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SEALED SILVER-OXIDE CADMIUM BATTERIES FOR SPACE FLIGHT

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ABSTRACT

Since sealed silver-oxide cadmium cells may be constructed without magnetic materials, this electrochemical system was used in secondary batteries on several scientific satellites (Explorers) which measured radiation and magnetic fields. In support of the flight programs, characterization and cycle life tests were performed and sponsored by the Goddard Space Flight Center. Battery designs were developed that could function in space, in orbital periods of five to one-hundred hours, as long as four years. Nominal depths of discharge were between 10% and 30%. Optimum temperatures for operation were between 0°C and 25°C. Energy densities to 0.9 volts per cell at 25°C were within 26 WH/Kg. and 31 WH/Kg. The charge and discharge characteristics are particularly affected by the two oxides of silver formed during battery operation. A unique charge control was developed that would prevent cell unbalance on charge and therefore minimize internal gas pressures. Manufacturing procedures and quality controls were formulated to assure high reliability.

Limited use of silver-oxide cadmium batteries was made in near earth orbits. Characterization tests showed feasibility of operation between -10°C and 25°C at a nominal depth of discharge of 33% in 1.5 hour orbital periods.

The report covers the period 1960 to 1977.

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SECTION I

INTRODUCTION

In 1960, NASA/Goddard Space Flight Center initiated a satellite program to study energetic particles and magnetic fields in space. Since that time, approximately twenty satellites have been launched by the United States and other countries to obtain information on these phenomena. One of the requirements placed on these satellites was that the instruments and components had to be essentially non-magnetic. For example, the magnetic moment requirement placed on batteries was less than ten gammas at 45.7 cm. from a magnetometer face. At that time two types of sealed, secondary, electrochemical systems could meet the non-magnetic requirement, silver-oxide zinc or silver-oxide cadmium. From available data, it was questionable that sealed silver-oxide zinc could meet the cycle life requirement for one year.

Although little data was available on sealed silver-oxide cadmium cells, the stability of cadmium and its compounds in potassium hydroxide electrolyte led to an intensive investigation of this system. The results of this investigation are the subject of this report. Tests involved orbital periods ranging from six hours to several days with nominal depths of discharge of 8% to 30%. Considerable effort was expended on determining the effects of float charging on internal gas pressures, cell unbalance during charge and discharge voltage characteristics. Also, investigations were carried out to determine ampere hour and watt hour efficiencies, ampere hour maintenance during cycling, storage effects, cell parameters during reversal and battery characteristics during parallel operation. Simulated orbital cycling programs lasted from several weeks to several years with some batteries cycled to failure. Data and information is presented on the cell sizes and battery designs flown on missions. Herein is also included some of the unusual operational requirements placed on batteries used on spacecraft with long orbital periods. Most of the investigations, testing and orbital information, are bracketed within the temperature range of -10°C to 42°C.

Investigations were carried out to determine the characteristics of sealed silver cadmium cells in near earth orbits, i.e., 100 minute orbits. The batteries were cycled over the temperature range of -10°C to 50°C with most of the tests operated at a nominal depth of discharge of 33%. Project support was given to a French satellite program which required a non-magnetic battery for a near earth orbiting satellite.

Other areas that are included in this report are the testing of large capacity cells up to 300 ampere hours, methods developed or used to maintain low internal gas pressures, electrodeposited coatings to retard silver migration and methods of analyses of the positive plates.

The main source of data from the report was internal memos, tabulated readings, recorder charts, graphs, specifications and procedures. Except for the latter two categories, very little of the data had been formalized. The volume of the data occupied four file cabinet drawers. Approximately two-thirds of the data was used. Some was repetitious while some was incomplete.

The reactions occurring in silver-oxide cadmium cells during charge and discharge are as follows:

$$(1)\quad 2AgO + Cd + H_2O \underset{C}{\overset{D}{\rightleftarrows}} Ag_2O + Cd(OH)_2$$

$$(2)\quad Ag_2O + Cd + H_2O \underset{C}{\overset{D}{\rightleftarrows}} 2Ag + Cd(OH)_2$$

These reactions result in two voltage plateaus on discharge usually referred to as the upper or AgO plateau and the lower or Ag_2O plateau. Two voltage plateaus are also present on charge, the lower or Ag_2O plateau and the upper or AgO plateau. Typical voltage curves on discharge and charge are shown in figures 1 and 2. During the program, it was observed that the upper plateau on discharge would flaten out so that the battery would discharge at nearly constant voltage. This occurred when a battery was cycled on long orbits with a high percentage of float time or the battery was placed on continuous float. Usually this lowering of the upper plateau would occur without a loss of ampere hour capacity and at times, a gain in ampere hour capacity. Also, this lowering of the upper discharge plateau would occur during charged storage, e.g., three months at room temperature. Herein there would be approximately a 5% loss of ampere hour capacity. Examples of the flatening of the upper plateau are given in figure 1 and throughout the report. Also, the two voltage plateau charge characteristic has an effect on charge current. When a current limited, constant potential charge set at 1.51 volts per cell is used, initially the current is constant. As the battery voltage approaches 1.51 volts per cell, the current tapers to a low value. A typical voltage curve on charge is shown in figure 2. Moderate rate, constant current charges exhibit a similar voltage profile but the charger voltage is set at a higher value, e.g., 1.55 volts per cell.

During the overall program, considerable attention was given to materials and quality control and to the formation of cells. Material problems such as excessive swelling of the cellophane separators and variations in the particle size

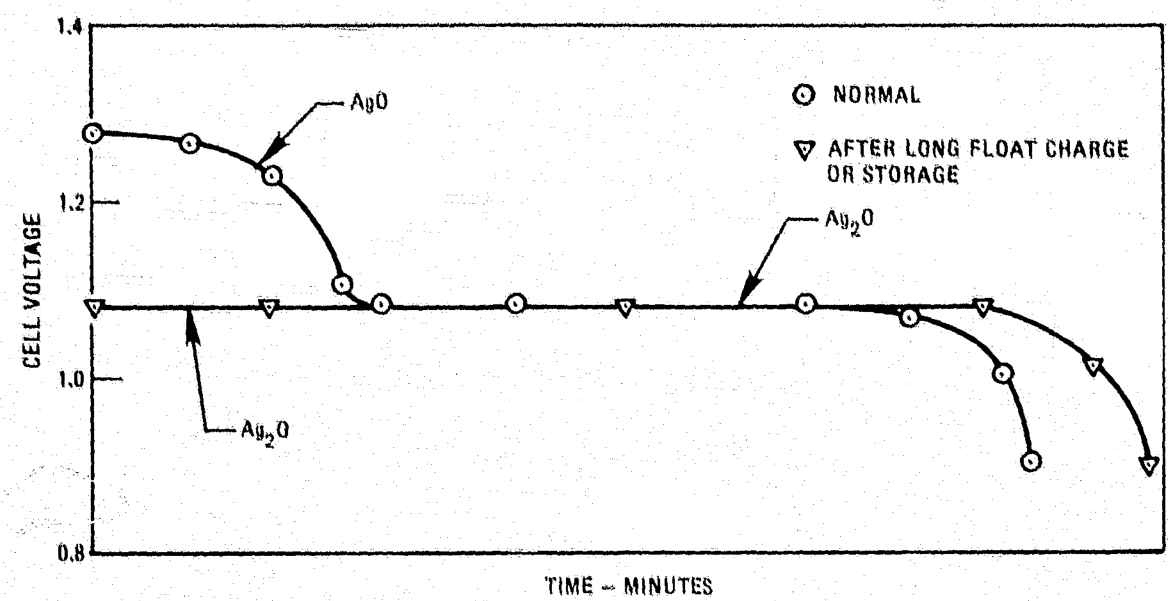


Figure 1. Typical Discharge Curves of Sealed Silver-Oxide Cadmium Cells

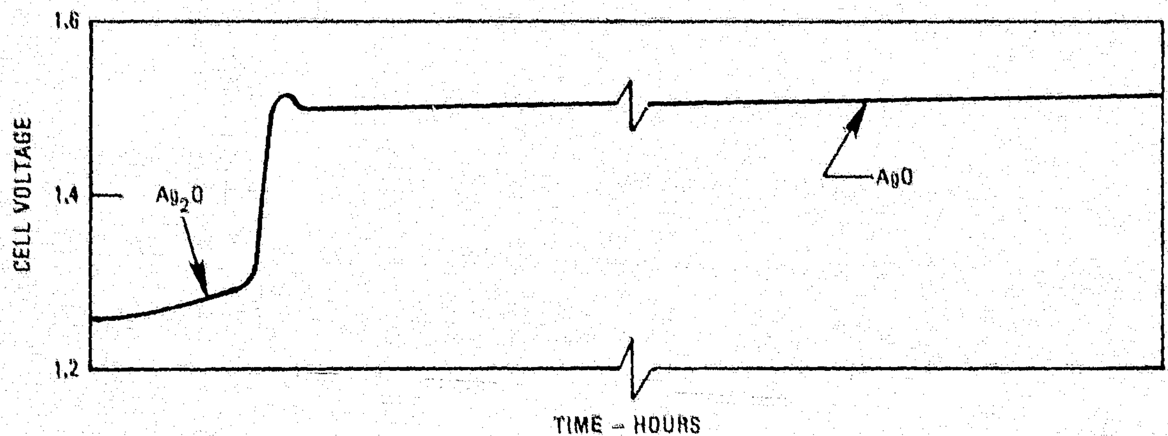


Figure 2. Typical Voltage Curve for Sealed Silver-Oxide Cadmium Cells for a Current Limited, Constant Potential Charge

of the CdO powders used in production required close surveillance. Manual formation of cells was not adequate to provide good matching of ampere hour capacities. As a result, automatic methods were developed for use at Goddard Space Flight Center. This equipment was used to prepare dry, unformed cells as required. Consequently, the wet life of the battery before flight could be minimized. Specifications for the purchase of cells and procedures for manufacturing batteries from dry, unformed cells are referenced in this report.

SECTION II

CHARACTERIZATION TESTS

This Section of the Report includes data and information that is of general interest to battery users and manufacturers. The type of information obtained from these and similar tests formed the basis for battery charging and system controls for orbital flight. Most of the work reported in this Section was performed in the period between 1960 and 1965. Almost all of the automatic cycling, or simulated orbital cycling, reported in this Section is based on long orbits, i.e., orbits of six hours or more. Also, long periods of sunlight were characteristic of these orbits, therefore, the operation of the batteries on long float charges was a major part of the overall program. Examples of the length of the shadow periods and the long sunlight periods encountered in the orbits is shown in Section IV.

The following data and information have been selected from the many tests that were available. However, most of the unreported tests were similar to those selected for this report or sufficient data was not available to draw observations and/or conclusions. The tests that are reported include a total of 78,000 hours of testing and a total of approximately 1,000 cycles of various types. The unreported tests included a similar number of cycles with at least 20,000 hours of testing. It was most fortunate that, during the test program period from 1960 to 1965, summaries were made of many tests in the form of internal reports, memos, graphs, tables, etc.

The tests enclosed address the following characteristics of sealed silver cadmium batteries:

(1) Ampere Hour Capacity, Function of Temperature and/or Charge Rate

(2) Ampere Hour Capacity Maintenance During Deep Discharging

(3) Discharge Voltage as a Function of Residual Battery Capacity and/or Discharge Temperature

(4) Simulated Orbital Cycling, Greater than 25 Cycles at Various Temperatures

(5) Ampere Hour and/or Watt Hour Efficiency

(6) Cell Unbalance During Float Charging and on Full Discharge

(7) Internal Pressure Rise as a Function of Over-charge Current and Float Charge Current

(8) Variation of AgO Plateau During Discharge as a Function of Cycling and Storage

(9) The Effects of the AgO and Ag_2O Plateaus on Charge Current

(10) Ampere Hour Increase During Simulated Orbital Cycling or Float Charging

(11) Cell Analysis after Cycling

(12) Effects of Acceleration and Vibration

(13) Charged Storage

(14) Discharged Storage

(15) Voltage Dip at Beginning of Discharge

(16) Low Rate Charging

(17) Cell Reversal

(18) Parallel Operation

These characteristics are cross-referenced with the test data and information, in this Section, by means of Table 1.

In missions with long orbits, constant potential, current limited charging was used. Early in the program it was determined that a voltage of 1.51 volts per cell would be adequate to recharge silver cadmium cells over the temperature range of 0°C to 50°C. However, as a battery became fully charged, a voltage unbalance would develop among the various cells. As demonstrated by the various tests, internal pressures would develop in cells at voltages greater than 1.51 volts. It was difficult to establish any relationship between ampere hour input, at very low currents, with internal pressure rise. In most cases, analyses of gases showed a high percentage of hydrogen. Oxygen rates of recombination in these cell designs were extremely low. As a result, a charge control system was devised that used a constant potential charge voltage of 1.51 volts per cell and when the charge current tapered to a value of nominal capacity divided by 100, a current sense circuit triggered the voltage limit to a value of 1.41 volts per cell. Since this is essentially the open circuit voltage of the silver cadmium cell, no cell unbalance or gas evolution occurred. Some loss of ampere hour capacity would result, e.g., a few tenths of an ampere hour in a five ampere hour cell, when using this type of charge control. However, some tests showed that, even at the low rates of current associated with the 1.41 volt per cell limit, capacity would be delivered to a cell or battery on prolonged float charges.

Table 1
Correlation of Battery and Cell Characteristics with Test Data and Information

Test Number	(1) Ampere Hour Capacity, Function of Temperature and/or Charge Rate	(2) Ampere Hour Capacity Maintenance During Deep Discharging	(3) Discharge Voltage as a Function of Residual Battery Capacity and/or Discharge Temperature	(4) Simulated Orbital Cycling, Greater than 25 Cycles at Various Temperatures	(5) Ampere Hour and/or Watt Hour Efficiency	(6) Cell Unbalance During Float Charging and on Full Discharge	(7) Internal Pressure Rise as a Function of Overcharge Current and Float Charge Current	(8) Variation of AgO Plateau During Discharge as a Function of Cycling and Storage	(9) The Effects of the AgO and Ag O Plateaus on Charge Current	(10) Ampere Hour Increase During Simulated Orbital Cycling or Float Charging	(11) Cell Analysis After Cycling	(12) Effects of Acceleration and Vibration	(13) Charged Storage	(14) Discharged Storage	(15) Voltage Dip at Beginning of Discharge	(16) Low Rate Charging	(17) Reversal	(18) Parallel Operation of Batteries
001				X		X		X										
002				X	X	X		X										
003				X						X								
004				X	X	X												
005	X	X			X								X					
006	X				X							X						
007	X		X												X			
008							X									X		
009							X				X					X		
010		X		X	X	X		X	X	X	X		X					
011	X			X	X	X	X	X										
012							X											
013							X		X									
014							X	X							X	X		
015							X									X		
016								X	X							X		
017									X									
018								X										
019 (A-E)						X		X					X					
020	X								X									
021																	X	
022														X				
023																		X

There are other battery/cell characteristics that may be of general interest, such as, high rate pulsing, charge/discharge pulsing, reversal, etc. These characteristics are covered in other Sections of the report.

No planned tests were run to determine the effects of dry, unformed storage of silver cadmium cells. During the program it was determined that it was advantageous to purchase the cells dry and unformed and to fill the cells with electrolyte, form the active materials and to seal the cells at Goddard Space Flight Center (GSFC). However, during the course of the overall program, cells that were stored dry and unformed for four years at room temperature were filled, formed and sealed and used on a spacecraft mission. No deterioration of the cells as a result of this type of storage resulted. Also, during the period 1960 to 1965, no planned program was performed to determine the effects of wet, uncharged storage on cell performance or cycle life. However, experience showed that to obtain satisfactory life and performance, the maximum wet life of a battery should be six months. During this period, some cycling would take place, i. e. , capacity checks, qualification cycling and cycling during spacecraft integrations. Usually the total number of cycles did not exceed fifty. During this six month period, operation of temperature limits were between -10°C and 40°C. Later on in the program, operational temperature limits were narrowed somewhat. In the last few years it has been practice to store the uncharged, wet batteries at low temperatures (-20°C) for long periods of time. For example, a ten ampere hour battery that was stored discharged for thirty-one months at -20°C could be charged and discharged at room temperature and deliver 10.4 ampere hours. The use of these batteries is restricted to prototype batteries used in integration. Ref. 3.

Each test reported has the following information in the heading:

(1) Test Number: A three digit number for designating the test. This number is not necessarily the test number used in the original test. This number appears in Table 1 to serve as a cross-reference between tests and battery/cell characteristics and performance.

(2) Test Unit and Serial Number: The serial number (S/N) is the same number as used on the original test unit. Cell design information is given for each test unit. For example, a five ampere hour silver cadmium battery of thirteen cells is designated as follows:

13x YS 5 S - 2 NM (*)

NM — Non-Magnetic

2 — Design Drawing or Specification Change Number

S — Sealed or Can Be Sealed

5 — Nominal Ampere Hours Capacity
In this case, five ampere hours.

YS — Yardney Silver-Cel (If another manufacturer's test units were used, the name of the manufacturer will be called out in the text. In this section of the report, only Yardney Silver-Cels were used as test units.

13x — Number of cells in the battery. In this case, thirteen. No designation here for a single cell.

*For YS11 cells, a (TA) or (Sh) will appear hear to differentiate a tall and a short eleven ampere hour cell.

(3) Total Cycling Time: This gives the total number of test hours. This includes periods of charged stand or float charging if these parts of the test are considered in the Test Brief or under Cycling.

(4) Number of Cycles: The number of cycles that were included in the test. In a few test descriptions, the total number of cycles may not appear, e.g., data on initial capacity checks that were not required to demonstrate battery/cell characteristics or a few cycles for which data could not be located.

(5) Test Period: Self-explanatory

Also, the following data and information is given for each test under the subheadings Test Brief, Cycling and Observations and Conclusions. These are explained as follows:

(1) Test Brief: A short description of each test. A reference to each cell design is shown at the bottom of each Test Brief. Reference is made to the Main Project that the tests were applied to in the overall program. Applicable Figures, that apply to each test, are called out. Also included is a Nominal Depth of Discharge (NDOD).

(2) Cycling: A synopsis of the cycling program with data or information that will support the battery or cell characteristics or performance that are described.

(3) Observations and Conclusions: The authors concept of the information resulting from the test.

TEST 001

Test Unit: Battery 17xYS3S-1NM
S/N 001

Test Period: 1961

Total Cycling Time: 2400 Hours.
Number of cycles: 291

TEST BRIEF

The battery consisted of seventeen, three ampere hour cells in series encapsulated in EPON 834. Simulated, orbital cycling was at 25°C and 42°C in 8.0 and 8.5 hour orbits with a 0.5 hour discharge. A voltage clamp and current limit were used during charging. The nominal discharge current was 600 ma. Constant resistance discharges were used. Discharge currents reported are averages. During cycling, total battery voltages were monitored for 65% of the cycling. Charge current curves were integrated for 70% of the cycling to determine amount of recharge. Wet life of the battery at the beginning of the test was approximately six months. During this time the battery was stored discharged at 25°C.

Cell Design Reference: Appendix A

Project: Explorer XII (S-3)

Applicable Figures: 3,4

Nominal Depth of Discharge: 10%

CYCLING

Cycle(s)(1) Half Cycle(s)	AHI (2)	AHO (2)	Cycling Parameters	Temperature °C
1C & 1D 2C & 2D 3C	2.5 3.0 2.9	2.5 3.0	300 ma. constant current charge until first cell reached 1.60 volts. Discharge at 550 ma.	25
3D to 28C			Constant potential charge at 1.47 volts per cell current limited at 300 ma. for 8.0 hours. Discharge at 580 ma. for 0.5 hours.	42

TEST 001 (Continued)

Cycle(s) Half Cycle(s)	AHI	AHO	Cycling Parameters	Temperature °C
28D		2.7	In-cycle capacity check. Discharge at 560 ma. to 0.9 volts per cell.	42
29C	2. 6		200 ma. constant current charge until first cell reached 1.60 volts.	25
29D to 54C			Constant potential charge to 1.47 volts per cell current limited at 300 ma. for 7.5 hours. Discharge at 580 ma. for 0.5 hours.	42
54D		2.8	In-cycle capacity check. Discharge at 580 ma. to 0.9 volts per cell.	42
55C	3.1		Same as 29C	42
55D to 106C			Cycles 55D to 78C Same as 29D to 54C	42
			Cycles 79C to 106C Constant potential charge at 1.50 volts per cell current limited at 300 ma. for 7.5 hours. Discharge same as 29D to 54C.	42
106D		2.8	In-cycle capacity check. Same as 54D.	25
107C	2.8		Same as 29C	42
107D to 201C			Same as 79C to 106C	
201D		2.5	In-Cycle capacity check. Same as 54D.	42

TEST 001 (Continued)

Cycle(s) Half Cycle(s)	AHI	AHO	Cycling Parameters	Temperature °C
202C	2.4		Same as 1C	25
202D		2.5	Same as 54D.	25
203C	2.6		Same as 29C.	25
203D to 291C			Constant potential charge at 1.50 volts per cell current limited at 1000 ma. for 7.5 hours. Discharge at 650 ma. for 0.5 hours.	25
291D		2.5	In-cycle capacity check. Discharge at 650 ma. to 0.9 volts per cell.	25

(1) C = Charge
D = Discharge
(2) AHI - Ampere Hours In
AHO - Ampere Hours Out

OBSERVATIONS AND CONCLUSIONS:

1. During simulated orbital cycling, the initial charge voltage approached the voltage clamp of 1.47 or 1.50 volts per cell within one minute from initiation of charge.

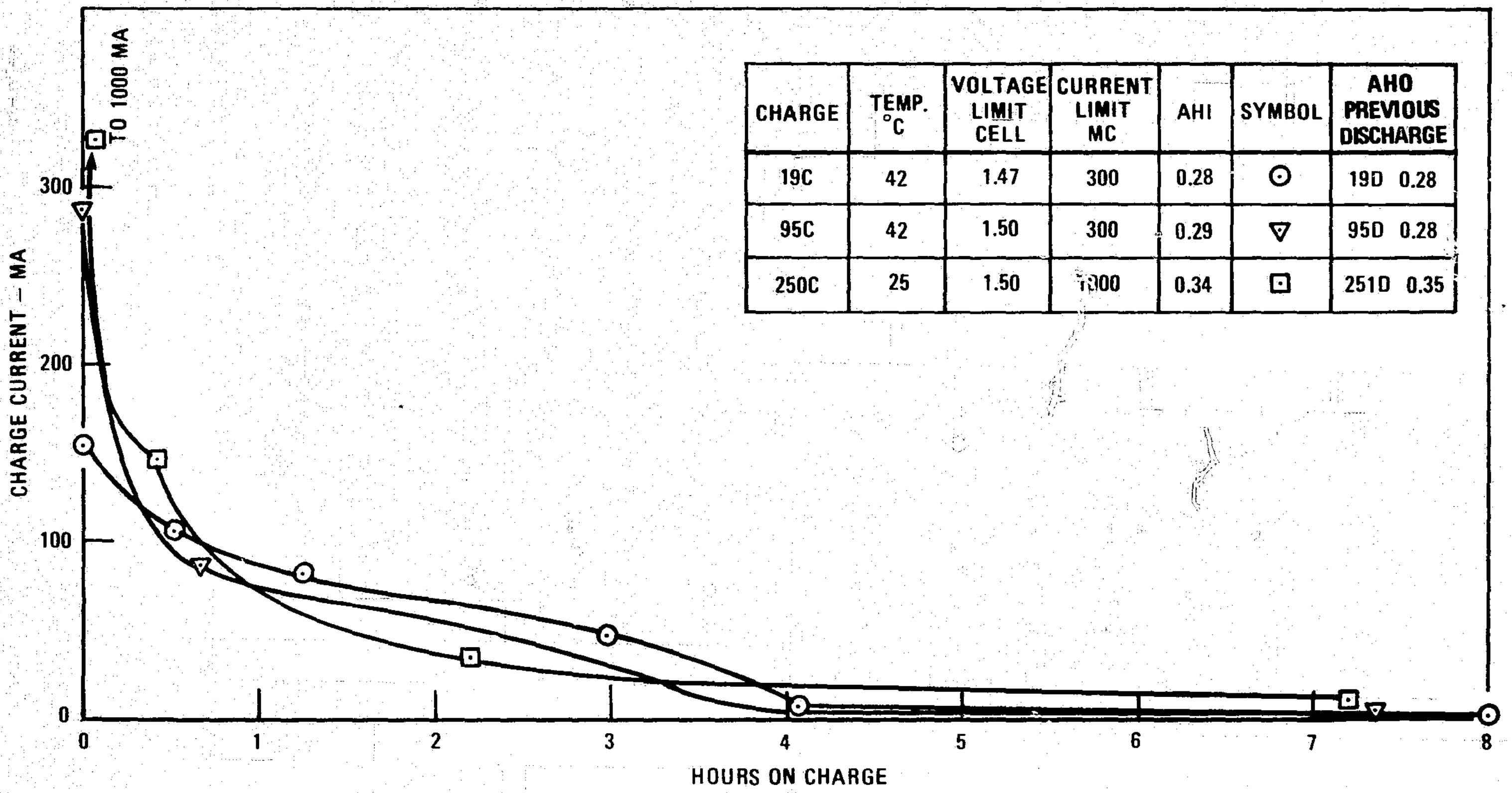
2. At temperatures of 25°C and 42°C, a charge voltage of 1.50 volts per cell would be satisfactory. Further testing would be required to determine if a charge voltage of 1.47 volts per cell would be satisfactory for both temperatures. The current limit could be set at a lower value than 200 ma. See Figure 3 for typical charge current curves.

3. During the simulated orbital cycles, the ampere hour efficiency was greater than 90%.

4. During simulated orbital cycling, the cell balance on charge was within ±0.030 volts of the cell voltage clamp. Cell unbalance on discharge occurred at in-cycle capacity check 201D with one cell going to zero volts while the remaining cells were between 0.9 and 1.0 volts.

5. There were no indications of cell failures. During the first 200 cycles a permanent loss of approximately 0.5 ampere hours, based on the initial capacity, resulted.

6. As shown in figure 4, the upper voltage plateau (AgO plateau) on discharge decreases with simulated orbital cycling. After in-cycle capacity checks, an upper plateau appears for a few cycles then gradually decreases to the lower level.



CHARGE	TEMP. °C	VOLTAGE LIMIT CELL	CURRENT LIMIT MC	AHI	SYMBOL	AHO PREVIOUS DISCHARGE
19C	42	1.47	300	0.28	⊙	19D 0.28
95C	42	1.50	300	0.29	▽	95D 0.28
250C	25	1.50	1000	0.34	⊡	251D 0.35

Figure 3. Current on Charge, Test No. 001, Battery 17xYS3S-1NM, S/N 001

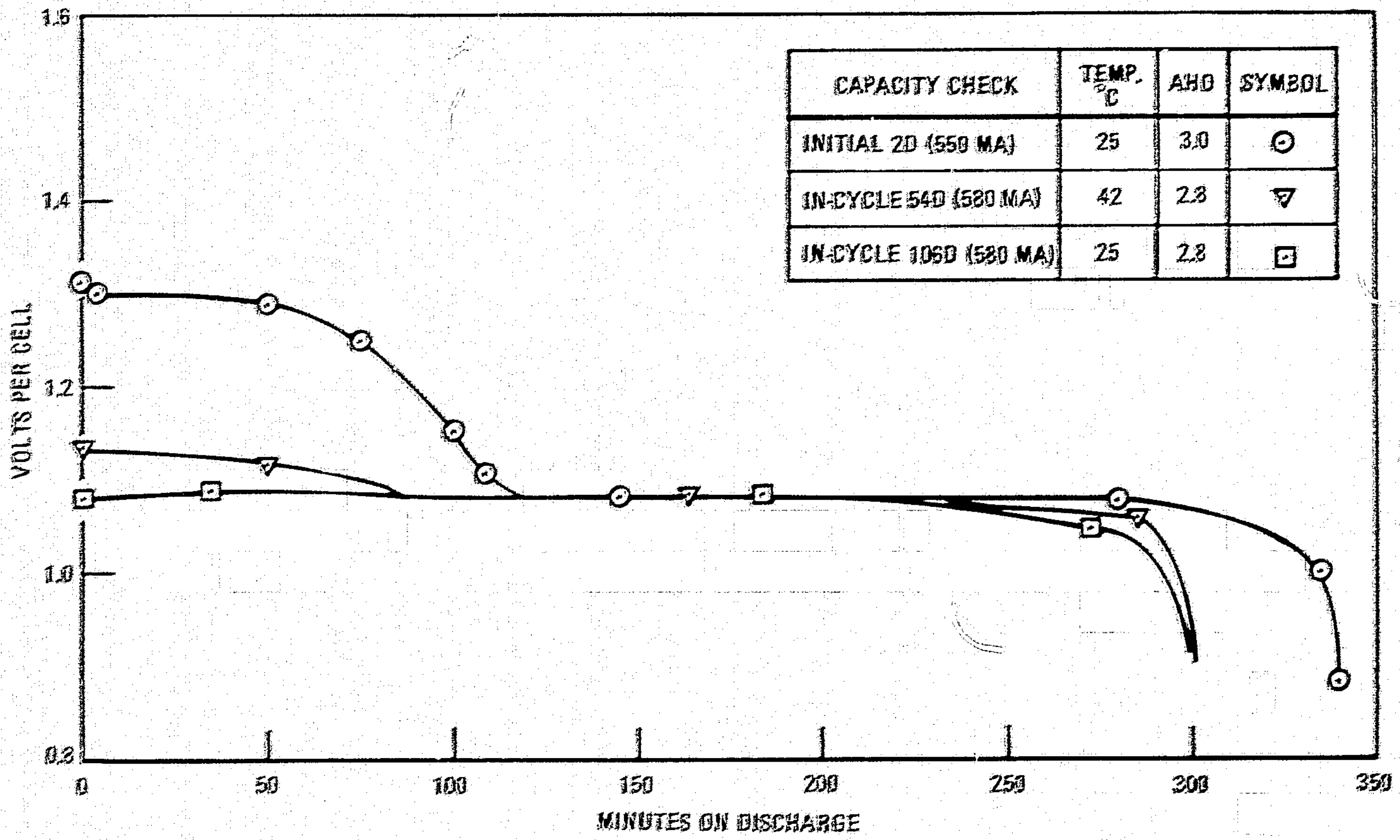


Figure 4. Voltage on Discharge, Test No. 001, Battery 17xYS3S-1NM, S/N 001

TEST 002

Test Unit: Battery 17xYS3S-1NM
S/N 002

Test Period: 1961

Total Cycling Time: 850 Hours
Number of cycles: 105

TEST BRIEF

The battery consisted of seventeen, three ampere hour cells in series encapsulated in EPON 834. Except for initial cycles at 25°C, all simulated orbital cycling was performed at 0°C in 8.0 hour orbits with a 0.5 hour discharge. A voltage clamp and current limit were used during charging. The nominal discharge current was 600 ma. Constant resistance discharges were used. Discharge currents reported are averages. During cycling, total battery voltages and currents were recorded and end of charge voltages were monitored on a recorder for 75% of the cycling. Charge current curves were integrated for 85% of the cycling to determine the amount of recharge. Wet life at the beginning of cycling was approximately seven months. During this time, the battery was stored discharged at 25°C.

Cell Design Reference: Appendix A

Project: Explorer XII (S-3)

Applicable Figures: 5,6

Nominal Depth of Discharge: 10%

TEST 002 (Continued)

CYCLING

Cycle(s)[1] Half Cycle(s)	AHI[2]	AHO[2]	Cycling Parameters	Temperature °C
1C and 1D 2C and 2D 3C and 3D 4C	2.5	2.3	200 ma. constant current charge until first cell reaches 1.60 volts. Discharge at 550 ma. to 0.9 volts per cell.	25
4D to 10D			Constant potential charge at 1.50 volts per cell current limited at 250 ma. for 8 hours. Discharge at 610 ma. for 0.5 hours.	25
11C to 104C			Same as 4D to 10D except 104C was a 280 hour charge.	0
104D		2.1	In-cycle capacity check. Discharge at 630 ma.	0
105C and 105D	2.5	2.3	200 ma. constant current charge until first cell reaches 1.60 volts. Discharge at 500 ma. to 0.9 volts per cell.	25

(1) C = Charge
D = Discharge
(2) AHI - Ampere Hours In
AHO - Ampere Hours Out

OBSERVATIONS AND CONCLUSIONS:

1. During simulated orbital cycling, the initial charge voltage approached the voltage clamp of 1.50 volts per cell within a few minutes of initiation of charge.

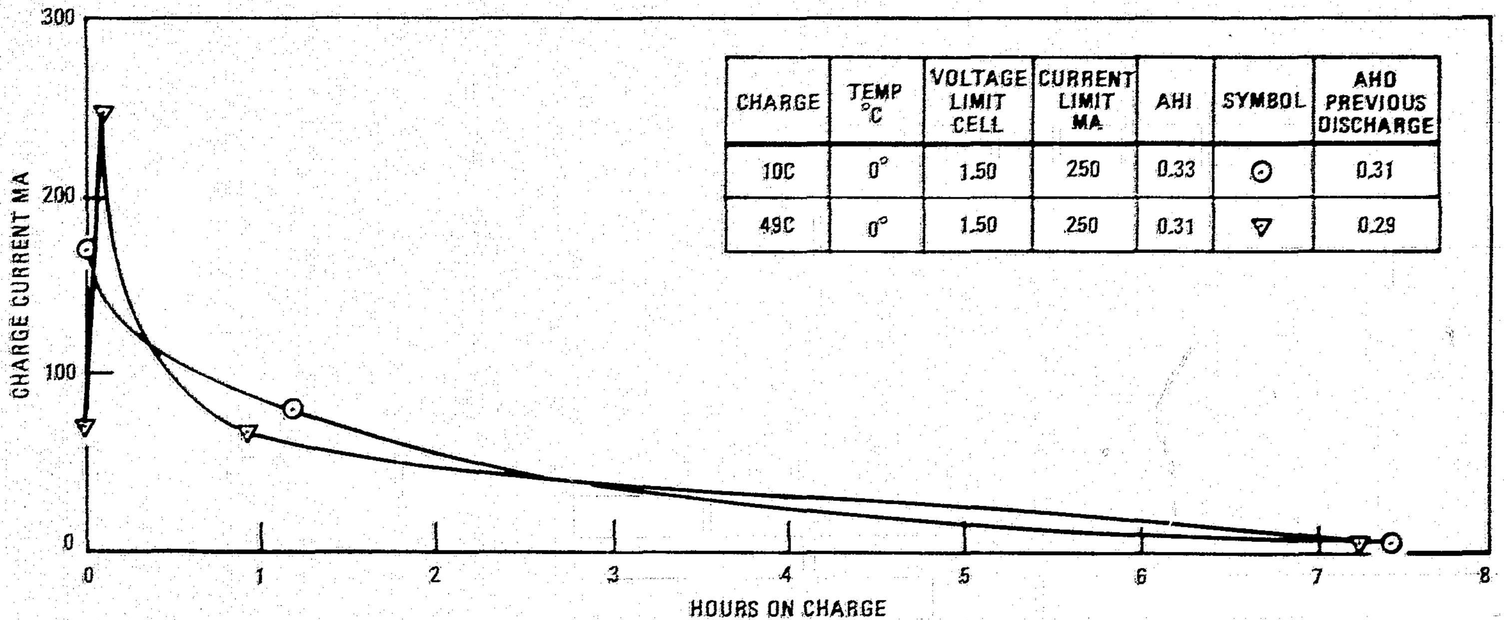
2. At the temperature of 0°C, a charge voltage of 1.50 volts per cell would be satisfactory. The available charge current could be less than 250 ma. As cycling progressed, the initial charge current was less than 100 ma., then approached the current limit followed by a gradual decrease with time. Charge 49C, figure 5, is typical of 80% of the charge current curves. Charge 10C is typical at the initial simulated orbital cycles.

3. During simulated orbital cycling, the average ampere hour efficiency was 95%.

4. During simulated orbital cycling, the cell balance at the end of charge was within ±0.03 volts of the cell voltage clamp. However, during one long charge (104C) of 280 hours, fifteen of the cells were within 0.02 volts of the cell voltage clamp and two cells measured 1.430 volts. The current at the time of this measurement was less than two ma. Cell unbalance on discharge occurred on cycle 104D with one of the cells going to zero volts while the remaining cells were between 0.8 and 1.0 volts.

5. There was no indications of cell failure. During the cycling program at 0°C, a loss of approximately 0.4 ampere hours, based on initial capacity at 25°C, resulted. In comparing an initial capacity check (2D) with the final capacity check at 25°C, the ampere hour loss was approximately 0.2 ampere hours.

6. As shown in figure 6, the upper plateau (AgO plateau) on discharge decreased with simulated orbital cycling.



CHARGE	TEMP °C	VOLTAGE LIMIT CELL	CURRENT LIMIT MA	AHI	SYMBOL	AHO PREVIOUS DISCHARGE
10C	0°	1.50	250	0.33	⊙	0.31
49C	0°	1.50	250	0.31	▽	0.29

Figure 5. Current on Charge, Test No. 002, Battery No. 17xYS3S-1NM, S/N 002

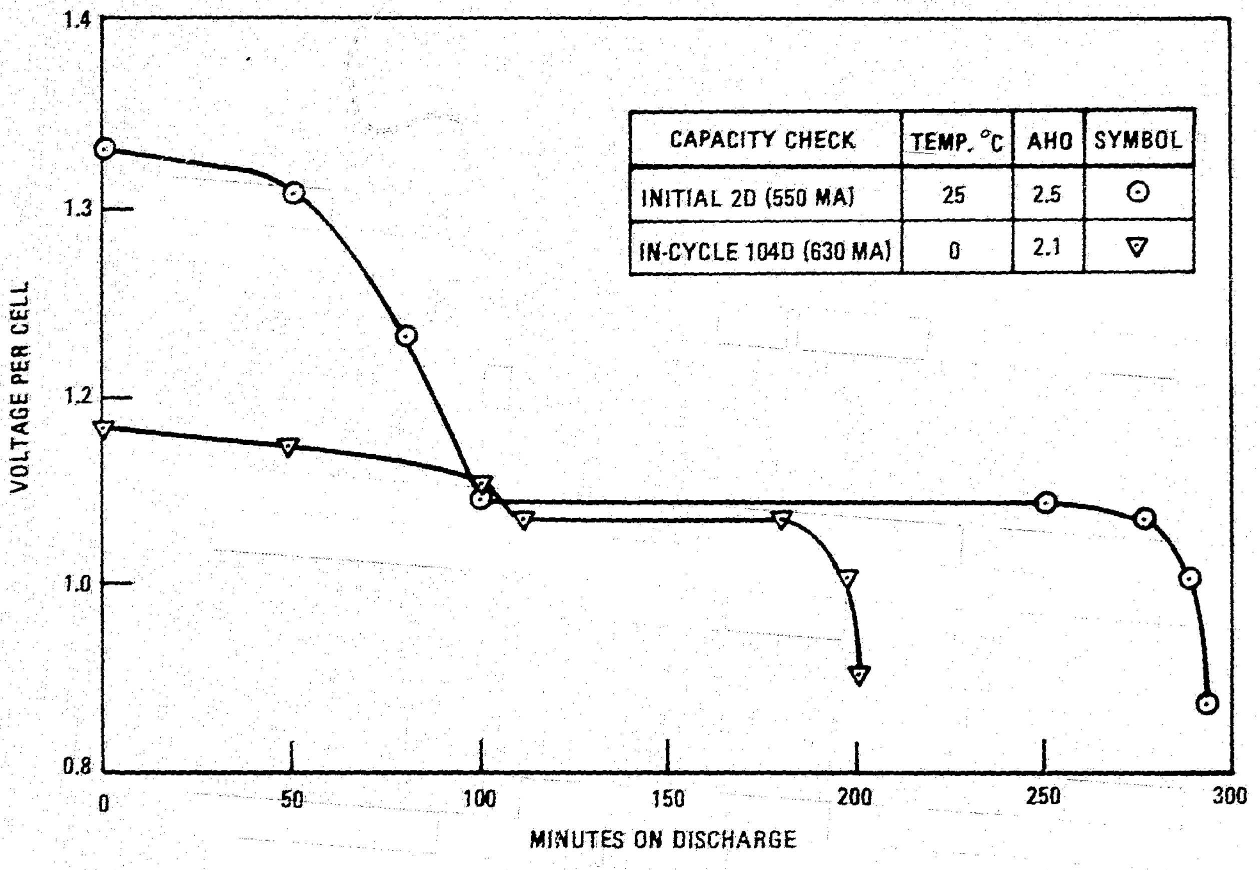


Figure 6. Voltage on Discharge, Test No. 002, Battery 17xYS3S-1NM, S/N 002

TEST 003

Test Unit: Battery 20xYS3S-1NM
S/N 003

Test Period: 1961

Total Cycling Period: 150 Hours
Number of Cycles: 25

TEST BRIEF

The battery consisted of twenty, three ampere hour cells in series. These cells were not encapsulated in EPON 834. The fill ports were sealed with polystyrene caps. Simulated orbital cycling was at 25°C in 6.0 hour orbits with a 0.5 hour discharge. A voltage clamp and current limit were used during cycling. The nominal discharge current was 560 ma. Constant current discharges were used. During cycling, total battery voltage and currents were recorded. Charge current curves were integrated for 100% of cycling to determine the amount of recharge. Wet life of the battery at the beginning of the test was approximately one year. The battery (cells) had been stored discharged at 25°C.

Cell Design Reference: Appendix A

Main Project: SERB (Study of Enhanced Radiation Belt) – Explorer XV

Applicable Figures: 7

Nominal Depth at Discharge: 9%

CYCLING

Cycle(s)[1] Half Cycle(s)	AHI[2]	AHO[2]	Cycling Parameters	Temperature °C
1C and 1D	INA[3]			
2C and 2D	INA	3.1	200 ma. constant current charge until average cell voltage is 1.57 volts per cell. Discharge at 600 ma., constant current.	25
3C	3.0		200 ma. constant current charge until average cell voltage is 1.55 volts per cell. Discharge at 580 ma., constant current.	25
3D to 24C			Constant potential charge at 1.50 volts per cell current limited at 200 ma. for 5.5 hours. Discharge at 560 ma. for 0.5 hours.	25
25D		3.5	In-cycle capacity check. Discharge at 570 ma. to 0.9 volt per cell.	25

(1) C = Charge
D = Discharge
(2) AHI = Ampere Hours In
AHO = Ampere Hours Out
(3) INA = Information Not Available

OBSERVATIONS AND CONCLUSIONS:

1. During simulated orbital cycling, the initial charge voltage approached the voltage clamp of 1.50 volts per cell within one minute from initiation of charge.

2. The charge voltage of 1.50 volts per cell was satisfactory. A plot of Ampere Hours In (AHI) and Ampere Hours Out (AHO) for simulated orbital cycling is shown in figure 7. Note that a build-up in ampere hours capacity occurs during the first twelve cycles. An increase in total capacity, in this case from 3.1 Ahr to 3.5 Ahr, has been observed many times in this type of testing during initial cycles (10 to 20 cycles). This is especially true when the battery is constant current charged followed by simulated orbital cycling with periods equal to or greater than six hours.

3. There were no indications of cell failures.

4. The average voltage at the upper plateau (AgO plateau), on initiation of discharge, decreased from 1.32 volts per cell to 1.24 volts per cell.

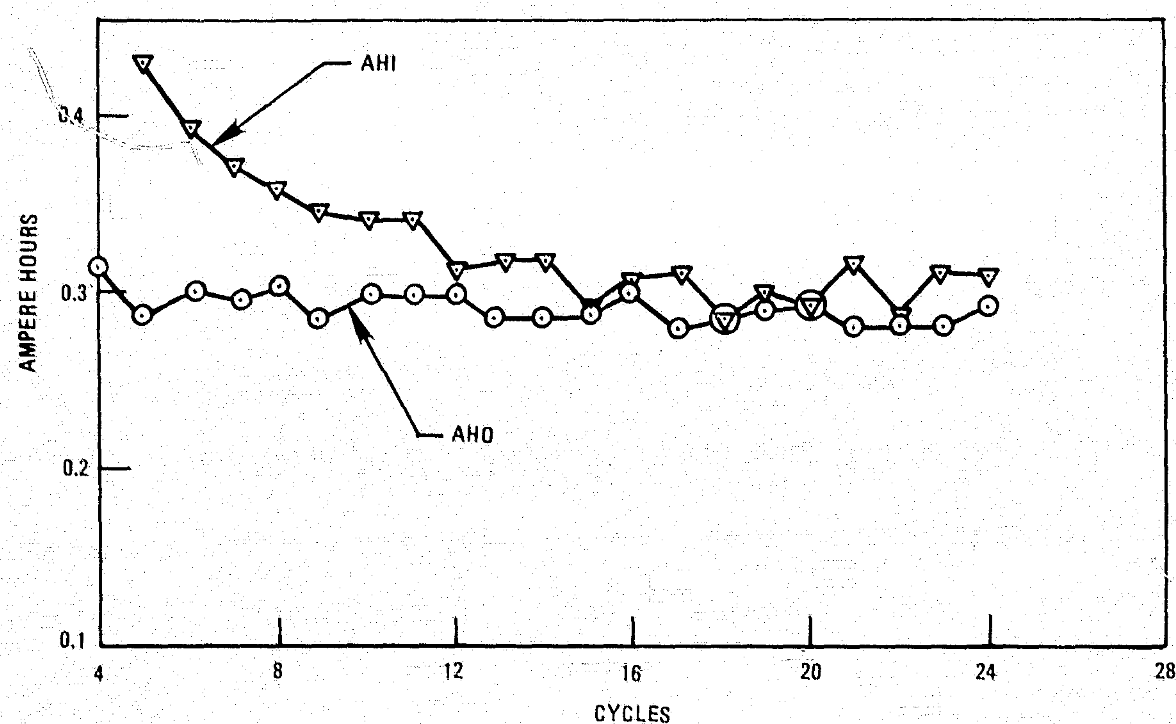


Figure 7. Ampere Hours Out (AHO) Compared to Ampere Hours In (AHI) Test No. 003, Battery 20xYS3S-1NM, S/N 003

TEST 004

Test Unit: Battery 17xYS5S-2NM
S/N 002

Test Period: 1961

Total Cycling Time: 900 Hours
Number of Cycles: 42

TEST BRIEF

The battery consisted of seventeen, five ampere hour cells in series encapsulated in EPON 834. Cycling was at 25°C and 0°C in orbits that varied between twelve and twenty-four hours. One long charge was included to determine the degree of cell unbalance during a charge at 0°C. The nominal discharge current was 800 ma. for one hour. In a few cycles, the discharge current was 200 ma. for one hour. Constant current discharges were used during simulated orbital cycling. During cycling, total battery voltages and currents were recorded and end of charge cell voltages were monitored for 90% of the cycling. Charge current curves were integrated for all cycling. Wet life of the battery at the beginning of the test was approximately six months. During this time, the battery was stored discharged at room temperature.

Cell Design Reference: Appendix A

Main Project: Explorer XII (S-3)

Applicable Figures: None

Nominal Depths at Discharge: 17%

CYCLING

Cycle(s)[1] Half Cycle(s)	AHI[2]	AHO[2]	Cycling Parameters	Temperature °C
1C and 1D	5.7	1.80	First cycle was a simulation of prelaunch operation. 270 ma. constant current charge until first cell reaches 1.60 volts. Discharge at 835 ma. for 128 minutes.	25

TEST 004 (Continued)

CYCLING

Cycle(s) Half Cycle(s)	AHI	AHO	Cycling Parameters	Temperature °C
2C to 25C			Constant potential charge at 1.50 volts per cell current limited at 200 ma. for twelve or twenty-four hours. Discharge at 830 ma. for one hour.	25
25D		5.2	In-cycle capacity check. Discharge at 770 ma. to 0.9 volts per cell.	25
26C	4.4		270 ma. constant current charge until first cell reaches 1.60 volts. Power failure shut off charger prematurely.	25
26D-39C			Constant potential charge to 1.53 volts per cell current limited at 200 ma. for twenty-four hours. Discharge at 750 ma. or 200 ma. for one hour.	0
39D		4.6	In-cycle capacity check at 25°C to 1.0 volt per cell.	25
40C and 40D	INA(3)			
41C and 41D	INA			

(1) C = Charge
D = Discharge
(2) AHI = Ampere Hours In
AHO = Ampere Hours Out
(3) INA = Information Not Available

Cycle(s) Half Cycle(s)	AHI	AHO	Cycling Parameters	Temperature °C
42C and 42D	5.4	5.6	275 ma. constant current until first cell reaches 1.60 volts. Discharge at 770 ma. to 0.9 volts per cell.	25

OBSERVATIONS AND CONCLUSIONS:

1. During simulated orbital cycling at 25°C, the initial charge voltage approached the voltage clamp of 1.50 volts per cell within one minute of initiation of charge. At 0°C cycling, this time period increased to approximately ten minutes.

2. At the temperature of 25°C, a charge voltage of 1.50 volts per cell would be satisfactory.

3. The ampere hour balance during cycling is shown in Tables 2 and 3. The ampere hour efficiencies of 0.97 at 25°C are typical of the ampere hour efficiencies obtained during simulated orbital cycling.

4. During simulated orbital cycling at 25°C, the cell balance or charge was within +0.01 or -0.08 volts of the cell voltage clamp. During cycling at 0°C, the cell balance on charge was within +0.01 or -0.02 volts of the cell voltage clamp. The battery had not been fully charged before 0°C cycling. This may have been the reason for the good cell balance. Cell unbalance during discharge occurred on in-cycle capacity check 39D when one cell went to 0.6 volts while the remaining cells were between 1.0 and 1.06 volts. During a 48 hour charge on 39C, the cell balance at end of charge was within +0.02 or -0.07 volts of the voltage clamp of 1.53 volts per cell. During this charge, the battery temperature was raised from 0°C to 25°C.

5. There were no indications of cell failure.

6. The degree of decay of the upper plateau of the discharge voltage during cycling was not as pronounced during this test as in previous tests (001, 002, and 003).

Table 2

TEST 004
Battery 17xYS5S-2NM

AMPERE HOUR BALANCE AT 25°C Cycles 1C to 25D		
Cycle	AHI	AHO
1	5.7	1.80
2	2.33	0.82
3	0.97	0.83
4	0.96	0.83
5	0.90	0.83
6	0.89	0.83
7	0.83	0.83
8	0.63	0.83
9	0.92	0.84
10	0.88	0.83
11	0.84	0.84
12	0.89	0.83
13	0.89	0.82
14	0.87	0.81
15	0.84	0.82
16	0.86	0.81
17	0.86	0.81
18	0.79	0.80
19	0.80	0.80
20	0.56	0.78
21	0.90	0.78
22	0.94	0.78
23	1.00	0.80
24	0.85	0.80
25	0.72	5.2
TOTAL AHI	26.77	
TOTAL AHO		25.93

$$\text{AMPERE HOUR EFFICIENCY} = \frac{25.93}{26.77} = 0.97$$

Table 3

TEST 004
Battery 17xYS5S-2NM

AMPERE HOUR BALANCE AT 0°C Cycles 26C to 39D			
Cycle	AHI	AHO	Remarks
26	4.44	0.75	Initial constant current charge (26C) at 25°C
27	0.90	0.74	
28	1.11	0.77	
29	1.07	0.74	
30	0.81	0.75	
31	0.80	0.75	
32	0.88	0.75	
33	0.92	0.20	
34	0.20	0.20	
35	0.17	0.20	
36	0.22	0.20	
37	0.19	0.20	
38	0.23	0.74	
39	0.68	4.6	Final Discharge (39D) at 25°C
Total AHI	12.62		
Total AHO		11.60	

$$\text{AMPERE HOUR EFFICIENCY} = \frac{11.60}{12.62} = 0.92$$

TEST 005

Test Unit: Battery 11xYS2S-1NM
S/N 001

Test Period: 1960/1961

Total Cycling Time: 2500 Hours
Number of Cycles: 21

TEST BRIEF

The battery consisted of eleven, two ampere hour cells in series encapsulated in EPON 834. Cycling was at 25°C, 8°C and -5°C. All charges were constant current to 1.60 volts per cell. The nominal discharge current was 400 ma. to less than 1.0 volts per cell. Constant resistance discharges were used. Discharge currents reported are averages. During cycling, total battery voltages and currents were recorded and end of charge voltages were monitored for all cycles. Discharge current curves were integrated for all of the cycling. Between the last charge and discharge, the battery was stored charged at room temperature for three months. Wet life of the battery at the beginning of the test was approximately four months. The battery was stored discharged at 25°C during this time.

Cell Design Reference: Appendix A

Main Project: Explorer XII (S-3)

Applicable Figures: 8, 9, 10

Nominal Depth of Discharge: 100%

TEST 005 (Continued)

CYCLING

Cycle(s) (1) Half Cycle(s)	AHI (2)	AHO (2)	Cycling Parameters	Temperature °C
1C and 1D	2.1	2.0	100 ma. Constant current charge to 1.60 volts per cell. Discharge at 400 ma. to 1.0 volts per cell.	25
2C	2.1		Same as 1C.	25
2D		1.5	Same as 1D.	-05
3C	2.0		Same as 1C.	25
3D		1.8	Same as 1D.	08
4C and 4D	2.1	1.8	Same as 1C and 1D.	25
5C and 5D	2.1	2.1	Same as 1C and 1D.	25
6C and 6D	2.2	2.1	Same as 1C and 1D.	25
7C and 7D	2.0	1.9	100 ma. Constant current charge to 1.57 volts per cell. Discharge at 400 ma. to 1.0 volts per cell.	25
8C and 8D	2.0	2.0	Same as 7C and 7D.	25

(1) C = Charge
D = Discharge

(2) AHI - Ampere Hours In
AHO - Ampere Hours Out

TEST 005 (Continued)

Cycle(s) Half Cycle(s)	AHI	AHO	Cycling Parameters	Temperature °C
9C and 9D	2.1	2.0	Same as 7C and 7D.	25
10C and 10D	2.0	2.0	Same as 7C and 7D.	25
11C and 11D	2.0	2.0	Same as 7C and 7D.	25
12C and 12D	2.1	2.0	Same as 7C and 7D.	25
16C to 19D	– Results Similar to 12C and 12D. –			25
20C and 21D	INA(3)			
21C	2.0		105 ma. constant current charge to 1.57 volts per cell. Battery stored charged for three months at 25°C.	25
21D		1.9	Discharged at 370 ma. to 1.0 volts per cell.	25

(3) INFORMATION NOT AVAILABLE

OBSERVATIONS AND CONCLUSIONS:

1. When discharged at -5°C, the battery delivered 68% of the 25°C capacity. When discharged at 8°C, the battery delivered 90% of the 25°C capacity.

2. At full charge and discharge at 25°C, the average ampere hour efficiency is close to 100%. A 1.57 volt per cell cut off on charge is adequate, at 25°C, for full charge. Watt hour efficiency, calculated with an average discharge voltage per cell of 1.13, is approximately 72%. See figure 8. This average voltage includes an average of the upper (AgO plateau) and lower (Ag_2O plateau) plateau voltages.

3. The discharge voltage at -5°C, based on the flat portion of the lower plateau (Ag_2O plateau) was 1.05 volts per cell. The average discharge voltage at 8°C based on the flat portion of the lower plateau (Ag_2O plateau) was 1.07 per cell.

4. The average voltage of the upper plateau (AgO plateau) did not decrease in value during the cycling program. See figure 8. Some increase was observed.

5. During constant current charging, the cell balance at the end of charge was within +0.03 or -0.04 volts of the cell voltage clamp (1.57 or 1.60 volts). A typical charge curve is shown in figure 9.

6. The battery was stored charged at 25°C for three months. During this storage, the battery lost approximately 5% of charge. The discharge curve after storage is shown in figure 10.

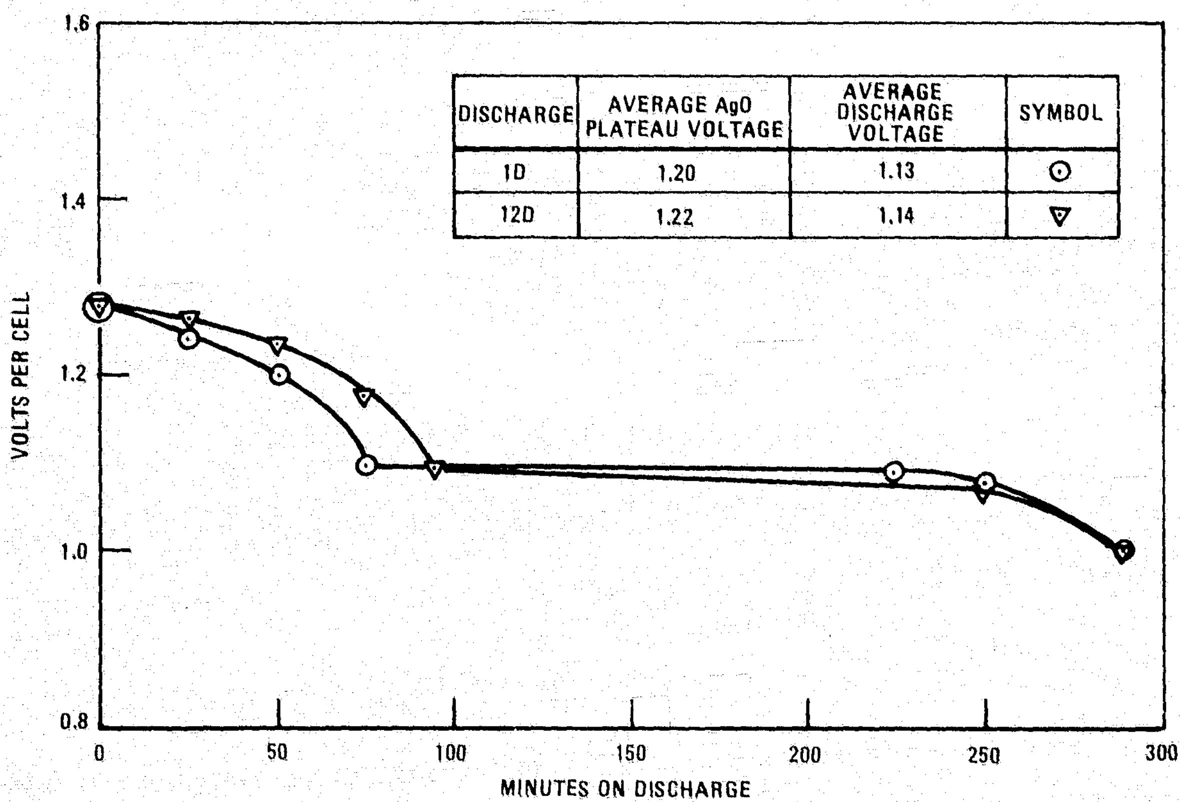


Figure 8. Voltage on Discharge, Test No. 005, Battery 11xYS2S-1NM, S/N 001

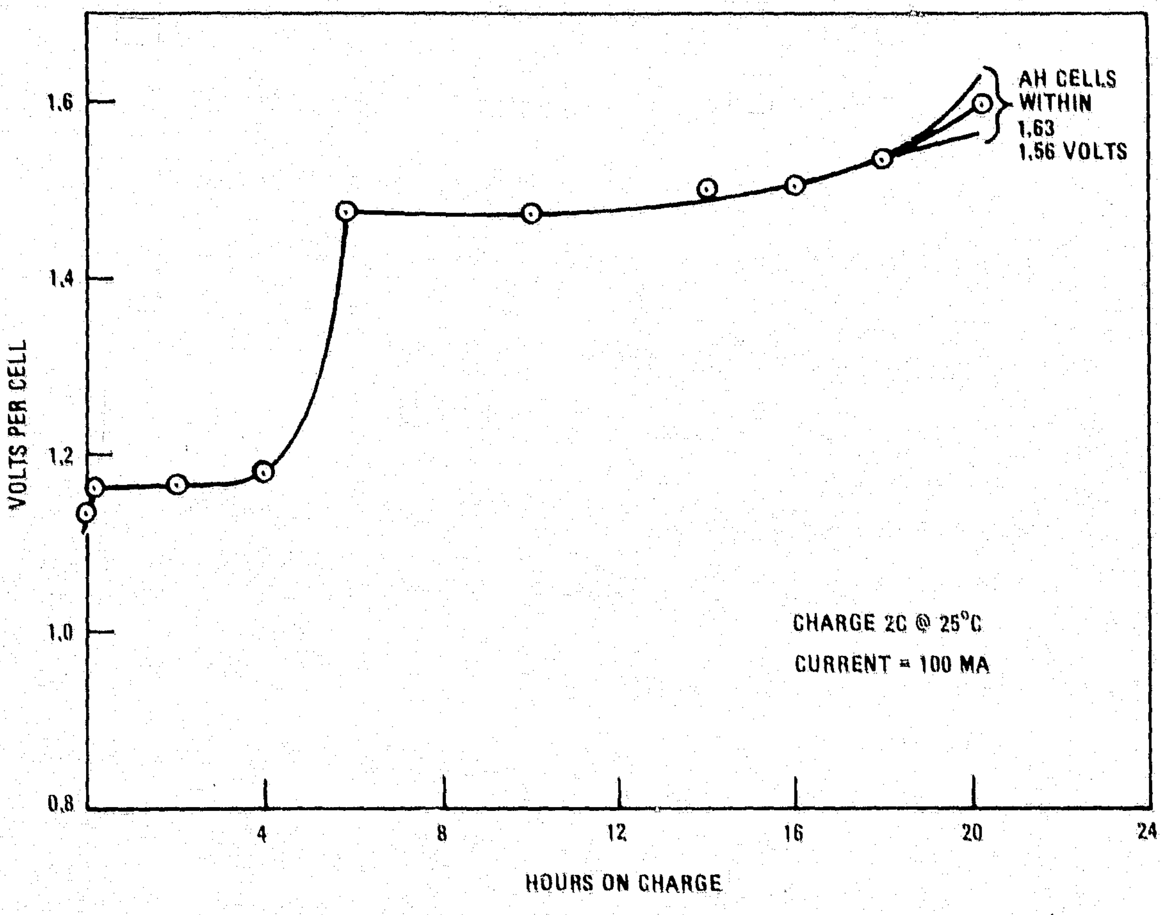


Figure 9. Voltage on Charge, Test No. 005, Battery 11xYS2S-1NM, S/N 001

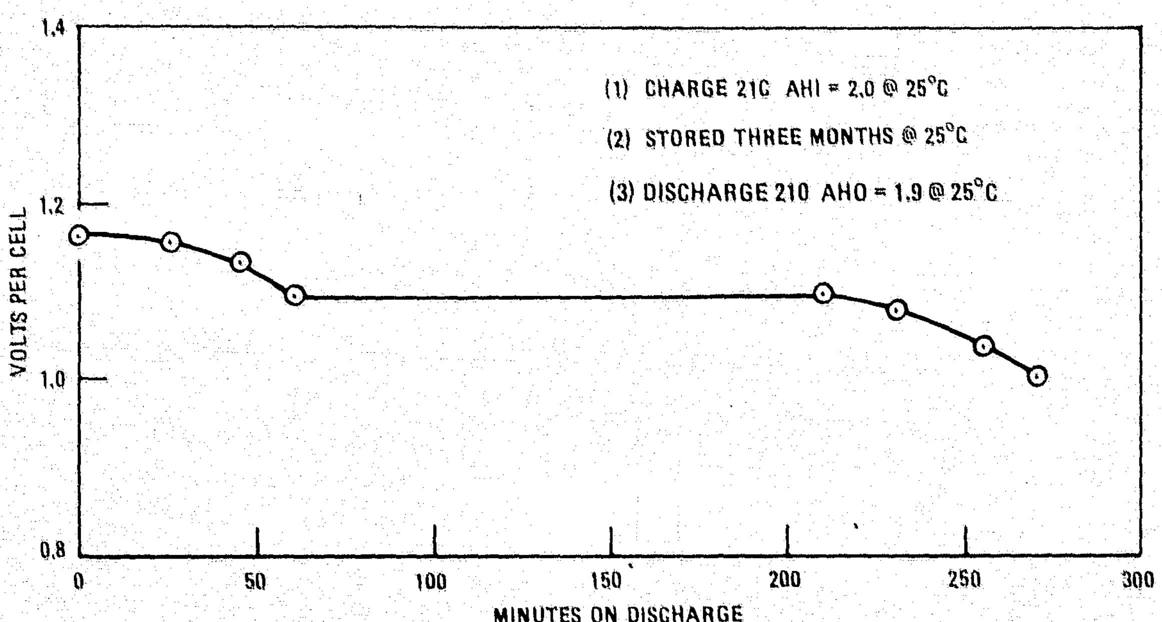


Figure 10. Voltage on Discharge, Test No. 005, Battery 11xYS2-1NM, S/N 001

TEST 006

Test Unit: Battery 11xYS2S-1NM
S/N 002

Test Period: 1960

Total Cycling Time: 175 Hours
Number of Cycles: 8

TEST BRIEF

The battery consisted of eleven, two ampere hour cells in series encapsulated in EPON 834. Cycling was at 25°C, 49°C and -6°C. All charges were constant current to 1.6 volts per cell. The nominal discharge currents were 400 ma. to less than 1.0 volts per cell. Constant resistance discharges were used. Discharge currents reported are averages. During cycling, total battery voltages and currents were recorded and end of charge voltages were monitored for three cycles. Discharge current curves were integrated for each cycle. During two discharges, the temperature rise of the battery was monitored. The battery was vibrated between a charge and discharge per the vibration schedule for the DELTA Launch Vehicle. Also during the test program, the battery was accelerated, per the DELTA Launch Vehicle Schedule, between a charge and discharge. Maximum acceleration force was nine times gravity for twenty seconds. Temperature during acceleration was 25°C. Wet life of the battery at the beginning of test was approximately five months. During the time, the battery was stored discharged at room temperature.

Cell Design Reference: Appendix A

Main Project: Explorer XII (S-3)

Applicable Figures: 11

Nominal Depth at Discharge: 100%

CYCLING

Cycle(s)[1] Half Cycle(s)	AHI[2]	AHO[2]	Cycling Parameters	Temperature °C
1C and 1D	1.96	2.01	100 ma. constant current charge to 1.60 volts per cell. Discharge at 400 ma. to 1.0 volts per cell.	25
2C and 2D	2.00	2.01	Same as 1C and 1D. The battery was vibrated, per DELTA Launch Vehicle Schedule, between charge (2C) and discharge (2D). Vibration was at 25°C.	25
3C and 3D	2.05	2.01	Same as 1C and 1D.	25
4C	2.05		Same as 1C.	25
4D		1.52	Same as 1D.	-6
5C and 5D	2.00	1.85	Same as 1C and 1D. The battery was accelerated, per the DELTA Launch Vehicle Schedule between charge (5C) and discharge (5D). Acceleration was at 25°C.	25
6C	2.10		Same as 1C.	25
6D		2.00	Same as 1D.	49

(1) C = Charge
D = Discharge

(2) AHI - Ampere Hours In
AHO - Ampere Hours Out

TEST 006 (Continued)

Cycle(s) Half Cycle(s)	AHI	AHO	Cycling Parameters	Temperature °C
7C and 7D	2.20	2.10	Same as 1C and 1D.	25
8C	2.4		Same as 1C. Battery was ruptured due to internal pressure rise. Charger cut off failed.	
8D		1.5	Same as 1D.	25

OBSERVATIONS AND CONCLUSIONS:

1. When discharged at 49°C, the battery delivered 95% of the 25°C ampere hour input capacity. The battery had been stored charged approximately 70 hours at 49°C before the discharge. During discharge, the temperature of the battery rose 3°C. Temperature was monitored by a thermocouple placed on the intercell connector of the center cell. When discharged at -6°C, the battery delivered 74% of the 25°C ampere hour input capacity. During discharge, the battery temperature rose approximately 5°C.

2. At full charge and discharge at 25°C, the ampere hour efficiency was close to 100%.

3. The average discharge voltage at 49°C, based on the lower plateau (Ag_2O plateau) was 1.09 volts. Some increase in upper plateau was observed. See figure 11. The average voltage at -6°C, based on the lower plateau, was 1.05 volts per cell.

4. No problems were encountered as a result of vibration or acceleration. The apparent loss of capacity after acceleration was due to a discharge during acceleration of 900 ma. for several minutes.

5. During charge 8C, the failure of the charger cut off (1.60 volts per cell) caused the battery to rupture. The battery was discharged after the rupture occurred and delivered approximately 1.5 ampere hours. During charge 8C, the battery was overcharged by approximately 0.4 ampere hours. It was estimated that the internal pressure at burst, assuming the evolved gas was hydrogen, was 10 atmospheres absolute.

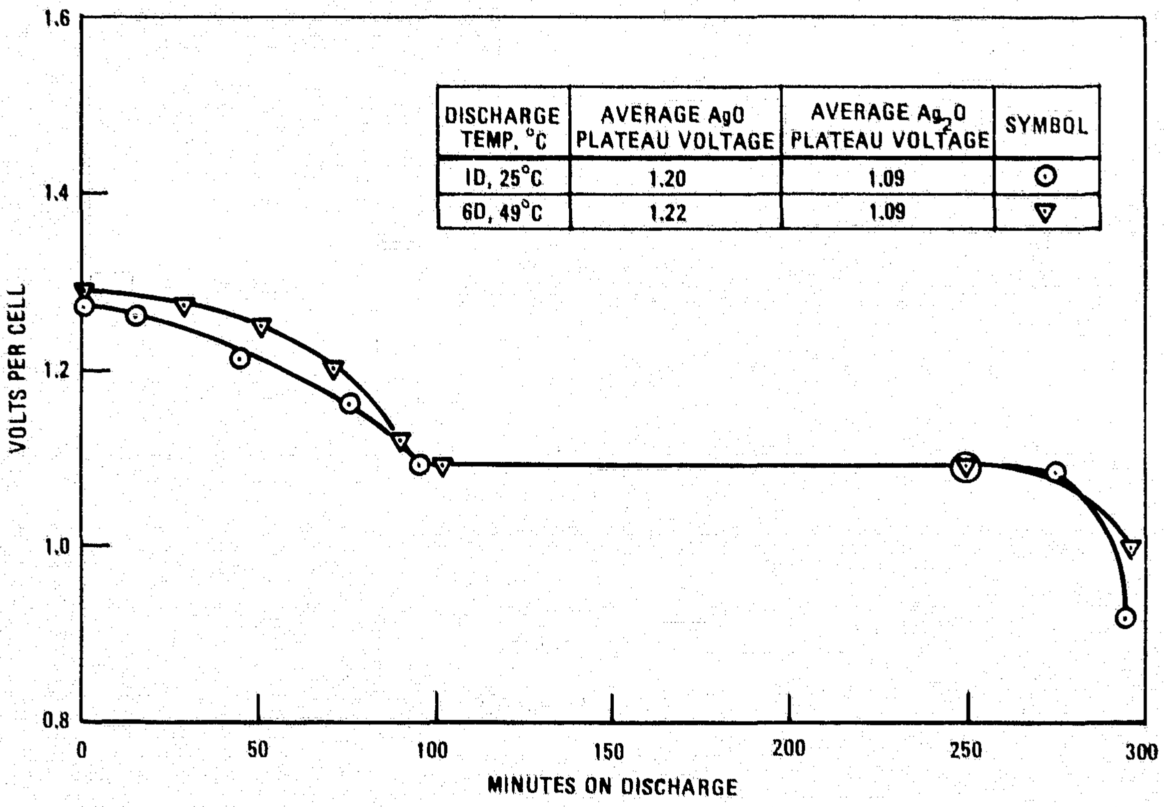


Figure 11. Voltage on Discharge, Test No. 006, Battery 11xYS2S-1NM, S/N 002

TEST 007

Test Unit: Battery 13xYS5S-2NM
S/N 006 & S/N 003

Test Period: 1961, 1962

Total Cycling Time: 120 hours
Number of cycles: 23

TEST BRIEF

Each battery consisted of thirteen, five ampere hour cells in series encapsulated in EPON 834. Cells were from the same production lot. The battery was assembled into two units designated as 2A and 2B that contained five and eight cells, respectively. Provisions were made so that cell voltages could be measured individually. A photo of the battery is shown in Illustration 1. This is the configuration flown on early Explorer satellites. Tests were performed to determine voltage, current, and temperature relationships as a function of constant power discharges of 13 & 33 watts. Also, tests were performed to determine the voltage, current and temperature characteristics as a function of the residual charge remaining in the battery. This latter characterization is significant because of the effect of the two levels of discharge voltage (AgO and Ag_2O) that are inherent in the silver cadmium system. Previous to these tests, each battery had received several routine cycles, at room temperature, but during the remaining time had been stored discharged at 25°C. The wet life of the batteries was less than ten months.

Cell Design Reference: Appendix A

Main Projects: Explorers XII, XIV, XV and XVIII

Applicable Figures: 12, 13, 14, 15, 16, 17, 18

Nominal Depth of Discharge: 100%

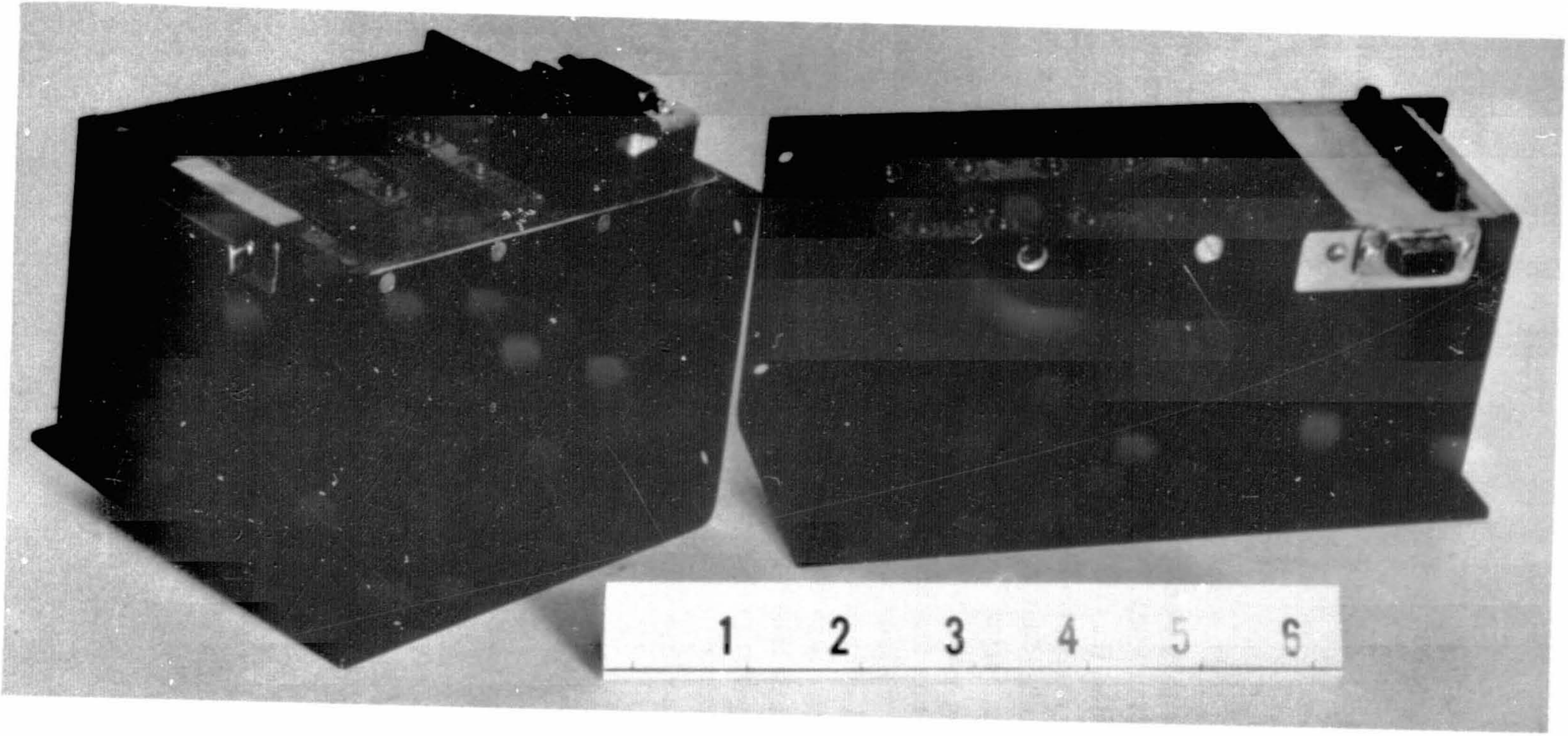


Illustration 1. Battery 13xYS5S-2NM Used on Explorer XII, XIV and XV

CYCLING

1. Constant Power (13 watts)

The battery was discharged on the Explorer XII power converter, with dummy loads, at 13 watts input. Test temperatures were 28°C, -10°C and 48°C. On each test, the battery was discharged to less than 0.93 volts per cell or until one of the cells approached zero volts. Previous to each test, the battery had been charged at room temperature at 300 ma. constant current to 1.55 volts per cell average. A summary of ampere hour inputs and outputs are as follows:

Cycle(s)(1) Half Cycle(s)	AHI(2)	AHO(2)	Cycling Parameters	Temperature °C
15C and 15D	5.4	5.1	300 ma. constant current to 1.55 volts per cell average. Constant power discharge of 13 watts to less than 0.93 volts or first cell to zero volts.	28
16C	5.4		Same as 15C	28
16D		4.7	Same as 15D	-10
17C	INA(3)		Same as 15C	28
17D		5.7	Same as 15D	48

2. Constant Power (33 watts)

The battery was discharged on the Explorer XVIII power converter, with dummy loads, at 33 watts input. Test temperatures were -10°C, 0°C, 24°C and 50°C. On each test the battery was discharged to 0.93

(1) C = Charge
D = Discharge
(2) AHI - Ampere Hours In
AHO - Ampere Hours Out
(3) INA - Information Not Available
Recorder off scale.

volts per cell or less. Information as to charging before each test is not available but the data indicates that charging before the constant power discharge was done at room temperature. The current during constant power discharges is a nominal 2.5 amperes.

3. Voltage and Current Characteristics as a Function of Residual Capacity and Temperature.

For each test, the battery was room temperature charged at 300 ma. for an ampere hour input of 5.2 Ahr. To obtain the residual capacities stated on figures 16, 17 and 18, the battery was drained at one ampere at the test temperature. Following this discharge, the battery was put on stand for fifteen minutes then the various current drains were applied to obtain the battery voltage as a function of residual capacity. At the lower temperatures, this current drain had to be applied for several minutes since the battery voltage tends to dip, especially at the higher current drains. The capacity removed during these current applications was considered when calculating residual capacities.

Herein, the term residual capacity may be misleading. This term means the approximate ampere hour capacity, remaining in the battery if the battery would deliver the 5.2 ampere hours under all conditions of discharge. Obviously, a lesser residual capacity is realized at low temperatures, e.g., 0°C and -9°C.

OBSERVATIONS AND CONCLUSIONS:

A. Constant Power Discharges at 13 Watts and 33 Watts.

1. As shown in figures 12, 13, 14 and 15, the batteries functioned quite good at the constant power discharges at room temperature and above. However, at the lower temperature, the battery voltage dips, initially. This was more pronounced at the 33 watts constant power discharges. This can be troublesome where a low voltage cut off is used, e.g., 0.9 volts per cell.

B. Voltage & Current Characteristics as a Function of Residual Capacity and Temperature

1. As shown in figures 16, 17 and 18, the presence of the upper (AgO plateau) has a pronounced effect on the discharge voltage. No single test could be found

that duplicated this test procedure when the upper plateau is not present. But several tests show that, if the upper plateau is not present, the 28°C voltage/current characteristics are similar to the voltage/current characteristics shown in figure 16, at 28°C, when greater than 50% of the capacity is removed.

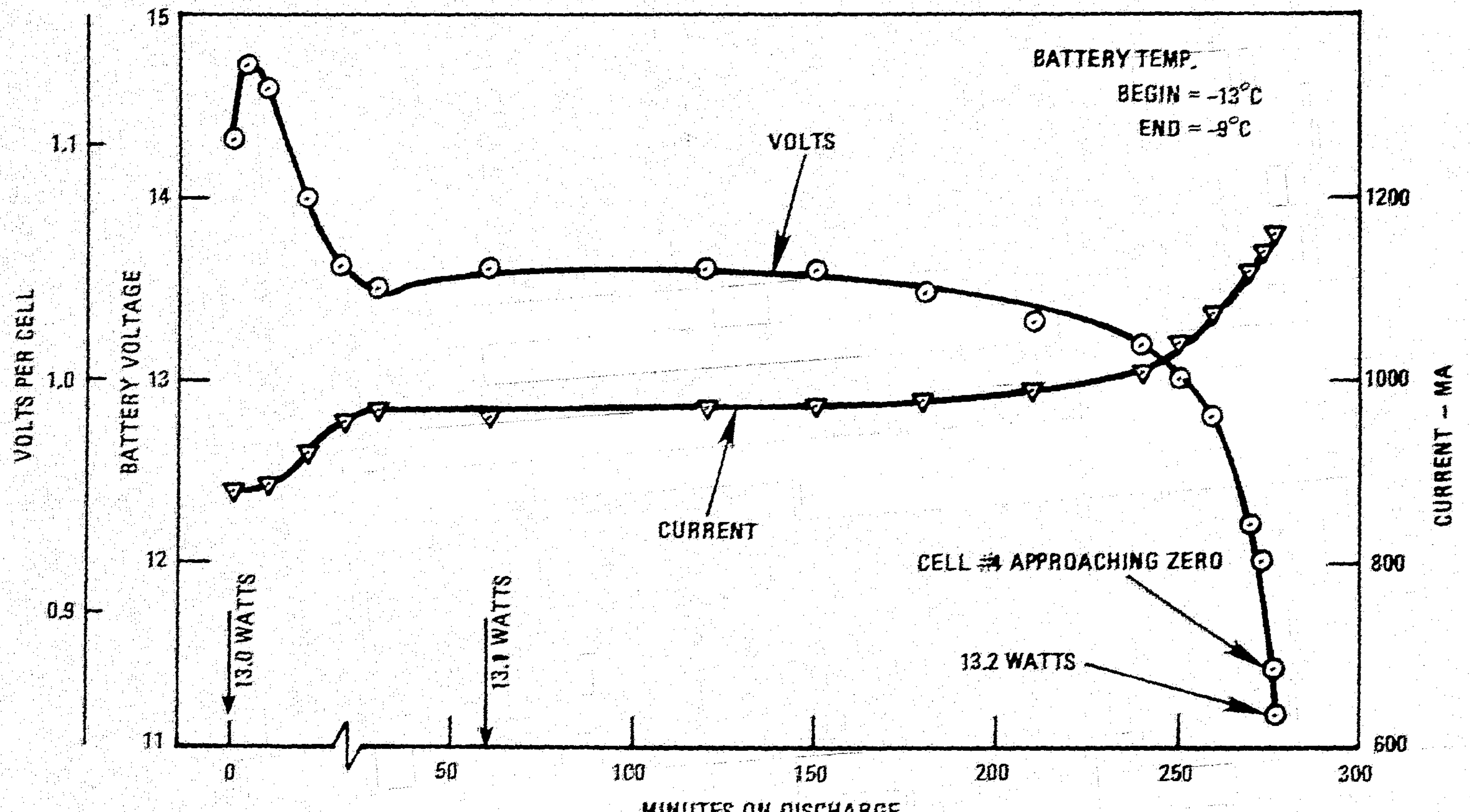


Figure 12. Constant Power (13 Watts) Discharge, Test 007
Battery 13xYS5S-2NM, S/N 003, -10°C

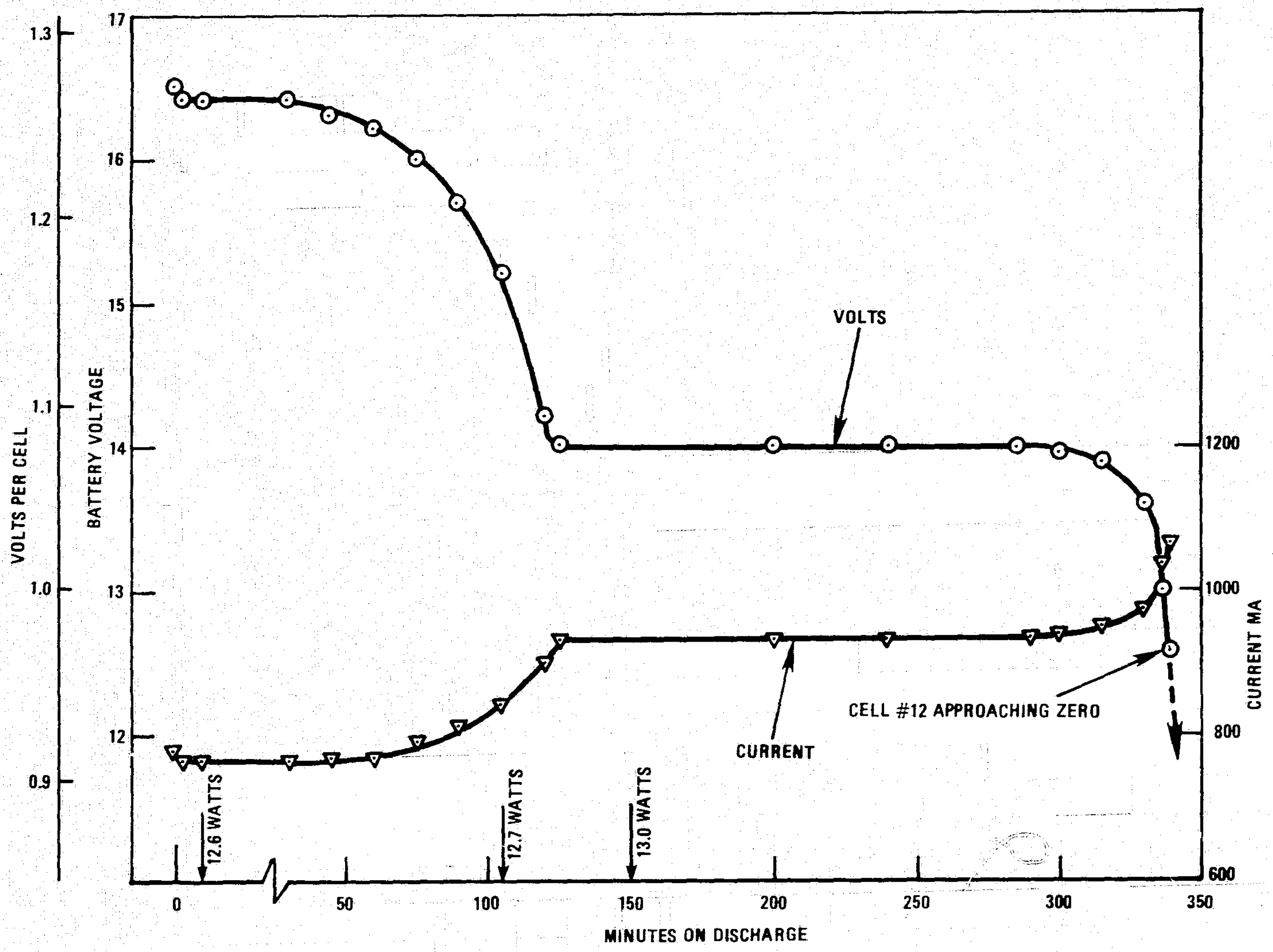


Figure 13. Constant Power (13 Watts) Discharge, Test 007
Battery 13xYS5S-2NM, S/N 003, 27°C

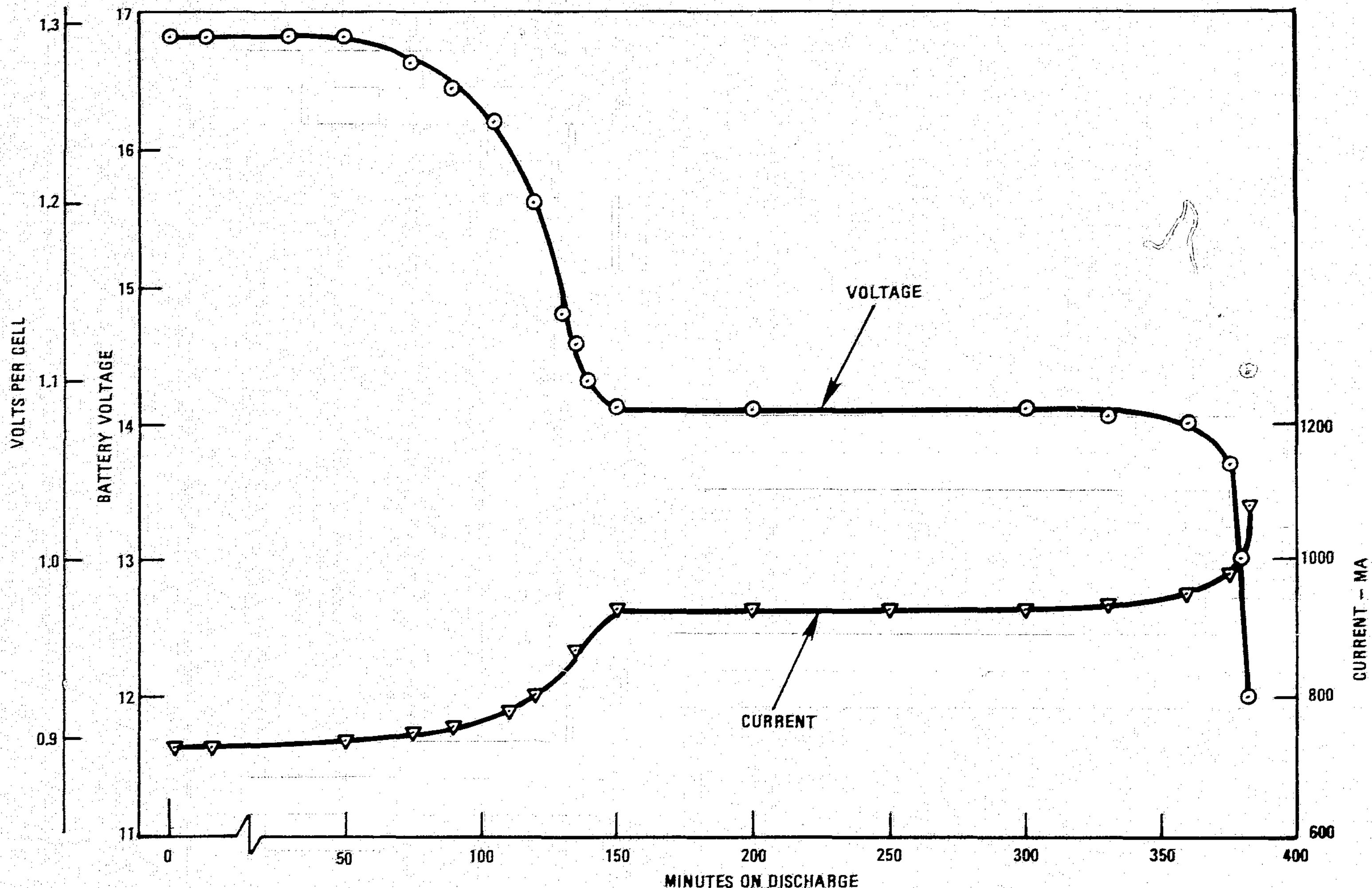


Figure 14. Constant Power (13 Watts) Discharge, Test 007
Battery 13xYS5S-2NM, S/N 003, 48°C

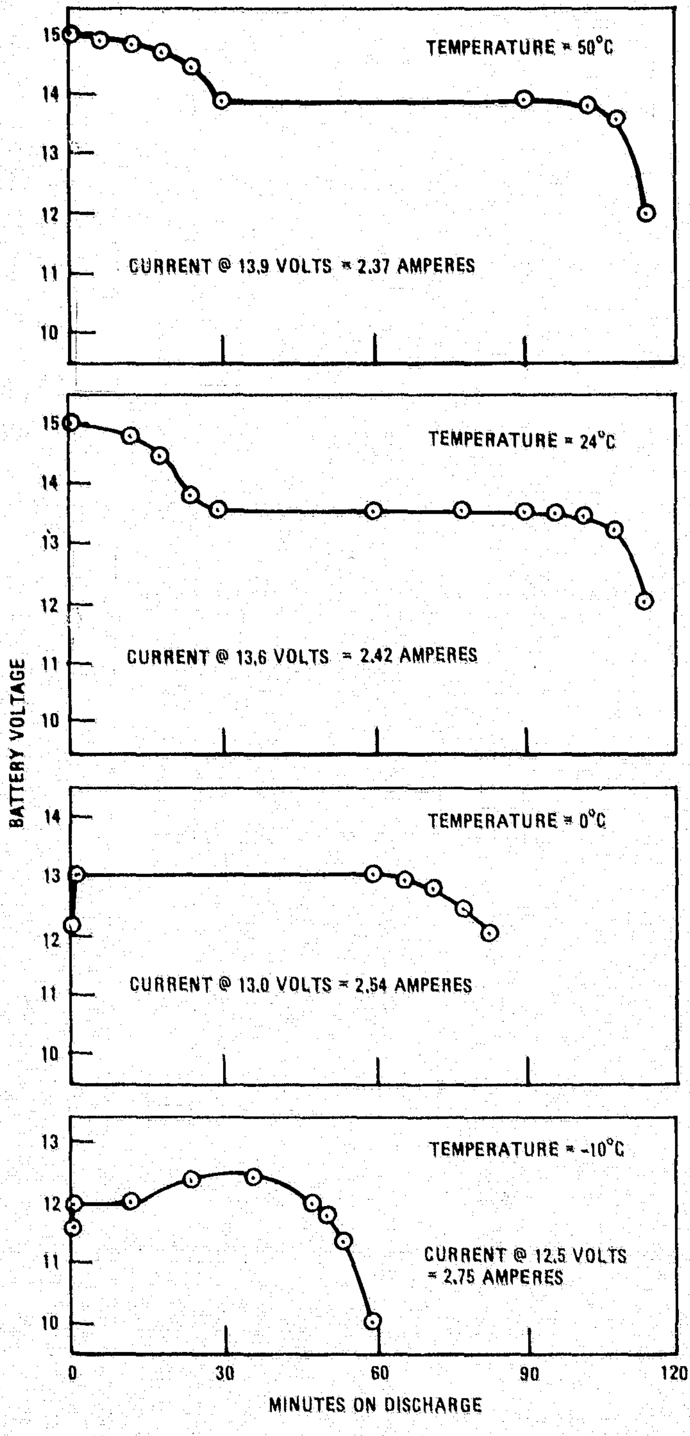


Figure 15. Constant Power (33 Watts) Discharge
Test 007, Battery 13xYS5S-2NM, S/N 006

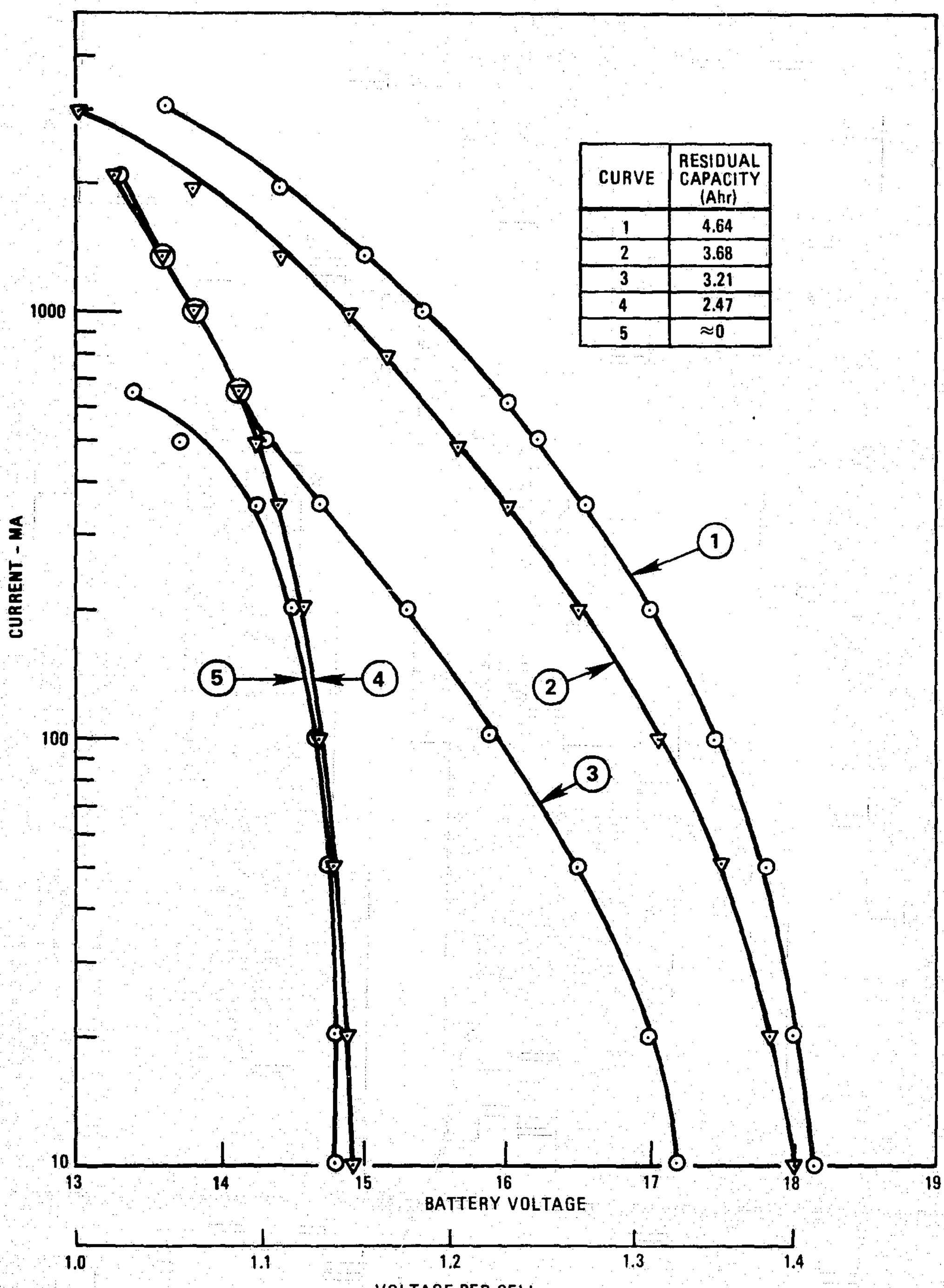


Figure 16. Voltage vs. Current as a Function of Residual Battery Capacity Test 007, Battery 13xYS5S-2NM, S/N 003, Temperature 28°C

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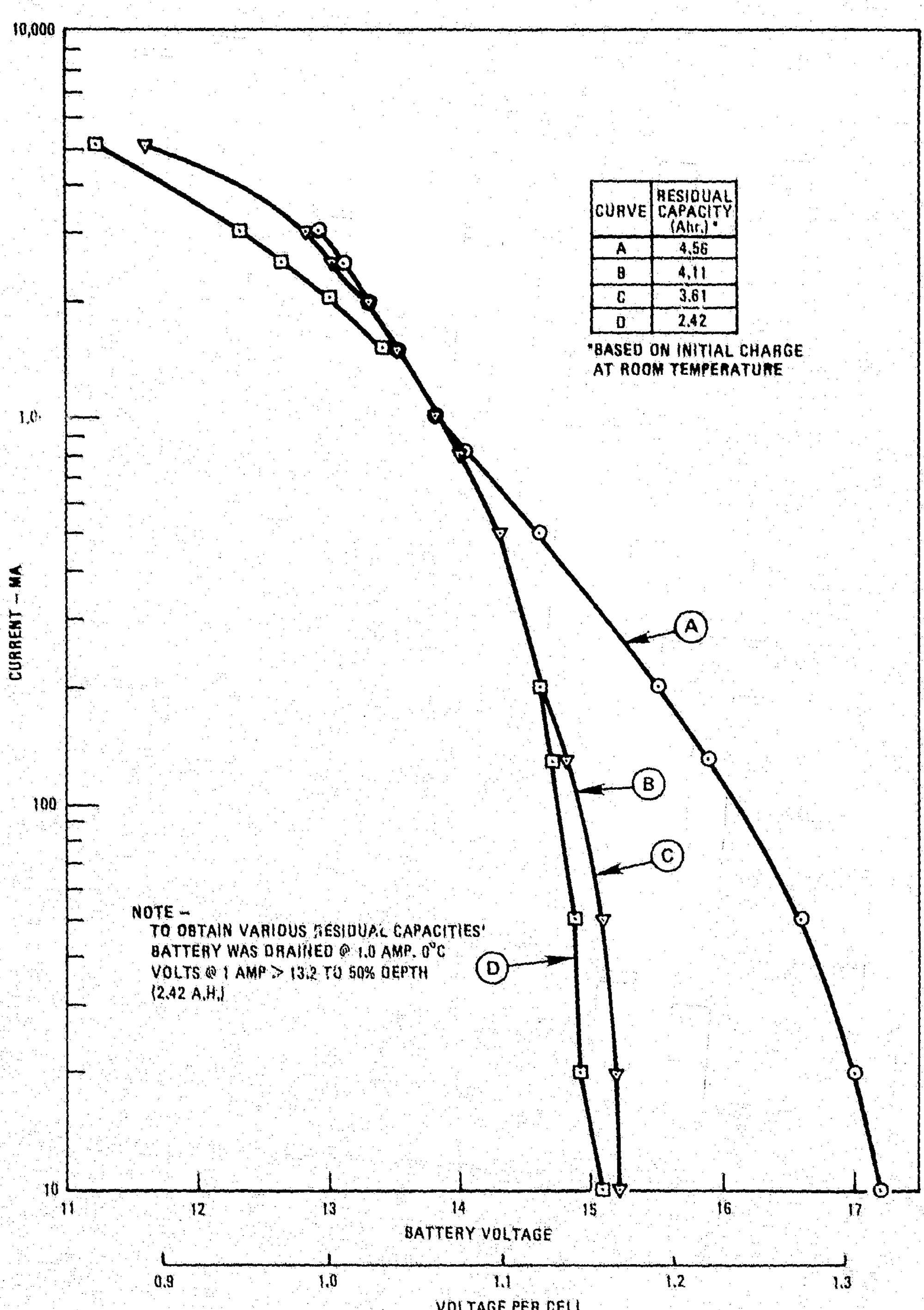


Figure 17. Voltage vs. Current as a Function of Residual Capacity
Test 007, Battery 13xYS5S-2NM, S/N 003, Temperature 0°C

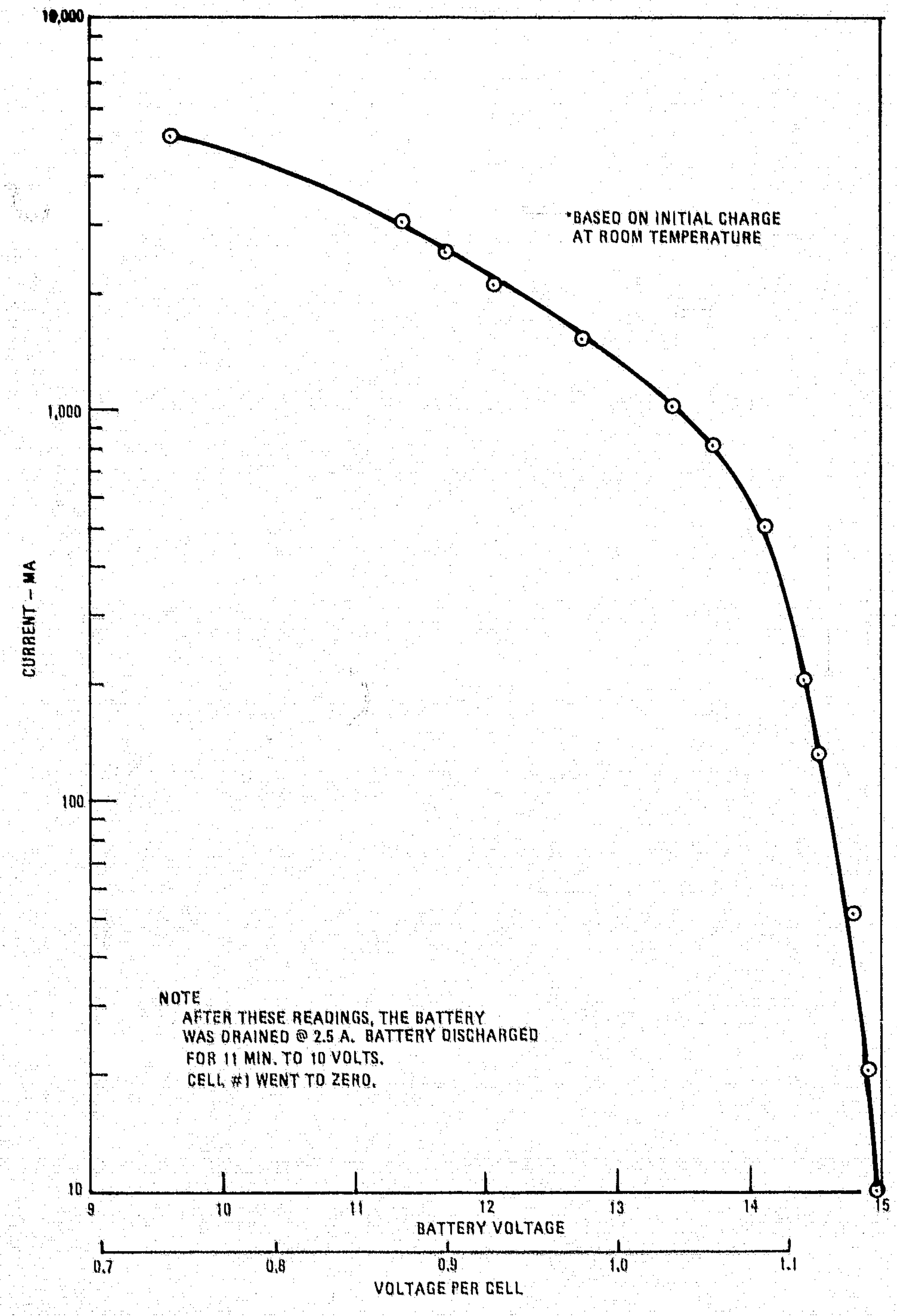


Figure 18. Voltage vs. Capacity as a Function of Residual Capacity
Test 007, Battery 13-YS5S-2NM, S/N 003, Temperature -9°C

TEST 008

Test Unit: Cell YS5S-2NM
S/N 1019

Test Period: 1962

Total Cycling Time: 190 Hours
Number of Cycles: Three

TEST BRIEF

The test unit was a single five ampere hour cell encapsulated in EPON 834. A pressure transducer was mounted on the cell by mounting the transducer on the fill port of the cell and forming a seal between the pipe threads and the epoxy. Initially the cell was constant current charged at 300 ma. to 1.60 volts. Further charging (overcharge) was done at 50 ma. constant current to determine internal pressure rise. Stand periods were used to determine recombination rates. Cell voltage and the voltage output of the transducer were recorded. Wet life of the cell at the beginning of test was two months. During this time the cell was stored in the discharged condition at 25°C. However, the data indicates that the cell had received two or three capacity checks before the above test was initiated.

Cell Design Reference: Appendix A

Main Project: Explorer XIV

Applicable Figure: 19

Nominal Depth at Discharge: 100%

CYCLING

Initially, the cell, was charged at 300 ma. constant current to 1.60 volts. At the end of charge, the internal pressure was approximately five PSIG. After a four hour stand period, the cell was charged at 50 ma. constant current until the voltage reached 2.2 volts. After a stand period of sixteen hours, the cell was again charged at 50 ma. constant current to 2.2 volts. During and after each charge, the pressure was recorded to observe increases and decreases in pressure. The total ampere hours delivered to the cell was 8.4 Ahr. On discharge at 990 ma., the cell delivered 6.9 Ahr. All testing was at 25°C to 27°C.

OBSERVATIONS AND CONCLUSIONS:

During the initial charge of 300 ma. constant current to 1.60 volts, the maximum pressure rise was five PSIG. On continuation of charging at 50 ma. constant current, the pressure rose to 125 PSIG with the cell voltage rising to 2.2 volts. During a stand period of sixteen hours following this charge, some recombination appears to take place. See figure 19. Additional charging at 50 ma. constant current further increased pressure. The pressure decay, during the stand period following this charge, at first is appreciable then decreased to a very low rate of 0.24 PSI/hour. As will be shown later, these types of non-magnetic cells are negative limited on charge. Consequently, it is concluded that most of the internal pressure rise was due to evolution of hydrogen. The low rate decline in pressure may have been due to some hydrogen recombination with silver oxide (ref. 4) or leakage or diffusion of hydrogen from the cell. It was concluded, that these types of sealed cells could not be subjected to any overcharges even at low current rates.

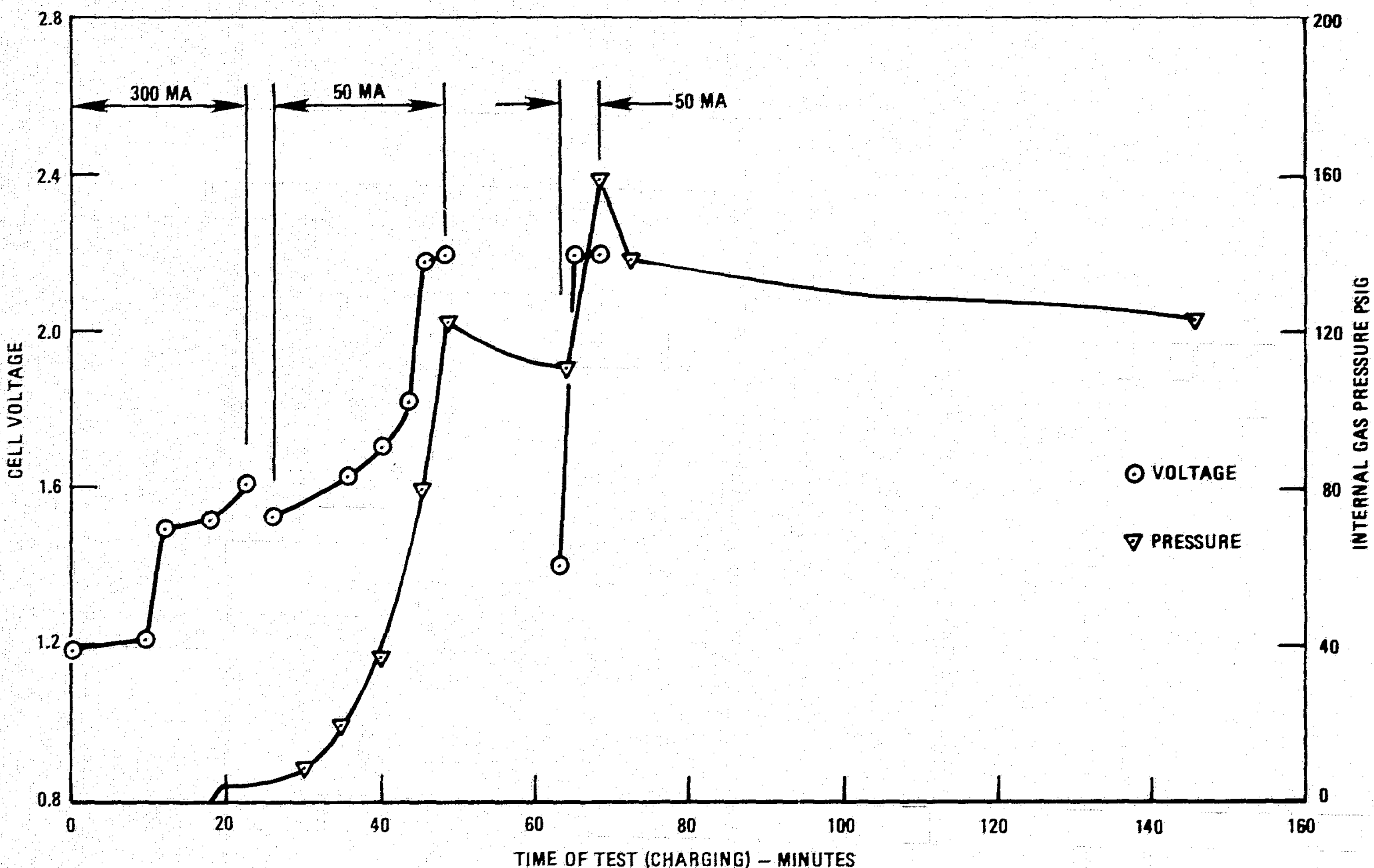


Figure 19. Internal Pressure Rise on Overcharge at 50 ma., Test No. 008
Cell YS5-2NM, S/N 1019

TEST 009

Test Unit: Cells YS10S-2NM
S/N 2018 and 2019

Test Period: 1962

Total Cycling Time: 100 hours
Number of Cycles: 2

The test units were ten ampere hour cells encapsulated in EPON 834. A pressure transducer was mounted on each cell by mounting the transducer or the fill port of the cell and forming a seal between the pipe threads and epoxy. A valve for venting was installed. The cells had been filled and formed at Goddard Space Flight Center but all the data is not available. The cells were filled with forty cc. of 40% potassium hydroxide. After formation, electrolyte was removed from one cell, after the final charge, so that the free electrolyte level was one centimeter for cell 2018 and six centimeters for cell 2019. Therefore, when the cells were sealed, cell 2018 was electrolyte starved and cell 2019 was essentially flooded. Initially the cells were charged at 500 ma. to 1.60 volts per cell. Overcharge currents of 100 and 200 ma. were used to determine magnitude of resultant internal pressures. Cell voltages and the voltage outputs of the transducers were recorded. Evolved gases were vented and analyzed between tests. All charges and discharges were constant current. Wet life of the cells at the beginning of test was one week.

Cell Design Reference: Appendix A

Main Project: Explorers

Applicable Figures: 20, 21

Nominal Depth of Discharge: 100%

CYCLING

Initially the cells were charged at 500 ma. constant current until each cell reached 1.60 volts. When each cell reached this voltage value, the current (overcharge) was lowered to 100 ma. The cells were discharged and the test repeated but the overcharge current was set at 200 ma. After both charges and overcharges, the cells delivered the following capacities.

TEST 009 (Continued)

Cycle(s)[1] Half Cycle(s)	AHI[2]	AHO[2]	Cycling Parameters	Temperature °C
1C and 1D Cell 2018	13.9	10.4	500 ma. constant current to 1.60 volts. Overcharge at 100 ma. Discharge at 1.6 amperes to less than 0.9 volts.	25 to 27
2C and 2D Cell 2018	13.7	11.7	Same as 1C and 1D. Except overcharge at 200 ma.	25 to 27
1C and 1D Cell 2019	14.4	11.2	500 ma. constant current to 1.6 volts. Overcharge at 100 ma. Discharge at 1.7 amperes to less than 0.9 volts.	25 to 27
2C and 2D Cell 2019	INA[3]	12.6	Same as 1C and 1D. Except overcharge at 200 ma.	25 to 27

(1) C = Charge
D = Discharge
(2) AHI - Ampere Hours In
AHO - Ampere Hours Out
(3) Information Not Available

CYCLING

Graphs showing voltages and currents on charge and overcharge and the related pressure characteristics are shown in figures 20 and 21. On cycle 002, the charging information for cell 2019 was incomplete. The internal pressure rise of cells 2018 and 2019 for cycle 002 were essentially the same.

OBSERVATIONS AND CONCLUSIONS:

1. High internal pressures were encountered when the cells were overcharged at 100 ma. or 200 ma. These pressures occurred in both the starved and flooded cells.

2. Analyses of the gas content of the cells after the 100 ma. overcharge showed that the gas was 93% and 95% hydrogen in cells 2018 and 2019, respectively.

3. It was concluded that these type of sealed cells could not be subjected to any overcharge even at low current rates.

4. The flooded cell discharge capacities were approximately one ampere hour greater than the capacities of the cell that was electrolyte starved.

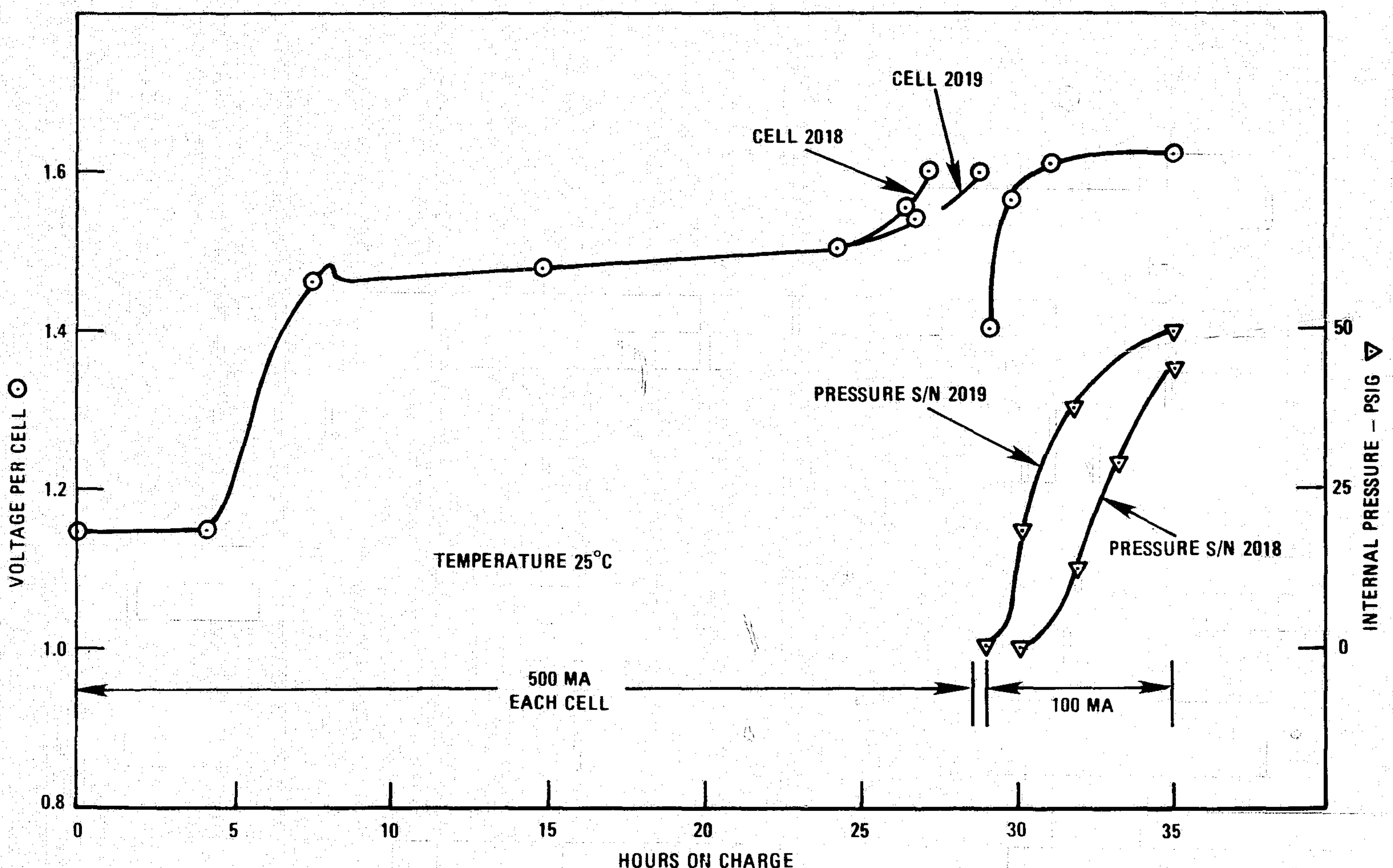
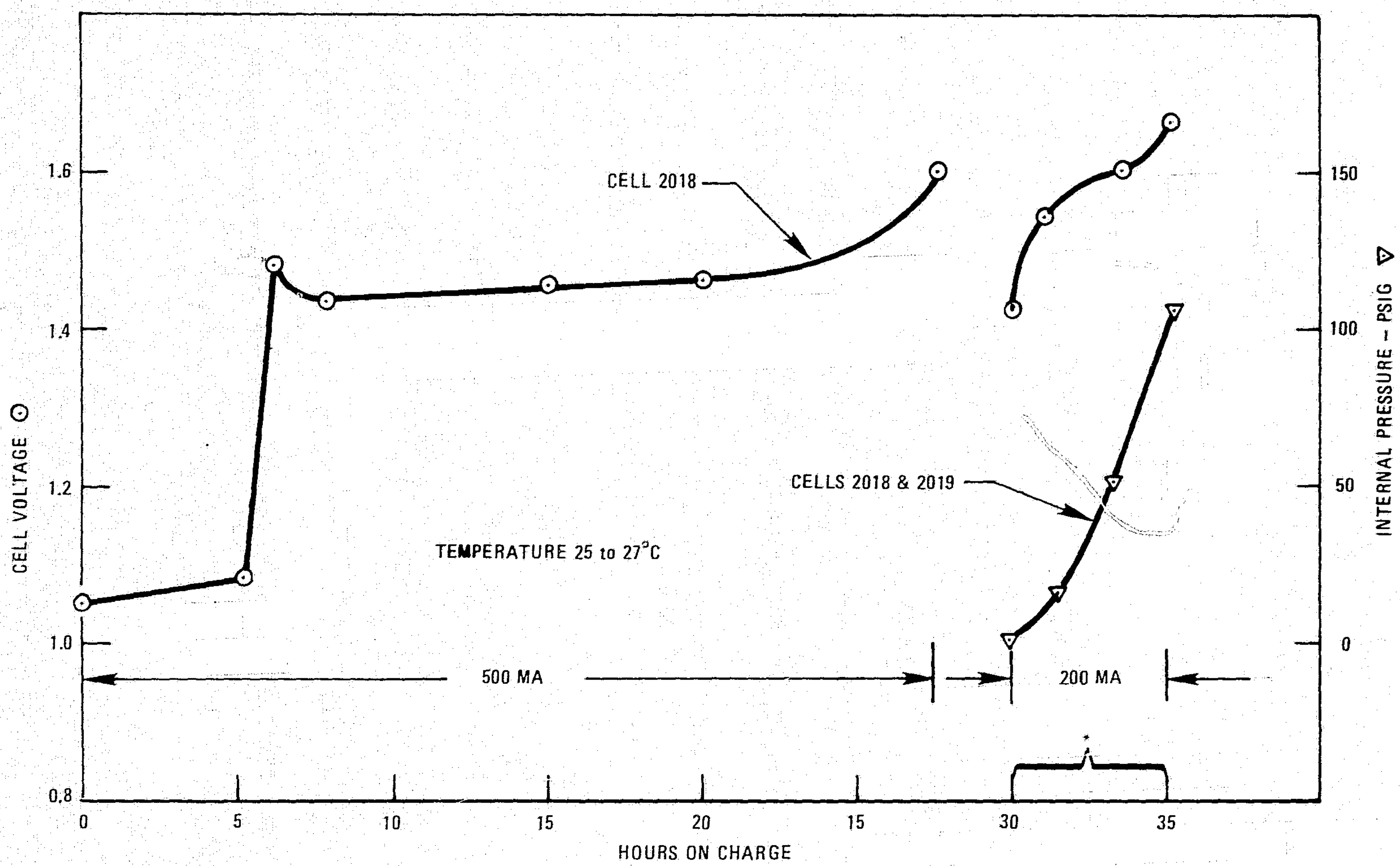


Figure 20. Internal Pressure Rise on Overcharge at 100 ma., Test No. 009
Cell YS10S-2NM



*THIS TIME PERIOD IS APPROXIMATE, i.e., 5 ± 1 HOURS

Figure 21. Internal Pressure Rise on Overcharge at 200 ma., Test No. 009
Cell YS10S-2NM

TEST 010

Test Unit: Battery 13xYS5S-2NM
S/N YAEL 006

Test Period: 1961 to 1964

Total Test Time: 20,000 Hours
Number of Cycles: 225

TEST BRIEF

The battery consisted of thirteen, five ampere hour cells in series encapsulated in EPON 834. The battery was assembled into two units designated as 2A and 2B that contained five and eight cells, respectively. Provisions were made so that cell voltages could be measured individually at a test connector. A photo of the battery is shown in Illustration 1. This is the configuration flown on early Explorer satellites. A simulated orbital test program was performed at Goddard Space Flight Center (GSFC) followed by testing at the Naval Weapons Support Center/Crane (NWSC/Crane) in Indiana. All of the simulated orbital cycling, performed at GSFC, was at room temperature with orbit times of eight to approximately twelve hours. Some simulated orbital cycling was done at NWSC/Crane. Also the effects of long float charging for a period of two years at room temperature were investigated at NWSC/Crane. Where charge or discharge currents were not constant current, the recorder curves were integrated. The cycling parameters, used at GSFC and NWSC/Crane, are outlined under Cycling below. Unless otherwise noted, brief storage periods between tests were at approximately 25°C. The wet life at the beginning of the test was approximately four months. During this time, the battery had been stored discharged at 25°C. After the cycling and float charging tests were completed, a section of the battery was returned to the manufacturer, the Yardney Electric Company, for analysis. Excerpts from a letter, ref. 5, pertaining to the analyses performed is included under Observations and Conclusions of this test (010). Information on simulated orbital testing at NWSC/Crane was taken from ref. 6.

Cell Design Reference: Appendix A

Main Projects: Explorers XII, XIV and XV.

Applicable Figures: 22, 23

Nominal Depth of Discharges: 8%, 12%, 22%, 25%

TEST 010 (Continued)

CYCLING

I Goddard Space Flight Center

Cycle(s)[1] Half Cycle(s)	AHI[2]	AHO[2]	Cycling Parameters	Temperature °C
1C to 1D	4.37	4.10	300 ma. constant current charge, constant potential of 1.53 volts per cell average. Discharge at 480 ma. to less than 0.9 volts per cell.	25
2C to 2D	3.71	3.64		
3C	4.09			
3D to 20D			Constant potential charge at 1.50 volts per cell current limited at 150 ma. for 7.5 hours. Discharge at 850 ma. for 0.5 hours.	25 to 28
21C to 170C			Constant potential charge at 1.50 volts per cell current limited at 450 ma. for 9.5 hours. Discharge at 1.1 amperes for 2.0 hours.	25 to 28
171D		5.80	Discharge at 1.0 amperes to 1.0 volts per cell. This discharge was done after the battery was removed from the cycling equipment for a period of 55 days, i.e., it was stored charged for 55 days at room temperature.	25 to 28

(1) C = Charge
D = Discharge

(2) AHI - Ampere Hours In
AHO - Ampere Hours Out

CYCLING[1]

II NAVAL WEAPONS SUPPORT CENTER/CRANE

A. The battery was subjected to 50 continuous cycles consisting of several time intervals of charge and discharge with various currents. All of the cycles were conducted at room ambient conditions of temperature and pressure.

1. Cycles 1A - 3A were constant current charges of 300 ma. to a cutoff voltage 1.58 volts per cell followed by discharges at 1.0 ampere to a cutoff voltage of 0.9 volts per cell.

2. Cycle 4A was a 24 hour constant potential charge, current limited to 500 milliamperes and voltage limited to 1.51 volts per cell followed by a 30 minute discharge at 1.0 ampere.

3. Cycles 5A - 24A were 7.5 hour constant potential charges, current limited to 300 milliamperes and voltage limited to 1.51 volts per cell followed by 30 minute discharges at 1.0 ampere.

4. Cycle 25A was similar to that of cycle 5A - 24A, except that the discharge at 1.0 ampere was continued to a cutoff voltage of 0.9 volts per cell.

5. Cycle 25A was followed by a 15 minute rest period.

6. Cycle 26A was an 8.0 hour constant potential charge, current limited to 5.0 amperes and voltage limited to 1.51 volts per cell. Discharges at 2.5 amperes for 30 minutes.

7. Cycles 27A - 33A were 24 hour constant potential charges, current limited to 100 milliamperes and voltage limited to 1.51 volts per cell discharges at 2.5 amperes for 30 minutes.

8. Cycle 34A was similar to that of cycles 27A - 33A except that the discharge at 2.5 amperes was continued to a cutoff voltage of 0.9 volts per cell.

9. Cycle 34A was followed by a 15 minute rest period.

(1) Cycle Numbers are designated as 1A, 2A, etc.

CYCLING

II NAVAL WEAPONS SUPPORT CENTER/CRANE (Continued)

10. Cycle 35A was an 8 hour constant potential charge, current limited to 5.0 amperes and voltage limited to 1.51 volts per cell discharge at 1.0 ampere for 30 minutes.

11. Cycles 36A - 46A were similar to cycles 5A - 24A.

12. Cycle 47A was similar to cycle 25A.

13. Cycles 48A - 50A were similar to cycles 1A - 3A.

B. The battery was monitored continuously. All charge and discharge voltages and charge currents, except constant current charges, were recorded. Ampere hour efficiencies were calculated for each cycle and watt hour efficiencies were calculated for cycles 10A, 20A, 30A, 35A, 40A and 46A. These data are tabulated in Tables 4 and 5.

C. After the above program, the battery was cycled as follows:

1. Cycle 51A - Constant potential charged at 1.58 volts per cell current limited at 300 ma. After the battery approached zero current (one to two ma.), the battery was left on float charge for approximately two years. Temperature was room ambient. Battery voltage was recorded continuously and cell voltages and currents were measured daily. During the float charge, capacity checks were made at several time intervals. The discharge during all capacity checks was one ampere, constant current. The battery voltage during float charge was 1.55 volts per cell.

OBSERVATIONS AND CONCLUSIONS:

I - GODDARD SPACE FLIGHT CENTER

1. The reason for the low ampere hours capacities on the initial cycles at GSFC is not known. This may be erroneous.

2. During simulated orbital cycling, the ampere hour efficiency was 93% or better.

3. During a capacity check cycle on cycle 70 (not shown above), the ampere hour capacity of the battery was 6.13 Ahr. During this type of cycling at 25°C, the total ampere hour capacity of the battery improved with cycling.

4. Little data was available on the cell balance on charge. However, the data showed the cell balance during the last few cycles to be within ±0.02 volts of the cell voltage clamp of 1.50 volts.

5. It is interesting to note the effect of the transition of the Ag_2O to AgO phases on the charging curve. This is shown in figure 22 where the back EMF of the battery cells results in a depression of the charge current curve. Additional information on the subject is given in TEST 017 of this Section of the report.

6. During simulated orbital cycling with deeper discharges, the upper plateau on discharge is not depressed to the degree shown in previous tests, e.g. TEST 001. See figure 23 for typical cycles on this test unit, YAEL 007.

7. There were no indication of cell failure during this phase of the test.

II - NAVAL WEAPONS SUPPORT CENTER/CRANE

1. The high rate charging surges of cycle 26A and 35A had no adverse effects on the battery. This is shown by the discharge capacity of cycle 1A, 5.67 Ahr. as compared to cycle 50A, 5.52 Ahr. See Table 4.

2. During each cycling sequence, the ampere hour efficiencies settled down to range from 90.0% to 97.9%. Watt hour efficiencies, during simulated orbital cycling, ranged from 68.8% to 92.4%. Ampere hour efficiencies are shown in Table 4. Watt hour efficiencies are shown in Table 5. It is interesting to observe, that, even though the battery accepted 4.79 Ahr. on the charge of 26A, a capacity build-up during cycling has resulted in a discharge of 5.43 Ahr. on capacity check 34A.

3. There were no indications of cell failure during this phase of the test.

4. During the float charge for two years, the cell voltage unbalance ranged from 1.4 to 2.0 volts per cell. The voltage shifted in cells, i.e., some cells that had high voltages would shift to a lower level and cells with low voltages would shift to a higher level. After two years of float charging, voltages on some cells were less than 1.41 volts. This is an indication of internal soft shorts. Capacity checks during the float charge did seem to have some effect on the cell balance, i.e., the voltage of some high cells became lower and some low cells float charged

at a higher level. Typical cell voltage data during the two year float charge is shown in Table 6.

5. Capacity checks were made during the float charge. The results were as follows:

YEARS ON FLOAT CHARGE	AMPERE HOURS OUT (AHO) TO 1.0 VOLTS PER CELL
0	5.7
1.1	5.5
1.6	6.0
1.8	4.5
2.1	1.3

Just previous to the last capacity check, cells 001 and 008 measured below 1.41 volts. Cell 001 was intermittent, i.e., at times the voltage was above 1.41 volts and at times would be below 1.41 volts. On the discharge at 2.1 years, these two cells went to zero volts while the remaining cells were greater than 1.0 volts. Therefore, the low voltages on float charge (1.41 volts) are indications of soft internal shorts. During all capacity checks, the voltage curves were essentially flat, i.e., the AgO plateau did not exist.

6. After the capacity check of September, 1964, (see Table 6) bulging and leakage of the battery was observed. After the last capacity check, the leakage was quite bad and the Test was discontinued.

7. From the above tests, it is concluded that the battery can be float charged at 1.55 volts per cell at 25°C for approximately two years and maintain good ampere hour capacity. It was determined later in the overall program that 1. 51 volts per cell for float charge was also satisfactory but the cell voltage unbalance would persist. Also as will be shown later, Test 019, a float voltage of 1.41 volts per cell was adequate and would avoid the problem of cell unbalance. Although cell voltage unbalance did not appear to be a problem in this test, the predictability of internal gas pressures due to cell voltage unbalance was difficult to establish.

8. Excerpts from a letter, ref. (5), pertaining to battery and cell analyses follows. The analyses was performed by the Yardney Electric Company.

Letter Title: Dissection Analysis of NASA YS-5S-2NM Battery, S/N 007

"Reference is made to the five cell section of the YS-5S-2NM battery which was on constant potential (trickle) charge for two years, and submitted by you for analysis by the Research Department. It is understood that the battery received several months of cycling prior to being placed on float.

Visual observations of the unit prior to dissection showed that the edges of the cases of the two middle cells (perpendicular to the plates) were cracked. Large carbonate deposits were noted along the bottom of the battery case. The cracked cases probably account for the high voltages observed during end of the float charge. One cell which appeared to be in good condition was given two cycles (charge at 0.5 amps to 1.6 volts and discharge at 2.0 amps to 0.6 volts), to determine its capacity. The respective input and output capacities after two cycles were 4.4 AH and 4.0 AH. A Hg/HgO reference electrode which was inserted in the cell showed that the negative plate was limiting the charge and discharge. The cell was then dissected and one positive and negative electrode was placed either between two fresh cadmium electrodes or two fresh silver electrodes, and given several deep cycles in 44% KOH. The capacities of the positive and negative electrodes respectively were 1.0 AH and 1.14 AH. It should be noted that the capacities of fresh silver and cadmium electrodes are 2.0 and 2.2 ampere-hours, respectively. (These are flooded capacities.)*

A second set of electrodes was washed free of alkali, dried, and weighed. It was found that the positive electrode had decreased 35% in weight and about 3 mils in thickness. The weight and thickness of the negative electrode remained essentially the same as a fresh electrode.

The free electrolyte available in the cell (0.6cc) prior to dissection was analyzed for OH^- and CO_3 content. The analysis showed 21.7% free KOH and 26.7% K_2CO_3 (314 mg/ml). The original KOH concentration was 44% and the KOH was essentially carbonate free. The carbonate content in the cycled cell is quite high, which is undoubtedly due to extensive silver attack on the separators. Silver analysis of the separators showed that this was indeed the case. The results are given below:

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*Author's note.

TEST 010 (Continued)

Layer No. (Starting from Positive Plate)	Mg. Ag/in.^{2}	Mg. Ag/cm.^{2}	Total Ag-(gm.)
Woven Nylon -1	22.7	3.52	0.22
Woven Nylon -2	16.5	2.56	0.16
C-19 -1 (a)	204	31.6	
C-19 -2			
C-19 -3	93.3	14.5	2.00
C-19 -4	24.3	3.77	0.92
C-19 -5	1.5	0.23	0.24
Woven Nylon -3	0.2	0.31	0.02
			0.002

Total Ag 3.56 gm./"U" Fold
1.78 gm.Ag loss plate

(a) C19 1 and 2 could not be separated. C-19 silver treated cellophane.

Initial Ag wt = 5.5 gm.) minus wt of grid and CdO
Final Ag wt = 3.7 gm.)

Note that the loss of silver from the electrode to the separators (32. 5%) agrees very closely with the results obtained by weighing the electrode. As can be seen, the silver attack is fairly severe, but considering that the life of the battery was about 40 months heavy silver penetration is not unusual.

Photographs (included with this letter) of the positive and negative plates, and of the separator system, show the condition of the components at the time of dissection. (Photographs, color, not included in this report.)*

The close-up photograph of the positive clearly shows organic deposits on the surface at the lower right portion of the plate. In the photograph of the end negative electrodes, fairly large white crystals of KOH and K_2CO_3 can be seen protruding from the C-19. This indicates that there was some evaporation of water from the cell, even though it appeared to be sealed. These crystals were analyzed chemically and found to contain 89% KOH and about 10% K_2CO_3."

*Author's note.

Table 4
TEST 010
Battery 13xYS5S-2NM
S/N YAEL 007
Ampere Hour Efficiencies

Cycle	A.H. Charge	A.H. Discharge	A.H. Efficiency	Cycle	A.H. Charge	A.H. Discharge	A.H. Efficiency
1A	5.85	5.67	96.92	26A	4.79	1.25	26.10
2A	5.75	5.73	99.65	27A	2.01	1.25	62.19
3A	5.70	5.67	99.47	28A	1.79	1.25	69.83
4A	4.95	0.500	N/A	29A	1.34	1.25	93.28
5A	0.643	0.500	77.76	30A	1.34	1.25	93.28
6A	0.589	0.500	84.89	31A	1.30	1.25	96.15
7A	0.600	0.500	83.33	32A	1.45	1.25	86.21
8A	0.559	0.500	89.45	33A	1.30	1.25	96.15
9A	0.569	0.500	91.07	34A	1.30	5.43	N/A
10A	0.555	0.500	90.09	35A	5.61	0.500	8.91
11A	0.544	0.500	91.91	36A	0.600	0.500	83.33
12A	0.547	0.500	91.41	37A	0.558	0.500	89.61
13A	0.554	0.500	90.25	38A	0.524	0.500	95.42
14A	0.553	0.500	90.42	39A	0.517	0.500	96.71
15A	0.547	0.500	91.41	40A	0.519	0.500	96.34
16A	0.551	0.500	90.74	41A	0.549	0.500	91.07
17A	0.538	0.500	92.94	42A	0.514	0.500	97.28
18A	0.543	0.500	92.08	43A	0.511	0.500	97.85
19A	0.541	0.500	92.42	44A	0.500	0.500	100.00
20A	0.529	0.500	94.51	45A	0.507	0.500	98.62
21A	0.530	0.500	94.34	46A	0.479	0.500	104.38
22A	0.537	0.500	93.11	47A	0.582	5.50	N/A
23A	0.538	0.500	92.94	48A	5.43	5.43	100.00
24A	0.531	0.500	94.16	49A	5.48	5.62	102.55
25A	0.533	0.47	N/A	50A	5.47	5.52	100.09

Table 5
TEST 010
Battery 13xYS5S-2NM
S/N YAEL 007
Watt Hour Efficiencies

Cycle	Watt Hour Input	Watt Hour Output	Watt Hour Efficiency
10A	10.82	8.38	77.44
20A	10.34	8.22	79.50
30A	26.01	17.90	68.81
40A	10.16	8.21	80.81
46A	9.38	8.67	92.43

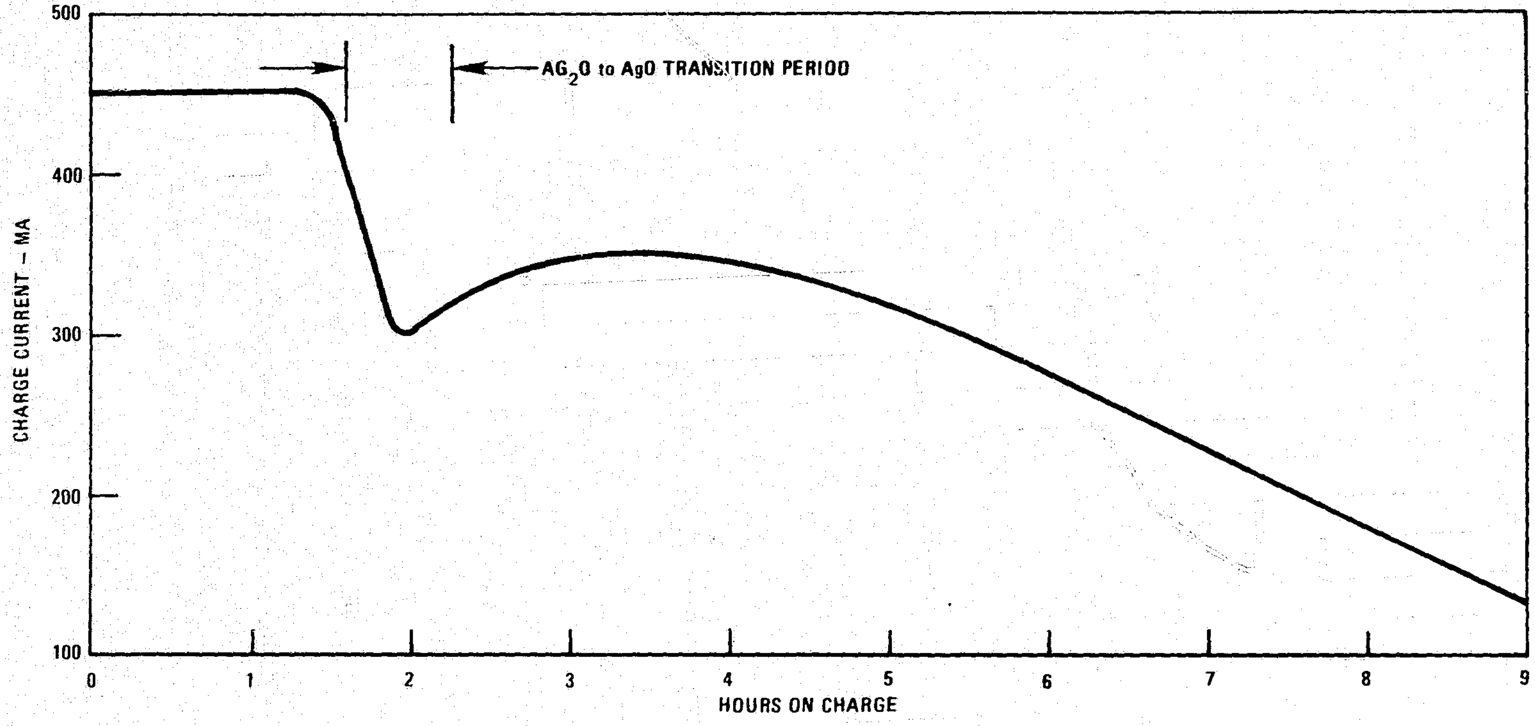

Figure 22. Current on Charge, Test No. 010
Battery 13xYS5S-2NM, S/N YAEL 007

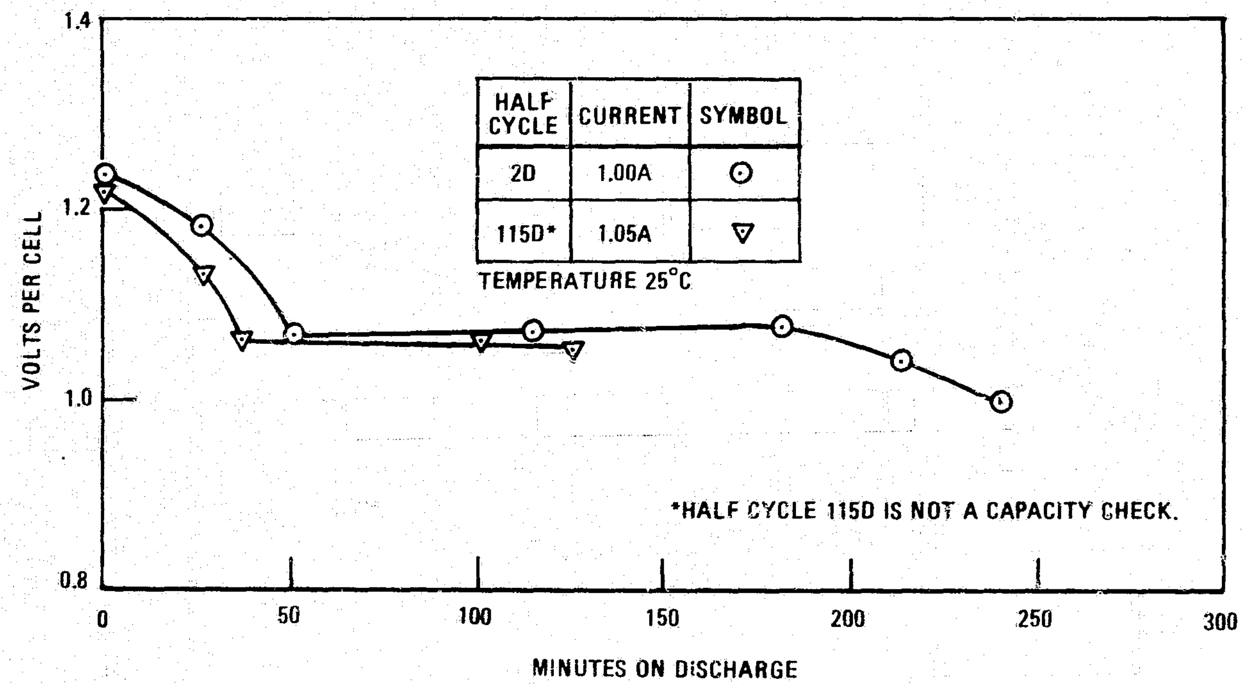

Figure 23. Voltage on Discharge, Test No. 010
Battery 13xYS5S-2NM, S/N YAEL 007

Table 6
TEST 010
Battery 13xYS5S-2NM
S/N YAEL 007

Cell Voltages[1] & Capacity Checks During Float Charge

Month/Year	11/62	12/62	1/63	6/63	12/63	12/63	1/64	5/64	6/64	6/64	8/64	9/64	9/64	11/64	12/64
Cell No.						Capacity Check AHO = 5.5 Ahr.			Capacity Check AHO = 6.0 Ahr.			Capacity Check AHO = 4.5 Ahr.			Capacity Check AHO = 1.3 Ahr.
001 (2)	1.53	1.66	1.65	1.68	1.75		1.71	1.86		1.41	1.48		1.48	1.46	
002	1.54	1.66	1.66	1.41	1.42		1.78	1.40		1.47	1.43		1.49	1.68	
003	1.55	1.71	1.66	1.50	1.65		1.46	1.44		1.46	1.41		1.60	1.64	
004	1.56	1.67	1.66	1.41	1.40		1.42	1.44		1.52	1.44		1.51	1.48	
005	1.54	1.42	1.42	1.70	1.40		1.58	1.44		1.43	1.43		1.48	1.43	
006	1.54	1.66	1.66	1.66	1.74		1.70	1.87		1.92	1.97		1.62	1.84	
007	1.55	1.41	1.41	1.42	1.42		1.43	1.46		1.42	1.82		1.42	1.48	
008	1.55	1.66	1.67	1.69	1.77		1.70	1.60		1.98	2.02		1.38	0.82	
(3)															
011	1.56	1.42	1.42	1.62	1.42		1.41	1.41		1.45	1.42		1.40	1.44	
012	1.57	1.41	1.41	1.42	1.74		1.72	1.43		1.52	1.41		1.50	1.48	
013	1.53	1.41	1.42	1.64	1.52		1.40	1.42		1.46	1.40		1.92	2.24	
Current	←—— 1 to 2 ma. ——→					1.0A	1 to 2 ma.		1.0A	1 to 2 ma.		1.0A	1 to 2 ma.		1.0A

(1) Total Battery Voltage = 20.2 Volts (1.55 Volts per cell)
(2) After the capacity check on 9/64, Cell 001 charged at less than 1.41 volts intermittently
(3) Cells 009 and 010 Not Recorded

TEST 011

Test Unit: Battery 5xYS10S-2NM
S/N 002

Test Period: 1962

Total Cycling Time: 2400 Hours
Number of Cycles: 97

TEST BRIEF

The battery consisted of five, ten ampere hour cells encapsulated in EPON 834 in an aluminum can. Provisions were made to measure individual cell voltages. Initially, four capacity checks were made, the fourth being a 25°C charge followed by an overnight stand at -10°C and then discharged at the cold temperature. All simulated orbital cycling was performed at 25°C in twenty-four hour periods. A voltage clamp and current limiting was used during charging. In most cases, all discharges were 2.5 amperes constant current for 0.5 hours. Battery voltages and currents were recorded. Cell voltages were measured several times daily, especially at end of charge.

On cycle seven (7C), the battery was charged for 120 hours to determine the degree of cell unbalance. During this time, cell number three of the battery was at greater than 1.70 volts while the remaining cells were less than 1.45 volts. At the end of this charge (7C), a pressure gage was installed on cell three to determine the pressure rise due to cell unbalance during simulated orbital cycling. Wet life of the cells previous to the test was approximately three months. The cells had been stored discharged at room temperature. A photograph of the battery, with the gage installed, is shown in Illustration 2. The dimensions of the test battery were length 11.4 cm. × width 7.4 cm. × height 13.5 cm. The height dimension does not include the electrical connection or gage. The battery weight before installation of the gage was 2.21 kg.

Cell Design Reference: Appendix A

Main Project: Anchored IMP (Lunar)

Applicable Figure: 24

Nominal Depth of Discharge: 13%, 100%

TEST 011 (Continued)

CYCLING

Cycle(s)[1] Half Cycle(s)	AHI[2]	AHO[2]	Cycling Parameters	Temperature °C
1C and 1D 2C and 2D 3C and 3D 4C	12.0 10.5 10.6 10.8	10.4 10.4 10.8	350 ma. constant current charge to 1.50 volts per cell average. Discharge at 2.3 amperes to less than 0.95 volts per cell.	25
4D		9.6	Discharge at 2.45 amperes to 0.6 volts per cell average.	-10
5C and 5D	9.8	10.8	Same as 1C and 1D.	25
6C and 6D	10.8	10.6	Same as 1C and 1D.	25
7C	11.2		Constant potential charge of 1.50 volts per cell current limited at 600 ma. Charge for 120 hours. [3]	25
7D to 28C			Constant potential charge of 1.50 volts per cell current limited at 140 ma. for 23.5 hours. Discharge at 2.6 amperes for 0.5 hours.	25

(1) C = Charge
D = Discharge

(2) AHI - Ampere Hours In
AHO - Ampere Hours Out

(3) After charge 7C, a pressure gage was installed on cell 03.

TEST 011 (Continued)

Cycle(s) Half Cycle(s)	AHI	AHO	Cycling Parameters	Temperature °C
28D		10.4	In-cycle capacity check. Discharge at 1.5 amperes to 0.9 volt per cell.	25
29C	10.6		500 ma. constant current charge to 1.55 volts per cell average.	25
29D - 97C			Constant potential charge of 1.50 volts per cell current limited at 185 ma. for 23.5 hours. Discharge at 2.5 amperes for 0.5 hours.	25
97D		10.8	In-cycle capacity check. Discharge at 2.4 amperes to 0.8 volts per cell.	25

OBSERVATIONS AND CONCLUSIONS:

1. At -10°C, on cycle four (4D), the battery delivered almost full capacity. However, the discharge voltage was between 0.95 and 1.0 volts during most of the discharge and dipped to 0.85 volts at the beginning of discharge. It appears that the capacity that was not delivered at -10°C on 4D was delivered on cycle five (5D).

2. The ampere hour efficiency during simulated orbital cycling was equal to or greater than 94%.

3. As can be seen in figure 24, some pressure was developed in cell number 3 during simulated orbital cycling. The voltage at end of charge on this cell, during cycling, was between 1.6 and 1.9 volts. All the remaining cells were between 1.43 and 1.48 volts. During cycling, the battery current during the last half of the charge time ($\approx$ 10 hrs) was less than two milliamperes.

4. During cycling, there were no indications of cell failure.

5. During most of the simulated orbital cycling and especially on the last discharge, the discharge voltage of the battery was flat at 1.07 volts per cell, i.e., no upper plateau (AgO plateau) was present.

Illustration 2. Battery 5xYS10S-2NM
S/N 002

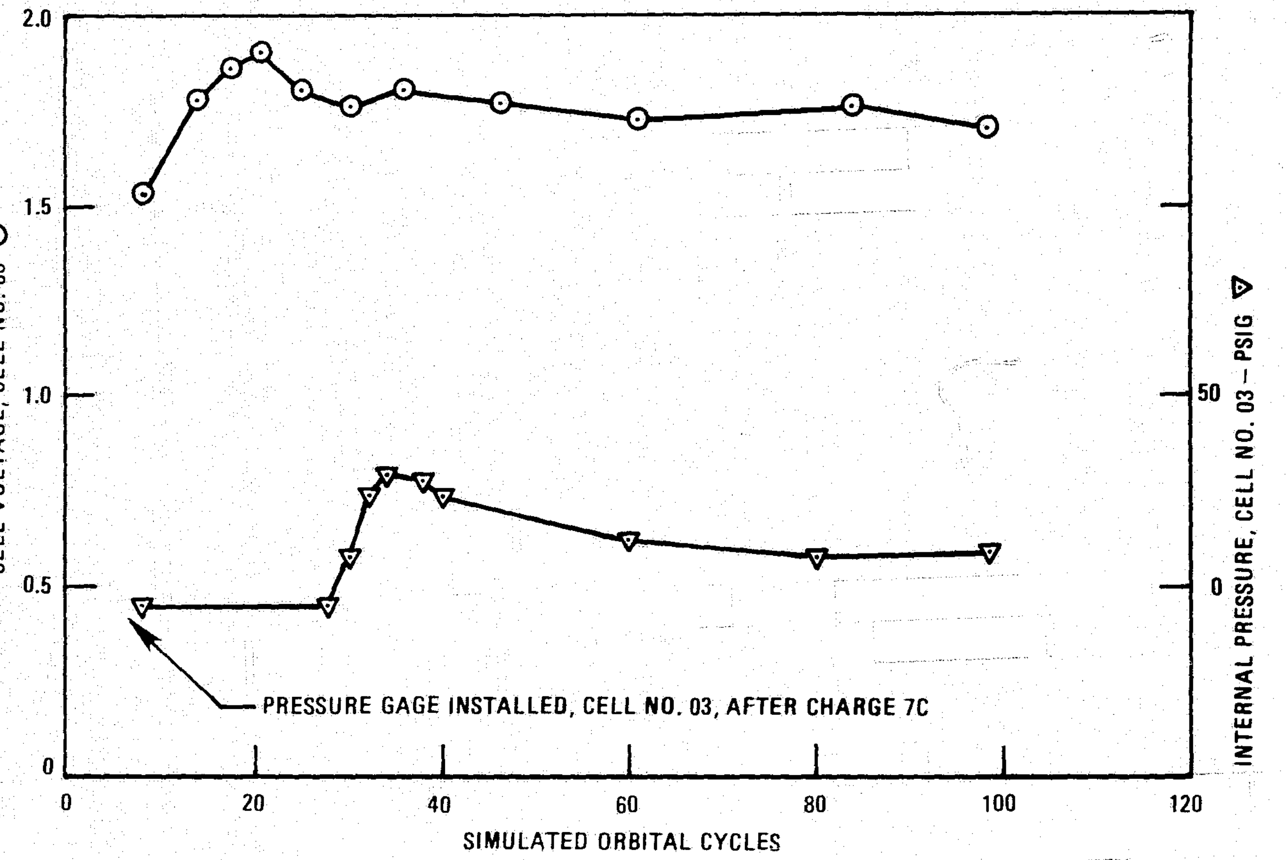

Figure 24. Cell Voltage and Pressure During Simulated Orbital Cycling
Test No. 011, Battery 5xYS10S-2NM S/N 002

TEST 012

Test Unit: Three Single Cells, YS5S-2NM, With Pressure Gages
S/Ns A,B,C.

Test Period: 1961 - 1962

Total Cycling Time: N/A
Number of Cycles: N/A

Three, five ampere hour cells were individually encapsulated in EPON 834 and pressure gages were mounted on each cell. The pressure gages were mounted on the fill port of the cells so that an epoxy to metal seal was obtained between the EPON 834 and the pipe threads on the gage. During the cycling of silver cadmium batteries with constant potential charging, followed by float charging of several weeks, it was noted that cells in series tended to unbalance. For example, eleven cells float charged at 1.55 per cell would have a voltage spread of 1.42 to 1.70 volts after one month of float charge at 25°C. The charge current during long float charges would be of the order of two milliamperes. A test was run to determine the magnitude of internal pressure build-up during float charging. Since these types of silver cadmium cells were negative limited on charge, if a gas was evolved, it would be hydrogen.

Cell Design Reference: Appendix A

Main Project: Early Explorers

Applicable Figure: 25

Nominal Depth at Discharge: 100%

CYCLING

The cells were given three capacity cycles as follows:

Cycle(s)(1) Half Cycle(s)	AHI(2)	AHO(2)	Cycling Parameters	Temperature °C
1C and 1D	5.3 (avg.)	5.2	300 ma. constant current charge until first cell reaches 1.55 volts. Discharge at 950 ma. constant current to 0.9 volt/cell.	25
2C and 2D	5.5 (avg.)	5.3	Same as 1C and 1D	25
3C	5.6 (avg.)		Same as 1C	25

(1) C = Charge
D = Discharge
(2) AHI - Ampere Hours In
AHO - Ampere Hours Out

FLOAT CHARGING

After charge 3C, each cell was float charged at 25°C as follows:

Cell Designation	Float Conditions
A	Constant potential of 1.50 volts.
B	Constant potential of 1.55 volts.
C	Current limited at one to two ma. No voltage control. Maximum voltage of power supply was five volts.

The pressure characteristics during the three conditions of float charging are shown in figure 25. During float charging at 1.50 and 1.55 volts, the current was between one and two milliamperes. The cell voltage of Test Unit C rose to 1.70 volts at 150 days of charge. During most of the charge, the voltage of Cell C was greater than 1.55 volts.

OBSERVATIONS AND CONCLUSIONS:

1. At float voltages of 1.50 and 1.55 volts, the internal pressure developed within the cell is far below the burst pressure of the cell case plus the epoxy encapsulation. The cell without a voltage limit rose to 1.70 volts at the end of 150 days. The reason for the sudden drop in pressure at 35 days was not determined. It is postulated that (1) the cell leaked, (2) hydrogen diffused through the case and seals or the hydrogen reacted with silver oxides at low rates (ref. 4). This pressure rise was of concern since, during orbit, the battery would be required to float for long periods of time. Since the cell unbalance would occur, several solutions to this problem evolved. These solutions will be discussed in other sections of the report.

2. The cell S/N C was discharged at one ampere after the 150 day float charge. The discharge curve was essentially flat, i.e., there was no upper plateau (AgO plateau).

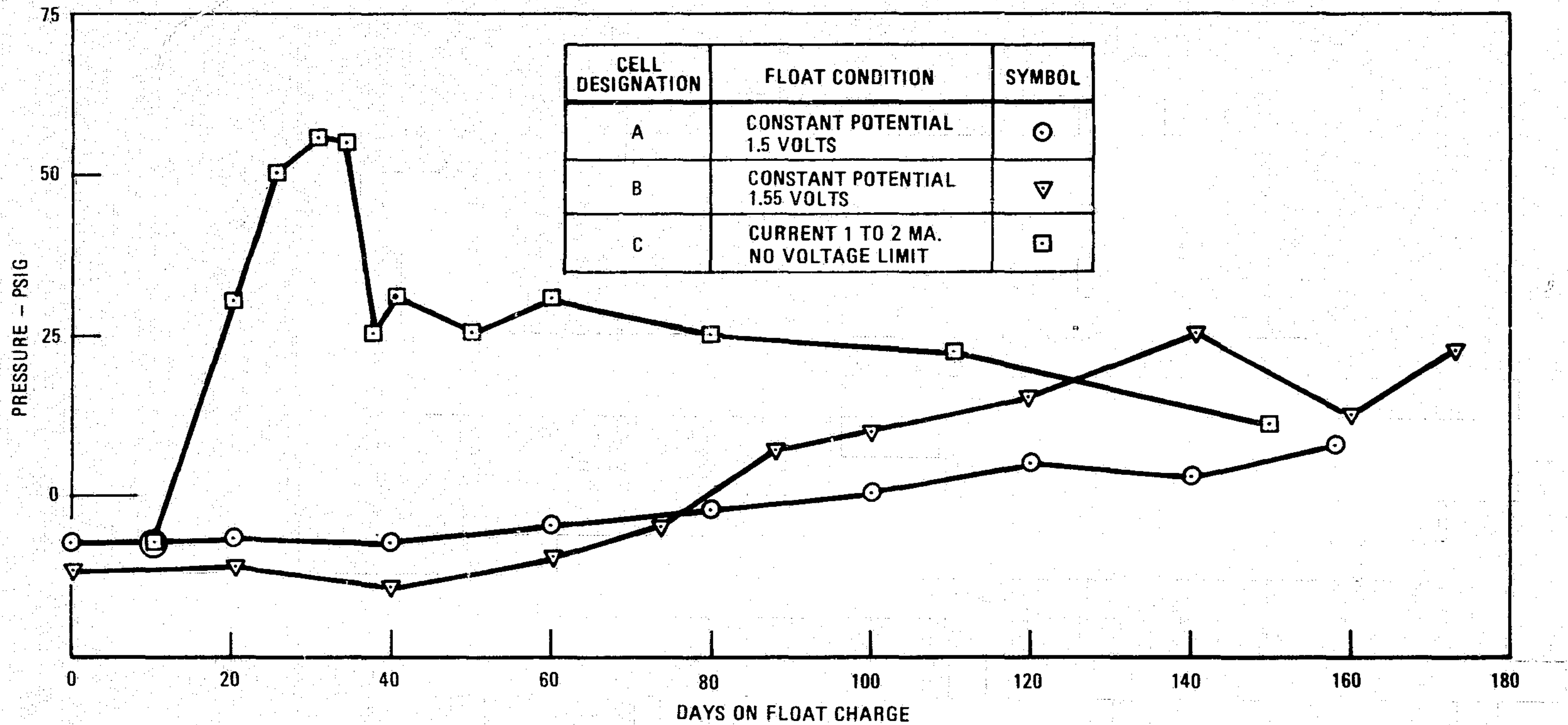

Figure 25. Pressure vs. Float Charging at 25°C
Test No. 012, Cells YS5S-2NM

TEST 013

Test Unit: Cell YS5S-2NM
S/N 6031

Test Period: 1964

Total Cycling Time: 200 hours.
Number of cycles: 3

TEST BRIEF

The test unit was a five ampere hour cell encapsulated in EPON 834. A pressure transducer was mounted to the cell by mounting the transducer on the cell fill port and forming a seal between the pipe threads and epoxy. The cell has given two capacity checks at 300 ma. constant current charge followed by one ampere discharges. On the third cycle, the cell was constant potential charged with a 1.51 voltage clamp current limited at 300 ma. When the current was less than ten ma., the charge was changed to three ma. constant current to determine the resultant pressure rise at this rate. Voltages, currents and pressures were recorded. The test temperature was 25°C. Previous to the test, the wet life of the cell was six weeks.

Cell Design Reference: Appendix A

Main Project: Explorers

Applicable Figure: 26

Nominal Depth at Discharge: 100%

CYCLING

The information on the first two cycles was not complete. On the first cycle the ampere hour capacity at a one ampere discharge was 5.7 Ahr.

The performance of the cell on the charge of the third cycle is shown in figure 26. There was no discharge data available following this charge.

TEST 013 (Continued)

OBSERVATIONS AND CONCLUSIONS:

1. During charge shown in figure 26, the ampere hour capacity delivered to the cell was approximately 6.4 Ahr.

2. The voltage peak, that occurs when the charge proceeds from the lower level (Ag_2O plateau) to the higher level (AgO plateau) is shown in the figure. Note that some depression in the current occurs at this point.

3. Even at this low overcharge rate of three milliamperes, the internal pressure of the five ampere hour cell rose to over 100 PSIG. The cell was placed on stand for one week in the charged condition and only a small decrease in pressure was observed.

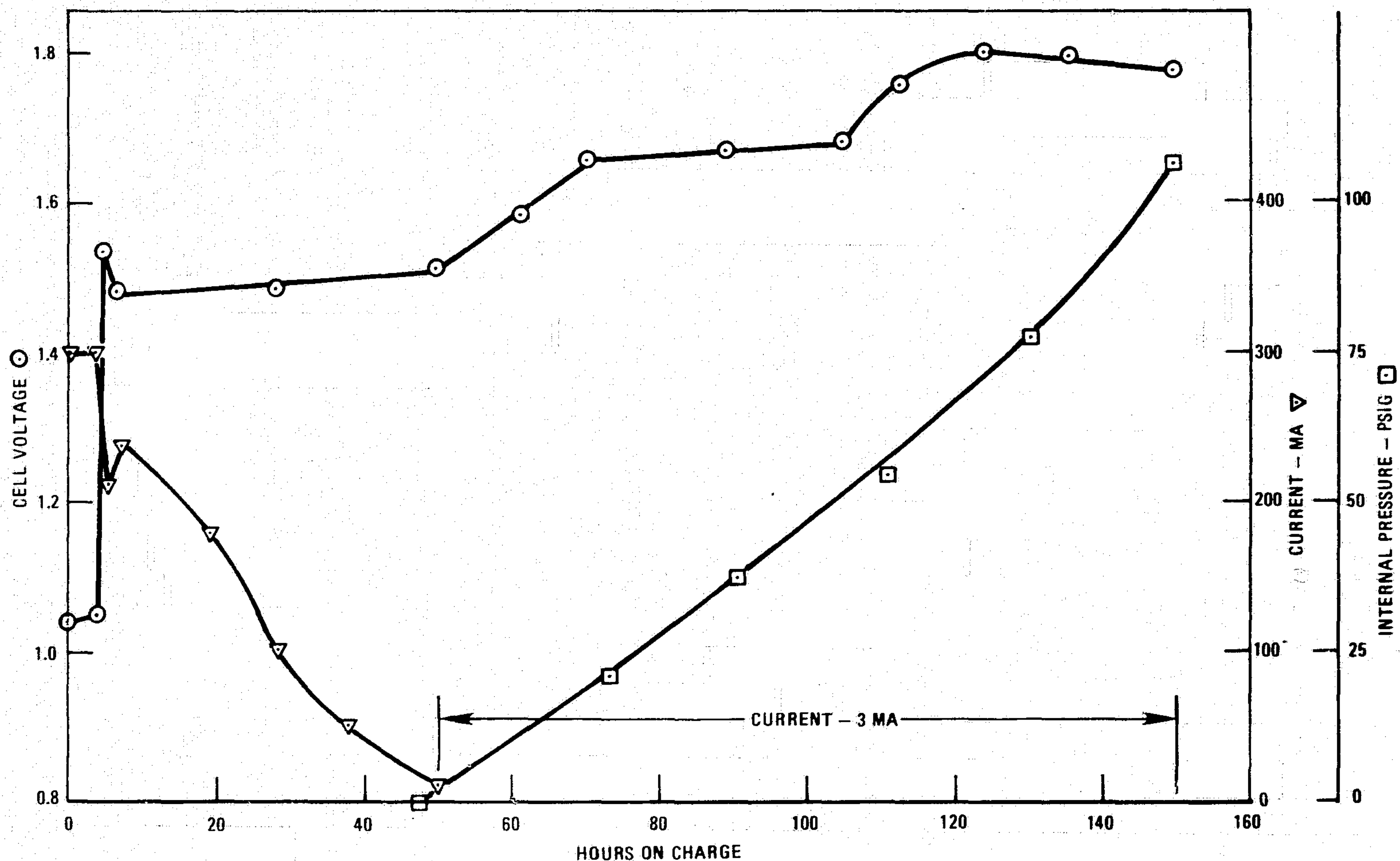

Figure 26. Internal Pressure Rise on Constant Current of 3 ma.
Test 013, Cell YS5S-2NM

TEST 014

Test Unit: Cell YS5S-2NM
S/N 1019

Test Period: 1962

Total Cycling Time: 2100 Hours
Number of cycles: 2

TEST BRIEF

The test unit was a five ampere hour cell encapsulated in EPON 834. A pressure gage was mounted on the cell and sealed to the cell fill port with epoxy. Initially the cell was given a capacity check, recharged to 1.53 volts and then overcharged for 85 days at 1.50 volts. During this latter charge, the charge current varied between 9.0 and 1.5 ma. During most of the overcharge, the current was 3.5 ma. At the end of overcharge, the cell was discharged at 935 ma. constant current. All tests were made at 25°C. Wet life of the cell prior to the test was approximately nine months.

Cell Design Reference: Appendix A

Main Project: Explorer XIV

Applicable Figures: 27, 28

Nominal Depth of Discharge: 100%

C-2

TEST 014 (Continued)

CYCLING

Cycle(s)[1] Half Cycle(s)	AHI[2]	AHO[2]	Cycling Parameters	Temperature °C
1C and 1D	5.6	5.5	INA[3]	25
2C	5.5		300 ma. constant current to 1.53 volts. Cell was continued on charge at 1.50 volts with current varied between 1.5 and 9.0 ma. Overcharged for 85 days.	25
2D		7.4	Discharged at constant current of 935 ma.	25

(1) C = Charge
D = Discharge
(2) AHI - Ampere Hours In
AHO - Ampere Hours Out
(3) INA - Information Not Available

OBSERVATIONS AND CONCLUSIONS:

1. At a float voltage of 1.50 volts and a current of 3.5 ma. the internal pressure of the cell exceeded 100 PSIG. See figure 27. However, some recombination does seem to occur. The reason for this recombination was not determined. As forementioned it could be leakage or diffusion of hydrogen or a low rate recombination of hydrogen with silver oxides (ref. 4).

2. Even at these low rates of charge/overcharge, useful capacity is stored in the cell. This is shown by the 7.4 Ahr. delivered after an initial charge of 5.5 Ahr. on charge 2C plus the capacity imparted to the cell during float charging.

3. On discharging the cell after the float charge of 85 days, the discharge voltage is very flat. See figure 28. Note that there is a slight dip in voltage at the beginning of discharge. This may be an indication of increased internal impedance at this point.

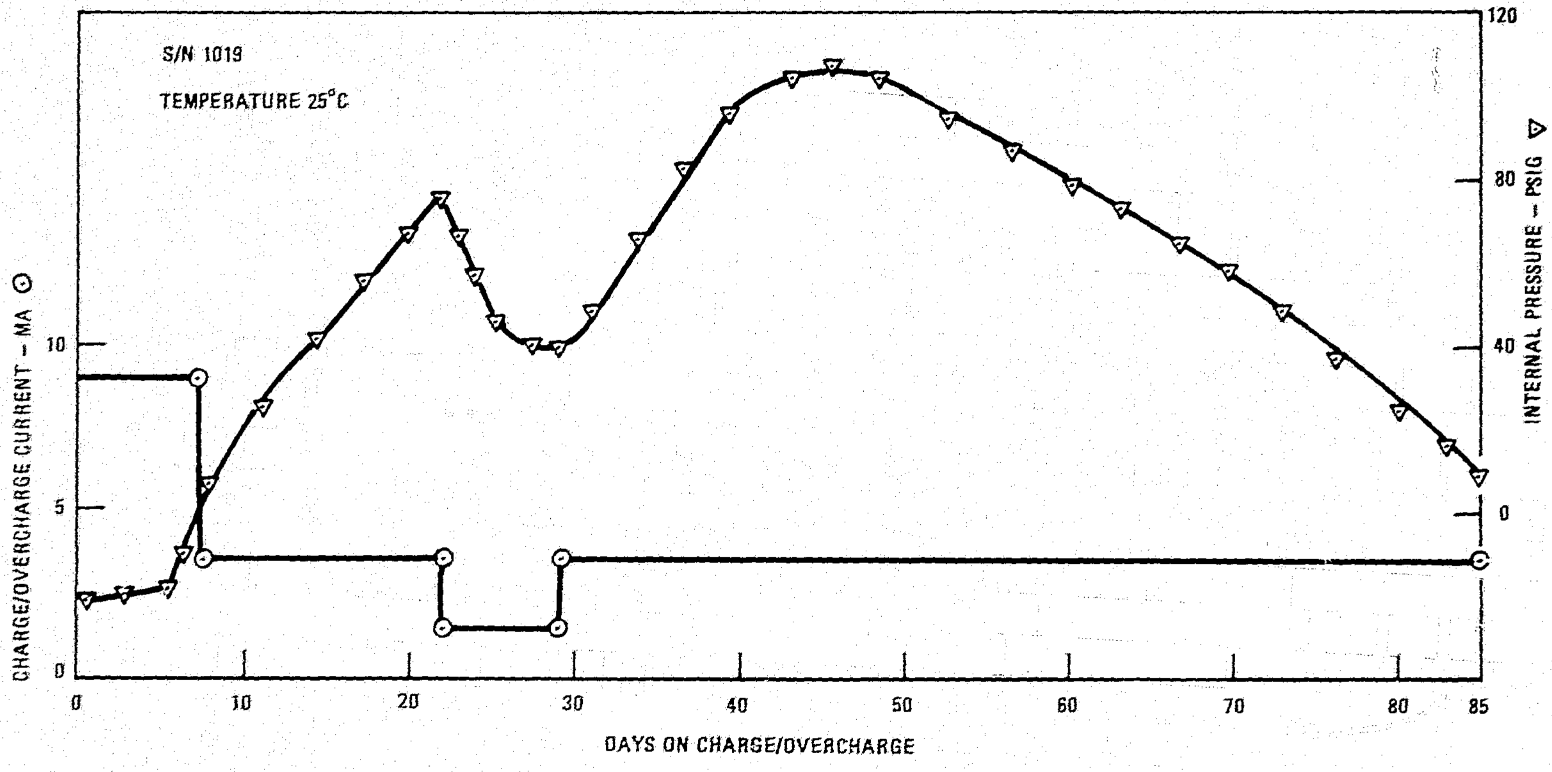

Figure 27. Internal Pressure Rise, Varying Currents, 1.5 to 9.0 ma.
Test 014, Cell YS5S-2NM

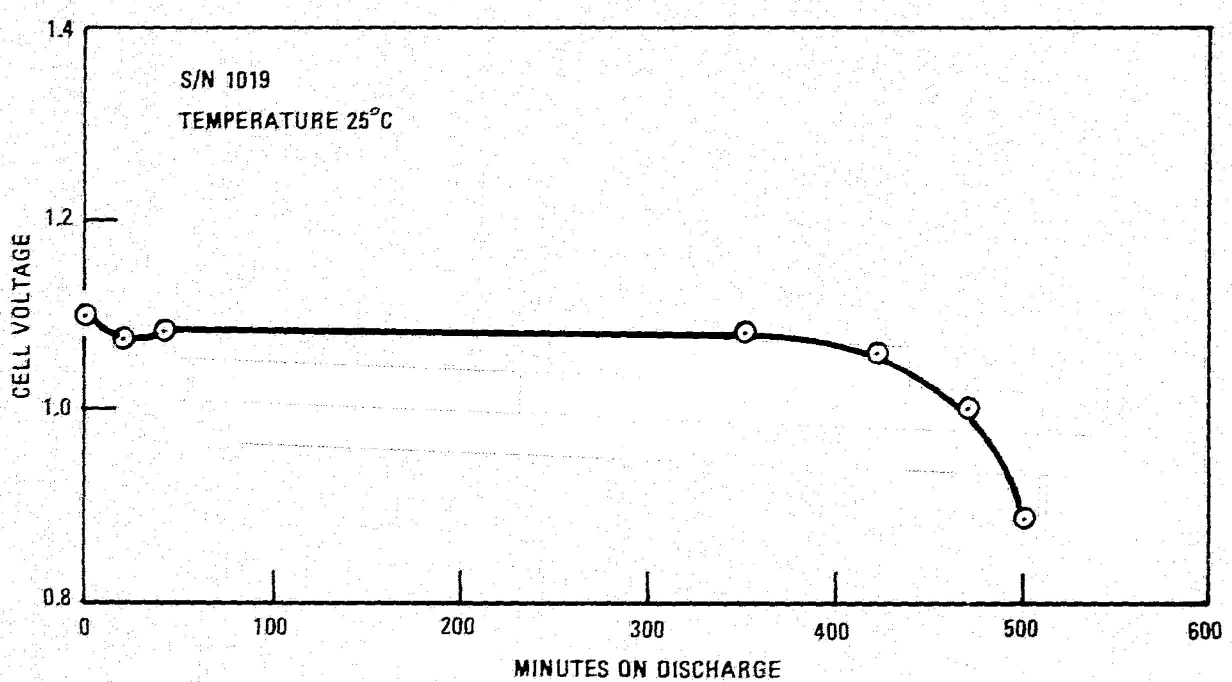

Figure 28. Voltage on Discharge at 935 ma.
Test 014, Cell YS5S-2NM, S/N 1019

TEST 015

Test Unit: Cell YS5S-2NM
S/N 375

Test Period: 1968

Total Cycling Time: 600 Hours
No. of Cycles: 3

TEST BRIEF

The test unit was a five ampere hour cell encapsulated in EPON 834. A pressure transducer was mounted on the cell with a special fitting and the fitting and pipe threads of the transducer were sealed with epoxy. After four months of storage, at 25°C, in the shorted condition the cell was charged at 300 ma. constant current and discharged at 950 ma. constant current. Then the cell was shorted on 0.5 ohms overnight followed by a 10 ma. constant current, charge for approximately 600 hours, then discharged at one ampere. Voltage and pressure was recorded and current monitored several times daily. The test temperature was 25°C.

Cell Design Reference: Appendix A

Main Project: Explorers

Applicable Figure: 29

Nominal Depth of Discharge: 100%

TEST 015 (Continued)

CYCLING

Cycle(s)[1] Half Cycle(s)	AHI[2]	AHO[2]	Cycling Parameters	Temperature °C
1C and 1D	6.0	5.6	300 ma. constant current charge until cell reached 1.57 volts. Discharge 950 ma. constant current to 0.9 volts.	25
2C	6.2		10 ± 1 ma.[3] constant current charge. No voltage limit	25
2D		5.2	Discharged at one ampere constant current to 0.9 volts.	25

(1) C = Charge
D = Discharge
(2) AHI - Ampere Hours In
AHO - Ampere Hours Out
(3) Constant current, at this low rate was difficult to control on equipment used.

OBSERVATIONS AND CONCLUSIONS:

1. Useful capacity was delivered to the cell when charging a discharged, five ampere hour cell at 10 ma. constant current.

2. At the low overcharge rate of 10 ma., gas is evolved in the cell. See figure 29.

3. After the cell was removed from charge, it was put on charged stand for several days. Negligible pressure decrease resulted.

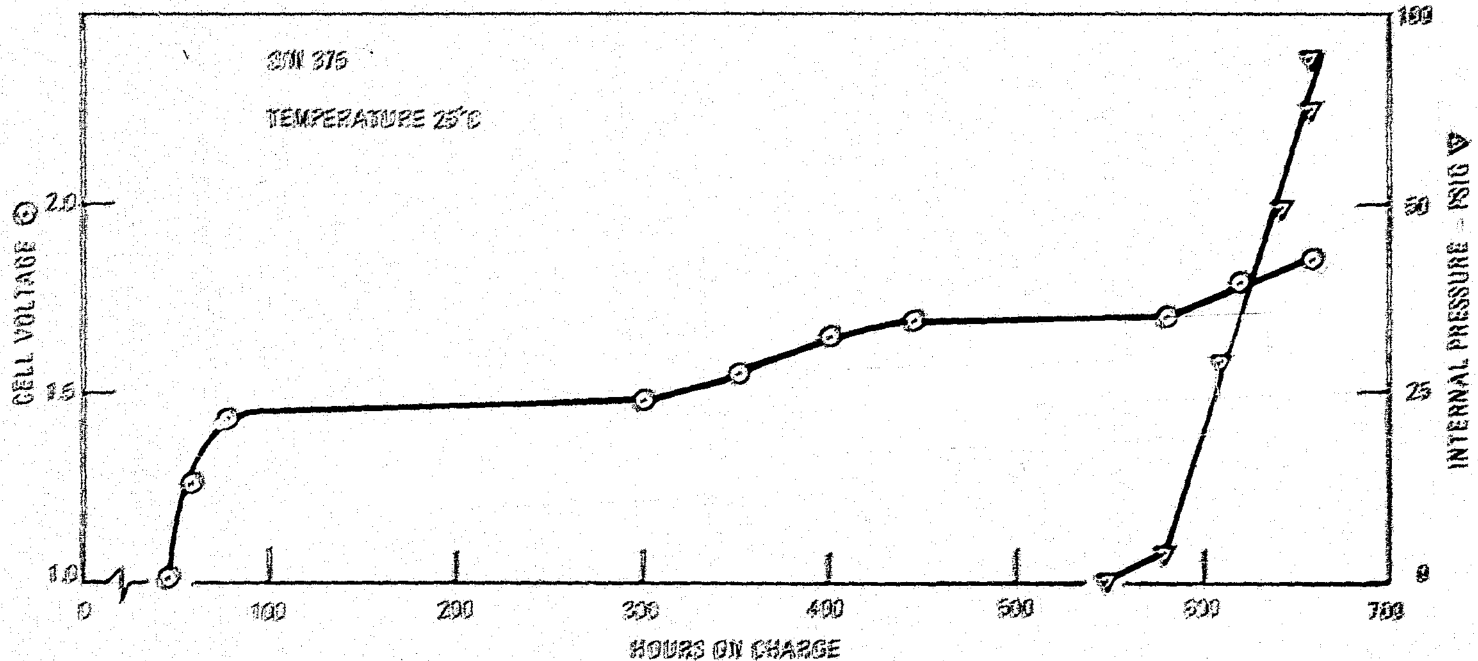

Figure 29. Internal Pressure Rise on Constant Current of 10 ma.
Test 015, Cell YS58-2NM, S/N 375

TEST 016

Test Unit: Battery 13xYS5S-2NM
S/N 209

Test Period: 1963

Total Cycling Time: 500 hours.
No. of Cycles: 3

TEST BRIEF

The battery consisted of thirteen, five ampere hour cells in series encapsulated in EPON 834. The battery was assembled into two units designated as 2A 2B that contained five and eight cells, respectively. This is the battery configuration flown on early Explorer satellites. See Illustration 1. After initial capacity checks, the battery was charged at low rates, 25 ma. and 50 ma. constant current, to determine ampere hour input at these rates. After each charge, the battery was discharged at one ampere constant current. Battery voltages and currents were recorded. All tests were made at room temperature. Wet life of the battery at the beginning of the test was approximately eight months. During this time, the battery had been stored discharged at room temperature.

Cell Design Reference: Appendix A

Main Project: Explorer XV, SERB (Study of Enhanced Radiation Belt)

Applicable Figures: 30, 31

Nominal Depth at Discharge: 100%

TEST 016 (Continued)

CYCLING

Initially, the battery was given several capacity checks. Most of the data was missing but one discharge showed a battery capacity of 5.7 Ahr.

Cycle(s)(1) Half Cycle(s)	AHI(2)	AHO(2)	Cycling parameters	Temperature °C
4C and 4D	7.7	6.5	25 +1 or -0 ma. constant current charge to 1.50 volts per cell. Before charge, each cell had been shorted on 0.5 ohms. Discharged at 1.0 ampere constant current to less than 0.9 volts per cell.	25
5C and 5D	6.5	6.1	50 +0 or -2 ma. constant current charge to 1.50 volts per cell. Discharged at 1.0 ampere to less than 0.9 volts per cell.	27
6C and 6D	5.8	5.7	300 ma. constant current charge to 1.52 volts per cell. Discharged at 1.0 ampere to less than 0.9 volts per cell.	25

(1) C = Charge
D = Discharge
(2) AHI - Ampere Hours In
AHO - Ampere Hours Out

OBSERVATIONS AND CONCLUSIONS:

1. Useful capacity was delivered to the five ampere hour battery at the low charge rates of 25 ma. and 50 ma. The ampere hour efficiencies were 84% and 94%, respectively. The latter efficiency is usually the value obtained at moderate charge rates (e.g. 300 ma.) Therefore, from the test, it is concluded that the 50 ma. charge rate is the lowest rate that can be used with a five ampere hour cell to obtain good ampere hour efficiency.

2. The capacity delivered to the battery during the lower portion (Ag_2O plateau) of the charge curve is much greater than observed at constant current charging at moderate (e.g. 300 ma.) rates. See figure 30.

3. The discharge curves, following the low rate charges, are essentially flat, i.e., the AgO plateau is non-existent. See figure 31. On the normal charge/discharge of 6C and 6D, following the low rate charging cycles, the upper plateau (AgO plateau) was present.

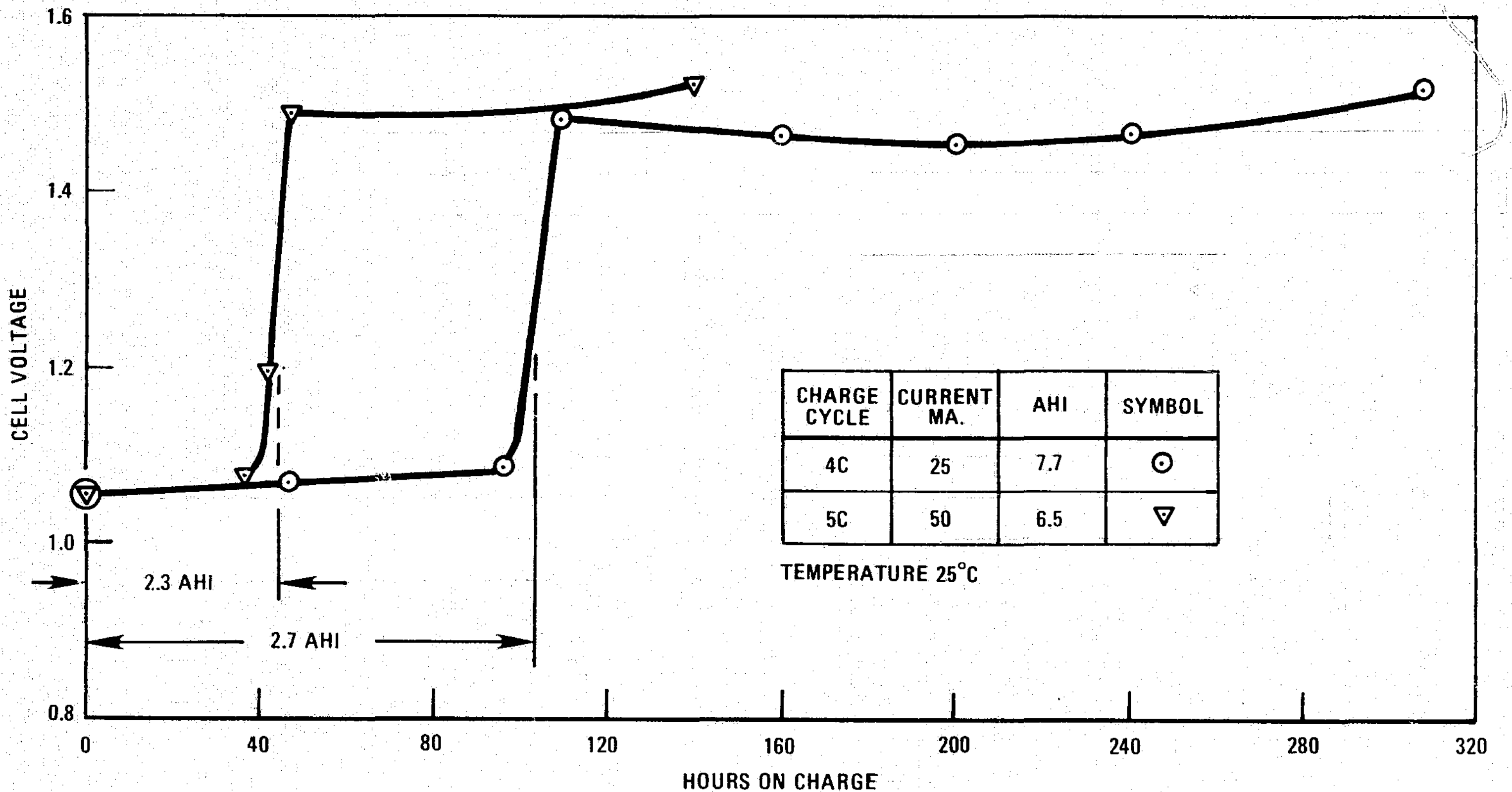

Figure 30. Low Rate Charging, Test 016
Battery 13xYS5S-2NM, S/N 209

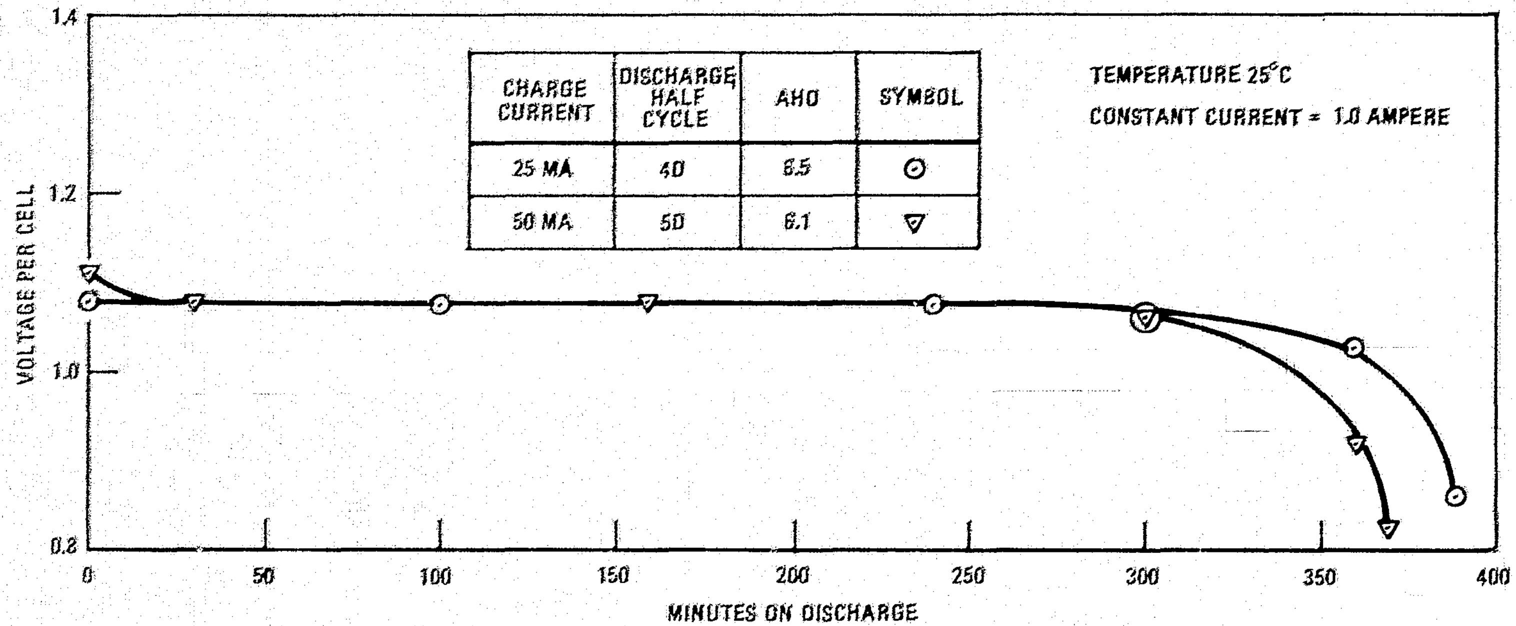

Figure 31. Voltage on Discharge, Test 016
Battery 13xYS5S-2NM, S/N 209

TEST 017

Test Unit: Battery 13xYS5S-2NM
S/N YAEL 002

Test Period: 1961

Total Cycling Time: 200 hours
Number of Cycles: 15

TEST BRIEF

The battery consisted of thirteen, five ampere hour cells in series encapsulated in EPON 834. The battery was assembled into two units designated as 2A and 2B that contained five and eight cells, respectively. See Illustration 1. Provisions were made so that the cell voltage could be measured individually at a test connection. This is the battery configuration flown on early Explorer satellites. During testing of the battery, recorders were used to measure the incremental voltage rise of the individual cells during the transition period from the lower charge plateau (Ag_2O plateau) to the upper charge plateau (AgO plateau). Also, the current during this transition period was recorded. Tests were run at 25°C, 0°C and -10°C. For most of the tests, the current limit of the charger was set at 300 ma. but one test at -10°C was run with the current limit set at 650 ma. The battery was charged to a three ampere hour input then discharged to less than 0.9 volt per cell overage.

Cell Design Reference: Appendix A

Main Project: General Testing

Applicable Figures: 32, 33

Nominal Depth at Discharge: N/A

CYCLING

Cycling was performed as described in the test brief. Twelve cycles were run at 25°C, one cycle at 0°C and one cycle at -10°C. Discharges between charges were performed at 1.5 amperes average on a constant resistance. All discharges were performed at room temperature.

OBSERVATION AND CONCLUSIONS:

Tests At 25°C

As can be seen in figure 32, the individual cells rise approximately 0.3 volts in a stepwise order. Timing of the rise of the cell is random, occasionally two cells rise at the same time. Also, during the twelve cycles run at 25°C, the order of the rise did not remain the same, e.g., if cell 2, rose first on the first cycle, it may be the fifth or last cell to rise on the following cycles. Later on during the battery program it was concluded that the order of rise of individual cells, during the transition period, could not be used as a basis for cell selection. One problem that is associated with battery charging as a result of this transition phenomena is that if a battery voltage cut off is used, there is a good probability that the battery will be removed from charge at the end of the transition period. In the example shown in figure 32, if the battery cut off was set at 19.5 volts (1.50 volts per cell) the battery would cut off at the end of the transition period. There is a good probability that two cells could rise simultaneously at the end of the transition period thereby causing the total battery voltage to rise over twenty volts. The transition period can also be troublesome during charging where individual cell sensing is used to remove cells from the charging circuit (e.g. formation cycling) or to remove the battery from the charging circuit when the first cell reaches a preset voltage (e.g. 1.50 volts). In either case, timers can be used so that the cell sense circuit is not operational until greater than 50% of the nominal or actual capacity is delivered to the cells or battery. At 25°C, the total time of the transition period, at moderate current rates, is 0.75 hours or less.

As shown in figure 33, at times, during constant potential charging, the charge current dips at the end of the battery voltage transition period. The magnitude of the dip appears to depend on the number of cells that rise simultaneously at the end of the transition period. It has also been observed, in other tests, that the magnitude of the current dip depends on the value of the current limit. The condition where two or more cells rise simultaneously coupled with high current limits (e.g. 1.5 amperes for a five ampere hour cell) results in a greater current dip.

Tests at 0°C and -10°C

At low temperatures, the individual voltage rise of each cell can be between 0.4 and 0.5 volts. This appears to be related to the current limit, i.e., at moderate currents, e.g. 300 ma., the cells rise approximate 0.4 volts and at high current limits, e.g. 650 ma., the rise may be closer to 0.5 volts. This phenomena can result in very high battery voltages at the end of the transition period, especially if two or more cells rise at the same time. For example, at -10°C with the current limit set at 650 ma., the battery voltage at the end of a transition period exceeded 22.0 volts. At low temperatures the same problems with cell voltage sensing and battery voltage sensing would occur. One additional problem that occurs due to the voltage transition of low temperatures is the decrease in charging current when a battery voltage clamp is used as in constant potential charging. As can be seen in figure 33, the charge current dips quite low and, depending on how many cells rise simultaneously at the end of the transition period, this current dip can approach zero. Usually at low temperatures, the total time of the transition period is greater than 0.75 hours.

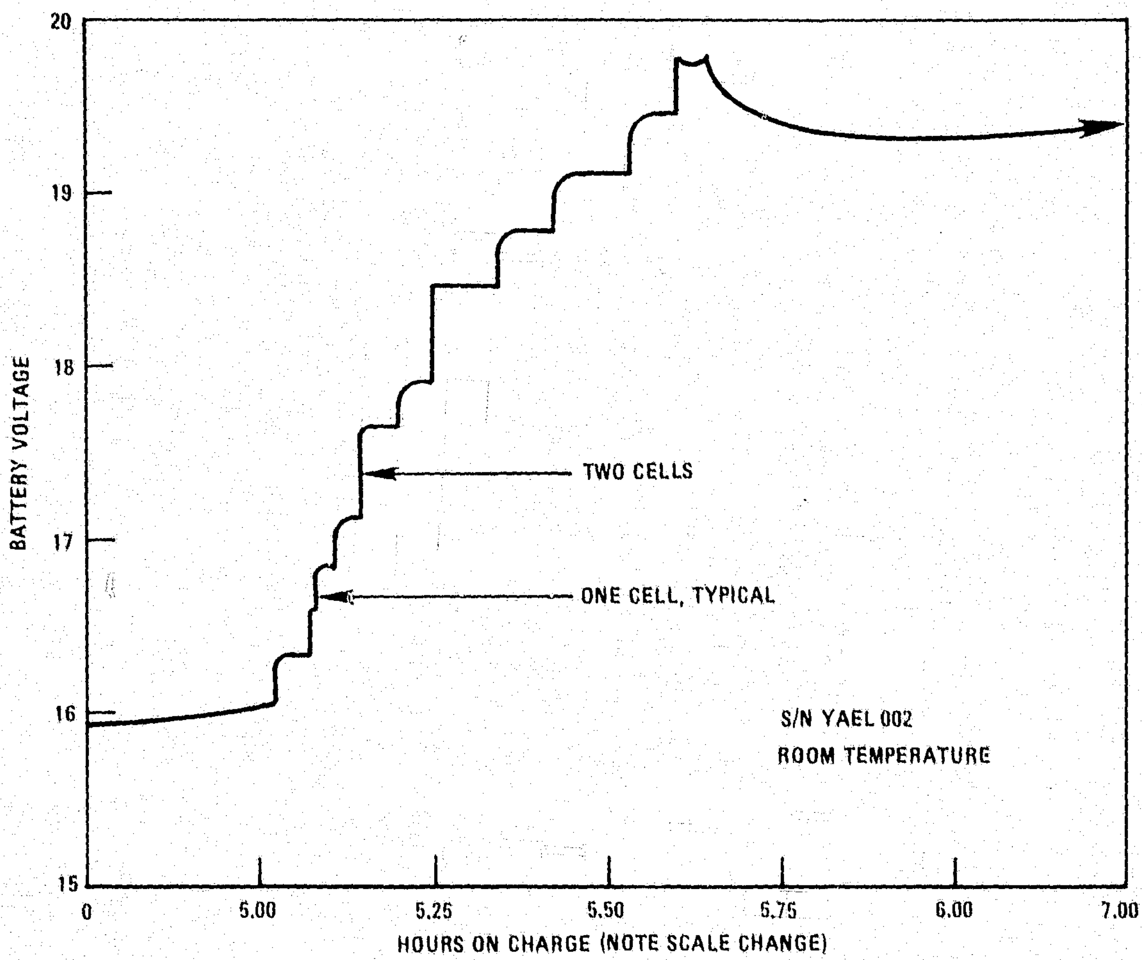

Figure 32. Voltage Rise of Cells in a Battery During the Transition Period
Test No. 017, Battery 13xYS5-2NM, S/N YAEL 002

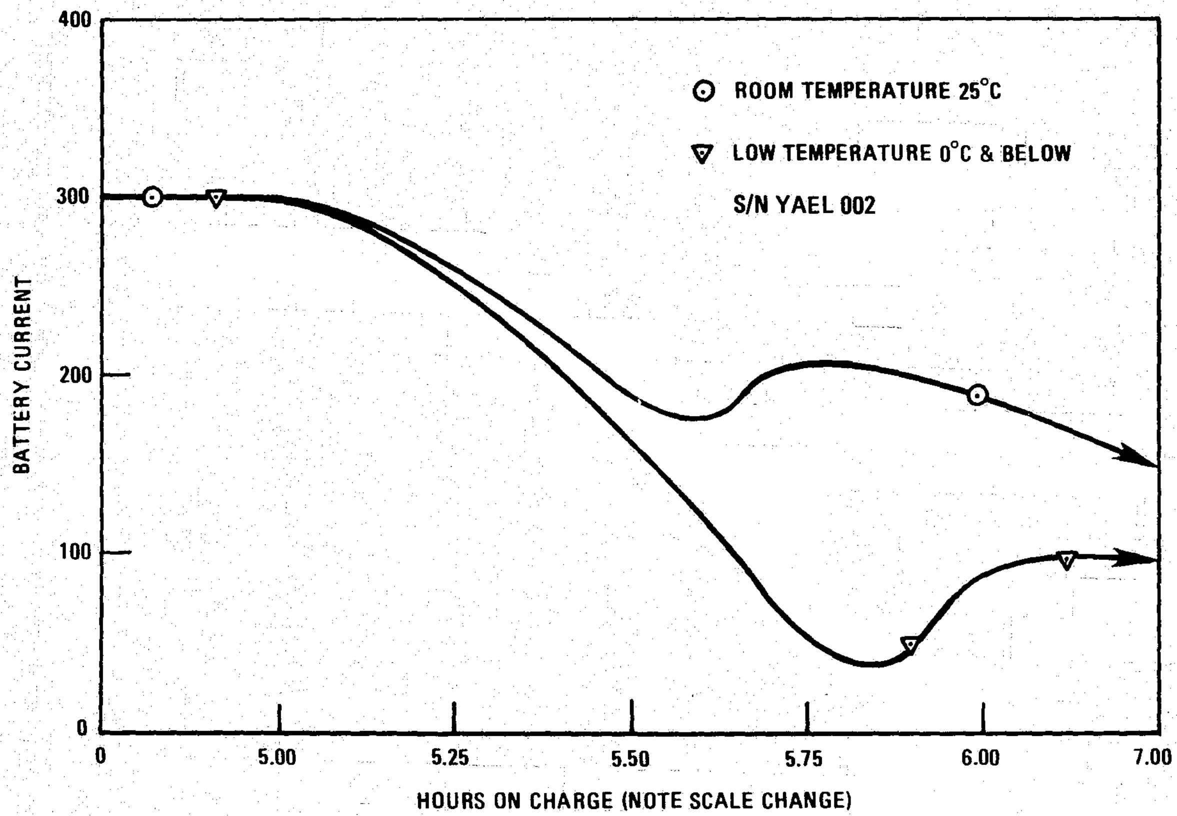

Figure 33. Charge Current During Transition Period
Test No. 017, Battery 13xYS5S-2NM, S/N YAEL 002

TEST 018

Test Unit: Battery 13xYS3S-1NM
S/N 001

Test Period: 1962

Total Cycling Time: 2600 hours
Number of Cycles: 102

TEST BRIEF

The battery consisted of thirteen, three ampere hour cells in series. Each cell was encapsulated in EPON 834. Simulated orbital cycling was done at 25°C to 28°C in twenty-four orbits with a 0.5 hour discharge. A voltage clamp and current limiting were used during cycling. The nominal discharge currents were 900 ma. Constant resistance discharges were used. The discharge currents reported are averages. During cycling total battery voltages and currents were recorded for all cycles and end of charge voltages monitored for most of the cycles. All current curves were integrated. During the cycle program, an analysis of the rate of decay of the upper plateau (AgO plateau) on discharge was performed.

Cell Design Reference: Appendix A

Main Project: Explorer XV

Applicable Figure: 34

Nominal Depth at Discharge: 16%

TEST 018 (Continued)

CYCLING

Cycle(s)[1] Half Cycle(s)	AHI[2]	AHO[2]	Cycling Parameters	Temperature °C
1C and 1D	3.2	3.1	200 Ma. constant current charge to 1.55 volts per cell average. Discharge at 400 ma. to less than 0.9 volts per cell average.	25 to 28
2C and 2D	3.2	3.1		
3C and 3D	3.4	3.4		
4C	3.4			
4D to 101D			Constant potential charge at 1.50 volts per cell current limited at 195 ma. for 23.5 hours. Discharge at 900 ma. for 0.5 hours.	27
102C			Constant potential charge at 1.50 volts per cell current limited at 195 ma. for 110 hours.	27
102D		2.7	Discharge at 880 ma. to less than 0.9 volts per cell average.	25

(1) C = Charge
D = Discharge

(2) AHI - Ampere Hours In
AHO - Ampere Hours Out

OBSERVATIONS AND CONCLUSIONS:

1. During simulated, orbital cycling, the average ampere hour efficiency was greater than 94%.

2. During simulated orbital cycling, one cell persistently charged at the 1.7 to 1.8 level when the charge current decreased to a low value (≈ 3 ma.). However, there were no indications of cell failure.

3. The upper voltage plateau (AgO plateau) on discharge decreased with simulated orbital cycling. The rate of decay of this plateau is shown in figure 34. After 70 simulated orbital cycles, the discharge voltage curves are essentially flat. On the last discharge (102D), over 92% of the battery capacity was delivered at 1.07 volts per cell.

4. During the 110 hour charge (103C), three of the cells were above 1.71 volts while the remaining cells were between 1.41 and 1.42 volts. This unbalance condition occurred after 20 hours of charge when the current was less than 2 ma. and continued for the remaining 90 hours of charge.

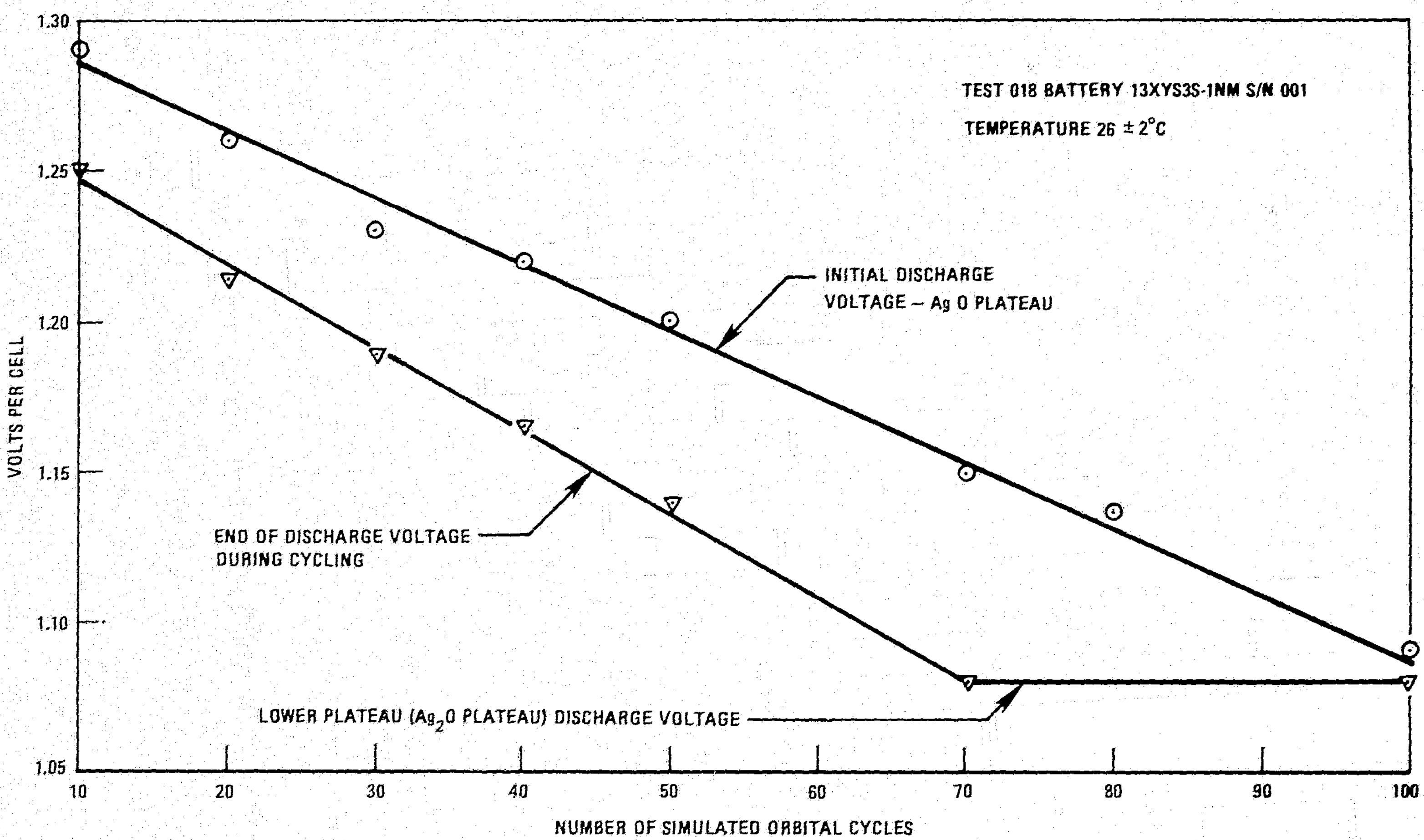

Figure 34. Rate of Decay of Upper Plateau (AgO Plateau) on Discharge During Simulated Orbital Cycling, Test 018, Battery 13xYS3S-1NM, S/N 001

TEST 019 (A thru E)
Several Test Batteries

TEST BRIEF

In addition to Tests 005 and 010, several charged stand and float charge tests were performed on batteries of various ampere hour capacities and cell designs.

All batteries were comprised of cells sealed in EPON epoxy. The test procedures are tabulated in Table 7 and applicable figures are included in figure 35. After the charged stand tests and the following discharges were completed, some of the batteries were given an additional capacity check to determine the condition of the battery.

Cell Design Reference: Appendix A

Main Project: General Tests

Applicable Figure: 35

Nominal Depth at Discharge: 100%

CYCLING

1. Several batteries were charged and put on stand or float charge for various periods of time at room temperature and 40°C. Information as to the method of charge, ampere hour capacity inputs, ampere hour output after the charged stand or float charge are given in Table 7. Data was available on three of the batteries that were given a capacity check after the storage tests were completed. These data are shown below. The test numbers refer to the data given in Table 7.

Test Number	AHI[1]	AHO[1]	Cycling Parameters	Temperature °C
019B	10.5	INA[2]	Constant potential charged at 1.51 volts per cell current limited at 500 ma. Charge cut-off at current of 100 ma.	25
019D	4.9	5.0	300 ma. constant current charge to 1.54 volts per cell average. Discharge at 1.0 ampere to 0.90 volts per cell.	27
019E	7.5	7.5	500 ma. constant current charge to 1.51 volts per cell average. Discharge at 2.0 amperes to 0.85 volts per cell.	27

(1) AHI - Ampere Hours In
AHO - Ampere Hours Out
(2) Information Not Available. Equipment failure ruptured the battery.

Table 7

TESTS 019 (A - E)

Charged Stand and Float Charge

Test Number and Battery Designation	Initial Charge	Stand Conditions	Discharge After Stand
019A 13xYS5S-2NM S/N 003	300 ma. constant current to 1.55 volts per cell average at 25°C. AHI(1) = 5.5	10 weeks at 40°C.	950 ma. constant current to 0.93 volts per cell at 26°C. AHO(2) = 4.9
019B 10xYS10S-4NM	Constant potential charged at 1.51 volts per cell, current limited at 500 ma. Charge cut-off at current of 100 ma., 26°C. AHI = 10.8	0.5 years on float charge of 1.41 volts per cell at room temperature.	4.0 amperes constant current to 0.95 volts per cell at 25°C. AHO = 10.9
019C 10xYS20S-3NM	1.0 ampere constant current to 1.56 volts per cell average at 26°C. AHI = 20.2	1.2 years at room temperature.	5.0 amperes constant current to 0.90 volts per cell at 28°C. AHO = 13.1
019D 13xYS5S-2NM S/N 208	350 ma. constant current to 1.54 volts per cell average at 25°C. AHI = 6.0	1.2 years at room temperature.	1.0 ampere constant current to 0.95 volts per cell at 27°C. AHO = 4.5
019E 13xYS10S-NM(3) S/N 4-13	500 ma. constant current to 1.52 volts per cell average at 27°C. AHI = 9.3 Ahr.	1.8 years at room temperature	2.0 amperes constant current to 0.85 volts per cell. AHO = 6.5

(1) AHI - Ampere Hours In

(2) AHO - Ampere Hours Out

(3) Design Drawing Number Not Available

OBSERVATIONS AND CONCLUSIONS:

1. Capacity maintenance on charged stand at room temperature is considered superior to most secondary electrochemical systems. This is particularly true with respect to the uniformity of capacity maintenance on a cell basis. Although little data was available on individual cells on discharge, the data does show that there was no wide dispersion of cell voltages during discharge and at the end of discharge.

2. Float charging at 1.41 volts is the charge voltage used in orbit during long sunlight periods. Since 1.41 volts is essentially the open circuit value of charged cells, the cells do not unbalance at this charge voltage. Therefore, no gas evolution will occur. During the float charge, intermittent current measurements showed that the charge current was less than one milliampere.

3. As shown by the capacity checks after the charged stands and float charge, there was no major deterioration of the batteries as a result of storage at room temperature. Since the cells in each battery were uniform in ampere hour capacity on the capacity check discharge, it was concluded that internal cell shorting did not occur.

4. Complete cell design information was not available on Battery 10xYS20S-3NM used in test 019C. However the main separator system, viewed from the positive plate, was one layer of woven nylon, two layers of polyvinyl alcohol (PVA) membrane and two layers of silver treated cellophane (C19). The separator system of the battery used in test 019D, viewed from the positive plate, was two layers of woven nylon, five layers of C19, and one layer of woven nylon. As shown on Table 7, the five layers of C19 resulted in better capacity maintenance than the PVA/C19 combination.

5. After storage, the discharge curves are essentially flat. See figure 35.

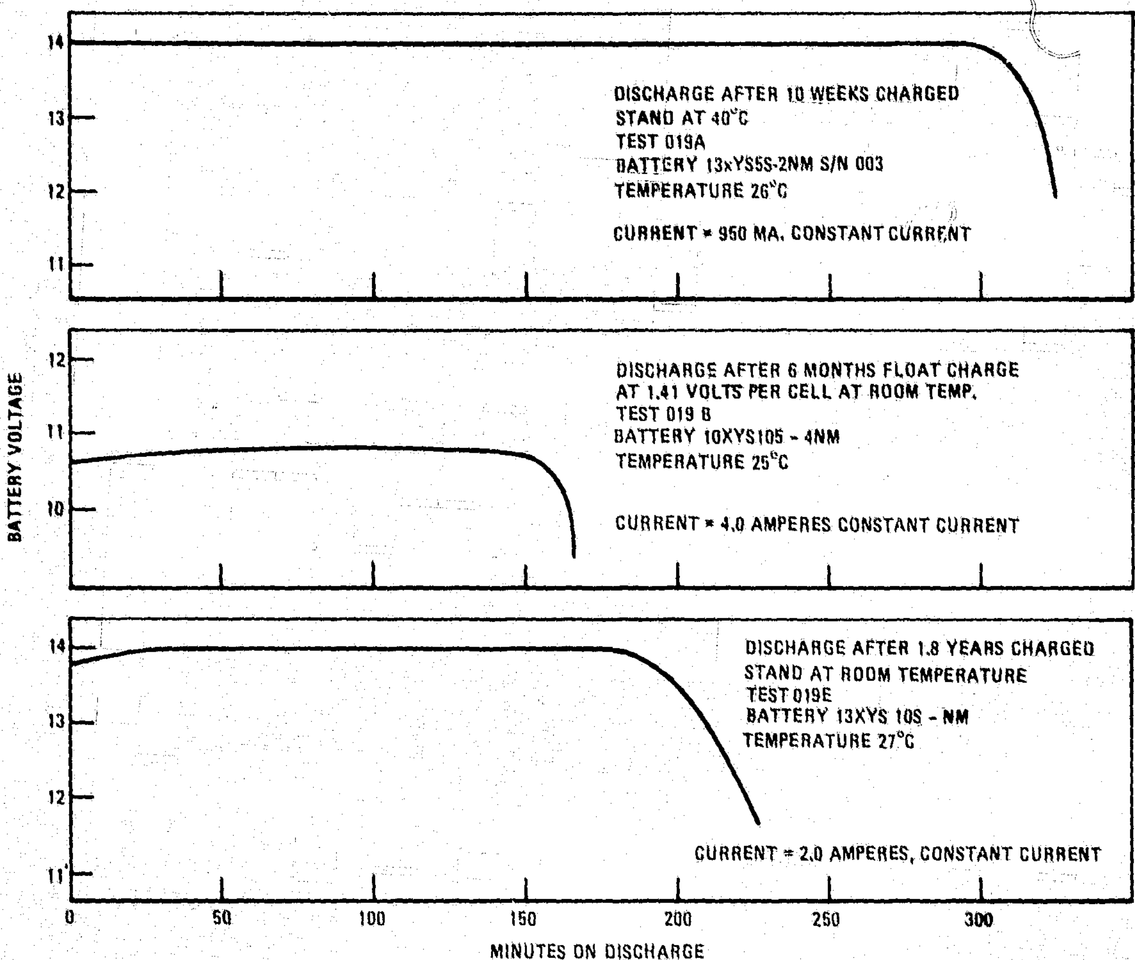

Figure 35. Discharge Characteristics of Batteries After Various Storage Periods

TEST 020

Test Unit: Battery 13xYS11S-NM(TA)[1]
S/N IMP-03

Test Period: 1965

Total Cycling Time: 300 hours
Number of Cycles: 13

TEST BRIEF

The battery consisted of thirteen, eleven ampere hour cells in series encapsulated in a mixture of EPON resins. Provisions were made so that the individual cells could be monitored at a test connector. The battery case was made of magnesium. A photograph of the battery is shown in Illustration 3. This is similar to the design flown on most of the spacecraft after 1964. However, later batteries utilized fourteen cells in series and contained heaters to maintain the battery at constant temperature. The battery was subjected to tests to determine the following characteristics.

1. The effect of constant potential charging of 1.51 volts per cell at high current limits.

2. The effect of temperature on 1 above, and

3. The capacity and voltage characteristics of the battery at low temperature when charged at a constant potential of 1.51 volts per cell with moderate current limits (500 ma.).

In the following discussion, the term lock-out voltage and turn-on voltage will be used. These are defined as follows:

1. Lock-out Voltage: During long eliptical orbits, during the course of a year, a satellite enters shadow periods of several hours, i.e., three to six hours. During these shadows, it was not possible to provide battery power to maintain full operation since the size and weight of the battery

Cell Design Reference: Appendix A

Project: Anchor Interplanetory Monitoring Platform (AIMP)

Applicable Figures: 36, 37, 38, 39, 40, 41, 42

Nominal Depth at Discharge: 100%

(1) Design Drawing Number Not Available

would be excessive. Therefore, during these long shadow periods the battery would be discharged to a lock-out voltage. This was a voltage value at which cell reversal would be unlikely. This voltage was 0.92 volts per cell. As long as just thirteen cells were in series, the lock-out would sense one cell going to zero volts as long as the voltage of the remaining cells were on the knee of the discharge curve ($\approx$1.0 volts at moderate temperatures.) In order to accomplish this uniformity the Goddard Space Flight Center (GSFC) personnel and the personnel from the cell manufacturer instituted hi-rel type quality and material control procedures in production. The results of this cooperative effort are shown in a typical cell process and material control specification as shown in ref. 1.

2. Turn-on Voltage: In some of the Explorer Satellites flown between 1965 to 1969, a turn-on voltage was used when a long shadow occurred and the satellite entered sunlight. Initially on entry, the total power from the array was used for charging the battery during the formation of Ag_2O. During the transition period of the lower charge plateau (Ag_2O plateau) to the upper plateau (AgO plateau), the voltage has a positive slope from a nominal 1.2 volts per cell to a nominal 1.5 volts per cell. The turn-on voltage, the voltage when the satellite experiments were turned on and the battery had to share power, was approximately 1.36 volts per cell. During this test period in 1965, investigations were also made to determine if timers would be useful to time the battery charge for a period of four or eight hours. The timer method would be used in lieu of the turn-on voltage method. In actual practice, the turn-on voltage method was used. However, this information, i.e., charging for four to eight hours at constant potential with high current limits is shown for information.

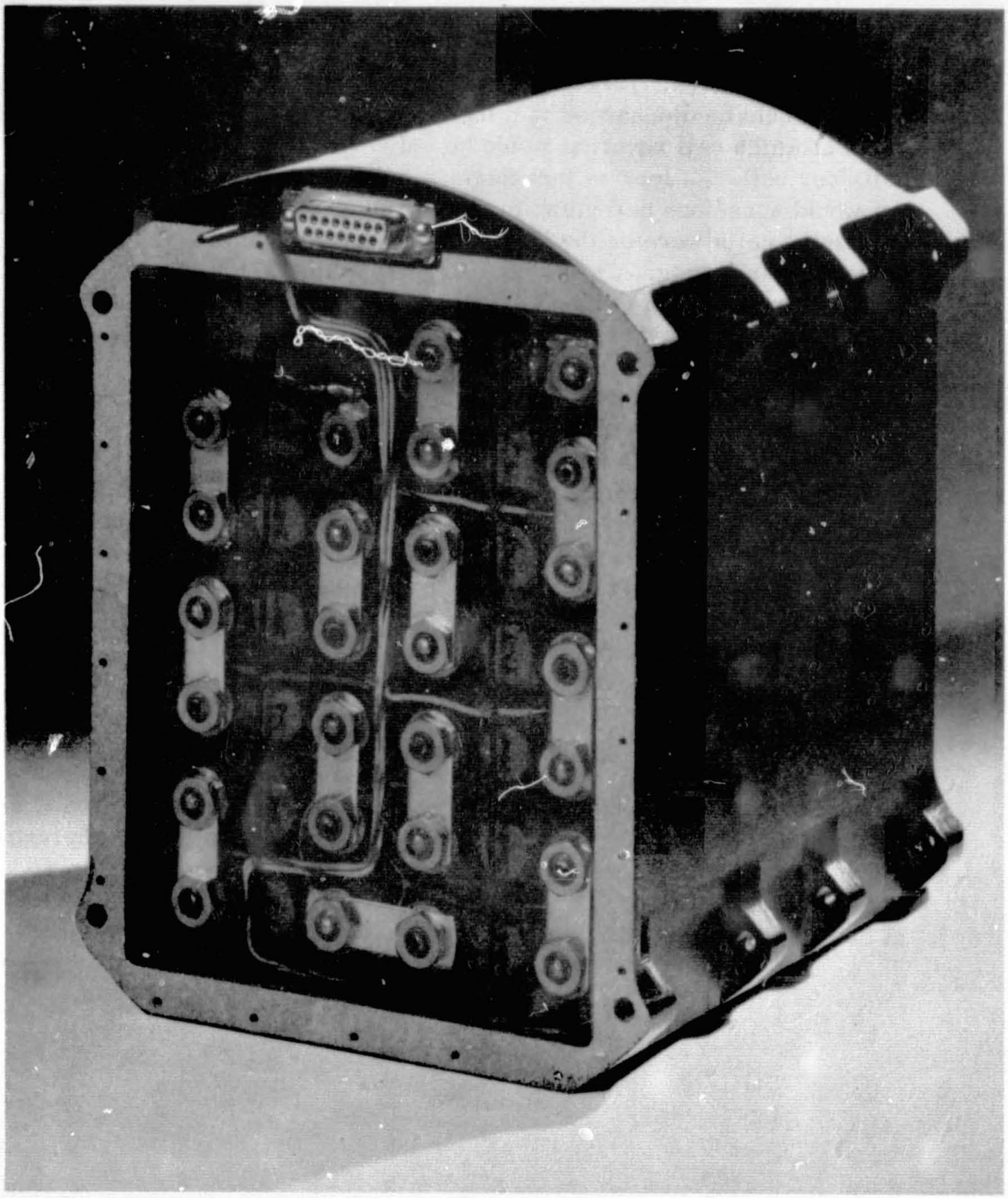

Illustration 3. Battery 13xYS11S-NM (TA)
S/N IMP-03

CYCLING

The cycling tests are best described from an internal memo (ref. 7) from which excerpts are presented with applicable figures 36, 37, 38, 39, 40, 41, 42, and table 8.

"At the request of the Anchor IMP Project Office, a special test program was initiated to determine the charge voltage characteristics of the 11 Ahr. silver cadmium battery so that an optimum threshold voltage could be selected to determine when the spacecraft could turn on after an under-voltage (lock-out) condition. In addition, this test program yielded valuable information of the battery discharge performance, both capacity and nominal voltage levels, over a temperature range of -20°C to +27°C. The cells used for this test were the "tall" 11 AH cells and they were "flooded" with electrolyte.

The silver cadmium battery is unique in the sense that it exhibits two distinct charge levels that are represented electrochemically as silver monoxide (Ag_2O) and silver peroxide (AgO). At room temperature the nominal charge voltages are 1.2 volts per cell for the Ag_2O level and 1.5 volts per cell for the AgO level. The transition from the Ag_2O to AgO level occurs at room temperature from 18% to 40% recharge depending on the charge rate and temperature. The Anchor IMP integration team has suggested utilizing this electrochemical characteristic of the silver cadmium battery to minimize the lock-out time of the spacecraft.

Fig. 36 illustrates the charge voltage levels and transition regions at constant current rates of 2.0, 4.0, and 6.0 amperes at 27°C. These values are plotted against ampere-hour capacity and percent recharge. A dotted line representing the tentative 17.7 (1) volt threshold is drawn for relative comparison of percent recharge for 0.5, 2.0, 4.0, and 6.0 amps charge. Fig. 37 and 38 illustrate similar information at 0°C and -20°C. Table 8 gives a comparison of ampere-hour recharge for the 17.7 (1) volt turn-on mode, a four hour lock-out period, and eight hour lock-out period. In Fig. 39, 40, and 41 are plotted the nominal charge current acceptance values of the battery at 19.6 (2) volts for temperatures of 27°C, 0°C, and -20°C, respectively. In Fig. 42 are illustrated the battery discharge voltage profiles for temperatures of -20°C, 0°C, and 27°C. Previous to these discharges the battery was charged at a constant potential of 1.51 volts per cell current limited at 500 ma. The batteries were charged at the same temperature that they were discharged. A dotted line representing the 12-volt lock-out value is illustrated.

The initial selection of a 17.7 [1] volt threshold is considered a good choice for all temperature ranges and current rates tested with the exception of the 6-amp charge at -20°C where the initial charge voltage is 18.5 [3] volts. The choice of 12.0 [4] volts for the undervoltage lock-out point is considered a good value for the temperature range of -20°C to +27°C."

(1) 1.36 volts per cell
(2) 1.51 volts per cell
(3) 1.41 volts per cell
(4) 0.92 volts per cell
Author's Note

OBSERVATIONS AND CONCLUSIONS:

1. A caution to the reader as to the data and information on this type of cell. This cell was originally designed to accept higher rates of charge and deliver higher rates of discharge than cells of similar physical and ampere hour size. In comparing the design of this cell (YS-11) with a comparable cell (YS-10), the latter cell had four positive plates and five negative plates while the YS-11 cell had six positive plates and seven negative plates. The height and width of the plates were approximately the same while the thickness of the YS-10 cell plates was greater than the YS-11 plates. For further information on these cells, see Appendix A.

2. The percent capacities at low temperatures, based on the room temperature capacity at 27°C, were as follows:

Temperature °C	Percent Ampere Hour Capacity Based on 27°C Capacity
27	100%
0	74%
-20	51%

Higher cold temperature capacities could be obtained by using a voltage clamp greater than 1.51 volts per cell. However, at this time in the overall program, 1.51 volts per cell on charge had been selected as the operational voltage clamp over the temperature range of -20°C to 40°C.

3. At 27°C, the ampere hours delivered to the battery on the lower charge plateau (Ag_2O plateau) increases as the current limit is decreased. See figures 36 and 39. (See also, test 016, this Section of the Report).

4. The percent of nominal ampere hour capacity delivered to the battery at the various current limits at temperatures of 0°C and 27°C and on the lower plateau (Ag_2O plateau) was adequate for mission requirements. See figures 36 and 37. The lower charge plateau (Ag_2O plateau) is essentially non-existent at the low temperature of -20°C. See figure 38.

5. As would be expected, the average charging current delivered to the battery after the 1.51 voltage clamp is reached decreases with decreasing temperature. See figures 39, 40 and 41.

6. On Table 8, the data for ampere hours delivered to the battery to the 1.36 volt per cell turn-on voltage and the ampere hour capacity delivered when the four and eight hour timers were used, is summarized.

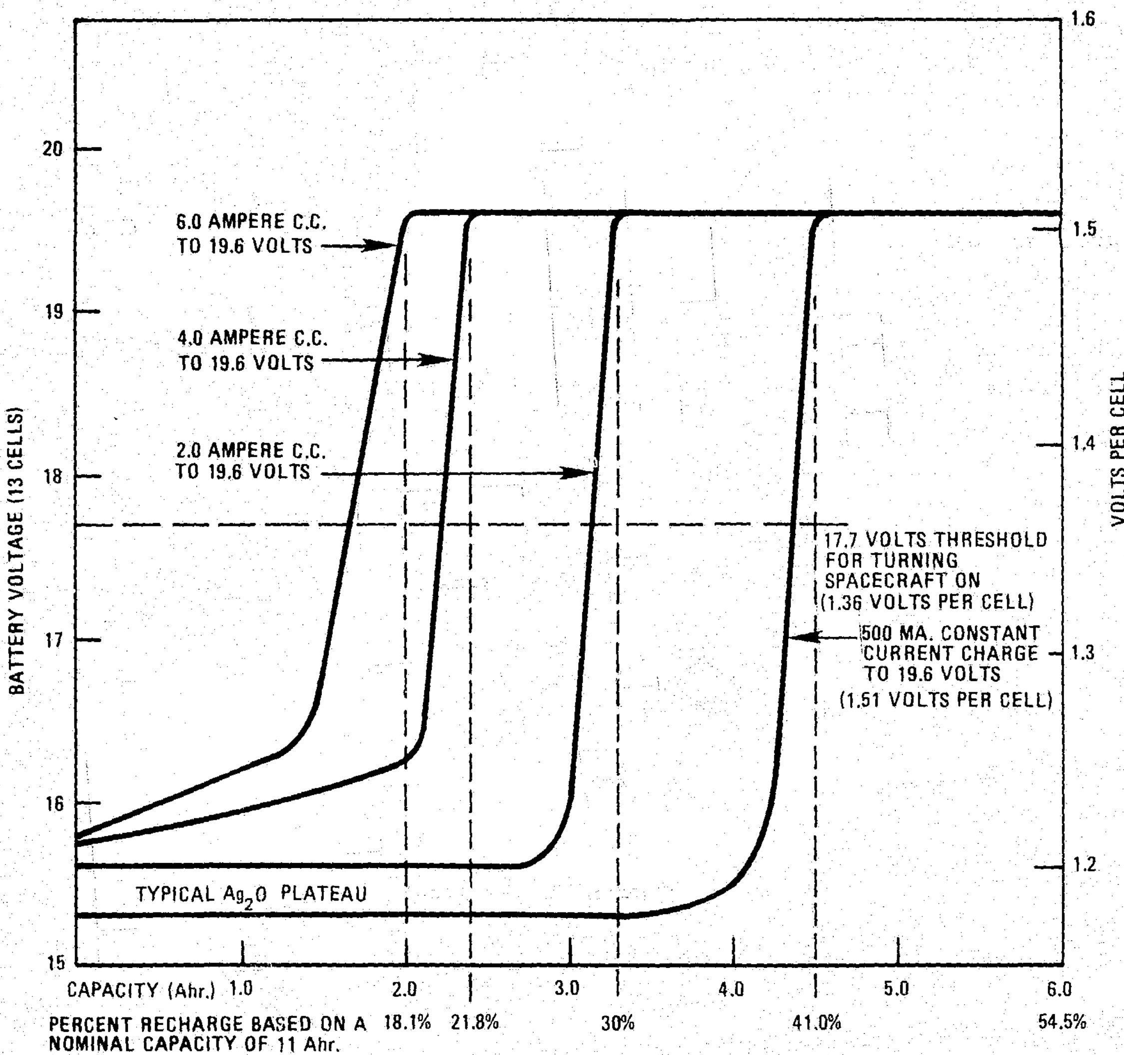

Figure 36. Battery Voltage as a Function of Charge Rate at 27°C
Test 020, Battery 13xYS11S-NM, S/N IMP 003

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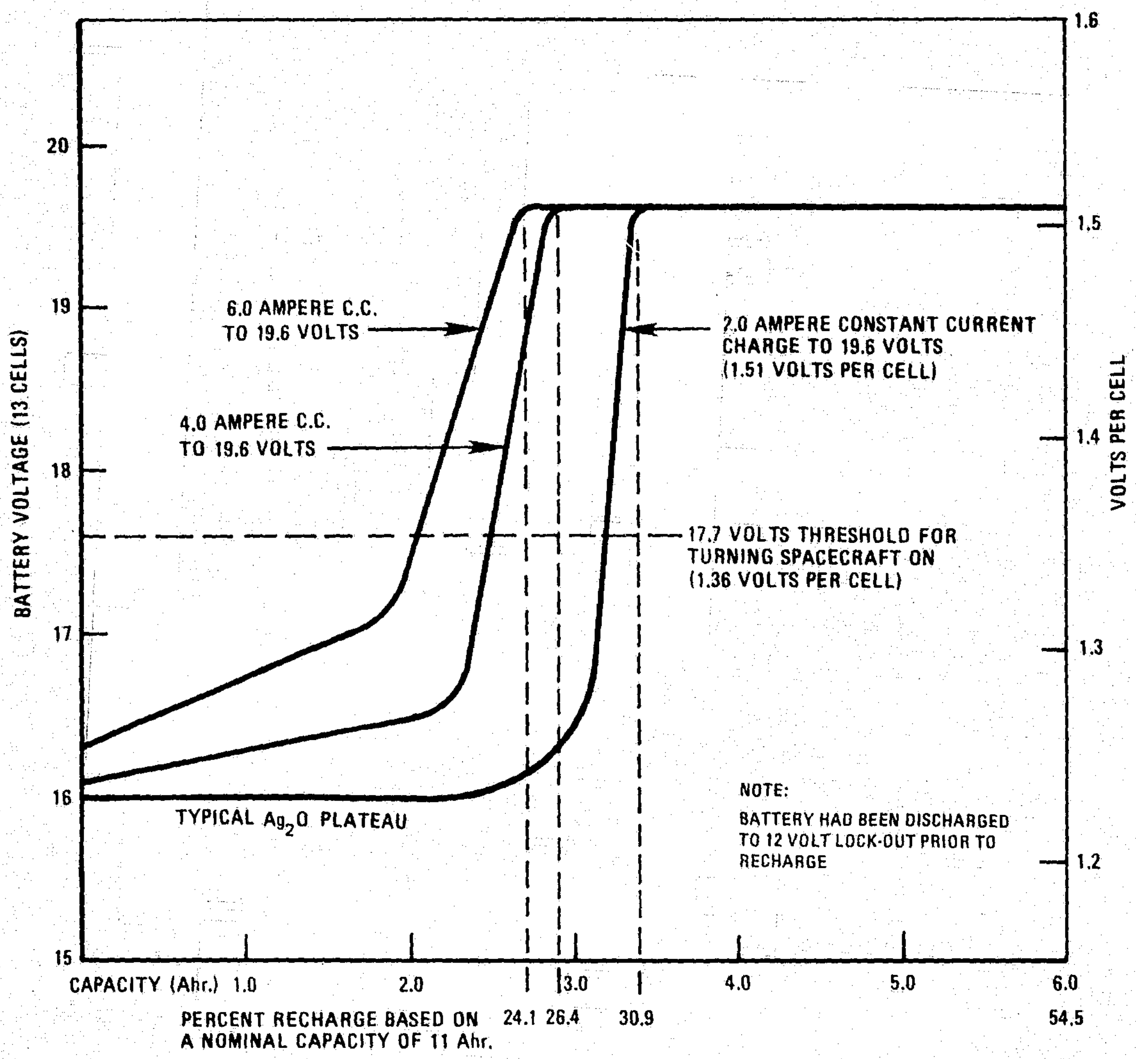

Figure 37. Battery Voltage as a Function of Charge Rate at 0°C
Test 020, B ttery 13xYS11S-NM, S/N IMP 003

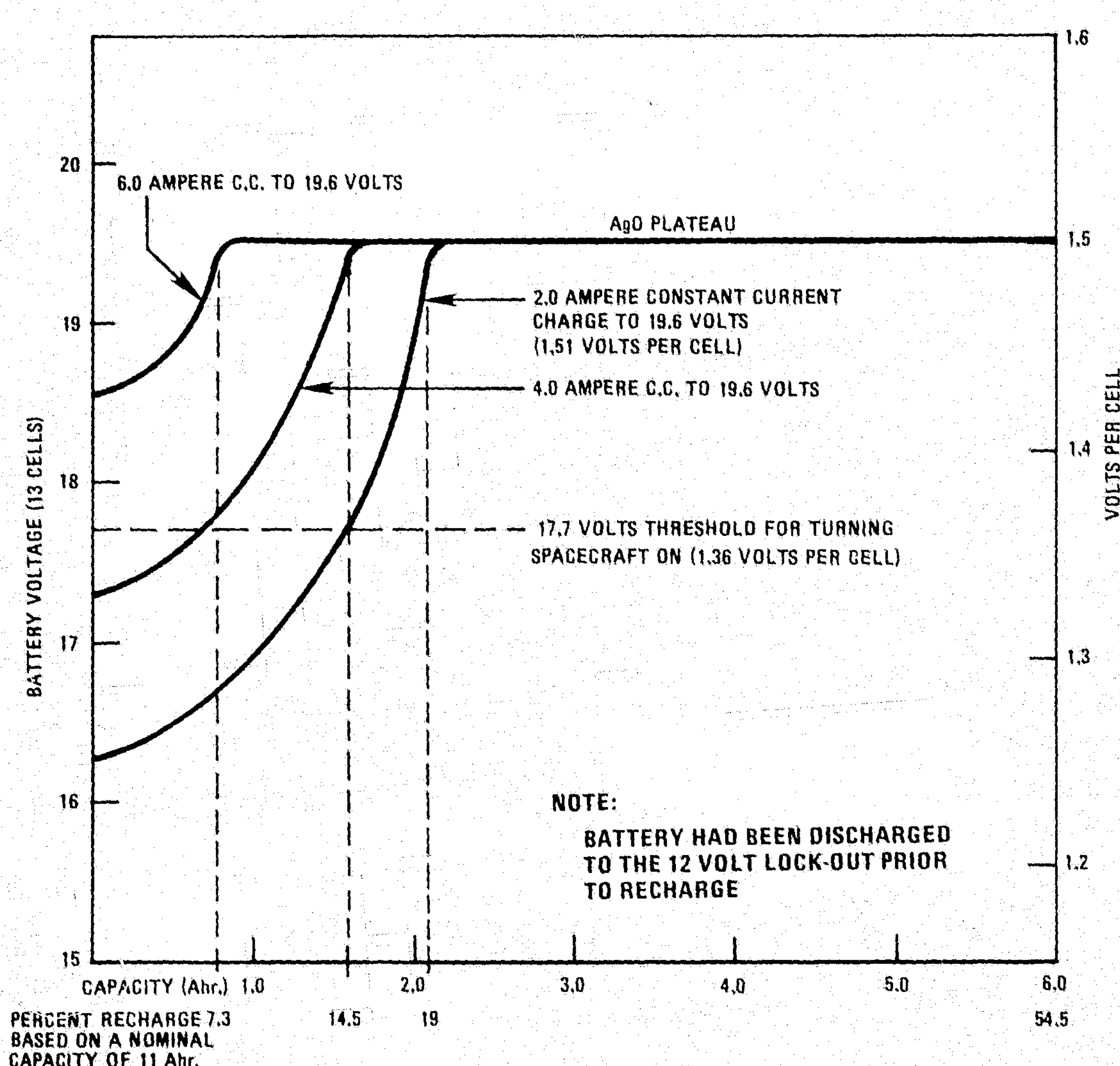

Figure 38. Battery Voltage as a Function of Charge Rate at -20°C
Test 020, Battery 13xYS11S-NM, S/N IMP 003

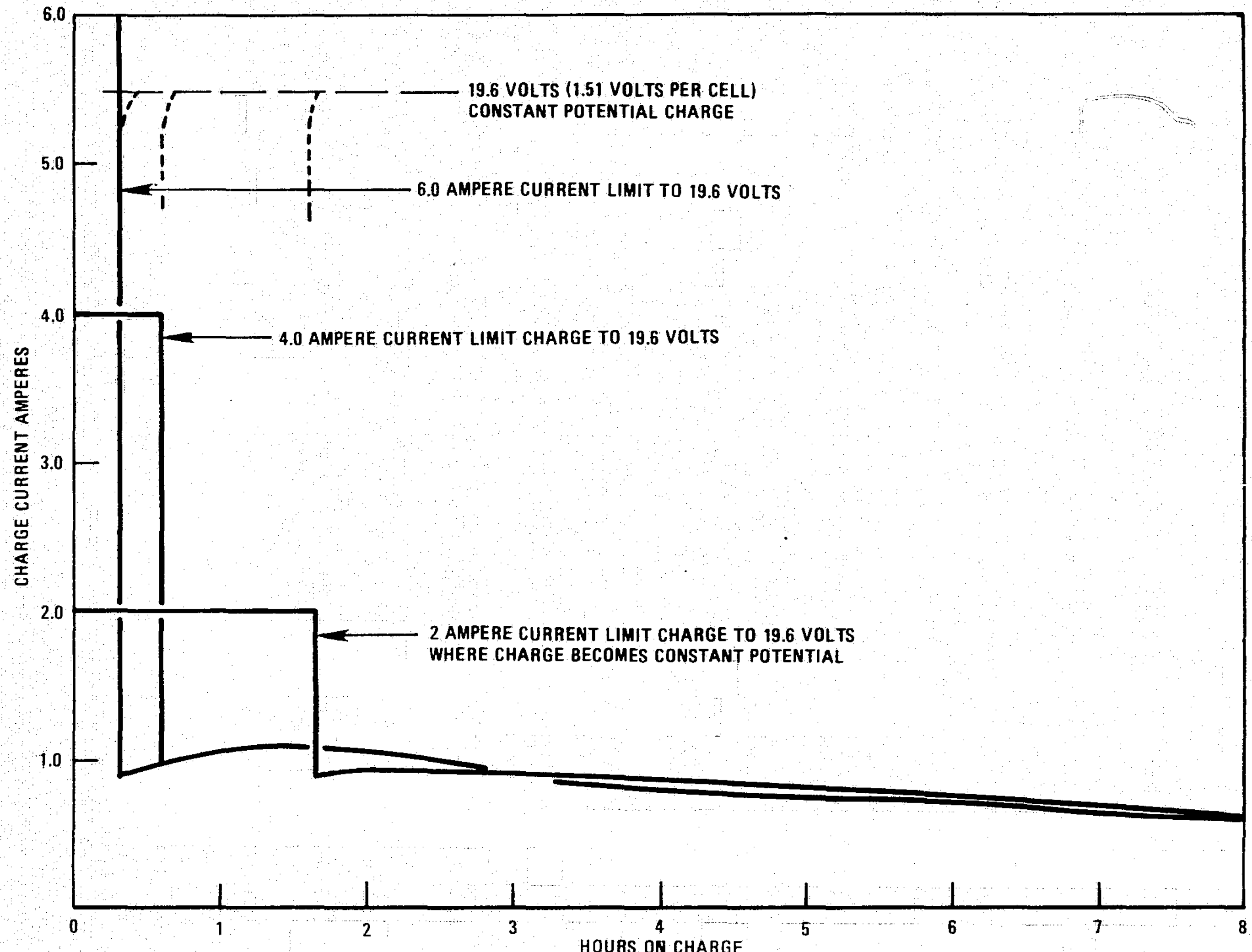

Figure 39. Battery Current as a Function of Time When Constant Potential Charged at 1.51 Volts Per Cell at 27°C, Test 020, Battery 13xYS11S-NM, S/N IMP 003

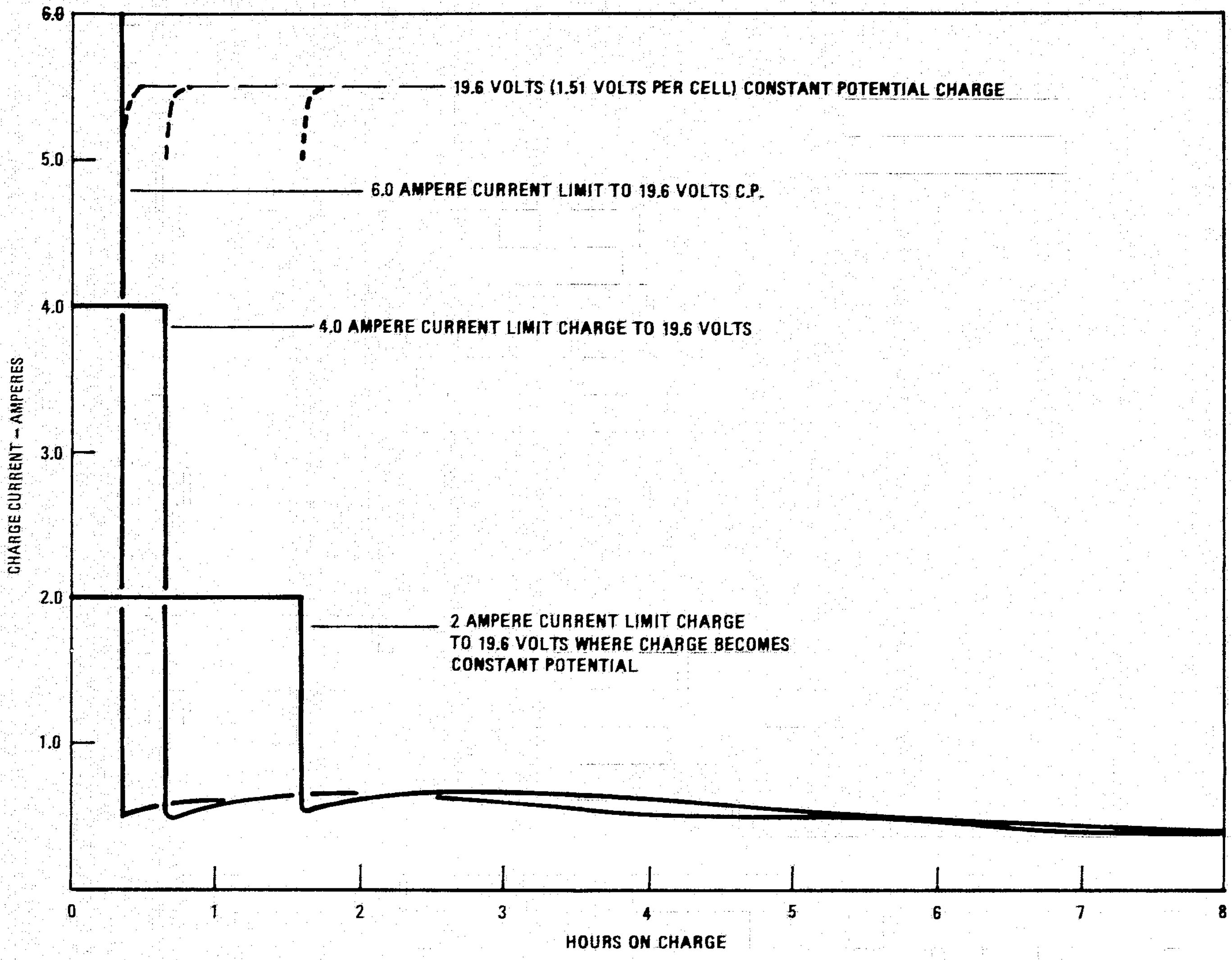

Figure 40. Battery Current as a Function of Time When Constant Potential Charged at 1.51 Volts Per Cell at 0°C, Test 020, Battery 13xYS11S-NM, S/N IMP 003

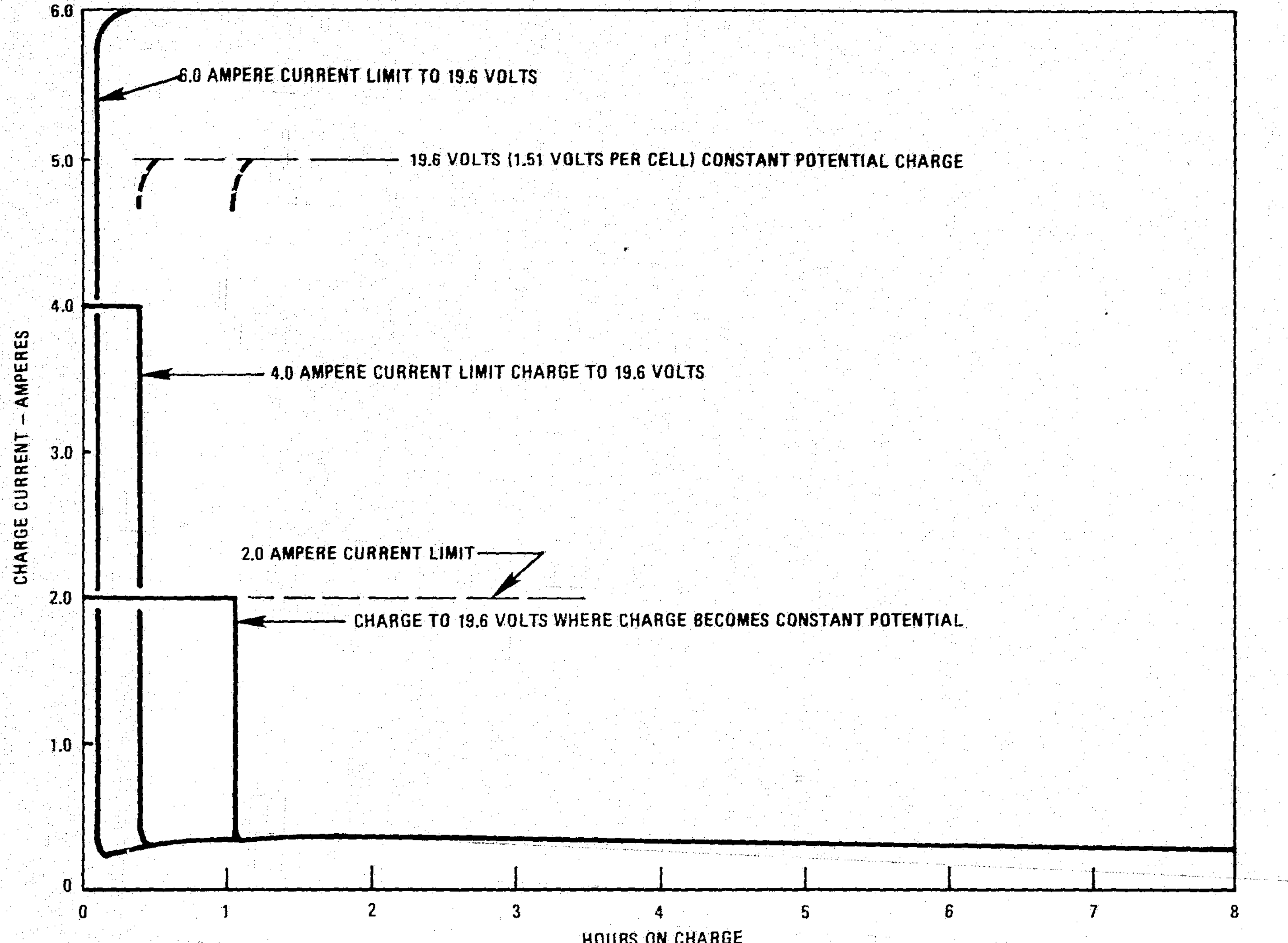

Figure 41. Battery Current as a Function of Time When Constant Potential Charged at 1.51 Volts Per Cell at -20°C, Test 020, Battery 13xYS11S-NM, S/N IMP-003

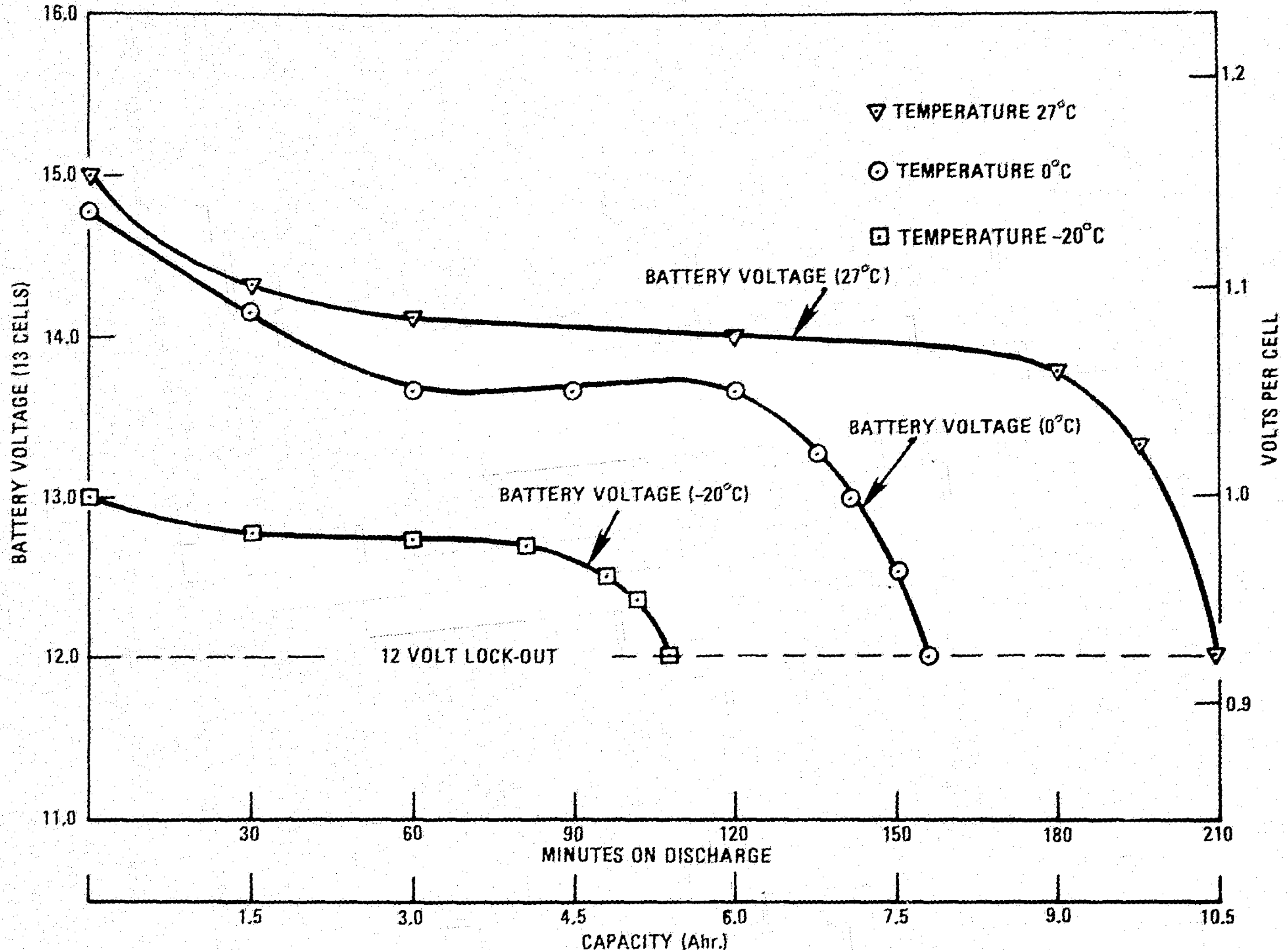

Figure 42. Discharge at 3.0 Amperes to 0.92 Volts Per Cell, Test 020
Battery 13xYS11S-NM, S/N IMP 003

Table 8

TEST 020

Battery 13xYS11S-NM S/N IMP 003

Battery Charge Capacity at 1. 36 Volts Per Cell and for 4 Hours and Eight Hours

Charge Current Limit Amperes	Charge Voltage Limit Volts Per Cell	Ampere Hours In To 1.36 Volts Per Cell	Ampere Hours In - 4 Hours	Ampere Hours In - 8 Hours	Temperature °C
2.0	1.51	3.1	5.7	7.9	27
4.0		2.2	5.4	8.2	27
6.0		1.7	5.3	8.1	27
2.0		3.2	4.7	6.8	0
4.0		2.6	4.7	6.4	0
6.0		2.1	4.6	6.3	0
2.0		2.1	2.8	3.8	-20
4.0		1.6	2.8	3.4	-20
6.0	1.51	0.8	—	—	-20

TEST 021

Test Unit: Cell YS3S-2NM
S/N 092 G8

Test Period: August, 1971

Total Cycling Time: N/A
Number of cycles: 1

TEST BRIEF

The test unit consisted of a three ampere hour cell with a pressure transducer mounted on the fill port. The cell was not encapsulated. There was no data on previous cycling of the cell but it appeared that the cell was an extra unit from a formation lot. Before the initiation of a one ampere reverse current, the cell had been discharged. Cell voltage and pressure were recorded and the one ampere reverse current was monitored on a 50 mv. shunt.

Cell Design Reference: Appendix A

Main Project: General Testing

Applicable Figure: 43

Nominal Depth of Discharge: N/A

CYCLING

The discharged cell was reversed at one ampere until an internal pressure rise resulted. The test temperature was 23°C.

OBSERVATIONS AND CONCLUSIONS:

1. An internal pressure rise of the cell was observed after 0.16 ampere hours was delivered to the cell in reverse. The voltage of the cell at this time was approximately -1.0 volts. See figure 43.

2. The decay voltage of the cell, after the reversal current was removed, is similar to the normal discharge voltage of a silver cadmium cell. This may be due to the fact that the silver electrode contains 10% by weight of CdO and the cadmium electrode contains 5% of silver powder plus a silver grid.

3. The reversal voltage at which the cell stabilized after sixteen minutes of test was monitored for a few minutes. However, during the overall program, it was observed, that if a five ampere hour cell was reversed for several tenths of an ampere hour, it would maintain a low value (-0.1) of negative voltage for several weeks.

4. Some information was found that showed that a five ampere hour cell had been reversed at 27 ma. for six hours and twelve minutes before an internal pressure rise was initiated. This would have resulted in a 0.17 ampere hour reversal. No curves were available.

NOTE: The reversal of cells in a battery causes the individual cells to exhibit unique characteristics quite different from a single cell reversal. Information on a reversal of cells in a battery, during discharge on a converter load, is shown in Section IV.

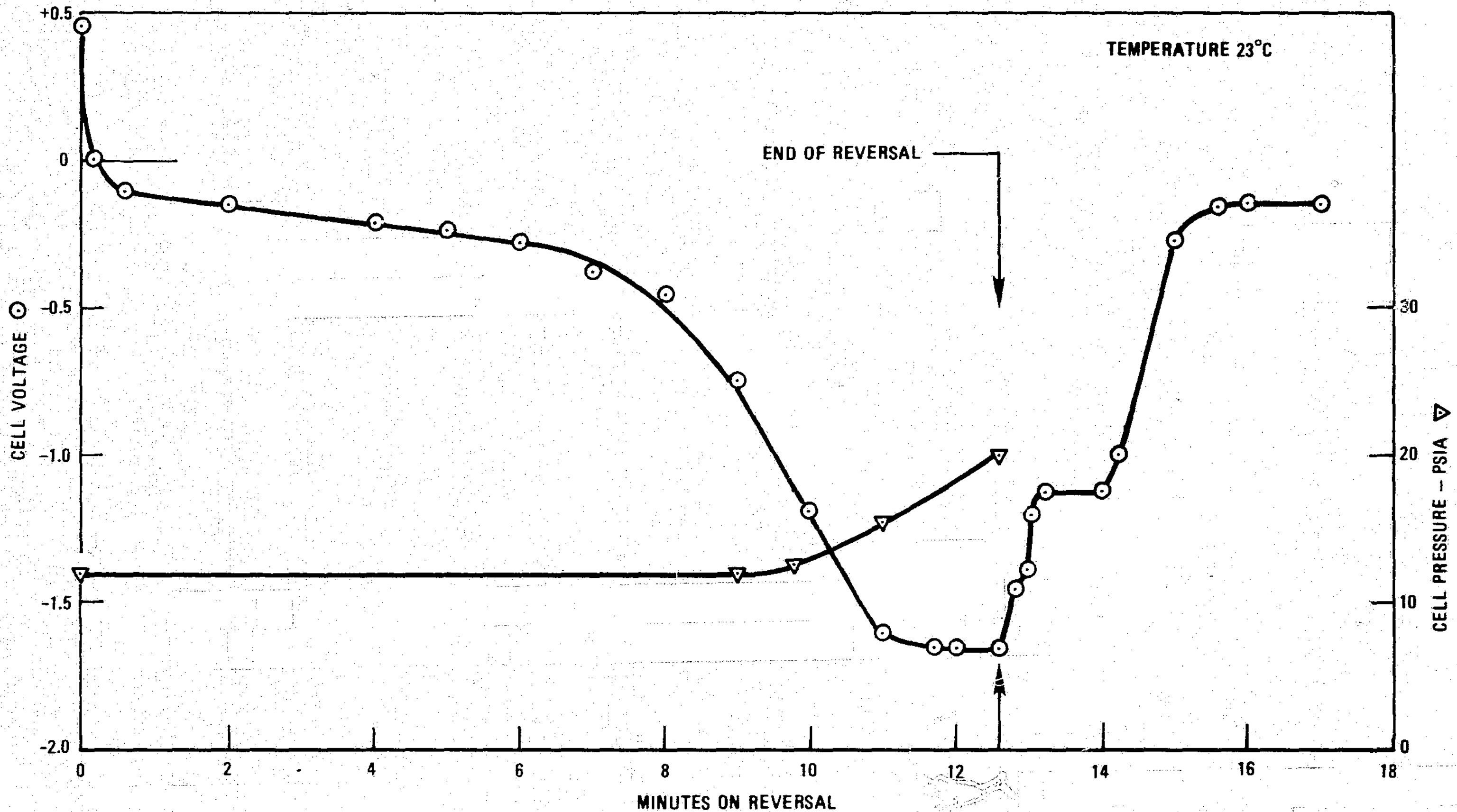

Figure 43. Voltage and Pressure Characteristics of a Three Ampere Hour Cell on 1.0 Ampere Reversal, Test No. 021, Cell YS3S-2NM, S/N 092G8

TEST 022

Test Unit: 10xYS11S-3NM(sh)
S/Ns 001 and 002

Test Period: 1966

Total Cycling Time: 100 hours
Number of Cycles: 3 each

TEST BRIEF

Each battery consisted of ten, eleven ampere hour cells in series. Each cell was individually encapsulated in EPON 834. This size cell was not used in the flight mission, it was designed for a change in mechanical design of the satellite structure. The cells were formed and sealed at GSFC. Twenty vented cells were formed in series and were selected, based on ampere hour capacity, to fabricate two, ten cell batteries, S/Ns 001 and 002. Battery S/N 001 had very closely matched cells. The batteries were stored discharged for seven months at room temperature. After seven months, two capacity cycles were performed on the cells. All cycling was done at room temperature.

Cell Design Reference: Appendix A

Project: Interplanetary Monitoring Platform

Applicable Figure: None

Nominal Depth of Discharge: 100%

TEST 022 (Continued)

CYCLING

Cycle(s)[1] Half Cycle(s)	AHI[2]	AHO[2]	Cycling Parameters (All tests at room temperature)
Fourth Formation Cycle, Cells Vented	12.00 (Average)	11.89 (Average)	Twenty cells were formed. 650 ma. constant current charge to 1.58 volts, each cell. Discharged at 3.0 amperes to 0.80 volts, each cell.
1C and 1D	S/N 001 11.7 S/N 002 11.0	10.17 10.00	687 ma. constant current to 1.55 volts per cell average. Discharge at 2.75 amperes to 0.8 volts, first cell.
2C and 2D	S/N 001 11.51	11.62 (Average)	687 ma. constant current to 1.55 volts per cell average. Note: Battery S/N 002 was removed from charge when the first cell reached 1.55 volts. Discharge at 2.75 amperes to 0.80 volts each cell. Note: Battery S/N 002 was removed from discharge at 0.86 volts per cell average.

(1) C = Charge
D = Discharge
(2) AHI - Ampere Hours In
AHO - Ampere Hours Out

OBSERVATIONS AND CONCLUSIONS:

1. Except for a small amount of loss of ampere hour capacity, there was no deterioration of the cells during the seven month discharged storage at room temperature.

2. Table 7 shows the benefits of good quality control and accurate formation procedures on cell matching with regards to cell capacity, maintenance of cell capacity during storage, charge voltages and uniformity of cell discharge voltage. Battery S/N 001, which contained cells that were matched within 1% by ampere hour capacity on the fourth formation cycle, maintained close capacity and uniform voltage parameters after storage.

Table 9
TEST 022
Cell Formation Capacities and Capacities After Storage
Batteries 10xYS11-3NM(sh) S/Ns 001 and 002

Formation Cycle Cell Number	Cell Formation Capacity Ahr.			Cell Capacity After Storage Cycle 2D			End of Charge and Discharge Voltages Battery S/N 001		End of Charge and Discharge Voltages Battery S/N 002	
	S/N 001		S/N 002	S/N 001		S/N 002	Cycle 2C	Cycle 2D	Cycle 2C	Cycle 2D
Battery S/N 001 3	11.91	Max.		11.68	Max.		1.55	0.80 All cells removed from discharge within 4 min.		
6	11.84			11.49	Min.		1.56			
7	11.84			11.68			1.56			
8	11.88			11.63			1.56			
9	11.84			11.65			1.55			
10	11.88			11.62			1.55			
14	11.89			11.68			1.55			
15	11.85			11.68			1.55			
18	11.86			11.68			1.55			
20	11.83	Min.		11.49			1.55			
Battery S/N 002 1			11.79			11.1 Ahr. Capacity to Cut-off of 0.86 Volts Per Cell Avg.			1.53	0.87
2			12.08						1.52	0.89
4			11.72	Min.					1.55	0.91
5			11.72						1.53	0.84
11			12.24	Max.					1.54	0.88
12			11.72						1.55	0.82
13			11.92						1.53	0.88
16			12.19						1.53	0.87
17			12.03						1.52	0.88
19			11.79						1.54	0.80*
Average →	11.86		11.92	11.62		11.1	1.55		1.53	0.86

*Battery S/N 002 Cut-Off when this Cell Reached 0.80 Volts

TEST 023

Test Units: Batteries 13xYS5S-2NM
S/N 009 and S/N 010

Test Period: 1965

Total Cycling Time: 200 Hours
Number of cycles: 20

TEST BRIEF

Each battery consisted of thirteen, five ampere hour cells in series encapsulated in EPON 834. The batteries were tested in parellel, with diode isolation on charge and discharge, as shown in the circuit diagram in figure 44. Most of the simulated orbital cycling was at 27°C in ten hour orbits with a one hour discharge time. A voltage clamp and current limit were used during charging. The total constant current on discharge delivered by the two batteries was 2.5 to 3.6 amperes. Wet life of the battery at the beginning of test was less than six months.

Cell Design Reference: Appendix A

Main Project: Development

Applicable Figures: 44, 45, 46, 47

Nominal Depth of Discharge (per battery): 27% to 36%

CYCLING

Cycle(s)[1] Half Cycle(s)	AHI[2]	AHO[2]	Cycling Parameters (All tests of 25°C to 27°C)
1C and 1D	5.6(009) 6.1(010)	5.5(009) 5.6(010)	Constant potential charge at 1.50 volts per cell average current limited at 2.0 amperes for 15.0 hours. Discharge at 2.5 amperes to less than 0.9 volts per cell average, each battery

(1) C = Charge
D = Discharge

(2) AHI - Ampere Hours In
AHO - Ampere Hours Out
} Numbers in ( ) refer to battery serial numbers

Cycle(s) Half Cycle(s)	AHI	AHO	Cycling Parameters (All tests of 25°C to 27°C)
2C	5.5(009 5.8(010)		Same as 1C
2D		1.7(009) 1.4(010)	Constant current discharge at 2.8 amperes for 1.15 hours.
3C	1.5(009) 1.3(010)		Constant potential charge at 1.50 volts per cell average current limited at 1.0 ampere for nine hours.
3D		1.7(009) 1.9(010	Constant current discharge at 3.6 amperes for 1.0 hours.
4C	2.2(009) 1.9(010)		Same as 3C.
4D		1.7(009) 1.2(010)	Constant current discharge at 2.8 amperes for 1.0 hours.
5C	1.4(009) 1.1(010)		Same as 3C.
5D		1.8(009) 1.2(010)	Constant current discharge at 2.9 amperes for 1.0 hours.
6C	1.8(009) 1.3(010)		Same as 3C

Information between 6D and 20C is incomplete

20D		5.2(009) 5.4(010)	Constant current discharge at 2.6 amperes to 0.9 volts per cell average, each battery.

Previous to cycle 12, the two batteries were unbalanced, i.e., 1.5 ampere hours were removed from battery S/N 009 and no capacity was removed from S/N 010. Then the two batteries were charged in parallel and as seen in figure 44. For a short time battery S/N 010 charged 009. During the charge, the diodes shown in fig. 44 were shorted. As can be seen on the last discharge (20D), the two batteries had equalized in capacity during the cycles following cycle 12.

OBSERVATIONS AND CONCLUSIONS:

1. On these short term tests, the batteries could be operated in parallel and the ampere hour capacity returned to each battery even though there was no equalization of capacity during each charge and discharge. Equalization of the battery capacities would occur, after eight cycles, even though the capacity of the two batteries were purposely unbalanced by 1.5 ampere hours. Figures 45, 46 and 47 are typical charge and discharge curves for this test.

2. Some data was located, on two, five cell, twelve ampere hour batteries that were operated in parallel for 1.5 years. These batteries were run in a ten hour orbital period with a one hour discharge time. Discharge current was 6.0 amperes for the two batteries. Charging was constant potential at 1.50 volts per cell average current limited at 2.4 amperes. A capacity check, made at 85 cycles, showed each battery to have greater than 4.5 ampere hours. On cycle 1310, the last cycle, the capacities were 2.8 and 3.5 ampere hours. This latter test was performed by the Naval Weapons Support Center, Crane, Indiana.

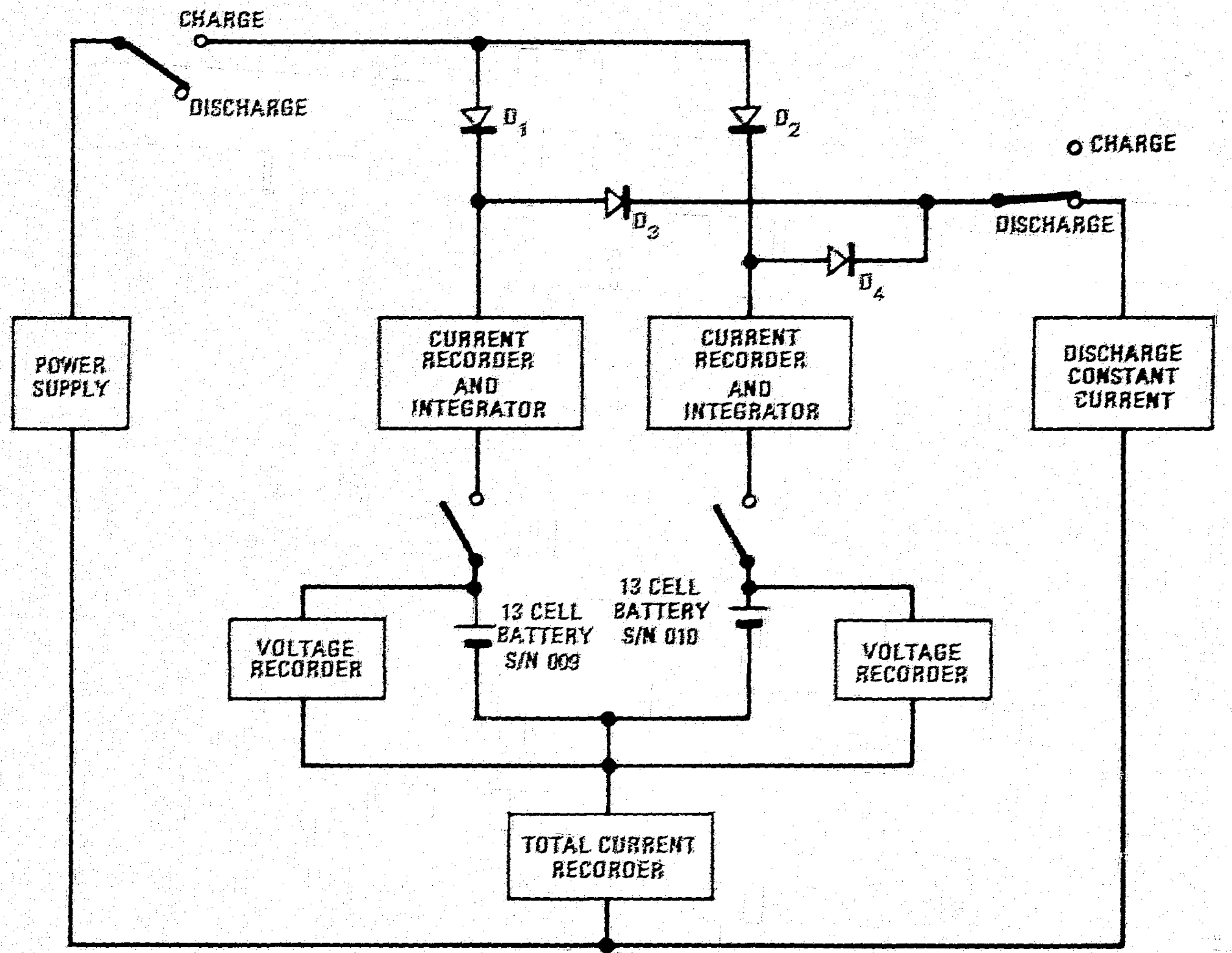

Figure 44. Equipment used in Parallel Charging Test

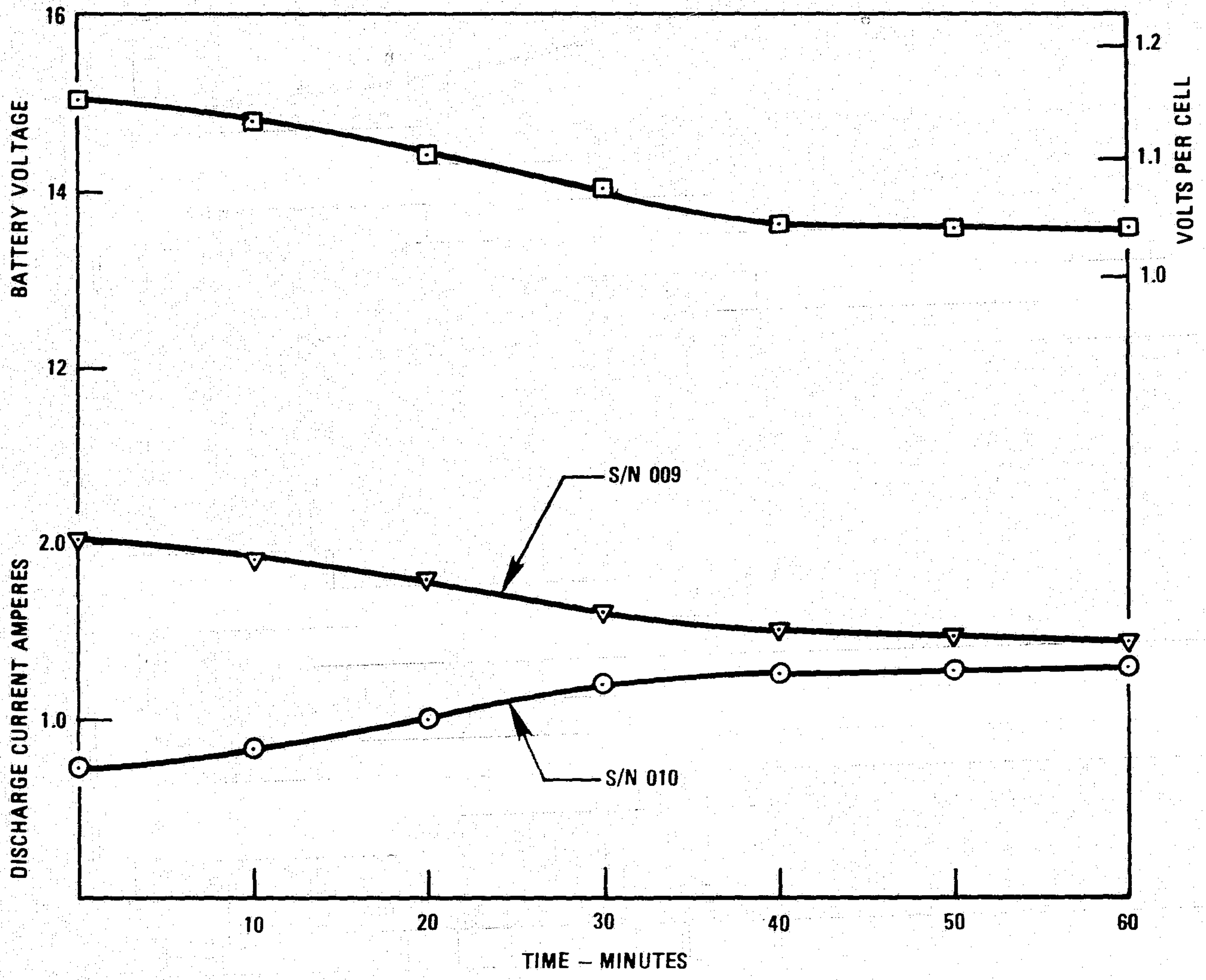

Figure 45. Parallel Operation of Silver Cadmium Batteries at 27°C
Test 023, Batteries 13xYS5S-2NM, S/N 009 and S/N 010

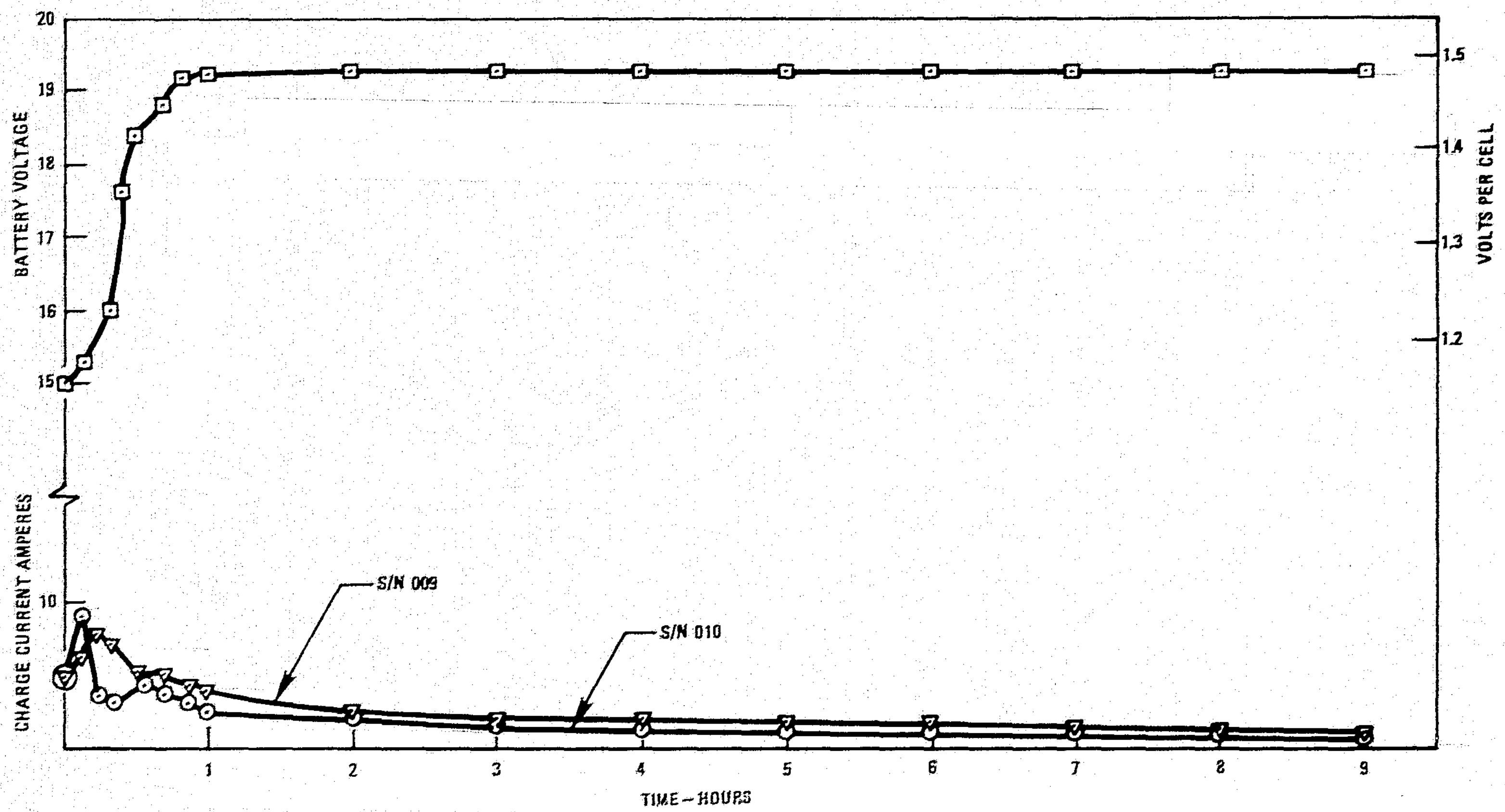

Figure 46. Parallel Operation of Silver Cadmium Batteries at 27°C
Test 023, Batteries 13xYS5S-2NM, S/N 009 and S/N 010

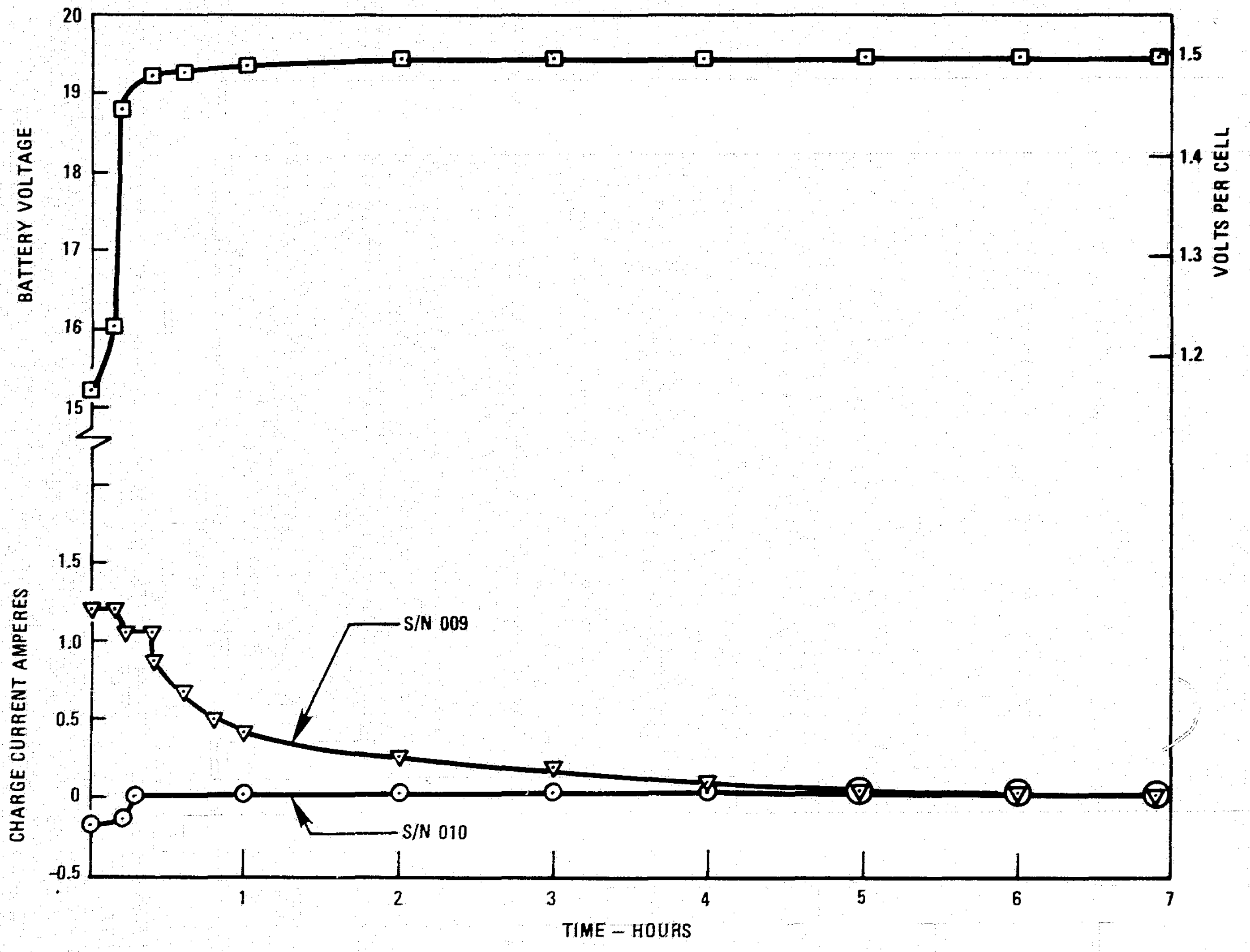

Figure 47. Parallel Operation of Silver Cadmium Batteries at 27°C
Test 023, Batteries 13xYS5S-2NM, S/N 009 and S/N 010

SECTION III

LONG TERM TESTS

This Section of the Report includes data and information related to long term cycling and cycling to failure of sealed silver cadmium batteries. All tests were performed at the Naval Weapons Support Center (NWSC) in Crane, Indiana. All test units were comprised of silver cadmium cells manufactured by the Yardney Electric Company. Automatic cycling, or simulated orbital cycling, reported in this Section is based on orbit times between 3.7 hours and 96 hours. Usually the design requirement for life in orbit was one year. However, since some satellites were monitored for greater than a year, the cycle tests were run to failure. Failure was the inability of the battery, or any of the cells, to deliver the nominal depth of discharge defined by the test plan. Over the test temperature range of -10°C to 40°C, it was required that this capacity be delivered at greater than 1.0 volt per cell.

The data and information is grouped as follows:

(1) Tests 100 through 105 are long term tests or cycled to failure tests. As in Section II of this Report, these test summaries include a TEST BRIEF, CYCLING and OBSERVATIONS AND CONCLUSIONS. All tests with the exception of Test 105 are project related.

(2) Tables 11 and 12 summarize the general testing of sealed silver cadmium batteries for long periods of time to failure. These tests are separated into twenty-four and eight hour orbits. These data should be coordinated with the capacity check data, for each Test Pack, on Tables 13 and 14. From the data it is concluded that the life of these cells, at low nominal depths of discharge (NDOD) and in twenty-four hour orbits, is 1.4 to 2.0 years at 25°C and approximately four years at 0°C. Life at 40°C is one year or less. (Note: One test, not shown, resulted in 0.2 year life at 50°C in a twenty-four hour orbit, 20% NDOD.) Combining the information of Tests 103 and 104 of the first group of tests with the tabulated data on eight hour orbits, Table 12, it is estimated that the cycle life at low nominal depths of discharge in eight hour orbits and between 0°C and 25°C is 1.4 years.

(3) Table 15 is a summary of project related tests that were removed from test before failure. These batteries were cycled for 0.41 and 0.47 years.

(4) Table 16 is a summary of cycle tests with early failure. Listed on Table 16 is the cell component, treatment or production defect that was the probable cause for early failure.

As in Section II of this report, cell design information follows the same method of coding and the cell design parameters are included in Appendix A. The special cell designs, called out in Tables 11 and 12, are included in Appendix A.

TEST 100

Test Unit: 13xYS5S-4NM
S/N IMP 18

Test Period: 1965 - 1966

Total Cycling Time: 5100 Hours
Number of Cycles: 1351

TEST BRIEF

The battery consisted of thirteen, five ampere hour cells in series encapsulated in EPON 834. The battery configuration, shown in Illustration 4, is the design flown on the first three Interplanetary Monitoring Platforms. After the initial capacity checks, the battery was put on simulated orbital cycling with a 1.3 ampere discharge for 0.5 hours followed by a constant potential charge for 3.23 hours current limited at 280 ma. For the first 670 cycles, the voltage clamp was set at 1.30 volts per cell. This clamp would limit charging to the lower plateau (Ag_2O plateau) and thereby avoid the problem of cell unbalance that occurs at end of charge when the battery is allowed to accept a full charge, e.g., at 1.51 volts per cell. After the completion of approximately 670 simulated orbital cycles, the battery was capacity checked, and another 670 cycles were performed on the battery except the voltage clamp was set at 1.51 volts per cell. Total battery voltage and currents were continuously recorded and cell voltages were monitored especially at end of charge and discharge. All tests were at room temperature. Wet life of the battery at the beginning of the cycling test was seven months. During this time, the battery had been stored discharged at room temperature.

Cell Design Reference: Appendix A

Project: Interplanetary Monitoring Platform

Applicable Figures: None

Nominal Depth of Discharge: 13%

TEST 100 (Continued)

CYCLING

Cycle(s)[1] Half Cycle(s)	AHI[2]	AHO[2]	Cycling Parameters (All Tests at Room Temperature)
1C and 1D	INC[3]		
2C and 2D	5.4	5.2	300 ma. constant current charge to 1.54 volts per cell average. Discharge at 1.3 amperes to 0.92 volts per cell average.
3C and 3D	5.5	5.5	300 ma. constant potential charge to 1.51 volts per cell average. Cut-off charge when current is 50 ma. Discharge at 1.3 amperes to 0.92 volts per cell average.
4C and 4D	1.5	1.6	300 ma. constant current charge to 1.30 volts per cell average. Discharge at 1.3 amperes to 0.92 volts per cell average.
5C	1.6		300 ma constant current charge to 1.30 volts per cell average.
6D and 675C			Discharge at 1.3 amperes for 0.5 hours. Constant potential charge to 1.30 volts current limited at 280 ma. for 3.23 hours.
675D		0.8	In-cycle capacity check. Discharge at 1.3 amperes to 0.52 volts per cell average.

(1) C = Charge
    D = Discharge
(2) AHI - Ampere Hours In
    AHO - Ampere Hours Out
(3) Information Not Complete

Cycle(s) Half Cycle(s)	AHI	AHO	Cycling Parameters (All Tests at Room Temperature)
675C and 676D	INC	2.3	Constant potential charge to 1.51 volts per cell average current limited at 1.3 amperes. Cut-off charge when current is 50 ma. Discharge at 3.0 amperes to 0.92 volts per cell average.
678C and 678D	3.9	3.7	Constant potential charge to 1.54 volts per cell average, current limited at 300 ma. Discharge at 1.3 amperes to 0.92 volts per cell average. Note: Previous to 697C, all cells shorted overnight on 0.5 ohms.
679C and 679D	4.2	3.6	
680C	3.8		
680D to 1350C			Discharge at 1.3 amperes for 0.5 hours. Constant potential charge to 1.51 volts per cell for 3.23 hours current limited at 280 ma.
1350D		3.3	In-cycle capacity check. Discharge at 1.3 amperes to 0.92 volts per cell average.
1351C and 1351D	3.3	3.4	300 ma. constant current charge to 1.54 volts per cell average. Discharge at 1.3 amperes to 0.92 volts per cell average.

OBSERVATIONS AND CONCLUSIONS:

1. The battery was subjected to 1351 cycles and no cell failures or leakage occurred. As a result of cycling, a permanent loss of approximately two ampere hours of battery capacity resulted.

2. When the battery was cycled with the 1.30 volt per cell clamps, the discharge voltage was maintained between 1.08 and 0.90 volts per cell during the first 330 cycles. For the remaining cycles, the battery voltage was maintained between 1.08 and 0.8 volts per cell. During this cycling, the cells maintained good balance at end of discharge. On in-cycle capacity check 675D, the cell voltages at end of discharge were between 0.50 and 0.60 volts.

3. When the battery was cycled with the 1.51 volt ampere cell clamp, the discharge voltage was maintained between 1.23 and 1.05 volts per cell. During this cycling, the cells had good balance at end of discharge. On in-cycle capacity check 1350D, the cell voltages at end of discharge were between 1.02 and 0.84 volts.

4. During cycling at the 1.30 volt per cell voltage clamp, an unbalance did occur at end of charge. Typical data is shown in Table 10. End of charge currents were of the order of 20 ma.

5. During cycling at the 1.51 volt per cell voltage clamp, end of charge voltages were between 1.49 and 1.53 volts per cell. This narrow voltage range was due to the fact that no low level of float charging occurred during the short charging time allowed. End of charge currents were of the order of 50 ma. As a result of this test the constant potential charge method was devised where charge current was sensed and the charge voltage lowered to 1.41 volts per cell when the current tapered to approximately 50 ma. In this case, as with other ampere hour size cells, this value of cut off current was approximately the nominal cell capacity divided by 100.

Table 10
TEST 100
Battery 13xYS5S-4NM
S/N IMP 18

Cell Unbalance at End of Charge with 1.30 Voltage Clamp

Cycle → Cell No.	11	90	150	250	350	450	550	650	674
1	1.43	1.43	1.43	1.44	1.45	1.43	1.45	1.42	1.46
2	1.46	1.17	1.18	1.35	1.32	1.30	1.34	1.18	1.18
3	1.45	1.50	1.17	1.44	1.18	1.30	1.19	1.18	1.17
4	1.16	1.16	1.17	1.42	1.18	1.17	1.34	1.24	1.18
5	1.45	1.17	1.43	1.27	1.18	1.17	1.37	1.22	1.17
6	1.16	1.16	1.17	1.19	1.24	1.31	1.20	1.18	1.17
7	1.18	1.28	1.17	1.18	1.18	1.17	1.20	1.32	1.37
8	1.17	1.17	1.17	1.19	1.18	1.17	1.20	1.17	1.18
9	1.18	1.6	1.34	1.17	1.45	1.31	1.19	1.42	1.47
10	1.45	1.44	1.43	1.44	1.45	1.43	1.45	1.44	1.46
11	1.45	1.44	1.43	1.44	1.44	1.35	1.44	1.44	1.45
12	1.17	1.44	1.45	1.18	1.44	1.43	1.44	1.44	1.44
13	1.20	1.45	1.43	1.44	1.46	1.44	1.44	1.44	1.46
Current ma.→	43	25	18	21	20	17	17	16	17

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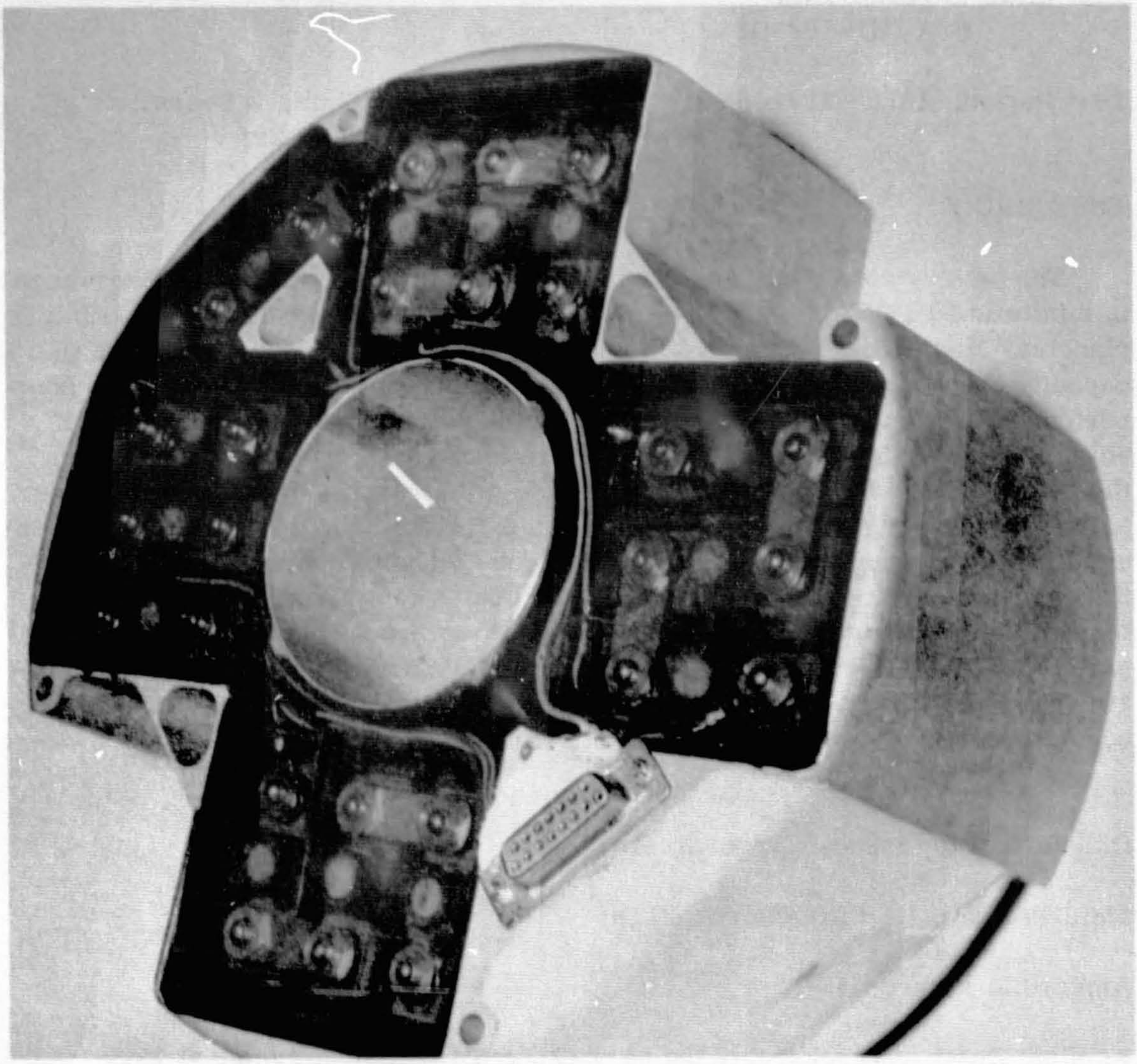


Illustration 4. Interplanetary Monitoring Platform Battery
S/N 18

TEST 101

Test Unit: 5xYS10S-4NM
S/N IMP-IP2-O2

Test Period: 1971 - 1974

Total Cycling Time: 3 Years
Number of Cycles: 291

TEST BRIEF

The battery consisted of five, ten ampere hour cells in series encapsulated in mixture of EPON resins. The cells were the remaining cells from the Interplanetary Monitoring Platform I (Explorer XLIII) formation lot. After the initial capacity checks, the battery was put on simulated orbital cycling with a 96 hour period and 0.5 hour discharge time. Charging was constant potential at 1.51 volts per cell with a lowering of the voltage clamp to 1.41 volts per cell when the charge current tapered to 100 ma. Charge current was limited to 1.0 amperes. Discharge currents during simulated orbital cycling ranged between 2.5 and 3.5 amperes for 0.5 hours. Approximately 90% of the discharges were at 2.75 amperes. Most cycling was performed between 0°C and 10°C. Total battery voltage and currents were continuously recorded. Cell voltages were recorded manually during charge and discharge. Wet life of the battery at the beginning of the test was less than one month. During this time the battery had been stored discharged at room temperature.

Cell Design Reference: Appendix A

Main Project: IMP I (Explorer XLIII)

Applicable Figure: 48

Nominal Depth at Discharge: Between 12% and 18%. Most cycles at 13%.

TEST 101 (Continued)

CYCLING

Cycle(s)[1] Half Cycle(s)	AHI[2]	AHO[2]	Cycling Parameters (All Tests at 0°C to 10°C)
1C and 1D 2C	8.1 INA[3]	8.0	Constant potential charge at 1.51 volts per cell average current limited at 1.0 ampere. Cut-off charge at 100 ma. Discharge at 4.4 amperes to 0.9 volts per cell average.
2D to 104C			Constant potential charge at 1.51 volts per cell average current limited at 1.0 ampere. Reduce voltage clamp to 1.41 volts per cell average when charge current tapers to 100 ma. Total charge time equals 95.5 hours. Discharge between 2.5 and 3.5 amperes for 0.5 hours.
104D		3.9	In-cycle capacity check. Discharge at 4.4 amperes to 0.9 volts per cell average.
105C	INA		Charge same as cycle interval 2D to 104C.
105D - 181C			Same as cycle interval 2D to 104C.
181D		INA	In-cycle capacity check. Discharge at 4.4 amperes to 0.9 volts per cell average.
182C	4.0		Charge same as in cycle interval 2D to 104C.
182D - 291C			Same as cycle interval 2D to 104C.
291D		2.4	In-cycle capacity check. Discharge at 4.0 amperes till the first cell reached 0.50 volts.

(1) C = Charge
D = Discharge
(2) AHI - Ampere Hours In
AHO - Ampere Hours Out
(3) Information Not Available

TEST 101 (Continued)

OBSERVATIONS AND CONCLUSIONS:

1. During the greater than three years of cycling at 0°C, there were no indications of cell failure. During cycling, there was a permanent loss of 5.6 ampere hours of battery capacity.

2. During simulated orbital cycling, the battery recharged, i.e., tripped to the lower voltage clamp in less than four hours. Cell voltage unbalance at the 1.41 per cell float voltage was negligible. When recorded, cell voltages previous to the trip did not exceed 1.55 volts.

3. No cell reversal occurred on the in-cycle capacity checks. On in-cycle capacity check 291D, the cell voltages at end of discharge were as follows: 1.025, 1.029, 1.013, 0.050, and 0.920.

4. As shown in figure 48, for greater than 95% of the simulated orbital cycling the discharge voltage was essentially flat. As forementioned, this voltage characteristic occurs when long periods of float charging are used. Occasionally during testing, fast speed recorders or scopes were used to determine the initial voltage during the initial few milliseconds of discharge at 2.75 to 3.50 amperes. These voltages ranged between 0.98 and 1.00 volts per cell.

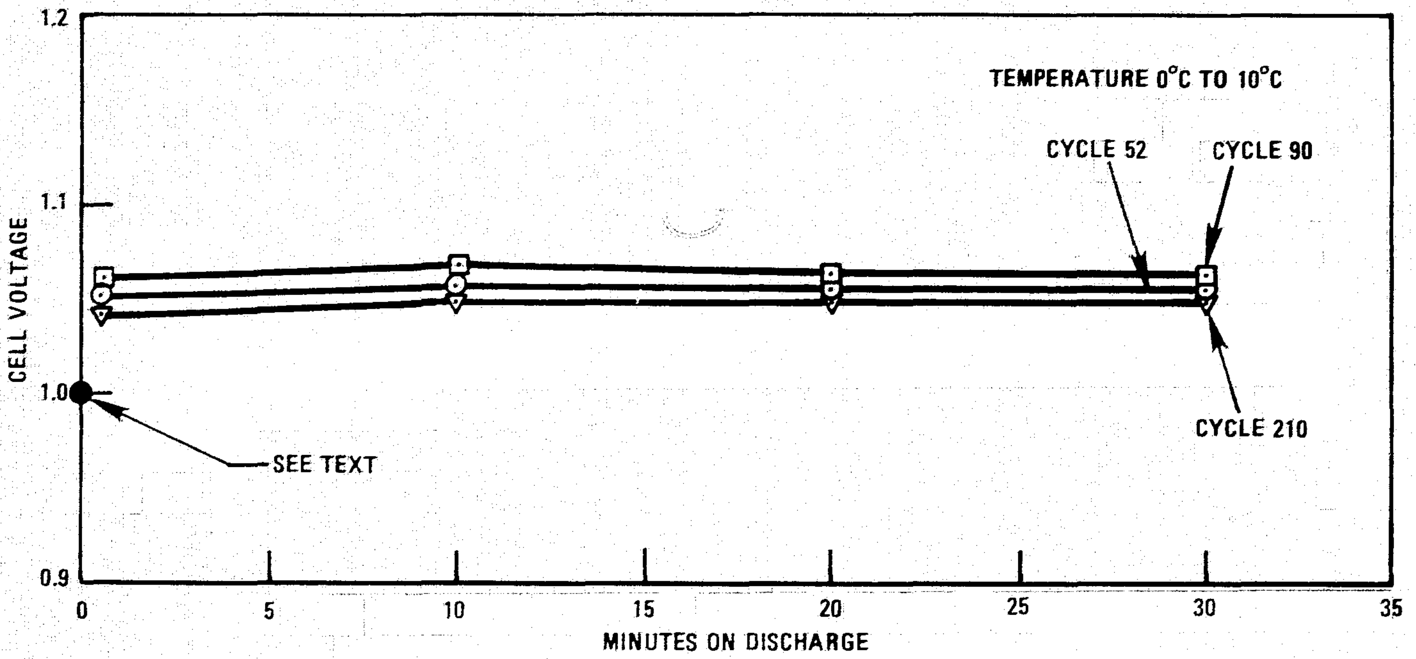


Figure 48. Voltage on Discharge at 2.75 Amperes, Test 101
Battery 5xYS10S-4NM, S/N IMP – IP2-02

TEST 102

Test Unit:	Battery 13xYS5-5NM S/N IMP-G-008 S/N IMP-G-004	IMP-G-008 Total Cycling Time: 3.2 Years Number of Cycles: 87
Test Period:	1967 - 1973	IMP-F-004 Total Cycling Time: 2.0 Years Number of Cycles: 23

TEST BRIEF

Each battery consisted of thirteen, five ampere hour cells in series, encapsulated in EPON resins. The battery configuration, shown in Illustration 5, is the design flown on Interplanetary Monitoring Platforms (IMP) F and G, Explorers XXXIV and XLI. Battery S/N IMP-G-008 was the flight spare battery for the IMP G Spacecraft and battery IMP-F-004 was the spare battery for the IMP F Spacecraft. Since these spacecraft were flown in highly elliptical orbits, with an orbital period of 3.3 days, the shadow times (discharge times) only occurred occasionally as shown in figure 49. Therefore, this test is primarily a charged storage test wherein the battery is on float charge, most of the time, at 1.41 volts per cell.

Two groups of twenty cells each were formed at GSFC and thirteen cells from each group, were selected for each spare battery. The cells were sealed in the battery configuration, vibrated per the DELTA Launch Vehicle Vibration Schedule and had been subjected to some cycling in thermal vacuum tests (-10°C to 40°C). During the life testing of each battery, the discharge currents were 2.5 amperes. The temperature of the IMP-G-008 battery was varied according to orbital changes. Low temperatures associated with in-cycle capacity checks correspond to the lowering of the temperature of the satellite as it transverses long shadows. In highly elliptical orbits, a satellite will encounter these long shadows occasionally when it goes through the earth's shadow at apogee. The temperature of the IMP-F-004 battery was maintained at 15°C during the test program. Wet life of the IMP-G-008 battery at the beginning of test was eight months and the wet life of the IMP-F-004 battery was ten months.

Cell Design Reference: Appendix A

Main Project: Interplanetary Monitoring Platforms (IMP) F and G.
(Explorers XXXIV and XLI)

Applicable Figure: 49

Nominal Depth of Discharge: Variable, See Test Brief.

CYCLING

I. Battery IMP-G-008

Cycling was performed as outlined in the Test Brief. Discharge times were varied as shown in figure 49 and changes in temperature followed the schedule as shown below. In-cycle capacity checks, on the days shown on figure 49, yielded the following results.

Day	Temperature °C		Ampere Hours Out
0	25		4.2
228	3	-17	4.7
231	10	-22	4.6
592	10	0	1.9
1150	0		0.8
1151	0	25	1.1

As indicated, on days 228, 231, and 592 the temperature was varied during the discharge to simulate the cooling of the satellite as it transversed the earth's shadow at apogee. On day 1151, the temperature of the battery was increased to compare the capacity with the initial capacity.

II. IMP-F-004

Cycling was performed as outlined in the Test Brief. However, only one series of discharges was run where the discharge times increased from five minutes to twenty-three minutes and then decreased to eight minutes. The shape of the curve, similar to Shadow Period II on figure 49, covered an 88 day period. These discharges were run at the beginning of the test program. After this discharge period, the battery was put on a float charge of 1.41 volts per cell for the remainder of the test.

OBSERVATIONS AND CONCLUSIONS:

I. Battery IMP-G-008

1. On day 481, cell S/N 002 began charging at a lower voltage of approximately 1.2 volts. This condition persisted for the remainder of the test. This cell would limit ampere hour capacity on the in-cycle capacity checks. On the final capacity determinations, this cell was leaking electrolyte.

II. Battery IMP-F-004

1. After one year of test, cell S/N 002 began charging at a lower voltage of approximately 1.2 volts. This condition persisted for the remainder of the test. After two years of test, the battery failed, i.e., most of the cells exhibited an open circuit voltage of less than 1.41 volts. The battery could not be discharged and leakage was occurring throughout the battery assembly.

General

From the test data, it appeared that this lot of cells was marginal in performance. The initial ampere hour capacities were low and the low voltage charging that occurred during float charging at 1.41 volts per cell occurred prematurely. However, the batteries flown on IMP G and IMP F lasted at least three years and two years, respectively.

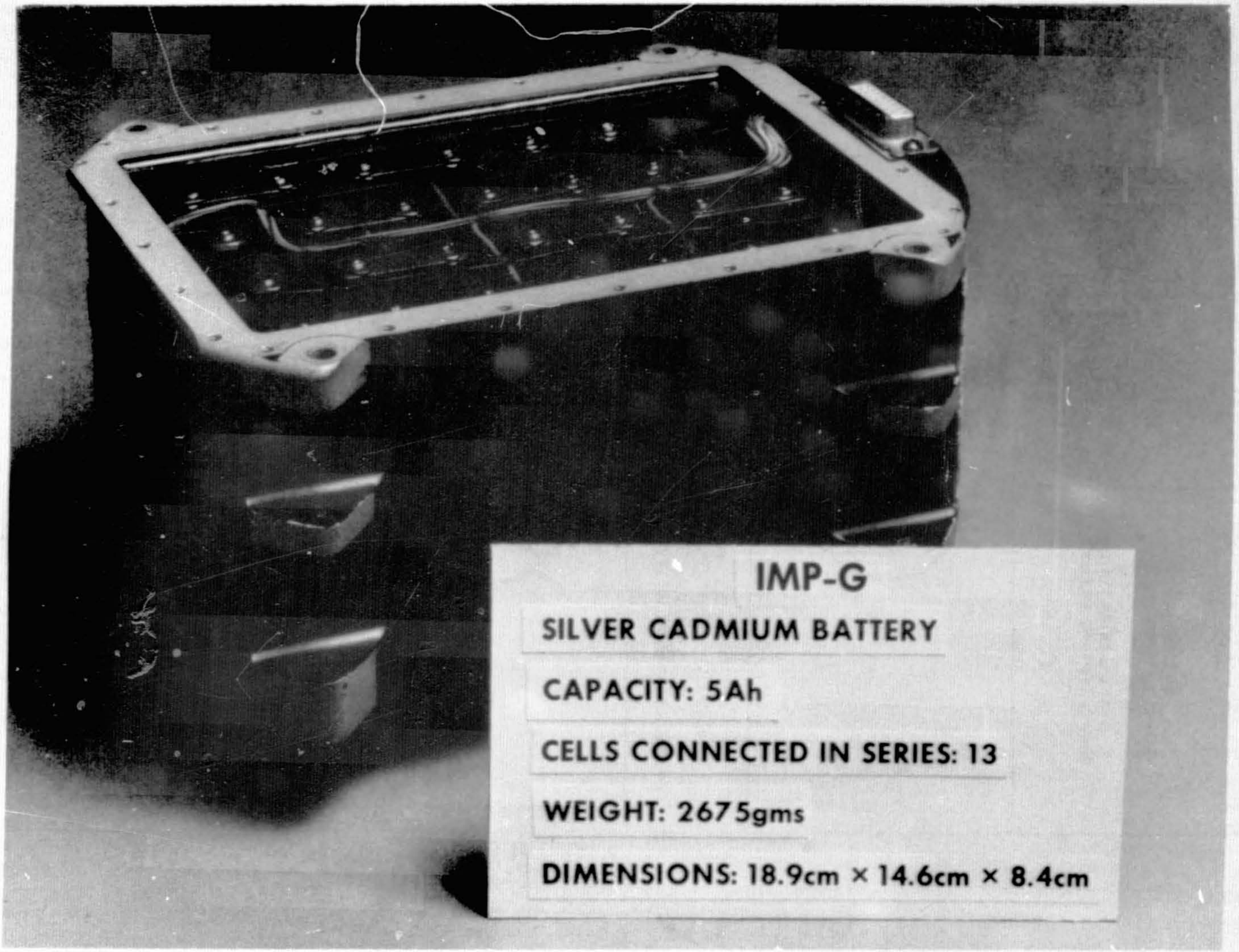


Illustration 5. Battery for Interplanetary Monitoring Platforms F & G

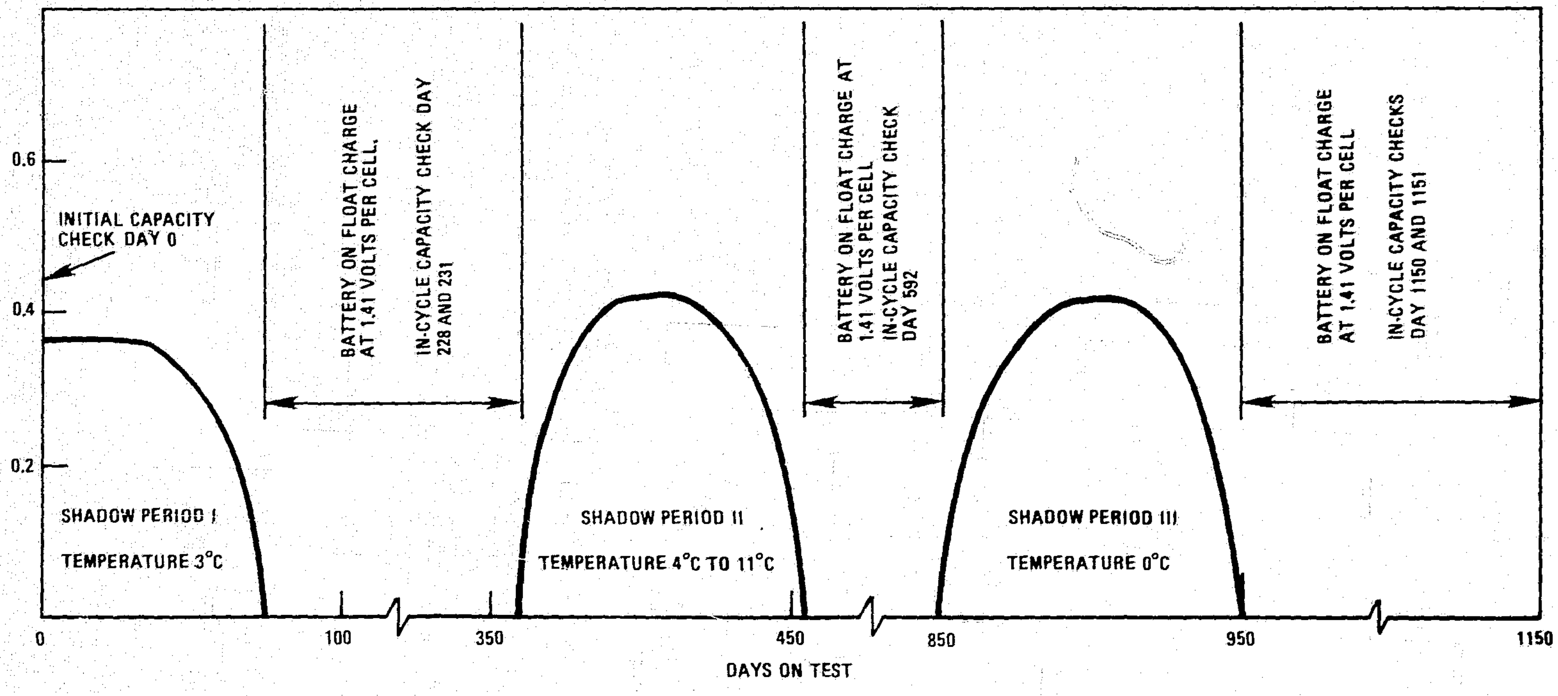


Figure 49. Discharge Times (Shadow Periods) During Test, Test No. 102
Battery 13xYS5S-5NM, S/N IMP-G-008

TEST 103

Test Unit: 13xYS10S-2NM
S/N IMP-10

Test Period: 1967 - 1969

Total Cycling Time: 1.4 Years
Number of Cycles: 1088

TEST BRIEF

The battery consisted of thirteen, ten ampere hour cells encapsulated in EPON resins as shown in Illustration 6. Twenty-seven cells were formed at GSFC in order to select cells that would have an ampere capacity within 5% of the average for thirteen cells. These cells were manufactured in 1962, before improved quality control methods were imposed on production. Test results of cells from the same formation lot are reported in Test 104. The battery test was performed on spacecraft power system equipment, obtained from a previous mission. After the initial capacity check, the battery was put on simulated orbital cycling with a 11.5 hour period and 0.5 hour discharge time. Discharge current was 2.8 amperes. Charging was constant potential at 1.51 volts per cells with a lowering of the voltage to 1.41 volts per cell when the charge current tapered to 100 ma. Charge current was limited to 2.5 amperes. Simulated orbital cycling was performed between the temperature ranges of 5°C and 10°C. Total battery voltages were continuously recorded. Cell voltages were recorded manually during charge and discharge.

Cell Design Reference: Appendix A

Main Project: Interplanetary Monitoring Platform E, (Explorer XXXV)

Applicable Figures: None

Nominal Depth of Discharge: 14%

TEST 103 (Continued)

CYCLING

Cycle(s)[1] Half Cycle(s)	AHI[2]	AHO[2]	Cycling Parameters (All simulated orbital cycles at 5° to 10°C. Initial and final capacity checks at 25°C)
Initial Capacity Check	12.2	12.0	Constant current charge at 600 ma. to 1.55 volts, first cell. Discharge at 2.5 amperes to 0.9 volts per cell, average.
2C	12.0		Charge same as above.
2D to 542C			Constant potential charge at 1.51 volts per cell average. Current limited at 2.5 amperes. Reduce voltage clamp to 1.41 volts per cell average when current tapers to 100 ma. Charge time eleven hours. Discharge at 2.5 amperes for 0.5 hours.
542D		6.5	In-cycle capacity check. Discharge current 2.8 amperes to 0.90 volts per cell average.
543C	6.2		Same as charge in cycle interval 2D to 542C except time was 24 hours.
543D to 1067C			Same as cycle interval 2D to 542C.
1067D		5.6	In-cycle capacity check. Same as in-cycle capacity check 542D.

(1) C = Charge
D = Discharge

(2) AHI - Ampere Hours In
AHO - Ampere Hours Out

TEST 103 (Continued)

Cycle(s) Half Cycle(s)	AHI	AHO	Cycling Parameters
1068C	5.7		Same as charge in cycle interval 2D to 542C except for 25 hours.
1068D to 1087C			Same as cycle internal 2D to 542C.
1087D		1.3	In-cycle capacity check. Same as in-cycle capacity check 542D.
1088C	1.4		Constant current charge at 600 ma. to 1.55 volts, first cell.

OBSERVATIONS AND CONCLUSIONS:

1. On cycle 1701 and thereafter, cell S/N 011 would float charge between 1.36 and 1.39 volts when the float voltage was 1.41 volts per cell.

2. On in-cycle capacity checks 542D and 1067D, cell voltages at the end of discharge were 0.86 to 0.91 and 0.87 to 1.0 volts, respectively. Cell reversal did occur on the last in-cycle capacity check.

3. For greater than 95% of the simulated cycling, the discharge voltage was essentially flat, i.e., there was no upper plateau (AgO plateau) present. Average discharge voltages were between 1.07 to 1.05 volts per cell.

4. On cycle 1087D the battery failed since it could only deliver the ampere hours required in the simulated orbital cycling test. At that time, the battery was leaking.

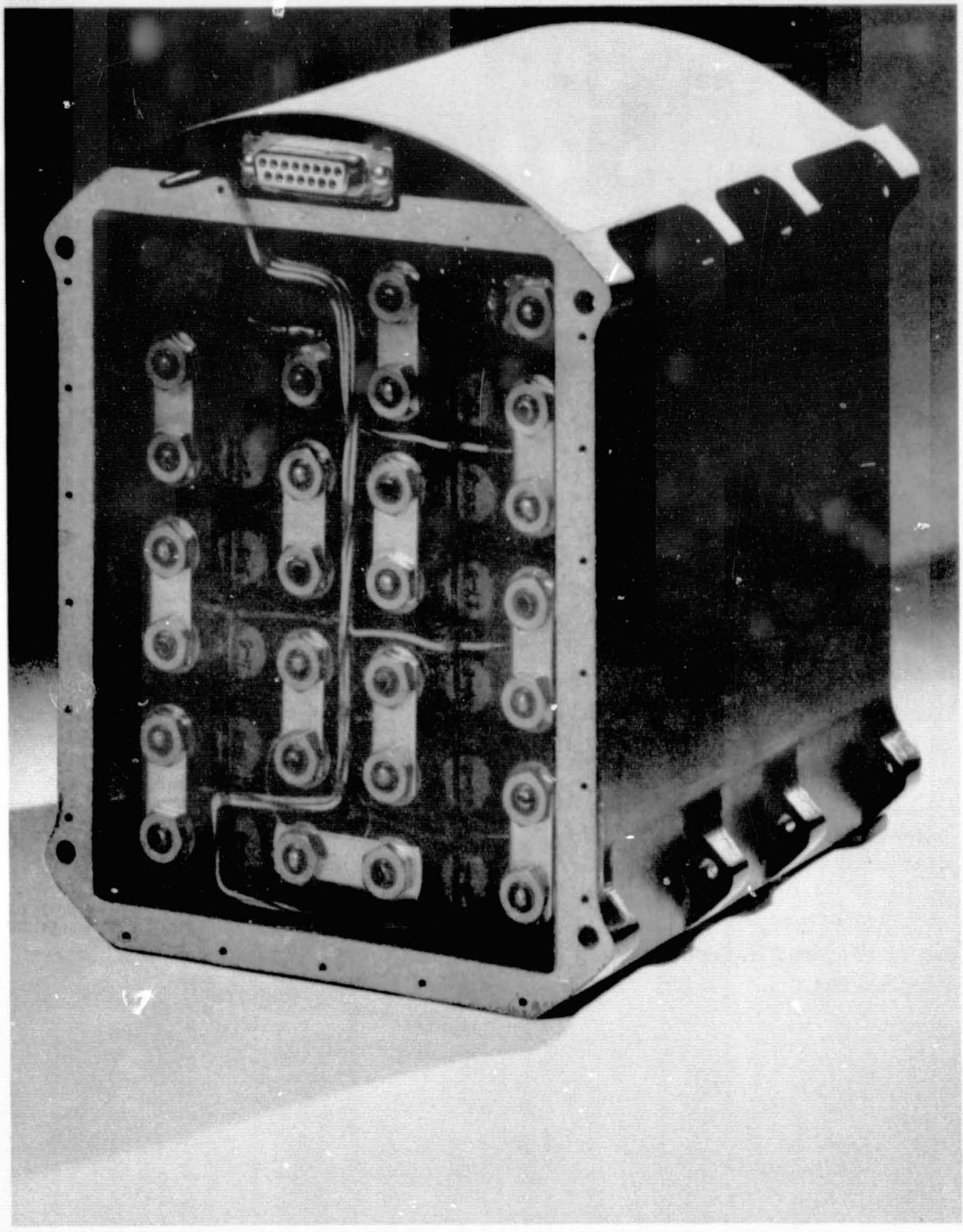


Illustration 6. Interplanetary Monitoring Platform Battery
S/N IMP-10

TEST 104

Test Unit: 5xYS10S-2NM
S/N IMP 45D

Test Period: 1967 - 1969

Total Cycling Time: 1.6 Years
Number of Cycles: 1756

TEST BRIEF

The battery consisted of five, ten ampere hour cells individually encapsulated in EPON resins. These cells were selected from the extra cells of the formation lot from which the IMP E (Explorer XXXV) cells were obtained. See Test 103. After an initial capacity check, the battery was put on simulated orbital cycling with a 8.0 hour orbit and 1.0 hour discharge time. The discharge current was 3.0 amperes. Charging was constant potential at 1.51 volts per cell average current limited at 0.5 amperes. With the nominal depth of discharge of 30%, a charge time of 7.0 hours and the current limit of 0.5 amperes, the end of charge would not taper to a low level so as to cause cell voltage unbalance at the end of charge. Although little data was available on the test, this was one of the tests that a routine in-cycle capacity check was performed. These data are a good example of the loss of total available ampere hour capacity as a silver cadmium battery cycles in long orbit cycling. Tests were run at room temperature.

Cell Design Reference: Appendix A

Main Project: Interplanetary Monitoring Platform E (Explorer XXXV)

Applicable Figure: 50

Nominal Depth of Discharge: 30%

CYCLING

Cycling was performed as described in the Test Brief.

OBSERVATIONS AND CONCLUSIONS:

1. One cell failed on cycle 1666 with the battery failing on cycle 1756, 1.6 years. The failure was inability of the cells to deliver the 3.0 ampere hours required by the test.

2. The variation and decay of the total available ampere hour capacity during simulated orbital cycling is shown in figure 50. These capacities were determined by a discharge at 3.0 amperes to 0.5 volts, first cell.

3. Several times during cycling the ampere hours delivered to the battery were determined after the in-cycle capacity check. On these cycles, the charge time was extended so that the charge current tapered to a few milliamperes. The results are as follows:

In-cycle Capacity Check	Recharge Following Capacity Check
90	9.0
180	9.6
270	11.5
360	11.0
450	—
640	9.6

4. The 13xYS10S-2NM battery flown on the Explorer XXXV spacecraft was cycled similar to the cycling test described for this five cell test battery. However, discharge times varied between 0.8 and 1.2 hours. The battery on the spacecraft lasted approximately 2.4 years and near the end of life, the capacity of the spacecraft battery was 2.7 ampere hours. During orbit, the temperature of the battery was between 0°C and 15°C.

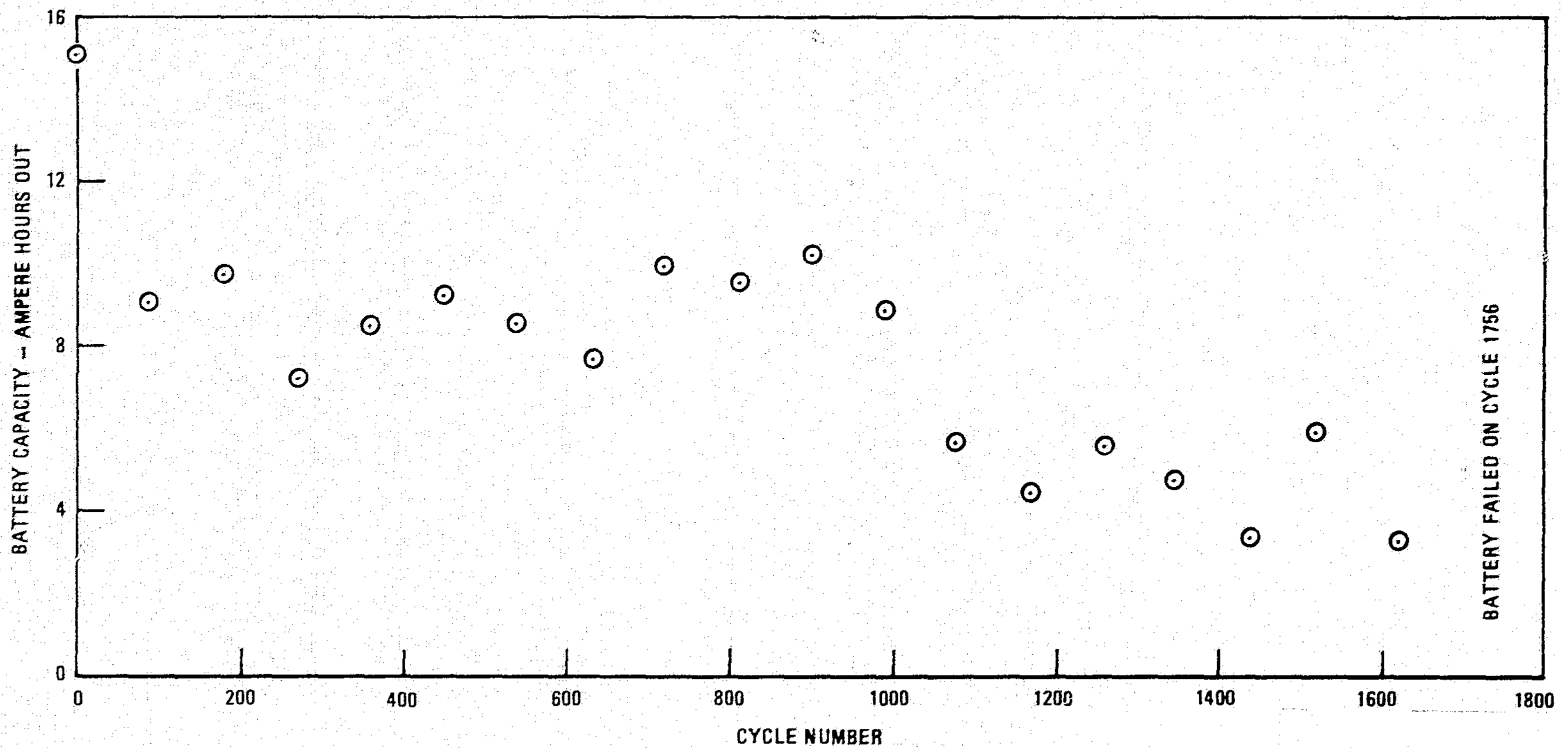


Figure 50. Ampere Hours Delivered during In-Cycle Capacity Checks at 3.0 Amperes, Test 104, Battery 5xYS10S-2NM, S/N IMP 45D

TEST 105

Test Unit: 9xYS12S-2ANM(20) with third electrode
S/N - Same as Test Unit

Test Period: 1965 - 1967

Total Cycling Time: 1.6 Years
Number of Cycles: 600+

TEST BRIEF

The battery consisted of five, twelve ampere hour cells individually encapsulated in EPON 834. Two positive plates, one negative plate and the separators adjacent to those plates were removed from the cells and a General Electric Fuel Cell Electrode, ref. 8, was placed in each cell. See Illustration 7. In operation, the terminal of the fuel cell electrode was connected to the negative terminal of the cell with a one ohm resistor. After an initial capacity check, the battery was put on simulated orbital cycling with a twenty-four hour orbit and a 1.0 hour discharge time. The discharge current was 5.2 amperes. Charging was constant potential at 1.51 volts per cell average current limited at 0.5 amperes. Discharge voltages were monitored and end of charge voltages were monitored daily. The voltage across the one ohm resistor was monitored at end of charge and end of discharge. The test was run at room temperature.

Cell Design Reference: Appendix A

Main Project: Development

Applicable Figures: None

Nominal Depth of Discharge: 43%

CYCLING

Cycling was performed as described in the Test Brief.

TEST 105 (Continued)

OBSERVATIONS AND CONCLUSIONS:

1. During the first 600 cycles, the end of charge currents were between 10 ma. and 20 ma. and the voltages across the one ohm resistors ranged between 0.0 and 18.0 mv. It appeared that recombination was occurring as described in ref. 8. Also, it was interesting to observe that there was essentially no cell voltage unbalance for the first 600 cycles, i.e., the end of charge voltage of each cell was within 2% of the 1.51 cell voltage clamp.

2. One cell failed on cycle 587. Data was not available after 600 cycles.

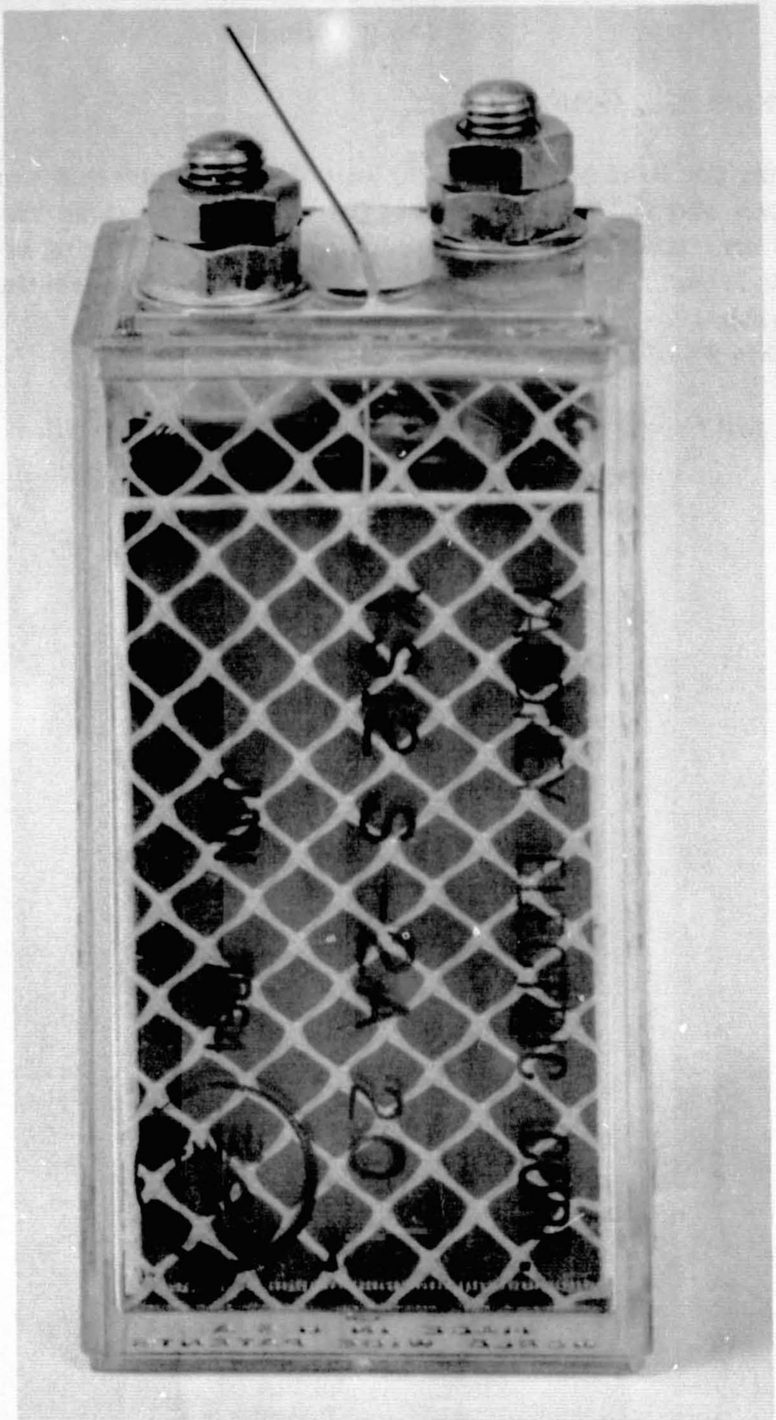


Illustration 7. Twelve Ampere Hour Silver Cadmium Cell with Third Electrode

Table 11
Summary of Life Cycle Tests at NWSC/Crane – Twenty-Four Hour Orbits

Test Pack Number	Cells In Series/ Nominal Ampere Hours	Cell[1] Design	Cycling Parameters	Failure Cycle First Cell/ Battery	Years on Test		Wet Life[3] or Testing Before Cycling at NSWC – Years
					NWSC	GSFC	
33B	5/5	M	NDOD[2] 20% @ 1.0A, 1.0 Hr. Orbit Period 24 Hours Temperature 25°C Voltage Limit 1.47/1.53 Current Limit 300 ma.	720/720	2.0	0.0	0.3
69A	5/5	N	Same as above.	494/595	1.6	0.1	0.4
77B	5/5	P	Same as above.	500/661	1.8	0.5	1.3
128B	5/5	P	Same as above except Temperature 40°C	123/269	0.7	0.0	0.5
113B	5/5	P	Same as above except Temperature 0°C	1592/1592	4.2	0.0	0.5
69B	5/11	Q	NDOD 18% @ 2.0A, 1.0 Hr. Orbit Period 24 Hours Temperature 25°C Voltage Limit 1.51	397/507	1.4	0.0	Information Not Available
57D	5/11	Q	Same as above except Temperature 0°C	436/1677	4.6	0.0	Information Not Available
33C	5/11	Q	Same as above except Temperature 40°C	326/447	1.2	0.0	Information Not Available

(1) See Appendix A
(2) NDOD = Nominal Depth of Discharge
(3) Times shown are for wet discharged storage at 25°C except for Pack 77B. This Pack had been subjected to thirty-three cycles at GSFC, similar to the cycles at NWSC. Also, the Pack had been float charged at GSFC for several months.

Table 12
Summary of Life Cycle Tests at NWSC/Crane – Eight Hour Orbits

Test Pack Number	Cells In Series/ Nominal Ampere Hours	Cell[1] Design	Cycling Parameters	Failure Cycle First Cell/ Battery	Years on Test		Wet Life[3] or Testing Before Cycling at NSWC – Years
					NWSC	GSFC	
118C	5/5	P	NDOD[2] 20% @ 1.0A, 1.0 Hr. Orbital Period 8 Hours Temperature 25°C Voltage Limit 1.47/1.53, Current Limit 300 ma.	1468/1505	1.4	0.0	0.5
114B	5/5	P	Same as above except Temperature 0°C	1496/1496	1.4	0.0	0.5

(1) See Appendix A
(2) NDOD = Nominal Depth Of Discharge
(3) Times shown are for wet discharged storage at 25°C.

Table 13
Ampere Hours Delivered On Capacity Checks During Cycling
Twenty Four Hour Orbits

Day of Capacity Check	Test Pack Number							
	33B	69A	77B	128B	113B	57D	69B	33C
	Ampere Hours Out							
100	5.8	5.0	5.0	5.5	5.3	4.1	7.5	8.7
200	6.1	4.2	4.9	1.2	4.1	7.2	7.0	6.8
300	6.3	3.2	4.8	–	4.7	4.1	3.5	5.2
400	5.4	4.4	4.7		5.5	–	2.2	4.8
500	2.1	1.1	4.7		4.0	8.3	1.8	–
600	1.9	2.0	1.2		5.1	4.8	–	
700	1.1	–	2.3		4.0	3.9		
800	–		–		5.1	2.9		
900					5.4	3.8		
1000					5.5	6.7		
1100					4.7	3.6		
1200					5.5	3.0		
1300					6.1	5.0		
1400					5.8	4.5		
1500					–	1.7		
1600					–	3.6		
1700						–		
Test Temperature °C	25	25	40	0	0	0	25	40

Table 14
Ampere Hours Delivered on Capacity Checks During Cycling
Eight Hour Orbits

Cay of Capacity Check	Test Pack Number		
	114B	118C	45D
	Ampere Hours Out		
30	4.0	5.4	See Test 104 This Section
60	3.1	5.4	
90	2.5	5.3	
120	2.9	6.5	
150	3.0	6.3	
180	3.5	5.2	
210	2.5	6.5	
240	1.5	6.3	
270	1.7	5.8	
300	1.2	5.1	
330	1.6	6.3	
360	1.2	5.7	
390	2.4	5.7	
420	1.0	6.0	
450	0.9	3.3	
	—	—	
Test Temperature °C	0	25	25

Table 15
Summary of Cycle Tests at NWSC/Crane that were Removed Before Failure

Test Designation	Cells In Series/ Nominal Ampere Hours	Cell (1) Design Reference	Cycling Parameters	Cycles (3) Completed @ NWSC	Years on Test	Wet Life Before Testing @ NWSC
S^3, No. 1	5/3	YS3S-1NM	NDOD (2) 33% Discharge: 1.0A for 34 Min. 2.5A for 10 Min. Orbit Period 7.5 Hours Temperature -10°C Voltage Limit 1.55 Current Limit 200 ma.	476	0.41	1.1
S^3, No. 2	5/3	YS3S-1NM	Same as Above Except Temperature 25°C Voltage Limit 1.50	476	0.41	1.1
45M	13/11	YS11S-3NM(sh)	NDOD 33% @ 3.6A for 1.0 Hr. Orbit Period 8 hours Temperature 25°C Voltage Limit 1.49/1.52 lowered to 1.41 volts when charge current tapers to 100 ma. Current Limit 450 ma.	516	0.47	0.6

(1) Cell Design Reference: Appendix A
(2) NDOD = Nominal Depth of Discharge
(3) No Cell Failures

Table 16
Summary of Cycle Tests at NWSC/Crane with Early Battery Failures

Test Pack Number	Battery Designation	Cycling Conditions (1)	Cell Component or Problem Area Being Evaluated	Cycle Battery Failed
57B 21A 45A	Similar to 5xYS5-4NM	0°C, NDOD (2) 20%, 24 Hr. Orbit 25°C, ——— SAME ——— 40°C ——— SAME ———	Separator replacement for C-19. Six layers of Methyl Cellulose/ Poly(methyl ether/maleic anhydride) 30% Ref. 9.	267 98 61
9C	5xYS5-2NM	25°C NDOD 20%, 24 Hr. Orbit	Battery had been subjected to a severe dose of radiation (2×10^7 rads.)	34
105B	Similar to 5xYS5-4NM	25°C NDOD 20%, 24 Hr. Orbit	Separator replacement for C-19. Three layers of Visking cellulose.	69
45B 21B	10xYS11-3NM(TA) SAME	0°C NDOD 40%, 24 Hr. Orbit 25°C ——— SAME ———	Production lot proved to be defective. Linked to process change in the manufacture of CdO powders, especially increase in the particle size three or four times.	121 69
21C 45C	Similar to 5xYS11-3NM(TA) 5xYS11-2NM(TA)	25°C 27%, 8 Hr. Orbit ——— SAME ———	Comparison of non-woven nylon (21C) and woven nylon (45C) in cells with the same CdO powders as in the above test. Approximately one year after this test, non-woven nylon was analyzed for the amount of wetting agent which turned out to be 7% to 8%. Additional cell tests were run with non-woven nylon containing 5.3% wetting agent. Test cells lost 30% of capacity in 23, eight hour cycles at a NDOD of 20%. This loss was permanent.	37 70
57A 33A	12 Ahr. Cells in Stn. Stl. Cans with Ceramic Seals	0°C NDOD 50%, 24 Hr. Orbit 40°C ——— SAME ———	Poor design of ceramic seals. Seals leaked before the test was initiated. Tried to repair with epoxy.	162 210
21D 9F	12 Ahr. Cells in glass cloth wrapped case with experimental epoxy.	0°C NDOD 43%, 24 Hr. Orbit 40°C NDOD 43%, 24 Hr. Orbit	Seals leaked early in cycle program.	60 258

(1) For additional cycling details, see ref. 10
(2) NDOD = Nominal Depth of Discharge

SECTION IV

FLIGHT PROJECTS AND ORBITAL EXPERIENCE

This section of the Report includes data and information related to satellite missions, with long orbits, i.e., missions with orbital periods of greater than 5.3 hours. All these satellite projects were directed by Goddard Space Flight Center (GSFC) and all missions used silver cadmium cells manufactured by the Yardney Electric Company. The subject matter is grouped into the following categories:

Category	Subject Matter
001	Cell Sizes
002	Batteries Used on Flight Missions
003	Magnetics
004	Charge Control
005	Shadow Times
006	Shadow Operation
007	Current Pulses
008	Voltage Depression at Beginning of Discharge
009	Battery Operations Under Conditions of Pulse Charge/Discharge
010	Reversal of Cells in a Battery
011	Procurement, Fabrication and Acceptance Testing of Batteries

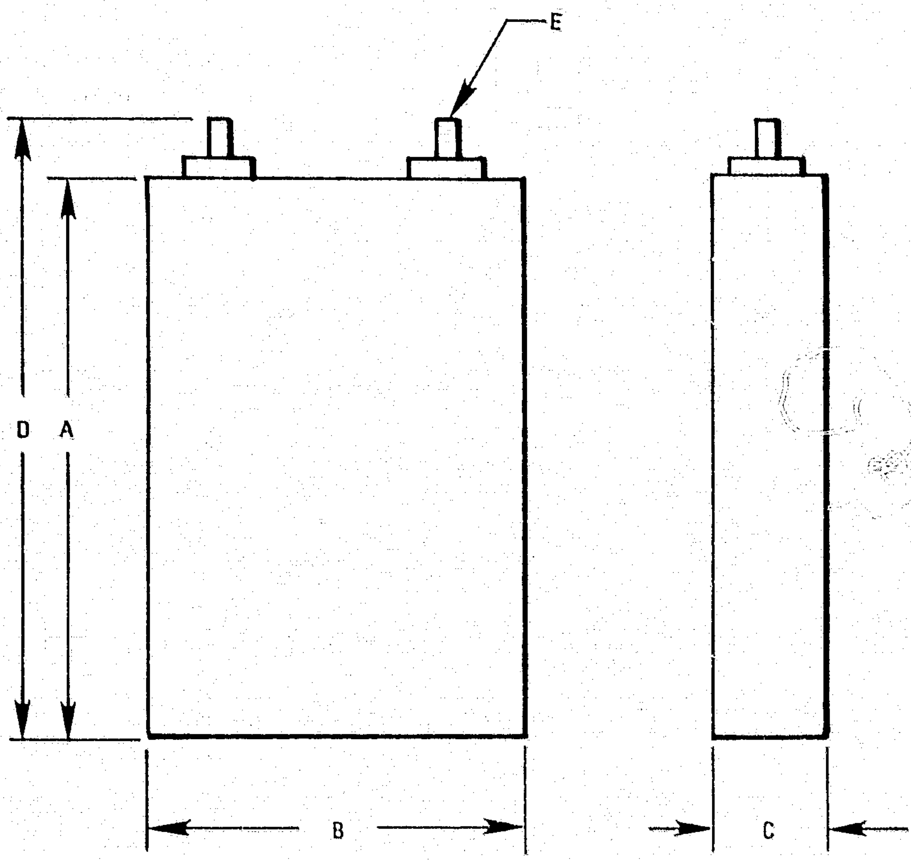
Category 001. Cell Sizes

Five sizes of cells were used in flight missions, namely, three, five, ten, eleven and sixteen ampere hour sizes. Sixteen ampere hour cells were used on a German Research Satellite in an eight hour orbit. Much of the preliminary work on this cell was done at GSFC. In fig. 51 the dimensions and dry and wet weights of the cells are given.

Category 002. Batteries used on Flight Missions

Table 17 is a listing of the various satellite missions and the types of batteries used on each flight, battery weights, some orbital parameters and the life of the batteries in orbit. An Illustration is included for each type of battery. Except for Explorer XV, the design life of the mission was one year although most satellites were monitored after one year. Two batteries failed prematurely, on Explorers XXI and XXXIII due to high temperature. During the latter few missions, it has been practice to place the battery in a cold area of the satellite and use heaters to bring the battery up to an operational temperature, 15°C to 20°C, when battery power is required. Heaters are placed between cells and the elements are structured so that magnetic signals are cancelled by opposing current flow. The heater elements, assembled to the cells, and the thermostats used for control are shown in Illustration 14.

The Battery Designations shown in Table 17 use the same coding as explained in Section II.



CELL TYPE	A CM	B CM	C CM	D CM	E	WEIGHT-GMS DRY	WET
YS-3	6.325	4.369	1.508	7.264 MAX.	10 – 32 THD	63	82
YS-5	6.238	5.270	$1.994^{+.101}_{-.025}$	7.381 MAX.	10 – 32 THD	106	133
YS-10	10.871	5.893	$1.880^{+.079}_{-.020}$	12.217 MAX.	1/4 – 28 THD	154	245
YS-11	10.716	5.834	2.062	11.509 MAX.	– –	187	254
YS-16	13.640	5.842	2.062	14.605 MAX.	– –	262	342

SILVER CADMIUM FLIGHT CELLS

(1) ALL DIMENSIONS IN CM.

(2) NUMBER IN CELL TYPE COLUMN IS NOMINAL AMPERE HOURS

(3) UNLESS OTHERWISE SPECIFIED, TOLERANCES WITHIN ±0.051 CM.

Figure 51. Silver Cadmium Flight Cells

Table 17
Batteries Used on Flight Programs

Explorer	Design Designation	Date of Launch	Orbital Period Hours	Load Watts	Battery Designation	Weight Kg.	Illustration	Remarks Battery Life
XII	S-3	Aug., 1961	26.5	13	13xYS5S-2NM	2.86[1]	8	Satellite Failed, 4 Months
XIV	S-3A	Oct., 1962	36.5	12	13xYS5S-2NM	2.86[1]	8	≈ 1.5 Years
XV	S-3B	Oct., 1962	5.3	12	13xYS5S-2NM	2.86[1]	8	90 Days, Design Life
XVIII	IMP A	Nov., 1963	94	35	13xYS5S-2NM	3.10	9	> One Year
XXI	IMP B	Oct., 1964	35	37	13xYS5S-2NM	3.10	9	Btry Temp > 50°C, Two Months
XXVI	EPE-D	Dec., 1964	7.6	14	13xYS5S-2NM	2.86[1]	8	> One Year
XXVIII	IMP C	May, 1965	–	38	13xYS5S-4NM	3.10	9	> One Year
XXXIII	IMP D	July 1966	–	35	13xYS11S-2NM (TA)	4.60	10	Btry Temp > 50°C, Two Months
XXXV(Lunar)	IMP E	July 1967	11.5	35	13xYS10S-2NM	4.50	10	> Two Years
XXXIV	IMP F	May 1967	80	33	13xYS5S-5NM	2.67	11	> Two Years
XLI	IMP G	June, 1969	80	35	13xYS5S-5NM	2.67	11	> Three Years
XLV	S^3	Nov., 1971	7.7	19/28	18xYS3S-2NM	2.36	12	≈ One Year
XLVII	IMP H[3]	Sept., 1972	300[2]	124	14xYS10S-4NM	5.0	13	> Four Years
XLIII	IMP I	Mar., 1971	105	133	14xYS10S-4NM	5.0	13	Two Years Satellite Re-Entered
L	IMP J[3]	Oct., 1973	300[2]	119	14xYS10S-4NM	5.0	13	Four Years
To Be Assigned	ISEE-A[3]	Oct., 1977	52	44	14xYS10S-4NM	5.0	13	
To Be Assigned	ISEE C[3]	July, 1978	52	44	14xYS10S-4NM	5.0	13	

(1) Includes weight at current sensor.
(2) Circular orbit, others are elliptical
(3) Contain heaters, see text.

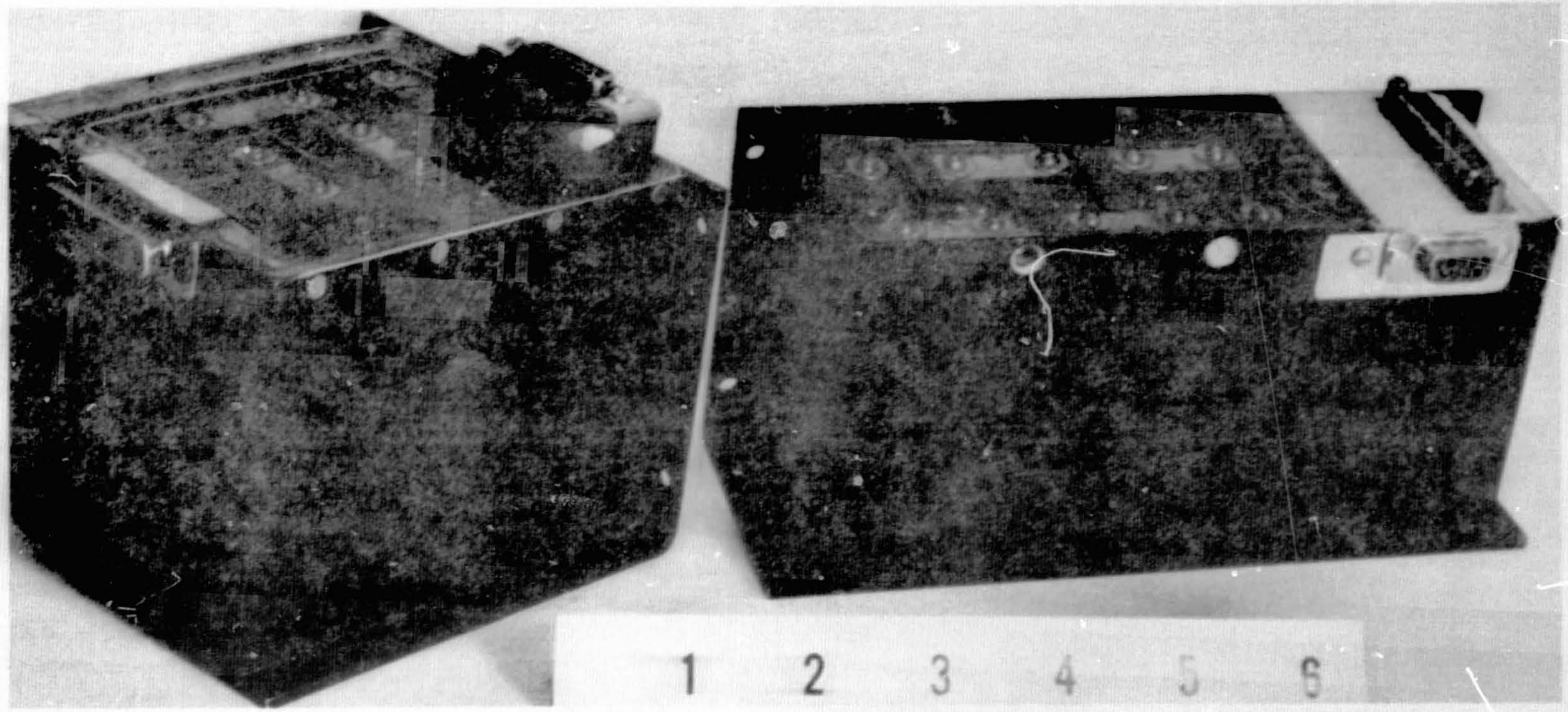


Illustration 8. Battery for Explorers XII, XIV, XV and XXVI
(Dimensions In Inches)

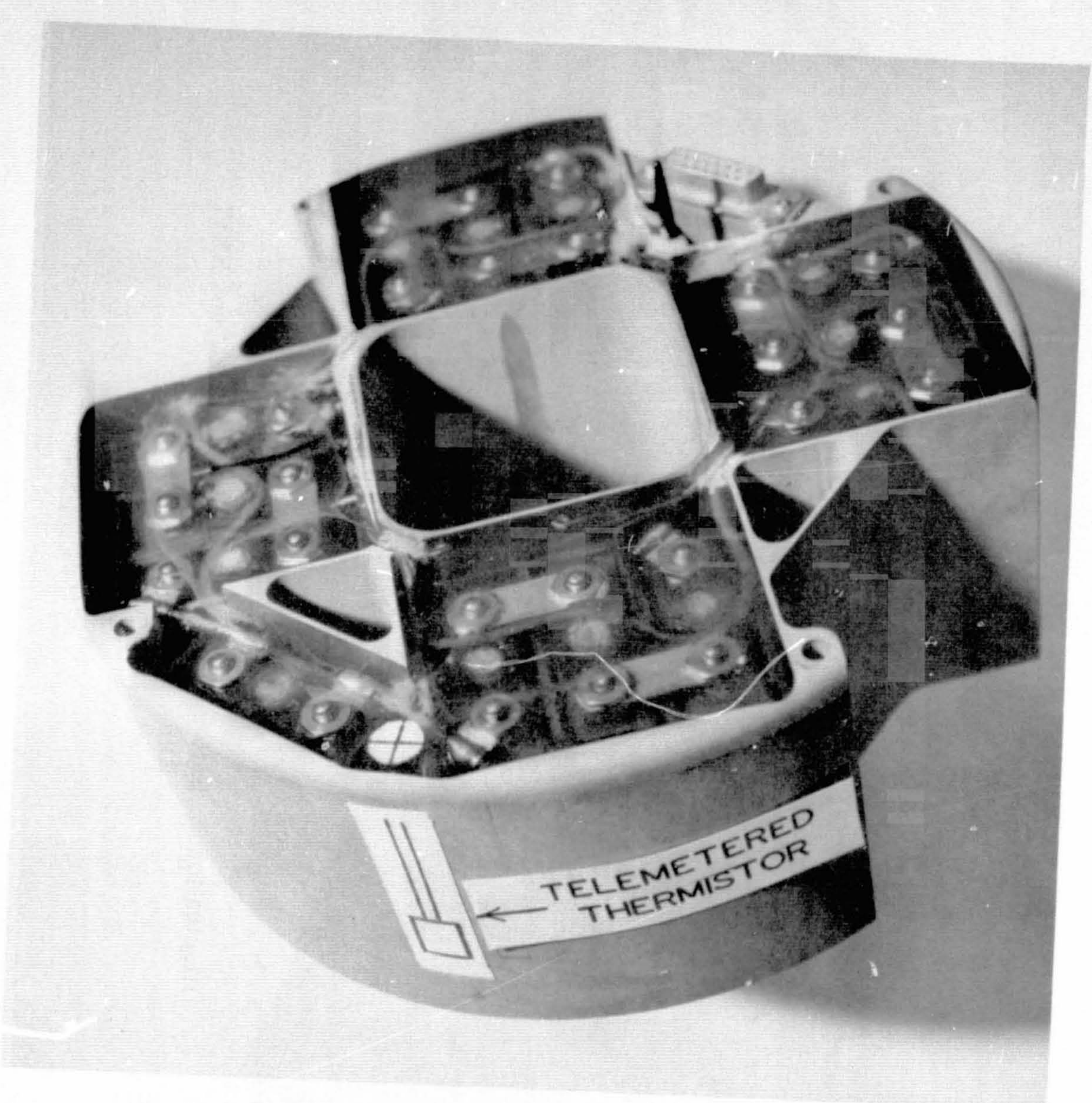


Illustration 9. Battery for Explorers XVIII, XXI and XXVIII

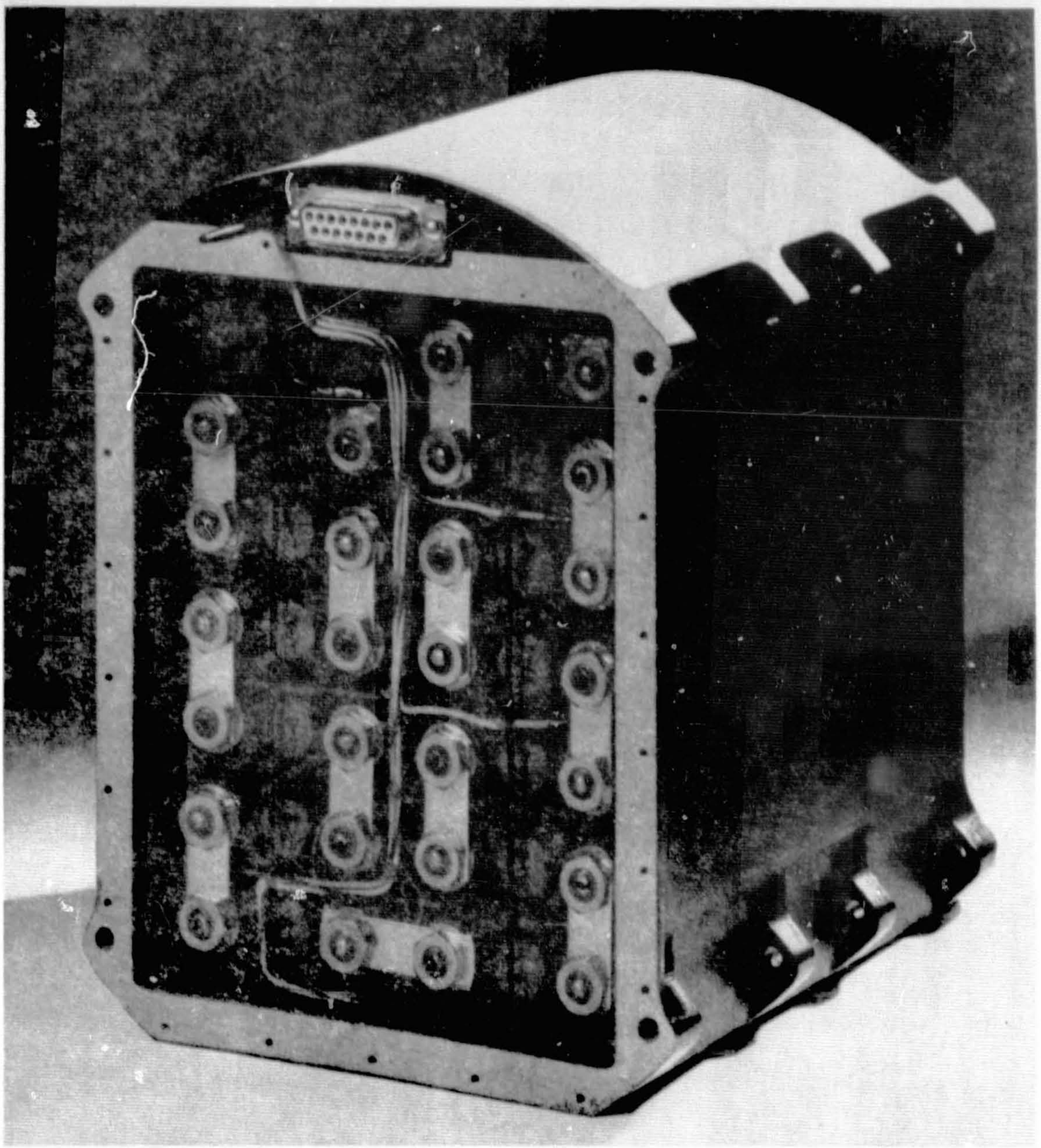


Illustration 10. Battery for Explorers XXXIII and XXXV (Lunar)

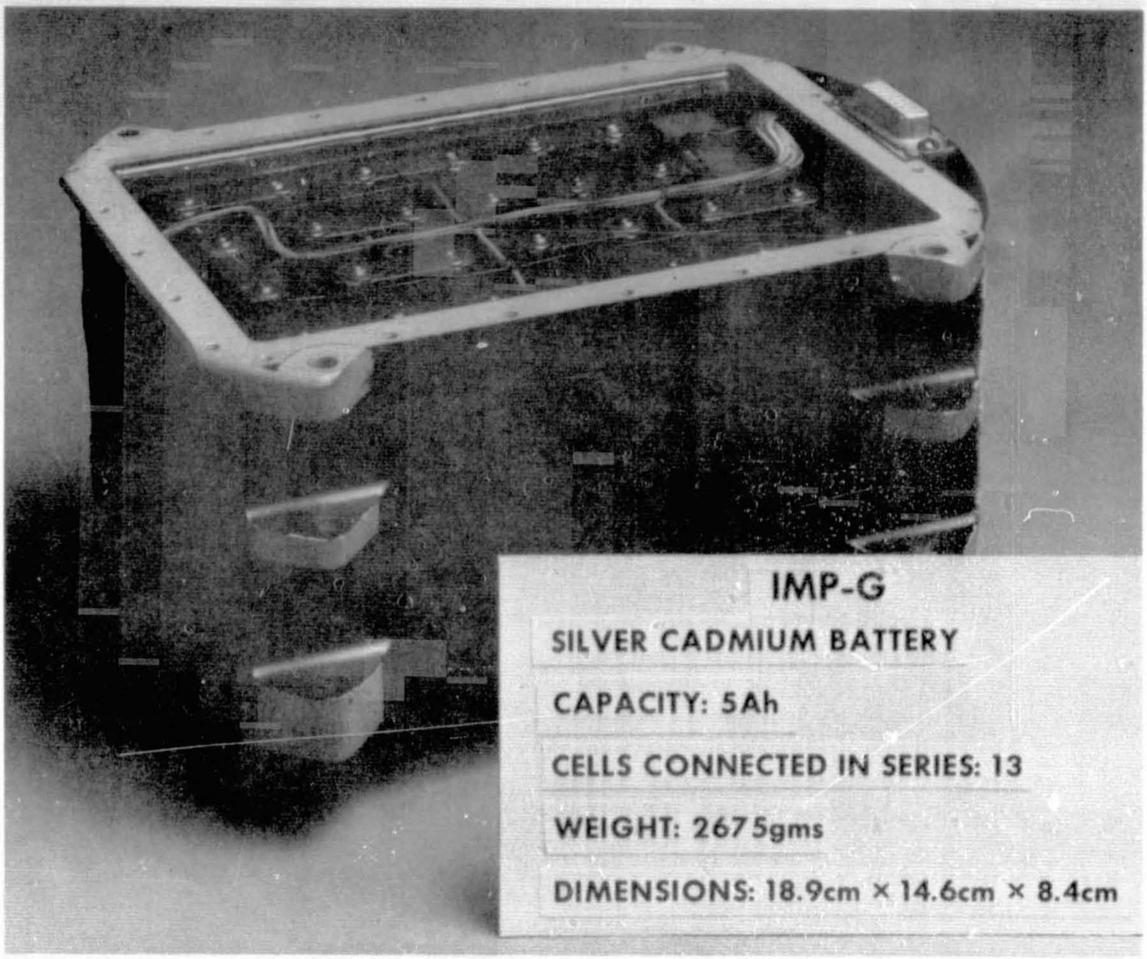


Illustration 11. Battery for Explorers XXXIV and XLI

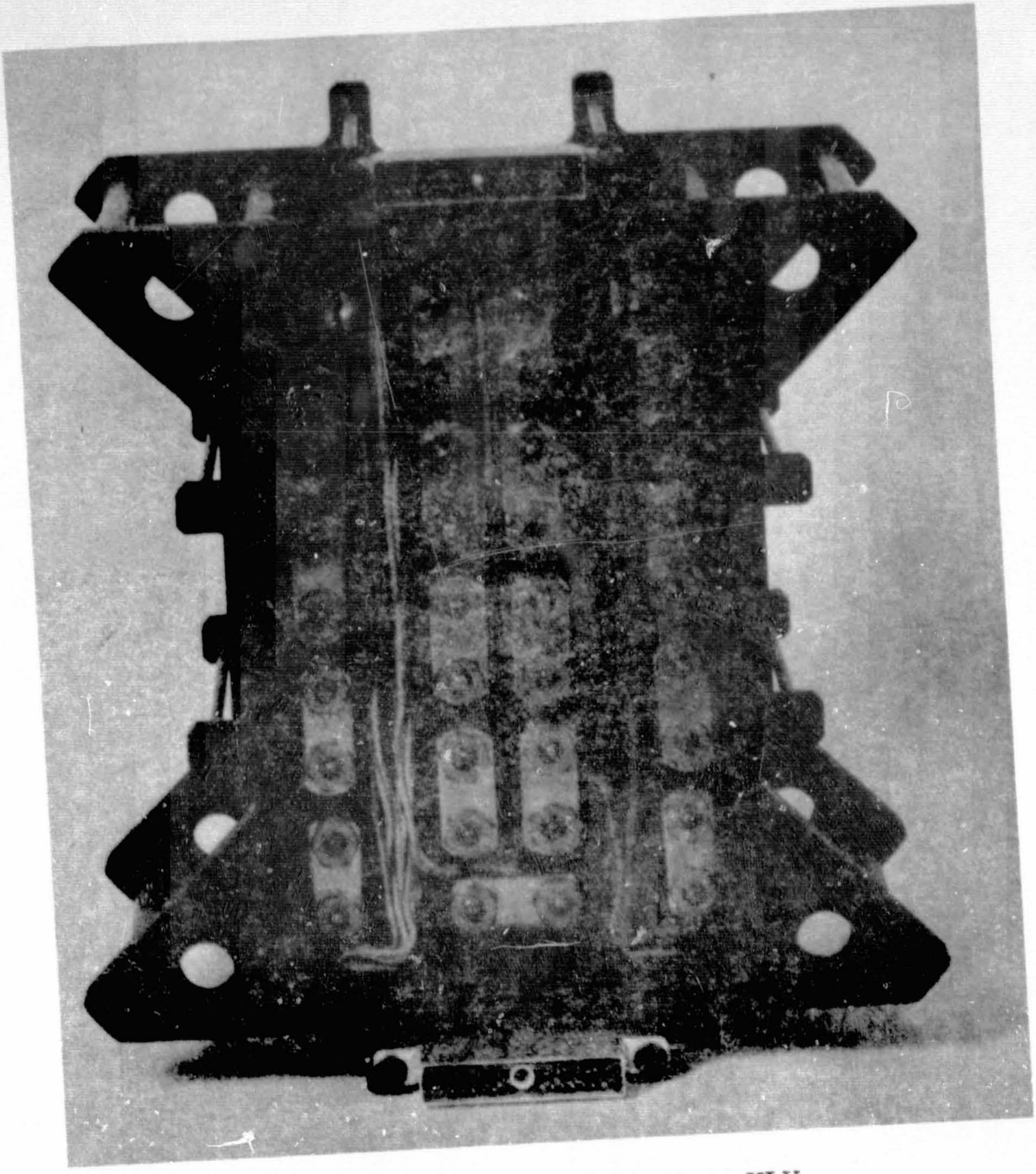


Illustration 12. Battery for Explorer XLV

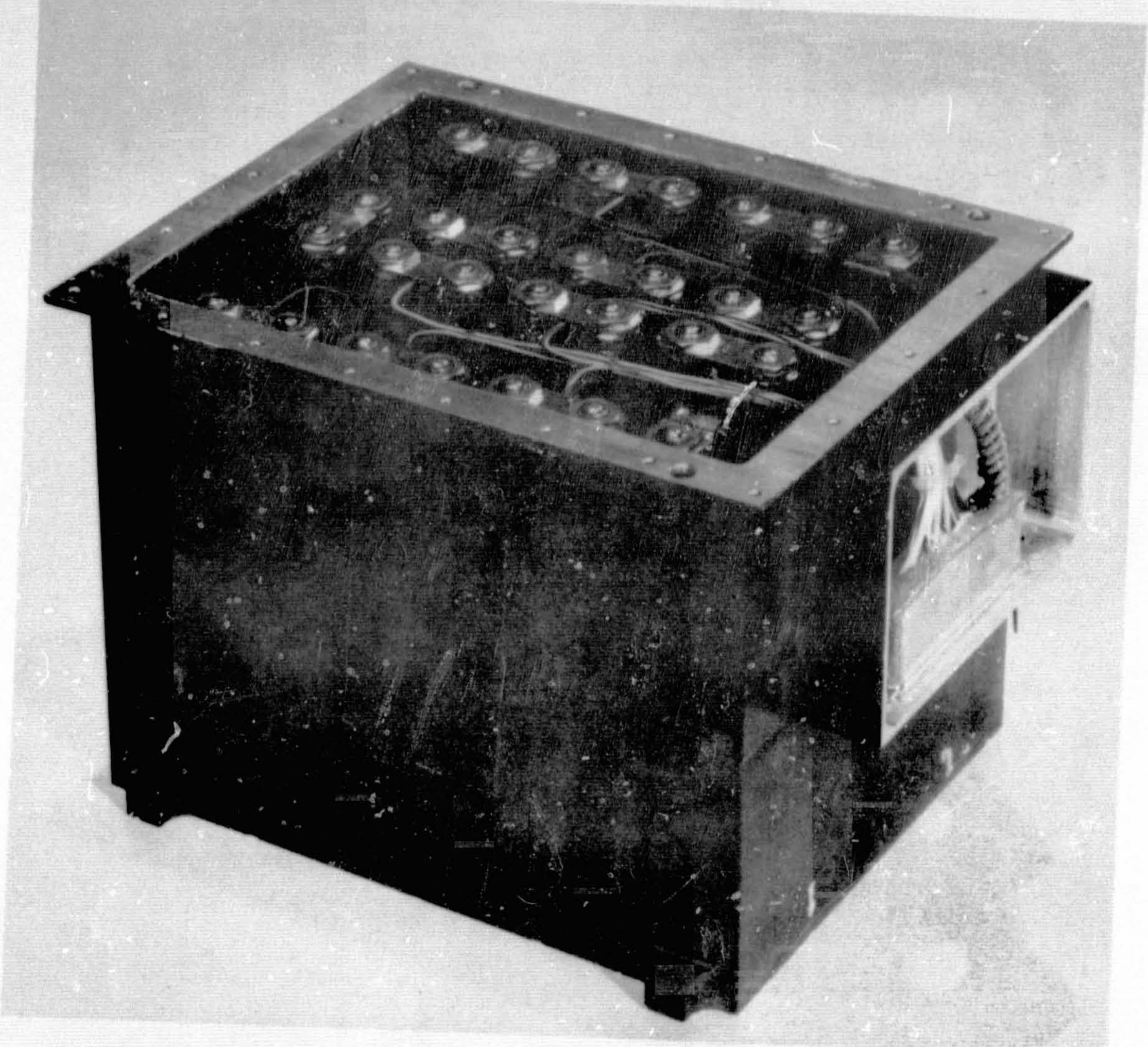


Illustration 13. Typical Battery Structure for Explorers XLVII, XLIII, L, ICEE-A and ICEE-C

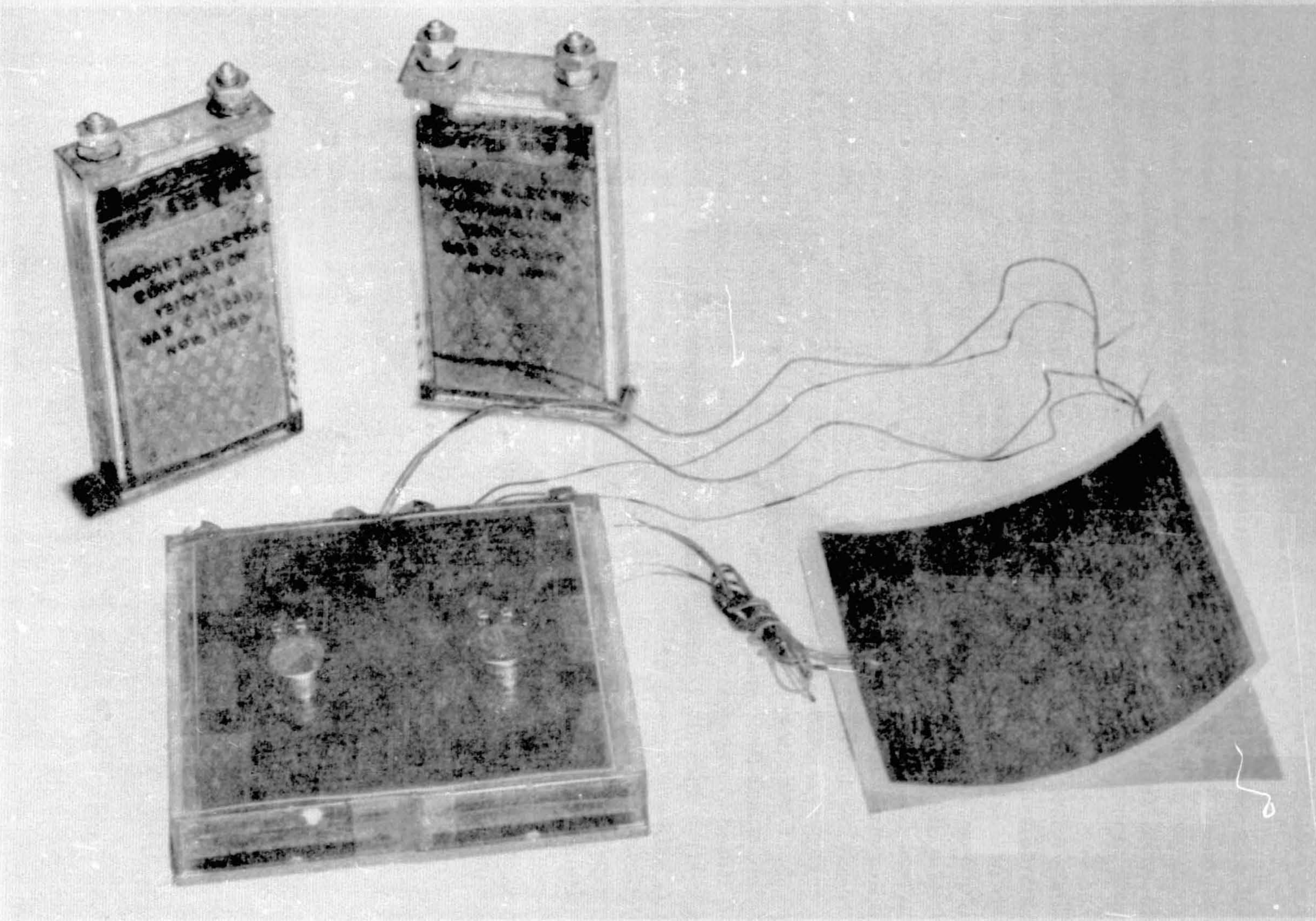


Illustration 14. Cells, Heater Elements and Thermostats used on Recent Missions

Category 003. Magnetics

All components, including the batteries, were required to have very low magnetic signals. Not only was it necessary to utilize magnetically clean sub-assemblies because of the magnetometer disturbance requirements but also, in the case of spin stabilized systems, it was preferable to avoid subassemblies with large magnetic moments. All satellites listed in Category 2 were spin stabilized.

Since silver cadmium cells and batteries are fabricated from materials that are considered to be non-magnetic, the magnetic signals measured on these components are extremely low. Even when exposed to a DC magnetic field of 25 gauss, the components do not perm-up, that is, the magnetic signal is low. There is some stray field magnetization associated with silver cadmium batteries due to the current flow on charge and discharge, the latter being the worse case. To obtain low stray field magnetization, special wiring techniques have to be used and usually, to obtain best results, the battery wiring is adjusted at a magnetometer facility. An example of the wiring and compensation loops required is given in ref. 11. One battery design that was extremely difficult to compensate for the stray field magnetism was the round design flown on Explorers XVIII, XXI and XXVIII listed in Category 2. The round design is a current loop which makes compensation difficult. Another difficulty experienced with this battery was grouping odd numbers of cells. When odd numbers of cells are grouped together, more compensation loops in the wiring are required. When even numbers of cells are grouped together, the current flow in each pair of cells tends to cancel stray field magnetism. On Table 18, typical magnetic characteristics of several batteries are listed. All measurements were made eighteen inches (45.7 cm.) from the magnetometer face. Additional information on other types of batteries and components is given in ref. 12.

Table 18
Magnetic Field Magnetization of Silver Cadmium Batteries
Made Eighteen Inches (45.7 cm.) from Magnetometer

Explorer	Design Designation	Initial (1) Perm gamma	Post (2) Exposure gamma	Post (3) Deperm gamma	Stray (4) Field gamma	Discharge Current for Stray Field amperes
XXI	IMP B	0.2	—	—	87.2 (5)	3.0
Same Battery Design					6.0	3.0
XXXIII	IMP D	0.4	0.4	0.4	7.5	3.0
XXXV	IMP E	0.2	0.2	0.2	6.5	3.0
XXXIV	IMP F	1.6	1.6	1.6	4.0 2.7	3.0 2.0

(1) Initial Perm: As received magnetic state of the item.
(2) Post Exposure: Magnetic state of the item after exposure to a 25 gauss DC magnetic field.
(3) Post Deperm: Magnetic state of the item after being demagnetized in a 50 gauss field (normally 60 Hz AC field).
(4) Stray Field: Magnetic state of item with current flowing in the item.
(5) Round Battery, See Category 2. Reading was reduced to 6.0 gamma after change in wiring and compensation loops.

C-3

Category 004. Charge Control

Early Explorer satellites used the Type I charge control shown in figure 52. Here, the battery would supply the spacecraft loads during shadow or assist the solar array during peak loads. Constant potential charging was used, i.e., after a shadow period, the battery would accept the excess current available from the array. As the battery terminal voltage approached 19.6 volts (1.51 volts per cell), the shunt regulator would dump the excess current. Eventually the charge current would taper to a low value. A typical charge curve for the Type I system is shown in figure 53.

During the period 1965 through 1970, the Type 2 charge control system, as shown in figure 52, was used. This was similar to the Type I system except a current detector, in series with the battery, measured the charge current and when this value tapered to $C_N/100$, the nominal capacity divided by 100, the shunt regulator voltage was reduced from 19.6 volts to 18.3 volts (1.41 volts per cell). The voltage and current profiles during this operation are shown in figure 54. This value of 18.3 volts was the open circuit voltage of the battery and at this voltage, cell unbalance would not occur. As aforementioned in Section II, it was difficult to predict the effect of long term float charging and the associated cell voltage unbalance at higher charge voltages. The shunt regulator would be reset to the higher value 19.6 volts, when the battery discharged through the detector at a current value greater than $C_N/100$.

In both systems, a low voltage detection sensed the battery and if the battery discharge voltage was less than 12.0 volts, 0.92 volts per cell, the battery would be removed from the line. Charging would commence when excess current was available.

Since 1970, another type of regulator/charge system has been used. This employs a series battery charger and a boost regulator for battery discharge. This system is described in ref. 13.

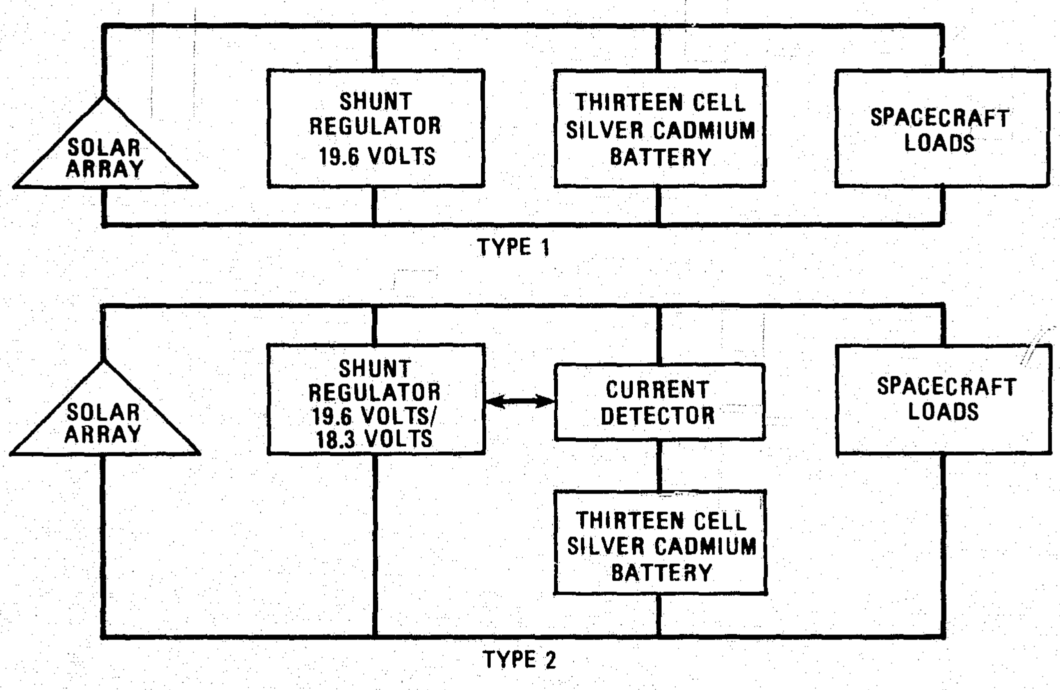


Figure 52. Explorer Satellite Power/Charging Systems 1960-1970

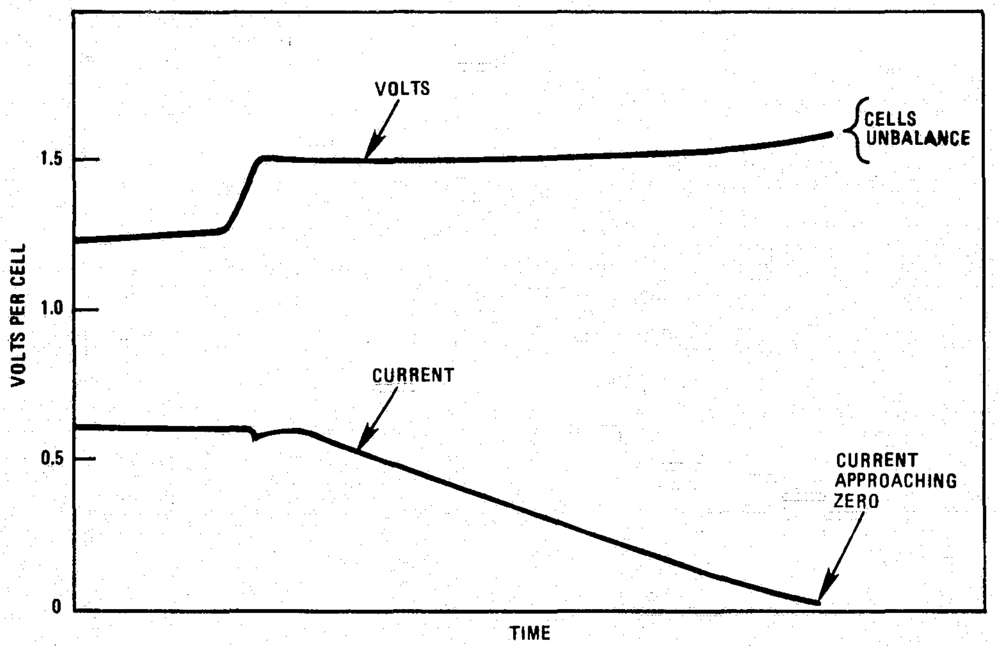


Figure 53. Charging Characteristics, Type 1 Charge System

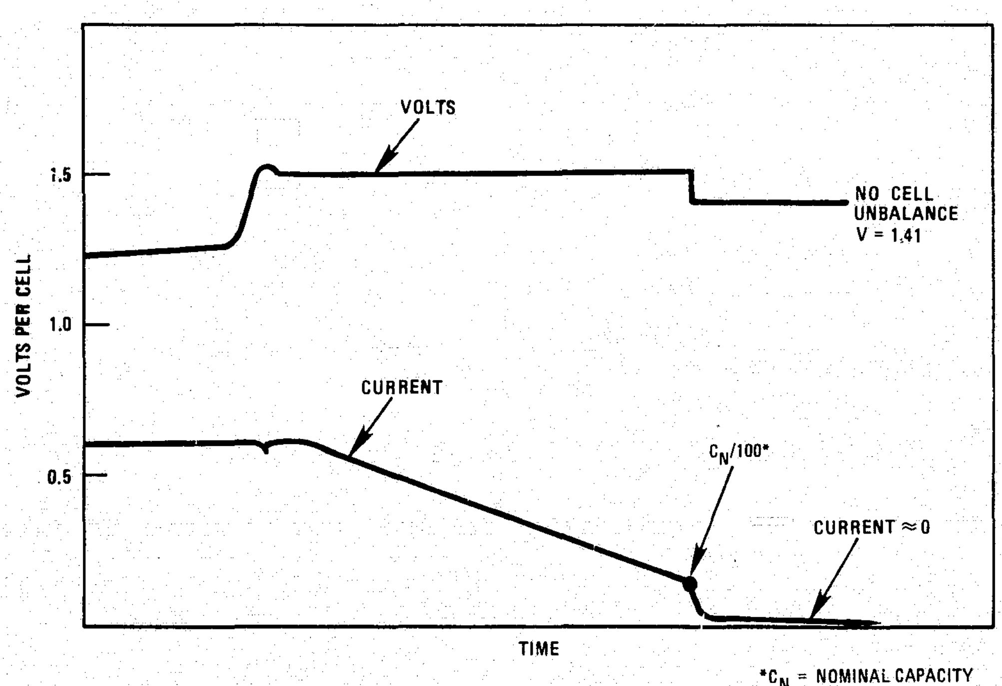


Figure 54. Charging Characteristics, Type 2 Charge System

Category 005. Shadow Times

In long orbits, satellites enter the earth's shadow intermittently. Shadow times versus days in orbit for Explorer XIV, shown on fig. 55, are typical of the types of shadow profiles of a satellite with a long orbital period. On fig. 56, the shadow periods experienced during a short orbital period are shown for Explorer XV. One exception was Explorer XXXV which was placed in a lunar orbit with an orbital period of 11.5 hours. This satellite had two shadow periods a day with times in shadow ranging between 0.8 and 1.2 hours. Shadow periods for Explorer XLI with a 3.3 day orbital period are shown in Section III, Test 102.

Category 006. Shadow Operation

Typical operation of the solar array and battery in a 0.57 hour shadow period and a 1.8 hour shadow period are shown for Explorer XIV on figures 57 and 58. During the short shadow, the satellite spends only 0.2 hours in complete darkness while in the longer shadow, the time in darkness is essentially equal to the shadow time of 1.8 hours. In both cases, payload or battery current increases during the shadow since the load is constant power. Only a slight temperature change of the battery taken place in the 0.57 hour shadow as compared to the 1.8 hour shadow. At times, in these types of orbits, the satellite would experience five to six hour shadows where the battery would be discharged to 0.9 volts per cell. A voltage sensor would remove the battery from the line at this lockout voltage but some low current drain (25 Ma.) would be required. During these long shadows, the battery temperature would decrease to a low value (-40°C) at a rate of 10°C per hour. It would usually take at least one orbit for the battery to warm up so that it would accept a charge.

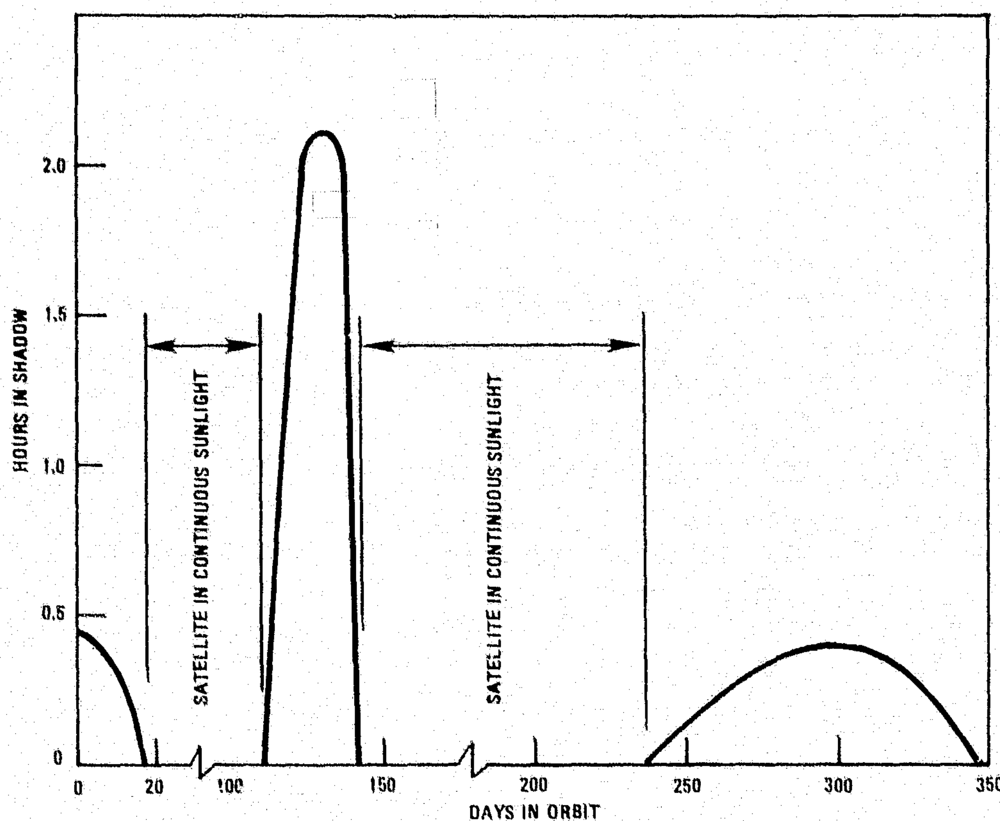


Figure 55. Explorer XIV (S-3A) Time in Shadow During Orbit
Orbital Period, 36.5 Hours

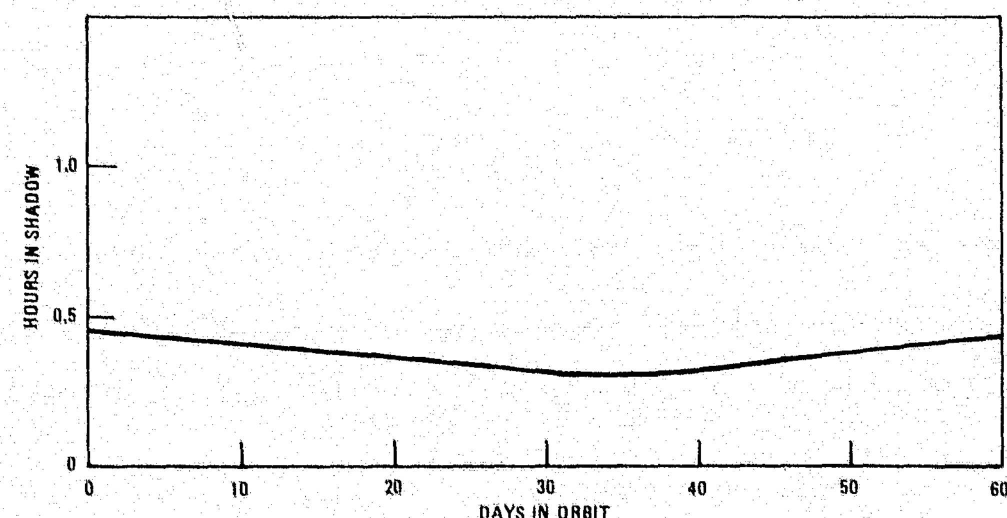


Figure 56. Explorer XV (SERB) Time in Shadow During Orbit
Orbital Period, 5.3 Hours

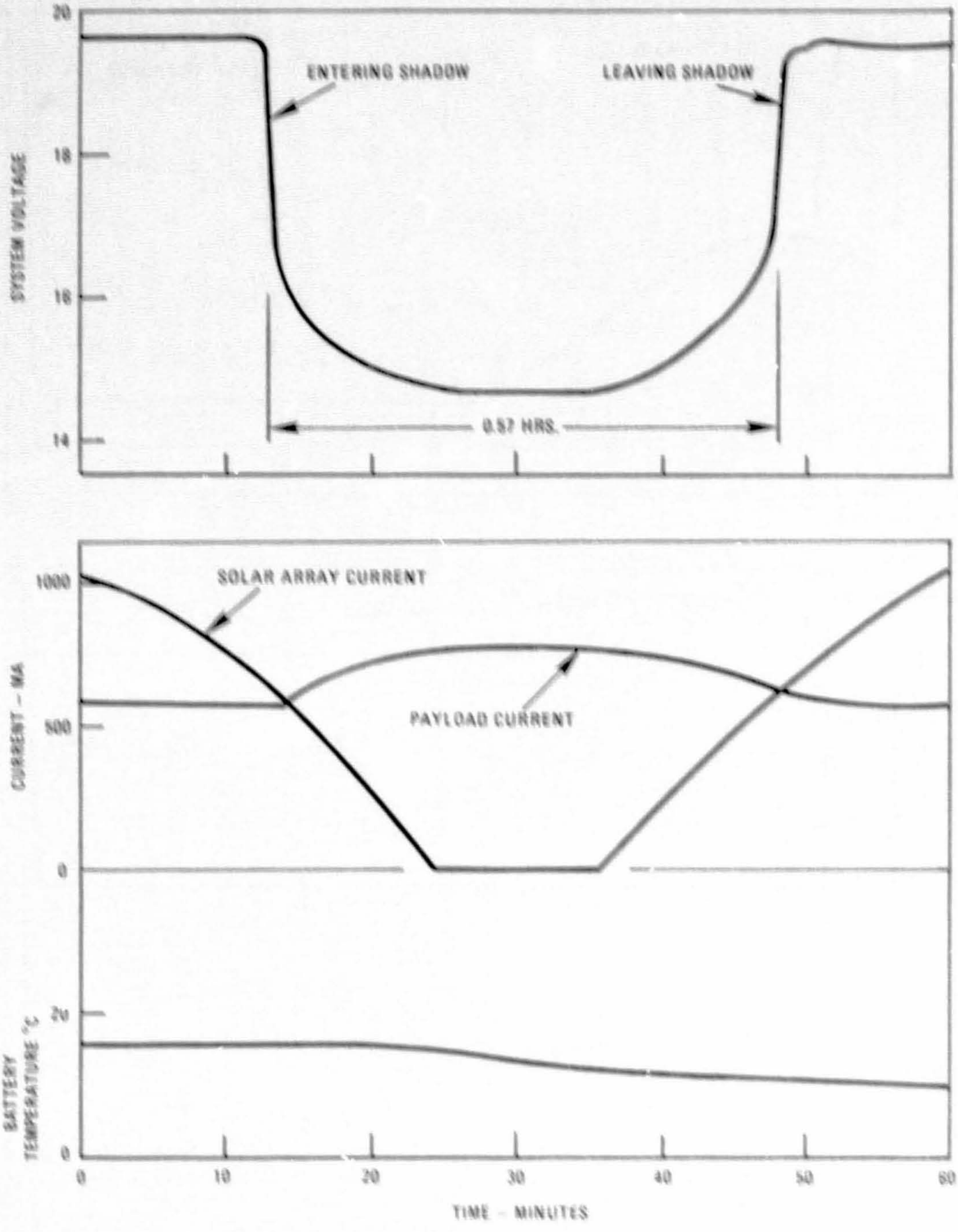


Figure 57. Explorer XIV (S3-A), Variation of System Voltage and Currents During Shadow on June 22, 1963

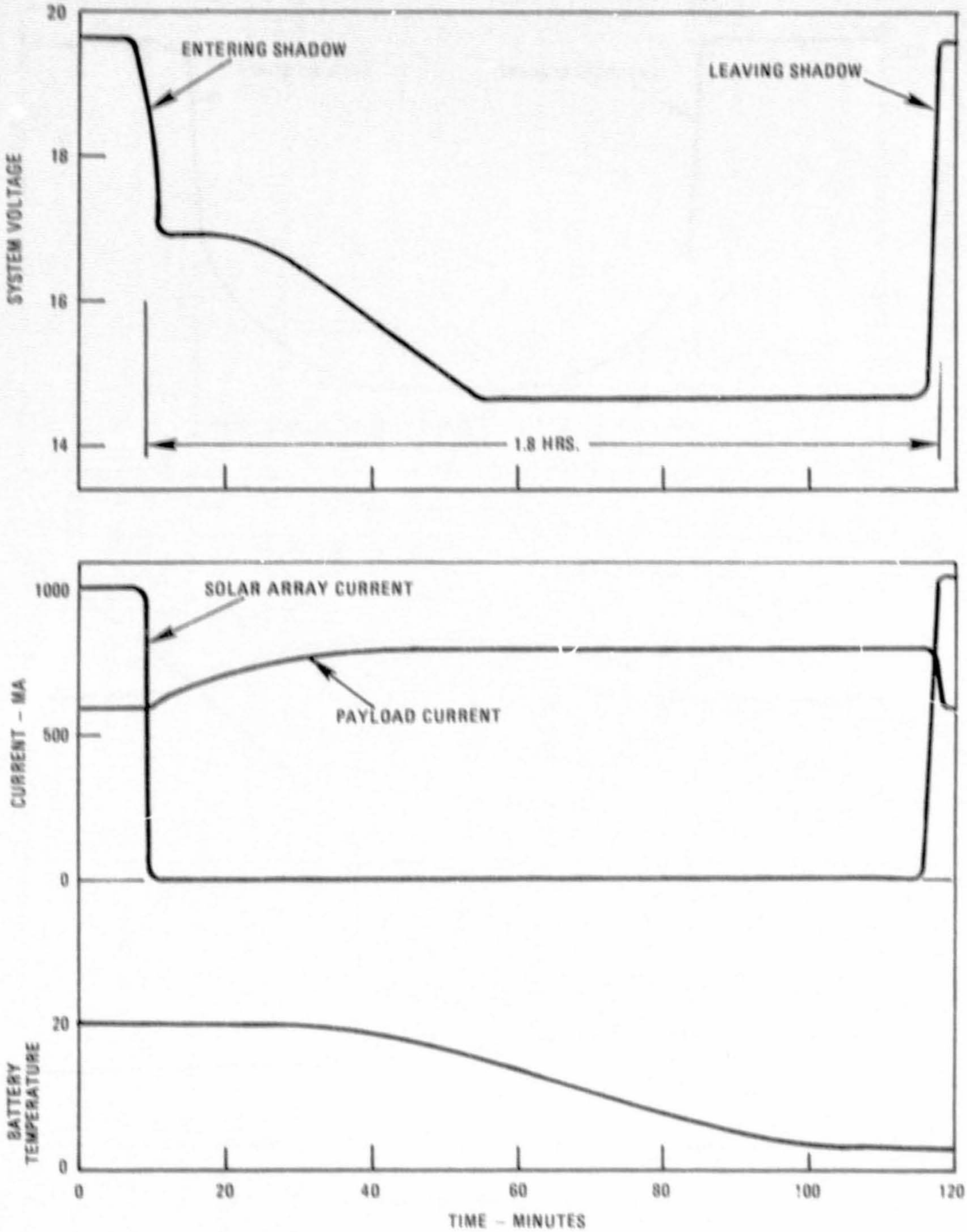


Figure 58. Explorer XIV, (S-3A), Variation of System Voltage and Currents During Shadow on Feb. 7, 1963

Category 007. Current Pulses

During the launch phase of a satellite, high rate current pulses were required from the battery to operate separation mechanisms or solid state motor ignition. These pulse widths were ten milliseconds or less. Usually these pulses occurred at 25°C but in the case of Explorers XXXIII and XXXV, where a deceleration motor was required to slow the satellite down for insertion into a lunar orbit, the motor ignition temperature was estimated to be between -10°C and 5°C.

In figures 59 and 60, a five ampere hour battery was pulsed while on a constant power discharge of 39 watts. In the former case, with the separation mechanism resistance of 0.5 ohms, the battery would dip below 0.9 volts per cell and therefore the lockout or low voltage sensor could shut off the spacecraft during launch. Therefore, eight ohms was placed in series with each of the four separation mechanisms. As shown in figure 60, the battery voltage does not read any value less than 0.9 volts per cell, especially at the beginning of discharge. Sufficient energy was available to fire the separation mechanism.

On figure 61 is shown the effect of temperature on battery discharge voltages. Pulses were performed on batteries that were fully charged or had a few percent of capacity removed previous to the current pulse.

Additional information on pulsing of ten ampere hour silver cadmium batteries for the ISEE-A Project is contained in ref. 14.

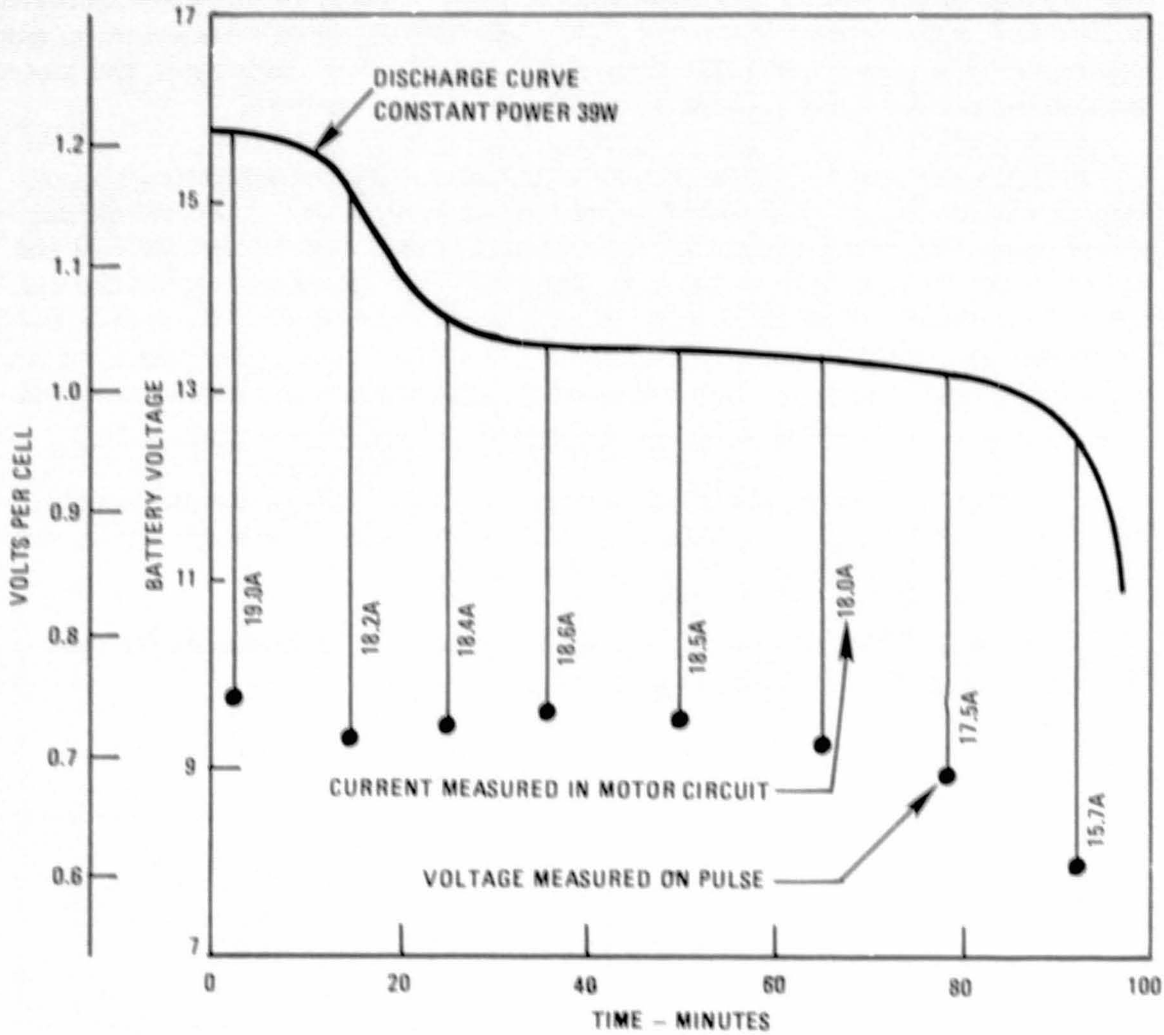


Figure 59. Pulsing of Battery During 39 Watt Constant Power Discharge at 27°C, Test Unit 13xYS5-2NM, IMP 002

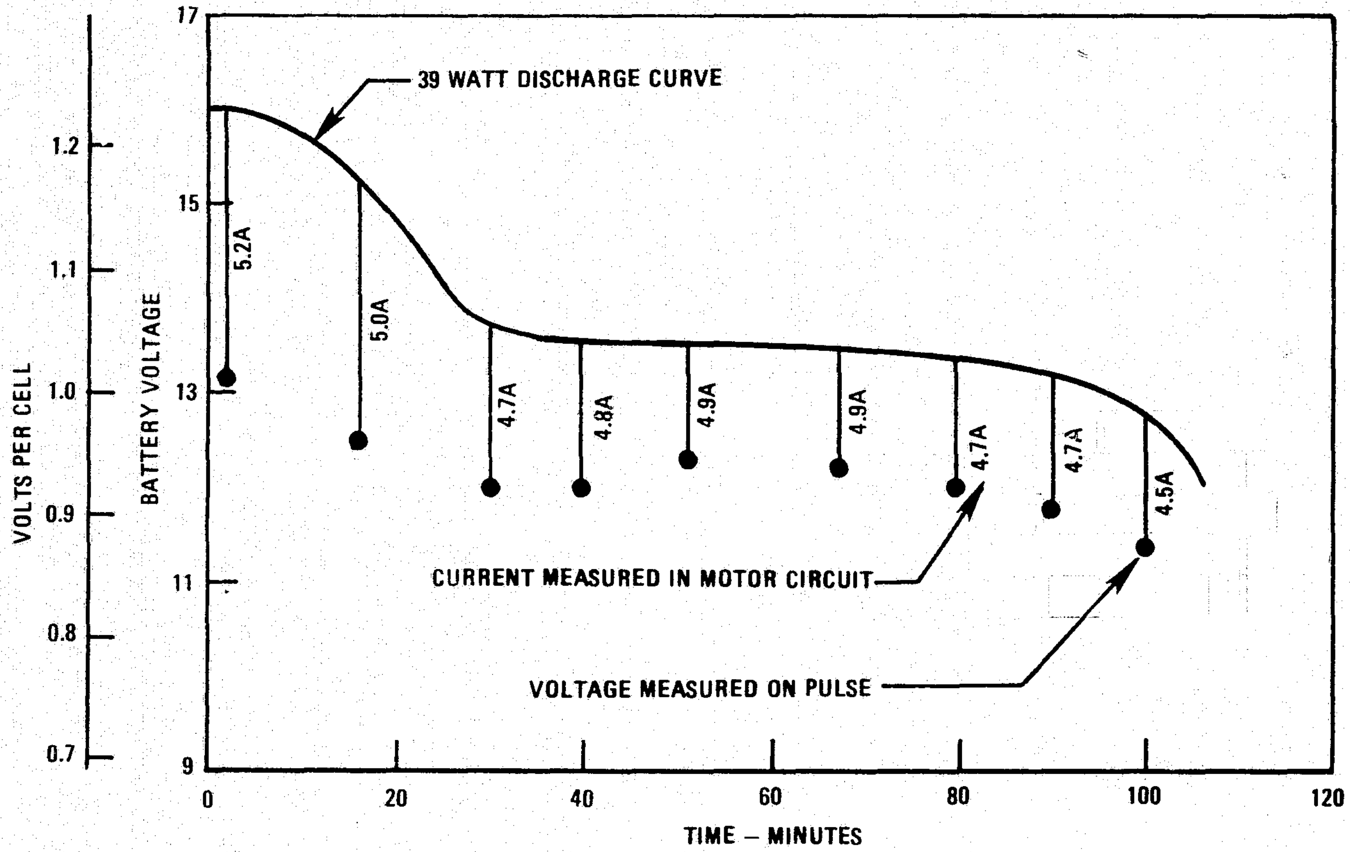


Figure 60. Pulsing of Battery During 39 Watt Constant Power Discharge at 27°C, Test Unit 13xYS5-2NM, IMP 002

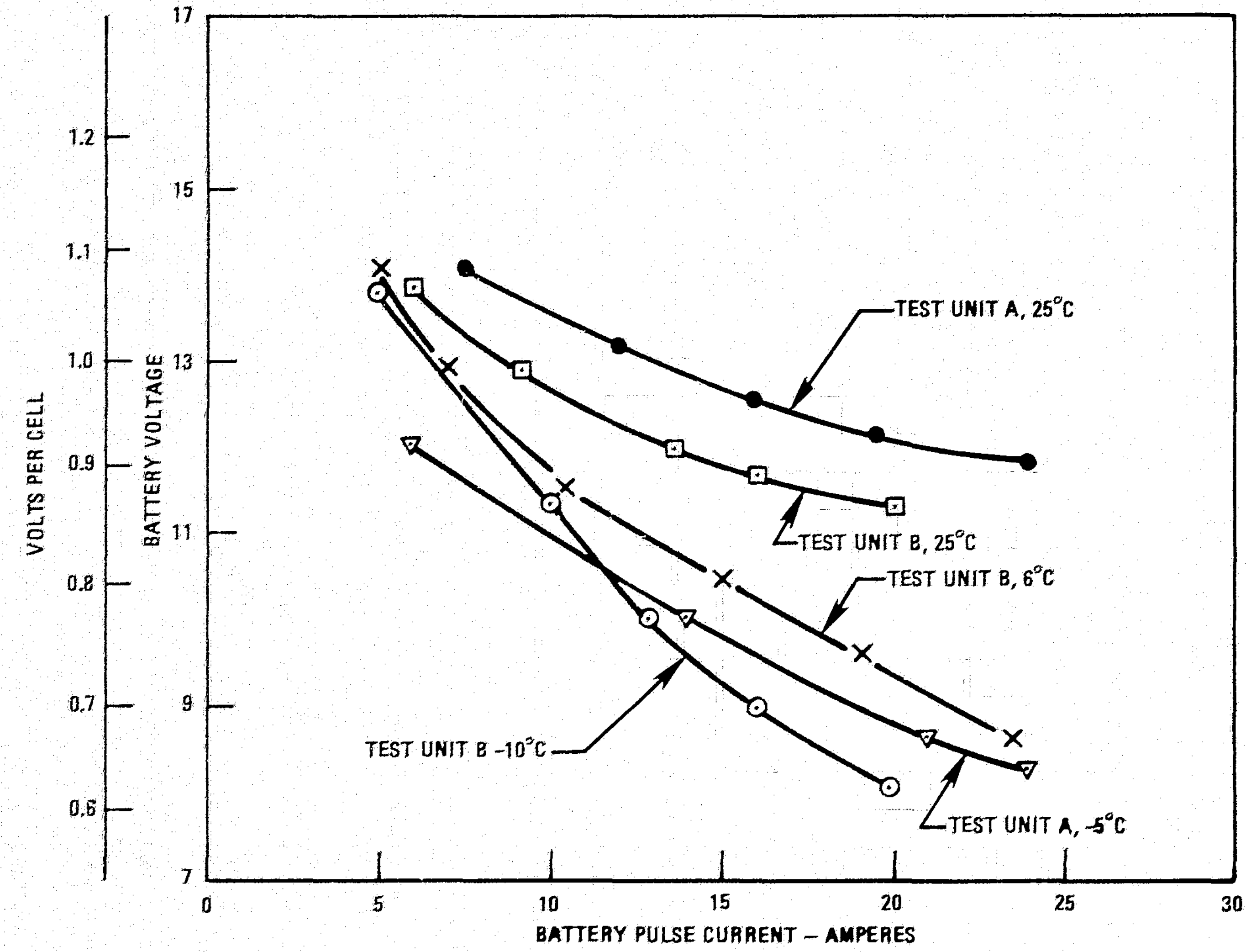


Figure 61. Pulsing of Ten and Eleven Ampere Hour Batteries
Test Unit A: 13xYS11S-2NM (TA)
Test Unit B: 13xYS10S-2NM

Category 008. Voltage Depression at Beginning of Discharge

One problem associated with silver cadmium cells is the voltage depression that occurs at the beginning of discharge after a long float charge or after a battery is cycled in an orbital period that includes long float times during the charge half-cycle. Although not as severe, this condition can occur if the battery is stored charged. The amount of dip of the voltage is very dependent on temperature. On figure 62 is shown the voltage depression that occurs, at 0°C, 15°C and 27°C on a ten ampere hour battery. Before each discharge, the battery had been cycled for several weeks in a 96 hour orbital period with a 0.5 hour discharge. On each charge half-cycle, the battery had been on float charge at 1.41 volts per cell for at least 90 hours. This low voltage condition could be very troublesome, especially at 0°C, where the voltage dipped to 0.9 volts per cell. This is the voltage that is used as the lockout voltage to remove the battery from the line. With the use of heaters in the battery to warm the battery to a temperature of 15°C to 20°C, this problem can be avoided at moderate discharge rates.

Other tests demonstrating this voltage depression are included in Section II, Tests 007 and 014.

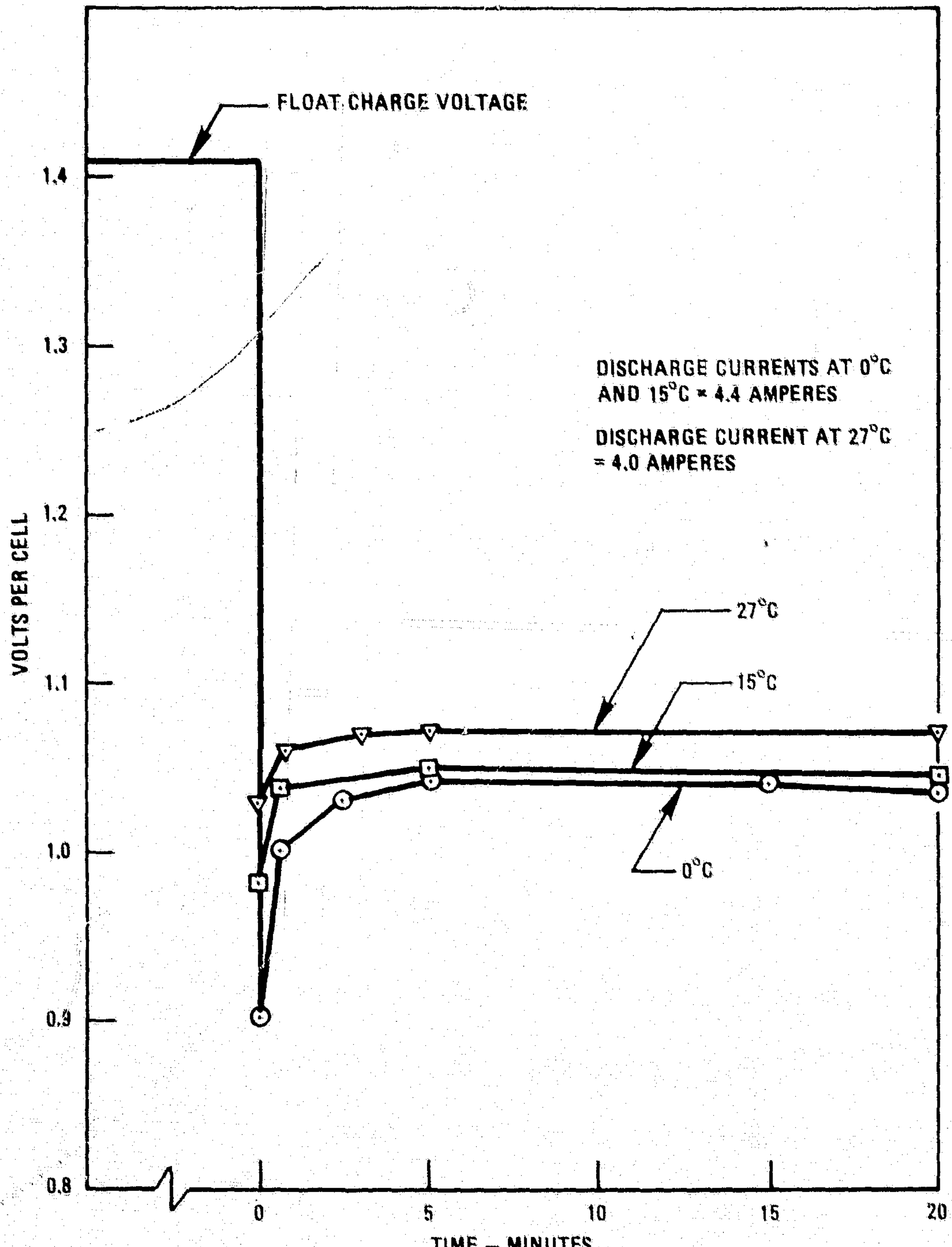


Figure 62. Discharge of Silver Cadmium Batteries after Long Periods of Cycling Including Long Float Charge Periods, Test Unit 13xYS10S-4NM

Category 009. Battery Operations Under Conditions of Pulse Charge/Discharge

During the early Explorer missions, occasionally the satellite power system would operate in a pulse charge/discharge mode. As shown in fig. 63, the battery would be required to support the solar array as the voltage oscillated from 19.6 to 15.0 volts. These oscillations, which would occur once or twice per satellite revolution, were caused by shadowing of the arrays by satellite appendages or by one array shadowing another array.

Several tests were run to determine if the battery could be charged under these pulsing conditions, especially when the satellite was entering shadows followed by pulse charge/discharge power system operation. The pulsing was simulated as shown in fig. 64. All tests were run so that the width of the charge pulse was 1.27 seconds and the height of the charge pulse was controlled by the 300 ma. current limit of the power supply and/or the voltage clamp maintained during charge. This value was 19.6 volts or 1.51 volts per cell for the thirteen cell, five ampere hour battery. The discharge current during pulsing was maintained at 250 ma. Tests were run at room temperature. In each test, approximately 0.5 ampere hours was removed initially from a charged battery, the battery was subjected to the pulse charge/discharge for approximately ten hours and then the battery was discharged, at 800 ma. to 0.9 volts per cell average. The results of two of the tests follows:

Initial Charge	Capacity Removed Initially	Ampere Hours Out to 0.9 Volts Per Cell After Pulsing
AHI	AHO	
5.6	0.56	5.7
5.5	0.57	5.6

These results show that the capacity removed during a shadow period can be replaced even though these conditions of charge/discharge are present. However, further tests showed that, if the satellite entered a period of continuous sunlight and the charge/discharge pulsing persisted as shown at A and B in fig. 64, internal pressure would develop in the cells. However, this problem was alleviated with the development of the Type 2 charge control system described in Category 004.

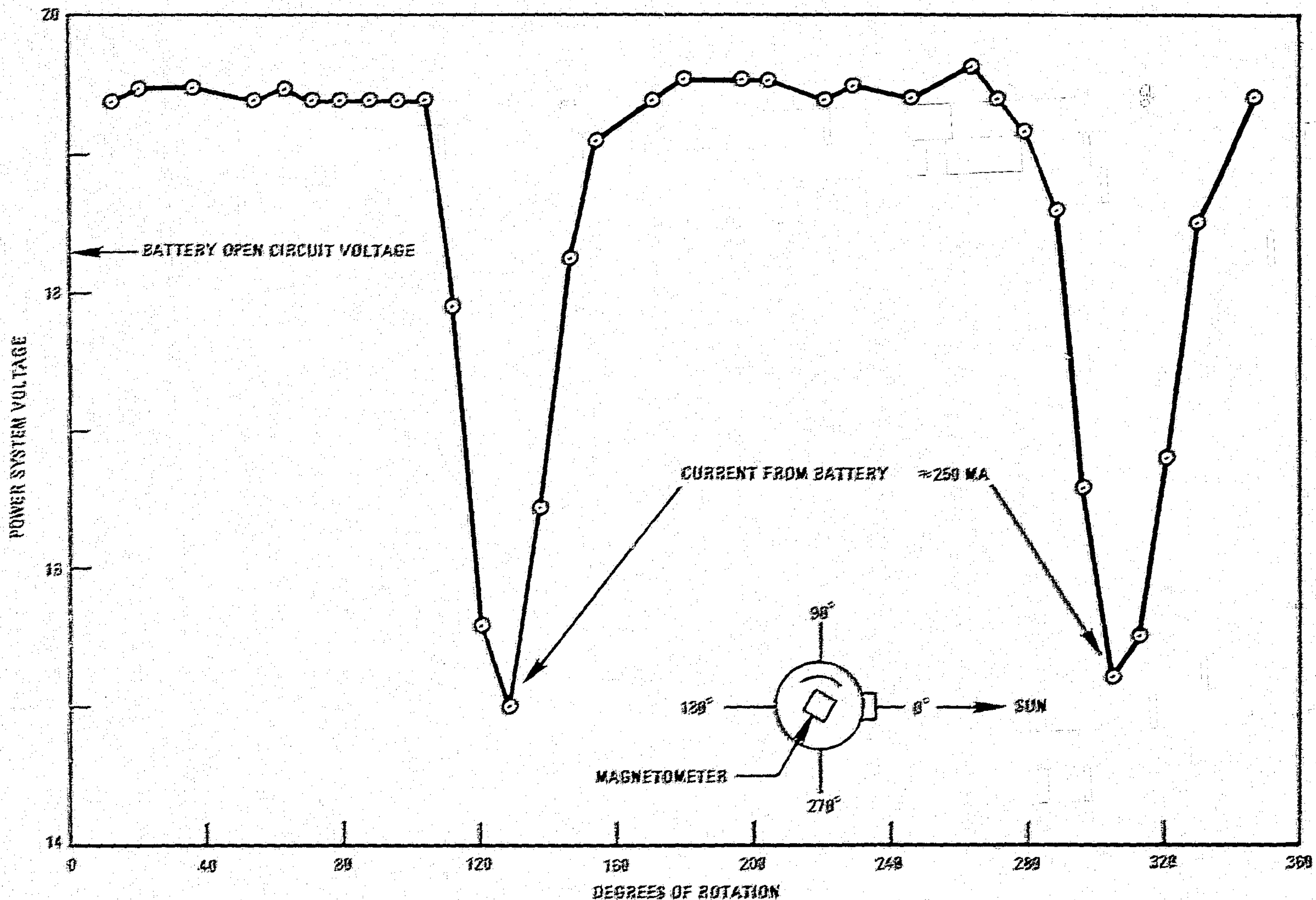


Figure 63. Explorer XII(S-3) Satellite for 360° of Rotation
Data Recorded on Dec. 3, 1961

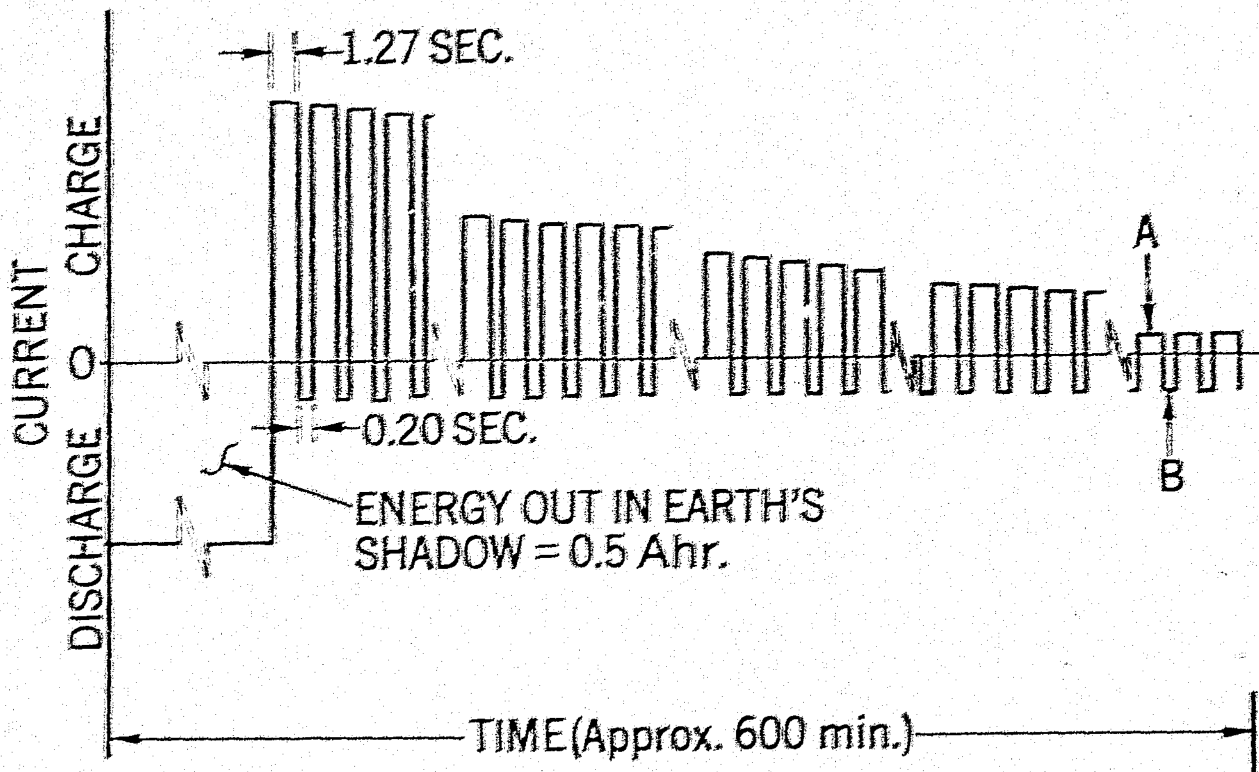


Figure 64. Pulse Charge/Discharge of a Silver Cadmium Battery

Category 010. Reversal of Cells in a Battery

As far as known, sealed batteries were adequately protected against reversal during testing and flight. However, in one case, the flight battery for the Explorer XLV (S^3) was reversed for three hours while on the launch platform. The cells of the eighteen cell, three ampere hour battery exhibited unusual characteristics during the reversal.

The circuitry used to duplicate the reversal at the launch site is shown in figure 65. The only load on the regulator was the instrument converter. Fortunately, the design of the regulator caused it to go out of regulation at approximately ten volts. The voltage sense or lockout that would have removed the battery from the line at sixteen volts was not on.

The decay of the battery current to the regulator for a three hour period after drop out of the regulator and instrument converter, is shown in figure 66. Also shown is the voltages of three cells as they are reversed. These curves do bear some resemblance to the normal charge curve of the silver cadmium cell. The reason for these characteristic curves may be due to the fact that the manufacturer adds 10% CdO to the positive plate and 5% silver powder to the negative plate. See ref. 15. The reason for these additions are reversal protection. However, all cells in the battery do not have these profiles in reverse. Table 19 presents the data on all the cells of the battery during the three hour reversal. As can be seen, some cells reverse and then return to a positive voltage while other cells reverse and then become less negative as the test continues.

The integrated ampere hours under the current curve on figure 66 are 0.07. As shown in Test 021 of Section II, single cells of this type can be reversed 0.16 ampere hours before any pressure rise becomes significant.

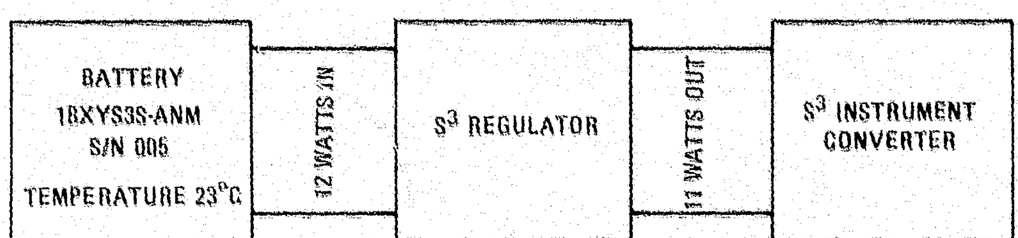


Figure 65. Regulator and Converter Test Set-Up for Reversal Test

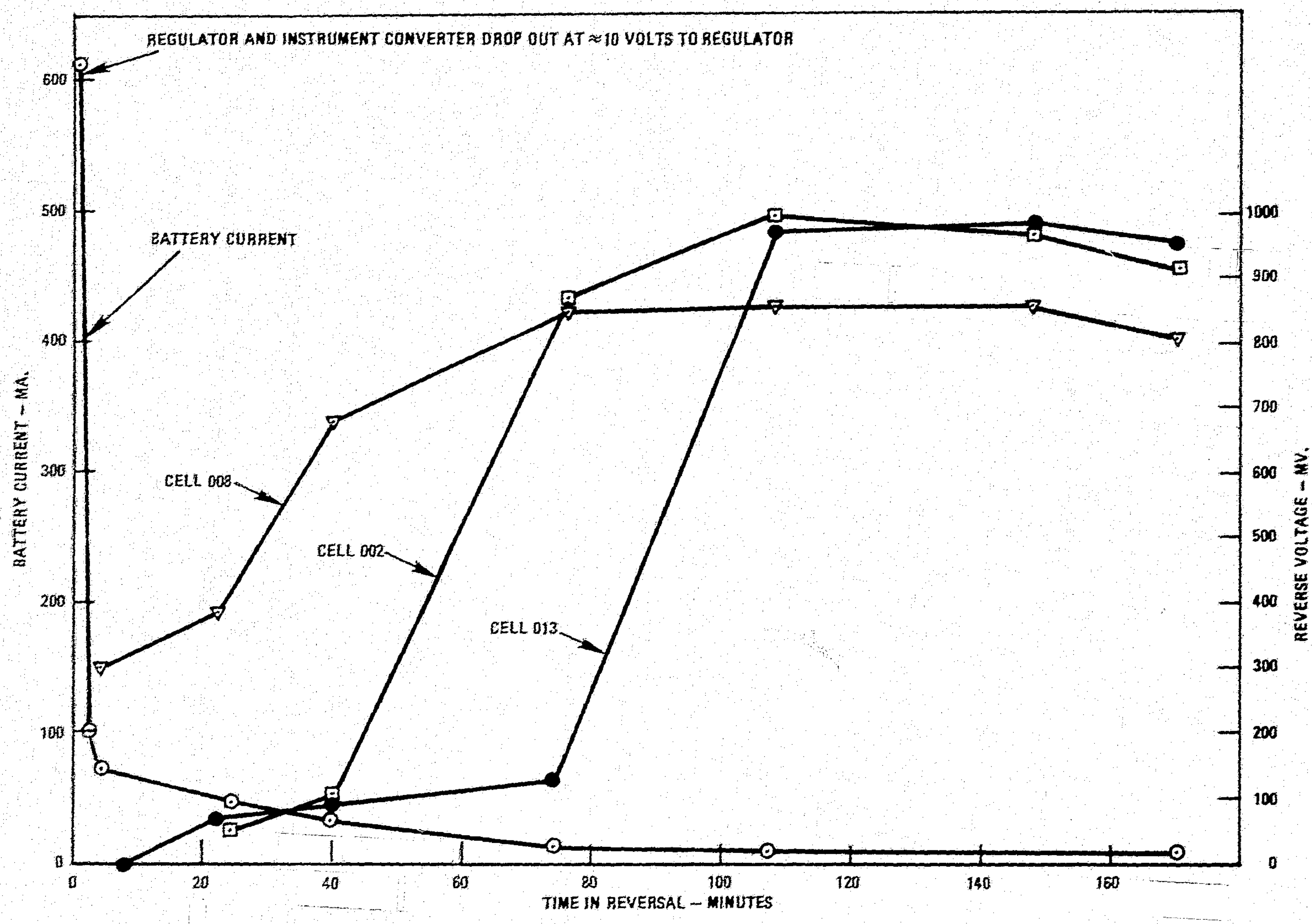


Figure 66. Reversal of Cells in an Eighteen Cell Battery
Test Unit: 18xYS3S-2NM, S/N 005

Table 19
Reversal of Cells in Explorer XLV Battery
Time — Minutes

Cell No.	0	22	40	75	108	148	170
	Cell Voltages						
001	0.799	0.761	0.723	-.182	-.176	-.168	-.159
002	0.404	-.051	-.104	-.868	-.987	-.965	-.912
003	0.179	-.038	-.063	-.056	0.102	0.130	0.232
004	0.766	-.181	-.209	-.186	-.171	-.163	-.155
005	0.713	0.580	0.438	0.358	0.436	0.140	-.520
006	0.682	0.456	0.164	0.136	0.198	0.231	0.314
007	0.814	0.802	0.774	0.828	0.891	0.905	0.916
008	-.322	-.384	-.668	-.848	-.856	-.865	-.818
009	0.244	-.038	-.066	-.006	0.050	0.065	0.097
010	0.121	-.072	-.100	-.024	0.066	0.094	0.161
011	0.839	0.766	0.726	0.749	0.748	0.721	0.704
012	0.195	-.029	-.048	0.003	0.083	0.105	0.149
013	0.150	-.064	-.096	-.130	-.971	-.993	-.955
014	0.866	0.831	0.811	0.856	0.894	0.909	0.922
015	0.902	0.878	0.858	0.881	0.910	0.922	0.933
016	0.834	0.749	0.706	0.727	0.726	0.698	0.686
017	0.884	0.832	0.791	0.880	0.932	0.947	0.953
018	0.874	0.848	0.850	0.899	0.914	0.923	0.473
No. of Cells Reversed	1	8	8	8	5	5	6

Category 011. Procurement, Fabrication and Acceptance Testing of Batteries

The following specifications, documents and procedures form guidelines for the procurement, fabrication and acceptance testing of batteries for flight use.

1. "GSFC Specification (S-716-P-24) For Silver Cadmium Cells" dated May, 1969 with Revision A dated September, 1974 published by Goddard Space Flight Center, Greenbelt, Md. 20771.

The purpose of this specification is to procure three, five, ten, eleven and sixteen ampere hour cells in the dry and unsealed condition intended for satellite use. It is a material and process control specification. The specification is used in conjunction with the Cell Design Sheets of Appendix A of this report.

2. Jackson, T. P. and Colston, E. F., Report X-716-70-113. "The Manufacture of Sealed Silver Cadmium Spacecraft Batteries From Dry Unsealed Cells" dated March, 1970 published by Goddard Space Flight Center, Greenbelt, Md., 20771.

This report describes electrolyte filling and adjustment, cell formation, wiring of the battery, the potting compound formula and method of encapsulation. Some detail is shown on typical magnetic compensation loops.

3. Goddard Space Flight Center, Drawing GE-1373282 "ISEE A&C Battery Assembly" dated February, 1976.

This set of drawings details the battery structural parts and wiring with connectors. It also details heater and thermostat assemblies. These drawings are for a fourteen cell, ten ampere hour battery.

4. The following test procedure is typical of the method used to compare and evaluate production lots. The procedure shown is for ten ampere cells. This test is performed at 25°C. The charge control used is the Type 2 charge control described in Category 004 of this Section and in ref. 16. A five cell battery is usually used for the test.

A. Short all cells on 1.0 ohms for 16 hours.

B. Constant potential charge battery at 1.51 volts per cell average current limited at 0.50 amperes. Cut charge off when current tapers to 100 ma.

C. Discharge at 3.0 amperes constant current to 0.8 volts per cell average.

D. Remove residual capacity on 1.0 ohms for 16 hours.

E. Charge per B above.

F. Discharge per C above.

G. Charge per B above.

H. Perform 30 cycles as follows:

(a) Orbital period – 8.0 hours
(b) Discharge at 2.5 amperes constant current for 1.0 hours.
(c) Constant potential charge at 1.51 volts per cell average current limited at 0.50 amperes for 7.0 hours. Current cutoff of charge at 100 ma. Float voltage to be 1.41 volts per cell average.
(d) On cycle 30, continue discharge at 2.5 amperes to 0.8 volts per cell, average.

I. Remove residual capacity on 1.0 ohms for 16 hours.

J. Charge per B above.

K. Discharge per C above.

L. Requirements: On the last cycle of the 30 cycle test and on discharge at K above, the battery shall deliver greater than 10.0 ampere hours.

5. Webster, W. H., "International Sun-Earth Explorer – A/C (ISEE-A/C) GSFC Document ISEE-711-76-002 dated July, 1976.

This document provides those precautions that must be exercised with regard to the battery between the time that it is delivered to the project and its integration into the spacecraft. Specific electrical and thermal constraints, and allowable operational modes during the integration phases are delineated in the document. Detailed test procedures, including a listing of test equipment are included. Information required to complete successful acceptance tests under ambient, vibration and thermal vacuum conditions are also included.

SECTION V

SHORT ORBIT TESTS

This Section of the report includes data and information related to characterization and life cycles tests of silver cadmium batteries in short orbits, i.e., 1.5 and 1.6 hour orbital periods. Most of the investigation was done with three ampere hour cells with life testing reported on a twelve ampere hour design. The cell design coding of these cells differs from the coding shown in Section II. The three ampere hour cell coding, YS5S-C3A-NM, designates a three ampere hour cell was constructed in a five ampere hour case. The cell contained six positive plates and seven negative plates rather than the four positives and five negatives used in the five ampere hour cell. The twelve ampere hour coding, YS12S-A2NM(20), designates a twelve ampere hour cell constructed in a twenty ampere hour case. Details of these three ampere hour and twelve ampere hour cells are given in Appendix A.

Characterizations of three ampere hour batteries involved 4500 hours which included approximately 2400 cycles at various test parameters. A flight battery design constructed of three ampere hour cells was operated 7280 cycles for 1.3 years to failure. Life cycling to failure of three, twelve ampere batteries resulted in a total of 2.2 years of test and a total of 12,560 cycles.

Most of the testing of three ampere hour cells was done at 16% and 33% nominal depths of discharge. The voltage clamps and currents used at the various temperatures on reported in Tests 200 through 204 inclusive. The batteries could be cycled over the temperature range of -10°C to 50°C. Because of separator deterioration, the upper range of temperature would shorten battery life. As shown in the test of the twelve ampere hour battery, S/N 85B, operation at -20°C at a nominal depth of discharge of 25% is questionable.

The flight battery design constructed of three ampere hour cells was tested for the FR-1 French Satellite Program. The battery weighed 2.1 Kg (4.6 lbs.). This would result in a nominal energy density, based on 1.1 volts per cell (9 cells) and three ampere hours, of 14.1 WH/Kg (6.4 WH/lb). As can be seen in Illustration 16, this battery was very heavy structurally. Using present battery designs, it is estimated that the energy density could be increased to 19 WH/Kg for a three ampere hour battery.

During cycling in short orbits, there was no indication of a flattening of the discharge voltage curve as experienced during long orbits. See Section II. It is suggested that the loss of the upper plateau (AgO plateau) is dependent on low current density on charge.

Several times the charged, three ampere hour batteries were placed on a float charge of 1.50 and 1.55 volts per cell average. A cell voltage unbalance would occur that would result in high internal pressures or cell rupture. These problems would occur within a short time as compared with the cells tested in long orbits. See Section II. Also, the float currents were higher. This may have been due to the increased plate area in the three ampere hour cells as compared to five ampere hour cells. See Appendix A. If these sealed cells were to be used in an application where long float periods were encountered, it is recommended that a Type 2 charge control, described in Section IV, be used.

Ref. 17 describes a series of tests performed by the Boeing Company on the same type of three ampere hour cells. The battery samples were three cells individually encapsulated in EPON. The orbital period was 100 minutes with a 55 minute discharge time. Heat sink temperatures were 21°C. The cycle life of these three cell batteries was as follows:

Nominal Depth of Discharge	Cycles to Failure
25%	16,700
35%	6500 – 7500
50%	4000 – 7400
65%	1800

Each test reported in this Section of the report is organized the same as in Section II, i.e., TEST BRIEF, CYCLING and OBSERVATIONS AND CONCLUSIONS.

TEST 200

Test Unit: 10xYS5S-C3A-NM
S/N 014

Test Period: 1962

Total Cycling Time: 1100 hours
Number of Cycles: 528

TEST BRIEF

The battery consisted of ten, three ampere hour cells in series encapsulated in EPON 834. Simulated orbital cycling was at 25°C and 42°C in 1.5 hour orbits with a 0.5 hour discharge. Constant resistance discharges were used. Discharge currents reported are averages. This was a series of characterization tests to determine the voltage clamps and current limits required for various nominal depths of discharge. During cycling, total battery voltage was recorded for all of the cycling while end of charge and discharge voltage of the cells were monitored. Currents were integrated by means of an ampere hour integrator with an accuracy of ±1.0 percent. Two calibrated thermistors were encapsulated within the battery assembly to determine the temperature rise during cycling at the various test parameters. These thermistors were located at the center of the battery assembly. Except for the latter groups of cycles, in-cycle capacity checks were not made when the nominal depth of discharge (NDOD) was changed.

Cell Design Reference: Appendix A

Main Project: General Testing

Applicable Figures: 67, 68

Nominal Depths of Discharge: 10%, 22%, 33%, 45%

TEST 200 (Continued)

CYCLING

Cycle(s)(1) Half Cycle(s)	AHI (2)	AHO (2)	Cycling Parameters and Discussion
1C to 5D	INA (3)	3.1 (Average)	300 ma. constant current to 1.6 volts per cell average. Discharge at 1.0 amperes constant current to 0.9 volts per cell average. Temperature: 26°C.
6C	3.0		300 ma. constant current to 1.56 volts per cell average. Temperature: 25°C.
6D to 226D			NDOD(4): 10% Temperature: 25°C. Constant potential charge to 1.50 volts per cell current limited at 0.5 amperes for 1.0 hours. Discharge at 600 ma. for 0.5 hours. During cycles 70 through 226, the ampere hour efficiency was close to 100%. The maximum temperature rise of the battery was 1.0°C.
227C to 242D			NDOD: 22% Temperature: 25°C. Constant potential charge to 1.50 volts per cell current limited at 0.73 amperes for 1.0 hours. Discharge at 1.3 amperes for 0.5 hours. During cycling, the battery was losing 0.07 ampere hours average during each charge. The maximum temperature rise of the battery was 2°C.

(1) C = Charge
D = Discharge

(2) AHI - Ampere hours in
AHO - Ampere hours out

(3) INA - Information Not Available

(4) NDOD - Nominal Depth of Discharge

Cycle(s) Half Cycle(s)	AHI	AHO	Cycling Parameters and Discussion
242C to 275D			NDOD: 22% Temperature: 25°C. Constant potential charge to 1.50 volts per cell current limited at 0.90 amperes for 1.0 hours. Discharge at 1.3 amperes for 0.5 hours. During cycling there seemed to be a slight loss in ampere hours delivered to the battery on each charge. The temperature rise of the battery was not measured.
276C to 321D			NDOD: 22% Temperature: 24°C. Constant potential charge to 1.55 volts per cell current limited at 0.90 amperes for 1.0 hours. Discharge at 1.3 amperes for 0.5 hours. During cycling there was an average gain of 0.02 ampere hour on each charge. The maximum temperature rise of the battery was 4°C.
322C to 326D			NDOD: 45% Temperature 24°C. Constant potential charge to 1.55 volts per cell current limited at 1.8 amperes for 1.0 hours. Discharge at 2.7 amperes for 0.5 hours. During cycling, there was an average loss of 0.07 ampere hours on each charge. The test could not be continued because the battery voltage was less than 1.0 volt per cell at end of discharge. The maximum temperature rise of the battery was 7.5°C.

Cycle(s) Half Cycle(s)	AHI	AHO	Cycling Parameters and Discussion
327C to 337D			NDOD: 33% Temperature: 25°C. Constant potential charge to 1.55 volts per cell current limited at 1.2 amperes for 1.0 hours. Discharge at 2.0 amperes for 0.5 hours. During these cycles, there was a loss of an average of 0.02 ampere hours on each charge. The temperature rise of the battery was not monitored.
338C to 342D			NDOD: 33% Temperature: 25°C. Constant potential charge to 1.55 volts per cell current limited at 1.3 amperes for 1.0 hours. Discharge at 2.0 amperes for 0.5 hours. During these cycles, there was a loss of an average of 0.03 ampere hours on each charge. The maximum temperature rise of the battery was 6°C.
343C to 401C			NDOD: 33% Temperature: 25°C. e: 25°C. Constant potential charge to 1.55 volts per cell current limited at 1.4 amperes for 1.0 hours. Discharge at 2.0 amperes for 0.5 hours. During these cycles, there was a gain of an average of 0.01 ampere hours on each charge. The maximum temperature rise of the battery was 6°C.
401D		2.4	In-cycle capacity check at 26°C. Discharge at 2.0 amperes to 0.9 volts per cell average.
402C	3.0		Constant potential charge to 1.55 volts per cell current limited at 300 ma. for 125 hours at 25°C.

TEST 200 (Continued)

Cycle(s) Half Cycle(s)	AHI	AHO	Cycling Parameters and Discussion
402D to 527C			NDOD: 33% Temperature: 42°C. Constant potential charge to 1.55 volts per cell current limited at 1.4 amperes for 1.0 hours. Discharge at 2.0 amperes for 0.5 hours. During these cycles there was again of an average of 0.07 ampere hours on each charge. The maximum temperature rise of the battery was 5°C.
527D		2.0	In cycle capacity check at 26°C. Discharge at 2.0 amperes to 0.9 volts per cell average.
528C	3.0		Same as 6C. Temperature: 25°C.
528D		3.0	Discharge at 1.0 amperes constant current to 0.9 volts per cell average. Temperature: 25°C.

OBSERVATIONS AND CONCLUSIONS:

1. Under the test conditions stated, the battery would operate satisfactorily at 10%, 22% and 33% nominal depths of discharge. Once the combination of voltage clamp and current limit was established, the ampere hour efficiency during cycling was close to 100%. Probably the battery could have been cycled at the 45% nominal depth of discharge if a higher voltage clamp was used, e.g., 1.6 volts per cell. The equipment available at the time did not have this higher voltage capability.

2. During short orbit cycling, the battery operates at a reduced capacity as shown by the in-cycle capacity checks. However, the nominal capacity can be restored to the battery by constant current or constant potential charging.

3. Voltage profiles on discharge, typical of the various tests, are shown on fig. 67. There is no flatening of the upper plateau (AgO plateau) during cycling as experienced during long orbit cycling. Voltage and current profiles of the charges following the above discharges are shown in fig. 68.

4. During cycle group 343C to 401C, the end of charge voltage were within 1.55 ± .02. During cycle group 402D to 527C, at 42°C, the end of charge voltages were within 1.55 ± .03. After 100 hours on float during charge 402C, one cell was charging at 1.78 volts. At this time the current was four milliamperes. The remaining cells were less than 1.60 volts.

5. Even though the cell cases were Bakelite C-11 and the cells were encapsulated in EPON 834 within an aluminum case, only a moderate temperature rise of the battery was observed. The maximum temperature rise of 7.5°C was experienced when the battery was cycled at a nominal depth of discharge of 45%.

6. There were no indications of cell failure during simulated orbital cycling. After the cycling test was completed, the battery was charged to 3.0 ampere hours and then put on a float charge of 1.55 volts per cell average. After the first day the charge current had decreased to less than three milliamperes. During the float charging, cell voltage unbalance occurred with two cells greater than 1.65 volts. After approximately three weeks of float charge, at least two cells were leaking electrolyte.

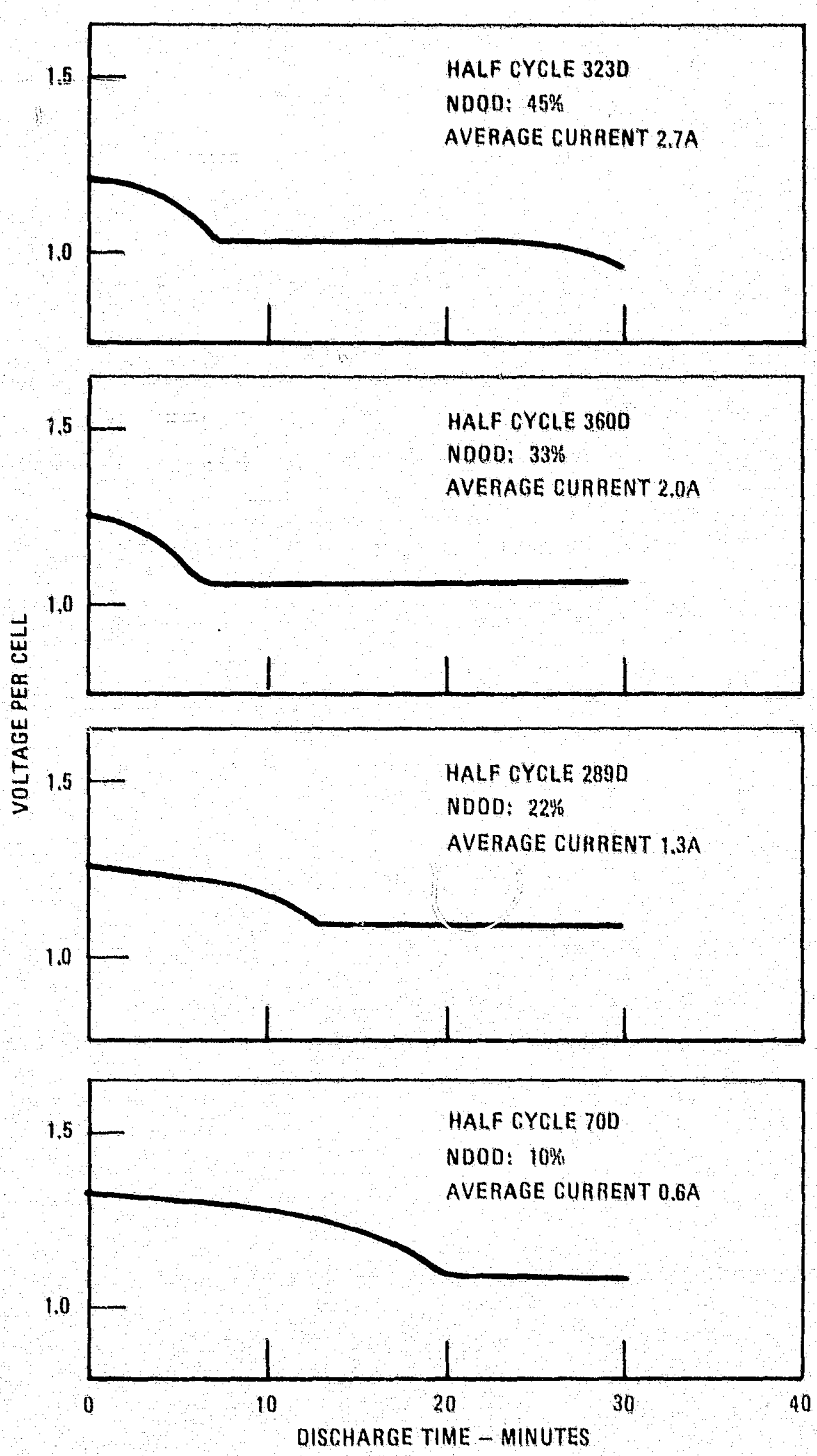


Figure 67. Voltage on Discharge at Various Nominal Depths of Discharge (NDOD) at 24/26°C, Test 200, Battery 10xYS5S-C3A NM, S/N 014

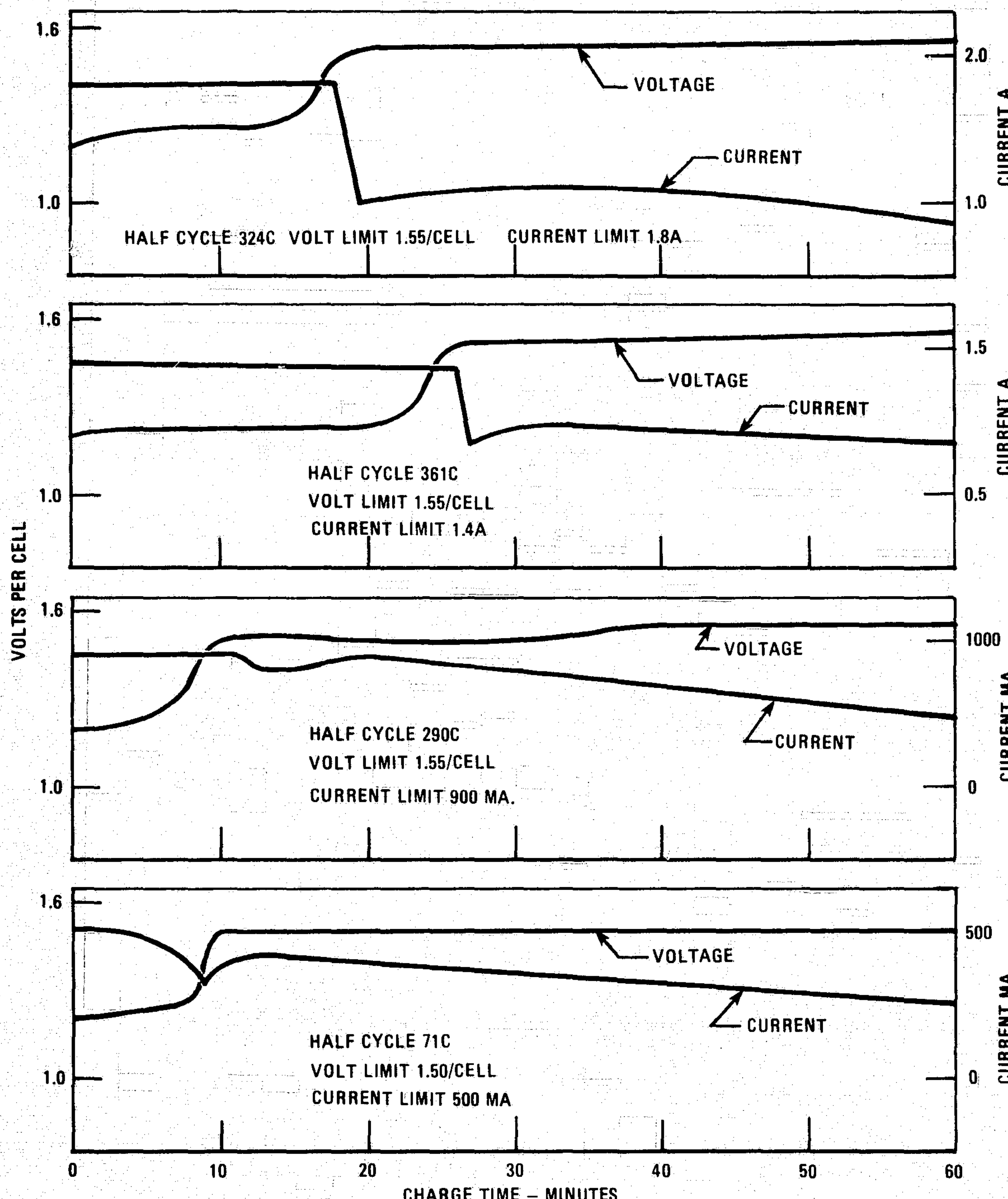


Figure 68. Voltage and Current Profiles During Charge, Temperature 24/26°C, Test 200, Battery 10xYS5S-C3A-NM, S/N 014

TEST 201

Test Unit: 10xYS5S-C3A-NM
S/N 002

Test Period: 1963

Total Cycling Time: 1700 Hours
Number of Cycles: 1030

TEST BRIEF

The battery consisted of ten, three ampere hour cells in series encapsulated in EPON 834 in a Fiberglass case. The battery is the square-shaped assembly shown in Illustration 15. Simulated orbital cycling was performed at room temperature in 1.5 hour orbits with a 0.5 hour discharge. Constant resistance discharges were used. Discharge currents reported are averages. This was a series of tests to determine the in-cycle capacity of the battery during short orbits, at a 33% nominal depth of discharge (NDOD). Also, during one section of testing, an ampere hour meter was used to determine the loss of capacity during initial cycling. During cycling, total battery voltages and currents were recorded. All current curves were integrated.

Cell Design Reference: Appendix A

Main Project: General Testing

Applicable Figure: 69

Nominal Depth of Discharge: 33%

CYCLING

Cycle(s) [1] Half Cycle(s)	AHI [2]	AHO [2]	Cycling Parameters All tests are at Room Temperature
1C and 1D 2C and 2D 3C and 3D 4C and 4D	3.6 3.5 3.5 3.5	3.3 3.4 3.5 3.4	200 ma. constant current charge to 1.55 volts per cell average. Discharge at 1.0 amperes constant current to 0.9 volts per cell average.
5C and 5D	INA [3]	3.4	Constant potential charge to 1.50 volts per cell average current limited at 220 ma. for 40 hours. Discharge at 1.0 amperes constant current to 0.9 volts per cell average.
6C	3.4		Same as 1C.
6D to 212C			Constant potential charge to 1.51 volts per cell current limited at 1.3 amperes for 1.0 hours. Discharge at 2.0 amperes for 0.5 hours.
212D		1.2	In-cycle capacity check. Discharge at 2.0 amperes to 0.9 volts per cell average.
213C	3.5		Same as 1C
213D to 418C			Constant potential charge to 1.54 volts per cell current limited at 1.3 amperes for 1.0 hours. Discharge at 2.0 amperes for 0.5 hours.

(1) C = Charge
D = Discharge
(2) AHI - Ampere Hours In
AHO - Ampere Hours Out
(3) INA - Information Not Available

TEST 201 (Continued)

Cycle(s) Half Cycle(s)	AHI	AHO	Cycling Parameters All tests are at Room Temperature
418D		2.3	Same as 212D.
419C	3.1		Same as 1C.
419D to 1028C			Same as 213D to 418C.
1028D		2.1	Same as 212D.
1029C and 1029D	2.4	2.5	Constant potential charge to 1.55 volts per cell current limited at 1.3 amperes for 20 hours. Discharge of 2.0 amperes to 0.9 volts per cell average.
1030C and 1030D	3.5	3.1	300 ma. constant current charge to 1.55 volts per cell average. Discharge at 2.0 amperes to 0.9 volts per cell average.

OBSERVATIONS AND CONCLUSIONS:

1. When cycling at a voltage clamp of 1.51 volts per cell, the in-cycle capacity of the battery, after 200 cycles, was 1.2 ampere hours. However, when the voltage clamp was raised to 1.54 volts per cell, the in-cycle capacity of the battery, after 200 cycles, was 2.3 ampere hours. As shown in figure 69 there is an ampere hour loss during the first eight simulated orbital cycles. In this case, there was a loss of approximately 1.2 ampere hours during the first eight cycles. After these few initial cycles, the ampere hour efficiency is close to 100%. After each in-cycle capacity check the battery could be charged and/or discharged to greater than three ampere hours.

2. Charge and discharge curves for this test are similar to the curves reported in this section of the report under Test 200, 33% nominal depth of discharge.

3. There was no indication of cell failures as a result of the 1030 simulated orbital cycles at 33% nominal depth of discharge. In tests run on the same type of cells under similar test conditions, the Boeing Company reported, ref. 17, a cycle life to failure of 6000 cycles of three cell batteries.

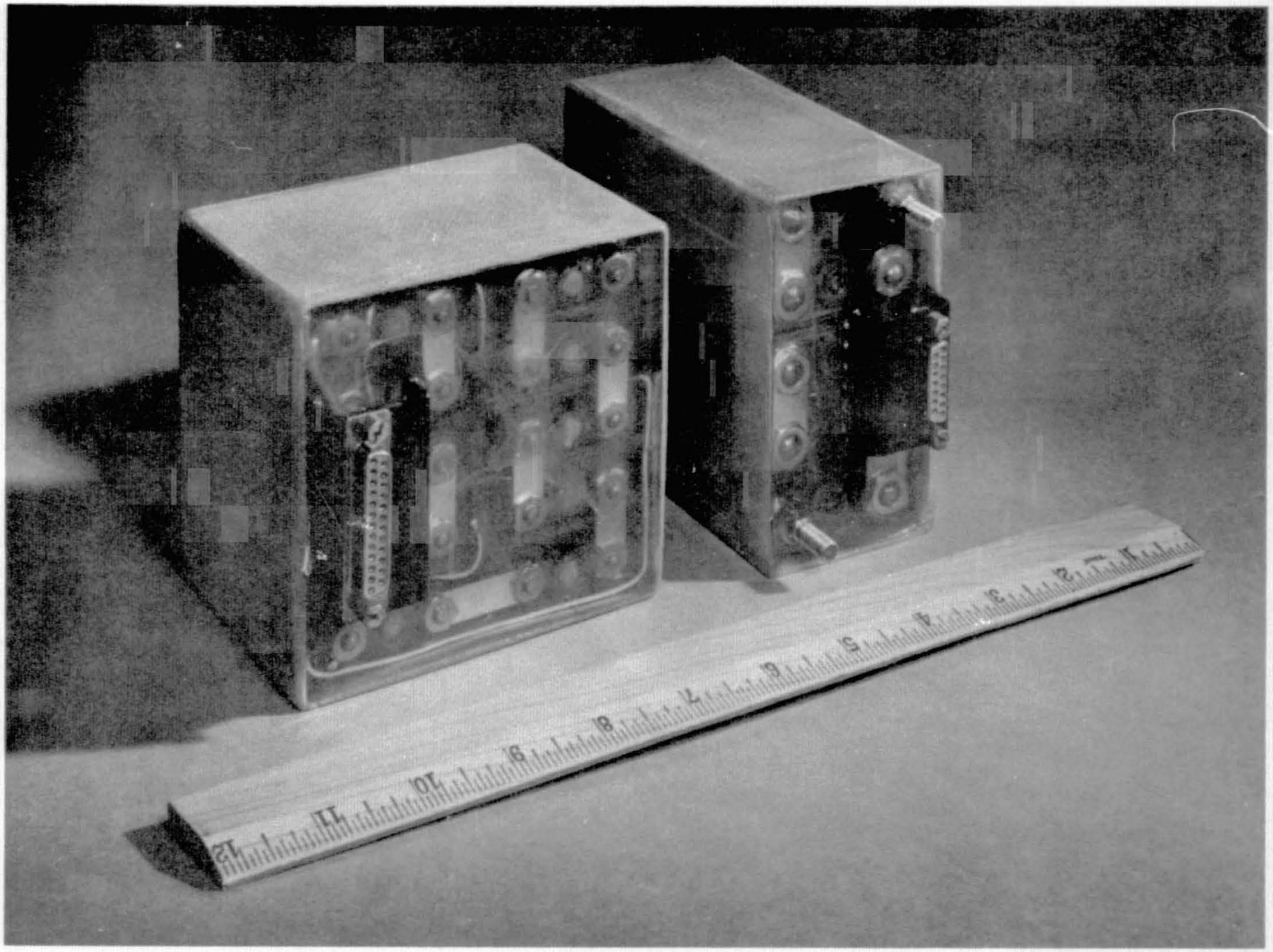


Illustration 15. Three and Ten Ampere Hour Cells Encapsulated
in EPON 834 in a Fiberglass Case

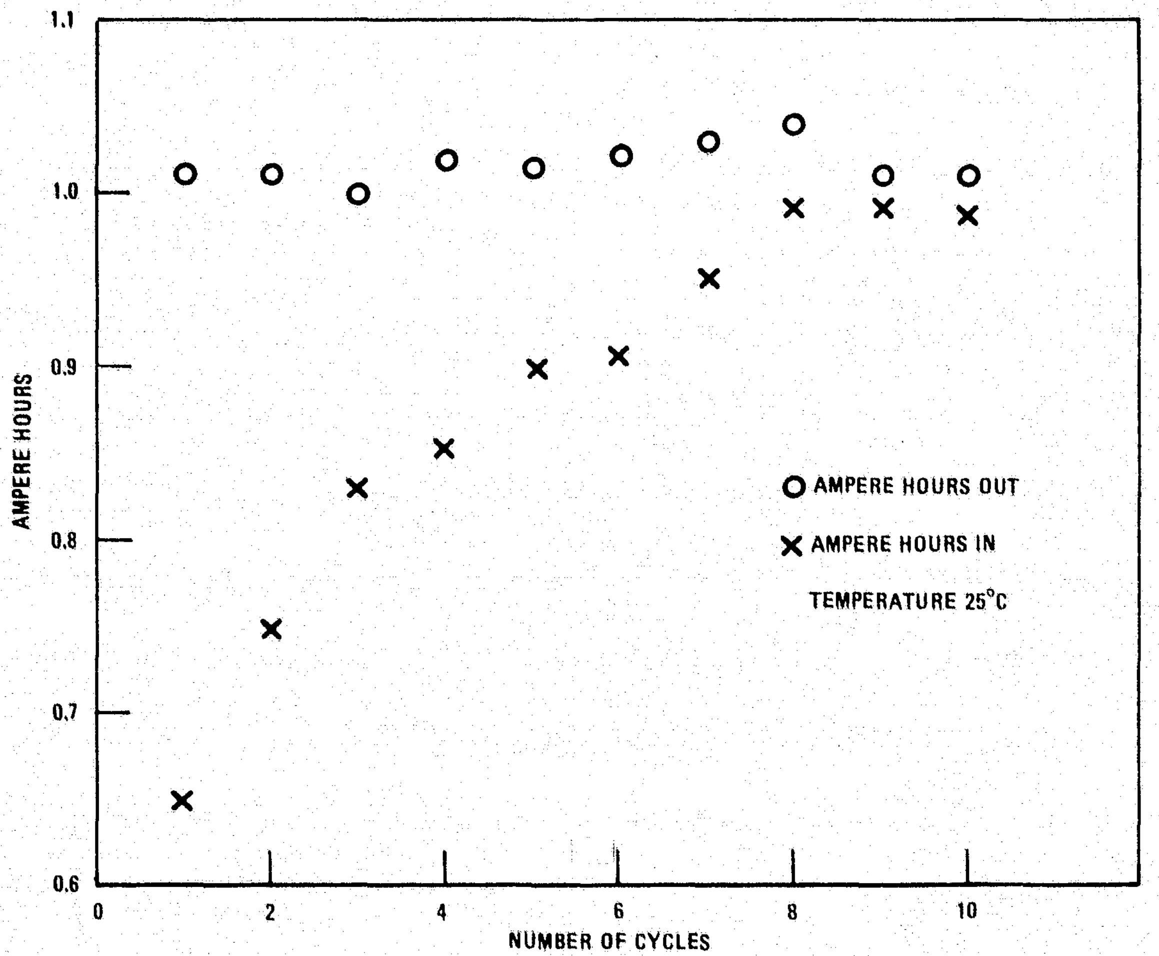


Figure 69. Ampere Hours in Vs. Ampere Hours Out During First Ten Cycles of Cycle Group 213D to 418C, Test No. 201, Battery 10xYS5S-C3A-NM, S/N 002

TEST 202

Test Unit: 10xYS5S-C3A-NM
S/N 015

Test Period: 1961

Total Cycling Time: 1100 Hours
Number of Cycles: 519

TEST BRIEF

The battery consisted of ten, three ampere hour cells in series encapsulated in EPON 834 in a Fiberglass case. The battery was of the same configuration as shown in this Section of the report, Test 201, Illustration 15. Simulated orbital cycling was performed at -10°C, 0°C, 26°C and 50°C in 1.5 hour orbital periods with a 0.5 hour discharge. Constant resistance discharges were used. Discharge currents reported are averages. This was a series of tests to determine the voltage clamps and current limits required for a 33% nominal depth of discharge (NDOD) at the temperatures listed above. Two calibrated thermistors were encapsulated within the battery assembly to determine the temperature rise during cycling at the various test parameters. Some of the tests were run in a vacuum of 100 microns of Hg. During cycling, total battery voltages and currents were recorded. End of charge and discharge voltages were monitored occasionally. All charge and discharge current curves were integrated.

Cell Design Reference: Appendix A

Main Project: General Testing

Applicable Figure: None

Nominal Depth of Discharge: 33%

TEST 202 (Continued)

CYCLING

Cycle(s)[1] Half Cycle(s)	AHI[2]	AHO[2]	Cycling Parameters (Note: Some tests at 100 microns Hg)	Temperature °C
1C and 1D	3.4	3.0	200 ma. constant current to 1.60 volts per cell average. Discharge at 950 ma. to 1.0 volts per cell average.	26
2C and 2D	3.1	3.0		
3C and 3D	3.1	3.0		
4C	3.2			
4D to 209C			Constant potential charge to 1.55 volts per cell current limited at 1.4 amperes for 1.0 hours. Discharge at 2.0 amperes for 0.5 hours. Maximum temperature rise of the battery was 7°C.	26
209D		2.6	In-cycle capacity check. Discharge at 2.0 amperes to 0.7 volts per cell average.	26
210C	3.1		INA[3]	26
210 to 253C			Constant potential charge to 1.60 volts per cell current limited at 1.4 amperes for 1.0 hours. Discharge at 2.0 amperes for 0.5 hours. Maximum temperature rise of the battery was 13°C.	-10C

(1) C = Charge
D = Discharge
(2) AHI - Ampere Hours In
AHO - Ampere Hours Out
(3) INA - Information Not Available

TEST 202 (Continued)

Cycle(s) Half Cycle(s)	AHI	AHO	Cycling Parameters (Note: Some tests at 100 microns Hg)	Temperature °C
253D		1.4	In-cycle capacity check. Discharge at 2.0 amperes to 0.7 volts per cell average.	-10
254C	3.6		Same as 1C.	28
254D to 367C			Constant potential charge to 1.58 volts per cell current limited at 1.4 amperes for 1.0 hours. Discharge at 2.0 amperes for 0.5 hours. Maximum temperature rise of the battery was 10°C.	0
367D		1.8	In-cycle capacity check. Discharge at 2.0 amperes to 0.9 volts per cell average.	0
368C and 368D	3.4	3.4	Same as 1C and 1D.	28
369C	3.7		Same as 1C.	27
369D to 451C			Vacuum of 100 microns Hg. Cycling same as 4D to 209C. Maximum temperature rise of the battery was 12°C.	25 (4)
451D		1.8	In-cycle capacity check. Discharge at 2.0 amperes to 0.9 volts per cell average.	25

(4) Where Vacuum Used,
Temperature is of Vacuum Chamber Wall

TEST 202 (Continued)

Cycle(s) Half Cycle(s)	AHI	AHO	Cycling Parameters (Note: Some tests at 100 microns Hg)	Temperature °C
452C	3.4		Constant potential charge to 1.55 volts per cell current limited at 1.35 amperes for 200 hours.	25
452D to 492C			Vacuum of 100 microns Hg. Constant potential charge at 1.58 volts per cell current limited at 1.4 amperes for 1.0 hours. Discharge at 2.0 amperes for 0.5 hours. Maximum temperature rise of battery was 19°C.	-10
492C to 500 D			INA	
500C	3.2		Same as 452C except for 24 hours.	25
500D to 518C			Constant potential charge to 1.51 volts per cell average current limited at 1.4 amperes for 1.0 hours. Discharge at 2.0 amperes for 0.5 hours. Maximum temperature rise of the battery was 9°C.	50
518D		2.8	In-cycle capacity check. Discharge at 2.0 amperes to 0.9 volts per cell average.	50
519C	3.1		Same as 452C.	26
519D		INA		

TEST 202 (Continued)

OBSERVATIONS AND CONCLUSIONS:

1. A voltage clamp of 1.55 volts per cell average and a current limit of 1.4 amperes were adequate for cycling at 26°C. A voltage clamp of 1.58 volts per cell average and a current limit of 1.4 amperes were satisfactory at 0°C. Other tests have shown that the voltage clamp can be lowered to 1.55 volts per cell and the current limit set at 1.3 amperes for a 33% NDOD at 0°C. Operation of the battery is marginal at -10°C with a voltage clamp of 1.6 volts per cell and a current limit of 1.4 amperes. Very few cycles were run at 50°C but the 1.51 voltage clamp and 1.4 ampere current limit were adequate.

2. Even though the cell cases were Bakelite C-11 and the cells were encapsulated in a Fiberglass case, only moderate temperature rises of the battery were observed. In a vacuum of 100 microns of Hg. the increase in the temperature rise, at chamber wall temperatures of 26°C and -10°C, were about 50% greater than temperature rises observed at ambient pressures.

3. Voltages of cells at end of charge at 25°C and -10°C were 1.55 ± 0.01 and 1.60 ± 0.01, respectively. During the 200 hour float charge, 452C, three cells exhibited voltages greater than 1.7 volts at 120 hours and remained above this voltage for the remainder of the charge. The other cells were less than 1.5 volts. During the last 100 hours of charge, the current was between two and three milliamperes.

4. The average voltage on discharge, on the lower plateau (Ag_2O plateau), at the various temperatures was as follows:

Temperature °C	Cell Voltage Average
-10	1.03
0	1.04
25	1.06
50	1.09

5. During cycling, there was no evidence of cell failure. After 519 cycles under various conditions, the battery could be charged to 3.1 ampere hours.

TEST 203

Test Unit: 10xYS5S-C3A-NM
S/N 003

Test Period: 1963

Total Cycling Time: 600 Hours
Number of Cycles: 349

TEST BRIEF

The battery consisted of ten, three ampere hour cells in series encapsulated in EPON 834 in an aluminum can. Simulated orbital cycling was performed at -10°C and 0°C in 1.5 hour orbits with a 0.5 hour discharge. Constant resistance discharges were used. Discharge currents reported are averages. This was a series of tests to determine the in-cycle capacity of the battery at low temperatures in 1.5 hour orbits. During cycling, total battery voltages and currents were recorded. All current curves were integrated.

Cell Design Reference: Appendix A

Main Project: General Testing

Applicable Figure: None

Nominal Depth of Discharge: 33%

CYCLING

Cycle(s)[1] Half Cycle(s)	AHI[2]	AHO[2]	Cycling Parameters	Temperature °C
1C and 1D	3.2	3.0	200 ma. constant current charge to 1.55 volts per cell average. Discharge at 1.0 ampere constant current to 0.9 volts per cell average.	27
2C and 2D	3.4	3.2		
3C and 3D	3.3	3.2		
4C	3.4			
4D to 96C			Constant potential charge to 1.55 volts per cell average current limited at 1.3 amperes for 1.0 hours. Discharge at 2.0 amperes for 0.5 hours.	-10
96D		1.0	In-cycle capacity check. Discharge at 2.0 amperes to 0.8 volts per cell average.	-10
97C and 97D	3.2	3.0	Same as 1C and 1D.	26
98C	3.3		Same as 1C.	26
98D to 148C			Constant potential charge to 1.55 volts per cell average current limited at 1.3 amperes for 1.0 hours. Discharge at 2.0 amperes for 0.5 hours.	0

(1) C = Charge
D = Discharge

(2) AHI - Ampere Hours In
AHO - Ampere Hours Out

TEST 203 (Continued)

Cycle(s) Half Cycle(s)	AHI	AHO	Cycling Parameters	Temperature °C
148D		2.0	In-cycle capacity check. Discharge at 2.0 amperes to 0.9 volts per cell average.	0
149C and 149D	3.5	3.3	Same as 1C and 1D.	26
150C	3.4		Constant potential charge to 1.55 volts per cell average current limited at 1.3 amperes. Charge continued until the current was 10 ma.	26
150D to 344C			Same as 98D to 148C.	0
344D		1.9	Same as 148D.	0
345C and 345D	2.1	2.2	Constant potential charge to 1.56 volts per cell average current limited at 1.3 amperes. Charge continued until the current was between 10 ma. and 12 ma.	25
349C and 349D	2.9	2.8	Same as 1C and 1D.	25

OBSERVATIONS AND CONCLUSIONS:

1. When cycling at -10°C with a 1.55 volts per cell clamp, the in-cycle capacity of the battery was essentially equal to the capacity removed during each cycle. During most of the cycles at -10°C, the end of discharge voltage of the battery was between 0.8 and 1.0 volts.

2. Operation of the battery at 0°C with a 1.55 volt per cell clamp was satisfactory. As shown in Test 202, the battery at 0°C does operate at an in-cycle capacity that is less than the nominal capacity.

3. There was no evidence of the cell failures as a result of the cycling at the colder temperatures. However, after the cycling test was completed, the capacity of the battery was less than the initial capacity measured.

TEST 204

Test Unit: 9xYS5S-C3A-NM*
S/N FR-1, P3-3

Test Period: 1965, 1966

Total Cycling Time: 1.3 Years
Number of Cycles: 7280

TEST BRIEF

The battery consisted of nine, three ampere hour cells in series encapsulated in EPON 834. This battery, shown in Illustration 16, was the design flown on the French Satellite Programs, FR-1 and FR-2. Initial simulated orbital cycling was performed at 27°C and -10°C in 1.67 hour orbital periods with a 0.67 hour discharge time. Constant resistance discharges were used. Discharge currents reported are averages. During cycling total battery voltage and currents were recorded. All charge and discharge current curves were integrated. After cycling for approximately three weeks at Goddard Space Flight Center, the battery was cycled to failure at the Naval Weapons Support Center/Crane (NWSC/Crane). Simulated orbital cycling was performed at 25°C in orbital periods of 1.5 hours with a 0.5 hour discharge time.

Cell Design Reference: Appendix A

Main Project: French Satellite Program

Applicable Figure: None

Nominal Depth of Discharge: 16%

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*During cycling tests of GSFC, two additional three ampere hour cells were connected in series with the nine cell battery. These cells were equipped with pressure gages. Consequently, the battery will be referred to as an eleven cell battery.

CYCLING

I. Goddard Space Flight Center (GSFC)

Cycle(s)[1] Half Cycle(s)	AHI[2]	AHO[2]	Cycling Parameters	Temperature °C
1C and 1D 2C and 2D 3C	3.5 3.3 3.4	3.3 3.2	300 ma. constant current to 1.54 volts per cell average. Discharge at 1.0 amperes to 0.8 volts per cell average.	27
3D to 122C			Constant potential charge to 1.50 volts per cell average current limited at 300 ma. for 1.0 hour. Discharge at 710 ma. for 0.67 hours.	27
122D		2.8	In-cycle capacity check. Discharge at 720 ma. constant current to 0.9 volts per cell average.	27
123C	3.6		Constant potential charge to 1.51 volts per cell average current limited at 600 ma. Charge continued until current was 20 ma.	27
123D to 238C			Constant potential charge to 1.52 volts per cell average current limited at 600 ma. for 1.0 hours. Discharge at 730 ma. for 0.67 hours.	-10

(1) C = Charge
D = Discharge
(2) AHI - Ampere Hours In
AHO - Ampere Hours Out
(3) INA - Information Not Available

Cycle(s) Half Cycle(s)	AHI	AHO	Cycling Parameters	Temperature °C
239D		2.6	In-cycle capacity check. Discharge at 700 ma. to 0.9 volts per cell average.	-10

II. Naval Weapons Support Center/Crane (NWSC/Crane)

1. Previous to cycling at NWSC/Crane, the battery was stored discharged for nine months at room temperature.

2. Only the nine cell battery was cycled, i.e., the two extra cells were not included in the test.

(Note: All tests are at 25°C)

240C and 240D	2.6	2.5	200 ma. constant current to 1.54 volts per cell average. Constant current discharges on 240D, 241D, and 242D were 1.0, 2.0, and 3.0 amperes, respectively, until the first cell reached 0.7 volts.
241C and 241D	2.8	2.7	
242C and 242D	2.6	2.6	
243C	2.8		
243D and 3050D			Constant potential charge to 1.52 volts per cell average current limited at 600 ma. for 1.0 hours. Discharge at 1.0 amperes constant current for 0.5 hours.
3051C and 3051D	INA	0.9	Capacity check 200 ma. constant current to 1.52 volts per cell average. Discharge at 1.0 amperes constant current.
3052C	INA		
3052D to 4460D			Same as 243D to 3050D.

TEST 204 (Continued)

Cycle(s) Half Cycle(s)	AHI	AHO	Cycling Parameters
4461C and 4461D	INA	0.9	Same as 3051C and 3051D.
4462C	INA		
4462D to 5870D			Same as 243D to 3050D.
5871C and 5871D	INA	0.7	Same as 3051C and 3051D.
5872C	INA		
Cycle 7280			Battery Failed.

OBSERVATIONS AND CONCLUSIONS:

I. Goddard Space Flight Center (GSFC)

1. At a nominal depth of discharge of 16% in a 1.67 hour orbital period, voltage clamps of 1.50 and 1.52 volts per cell were adequate at temperatures of 25°C and -10°C, respectively. Current limits of 300 ma. at 25°C and 600 ma. at -10°C were adequate.

2. An additional charge was run at GSFC wherein the battery was constant potential charged at 27°C at 1.50 volts per cell average. When the charge current decreased to 40 ma., a cell voltage unbalance began with the cell voltages ranging between 1.45 and 1.60 volts. The pressure of one of the extra cells, that float charged at 1.60 volts, rose 33 PSIG in 16 hours without stabilizing. The average charge current during this time was 20 ma.

II. Naval Weapons Support Center/Crane (NWSC/Crane)

1. Except for the last few cycles, the end of charge voltage of the cells was 1.08 volts per cell. Ampere hour efficiencies were close to 100%. When measured, the in-cycle capacity of the battery was less than one ampere hour.

2. On cycle 7280, the battery ruptured. It is suspected that cell reversal and a resultant internal pressure rise caused failure.

3. Batteries of the same design, 9xYS5S-C3A-NM, were flown on the French Program Missions FR-1 and FR-2. The nominal depth of discharge was 16%. The life of the FR-1 Satellite was approximately 400 days. No problems were associated with the battery.

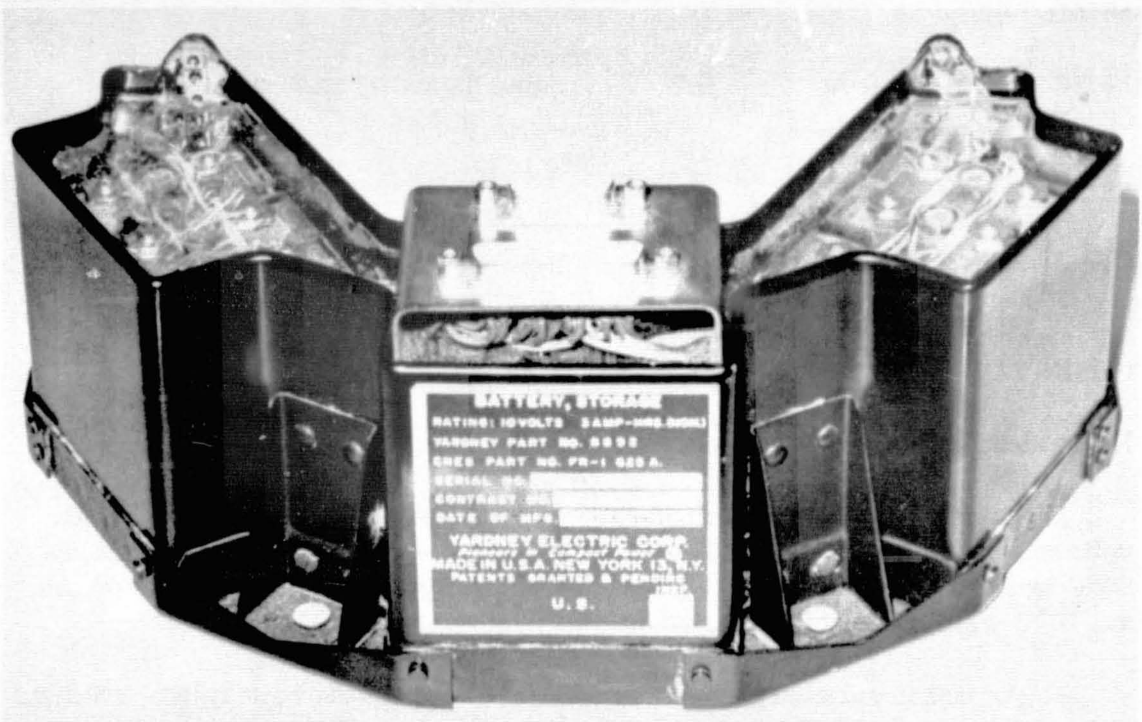

Illustration 16. Three Ampere Hour Battery
for the French Satellite Program

TEST 205

Test Units: 5xYS12S-2ANM(20)
S/Ns 82B, 85B and 97B

Test Period: 1965, 1966

Total Cycling Time: 2.2 Years
Total Cycles: 12, 560

TEST BRIEF

Each battery consisted of five, twelve ampere hour cells encapsulated individually in EPON 834. Simulated orbital cycling was performed at the Naval Weapon Support Center/Crane (NWSC/Crane). The batteries were cycled at 0°C, 25°C and 40°C in a 1.5 hour orbital period with a 0.5 hour discharge. The battery operated at 40°C was initially cycled at -20°C. However, due to low voltage and loss of capacity at -20°C, on cycle 214, the temperature was charged to 40°C. Battery voltages and currents were recorded on every thirty cycles.

At Goddard Space Flight Center, the batteries were given three capacity checks at 25°C as follows: (1) charge at 750 ma. to 1.52 volts per cell average and (2) discharge at 3.5 amperes to less than 1.0 volts per cell. On these three cycles the capacities of the fifteen cells was 12.8, 12.9 and 12.8 ampere hours.

Previous to cycling at NWSC/Crane, the batteries had been stored discharged for three months at room temperature.

Cell Design Reference: Appendix A

Main Project: General Testing

Applicable Figure: None

Nominal Depth of Discharge: 25%

CYCLING

Following is a summary of the tests of the three, five cell batteries at NWSC/ Crane. These tests are designated at 205A, 205B and 205C.

TEST 205 A
Battery S/N 82B at 25°C

Cycle(s) (1) Half Cycle(s)	AHI (2)	AHO (2)	Cycling Parameters
1C and 1D	INA (3)	13.3	600 ma. constant current charge to 1.55 volts per cell average. Discharge at 6.0 amperes constant current until first cell reached 0.5 volts.
2C	13.3		Same as 1C.
2D to 1410D			Constant potential charge to 1.55 volts per cell average current limited at 3.9 amperes for 1.0 hours. Discharge at 6.0 amperes constant current for 0.5 hours.
1411C and 1411D	INA (3)	4.5	Capacity check. Same as 1C and 1D.
1412C	INA (3)		Same as 1C.
1412D to 2816D			Same as 2D to 1410D.
2817C and 2817D	INA (3)	2.9	Capacity check. Same as 1C and 1D.

(1) C = Charge
D = Discharge
(2) AHI - Ampere Hours In
AHO - Ampere Hours Out
(3) INA - Information Not Available

Test 205 A (Continued)

Cycle(s) Half Cycle(s)	AHI	AHO	Cycling Parameters
2818C	3.3		Same as 1C.
2818 to 4224D			Same as 2D to 1410D.
4225C and 4225D	INA	3.3	Capacity check. Same as 1C and 1D.
4226C	INA		Same as 1C.
4467			First Cell Failed.
4225D to 4559			Same as 2D to 1410D. Two cells failed on cycle 4559. Test terminated.

TEST 205 B
Battery S/N 97B at 0°C

Cycle(s) Half Cycle(s)	AHI	AHO	Cycling Parameters
1C and 1D	INA	9.0	600 ma. constant current charge to 1.58 volts per cell average. Discharge at 6.0 amperes constant current until first cell reaches 0.5 volts. Temperature 0°C.
2C	INA		Same as 1C.
2D to 1410D			Constant potential charge to 1.58 volts per cell average current limited at 3.9 amperes for 1.0 hours. Discharge at 6.0 amperes constant current for 0.5 hours.
1411C and 1411D	INA	INA	Capacity check. Same as 1C and 1D.
1412C	INA		Same as 1C.

TEST 205 B (Continued)

Cycle(s) Half Cycle(s)	AHI	AHO	Cycling Parameters
1412D to 2816D			Same as 2D to 1410D.
2817C and 2817D	INA	3.5	Capacity check. Same as 1C and 1D.
2818C	3.4		Same as 1C.
2818D to 4224D			Same as 2D to 1410D.
2972, 3186			One cell failed on each cycle.
4224C and 4225D	INA	5.7	Capacity check. Same as 1C and 1D.
4226C	INA		Same as 1C.
4226D to 5631D			Same as 2D to 1410D.
4481			Third Cell failed.
5632C and 5632D	INA	3.7	Capacity check. Same as 1C and 1D. Test terminated.

TEST 205 C
Battery S/N 85B at -20°C and 40°C

1C and 1D	INA	5.4	600 ma. constant current charge to 1.60 volts per cell average. Discharge at 6.0 amperes constant current until first cell reaches 0.5 volts. Temperature -20°C.
2C	INA		Same as 1C.
2D to 214D			Constant potential charge to 1.60 volts per cell average current limited at 3.9 amperes for 1.0 hour. On half cycle 214D, battery discharge voltage below 1.0 volts per cell. Battery removed from test.

TEST 205 C (Continued)

Note: After cycle 214, the data is not clear as to the performance of capacity checks with cycle numbers. After cycle 214 the battery was cycled at 40°C in a constant potential charge to 1.55 volts per cell average for 1.0 hours. The discharge was 6.0 amperes constant current for 0.5 hours. Cell failure occurred at cycles 1978 and 2245 with the remaining cells failing at cycle 2375.

OBSERVATIONS AND CONCLUSIONS:

1. The cell failures called out in the test were due to low cell voltage on discharge, i.e., less than 1.0 volts and/or failure of the cells to deliver the three ampere hours during simulated orbital cycling.

2. Several cells from each test were opened and examined after failure. Each layer of cellophane separator (C-19) was badly deteriorated and the tensile strength was essentially zero. After several months of cycling, some of the cells developed leaks at the terminals.

SECTION VI

OTHER DEVELOPMENTS RELATED TO SILVER CADMIUM CELLS

This Section of the report includes the following data and information: (1) test results on prototype cells of 20 through 300 ampere hour sizes, (2) summary of developments that were shown to be feasible for mission use, (3) positive electrode analysis and (4) test results obtained on cells from suppliers other than the Yardney Electric Company. Three of the developments that were proven to be feasible but were not reduced to practice were (1) electrodepositing $Ca(OH)_2$ on positive plates to retard the solubility of silver oxides, (2) use of silver palladium alloy membranes to allow hydrogen to diffuse from the cells during float charging and (3) use of bellows devices for electrolyte level control to enhance gas recombination in flooded cells.

LARGE AMPERE HOUR CAPACITY CELLS

Between 1962 and 1963, several large ampere hour capacity cells were procured from the Yardney Electric Company. The ampere hour sizes were 20, 40, 115, 150 and 300. These cells were not evaluated on simulated orbital cycling. The main tests consisted of determining the capacity of these cells when discharged at moderate rates to less than 1.0 volts per cell. The larger capacity cells were not sealed during the tests. The test results are shown in Table 20.

Non-magnetic construction was used and the cell designs are shown in Appendix A.

Table 20
Typical Cycle Data on Large Ampere Hour Capacity Cells Discharged to Less than 1.0 Volts Per Cell

Cell Battery [1] Designation	Cells in Series/ Nominal Ampere Hours	Cycling Parameters	AHI/AHO [2]	Remarks
10xYS20S-3NM	10/20	1.25 ampere constant current charge to 1.55 volts per cell average. Discharge at 4.5 amperes (average) to 0.5 volts per cell.	22.7/22.7	Three cycles performed. Battery sealed in EPON 834. Battery weighed 7.6 Kg.
10xYS40S-2NM	10/40	2.50 ampere constant current charge to 1.56 volts per cell average. Discharge at 7.7 amperes to 0.9 volts per cell.	37.0/36.5	Data based on two cycles. Battery sealed in EPON 834.
6xYS115S-1NM	6/115	9.8 ampere constant current charge to 1.65 volts per cell average. Discharge at 25.0 amperes (average) to less than 0.5 volts.	161/159	Three cycles performed. Cells not sealed.
5xYS150S-3NM	5/150	6.8 ampere constant current charge to 1.55 volts per cell average. Discharge at 30.0 amperes constant current to 0.6 volts per cell.	187/180	Data based on three cycles. Cells not sealed.
YS300S-1NM	1/300	17.5 ampere constant current charge to 1.61 volts. Discharge at 60 amperes to less than 0.5 volts.	495/455	Data based on three cycles. Cell not sealed.

(1) Cell Design Reference: Appendix A
(2) AHI - Ampere Hours In
AHO - Ampere Hours Out

INVESTIGATION OF ELECTRODEPOSITED $Ca(OH)_2$ COATINGS ON POSITIVE PLATES

At the conclusion of Contract NAS5-9168 with the General Electric Company, ref. 18, sample five ampere hour silver cadmium cells were delivered to GSFC. In addition to control cells, samples were delivered that had 0.05 mm. (2 mil) and 0.13 mm. (5 mil) thick coating of $Ca(OH)_2$ on the silver plates. During the course of the contract it had been shown that coatings of $Ca(OH)_2$ on the positive plates could retard silver migration. The sample cells used, YS5-8NM, were similar to the YS5-2NM design, Appendix A, except the separators were reverse wrapped, i.e., the separators were wrapped on the negative plates rather than the positive plates. This was done in order to facilitate removing the positive plates from the cell to apply the $Ca(OH)_2$ coating and reassembly of the plates. The cells were filled and formed as shown in Table 21.

After the formation, one of each type of cell was opened and the cellophane separators observed visually and photographed. The cellophane from the control cell was heavily coated with silver, especially on the layers of cellophane nearest the positive plates. The cells coated with $Ca(OH)_2$ had very little silver on the first layer of cellophane but there was some darkening of the cellophane adjacent to the edges of the silver plates. Illustration 17 is a photograph of the cellophane separators from these three cells. The material at the bottom of the photograph was closest to the silver electrodes. After formation and an additional charge, five vented cells, one control and two each of the 0.05 and 0.13 mm. were cycled thirty-five times at 25°C in the following manner: (1) 0.5 hour discharge at 2.0 amperes, constant current, followed by a 7.5 hour charge current limited at 350 ma. and voltage limited at 1.50 volts per cell and (2) when the charge current decreased to 100 ma., the charge voltage was reduced to 1.41 volts per cell. On half cycle 35D, the battery was discharged to 0.7 volts, each cell. On cycle 36, the cells were charged for twenty-two hours with a constant potential charge voltage limited at 1.50 volts per cell and current limited at 350 ma. This was followed by a discharge at 2.0 ampere, constant current, to 0.7 volts, each cell.

Table 21
Formation of YS-5-8NM Cells Containing Silver Plates Electrodeposited by the General Electric Company with 0.05 and 0.13 mm. of $Ca(OH)_2$

Cell Number	Formation Cycle				Remarks
	FC-1, AHI (1)	FD-1, AHO (2)	FC-7, AHI	FD-7, AHO	
1	9.26	5.85	5.62	5.16	Cells 1 to 4, 0.05 mm. $Ca(OH)_2$ coating.
2		4.87	4.68	4.34	
3		5.77	5.96	5.52	
4		5.98	5.81	5.37	
5		3.92	4.05	3.74	Cells 5 to 8, 0.13 mm. $Ca(OH)_2$ coating.
6		3.64	4.23	3.95	
7		5.00	5.14	4.76	
8		4.61	4.82	4.40	
9		6.25	6.22	5.79	Cells 9 and 10. No Coating. Control cells.
10	9.26	5.95	6.62	6.06	

Formation Procedure:

(1) All cells were filled with 18.5 cc. of 40% KOH and allowed to soak for 72 hours. During this operation, the cells were clamped with end plates and tie rods.
(2) Cells were charged on the first formation cycle (FC-1) at 300 ma., constant current, for 31 hours.
(3) On the first formation discharge (FD-1), the cells were discharged at 2.0 amperes, constant current, to 0.8 volts, each cell.
(4) Cells were charged at 300 ma., constant current, to 1.58 volts, each cell.
(5) Cells were discharged at 2.0 amperes, constant current, to 0.8 volts, each cell.
(6) Steps (4) and (5) were repeated five times more making a total of seven formation cycles.

(1) FC - Formation Charge
AHI - Ampere Hours In.
(2) FD - Formation Discharge
AHO - Ampere Hours Out

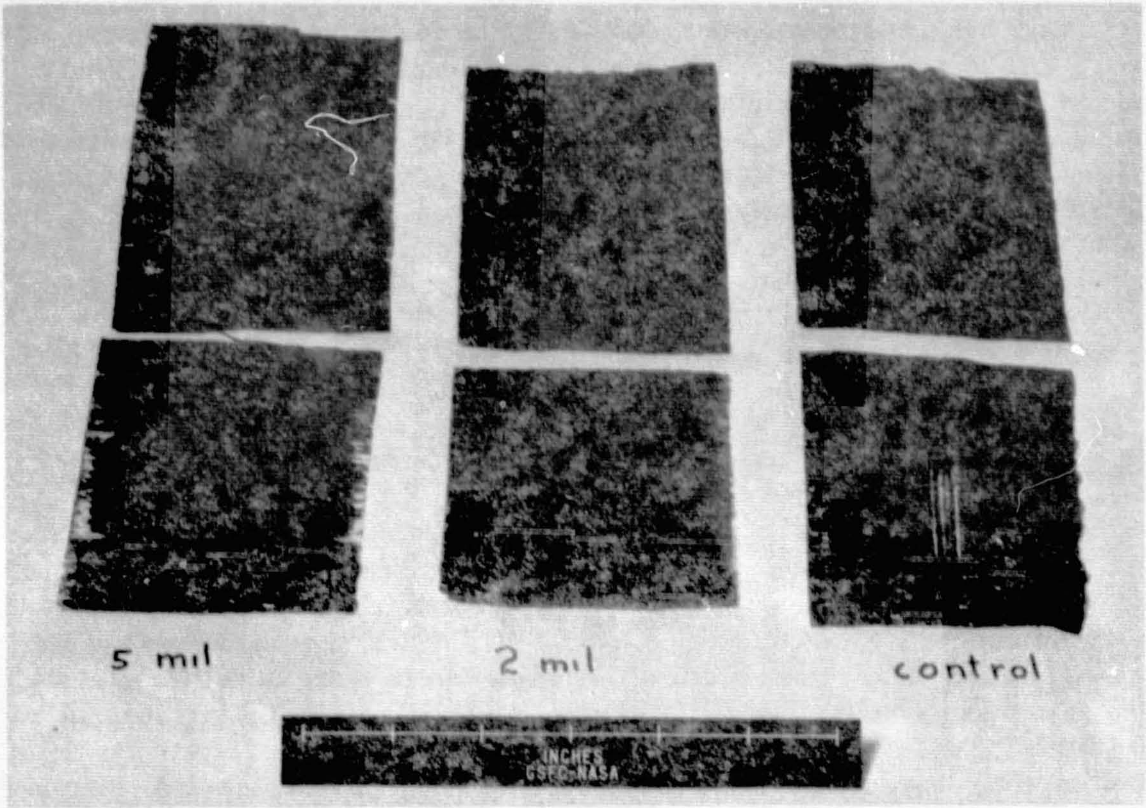

Illustration 17. Cellophane Separators Removed from Cells with 0.13 mm. (5 mil), 0.05 mm. (2 mil) and 0.0 mm. (Control) $Ca(OH)_2$ Coatings on the Positive Plates.

The results of the discharges on cycle 35D and 36D are shown below.

Cell S/N	Coating Thickness mm.	Cycle 35D[1] Ag O Plateau voltage	Cycle 35D Ampere Hour Capacity	Cycle 36D[1] Ag_2O Plateau Voltage	Cycle 36D Ampere Hr. Capacity
1	0.05	1.00	3.3	1.04	4.4
2	0.05	1.00	3.4	1.04	5.0
3	0.13	0.89	2.9	0.92	4.4
4	0.13	0.90	2.5	0.94	4.0
5	0	1.04	3.6	1.06	3.6

(1) D - Discharge

After cycle 36, three cells were opened, the control, a 0.05 mm. coated cell and a 0.13 mm. coated cell. The amount of silver pick-up visually observed on the cellophane was approximately the same as observed after the formation cycles. An analysis was made of the amount of silver in the first layer of cellophane, adjacent to the positive plates, and the following two layers. The results of this analysis follows.

Coating Thickness mm.	Silver in Cellophane Next to Silver Plate-mg./cm.^{2}	Silver in Following Two Layers of Cellophane-mg./cm.^{2}
0.13	0.273	0.079
0.05	0.279	0.089
0	3.080	0.355

The inner surface of the cell case of the control cell was heavily coated with silver and silver particles were observed in the electrolyte. This was not observed in the cells with coated electrodes. A comparison of the weights of the control silver plates after cycling showed a 20% to 25% loss in weight as compared to the original wet weight. This loss of silver from the plates may have been due to the reverse wrapping of the separator. The loss of silver did result in a capacity loss in the control cell. The loss of weight of the coated electrodes was less than four percent. There was no further investigation to determine the reason for the lower capacities of the cells with coated plates. However, cells with coated 0.05 mm. and 0.13 mm. plates were discharged at lower currents of 0.5 amperes. At this drain the discharge voltage, on the Ag_2O plateau, was 1.07 volts for each cell at 25°C. The capacity of each cell was greater than five ampere hours.

HYDROGEN DIFFUSION EXPERIMENTS

As a result of the accumulation of hydrogen due to the unbalance of cells during float charging, the feasibility of diffusion of hydrogen through silver palladium membranes was investigated. Such a membrane could be mounted on a tube and inserted in the fill port of the cell. The membranes would be protected by a thin film of polyethylene so that the inside surface of the membrane would not contact the electrolyte.

Melpar, Inc., ref. 19, performed several experiments to determine diffusion rates as a function of hydrogen pressure, temperature and membrane thickness, i.e., the thickness of the palladium black deposited as a silver palladium base. The results of the diffusion experiments are shown in figures 70 and 71.

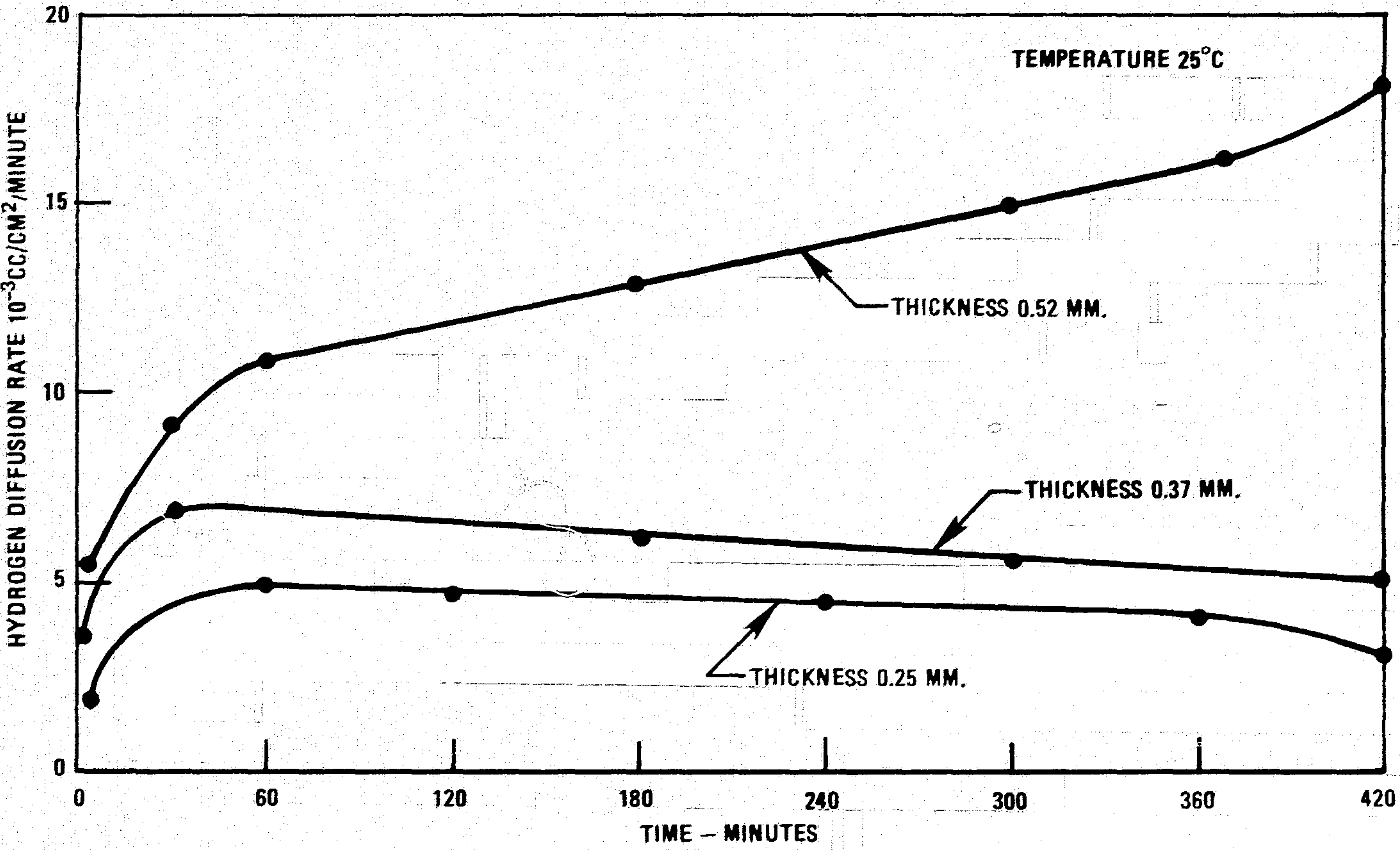

Figure 70. Hydrogen Diffusion Rates Through Silver Palladium Membranes of Different Thickness to a Vacuum of 10^{-5} Torr, Hydrogen Pressure 1.0 ATM, Temperature 25°C

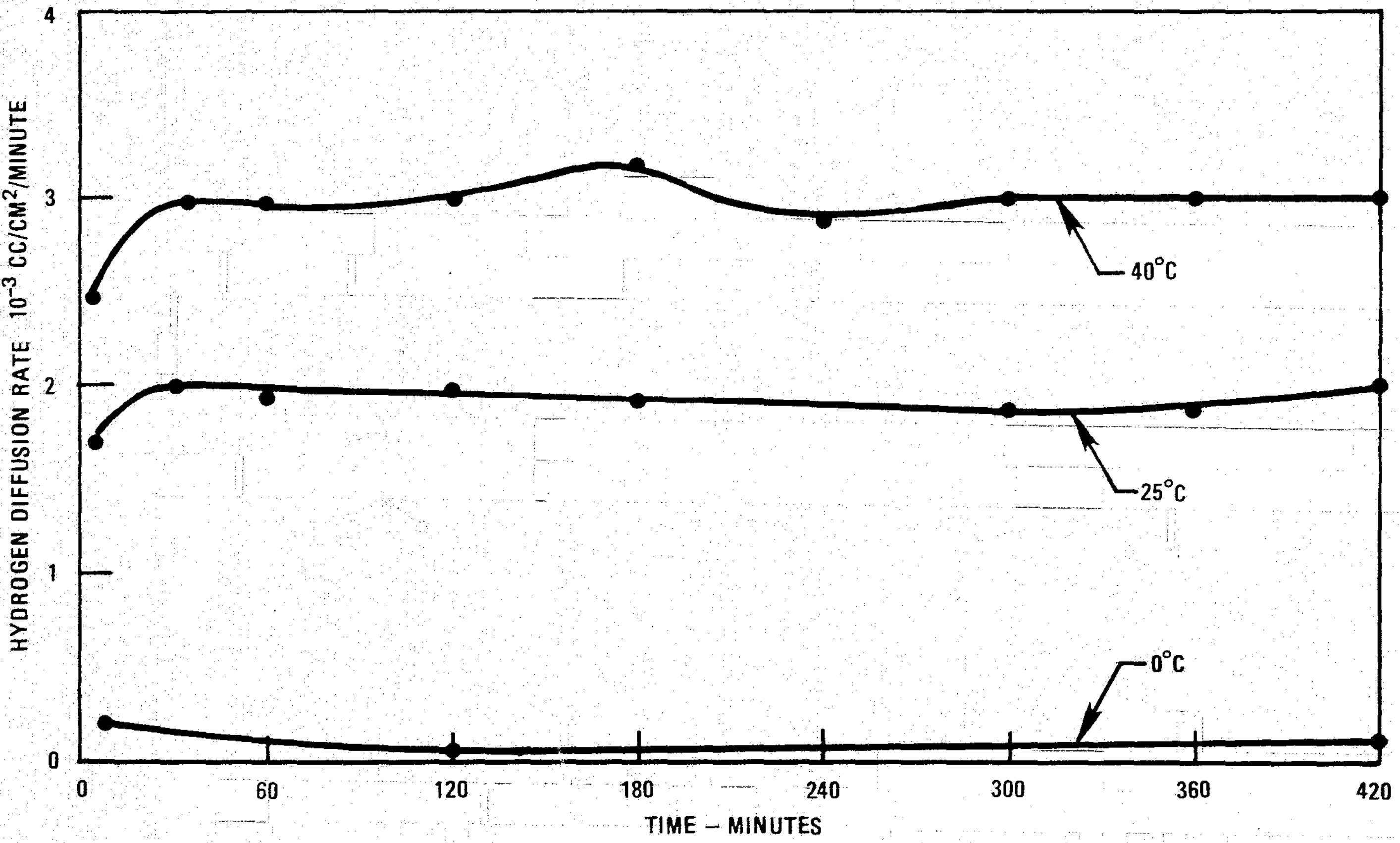

Figure 71. Hydrogen Diffusion Rates Through Silver Palladium 0.25 mm. Thick at 0°C, 25°C and 40°C to a Vacuum of 10^{-5} Torr, Hydrogen Pressure 0.5 ATM

The conclusions excerpted from this report follow:

"(1) Temperature - Higher temperatures promote greater diffusion of hydrogen through a membrane of constant thickness. (At the temperature of 0°C, diffusion rates approach zero.)

(2) Pressure - Hydrogen diffusion rates significantly increase with an increase of hydrogen pressures. At higher pressures, the diffusion rates decrease with time while at lower pressures, the rates remain fairly constant with time.

(3) Membrane Thickness - There appears to be an optimum thickness for silver palladium membranes to control H_2 diffusion rates within a limited range. From the limited data obtained in this study, the optimum thickness value is about 0.38 mm."

This technique was not put to practice. However, it appeared that the use of these membranes, to maintain low internal cell pressures, during float charging would be practical. For example, the H_2 evolution rate of five ampere hour cells during long periods of float charging at 1.51 volts per cell was of the order of 10^{-4} cc. per minute. However, diffusion rates were extremely low at 0°C.

ANALYSIS OF SILVER PLATES

During the course of the overall program, analysis of the composition of electrodes was made. Contained herein is some data for silver plates removed from charged and partially discharged cells, that had not been cycled to any extent. Similar data was obtained on negative plates but is not available. The analytical work was performed at Melpar, Inc. on contract NAS5-3753, refs. 20 and 21.

The sealed cells used in this analyses were five ampere hour cells, YS5S-2NM. Both cells had been charged at 300 ma. constant current to 1.55 volts. Approximately 1.5 amperes was removed from one cell so that most of the AgO had been discharged. All tests were performed at 25°C. The results of the analysis of these charged and partially discharged cells are shown in Tables 22 and 23. The analytical procedures are shown in Appendix B.

Table 22
Plate Analysis
Charged Cell

Sample Designation	Total Silver as Ag, %	NH_4OH Soluble Silver as Ag, %	Silver/as Metal Ag, % *	Silver as AgO, % *	Silver as Ag_2O, % *	Total Oxygen %	Occluded Oxygen %	Total Loss on Ignition: Total %	As Water % *	As Carbon-ate % *	As Oxygen %	Potassium as KOH, % *	Cadmium as Cd, * %	Total
Electrode 1	81.46	73.05	8.41	20.51	59.31	6.77	0.52	9.02	2.21	0.42	6.77	0.123	8.59	99.71
Electrode 2	81.05	70.13	10.92	19.56	57.06	6.51	0.58	9.21	2.67	0.024	6.51	0.034	9.09	99.93
Electrode 3	80.73	70.94	9.79	23.12	54.60	6.78	0.33	9.78	2.98	0.019	6.78	0.087	9.21	100.14
C19 Cellophane One Wrap	0.370	–	–	–	–	–	–	–	–	–	–	–	–	–
Woven Nylon One Wrap	0.0583	–	–	–	–	–	–	–	–	–	–	–	–	–

*Included in the Total

Table 23
Plate Analyses
Partially Discharged Cell

Sample Designation	Total Silver as Ag, %	NH_4OH Soluble Silver as Ag, %	Silver/as Metal Ag, % *	Silver as AgO, % *	Silver as Ag_2O, % *	Total Oxygen %	Occluded Oxygen %	Total Loss on Ignition				Potassium as KOH, % *	Cadmium as Cd, * %	Total
								Total %	As Water % *	As Carbon-ate % *	As Oxygen %			
Electrode 1	85.50	35.02	50.48	0	37.63	2.63	0.45	5.27	2.58	0.58	2.63	0.038	8.36	99.60
Electrode 2	83.92	49.41	34.51	0.86	52.29	4.74	0.39	7.64	2.85	0.051	4.74	0.057	8.98	99.99
Electrode 3	83.66	49.54	34.12	2.65	50.75	3.87	1.09	6.36	2.44	0.049	3.87	0.081	8.43	99.61
C19 Cellophane One Wrap	0.459	–	–	–	–	–	–	–	–	–	–	–	–	–
Woven Nylon One Wrap	0.1014	–	–	–	–	–	–	–	–	–	–	–	–	–

*Included in the Total

OTHER SUPPLIERS

During the program, silver cadmium cells were obtained from other suppliers in an attempt to obtain a second source. In most cases, these efforts were not successful. Reported herein are the results of tests on cells from two suppliers, one being a second source and the other a company which developed an electrolyte control mechanism. This later development was investigated for use in large ampere hour capacity cells.

A second source that produced cells very similar in performance to the Yardney Electric Company cells, was the Electromite Corporation. (Presently, this company does not exist.) A sample lot of thirty cells built to the GSFC Specification, ref. 1, were delivered to GSFC in early 1970. These were seven ampere hour cells and the cell design information is given in Appendix A.

Three of these cells were tested at the Naval Weapons Support Center/Crane (NWSC/Crane). Simulated orbital cycling was performed in an eight hour orbit with a one hour discharge time. The nominal depth of discharge was 25%. The cells were charged to 1.51 volts per cell average while the charge current was limited to 0.4 amperes. The test temperature was 20°C. At the beginning of the test, the wet life of the cells was six months. The cells were cycled 4,224 times and then the test was terminated. Capacity checks were run during cycling and the ampere hours delivered, to less than 1.0 volts per cell average, were as follows:

Capacity Checks on Electromite Cells During
NWSC/Crane Tests

Cycles	Ampere Hours Out
0	8.0
270	4.1
792	7.5
1056	8.1
1580	7.7

During simulated orbital cycling cell voltages were greater than 1.05 volts on discharge. There were no cell failures during cycling. Total test time was 1.5 years.

Early in the program, it was observed that the ampere hour capacity and voltage characteristics were improved if the sealed silver cadmium cells were operated flooded with electrolyte. Cells cycled in the limited electrolyte condition did have some recombination capability. An investigation was carried out in cells that would be essentially flooded in normal operation but when gases evolved internally, a bellows device would allow a lowering of the electrolyte level. Such a device would be practical in large cells, e.g., 100 ampere hour sizes or larger. Developmental work on controlled electrolyte cells, of eight and one-hundred ampere hour cells was performed by the Electric Storage Battery Company, ref. 22.

Sample cells, resulting from the development program were tested at the Naval Weapons Support Center/Crane (NWSC/Crane). Simulated orbital cycling of an eight ampere hour, five cell battery was as follows: (1) orbital period of eight hours with a one hour discharge at a nominal depth of discharge of 25% and (2) 2.0 ampere current limited charge with a voltage limit of 1.51 volts per cell average. The test temperature was 25°C. One cell failed at 1379 cycles, the second cell failed at 3253 cycles and the remaining cells failed at 3875 cycles. Data from capacity checks follows:

Capacity Checks of ESB Eight Ampere Hours Cells During NWSC/Crane Tests

Cycles	Ampere Hours Out
0	8.2
630	12.2
1094	9.1
1377	4.8
2082	5.2
2707	4.3
3282	2.7
3638	4.0
3875	2.4

The above capacity checks were obtained by discharging the cells at 2.0 amperes until the first cell reached 0.5 volts. Early failures were due to leakage. Final cell failures were due to severe separator deterioration and electrolyte leakage. The total test time was 3.5 years.

Simulated orbital cycling of the one-hundred ampere hour, five cell battery was as follows: (1) orbital period of twenty-four hours with a two hour discharge time at a nominal depth of discharge of 30% and (2) 3.0 ampere current limited charge with a voltage limit of 1.51 volts per cell average. The test was run at room temperature. One cell was removed from test on cycle 624 because of low discharge voltage. The remaining cells operated for 701 cycles and then the test was terminated. Pressures of the cells during the test ranged between vacuum and 17 PSIG. Cell discharge voltages were 1.01 volts or greater. Maximum cell voltage unbalance at end of charge was 1.43 to 1.58 volts. The initial capacity of the five cells ranged between 138 and 141 ampere hours. On cycle 500 a capacity check yielded 84 ampere hours. The total test time was 1.9 years.

During the testing of the one-hundred ampere hour cells it was observed that the electrolyte level did change significantly when pressures of 17 PSIG were observed. It was difficult to evaluate this effect on gas recombination. The fact that low pressures were observed throughout the test with high end of charge voltages may be an indication that the electrolyte control was useful.

SECTION VII

SUMMARY AND CONCLUSIONS

A. Long Orbit with Periods Greater than Five Hours

(1) At nominal depths of discharge (NDOD) less than 30% and over the temperature range of 0°C to 40°C, a voltage clamp of 1.51 volts per cell is adequate for constant potential charging. Constant current charging should only be used for ground use, e.g., ampere hour capacity determination. Herein, a voltage cutoff of 1.55 volts per cell is adequate at 25°C. Constant currents of $C_N/10$ (nominal capacity divided by ten) are satisfactory. However, the cells can be charged at very low currents, e.g., $C_N/500$.

(2) The sealed silver cadmium system has two voltage plateaus on discharge, the AgO plateau, and the Ag_2O plateau. During several of the cycling programs, it was observed that the upper plateau (AgO plateau) would flatten out so that a battery would discharge at nearly constant voltage. This occurred when a battery was cycled on long orbits with a high percentage of float time or the battery was placed on continuous float. Usually this lowering of the upper plateau would occur without a loss of ampere hour capacity. Also, this lowering of the upper discharge plateau would occur during charged storage. Some loss of capacity would result. When the flattening of the upper plateau occurred, this was usually accompanied by a dip in voltage on initial discharge. The magnitude and time of this voltage depression was dependent on discharge current and temperature.

(3) The ampere hour efficiency of the sealed silver cadmium system is very high and approaches 100% during simulated orbital cycling. Watt hour efficiencies ranged between 70% and 90%. However, in most cycling tests the watt hour efficiency approached the lower value.

(4) During cycling of sealed silver cadmium batteries during long orbits, the individual cells will exhibit a voltage unbalance at the end of charge and during float charge. This occurs during constant potential charging when the charge current is very low. Voltages greater than 1.7 were observed when the voltage clamp was maintained at 1.51 volts per cell. These high voltages could result in internal gas pressures, usually hydrogen, that could exceed the burst pressure of the battery casing. A constant potential charge control method was devised that sensed the charge current. When the battery was near fully charged, i.e., the charge current tapered to $C_N/100$, the charge voltage was reduced to 1.41 volts per cell. This voltage was slightly higher than the open circuit value of the cells and no

pressure rise would occur. Tests showed that this value of float charge voltage would keep the charged battery at full ampere hour capacity for at least six months. Other methods that were shown feasible to minimize internal gas pressure were diffusion of hydrogen through silver palladium membranes and electrolyte level control during operation.

(5) During the early part of the program, same difficulties were experienced with cell unbalance on discharge, e.g., near the end of discharge one cell would approach zero volts while the remaining cells would be greater than one volt. As process and material controls and formation procedures improved, cell unbalance on discharge seldom occurred. The use of these controls and procedures did not provide improvement of cell unbalance on charge.

(6) The electrical performance of sealed silver cadmium batteries degrades below 0°C while the life of these batteries is shortened above 40°C. Conversely, life is extended at low temperatures while the electrical performance is optimum at higher temperature, e.g., 20°C to 50°C. At low temperatures, the main problems are (1) capacity maintenance during cycling and (2) a dip in voltage on initiation of discharge. Operational and test programs have shown cycle life periods of greater than three years at low temperatures. At temperatures of 40°C to 50°C, the cycle life is one year and 0.2 years, respectively. The cycle life at moderate temperatures is between 1.4 and 2.0 years.

(7) There were few infantile cell failures in controlled production lots. Wear out failures were attributed to silver solubility and complete deterioration of the cellophane separators.

(8) During the transition phase from the lower plateau (Ag_2O plateau) to the upper plateau (AgO plateau) on charge, high voltage peaks may be experienced, especially at low temperatures. This should be taken into consideration when battery voltage cutoffs or cell voltage cutoffs are used during charging. These voltage peaks can also cause a depression of the charge current when constant potential charging is used. This latter effect is most pronounced at temperatures less than 0°C.

(9) The amount of ampere hour capacity delivered to a battery at the lower plateau (Ag_2O plateau) is dependent on the current value and temperature. At low charge currents, approximately fifty percent of nominal capacity will be delivered to the battery while at moderate rates this value will be less than 25%. At low temperatures (-20°C) and high charge rates, the lower plateau does not exist.

(10) Capacity maintenance on charged stand at room temperature is considered superior to most secondary electrochemical systems. This is particularly true with respect to uniformity of capacity maintenance on a cell basis. In one case, a battery stored charged for 1.8 years at room temperature delivered 70% of its initial ampere hour capacity.

(11) Reversal of sealed silver cadmium cells should be avoided. For example, the internal pressure of a five ampere hour cell begins to rise after a 0.16 ampere hour reversal.

(12) Two silver cadmium batteries can be operated in parallel and the ampere hour capacity returned to each battery even though there was no equalization of capacity during each charge and discharge.

(13) The energy density of flight batteries, including cells, case, potting compounds, wiring and connectors ranged between 26WH/Kg. and 31WH/Kg. The temperature rise of sealed silver cadmium batteries during orbital shadows is of the order of a few degrees Centigrade. Charging is endothermic.

B. Short Orbits With Periods of 1.5 and 1.6 Hours

(1) Based on the characterization tests performed, sealed, three ampere hour cells can be cycled in 1.5 hour orbits up to a 33% nominal depth of discharge. At the temperatures of -10°C, 25°C and 50°C the voltage clamp for constant potential charging would be 1.60, 1.55 and 1.51 volts, respectively.

(2) During cycling, the three ampere hour cells operated at a reduced capacity. Most of the capacity loss occurred during the initial cycling. Full capacity could be restored to the battery during out-of-cycle capacity checks.

(3) Flattening of the discharge curves during cycling, as experienced in long orbits, did not occur during short orbit cycling.

(4) During long float charging where the charge current tapered to a low value, the individual cell voltages would unbalance. Values exceeding 1.7 volts were observed.

(5) During cycling, the ampere hour efficiencies approached 100%. Watt hour efficiencies were approximately 75%.

(6) There was a moderate temperature rise, in the epoxy encapsulated batteries, during cycling. The temperature does stabilize after the initial cycles.

With a 33% nominal depth of discharge at -10°C, the rise was 13°C. At 50°C, the temperature rise was 9°C.

(7) One, three ampere hour battery was cycled to failure. This test was performed at 25°C with a 16% nominal depth of discharge. On cycle 7280, the battery ruptured.

(8) Three, five cell, twelve ampere hour batteries were cycled to failure. These tests were performed at 0°C, 25°C and 40°C with a 25% nominal depth of discharge. First cell failures occurred at 4467 (25°C), 2972 (0°C) and 1978 (40°C) cycles. Previous to failure, several of the individually sealed cells, in each test unit, developed leaks.

SECTION VIII

LIST OF REFERENCES

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APPENDIX A

CELL DESIGN SHEETS

Appendix A contains Cell Design Sheets for the Yardney Electric Corporation (YEC) and the Electromite Corporation. It also has cell design information on some developmental cells that were cycled at the Naval Weapons Support Center/Crane as described in Section III. The following definitions and abbreviations apply to the Cell Design Sheets.

(1) Standard Positive Composition - 90% Ag, 10% CdO (Sintered)
(2) Standard Negative Composition - 94.5% CdO, 5% Ag, 0.5% PVA Powder (Pressed)
(3) Woven Nylon, Untreated - No treatment by YEC
(4) Woven Nylon - Proprietary treatment by YEC
(5) C19 - Silver treated cellophane
(6) PVA - Polyvinyl Alcohol Membrane
(7) Pellon - Non-woven nylon, usually 2506K
(8) Electrolyte fill in cc. - This is the initial fill. Some may be removed after formation. See ref. 2.
(9) Typical Separator System Nomenclature
Example: Positive Plate/2-Woven Nylon, 6-C19, 2-Woven Nylon/Negative Plate

The separator system, from a positive to a negative plate, is two layers of woven nylon, six layers of silver treated cellophane, and two layers of woven nylon.
(10) Half negatives - Placed on the outside of the separator/plate stack, adjacent to the cell case.

TABLE OF CONTENTS

CELL DESIGN SHEET

Cell Designation YS2S-1NM　　　　Nominal Ampere Hours 2

Positives: 4 per cell

3.33H × 3.49W × 0.046T cm.

Composition Std

Weight (w/o tabs) 2.55 gm.

Silver grid identification Exmet 5Ag 15-1

Silver lead 2 Wires, 0.040 cm. dia.

NEGATIVES: 5 per cell, 3 full thickness and 2 half thickness

3.33H × 3.49W × 0.112T cm. (full) × 0.060T cm. (half)

Composition Std

Weight (with leads) 4.40 gm. (full) 2.43 gm. (half)

Silver grid identification Exmet 5 Ag. 15-1

Silver lead 2 Wires 0.40 cm. dia.

SEPARATOR SYSTEM

Positive Plate / 1-Woven Nylon, 5-C19 / Negative Plate

Electrolyte: 45% Potassium Hydroxide

Cell Dimensions 5.48 H × 4.3 W × 1.49 T cm. Height to top of Terminal 6.48 cm.

Max. Wet Weight 70 gm.

CELL DESIGN SHEET

Cell Designation YS5S-C3A, NM   Nominal Ampere Hours 3

Positives: 6 per cell

3.81H × 4.13W × 0.033T cm.

Composition Std

Weight (w/o tabs) 2.77 gm.

Silver grid identification Exmet - 5 Ag. 15-1

Silver lead 2 Wires, 0.040 cm. dia.

NEGATIVES: 7 per cell, 7 full thickness and 0 half thickness

3.81H × 4.13W × 0.063T cm. (full) × N/A T cm. (half)

Composition Std

Weight (without leads) 2.95 gm. (full) N/A gm. (half)

Silver grid identification Exmet 5 Ag. 15-1

Silver lead 2 Wires, 0.040 cm. dia.

SEPARATOR SYSTEM

Positive Plate / 2-Woven Nylon, 6-C19, 2 Woven Nylon / Negative Plate

Electrolyte: 45% Potassium Hydroxide

Cell Dimensions 6.24H × 5.27W × 1.99T cm. Height to Top of Terminal 7.38 cm. max. Wet Weight 111 gm. High Rate 3 Ahr. cell used for 100 minute orbits.

CELL DESIGN SHEET

Cell Designation YS3S-1NM Nominal Ampere Hours 3

Positives: 4 per cell

4.13H × 3.49W × .046T cm.

Composition Std

Weight (w/o tabs) 3.95 gm.

Silver grid identification Exmet 5 Ag 15-1

Silver lead 2 Wires, 0.040 cm. dia.

NEGATIVES: -5 per cell, 5 full thickness and 0 half thickness

4.13H × 3.49W × 0.081T cm. (full) × N/A T cm. (half)

Composition Std

Weight (mix only) 3.6 gm. (full) N/A gm. (half)

Silver grid identification Exmet 5 Ag. 15-1

Silver lead 2 Wires, 0.040 cm. dia.

SEPARATOR SYSTEM

Positive Plate / 2 Untreated Nylon, 5-C19, 1-Untreated Nylon / Negative Plate

Electrolyte: 45% Potassium Hydroxide

Cell Dimensions 6.32H × 4.37W × 1.51T cm. Height to Top of Terminals 7.26 cm. Max. Design Obsolete. Positives pressed rather than sintered.

CELL DESIGN SHEET

Cell Designation YS3S-2NM Nominal Ampere Hours 3

Positives: 4 per cell

4.13H × 3.49W × 0.046T cm.

Compositon Std

Weight (w/o tabs) 3.30 gm.

Silver grid identification Exmet 5 Ag. 15-1

Silver lead 2 Wires, 0.040 cm. dia.

NEGATIVES: 5 per cell, 5 full thickness and 0 half thickness

4.13H × 3.49W × 0.081T cm. (full) × N/A T cm. (half)

Composition Std

Weight (with leads) 4.05 gm. (full) N/A gm. (half)

Silver grid identification Exmet, 5 Ag. 15-1

Silver lead 2 Wires, 0.040 cm. dia.

SEPARATOR SYSTEM

Positive Plate / 2-Woven Nylon, 5-C19, 1 Woven Nylon / Negative Plate

Elecrolyte: 40% Potassium Hydroxide, 14.5 cc.

Cell Dimensions 6.32H × 4.37W × 1.51T cm. Height to Top of Terminals 7.26 cm. Max. Wet Weight 82 gm.

CELL DESIGN SHEET

Cell Designation YS5S-2NM | Nominal Ampere Hours 5

Positives: 4 per cell

3.81H × 4.13W × 0.071T cm.

Composition Std

Weight (w/o tabs) 6.36 gm.

Silver grid identification Exmet 5 Ag. 15-1

Silver lead 2 wires, 0.040 cm. dia.

NEGATIVES: 5 per cell, 5 full thickness and 0 half thickness

3.81H × 4.13W × 0.071T cm. (full) × N/A T cm. (half)

Compositon Std

Weight (without leads) 8.29 gm. (full) N/A gm. (half)

Silver grid identification Exmet 5 Ag. 15-1

Silver lead 2 wires, 0.040 cm. dia.

SEPARATOR SYSTEM

Positive Plate / 2-Woven Nylon, 5-C19, 1-Woven Nylon / Negative Plate

Electrolyte: 45% Potassium Hydroxide, 18.5 cc.

Cell Dimensions 6.24H × 5.27W × 1.99T cm. Height to Top of Terminals 7.38 cm. Max. Wet Weight 133 gm.

CELL DESIGN SHEET

Cell Designation YS5S-4NM | Nominal Ampere Hours 5

Positives: 4 per cell

3.81H × 4.13W × 0.071T cm.

Composition Std

Weight (w/o tabs) 6.36 gm.

Silver grid identification Exmet. 5 Ag. 15-1

Silver lead 2 Wires, 0.040 cm. dia.

NEGATIVES: 5 per cell, 3 full thickness and 2 half thickness

3.81H × 4.13W × 0.152T cm. (full) × 0.102T cm. (half)

Compositon Std

Weight (without leads) 8.29 gm. (full) 5.59 gm. (half)

Silver grid identification Exmet 5 Ag. 15-1

Silver lead 2 wires, 0.040 cm. dia.

SEPARATOR SYSTEM

Positive Plate / 2-Woven Nylon, 5-C19, 1 Woven Nylon / Negative Plate

Electrolyte: 45% Potassium Hydroxide, 18.5 cc.

Cell Dimensions 6.24H × 5.27W × 1.99T cm. Height to Top of Terminals 7.38 cm. Max. Wet Weight 135 gm.

CELL DESIGN SHEET

Cell Designation YS5S-5NM Nominal Ampere Hours 5

Positives: 4 per cell

3.81H × 4.13W × 0.660T cm.

Composition Std

Weight (w/o tabs) 5.33 gm.

Silver grid identification Exmet 5 Ag. 15-1

Silver lead 2 wires, 0.040 cm. dia.

NEGATIVES: 5 per cell, 3 full thickness and 2 half thickness

3.81H × 4.13W × 0.163T cm. (full × 0.086T cm. (half)

Composition Std

Weight (with leads) 9.7 gm. (full 5.2 gm. (half)

Silver grid identification Exmet 5 Ag. 15-1/0

Silver lead 2 wires, 0.040 cm. dia.

SEPARATOR SYSTEM

Positive Plate / 1-Pellon P5, 5-C19, 1-Pellon P5 / Negative Plate

Electrolyte: 40% Potassium Hydroxide, 23 cc.

Cell Dimensions 6.24H × 5.27W × 1.99T cm. Height to Top of Terminals 7.38 cm. Max. Wet Weight 1.31 gm.

CELL DESIGN SHEET

Cell Designation YS10S-1NM   Nominal Ampere Hours 10

Positives: 4 per cell

7.30H × 4.60W × 0.071T cm.

Composition Std

Weight (w/o tabs) 12.72 gm.

Silver grid identification Exmet 5 Ag. 15-1

Silver lead 4 wires, 0.040 cm. dia.

NEGATIVES: 4 per cell, 4 full thickness and 0 half thickness

7.30H × 4.60W × 0.137T cm. (full) × N/A T cm. (half)

Composition Std

Weight (mix) 15.8 gm. (full) N/A gm. (half)

Silver grid identification Exmet 5 Ag. 15-1

Silver lead 4 wires, 0.040 cm. dia.

SEPARATOR SYSTEM

Positive Plate / 1-Untreated Nylon, 5-C19, 1-Untreated Nylon / Negative Plate

Electrolyte: 45% Potassium Hydroxide, 38 cc.

Cell Dimensions 10.87H × 5.89W × 1.88T cm. Height to Top of Terminals 12.22 cm. Max. Wet Weight 260 gm. Design Obsolete

CELL DESIGN SHEET

Cell Designation YS10S-2NM

Nominal Ampere Hours 10

Positives: 4 per cell

7.62H × 4.76W × 0.071T cm.

Composition Std

Weight (w/o tabs) 12.80 gm.

Silver grid identification Exmet, 5 Ag. 11-1

Silver lead 4 wires, 0.040 cm. dia.

NEGATIVES: 5 per cell, 5 full thickness and 0 half thickness

7.62H × 4.76W × 0.127T cm. (full) × N/A T cm. (half)

Composition Std

Weight (with leads) 14.9 gm. (full) N/A gm. (half)

Silver grid identification Exmet 5 Ag. 11-1

Silver lead Silver Clad Copper

SEPARATOR SYSTEM

Positive Plate / 1-Woven Nylon, 1-PVA, 3-C19 / Negative Plate

Electrolyte: 38% Potassium Hydroxide, 40 cc.

Cell Dimensions 10.87 × 5.89W × 1.88T cm. Height to Top of Terminals 12.22 cm. Max. Wet Weight 257 gm.

CELL DESIGN SHEET

Cell Designation YS10S-4NM   Nominal Ampere Hours 10

Positives: 4 per cell

7.94H × 4.84W × 0.056T cm.

Composition Std

Weight (w/o tabs) 10.26 gm.

Silver grid identification Exmet 5 Ag. 15-1

Silver lead Tab, 0.32 × 0.013 cm.

NEGATIVES: 5 per cell, 3 full thickness and 2 half thickness

7.94H × 4.84W × 0.129T cm. (full) × 0.071T cm. (half)

Composition Std

Weight (with leads) 17.4 gm. (full) 9.4 gm. (half)

Silver grid identification Exmet 5 Ag. 15-1

Silver lead 4 wires, 0.040 cm, dia.

SEPARATOR SYSTEM

Positive Plate / 1 Woven Nylon, 5-C19, 1 Woven Nylon / Negative Plate

Electrolyte: 40% Potassium Hydroxide, 39 cc.

Cell Dimensions 10.87H × 5.89W × 1.88T cm. Height to Top of Terminals 12.22 cm. Max. Wet Weight 245 gm.

CELL DESIGN SHEET

Cell Designation YS11S-2NM(TA) Nominal Hours 11

Positives: 6 per cell

7.94H × 4.84W × 0.038T cm.

Composition Std

Weight (w/o tabs) 7.1 gm.

Silver grid identification Exmet 5 Ag. 15-1

Silver lead Tab, 0.32 × 0.013 cm.

NEGATIVES: 7 per cell, 7 full thickness and 0 half thickness

7.94H × 4.84W × 0.079T cm. (full) × N/A T cm. (half)

Composition Std

Weight (with leads) 10.7 gm. (full) N/A gm. (half)

Silver grid identification Exmet 5 Ag. 15-1

Silver lead 4 wires, 0.040 cm. dia.

SEPARATOR SYSTEM

Positive Plate / 1-Pellon, P5, 5-C19, 1-Pellon P3 / Negative Plate

Cell Dimensions 10.72H × 5.83W × 2.06T cm. Height to Top of Terminals 11.51 cm. Max. Wet Weight 254 gm.

CELL DESIGN SHEET

Cell Designation YS11S-3NM(sh) Nominal Ampere Hours 11

Positives: 8 per cell

4.13H × 4.13W × 0.066T cm.

Composition Std

Weight (w/o tabs) 5.01 gm.

Silver grid identification Exmet 5 Ag. 15-1

Silver lead Tab, 0.24 × 0.010 cm.

NEGATIVES: 9 per cell, 7 full thickness and 2 half thickness

4.13H × 4.13W × 0.142T cm. (full) × 0.076T cm. (half)

Composition Std

Weight (without leads) 8.22 gm. (full) 4.37 gm. (half)

Silver grid identification Exmet 5 Ag. 15-1/0

Silver lead 2 wires, 0.040 cm. dia.

SEPARATOR SYSTEM

Positive Plate / 1 Pellon P5, 5-C19, 1 Pellon P5 / Negative Plate

Electrolyte: 40% Potassium Hydroxide, 44 cc.

Cell Dimensions 6.28H × 5.26W × 3.32T cm. Height to Top of Terminals 7.41 cm. Max.

CELL DESIGN SHEET

Cell Designation YS12S-2ANM(20)[1] Nominal Ampere Hours 12

Positives: 14 per cell

6.35H × 4.13W × 0.036T cm.

Composition Std

Weight (w/o tabs) 4.67 gm.

Silver grid identification Exmet 5 Ag. 15-1

Silver lead Tab 0.32 × 0.013 cm.

NEGATIVES: 15 per cell, 15 full thickness and 0 half thickness

6.35H × 4.13W × 0.071T cm. (full) × N/A T cm. (half)

Composition Std

Weight (without leads) 5.63 gm. (full) N/A gm. (half)

Silver grid identification Exmet 5 Ag. 15-1

Silver lead 3 wires, 0.040 cm. dia.

SEPARATOR SYSTEM

Positive Plate / 2-Woven Nylon, 6-C19, 2-Woven Nylon / Negative Plate

Electrolyte: 45% Potassium Hydroxide

Cell Dimensions 9.24H × 5.20W × 1.86T cm. Height to Top of Terminal 10.95 cm. Max.

(1) Denotes a 20 Ahr. case was used.

CELL DESIGN SHEET

Cell Designation YS16S-4NM   Nominal Ampere Hours 16

Positives: 6 per cell

10.2H × 4.92W × 0.048T cm.

Composition Std

Weight (w/o tabs) 11.75 gm.

Silver grid identification Exmet 5 Ag. 15-1

Silver lead Tab 0.32 × 0.013 cm.

NEGATIVES: 7 per cell, 5 full thickness and 2 half thickness

10.2H × 4. 92W × 0.102T cm. (full) × 0.063T cm. (half)

Composition Std

Weight (without leads) 16.2 gm. (full) 10.9 gm. (half)

Silver grid identification Exmet 5 Ag. 15-1

Silver lead 4 wires, 0.040 cm. dia.

SEPARATOR SYSTEM

Positive Plate / 1 Pellon P5, 5-C19 / Negative Plate

Electrolyte: 42% Potassium Hydroxide, 57 cc.

Cell Dimensions 13.64H × 5.84W × 2.06T cm. Height to Top of Terminals 14.60 cm. Max. Wet Weight 342 gm.

CELL DESIGN SHEET

Cell Designation YS20S-3NM　　Nominal Ampere Hours 20

Positives: 16 per cell

6.35H × 4.13W × 0.043T cm.

Composition Std

Weight (w/o tabs) 5.99 gm.

Silver grid identification Exmet 5 Ag. 15-1

Silver lead 3 wires, 0.040 cm. dia.

NEGATIVES: 17 per cell, 17 full thickness and 0 half thickness

6.35H × 4.13W × 0.96T cm. (full) × N/A T cm. (half)

Composition Information Not Available

Weight (without leads) 8.94 gm. (full) N/A gm. (half)

Silver grid identification Exmet 5 Ag. 15-1

Silver lead 3 wires, 0.040 cm. dia.

SEPARATOR SYSTEM

Positive Plate / 1 Woven Nylon, 2-PVA, 2-C19 / Negative Plate

Electrolyte: 45% Potassium Hydroxide, 65 cc.

Cell Dimensions 9.24H × 5.20W × 1.86T cm. Height to Top of Terminals 10.95 cm. Max. Design is Obsolete. Positives pressed rather than sintered.

CELL DESIGN SHEET

Cell Designation YS40S-2NM   Nominal Ampere Hours 40

Positives: 6 per cell

12.7H × 6.99W × 0.071T cm.

Composition Std

Weight (w/o tabs) 30.3 gm.

Silver grid identification Exmet 5 Ag. 15-1

Silver lead 6 wires, 0.040 cm. dia.

NEGATIVES: 7 per cell, 7 full thickness and 0 half thickness

12.7H × 6.99W × 0.129T cm. (full × N/A T cm. (half)

Composition Std

Weight (without leads) 38.8 gm. (full) N/A gm. (half)

Silver grid identification Exmet 5 Ag. 15-1

Silver lead 6 wires, 0.040 cm. dia.

SEPARATOR SYSTEM

Positive Plate / 1-Woven Nylon, 2-PVA, 2-C19 / Negative Plate

Electrolyte: 45% Potassium Hydroxide

Cell Dimensions 16.20H × 8.25W × 2.51T cm. Height to Top of Terminals 17.98 cm. Max. Wet Weight 735 gm.

CELL DESIGN SHEET

Cell Designation YS115S-1NM **Nominal Ampere Hours 115**

Positives: 14 per cell

19.7H × 9.05W × 0.048T cm.

Composition Std

Weight (w/o tabs) 44.7 gm.

Silver grid identification Exmet 5 Ag. 15-1

Silver lead Tab 0.32 × 0.020 cm.

NEGATIVES: 15 per cell, 15 full thickness and 0 half thickness

19.7H × 9.05W × 0.107T cm. (full) × N/A T cm. (half)

Composition Std

Weight (without leads) 61.25 gm. (full) N/A gm. (half)

Silver grid identification Exmet 5 Ag. 15-1

Silver lead Tab 0.32 × 0.020 cm.

SEPARATOR SYSTEM

Positive Plate / 1-Woven Nylon, 3-PVA / Negative Plate

Electrolyte: 40% Potassium Hydroxide, 380 cc.

Cell Dimensions 24.29H × 10.56W × 4.50T cm. Height to Top of Terminals 25.88 cm. Wet Weight 2.64 Kg.

CELL DESIGN SHEET

Cell Designation YS150S-3NM   Nominal Ampere Hours 150

Positives: 10 per cell

19.7H × 9.04W × 0.081T cm.

Composition Std

Weight (w/o tabs) 74.3 gm.

Silver grid identification Exmet 5 Ag. 15-1

Silver lead Tab 0.32 × 0.020 cm.

NEGATIVES: 11 per cell, 11 full thickness and 0 half thickness

19.7H × 9.04W × 0.165T cm. (full) × N/A T cm. (half)

Composition Std

Weight (with leads) 100.5 gm. (full) N/A gm. (half)

Silver grid identification Exmet 5 Ag. 15-1

Silver lead Tab 0.32 × 0.020 cm.

SEPARATOR SYSTEM

Positive Plate / 1-Pellon P5, 3 PVA / Negative Plate

Electrolyte: 45% Potassium Hydroxide, 370 cc.

Cell Dimensions 24.50H × 10.60W × 4.50T cm. Height to Top of Terminals

26.00 Max. Wet Weight 2.91 Kg.

CELL DESIGN SHEET

Cell Designation YS300S-NM　　　　Nominal Ampere Hours 300

Positives: 16 per cell

22.2H × 10.8W × –T cm.

Composition Std

Weight (w/o tabs) – gm.

Silver grid identification Exmet 5 Ag. 15-1

Silver lead –

NEGATIVES: 17 per cell, 17 full thickness and 0 half thickness

22.2H × 10.8W × – T cm. (full) × N/A T cm. (half)

Composition Std

Weight (with leads) – gm. (full)

Silver grid identification Exmet 5 Ag. 15-1

Silver lead –

SEPARATOR SYSTEM

Positive Plate –

Electrolyte: 40% Potassium Hydroxide, 980 cc.

Cell Dimensions (case only) 28.3H × 12.4W × 7.8T cm. Height to Top of Terminal 29.8 cm. This is not the standard cell case.

CELL DESIGN SHEET

Cell Designation Electromite   Nominal Ampere Hours 7

Positives: 4 per cell

4.85H × 4.85W × 0.102T cm.

Composition 90% Ag, 10% CdO

Weight (w/o tabs) 9.3 gm.

Silver grid identification Not Available

Silver lead Not Available

NEGATIVES: 5 per cell, 5 full thickness and 0 half thickness

4.98H × 4.98W × 0.162T cm. (full) × N/A T cm. (half)

Composition 94.5% CdO, 5% Ag, 0.5% PVA

Weight (with leads) 13.5 gm. (full) N/A gm. (half)

Silver grid identification Not Available

Silver lead Not Available

SEPARATOR SYSTEM

Positive Plate / 1 Pellon 2506 K4, 3-Fibrous Sausage Casing Unglycerated and Desulfonized / Negative Plate

Electrolyte: 40% Potassium Hydroxide

Cell Dimensions (Case Only) 7.64H × 5.79W × 2.67T cm. Cell Weight, Wet 250 gm.

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SPECIAL CELL DESIGNS LIFE CYCLED AT NWSC/CRANE

Cell Design	
M	YS5S-2NM See Cell Design Reference, Appendix A.
N	Same as YS5S-2NM except one layer of calandered non-woven nylon (PELLON 2506K) on Positive and Negative in lieu of woven materials.
P	Positives – 4 per cell 3.80H × 4.13W × 0.070T cm. 4.2 gm. Ag/cc. of electrode (low density silver) Negatives – 5 per cell, 3 full thickness and 2 half thickness 3.80H × 4.13W × 0.165T cm. (full) × 0.086T cm. (half) Composition – 93.9% CdO + 5% Ag + 1% Teflon + 0.1% Nylon Fibers. Separator System Positive Plate / One Layer 2506K bag / Five Layers C-19 / One Layer 2506K U-Fold / Negative Plate 2506K = PELLON calandered non-woven nylon C-19 – Silver treated cellophane, PUDO 300 Grids – Expanded Silver Metal (EXMET) Electrolyte – 40% Potassium Hydroxide
Q	Positives – 4 per cell 9.74H × 4.44W × 0.056T cm. Composition – 100% Ag Powder Silver Powder Density – 4.39 gm./cc Grid – EXMET No. 5Ag15-1/0 Leads – one silver tab, 0.317 w × 0.013 t cm. Weight (Lead not included) 22.89 gm. Negatives – 5 per cell, 3 full thickness and 2 half thickness 9.74h × 4.44w × 0.135t cm. (full) × 0.071t cm. (half) Composition – 93.85% Cadmium Oxide Powder 5.0% Silver Powder 1.0% Teflon 0.15% Nylon fibers Cadmium Density – 2.80 gm./cc. Grid – Same as Positive Leads – two Ag wires, 0.041 cm. dia.

Separator System

Positive Plate /	One Layer 2504K bag	Five Layers C-19	One Layer 2504K U-Fold	/ Negative Plate

2504K = PELLON calandered non-woven nylon
C-19 = Silver treated cellophane. PUDO 300

Electrolyte – 40% Potassium Hydroxide

Third Electrode

Type – American Cyananide Type AB-6X with hydropobic film.

Position – Perpendicular to positive and negative plates.

Separation form cell pack – two layers of non-woven nylon.

Separation on gas surface – Vexar plastic netting 15 ADS 129 NL (Polyethylene)

APPENDIX B

SILVER PLATE ANALYSIS FOR CHARGED AND DISCHARGED PLATES

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INTENTIONALLY BLANK

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1. ANALYTICAL PROCEDURE FOR SILVER PLATES

The procedures followed in obtaining the analyses are detailed below.

1.1 Sample Preparation

The electrodes were carefully removed from the supplied battery by cutting the plastic casing. The samples were cleaned in distilled water and were dried in an oven maintained at 110°C.

1.2 Total Silver

A 0.2 gm sample was transferred to a 400 ml beaker and was dissolved in 1:1 nitric acid (approximately 30-50 ml). The resultant solution was diluted to 200 ml and titrated with N/10 KCNS solution according to Volhard's method[1] using a ferric indicator. The reactions that take place during titration are given below:

$$AgNO_3 + KCNS = KNO_3 + AgCNS$$

$$Fe(NO_3)_3 + 3KCNS = 3KNO_3 + Fe(CNS)_{3RED}$$

Total silver present in the sample was calculated as shown below:

1 ml N/10 KCNS = 10.79 mg of silver

(ml of N/10 KCNS) (10.79) = mg of silver in the test sample

1.3 Ammonia Soluble Silver (Total Silver Oxides)

From the bulk ground sample, 0.2 gm was transferred to a 250 ml beaker. The sample was dissolved in 1:1 ammonia solution. The solution was acidified with nitric acid and titrated with N/10 KCNS according to Volhard's method[1] using a ferric indicator. In this method, since the metallic silver remains insoluble, the amount of silver precipitated is present as silver oxides.

1.4 Silver Peroxide (AgO)

The oxalate method was used for AgO determination.[2] A 0.2 gm sample was dissolved in 1:10 H_2SO in the presence of a measured amount of oxalic acid. The excess oxalic acid was titrated with potassium permanganate. A blank sample was also run. The volume difference in the amounts of titrant between the test sample and the blank was used to compute AgO.

$$2AgO + H_2SO_4 + (COOH)_2 = Ag_2SO_4 + 2H_2O + 2CO_2$$
$$1 \text{ ml } N/10\ (COOH)_2 = 12.39 \text{ mg of silver}$$

1.5 Total Loss on Ignition

A sample size of 0.4 gm was weighed into a sample boat of carbon and hydrogen combustion train. The apparatus was connected to pre-weighted hydrogen and carbon dioxide adsorption tubes. The sample was then heated gradually to 700°C and held at that temperature for 15-20 minutes. The total loss due to ignition was determined by noting the difference in the boat weight before and after test. The weight increase in the hydrogen adsorption tube was taken as the water content while the weight gain in CO_2 tube was taken as carbonate content of the sample. The difference between the sample weight loss and the combined water and carbonate values gave the oxygen content of the sample. This figure included both the adsorbed and combined oxygen (as silver oxides) values.

1.6 Absorbed Oxygen

Ten gm ground sample was flushed with nitrogen in a high vacuum system for 20 minutes. The outlet gases were collected in a large evacuated container and the percent of oxygen present in the collected gases was determined by Gas Chromatography using a molecular sieve column, helium as carrier gas and cross section detector.

1.7 Silver Oxide (Ag_2O)

The amount of silver oxide (Ag_2O) was determined as follows: First, the total oxygen content of the test sample was determined. This was followed by the determination of adsorbed oxygen. The amounts of oxygen combined with silver (as oxides) were then computed.

Total oxygen - adsorbed oxygen = oxygen combined with silver

This amount of oxygen was assumed to be combined with silver partly as AgO and partly as Ag_2O. The amount of AgO was determined by oxalate method. The remaining oxygen not combined as AgO was assumed to be present as Ag_2O.

1.8 Potassium

A two gm sample was soaked in distilled water for 30 minutes. The resultant solution after four decantations was acid titrated, and the amount of potassium present in the sample was calculated as KOH.

1.9 Cadmium

Cadmium was determined by emission spectroscopy using the Jarrell-Ash meter grating spectrograph. Pure cadmium oxide was mixed with silver oxide to give standards of approximately the same matrix composition as the electrode sample. Lead as red oxide (Pb_3O_4) was added in equal amounts to both the standards and the test samples. Both standards and the samples were excited in a DC arc at 17 amperes using a 10% step filter and burn time of 35 seconds. The emitted lines were recorded on a spectrograph plate (SA No. 1) in the ultraviolet region (2300-3400Å). The ratio of intensities of the cadmium line at 3261.1Å and the lead line at 2628.3Å were measured on a Jarrell-Ash microdensitometer and plotted against the concentration of cadmium to obtain a standard curve. The ratio intensities of the lines were determined and used to estimate the amount of cadmium in the electrodes.

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1. Scott's Standard Methods of Chemical Analysis, Volume 1, Fifth Edition, DiVan Nostrand Company, Inc., New York, 1954.

2. Kolthoff and Stenger "Volumetric Analysis" Volume 1, Inter-Science Publishers, Inc., New York.