MANAGEMENT AND PERFORMANCE OF APPLE BATTERY IN HIGH TEMPERATURE ENVIRONMENT

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ABSTRACT

India's first experimental communication satellite, APPLE, carried a 12 AH Ni-Cd battery for supplying power during eclipse. Failure to deploy one of the two solar panels resulted in the battery operating in a high temperature environment— around 40 C. This also resulted in the battery being used in diurnal cycles rather than just half yearly eclipse seasons. This paper describes the management and performance of the battery during its life of two years. An attempt to identify the probable degradation mechanisms is also made.

INTRODUCTION

APPLE (Ariane Passenger Payload Experiment) spacecraft was launched by Ariane LO3 on June 19, 1981. This was a 380 Kg (in orbit mass) three-axis stabilized satellite parked at 102 E longitude and designed for a two-year life to conduct communication experiments. The power system was comprised of two deployable, sun-tracking solar panels supplying 250 watts of power to a regulated 28 volt bus. A 12 AH, 16 cell Ni-Cd battery was employed to supply eclipse, transfer orbit, and peak loads. Figure 1 shows the block schematic of the power system.

The battery charge path had two chargers—one for the transfer orbit phase and the other for the on orbit phase. The on-orbit charger was a fixed 2 ampere charger with the 8-level voltage-limited auto and manual control for the changeover to a 350 mA trickle charge. The transfer orbit charger was a variable current charger which maintained the bus voltage at 33 volts or 28 volts as selected by ground command, and thereby pumping all the extra current into the battery. Control of the transfer orbit charger was also possible by the 8-level voltage limit or by ground command. However, the transfer orbit charger opened the charge path once the battery was completely charged.

BATTERY DESIGN

The battery was a single, 16 cell, 12 AH battery supplied by SAFT, France. The cell case was, in fact, identical to that of the 10 AH cell, and cells with a slightly higher loading were selected to achieve the capacity of 12 AH. The design parameters and constructional details of the battery are given in Tables 1 and 2. The cell details are provided in Table 3. The battery was designed for an operational life of two years at 72% maximum depth of discharge, thereby undergoing four eclipse seasons. Complete reconditioning was not envisaged in view of its short life, and limited reconditioning to about 17.6 volts was possible by proper choice of charger and control combinations.

Table 1

Battery Design Parameters

Capacity	12 AH
Number of cells in series	16
Operating voltage range	19-24 volts
Temperature range of operation	0 C-25 C (Average 20 C)
Peak depth of discharge	72%
Operating life	2 years - 180 cycles (4 eclipse seasons)
Charge current onorbit	1.8 0.2 Amps
Transfer orbit	0 to 5 Amps
Trickle charge current onorbit	120 10 mA
Transfer orbit	0 (No trickle-battery open)
Discharge current	6 Amps
Expected EOL capacity	9.5 AH
Expected EOL discharge Voltage	18.6 volts at the end of 70% discharge
Thermal control	Passive

Table 2

Battery Details

Battery type	Nickel Cadmium
Capacity	12 AH (Nominal)
Dimensions	225 x 135 x 225 mm
Mass	9.3 Kg
Thermal cutout	35 2 C
Temperature sensor	4K thermistors (two)
Cell type	VO 10 S2
Vendor	SAFT, France
Cell bypass diodes	Provided
Heaters	5 Watts (two)
Mounting	Under the ABM strut on the bottom deck

Table 3

Cell Details

Cell type	VO 12 S2
Capacity	12 AH
Mass	490 gms
Dimensions	85 x 29.2 x 76.2 mm
Positive Electrode Number	12
Thickness	0.76 mm
Loading	13.2 gm/dm^2
Negative Electrode Number	13
Thickness	0.89 mm
Loading	17.5 gm/dm^2
Negative to Positive Ratio	1.8
Case Thickness	0.4 mm
Negative Treatment	None
Inter-electrode Distance	0.26 mm
Separator	Villidon 2119
Electrolyte	KOH
Specific Gravity	1.306

Figure 2 shows the life predictions by SAFT for their cells and it is seen that the design was adequate to meet the two-year life goal at 20 C with 0.99 reliability. The thermal control of the battery was passive control backed up by two heaters.

ORBIT OPERATION

The spacecraft was put into synchronous orbit on the sixth transfer orbit, but the north solar panel could not be deployed resulting in covering a large area provided for thermal control. The battery temperature thus attained very high values. Another problem also arose as a consequence. As can be seen from the power system schematic, certain heater loads were directly connected onto the battery apart from the emergency and power control loads. It was envisaged in the design that the charger current in the trickle charge mode be set to 500 mA which 370 mA was assigned to the loads and 130 mA for charging the battery. However, due to the thermal problems, these heaters were not switched ON reqularly and about 350 mA was flowing into the battery. In trickle charge mode, this would be wasted as heat resulting in the battery attaining a higher temperature. It was thus decided to change over to the transfer orbit charger in trickle mode, subsequent to the charging by the on-orbit charger. Since the transfer orbit charger in trickle mode opens the charge path, a small amount of discharge (120 mA) was experienced by the battery. During the non-eclipse seasons, thus, the battery was discharged daily to about 19.8 volts at 120 mA and was charged subsequently at a time when the temperature was low, ie., around 5 UT.

The battery was thus subjected to diurnal cycles apart from the eclipse cycles. The operating temperatures were too high from any standards for a battery. Reduced generated power due to the nondeployment of one solar panel did not cause much problem as the margin available was large but the thermal problems were acute. The eclipse loads were reduced to a minimum to enhance the life of the battery. The maximum discharge was about 3 AH during the peak eclipse at 2.5 A rate and during the non-eclipse season it was about 2 AH at 0.12 A rate.

In Figure 3, battery voltage, current, and temperature are plotted for one complete day, September 20, 1981, a day on which the eclipse duration was 64 mins. It is obvious that the battery spends most of the time with low discharge in the transfer orbit trickle charge mode. Prior to and soon after eclipse, the battery was charged.

Table 4 lists the major events in the life of the battery in chronological order. The battery was not reconditioned prior to the first and second eclipses. Before the third eclipse, limited conditioning was done. Perhaps, it is more appropriate to call them just deep discharges as the battery was discharged only up to 19.5 volts at 300 mA. The problem about reconditioning was that manual control of charge/discharge was possible only with the redundant charger system and when all the main systems were working satisfactorily, changeover to the redundant system was not advisable. Only prior to the fourth eclipse season a meaningful reconditioning was possible and even then the discharge was not complete as the battery was required to supply peak power to the momentum wheel assembly.

Table 4

Major Events In The Life Of The Battery

Launch	June 19, 1981
Orbit acquisition	June 22, 1981
First eclipse season	August, September 1981
Second eclipse season	February, March 1982
Limited reconditioning	August 11, 1982
Third eclipse	August, September 1982
Reconditioning after change-over to redundant systems	February 17, 1983
Fourth eclipse season	February, March 1983
Reconditioning cycle	August 16, 1983
Fifth eclipse season	August 24, 1983
End of mission	Spetember 12, 1983

In the reconditioning performed on February 17, 1983, discharge was up to 18.7 volts in the first cycle and up to 18.5 volts in the second cycle. Discharge beyond 18.5 volts was not attempted as the eleventh cell voltage reached 0.7 volts, whereas the other cell voltages were still above 1.15 volts. The charge/discharge characteristics of these two cycles are shown in Figure 4. The improvement in the characteristic is evident.

Before the fifth eclipse season, three reconditioning cycles were completed but this time reconditioning was done, rather inadvertantly, down to 17.1 volts. The fifteenth cell reversed to -0.16 volts for a few minutes. Figure 5 shows the charge/discharge cycles. The improvement in capacity from 5 AH to 6.5 AH and improvement in the voltage performance are clearly evident.

On September 12, 1983, during the fifth eclipse season, soon after an eclipse, the solar panel failed to track the sun resulting in a total discharge of the battery down to zero volts. This was the first opportunity when the battery capacity was measured at normal discharge rate of 2.5 amps. During this discharge, the battery delivered 6.25 AH down to zero volts. The 12 AH battery had degraded by 50%! Considering the extremes of strain to which the battery was subjected, this was a remarkably good performance.

BATTERY PERFORMANCE

Figures 6 and 7 show the variation of the battery temperature. Figure 6 shows the diurnal variation for days which are approximately six months apart and Figure 7 shows the variation of the maximum and minimum temperatures over its life. The days selected in Figure 6 correspond to the minimum temperature encountered by the battery during the equinoxes and the maximum temperature during the winter solstice. It is observed that for most of the time, the battery temepratures were above 30 C and for a considerable time, above 40 C, reaching a maximum of 55 C on certain days (not shown in the figure). Increase in the battery temperature over its life was also due to the degradation of the passive thermal control elements - OSR. Consequent to this, a crucial problem regarding battery management was the setting of the voltage at which the battery should change over from charge to trickle charge. Improper setting would result in the battery getting either grossly undercharged or overcharged. No data is available regarding battery performance at temperatures above 30 C making predictions almost impossible.

Table 5 summarizes the details of the performance of the battery during the four eclipse seasons. The battery temperature during charge was maintained within a degree. The post-eclipse end-of-charge voltage varied from 22.83 volts to 23.13 volts. These values are the forced values rather than the values that would have been attained had the battery been allowed to charge completely under normal circumstances. In fact, it is evident that during the third and fourth eclipse seasons the battery was not charged completely. However, the battery was charged sufficiently before every eclipse to supply the required 3 AH of discharge.

A comparison of the change in the charge voltage can be made by examining the battery charge characteristics during reconditioning before the fourth and fifth eclipse seasons—refer Figures 4 and 5. During reconditioning the charging was done in the manual mode and the battery was charged until it definitely showed signs of overcharge. During the first reconditioning, the battery charge voltage was 23.25 volts and during the second reconditioning, 24.75 volts. These two values correspond to temperatures of about 31 C. End-of-charge voltages on average cell basis correspond to 1.55 volts during the second reconditioning. This was rather unexpected and clearly shows a significant increase in the over potentials—increase in the internal resistance. The charge characteristic also is very much different from what one would normally expect at this temperature—not flat and sharply rising while nearing end-of-charge. The over charge factors calculated from these cycles are around 1.2.

If one looks at the discharge characteristics--refer to Figure 8--one cannot figure out much, as there is hardly any change in them from the first eclipse season to the fourth eclipse cycle. Our first opportunity to measure the capacity was during the first reconditioning cycle before the fourth eclipse season. For a discharge rate of 0.3 amps, the capacity down to 18.4 volts (1.15 volts/cell) was 6 AH. In the second reconditioning cycle, the battery delivered 6.25 AH at the same rate. The actual details of the discharge cycle are shown in Figure 9.

Figure 10 compares the discharge characteristics with those of the fresh battery, as determined by ground tests prior to launch. Superposed over its characteristics are the discharge characteristics during the first eclipse and the last discharge cycle. It is observed that up to 2.5 AH discharge, there is absolutely no voltage degradation.

CONCLUSIONS

In conclusion, one can observe the following degradation modes:

(a) Very high end-of-charge voltage—1.55 volts—an abnormal value for this high operating temperature.

(b) Reduction in the battery capacity by about 50%.

(c) No appreciable discharge voltage degradation up to 2.5 AH, but a sudden fall subsequently.

Abnormal end-of-charge voltages indicate very high internal impedance due to the hydrolysis of the separator resulting from operation at high temperatures. This could also partly be due to electrolyte redistribution. The charge characteristics also indicate a significant loss of negative electrode capacity, approaching negative capacity limitation. The loss in capacity is due to the combined effects of separator hydrolysis and electrode degradation.

The surprising fact is the non-appearance of voltage degradation. Considering the fact that the battery has undergone 730 diurnal cycles in addition to the eclipse cycles and without proper reconditioning, this is remarkable.

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Table 5

Battery Performance During Eclipse Seasons

					Post eclipse charging			
Eclipse Season	Date	Eclipse duration minutes	Eclipse discharge AH	End of discharge voltage	End of charge voltage	End of charge temperature	Charge input AH	Remarks
1	Sept.20, '81	64	2.7	19.43 1.214/ cell	22.83 1.427/ cell	20°C	3.1	
2	Mar. 20, '82	69	2.9	19.53 1.22V/ cell	23.13 1.45V/ cell	28.3°C	2.9	
3	Sept.18, '82	70	2.92	19.04 1.19V/ cell	23.13 1.45V/ cell	28.7°C	2.75	
4	Mar. 8, '83	66	2.75	19.14 1.196V/ cell	23.13 1.45V/ cell	31.5°C	2.7	Battery conditioned before eclipse

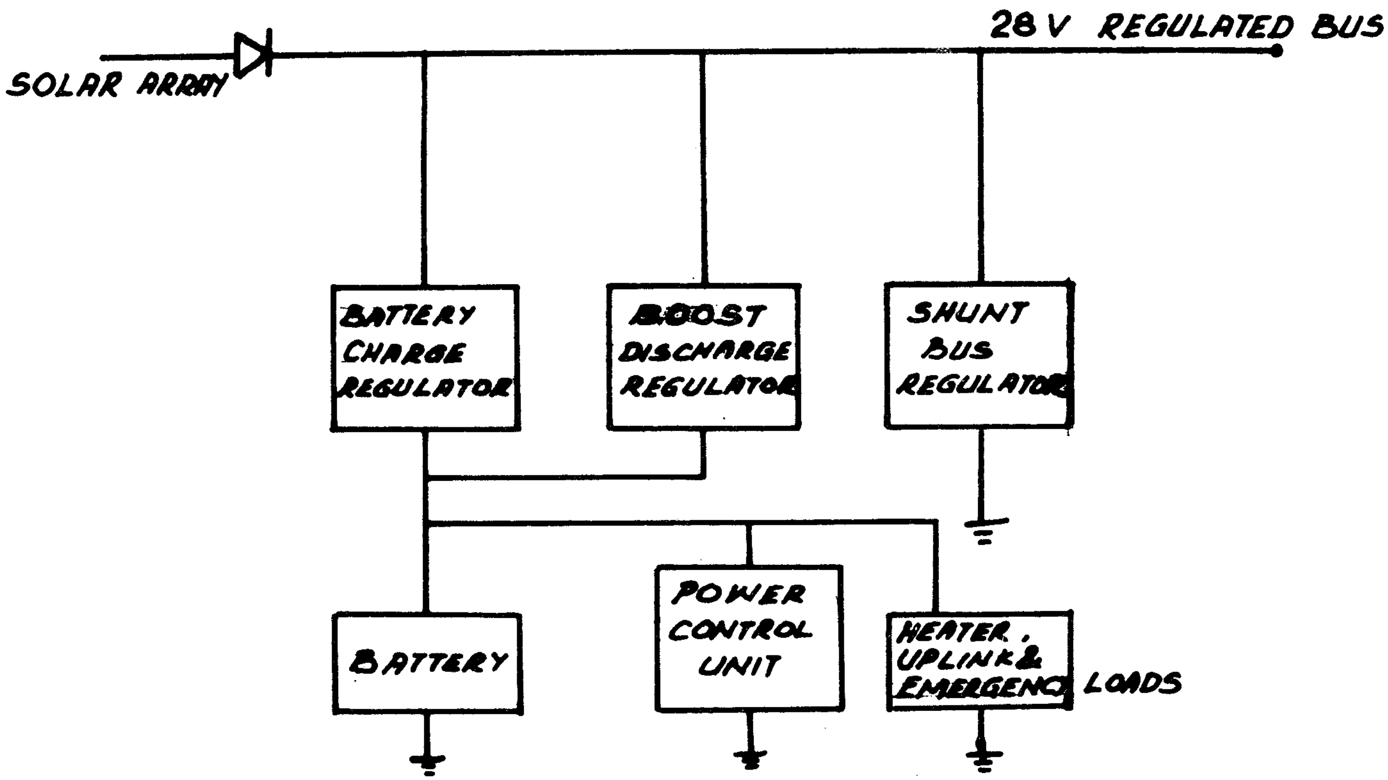

Figure 1. Apple power system schematic.

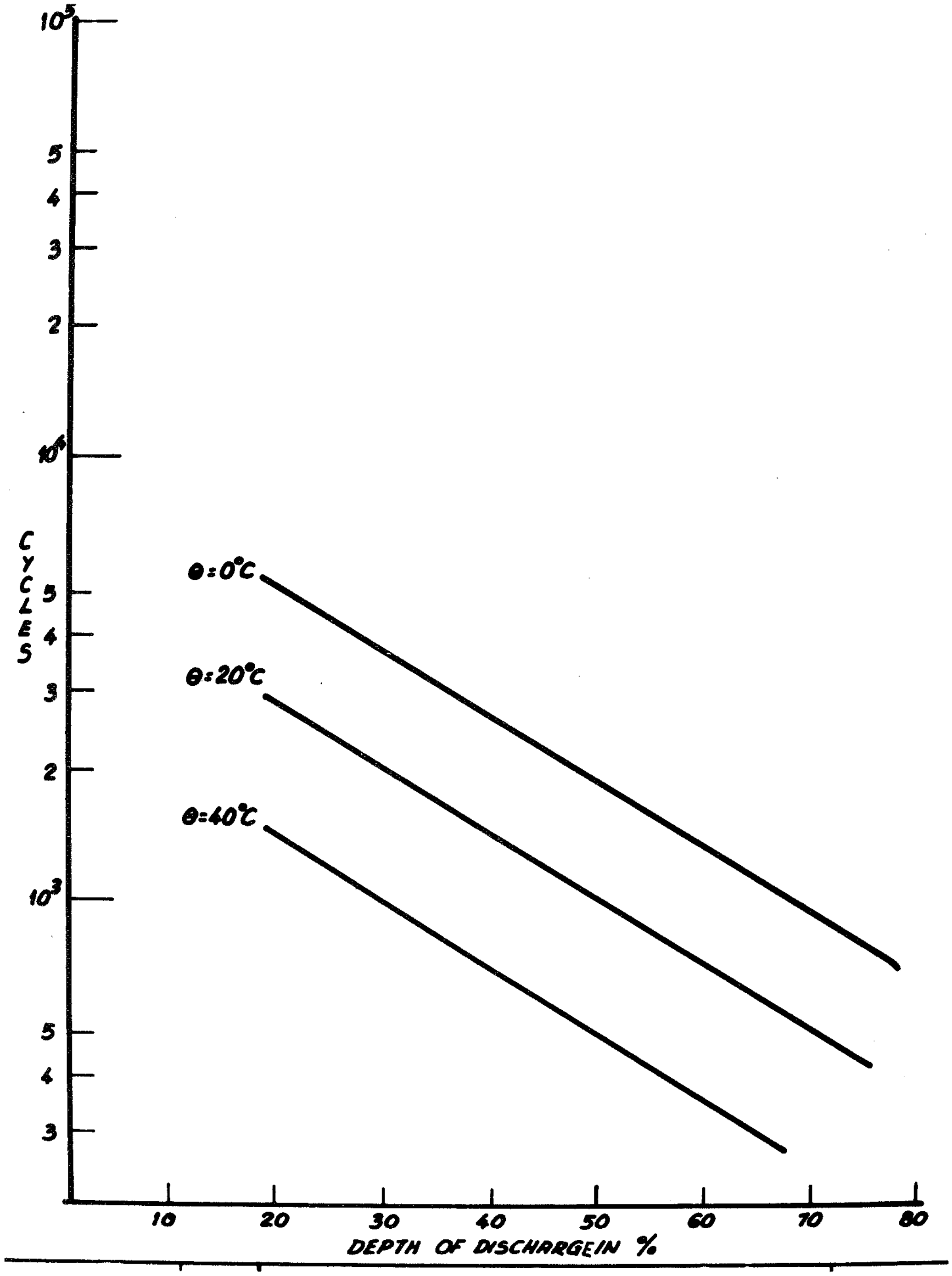

Figure 2. Life expectancy of Ni-Cd cells 24h orbit.

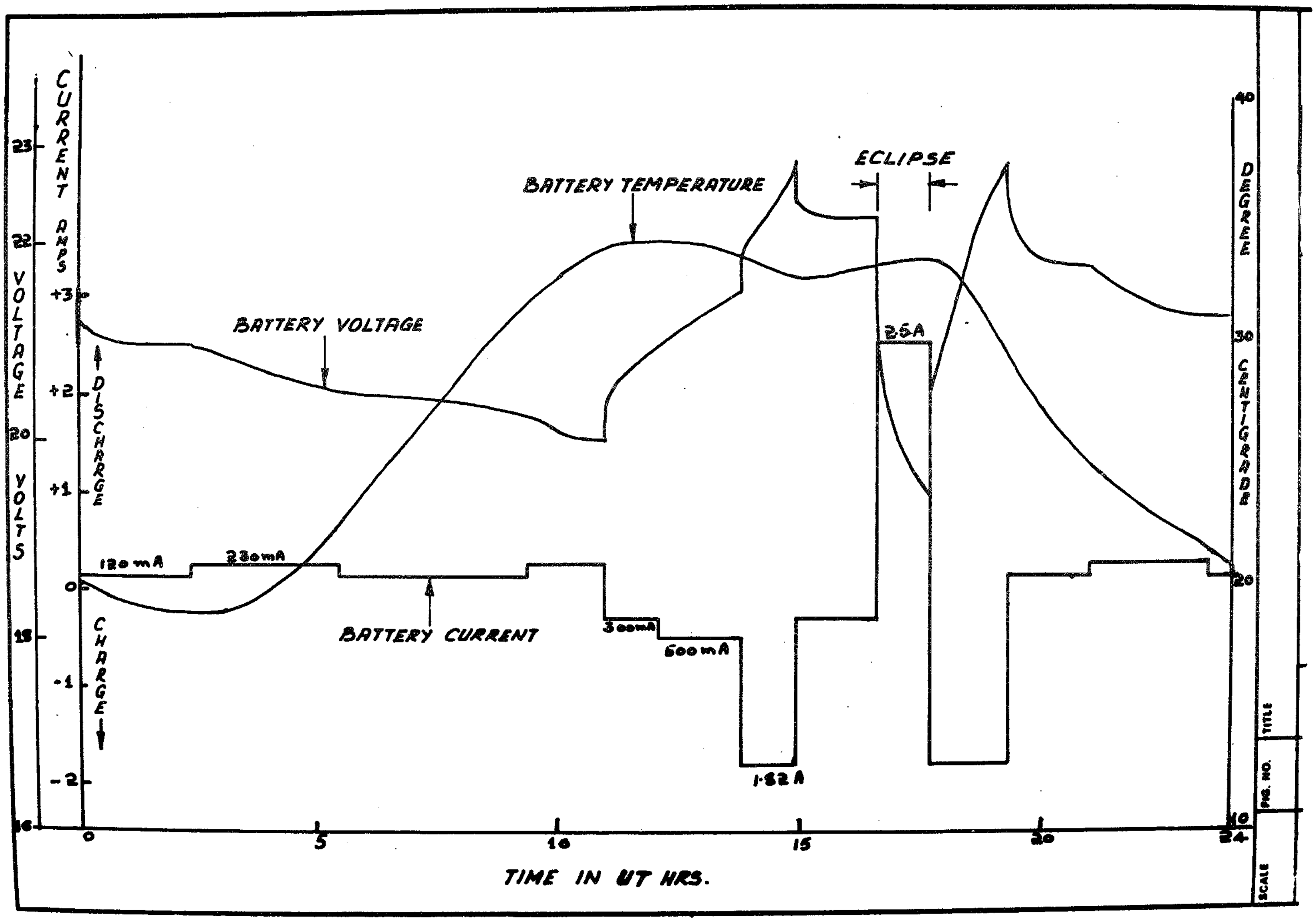

Figure 3. Battery Diurnal cycle (Sept.20, 1981).

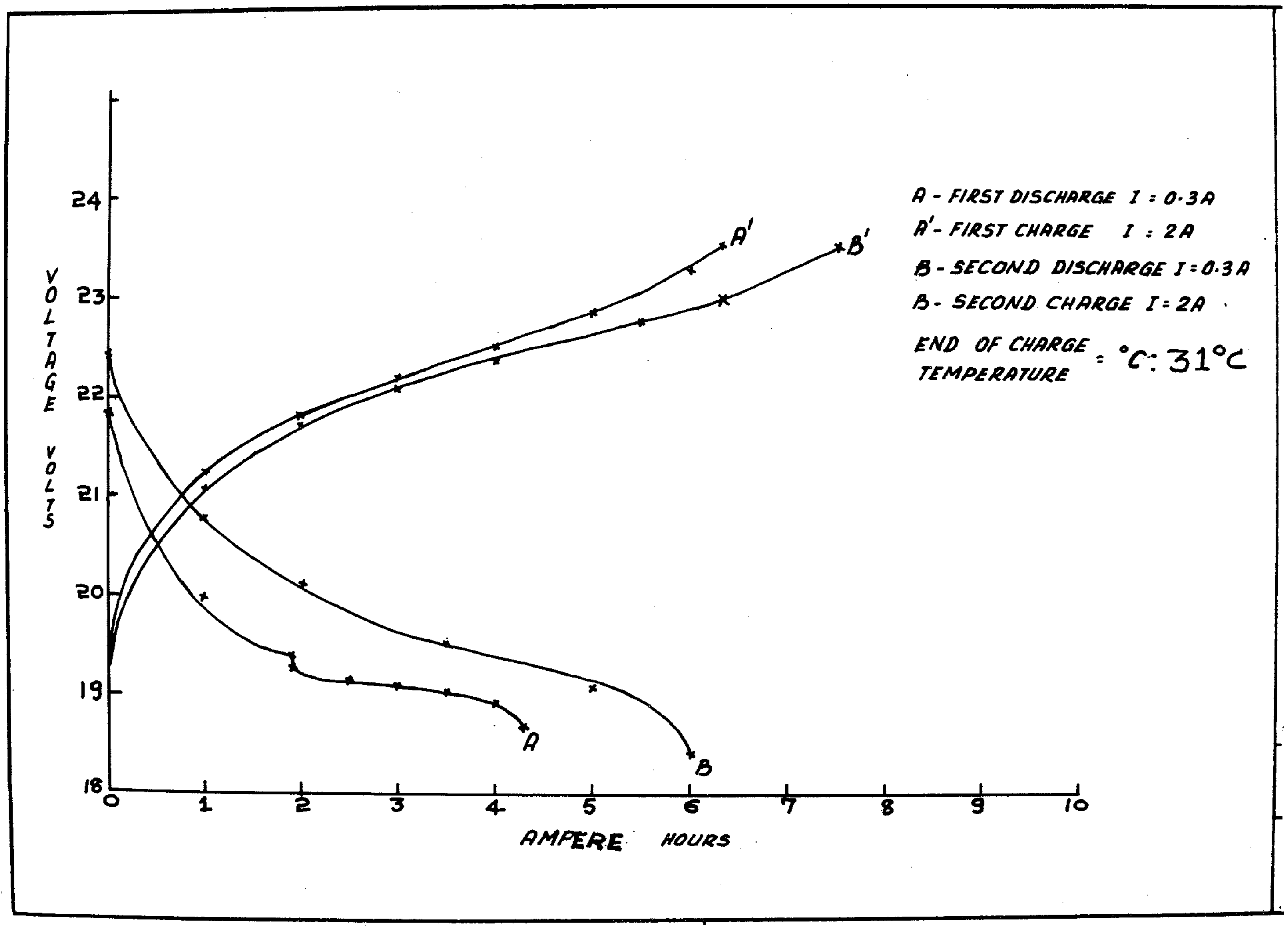

Figure 4. First reconditioning (before 4th eclipse).

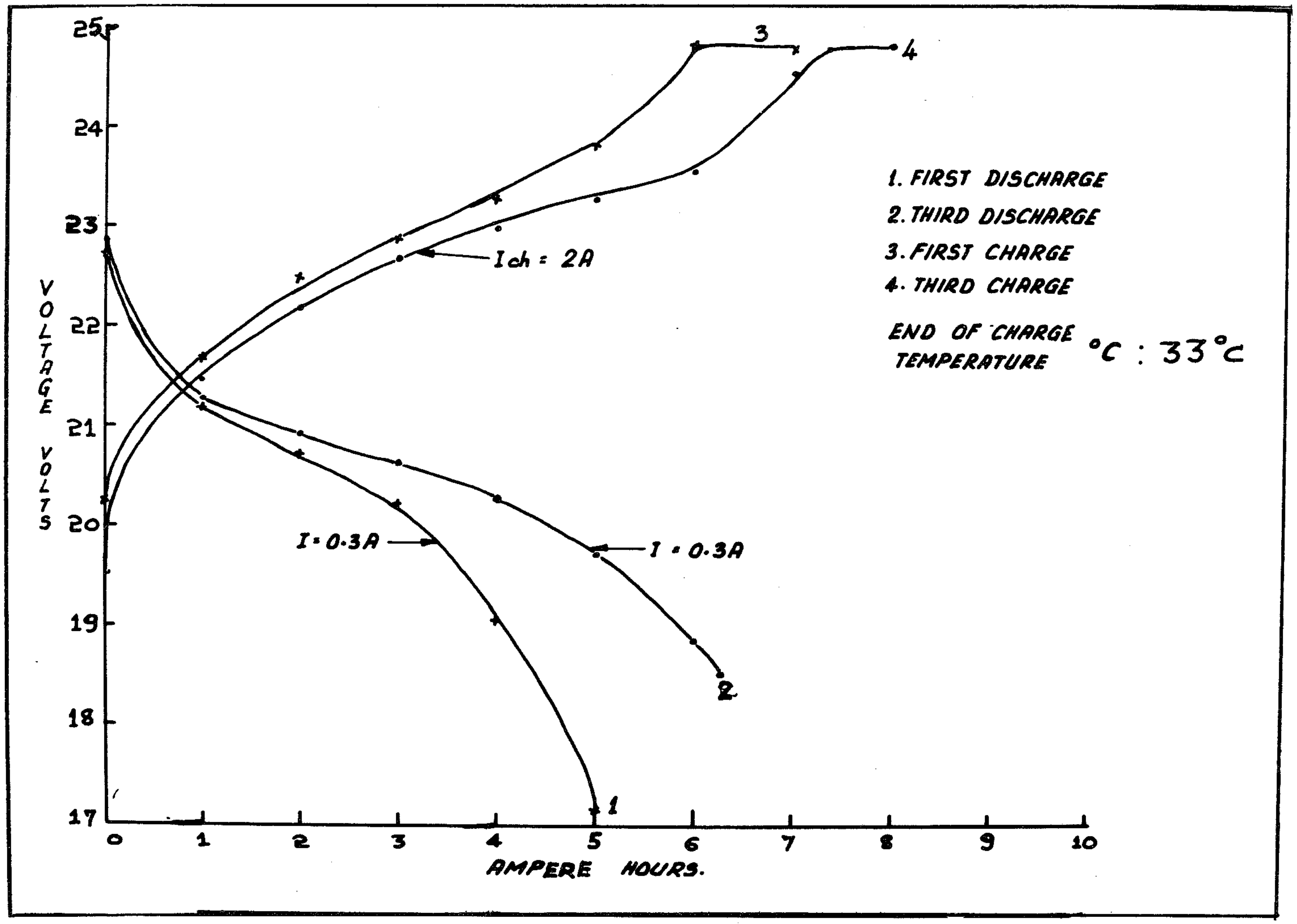

Figure 5. Second reconditioning (before 5th eclipse).

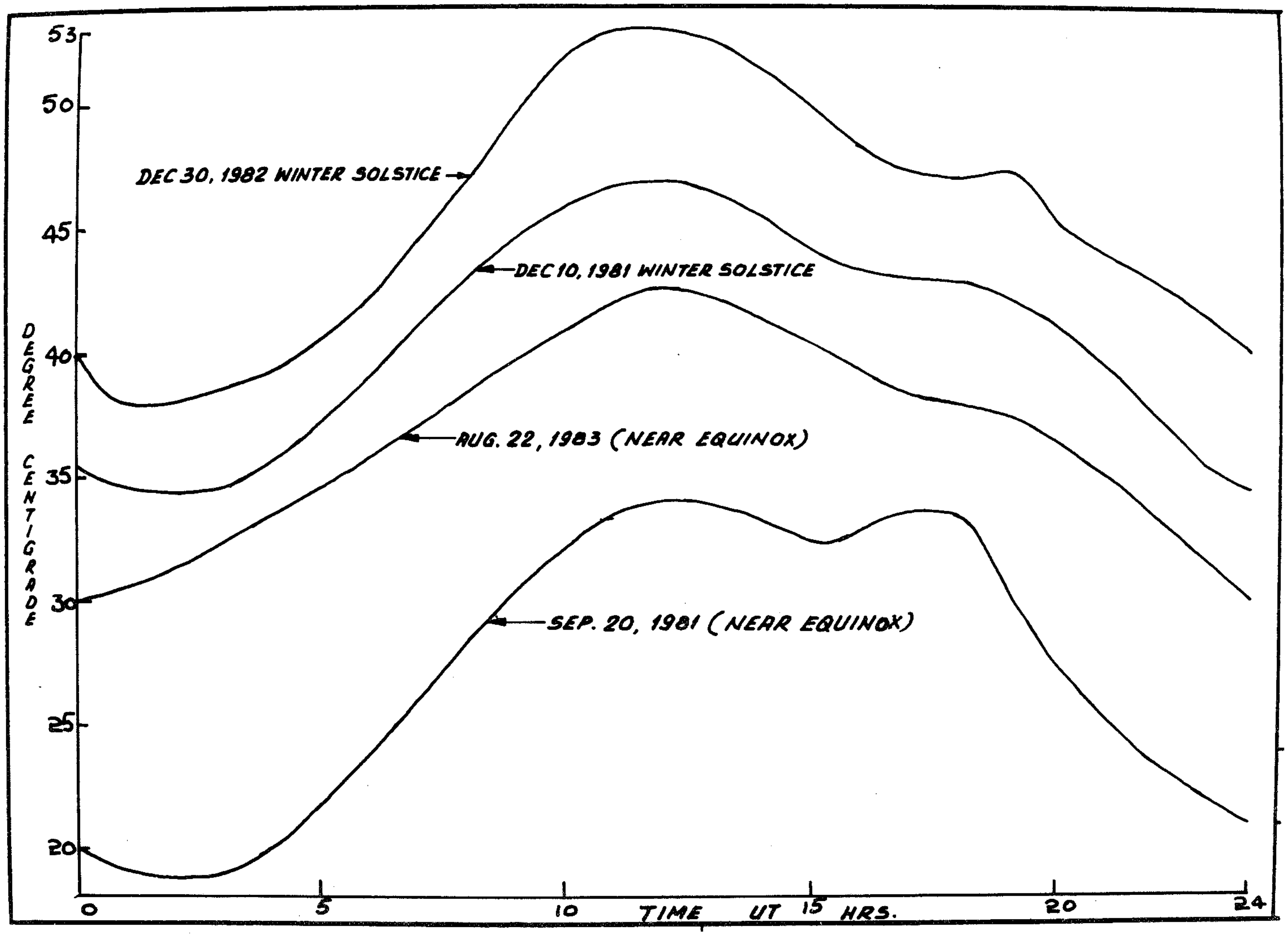

Figure 6. Diurnal variation of battery temperature.

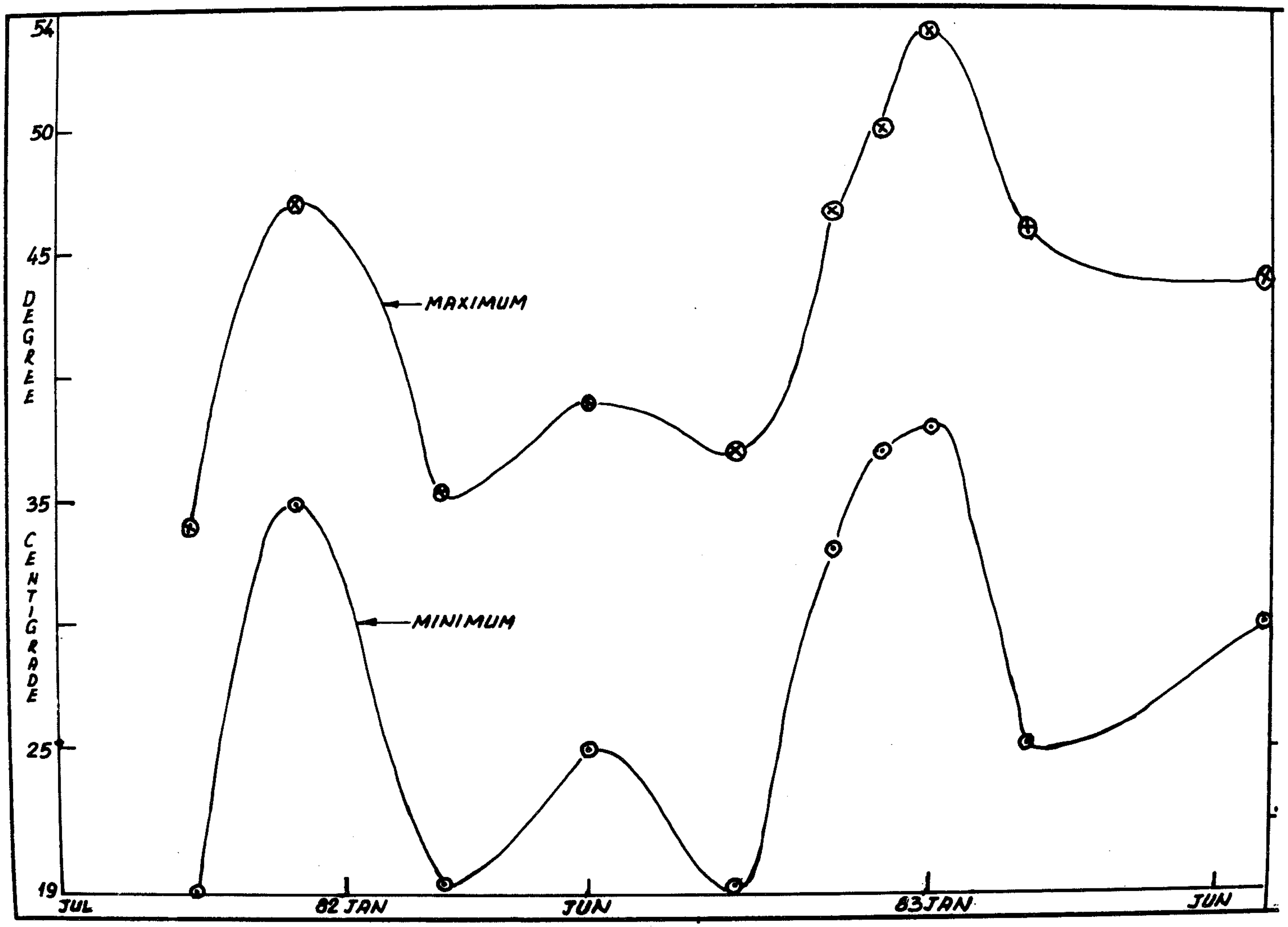

Figure 7. Variation of maximum & minimum temperature over life.

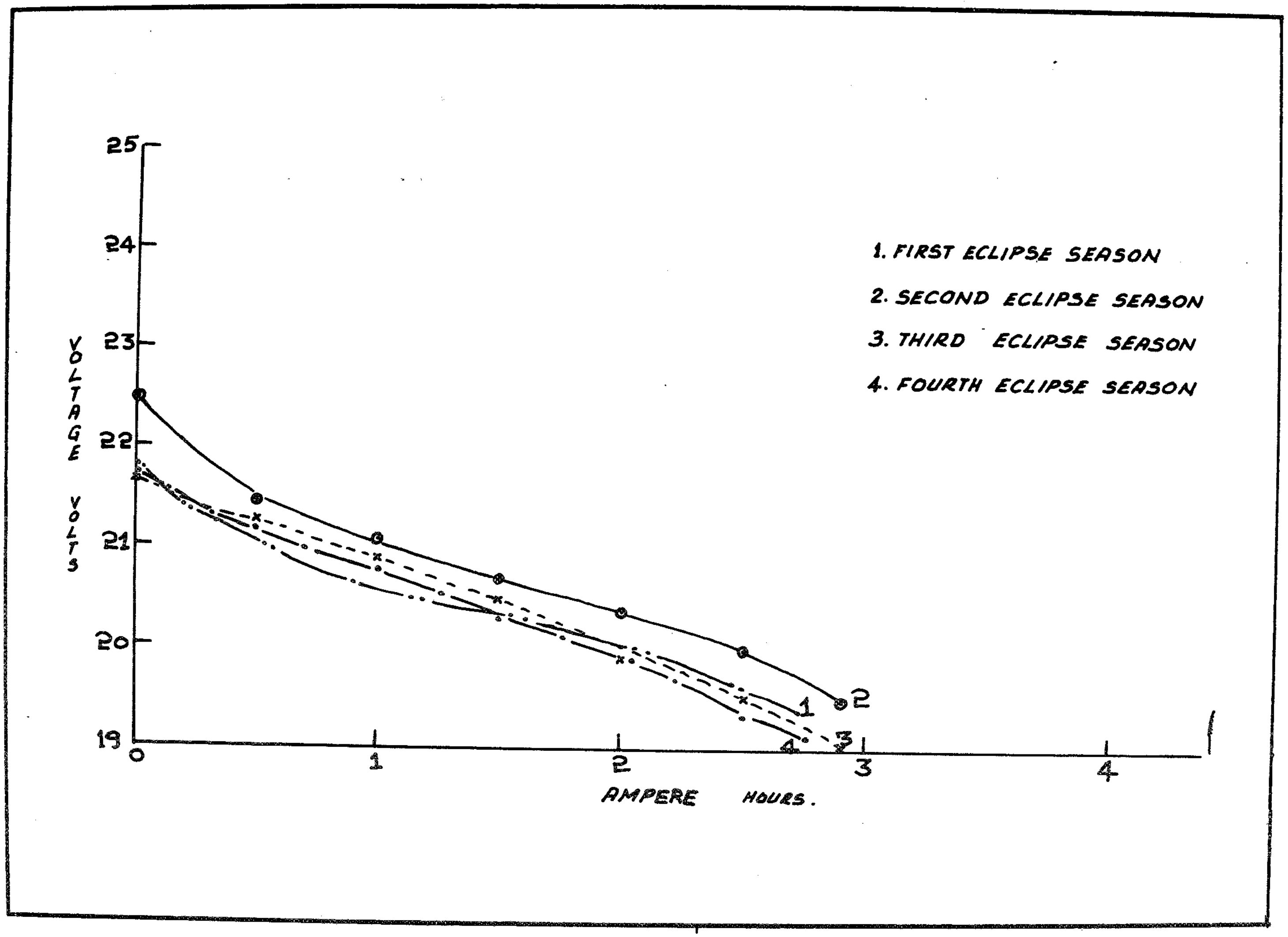

Figure 8. Eclipse discharge characteristics.

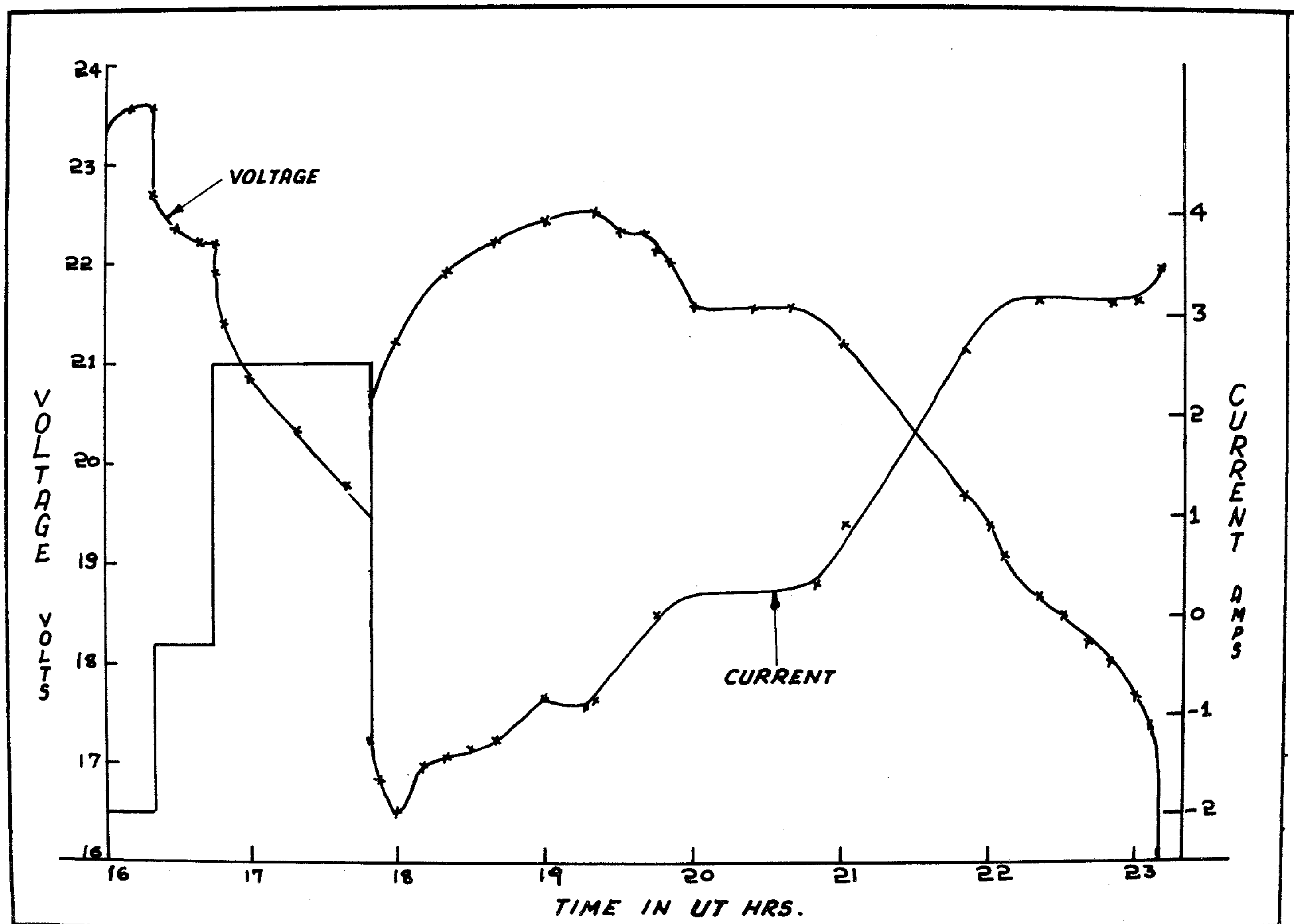

Figure 9. Final battery discharge (Sept.12, 1983).

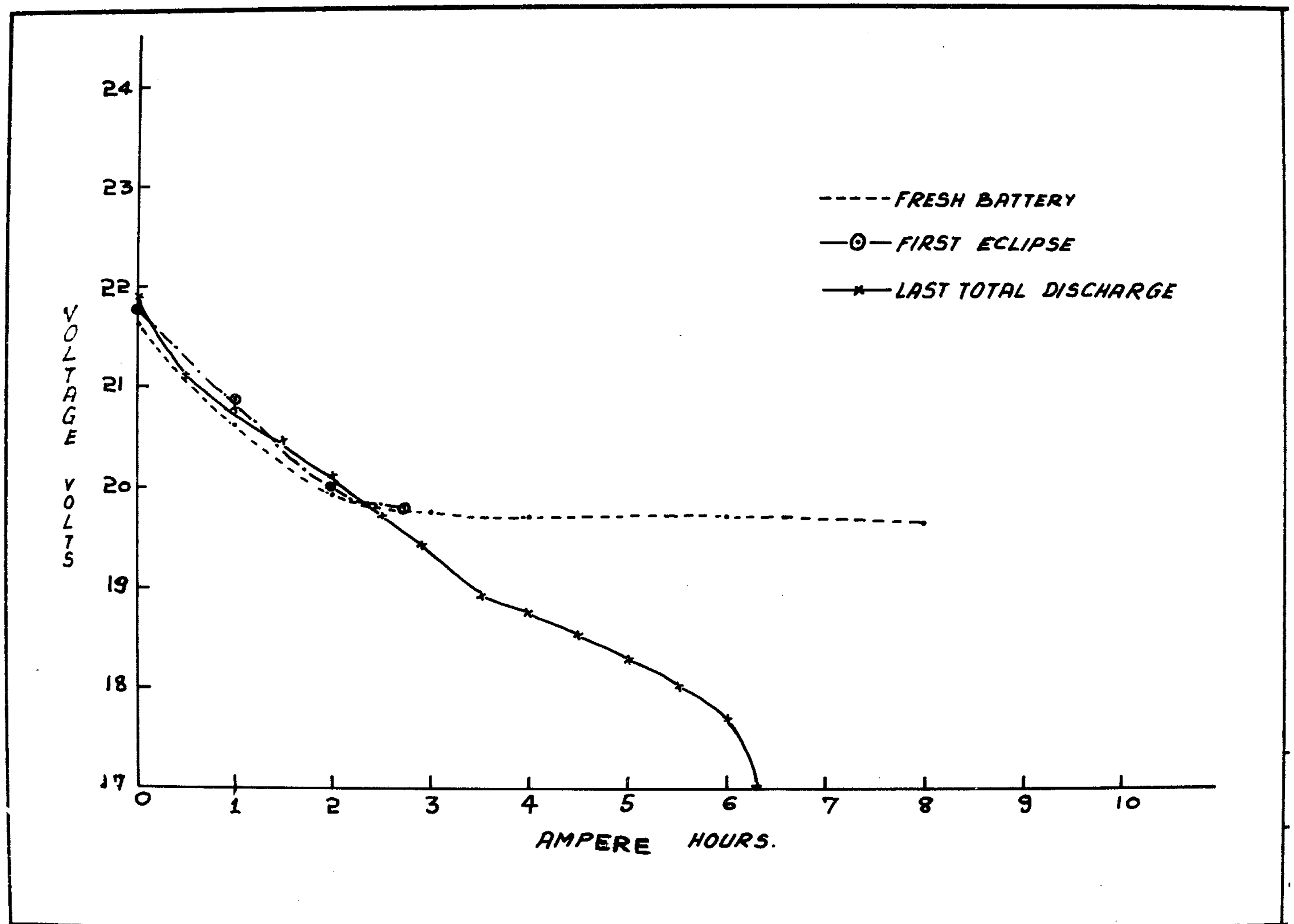

Figure 10. Comparison of discharge characteristics.