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# TOPEX/Poseidon Electrical Power System - Performance

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## ABSTRACT

This paper shows that the power system performance (batteries, solar array, power regulator) on-board the TOPEX/Poseidon satellite has met or exceeded pre-launch predictions, and has successfully managed the performance of NiCd batteries which had shown anomalous performance on other missions such as UARS and GRO. The battery performance is addressed through the following parameters: end-of-discharge voltage, peak charge current, charge to discharge ratio, and voltage differential. The solar array performance discussion includes voltage, current and power. There is also a discussion of the power regulator efficiency and the satellite load power history.

## INTRODUCTION

TOPEX/Poseidon (TOPEX), jointly conducted by NASA and the French Centre National d'Etudes Spatiales (CNES), was launched successfully on August 10, 1992. The 3.7 year successful operation to date of the TOPEX satellite and power subsystem has enabled the science community to make enormous gains in measuring and understanding global ocean phenomena such as circulation, tides, and their effects on climate. TOPEX is powered by the Modular Power Subsystem (MPS) containing 3 NASA Standard 50 Ah capacity Nickel Cadmium (NiCd) batteries manufactured by McDonnell Douglas and a deployable, sun tracking, rigid, single-wing, rectangular silicon solar array with overall dimensions of approximately 26 by 11 feet.

Batteries of identical design and similar manufacturing history on board other NASA satellites experienced battery anomalies early in life. These satellites include the Extreme Ultraviolet Explorer (EUVE), the Upper Atmosphere Research Satellite (UARS), and the Gamma Ray Observatory (GRO). These satellites exhibited large divergence of the half-battery voltage within the first 4-7 months after launch. This deteriorating condition normally would be exhibited near the battery end-of-life, which was designed to be on the order of 3-5 years in a Low Earth Orbit regime. In order to avoid similar battery problems on TOPEX, an Investigation Team and the Battery Management Team were formed prior to launch to make operational recommendations for the TOPEX batteries. The recommendations included using novel battery management techniques to maintain the battery health throughout the primary mission. These techniques have been referred to as TLC or Tender-Loving-Care. The TLC techniques included: limit the battery peak charge current to less than 20 A, control the recharge ratio to 1.05±.03, and use the low current sensor for recharge ratio calculations when charge current is less than 3 A. These successful operational techniques for the TOPEX batteries have been continued during the extended mission in anticipation of battery life well beyond the primary mission.

The TOPEX satellite has an orbit with a period of 112.5 minutes and eclipse duration varying from 0 to 35 minutes. The occultation periods alternate between approximately 42 days and 84 days with periods of full sun of about 10 to 20 days in between. This behavior repeats throughout the duration of the mission.

The primary source of power for TOPEX is a rigid single-wing solar array. The solar array provides power to the satellite loads and charges batteries while in orbit daytime. The array tracks the sun and is offset from normal to the sun line by (currently) 50.5° to reduce the charge current on the batteries. The solar array temperature varies between -80° to +40°C and the differential temperature between the front and back of the array varies from 0 to 10°C.

The load requirements on the TOPEX power system range from 700 to 1050 W. The variation is caused by heater cycling and switching between the NASA altimeter and the CNES altimeter.

Battery charging on TOPEX is carried out by the Standard Power Regulator Unit (SPRU) using 2 different modes: peak power tracking mode and voltage limit mode. Peak power tracking is utilized at the beginning of each satellite orbit until the selected charge voltage/temperature (V/T) level is reached. At this point, the SPRU enters voltage limit mode, also known as taper charge mode. The V/T controller in the SPRU senses the battery voltage and limits the voltage to the preset limit defined by the V/T level. The V/T levels are used effectively in controlling battery recharge. TOPEX operates using V/T levels 2,3 & 4 from the NASA standard Ni-Cd battery manual. V/T level 2 is used during periods of full sun. V/T level 3 is used when the earth occultation periods are < 28 minutes and V/T level 4 is used during earth occultation periods between 28 and 35 minutes. The battery temperature varies between 5-8° C and is controlled using heat pipes and heaters.

## BATTERY GROUND TESTS

Four months prior to launch, a mission simulation ground test using TOPEX cells from the flight lot was initiated as standard operational procedure in support of flight projects. The objective of this test was to predict mission performance and to provide quantitative data to aid in the management of the spacecraft batteries. Because the mission simulation test was initiated prior to the launch, the operational changes for the Tender-Loving-Care environment were not yet implemented and not incorporated in the test. In addition, another ground test was started 2 months after launch to assess the effects of charging at a lower temperature. The cell temperature was 10° C for the mission simulation test and 0° C for the temperature effect test. In both tests, a pack of 5 flight cells was charged at 25 amperes to V/T level 5. The discharge rate was 10 amperes to a maximum 12% depth of discharge (D.O.D.). The orbit duration was 112 minutes with a discharge duration ranging from 23.5 minutes to 35.5 minutes maximum. The discharge duration simulates the TOPEX/POSEIDON satellite eclipse duration.

## SOLAR ARRAY PERFORMANCE

The solar array power is a function of the solar intensity and the solar array offset angle. The solar intensity increases from aphelion (July 1) to perihelion (January 3) and then decreases back to aphelion. By monitoring the solar array degradation and solar intensity cycles, the array was positioned to maintain the peak charge current within the recommended operational range (15-20 A). The following table lists solar array offset angle changes since launch.

| Dates | Offset Angle |
|---|---|
| Aug. 92-Aug. 93 | 57.5° |
| Aug. 93-Nov. 95 | 54° |
| Nov. 95-present | 50.5° |

**Table 1. SOLAR ARRAY OFFSET ANGLE CHANGES**

The solar array was maintained at an offset angle of 57.5° for approximately one year since launch. The solar array was then switched to 54° offset and was maintained at that position until November 1995 (approximately two years). It was possible to maintain the solar array offset at 54° for a longer period of time than at 57.5° due to the lower solar array degradation after the second year. Solar array degradation is caused primarily by radiation, with lesser effects from ultra-violet light, micrometeoroid damage and thermal cycling. Table 2 lists the degradation rate of the solar array compared to the pre-launch prediction.

| | Actual | Prediction |
|---|---|---|
| **Year 1** | 10.56%/year | 10.3%/year |
| **Year 2 - present** | 3.61%/year | 6.3%/year |

**Table 2. ANNUALIZED SOLAR ARRAY DEGRADATION**

The degradation during the first year was slightly higher than predicted. Since that time, the degradation rate has been significantly less. The degradation was computed by taking a 3 minute average of the solar array power during peak power tracking. This number is then normalized for a 0° array offset angle and for the reflection and defraction caused by the cover glass. The data is trended at a constant solar array temperature of -55° at a beta prime angle of 0°. A graph of these points is exhibited in Figure 1. The solar array degradation rate has been declining since launch. The lower-than-predicted solar array degradation may be due to; operating with an offset angle minimized the frontal area of the array to radiation effects, the solar cycle has been at the solar minimum, and the front-to-back differential temperature of the array is lower than pre-launch predictions. The lower degradation rate, if it continues, will contribute several years to the predicted life of the solar array.

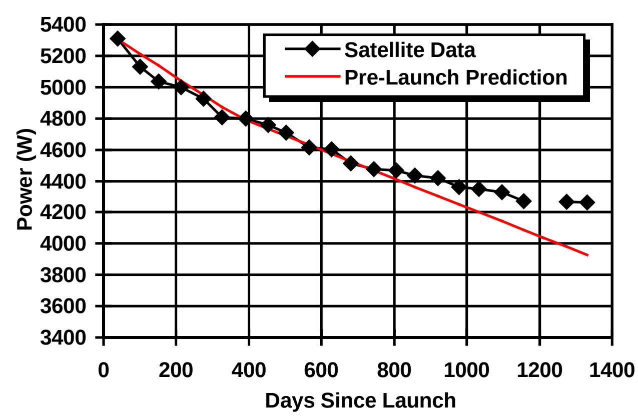


**Figure 1. NORMALIZED SOLAR ARRAY POWER**

## BATTERY PERFORMANCE

### Peak Charge Current

The peak charge current is the maximum charge current the batteries experience during each orbit. This current varies as a function of the power output of the solar array and usually occurs at the beginning of the orbit when the solar array output is highest. Under the TLC strategy, the recommended range for the peak charge current is < 20 amps. In addition, the average peak charge current should be maintained above 15 amps to achieve the desired charge to discharge ratio. As the solar array degrades, the solar array offset is periodically reduced to maintain the operational recommended range.

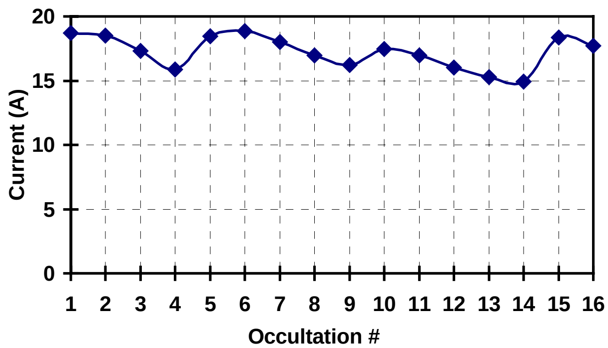


**Figure 2. AVG. BATTERY PEAK CHARGE CURRENT**

Figure 2 exhibits the average peak charge current during each occultation period since launch. The average peak charge current was maintained below the TLC recommended 20 amperes and above 15 amperes during all of the occultation periods.

## End-Of-Discharge Voltage

The end-of-night battery voltage (EONV) or end-of-discharge voltage (EODV) is the lowest voltage the battery reaches during the end of the eclipse portion of each orbit. This parameter may be used as an efficiency factor or wear-out indicator. The internal impedance of the batteries varies as a function of state-of-charge. As the state-of-charge decreases, the internal impedance increases. Thus, the higher the DOD the higher the internal impedance and hence the lower the EONV of the batteries. In addition, as the batteries age, it is expected that the efficiency of the batteries decreases and the internal impedance increases. This results in lower EONV with aging. This parameter is important in supporting the voltage requirements of the various satellite instruments.

Figure 3 exhibits the minimum battery end-of-night voltage at the maximum D.O.D. of each occultation period for the spacecraft batteries and compares that to the equivalent battery voltage (scaled up to a 22-cell configuration) for the cells cycled on the ground. The end-of-night voltage was the first battery parameter to exhibit a degradation To date the end-of-night voltage has degraded from 27.5 volts to 26.40 volts The degradation rate of the end-of-night voltage increased during the eleventh and twelfth occultation periods. Along with this EONV degradation, the battery exhibited a spread in the voltage at the end-of-night which caused a voltage differential divergence (described in the Voltage Differential section of this report). It is interesting to note that the EONV degradation rate of the flight batteries has been slower than the EONV degradation of the TOPEX mission simulation ground test cells. This is indicative that the TLC strategies applied to the flight batteries are indeed lowering the overall cell degradation, therefore, they are essential in contributing to the mission extension.

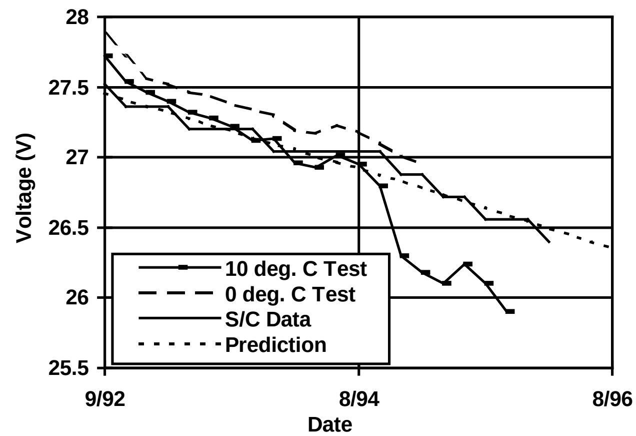


**Figure 3. BATTERY EON VOLTAGE AT MAX. ECLIPSE**

## Charge To Discharge Ratio

The charge to discharge ratio (C/D) monitors energy balance and overcharge and is a good indicator of load sharing. The parameter is computed every orbit on-board the satellite by dividing the net charge (amp/min.) by the net discharge (amp/min.). The recommended operational C/D ratio is 105±3% at 5°C.

Figure 4 exhibits the average C/D performance for each occultation region for the satellite and the ground cells. The C/D increased during the first eight occultation periods and slowly declined during the last nine occultation periods. This behavior is typical for Nickel-Cadmium batteries while cycling in Low Earth Orbit regimes. This type of behavior is mostly due to the positive electrode expansion during the initial portion of the battery life, which improves cell efficiency. As the cycle life increases, the positive electrode expansion reaches a maximum and the cell efficiency begins to decrease, thus the decline in recharge fraction. This type of behavior was also observed on the ground tests. The rate of C/D ratio increase was much faster for the cells tested on the ground. This implies that the Tender-Loving-Care conditions applied to the flight batteries have successfully decreased the rate of normal degradation.

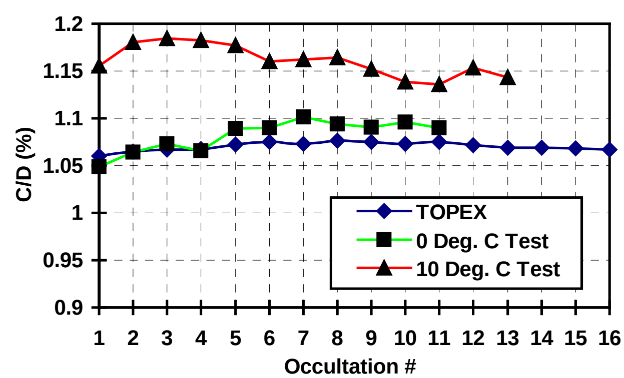


**Figure 4. AVG. CHARGE TO DISCHARGE RATIO**

## Voltage Differential

The voltage differential parameter has historically been trended to evaluate battery state of health. The voltage differential is the difference of the two half-battery voltages. Historically, this parameter would remain under 100 mV until the end-of-life of the battery.

The three batteries to date have exhibited voltage differentials lower than 50 mV, however, certain trends have been observed. Two trends observed to date are: "peak power voltage differential spikes" and "end-of-night differential voltage divergences". Figure 5 exhibits the peak power voltage differential spike behavior for battery #1 during one the earliest occultation periods. The peak power voltage differential spikes were normally observed during the first and last few days of an occultation region and occurred during the peak power tracking portion of the orbit. During these portions the eclipse duration was small, therefore, the battery State-of-Charge (SOC) after discharge remained high (above 95%). When the batteries are at a high SOC and are then charged with a high current, a temporary imbalance of the cells is created until the V/T level is reached. It appears that these peak power voltage differential spikes are not a cause of a degradation process. Peak power voltage differential spikes have been observed frequently with batteries on ground tests and on other spacecraft and are considered normal. Healthy batteries such as the ones flown on the Compton Gamma Ray Observatory (GRO) and Landsat 4 also exhibited voltage differential spikes during peak power tracking. The magnitude of these spikes can be controlled by the peak power tracking charge current. The TOPEX batteries have exhibited relatively small peak power voltage differential spikes because the peak power charge currents have been reduced. The reduction of the peak power charge current has been part of the TLC strategies implemented on the TOPEX batteries since launch. The charge current during peak power tracking has been controlled to below 20 A, hence minimizing the peak power voltage differential spikes.

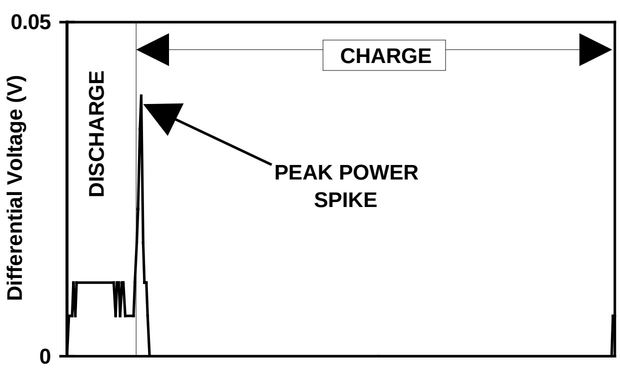


**Figure 5. PEAK POWER VOLTAGE DIFFERENTIAL SPIKE (+39mV)**

Figure 6 exhibits the end-of-night voltage differential divergence behavior for battery #2 during one the latest occultation periods. This divergence is different from the peak power spikes because it occurs at the end of battery discharge while the eclipse durations are long instead of during the beginning of battery charge while the eclipse durations are short. It is considered to be a degradation process. As the cells degrade they develop unused active material which operates at a lower potential. The rate of this degradation process cannot be controlled equally for the 22 individual cells within a battery, therefore, the voltage differential increases during the end-of-night. This type of behavior was also exhibited by the cells cycled in the test lab six months prior to the observation made on the flight batteries. The voltage differential divergence is also associated with a drop in the end-of-night voltage.

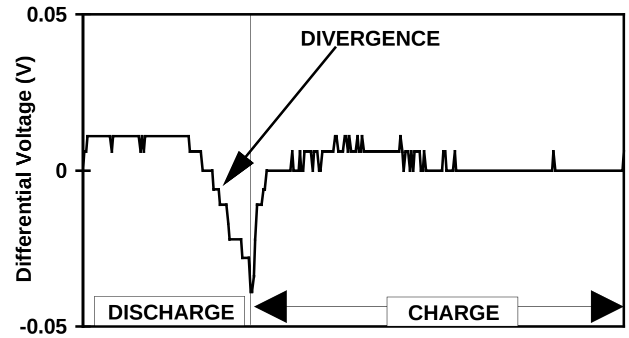


**Figure 6. END OF NIGHT VOLTAGE DIFFERENTIAL "DIVERGENCE"**

The voltage differential for battery #1 has been limited between ±22 mV throughout the mission to date. Battery #1 had not exhibited any significant changes in voltage differential until occultation #9. During this period battery #1 exhibited peak power voltage differential spikes. The magnitude of the peak power spikes were as high as -16mV and disappeared as the eclipse season increased above 10 minutes. These spikes appeared throughout occultation #14 and had a magnitude of -22mV, -16mV, -22mV and -16mV for occultation periods #11, #12, #13 and #14 respectively. Battery #1 also exhibited end-of-night voltage differential divergences during occultation #12. The divergence was 16 mV in magnitude and increased to 22 mV during the next two occultation periods.

Battery #2 has exhibited the highest end-of-night voltage differential divergence among the three batteries. The end-of-night voltage differential divergences have reached as high as -44 mV during occultation period #14 (approximately 3.5 years into the mission). Battery #2 has also exhibited peak power spikes during earlier occultation periods. The highest these spikes have reached has been -22 mV approximately 1.5 years after launch.

Battery #3 has exhibited the highest peak power voltage differential spikes among the three batteries. The peak power voltage differential spikes for battery #3 have reached as high as +44 mV approximately 3 years after launch. Battery #3 has not exhibited any significant end-of-night voltage differential divergence behavior to date.

It should be noted that the TOPEX battery data is the first of this kind monitored and trended in such detail from the initial phase of a mission. TPower, an automated database program, was designed and developed to address the need for detailed data trending. The voltage divergence of all three batteries observed to date is low and would not have been noticed if the battery data had not been trended carefully. Changes in the cells within the batteries are taking place and this is reflected on the voltage differential, however, the rate of change is considered low and not alarming. This low rate of degradation may be due to the TLC conditions implemented since launch.

## SPRU PERFORMANCE

The TOPEX Standard Power Regulator Unit (SPRU) is used to convert the solar array power into battery charging power and load bus power. Figure 7 exhibits the TOPEX SPRU efficiency since launch. This efficiency is calculated by dividing the sum of the total battery charge power and load power by the solar array power. The efficiency was averaged over 3 minutes during the peak power tracking portion of the orbit. Two separate solar array temperatures were chosen to correlate temperature with efficiency, -55°C and -30°C. The average SPRU efficiency for each solar array temperature was 92.4% and 93.2% respectively. The efficiency of the TOPEX SPRU was designed to be 91.5%. The higher-than-predicted SPRU efficiency will contribute several months to the mission life.

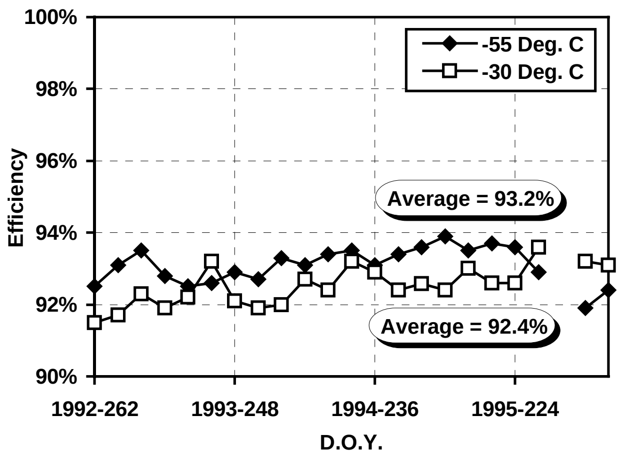


**Figure 7. SPRU EFFICIENCY AT $\beta$'=0°**

## SATELLITE LOAD VARIATIONS

The average TOPEX load power during maximum eclipse has been trended since launch and is shown on Figure 8. The load power has been gradually decreasing from a high of 870 watts shortly after launch to about 846 watts in July 1995. The load power decrease shortly after launch was caused by one of the two transmitters being powered off. This second transmitter was turned back on in July 1995. Between July 1995 and April 1996, the load power decreased 5 watts. A possible explanation for the long-term load power decrease is that the heaters might be consuming less power due to degradation of the thermal blankets. The thermal blankets are absorbing more solar energy thus requiring less heater activation. This trend was reported in IECEC-95 AP-27 and appears to be continuing. Because the rate at which the loads are decreasing is small, there has been no work done to positively identify the causes of the load power decrease. The pre-launch prediction for end-of-life (5 years) power consumption was 933 W. Because the power consumption is currently below this figure and falling, mission life should be extended by several months.

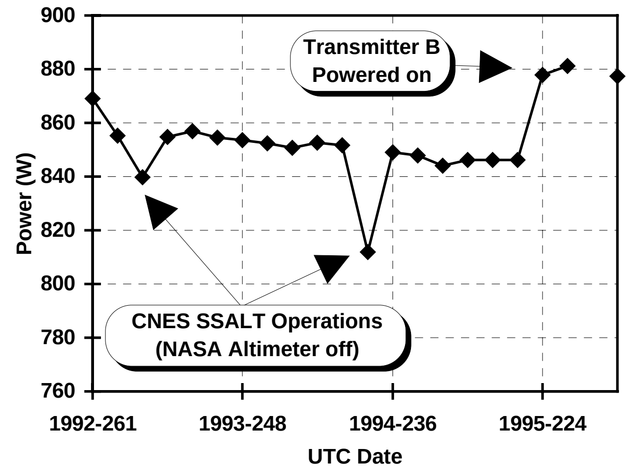


**Figure 8. AVG. DAILY LOAD POWER AT $\beta$'=0°**

## CONCLUSIONS

The TOPEX/Poseidon satellite has completed 3.7 years of successful operation. Prior to launch several changes in the operation of the power subsystem were made. These changes included lowering the V/T levels of battery charging, and offsetting the solar array from the normal position to reduce the peak power tracking charge current.

Based on the satellite engineering data to-date it appears that the TLC operational conditions implemented since launch not only have been successful in controlling the battery overcharge (which was the original intent) but also aided in reducing the degradation rates of several power subsystem components. It appears the solar array degradation is lower than predicted prior to launch which may be due to the solar array offset implemented since launch. The lower solar array degradation rate will contribute significantly to the extended mission lifetime of TOPEX. The Standard Power Regulator Unit has been operating at approximately 93% efficiency and has shown no signs of degradation. It also appears that the TLC conditions have reduced the battery end-of-night voltage degradation. The lower degradation rate may also aid in extended the mission by several months.

Using previously untested battery management techniques, the TOPEX batteries have been the model of success considering that they are of the same type that have exhibited anomalous behavior on other satellites. The TOPEX Tender-Loving-Care (TLC) battery management strategy has made possible an extended mission by decreasing the rate of battery degradation. TOPEX battery management techniques are changing the way that Ni-Cd batteries are operated in low Earth orbit satellites.

## ACKNOWLEDGMENTS

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