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"Design and Performance of Tropical Rainfall Measuring Mission (TRMM) Super NiCd Batteries"

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ABSTRACT

The Tropical Rainfall Measuring Mission (TRMM) is a joint mission between NASA and the National Space Development Agency (NASDA) of Japan. The observatory is designed to monitor and study tropical rainfall and the associated release of energy that helps to power the global atmospheric circulation shaping both weather and climate around the globe. The spacecraft was launched from Japan on November 27, 1997 via the NASDA H-II launch vehicle. The TRMM Power Subsystem is a Peak Power Tracking system that can support the maximum TRMM load of 815 watts at the end of its three year life. The Power Subsystem consists of two 50 Ampere Hour Super NiCd batteries, Gallium Arsenide Solar Array and the Power System Electronics.

This paper describes the TRMM Power Subsystem, battery design, cell and battery ground test performance, and in-orbit battery operations and performance.

Introduction

The Tropical Rainfall Measuring Mission (TRMM) is a part of the National Aeronautics and Space Administration (NASA) Earth probe series of satellites designed to study the planet Earth. The observatory, designed and developed in-house at the Goddard Space Flight Center (GSFC), is a three axis stabilized spacecraft consisting of five instrument payloads. The objective of the TRMM observatory is to obtain and study multi-year data of tropical and subtropical rainfall measurement, and to understand how interactions among sea, land, and air produce changes in the global environment.

TRMM was launched from Japan's Tanegashima Space Center aboard a NASDA H-II launch vehicle on November 27, 1997. The orbit is a circular 350 km attitude with an inclination of 35 degrees to the equator.

Power System Design

The TRMM Power Subsystem is a Peak Power Tracking system consisting of two 22 cell 50 Ampere Hour (Ah) Super Nickel Cadmium (NiCd) batteries, two deployable Gallium Arsenide solar array wings, and the Power System Electronics (PSE) as shown in Figure 1. The Power Subsystem can support up to 1100 Watts of power at a bus voltage of 28 +/- 7 V at its output.

The PSE contains a Standard Power Regulator Unit (SPRU), Power Bus Interface Unit (PBIU), and the Power System Interface Box (PSIB). The SPRU conditions the solar array power and controls the charging of the batteries. The SPRU has four autonomous modes of operation: Peak Power Tracking Mode, Voltage Limit Mode, Constant Current Mode, and Standby Mode. When the spacecraft enters sunlight or whenever the bus load demands and battery charging requirements exceed the available power from the solar arrays, the SPRU will autonomously transition into the Peak Power Tracking Mode. In this mode, the SPRU will draw the maximum power from the solar arrays and will distribute power to the loads. Any remaining power will be provided to charge the batteries. The SPRU will autonomously transition to the Voltage Limit Mode any time the ground selected voltage limit is reached for the battery temperature. There are eight ground selectable NASA Standard Voltage Temperature (VT) levels. Each battery has its own VT controller. The VT controller for the two batteries are "OR'ed" together, resulting in parallel battery charging controlled by the first battery which hits the VT limit. When the Ampere Hour Integrator has determined that the batteries are at the ground selected Charge-to-Discharge (C/D) ratio, the SPRU goes into Constant Current Mode of 0.75 A (0.375 A/battery) to limit the overcharging of the batteries. Constant Current Mode can also be used when first entering sunlight to limit the maximum current being applied to the batteries. There are seven ground selectable constant current charge levels: 48.0, 24.0, 12.0, 6.0, 3.0, 1.5, and 0.75 A.

The SPRU autonomously transitions to a Standby Mode when the Solar Array voltage falls below 44 V

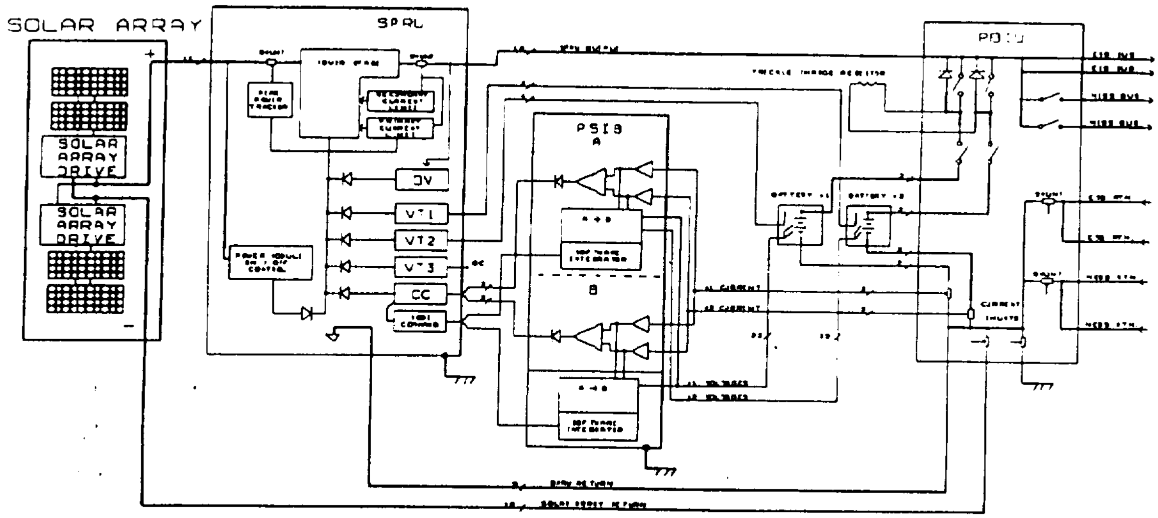

Figure 1: TRMM Power System Block Diagram

(generally during eclipse). The SPRU will remain in the Standby Mode until the solar array reaches 53.5 V. During the Standby Mode the spacecraft is powered via the batteries. The PSE also contains the circuitry to support in-orbit battery reconditioning and provides individual battery cell voltage monitoring. The PSE interface with the Flight Data System via a 1773 bus.

Battery

The TRMM spacecraft uses two 50 Ampere Hour (Ah) Super NiCd batteries (Figure 2). The batteries were sized to support a maximum 25 % Depth-of-Discharge (DOD) load. The actual on-orbit load has been averaging 15 % DOD. The 50 Ah Super NiCd battery design has been used before by NASA/GSFC on the Bruno B. Rossi X-ray Timing Explorer (RXTE). The batteries are capable of operating at - 5 to + 25 degrees C for 21,000 cycles in a Low Earth Orbit (LEO). The batteries were designed, fabricated, and tested by Hughes Space and Communications (HSC) of Torrance, California.

Battery and Cell Design

The 50 Ah Super NiCd battery consists of 22 hermetically sealed prismatic cells with dual ceramic seals. The cells were manufactured by Eagle Picher Technology (EPT) of Colorado Springs, Colorado. The Super NiCd cell design consists of polybenzimidazole (PBI) impregnated zircar separator, electrochemically deposited plates, and a 31 % potassium hydroxide electrolyte with HSC proprietary additive.

The 50 Ah Super NiCd battery has the dimensions of 25.4 cm x 30.5 cm x 49.5 cm (10 in x 12 in x 19 in), and weighs 59.54 Kg (131 lbs.). Each battery has 3 connectors (test, signal, and power) on an angled bracket on the end panel (See Figure 2). The angled bracket shortens the battery envelope and reduces the spacecraft harness runs. During ground operations, the test connector is used for monitoring cell voltages and temperature, and for trickle charging the battery prior to flight. The test connector is only used for ground operations, and is capped for flight. The signal connector is used for monitoring total battery voltage, battery temperature, and individual cell voltages in flight. Both the signal and the test connectors are fused to protect the battery and each cell from being inadvertently shorted by ground support

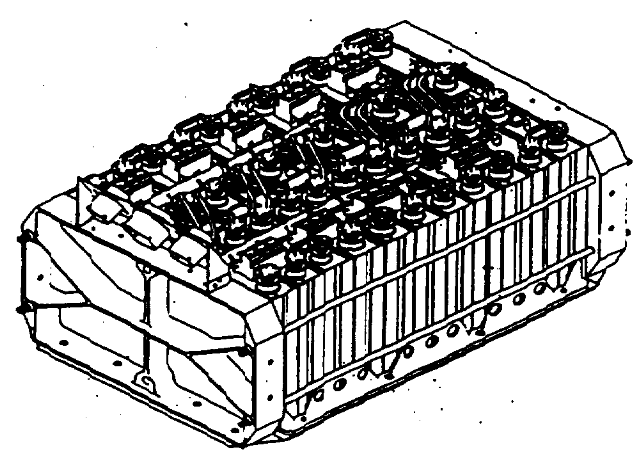

Figure 2: TRMM 50 Ah Super NiCd Battery

equipment.

The thermal sensors consist of one platinum temperature transducer and one thermistor mounted in the center of the battery, while another platinum temperature transducer and three thermistors are mounted on top of the battery. The transducers are used for charge control and the thermistors are used for telemetry.

Battery Fabrication

Eight 50 Ah Super NiCd batteries were procured from HSC for the RXTE and the TRMM programs: one qualification, one Integration and Test (I&T), and 6 flight batteries. The RXTE spacecraft was launched in December 1995, and the TRMM spacecraft in November 1997. Each spacecraft used two flight batteries.

This battery design was first implemented on the EPT Lot 1 cells, which formed the qualification battery Serial Number (SN) 001. The EPT Lot 2 cells were built into two flight batteries, SN 002 & SN 003.

The SN 002 battery developed a short on one cell during the Acceptance Test (AT). The anomaly was caused by bent electrodes at the lower corner of one of the cells, resulting in a mechanical short. Subsequently, HSC developed an X-ray Imaging Technique to screen SN 002 and SN 003 batteries and their spare cells for bent electrodes. The defective cells were found and replaced in SN 002 battery with x-ray screened flight spare cells, and SN 002 battery successfully repeated AT. Both batteries were then placed on trickle charge storage.

A corrective action consisting of radiographic examination of cells and modifying plate packaging technique was taken at the cell manufacturer (EPT) to preclude this anomaly from recurring. The EPT Lot 3 cell build was accelerated due to the anomaly seen in the Lot 2 batteries. The Lot 3 cells, which were x-ray screened prior to the cell buy off, were built into flight batteries SN 004 and SN 005. Due to the RXTE launch schedule, the Lot 3 batteries were used as the flight batteries on RXTE. Because of the AT anomaly, Lot 2 batteries were considered as the RXTE flight spares, pending successful completion of mission and stress cycling tests.

Similarly, the remaining Lot 1 cells were built into the TRMM I&T battery SN 006, and Lot 4 cells were built into two flight batteries SN 007 and SN 008. SN 008 had a 9.2 % lower capacity at 0 degrees C than the SN 007 battery. The loss of capacity may be due to the growth of cadmium crystals associated with low rate charging and high rate discharging. These cells recovered capacity (temporarily) when cycled in LEO simulations. The Lot 2 batteries were designated as the TRMM flight batteries because of their excellent ground test history including successful completion of mission and stress cycling tests (see the Cell Life Cycle Testing section and Table 2). The Lot 4 batteries were designated as the TRMM flight spares.

Battery Ground Testing

Once the batteries are delivered to GSFC from the manufacturer, the batteries undergo additional testing. This testing consists of capacity test and LEO cycling at various VT levels to determine the optimum VT level for the actual spacecraft load. Once the testing is completed, the batteries are placed in cold storage until the spacecraft need date. Cold storage consists of a fully charged battery being trickle charged at a rate of C/100 at 0 +/- 3 degrees C. If the batteries will be needed before 90 days, the charged batteries are kept on C/100 trickle charge or open circuit at 18 +/- 5 degrees C.

Once the 50 Ah Super NiCd batteries are integrated into the spacecraft, they are also kept on either C/100 trickle charge or open circuit at 18 +/- 5 degrees C. When the batteries are stored open circuit, they receive a top off charge every 4 to 7 days. The top off charge consists of discharging the batteries for 5 minutes at a rate of 1 to 2 A, followed by a 2.5 A charge to a peak voltage point plus 30 minutes.

The Lot 1 batteries were used for integration and testing at the spacecraft level at GSFC. The flight batteries needed to be integrated to the spacecraft at GSFC prior to shipment to the launch site in Japan. This was going to exceed the 14 day open circuit stand limit recommended by HSC. The predicted open circuit stand for the batteries during shipment was up to 30 days. Since the batteries may lose capacity during open circuit stand, an open circuit stand capacity test was conducted on 6 spare cells at COMSAT Laboratories in Clarksburg, Maryland.

Table 1 shows the result of the discharged 30 day open circuit battery storage tests. Separate two cell sets were stored at 0 degrees C, at 10 degrees C, and at 28 degrees C. Each cell's capacity was measured prior to storage and after a storage period of 30 days at 0 C, 10 C, and 20 C. The test was then repeated.

Although all cells lost about 2 Ah of capacity after the initial 30 day storage, the cells stored at 0 C and 10 C actually gained most of the lost capacity after the second storage period. TRMM batteries predicted flight temperature was 10 C. The cells stored at 28 degrees C lost capacity after the first storage period for the 0 C, 10 C, and the 20 C tests. After the second storage period, one of the cells stored at 28 C had a 0.2 % higher capacity for the 10 C capacity test. The other cell stored at 28 C had a 1.3

% lower capacity for the 10 C capacity test. Because these losses and gains were within the tolerance of the capacity measurements, the open circuit stand did not have significant detrimental affect on this particular lot of cells. Based on this data, the decision was made to ship the batteries integrated into spacecraft discharged open circuit at less than 28 degrees C. They arrived at the launch site and were recharged within 12 days.

After arrival at the launch site, the batteries were charged and placed on trickle charge. Also, the batteries were reconditioned within 14 days prior to launch. The performance of the flight batteries was nominal during ground operations.

Table 1: Open Circuit Stand Capacity Test Data

	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
Storage Temp	0 C	0 C	10 C	10 C	28 C	28 C
Initial Test						
20 C	59.8	59.2	58.9	58.9	59.3	59.3
10 C	61.7	61.3	60.8	61.0	61.1	61.3
0 C	62.6	62.1	61.6	61.9	61.9	62.1
After 30 Days Storage						
20 C	57.8	57.7	57.4	57.5	56.8	56.7
10 C	59.6	59.4	58.9	58.7	56.8	57.0
0 C	60.9	60.5	59.9	59.6	57.7	58.2
After Second 30 Day Storage						
20 C	57.0	56.7	56.8	56.8	55.9	55.9
10 C	63.6	62.9	62.5	63.1	61.2	60.5
0 C	65.0	64.2	63.7	63.9	62.1	61.3

Cell Life Cycle Testing

7 different cell packs from the 50 Ah Super NiCd RXTE/TRMM battery lots have been life cycle tested (See Table 2). Packs "Q", "M" and "S" were tested at COMSAT Laboratories, and the packs 0052T, 0053T, 6151T, and 6152T were tested at Naval Surface Warfare Center in Crane, Indiana. Each lot was tested for a stress test and either RXTE's or TRMM's predicted mission profile. The Lot 1 pack, "Q", was tested for a stress test of 50 % DOD and two pseudo-mission profiles of 10 % and 25 % DOD. Table 2 shows the life cycle packs and their status as of November 1, 1998.

It is noteworthy that the Pack # 0053T is made up of the removed cells from the SN 002 battery. After the AT anomaly but prior to rework, these cells were stress tested at 50 % DOD at 20 degrees C for 4,500 cycles. Upon successful completion of the stress test, they were placed on the predicted TRMM mission profile of 17 % DOD at 0 degrees C. They have successfully completed 13,320 mission profile cycles for a total of over 17,800 cycles, and are still being LEO cycled. This is equivalent to approximately the TRMM mission life of 3.5 years.

In-Orbit Performance

The TRMM spacecraft was launched on November 27, 1997. Initially, the batteries were charged using Peak Power Tracking. When the batteries entered sunlight, they were charged at a rate of 45 A per battery until they hit the VT 5 limit (31.6 V @ 10 degrees C). Then, the battery current tapered until reaching a C/D ratio of 1.045. When the batteries reached 1.045, the current was reduced to a constant current of 0.375 A per battery. The battery DOD has ranged between 14 and 17 percent. The battery temperature range is 5.8 to 10.8 degrees C for Battery 1, and 8.8 to 12.2 degrees C for Battery 2. The difference in temperature between the two batteries is due to the different radiator path of the two batteries.

A few days after launch, Battery 2 cell #1 voltage began diverging from the other cells. 40 days after launch, the cell voltage began to hit a high of 1.5 V. This is a divergence of 70 mV from the other cells. The Battery 2 Cell #1 voltage peaked at a maximum of 1.51 to 1.52 V approximately 60 days after launch. The peak occurs during peak power charge, peaking at the VT limit. As the battery charge current tapers, the voltage becomes aligned with the other cells in the battery (See Figure 3). The cause of the cell divergence is unknown. Ground test data was reviewed but it did not show any signs of similar anomalous behavior. But, similar divergence has been seen in flight on the RXTE spacecraft. The divergence on RXTE began about 8 months after launch.

The RXTE batteries have two cells that sometimes reach 1.5V during initial charging. This is a divergence of 50 mV from the remaining cells. The cell divergence peaks at the VT limit. As soon as the batteries hit the VT limit, the 1.5 V maximum starts to decrease until it is at the same level as the other cells. The peak occurs when the batteries are operated in VT 6. The higher the VT limit, the longer time the battery is in peak current charging. When the batteries are in VT 5 on RXTE, the 2 cells still diverge but they do not reach 1.5 V. This is because the VT limit is hit earlier and the peak voltage begins to taper back in alignment with the other cells. RXTE maximum charge current for each battery is 11 - 16 Amps at 10 degrees C. VT 6 mode is used minimally on RXTE in order to minimize the cell divergence. RXTE has

Table 2: 50 Ah Super NiCd LEO Cycling Test Data

PACK	Lot #	# Cells	DOD (%)	Temp (C)	C/D Ratio	VT Level	EOD V	Cycle #	Status
"Q"	1	10	10 25 50	0 0 0	1.03 1.04 1.11	7 7 7	1.24 1.19 1.13	11,800	Discont'd
"M"	2	5	14 25	11 10	1.07 1.06	5 5.5	1.218 1.19	5,521 14,857	Discont'd
"S"	2	5	40 50	20 20	1.11 1.09	6 7	1.175 1.146	985 16,000	Discont'd
0053T	2 (Reworkd)	4	50 17	20 0	1.10 1.08	6 6	1.137 1.199	4,502 13,320	Cycling
0052T	3	9	50 14	20 10	1.10 1.12	7 6	1.118 1.235	5,225 13,568	Cycling
6151T	4	5	25	10	1.08	5	1.181	11,537	Cycling
6152T	4	5	17	0	1.08	5	1.201	12,724	Cycling

not exceeded 1.5 V. The batteries are operating nominally.

On the TRMM spacecraft, steps were taken to inhibit the further increase in Battery 2 Cell # 1 peak voltage and to stabilize the batteries' performance. This included the following: On February 12, 1998 (67 days after launch), the VT limit was lowered from VT 5 to VT 4. Then, during the next orbit, the battery charging was changed from Peak Power Tracking Mode (PPT) to a Constant Current Mode (CCM) of 24. This lowered the battery initial charge rate from 45 A to 12 A per battery. But, because the PSE takes approximately 30 seconds to go into CCM when entering day, the batteries see a peak of about 28 - 45 A each for 30 seconds before going to the 12 A rate. This results in a transient cell voltage rise as shown in Figure 3. Also during this orbit, the C/D Ratio setting was lowered from 1.045 to 1.03. This is the ratio setting where the batteries are switched to 0.375 A trickle charge rate. The batteries' VT level was switched back to VT 5 six days later because a recharge ratio of 1.02 to 1.03 could not be maintained. This is the minimum C/D ratio required to insure proper battery charging.

These changes were implemented beginning 67 days after launch. These changes had no affect on the spacecraft and science operations. Since implementing these changes nine months ago, the Battery 2 Cell # 1 maximum voltage has not increased from 1.52 V except for one anomalous orbit (See Figure 4). The Battery 2 Cell # 1 voltage hit a peak of 1.62 V for one orbit when the spacecraft inadvertently went into load shed causing the PSE to be reset into PPT Mode of 50 Amps per battery. The PSE was reset during the next orbit into CCM and the cell voltage has not increased from 1.52 V. Since then, all the PSE safing software has been rewritten to put the PSE into CCM of 12 A per battery instead of PPT Mode.

The batteries are continuously monitored and trended. Figures 5 & 6 show the trended maximum and minimum battery voltage, and battery temperature since launch.

Summary

Except for the one cell voltage divergence anomaly, the batteries' performance has been nominal. The voltage divergence is being successfully managed by a change in the charging scheme. The TRMM Power System design is such that there is considerable flexibility in managing battery charging and for monitoring the health and status of the batteries. We believe that these batteries will successfully meet the mission lifetime requirement of 3.5 years.

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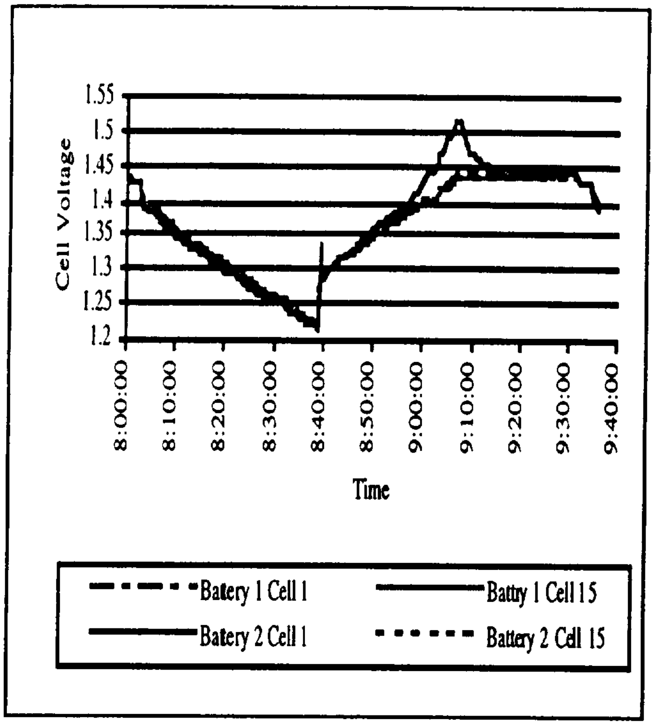

Figure 3: Individual Battery Cell Voltages for Orbit # 4980 (10/25/98)

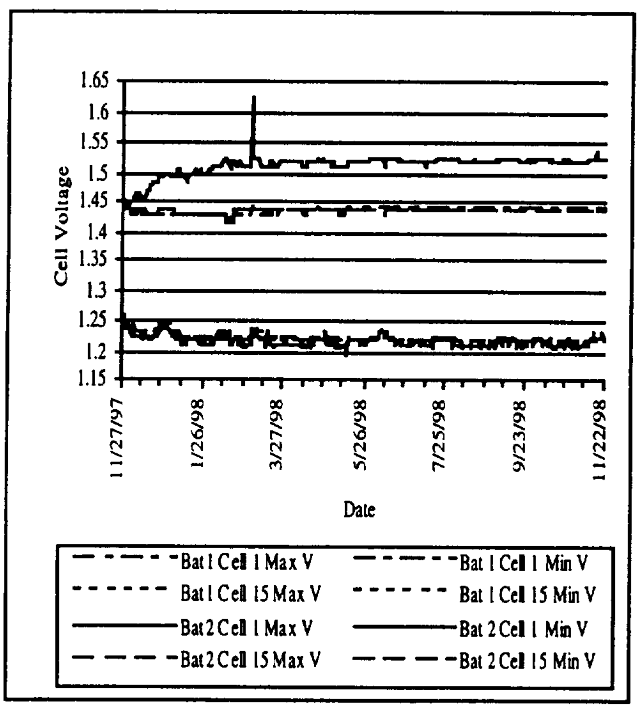

Figure 4: Battery 1 & 2 Cell Voltage Trend

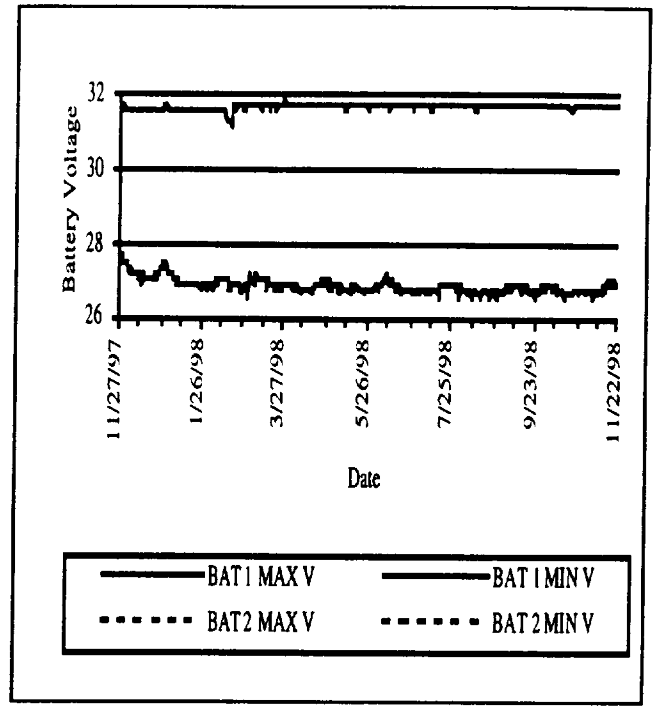

Figure 5: Maximum and Minimum Battery Voltages

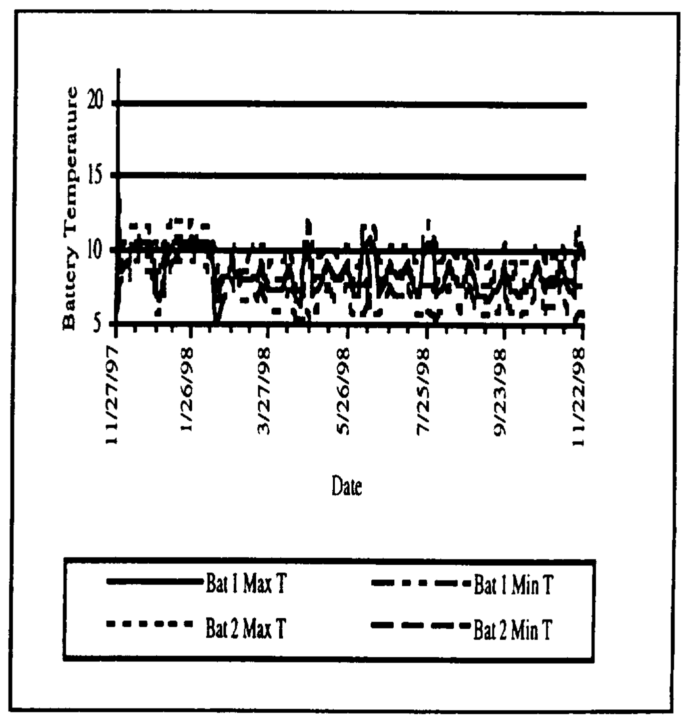

Figure 6: Battery 1 & 2 Maximum and Minimum Temperature