4/72063

1998 NASA Aerospace Battery Workshop

When: *October 27-29, 1998*

Where: *Huntsville Hilton*

Fee: *Once again, there will be no fee for this year's Workshop.*

Topics included:

Focused session on destructive physical analysis techniques and results is being planned. Other general sessions will be open to discuss topics submitted in abstracts which will likely include nickel-hydrogen, nickel-cadmium, and advanced technology cells and batteries.

Direct all correspondence and inquiries to:

Jeff Brewer
NASA Aerospace Battery Workshop
MS EB12
Marshall Space Flight Center, AL 35812
Phone: (256) 544-3345
FAX: (256) 544-5841
E-mail: jeff.brewer@msfc.nasa.gov

Visit the Workshop's home page at: http://marvin.msfc.nasa.gov/battshop/

Abstract Information

To make a presentation at the Workshop, submit a typed abstract by September 4, 1998. Include names and addresses of authors. ***Indicate who will be presenting so they can receive follow-up correspondence.***

Lodging Information

Huntsville Hilton
401 Williams Avenue
Huntsville, AL 35801

Phone: *(205) 533-1400 Main switchboard*
1-800-544-3197 Toll-free

Rate: *$65 / $76 Std / King (tax incl.)*

Mention the NASA Battery Workshop.

Display / Exhibit Information

To set up a display or exhibit, contact Caroline White at the Huntsville Hilton.

An agenda and an area map will be sent in late September to all who respond as "planning to attend".

1998 NASA Aerospace Battery Workshop

October 27-29, 1998
Huntsville Hilton

Agenda

Tuesday, October 27

7:30 **Registration**
Huntsville Hilton Lobby

8:30 **Automated Battery/Cell Configuration and Design Using Rule Based Technology**
John C. Lambert, Design Automation Associates, Inc.

9:00 **Thermal Control Using Electrochromism**
Hari Vaidyanathan, COMSAT Laboratories; and Gopalakrishna M. Rao, NASA Goddard Space Flight Center

9:30 **Battery/Ultracapacitor Hybrid for X-38 and SAFER**
Eric C. Darcy, NASA Johnson Space Center, and Bradley D. Strangways, Symmetry Resources, Inc.

10:00 **Break**

10:15 **Mars Microprobe Battery Development**
Jet Propulsion Laboratory

10:45 **Design and Flight Performance of NOAA-K Spacecraft Batteries**
Gopalakrishna M. Rao, P.R.K. Chetty, and Tom Spitzer, NASA Goddard Space Flight Center

11:15 **Lunch**

1:30 **Status of NASA/DOD Li-Ion Battery Program**
Jet Propulsion Laboratory

2:00 **The Applicability of Lithium-Ion Secondary Battery Cells**
Yoshitsugu Sone, Hiroaki Kusawake, and Saburo Kuwajima, NASDA

2:30 **Testing of the Eagle-Picher Lithium-Ion System**
Chad Kelly and Shellie Wilson, Eagle-Picher Technologies, LLC

3:00 **Break**

3:15 **Evaluation of Safety and Performance of Sony Lithium-Ion Cells**
Judith A. Jeevarajan and Bobby J. Bragg, NASA Johnson Space Center

3:45 **Bipolar Ni-MH Battery Development**
John Cole, Electro Energy, Inc.

6:00 **Movie at Space & Rocket Center**
Leave hotel lobby at 5:30

7:00 **Reception**
Huntsville Hilton

Wednesday, October 28

Focused Session: Recent Findings Resulting from the Destructive Physical Analysis of Cells
Lawrence H. Thaller and Albert H. Zimmerman, The Aerospace Corporation

8:00 **Expert System for Ni-H_2 Battery Cell Analysis**
Albert H. Zimmerman and Lawrence H. Thaller, The Aerospace Corporation

8:30 **Deactivation of Nickel Electrodes in Ni-H_2 Cells**
Albert H. Zimmerman, Michael V. Quinzio, Paul Adams, and Lawrence H. Thaller, The Aerospace Corporation

9:00 **Studies of Component Degradation, Silver Migration, and Shape Change in Experimental Silver-Zinc Cells**
Harlan Lewis, Naval Surface Warfare Center, Crane Division

9:30 **Break**

9:45 **Studies of Component Degradation During Testing of Nickel-Hydrogen Cells**
Harry Brown, Naval Surface Warfare Center, Crane Division

10:15 **Destructive Physical Analysis of Flight- and Ground-Tested Sodium-Sulfur Cells**
Margot L. Wasz and Boyd J. Carter, The Aerospace Corporation; Lt. Charles M. Donet, Air Force Research Laboratory; and Richard S. Baldwin, NASA Lewis Research Center

10:45 **Using DPA Results from Boiler Plate Ni-H_2 Cells to Help Understand Design Limitations and Validate New Cell Components**
Thierry Jamin, CNES; and Max Schautz, ESTEC

11:15 **Destructive Physical Analysis of Lithium-Ion Cells**
Nathan Isaacs, Joseph Bytella, John Baker, Ken Richardson, and Brian Stein, Mine Safety Appliances Company

11:45 **Lunch**

1:30 **Proposed Convention for Assigning Ni-H_2 Cell Capacity**
James R. Wheeler, Eagle-Picher Technologies, LLC

2:00 **Nickel-Hydrogen Reliability Update**
Doug Hafen

2:30 **High DOD LEO Life Cycling**
Jeff Dermott, Eagle-Picher Technologies, LLC

3:00 **Break**

3:15 **Ni-H_2 Batteries Performance On-Board Communication and Broadcasting Engineering Test Satellite**
Hiroaki Kusawake, Toshiaki Nakamura, Yoshitsugu Sone, and Saburo Kuwajima, NASDA

3:45 **Reversal Testing of Nickel-Hydrogen Cells**
Jack N. Brill and Ronald Smith, Eagle-Picher Technologies, LLC

Thursday, October 29

8:30 **MGS 2-Cell CPV Ni-H_2 Batteries**
Jet Propulsion Laboratory

9:00 **CPV Flight Experience**
William Cook and Jack Brill, Eagle-Picher Technologies, LLC

9:30 **Status of SPV/CPV Testing at Crane Division NSWC**
Harry Brown and Steve Hall, Naval Surface Warfare Center, Crane Division

10:00 **Break**

10:15 **Ni-H_2 SPV Battery Test Results**
Steve Sterz, Beth Parmley, and Dwight Caldwell, Eagle-Picher Technologies, LLC

10:45 **Lightweight Silver-Hydrogen Cell Design**
D.K. Coates, S.C. Cooper, and D.P. Bemis, Eagle-Picher Technologies, LLC

Design and Flight Performance of NOAA-K Spacecraft Batteries

Gopalakrishna M. Rao, P. R. K. Chetty*, Tom Spitzer, and P. Chilelli**
NASA Goddard Space Flight Center
Greenbelt, Maryland 20771
(301)286-6654

ABSTRACT

The US National Oceanic and Atmospheric Administration (NOAA) operates the Polar Operational Environmental Satellite (POES) spacecraft (among others) to support weather forecasting, severe storm tracking, and meteorological research by the National Weather Service (NWS). The latest in the POES series of spacecraft, named as NOAA-KLMNN', one is in orbit and four more are in various phases of development. The NOAA-K spacecraft was launched on May 13, 1998. Each of these spacecraft carry three Nickel-Cadmium batteries designed and manufactured by Lockheed Martin. The battery, which consists of seventeen 40 Ah cells manufactured by SAFT, provides the spacecraft power during the ascent phase, orbital eclipse and when the power demand is in excess of the solar array capability. The NOAA-K satellite is in a 98 degree inclination, 7:30AM ascending node orbit. In this orbit the satellite experiences earth occultation only 25% of the year. This paper provides a brief overview of the power subsystem, followed by the battery design and qualification, the cell life cycle test data, and the performance during launch and in orbit.

I. INTRODUCTION

The advanced Television Infrared Observation satellite program is a cooperative effort between the National Aeronautics and Space Administration (NASA), the NOAA, the United Kingdom, Canada and France, for providing day and night global environmental and associated data. The NASA is responsible for procurement, launch, and checkout of these spacecraft before transferring them over to NOAA. The Lockheed Martin Missiles and Space (LMMS) Company is the prime contractor responsible for building these spacecraft.

A typical operational system, known as Polar Operational Environmental Satellites (POES), consists of two satellites in sun-synchronous (near polar) orbits, one in a morning (AM) orbit at 833 km, and the other in an afternoon (PM) orbit at 870 km. Figure-1 shows the NOAA-K spacecraft in orbital configuration. The K-Spacecraft of the latest POES series was launched on May 13, 1998 while the other four are in various phases of development and fabrication at LMMS.

To date, the overall Electrical Power Subsystem (EPS) including the batteries has been exhibiting nominal performance per design requirements. Continuous data has been obtained through housekeeping telemetry, and has been analyzed to verify the performance of the power system. This paper provides first a brief

*Kris Engineering, Inc., 14120 Stonecutter Drive, N. Potomac, MD 20878.
** LMMS, Newtown, PA

overview of the overall power subsystem, followed by a description of the battery, design and qualification, the cell life cycle test data, and performance during launch and in orbit.

II. POWER SYSTEM

The NOAA-K EPS, as shown in Figure-2, is based on the principle of Direct Energy Transfer (DET) from the solar cell array. This EPS implements a centralized regulation concept utilizing a partial shunt regulated main power bus approach. Within the power subsystem, three rechargeable batteries are the uninterrupted source of energy for the spacecraft. The EPS consists of a single wing solar array, Solar Array Telemetry Commutator Unit, Solar Array Drive, Array Drive Electronics, Batteries, Battery Current Sensors, Battery Charge Assemblies (BCAs), Power Supply Electronics (PSE), Power Converter, and Controls Power Converter. The batteries supply power to the loads during orbital eclipse and during the periods when the load power demand exceeds the solar array capability.

During normal operation of the power subsystem, satellite load power is supplied by either the solar array or batteries. In sunlight, the solar array supplies the load power directly and provides for battery recharge via the charge regulators. When the spacecraft is in eclipse, the three batteries supply the power for the loads via the discharge diodes and the boost voltage regulator.

Each of these spacecraft carry three conventional nickel-cadmium batteries designed and manufactured by Lockheed Martin. Each battery consists of seventeen 40-Ah capacity cells manufactured by SAFT. Battery cell design has been guided by the life and reliability requirements of 3-years (goal) in orbit performance in addition to a 5-year ground storage.

III Battery Design

The battery system consists of three 40 Ah rated batteries to provide a combined capacity of 120 ampere-hours. Each battery is comprised of 17 series-connected closely matched cells, physically subdivided into two packs: one containing nine cells and the other containing eight (Figure-3). At cell level, all cells in each battery have a) capacities within $\pm$ 3% of the 17 cell average and b) end of charge voltages within $\pm$ 0.008V of the 17 cell average at 21^{0}C and 0^{0}C. Each pack has the same outer dimensions, and the commonality is achieved by using an additional dummy cell in the 8-cell pack. Figure-4 shows the details of a cell thermal sleeve whereas Figure-5a shows an assembled 9-cell pack without radiator. A 9-cell pack employs a dummy cell for easy mechanical design. Figure-5b shows the same 9-cell pack with its radiator, connector brackets and spacecraft attaching struts integrated. The same assembly is shown mounted on the spacecraft in Figure-6a. Figure-6b shows a top view of the spacecraft with all six battery packs integrated.

<u>Module Assembly Design</u>

The battery modules are capable of being mounted to the spacecraft, using the predefined interfaces. The 8 and 9 cell packs are designed such that an 8 cell pack can not mechanically mount to the spacecraft in a 9 cell location and viceversa. Battery mechanical interfaces with the spacecraft provide for thermal isolation. The battery is designed such that the thermal control electronics (TCE) connector is easily accessible when the pack is mounted on the spacecraft. The use of dissimilar metals in direct contact with the cells and their modules is avoided. Use of any magnetic material (except energy storage cells) is avoided. The cell assembly is replaceable without degrading the performance or reliability of other battery components. Each battery module is designed to withstand individual cell pressures of up to 65 psig.

The battery module assembly includes the battery module, the module's secondary support structure, and all thermal control components (including the TCE). The maximum weight of a 9-cell module is 52.5 lbs and 8-cell module is 46.6 lbs.

Thermal Design

Battery packs are designed to achieve orbital average cell temperature from 3°C to 7°C during nominal 3-battery operation and from -5°C to 18°C during 2-battery operation under worstcase end-of-life conditions. However, under optimum conditions, cell temperature between 0°C to 7°C during nominal 3-battery operation and -5°C to 15°C during 2 battery operation were achieved. In addition, a maximum gradient within a cell of <5°C, a maximum cell to cell gradient within a battery of <5°C and the orbital average battery temperature between 3°C and 5°C were achieved. The battery packs are thermally isolated from the spacecraft.

Following are some of the definitions with respect to various temperatures referred in this section. Cell temperature is defined as the average of the temperature of all of the nodes in the cell. Pack temperature is defined as the average of the cell temperatures within the pack. Battery temperature is defined as the average of the 17 cell temperatures within the battery. Maximum gradient within a cell is defined as the maximum temperature difference between any two nodes on the cell. Maximum gradient within the pack is defined as the maximum temperature difference between cells in a pack. Gradient within the battery is defined as the maximum temperature difference between cells in a battery.

The battery temperature control is achieved by active and passive means. Passive temperature control is accomplished by means of a fixed radiative surface, and a multi-layer insulation (MLI) blanket on each module, whereas active temperature control is exercised through a strip heater on each module, controlled by the TCE. Separate strip heaters controlled by two series thermostatic switches serve as back-up to the primary heater circuit.

A functional block diagram for the two packs that make up any one of the three identical 40 Ah batteries is presented in Figure-7. Each pack contains 2 thermistors for the battery voltage/temperature (V/T) limiting reference circuit in the battery charge control electronics. Thermistors bonded to the end surface of cells 6A and 2B provide a combined voltage proportional to temperature for the primary control circuit, and thermistors bonded to the end surface of cells 2A and 5B provide the combined output voltage for the backup control circuit.

A 25% heater margin for the cold case and heater control authority of 25% of the battery average power dissipation during the hot case are incorporated in the thermal design. The battery thermal design allows a continuous trickle charge (0.50 Amps ± 0.20A) operation at any temperature between -5°C and 30°C during integration and test. The thermistors are operable over the temperature range of -10°C to +40°C. The placement of the V/T telemetry thermistor is optimized such that the temperature sensed by the thermistor is as close to the average pack temperature as possible.

Electrical Design

The electrical harness is designed such that the maximum voltage drop between the battery terminals and input to the battery discharge regulator is <1.0 volt during normal operations and is capable of a maximum charge rate of 15 amps. During ground operations, the battery is capable of being discharged at up to 35 amperes for a minimum of 35 minutes, over the temperature range -5°C to +30°C. Each battery provides an output for the Electro Explosive Device bus with a voltage range of 19.5 V to 25.8 V, and up to a 10.0A current under normal operating conditions. A means for electrically grounding the battery structure to the spacecraft structure is provided.

Each module has provisions for connecting individual cells (one wire connection to each cell positive terminal and one to each cell negative terminal) to the battery reconditioning unit via a separate dedicated connector and to ground reconditioning unit via another separate connector. The battery chassis is electrically double isolated from any cell terminal.

Thermistor circuits bonded to the end surface of cells 3A and 7B provide a separate temperature telemetry signal from each pack for the spacecraft telemetry system. A second set of thermistor circuits, similar to that used for telemetry, are bonded to cells 4A and 4B. These circuits are used only during ground test operations to permit battery pack temperature monitoring while the batteries are charged externally with spacecraft power off. Power for these test thermistor circuits is supplied by the ground support equipment.

In addition to the temperature sensing and control circuits, the battery includes a battery voltage telemetry circuit, test point isolation resistors for monitoring battery voltage during ground testing, and an isolation diode for protection when the battery is charged from a power source external to the satellite during ground checkout.

IV. Battery Qualification/Acceptance Testing

A qualification battery consisting of a 9 cell module and an 8 cell module was constructed and was subjected to the qualification tests as outlined in Figure-8.

All flight batteries were acceptance•flight tested following the outline in Figure-9. Each battery is discharged at the 10.0 amperes rate during the random vibration tests. Vibration levels are presented in Table-1.

V. Cell Life Cycle Tests

The intent of the life cycle testing is to evaluate the flight-worthiness of cells from this manufacturer for POES spacecraft batteries. The purpose of the first pack (10 cells) is to simulate the worst-case LEO mission-profile expected for the POES program whereas the second pack (5 cells) reveals performance of these cells under a NASA-Standard stress test LEO mission profile. The test parameters for these tests are summarized in Table-2.

Both the tests were successful. The Mission-Profile test completed 9848 cycles before it was stopped as these batteries were meant for the NOAA-K spacecraft operating in the AM orbit. In this orbit, the spacecraft experiences only about 2100 eclipses per year. The Stress test completed 7106 cycles before it was stopped as this reflects more life than the POES mission requirement.

VI. Battery Charge Control

The three batteries are charged individually by separate charge regulators, but are discharged in parallel through the discharge isolation diodes. Battery charge control is performed by charge regulators which protect the batteries from overcurrent and overvoltage conditions. This function is performed by monitoring battery charge current, voltage, and temperature parameters.

During normal recharge and before the overcharge condition, charge current to each battery is limited to any one of four ground-commandable rates: 12.5, 10.0, 7.5, or 0.5 amperes. The only limitation is that the sum of the three charge rates cannot exceed 30 amperes due to thermal design constraint.

When the battery voltage reaches one of sixteen ground commandable voltage levels (which are a function of battery temperature), the battery current is reduced by a tapering action so that the battery voltage level remains limited to the commanded level. Any one of the sixteen limits, as shown in figure-10a, can be independently selected for each battery.

The sixteen levels have been chosen on the following basis: I) V/T curve 3 is the curve of choice for supporting the maximum satellite load during an 80^0 sun angle orbit (longest eclipse time) after 2 years life; ii) V/T curves 1 and 2 are held in reserve in the event that battery cell charge voltage characteristics increase with age; iii) V/T curves 4 and 5 are available to control battery overcharge and trim C/D ratios with changes in spacecraft loading and sun angle; iv) V/T curves 6, 7, and 8 are available to taper back charge current to safe values (~ 0.5A) during periods of extended overcharge; v) V/T curve levels below level 8 (9-16) are designed to accommodate a variety of conditions which include a possible reduction in cell charge voltage characteristic with aging, development of partial or soft short circuit conditions in some cells, or the actual presence of a full short in one single cell out of the 17 series cells that comprise a battery; and vi) The shape of all 16 voltage limit curves has been purposely depressed at higher battery temperatures to reduce the possibility for thermal runaway.

The specific selection of the V/T curve to be used for charging each battery during any given set of circumstances should have as its goal the achievement of orbital energy balance without excessive battery overcharge. Figure-10b presents a curve showing the minimum charge-to-discharge ratio recommended for ensuring energy balance as a function of battery temperature.

VII. NOAA-K BATTERY OPERATIONS & PERFORMANCE

The NOAA-K spacecraft was launched into an orbit with a period of approximately 102 minutes with eclipse duration varying from 0 to 24 minutes.

A. Operations

Pre-launch recharge controls are set high (charge rate of 10 amps per battery, V/T Level of 4) as a precaution to provide a high recharge level and maintain power balance, in the event of anomalous launch conditions (solar array not tracking the sun or spacecraft attitude error). During the first day in orbit, the V/T level was changed from 4 to 5 for each of the three batteries. On the fifth day, the battery charge rate was reduced from medium rate charge (10 amps) to a low rate charge (7.5 amps). Battery power requirements increased over a two week period as the payload instruments were individually turned-on. Table-3 presents the changes made since launch which influence the performance of the batteries.

The sun angle is expected to decrease with a corresponding decrease in eclipse period, finally towards full sun season with no eclipses. This is a cyclic phenomenon over the life of the mission.

B. Performance

1. Charge Discharge Ratio Control

The charge/discharge trigger was enabled after assuring that batteries have been fully charged-up and this occured about 24 hours after launch. Once this trigger is enabled, power management software computes the charge-discharge ratio and issues commands to lower the charge current from previously selected charge rate (high, medium or low) to trickle charge rate when the charge-discharge ratio reaches preselected value. The trickle charge rate is indirectly enforced by commanding a V/T level that is 3 or more levels higher than preselected V/T level used at sunrise. For example, the V/T level was changed from 5 to 9. This is illustrated in Figure-11, where the battery voltage, charge current and discharge currents versus time are shown. The charge current of 7.5 amps at sunrise was held constant until the battery voltage reached the V/T limit (corresponding to V/T level 5). Then it started tapering until charge-discharge ratio reached the preselected value of 1.04, where the charge current was reduced to 0.5 amps. A 3 or more levels higher than preselected V/T level reduces the charge current to lower than trickle charge current, however, the hardwired minimum charge current is equal to trickle charge rate of 0.5 amps. Figure-12 is similar to Figure-11 but the C/D control was not enabled yet.

The V/T level is reestablished to normal (predetermined) level at the next sun-return. Ephemeris sun-return is normally a few degrees after the actual orbital sun-rise.

2. Charge Discharge Ratio Control Accuracy

Traces were run to collect data (charge currents, discharge currents, battery voltage, V/T levels, battery temperatures) over an entire orbit sampled at every 8 seconds. Battery charge current and voltage are multiplied and integrated at 8 second integration. The amount of watt-hours of energy taken out during the eclipse and charged during the day are computed.

To compute for the charge to discharge ratio, the amount of energy put into the battery is divided by the amount of energy taken out of the battery. This value is compared with the on-board computer programmed battery recharge ratio and the results are tabulated below:

Battery No.	**AH Discharge**			**C/D Ratio**		**Temperature**
	Ground Computed	On-board Computer	Difference (%)	Ground Computed	On-board Computer Programmed	
Battery-1	3.90 AH	3.91 AH	0.3%	1.04	1.04	3.8^{0}C
Battery-2	4.07 AH	4.08 AH	0.2%	1.04	1.04	3.0^{0}C
Battery-3	3.97 AH	3.97 AH	0.0%	1.04	1.04	3.0^{0}C

The AH discharge and C/D ratios computed by on-board Computer (OBC) are in close match with the ground computed values.

3. Thermal Control of Batteries

Figures-13, 14, & 15 present the battery-1A & 1B temperature and heater status over a time span of two hours for day-of-the-year 135, 155 and 257 respectively. The battery temperature has been maintained between 2.5^{0}C and 4.7^{0}C and heater duty ratio varied over a range. The battery heater is turned-ON by TCE when the lower temperature limit is reached and turned-OFF when the upper temperature limit is reached. In fact, when the heater is turned-ON, it cycles ON and OFF at 14 cycles per second until the upper temperature limit is reached. Due to this cycling nature when it is commanded-ON, it is difficult to predict the duty ratio of the heater due to coincidence/non-coincidence of telemetry sampling with respect to heater cycling as (a) telemetry sampling rate is different from heater cycling rate and (b) both rates are not synchronized. Thus, there is only 50% chance that heater status telemetry gives actual heater duty cycle. The telemetry values are 4.5V for heater OFF indication and is 2.5V for ON indication.

Figure-16 presents the temperature of battery packs 2B and 3A since launch. The temperature of the battery packs should have been maintained above 3^0C (based on ground testing) through out the mission life even though the internal dissipation and external heat fluxes are expected to vary over a wide range depending upon the spacecraft sun angle, eclipse duration, spacecraft eclipse load demands, etc. From the Figure-16, it is clear that at least packs 2B and 3A dipped below 3^0C. This dip may be attributed to the location of the temperature sensor used for thermal control which is different from the location of the temperature sensor used for telemetry (see Figure-7). In addition, a solar array leading offset of $+53^0$ might have created adverse heat fluxes for these battery packs as evidenced from days 139 to 187. On day 187, the offset was changed from $+53^0$ to -45^0 and the battery temperature started increasing even though the eclipse period was gradually diminishing to zero. Preliminary indications are that solar array leading offset might have created external heat fluxes which might have resulted in temperature dip. Also, it is possible that the leading solar array offset might have not been considered in the original analysis. Further analysis to correlate with the flight data is in progress. If determined, the heater size will be increased for NOAA-L and onwards. The current battery pack temperatures will certainly support the mission life goal of 3 years.

4. Load (AH) sharing by Batteries

As explained above, the batteries are ORed using diodes and discharged together. Thus, there is no active effort to force load sharing equally among the three batteries. Table-4 presents the ampere-hour load sharing among three batteries. Their sharing is excellent, each battery supplying about one-third of the total spacecraft load. This reflects on well matched batteries consisting of cells, wiring within each pack, wiring between packs, and wiring to the ORing diodes.

5. Peak Discharge Current.

The battery peak discharge current occurs at the end-of-night. This current is the highest discharge current from the battery because the battery voltage is lowest at the end of this constant power discharge. The peak discharge current observed was in the range of 9 to 10.5 amps, which is about C/4.

VIII. CONCLUSION

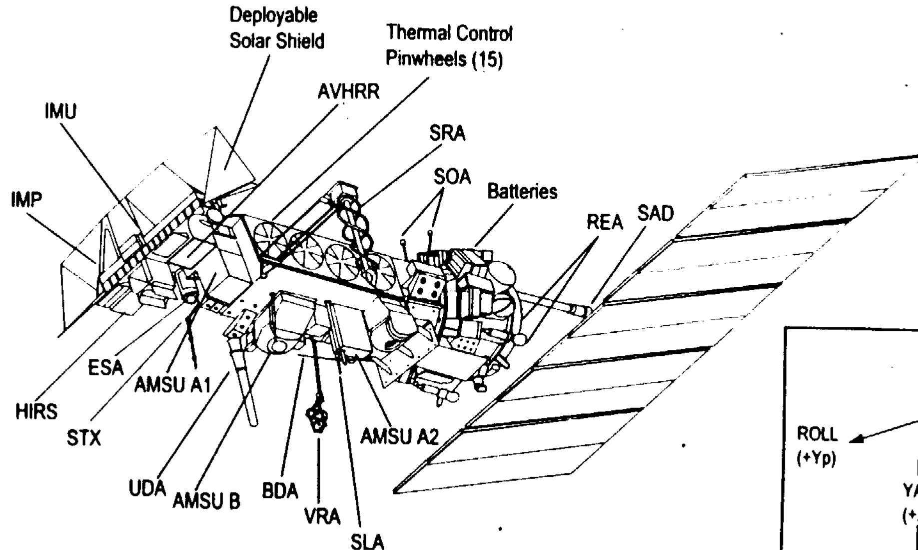
With proper in-orbit power system operation, the NOAA-K batteries will continue to perform nominally.

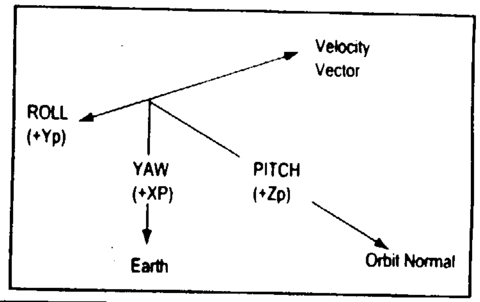
Table-1 Random Vibration Test Levels			
Frequency (Hz)	PSD (G2/Hz)	Duration/Axis	Overall
Qualification Test Levels			
20-70 70-140 140-500 500-1000 1000-2000	0.05 flat +7 dB/octave 0.25 flat -7 dB/octave 0.05 flat	1 minute perpendcular axis	14.5 Grms
20-70 70-140 140-500 500-1000 1000-2000	0.05 flat +7 dB/octave 0.11 flat -7 dB/octave 0.05 flat	1 minute horizontal axis	11.9 Grms
Flight Test Levels			
20-70 70-140 140-500 500-1000 1000-2000	0.05 flat +7 dB/octave 0.11 flat -7 dB/octave 0.05 flat	1 minute perpendcular axis	11.9 Grms
20-70 70-140 140-500 500-1000 1000-2000	0.05 flat +7 dB/octave 0.05 flat -7 dB/octave 0.05 flat	1 minute horizontal axis	7.9 Grms

Table-2 POES NOAA-K, L, M, N, N' Battery Life Test Parameters		
Parameters	Mission-Profile	Stress Test
Temperature	5^0C	20^0C
Orbit duration	102 minutes	90 minutes
Discharge duration	36 minutes	30 minutes
Depth of Discharge	21%	40%
Discharge Rate	14.0 amps constant current	32 amps constant current
Charge rate	10 amps constant current to V/T	32 amps constant current to V/T
V/T level (typical)	NASA V/T Level-5	NASA V/T Level-5
C/D ratio	105% min, 110% max	120% max
Failure Criteria	<4200 cycles for AM orbit <10400 cycles for PM orbit	<5200 cycles
Min Cell Voltage EOD	10 cell pack voltage <11 volts	5 cell pack voltage <5.5 volts
Max Cell Voltage EOC	Any cell >1.56 volts	Any cell >1.56 volts
Cell Voltage Divergence	>100 mV EOC; no limit EOD	>100 mV EOC; no limit EOD

Table-3 Summary of Battery Related Operational Changes		
Day/Time	Command	Description/Function
133:15:50	Spacecraft launched	Spacecraft launched. Charge rate of 10 amps and V/T level of 4 for all batteries
133:16:26	PMCTL BFFF	Monitoring of battery parameters was enabled. State of charge of all three batteries was initialized to 34AH.
133:19:02	CMD B123V05	Enabled sun-return (V/T level-5 for all batteries) and cut back (V/T level-9) V/T levels.
134:15:26	CP POWRC (CMD FIPSI) (CMD CPSTA) (PMTRG 1C00)	Set battery temperature limits to level-1 for on-orbit mode operation (lowered from 28°C to 14°C). Enable battery C/D ratio V/T commanding.
	CP ARRAY30LG	Solar array was offset to -30° (lag).
134:18:42	PMTRG 1E00	Use patch for state of charge calculations.
135:13:25	CP ARRAY55LG	Solar array offset was changed from -30° (lag) to -55° (lag).
136:16:17	CP CLMVALU	Set PMS charge state initialization values to 40AH.
137:19:14	CMD BCLLL	Charge Rate was lowered from 10 amps to 7.5 amps.
139:21:48	CP ARRAY53LD	Solar array offset was changed from -55° (lag) to +53.2° (lead).
146:19:22	PMTRG FE7E	Enabled Battery/BCA overtemperature commanding.
169:16:17	CMD B123V06	Changed V/T level from 5 to 6 for all batteries.
187:17:40	CP ARRAY45LG	Solar array offset was changed from +53.2° (lead) to -45° (lag).
197:14:05	CMD B1V07 CMD B3V07	Changed V/T level from 6 to 7 for battery 1. Changed V/T level from 6 to 7 for battery 3.
216:18:44	CMD B2V07	Changed V/T level from 6 to 7 for battery 2.

Table-4 Ampere-Hour Load Sharing Among Three Batteries						
Year/Day/Time	State-of-Charge (AH) during discharge			Load sharing		
	Battery-1	Battery-2	Battery-3	Battery-1	Battery-2	Battery-3
98/139/06:00:47.4	37.05	37.02	37.09	0.33	0.34	0.33
98/141/12:00:47.4	36.41	36.30	36.41	0.33	0.34	0.33
98/143/18:00:47.4	36.31	36.20	36.28	0.33	0.34	0.33
98/147/00:00:47.4	36.25	36.11	36.20	0.33	0.34	0.33
98/150/00:00:47.4	36.33	36.38	36.41	0.34	0.33	0.33
98/152/06:00:47.4	36.19	36.03	36.13	0.33	0.34	0.33
98/154/06:00:47.4	36.14	35.98	36.08	0.33	0.34	0.33
98/157/00:00:47.4	36.11	35.95	36.05	0.33	0.34	0.33
98/160/06:00:47.4	36.11	35.95	36.05	0.33	0.34	0.33
98/163/00:00:47.4	36.13	35.97	35.98	0.32	0.34	0.34
98/164/18:00:47.4	36.06	35.91	36.02	0.33	0.34	0.33



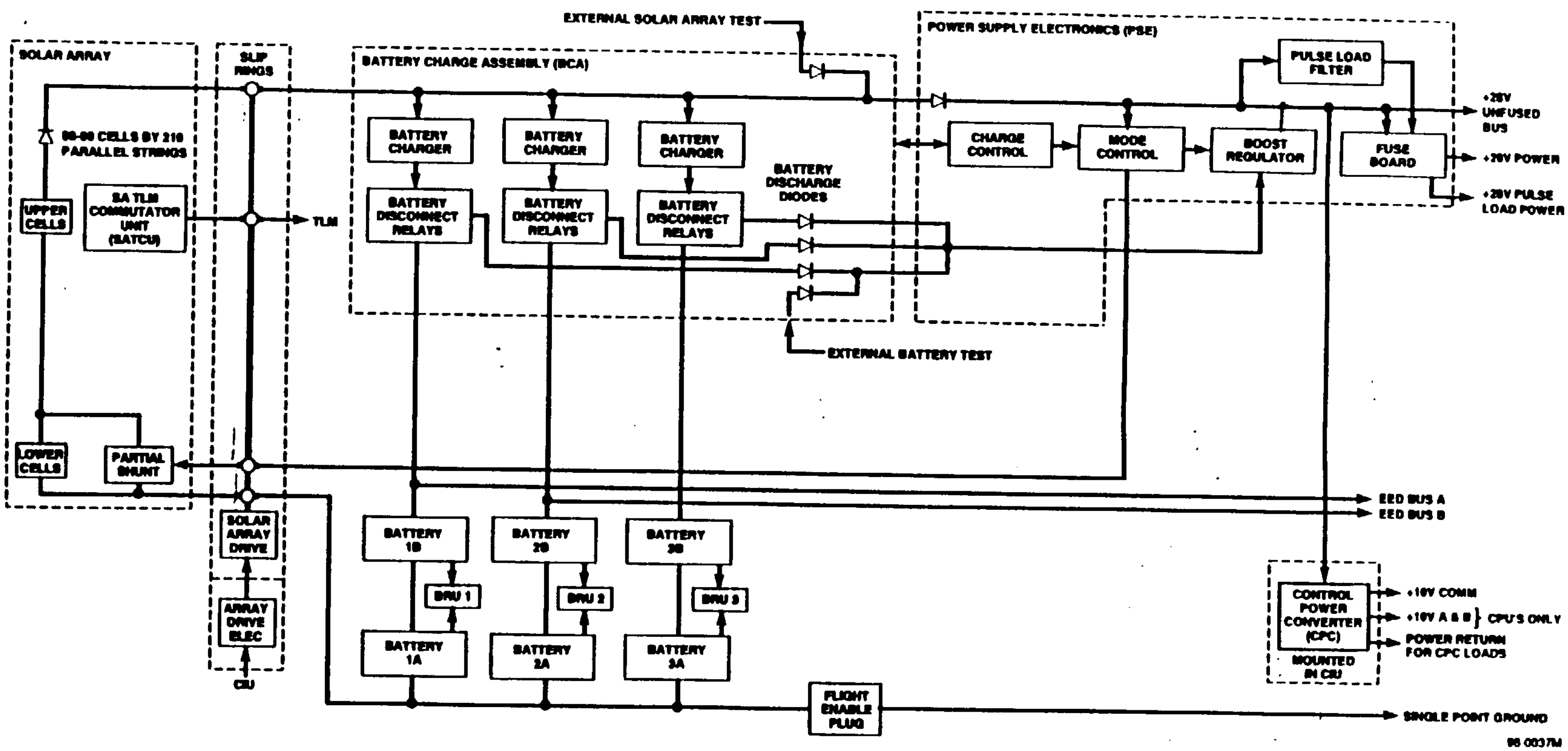


LEGEND

AMSU	Advanced Microwave Sounding Unit	SAD	Solar Array Drive
AVHRR	Advanced Very High Resolution Radiometer	*SAR	Search and Rescue
BDA	Beacon Transmitting Antenna–	SEM	Space Environment Monitor
*DCS	Data Collection System	SRA	Search-and-Rescue Receiving Antenna
ESA	Earth Sensor Assembly	STX	S-Band Transmitting Antenna (1 of 4 shown)
HIRS	High Resolution Infrared Radiation Sounder	SLA	Search and Rescue Transmitting Antenna (L-Band)
IMP	Instrument Mounting Platform	SOA	S-Band Omni Antenna (2 of 6 shown)
IMU	Inertial Measurement Unit	*TED	Total Energy Detector
*MEPED	Medium Energy Proton/Electron Detector	UDA	Ultra High Frequency Data Collection System Antenna
REA	Reaction Engine Assembly	VRA	Very High Frequency Real-time Antenna

* Not shown in this view

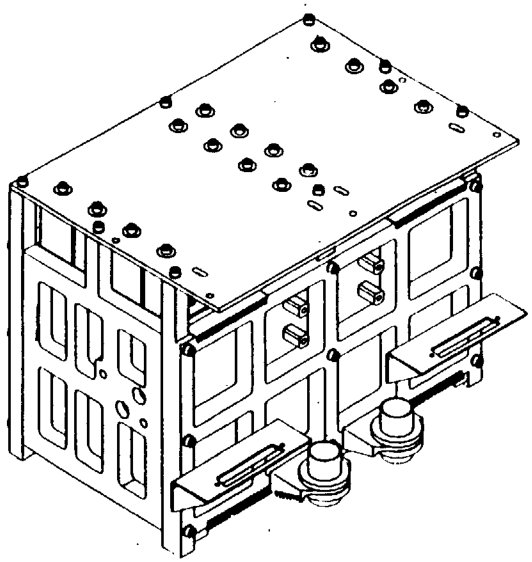
FIGURE-1



Power Subsystem Functional Block Diagram

FIGURE - 2

8 CELL - TDRSS



9 CELL - TDRSS

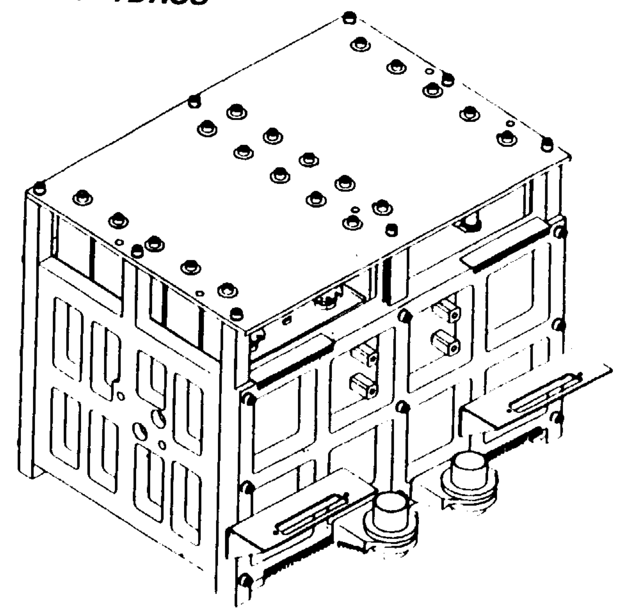


FIGURE-3

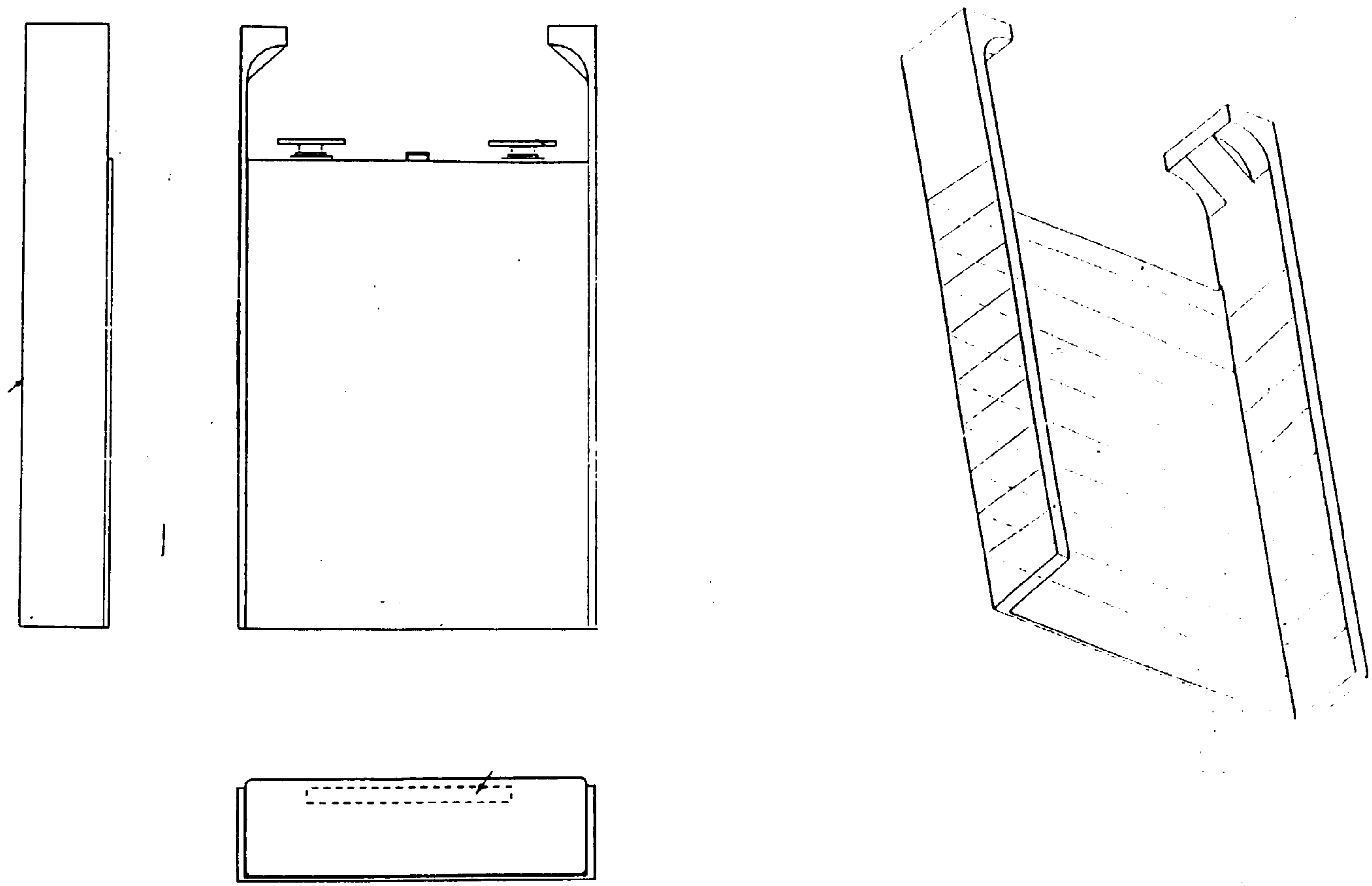
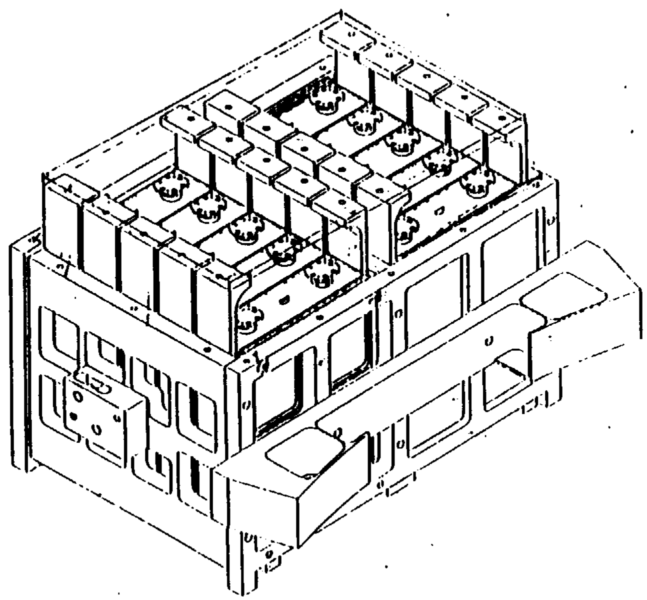
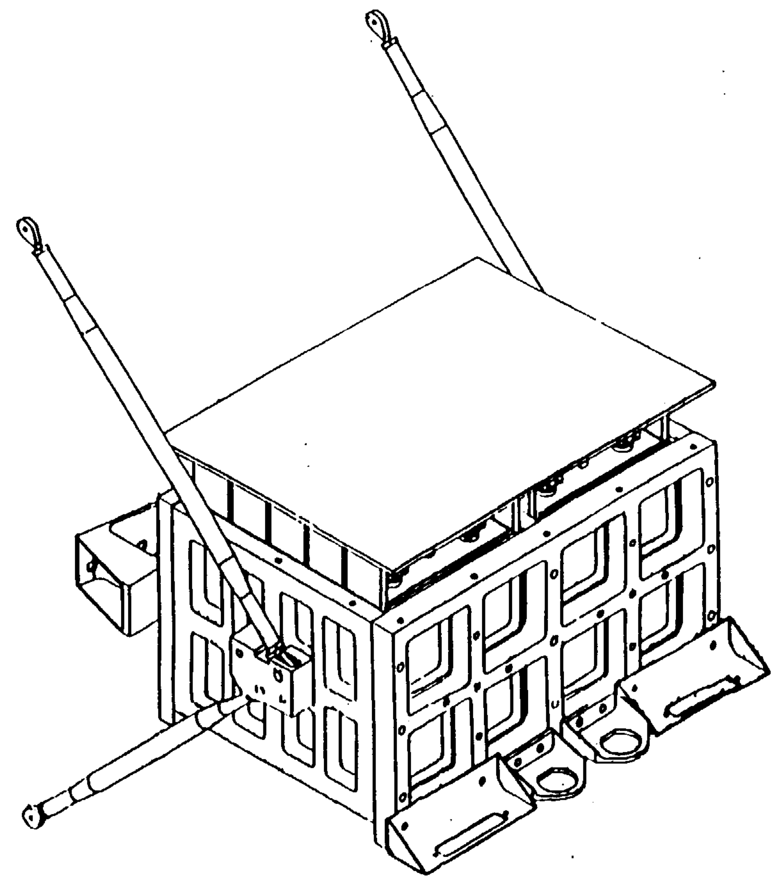


FIGURE -4

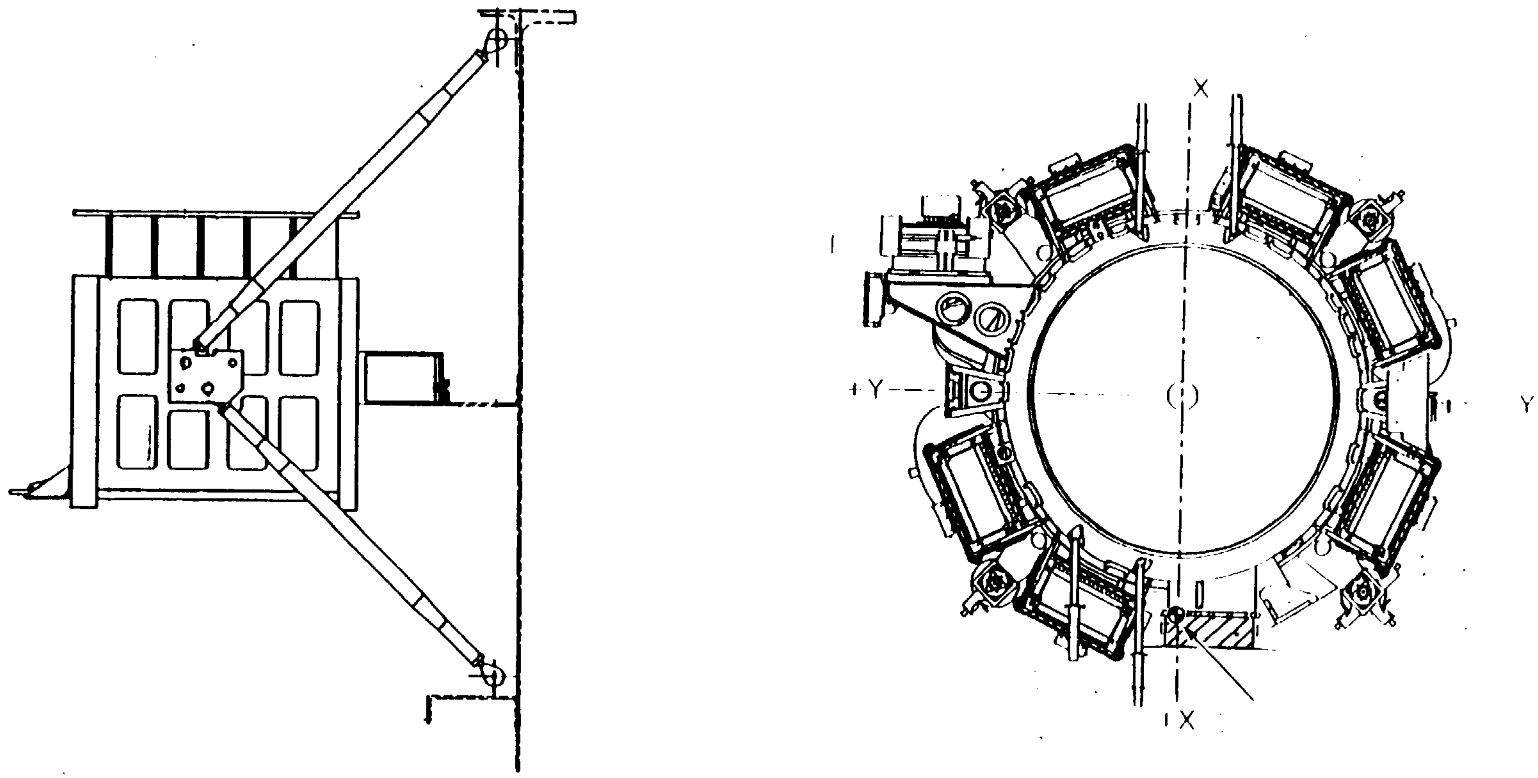


(a)



(b)

FIGURE-5



(a) (b)

FIGURE - 6

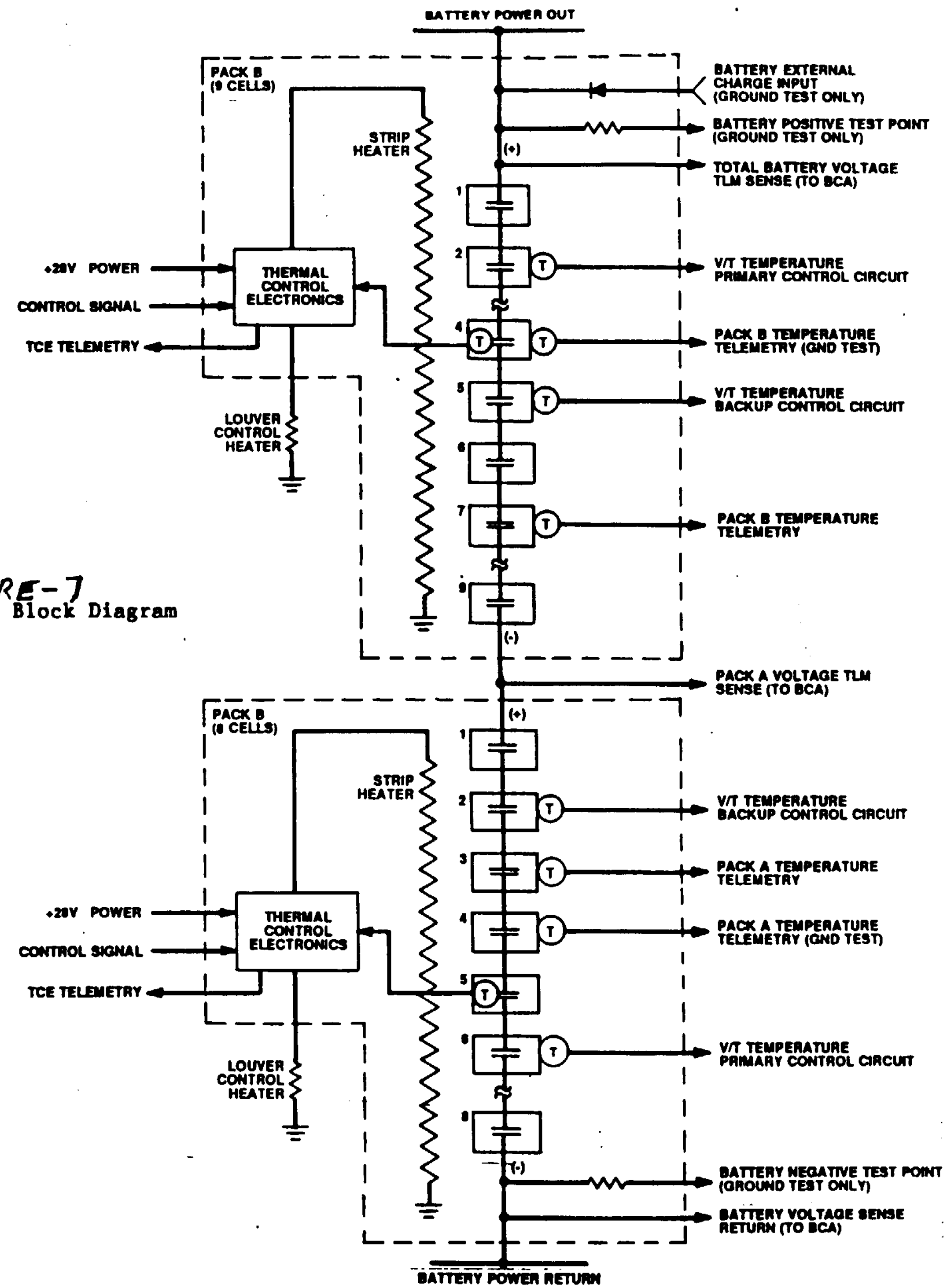


FIGURE-7
Battery Functional Block Diagram

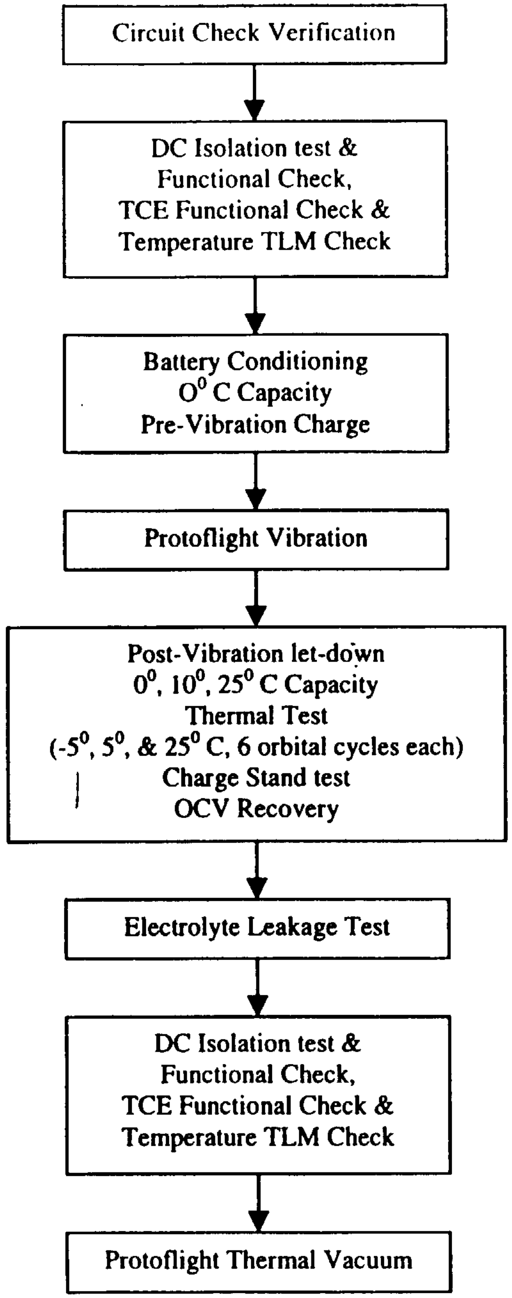


FIGURE-8

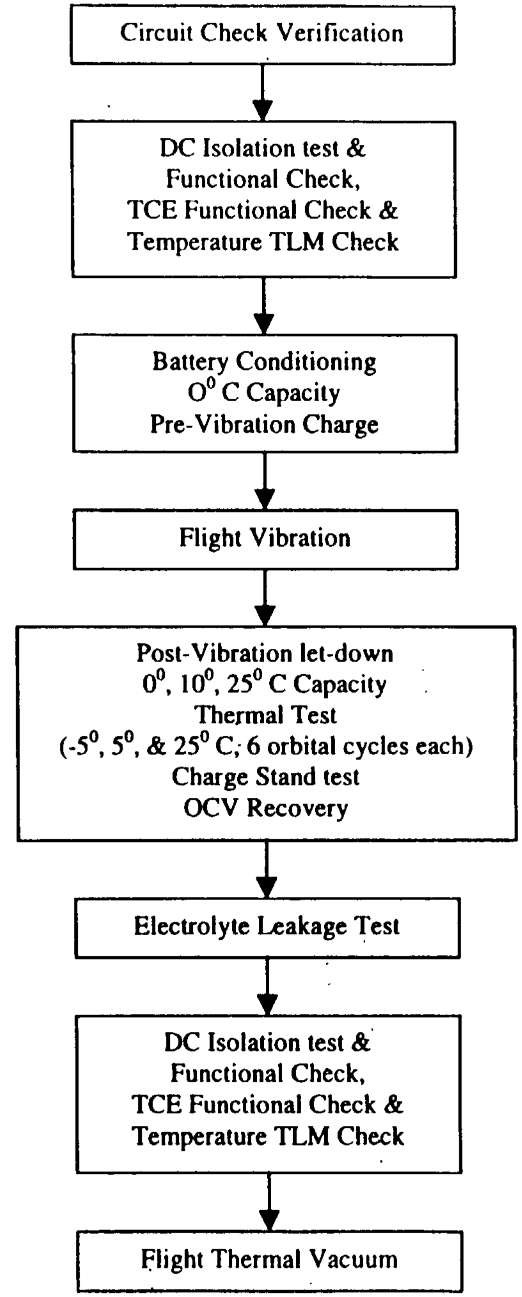
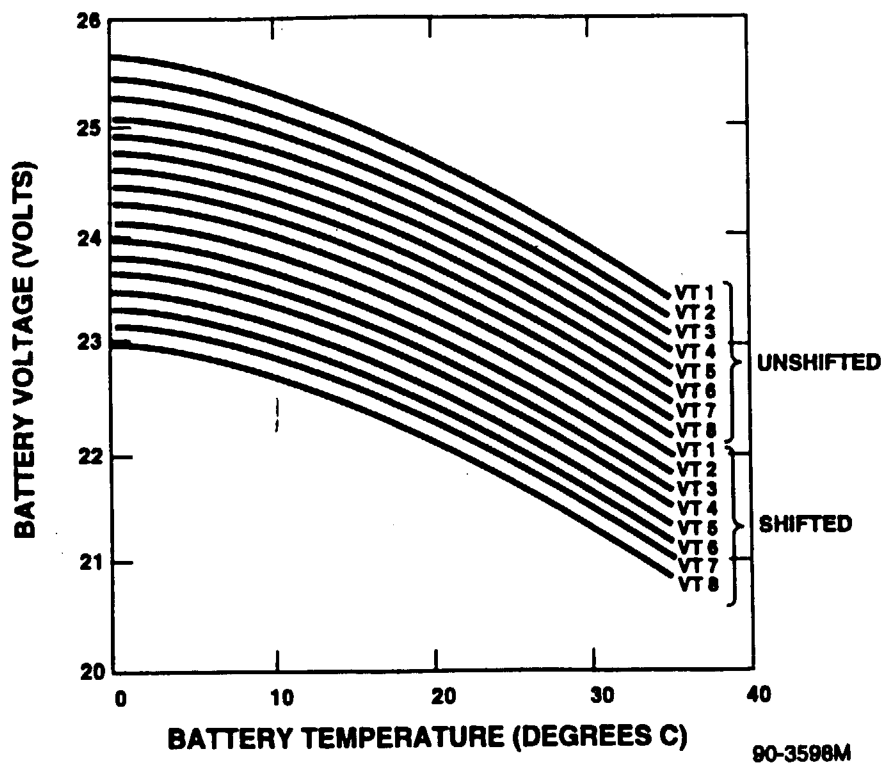
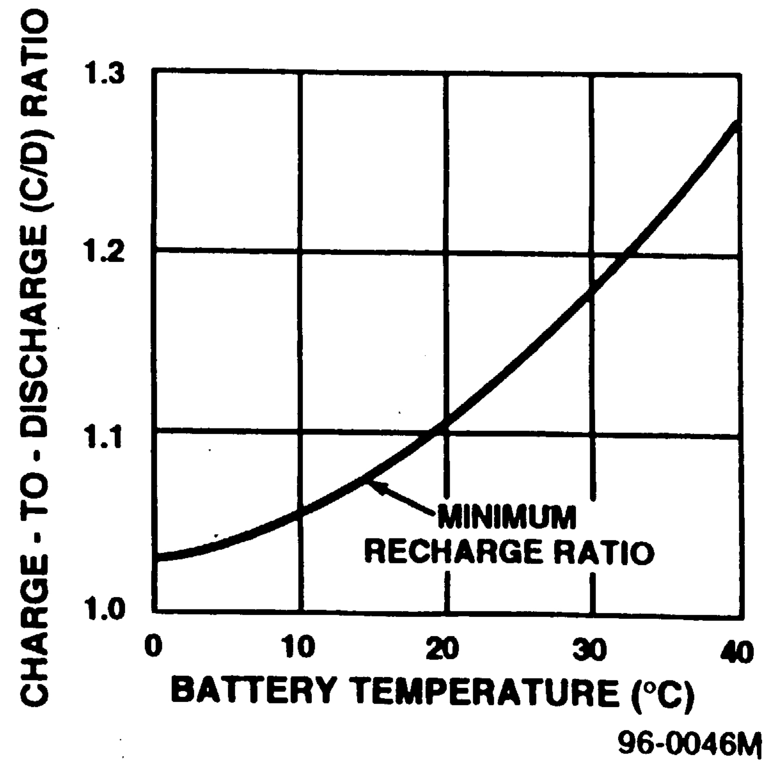


FIGURE-9


26
25
24
23
22
21
20
BATTERY VOLTAGE (VOLTS)
0
10
20
30
40
BATTERY TEMPERATURE (DEGREES C)
VT 1
VT 2
VT 3
VT 4
VT 5
VT 6
VT 7
VT 8
UNSHIFTED
VT 1
VT 2
VT 3
VT 4
VT 5
VT 6
VT 7
VT 8
SHIFTED
90-3598M

(a)


CHARGE - TO - DISCHARGE (C/D) RATIO
1.3
1.2
1.1
1.0
0
10
20
30
40
BATTERY TEMPERATURE (°C)
MINIMUM
RECHARGE RATIO
96-0046M

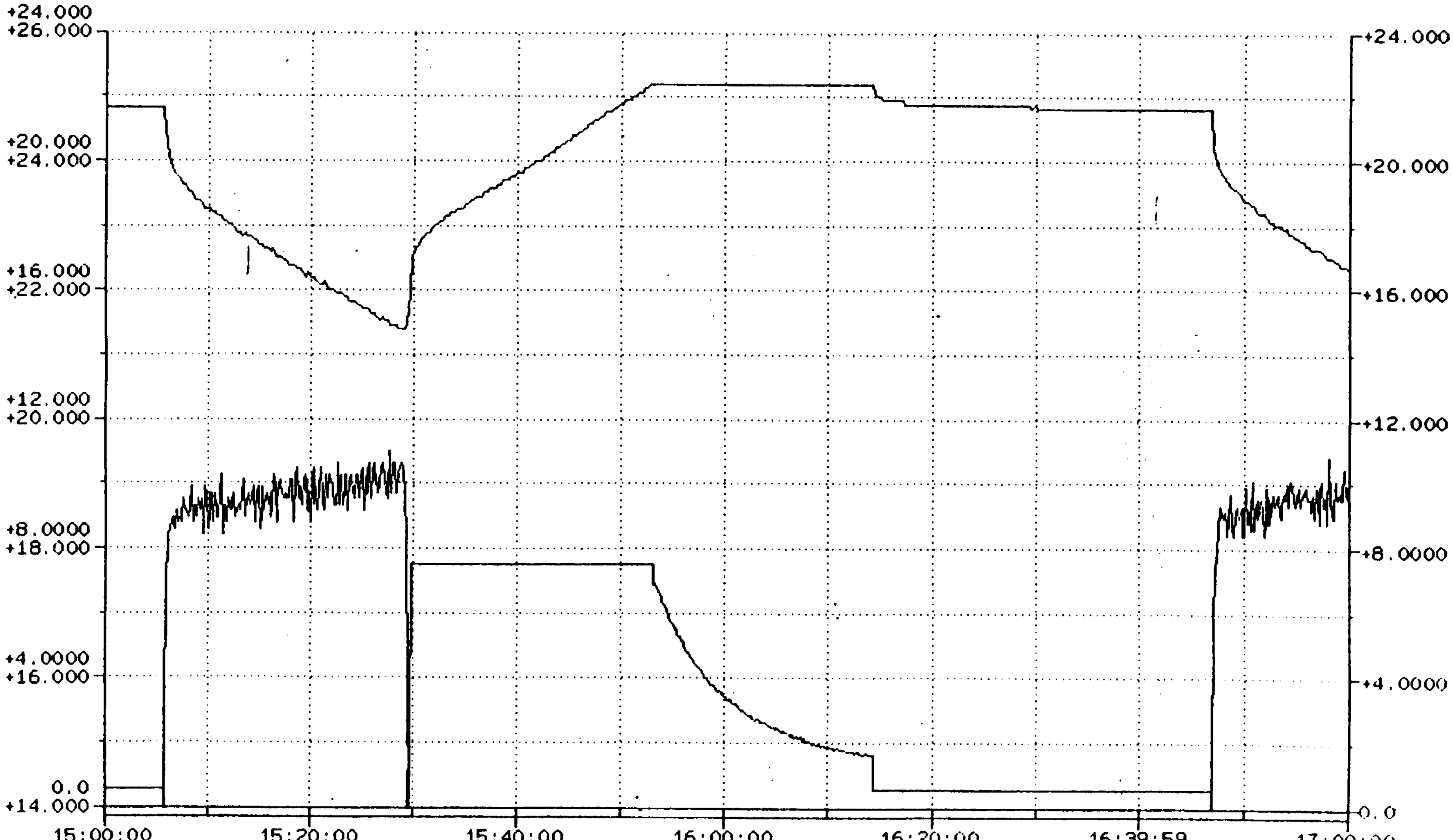
(b)

FIGURE-10

FIGURE - 11

PLOT NAME:	NRT_OPS$HISPLOT_PLOT:N15PPLT3	SC ID:	15
TITLE:	N15PLR3	PLOT CREATION DATE:	155/20:15:49
DESCRIPTION:	NOAA-15 POWER PLOT #3	PLOT PRINT DATE:	155/20:45:49
SETUP FILENAME:	NRT_OPS$HISPLOT_SETUP:N15PLR3	SAMPLING PERIOD:	000/00:00:08.00
START/STOP TIME:	98/155/15:00:00.0 - 98/155/17:00:00.0		

Y-DATA	CHAN	UNITS	TYPE	VS X_DATA	CHAN	UNITS	TYPE	SYM	GPH	Y-DATA	CHAN	UNITS	TYPE	VS X_DATA	CHAN	UNITS	TYPE	SYM	GP
NBAT1V	FA480	VOL	EU	TIME		HRS		—	1										
NBAT1DCH	FA332	AMP	EU	TIME		HRS		—	1										
NBAT1CHI	FA300	AMP	EU	TIME		HRS		—	1										

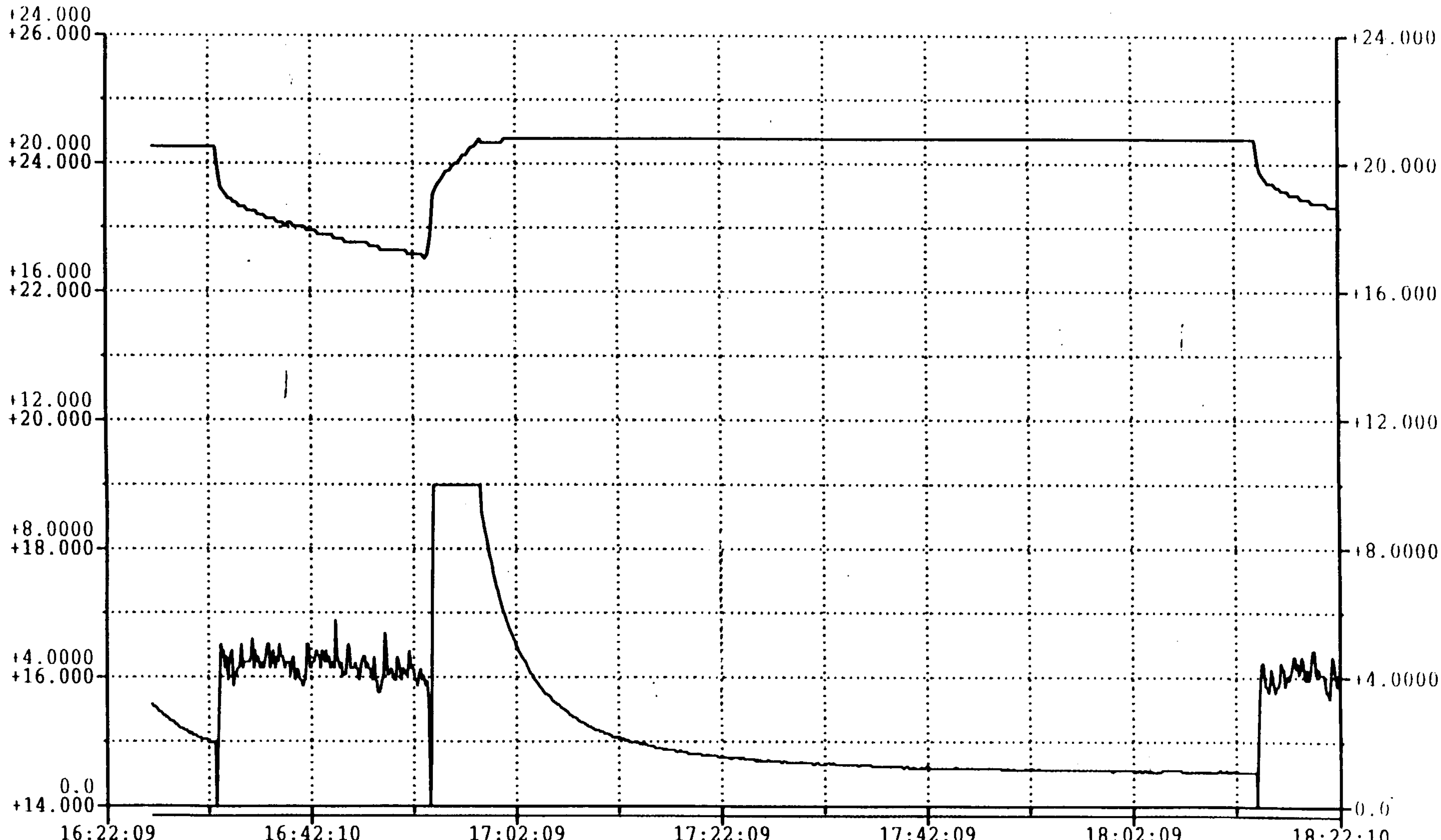


GRAPH 1 CONTAINS CLIPPED DATA POINTS GRAPH 1: HRS

EPS7-24

PLOT NAME:	NRT_OPS$HISPLOT_PLOT:N15PPLT3	SCID:	15
TITLE:	N15PLR3	PLOT CREATION DATE:	136/04:38:31
DESCRIPTION:	NOAA-15 POWER PLOT #3	PLOT PRINT DATE:	136/04:43:58
SETUP FILENAME:	NRT_OPS$HISPLOT_SETUP:N15PLR3	SAMPLING PERIOD:	000/00:00:08.00
START/STOP TIME:	98/133/16:22:10.0 - 98/133/18:22:10.0		

Y DATA	CHAN	UNITS	TYPE	VS	X_DATA	CHAN	UNITS	TYPE	SYM	GPH	Y-DATA	CHAN	UNITS	TYPE	VS	X_DATA	CHAN	UNITS	TYPE	SYM	GPH
IBAT1V	FA480	VOL	EU		TIME		HRS		—	1											
IBAT1DCH	FA332	AMP	EU		TIME		HRS		—	1											
IBAT1CHI	FA300	AMP	EU		TIME		HRS		—	1											



GRAPH 1 CONTAINS CLIPPED DATA POINTS GRAPH 1: HRS

EPSL-4

FIGURE-12

PLOT NAME: NRT_OPS$HISPLOT_PLOT:N15PPLT6
TITLE: N15PLR6
DESCRIPTION: NOAA-15 POWER PLOT #6
SETUP FILENAME: NRT_OPS$HISPLOT_SETUP:N15PLR6
START/STOP TIME: 98/135/14:36:30.0 - 98/135/16:36:30.0

SCID: 15
PLOT CREATION DATE: 135/17:18:23
PLOT PRINT DATE: 135/22:00:53
SAMPLING PERIOD: 000/00:00:32.00

Y DATA	CHAN	UNITS	TYPE	VS	X_DATA	CHAN	UNITS	TYPE	SYM	GPH	Y-DATA	CHAN	UNITS	TYPE	VS	X_DATA	CHAN	UNITS	TYPE	SYM	GPH
NBAT1AT	FA026	DEG	EU		TIME		HRS		—	1											
BAT1BT	FA034	DEG	EU		TIME		HRS		—	1											
TCE1H	FA201	VOL	EU		TIME		HRS		—	2											
TCE2H	FA217	VOL	EU		TIME		HRS		—	2											

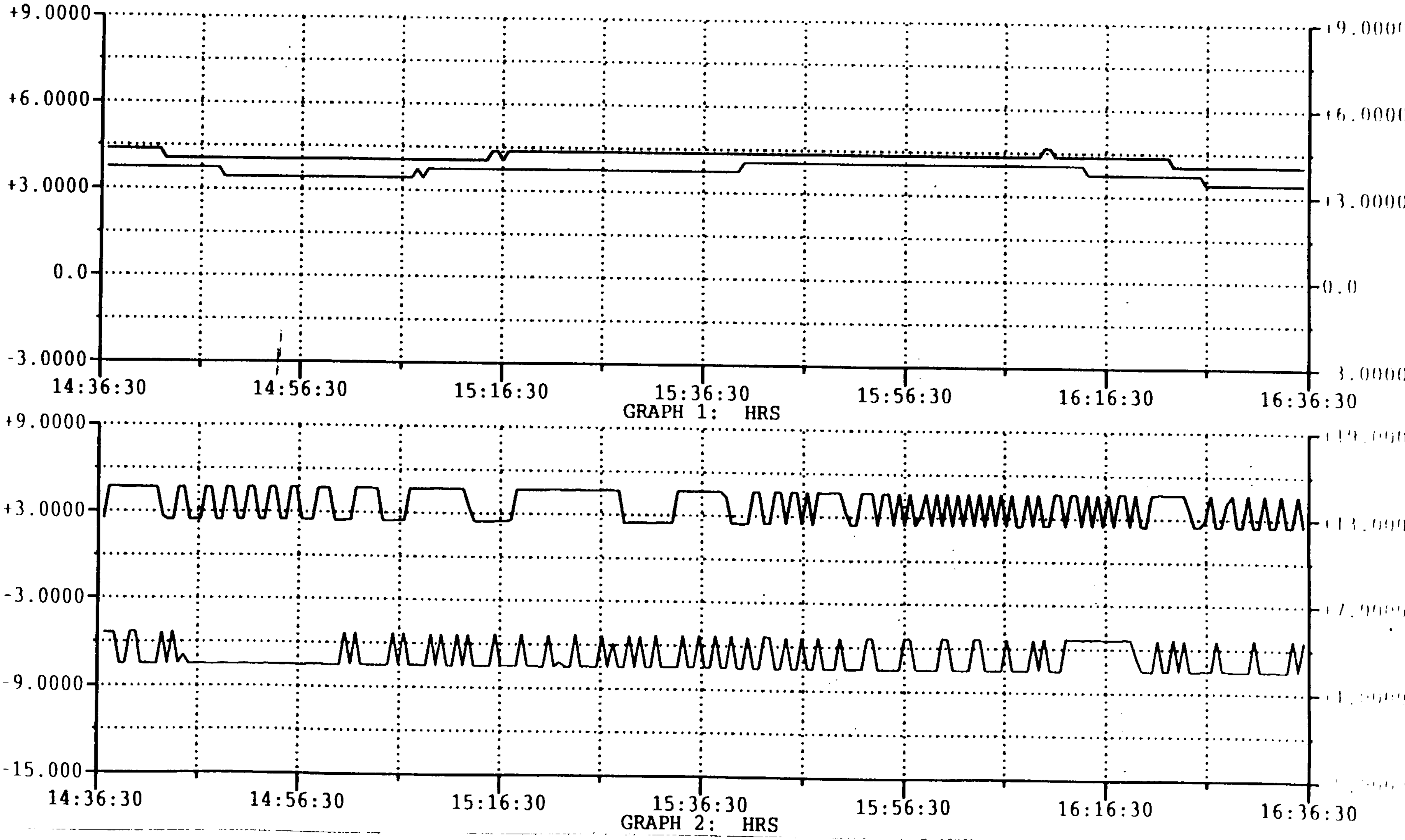


FIGURE - 13

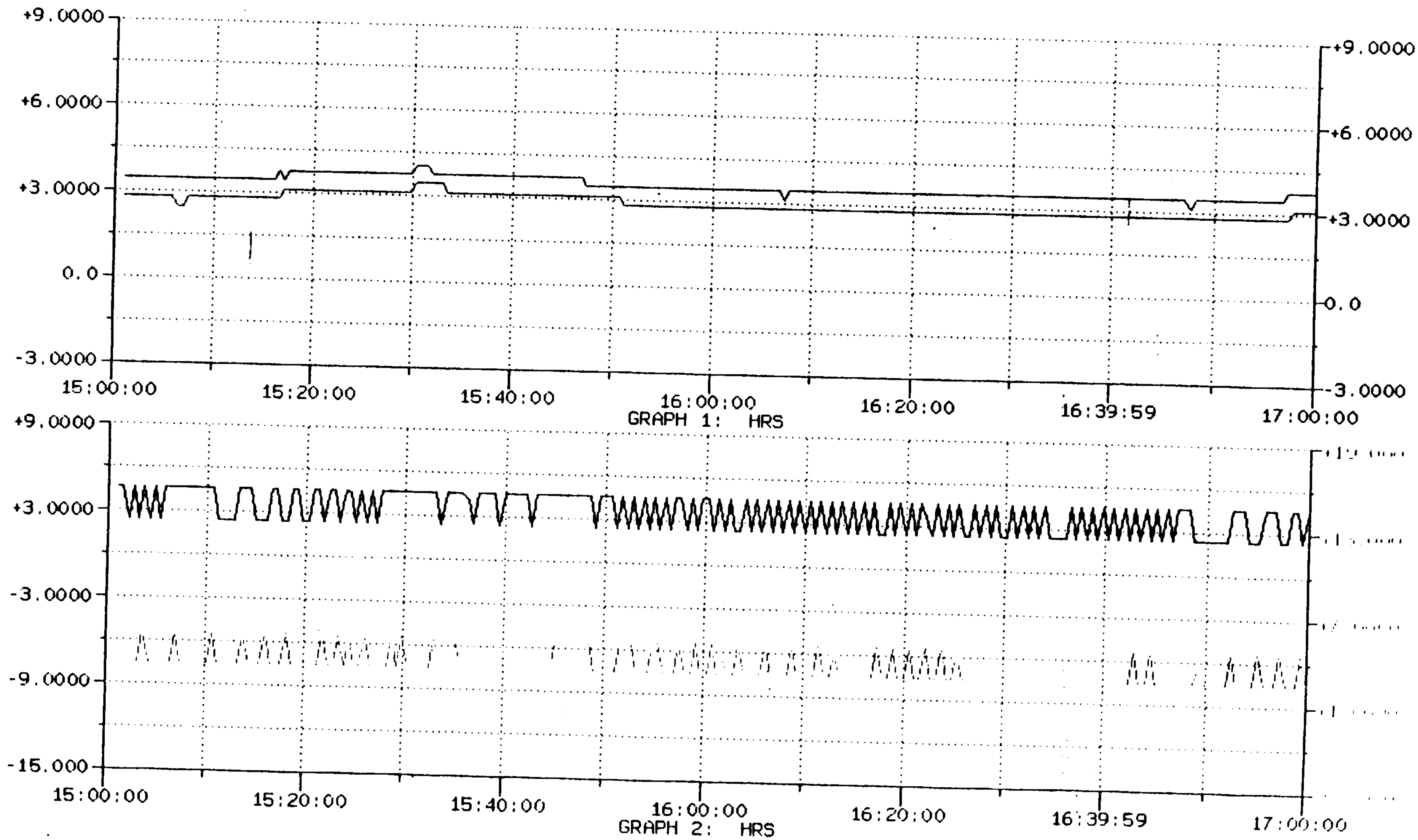
EPS7-12

FIGURE-14

PLOT NAME: NRT_OPS$HISPLOT_PLOT:N15PPLT7
TITLE: N15PLR7
DESCRIPTION: NOAA-15 POWER PLOT #7
SETUP FILENAME: NRT_OPS$HISPLOT_SETUP:N15PLR7
START/STOP TIME: 98/155/15:00:00.0 - 98/155/17:00:00.0

SCID: 15
PLOT CREATION DATE: 155/20:17:52
PLOT PRINT DATE: 155/20:47:53
SAMPLING PERIOD: 000/00:00:32.00

Y-DATA	CHAN	UNITS	TYPE	VS X_DATA	CHAN	UNITS	TYPE	SYM	GPH	Y-DATA	CHAN	UNITS	TYPE	VS X_DATA	CHAN	UNITS	TYPE	SYM	GPH
NBAT2AT	FA042	DEG	EU	TIME		HRS		——	1										
NBAT2BT	FA050	DEG	EU	TIME		HRS		——	1										
NTCE3H	FA233	VOL	EU	TIME		HRS		——	2										



EPS7-28

ITLE:	N15PLR7	SCID:	15
ESCRIPTION:	NOAA-15 POWER PLOT #7	PLOT CREATION DATE:	257/15:45:15
ETUP FILENAME:	NRT_OPS$HISPLOT_SETUP:N15PLR7	PLOT PRINT DATE:	257/15:50:51
TART/STOP TIME:	98/257/04:45:00.0 - 98/257/06:45:00.0	SAMPLING PERIOD:	000/00:00:32.00

DATA	CHAN	UNITS	TYPE	VS X_DATA	CHAN	UNITS	TYPE	SYM	GPH	Y-DATA	CHAN	UNITS	TYPE	VS X_DATA	CHAN	UNITS	TYPE	SYM	GPH
BAT2AT	FA042	DEG	EU	TIME		HRS		——	1										
BAT2BT	FA050	DEG	EU	TIME		HRS		——	1										
TCE3H	FA233	VOL	EU	TIME		HRS		——	2										
TCE4H	FA031	VOL	EU	TIME		HRS		——	2										

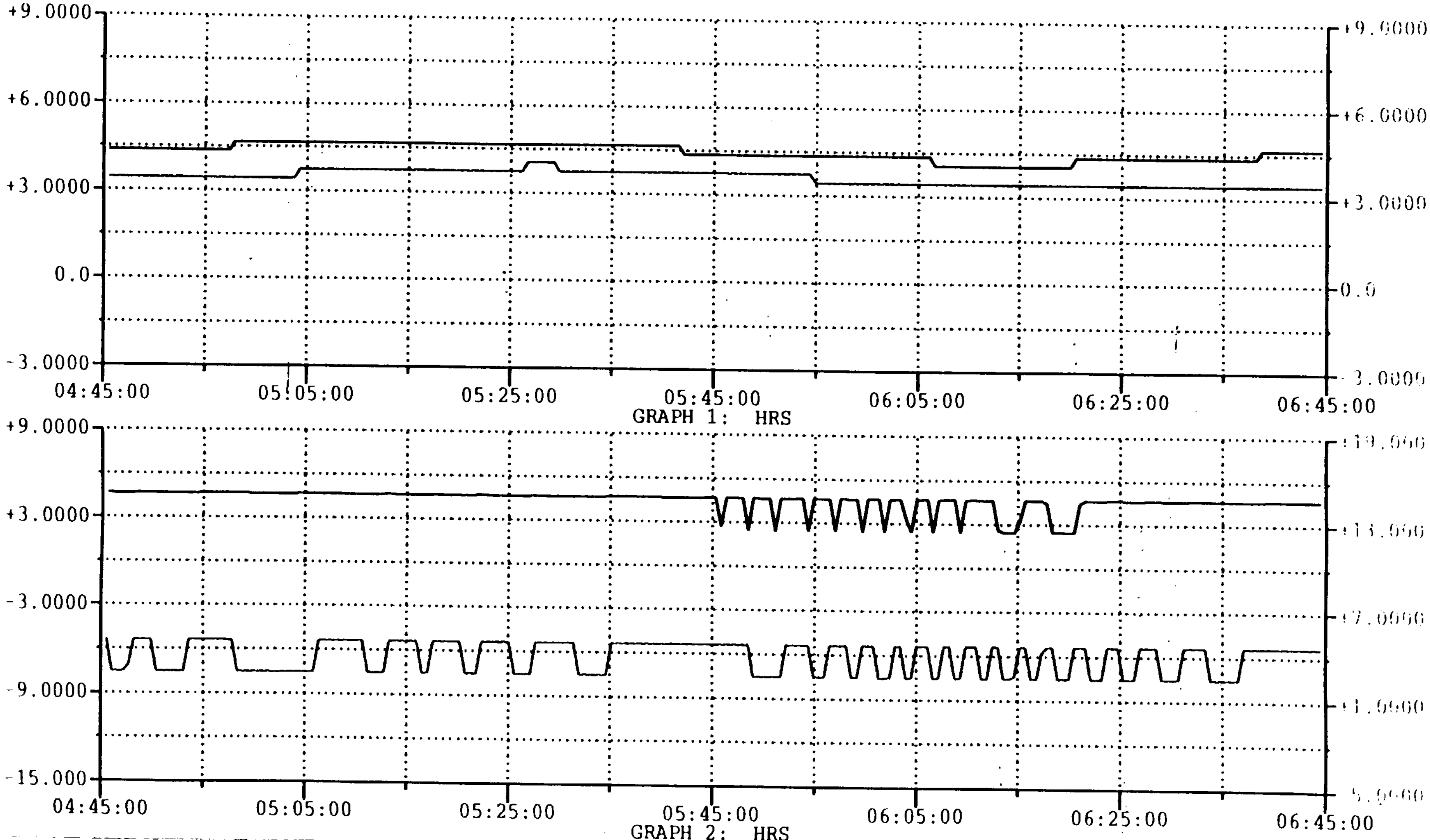
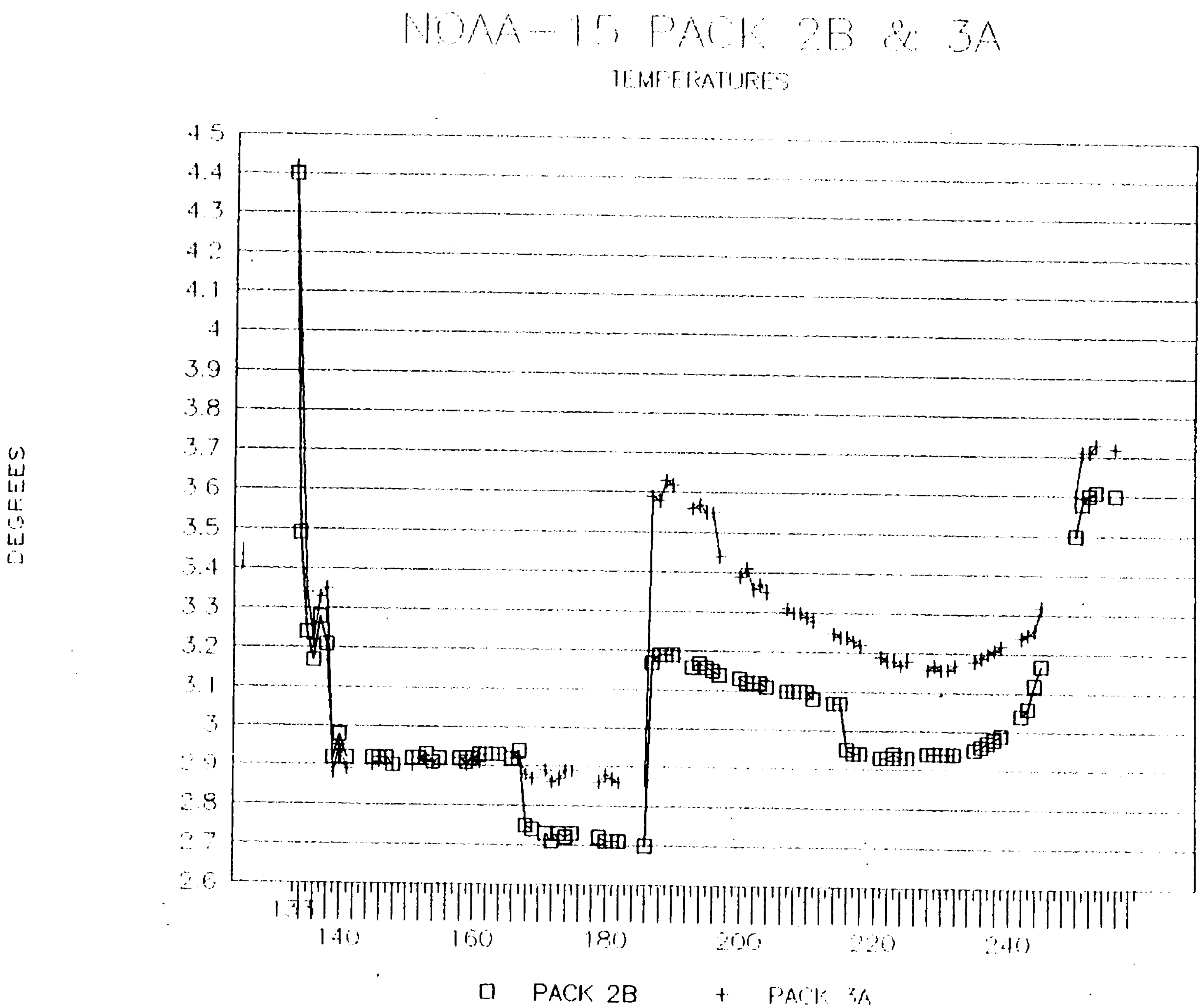


FIGURE-15



NOAA-15 PACK 2B & 3A
TEMPERATURES
DEGREES
4.5
4.4
4.3
4.2
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4
3.3
3.2
3.1
3
2.9
2.8
2.7
2.6
133
140
160
180
200
220
240
PACK 2B
PACK 3A

FIGURE - 16