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Orbital Management and Design Considerations for NiCd Satellite Power Systems

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Abstract

Several recently manufactured 50 and 60 ampere hour aerospace NiCd battery cell lots, produced by Gates Aerospace Batteries, are prone to premature on orbit performance degradation. The failure mechanism is cadmium migration, and the consequent development of soft shorts. A Martin Marietta Astronautics satellite program instituted an orbital management strategy for a set of these batteries that reduced the rate of degradation and brought the system to stable operation. This strategy involves: a) minimizing the accumulated battery overcharge, b) regular discharge exercises, and c) periodic battery reconditioning. Because of changes in the NiCd cell manufacturing process the actual performance of subsequent lots of NiCd cells is open to question. Future NiCd based power system designs should therefore allow for fine control of charge parameters, and an on orbit battery reconditioning capability. To minimize risk it is much better to perform a full life test to qualify the cells before launch, rather than in parallel with orbital operations. If there are any changes in the manufacturing process of cells, it is extremely important to maintain very strong cognizance of secondary subcontractors, recognizing that the cell and battery manufacturing discipline is easily atrophied.

Root Cause of Cell Degradation

Investigation into several recent plate lots from Gates Aerospace Batteries [1] led to the conclusion that defects in the negative electrode was the primary cause of the performance degradation. The observations of monitored manufacturing parameters and more esoteric parametric relationships that are not routinely monitored support this. Ground test cells used in the investigation provided data, but correlation to on orbit degradation was the final criteria for comparison. In particular, two NASA missions, Gamma Ray Observatory (GRO), and Upper Atmosphere Research Satellite (UARS), have exhibited severe performance problems early in the mission.

The actual cause of the changes in negative plate parameters is still under investigation. Most are the result of subtle changes and a deterioration in the manufacturing process that accumulated over several years. Over sixty parameters were investigated. Items that showed correlation relate to the negative plate. High N/P ratio, high negative plate utilization, high 0° C capacity, and the ratio of cell 0° C capacity to battery 0° C capacity all correlate very well to bad cell lots. Cells with these characteristics are extremely sensitive to overcharge.

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Common Bus Regulated Battery Charging

Batteries require overcharge to maintain state of charge. Constant current charging can lead to thermal runaway. To prevent thermal runaway, a power regulator unit (PRU) with a voltage temperature (V/T) control charging mode was developed.[2] This limits the maximum battery voltage during charge based on battery temperature: the higher the temperature, the lower the terminal voltage. The regulator controls voltage by reducing the charge current into the batteries.

This design is the basis for the McDonnell Douglas Modular Power Subsystem (MPS). The MPS is the power subsystem for NASA Multi-Mission Modular Spacecraft[3] Common bus applications. Parallel charging common bus applications, developed in the late 1960's, have successfully flown straight V/T control for years. Specific examples of this are the early Landsat satellites and the Solar Maximum Mission (SMM).

As the batteries charge, the terminal voltage increases to the V/T limit and the PRU reduces the charge current to the batteries. The current tapers off over the charge cycle. This effect is taper charging. In this mode, altering the V/T level controls the state of charge of the batteries. The higher the V/T level, the higher the current at the end of charge. The higher the current, the more overcharge returned to the batteries. The use of V/T charging eliminated the concern about thermal runaway, and many "old" battery designs accepted overcharge very well. There are many batteries in GEO that have overcharged for years with no problems.

Astronautics Satellite Electrical Power Subsystem (EPS) Configuration

The Astronautics satellite uses an MPS based power system. Figure 1 shows the EPS functional diagram. There are three, 22 cell, 60 ampere hour, Gates 50AB22 lot 13 batteries in the MPS. The PRU uses NASA standard V/T levels 2 through 8. The PRU also has a current mode with three charge rates. The current mode limits the maximum charge current to 0, 5, or 10 amperes, total for all three batteries. There is a $\pm$ .25 ampere tolerance in current mode. Current mode is secondary to V/T control. If the battery voltage is greater than the selected V/T level with the 10 ampere current mode selected, V/T control will limit the battery charge current accordingly. The 0 ampere current mode is useful in strict control of battery overcharge and in performing on orbit battery capacity tests.

There are two relays for each battery in the MPS. The batteries connect to the bus in a primary or redundant mode, disconnect from the bus, or are diode isolated from the bus. Off line batteries can connect to reconditioning load banks or a charger external to the MPS. The reconditioning load bank has a high rate discharge at 22 ohms, and a low rate discharge at 66 ohms. The reconditioning battery charger is a constant current charger at a low rate 1.25 or a high rate of 2.5 amps.

The design of the Astronautics MPS allows for on orbit battery capacity tests. During a battery capacity test, called BATMAN, the batteries discharge normally during an eclipse period. Selecting a current mode of 0 amperes, during the eclipse, prevents the batteries from charging during the next sunlit period of the orbit. The batteries enter the next eclipse period at a higher than normal DOD. These exercises reduce the memory effect and determine operational performance margins. A modified version of a BATMAN, in which loads are turned on and off during the final eclipse, is a BATIFT. This test characterizes performance at high discharge currents. The maximum load seen during nominal operations and BATIFT exercises is 25 amperes per battery.

Electrical Power Subsystem Functional Diagram

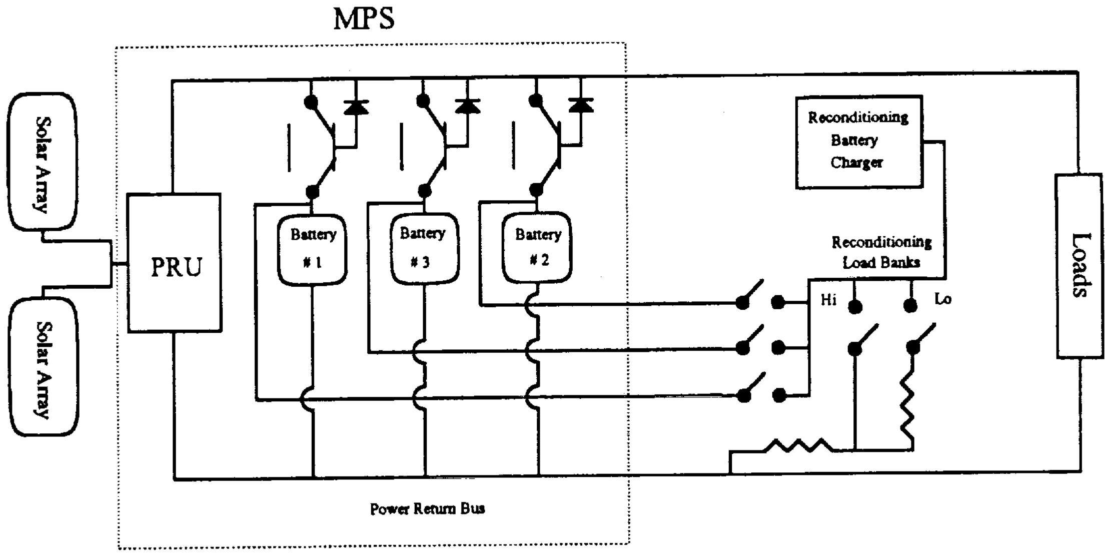

Figure 1.

Circuitry external to the MPS provides orbital reconditioning capability. A full reconditioning starts with high rate discharge using the 22 ohm load bank. High rate discharge continues to 22.44 volts, or approximately 1 volt per cell. The on board computer (OBC) detects the voltage and commands the low rate load bank. The battery continues to discharge into the low rate load bank until it reaches 10 volts and the OBC commands the battery open circuit. The charge cycle begins with one to four hours at a low rate of 1.25 amperes. A high rate charge of 2.5 amperes follows low rate. The amount of time on high rate charge is a function of the ampere hours discharged from the battery, and the thermal response. Reconditioning takes place during short eclipse periods and full sun orbits. Only one battery is reconditioned at a time, and at least two batteries remain on the bus.

On Orbit Symptoms

In the MPS design all three batteries operate in parallel on a common bus. Battery charge current, which is controlled by the PRU, is shared among all three batteries. Parallel charging on a common bus requires similar battery performance to succeed. Flight V/T levels are based on the expected depth of discharge (DOD) and a desired charge to discharge (C/D) ratio. Given a constant orbital eclipse duration, the natural effect of V/T control is that the lower the DOD, the higher the C/D ratio. On orbit C/D ratio's greater than 1.10 are common, and there are several instances of C/D ratio's at 1.20 and above. The high C/D ratios ensure that the batteries are fully charged every orbit, and end of night discharge voltage will support mission operations. The SMM and Landsat satellites operated successfully this way for years, without reconditioning.

As the recent lots of Gates cells were launched, it became clear that straight V/T charging and high C/D ratio's accelerated battery performance degradation. After a few months of straight V/T control, UARS and GRO started observing divergence in battery performance. Performance divergence occurred in an Astronautics satellite for similar reasons. C/D ratios increased, load sharing became unequal and temperatures diverged. Parallel charging, common bus regulated power systems depend on similar characteristics for each battery. As cells in each battery suffered degradation at different rates, the battery performance suffered. Ultimately, one battery on GRO developed a hard short, and was taken off the bus.

The result of the generation of soft shorts is differences in cell performance within a battery. The differences within a battery when small are invisible, but will manifest themselves on a battery to battery level when deviations are large. On an MPS there are telemetry sensors that monitor battery differential voltage. This is the difference between the sum of the voltages of two sets of 11 cells. The first indication of cell divergence is usually a non zero reading in differential voltage.

V/T level control assumes that each cell voltage is very close to the battery voltage divided by the number of cells. In cases where the battery differential voltage is high, some cells will be at higher voltages than others. Since the battery is a series of cells, all the cells see the same charge and discharge current. The consequence of mismatched cells is that a good cell will have a higher voltage than a bad cell during charge. High charge currents at elevated voltages can cause damage to the cell. Under V/T control with mismatched cells, the system is at a level that will maintain the weak cell, with the potential of damaging good cells.

As the number of cells that are off nominal increases within a battery, the overall performance of the battery becomes affected. All three batteries are on a common bus, and the voltage of each battery is the same. Cell mismatches within each battery cause differences in voltage versus current performance. These differences manifest themselves in battery temperatures and load sharing. What happens on a cell by cell basis within a battery, is now evident on a battery to battery level.

Satellite Anomaly History

The Astronautics satellite is in an inclined low earth orbit. Several times a year, there are full sun periods of more than a week. Figure 2 shows a typical eclipse profile. V/T 5 was the nominal charge level after launch. No overcharge limiting control was in place[4]. The differential voltage divergence began about 9 months after launch, after a full sun period, and the V/T level remained unchanged. The batteries underwent a normal reconditioning during full sun. Four months after the full sun period the differential voltage rose to greater than 200 mv and battery performance degradation became evident. Figure 3 shows the median value of the differential voltages over time. The long period at V/T 5 during full sun caused soft shorts in the cells. The continued use of V/T 5 caused a runaway soft short situation. As the shorts developed, the battery charge current increased and caused more shorts.

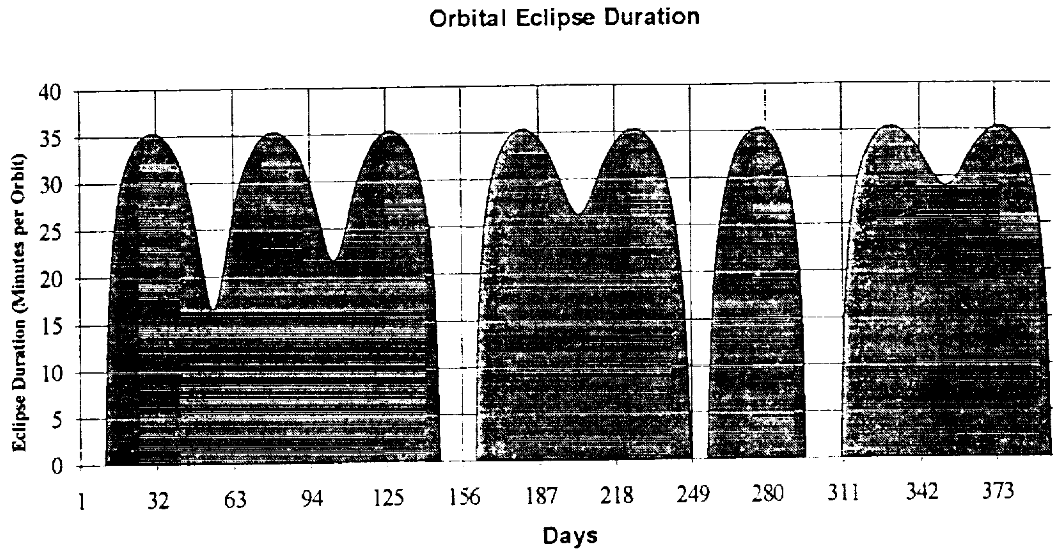

Figure 2.

A change to V/T 4 occurred 12 months into the mission. This was to compensate for the mismatched performance. The C/D ratios reduced slightly but performance continued to degrade. A second reconditioning occurred 14 months after launch. The discharge performance of the batteries on the 22 ohm and 66 ohm load indicated a large discrepancy among cell capacities. Approximately 74 ampere hours discharged out of each battery to approximately 10 volts. Analysis of the data showed that some cells were in reversal for more than 30 ampere hours. There was no concern about pressure in the cell at such a low rate. There was a concern regarding damage to cells because this phenomenon was totally unexpected. The reconditioning demonstrated that straight V/T control did not effectively limit C/D ratios, and was damaging to the batteries.

After the second reconditioning, battery overcharge reduction continued by using the recharge fraction (RCF) method. The use of this charge control method would ultimately lead to a stable operating regime, but the battery degradation had progressed too far to see results in a short time. Performance divergence reached a 5 ampere difference in load sharing at a 70 ampere bus load. There was as much as 3 degrees C difference in battery top of cell temperatures. Differential voltages were very high. The culmination of poor battery performance occurred when a low voltage incident developed during a BATMAN exercise.

The BATMAN exercise spanned three eclipse periods. Load sharing during the first two eclipses was typical of the degraded performance observed before the exercise. During the third eclipse load sharing became poor. Two batteries provided less than 10% of the 30 ampere bus load, and the third battery provided 80%. The consequence of one battery supplying the load at the elevated

DOD of the third eclipse was a steep drop in voltage that resulted in a bus voltage of 24 volts. Minimum voltage allowed without entering safehold mode is 25.12 volts. The low voltage incident prompted changes in the orbital management of the power subsystem.

To minimize overcharge, 0 ampere mode RCF control at V/T 4 to an RCF = 1.08, was instituted. When the ampere hours returned is 108 % of ampere hours removed, the OBC commands the PRU to 0 ampere mode, terminating battery charge. Weekly BATIFT capacity checks to DOD's greater than the nominal mission range were instituted to reduce the memory effect, and to determine operational performance. Future reconditioning would be less stressful.

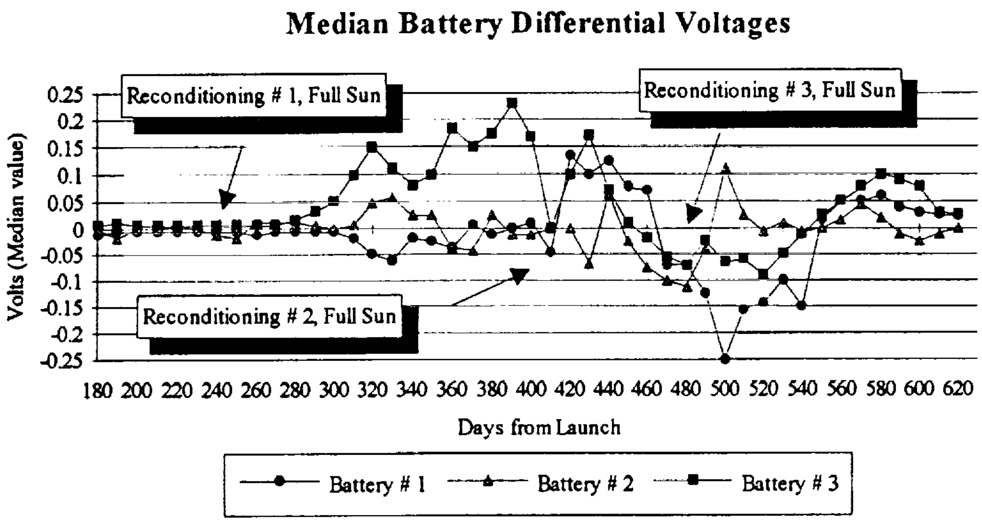

Figure 3.

RCF Control

The Astronautics satellite has OBC software that allows tuning of charge control parameters. RCF, the ratio of ampere hours charged to ampere hours discharged, is the charge control method employed. RCF control limits the percentage of overcharge allowed. To accomplish this, the OBC modifies normal DOD by a predetermined RCF value, and terminates battery charge once the adjusted DOD reaches zero. OBC commanding of the PRU to zero ampere current mode terminates battery charging. The OBC detects battery discharge during the eclipse portion of the orbit and commands the PRU back to a normal V/T 4 charge mode. Specifically, the equation for normal DOD is:

$$DOD(N) = ([\Sigma_{n=0} I_{\text{discharge}}(N)_n \times \Delta t] - [\Sigma_{n=0} I_{\text{charge}}(N)_n \times \Delta t]) \div NAMEPLATE$$

DOD adjusted by an RCF is:

$$DOD(N) = ([\Sigma_{n=0} I_{\text{discharge}}(N)_n \times \Delta t] - [\Sigma_{n=0} \{I_{\text{charge}}(N)_n \times \Delta t\} \div RCF]) \div NAMEPLATE$$

Where :

N = Battery #1, #2, #3
n = Iteration
t = Time
$I_{discharge}$ = Battery Discharge Current
I_{charge} = Battery Charge Current
NAMEPLATE = Rated nameplate capacity of the battery
RCF = Recharge Fraction

The computer performs these calculations every 1.024 seconds. The current sensors used for integration have a resolution of .4 amperes. The granularity of the current sensor data and the integration introduce errors into the calculation, but the relative difference between RCF values remains constant. In other words, an RCF value of 1.06 may be in the actual range of 1.03 to 1.09, but an RCF of 1.07 is greater than 1.06.

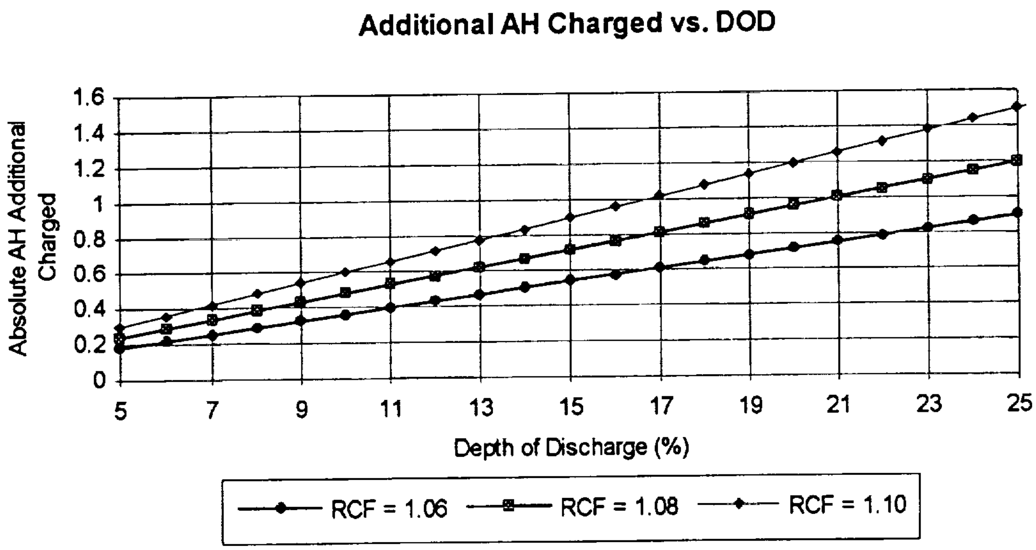

Figure 4.

Closer inspection of the RCF control equation reveals that the ampere hours overcharged during each cycle is a function of DOD and RCF. Figure 4 shows ampere hours overcharged versus DOD and RCF. There are equivalent ampere hours overcharged at an RCF of 1.10 at 10 % DOD and at an RCF of 1.06 at 17 % DOD. Experience has shown that .4 to .5 ampere hours overcharge at 10 % to 15 % DOD provides enough overcharge to adequately maintain voltage, without exacerbating the generation of soft shorts. In short eclipse periods, the overcharge drops to a much smaller number and there is a corresponding drop in the end of night voltage. Generally, the drop in voltage is not enough to cause an impact to the mission.

Orbital Management Corrective Actions

The Astronautics satellite's peak power loads are random and can occur at anytime during the orbit. Maximum DOD's for a nominal mission are 19 % with average DOD's of 12 % to 15 %. Eclipse duration and peak power loads are the main factors that drive orbital DOD. Figure 5 shows nominal mission maximum DOD's and eclipse duration. This data does not include any battery capacity tests that are generally in the 25 % to 35 % DOD range.

Coincident with 0 amp mode RCF control, weekly battery performance exercises and capacity tests, called BATIFT's, started. Performance was extremely poor, and normal operations were very close to putting the satellite into safe hold mode due to low battery voltage. The BATIFT exercises determine the bounds of the performance envelope. The initial exercises started by turning on timed peak power loads during an eclipse period, and assessing performance. This process continued through the eclipse as long as the load sharing and voltage was satisfactory. The combination of the RCF control, the low voltage incident, and the weekly BATIFT exercises, brought the batteries back under control.

Improved performance warranted extending the BATIFT exercises over two eclipses, similar to a BATMAN. The performance during the first eclipse of the exercise determined if extending to two eclipses was warranted.. Good voltage response, load sharing and discharge voltage fulfilled the criteria for continuation. In the subsequent sun period, no charge was applied to the batteries. Using two eclipses allowed DOD excursions beyond the nominal mission DOD. This served two purposes. First, exercise beyond the normal limits helps reduce voltage depression due to the NiCd memory effect. Second, the increase or decrease in performance of the battery is more evident at higher DOD's. BATIFT exercises continued weekly until the next full sun period. During this full sun period reconditioning number three took place.

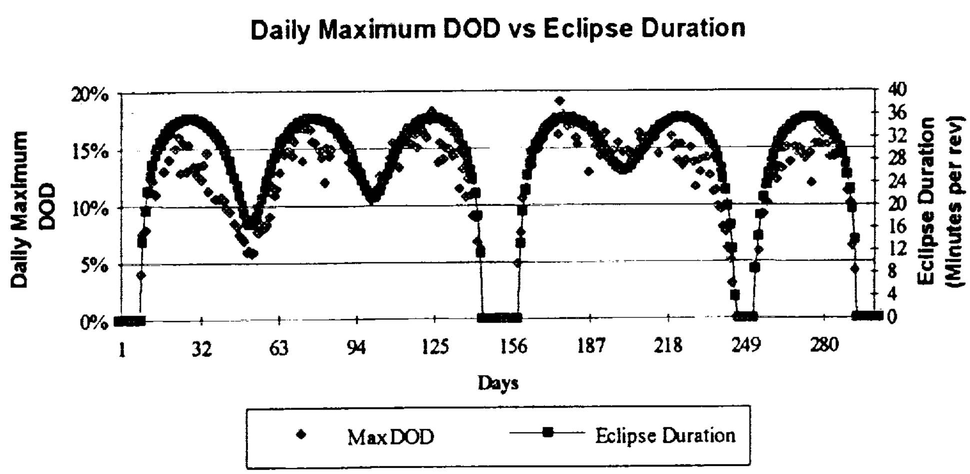

Figure 5.

Normal reconditioning uses the 22 ohm and 66 ohm load banks to discharge each battery individually. Cells were in reversal for extended periods during the second reconditioning. The voltage and differential voltage response to long periods of reversal indicates that this is detrimental to the long term health of the batteries. The batteries that were not on the reconditioning load bank were being trickle charged during full sun at V/T 3. This proved to be extremely damaging to the batteries. Performance after the second reconditioning quickly became worse than before the reconditioning.

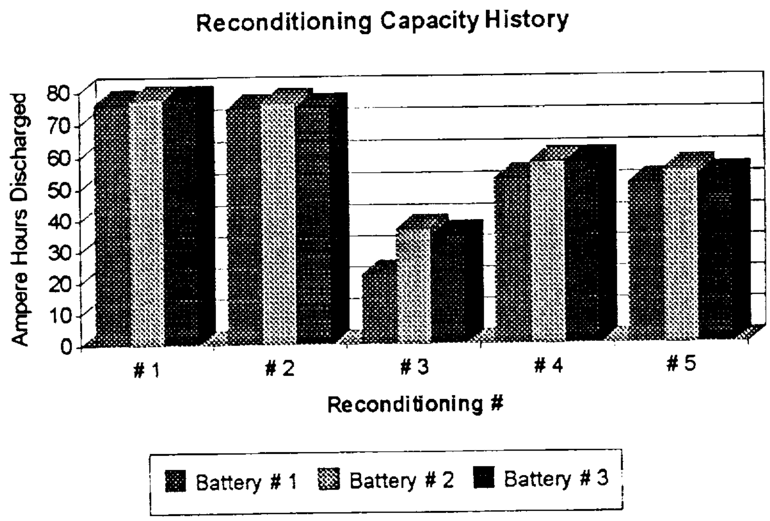

Figure 6.

Reconditioning number three occurred at approximately 16 months of mission life. The approach to reconditioning was to limit the time in reversal, and reduce the overcharge during full sun. To reduce the stress on the weaker cells, the reconditioning discharge terminated at the first cell reversal. The battery voltage, current, differential voltage and ampere hours discharged determine a cell reversal. A spreadsheet assisted in the determination of cell reversal. V/T 2 is selected when full sun is entered to reduce the trickle charge current to an acceptable level. Instead of overcharging after discharge, the battery charged to a specific voltage. In this case the voltage was about 1 1/2 volts above the V/T 2 level bus. The sensitivity of these batteries to overcharge warranted this approach. Also, there is no reason to charge the battery to a higher voltage just to let it discharge when connected to the bus.

Reconditioning to cell reversal proved to be a limited success. The three batteries discharged 22, 37 and 35 ampere hours respectively. The reconditioning sequence completed with several days of full sun left. Selecting the 0 ampere current mode for the remaining days of full sun further reduced overcharge. A design compatibility problem prevents the 0 ampere current mode from being used while any battery is on the reconditioning bus. In the 0 ampere current mode, it became evident that a significant amount of soft shorts remained in the batteries. The bus voltage dropped over a volt per day due to the self discharge effect of the shorts. The differential voltages also increased during this period. A daily V/T 2 short duration charge was used to maintain bus voltage at acceptable levels.

After the third reconditioning, voltage performance improved slightly and battery temperatures came back into line. Differential voltages still were very high, and load sharing was acceptable. Weekly BATIFT exercises resumed after reconditioning. After each BATIFT exercise the load sharing improved, and the differential voltages would tend toward zero. The response of the differential voltage was a byproduct of the BATIFT, and not an objective. Differential voltages provided useful information, but steps taken for remedial treatment of the batteries were not in response to differential voltage signatures. Voltage performance, thermal response and load sharing were the indicators used for state of health assessment. It took several weeks for the batteries to become fairly well matched.

Telemetry analysis became a sizable effort. Determining operational margins at nominal mission DOD's was difficult. The BATIFT performance determined mission margins and limits to the mission. The system performance was good for the next 5 months. The RCF value of 1.08 maintained state of charge, and did not generate more soft shorts.

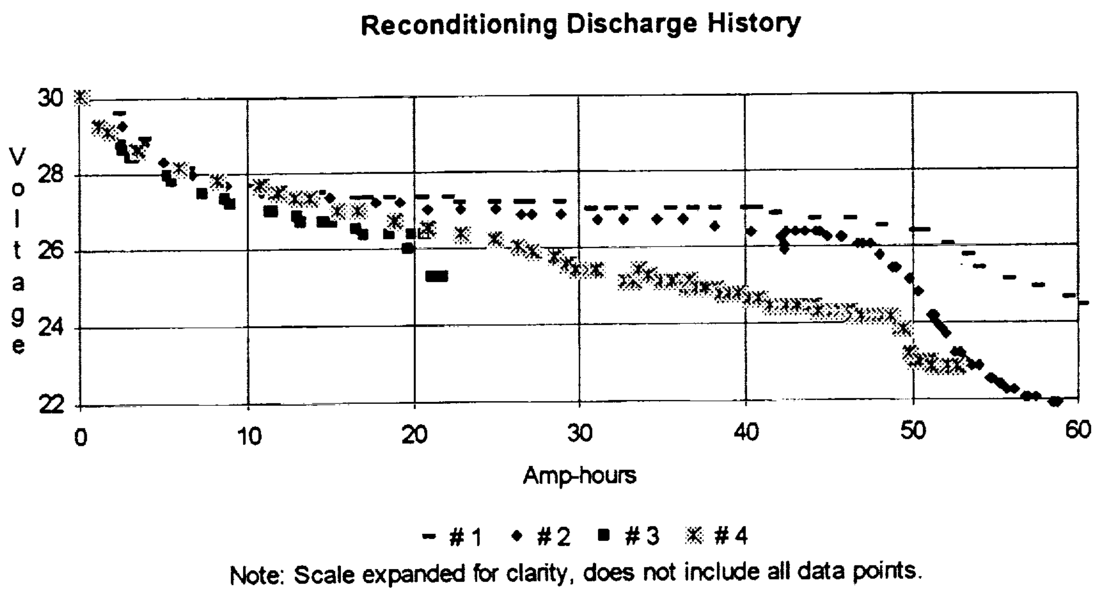

Figure 7.

Reconditioning number four occurred at 19 months into the mission. The rules for this reconditioning were the same as the third one. The performance to cell reversal of this reconditioning improved. Figure 6 shows reconditioning ampere hours discharged for all reconditioning activities. The higher values indicate smaller relative differences among the cells. The I-V curves for reconditioning do not indicate any significant plateau out to 50 ampere hours. This type of reconditioning enhances voltage but it does not recover a long term NiCd plateau. Figure 7 shows voltage versus ampere hours discharged. Reconditioning number one shows a typical I-V curve, and reversals are evident in reconditioning number two. Also shown is the limited reconditioning number three, and the lack of a plateau and downward slope of reconditioning number four. Reconditioning provides a boost in operational voltage that allows the mission to continue without restrictions.

RCF control at 1.06 started after the fourth reconditioning. Differential voltages increased for about 2 months. Load sharing differences were slightly greater than at an RCF of 1.08. After a period of about 3 months, the batteries became well matched again and performed adequately. The most recent reconditioning took place 26 months into the mission and the results were comparable to the previous reconditioning. The load sharing has improved, and differential voltages are now under 30 millivolts. All mission objectives are being met, and the system has reached stability.

Conclusions

Many future satellites will have to rely on aerospace NiCd battery technology. Changes in the United States aerospace battery manufacturing industry indicate that the future is uncertain at best. Process, personnel and material changes have a large effect on the final product. Isolating the cause of the orbital anomalies to parametric relationships in the manufacturing process was a huge undertaking. The use of the Toft discriminators for 50 ampere hour cells provides early indications into the relative hardiness of a plate lot. This level of effort and scrutiny may not be possible for all future cell builds. Flexibility provided in the design of a satellite power system allows the ability to react to sensitivities of different types of cells.

Variable charge control and orbital reconditioning capability are especially important in parallel charging common bus applications. The MPS is an extremely reliable system. As long as the batteries tolerate overcharge, the system has performed well beyond its intended design life. When cells diverge and batteries become degraded, straight V/T control contributes to further degradation. Hardware and software on the Astronautics satellite provided the tools to mitigate battery degradation through overcharge control. Having a 0 ampere current mode, which is paramount in managing overcharge, was also extremely useful for battery capacity checks

Overcharge is extremely damaging during full sun and short eclipse orbits. Lowering the V/T level or using zero ampere current mode are effective methods to reduce overcharge during the long period of trickle charge. RCF control is effective in limiting overcharge during orbits with long eclipse periods. Eliminating the battery's ability to continue to charge reduces the continued generation of soft shorts, and improves overall battery performance. Daily overcharge limitation is the most important aspect in controlling battery degradation.

The battery capacity checks and reconditioning provided methods for remedial treatment of severe battery degradation. Orbital capacity tests used to determine the performance envelope provided needed exercise for the batteries. Frequent excursions beyond the normal DOD range control the NiCd memory effect. There is little doubt that these controls enabled the mission to continue.

A reconditioning capability in LEO provides a method to recover voltage performance for NiCd based satellite power systems. Overcharge limitation results in batteries operating at a lower state of charge. Depressed voltage performance is a consequence of operating at a lower state of charge. Reconditioning enhances voltage performance. Reconditioning to different levels has not proven to be a liability. Batteries become matched quickly after reconditioning reacting to the RCF charge control.

Differential voltage monitors provide information about the relative likeness of cells within a battery. The charge control level should not be changed based solely on differential voltage. This could result in a condition of increased overcharge meant to bring the cells closer to one another in performance. Initially the differential voltage will reduce and the change appears to be effective. As the overcharge increases more shorts develop and the differential voltage returns to a high value. Continued overcharge on these types of batteries can lead to a hard short. Differential voltage as an indicator of cell compatibility is useful. The criteria for adequate orbital performance should be voltage, load sharing and thermal response.

Uncertainties in future battery designs indicate that cognizance of battery overcharge should start before launch and continue throughout the mission. Steps to limit overcharge begin immediately after launch. Limiting overcharge early in the mission may prevent the onset of severe degradation. The ability to control overcharge through variable RCF control and zero ampere current mode has proven very effective. Future common bus parallel charge systems should include these capabilities to provide the flexibility to respond to the uncertainties of future battery performance.

[1] Mark R. Toft, "Preliminary Results: Root Cause Investigation of Orbital Anomalies and Failure in NASA Standard 50 Ampere-Hour Nickel-Cadmium Batteries", Proceedings of the 1992 NASA Aerospace Battery Workshop

[2] Robert Gruber, "High Efficiency Solar Cell Array Peak Power Tracker and Battery Charger", IEEE Transactions on Aerospace and Electronic Systems, Power Conditioning Specialists Conference, 1970 Record

[3] Bob Kichack, "Standard Power Regulator for the Multi-Mission Modular Spacecraft," Distributed by McDonnell Douglas Corporation

[4] RCF control is always in effect, although it may not limit overcharge. During the early phases of the mission, RCF control to a current mode of 5 amperes was used. The 5 ampere current mode equates to about 1.7 amperes per battery. When the switch to 5 ampere current mode was commanded by the OBC, the charge current had tapered below 1.7 amperes per battery. V/T control supersedes current mode, so the effective control mode was straight V/T 5. The taper charge under V/T 5 control contributed a substantial amount of current to overcharge the batteries.