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A NICKEL-CADMIUM BATTERY RECONDITIONING CIRCUIT

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16. ABSTRACT

The circuit presented in this paper is simple and small enough to be included in a typical battery charge/power control assembly, yet provides the advantage of a complete "ground-type" battery reconditioning discharge. Test results on the circuit when used to recondition two 24 cell, 20 A-h nickel-cadmium batteries are given. These results show that a battery reconditioned with this circuit returns to greater than 90 percent of its original capacity (greater than nameplate capacity) and follows a typical new battery degradation curve even after over 20 000 simulated orbital cycles for a 4 year period.

This report addresses applications of the circuit and makes recommendations relative to its use. Its application in low voltage (22 to 36 Vdc) power systems and in high voltage (100 to 150 Vdc) power systems is discussed. The implications are that the high voltage systems have a greater need for battery reconditioning than its low voltage counterpart, and that using these circuit techniques, the expected life of a battery in low Earth orbit can be up to 5 years.

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A NICKEL-CADMIUM BATTERY RECONDITIONING CIRCUIT

SUMMARY

The degradation of the voltage discharge characteristic of a nickel-cadmium battery, sometimes called "memory effect" or "fading," is a problem in space electrical power systems that depend on use of the energy stored in the battery at some minimum voltage. A minimum voltage is normally required for bus regulation for users and to preclude system shut-down by an automatic low voltage sense device. The problem occurs because, with time and cycling, the percentage of total battery energy available at a particular voltage, typically 1.0 to 1.1 V/cell, decreases significantly. The voltage degradation dependence upon environmental parameters and cycle life is demonstrated graphically. Battery reconditioning, which consists of completely discharging a battery for a predetermined time, has been done on the ground by individually loading the battery cells. The equipment required for this process has in the past been too bulky and complex for space flight. Flight battery reconditioning, when used, has typically consisted of removing a battery from the bus, loading the entire battery with a load resistor, and discharging the battery to 0.9 to 1.0 V/cell. The voltage enhancement obtained in this manner has been shown to be minimal and temporary.

INTRODUCTION

Nickel-cadmium (Ni-Cd) batteries have been the primary means of storing electrical energy on space vehicles designed for low Earth orbit operation, which require repeated discharge-charge cycles, since the inception of space exploration. These batteries, typically constructed with 18 to 30 Ni-Cd cells connected in series, may be operated alone or in parallel with other nearly identical batteries. In all of the applications, the batteries are called upon to store energy (usually supplied by a solar array) during a portion of the orbit for use later in the orbit. To assure reliable, long life operation, the batteries are treated with care, limiting the temperature and depth of discharge (DOD) where DOD is defined as:

$$DOD = (\text{A-h out}/\text{A-h rated}) \times 100\%$$

where

DOD = battery depth of discharge

A-h out = the ampere hours discharged

A-h rated = the battery rated capacity.

In spite of this, Ni-Cd batteries voltage capacity characteristics typically degrade with time as shown in Figure 1.

The battery voltage degradation, sometimes called "memory" or "fading," depends on several parameters such as charge characteristics, temperature, and DOD. It causes a problem because the battery is used as a voltage source, and if the energy is not available at or above some minimum voltage the system cannot use this energy. The minimum acceptable voltage is usually 1.0 to 1.1 V/cell. In addition, operation at cell voltages below this level risks reversing the potential on one or more cells in a battery and damaging these cells.

The voltage characteristic degradation in a Ni-Cd battery is largely a reversible process, and the characteristic can be restored to its original state by a process called "reconditioning" whereby each cell in the battery is completely discharged for some predetermined period of time. Reconditioning has historically been performed on the ground by individually loading and discharging each battery cell through a relay and resistor network. However, this has generally been considered too complex, bulky, and/or heavy for flight use where reliability, weight, and space are at a premium. A recent report [1] recognized this limitation as still valid. This report presents a circuit that can be packaged in a space approximately the size of two 20 A-h or larger cells of a battery and is capable of providing the necessary operations for reconditioning a Ni-Cd battery. The circuit reliability can be of the same order as the battery charging circuit, and the circuit can be designed to protect against certain battery failures. Thus, reconditioning of Ni-Cd batteries need no longer be considered as only a ground operation, and flight reconditioning need not be considered a

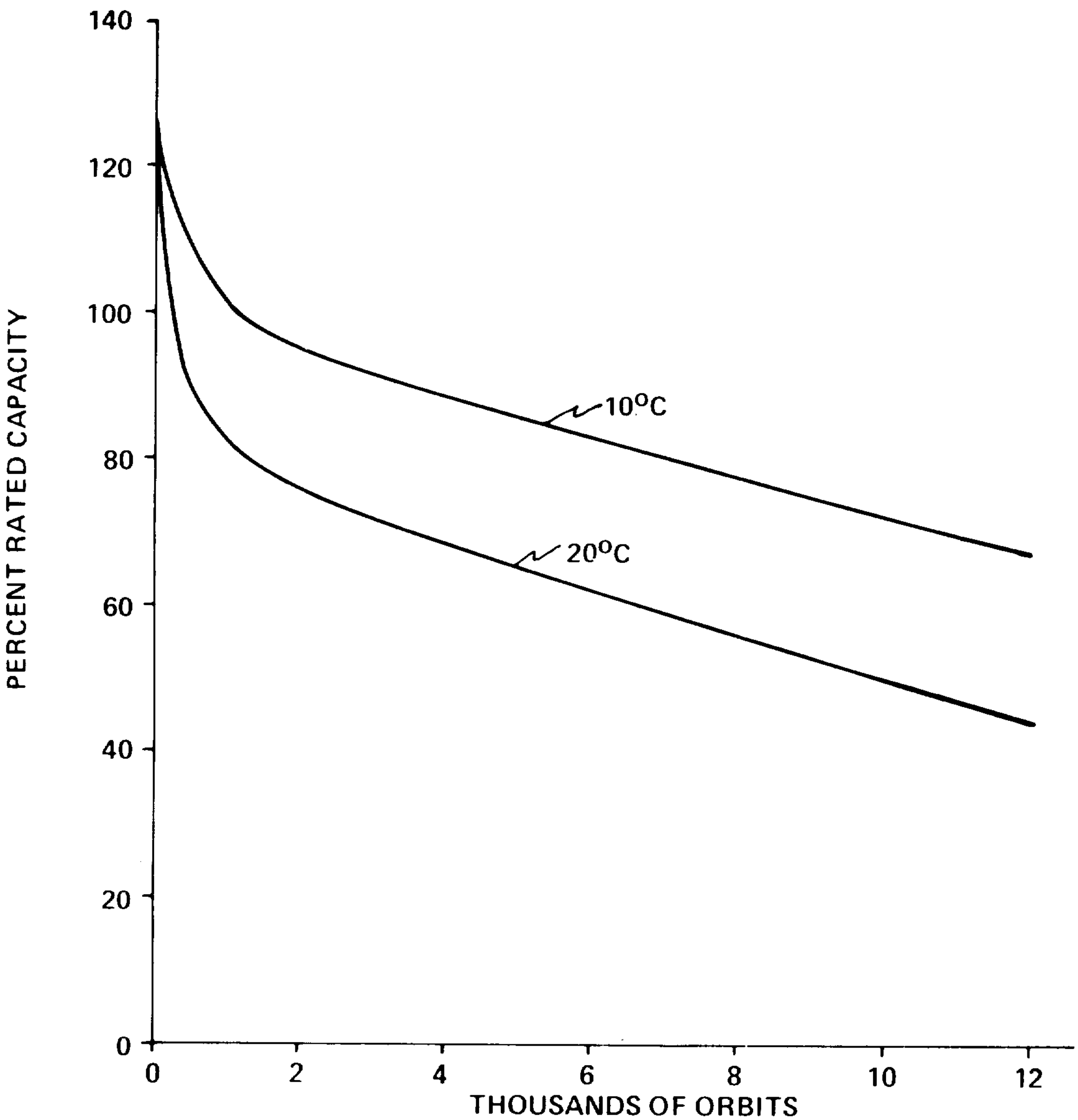

Figure 1. Battery capacity above 26.4 V for a 20 A-h battery.

superficial discharge to only 0.9 to 1.0 V/cell which provides a brief voltage enhancement at best. Reconditioning of batteries in space can be accomplished without bulky equipment, and to the degree previously available only in ground operations, using this circuit. Electrical power systems designed for long life operations in space should realize a significant advantage using the circuit presented to provide reconditioning assuring adequate voltage characteristics and reserve capacity throughout the mission.

BACKGROUND

A Charger/Battery/Regulator Module (CBRM) life test was initiated on two CBRM's in October 1972 to establish the capabilities of the Skylab Apollo Telescope Mount (ATM) batteries during the upcoming mission. The batteries, Part No. 40M26202, Serial numbers 80 and 84, were assembled from twenty-four 20 A-h Ni-Cd sealed cells with recombination and signal electrodes. The signal electrodes were used for charge termination of the battery to minimize overcharge in the application which used passive radiative heat removal.

The charge-discharge cycles on the batteries were 58 and 35 min, respectively. The charge regime consisted of a current limited mode of up to 15 A to a temperature compensated voltage. The voltage was then held constant, resulting in a tapering charge current, until charge was terminated by the signal electrode. The battery DOD averaged 25 percent, and the recharge fraction was typically 1.05 to 1.10. Recharge fraction is defined as:

$$RF = (\text{A-h in}/\text{A-h out}) \qquad (1)$$

where

RF = the battery recharge fraction

A-h in = the ampere hours charged

A-h out = the ampere hours discharged.

Battery temperatures were maintained between 5°C and 15°C by controlling the CBRM radiative view factor to a cold plate in the vacuum environment of the test. All of these factors were consistent with expected Skylab flight conditions. The test ran for approximately 7 months (3000 orbits) with expected results prior to the Skylab launch.

The Skylab launch was marred by the failure and loss of a heat shield on the Orbital Workshop (OWS), which caused the loss of one of two solar wings on the OWS, and a failure to deploy the other OWS solar wing. This wing was deployed with the assistance of the crew several weeks later. However, the heat shield loss required orientation of the vehicle and the ATM solar arrays in a direction 40° to 60° from the Sun to prevent overheating of the OWS living quarters. This resulted in several days of power system operation with the batteries at or near energy balance and temperature of 15° to 30°C. During this phase of the mission the ATM power system supplied power for the entire vehicle. After arrival of a crew, correction of the OWS problems, and the subsequent return to near normal operating conditions, the ATM batteries were discovered to have only 10 to 12 A-h of useable capacity. The life test immediately became a test bed to evaluate and attempt to define a method to correct this flight anomaly. The anomaly was simulated and, as shown in Figure 2, a comparable loss of usable capacity was experienced. Efforts to restore the capacity with the limitation of the Skylab hardware were unsuccessful. However, it was known that a ground reconditioning procedure of completely discharging the battery cells, protecting against cell reversal and its damaging effects, and recharging the cells using a tried procedure would restore most of the useable capacity of the battery. This procedure had not been proposed for space flight because of the large complex equipment required to implement it. The Skylab problem indicated a need for a battery reconditioning method applicable to flight. A solution to meet this need has been developed and tested using the CBRM life test as a test bed. The circuit developed and the test results obtained are the subject of this report.

SYSTEM DESCRIPTION

The block diagram of the ATM Electrical Power System in Figure 3 is considered typical of systems in which a reconditioning circuit would be useful. It is characterized by multiple parallel energy storage/power processing stages

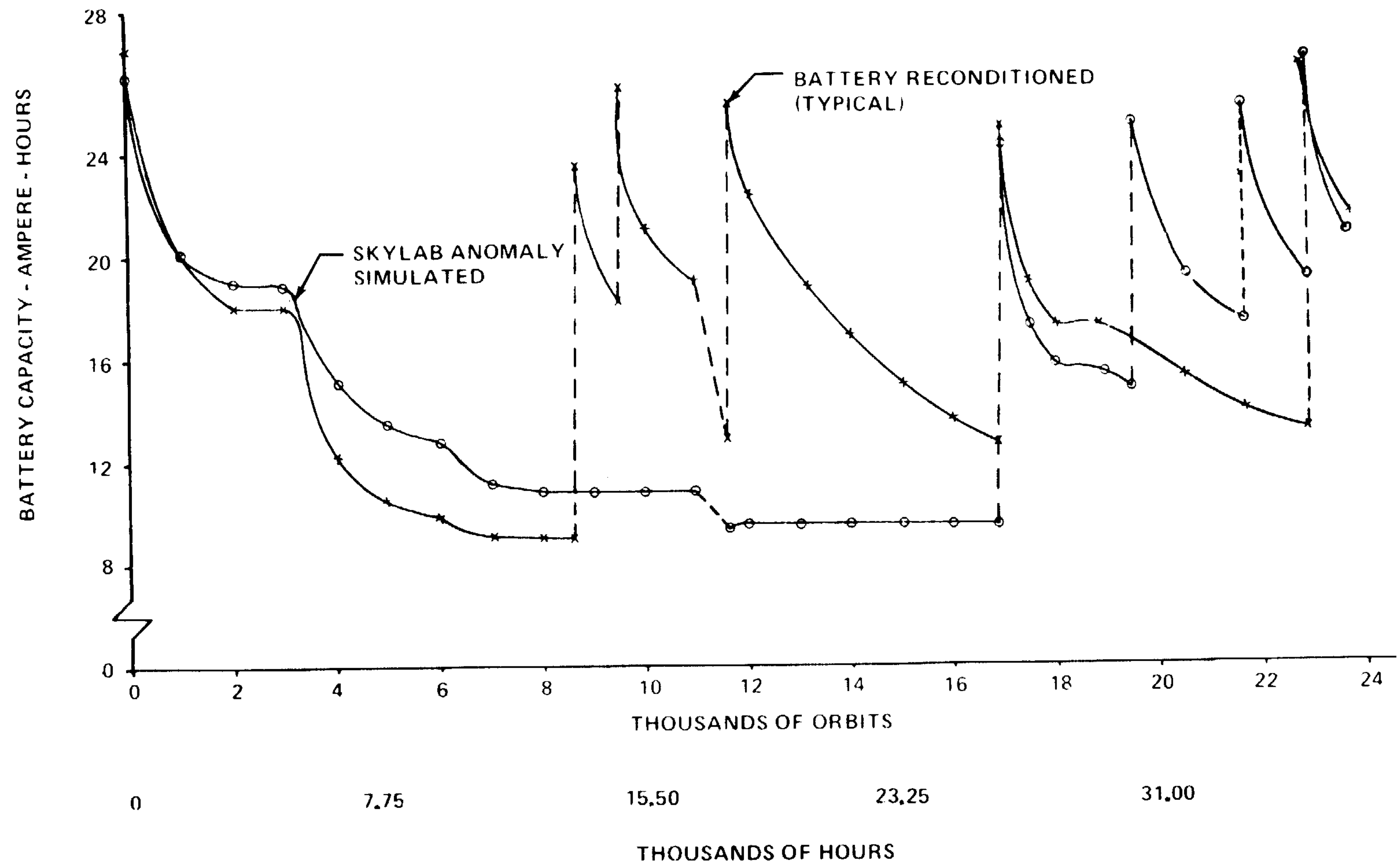

Figure 2. Cyclic life test capacities.

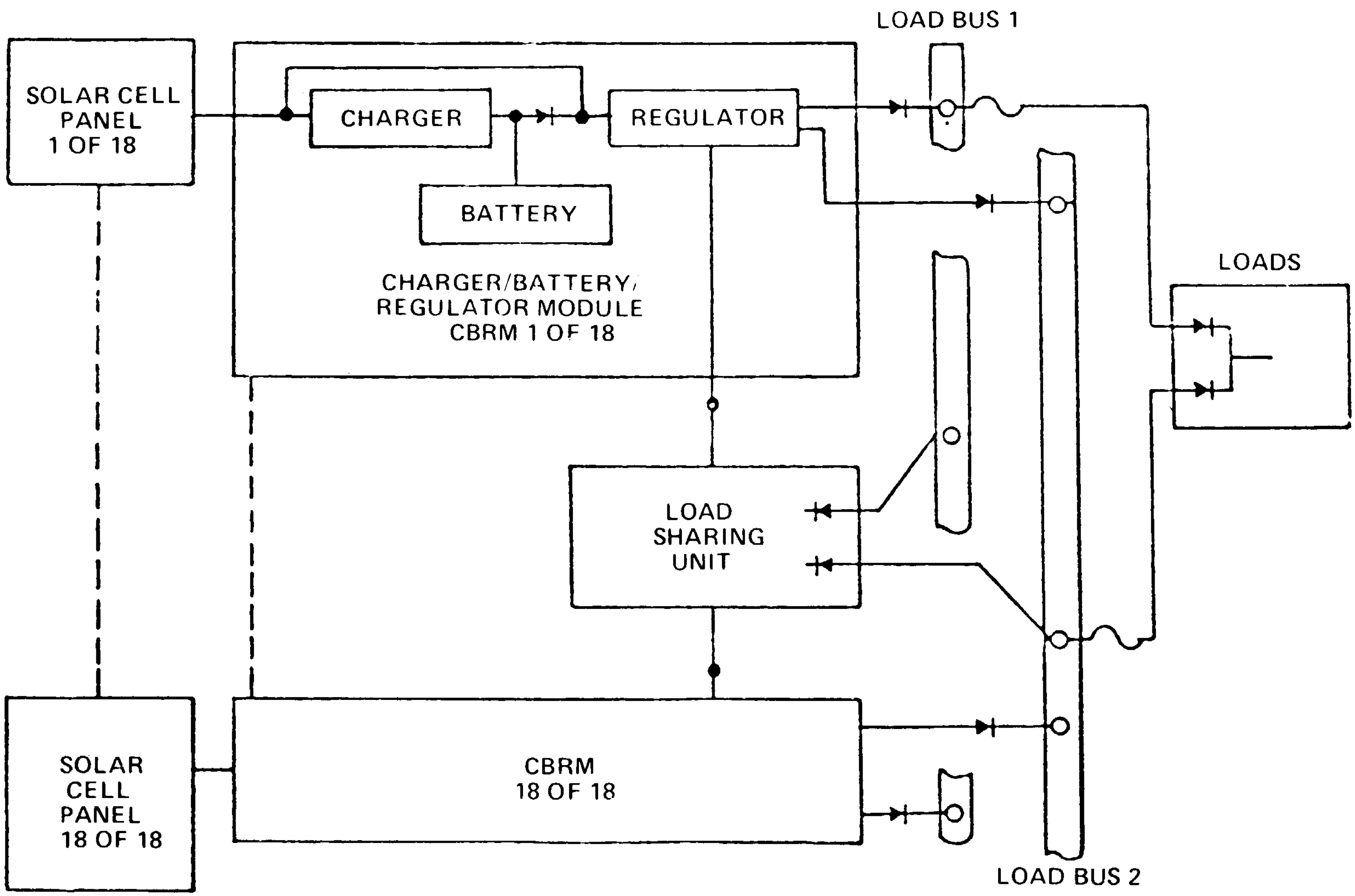

Figure 3. ATM Electrical Power System.

and multicell Ni-Cd batteries for energy storage. The system also has the capability to isolate the batteries for reconditioning and to assure proper energy sharing between batteries that have been recently reconditioned and those which have not.

The ATM batteries were charged from the solar arrays by the charger during the "day" portion of the orbit. The charger sensed battery voltage, current, temperature and signal electrode voltage, and solar array current and voltage to assure proper battery charging without collapsing the solar array. During the "night" portion of the orbit, the battery discharged through the regulator to supply the loads. The regulators shared the output load based on a signal from the load sharing circuit to assure approximately equal DOD in each battery. The batteries were protected from cell reversal by a circuit which disconnected the battery if its voltage fell below 26.4 V (1.1 V/cell).

The life test configuration being used as a test bed for the reconditioning circuit discussed herein consists of two of the parallel elements from the ATM Electrical Power System as shown in Figure 4.

CIRCUIT DESCRIPTION

A circuit to recondition a battery must meet several requirements and objectives. The requirements are that it must completely discharge every cell in the battery and it must not allow the polarity of any cell to be reversed. Test results to be discussed later have shown that discharge to less than 0.5 V/cell is adequate to restore the battery useable capacity to approximately 90 percent or greater of its initial useable capacity. This is typically 25 percent greater than the nameplate capacity of the battery. The desired objectives for a reconditioning circuit will vary somewhat, depending on system constraints and requirements. However, some key objectives that will be generally desirable may be described. The circuit should be as simple and reliable as practical. It should be very small compared to the battery size. It should be easy to use, probably fully automated, and should complete the reconditioning in the least practical time. Cost should be minimized, but is not a key feature because the savings that result from extending the time between replacing batteries or the reduced number of batteries required as a result of having a greater useable capacity for a given mission will far exceed the cost of the reconditioning circuit.

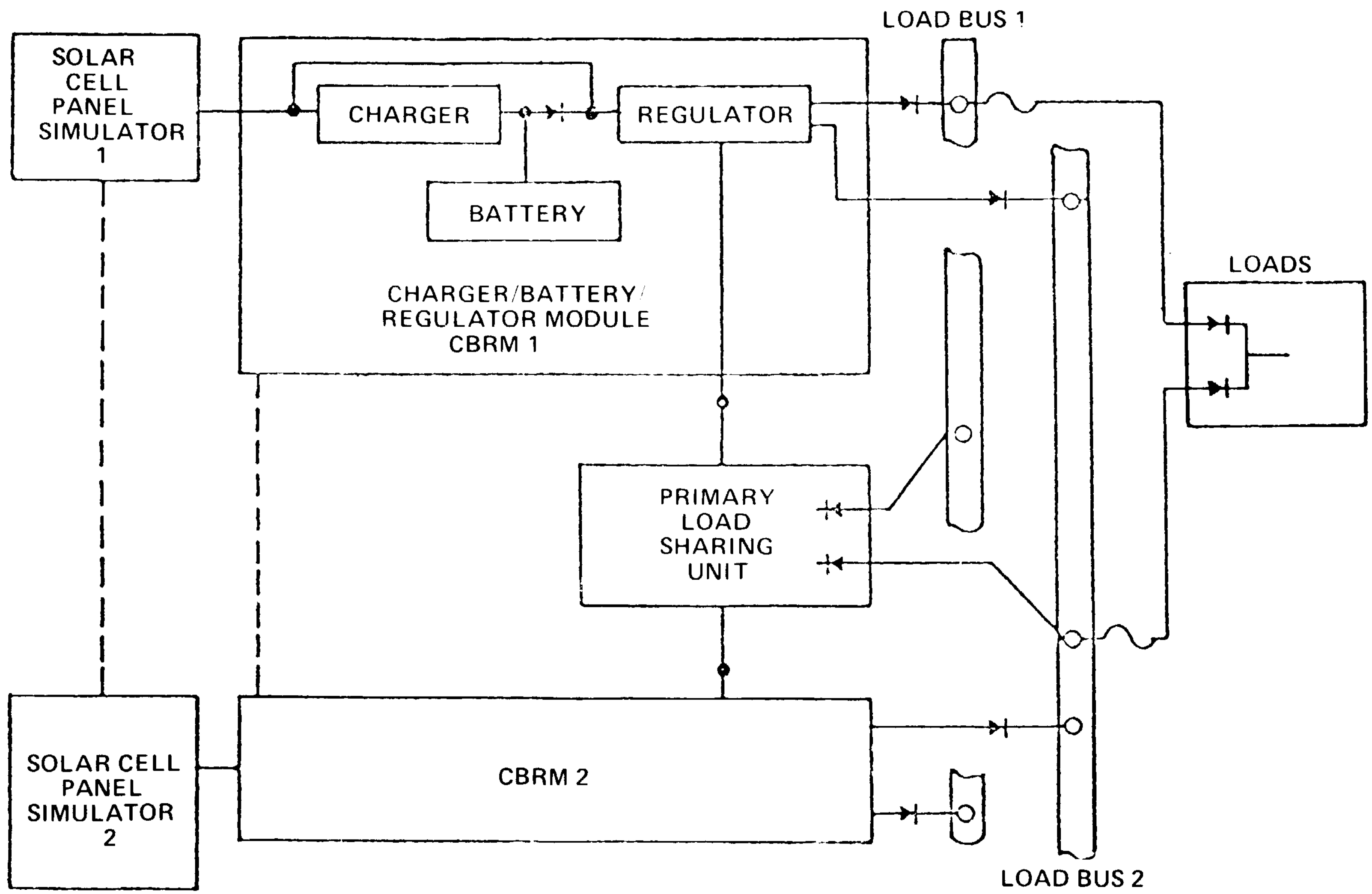

Figure 4. Life test configuration.

A circuit to satisfy the previously stated requirements and objectives is shown in its simplest form in Figure 5. This circuit has been breadboarded and used in reconditioning the two test batteries previously discussed. The results of reconditioning the batteries to be discussed in detail later are shown in Figure 2. The circuit consists of a simple dc-to-dc converter with a low voltage full wave rectified output connected in parallel with each battery cell. The ability to sense current for decision making is provided. The breadboard circuit tested is limited to approximately 1.5 A/low voltage output and 10 W total output. The current sense circuit and associated logic provide signals to switch the reconditioning load resistor's relays to assure continuing the battery discharge at the desired rate while protecting the circuit components. No exotic components or circuitry is required. However, hot carrier diodes are recommended for the low voltage output rectifiers to minimize the heat generated in the circuit and to enhance the output voltage characteristic of the low voltage outputs. A typical circuit for a 22 cell, 20 A-h battery can be packaged in approximately 350 cm^3, excluding the reconditioning resistors and relays.

CIRCUIT APPLICATION

The following description of circuit operation applies primarily to the breadboard circuit shown in Figure 5. This operation would be typical of any reconditioning circuit of this type, but operation for a specific application could vary in certain aspects. Some unique advantages that can be realized by proper design and application of the circuit will be discussed later.

A typical battery reconditioning is implemented by terminating charge on a battery and allowing it to discharge to its lower limit (1.1 V/cell in this test). The battery is then disconnected from the system regulator, and the reconditioning circuit and load resistors are energized. The configuration tested has three load resistor combinations, 5, 15, and 26 ohms. As the reconditioning discharge starts, the low voltage outputs are inactive because the battery cell voltages are typically greater than 1.0 V and the output diodes are reverse biased. Standby power in the circuit is less than 1 W for this condition. As the battery discharges, the cell voltages drop and at some point one of the cell voltages will be low enough for its associated low voltage output to begin conduction. The output characteristic of the low voltage outputs in Figure 6 shows that this transition begins at a cell voltage of approximately 0.7 V. For hot-carrier diodes this could be 0.5 V. When this occurs the reconditioning

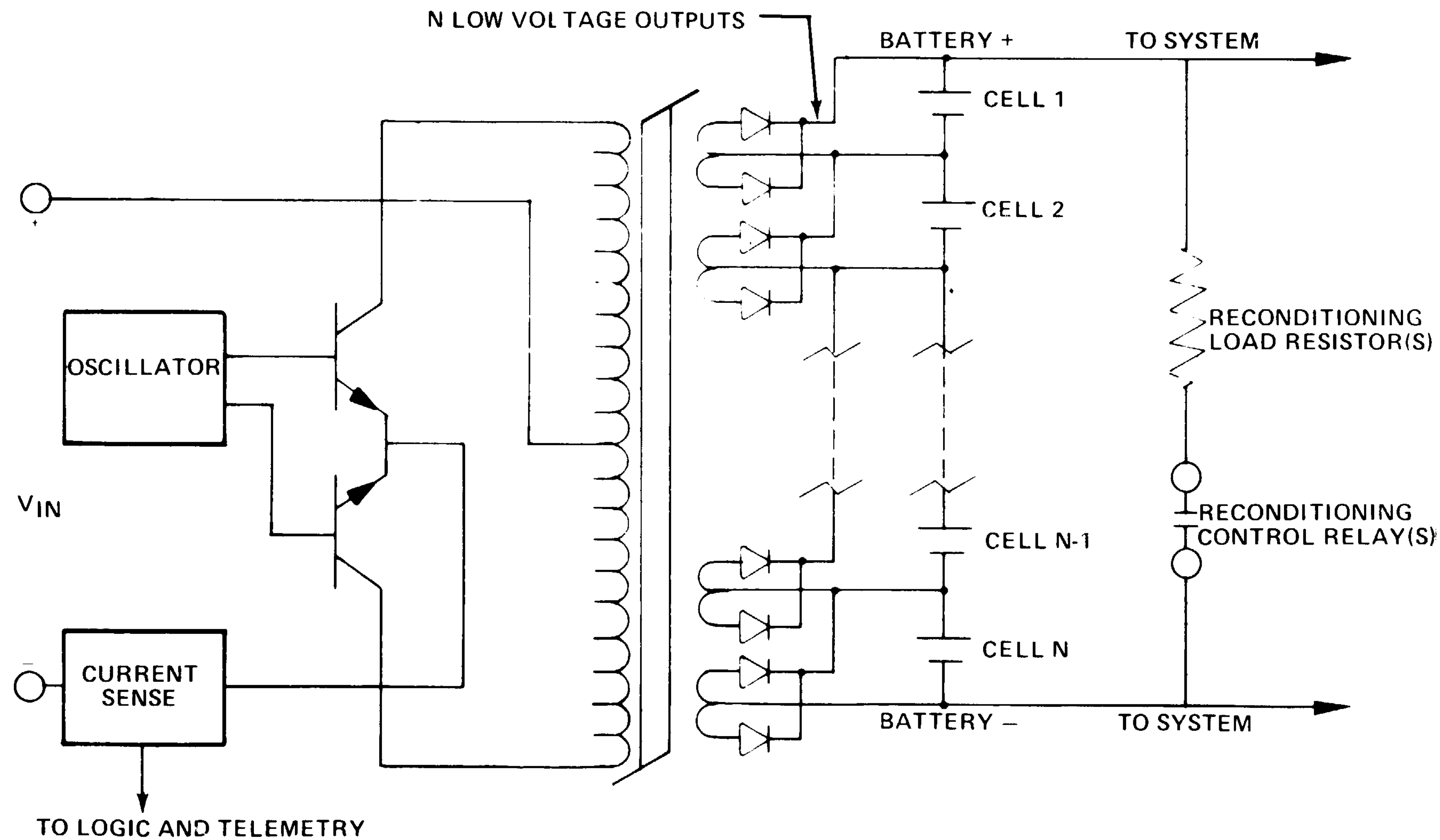

Figure 5. Simplified flight reconditioning circuit.

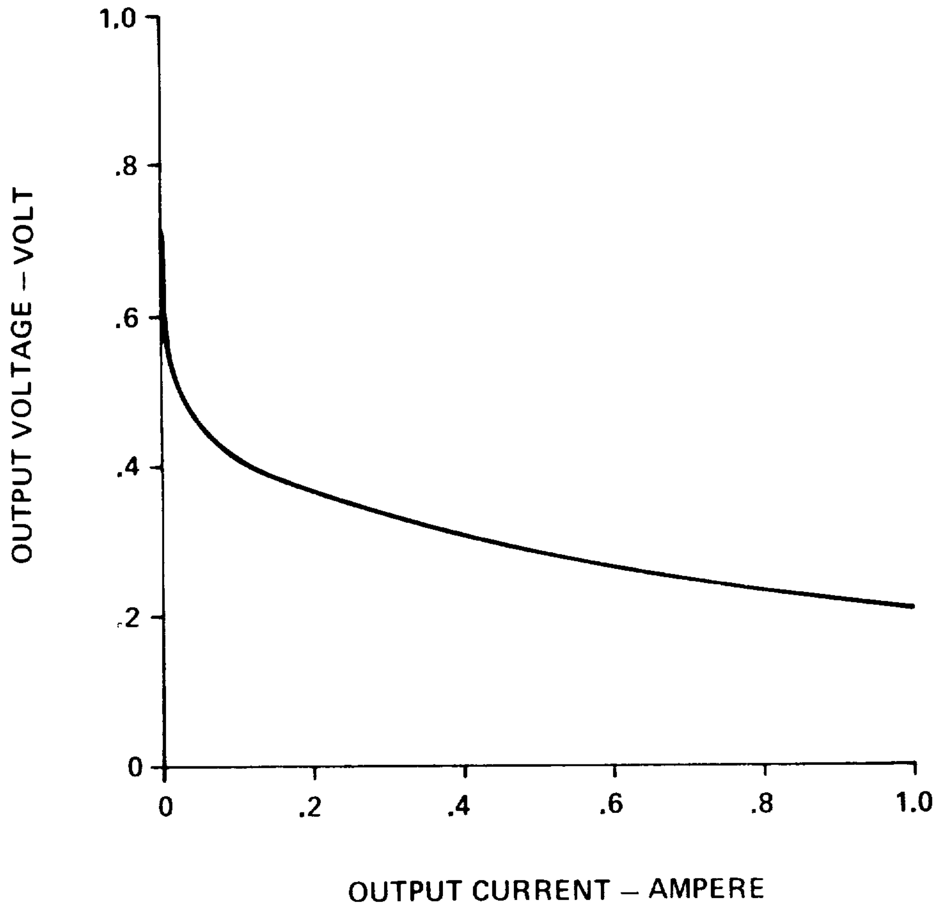

Figure 6. Battery reconditioning circuit output characteristic.

circuit begins to share the low cell load so that there is a tendency for the cells to equalize in voltage. The decreasing cell voltages require more power from the circuit until the current sense and logic circuitry signal for a step increase in load resistance, thus decreasing the discharge rate. This sequence is repeated at the lower rate until the final resistance value is selected. This value is chosen so that the circuit can handle the entire load at a battery voltage of 0.2 to 0.5 V/cell. The battery continues to discharge in parallel with the low voltage outputs as long as required to completely discharge the battery. Upon completion of the discharge, the battery is trickle charged at a 1 A rate to 1 or more A-h and placed on line at an orbit sunrise. The charger takes over and completes the charge over a series of orbits, the number of which depends on the load and reserve solar array capacity.

TEST RESULTS

A summary of the results of reconditioning the two life test batteries is shown in Figure 2 and the Table. These and related results are discussed as follows.

Battery Capacity

The battery capacities in these tests were measured with an average ATM load (Fig. 3) that resulted in an average discharge current of approximately 7 A. The recorded capacity is the available energy when the battery is discharged to the CBRM automatic voltage protection limit of 26.4 V (1.1 V/cell) at this discharge rate. Apparently the degraded battery still retains its original energy storage capacity, but much of the energy is available only at low rates and voltage as a result of crystal growth on the cell plates as described by Bauer (2). The reconditioning circuit and procedure recognize this limitation and provide for extraction of this low grade energy at a voltage and rate at which it is available while protecting weaker cells from reversal. This apparently restores the original plate structure, and upon completion of reconditioning the battery performance is near its original performance. Original capacity for 20 A-h nameplate cells of the type tested was 26 to 28 A-h. The time allowed to hold the battery cells at 0.3 V for discharge and the length of time since the battery was last reconditioned contribute to the rate and degree of recovery. The data reflect this in that the first reconditioning of each battery produced the least recovery. The first reconditioning on battery 2 was a 3 day discharge and was slightly less effective than subsequent reconditionings. However, battery 3 was first discharged for 4 days and then discharged for 3 days on the second reconditioning with similar results. A 5 day discharge run at approximately 22 800 orbits resulted in slightly higher capacity restoration in both batteries.

A method used to determine the degree of discharge of the batteries was to measure the cell discharge current into a diode and 0.5 ohm resistor network. The data for the highest cell discharge current in a battery at the end of a reconditioning is given in column 6 of the Table. This current is somewhat indicative

TABLE. SUMMARY OF THE RESULTS OF RECONDITIONING THE TWO LIFE TEST BATTERIES

Battery No.	Orbital Cycles	Capacity Before Reconditioning, A-h	Capacity After Reconditioning, A-h	Time Discharged, h	High Cell Current, mA
1	16 870	9.7	24.2	-	-
1	19 532	14.5	24.9	94	19
1	21 718	17.2	25.5	73	20
1	22 893	18.9	27.6	119	1
2	8 700	9.2	23.1	70	22
2	9 279	18.0	26.4	92	9
2	11 522	12.8	25.8	93	-
2	16 870	12.6	24.7	-	-
2	22 772	13.2	27.0	112	3

of the energy remaining in a battery and implies that, for the cells tested, after 5 days of discharge there is essentially no energy in the cells. However, after 3 to 4 days discharge there is little gain in additional post-reconditioning capacity. Figure 7 shows the capacity taken from battery 2 on its first reconditioning with the test circuit. The sharp knee at 25 h is the point beyond which very little additional energy is extracted from the battery and indicates that 25 to 30 h may provide adequate reconditioning. Until the process is better understood, a test program is recommended to establish the minimum acceptable discharge time for proper reconditioning. Data to date indicate that a time between 2 and 5 days is optimum.

Battery Voltage Characteristics

The key parameters under consideration when using a battery as a voltage source is its discharge characteristics. Figure 8 shows the discharge characteristics for battery 2 prior to reconditioning, immediately after reconditioning, and at several points later. Note that for the first 3 A-h (15 percent DOD), the characteristics match except for the curve taken immediately after reconditioning. Figure 9 shows the mismatch up to 15 percent DOD between a newly reconditioned battery and one which has not been reconditioned for several hundred orbits. Figure 10 shows the rate at which the characteristics converge after reconditioning. There are typically 300 or more orbits representing more than 3 weeks before the batteries approach the same discharge characteristic. This dictates a method of sharing the load between batteries to preclude overload and overheating of a newly reconditioned battery.

Other Results

An unexpected benefit from reconditioning the batteries was observed in connection with two anomalies that occurred during the test.

An erratic end of discharge cell voltage was observed in battery 2 at approximately 14 000 orbits. Figure 11 shows the voltage of the erratic cell compared with a typical cell in the battery. The cause of the voltage fluctuations is not known at the present time. However, the fluctuations were observed over a period of 6 months with several capacity tests (Note 1 in Fig. 11) where the battery was discharged to the automatic voltage protection limit of 1.1 V/cell with no improvement. A reconditioning test, the fourth on battery 2, was then

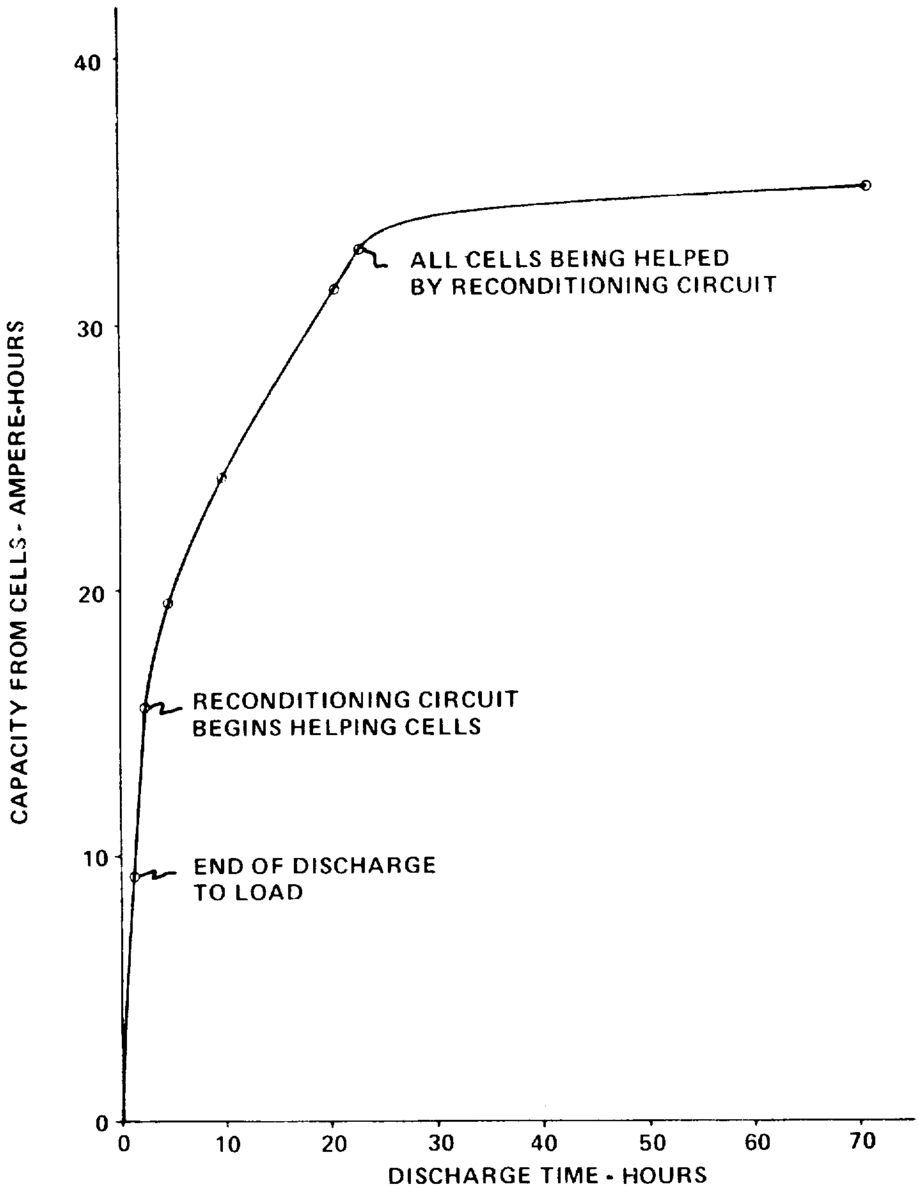

Figure 7. Energy extraction from battery 2
during first reconditioning.

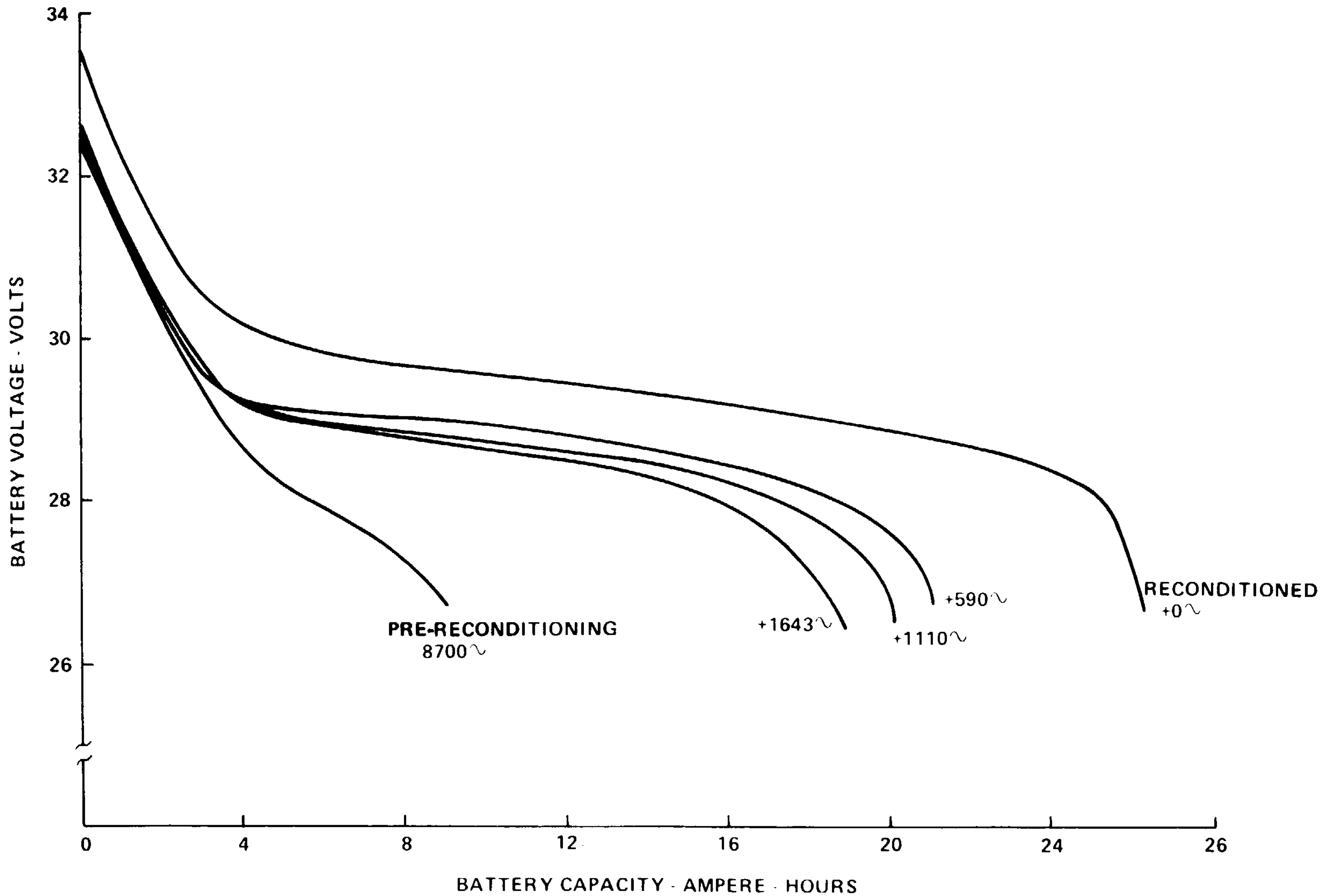

Figure 8. Battery 2 voltage discharge profile.

BEFORE RECONDITIONING

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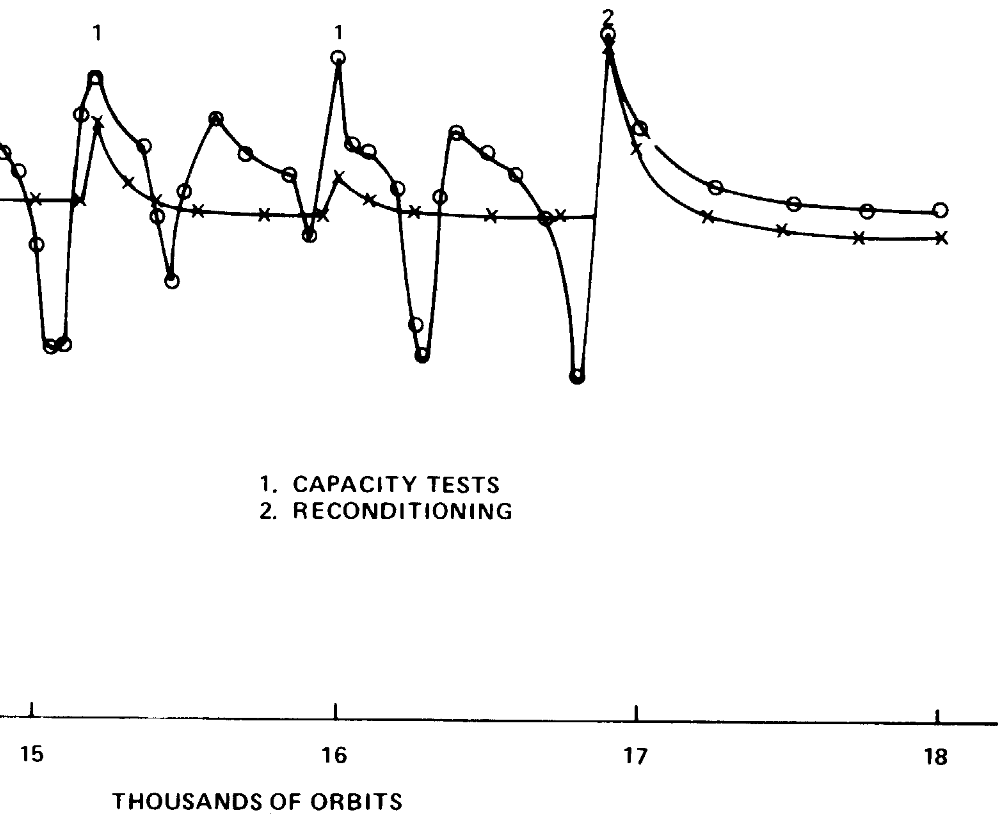
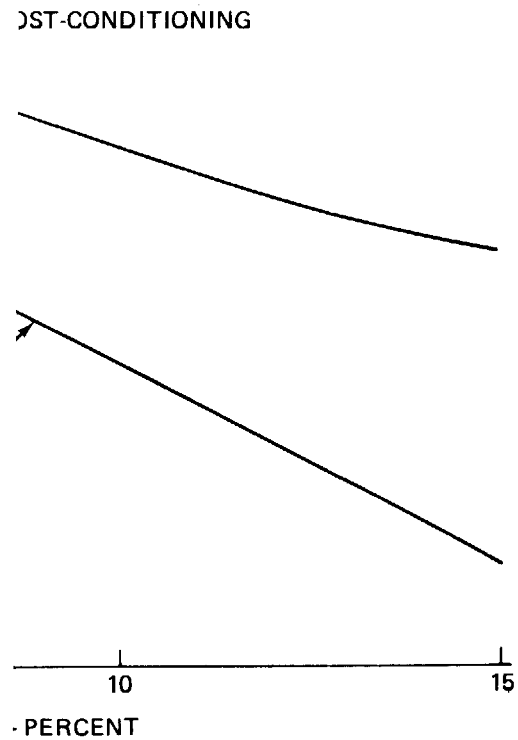


ttery 2 cell voltages at end of discharge.



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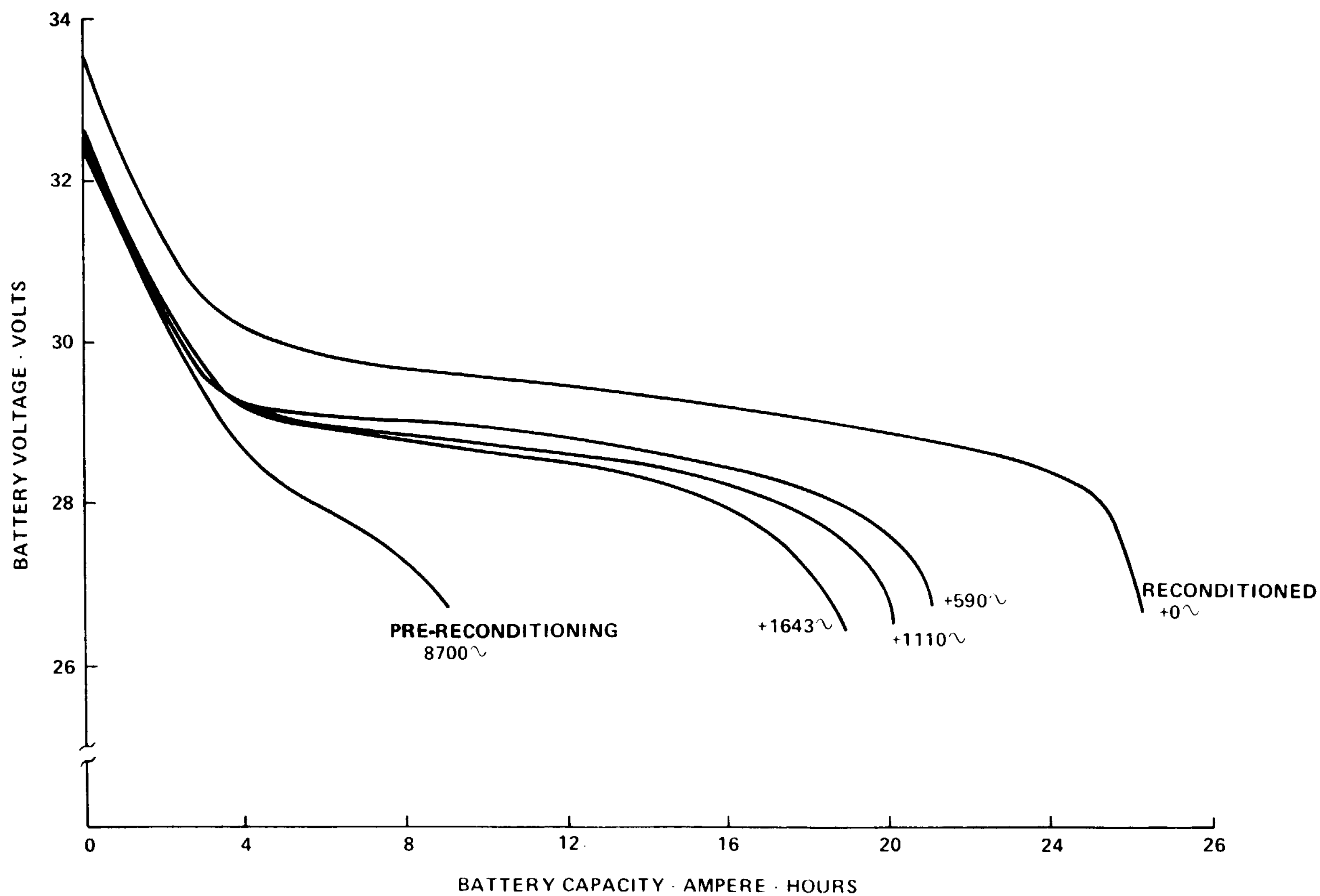

Figure 8. Battery 2 voltage discharge profile.

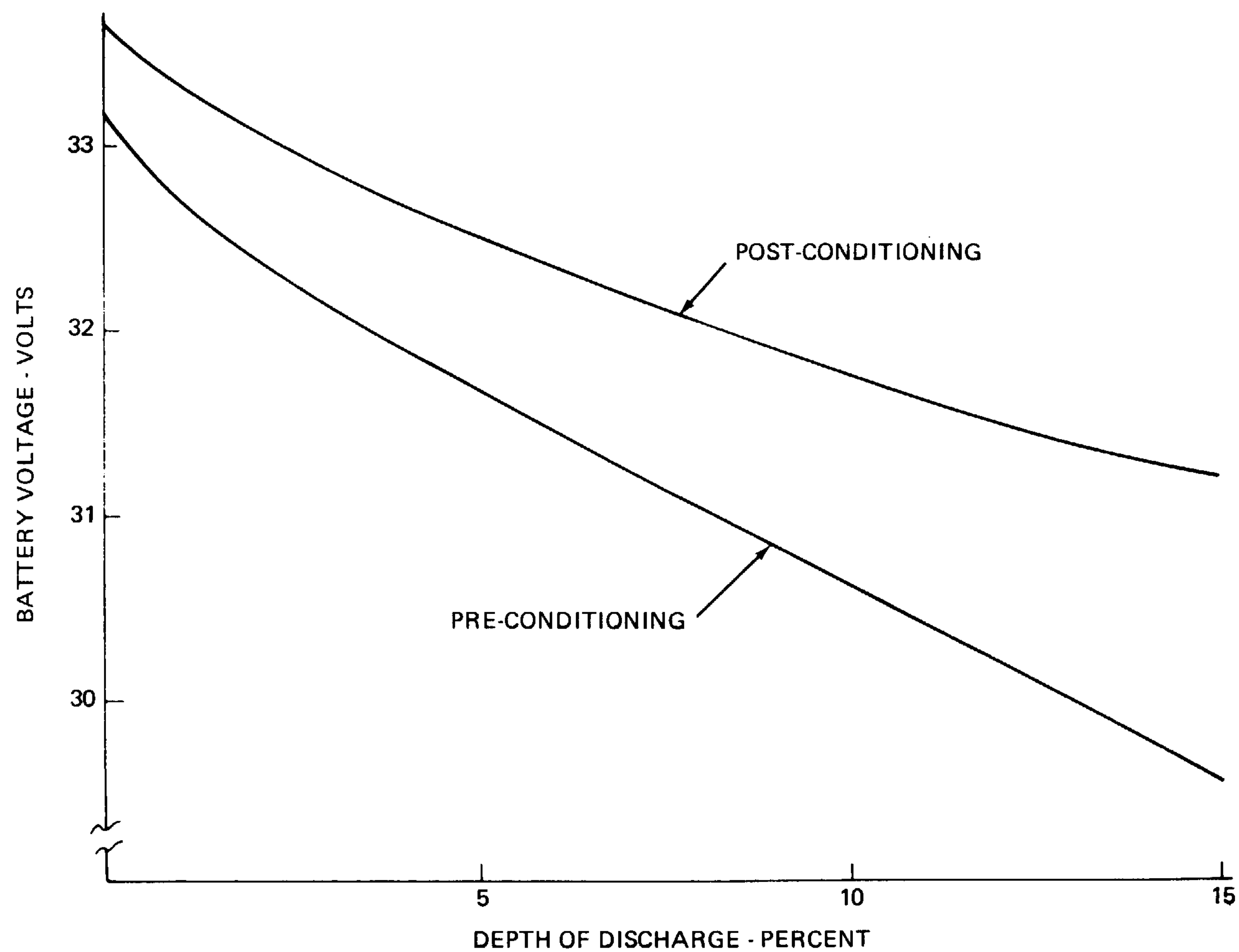

Figure 9. Battery mismatch characteristics.

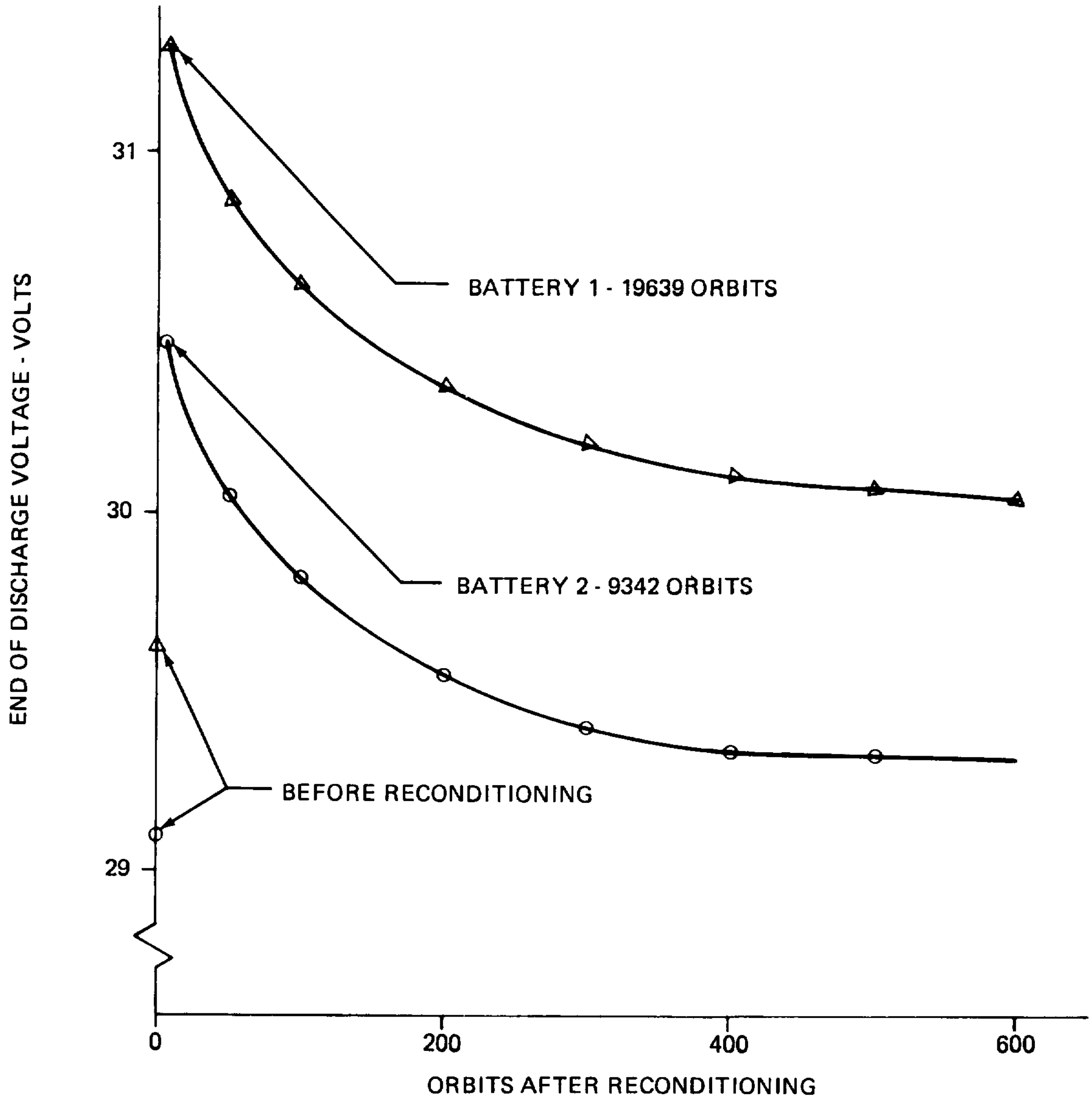

Figure 10. Typical end of discharge voltage before and after reconditioning.

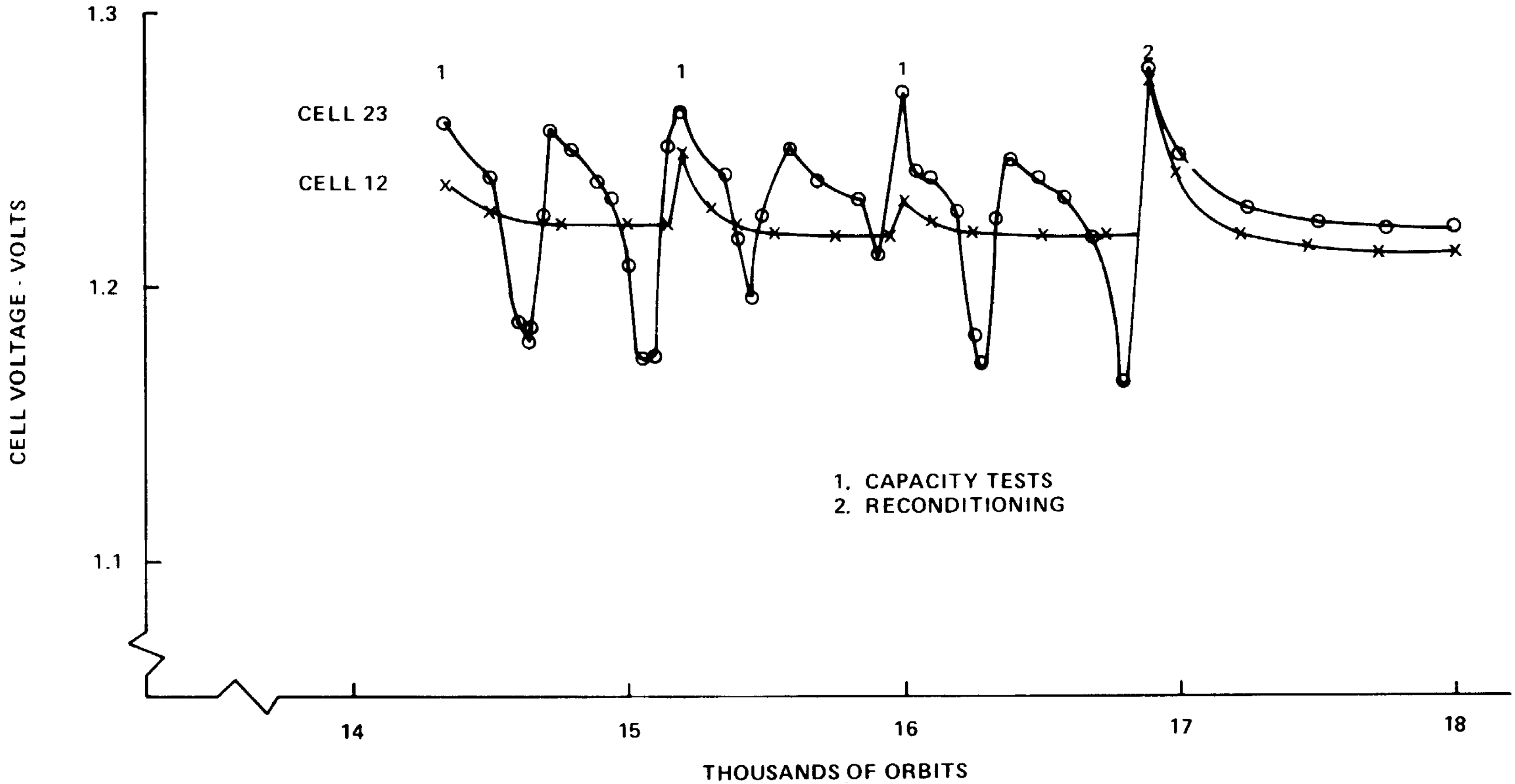

Figure 11. Battery 2 cell voltages at end of discharge.

performed, and the cell voltage stabilized as shown in the figure. In more than 1 year since, the anomaly has not reoccurred and the cell continues to function normally.

The recharge fraction in battery 1 is normally 1.08 to 1.10 under the test conditions. After approximately 20 000 orbits, the recharge fraction, which is controlled by three redundant signal electrodes, began to rise as shown in Figure 12. The recharge fraction continued to rise for 1600 orbits, causing an efficiency decrease and a battery temperature rise. The battery was reconditioned, and the recharge fraction returned to normal as shown in the figure. However, the recharge fraction again began to increase and returned to 118 percent after approximately 2 months. The battery was again reconditioned, and the recharge fraction again returned to normal. A theory as to the possible cause of this anomaly is that some form of contamination or gas bubbles is collecting on the signal electrodes and being redistributed during reconditioning.

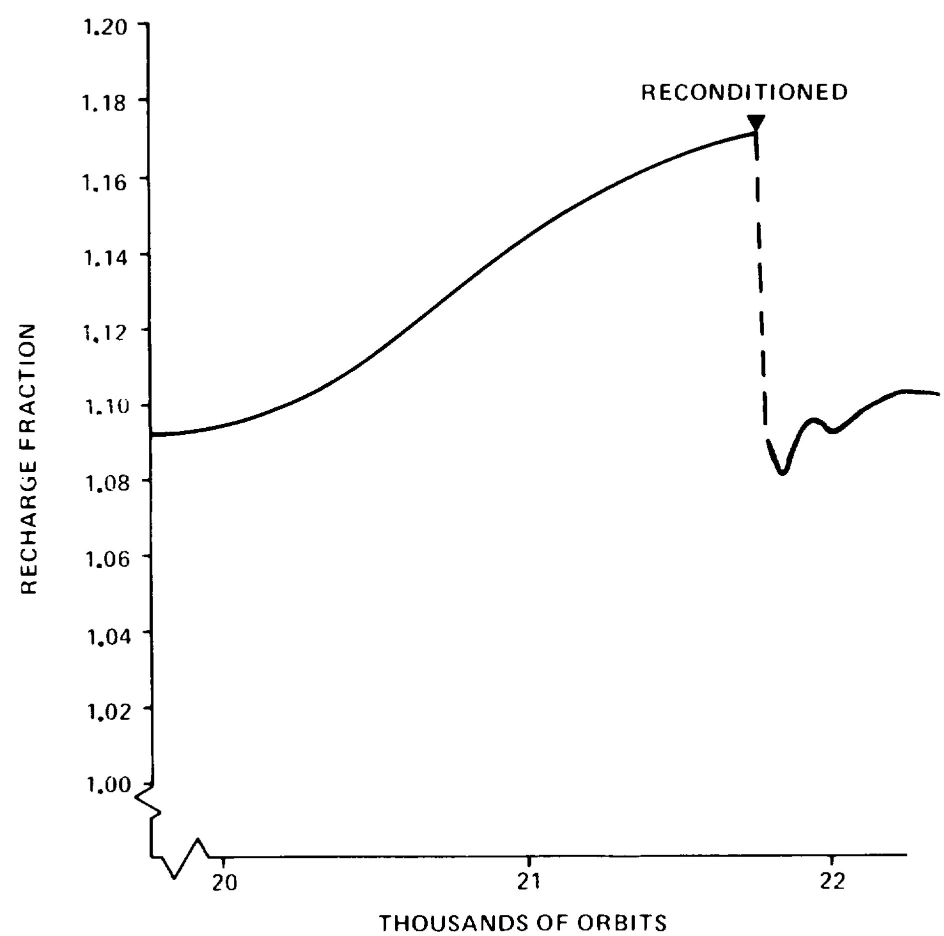

Figure 12. Battery 1 recharge fraction anomaly.

However, the condition must occur on all three signal electrodes to cause the anomaly. In addition no evidence of this sort of anomaly has occurred in battery 2. Even so, a reconditioning did correct a situation that could cause battery overheating and subsequent loss. A reconditioning at 2 month intervals would be small cost to save a battery on a mission.

OTHER APPLICATIONS

The discussion of the circuit in Figure 5 thus far has been considering its designed use to protect a battery during discharge for reconditioning. Some other potential uses for the circuit are now considered.

The circuit may be connected to the battery and activated continually to use it as a detector for low cell voltage. This will normally allow greater depth of discharge of the battery before termination of discharge than a voltage sensor across the entire battery and provide better protection. This results from the requirement to allow for cell mismatch in the battery sense circuit while the reconditioning circuit senses individual cell voltage by assuming the cell load when the cell voltage collapses. The current sense circuit detects the collapse and gives an output signal indicating cell discharge or failure. This signal would be used to terminate discharge and initiate other action as deemed necessary.

The next step beyond discharge or failure detection and indication is cell failure bypass. If the battery reconditioning circuit is designed to handle the maximum load current of a cell, the circuit can overcome certain battery failure modes. Typical cell failure modes are open circuit or short circuit of a low or high impedance nature inside the cell. Early cells similar to the type used in this test failed with high impedance shorts that exhibited characteristics similar to a good cell during charge but had no output under load. The reconditioning circuit could supply the load for a small number of cells, probably one or two, and thus prevent failure of an entire battery as a result of cell failures.

CONCLUSION

The reconditioning circuit discussed has been shown to be effective in restoring the effective capacity of a Ni-Cd battery by completely discharging all battery cells while protecting the cells against reversal. The flexibility of the circuit was demonstrated by connecting it to an existing typical space power system and achieving excellent results with no system or component redesign. Use of a circuit similar to this can minimize cell matching requirements because it can sense cell discharge voltage collapse and either terminate charge or assist the weak cell depending on the design requirements. This is expected to be even more useful in high voltage electrical power systems being considered for future large space systems. The problem of cell matching and cell failure are both multiplied as additional cells are placed in series. However, with a combination reconditioning/failure protection circuit designed to handle cell failures, a battery designed to supply a 110 V or higher bus is considered feasible.

Plans are underway at MSFC to build and test a battery of approximately 120 series cells using a circuit like this for protection and reconditioning. The cells will be matched to only 10 percent manufactured capacity compared to approximately 2 percent selection used in the Skylab program. It is anticipated that any type battery using the reconditioning/protection scheme discussed can be expected to have a longer useful life and higher reliability. Ni-Cd batteries, which were considered to have a useful life of approximately 2 years in low Earth orbit space applications, have been demonstrated to last for 4-1/2 years and are still performing well. Significant advantages and cost reductions are anticipated as a result of using the techniques discussed herein.

MSFC has applied for a patent on this device. Application for a license to use this invention, if a patent is granted, should be directed to the patent counsel at MSFC.

George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812, April 1977

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