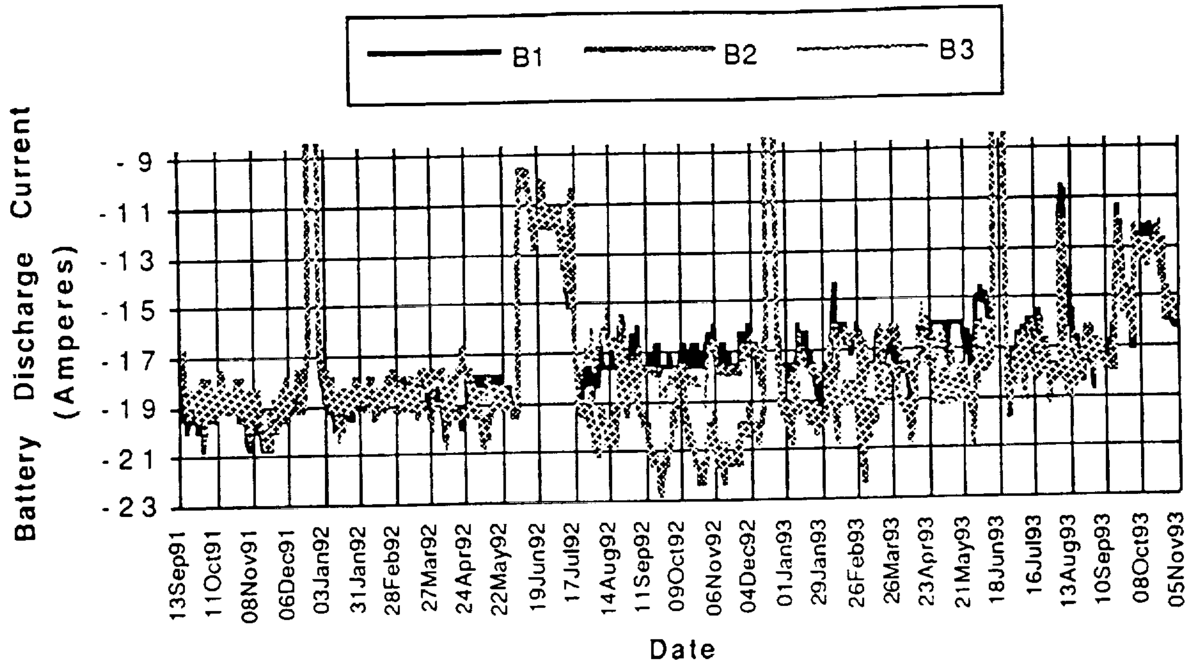

Figure 17. Daily Average Battery Load Sharing

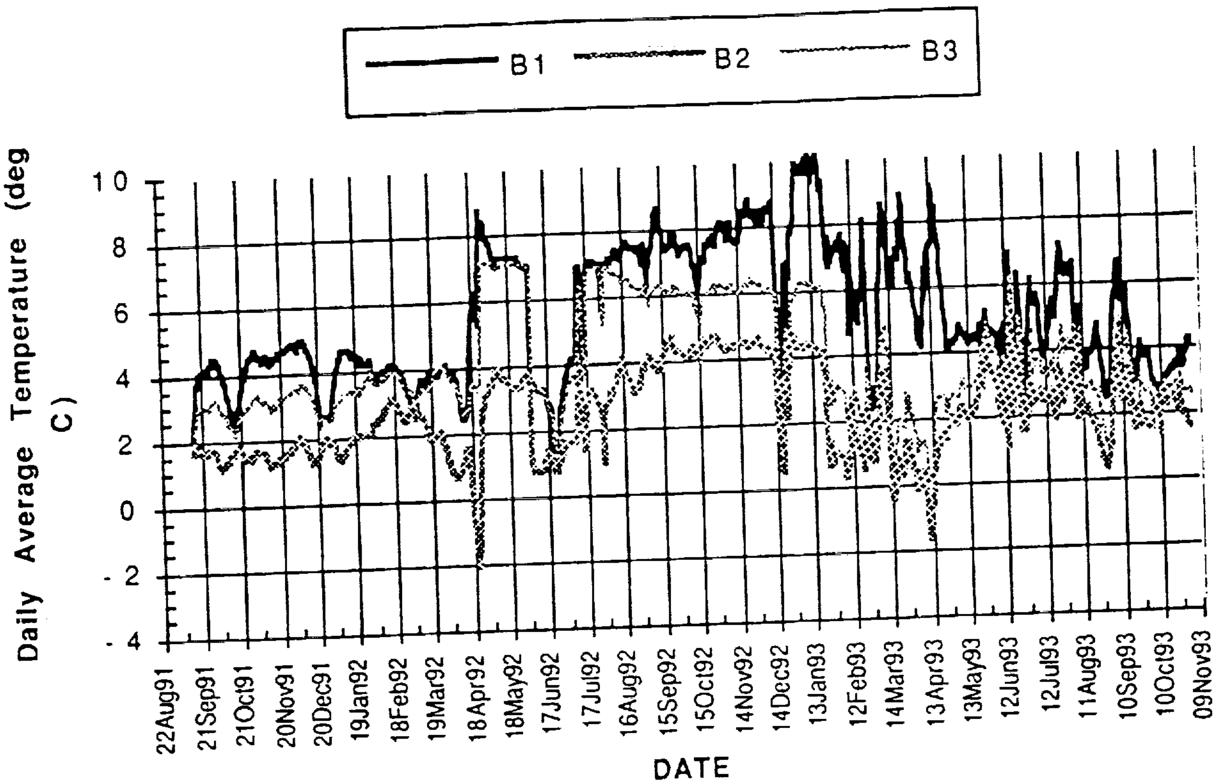

Figure 18. Daily Average Battery Temperatures

Thus, better current sharing; lower recharge ratio, differential voltage, and delta temperature; and fairly stable EON voltage indicate improved battery performance over the past several months. These trends began when overcharge was limited by switching from VT control mode to CCM based on the selected battery 1 C/D ratio.

Conclusions

Anomalous battery performance was first observed in January 1992. During this early mission period, the onset of Half Battery Differential Voltage excursions were considered a problem. However, Half Battery Differential Voltage changes do not tell us whether those changes are an effect of just one or of many cells. As a result, Half Battery Differential Voltages are used as a "first warning" or an indicator of battery degradation. Other battery characteristics and performance parameters must be monitored for additional information. These parameters are used to manage battery performance.

Because the batteries are in parallel in the MPS design (Figure 1), the effective operation of the MPS relies heavily upon having batteries that are well matched. The UARS batteries, although well matched at mission start, have operated with delta temperatures since launch. Temperature differences between batteries along with the battery temperatures have served as good indicators of relative battery performance.

Battery charge and discharge current sharing have both shed light on the battery performance puzzle. Charge and Discharge current sharing go hand-in-hand with battery temperatures in pointing to both the most efficient and the weakest performing batteries. For example, Battery #1 has had the greatest Half Battery Differential Voltage range and the highest temperature. It has also accepted the most charge current while providing the least discharge current, and is hence considered the weakest performer.

In addition, the weakest performer has been the battery receiving the greatest overcharge. Battery and MPS operations during the early part of the mission -- charging at V/T 6 to a system C/D=1.00 and then switching to V/T 5 with taper, probably contributed to battery overcharge.

Aggressive management of overcharge has been the underlying operation leading to improvements and relative stabilization of battery behavior. Battery temperatures, delta temperatures, and current sharing during charge and discharge have all trended back to more nominal behavior.

Battery exercise certainly helps to limit overcharge during low load (high beta angle/minimum S/C night) periods. Cycling the SA Offset to achieve a power negative condition and allowing the batteries to "spiral down" in SOC for several orbits, exercises the batteries during those low load periods when DODs of only 6-10% are expected. The result is a DOD of 12-18% at least once per day over a week when low loads are the norm. In addition, this battery exercise may minimize the so called "memory effects" which are common for NiCd batteries[6].

Deep Discharges have been performed during the bi-annual Full-Sun periods to minimize overcharge and to attempt to improve battery performance. UARS utilizes these very low load (~1-6% DOD) intervals to condition the batteries through low rate, deep discharges up to 40% DOD and followed by low rate recharge. This operation has been added to our operational list in an effort to maintain and possibly boost EON LBV.

Even though these batteries have met the minimum mission requirements, we contend that the amount of "care and feeding" they have required has been considerably greater than was originally anticipated. One of the biggest obstacles the FOT has had to overcome in operating the UARS power subsystem is both the limited number and selection of telemetry points available to trend. Individual cell voltage monitors, more accurately calibrated current sensors, and the addition of battery temperature sensors on and around each battery would indicate early anomalous behavior and overcharge conditions, and would certainly have helped in managing the battery operations as discussed above.

Recognizing that the case for Low-Earth Orbit Battery Reconditioning is still being debated, we have found deep conditioning discharges and periodic battery exercise during low load periods to be beneficial. To aid these operations, it would be useful to have "reconditioning" circuitry available in the S/C Power Subsystem. Deep Discharge is only possible on UARS during the periods of Full-Sun (almost full orbit opportunities to charge batteries) that the S/C experiences bi-annually.

Several additional MPS features that would have been advantageous in conducting the operations outlined above are:

- Independent charge controller for each battery.
- Single commands for each V/T level/MPS charge mode selection.
- Greater thermal control over the MPS.
  - Incorporation of the heat pipe used successfully on other S/C.
  - Additional MPS/Battery heaters and /or heater control.

and

- Incorporation of a charge system based on controlling overcharge.
  - Switching MPS modes at a specific C/D, etc.

NASA is currently implementing some of these features in GSFC's up-coming low-Earth orbiting S/C's Power Subsystem designs.

Finally, the success of the UARS mission and the power subsystem in particular has been directly affected by the successful management of the MPS and the batteries. Anomalous battery performance and its resultant effects have been aggressively attacked through monitoring and managing the following parameters:

Monitor:
- Voltage (EON/EOD/Instantaneous),
- Current Sharing during Charge and Discharge (High and Low currents)
- Half Battery Differential Voltage,
- SOC, and
- Eclipse Time (Beta Angle),

Manage:
- Battery Overcharge,
- Temperature,
- Recharge ratio,
- DOD,
- Time in peak Power Tracking,
- Time in Taper,
- Solar Array Offset (Peak Charge Current),
- V/T control mode, and
- Constant Current Mode.

It is our fervent hope that the Trials, Tribulations, and Successes experienced by the UARS Power Subsystem Operations Group, which includes the UARS GSFC Project Staff, GSFC's Space Power Applications Branch, the UARS FOT, UARS Mission Planning Group/Space Systems Applications Incorporated (SSAI), and MDESC can aid future Power Subsystem Designers and Operators by documenting the problems encountered, solutions stumbled across, and of course the planned, successful operations performed during UARS mission operation to date.

Acknowledgments

The authors wish to sincerely thank all of the extremely professional and expert NASA, Martin Marietta, MDESC, and SSAI employees involved with the UARS MPS and battery operations for their efforts over the design and operational lifetimes of this project. Without their hard work and steadfast dedication, the UARS Project would truly not be what it is today.

Special Thanks to:

<u>NASA/GSFC, Space Power Applications Branch:</u>
Dr. John Day
Marlon Enciso
Jim Jagielski
Dave Jung
Ernie Rodriguez

<u>NASA/GSFC, UARS-Project:</u>
Ken Dolan
John Donley
Sam Osler
Dave Lorenz

<u>Martin Marietta-UARS FOT</u>
Hal Collins
Gene Pearlman
Nick Chilelli
Erik Larson
Rich Calvin
Rich Beck
All On-line Operations Team Members

<u>McDonnell Douglas Electronic Systems Company</u>
Mark Toft
Mo Zollner
Bob Green

<u>Space Systems Applications Incorporated:</u>
Dan Wise
Bob Neff
Barb Holt
Ravi Bahethi
Kim McCarty

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