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PERFORMANCE OF NICKEL-CADMIUM BATTERIES ON THE POES SERIES OF WEATHER SATELLITES

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ABSTRACT

The advanced Television Infrared Observation satellite program is a cooperative effort between the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), the United Kingdom, Canada and France, for providing day and night global environmental and associated data. NASA is responsible for procurement, launch, and checkout of these spacecraft before transferring them over to NOAA, who operates the spacecraft to support weather forecasting, severe storm tracking, and meteorological research by the National Weather Service. These spacecraft with all weather monitoring instruments imposed challenging requirements for the onboard electrical power subsystem (EPS). This paper provides first a brief overview of the overall power subsystem, followed by a description of batteries. A unique power subsystem design which provides "tender-loving-care" to these batteries is highlighted. This is followed by the on-orbit maintenance and performance data of the batteries since launch.

I. INTRODUCTION

The advanced Television Infrared Observation satellite program is a cooperative effort between the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (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 in East Windsor, N.J. is the prime contractor, responsible for building these spacecraft, with components procured from many vendors and/or instruments supplied by NASA as Government-furnished equipment.

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-14 spacecraft in orbital configuration. Some of the latest POES series of spacecraft are in orbit whereas others are in various phases of development and fabrication at LMMS. Thus, these spacecraft with all weather monitoring instruments imposed challenging requirements for the onboard electrical power subsystem(EPS).

The overall 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 overview of the overall power subsystem, followed by a description of batteries. A unique power subsystem design which provides "tender-loving-care" to these batteries is highlighted. This is followed by the on-orbit maintenance and performance data of the batteries since launch.

III. POWER SYSTEM

The EPS provides power to the spacecraft prior to launch, during launch, and post launch operation of the spacecraft mission. The NOAA-14 Power System 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, as shown in the block diagram of

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Figure 2. Within the power subsystem, three rechargeable batteries are the uninterrupted continuous 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, with batteries designed and manufactured by Lockheed Martin and cells manufactured by SAFT (Gates Aerospace Batteries prior in 1993). Each battery consists of 17 cells with a 26.5 Amp-Hour (Ah) or 40 Ah capacity. Battery cell design has been guided by the life and reliability requirements of a 3-year (goal) in orbit in addition to a 5-year ground storage. The spacecraft in the PM orbit experiences earth eclipses regularly, whereas in the AM orbit, the spacecraft face mostly full sun seasons with only about 25% of the year in eclipses. To meet these varying requirements, these batteries are managed "with tender-loving-care".

A. Battery Design

The battery system consists of three 26.5 Ah rated batteries to provide a combined capacity of 75.5 ampere-hours. Each battery is comprised of 17 series-connected cells, physically subdivided into two packs: one containing nine cells and the other containing eight. Each pack has the same outer dimensions, and the commonality is achieved by using an additional dummy cell in the 8-cell pack.

A functional block diagram for the two packs that make up any one of the three identical 26.5 Ah batteries is presented in Figure 3. Each pack contains 2 thermistors for the battery voltage/temperature (V/T) limiting reference circuit in the PSE. 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 thermistor bonded to the surface of cell 4 in each pack is provided as the sensing element for the Thermal Control Electronics (TCE). A separate TCE unit is contained within each battery pack. Its function is to control the temperature of the battery pack through either a strip heater bonded across all cells in the pack, or by operation of cooling louvers which are a separate assembly. The louver assembly becomes associated with each battery pack when the pack is mounted on the spacecraft. This active temperature control system is designed to maintain the battery temperature within a -2°C to +7°C range. If the active temperature control fails or is disabled, passive temperature control is expected to maintain the battery temperature below +24°C under normal battery charge conditions.

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.

B. Battery Charge Control

The three batteries are charged separately by separate charge regulators in the BCA, but are discharged together through the discharge isolation diodes also located within the BCA. 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. Two battery protection modes are provided for each battery.

During normal recharge and before the overcharge condition, charge current to each battery is limited to any one of four ground-commandable rates: 10.0, 7.5, 6.0, or 0.5 amperes. The only limitation is that the sum of the three charge rates cannot exceed 22.5 amperes.

When the battery voltage reaches one of sixteen ground commandable preset 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 this preset value. Any one of the sixteen limits, as shown in figure-4, 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° 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 charges 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 when the batteries cannot be accessed from the ground.

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 5 presents a curve showing the minimum ampere-minute charge-to-discharge ratio recommended for ensuring energy balance as a function of battery temperature. For a battery operating at +5°C, this minimum charge-to-discharge ratio is given as 1.04.

IV. NOAA-14 BATTERY OPERATIONS & PERFORMANCE

The NOAA-14 spacecraft has an orbit with a period of approximately 102 minutes with eclipse duration varying from 24 to 35 minutes.

A. Operations

Pre-launch recharge controls are set high as a precaution, to provide a high recharge level and maintain power balance, in the event of anomalous launch conditions (Array not tracking the sun or Spacecraft attitude error). During the first day in orbit, the battery charge rate was reduced to a low rate charge (6 amp.) with the V/T-5 level for each of the three batteries. Battery power requirements increased over a two week period as the payload instruments were individually turned-on. After payload stabilization, the V/T-4 level was set for each battery. Shortly after this initial V/T selection, slightly higher overcharge of Battery #2 prompted the selection of V/T-5 for this battery. Overcharge is limited by the On Board Processor Software that forces trickle charge level (by going to a V/T level that is three levels higher than the current V/T level) when the recharge level reaches battery capacity. Table-1 presents the changes made since launch.

Table-1 Operational Changes made since launch

Date	Command	Description
12/31/94	Proc. GIL2	Batteries to Low Rate Charge (day after launch). Enable PMS Charge State Control, V/T to 5
01/05/95	Proc. B123VT	Battery V/T from 5 to 4
01/30/95	Proc. B2VT5	Battery #2 V/T from 4 to 5

Small sun angle changes over the past three years have resulted in a relatively stable eclipse period of approximately 33 minutes. As the orbit drifts over the next few years, the sun angle is expected to decrease with a corresponding decrease in eclipse period.

B. Performance

1. Battery Current Profiles. Figure 6 presents superimposed battery current profiles for orbits taken 3 years apart. Sun angle changes over a range, thereby the eclipse duration also changes while the period is held constant. The on-board computer computes the ampere-hour charge-discharge ratio, and commands V/T level-7 (from previous V/T level-3 or -4), which can be seen occurring at different intervals during 1995 versus 1998. This can be due to a) change in the eclipse duration; b) change in the load power consumption; c) ephemeris sun-return accuracy; d) battery operating temperature; e) etc.. Ephemeris sun-return is normally a few degrees after the orbital sun-rise, and the V/T level is reestablished to normal (predetermined) level at sun-return. The difference between the V/T level-7 and either V/T level-3 or -4 is such that the charge current is normally reduced to an

amount equivalent to the trickle charge rate.

2. State-of-Charge of Batteries vs Time. Figure 7 presents the sun angle variation over a year for NOAA-14 and battery state-of-charge at end-of-night. As the sun angle decreases, the eclipse duration decreases. This in turn reduces the amount energy taken out of the battery during eclipse, which is evident from the figure 7 where the state of the charge is increasing as the sun angle is decreasing.

3. End-of-Charge voltage of Batteries and Temperature. Figure 8 presents the battery voltage and battery temperature over a one year period. The end-of-charge voltage is determined as a function of temperature by the voltage-temperature curve.

4. Temperature of Batteries and Louver Control. Figure 9A presents the battery-1A temperature, louver control and heater status over a one year period. The battery temperature has been maintained between -2°C and 7°C by employing the louvers and heaters. Once the louver control has reached its limit, it is completely shut (closed), and the heater is turned on. As seen from this figure, the louver opening was in the range of 8% to 17% for first 250 days. This variation is due to the changes in heat fluxes from external and internal sources. Later the louver opening was 0%, closed completely, to maintain the battery temperature. The battery temperature during this period dipped to 1.9°C. However, if it reached 1°C, then the heater would have turned on to maintain the batteries within the temperature range [see battery-1B]. Figure 9B presents the battery-1B temperature, louver control and heater status over a one year period. The temperature reached 1°C and heater was turned on.

5. End-of-night Battery Voltage and Depth of Discharge. Figure 10 presents the end-of-night battery voltage and its depth-of-discharge (DOD). Even though the battery DOD is changing over a range of 10.7% to 12.8%, the battery voltage is almost constant. From this figure, it is evident that the battery is exhibiting a very low internal impedance and a very flat discharge voltage characteristic.

6. Load (AH) sharing by Batteries. Figure 11 presents the ampere-hour load sharing among three batteries. Their sharing is excellent, each battery supplying one-third of the total spacecraft load. This reflects on well matched design batteries and perhaps, even degrading/ageing even after more than three years of operation, which is beyond the spacecraft life of two years.

7. 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. Figure 12 shows a trending plot of in-flight battery peak discharge current. The peak discharge current is lower than C/2.5.

V. CONCLUSION

With TLC care applied to the batteries, the battery performance in the NOAA-14 spacecraft is nominal after three years, which is one year beyond the design life.

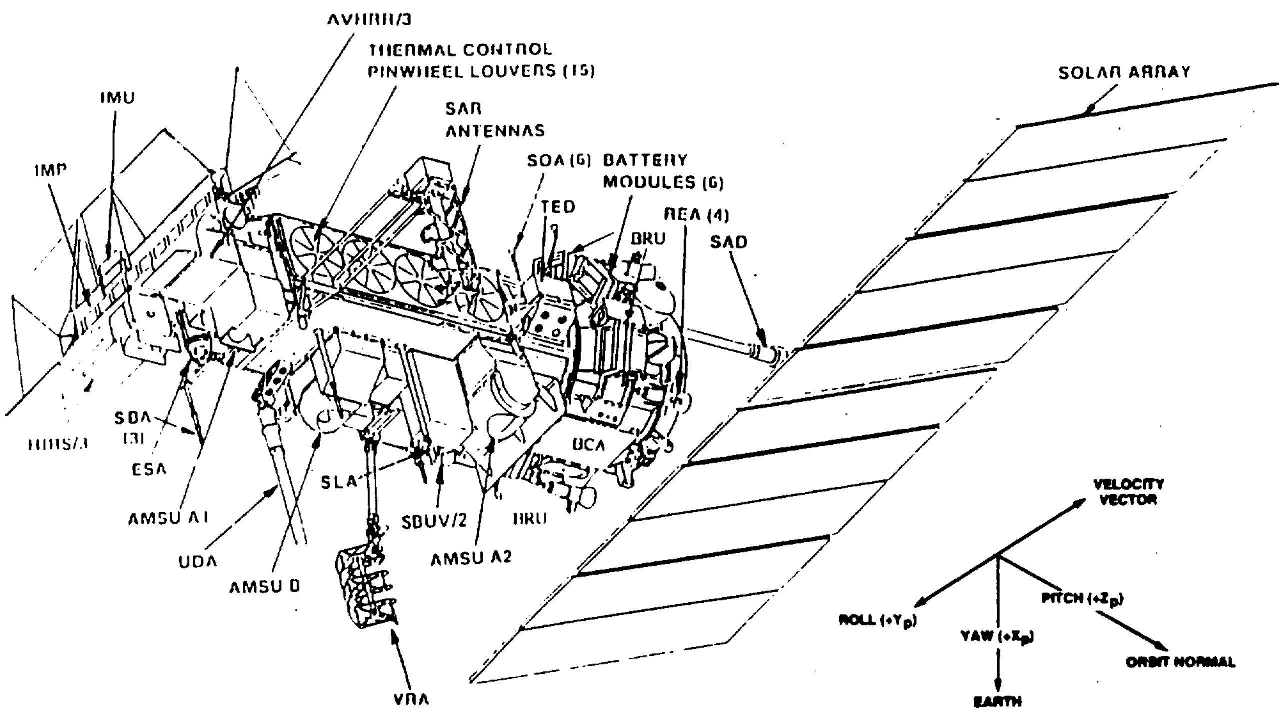

Figure 1 NOAA-14 On Orbit Configuration

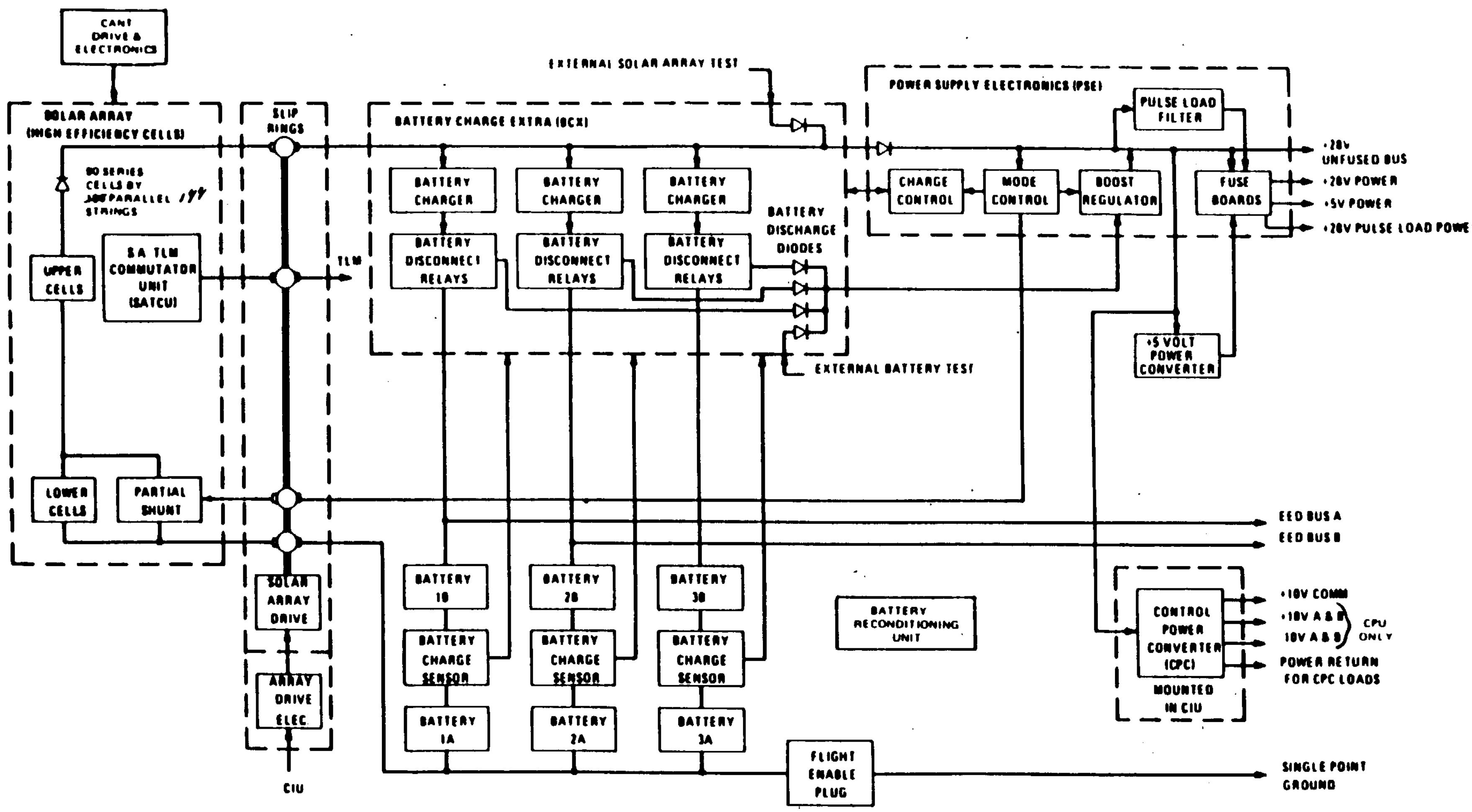

Figure 2 Functional Block Schematic of the Electrical Power System

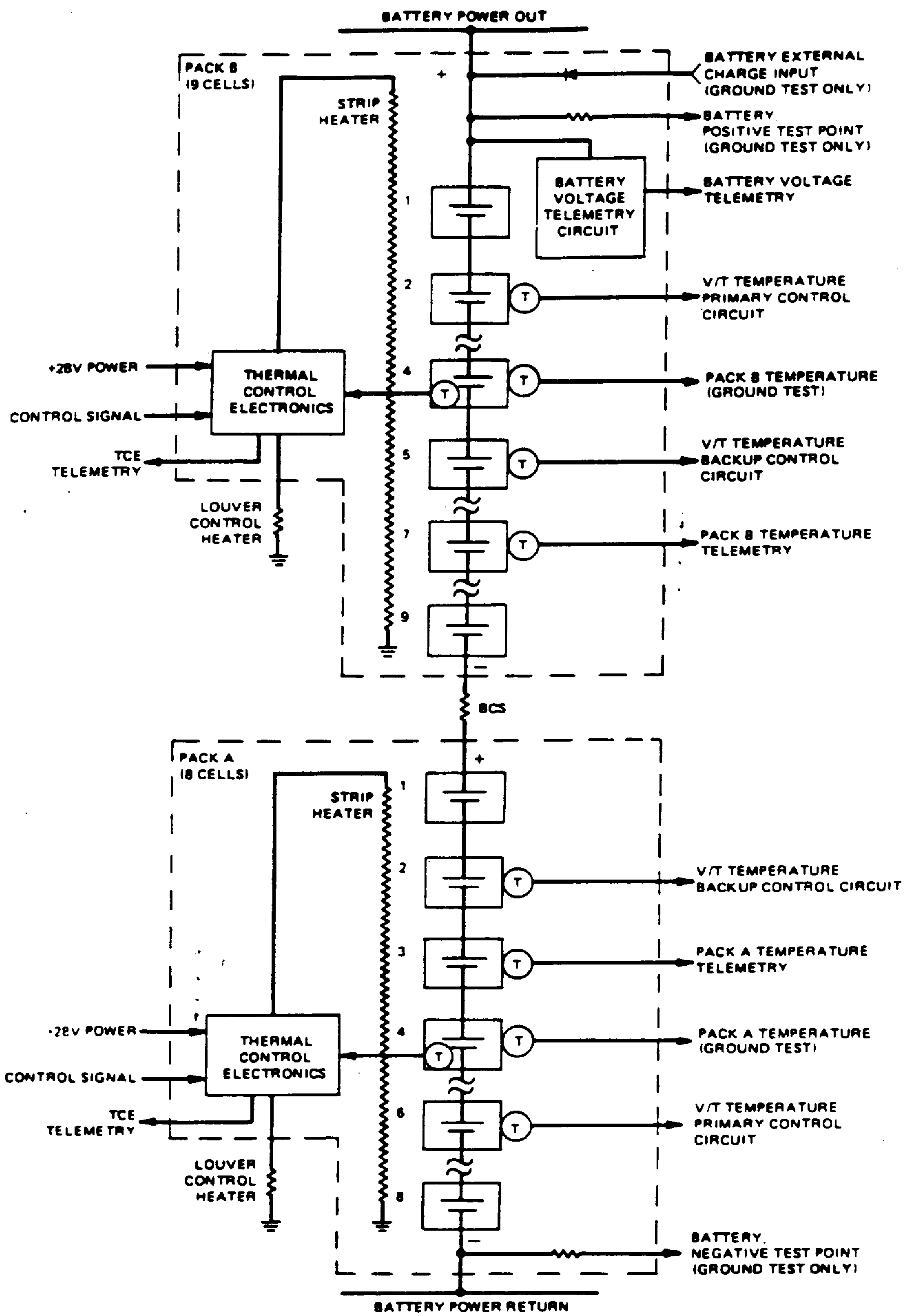

Figure 3 26.5 Ampere Hour Battery Configuration

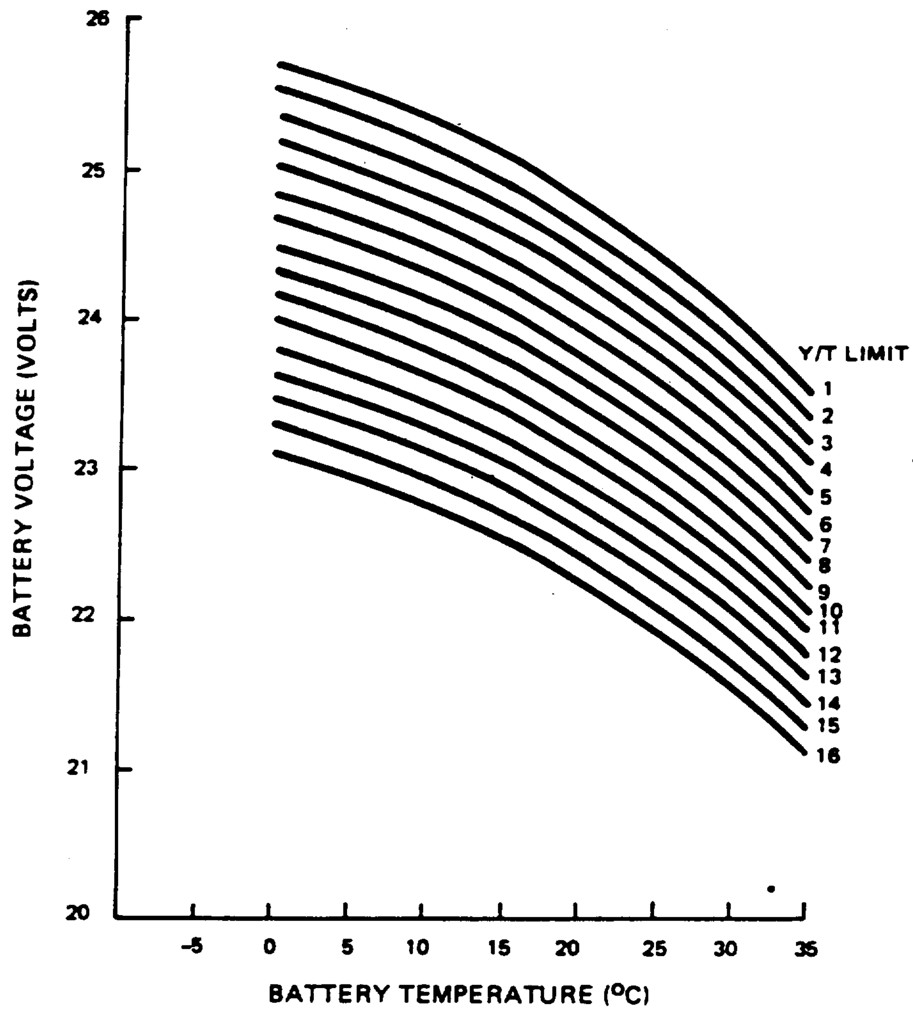

Figure 4 Temperature Compensated Voltage (V/T) Levels

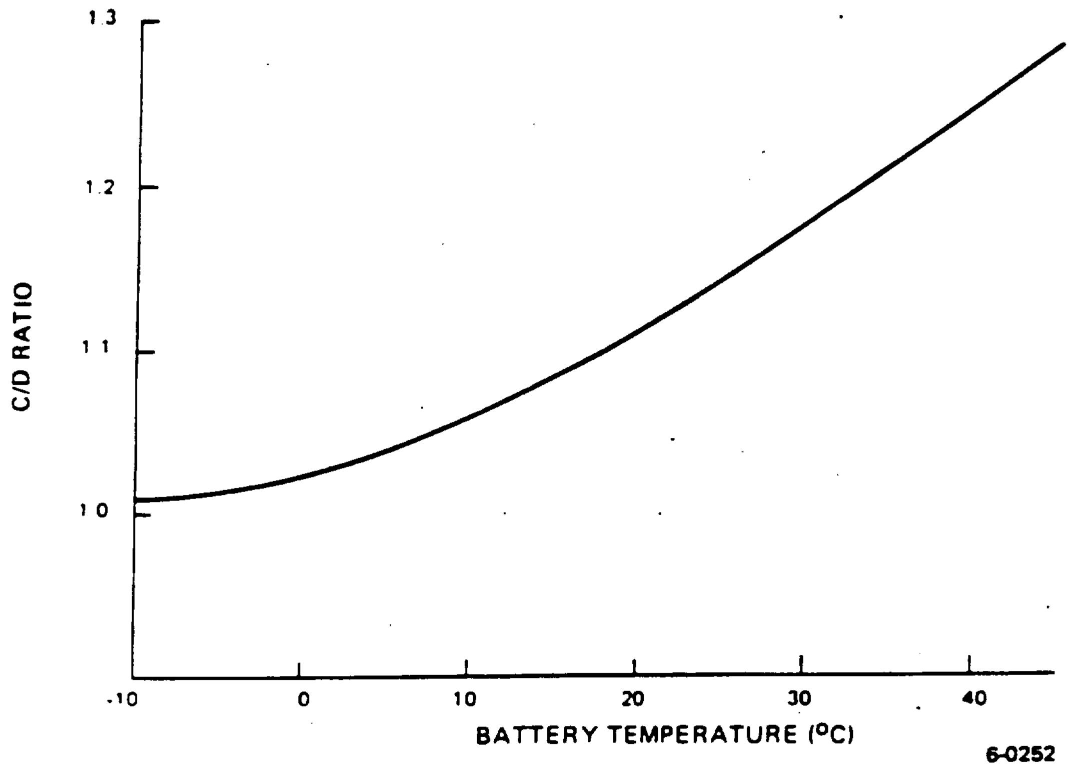

Figure 5 Minimum Charge/Discharge Ratios

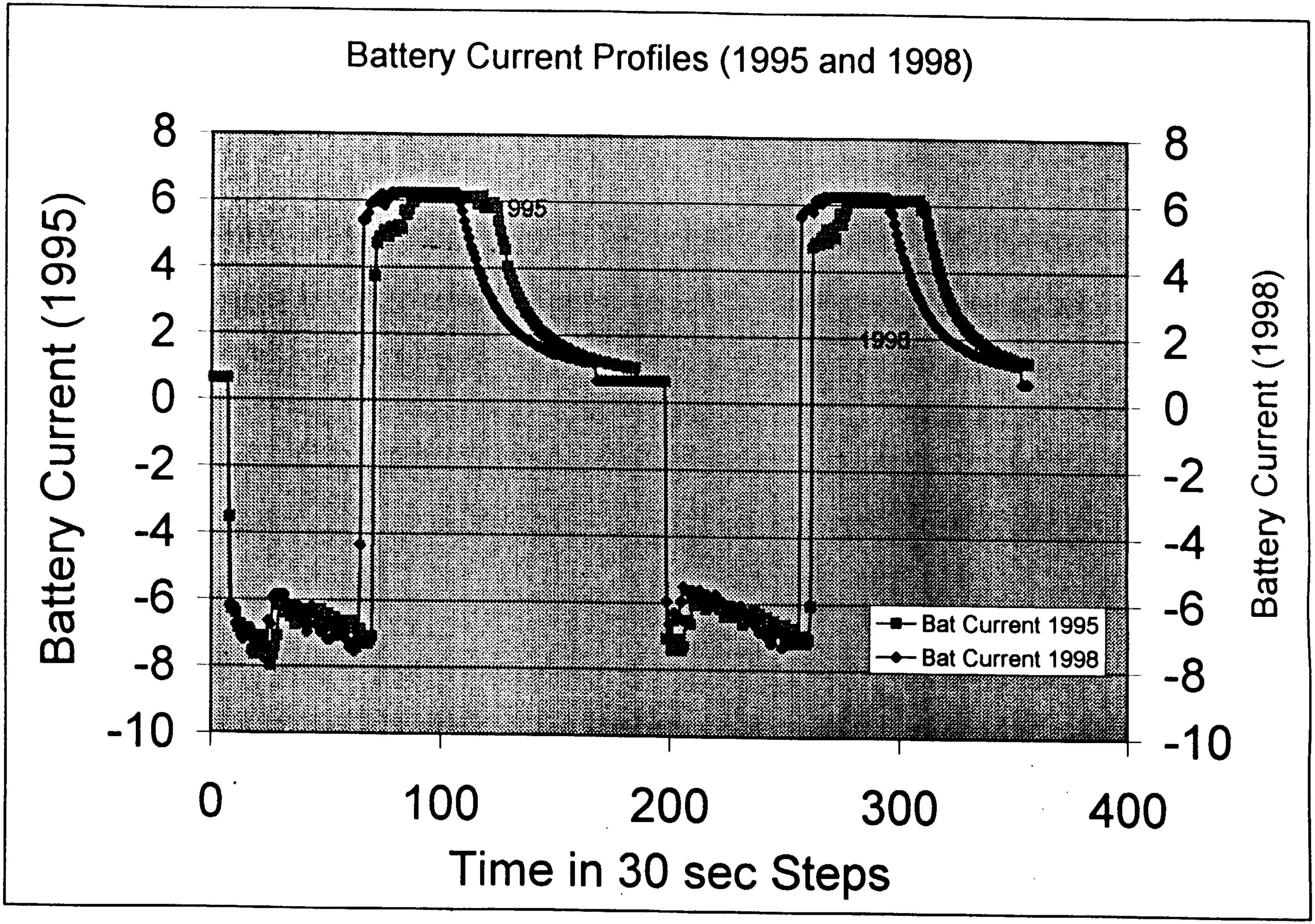

Figure 6 Battery Current Profiles

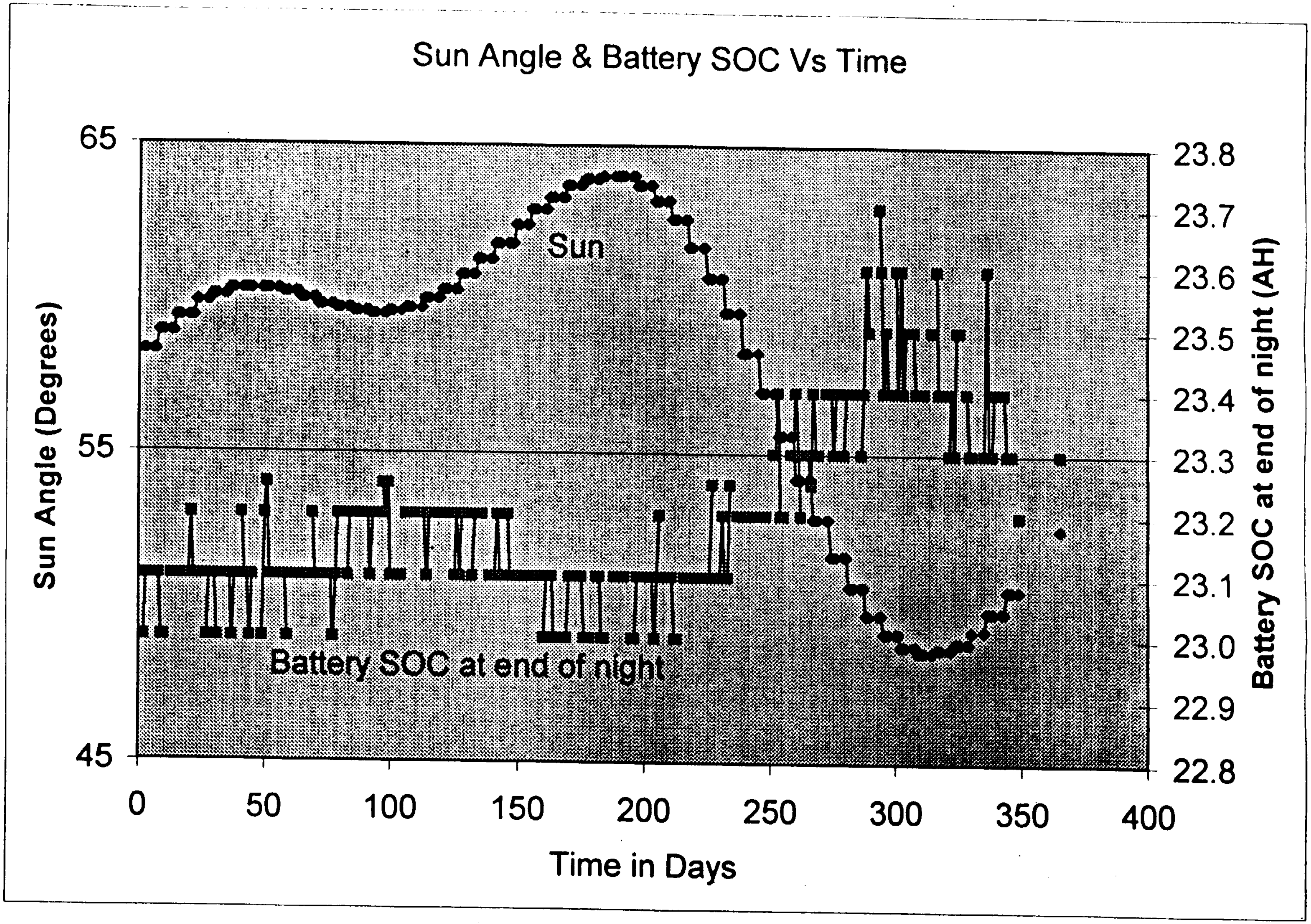

Figure 7 State of Charge of Batteries Vs Time

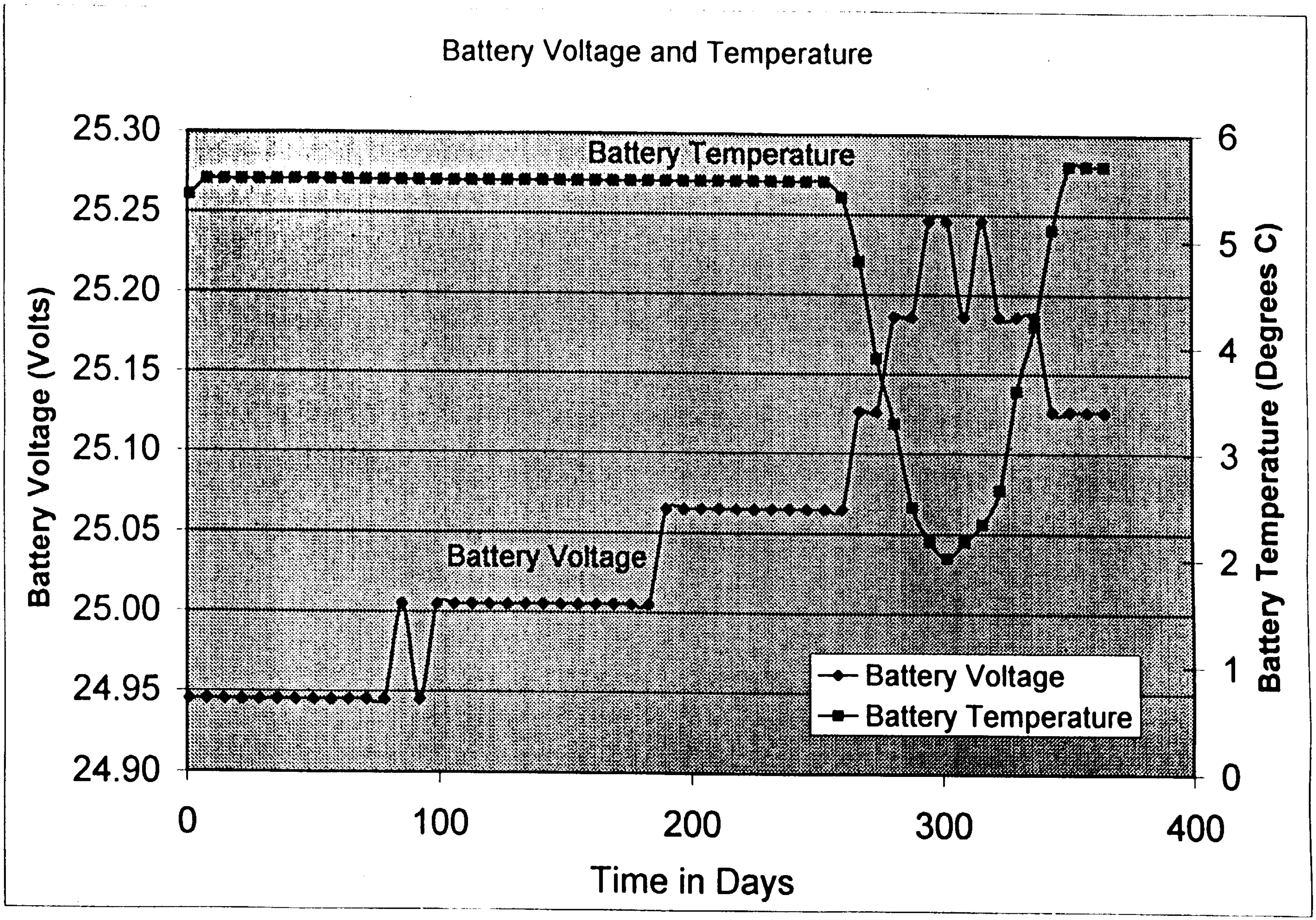

Figure 8 End of Charge voltage of Batteries and Temperature

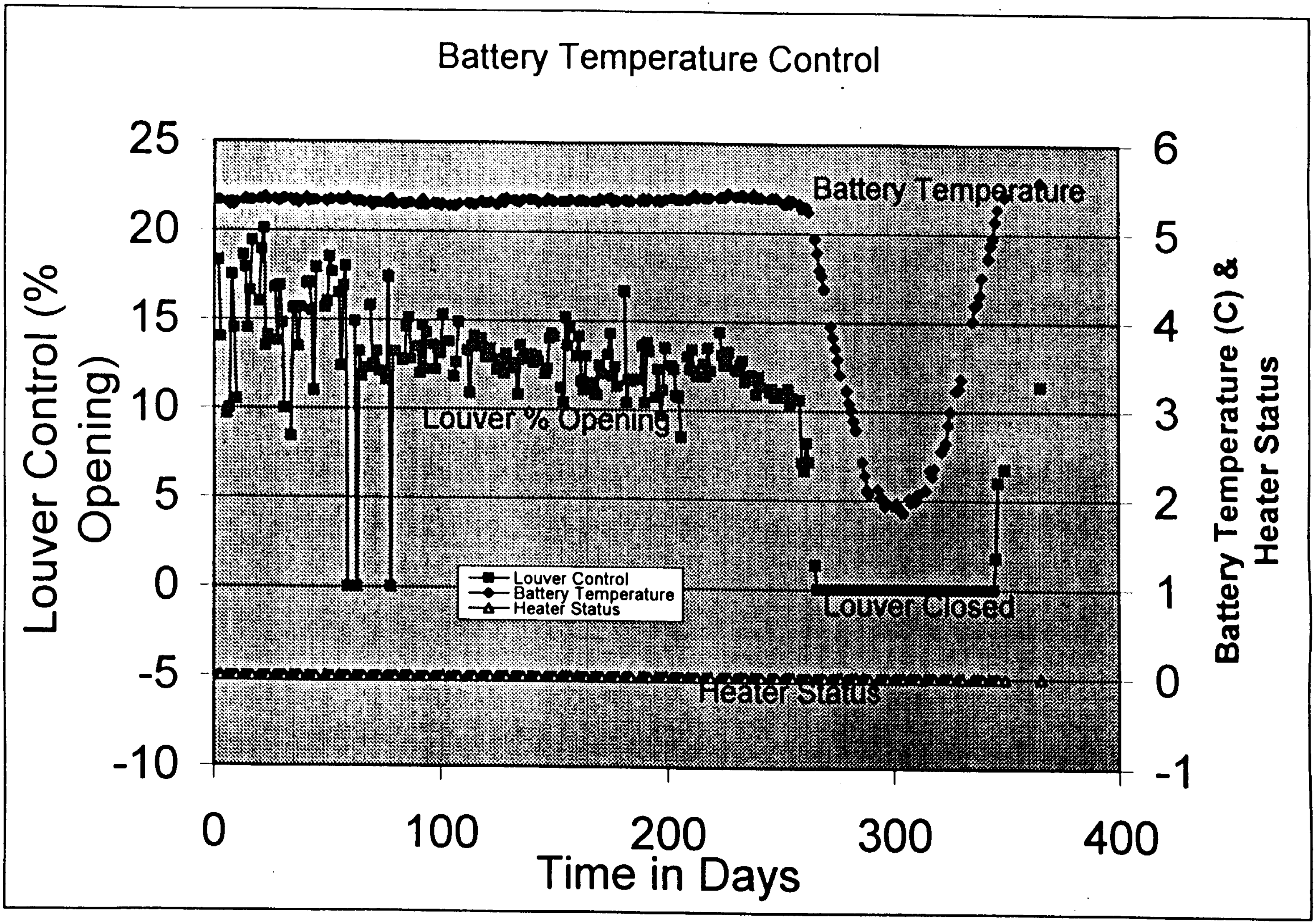

Figure 9A Battery-1A Temperature, Louver Control and Heater Status

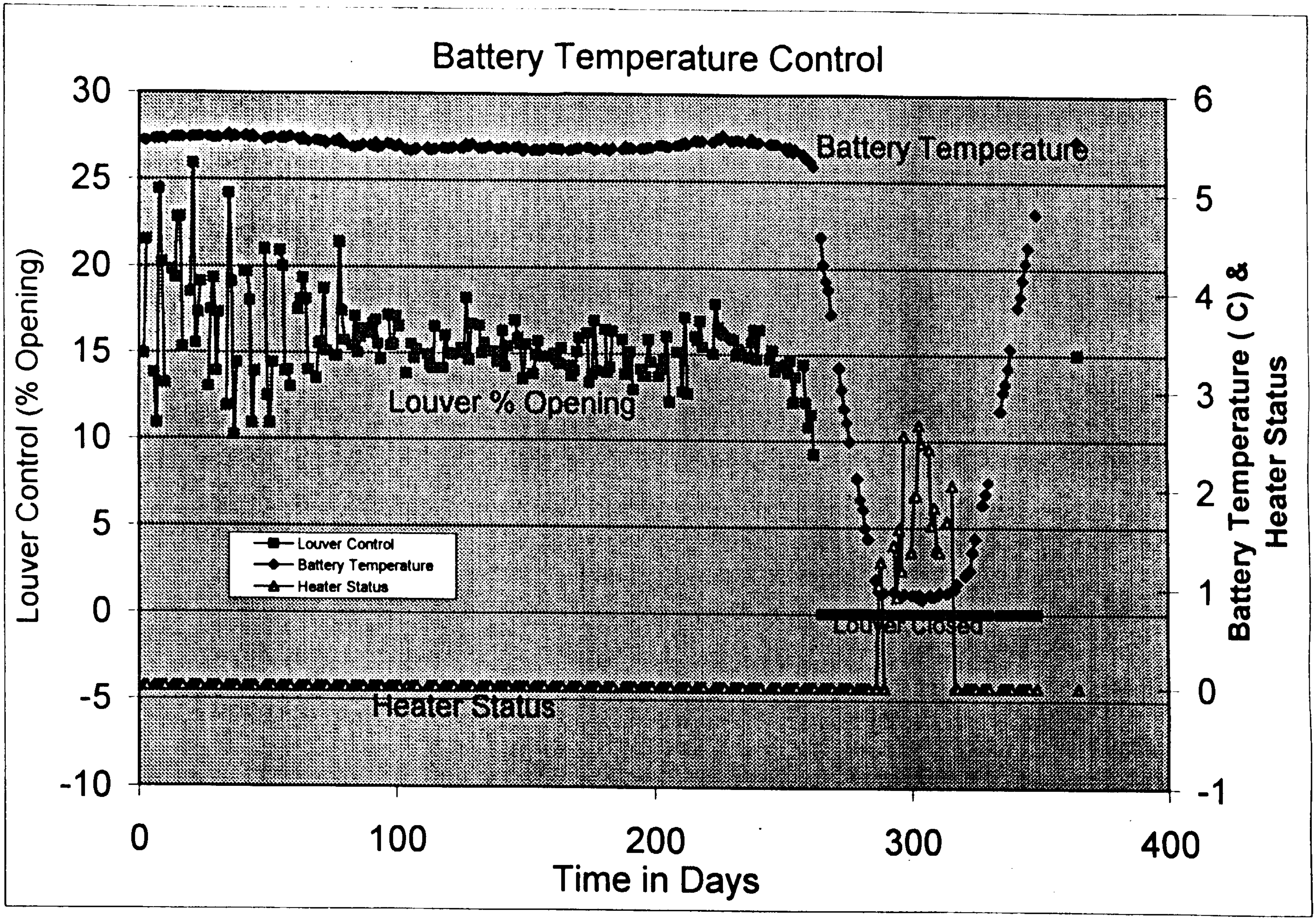

Figure 9B Battery-1B Temperature, Louver Control and Heater Status

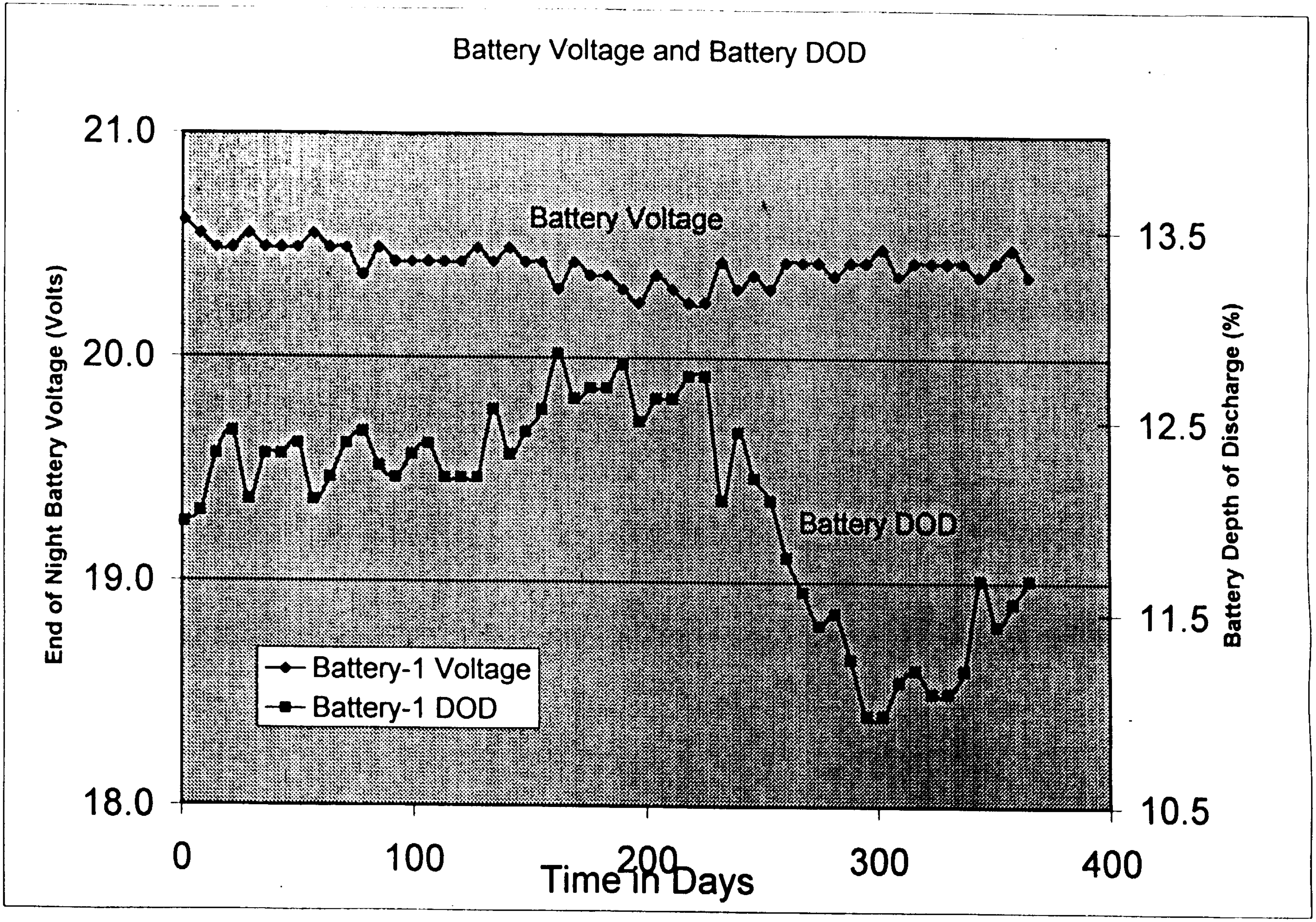

Figure 10 End of night Battery Voltage and Depth of Discharge

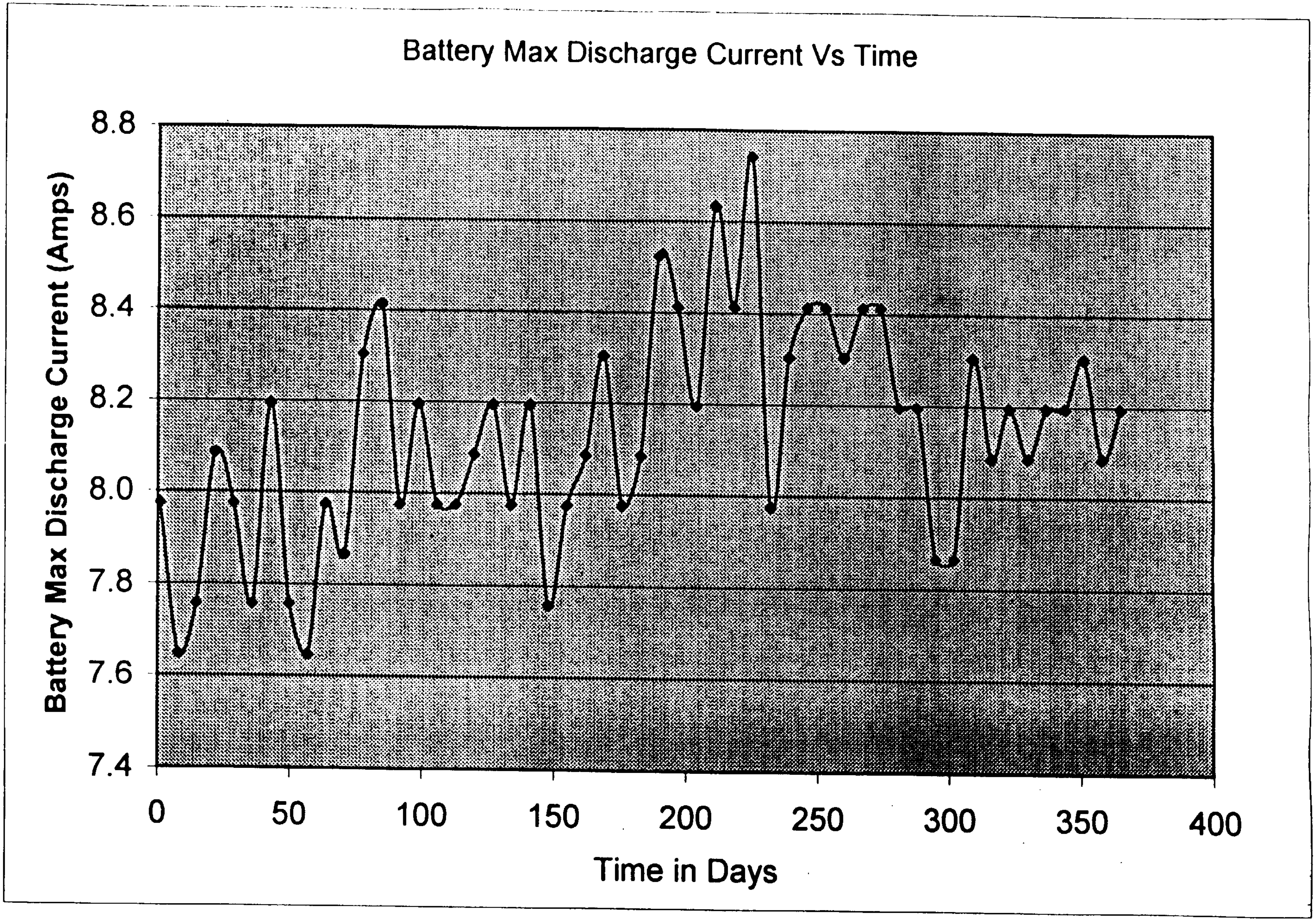

Figure 12 Peak Discharge Current