

Alternate Charging Profiles for the Onboard
Nickel Cadmium Batteries of the
Explorer Platform/ Extreme Ultraviolet Explorer

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ABSTRACT

The Explorer Platform/ Extreme Ultraviolet Explorer (EP/EUVE) spacecraft power is provided by the Modular Power Subsystem (MPS) which contains three 50 ampere-hour Nickel Cadmium (NiCd) batteries. The batteries were fabricated by McDonnell Douglas Electronics Systems Company, with the cells fabricated by Gates Aerospace Batteries (GAB), Gainesville, Florida.

Shortly following launch, the battery performance characteristics showed similar signatures as the anomalous performance observed on both the Upper Atmosphere Research Satellite (UARS) and the Compton Gamma Ray Observatory (CGRO). This prompted the development and implementation of alternate charging profiles to optimize the spacecraft battery performance. The Flight Operations Team (FOT), under the direction of Goddard Space Flight Center's (GSFC) EP/EUVE Project and Space Power Applications Branch have monitored and managed battery performance through control of the battery Charge to Discharge (C/D) ratio and implementation of a Solar Array (SA) offset. This paper provides a brief overview of the EP/EUVE mission, the MPS, the FOT's battery management for achieving the alternate charging profile, and the observed spacecraft battery performance.

INTRODUCTION

The EP/EUVE spacecraft was designed, built, and managed by NASA, GSFC. EP/EUVE is operated by NASA and Loral AeroSys with the primary payload, the Extreme Ultraviolet Explorer (EUVE), operated by the University of California at Berkeley. The Explorer Platform (EP) spacecraft design was based on the Multimission Modular Spacecraft (MMS). The platform can support a variety of remote sensing, Low-Earth-Orbit (LEO) missions requiring solar, stellar, or earth pointing missions. The EP provides a space based platform from which the explorer class instruments and equipment can be remotely exchanged during Space Shuttle-based servicing missions. The MMS structure supports the Platform Equipment Deck (PED), which serves as the EP interface to the payload. The payload module, currently EUVE, is mounted on the PED and the

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mission-unique equipment has been placed within removable PED modules. When EP was integrated with its payload module, EUVE, it became the mission-unique EP/EUVE satellite.

The EP/EUVE spacecraft was launched on a Delta II Expendable Launch Vehicle (ELV) from Cape Canaveral Air Force Station, Florida on June 7, 1992 into a circular orbit 528 km in altitude with an inclination of 28 degrees. The EUVE is a LEO astronomical survey mission that has produced the first definitive sky map and catalog in the portion of the electromagnetic spectrum that extends from approximately 100 to 1000 angstroms. Scientifically, the mission includes three objectives, all-sky survey, deep survey and spectroscopy. The all-sky survey and deep surveys were performed concurrently during the first 6 months of the mission and completed in January, 1993 with gap filling completed in July, 1993. The balance of the EUVE mission is being used for additional spectroscopy experiments.

During the two spacecraft modes of operation, the spacecraft orientation is defined as follows. In survey mode, the spacecraft maintains a constant rotation of 0.18914 +/- .00005 degrees per second. In spectroscopy mode the spacecraft will be inertially fixed such that the spacecraft is pointed within the design constraints of 0 to 110 degrees with respect to the $-X_{sc}$ axis and +/- 33 degrees with respect to the Command and Data Handling (C&DH) roll axis.

MODULAR POWER SUBSYSTEM

The EP/EUVE MPS is comprised of all the power control, distribution, regulation, provision, and other power-related hardware. This includes the McDonnell Douglas MPS and the two Solarex solar arrays. Figure 1 illustrates the subsystem interfaces.

The functions of the EP/EUVE major power subsystem components are presented in Table 1.

Table 1: EP/EUVE Major Power Subsystem Components

| Power Subsystem Component | Function |
|--------------------------------------|---|
| Bus Protection Assembly (BPA) | Fusing of internal MPS loads |
| 50 Ampere Hour Batteries (3) | Energy storage |
| Power Control Unit (PCU) | Power distribution |
| Remote Interface Unit (RIU) (2) | Command & Data Handling interface |
| Signal Conditioning Assembly (SCA) | Command and telemetry conditioning |
| Solar Arrays (2) | Energy conversion |
| Solar Array Drives (2) | Maintains solar array position as determined by the Solar Array Drive (SAD) flight software and commanded by the Solar Array Drive Electronics (SADE) |
| Solar Array Drive Electronics (2) | Monitors and commands the SAD movement as determined by the SAD flight software or ground issued commands |
| Standard Power Regulator Unit (SPRU) | Battery charge control |
| Thermal Control Subsystem | Battery system thermal regulation |

The batteries onboard the EP/EUVE spacecraft are three 50 amp-hour conventional NiCd batteries in parallel configuration. Each battery contains 22 serially connected cells. The plates were fabricated at GAB during the 1/85 to 5/85 time period. The cells were activated in March 1988.

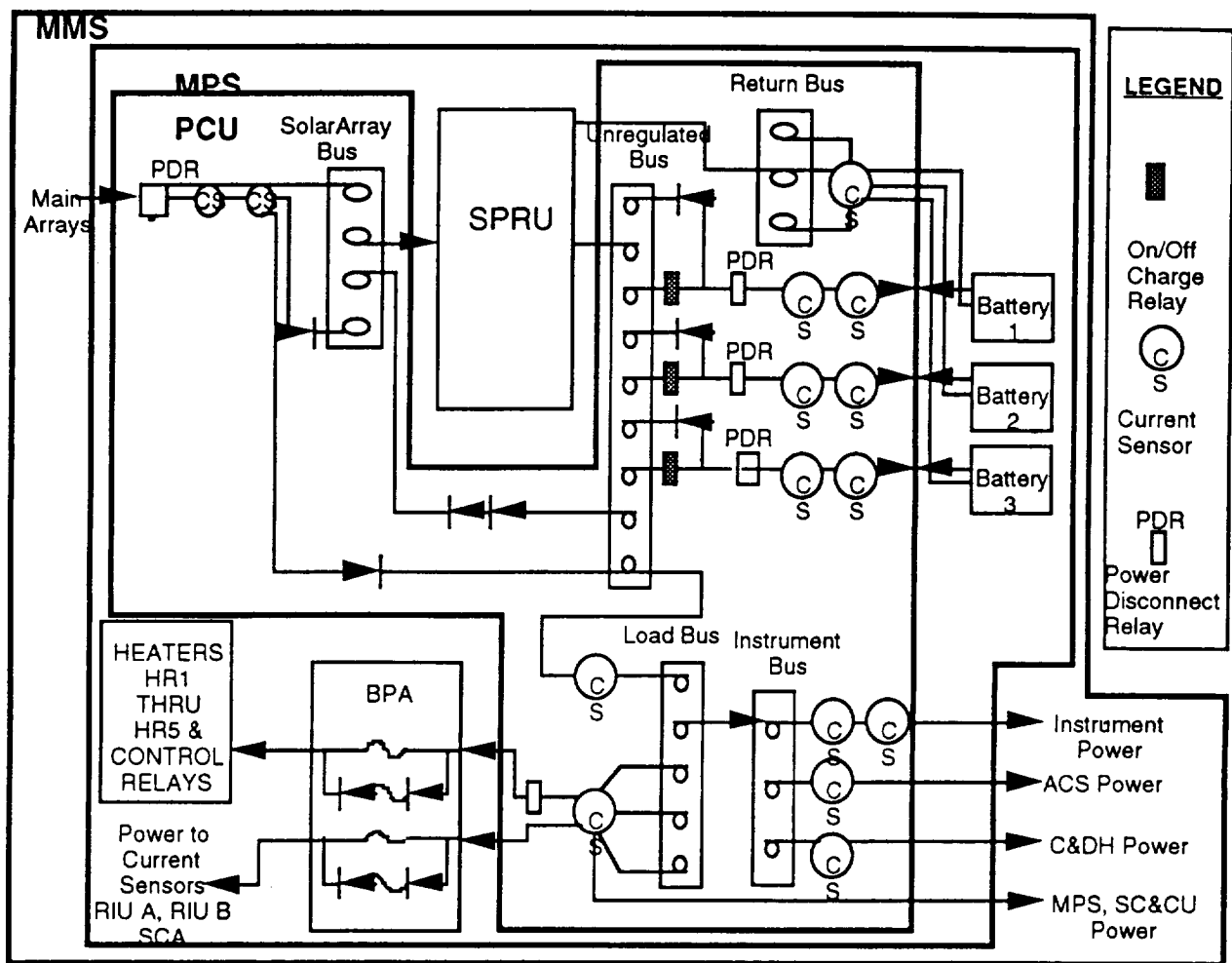


Figure 1: EP/EUVE Power Block Diagram

POWER SUBSYSTEM OPERATIONS

The MPS operations have evolved on-orbit to rely heavily on various SPRU modes of operation. The modes of SPRU operation are discussed in Table 2.

EARLY MISSION OPERATIONS

At launch, the Voltage Limit Mode of SPRU was set at V/T level 5; however, the level was commanded to V/T level 4 on launch day based on the observed high average C/D ratio values (1.286, 1.241 and 1.224 for batteries 1, 2 and 3, respectively). The level was later lowered to V/T level 3 on May 5, 1993 to further reduce the C/D ratio.

Thermostat control was also implemented during early mission operations. MPS battery temperature regulation was implemented to maintain a specific battery temperature operating range greater than the thermistor set points for the battery heater controls. This can be performed on the EP spacecraft because the MPS configuration includes an externally mounted heat pipe implementation that maintains a stable thermal environment between all three batteries. Current operation maintains a battery baseplate temperature of greater than 5 degrees C and less than 8 degrees C. This temperature range is maintained through Onboard Computer (OBC) Telemetry Monitor (TMON) control. The original operational implementation was introduced on September

8. 1992 based on a temperature goal of 2 degrees C. This goal was changed, in steps, to the current operational temperature range on October 23, 1992. The battery temperature trends for the length of the mission is presented in Figure 2. This thermostat control showed no appreciable impact on the battery charge profile.

Table 2: SPRU Modes of Operation

| SPRU Modes of Operation | |
|--------------------------|--|
| Standby Mode | The MPS power is supplied by the batteries due to no available solar array power. The SPRU is able to receive commands and retains a memory of its last commanded state in this mode. |
| Peak Power Tracking Mode | The maximum SA output power point will be maintained to provide all available power to the spacecraft load and recharging the batteries until the Voltage-Temperature (V/T) set point is reached or the constant current mode is enabled. |
| Voltage Limit Mode | The battery voltage limit is determined by one of the eight commandable NASA standard V/T limits. When the battery terminal voltage rises to the limit, the battery current is reduced to a taper profile. |
| Current Limit Mode | The current limit is an externally commanded mode which limits the total battery charge current to one of the three selectable levels, 0.75 amps, 1.5 amps or 3.0 amps. |
| Safe Mode | In the event of three consecutive pulses being missed to the MPS Computer Status Monitor (CSM), the SPRU will be commanded to the appropriate V/T level based on the selected V/T level (currently V/T level 1). No external commanding will be allowed to the SPRU until the CSM has been disabled. |

CURRENT POWER OPERATIONS

The C/D ratio and the net overcharge of all three batteries remained higher than recommended for the batteries. This is due in part to the small loading requirements of the spacecraft and the large size of the SAs. Because the arrays were designed to support a 10-year Platform mission life integrated with EUVE and a variety of follow-on Explorer class Instruments, the available power to the payload was budgeted at 300 watts for an orbital average with peaks of 1000 watts. On-orbit EUVE payload power needs, however, have been an orbital average of 200 watts with peaks of 300 watts during both spectroscopy and survey modes.

The FOT currently utilizes three of the SPRU modes - the constant current mode, the peak power track mode and the voltage limited mode, on an orbital basis for nominal battery operations. These standard operational procedures for a single EP/EUVE orbit are presented in Figure 3.

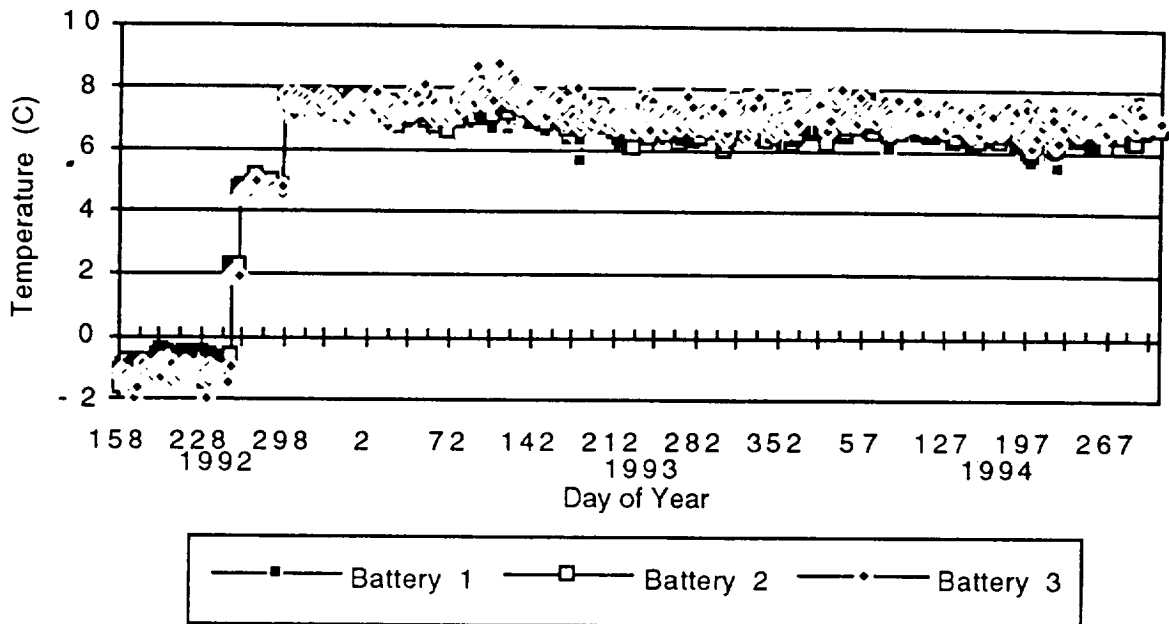


Figure 2: Mean Battery Temperatures for the Mission Life

Constant Current Mode at Orbital Sunrise

Constant Current Mode (CCM) at Orbital Sunrise (OS) was implemented to regulate the high battery charge current from the SAs when the arrays are cold. The operational goal has been about 20 amps. The onboard implementation uses the OBC Orbital Time Processor (OTP) flag 6 to trip when the spacecraft to sun vector cosine is -0.5 corresponding to an angle of 120 degrees. This equates to approximately 2 minutes prior to spacecraft day. The flag executes a Relative Time Sequence (RTS) that commands the SPRU to 3.0 amp CCM at orbital sunrise then returning the SPRU to V/T control approximately 10 minutes into day.

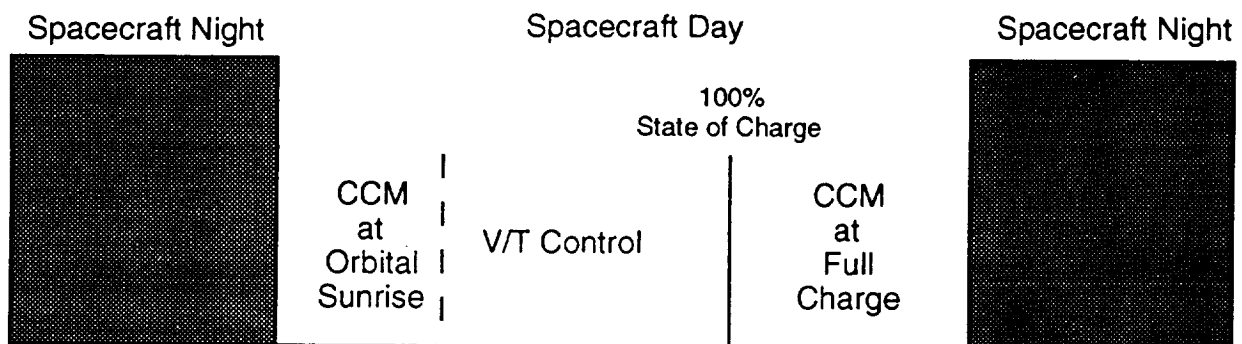


Figure 3: Standard EP/EUVE Orbital Battery Management

Constant Current Mode at Full Charge

CCM at full charge was implemented to minimize the batteries overcharge. Proactive steps have been taken to maintain a ground minus CCM calculated C/D ratio goal range of 1.02 to 1.07 and hence minimize the batteries overcharge. In this implementation, the SPRU commands 0.75 amp

CCM to maintain a trickle charge on the batteries while still in spacecraft day after the C/D ratio goal has been reached as determined through TMON sampling of the battery state of charge. The C/D Ratio goal is based on the assumption that when the battery reaches 100 percent state of charge at a specified 0.98 Power Monitor (PMON) processor battery charge efficiency, the C/D ratios approximate 1.02.

PMON battery efficiency changes

The PMON battery efficiency changes were implemented to stabilize the End-of-Night Load Bus Voltage (ENLBV), which was decreasing during extended maximum eclipse period. The PMON battery efficiency is decreased by 0.01 during the maximum eclipse period to allow additional charge on to the batteries while marginally increasing the C/D ratio by 1 percent. The CCM at full charge target C/D ratio may be changed by changing the Battery 1, 2, and 3 charge efficiencies in the PMON processor via OBC system table load. This is routinely being performed by changing the target C/D ratio. The efficiency is set to 0.97 for spacecraft eclipse periods of greater than 34.5 minutes and set to 0.98 for eclipse periods less than 34.5 minutes. The PMON efficiency changes are presented with the length of spacecraft day in Figure 4.

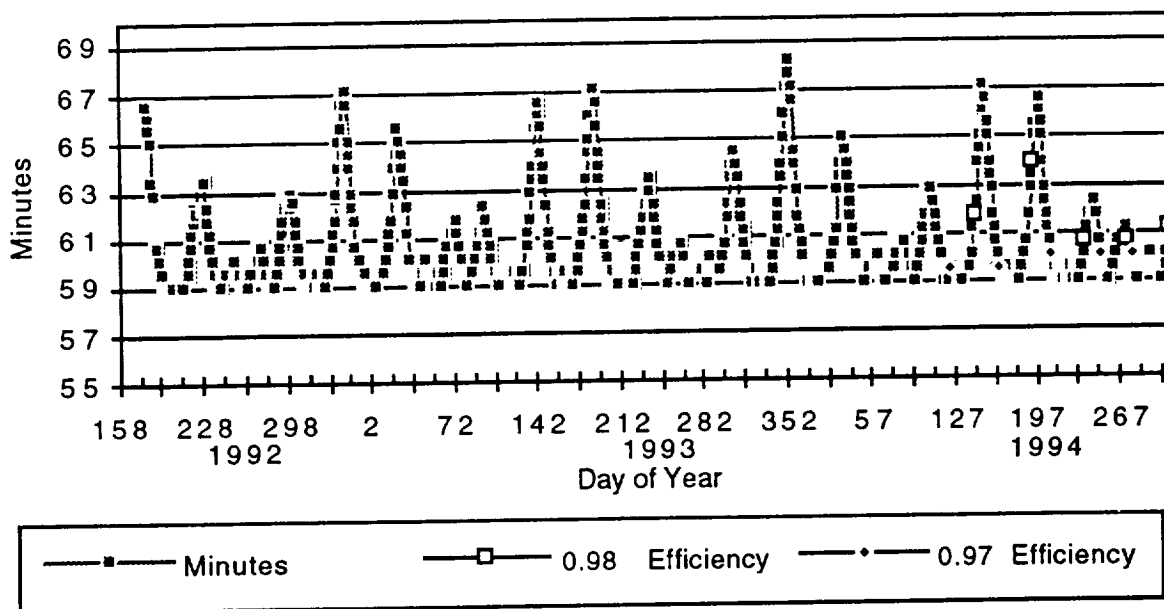


Figure 4: Length of Spacecraft Day for the Mission Life

Solar Array Offset

The SADs remained powered off during the first 13 months of the EP/EUVE mission, In-Orbit Checkout (IOC), survey, and 6 months of inertial point mode. Then, following the completion of the gap fill-in portion of the all sky survey in July 1993, the SADs were validated during a mini-IOC. Two SA hardware limitations, specular reflection and an Extra Vehicular Activity (EVA) handrail, were identified during the validation. The spacecraft body, specifically the Signal Conditioning and Control Unit (SC&CU), reflects sunlight onto the solar array panel 1. This causes heating of the panel in the vicinity of thermistor 3 to the solar panel red high temperature

qualification limit, 114 degrees C. Additionally, an EVA handle prevents the movement of solar array 2 past 83 degrees $-X_{acs}$, limiting the range of possible SA motion. A flight software change has been implemented which will maintain the solar arrays at a table-defined offset. This flight software implementation repositions the SAs to the offset position, currently 40 degrees to avoid specular reflection, taking into account the EVA handrail limitations, when the spacecraft slews to a new target. The change in the spacecraft attitude may be seen in the effective solar array offset (figure 5).

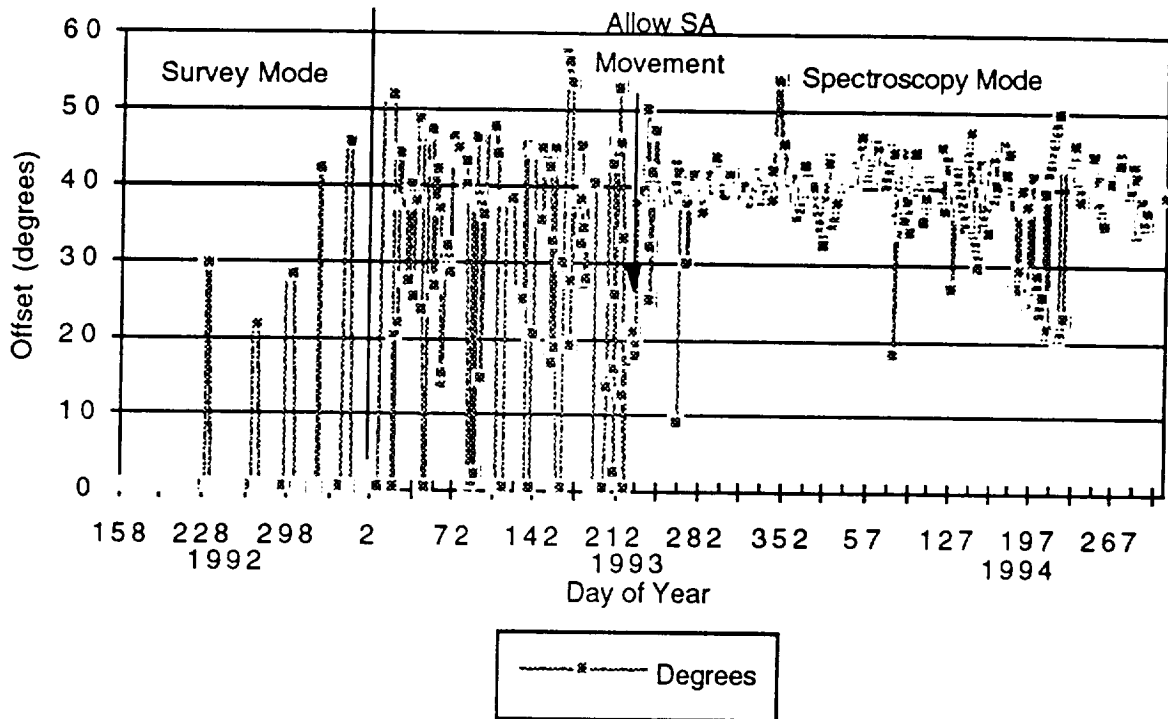


Figure 5: Effective Solar Array Offset for the Mission Life

DATA

With the implementation of CCM and SA offset management, the charge-to-discharge ratios have decreased for the length of the mission (figure 6). The average IOC C/D ratios (including CCM) of 1.08 to 1.09 in comparison with the current values of 1.06 to 1.07 showing an improvement of 2 percent for batteries 1 and 2 and of 1.5 percent for battery 3. The battery C/D ratios show stable in-family trending of high numbers during the survey portion of the mission with the SA position constantly normal to the sun. The C/D ratios diverged in January 1994 with the spacecraft transition to inertial point mode and the introduction of CCM at OS. During this mission phase, the SADs remained fixed, while the spacecraft changed pointing positions throughout the sky on a daily and sometimes orbital basis. This varied the effective SA offset to the sun from 0 to 55 degrees, and thus varied the available solar array current to the batteries. Two operational events, a deep discharge of the batteries (24.5%) on June 17, 1993 (DOY 168) and the implementation of a constant 40 degree SAD offset on August 6, 1994 (DOY 218), have contributed to the stable and lower C/D ratio values seen since June of 1993.

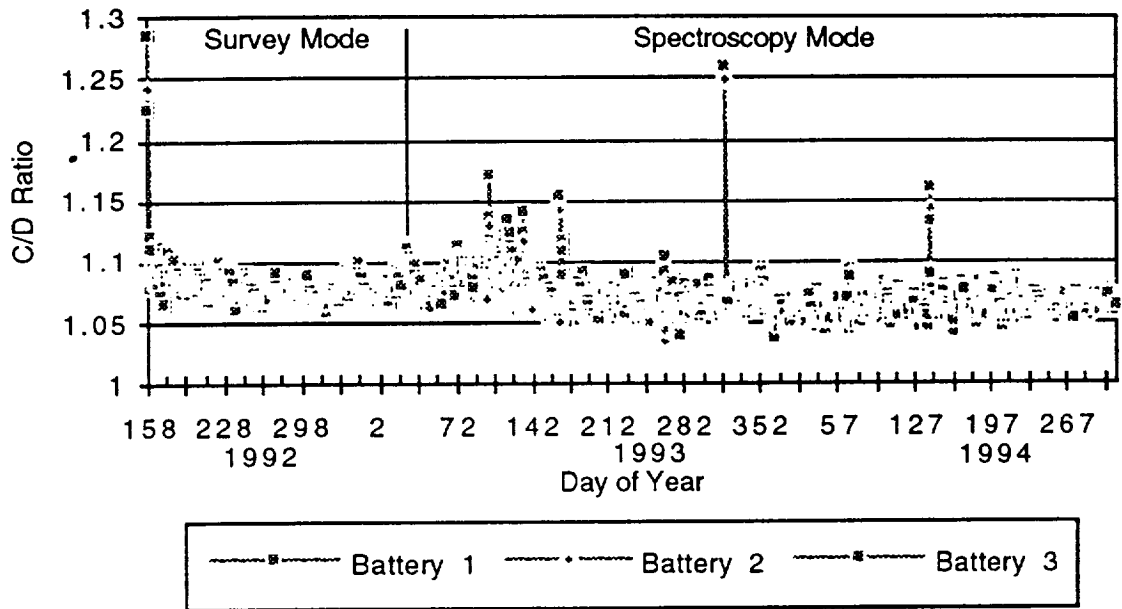


Figure 6: C/D Ratio for the Mission Life

Half battery differential voltages for batteries 1, 2, and 3 are presented in Figure 7. The battery differential voltages showed similar degraded features with all three batteries crossing zero as the spacecraft to inertial point mode. An improvement is evident in all three half battery differential voltages. The half battery differential voltages for battery 1 continues to near zero, while batteries 2 and 3 are approaching toward zero.

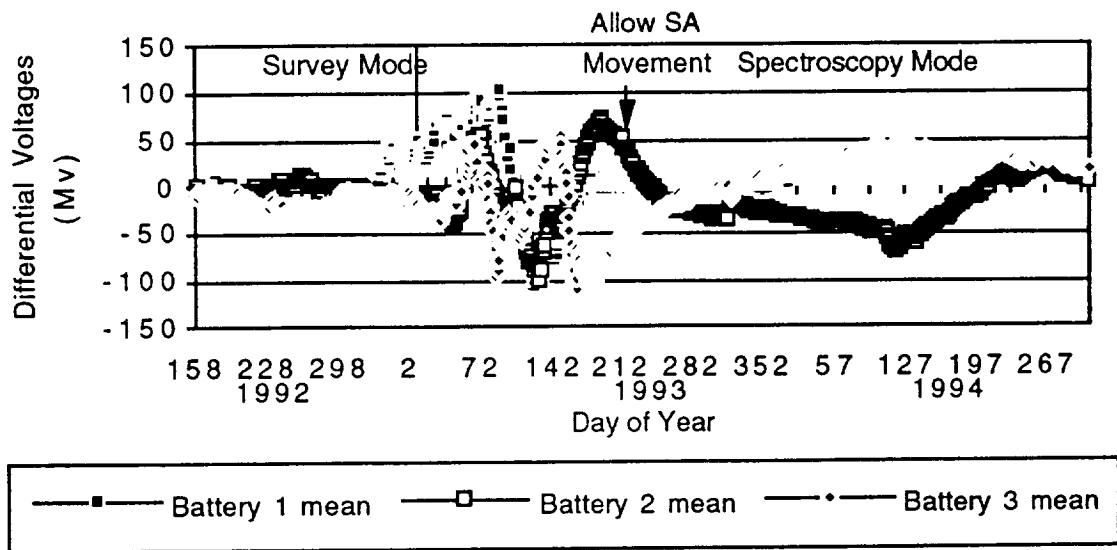


Figure 7: Half Battery Differential Voltages for the Mission Life

A significant improvement in the end-of-night load bus voltage is apparent from Figure 8 for the last six months. The end-of-night load bus voltage has been approximately 26.88 volts for this period.

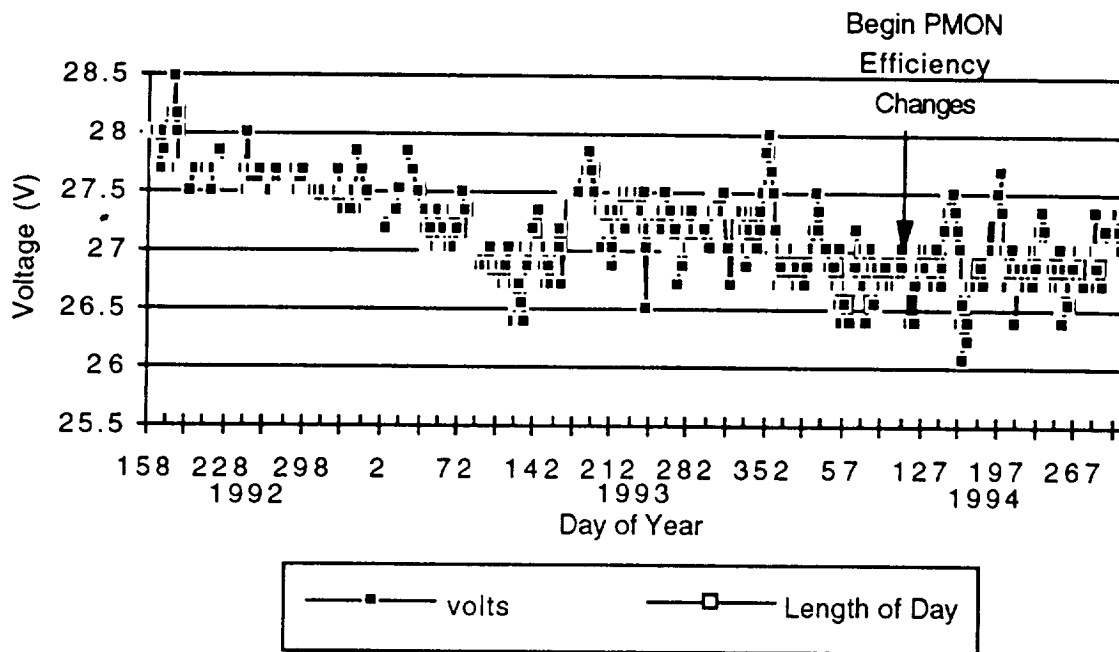


Figure 8: End-of-Night Load Bus Voltage for the Mission Life

CONCLUSIONS

The constant current mode implementation successfully limits the C/D ratio to a specified goal. This has been enhanced by the use of the battery efficiency change which allow the end of night load bus voltage to stabilize about 26.88 volts during periods of maximum eclipse. The 40 degree solar array offset maintains a battery current input between 13 amps and 20 amps. The implementation of the CCM charge control, PMON efficiency change, and the SA offset have optimized battery operation for the EP/EUVE spacecraft.

**DATABASE FOR MANAGEMENT OF THE UPPER
ATMOSPHERE RESEARCH SATELLITE'S
BATTERIES**

**Presented to
1994 NASA AEROSPACE BATTERY WORKSHOP**

**By
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BACKGROUND

- **UPPER ATMOSPHERE RESEARCH SATELLITE (UARS)** launched on space shuttle discovery on September 12, 1991 for a nominal 36-month mission
- 96-minute LEO orbit inclined 57 degrees to the equator (results in at least two full-sun periods per year)
- Spacecraft built by General Electric (now Martin Marietta) and incorporates Multimission Modular Spacecraft (MMS)

BACKGROUND - continued

- **Maximum spacecraft load was projected as 1600 watts**
- **The MMS design utilizes the Modular Power Subsystem (MPS) built by McDonnell Douglas**
- **The MPS contains three NASA Standard 50 Ah Nickel Cadmium batteries in a parallel configuration**
 - **batteries contain 22 series-connected cells**
 - **battery instrumented to measure the voltage difference between the first 11 cells in series and the second 11 cells in series (differential voltage)**
- **The MPS also contains a NASA Standard Power Regulator Unit (SPRU) that employs NASA Standard VT levels and constant current modes for the charging of batteries**

CHRONOLOGY

- **9/91.** Power system configuration - VT 6 to 1.11 C/D ratio, then trip to VT 5
- **12/91:** First full-sun period
- **1/92:** Differential voltage on all three batteries becomes non-zero, exceeding 50 mV; switch to full-time use of VT 5
- **3/92:** Differential voltages exceed 150 mV; switch to VT 4
- **4/92:** Differential voltages exceed 300 mV

Raising VT level from 4 to 5 causes differential voltages to exceed 400 mV and temperature spread between battery 1 (inboard - facing earth) and battery 2 (outboard - facing space) diverged from nominal value of 3 °C to almost 8 °C

CHRONOLOGY - continued

- 4/92 (cont.) Return to VT 4 reduced spread in temperature; Battery heater thermostats bypassed to raise nominal battery temperatures $\sim 4^{\circ}\text{C}$, to a nominal value of 5°C
- 5/92: Solar array drive anomalies caused Solar array to be parked at “spacecraft noon”; load partially shed as battery charging (and spacecraft operation) is temporarily altered to a cosine power curve
- 7/92: Solar array drive restarted; median value of battery differential voltages now different by as much as 500 mV from two months before

CHRONOLOGY - continued

- **8/92: Incorporation of Solar Array offset to limit charge currents at spacecraft sunrise below 25 amps per battery**
- **12/92: Introduction of a deep conditioning discharge on batteries during full-sun periods - average DOD this first time was 31%; first use of VT 3 for shallow DOD periods**
- **3/93: Introduction of the use of a constant current charge mode at the end of spacecraft day to control C/D ratio**

CHRONOLOGY - continued

- **6/93: Second full-sun deep conditioning discharge**
 - Deep discharges were conducted on two consecutive days and approached 40% DOD on the second day
 - Artificial eclipses between 10% and 20% DOD were also accomplished on the days before and after the deep discharges
- **12/93: Third full-sun deep conditioning discharge**
 - Deep discharges were conducted on two consecutive days and approached 36% DOD on the second day
- **6/94: Fourth full-sun deep conditioning discharge**
 - Deep discharges were conducted on two consecutive days and approached 32% DOD on the second day

DATABASE

- **Data accumulation began in April 1992 and continues to this day**
- **Data presented in this paper is limited to 1994**
- **The database consists of 27 ground-processed telemetry values and focuses on daily averages and/or daily ranges:**
 1. **Daily average Beta Angle (degrees)**
 2. **Daily average battery Net Charge (Amp-minutes) (3)**
 3. **Daily average battery discharge (Amp-minutes) (3)**
 4. **Daily maximum battery discharge (Amp-minutes) (3)**
 5. **Daily average C/D ratio (3)**
 6. **Daily maximum discharge current (Amps) (3)**

DATABASE - continued

- **Telemetry values (continued):**
 7. Daily average end-of-night load bus voltage (V)
 8. Minimum battery differential voltage (mV) (3)
 9. Maximum battery differential voltage (mV) (3)
 10. Daily average battery temperature ($^{\circ}$ C) (3)
 11. Daily average maximum charge current (Amps)
- **There are also 11 trend values derived from the ground-processed telemetry:**
 12. Load-sharing differential between battery 1 and battery 2 (Amp-minutes - from daily average load and daily maximum load) (2)

DATABASE - continued

- **Trend values (continued):**
 13. **Average battery depth of discharge (Amp-minutes - from daily average and daily maximum) (2)**
 14. **Median battery differential voltage (mV - average of daily max and daily min) (3)**
 15. **Differential voltage span (mV - difference between daily max and daily min) (3)**
 16. **Temperature spread between battery 1 & 2 (°C)**
- **All of the data is entered into an Excel© spreadsheet along with Day of year, Mission Day #, the VT level, the C/D ratio goal (if Constant Current Mode is being used) and operational "Notes"**

Sample of UARS Flight Battery Database

| | A | B | C | D | E | F | G | H | I | J | K | L | M |
|-----|-------------|------|-----|------|------|------|------|---------|---------|---------|-------|--------|-------|
| | MISSION DAY | YEAR | DOY | BETA | NET1 | NET2 | NET3 | DISCHG1 | DISCHG2 | DISCHG3 | DI-D2 | AVGDOD | CD1 |
| 150 | 963 | 1994 | 121 | 29.9 | 19.2 | 5.2 | 14 | 517 | 476 | 484 | 41 | 16.4% | 1.037 |
| 151 | 964 | 1994 | 122 | 32.3 | 17.5 | 3.2 | 12 | 510 | 469 | 477 | 41 | 16.2% | 1.034 |
| 152 | 965 | 1994 | 123 | 34.5 | 13.8 | 0.9 | 9.4 | 513 | 462 | 476 | 51 | 16.1% | 1.027 |
| 153 | 966 | 1994 | 124 | 36.3 | 24.2 | 11.4 | 19.6 | 500 | 453 | 466 | 47 | 15.8% | 1.048 |
| 154 | 967 | 1994 | 125 | 37.8 | 26.4 | 10.4 | 19.3 | 482 | 455 | 459 | 27 | 15.5% | 1.055 |
| 155 | 968 | 1994 | 126 | 38.9 | 27.2 | 10 | 19 | 478 | 451 | 456 | 27 | 15.4% | 1.057 |
| 156 | 969 | 1994 | 127 | 39.5 | 27.6 | 9.9 | 18.8 | 475 | 448 | 453 | 27 | 15.3% | 1.058 |
| 157 | 970 | 1994 | 128 | 39.8 | 27.3 | 8.9 | 17.9 | 477 | 448 | 453 | 29 | 15.3% | 1.057 |
| 158 | 971 | 1994 | 129 | 39.5 | 25.5 | 7.3 | 16.2 | 496 | 457 | 468 | 39 | 15.8% | 1.051 |
| 159 | 972 | 1994 | 130 | 38.9 | 27.7 | 8.5 | 17.9 | 520 | 479 | 491 | 41 | 16.6% | 1.053 |
| 160 | 973 | 1994 | 131 | 37.8 | 29.7 | 9.5 | 19 | 519 | 482 | 492 | 37 | 16.6% | 1.057 |
| 161 | 974 | 1994 | 132 | 36.3 | 30.3 | 9.7 | 19.2 | 522 | 485 | 495 | 37 | 16.7% | 1.058 |
| 162 | 975 | 1994 | 133 | 34.4 | 30.5 | 9.7 | 19.3 | 529 | 493 | 502 | 36 | 16.9% | 1.058 |
| 163 | 976 | 1994 | 134 | 32.2 | 31 | 9.9 | 19.4 | 533 | 497 | 506 | 36 | 17.1% | 1.058 |
| 164 | 977 | 1994 | 135 | 29.7 | 30.1 | 9.1 | 18.7 | 544 | 507 | 517 | 37 | 17.4% | 1.055 |
| 165 | 978 | 1994 | 136 | 27 | 29.8 | 9 | 18.6 | 554 | 516 | 527 | 38 | 17.7% | 1.054 |
| 166 | 979 | 1994 | 137 | 24 | 28.4 | 7.4 | 17.1 | 564 | 525 | 536 | 39 | 18.1% | 1.050 |
| 167 | 980 | 1994 | 138 | 20.9 | 37.5 | 13.1 | 22.8 | 570 | 526 | 539 | 44 | 18.2% | 1.066 |
| 168 | 981 | 1994 | 139 | 17.5 | 30.6 | 6 | 15.9 | 545 | 513 | 518 | 32 | 17.5% | 1.056 |
| 169 | 982 | 1994 | 140 | 14 | 31 | 8.5 | 18.1 | 541 | 508 | 514 | 33 | 17.4% | 1.057 |
| 170 | 983 | 1994 | 141 | 10.4 | 30.4 | 7.7 | 17.8 | 549 | 514 | 522 | 35 | 17.6% | 1.055 |
| 171 | 984 | 1994 | 142 | 6.7 | 31.4 | 8.7 | 18.6 | 555 | 520 | 527 | 35 | 17.8% | 1.057 |
| 172 | 985 | 1994 | 143 | 2.4 | 32.7 | 11 | 20.6 | 550 | 514 | 521 | 36 | 17.6% | 1.059 |
| 173 | 986 | 1994 | 144 | 1 | 34.1 | 9.7 | 19.2 | 525 | 495 | 498 | 30 | 16.9% | 1.065 |
| 174 | 987 | 1994 | 145 | 5 | 33.2 | 9.4 | 19.2 | 552 | 518 | 524 | 34 | 17.7% | 1.060 |
| 175 | 988 | 1994 | 146 | 9 | 32.3 | 8.1 | 18 | 547 | 513 | 520 | 34 | 17.6% | 1.059 |
| 176 | 989 | 1994 | 147 | 13.1 | 31.9 | 8 | 18 | 544 | 509 | 516 | 35 | 17.4% | 1.059 |
| 177 | 990 | 1994 | 148 | 17.2 | 33.9 | 8.8 | 18.5 | 538 | 503 | 510 | 35 | 17.2% | 1.063 |
| 178 | 991 | 1994 | 149 | 21.4 | 34 | 8.4 | 17.8 | 534 | 498 | 505 | 36 | 17.1% | 1.064 |
| 179 | 992 | 1994 | 150 | 25.6 | 35.5 | 9 | 18.4 | 524 | 490 | 496 | 34 | 16.8% | 1.068 |
| 180 | 993 | 1994 | 151 | 29.2 | 30.9 | 3.4 | 12.7 | 508 | 475 | 480 | 33 | 16.3% | 1.061 |
| 181 | 994 | 1994 | 152 | 34.1 | 29.2 | 7.5 | 15.2 | 479 | 440 | 450 | 39 | 15.2% | 1.061 |
| 182 | 995 | 1994 | 153 | 38.3 | 29.5 | 8 | 15 | 470 | 430 | 440 | 40 | 14.9% | 1.063 |
| 183 | 996 | 1994 | 154 | 42.6 | 30.2 | 8 | 15.4 | 451 | 416 | 424 | 35 | 14.3% | 1.067 |

Sample of UARS Flight Battery Database

| | C | N | O | P | Q | R | S | T | U | V | W | X | Y |
|-----|-----|-------|-------|-------|-------|-------|----------|-----------|------|------|------|--------|--------|
| | DOY | CD2 | CD3 | MAXDI | MAXD2 | MAXD3 | MAXDI-D2 | AVGMAXDOD | | | | EONLBY | DVIMIN |
| 150 | 121 | 1.011 | 1.029 | 532 | 491 | 499 | 41 | 16.9% | 18.1 | 12 | 13 | 25.56 | -97 |
| 151 | 122 | 1.007 | 1.025 | 521 | 480 | 489 | 41 | 16.6% | 17.6 | 15.4 | 16.2 | 25.58 | -59 |
| 152 | 123 | 1.002 | 1.020 | 525 | 476 | 489 | 49 | 16.6% | 17.9 | 15.3 | 16 | 25.20 | -53 |
| 153 | 124 | 1.025 | 1.042 | 514 | 460 | 477 | 54 | 16.1% | 18.2 | 15.5 | 16.4 | 25.63 | -18 |
| 154 | 125 | 1.023 | 1.042 | 494 | 466 | 470 | 28 | 15.9% | 17.4 | 15.2 | 15.9 | 26.49 | -22 |
| 155 | 126 | 1.022 | 1.042 | 492 | 464 | 468 | 28 | 15.8% | 17 | 15.4 | 15.8 | 26.38 | -36 |
| 156 | 127 | 1.022 | 1.042 | 482 | 455 | 460 | 27 | 15.5% | 17 | 15.3 | 15.9 | 26.33 | -55 |
| 157 | 128 | 1.020 | 1.040 | 484 | 454 | 461 | 30 | 15.5% | 17.4 | 15.6 | 16.1 | 26.30 | -60 |
| 158 | 129 | 1.016 | 1.035 | 528 | 484 | 497 | 44 | 16.8% | 19.1 | 16.2 | 17.6 | 25.83 | -67 |
| 159 | 130 | 1.018 | 1.036 | 573 | 529 | 540 | 44 | 18.2% | 19.5 | 17.3 | 18 | 25.68 | -66 |
| 160 | 131 | 1.020 | 1.039 | 528 | 489 | 500 | 39 | 16.9% | 19.1 | 16.5 | 17.6 | 25.69 | -95 |
| 161 | 132 | 1.020 | 1.039 | 527 | 491 | 501 | 36 | 16.9% | 19.2 | 16.6 | 17.6 | 25.59 | -112 |
| 162 | 133 | 1.020 | 1.039 | 533 | 497 | 507 | 36 | 17.1% | 19.1 | 16.4 | 17.6 | 25.42 | -101 |
| 163 | 134 | 1.020 | 1.037 | 541 | 505 | 515 | 36 | 17.3% | 19 | 16.4 | 17.7 | 25.37 | -66 |
| 164 | 135 | 1.018 | 1.036 | 557 | 517 | 528 | 40 | 17.8% | 19.2 | 16.7 | 18.1 | 25.25 | -94 |
| 165 | 136 | 1.017 | 1.032 | 567 | 528 | 539 | 39 | 18.2% | 19.1 | 16.6 | 18.2 | 25.10 | -109 |
| 166 | 137 | 1.014 | 1.043 | 571 | 532 | 543 | 39 | 18.3% | 19.1 | 16.6 | 18.4 | 24.96 | -111 |
| 167 | 138 | 1.025 | 1.029 | 583 | 537 | 550 | 46 | 18.6% | 19.1 | 16.9 | 18 | 25.20 | -122 |
| 168 | 139 | 1.012 | 1.035 | 573 | 543 | 548 | 30 | 18.5% | 18 | 17.1 | 17.3 | 25.85 | -169 |
| 169 | 140 | 1.017 | 1.035 | 547 | 514 | 520 | 33 | 17.6% | 17.6 | 15.9 | 16.4 | 25.28 | -171 |
| 170 | 141 | 1.015 | 1.036 | 558 | 522 | 530 | 36 | 17.9% | 18.1 | 16 | 17.3 | 25.04 | -178 |
| 171 | 142 | 1.017 | 1.039 | 566 | 528 | 538 | 38 | 18.1% | 17.7 | 16 | 16.9 | 24.98 | -165 |
| 172 | 143 | 1.021 | 1.037 | 576 | 537 | 546 | 39 | 18.4% | 18.1 | 16.1 | 17.1 | 25.03 | -146 |
| 173 | 144 | 1.020 | 1.039 | 553 | 520 | 525 | 33 | 17.8% | 18.2 | 16 | 17.3 | 25.38 | -130 |
| 174 | 145 | 1.018 | 1.034 | 562 | 528 | 535 | 34 | 18.1% | 17.6 | 16.2 | 16.9 | 25.03 | -83 |
| 175 | 146 | 1.016 | 1.035 | 547 | 522 | 529 | 25 | 17.8% | 17.7 | 16 | 17 | 25.03 | -62 |
| 176 | 147 | 1.016 | 1.036 | 544 | 517 | 524 | 27 | 17.6% | 17.8 | 16 | 16.9 | 25.05 | -42 |
| 177 | 148 | 1.017 | 1.035 | 538 | 515 | 523 | 23 | 17.5% | 17.7 | 16 | 16.5 | 25.21 | -38 |
| 178 | 149 | 1.017 | 1.036 | 544 | 511 | 519 | 33 | 17.5% | 18 | 16 | 16.8 | 25.24 | -42 |
| 179 | 150 | 1.018 | 1.026 | 524 | 501 | 507 | 23 | 17.0% | 17.8 | 16.2 | 16.3 | 25.31 | -52 |
| 180 | 151 | 1.007 | 1.032 | 508 | 493 | 499 | 15 | 16.7% | 17.6 | 15.9 | 16.1 | 25.56 | -76 |
| 181 | 152 | 1.017 | 1.033 | 490 | 449 | 460 | 41 | 15.5% | 17.4 | 14.9 | 15.8 | 25.02 | -87 |
| 182 | 153 | 1.019 | 1.035 | 487 | 444 | 455 | 43 | 15.4% | 17.2 | 14.8 | 15.7 | 25.09 | -55 |
| 183 | 154 | 1.019 | 1.033 | 470 | 430 | 440 | 40 | 14.9% | 17.1 | 14.9 | 15.4 | 25.46 | -25 |

Sample of UARS Flight Battery Database

| C | Z | AA | AB | AC | AD | AE | AF | AG | AH | AI | AJ | AK | AL |
|-----|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|------|------|
| DOY | DV1MAX | DV1MED | DV1MAG | DV2MIN | DV2MAX | DV2MED | DV2MAG | DV3MIN | DV3MAX | DV3MED | DV3MAG | TI | T2 |
| 150 | 121 | -19 | 156 | -17 | 13 | -2 | 30 | -22 | 22 | 0 | 44 | 5.2 | 2.25 |
| 151 | 122 | 2.5 | 123 | -15 | 13 | -1 | 28 | -20 | 22 | 1 | 42 | 5.16 | 2.14 |
| 152 | 123 | 12.5 | 131 | -11 | 25 | 7 | 36 | -22 | 22 | 0 | 44 | 5.02 | 1.92 |
| 153 | 124 | 36 | 108 | -15 | 25 | 5 | 40 | -20 | 36 | 8 | 56 | 4.81 | 1.79 |
| 154 | 125 | 34 | 112 | -17 | 18 | 0.5 | 35 | -7 | 35 | 14 | 42 | 4.62 | 1.74 |
| 155 | 126 | 22.5 | 117 | -17 | 15 | -1 | 32 | -10 | 32 | 11 | 42 | 4.64 | 1.7 |
| 156 | 127 | 11.5 | 133 | -15 | 15 | 0 | 30 | -8 | 35 | 13.5 | 43 | 4.68 | 1.65 |
| 157 | 128 | 9 | 138 | -17 | 17 | 0 | 34 | -7 | 36 | 14.5 | 43 | 4.84 | 1.65 |
| 158 | 129 | 7 | 148 | -15 | 14 | -0.5 | 29 | -13 | 34 | 10.5 | 47 | 5.16 | 1.8 |
| 159 | 130 | 10.5 | 153 | -22 | 13 | -4.5 | 35 | -22 | 28 | 3 | 50 | 5.58 | 2.07 |
| 160 | 131 | -7.5 | 175 | -22 | 13 | -4.5 | 35 | -21 | 29 | 4 | 50 | 5.78 | 2.28 |
| 161 | 132 | -24 | 176 | -22 | 11 | -5.5 | 33 | -25 | 25 | 0 | 50 | 6.77 | 3.31 |
| 162 | 133 | -10.5 | 181 | -22 | 11 | -5.5 | 33 | -34 | 22 | -6 | 56 | 7.44 | 3.83 |
| 163 | 134 | 5.5 | 143 | -22 | 11 | -5.5 | 33 | -34 | 22 | -6 | 56 | 7.64 | 4.18 |
| 164 | 135 | -12 | 164 | -22 | 11 | -5.5 | 33 | -34 | 22 | -6 | 56 | 7.81 | 4.37 |
| 165 | 136 | -25 | 168 | -22 | 13 | -4.5 | 35 | -35 | 22 | -6.5 | 57 | 8.05 | 4.49 |
| 166 | 137 | -29.5 | 163 | -22 | 18 | -2 | 40 | -35 | 21 | -7 | 56 | 8.26 | 4.88 |
| 167 | 138 | -31 | 182 | -18 | 20 | 1 | 38 | -34 | 22 | -6 | 56 | 8.56 | 4.88 |
| 168 | 139 | -56.5 | 225 | -21 | 11 | -5 | 32 | -31 | 22 | -4.5 | 53 | 8.45 | 4.58 |
| 169 | 140 | -73 | 196 | -21 | 11 | -5 | 32 | -34 | 22 | -6 | 56 | 7.98 | 4.36 |
| 170 | 141 | -78.5 | 199 | -17 | 21 | 2 | 38 | -34 | 22 | -6 | 56 | 8.18 | 4.44 |
| 171 | 142 | -71.5 | 187 | -13 | 24 | 5.5 | 37 | -34 | 24 | -5 | 58 | 8.27 | 4.75 |
| 172 | 143 | -57.5 | 177 | -14 | 32 | 9 | 46 | -34 | 22 | -6 | 56 | 8.24 | 4.84 |
| 173 | 144 | -46 | 168 | -20 | 17 | -1.5 | 37 | -34 | 22 | -6 | 56 | 8.04 | 4.44 |
| 174 | 145 | -16.5 | 133 | -17 | 25 | 4 | 42 | -35 | 21 | -7 | 56 | 8.69 | 4.98 |
| 175 | 146 | -6.5 | 111 | -17 | 29 | 6 | 46 | -36 | 20 | -8 | 56 | 8.46 | 4.73 |
| 176 | 147 | 7 | 98 | -14 | 29 | 7.5 | 43 | -36 | 21 | -7.5 | 57 | 8.06 | 4.35 |
| 177 | 148 | 9 | 94 | -13 | 24 | 5.5 | 37 | -34 | 20 | -7 | 54 | 8.01 | 4.16 |
| 178 | 149 | 7 | 98 | -17 | 22 | 2.5 | 39 | -34 | 18 | -8 | 52 | 7.95 | 3.89 |
| 179 | 150 | 2 | 108 | -21 | 15 | -3 | 36 | -34 | 15 | -9.5 | 49 | 7.69 | 3.58 |
| 180 | 151 | -13.5 | 125 | -22 | 13 | -4.5 | 35 | -34 | 22 | -6 | 56 | 7.67 | 3.35 |
| 181 | 152 | -29 | 116 | -20 | 28 | 4 | 48 | -34 | 22 | -6 | 56 | 5.99 | 2.12 |
| 182 | 153 | -8 | 94 | -11 | 31 | 10 | 42 | -32 | 22 | -5 | 54 | 5.33 | 1.56 |
| 183 | 154 | 15 | 80 | -11 | 25 | 7 | 36 | -29 | 22 | -3.5 | 51 | 6.06 | 2.59 |

Sample of UARS Flight Battery Database

| C | AM | AN | AO | AP | AQ |
|-----|-------|----------|------|---------------|-------|
| DOY | T1-T2 | AVGPEAKI | VT | EFF. C/D GOAL | |
| 150 | 13 | 2.95 | 18.2 | 4 | 1.035 |
| 151 | 3.57 | 3.02 | 18.3 | 4 | 1.025 |
| 152 | 3.52 | 3.1 | 18.3 | 4 | 1.025 |
| 153 | 3.35 | 3.02 | 18.5 | 4 | 2 |
| 154 | 3.12 | 2.88 | 17.3 | 4 | 2 |
| 155 | 3.05 | 2.94 | 17.1 | 4 | 2 |
| 156 | 3.03 | 3.03 | 17.1 | 4 | 2 |
| 157 | 2.95 | 3.19 | 16.9 | 4 | 1.05 |
| 158 | 3.03 | 3.36 | 17.2 | 4 | 2 |
| 159 | 3.27 | 3.51 | 17.6 | 4 | 2 |
| 160 | 3.58 | 3.5 | 17.7 | 4 | 2 |
| 161 | 3.71 | 3.46 | 17.7 | 4 | 2 |
| 162 | 4.8 | 3.61 | 18.3 | 4 | 2 |
| 163 | 5.34 | 3.46 | 18.4 | 4 | 2 |
| 164 | 5.61 | 3.44 | 18.2 | 4 | 2 |
| 165 | 5.74 | 3.56 | 17.6 | 4 | 2 |
| 166 | 5.95 | 3.38 | 17.6 | 5 | 1.04 |
| 167 | 6.23 | 3.68 | 17.6 | 5 | 2 |
| 168 | 6.4 | 3.87 | 17.9 | 4 | 2 |
| 169 | 5.99 | 3.62 | 17.6 | 4 | 2 |
| 170 | 5.69 | 3.74 | 16.9 | 4 | 2 |
| 171 | 5.83 | 3.52 | 17.2 | 4 | 2 |
| 172 | 6.05 | 3.4 | 16.9 | 4 | 2 |
| 173 | 6.14 | 3.6 | 17.8 | 4 | 2 |
| 174 | 5.7 | 3.71 | 19 | 4 | 2 |
| 175 | 6.29 | 3.73 | 18.1 | 4 | 2 |
| 176 | 6.06 | 3.71 | 17.1 | 4 | 2 |
| 177 | 5.72 | 3.85 | 17.1 | 4 | 2 |
| 178 | 5.58 | 4.06 | 17.3 | 4 | 2 |
| 179 | 5.42 | 4.11 | 16.8 | 4 | 2 |
| 180 | 5.07 | 4.32 | 18 | 3 | 2 |
| 181 | 4.89 | 3.87 | 17.7 | 3 | 2 |
| 182 | 3.61 | 3.77 | 16.7 | 3 | 2 |
| 183 | 3 | 3.47 | 16 | 3 | 2 |
| 184 | 3.99 | | | | |

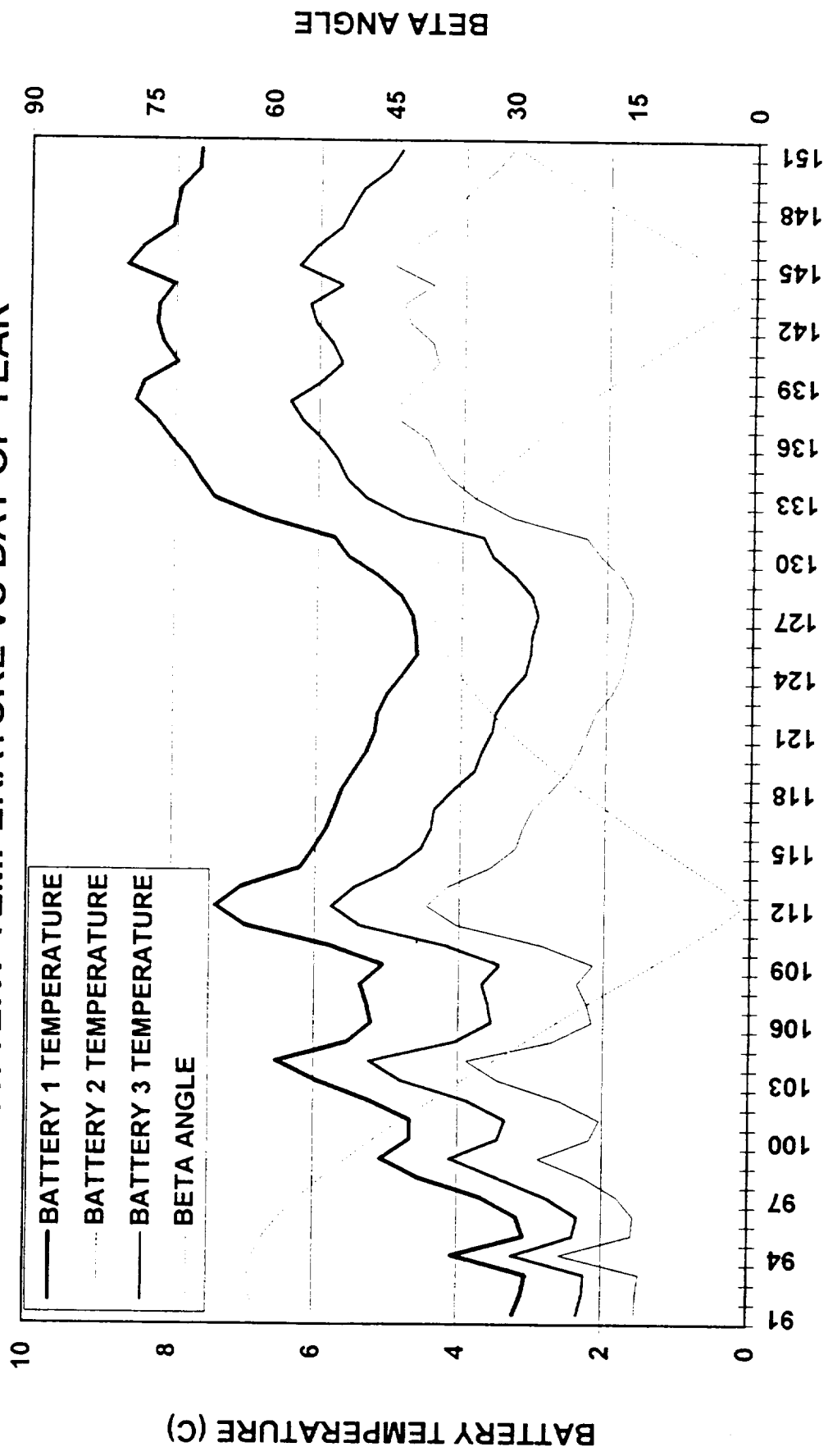
Sample of UARS Flight Battery Database

| | C | AR |
|-----|-----|--------------------------------------|
| 1 | DOY | NOTES |
| 150 | 121 | |
| 151 | 122 | |
| 152 | 123 | |
| 153 | 124 | STRAIGHT VT4; |
| 154 | 125 | |
| 155 | 126 | |
| 156 | 127 | |
| 157 | 128 | |
| 158 | 129 | ISAMS TO HIGH POWER; STRAIGHT VT4; |
| 159 | 130 | STRAIGHT VT4; SOLAR ECLIPSE; |
| 160 | 131 | STRAIGHT VT4; |
| 161 | 132 | STRAIGHT VT4; |
| 162 | 133 | STRAIGHT VT4; |
| 163 | 134 | STRAIGHT VT4; |
| 164 | 135 | STRAIGHT VT4; |
| 165 | 136 | STRAIGHT VT4; |
| 166 | 137 | |
| 167 | 138 | 1.05 C/D GOAL, THEN STRAIGHT VT5; |
| 168 | 139 | ISAMS TO LOW POWER; STRAIGHT VT4; |
| 169 | 140 | STRAIGHT VT4; |
| 170 | 141 | STRAIGHT VT4; |
| 171 | 142 | STRAIGHT VT4; |
| 172 | 143 | STRAIGHT VT4; ISAMS OFF; YAW-AROUND; |
| 173 | 144 | STRAIGHT VT4; ISAMS TO LOW POWER; |
| 174 | 145 | STRAIGHT VT4; |
| 175 | 146 | STRAIGHT VT4; |
| 176 | 147 | STRAIGHT VT4; |
| 177 | 148 | STRAIGHT VT4; |
| 178 | 149 | STRAIGHT VT4; |
| 179 | 150 | STRAIGHT VT4; |
| 180 | 151 | STRAIGHT VT3; ISAMS OFF; |
| 181 | 152 | STRAIGHT VT3; |
| 182 | 153 | STRAIGHT VT3; |
| 183 | 154 | STRAIGHT VT3; |

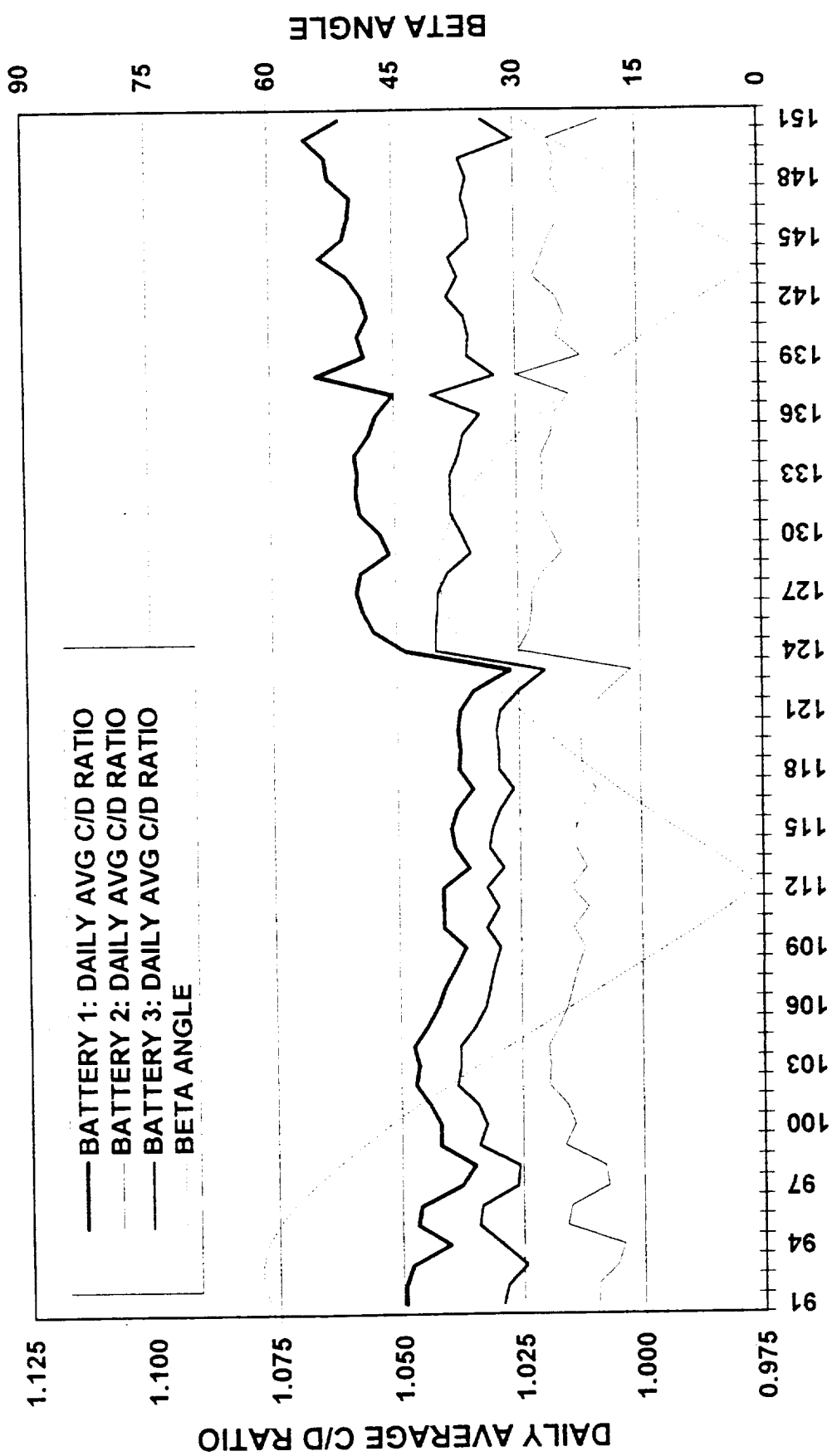
DATABASE FIGURES

- **Each of these 16 parameters (except #2 and #4) are plotted versus Day of Year**
- **The Beta Angle is on each figure as a reference**
- **Some figures cover the entire year on a single page while others are confined to 60-day intervals for greater utility**

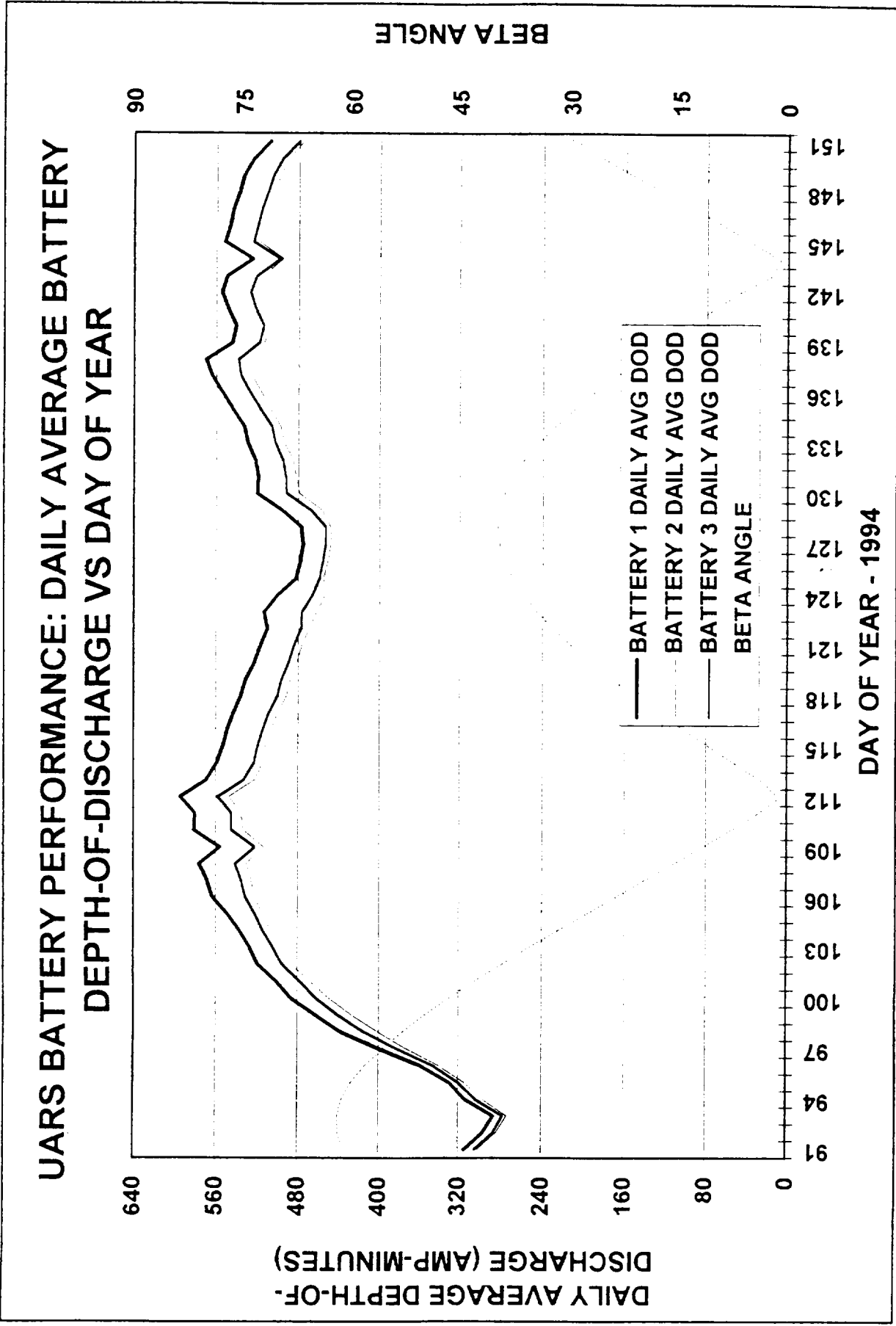
UARS BATTERY PERFORMANCE: DAILY AVERAGE BATTERY TEMPERATURE VS DAY OF YEAR



UARS BATTERY PERFORMANCE: DAILY AVERAGE BATTERY C/D RATIO VS DAY OF YEAR

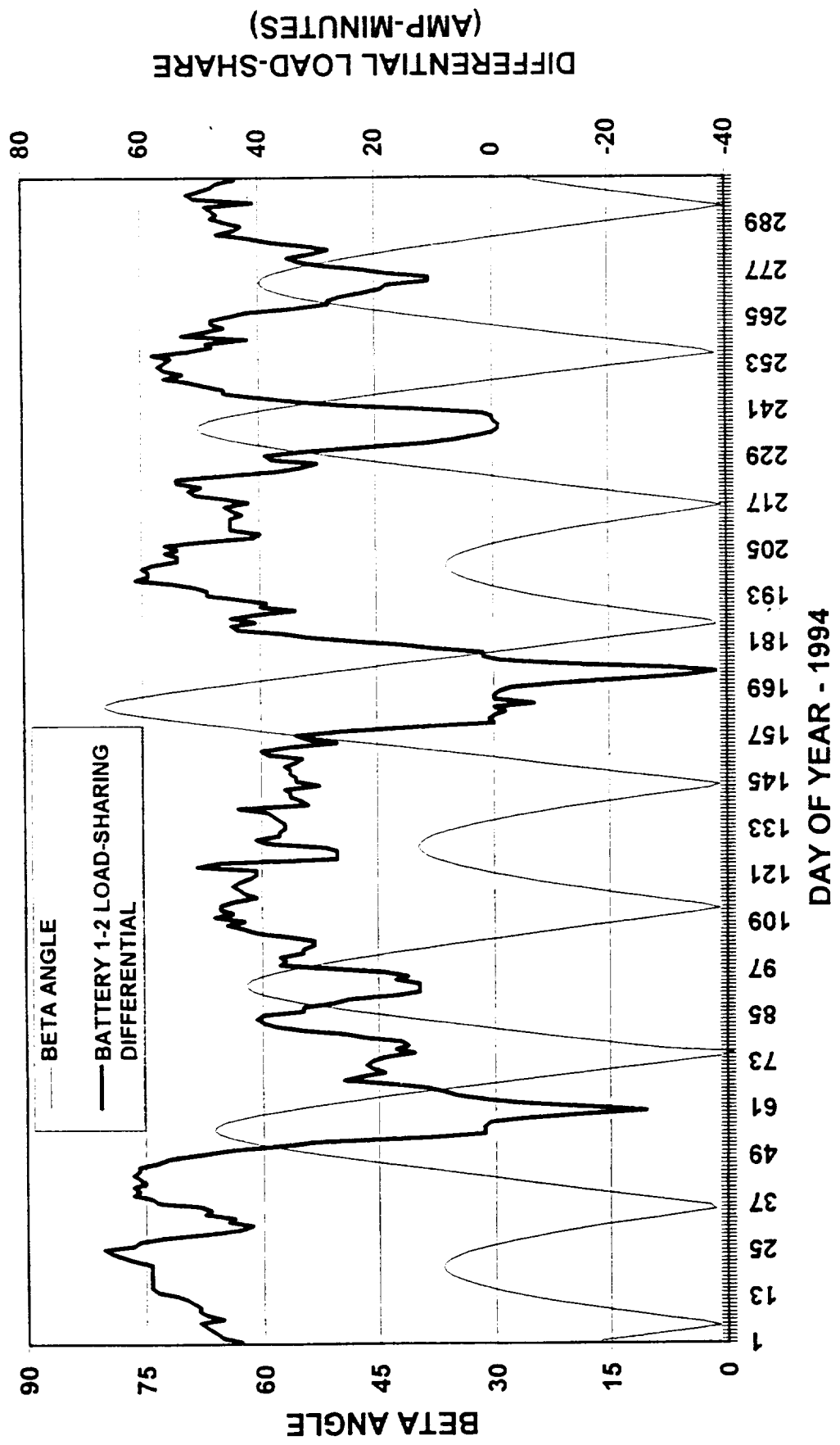


627

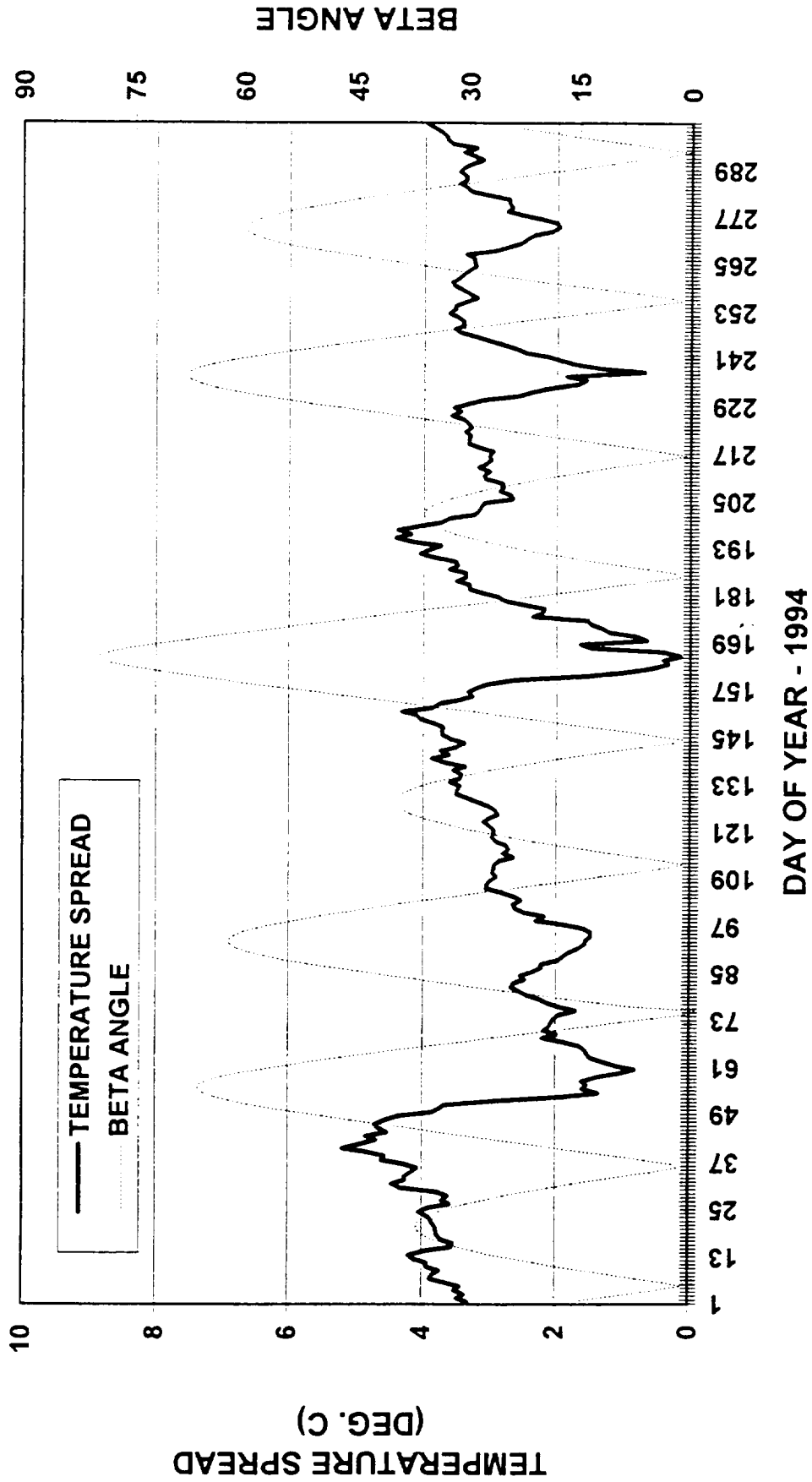


628

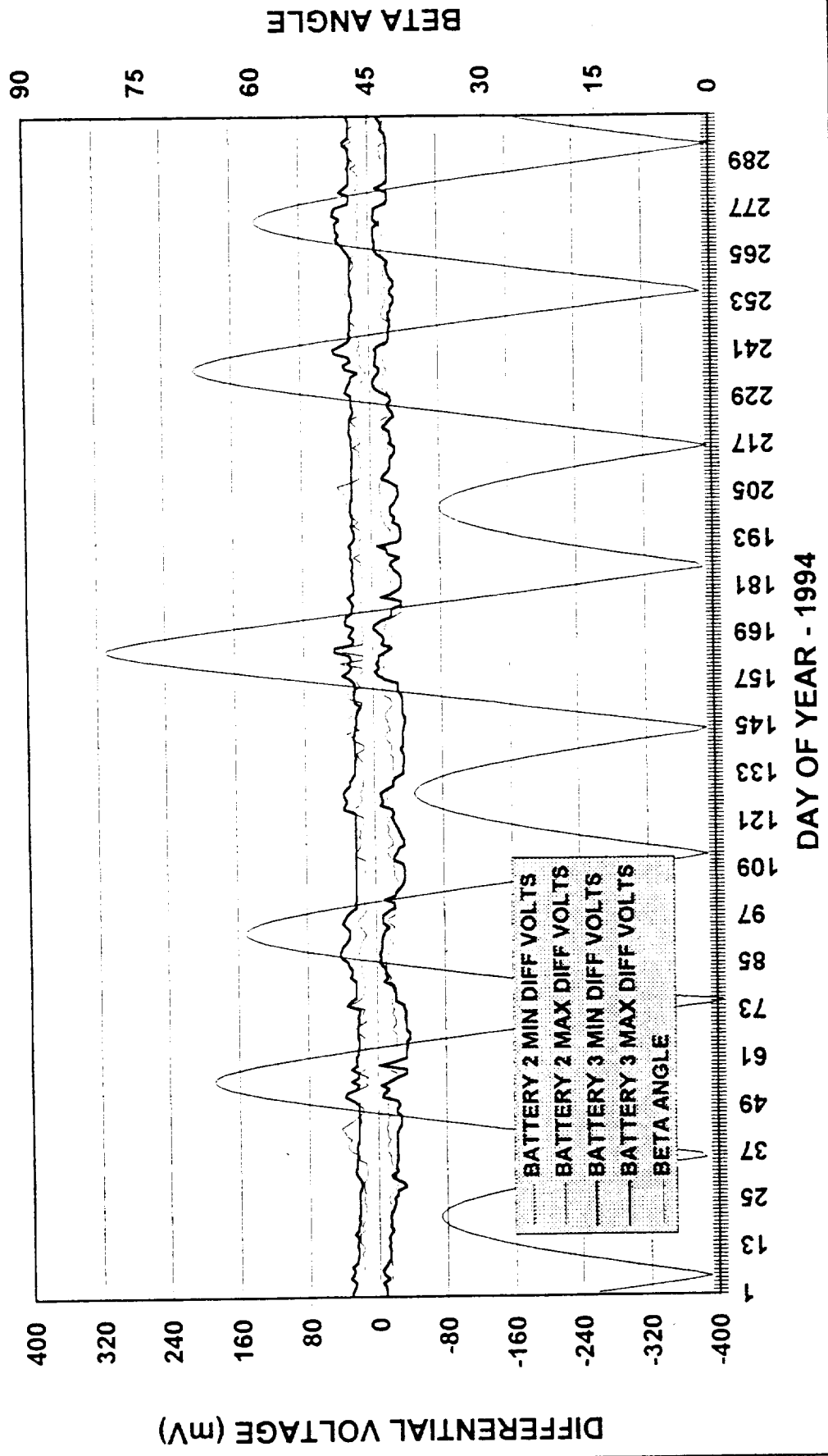
UARS BATTERY PERFORMANCE: DAILY LOAD SHARE DIFFERENTIAL BETWEEN BATTERY 1 & 2 VS DAY OF YEAR



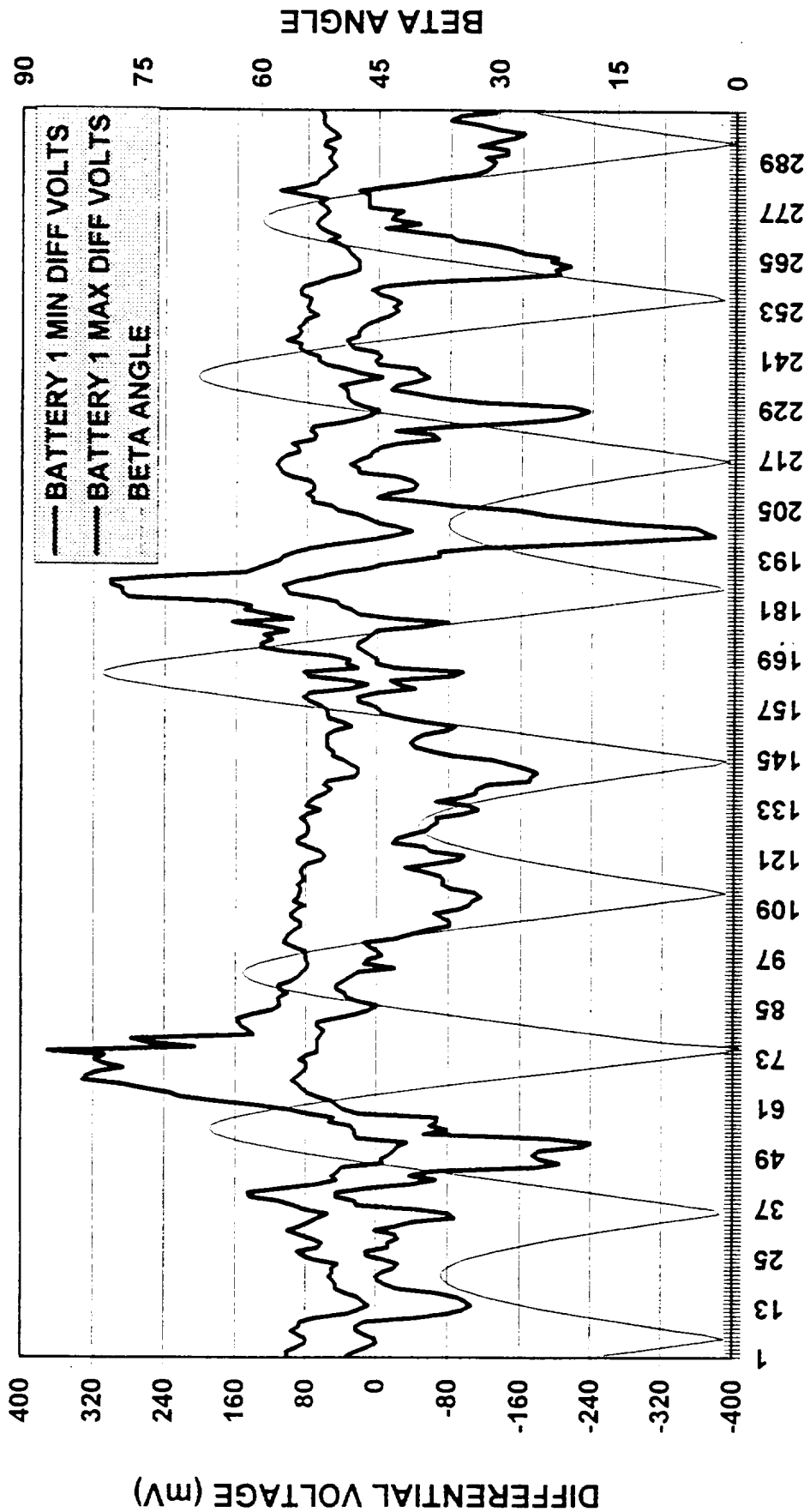
UARS BATTERY PERFORMANCE: DAILY AVERAGE TEMPERATURE SPREAD BETWEEN BATTERY 1 AND 2 VS DAY OF YEAR



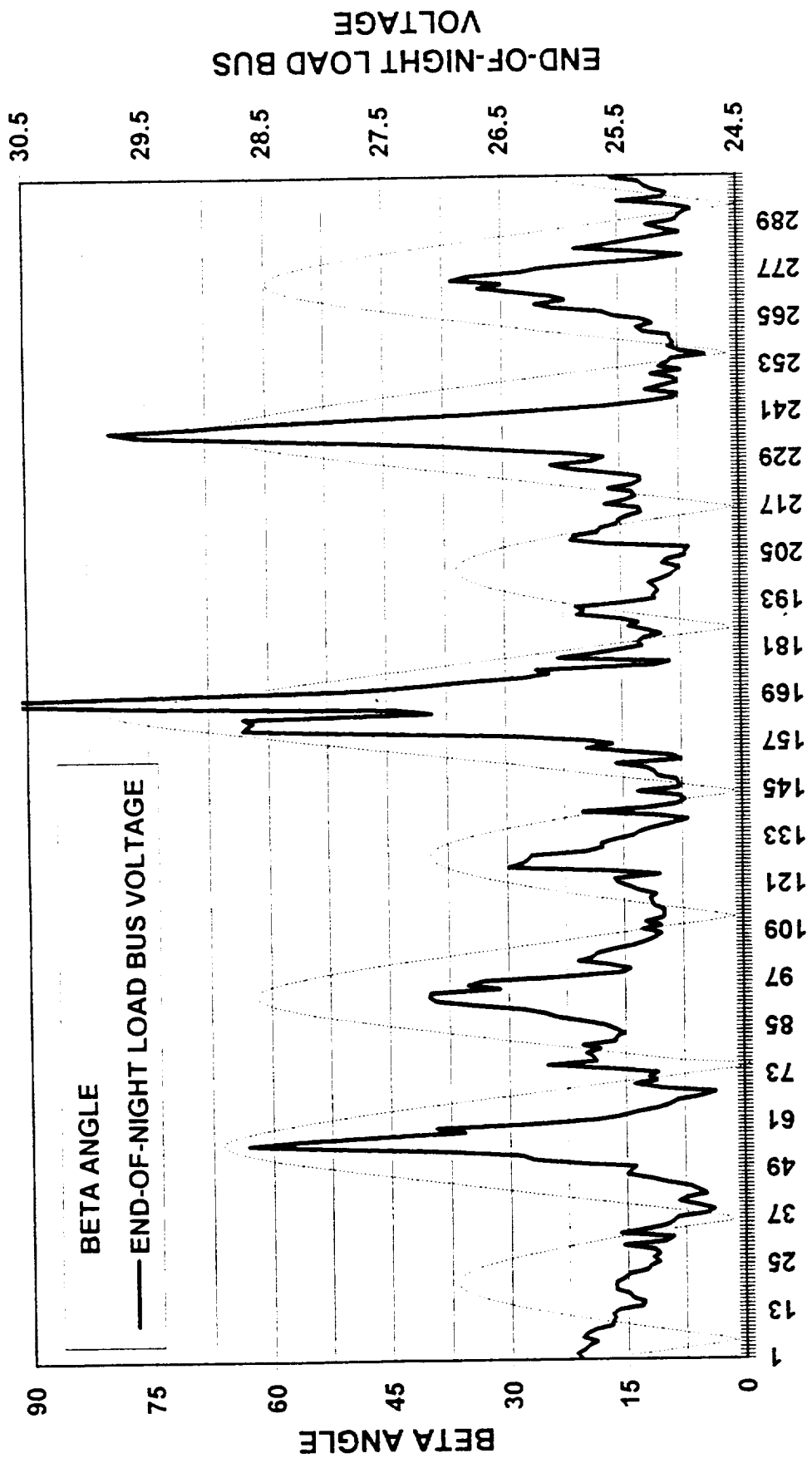
UARS BATTERY PERFORMANCE: DAILY BATTERY DIFFERENTIAL VOLTAGE VS DAY OF YEAR



UARS BATTERY PERFORMANCE: DAILY BATTERY DIFFERENTIAL VOLTAGE VS DAY OF YEAR



UARS BATTERY PERFORMANCE: DAILY AVERAGE END-OF-NIGHT LOAD BUS VOLTAGE VS DAY OF YEAR

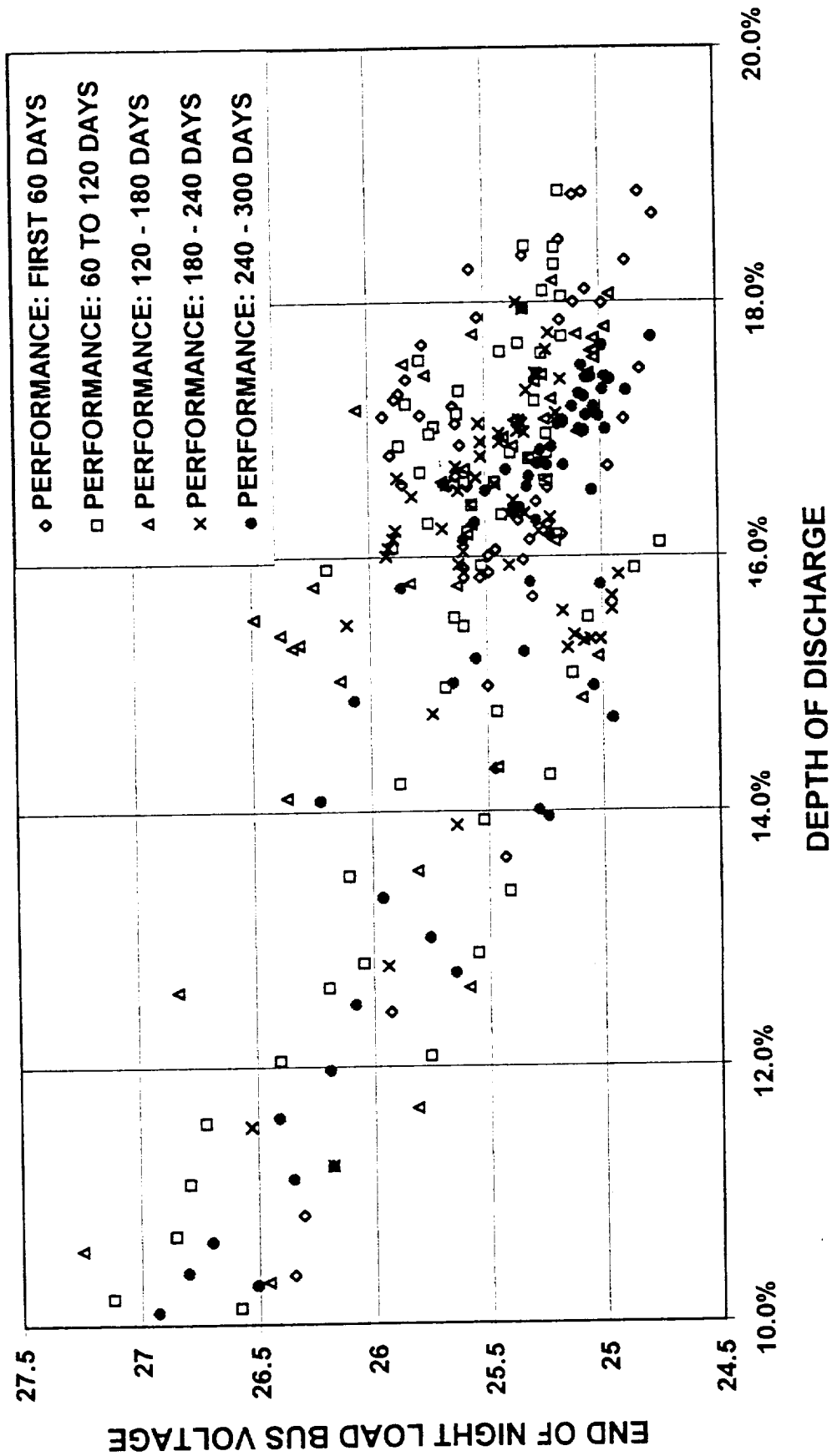


DATABASE FIGURES - continued

- **Daily Average End of Night Load Bus Voltage could be a misleading indicator of battery health and state-of-charge and should be correlated to Daily Average Battery Depth-of-Discharge.**
- **An additional figure examines this relationship. The figure covers the first 300 days of 1994, and is broken out into discrete 60-day periods. It suggests that battery voltage performance has not significantly degraded over the last 300 days.**

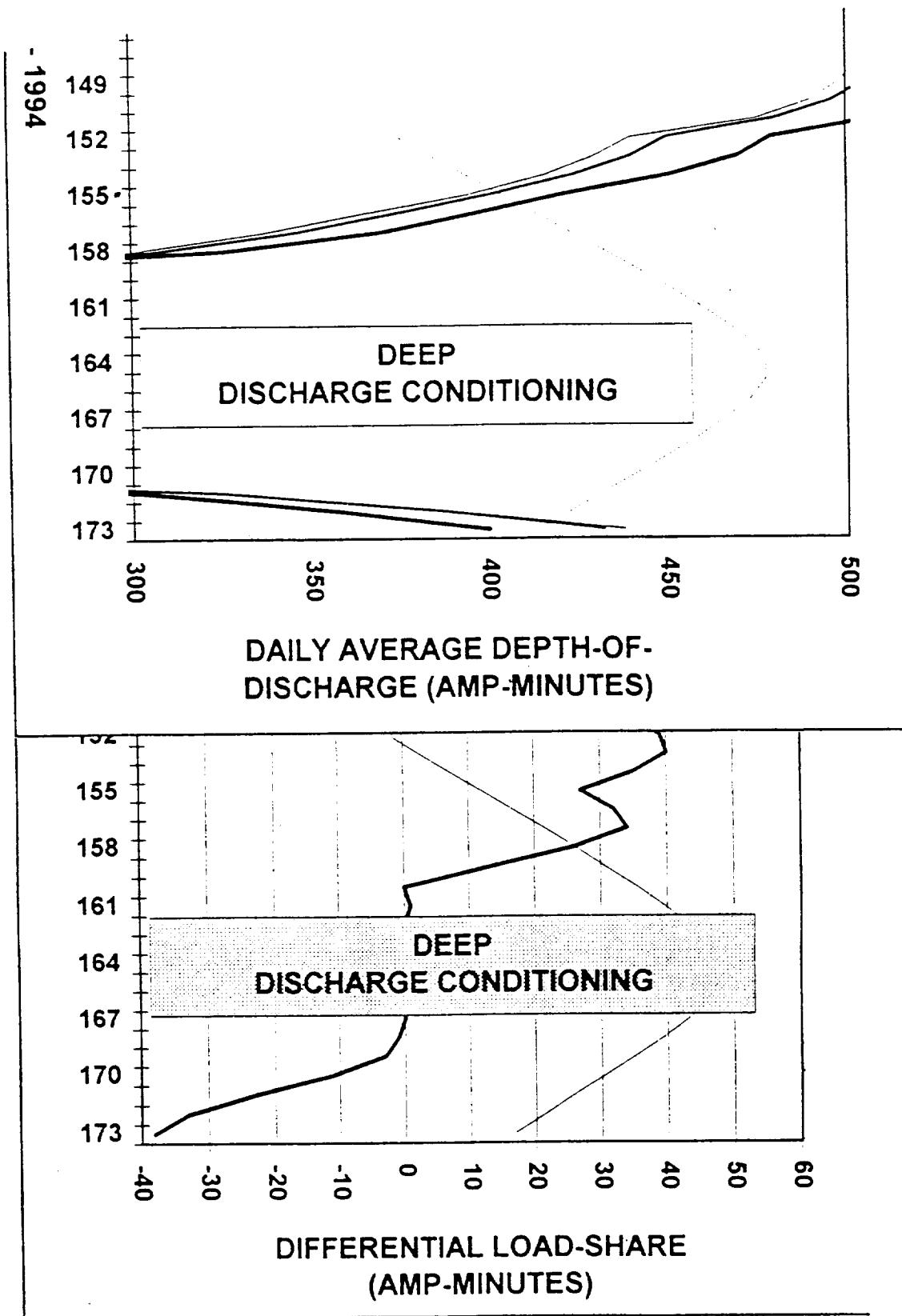
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UARS BATTERY PERFORMANCE: DAILY AVERAGE DEPTH OF DISCHARGE VS DAILY AVERAGE END OF NIGHT LOAD BUS VOLTAGE FOR SPECIFIC PERFORMANCE PERIODS

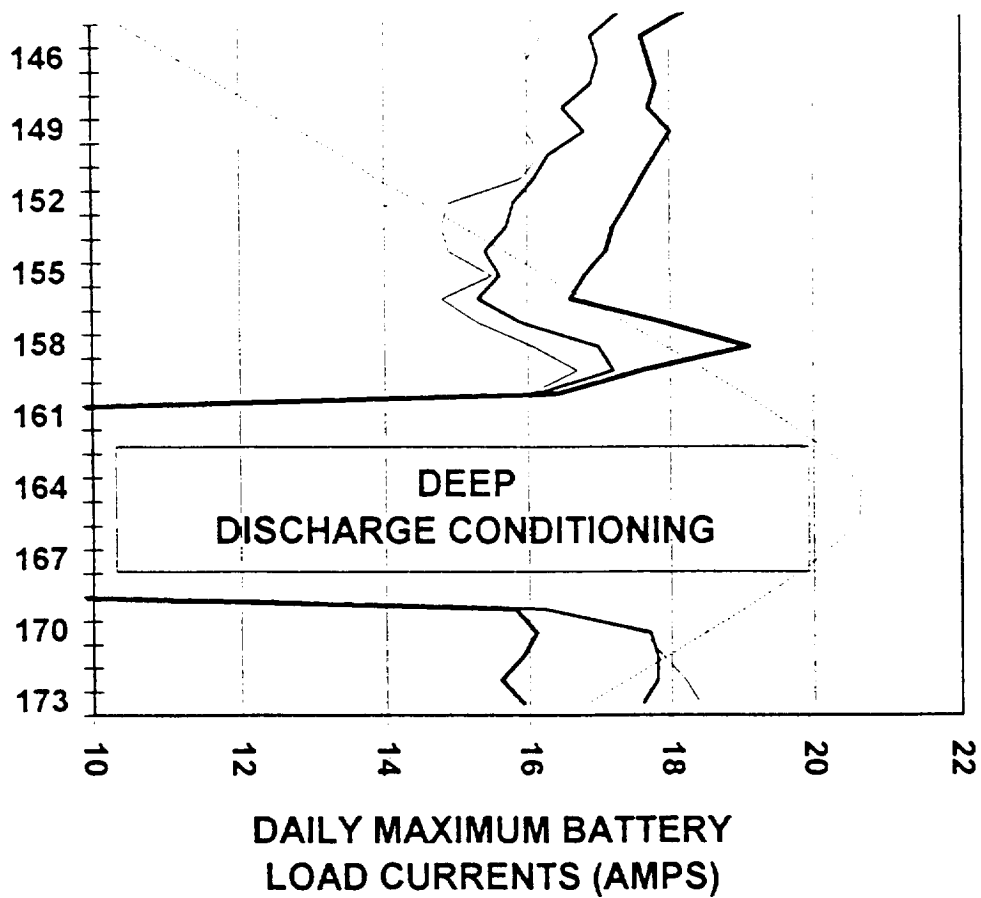


APPLICATION OF THE DATABASE

- **To illustrate the usefulness of the database and its applicability for future battery operations and management, let us examine three of the many operational modes employed in 1994:**
 - 1. Deep discharge conditioning on DOY 164 and 165**
 - 2. Control C/D ratio by switching from “straight” VT 3 to a combination of VT 4 and Constant Current Mode for a C/D ratio goal of 1.04 on DOY 174**
 - 3. Use of straight VT 4 from DOY 188 to 192**



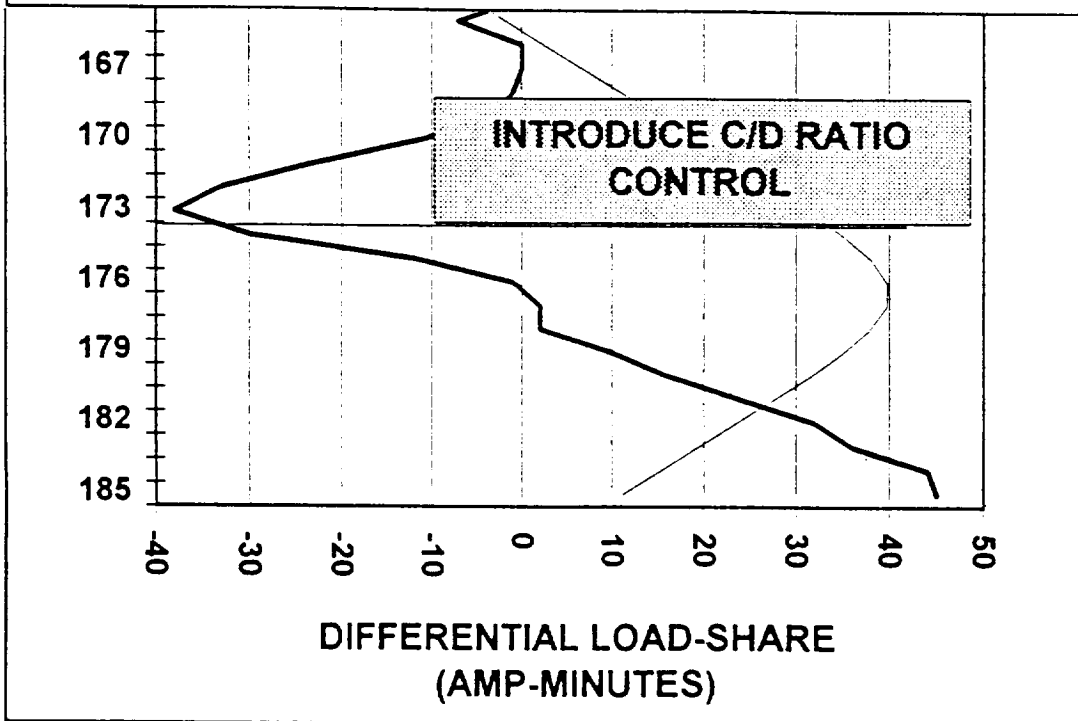
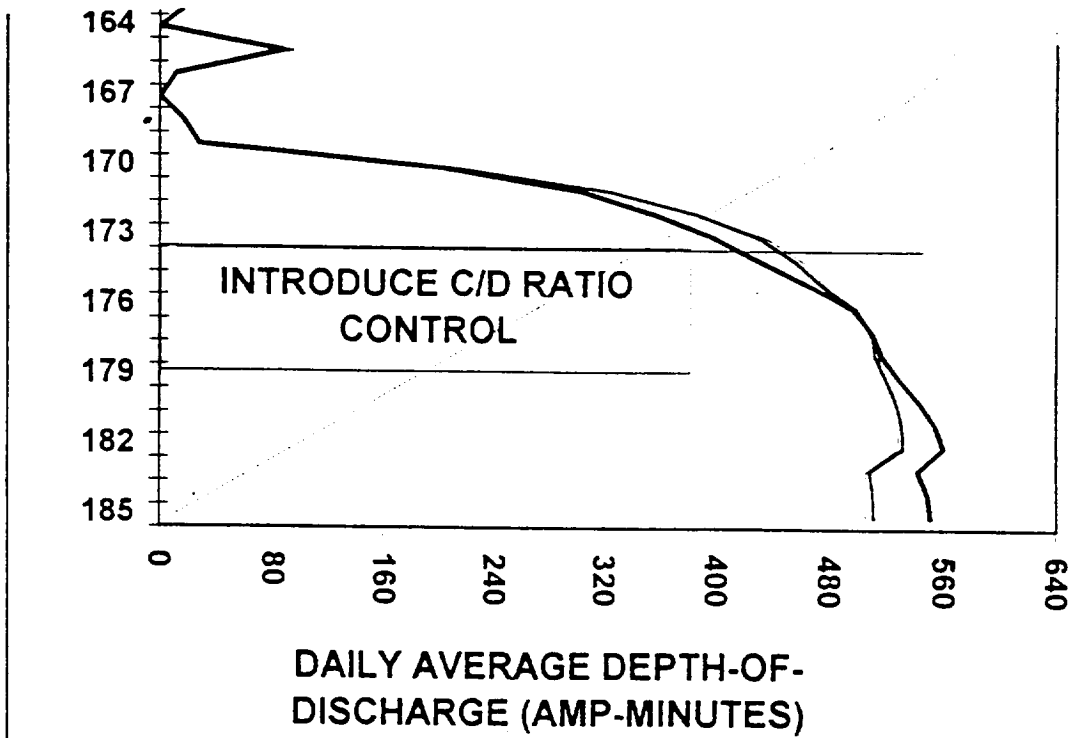
Example 1: Effects of Deep Discharge Conditioning



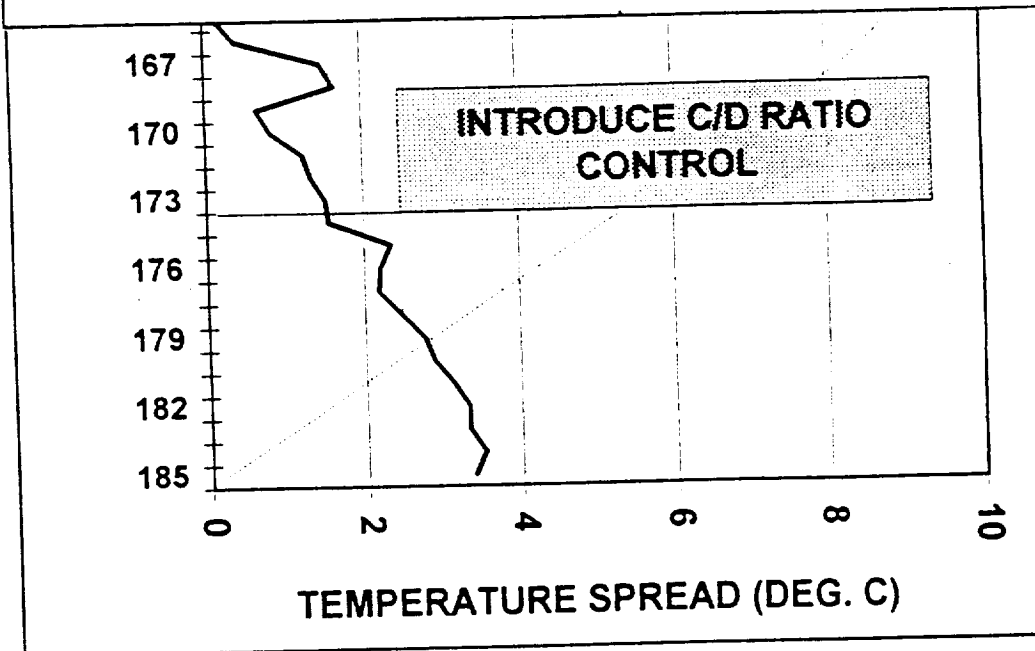
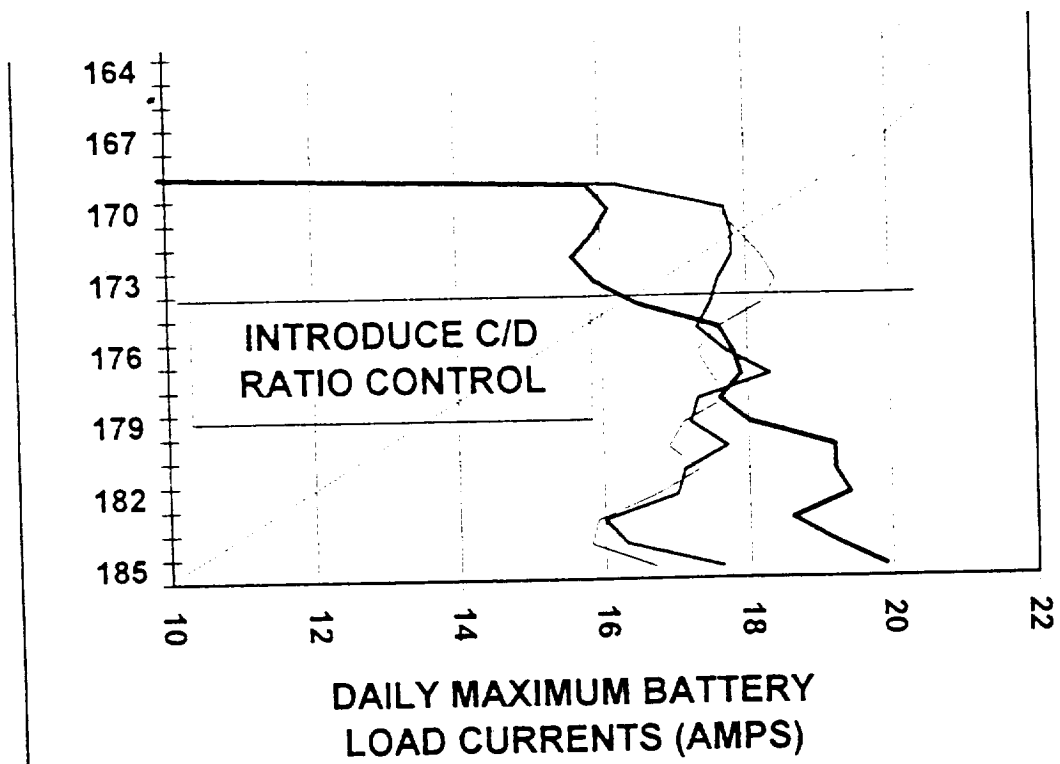
Example 1: Effects of Deep Discharge Conditioning
(continued)

CONCLUSIONS FROM EXAMPLE.1

- **Deep discharge conditioning temporarily improves battery performance**
- **Improved battery performance also probably arises from the convergence of battery temperatures during full-sun periods**



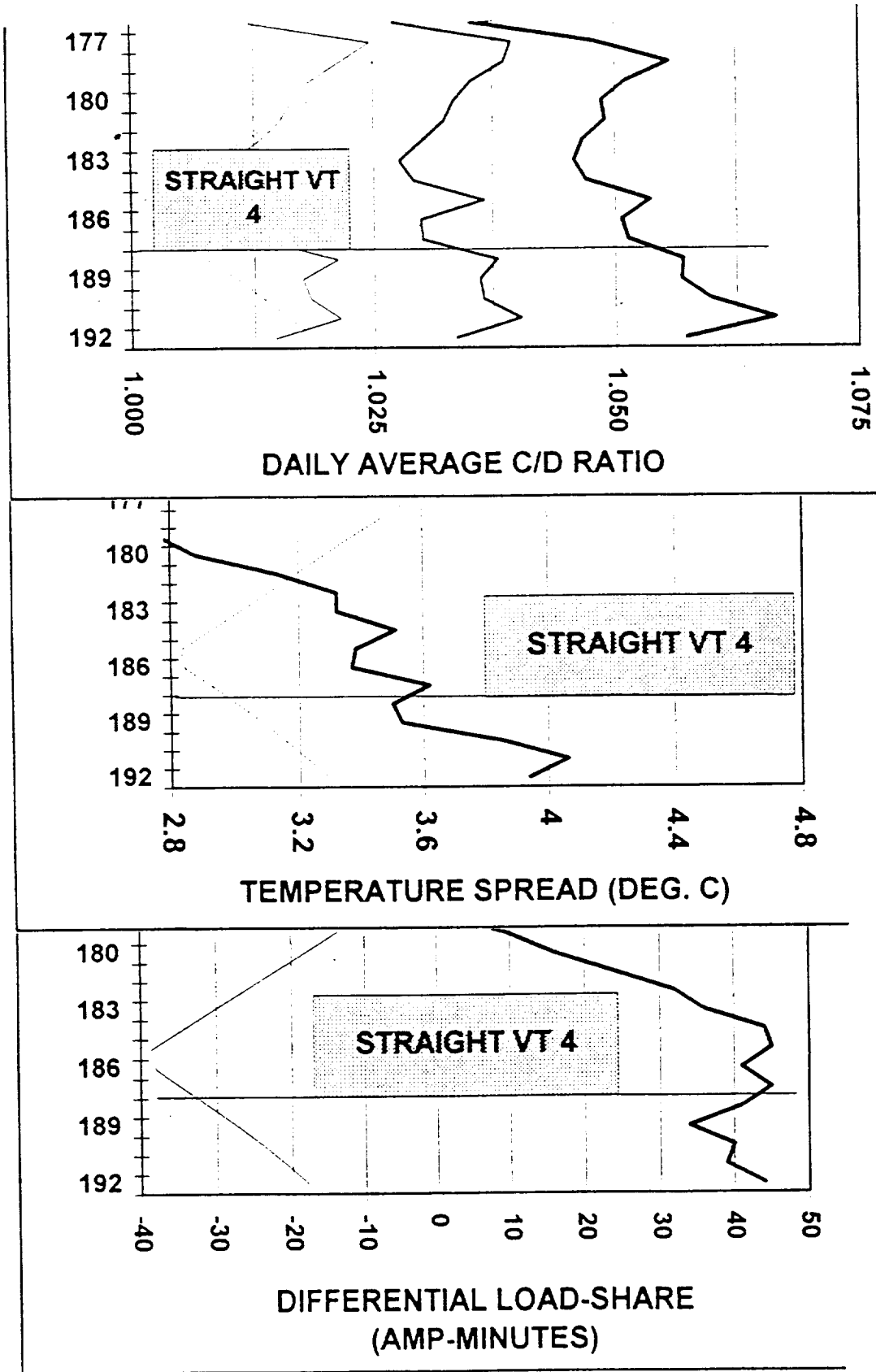
Example 2: Effect of C/D Ratio Control



Example 2: Effect of C/D Ratio Control
(continued)

CONCLUSIONS FROM EXAMPLE 2

- Performance improvements realized from deep discharge conditioning appear to be temporary
- Minimizing overcharge on the warmest battery can result in undercharging of colder batteries and a state-of-charge imbalance among the three batteries
- Divergence of some battery performance parameters is probably due to state-of-charge divergence
- Presently, for UARS, the use of Constant Current Mode to control C/D ratio is not preferred when the Beta angle is decreasing (eclipse duration increasing / length of S/C day decreasing)



Example 3: Effect of Straight VT 4

CONCLUSIONS FROM EXAMPLE 3

- **Straight VT charging yields better load-sharing in the short run, but leads to divergence in the long run**
- **Ensuring an adequate level of overcharge on the coldest battery by this method can be detrimental to the warmest battery (generates waste heat at end of charge, increases the C/D ratio). Divergence in states-of-charge is a likely result**
- **For the present, on UARS, use of straight VT charging is not preferred when the Beta angle is increasing (eclipse duration decreasing / length of S/C day increasing)**

PRESENT OPERATIONAL STRATEGIES

- **Hold sunrise battery charge currents below 20 amps via Solar Array offset**
- **Use VT 3 unless DOD exceeds 15% or end-of-night Load Bus Voltage drops to 24.8 V; then use VT 4**
- **Use Constant Current Charge Modes only as necessary to maintain C/D ratios below 1.06**
- **Use Constant Current Charge Mode to control C/D ratios only when the Beta angle is increasing**
- **Use straight VT charging only when the Beta angle is decreasing**

PRESENT OPERATIONAL STRATEGIES - continued

- **Execute deep conditioning discharges and/or artificial eclipsing during every full-sun period**
- **Maintain temperature spread between battery 1 and battery 2 below 4 °C**
- **Monitor battery differential voltages to detect unusual signatures:**
 - **“spikes” during charge, of 50mV or more**
 - **rapid changes at the end of discharge exceeding 300 mV**
 - **an absolute value exceeding 350 mV at any time in an orbit**

SUMMARY

- **Anomalous performance of the UARS batteries has necessitated intensive battery management characterized by frequent changes in operational modes and close monitoring of trends**
- **Establishment and use of a battery performance database has aided in this management effort:**
 - Identified the operational strategies that have led to poor performance
 - Identifies the operational strategies that are yielding acceptable performance
 - Suggests operational strategies that may lead to optimum performance

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