N95- 26796

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 $-X_{acs}$ 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.

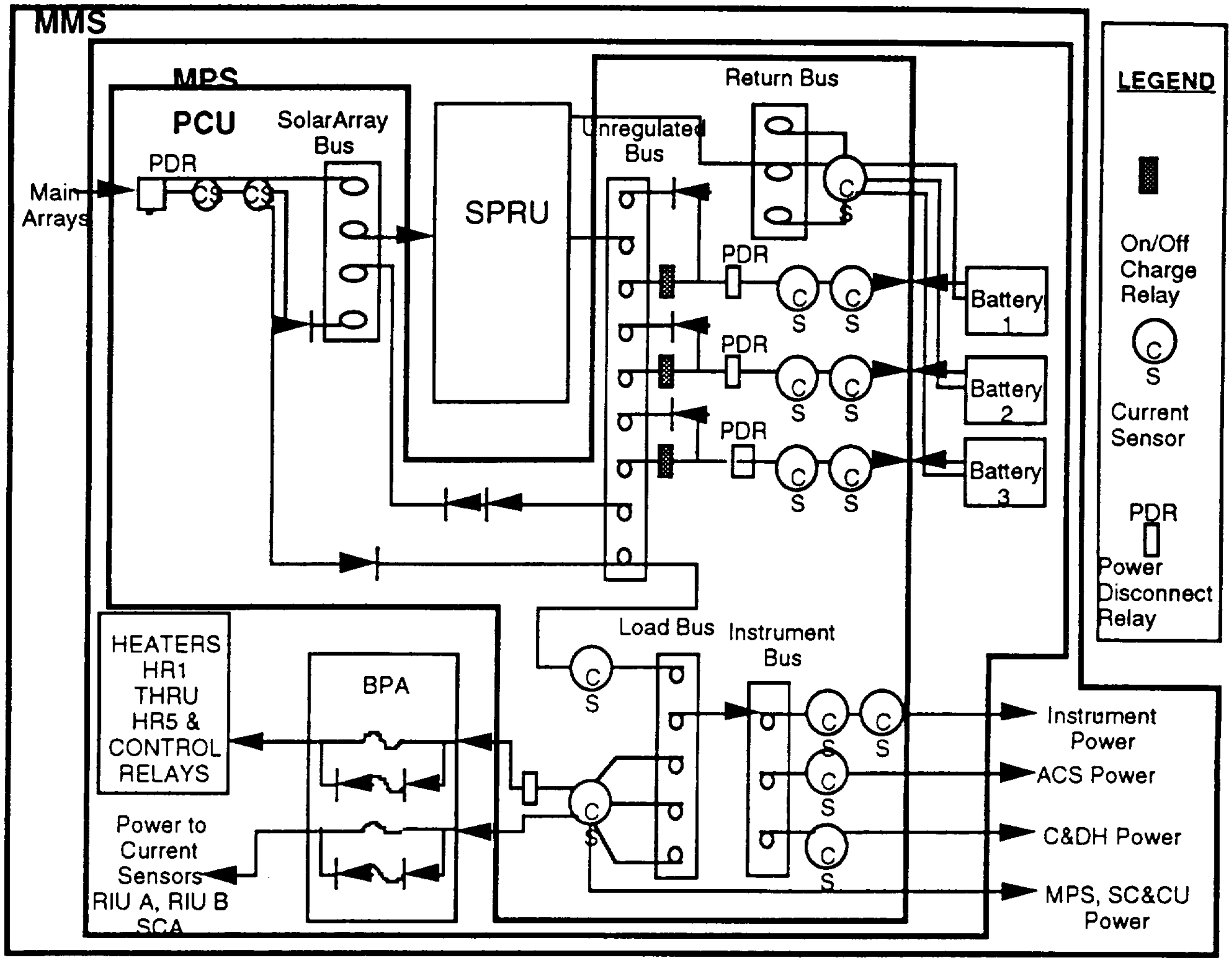

Figure 1: EP/EUVE Power Block Diagram

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.

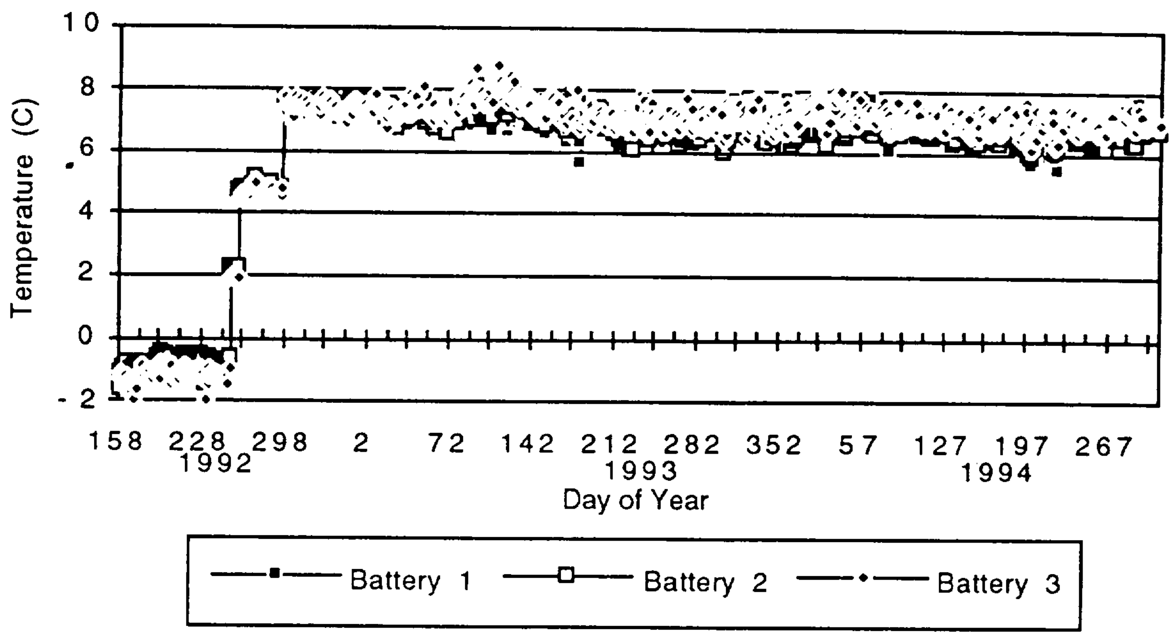

Figure 2: Mean Battery Temperatures for the Mission Life

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.

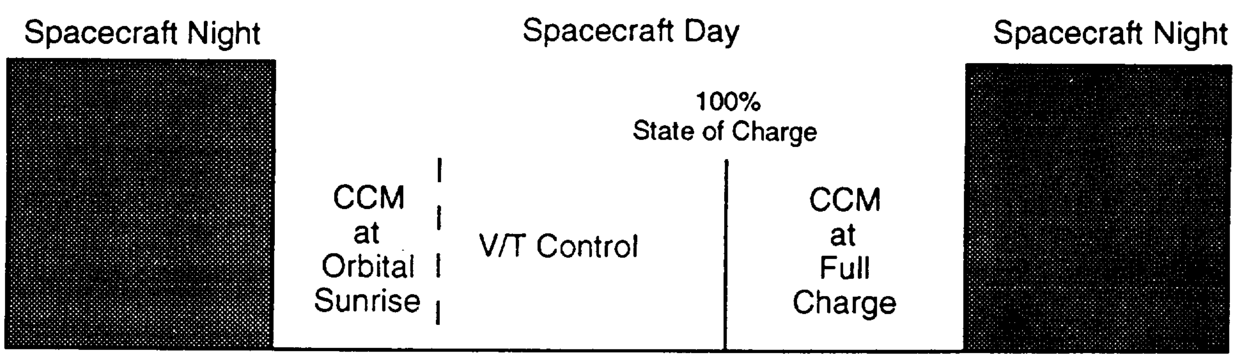

Figure 3: Standard EP/EUVE Orbital Battery Management

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.

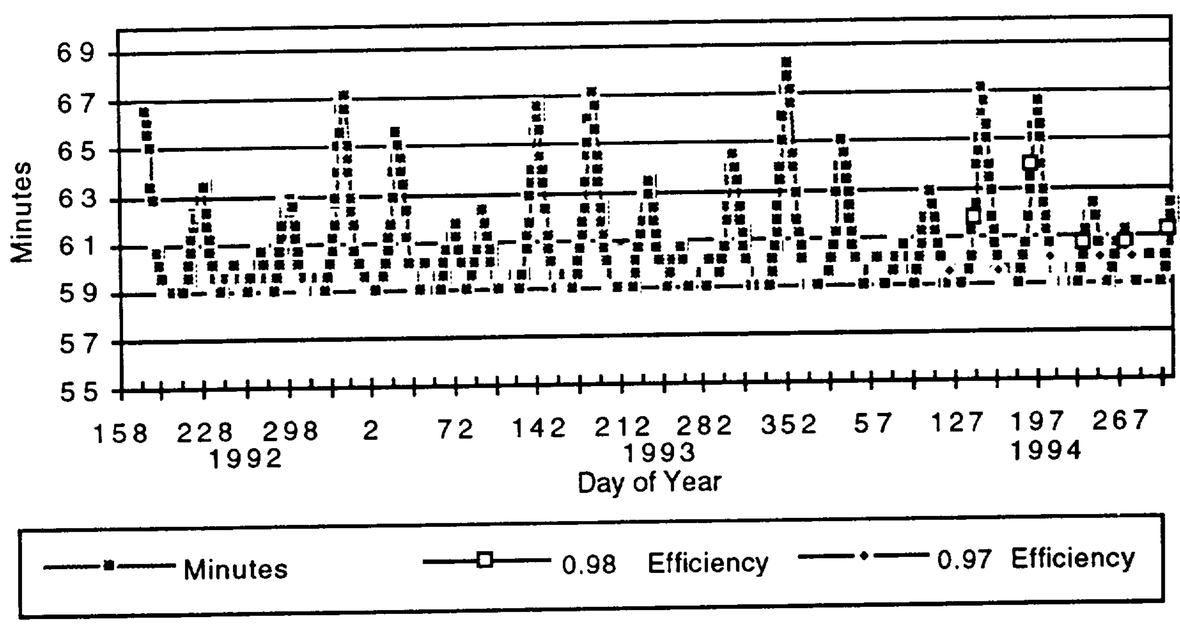

Figure 4: Length of Spacecraft Day for the Mission Life

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).

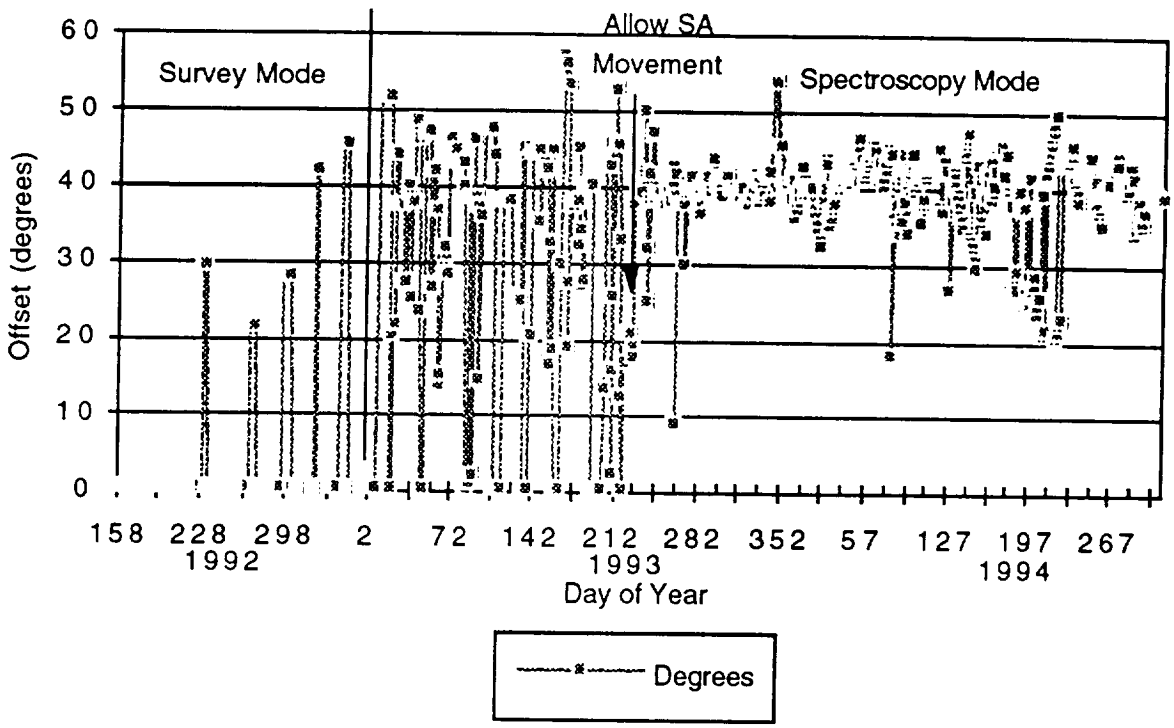

Figure 5: Effective Solar Array Offset for the Mission Life

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.

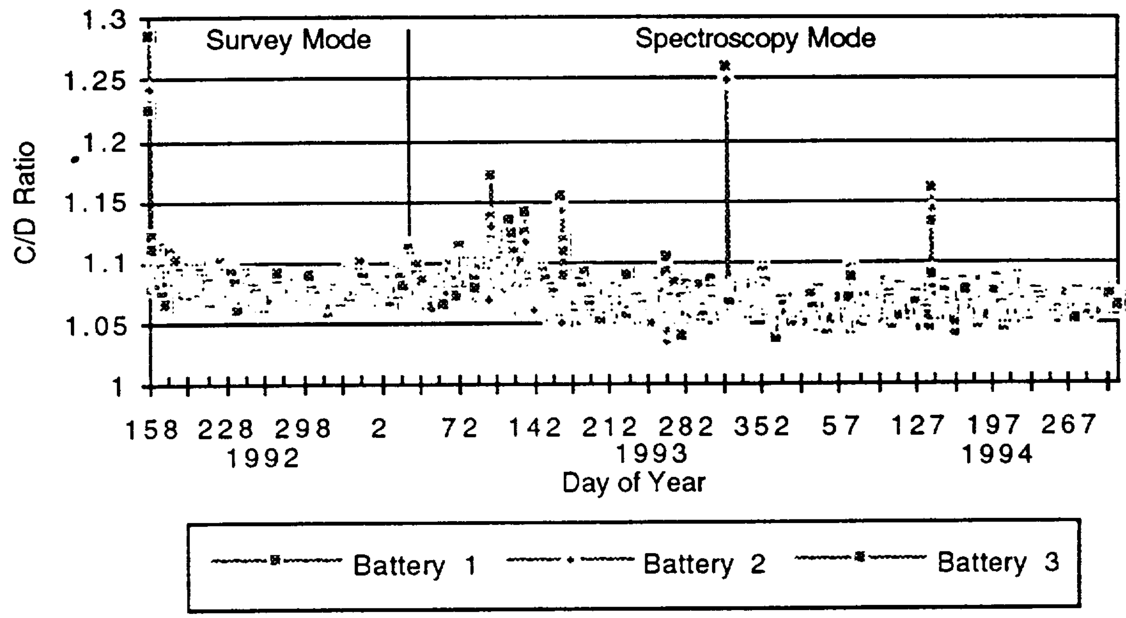

Figure 6: C/D Ratio for the Mission Life

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.

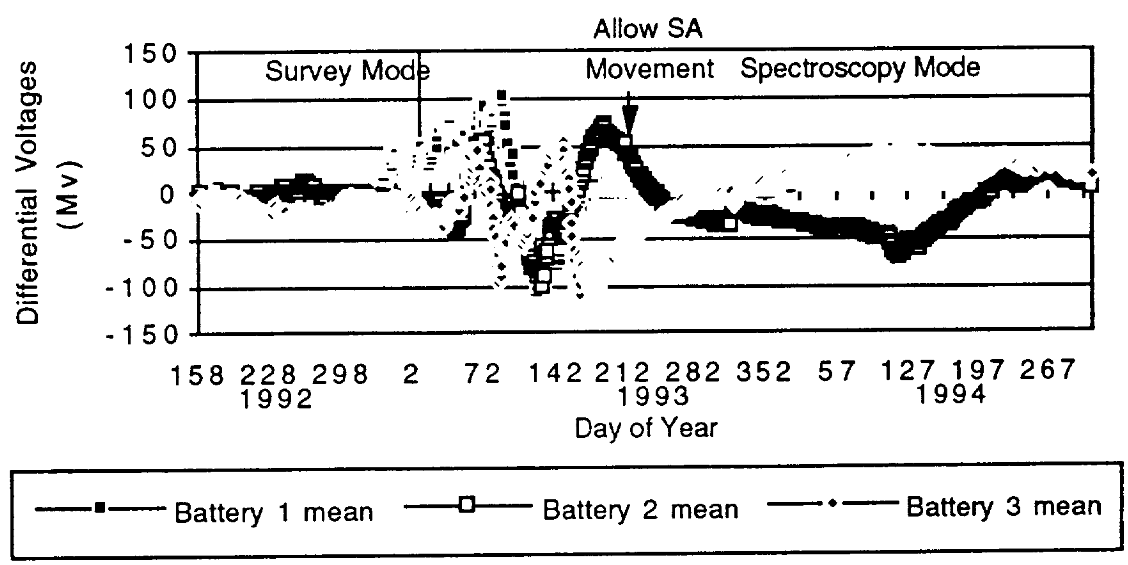

Figure 7: Half Battery Differential Voltages for the Mission Life

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.

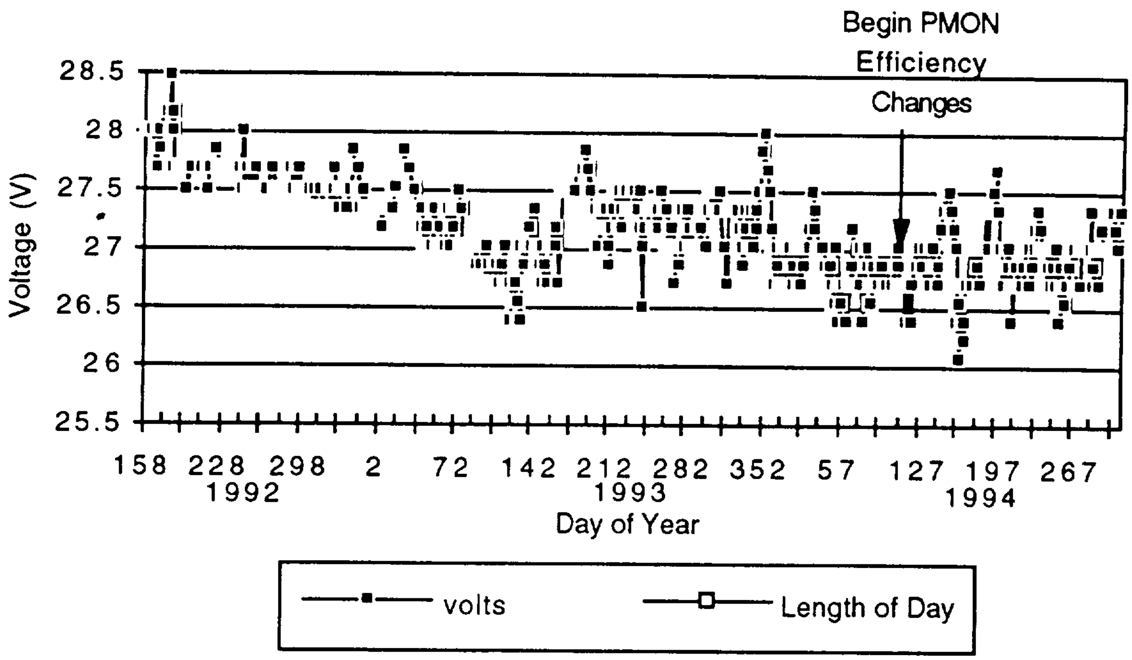

Figure 8: End-of-Night Load Bus Voltage for the Mission Life

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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November 15 - 17, 1994

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 ~4 °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 (°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© spread-sheet 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
1	MISSION DAY	YEAR	DOY	BETA	NET1	NET2	NET3	DISCHG1	DISCHG2	DISCHG3	D1-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
1	DOY	CD2	CD3	MAXD1	MAXD2	MAXD3	MAXD1-D2	AVGMAXDOD	I1	I2	I3	EONLBV	DV1MIN
150	121	1.011	1.029	532	491	499	41	16.9%	18.1	15.4	16.2	25.56	-97
151	122	1.007	1.025	521	480	489	41	16.6%	17.6	15.3	16	25.58	-59
152	123	1.002	1.020	525	476	489	49	16.6%	17.9	15.5	16.4	25.20	-53
153	124	1.025	1.042	514	460	477	54	16.1%	18.2	15.2	16.4	25.63	-18
154	125	1.023	1.042	494	466	470	28	15.9%	17.4	15.5	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
1	DOY	DV1MAX	DV1MED	DV1MAG	DV2MIN	DV2MAX	DV2MED	DV2MAG	DV3MIN	DV3MAX	DV3MED	DV3MAG	T1	T2
150	121	59	-19	156	-17	13	-2	30	-22	22	0	44	5.2	2.25
151	122	64	2.5	123	-15	13	-1	28	-20	22	1	42	5.16	2.14
152	123	78	12.5	131	-11	25	7	36	-22	22	0	44	5.02	1.92
153	124	90	36	108	-15	25	5	40	-20	36	8	56	4.81	1.79
154	125	90	34	112	-17	18	0.5	35	-7	35	14	42	4.62	1.74
155	126	81	22.5	117	-17	15	-1	32	-10	32	11	42	4.64	1.7
156	127	78	11.5	133	-15	15	0	30	-8	35	13.5	43	4.68	1.65
157	128	78	9	138	-17	17	0	34	-7	36	14.5	43	4.84	1.65
158	129	81	7	148	-15	14	-0.5	29	-13	34	10.5	47	5.16	1.8
159	130	87	10.5	153	-22	13	-4.5	35	-22	28	3	50	5.58	2.07
160	131	80	-7.5	175	-22	13	-4.5	35	-21	29	4	50	5.78	2.28
161	132	64	-24	176	-22	11	-5.5	33	-25	25	0	50	6.77	3.31
162	133	80	-10.5	181	-22	11	-5.5	33	-34	22	-6	56	7.44	3.83
163	134	77	5.5	143	-22	11	-5.5	33	-34	22	-6	56	7.64	4.18
164	135	70	-12	164	-22	11	-5.5	33	-34	22	-6	56	7.81	4.37
165	136	59	-25	168	-22	13	-4.5	35	-35	22	-6.5	57	8.05	4.49
166	137	52	-29.5	163	-22	18	-2	40	-35	21	-7	56	8.26	4.88
167	138	60	-31	182	-18	20	1	38	-34	22	-6	56	8.56	4.88
168	139	56	-56.5	225	-21	11	-5	32	-31	22	-4.5	53	8.45	4.58
169	140	25	-73	196	-21	11	-5	32	-34	22	-6	56	7.98	4.36
170	141	21	-78.5	199	-17	21	2	38	-34	22	-6	56	8.18	4.44
171	142	22	-71.5	187	-13	24	5.5	37	-34	24	-5	58	8.27	4.75
172	143	31	-57.5	177	-14	32	9	46	-34	22	-6	56	8.24	4.84
173	144	38	-46	168	-20	17	-1.5	37	-34	22	-6	56	8.04	4.44
174	145	50	-16.5	133	-17	25	4	42	-35	21	-7	56	8.69	4.98
175	146	49	-6.5	111	-17	29	6	46	-36	20	-8	56	8.46	4.73
176	147	56	7	98	-14	29	7.5	43	-36	21	-7.5	57	8.06	4.35
177	148	56	9	94	-13	24	5.5	37	-34	20	-7	54	8.01	4.16
178	149	56	7	98	-17	22	2.5	39	-34	18	-8	52	7.95	3.89
179	150	56	2	108	-21	15	-3	36	-34	15	-9.5	49	7.69	3.58
180	151	49	-13.5	125	-22	13	-4.5	35	-34	22	-6	56	7.67	3.35
181	152	29	-29	116	-20	28	4	48	-34	22	-6	56	5.99	2.12
182	153	39	-8	94	-11	31	10	42	-32	22	-5	54	5.33	1.56
183	154	55	15	80	-11	25	7	36	-29	22	-3.5	51	6.06	2.59

Sample of UARS Flight Battery Database

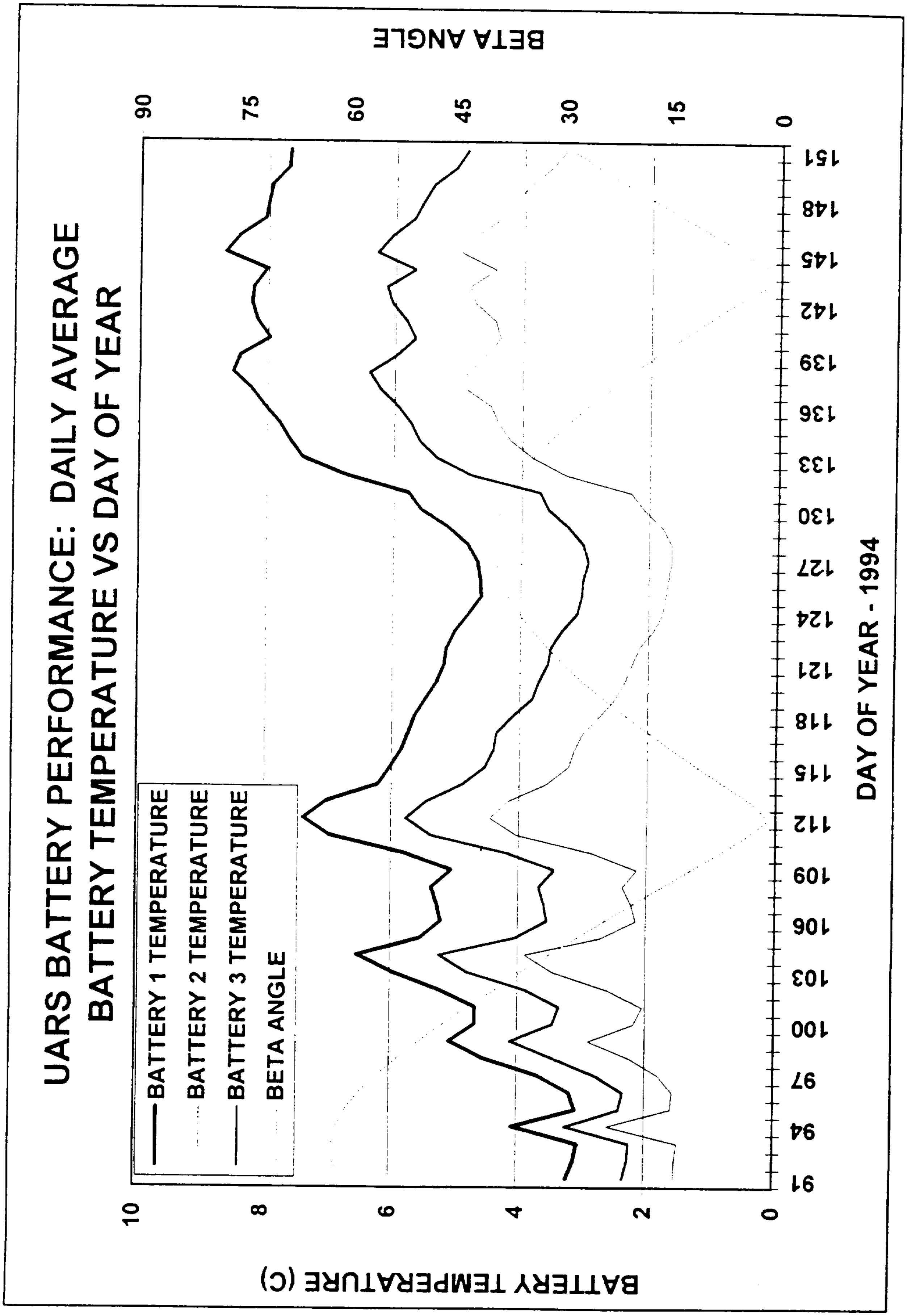
	C	AM	AN	AO	AP	AQ
1	DOY	T3	T1-T2	AVGPEAKI	VT	EFF. C/D GOAL
150	121	3.57	2.95	18.2	4	1.035
151	122	3.52	3.02	18.3	4	1.025
152	123	3.35	3.1	18.3	4	1.025
153	124	3.12	3.02	18.5	4	2
154	125	3.05	2.88	17.3	4	2
155	126	3.03	2.94	17.1	4	2
156	127	2.95	3.03	17.1	4	2
157	128	3.03	3.19	16.9	4	1.05
158	129	3.27	3.36	17.2	4	2
159	130	3.58	3.51	17.6	4	2
160	131	3.71	3.5	17.7	4	2
161	132	4.8	3.46	17.7	4	2
162	133	5.34	3.61	18.3	4	2
163	134	5.61	3.46	18.4	4	2
164	135	5.74	3.44	18.2	4	2
165	136	5.95	3.56	17.6	4	2
166	137	6.23	3.38	17.6	5	1.04
167	138	6.4	3.68	17.6	5	2
168	139	5.99	3.87	17.9	4	2
169	140	5.69	3.62	17.6	4	2
170	141	5.83	3.74	16.9	4	2
171	142	6.05	3.52	17.2	4	2
172	143	6.14	3.4	16.9	4	2
173	144	5.7	3.6	17.8	4	2
174	145	6.29	3.71	19	4	2
175	146	6.06	3.73	18.1	4	2
176	147	5.72	3.71	17.1	4	2
177	148	5.58	3.85	17.1	4	2
178	149	5.42	4.06	17.3	4	2
179	150	5.07	4.11	16.8	4	2
180	151	4.89	4.32	18	3	2
181	152	3.61	3.87	17.7	3	2
182	153	3	3.77	16.7	3	2
183	154	3.99	3.47	16	3	2

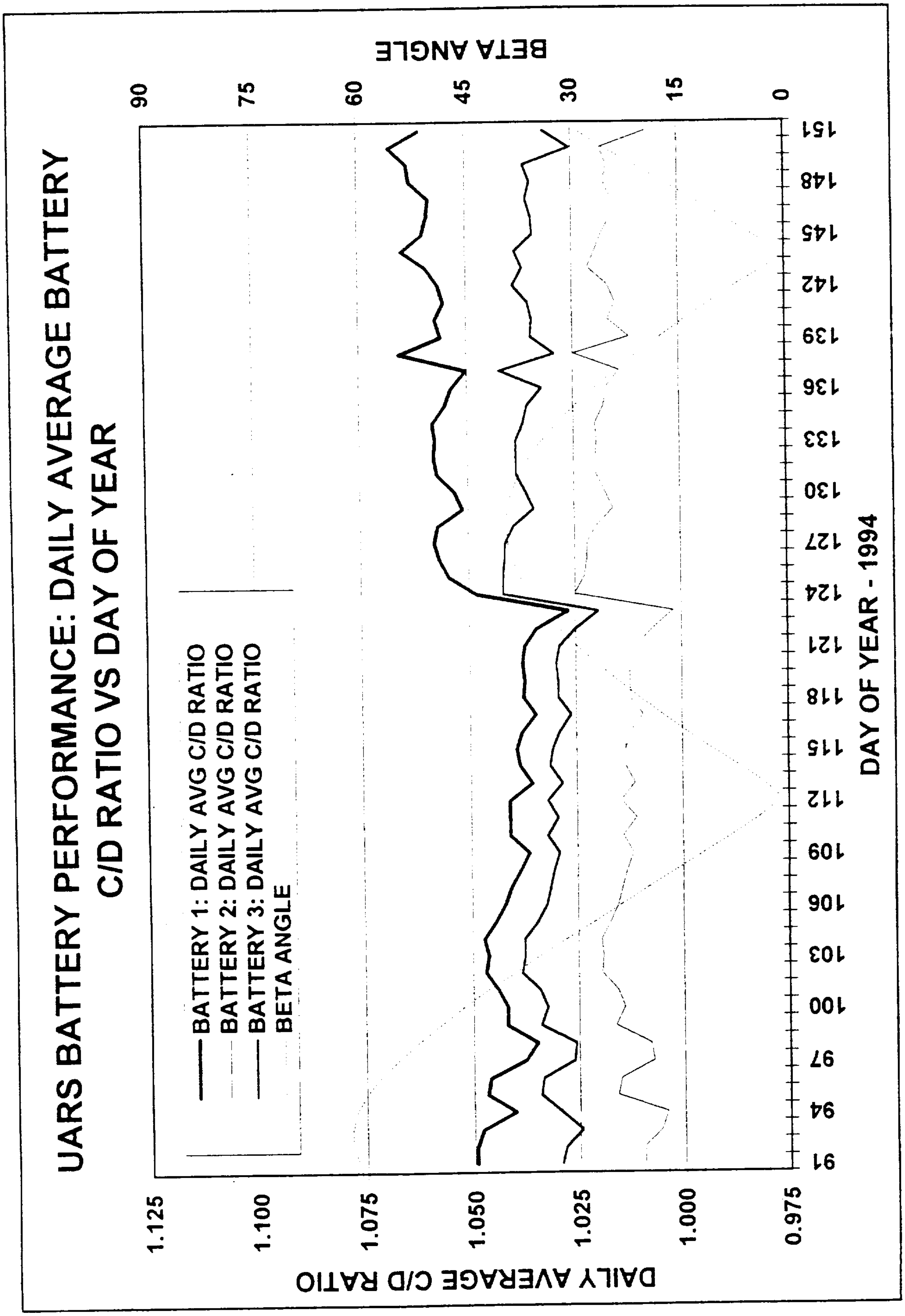
Sample of UARS Flight Battery Database

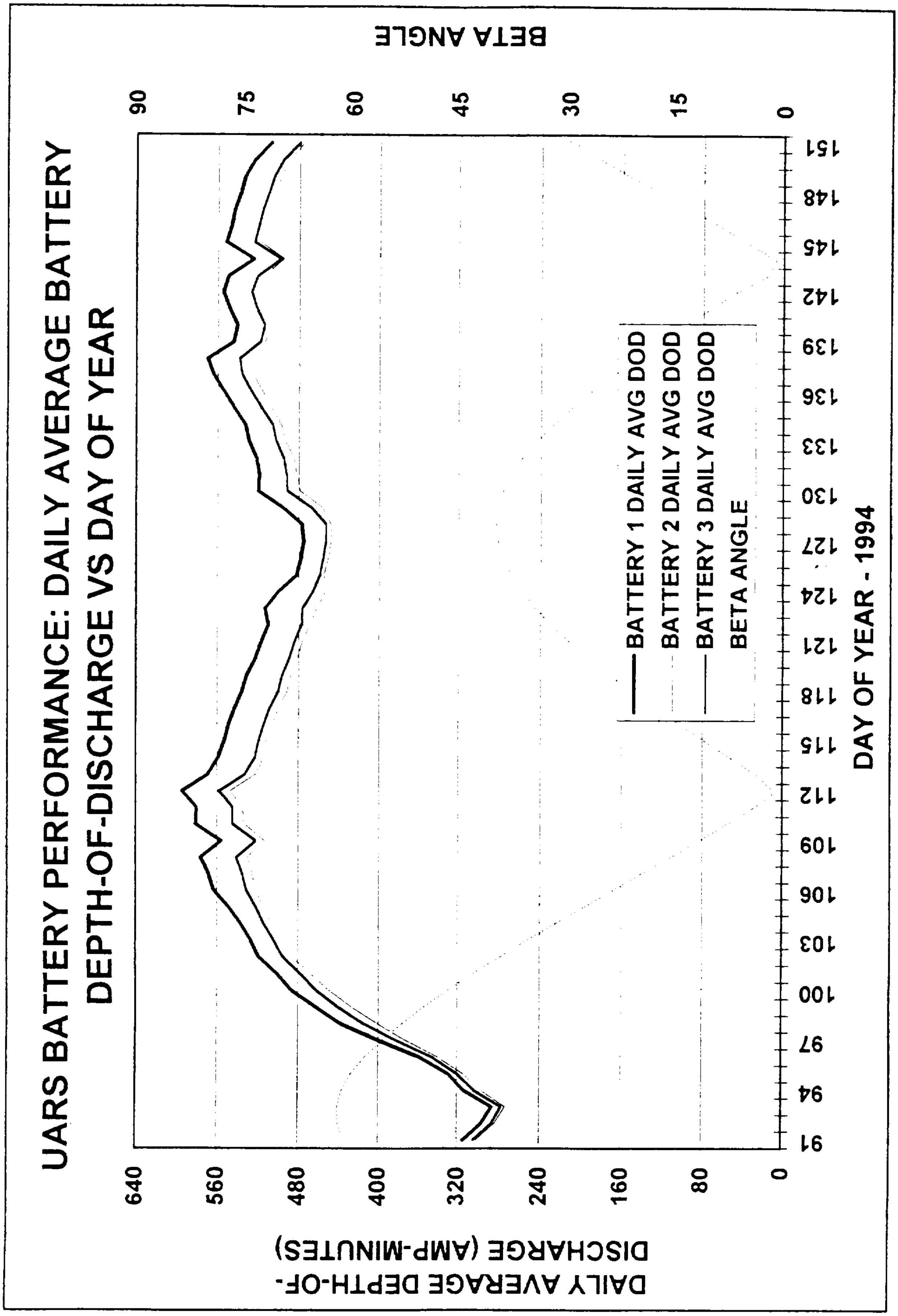
	C	AR
1	DOY	NOTES
150	121	
151	122	
152	123	
153	124	STRAIGHT VT4;
154	125	
155	126	
156	127	
157	128	
158	129	ISAMS TO HIGH POWER; STRAIGHT VT4;
159	130	STRAIGHT VT4; SOLAR ECLIPSE;
160	131	STRAIGHT VT4;
161	132	STRAIGHT VT4;
162	133	STRAIGHT VT4;
163	134	STRAIGHT VT4;
164	135	STRAIGHT VT4;
165	136	STRAIGHT 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

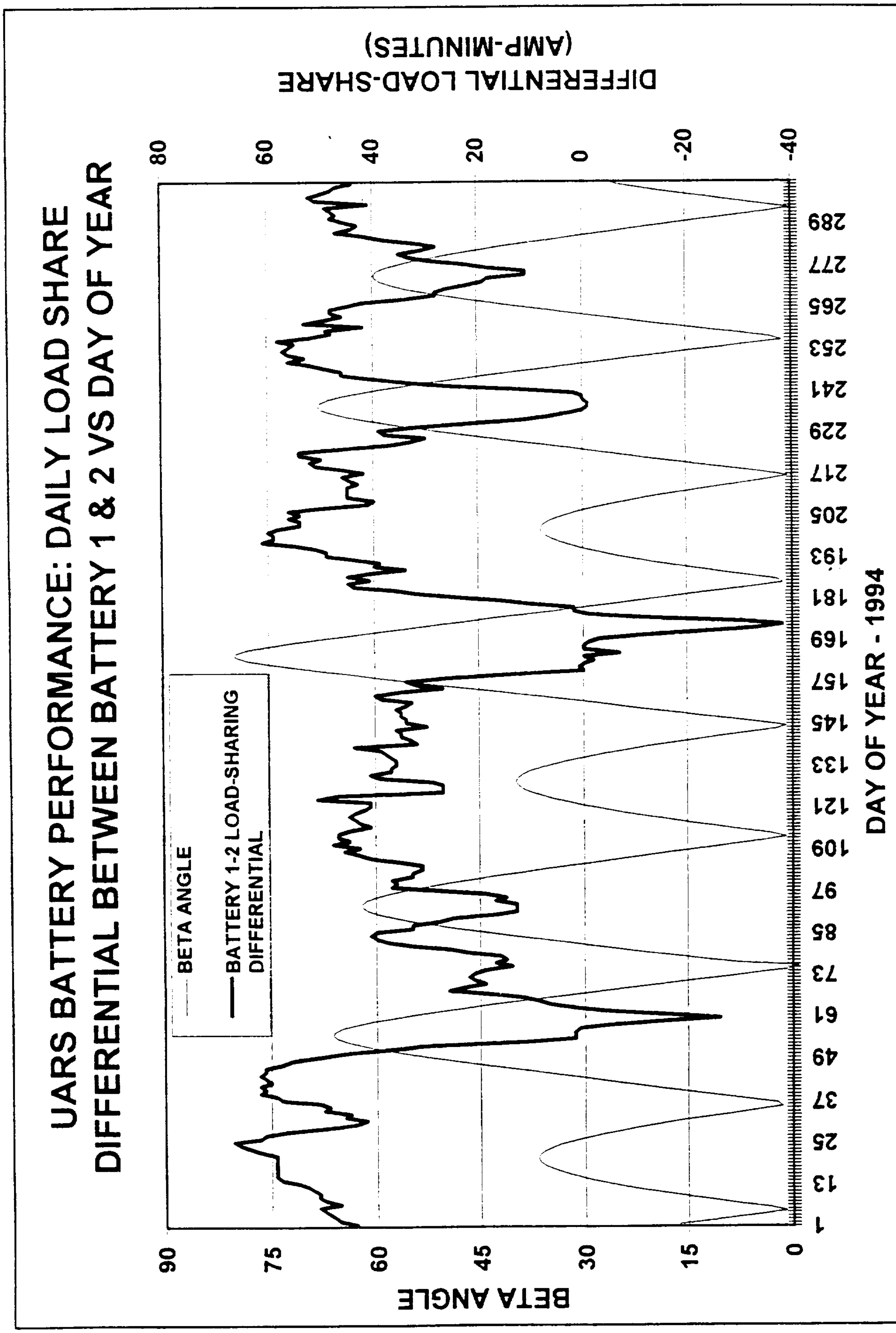
- Each of these 16 parameters (except #2 and #4) are plotted versus Day of Year
- The Beta Angle is on each figure as a reference
- Some figures cover the entire year on a single page while others are confined to 60-day intervals for greater utility

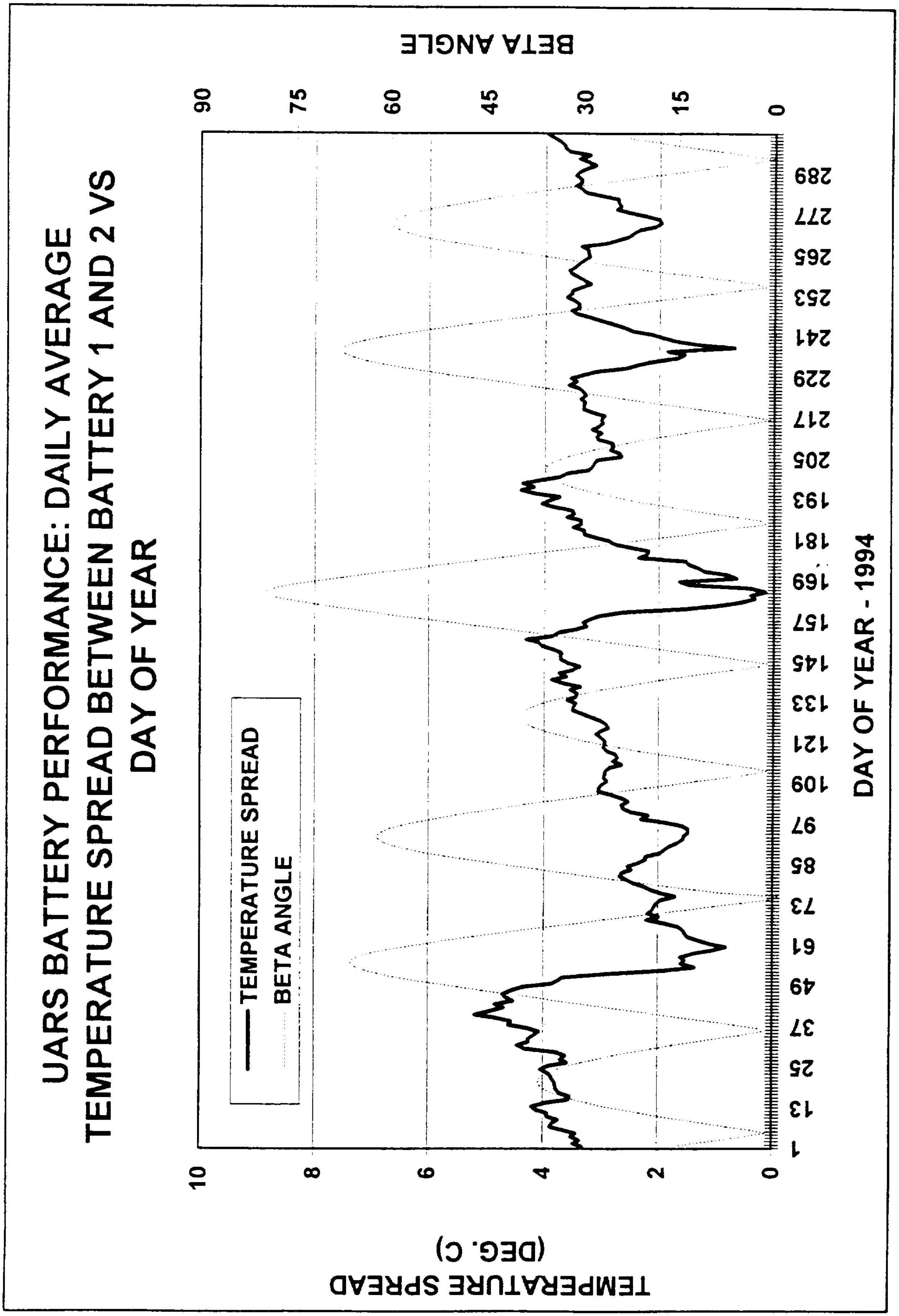

UARS BATTERY PERFORMANCE: DAILY AVERAGE
BATTERY TEMPERATURE VS DAY OF YEAR
BATTERY 1 TEMPERATURE
BATTERY 2 TEMPERATURE
BATTERY 3 TEMPERATURE
BETA ANGLE
BATTERY TEMPERATURE (C)
BETA ANGLE
DAY OF YEAR - 1994
0
2
4
6
8
10
0
15
30
45
60
75
90
91
94
97
100
103
106
109
112
115
118
121
124
127
130
133
136
139
142
145
148
151


UARS BATTERY PERFORMANCE: DAILY AVERAGE BATTERY C/D RATIO VS DAY OF YEAR
BATTERY 1: DAILY AVG C/D RATIO
BATTERY 2: DAILY AVG C/D RATIO
BATTERY 3: DAILY AVG C/D RATIO
BETA ANGLE
DAILY AVERAGE C/D RATIO
1.125
1.100
1.075
1.050
1.025
1.000
0.975
BETA ANGLE
90
75
60
45
30
15
0
DAY OF YEAR - 1994
91
94
97
100
103
106
109
112
115
118
121
124
127
130
133
136
139
142
145
148
151

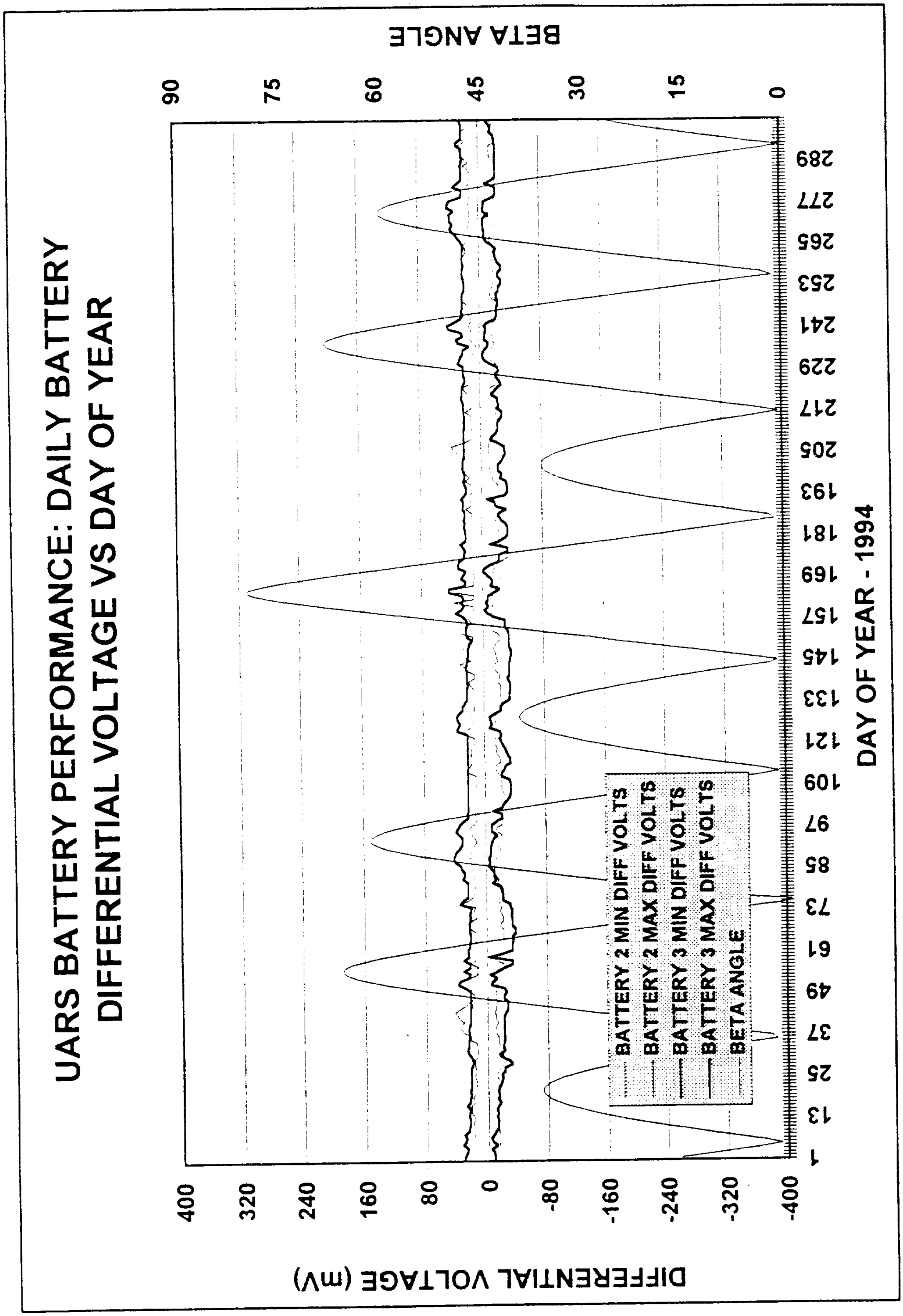

UARS BATTERY PERFORMANCE: DAILY AVERAGE BATTERY
DEPTH-OF-DISCHARGE VS DAY OF YEAR
DAILY AVERAGE DEPTH-OF-DISCHARGE (AMP-MINUTES)
640
560
480
400
320
240
160
80
0
BETA ANGLE
90
75
60
45
30
15
0
BATTERY 1 DAILY AVG DOD
BATTERY 2 DAILY AVG DOD
BATTERY 3 DAILY AVG DOD
BETA ANGLE
91
94
97
100
103
106
109
112
115
118
121
124
127
130
133
136
139
142
145
148
151
DAY OF YEAR - 1994

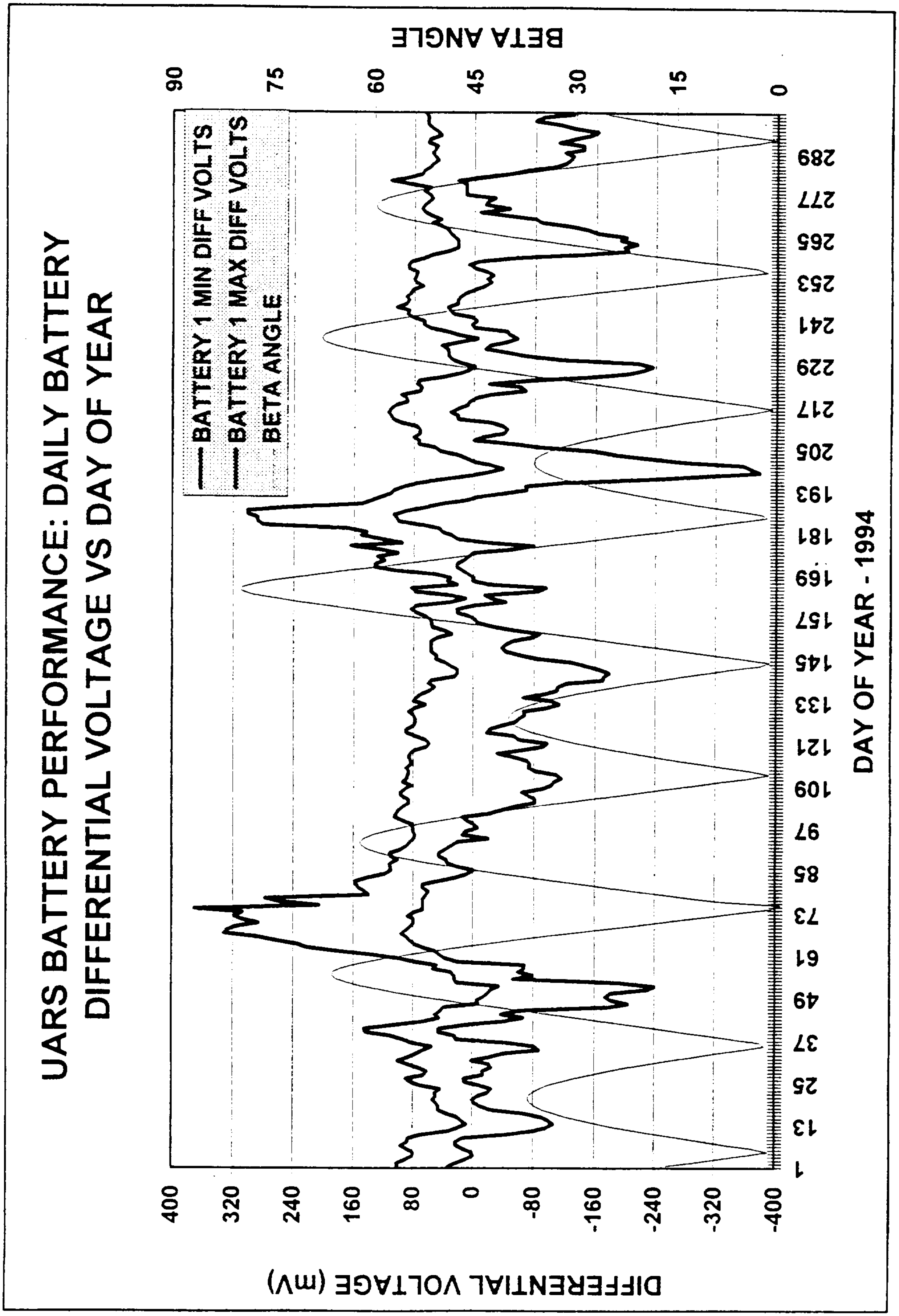
628


UARS BATTERY PERFORMANCE: DAILY LOAD SHARE
DIFFERENTIAL BETWEEN BATTERY 1 & 2 VS DAY OF YEAR
BETA ANGLE
BATTERY 1-2 LOAD-SHARING DIFFERENTIAL
BETA ANGLE
90
75
60
45
30
15
0
DIFFERENTIAL LOAD-SHARE (AMP-MINUTES)
80
60
40
20
0
-20
-40
1
13
25
37
49
61
73
85
97
109
121
133
145
157
169
181
193
205
217
229
241
253
265
277
289
DAY OF YEAR - 1994


UARS BATTERY PERFORMANCE: DAILY AVERAGE TEMPERATURE SPREAD BETWEEN BATTERY 1 AND 2 VS DAY OF YEAR
TEMPERATURE SPREAD
BETA ANGLE
TEMPERATURE SPREAD (DEG. C)
BETA ANGLE
DAY OF YEAR - 1994
0
2
4
6
8
10
0
15
30
45
60
75
90
1
13
25
37
49
61
73
85
97
109
121
133
145
157
169
181
193
205
217
229
241
253
265
277
289

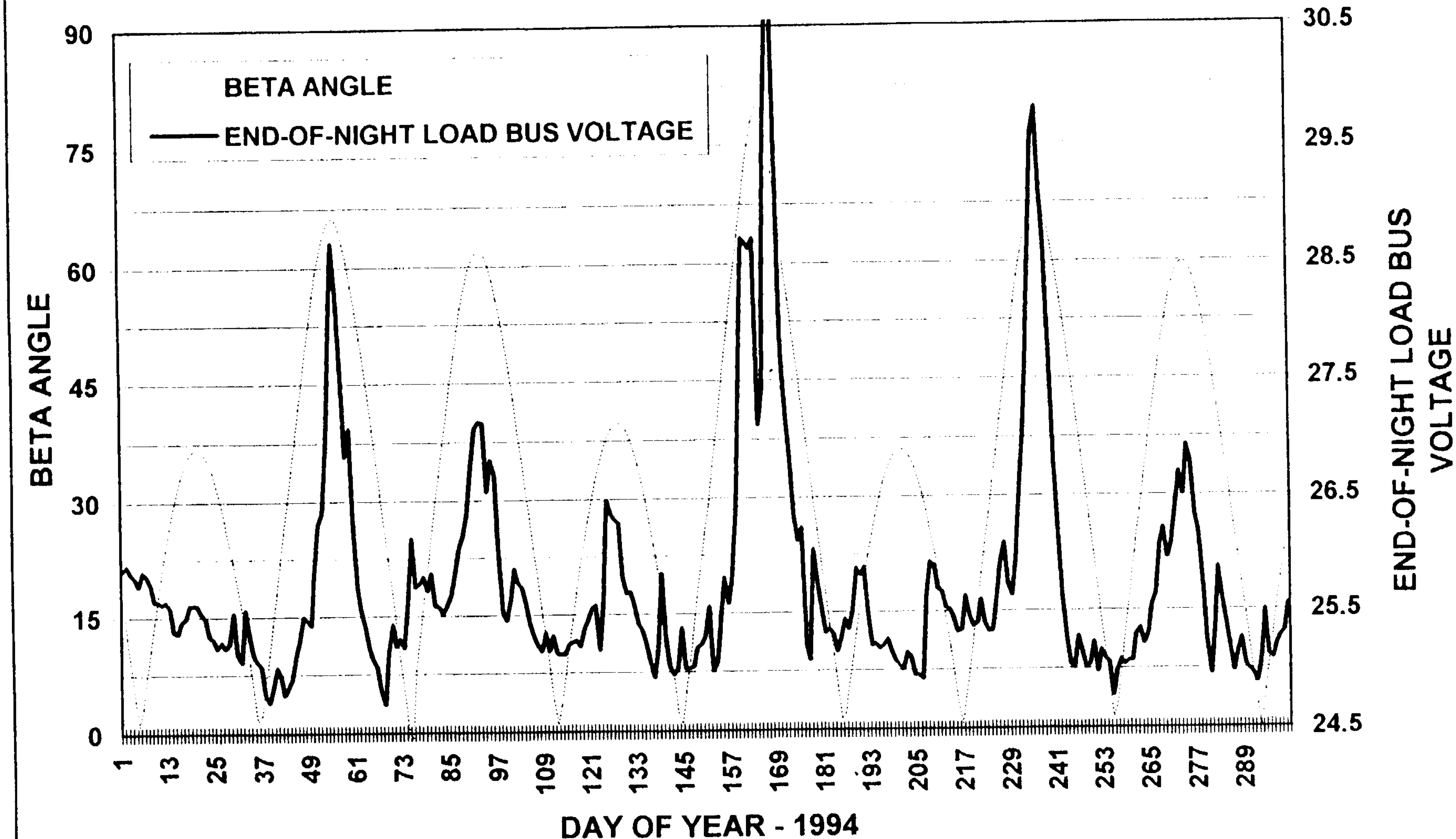
630


UARS BATTERY PERFORMANCE: DAILY BATTERY
DIFFERENTIAL VOLTAGE VS DAY OF YEAR
DIFFERENTIAL VOLTAGE (mV)
400
320
240
160
80
0
-80
-160
-240
-320
-400
BETA ANGLE
90
75
60
45
30
15
0
1
13
25
37
49
61
73
85
97
109
121
133
145
157
169
181
193
205
217
229
241
253
265
277
289
DAY OF YEAR - 1994
BATTERY 2 MIN DIFF VOLTS
BATTERY 2 MAX DIFF VOLTS
BATTERY 3 MIN DIFF VOLTS
BATTERY 3 MAX DIFF VOLTS
BETA ANGLE



UARS BATTERY PERFORMANCE: DAILY BATTERY DIFFERENTIAL VOLTAGE VS DAY OF YEAR
BATTERY 1 MIN DIFF VOLTS
BATTERY 1 MAX DIFF VOLTS
BETA ANGLE
DIFFERENTIAL VOLTAGE (mV)
400
320
240
160
80
0
-80
-160
-240
-320
-400
BETA ANGLE
90
75
60
45
30
15
0
1
13
25
37
49
61
73
85
97
109
121
133
145
157
169
181
193
205
217
229
241
253
265
277
289
DAY OF YEAR - 1994

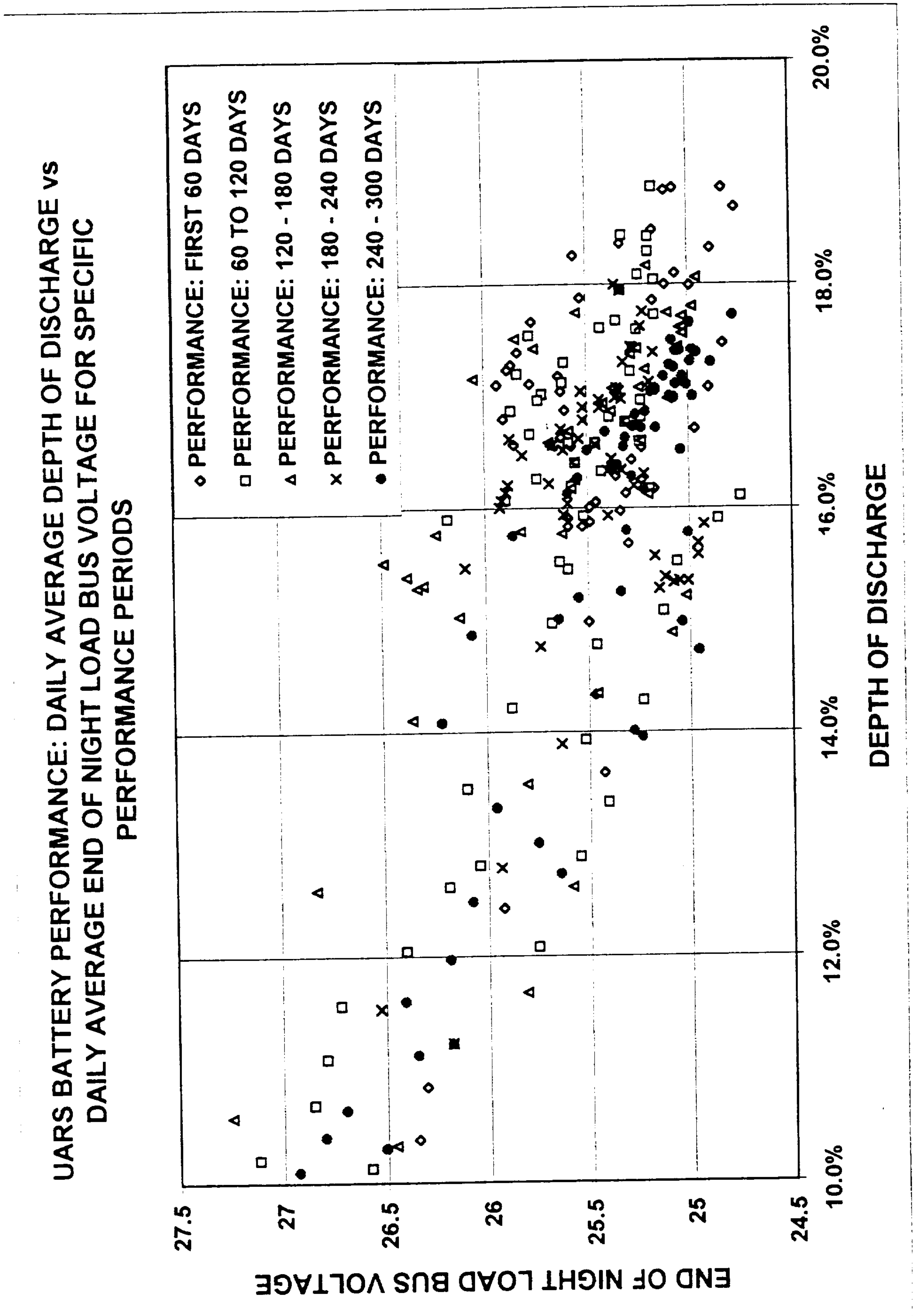
UARS BATTERY PERFORMANCE: DAILY AVERAGE END-OF-NIGHT LOAD BUS VOLTAGE VS DAY OF YEAR



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.

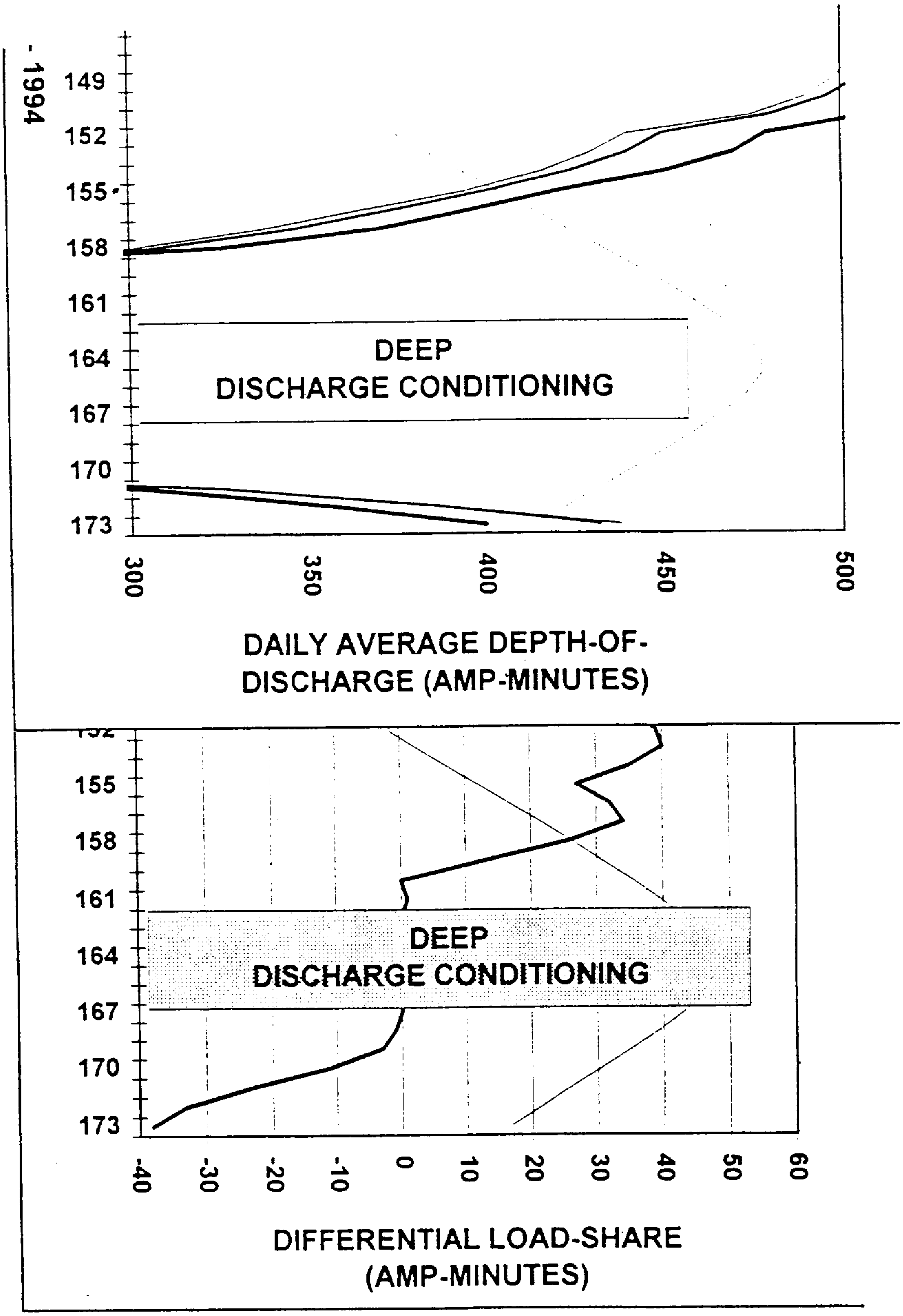
634


UARS BATTERY PERFORMANCE: DAILY AVERAGE DEPTH OF DISCHARGE vs DAILY AVERAGE END OF NIGHT LOAD BUS VOLTAGE FOR SPECIFIC PERFORMANCE PERIODS
◇ PERFORMANCE: FIRST 60 DAYS
□ PERFORMANCE: 60 TO 120 DAYS
△ PERFORMANCE: 120 - 180 DAYS
× PERFORMANCE: 180 - 240 DAYS
● PERFORMANCE: 240 - 300 DAYS
END OF NIGHT LOAD BUS VOLTAGE
27.5
27
26.5
26
25.5
25
24.5
DEPTH OF DISCHARGE
10.0%
12.0%
14.0%
16.0%
18.0%
20.0%

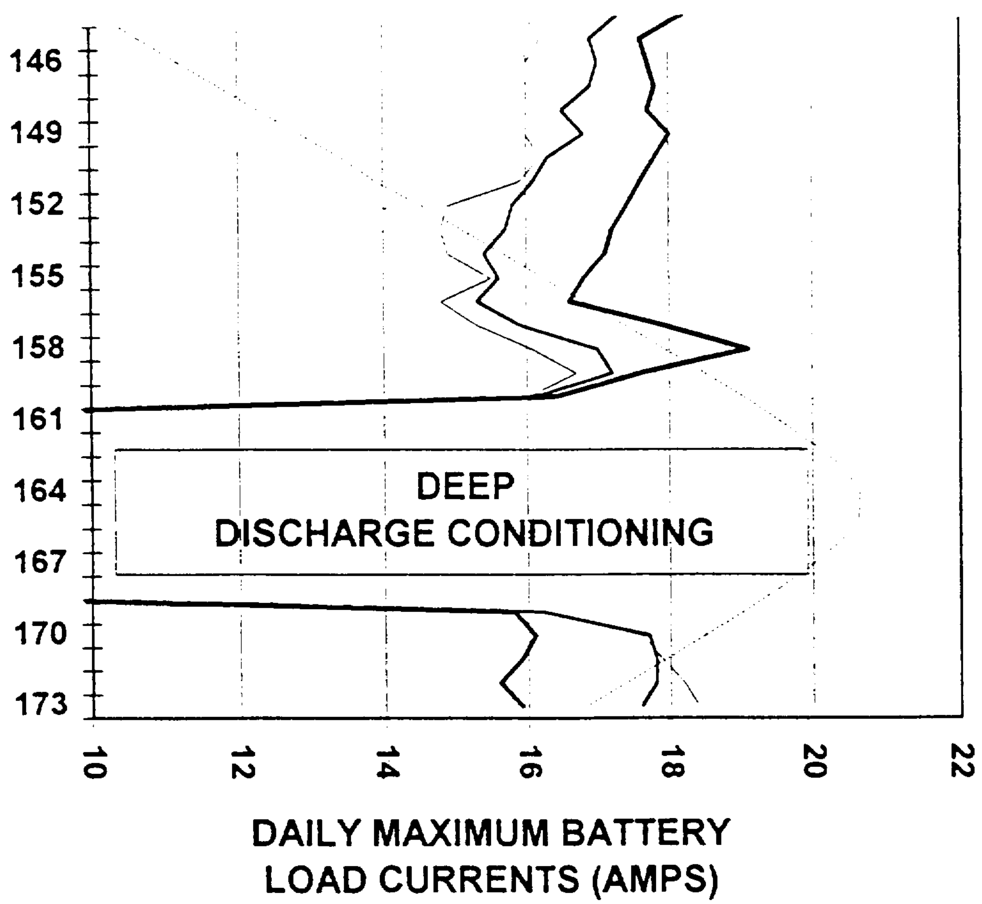
APPLICATION OF THE DATABASE

- 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



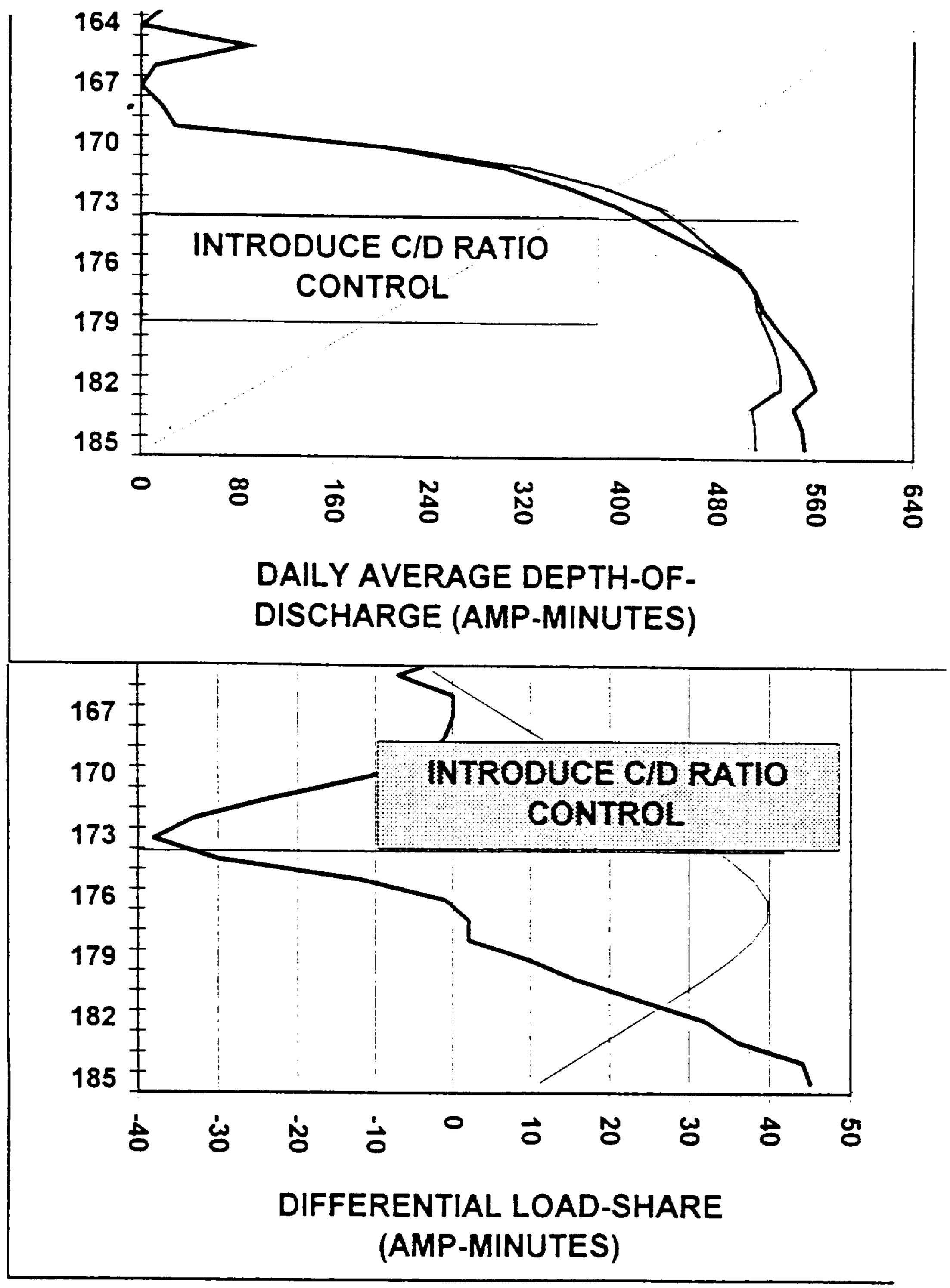
Example 1: Effects of Deep Discharge Conditioning



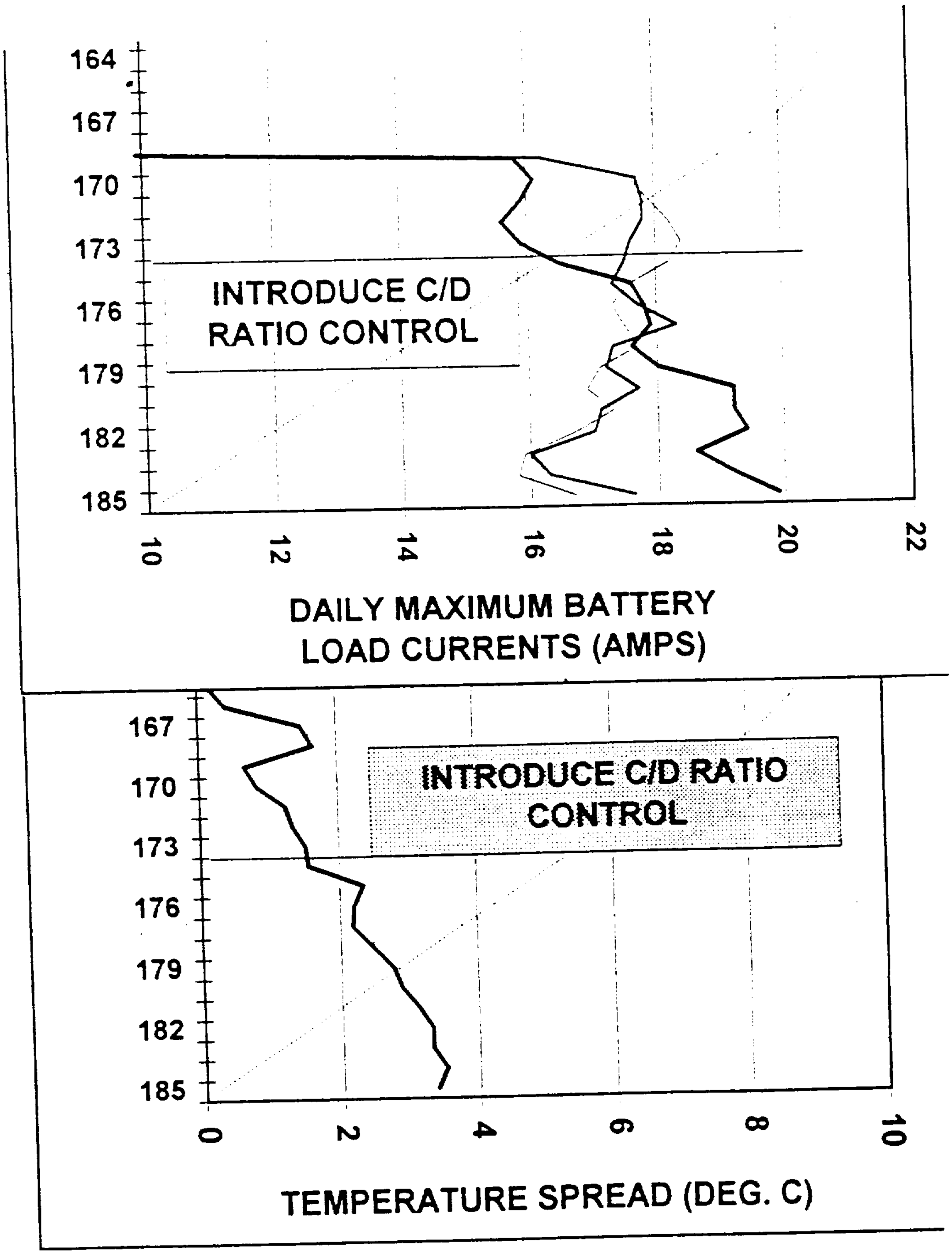
Example 1: Effects of Deep Discharge Conditioning
(continued)

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



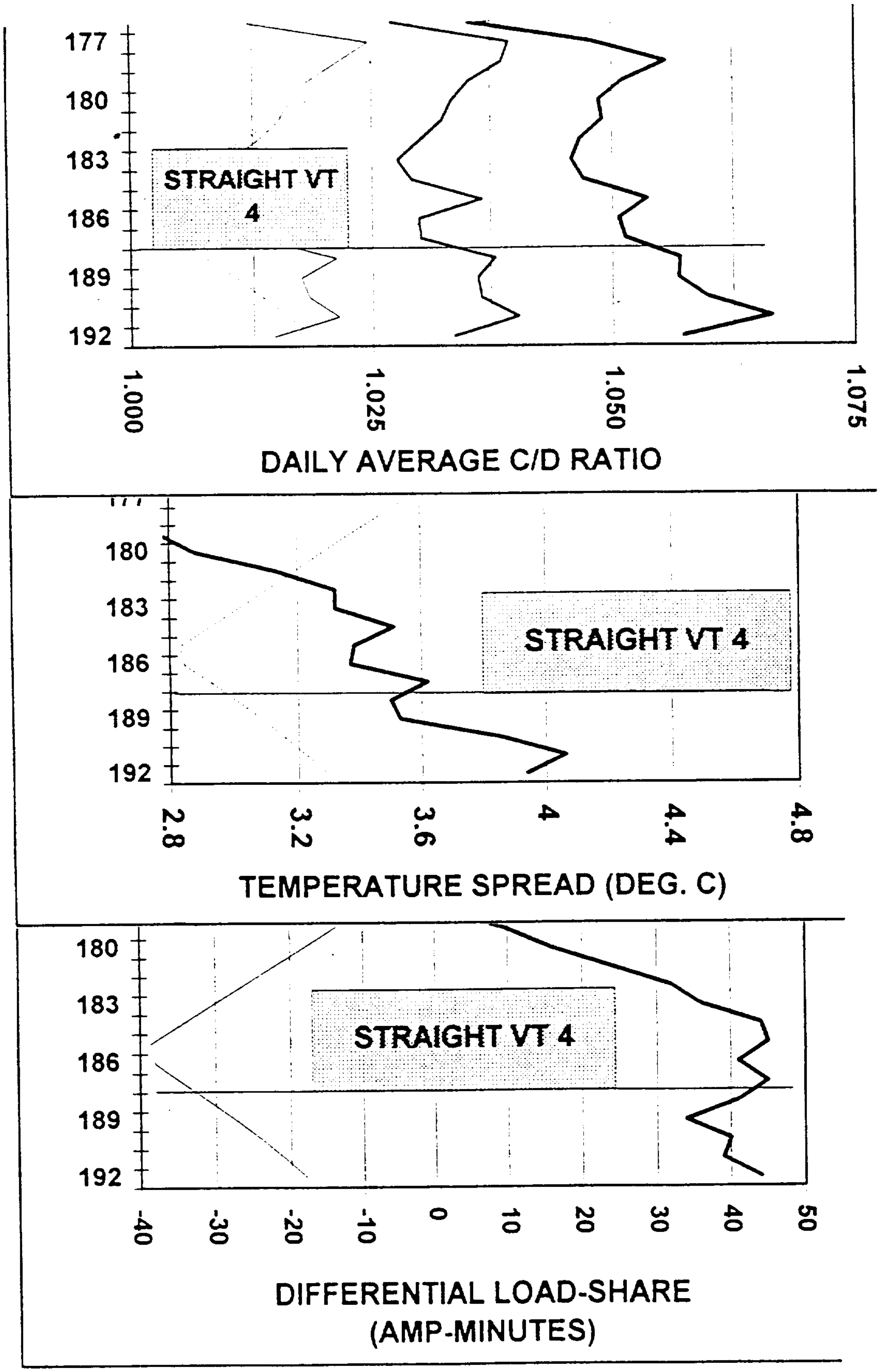
Example 2: Effect of C/D Ratio Control



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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☆ U.S. GOVERNMENT PRINTING OFFICE 1995-633-109/20019

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
February 1995

3. REPORT TYPE AND DATES COVERED
Conference Publication

4. TITLE AND SUBTITLE
The 1994 NASA Aerospace Battery Workshop

5. FUNDING NUMBERS

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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10. SPONSORING/MONITORING AGENCY REPORT NUMBER
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11. SUPPLEMENTARY NOTES
Proceedings of workshop sponsored by the NASA Aerospace Flight Battery Systems Program, hosted by the Marshall Space Flight Center, and held at the Huntsville Marriott on November 15-17, 1994.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited

Subject Category: 44

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
This document contains the proceedings of the 27th annual NASA Aerospace Battery Workshop, hosted by the Marshall Space Flight Center on November 15-17, 1994. The workshop was attended by scientists and engineers from various agencies of the U.S. Government, aerospace contractors, and battery manufacturers, as well as international participation in like kind from a number of countries around the world.

The subjects covered included nickel-cadmium, nickel-hydrogen, nickel-metal hydride, and lithium based technologies, as well as flight and ground test data.

14. SUBJECT TERMS battery, nickel-cadmium, nickel-hydrogen, nickel-metal hydride, lithium, cadmium, battery tests, electrode, pressure vessel

15. NUMBER OF PAGES
660

16. PRICE CODE
A99

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500 Standard Form 298 (Rev 2-89)