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LARGE SILVER-CADMIUM TECHNOLOGY PROGRAM

by

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GULTON INDUSTRIES, INC.

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16. Abstract

Objectives were to determine the effects of varying cell design on operation factors on the electrochemical performance of large, sealed, silver-cadmium cells. The objectives were carried out through a factorial experiment, 1/16 block of $2^{(9)}$, for all test cells constructed with organic separators. This experiment evaluated 3 operating factors: temperature, depth-of-discharge, and charge rate. The six construction factors were: separator, absorber, electrolyte quantity, cadmium electrode type, cadmium-to-silver ratio, and auxiliary electrode. Test cells of 4 Ah capacity were fabricated and cycled in accordance with the factorial experiment design. Cycling data show that the best performing cells, on a 94 minute orbit, at 40% depth-of-discharge, were those containing silver-treated fibrous sausage casings as the separator and teflonated pressed cadmium electrodes. Irradiated polyethylene (RAI2291) material did not prove satisfactory as a separator in this program.

Cycling data of cells with inorganic separators (Astroset) are given. Best performance was shown by cells with non-woven nylon absorbers. Rigid inorganic separators provided the best barrier to silver migration.

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FOREWORD

The work described herein, which was conducted by the Gulton Industries Battery & Power Sources Division, was performed under NASA contract NAS 3-13233, with Mr. William Robertson of Lewis Research Center as Project Manager.

The authors wish to acknowledge their gratitude to Mr. B. Schmidt and Mr. J. Malyszko of Gulton Industries for their assistance in the performance of the factorial experiment.

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ABSTRACT

The objectives of this program were to determine the effects of varying cell design on operation factors on the electrochemical performance of large, sealed, silver-cadmium cells.

The objectives were carried out through a factorial experiment, 1/16 block of $2^{(9)}$, for all test cells constructed with organic separators. This experiment evaluated three operating factors: temperature, depth-of-discharge, and charge rate. The six construction factors were: separator, absorber, electrolyte quantity, cadmium electrode type, cadmium-to-silver ratio, and auxiliary electrode.

Test cells of 4 ampere-hour capacity were fabricated and cycled in accordance with the factorial experiment design. Cycling data show that the best performing cells, on a 94 minute orbit, at 40% depth-of-discharge, were those containing silver-treated fibrous sausage casings as the separator, and teflonated pressed cadmium electrodes.

Irradiated polyethylene (RAI2291) material did not prove satisfactory as a separator in this program.

Cycling data of cells with inorganic separators (Astroset) are given. Best performance was shown by cells with non-woven nylon absorbers. Rigid inorganic separators provided the best barrier to silver migration.

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I. SUMMARY

The objectives of this program were to determine the effects of varying cell design and operation factors on the electrochemical performance of large, sealed silver-cadmium cells.

A factorial experiment, consisting of 1/16 block of $2^{(9)}$, was designed and put into operation. Nine (9) factors were evaluated. Three operating and six construction factors. The three operating factors were: temperature (0°C and 25°C), depth of discharge (40% and 60%; 20 and 30 mA/cm^2 respectively), and charge rate. The six construction factors were: type of organic separator, absorber, electrolyte quantity, type of cadmium electrode, cadmium-to-silver ratio, and auxiliary electrode.

Test cells were constructed, sealed in plastic cases (4 Ah capacity), and cycled on a 94 minute orbit--36 minute discharge and 58 minute charge.

Analysis of the cycling data show that the best performing cells were those in which the factor levels were as follows:

1) Teflonated cadmium hydroxide negative electrodes
2) Cell balance ratio Cd/Ag, 1.5:1
3) Fibrous sausage casing separator
4) Fuel cell asbestos absorber
5) Cell flooded with electrolyte
6) Inclusion of an auxiliary electrode
7) Depth of discharge of 40% (20 mA/cm^2)
8) Operating temperature of 25°C

A test cell constructed with 2 layers of treated fibrous sausage casings and non-woven nylon absorber completed over 5000 cycles at 60% (30 mA/cm^2) depth-of-discharge, and an additional 2000 cycles at 50% (25 mA/cm^2) depth, and is continuing to cycle. Irradiated polyethylene material (RAI2291) did <u>not</u> prove satisfactory as a separator in this program.

Cells were also constructed with Astroset inorganic separators. One "rigid" type and two "flexible" types were used. The absorbers were: non-woven nylon and potassium titanate (KT). Cells with non-woven nylon absorbers cycled two to three times longer than cells with KT absorbers, for the same separators. The rigid Astroset separator povided the best barrier to silver migration.

II. INTRODUCTION

The silver-cadmium battery for aerospace applications is used primarily for its magnetic requirements and higher energy density, and with no current is essentially non-magnetic. In terms of energy density, the silver-cadmium battery has about a 50% higher watt-hour/pound figure than a comparable nickel-cadmium battery.

The two main disadvantages of the silver-cadmium battery are:

(a) reduced cycle life caused by the deterioration of cellulosic separators, due to attacks by soluble silver and strong alkali;

(b) a fading phenomenon of the negative electrode, which leads to negative limiting cells, hence reduced capacity and cycle life.

On NASA program NAS 3-11829 (Report No. NASA CR-72805, 1971), we described the development of a non-magnetic cadmium electrode with stable capacity features during cycling.

The electrodes fabricated from a teflonated mix of non-commerical cadmium hydroxide $[Cd(OH)_2]$ exhibited utilization characteristics of better than 80% of theoretical capacity on early cycles. This utilization stabilized to approximately 65% on continued cycling. Standard pressed cadmium-oxide electrodes (CdO), at present, show a utilization of about 40%.

Jackson and Colston(1) reported that silver-cadmium batteries are subjected to typical orbits of 8 hours to 4 days at 0°C to 30°C. The discharge period is held to 30 minutes at about 20% depth. Under these conditions, and when using a two-step voltage regulation charge control, the batteries have a life of about 2 years, or up to approximately 2200 cycles.

The objectives of this program were to determine the effects of varying cell design and operation factors on the performance of a large, sealed silver-cadmium secondary cell. The program was concerned primarily with the effects of these factors on the performance of a silver-cadmium cell to cycle on a 94 minute orbit, with 58 minutes of charge and 36 minutes of discharge at a discharge depth of 40% to 60% of capacity. The operating temperatures were 0°C and 25°C.

The silver-cadmium cells used in this test program were constructed of 3 electrodes--two negatives and a positive-- and sealed in a plastic container. They were rated at 4.0 Ah capacity at the 2-hour rate.

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(1) Jackson, T.P. and Colston, E. F., "The Manufacture of Sealed Silver-Cadmium Spacecraft Batteries From Dry, Unsealed Cells", National Aeronautics & Space Administration

The cell parameters under investigation were:

a) Cell balance - ratio of Cd/Ag
b) Separator material
c) Absorber material
d) Cadmium electrode type
e) Electrolyte quantity
f) Auxiliary electrode

An additional experiment was conducted to obtain cycle life data of the teflonated cadmium hydroxide negative electrodes. A cell with a known separator system, using teflonated cadmium electrodes, was assembled.

The separator system employed was one layer of dynel and two layers of silver treated fibrous sausage casing on the positive silver electrode, and one layer of 0.007" non-woven nylon on the negative electrode.

The cell was subjected to cycling on a 90 minute orbit at 25°C. Over 5000 cycles were accumulated at 60% depth of discharge to an end voltage of 0.6 V, and an additional 2000 cycles at 50% depth of discharge to an end voltage of 0.9 V. The total number of cycles was accumulated over 15 months.

At the 60% depth, the cell was discharged at a current density of 29.5 mA/cm^2, and was charged at a current density of 33 mA/cm^2 of the positive plate (total area). This high rate of charge and discharge greatly exceeds the known rates for silver-cadmium batteries in use. The body of this report gives detailed descriptions of these experiments, the results, and an analysis of pertinent data where applicable.

A set of process specifications for the manufacture of electrodes in the 4 Ah size is given in the Appendix to this report.

III. PROGRAM DESIGN

A. TEST CELL DESIGN

In order to achieve the objectives of this program, test cells of uniform size were designed and constructed. Each cell consisted of three electrodes--one silver and two cadmium. All electrodes were of a size 3.0 inches high x 3.5 inches wide. Each set of electrodes was welded to a silver-plated steel terminal (#10-32 thread size) and was assembled into a nylon case with its appropriate organic separator system, which was then sealed. The cells were filled with electrolyte to the designated levels, and provided with stainless steel pressure gauges to observe and record pressure rise on charge.

The size of the positive electrodes for test cells with inorganic separators was trimmed to 3.25 inches wide by 2.63 inches high to facilitate potting of the rigid separators around the periphery of the electrode.

Figure 1 shows a cell assembly giving overall dimensions of the cell.

B. SEPARATOR - ABSORBER SYSTEMS

1. Separator Material

As part of this program, a number of separator-absorber systems were evaluated.

The separator (barrier) materials evaluated were:

a. Silver-treated fibrous sausage casing - The casings were manuby Union Carbide Inc. and the silver treatment was performed at Gulton.

b. RAI-2291 manufactured by RAI Research Inc. - This material is a radiation grafted polyethylene.

c. Astroset Inorganic Separators manufactured by Astropower Division MacDonnell Douglas Corp. - This material was supplied in three types--two flexible types designated 3420-09 and 3420-25, and a rigid type designated 3420-09.

2. Absorber Materials

The absorber materials evaluated under this program were:

a. Potassium Titanate (KT) Paper manufactured by the Mead Corp.

b. Fuel Cell Asbestos manufactured by Johns Manville Corp.

c. Non-Woven Nylon (Pellon) manufactured by the Pellon Corp.

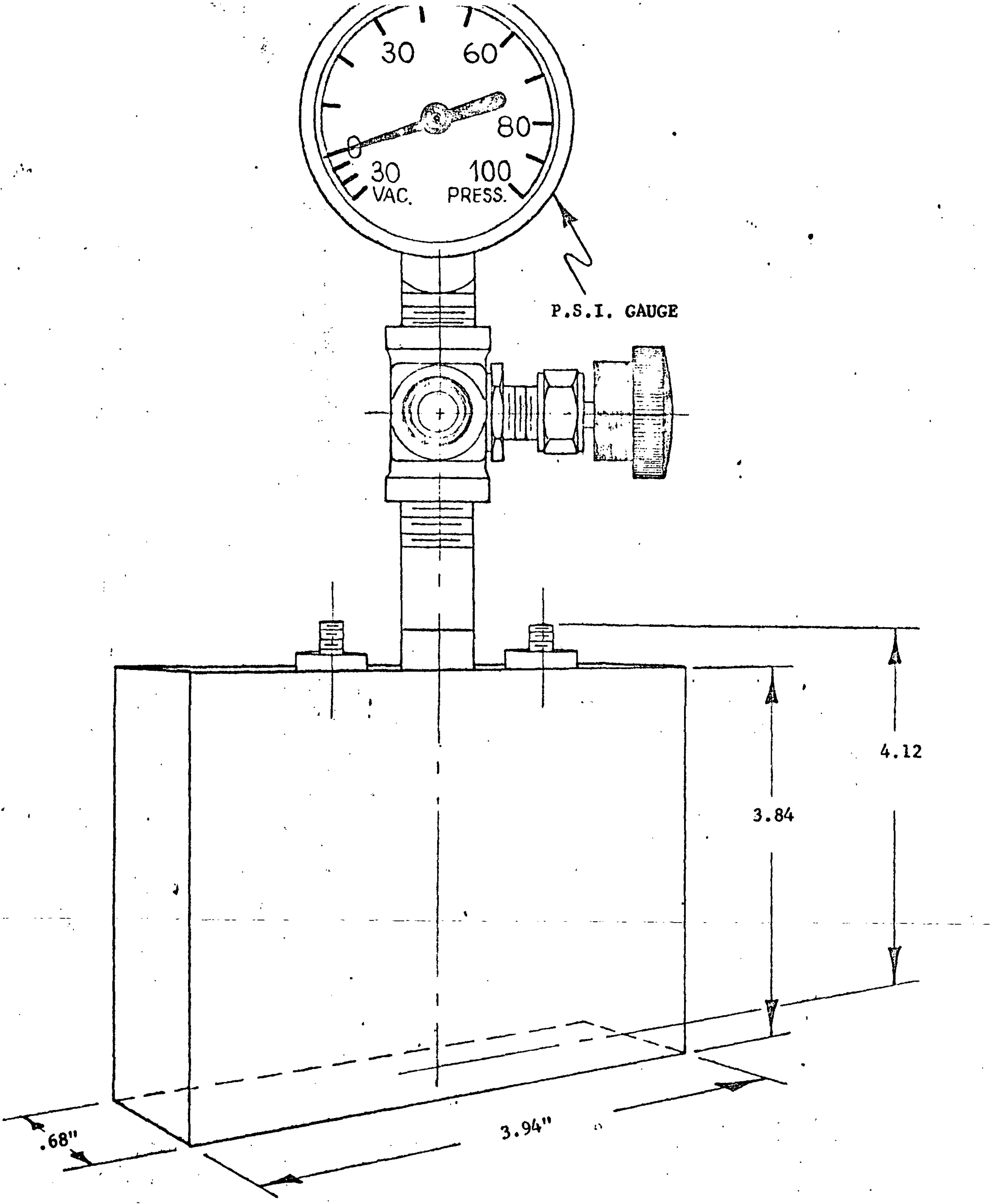


FIGURE 1 THREE-PLATE TEST CELL FOR LARGE SILVER-CADMIUM TECHNOLOGY PROGRAM

3. Separator-Absorber Properties

a. Resistivity Measurements

Tests were conducted to measure the resistivity of separators used in Experiment I of this program.

Figure 2 shows a test device which was constructed for conducting these measurements. The measurements were made in the following manner.

Two reference electrodes were inserted, one on each side of the empty plastic sample holder, emersed in KOH, 34% aqueous solution. A current of 50 mA/cm^2 was passed between the two reference electrodes, and the voltage (V_b) between the two reference electrodes was recorded. Samples of the separators, which were to be evaluated, were presoaked in KOH (34% aqueous solution) for 24 hours prior to testing. The presoaked samples were inserted into the plastic holder, between the two reference electrodes, and a current of 50 mA/cm^2 was again passed, and the voltage between the two reference electrodes was recorded.

The resistivity of each separator sample was calculated from the following equation:

$$R^1 = \frac{V_s - V_b}{I} \times A$$

where: R^1 = the resistivity of the separator tested = ρL^*
V_b = The voltage of the blank holder
V_s = The voltage of the sample
I = Current passed (50 mA/cm^2 = 325 mA/in^2)
A = Area of separator (in this test all separators had an area of 1 in^2)

Table I gives the resistivity of the separator samples tested. *ρ is the effective resistivity and L is the thickness of the samples. R^1 is the value of resistance obtained in the measurement and is set equal to the product ρ x L.

TABLE I. - RESISTIVITY OF SEPARATORS

SEPARATOR TYPE	RESISTIVITY IN MILLIOHMS - CM^2
K.T. paper - 20 mils thick	103 milliohms-cm^2
Fuel Cell Asbestos* - 15 mils thick	142 milliohms-cm^2 *
Pellon 2505K - 12 mils thick	45 milliohms-cm^2
Treated Cellulose - 3 mils thick	110 milliohms-cm^2
RAI-2291 - 1.5 mils thick	445 milliohms-cm^2
Dynel - 2 mils thick	123 milliohms-cm^2

* Fuel cell asbestos was only presoaked for several minutes. The material fell apart when it was left in the electrolyte unsupported, and formed a pulpy mass.

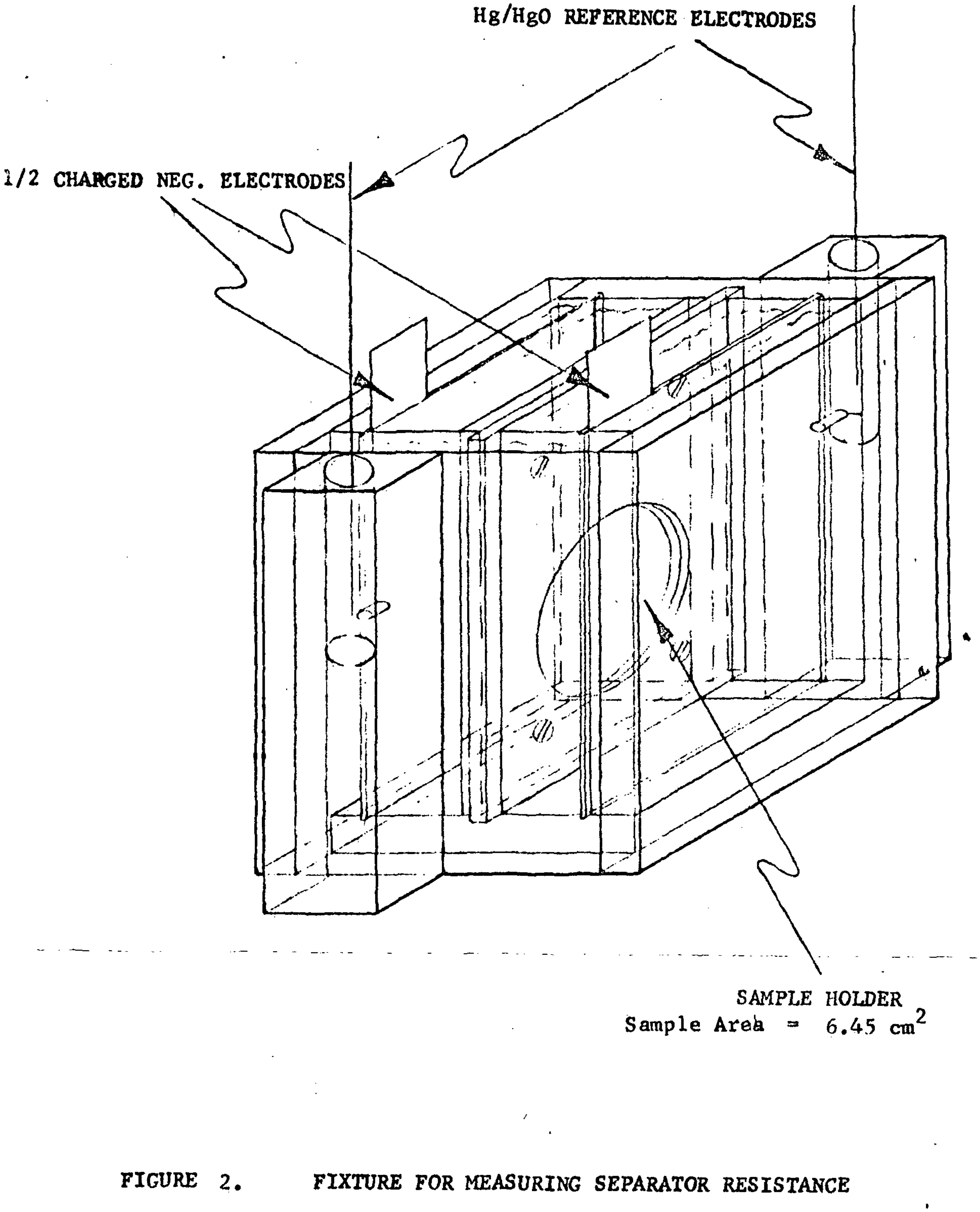


FIGURE 2. FIXTURE FOR MEASURING SEPARATOR RESISTANCE

b. Absorption Properties

Two separator materials have been tested for absorption properties of KOH. One was KT paper; the other fuel cell asbestos. The results are given in Table II. Sample pieces, 1" x 3" of each were cut and soaked in 34% KOH for 6 minutes, air dried for 2 minutes, then weighed.

TABLE II. - ABSORPTION PROPERTIES OF THREE SEPARATOR MATERIALS K.T. PAPER - 20 MILS THICK AND FUEL CELL ASBESTOS 15 MILS THICK

MATERIAL	WEIGHT OF 4 PIECES 1" x 3" IN GRAMS		% ABSORPTION
	DRY	WET	
K.T. Paper - Sample 1	1.15 gms	4.75 gms	304%
K.T. Paper - Sample 2	1.20	4.90	309%
K.T. Paper - Sample 3	1.20	5.00	316%
*Fuel Cell Asbestos - Sample 1	2.35	16.50	604%
*Fuel Cell Asbestos - Sample 2	2.35	16.75	613%
Non-Woven Nylon - Sample 1	0.083	0.798	864%
Non-Woven Nylon - Sample 2	0.093	0.876	840%

* After soaking for 6 minutes, unsupported, fuel cell asbestos became difficult to handle and had to be removed between two flat plates for drying on the scale. After drying, the asbestos turned into a pulpy mass.

C. SUBSTRATE MATERIAL

The substrate material used for both positive and negative electrodes consisted of an expanded 0.005 inch thick sheet of 99.9% fine silver. The expanded openings were 0.125 inch wide.

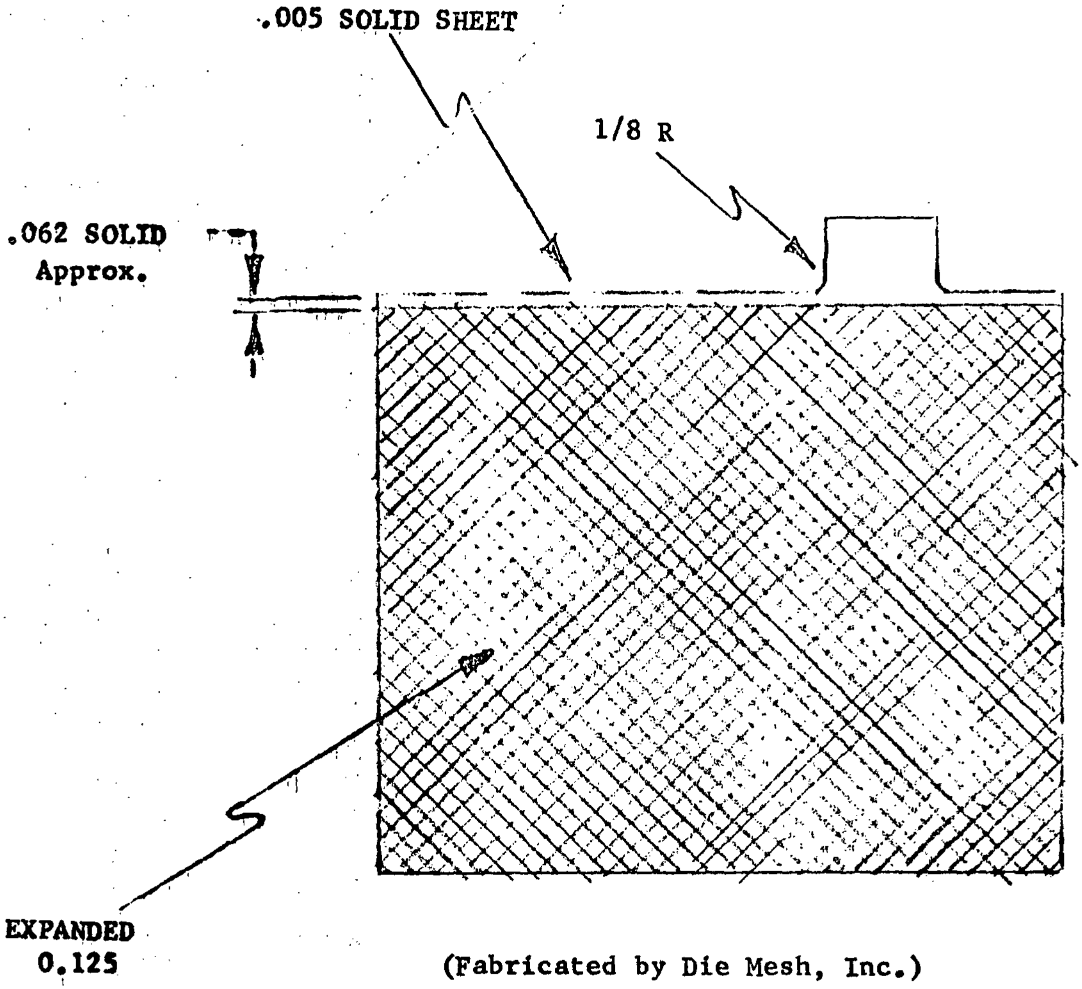
The substrates were fabricated with an integral tab which extended the full width of the substrate. This type of construction reduces voltage gradients within the plate and provides for greater utilization and higher voltage levels during high rate discharge.

A sketch of the substrate is shown in Figure 3.

D. POSITIVE ELECTRODES

The positive silver electrodes were fabricated from Handy & Harmon Silpowder 150. This material has a particle size range of 9-11 microns. All electrodes were of the sintered type, using the "lost wax" (paraffin wax) process of fabrication. All electrodes fabricated for use with organic separators contained 18 grams of silver for a theoretical capacity of 9 ampere-hours. All electrodes fabricated for use with the Astroset material (inorganic separators) contained 14.7 grams of silver for a theoretical capacity of 7.35 ampere-hours.

A more detailed description of positive electrode fabrication is given in the Appendix.



(Fabricated by Die Mesh, Inc.)

FIGURE 3. EXPANDED SILVER SUBSTRATE

E. NEGATIVE ELECTRODES

Two types of negative electrodes were evaluated during this program.

The first type was the "Gulton Standard Electrode" which was manufactured of a mixture of 2/3 commercial cadmium oxide and 1/3 cadmium hydroxide (synthesized at Gulton). Five percent of silver powder, by weight, was added to the mix as a conductive diluent. The mixture was then pressed onto an expanded silver substrate (see Figure 3).

The second type of electrode evaluated was the "Teflonated Cadmium Hydroxide Electrode". This electrode was prepared by adding 5 weight percent Dupont P-30 Teflon emulsion to a mixture of 95% non-commercial cadmium hydroxide (synthesized at Gulton) and 5%, by weight, of silver powder as a conductive diluent. The Teflon-cadmium hydroxide mixture was then cured at 275°C for 20 minutes. The resulting product was ground up to pass through an 80 mesh screen and pressed on an expanded silver substrate, shown in Figure 3.

Each type of electrode was constructed to give cadmium-to-silver ratios of both 1.3:1 and 1.5:1.

A fully detailed description of negative electrode fabrication is given in the Appendix.

F. CHEMICAL ANALYSIS

A semi-quantitative elemental analysis, by emission spectroscopy, was performed on cell electrode materials. The analysis was performed by U. S. Testing Co., Hoboken, N. J.

The results of these analyses, given in Table III, indicate the high degree of purity of the materials. While the wax and Teflon emulsion contain higher levels of metallic impurities than the electroactive materials, the wax is 99.7% pure and the Teflon emulsion is 99.5% pure.

TABLE III. - SEMI-QUANTITATIVE SPECTROGRAPHIC ANALYSIS OF CONSTITUENTS OF SILVER-CADMIUM ELECTRODES

ELEMENT	ASARCO CdO	GULTON $Cd(OH)_2$	H&H Silpowder 150	SILVER ELECTRODE	PARAFFIN WAX	DUPONT TEFLON P-30
Cu			<0.01%	0.01-0.05%	<0.01%	<0.01%
Fe	<0.01%			<0.01%	<0.01%	<0.01%
Pb	0.01-0.1%					
Ag		<0.01%			0.01-0.1%	<0.01%
Al						<0.01%
Ca						0.01-0.1%
Mg					<0.01%	<0.01%
Ni					0.01-0.1%	
Na						0.1-0.5%
Si					0.01-0.1%	<0.01%
Ti					<0.01%	<0.01%
% Ash					0.003%	0.0001%

G. ELECTROLYTE

An aqueous solution of potassium hydroxide (KOH) was used as the electrolyte in the test cells under this program. It was procured in 55 gallon drums as "Mercury Grade Potassium Hydroxide" with a specified high degree of purity, 45% aqueous solution.

The specifications governing the procurement of the electrolyte is given in the Appendix.

The bulk electrolyte was diluted with distilled water to the required concentration, 38% or 40%, as dictated by the experiments.

H. AUXILIARY ELECTRODES

The factorial experiment indicated the use of an auxiliary electrode ~~(3rd electrode)~~ to function as a gas recombination element in some of the test cells. The auxiliary electrode used was manufactured by American Cyanamid Corp. and was designated as AB-6. It is basically a teflon bonded platinum black on a gold plated nickel screen. The auxiliary electrodes were .010 inch thick and were cut into 3 inch squares. A nickel tab was welded to one corner of the electrode and enclosed in a PVC screen bag. The electrode was then welded to one of the negative terminals on the outside of the electrode stack.

IV. TEST EVALUATION PROGRAM

A. FACTORIAL DESIGN

The objectives of this program were to determine the effects of varying cell design parameters and operating conditions on the electrochemical performance of sealed silver-cadmium cells. These objectives were to be achieved through a factorial type of experiment.

For this program a $2^{(8)}$ factorial requiring 256 separate experiments was designed originally. This was reduced to a quarter block of $2^{(8)}$, or 64 experiments carried out in triplicate, to give greater statistical meaning to the test data.

The latter design required the construction of 64 cells, in triplicate, (192 cells total) with six different construction factors at two levels. These cells, when constructed, were to be tested under varying conditions of temperature and depth-of-discharge.

Table IV gives a gives a listing of the construction factors and levels, as well as operating conditions of the 192 cells with organic separators which were constructed under this program.

TABLE IV. - ORGANIC SEPARATOR TEST CELLS
DESIGN FACTORS & LEVELS
[1/4 block $2^{(8)}$]

EXPERIMENT #1

FACTOR LEVEL	FACTOR DESCRIPTION	LOW LEVEL	HIGH LEVEL
a	Temperature	0°C	25°C
b	Depth-of-Discharge	40 %	60 %
c	Cell Balance-Ratio Cd:Ag	1.3 : 1	1.5 : 1
d	Separator Materials	Silver Treated Fibrous Sausage Casing-Cellulose	RAI-2291-Irradiated Polyethylene
e	Electrolyte Quantity	Starved-25% of Cell Ht.	Flooded-75% of Cell Ht.
f	Absorber Material	KT Paper	Fuel Cell Asbestos (FCA)
g	Cadmium Electrode Type	Pressed-$3CdO/1Cd(OH)_2$	Teflonated $Cd(OH)_2$
h	Auxiliary Electrode	None	American Cyanamid AB-6

NOTE: Unless otherwise specified, 45% KOH was used as the electrolyte in all cells.

Precycling tests, conducted on several cells which were constructed to represent the test cells described, were performed prior to completion of the 192 test cells. These tests were preliminary, and were designed to ascertain cell performance. It became apparent that the charging rate would have an effect on the cycling of the cells, particularly on those subjected to a 60% depth-of-discharge.

It was, therefore, decided to add charging rate as an additional factor to the experiment. This expanded the factorial design to a $2^{(9)}$ experiment. To keep the statistical model within controllable limits, it was decided to chose a 1/16 block of the $2^{(9)}$ factorial experiment, in triplicate. This experiment now required 96 cells in place of the original 192 cells.

Table V gives a complete listing of the 1/16 block of the $2^{(9)}$ factorial experiment. Cells 1 to 32 (in triplicate) were ultimately placed on cycling tests in accordance with the factors and levels shown in Table V, as Experiment #1.

B. INSTRUMENTATION & MEASUREMENTS

The cycling requirements for the cells covered by Experiment #1 were based on a 94 minute orbit. The charge portion of the orbit was 58 minutes, and the discharge, 36 minutes. Over a 24 hour period, each cell completed 15.3 orbits.

The design and construction of the automatic cycling system was governed by the short time orbit and the number of cells it had to accommodate. Figure 4 shows a schematic diagram of the automatic cycling system.

The instrumentation system was based upon an orbital timer (K_1T), which activates an auxiliary timer (K_2T). Figure 5 shows an Event Bar Chart for the automatic cycling of the cells. The cells were arranged into four groups (A, B, C. & D) to be served by separate power supplies. Each group of cells, in series, was charged and discharged at constant current from its own power supply at the required rates, based on the depth of discharge.

Referring back to Figure 4, each group of cells was connected to its power supply through normally open contacts, K_1C on charge and K_1D on discharge. In the event of any control power loss or power interruption, the cell groups were disconnected from the circuit.

As an additional safety device, the "start relay", SR, was a D.C. relay connected through an RC delay timing circuit with a time constant of ten (10) seconds. This circuit prevented the cell groups from being disconnected from the cycling circuit due to a momentary reduction or loss in power. The cells were disconnected from the cycling circuit if the line voltage fell to below 80 volts, or if power was lost for more than ten seconds.

Figure 6 is a photograph of the cycling control panel. The orbital timer (K_1T) is shown at the top right and the auxiliary timer (K_2T) is shown at top center.

TABLE V. ORGANIC SEPARATOR TEST CELLS
DESIGN FACTORS & LEVELS

3 Cells Each Test
1/16 Block 2(9)

FACTOR	FACTOR DESCRIPTION	LOW LEVEL (0)	HIGH LEVEL (1)
a	Temperature	0°C	+25°C
b	Depth of Discharge	40%	60%
c	Auxiliary Electrode	None	AB-6
d	Separator Materials	Ag Treated Sausage (Cellulose)	RAI 2291
e	Electrolyte Quantity	Starved (25% of Cell Height)	Flooded (75% of Cell Ht.)
f	Absorber Material	KT Paper	Fuel Cell Asbestos
g	Cadmium Electrode Type	Pressed $3CdO/1Cd(OH)_2$	Teflonated $Cd(OH)_2$
h	Cell Balance Ratio Cd/Ag	Cd/Ag = 1.3 : 1	Cd/Ag = 1.5 : 1
j	Charging Rate	4.25 Amp	5.25 Amp

TEST NO.	CELL NUMBERS	FACTOR LEVELS									REMARKS
		a	b	c	d	e	f	g	h	j	
1	1-1, 1-2, 1-3	0	0	0	0	0	0	0	0	0	
2	2-1, 2-2, 2-3	1	0	1	0	0	1	1	1	1	
3	3-1, 3-2, 3-3	1	0	0	1	1	0	1	1	1	
4	4-1, 4-2, 4-3	0	0	1	1	1	1	0	0	0	
5	5-1, 5-2, 5-3	1	0	1	0	0	1	1	0	0	
6	6-1, 6-2, 6-3	0	0	0	0	0	0	0	1	1	
7	7-1, 7-2, 7-3	0	0	1	1	1	1	0	1	1	
8	8-1, 8-2, 8-3	1	0	0	1	1	0	1	0	0	
9	9-1, 9-2, 9-3	0	0	1	1	0	0	1	1	0	
10	10-1, 10-2, 10-3	1	0	0	1	0	1	0	0	1	
11	11-1, 11-2, 11-3	1	0	1	0	1	0	0	0	1	
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25	25-1, 25-2, 25-3	1	1	1	1	0	0	0	0	0	
26	26-1, 26-2, 26-3	0	1	0	1	0	1	1	1	1	
27	27-1, 27-2, 27-3	0	1	1	0	1	0	1	1	1	
28	28-1, 28-2, 28-3	1	1	0	0	1	1	0	0	0	
29	29-1, 29-2, 29-3	0	1	0	1	0	1	1	0	0	
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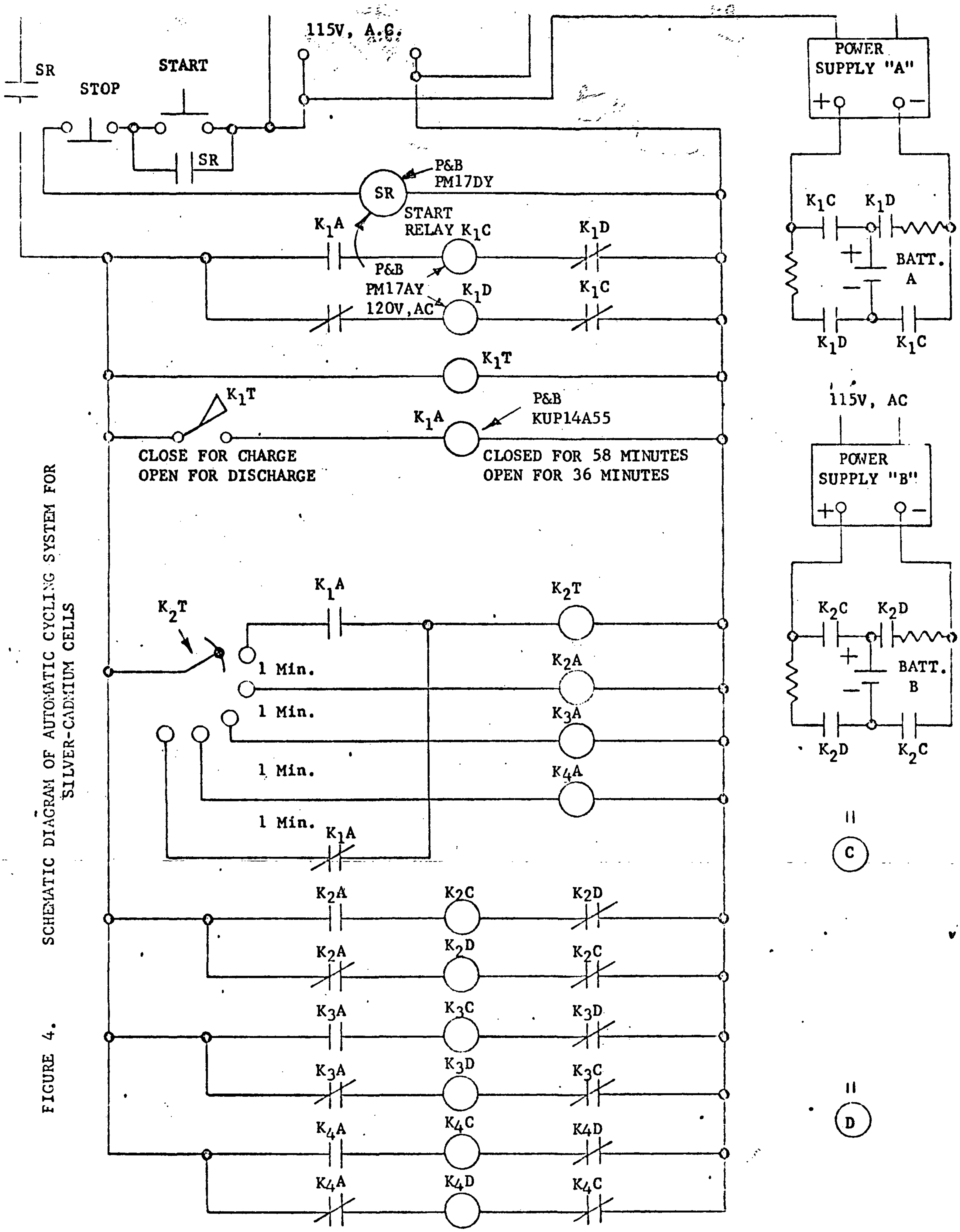
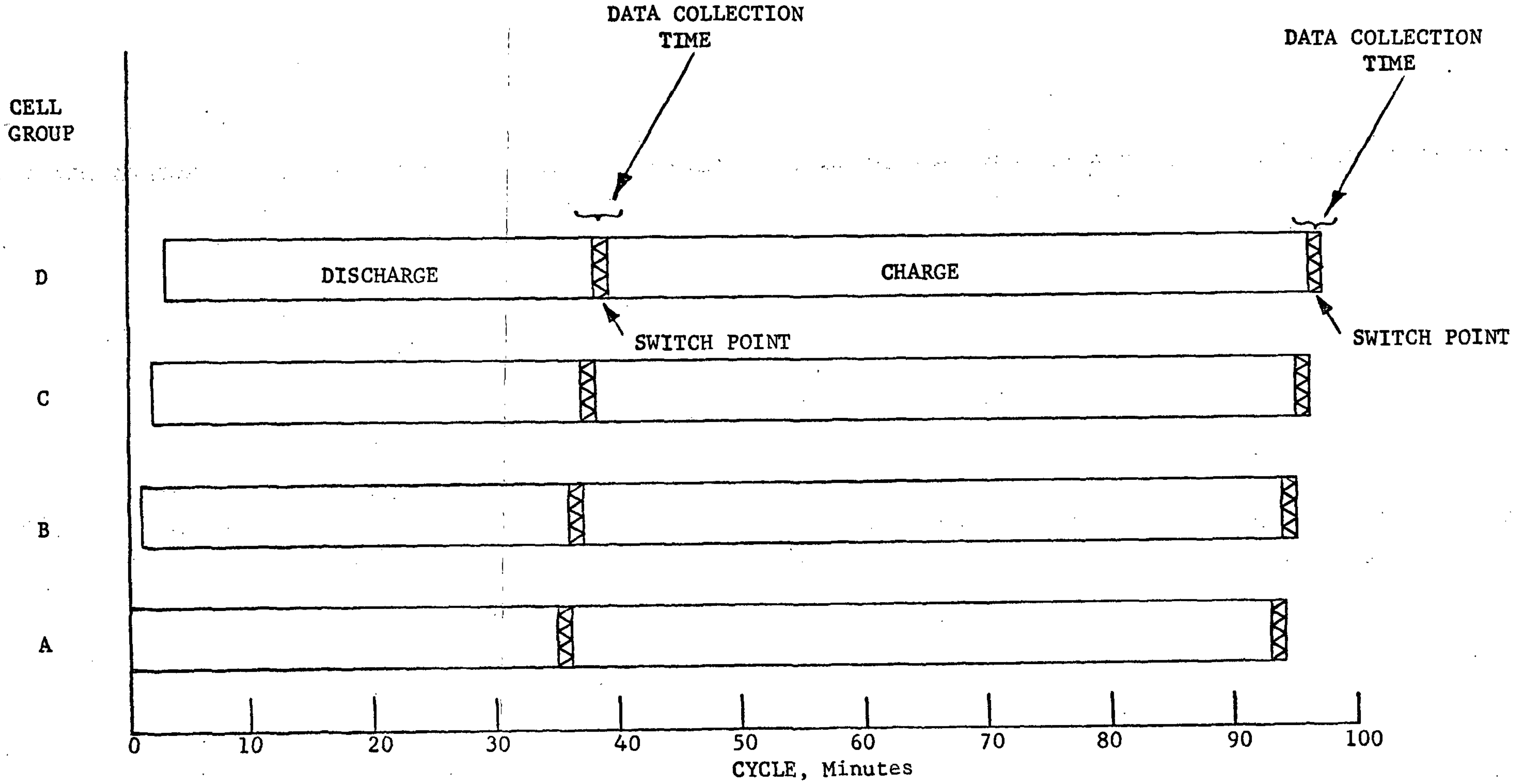


FIGURE 4. SCHEMATIC DIAGRAM OF AUTOMATIC CYCLING SYSTEM FOR SILVER-CADMIUM CELLS

FIGURE 5 EVENT BAR CHART FOR AUTOMATIC CYCLING OF SILVER-CADMIUM CELLS



5-2984

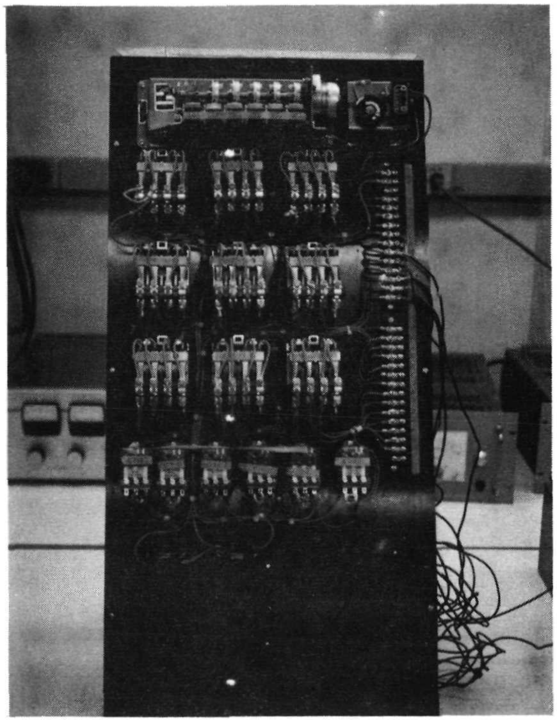


FIGURE 6. PHOTOGRAPH OF CYCLING CONTROL PANEL FOR SILVER-CADMIUM CELLS

Through the timer action, the four groups of cells were sequentially switched from the charge mode to the discharge mode of the orbit, and so on. This function was accomplished by the orbiting timer (K_1T) energizing the auxiliary timer (K_2T) whenever the position of the orbiting timer (K_1T) was changed ("closed" or "open").

The auxiliary timer (K_2T) then proceeded at one minute intervals to reverse the power supply polarity to each group of cells. When the orbiting timer (K_1T) changed position, the Data Acquisition System (an NLS Digital Voltmeter & Printer) was energized. The voltages of the separate cells were read and recorded through the mechanism of a 300 channel NLS crossbar scanner. Using the sequencing technique, the cell voltages were recorded at the end of the charge and discharge cycles through a single triggering of the data acquisition system. As soon as a cell group was read and recorded, that cell group was reversed in its connections with respect to its power supply and the next cell group was scanned.

Figure 7 shows the test configuration setup with the cycling control panel on the left, test cells in the center, and data acquisition system on the right.

C. CHARGE CONTROL

Silver-cadmium cells are sensitive to charge control due, mainly to the system's lack of tolerance for overcharge. Sealed silver-cadmium cells at Gulton have been charged to a maximum of 1.65 volts per cell to avoid oxygen evolution from the silver electrode.

The chosen range of end-of-charge voltages was set at 1.55 volts to 1.65 volts per cell.

In order to control the charge within the stated voltage range, the following charge control system was chosen: Two diodes (#1N1191-20 amp rating) were connected in series and then assembled in parallel with the cell, in the forward direction. Figure 8 shows a schematic diagram of a charging circuit using diodes. In this configuration, the diodes assume the same potential as the cell. When the cell voltage, and the corresponding voltage of the diode set, are low, most of the charging current passes through the cell. The diodes, whose resistance at the low voltage is high, pass a minimal amount of current. As the cell charges, its voltage rises and so does the voltage of the diode set (two diodes in series) connected in parallel with the cell. Toward the end of charge, as voltages of the cell and diodes rise, the diodes begin to conduct and share the total charging current with the cell. The higher the cell voltage, the greater the percentage of current that passes through the diodes.

Figure 9 shows a typical curve of current versus voltage for two series connected 1N1191 diodes. As the cell reaches 1.60 volts, the diodes will conduct 3.80 amperes. For a charging current of 4.25 amperes, this amounts to 90% of the charge rate. At the same time, only about 10%, or 0.45 amperes, will flow through the cell.

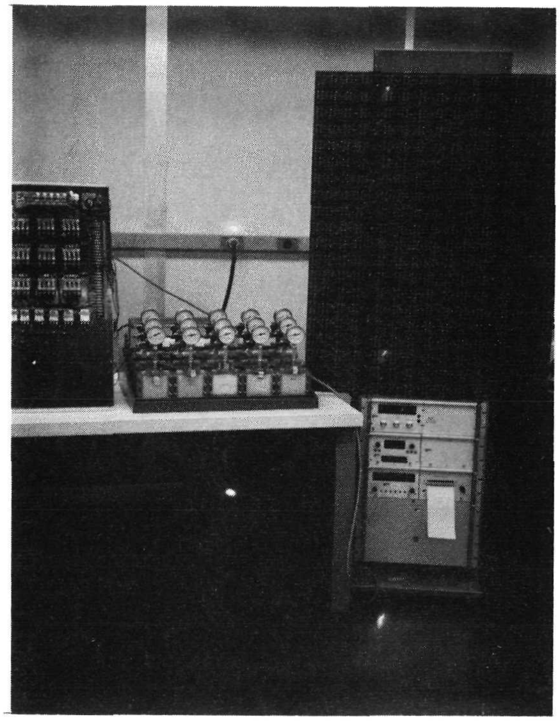


FIGURE 7. PHOTOGRAPH OF TEST & DATA ACQUISITION EQUIPMENT FOR CYCLING SILVER-CADMIUM CELLS

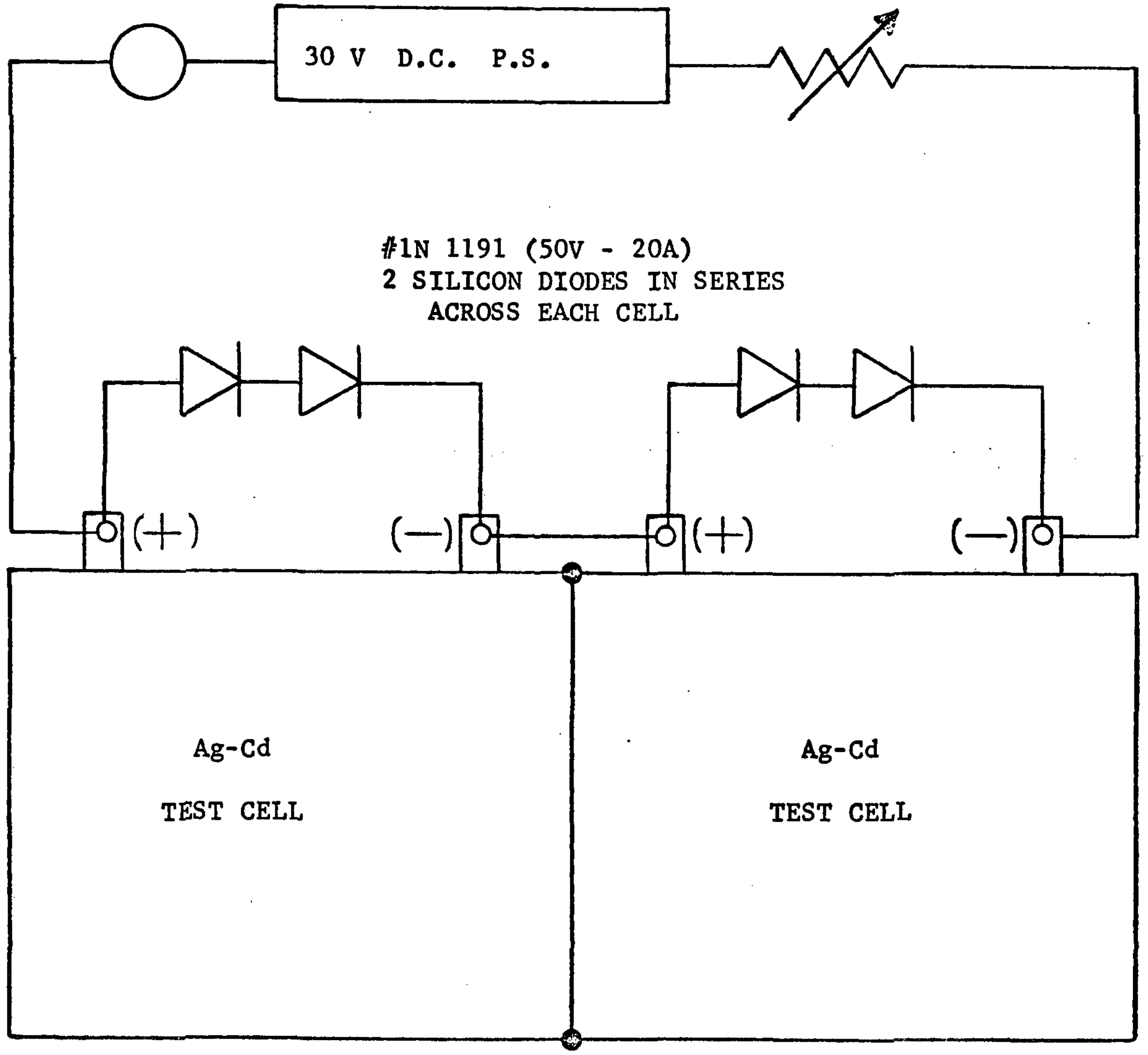


FIGURE 8. SCHEMATIC DIAGRAM OF A CHARGING CIRCUIT
TWO Ag-Cd CELLS IN SERIES WITH PROTECTIVE DIODES TO
LIMIT OVERCHARGING

5-3032

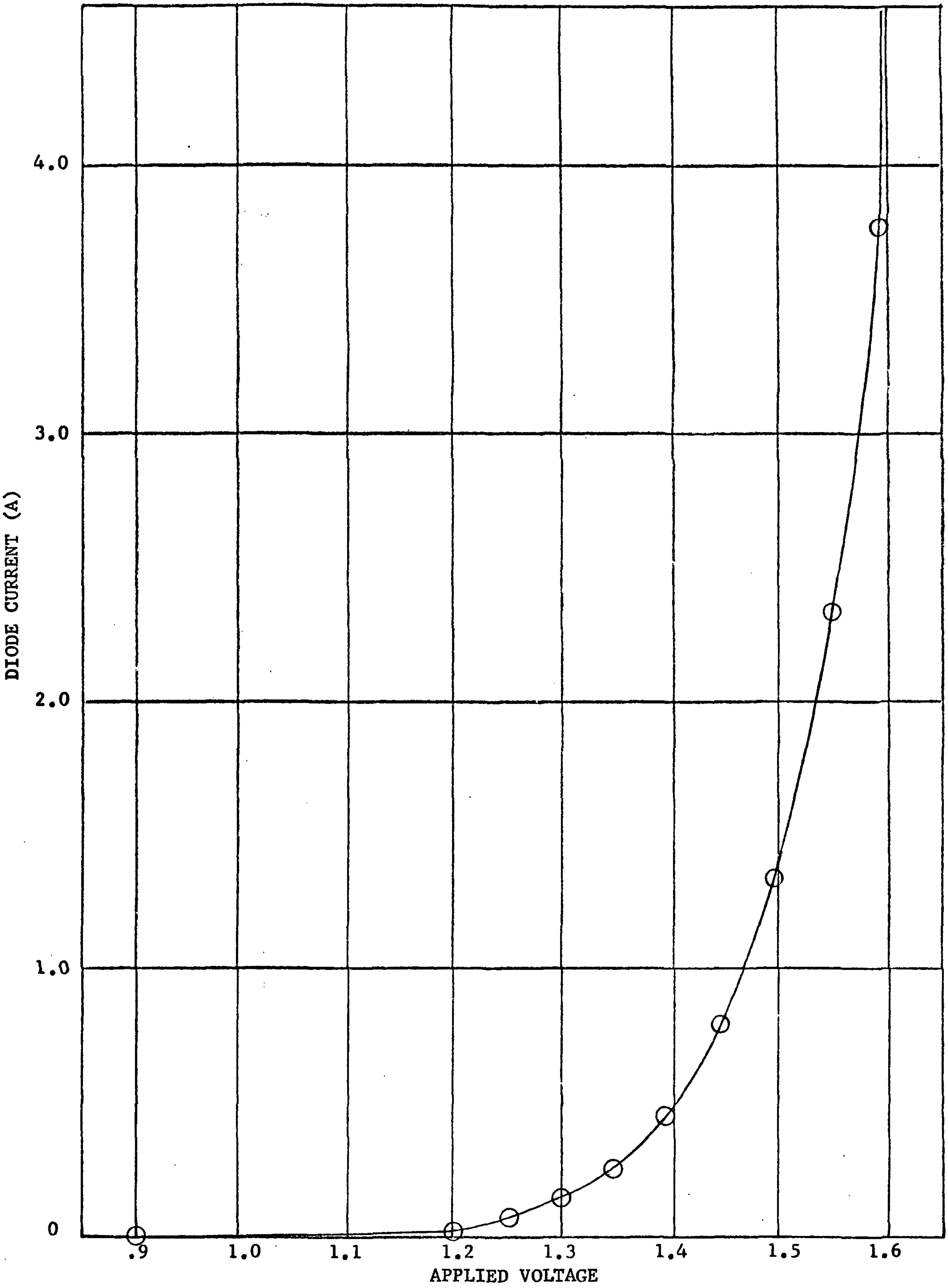


FIGURE 9. CURRENT-VOLTAGE CHARACTERISTICS OF 2 SERIES CONNECTED 1N1191 DIODES

Each diode used in the experiment was carefully matched. A voltage was impressed on each diode and the corresponding current passing through it was recorded. Only diodes with similar characteristics were chosen to make up sets of two, to be assembled, in parallel, with each cell. Furthermore, the selection of diodes was governed by the following criteria. Each diode, when impressed with 1.60 volts, should not pass a current in excess of 4.20 amperes at room temperature. This criteria gave assurance that some current would flow through the cell when the cell voltage reached 1.60 volts at the charging rate of 4.25 amperes. During cell operation, all diodes were cooled with a stream of air from an oscillating fan.

Other charge control systems were considered. However, we found that the required electronic circuitry was too complex to use within the scope of this program.

V. EXPERIMENTAL RESULTS

A. VERIFICATION OF ELECTRODE PERFORMANCE

The absorber and separator materials investigated under this program were sufficiently different from the separator materials previously used to require a verification of cell performance against a "known" separator system.

In the "known" separator system, each negative electrode was individually bagged in a 0.007 inch non-woven nylon, and each positive electrode was individually wrapped in a 0.002 inch dynel. These materials served as absorbers. Each dynel bagged positive electrode was inserted into a double silver-treated fibrous sausage casing (cellulosic) bag, as the main separator.

A three-plate cell (all cells tested under this program were constructed of 3 plates), containing one positive and two negative electrodes, with a "known" separator system (non-woven nylon/dynel-treated fibrous sausage casing) was fabricated.

The cell was filled with 38% aqueous solution of KOH and given two formation cycles as follows:

Cycle #1 - Charged at 11 mA/cm^2 (1.5 A) constant current for 24 hours. Discharged at 7.4 mA/cm^2 (1.0 A) to minus 0.8 volts to fully discharge the negative electrode.

Cycle #2 - Charged at 11 mA/cm^2 (1.5 A) for 24 hours. Discharged at 11 mA/cm^2 (1.5 A) to minus 0.8 volts.

The total capacities of both positive and negative electrodes are shown in Table VI.

TABLE VI. - CELL & ELECTRODE CAPACITIES FOR TWO FORMATION CYCLES

ELECTRODE CAPACITIES	CELL NO. 1	
	CYCLE NO. 1	CYCLE NO. 2
Positive Capacity	6.0 Ah	4.0 Ah
Negative Capacity	9.9 Ah	8.0 Ah

Following the two formation cycles, two diodes, in series, were connected across the cell. The cell was charged at constant current at a rate equal to 29.5 mA/cm^2 (4.0 A) for 24 hours. At the end of charge, the electrolyte volume was adjusted to within 75% of separator height. The cell was assembled with a pressure gauge and manually operated valve. The cell was evacuated, removing the air from the cell before closing the valve, and was then sealed.

The cell was placed on a cycling regime consisting of 55 minutes charge and 35 minutes discharge at 60% depth of discharge (based on the hourly rated capacity), corresponding to a discharge of 29.5 mA/cm^2 (4.0 A) and a charge of 33 mA/cm^2 (4.5 A).

The cell cycled on this regime for 502 cycles when it went into reverse, generating high gas pressure. Analysis showed the gas to be hydrogen, indicating that the positive electrode had gone into reverse. A post mortem study of the cell showed that it had shorted in the tab area, when a negative tab touched the positive electrode.

The electrodes were removed, washed, and dried and reassembled into a new cell case with shrink tubing covering the negative electrode tab in order to prevent a reoccurrence of the shorting problem.

The cell was filled with 45% KOH and charged at 29.5 mA/cm^2 (4.0 A) for 24 hours. The electrolyte was adjusted to the previous level (75% of separator height) and sealed. The cell was fitted with current limiting diodes and placed on the 60% depth cycling regime.

During the first 400 cycles, the cycling temperature was alternated equally between 25°C and 0°C.

Figure 10 shows a graph of the end-of-discharge voltage versus cycle number for the first 400 cycles. Figures 11 and 12 show typical charge-discharge curves for Cycle 243 at 25°C and Cycle 337 at 0°C.

After completion of the 400th cycle, the cell was cycled at 25°C only. Figure 13 is a plot of end-of-discharge voltage versus cycle number for Cycles 400 through 4515 (5017 cycles for the electrodes). During the cycling, the end-of-discharge voltage did not fall below 0.9 V until Cycle 3270. Between Cycle 3270 and 4515, end-of-discharge voltage fell below 0.9 V. Figures 14 and 15 are typical charge-discharge curves for Cycles 3204 and 4271.

Figure 16 shows a charge-discharge curve of Cycle 4515, the last cycle, at 60% depth-of-discharge.

Inspection of the discharge portion of Figures 13, 14, and 15 shows that the rapid fall-off in voltage occurs after 30 minutes of discharge. The cell voltage stays above 1.0 V at the end of thirty minutes of discharge. If length of discharge were reduced to thirty minutes, corresponding to a 50% depth-of-discharge, higher end-of-discharge voltages as well as extended cycle life, could be expected.

After the cell was removed from cycling, it was given two charge-discharge cycles in the sealed condition to determine the amount of capacity remaining. Charge control diodes were left on the cell. Each cycle consisted of a 20 hour charge at 29.5 mA/cm^2 (4.0 A) and a 15 mA/cm^2 (2.0 A) discharge to exhaustion of the limiting electrode. The discharge curves are shown in Figure 17. The formation cycle discharge curve is also shown for reference purposes.

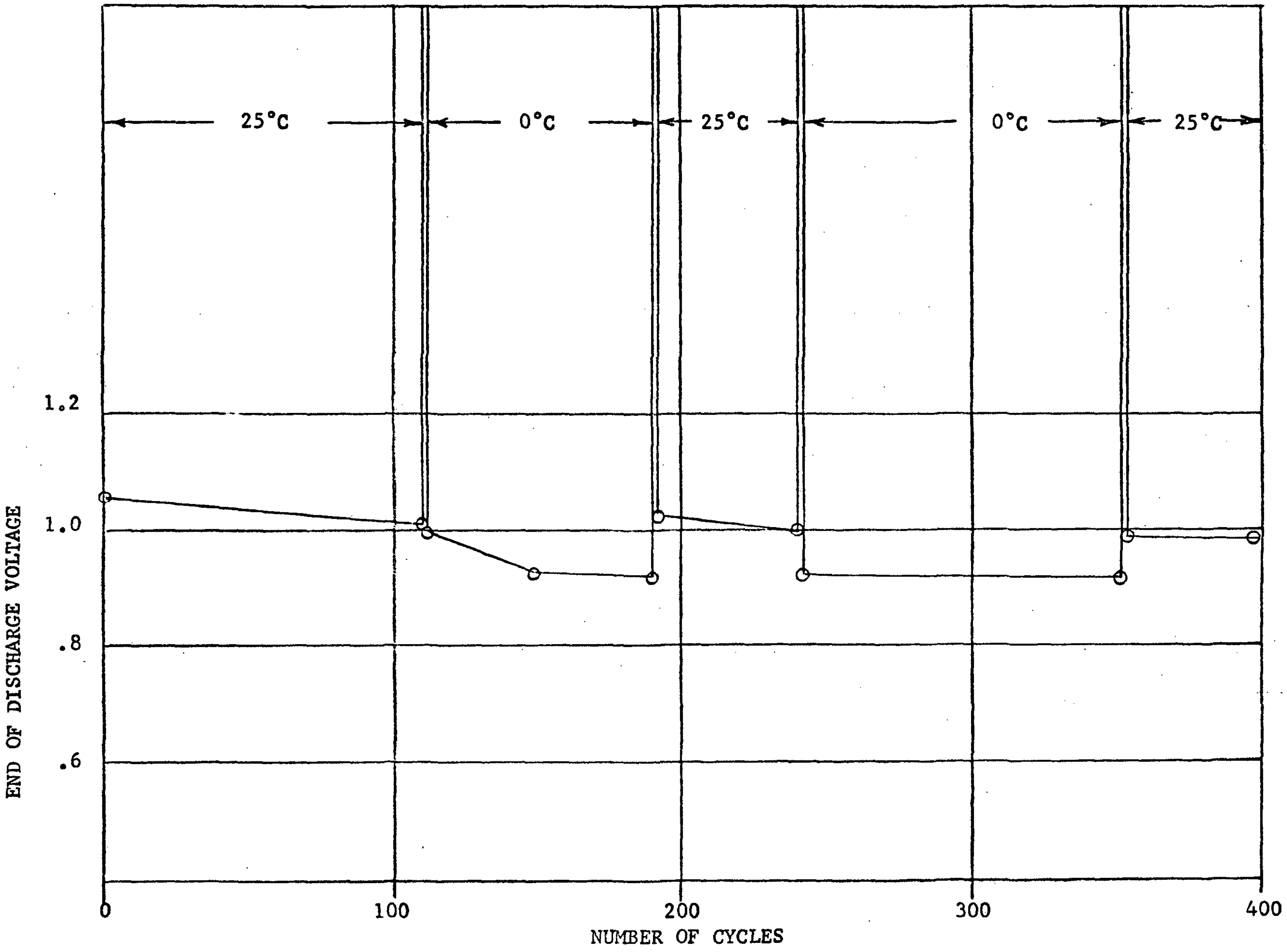


FIGURE 10. END OF DISCHARGE VOLTAGE Vs CYCLE NUMBER FOR A 3-PLATE SEALED SILVER-CADMIUM CELL 60% DEPTH OF DISCHARGE, 90 MINUTE ORBIT (45% KOH), AT TWO DIFFERENT TEMPERATURES ($29.5\ mA/cm^2$) (Cell Electrodes have 502 additional cycles)

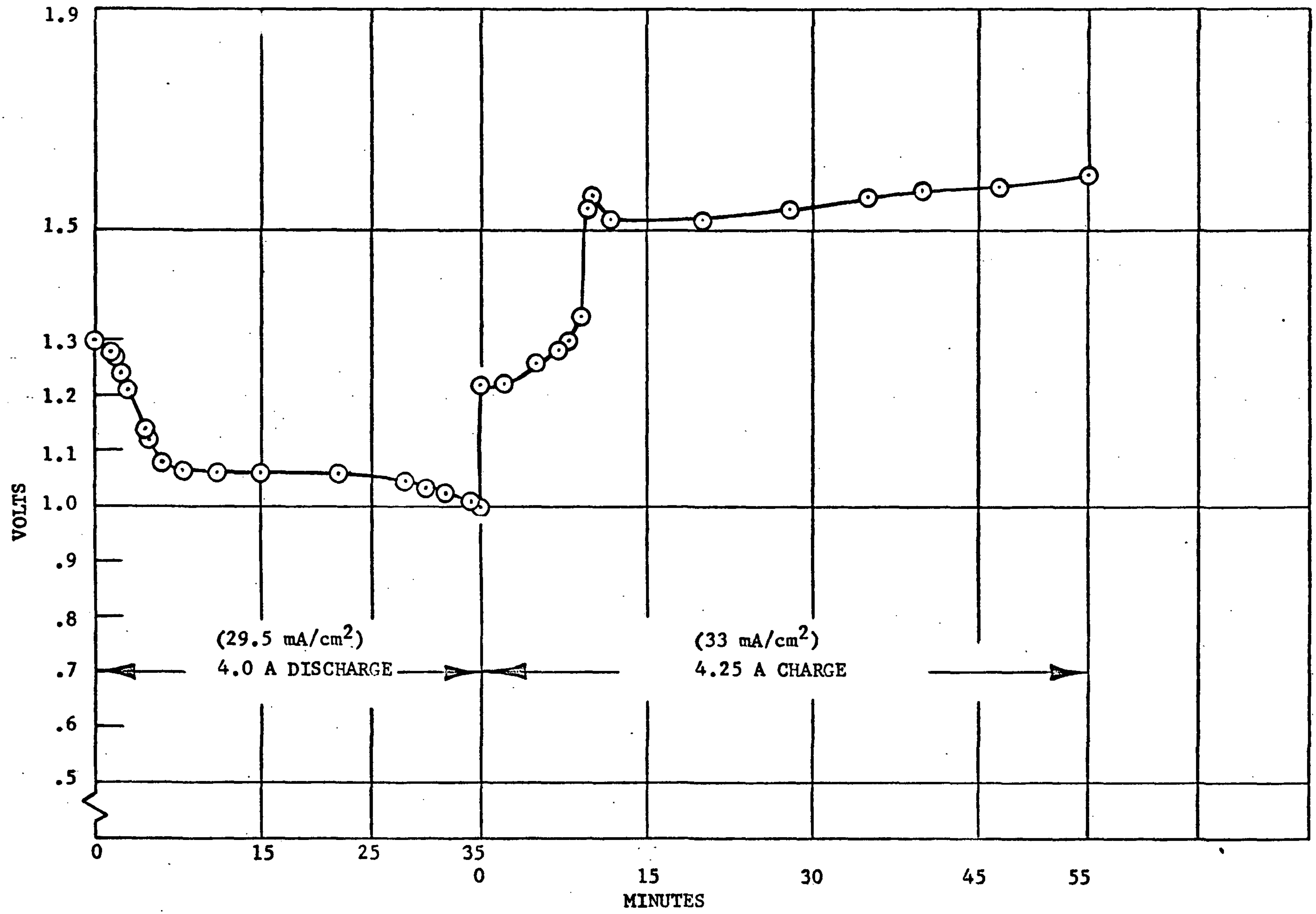


FIGURE 11. CHARGE-DISCHARGE CURVE FOR A SEALED 3-PLATE Ag/Cd TEST CELL EQUIPPED WITH CURRENT LIMITING DIODES, 60% DEPTH OF DISCHARGE AT 25°C (Cycle #243)

4-3087

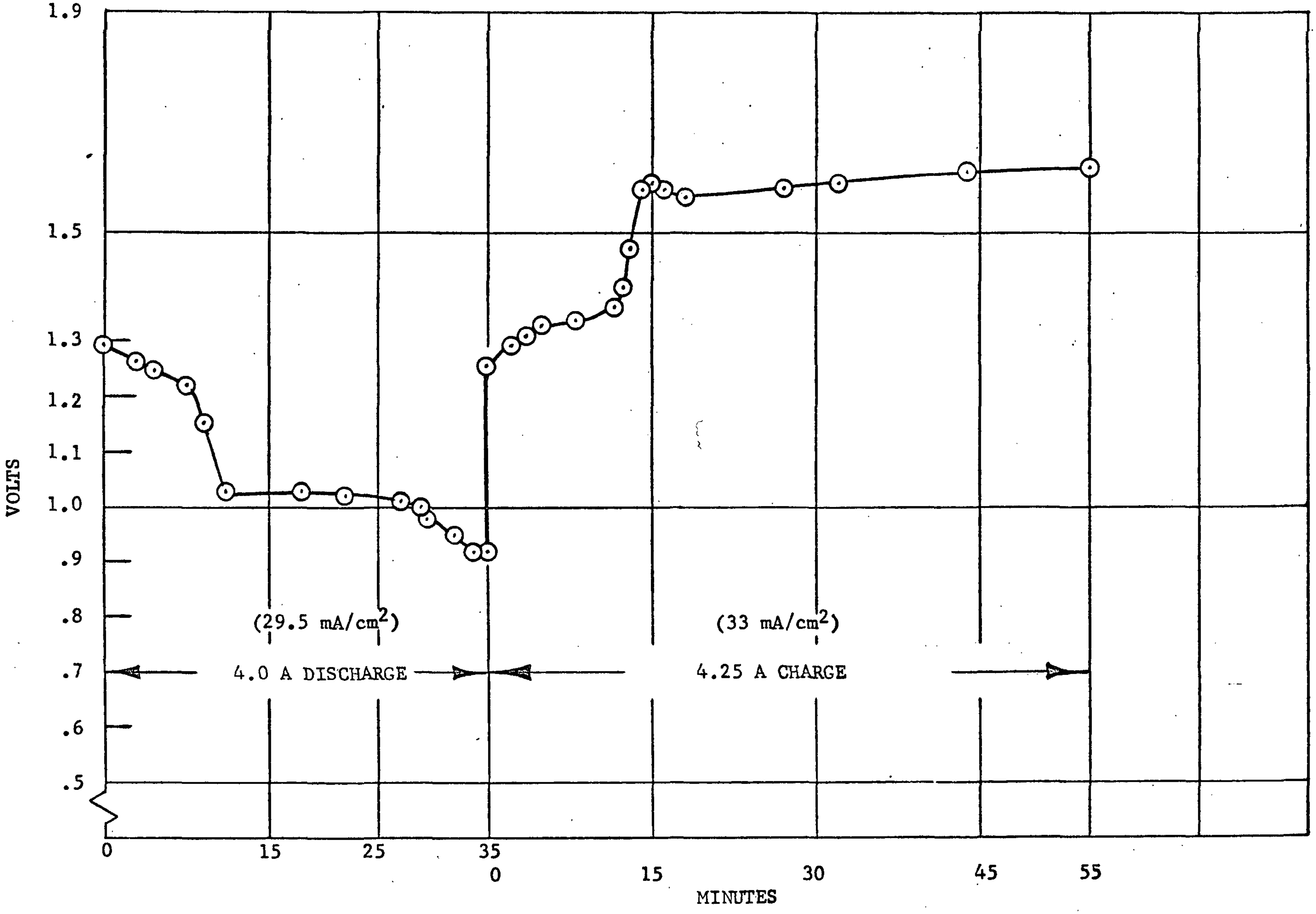


FIGURE 12 CHARGE-DISCHARGE CURVE FOR A SEALED, 3-PLATE Ag-Cd TEST CELL
EQUIPPED WITH CURRENT LIMITING DIODES
60% DEPTH OF DISCHARGE AT 0°C
(Cycle #337)

4-3088

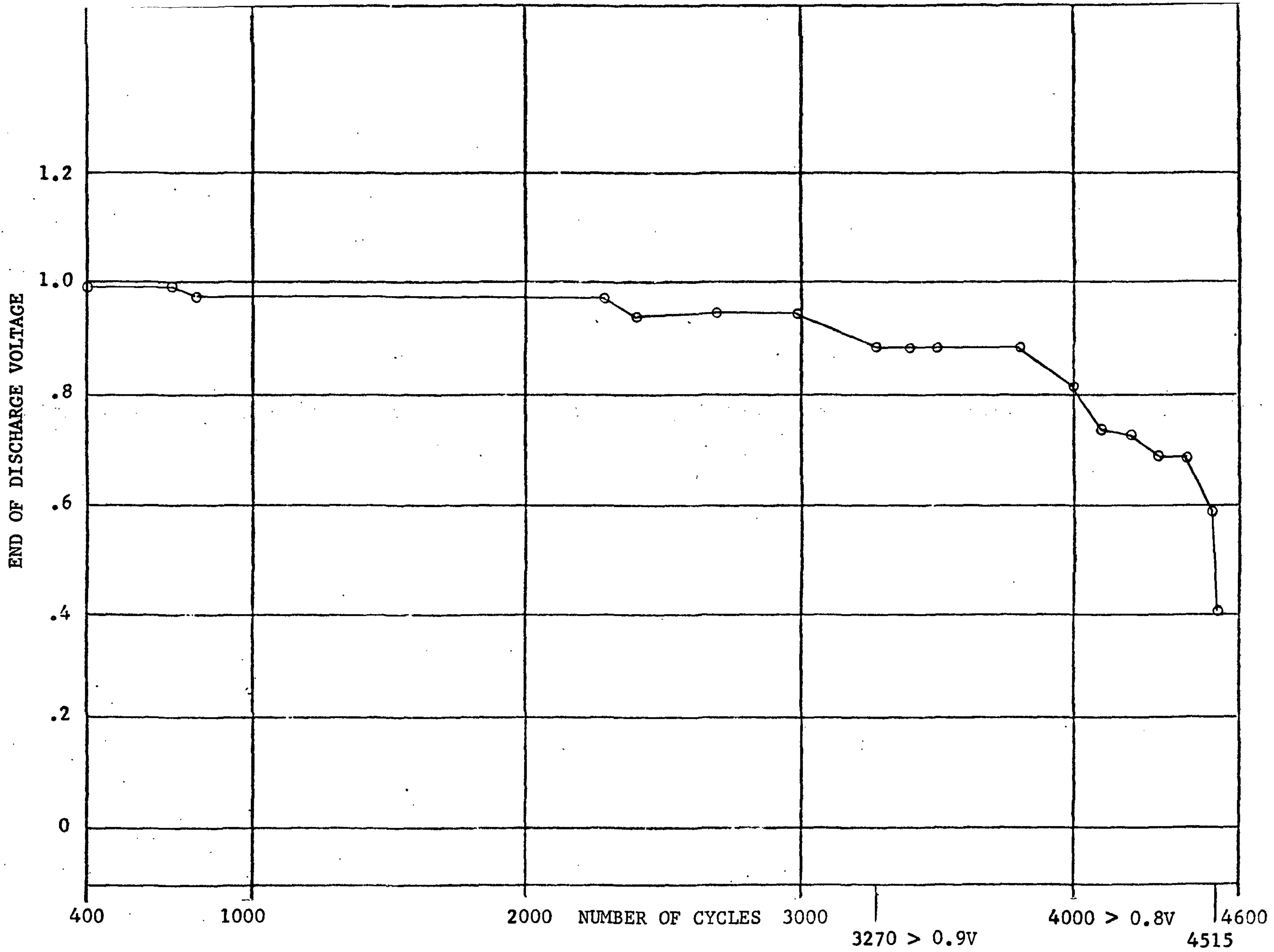


FIGURE 13. END OF DISCHARGE VOLTAGE Vs CYCLE NUMBER FOR A 3-PLATE SEALED SILVER-CADMIUM CELL 60% DEPTH OF DISCHARGE, 90 MINUTE ORBIT, CYCLES 400-4515 (Cell Electrodes Have 502 Additional Cycles)

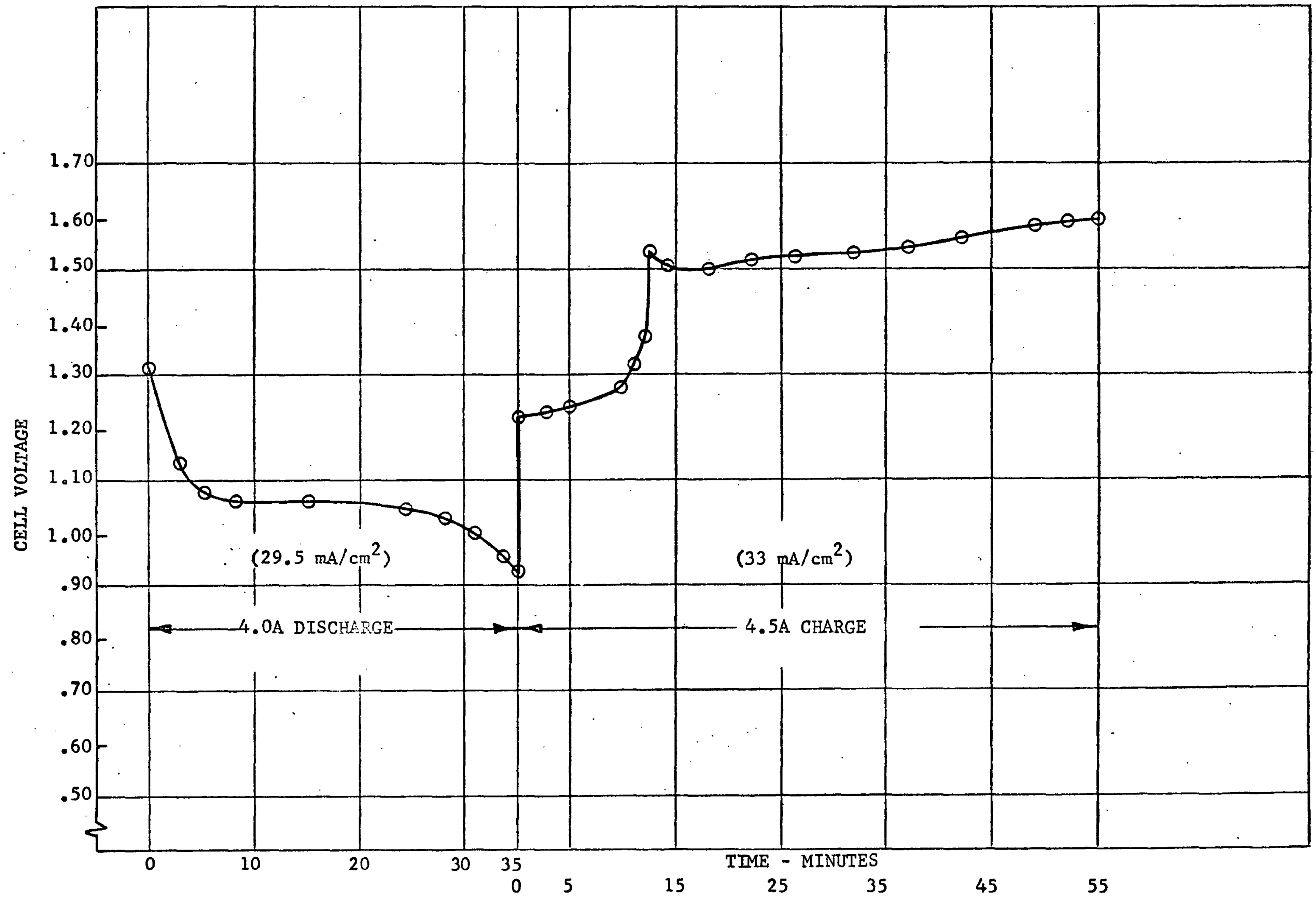


FIGURE 14. CHARGE-DISCHARGE CURVE FOR A SEALED, 3-PLATE SILVER-CADMIUM CELL EQUIPPED WITH CURRENT LIMITING DIODES, 60% DEPTH OF DISCHARGE AT 25°C (Cycle No. 3204)

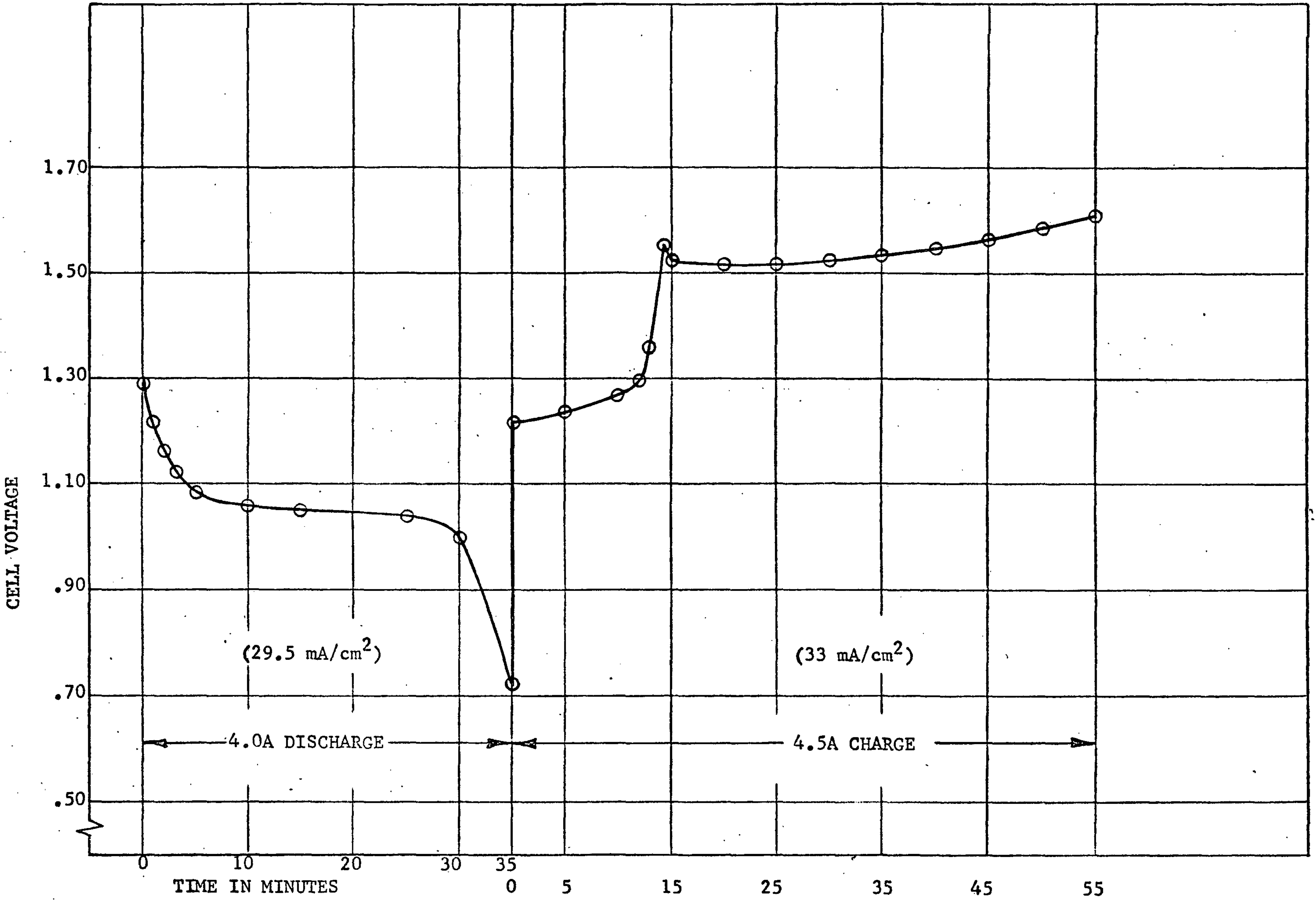


FIGURE 15. CHARGE-DISCHARGE CURVE FOR A SEALED 3-PLATE SILVER-CADMIUM CELL EQUIPPED CURRENT LIMITING DIODES - 60% DEPTH-OF-DISCHARGE AT 25°C - CYCLE NO. 4271

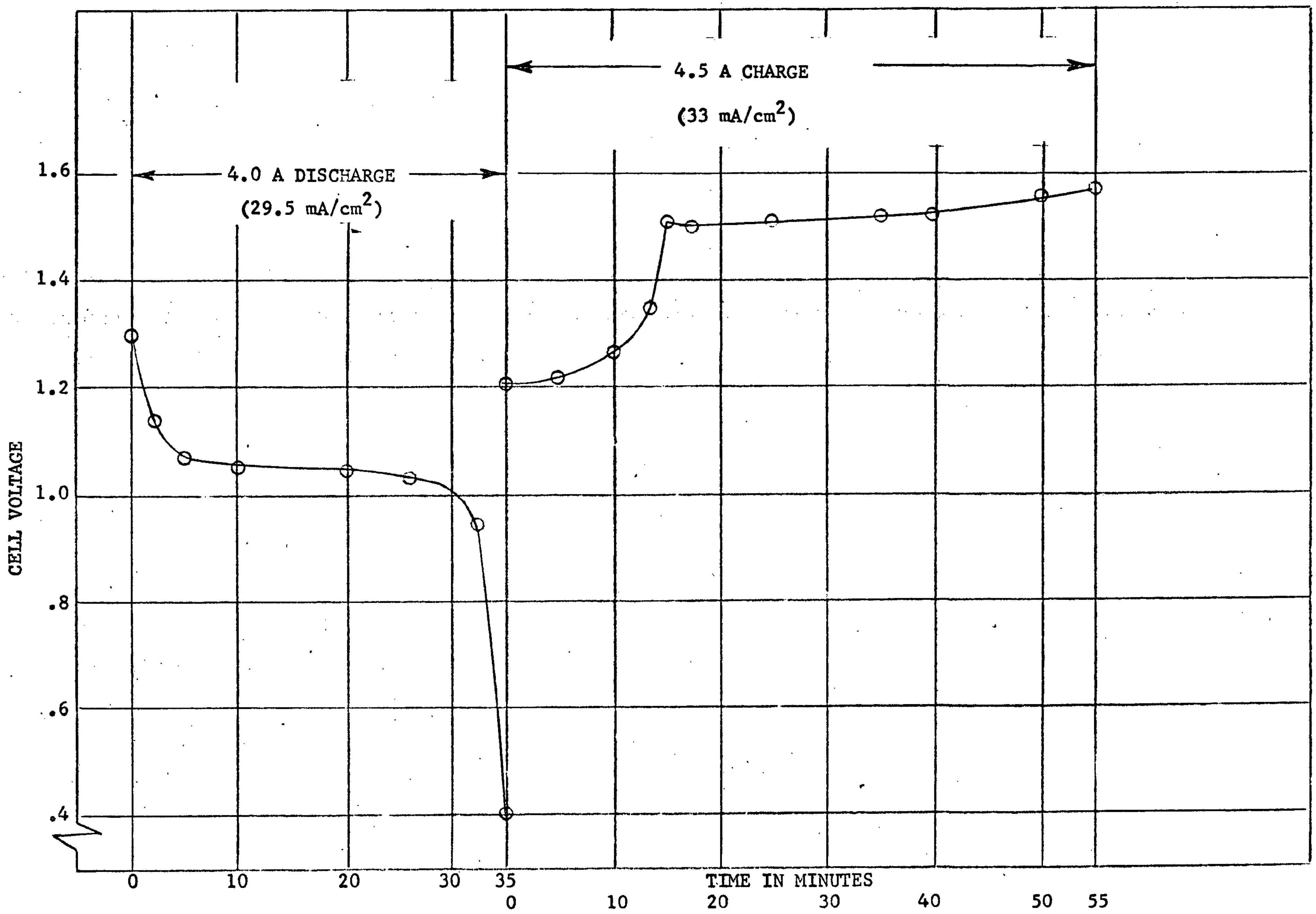


FIGURE 16. CHARGE-DISCHARGE CURVE FOR A SEALED 3-PLATE SILVER-CADMIUM CELL EQUIPPED WITH CURRENT LIMITING DIODES - 60% DEPTH OF DISCHARGE AT 25°C, CYCLE NO. 4515

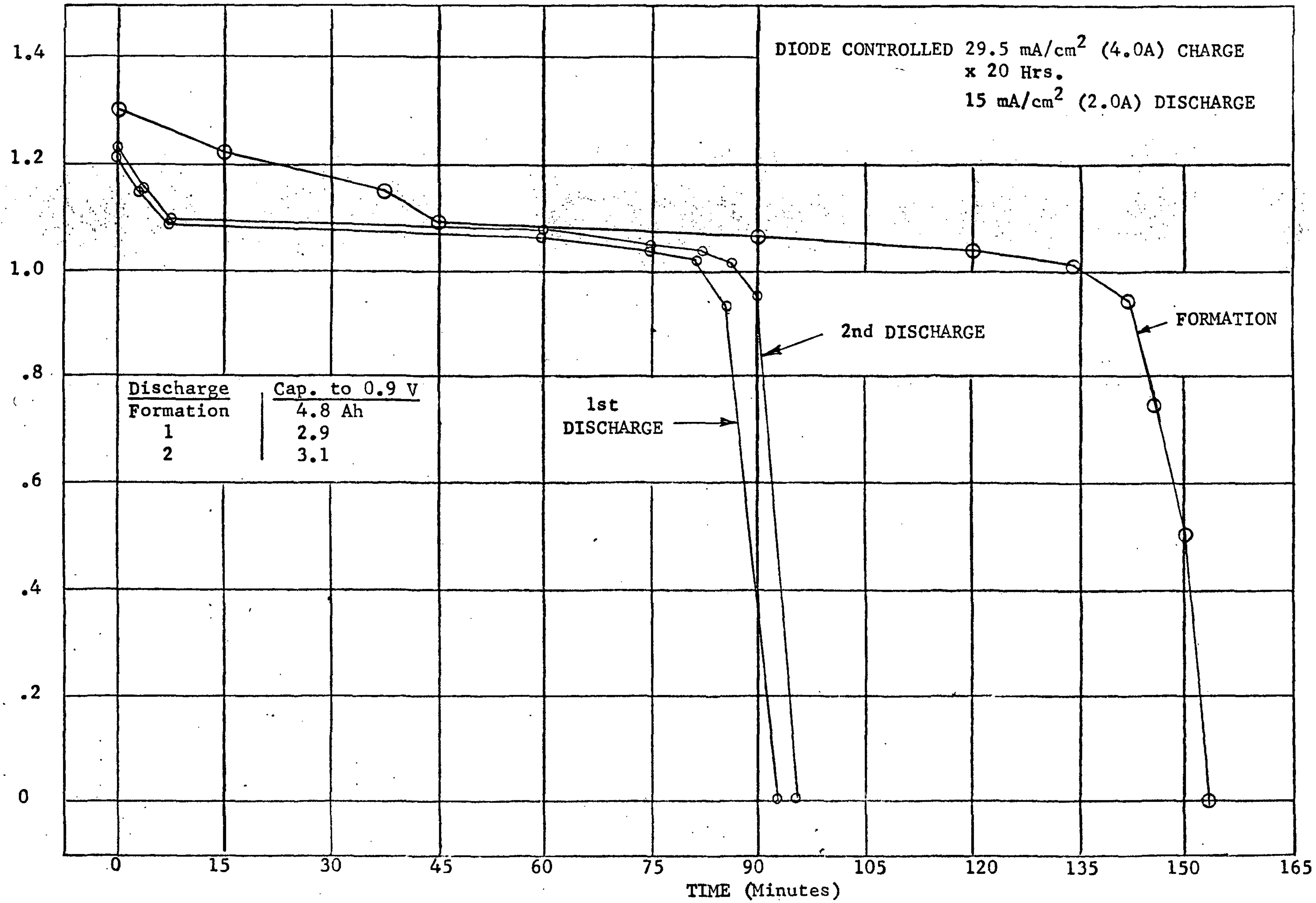


FIGURE 17. MANUAL DISCHARGE AFTER 4515, 60% DEPTH OF DISCHARGE CYCLES OF A PLATED SEALED SILVER-CADMIUM CELL -- COMPARED WITH FORMATION DISCHARGE PRIOR TO CYCLING

Table VII lists the cell's capacities to 0.9 and 0.0 V respectively, and compares them with the formation cycle prior to the start of cycling. Both discharge cycles show the cell to be positive limiting.

TABLE VII. - DISCHARGE CAPACITIES (After 4515 Automatic Cycles)

CYCLE	CAPACITY TO 0.9 V	CAPACITY TO 0.0 V	REMARKS
1	2.9 Ah	3.1 Ah	
2	3.1 Ah	3.2 Ah	
Formation*	4.8 Ah*	5.2 Ah*	* For reference only

Data presented in Table VII and Figure 17 show that extended cycling caused a 35% decrease in capacity when discharged to 0.9 V. The cycling, however, had no effect on the plateau voltage of the cell. In other words, the operating curves of the cell are the same after 30 minutes of discharge through 4500 cycles of testing.

After the second discharge, the cell was recharged and replaced on cycling regime at 50% depth of discharge.

At the end of the program, the cell had completed an additional 2000 cycles, with an end-of-discharge voltage above, or at, 0.90 volt.

The cell voltage stayed above 1.0 volt for the first 33 minutes of discharge. The charge-discharge curve for cycle 2000 is shown in Fig. 18. This brings the total number of cycles on the cell's electrodes to 7,017, as of the end of the program.

The total number of cycles was accumulated over a 15 month period.

B. PRELIMINARY EXPERIMENTS

Prior to the construction of the cells for the factorial experiment, a number of test cells were fabricated and tested in order to determine the optimum number of layers of barrier material; i.e., silver treated cellulose and RAI-2291.

1. Cell Fabrication

Nine vented silver-cadmium cells were fabricated. The separator-absorber construction factors are given in Table VIII.

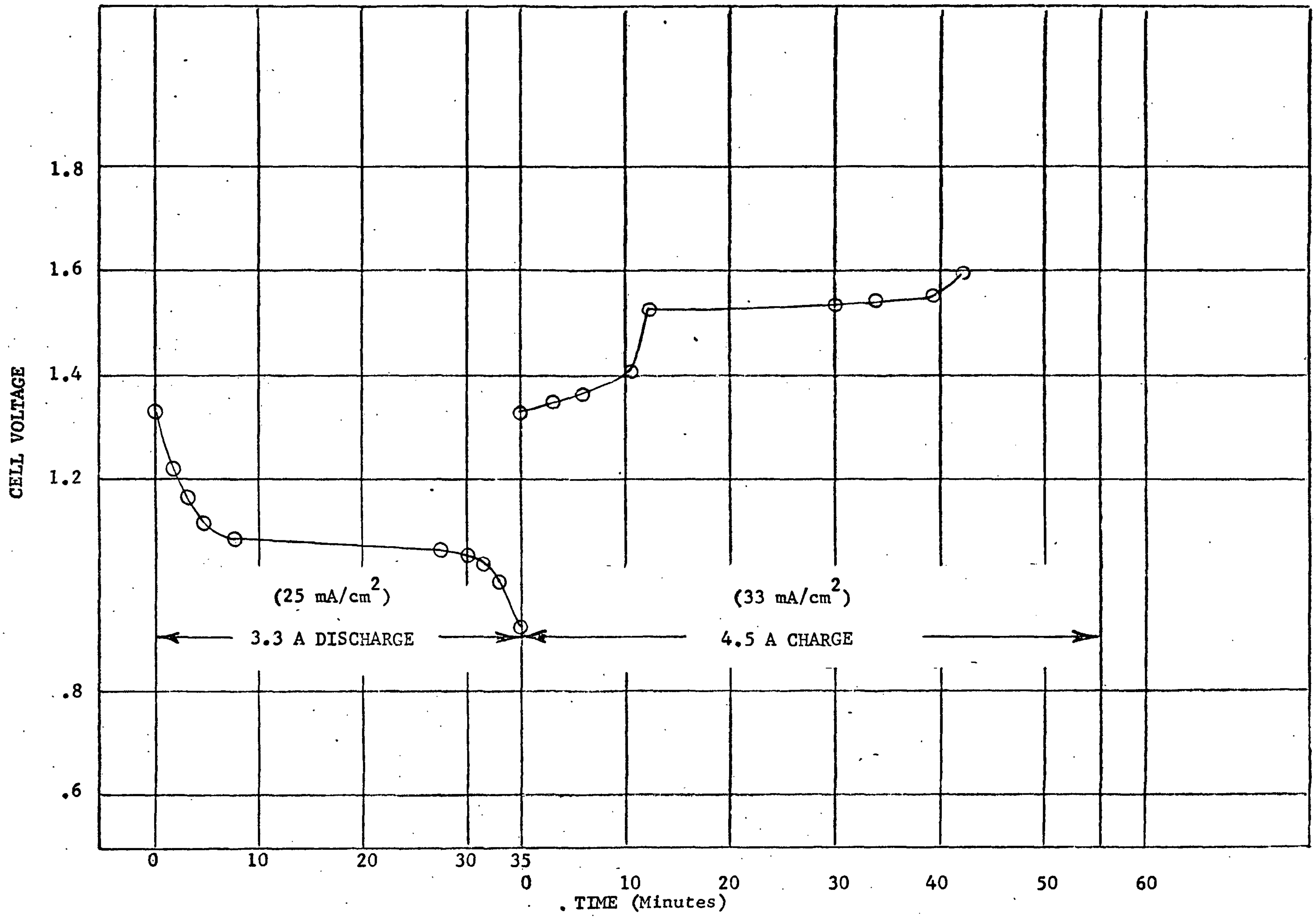


FIGURE 18. CHARGE-DISCHARGE CURVE FOR A SEALED SILVER-CADMIUM CELL EQUIPPED WITH CURRENT LIMITING DIODES 50% DEPTH OF DISCHARGE AT 25°C, CYCLE #2000

TABLE VIII. - SEPARATOR-ABSORBER CONSTRUCTION FACTORS

CELL	ABSORBER	SEPARATOR
1	0.020" Potassium Titanate Paper	1 layer cellophane
2	0.020" Potassium Titanate Paper	2 layers cellophane
3	0.020" Potassium Titanate Paper	2 wraps RAI 2291
4	0.020" Potassium Titanate Paper	3 wraps RAI 2291
5	0.020" Potassium Titanate Paper	4 wraps RAI 2291
6	0.007" Non-woven Nylon	1 layer cellophane
7	0.008" Non-woven Nylon	2 layers cellophane
8	0.015" Fuel Cell Asbestos	1 layer cellophane
9	0.015" Fuel Cell Asbestos	2 layers cellophane

All cells contained negative electrodes of the higher level (in the experiment) teflonated cadmium hydroxide type.

2. Cell Testing

All cells were formed by charging at 5.5 mA/cm^2 (0.75 A) for 24 hours to convert all the electroactive material to the charged state. The cells were then discharged at 7.5 mA/cm^2 (1.0 A) to negative exhaustion, to minus 1.5 volts.

Subsequent charges were at a rate of 5.5 mA/cm^2 (0.75 A) for 24 hours to a diode limited end-of-charge voltage (1.55-1.65 V).

Discharges were carried out at both 20 mA/cm^2 (2.7 A) and 29.5 mA/cm^2 (4.0 A) to 0.5 V.

Based on the results of these tests, a decision was reached to construct the cells for the factorial experiment using either two layers of silver treated sausage casing, or four wraps of RAI 2291 as the barrier material.

Figures 19 and 20 show typical discharges of cells with the final number of barrier layers, at 20 mA/cm^2 (2.7 A) and 29.5 mA/cm^2 (4.0 A) respectively (20 mA/cm^2 and 29.5 mA/cm^2 are the discharge rates used in the 40% and 60% depth-of-discharge for a 36 min. discharge).

3. Internal Impedance Measurements

Three cells with double layers of cellulosic barriers and 4 wraps of RAI 2291 were subjected to internal resistance measurements using an AC impedance bridge. The three cells, after undergoing capacity discharge cycles, were fully charged and then discharged to remove approximately 50% of their rated capacity.

The cell internal resistances, at 60 cycles and 1000 cycles, are shown in Table IX.

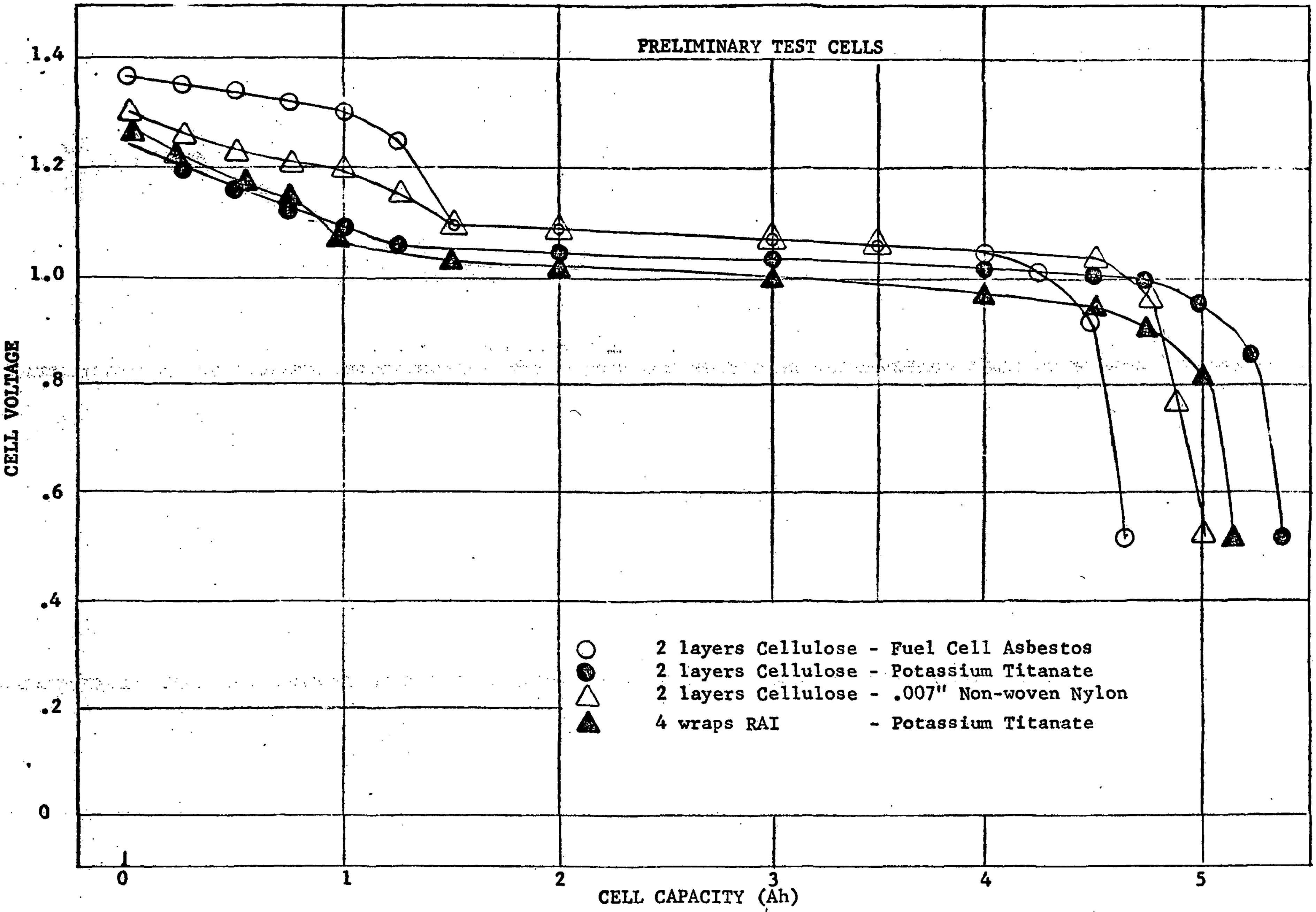


FIGURE 19. DISCHARGE CURVES OF FOUR SILVER-CADMIUM TEST CELLS - DISCHARGE RATE 20 mA/cm^2 (2.7 A)

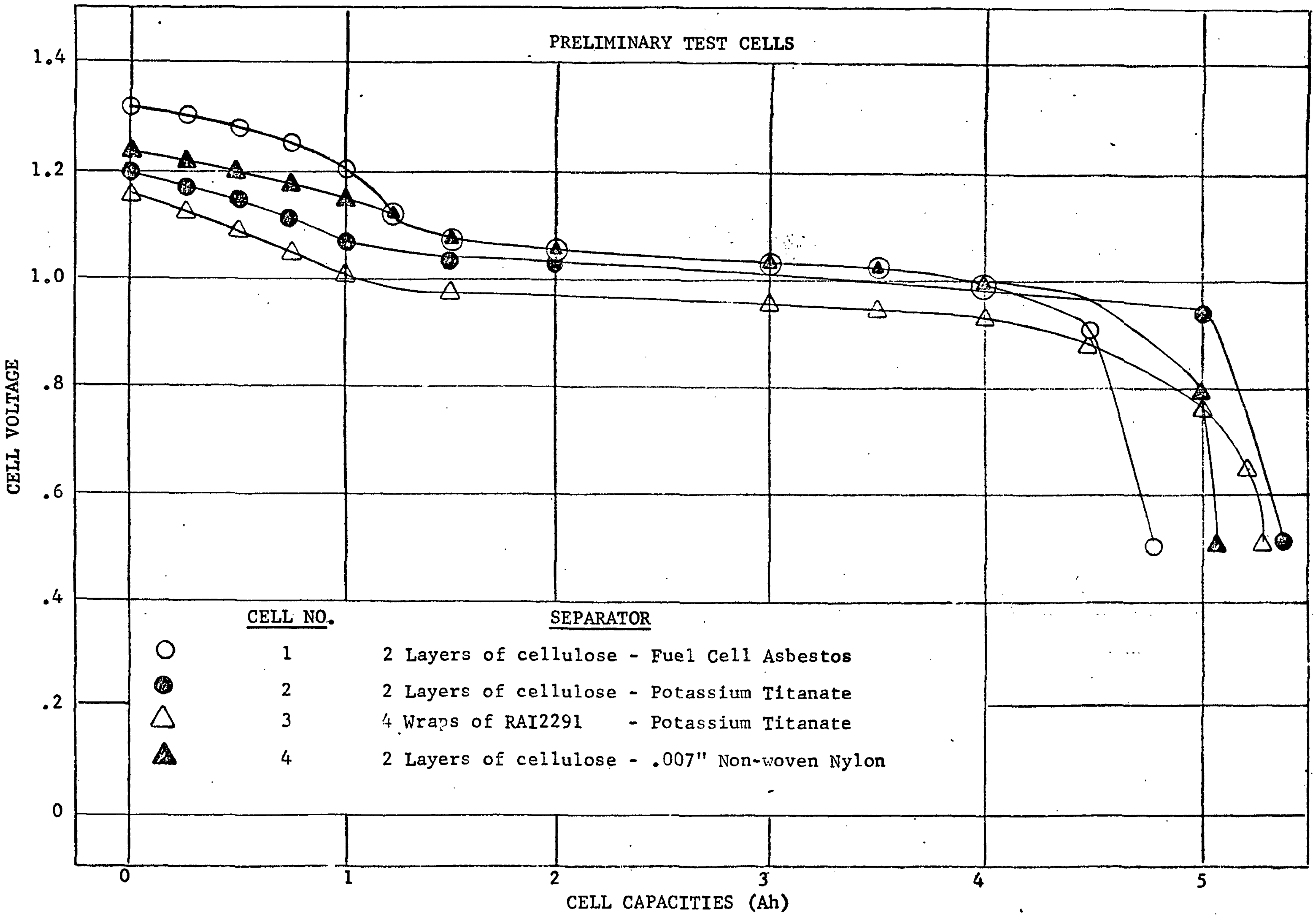


FIGURE 20. DISCHARGE CURVES OF FOUR SILVER-CADMIUM TEST CELLS
DISCHARGE RATES: 29.5 mA/cm^2 (4 A)

TABLE IX. - INTERNAL CELL RESISTANCE AS MEASURED BY AN AC IMPEDANCE BRIDGE

CELL TYPE & SEPARATOR SYSTEM	CELL INTERNAL RESISTANCE	
	AT 60 CYCLES AC*	AT 1000 CYCLES AC
3-Plate Cell, KT + 2 Layers Cellulose	0.018 ohms	0.035 ohms
3-Plate Cell, Asbestos + 2 Layers cellulose	0.021 ohms	0.041 ohms
3-Plate Cell, KT + 4 wraps RAI-2291	0.031 ohms	0.069 ohms

This is approximately equivalent to DC impedance

The above data indicate that the RAI-2291 separator increases the internal cell impedance by a factor of 1.5-2. This higher impedance results in higher cell voltages on charge and lower plateau voltages on discharge.

C. EXPERIMENT I - FACTORIAL EXPERIMENT

The design of the factorial experiment under this program was described in Section III.A., and tabulated in Table V. Briefly, the design consisted of a 1/16 block of a $2^{(9)}$ factorial. Each experiment was carried out in triplicate for a total of 96 cells.

1. Positive Electrodes

One hundred serially numbered positive electrodes were fabricated. Each electrode was 3.5 inches wide by 3.0 inches high, by 0.025 inches nominal thickness. Each electrode contained 18 grams of silver powder, corresponding to a theoretical capacity of 9 ampere-hours. To assure uniformity, each electrode was weighed and its average thickness measured. The data were recorded in an "electrode log book".

2. Negative Electrodes

Two types of negative electrodes were evaluated. They were:

a. The Gulton standard electrode - a mixture of 3 parts cadmium oxide (ASARCO Battery Grade), 1 part cadmium hydroxide, and 5 weight percent silver powder as the conductive diluent.

b. The teflonated cadmium hydroxide electrode.

Each electrode type was further subdivided so that 1/4 of the cells had thin standard electrodes with the Cd:Ag ratio of 1.3 : 1; one quarter of the cells had standard thick electrodes with the Cd:Ag ratio of 1.5 : 1; and a similar procedure was followed with the teflonated cadmium hydroxide electrodes.

Fifty electrodes of each sub-type were fabricated. Each individual electrode was weighed and its thickness measured. This data was entered in the "log book". The electrode dimensions were 3.5 inches wide x 3.0 inches high. Table X lists the nominal thickness of each type of electrode along with the weight of active materials per electrode type.

TABLE X. - NEGATIVE ELECTRODE THICKNESS & WEIGHT

TYPE	Cd : Ag Ratio	NOMINAL THICKNESS (inches)	WT. OF ACTIVE MTL. (grams)
Standard	1.3 : 1	0.030 in.	14.90 gms
Standard	1.5 : 1	0.032	16.75
Teflonated	1.3 : 1	0.033	16.75
Teflonated	1.5 : 1	0.036	18.60

3. Randomization of Electrodes

To insure randomness, all electrodes were randomized prior to cell assembly. Positive electrodes, numbered from 1 to 100, were randomized in the following manner. Identical sized poker chips were numbered 1 to 100 and placed into a glass jar. The jar was thoroughly mixed and one chip at a time was removed. The numbers on the chips (representing the silver electrodes) were assigned to consecutive cell numbers.

A similar procedure was used to randomize the negative electrodes. Chips numbered from 1 to 50 were used for randomizing the teflonated low level electrodes (ratio of 1.3 to 1 Cd/Ag), and 51 to 100 for high level.

Electrodes fabricated from the standard Gulton mix were numbered 101 to 150 for the low level. The high level electrodes were numbered from 151 to 200.

4. Cell Fabrication

After randomization, the positive and negative electrodes for each cell, and the auxiliary electrode where required, were assembled into their respective separator-absorber systems. A small piece of heat shrinkable tubing was placed over the lower part of each electrode tab to minimize the possibility of shorting due to silver migration. The electrodes were then placed in a welding fixture which allowed the terminals to be welded to the electrode tabs.

After the electrode stack and terminal weldments were assembled to the plastic cover, the exposed portions of the tabs and terminals (internal to the case) were coated with an epoxy compound. The assembled electrode stacks were placed into a plastic case, which was shimmed with polyethylene spacers, to compensate for the different cell stack thicknesses due to varying design and construction factors.

In cells with cellulosic separators, sufficient space was allowed for swelling of the cellulosic barriers due to wetting with electrolyte.

Each cover was sealed to the case (air-tight) by means of an epoxy sealant. After curing the seal, every cell was fitted with a pressure gauge and assembled between two plastic plates to prevent bulging. They were then leak checked at 45 psig of air pressure. The cells were weighed in the dry condition, then filled with electrolyte to the top of the separator and allowed to soak for 72 hours. Electrolyte was again added to the top of the separators, where needed, and the cells were placed in a vacuum chamber at 27" Hg for 10 minutes. The electrolyte levels were again adjusted to the top of the separators. Each cell was then fitted with a glass electrolyte overflow tube to prevent spewing of electrolyte at the end of charge.

5. Formation

Prior to placing the cells on the automatic cycling rack, they were given two vented formation cycles. The capacities of the second formation cycle were recorded and are shown in Table XI.

The capacities of each cell have been recorded to positive and negative exhaustion at the rate corresponding to 15 mA/cm^2 of positive electrode (2 A). All cells were positive limiting, with a positive capacity of 4.0 Ah or better.

After the two cycles, the cells were placed in a vacuum chamber to evacuate accumulated gases. The cells were assembled with current limiting diodes and given a charge at 29.5 mA/cm^2 (4.0 A) for 16 hours.

Upon completion of the charge, the diodes were removed, the electrolyte level adjusted to either 25% or 75% of electrode stack height, as required, and the cells weighed. The volume of electrolyte in each cell was calculated by the difference between the wet and dry cell weights and the density of 45% KOH.

Table XII shows the weights for dry and filled cells, including the calculated volume of electrolyte (in cubic centimeters) for each test cell of Experiment #1. The differences in volume are due to the differences in the cell pack makeup and the number of shims per cell, based on the design factors and levels for the cell construction.

TABLE XI. - FORMATION CAPACITIES, CYCLE #2

To Positive & Negative Exhaustion
Discharge Current Density 15 mA/cm^2

CELL NO.	CAPACITIES, Ah		CELL NO.	CAPACITIES, Ah	
	POSITIVE	NEGATIVE		POSITIVE	NEGATIVE
1-1	4.52	4.8	13-1	4.60	5.16
1-2	4.60	4.87	13-2	4.00	5.30
1-3	4.94	5.85	13-3	4.00	5.30
2-1	5.32	7.00	14-1	4.26	5.33
2-2	4.70	6.68	14-2	4.84	6.84
2-3	5.00	6.68	14-3	4.84	6.70
3-1	4.00	8.06	15-1	5.00	5.66
3-2	4.30	8.20	15-2	4.67	5.34
3-3	4.30	8.26	15-3	5.34	6.34
4-1	5.65	6.16	16-1	4.60	5.34
4-2	6.00	6.16	16-2	5.17	5.66
4-3	5.15	6.00	16-3	4.94	6.34
5-1	5.32	5.65	17-1	4.70	9.10
5-2	4.15	5.00	17-2	5.20	9.70
5-3	4.20	4.88	17-3	4.18	10.20
6-1	5.17	5.68	18-1	5.00	7.70
6-2	5.50	5.68	18-2	4.35	6.50
6-3	5.17	5.68	18-3	5.00	7.70
7-1	6.32	7.00	19-1	4.18	7.35
7-2	5.85	6.32	19-2	4.66	7.35
7-3	6.18	7.00	19-3	5.00	8.00
8-1	4.76	7.94	20-1	5.50	7.17
8-2	5.00	9.66	20-2	4.18	8.67
8-3	5.27	5.57	20-3	4.50	10.30
9-1	4.30	7.40	21-1	4.84	8.00
9-2	4.30	8.06	21-2	5.18	8.50
9-3	4.33	6.34	21-3	5.35	8.34
10-1	5.20	5.96	22-1	4.30	9.70
10-2	5.30	5.54	22-2	4.70	9.10
10-3	4.60	7.16	22-3	4.34	9.65
11-1	4.40	5.35	23-1	4.18	10.20
11-2	4.54	5.16	23-2	5.30	7.20
11-3	4.60	5.00	23-3	4.68	8.84
12-1	5.34	6.34	24-1	4.50	8.00
12-2	4.66	5.34	24-2	4.50	8.00
12-3	4.66	4.94	24-3	4.18	7.70

continued.....

TABLE XI. - Continued

CELL NO.	CAPACITIES, Ah	
	POSITIVE	NEGATIVE
25-1	5.00	6.50
25-2	5.34	7.00
25-3	5.18	7.00
26-1	5.34	10.50
26-2	4.50	10.30
26-3	5.00	10.00
27-1	4.50	9.00
27-2	5.10	9.70
27-3	4.18	9.30
28-1	4.85	7.35
28-2	5.00	6.50
28-3	4.66	7.00
29-1	5.35	10.30
29-2	4.50	10.20
29-3	5.18	10.30
30-1	4.50	8.00
30-2	4.18	7.70
30-3	5.00	8.18
31-1	4.85	8.18
31-2	4.50	8.18
31-3	5.00	8.34
32-1	4.18	9.50
32-2	4.90	9.20
32-3	4.70	9.00

TABLE XII. - WEIGHT CHARACTERISTICS OF Ag-Cd TEST CELLS AND VOLUME OF ELECTROLYTE PER CELL

CELL NO.	WT., gms DRY	WT., gms WET	WT., gms KOH	VOL. KOH cc	CELL NO.	WT., gms DRY	WT., gms WET	WT., gms KOH	VOL. KOH cc
1-1	171.8	239.5	67.7	46.9	13-1	200.9	244.0	43.1	29.8
1-2	168.3	233.0	64.7	44.8	13-2	204.5	249.3	44.8	30.8
1-3	177.3	243.6	66.3	45.9	13-3	203.0	249.1	46.1	31.7
2-1	181.8	258.5	76.7	53.1	14-1	190.3	253.4	63.1	43.7
2-2	185.4	259.2	73.8	51.1	14-2	190.0	246.0	56.0	38.7
2-3	183.2	259.2	75.8	53.5	14-3	188.1	250.2	62.1	42.7
3-1	193.9	250.7	56.8	39.4	15-1	186.7	254.8	68.1	47.1
3-2	193.8	254.0	57.4	39.7	15-2	189.2	260.7	71.5	49.5
3-3	192.7	253.0	59.4	41.1	15-3	181.9	262.5	80.6	55.8
4-1	195.1	251.5	55.4	38.3	16-1	174.9	272.1	97.2	67.3
4-2	196.4	251.0	57.6	39.9	16-2	177.5	272.2	94.7	65.5
4-3	195.3	257.4	57.7	39.9	16-3	172.6	273.7	101.1	70.0
5-1	176.9	246.0	74.6	51.6	17-1	183.2	239.9	56.7	38.9
5-2	181.3	239.0	69.7	48.2	17-2	177.0	241.7	64.7	44.4
5-3	182.0	243.4	75.4	52.2	17-3	169.9	247.3	77.4	53.6
6-1	175.4	258.5	70.6	48.9	18-1	173.5	249.3	75.8	52.5
6-2	176.8	257.1	62.2	43.0	18-2	182.1	250.7	68.6	47.5
6-3	178.8	257.2	64.6	44.7	18-3	176.6	252.7	76.1	52.7
7-1	204.5	258.5	54.0	37.4	19-1	188.7	254.4	56.7	39.2
7-2	196.7	257.1	60.4	41.8	19-2	188.0	244.9	56.9	39.4
7-3	201.7	257.2	55.5	38.4	19-3	187.8	245.3	57.5	39.8
8-1	191.0	252.4	61.4	42.5	20-1	201.0	260.7	59.7	41.3
8-2	192.0	250.8	58.8	40.5	20-2	202.3	258.8	56.5	39.1
8-3	187.2	252.1	64.9	44.7	20-3	201.2	264.6	63.4	43.9
9-1	188.3	251.0	62.7	43.1	21-1	180.3	253.0	72.7	50.3
9-2	194.4	249.3	54.9	37.8	21-2	180.4	251.5	71.1	49.2
9-3	191.8	248.5	56.7	39.2	21-3	179.3	255.4	76.1	52.7
10-1	201.4	237.5	36.1	24.9	22-1	176.2	241.5	65.3	44.9
10-2	200.3	243.9	43.6	30.1	22-2	178.8	245.8	67.0	46.0
10-3	194.8	243.6	48.8	33.6	22-3	180.8	247.1	44.4	30.7
11-1	171.4	251.0	79.6	55.1	23-1	197.7	258.5	60.8	42.1
11-2	170.6	252.6	82.0	56.7	23-2	201.0	259.0	58.0	39.8
11-3	168.7	259.0	90.3	62.5	23-3	202.7	261.0	58.3	40.3
12-1	187.4	261.6	74.2	51.3	24-1	191.2	248.7	57.5	39.8
12-2	192.0	263.1	71.1	49.2	24-2	188.7	248.8	60.1	41.6
12-3	189.4	262.2	72.8	50.4	24-3	188.1	246.8	58.7	40.6

continued............

TABLE XII - Continued

CELL NO.	WT., gms DRY	WT., gms WET	WT., gms KOH	VOL. KOH cc	CELL NO.	WT.,gms DRY	WT.,gms WET	WT.,gms KOH	VOL. KOH cc
25-1	185.9	242.6	56.7	39.2	29-1	198.3	249.9	51.6	35.7
25-2	188.6	248.5	59.9	41.5	29-2	201.3	250.0	48.7	33.7
25-3	188.0	245.7	57.7	39.9	29-3	203.8	250.7	46.9	32.5
26-1	203.6	254.2	50.6	35.0	30-1	186.4	246.2	59.8	41.4
26-2	203.4	251.7	48.3	33.4	30-2	188.5	248.3	59.8	41.4
26-3	201.0	252.4	51.4	35.6	30-3	187.9	249.3	61.4	42.5
27-1	178.0	260.1	82.1	56.4	31-1	187.3	256.2	68.9	47.7
27-2	179.5	262.8	83.3	57.2	31-2	196.9	250.7	63.8	44.2
27-3	181.1	262.9	81.8	56.6	31-3	180.3	258.1	77.8	53.8
28-1	179.9	255.2	75.3	52.1	32-1	175.7	262.2	86.5	59.9
28-2	177.5	252.9	75.4	52.2	32-2	175.0	263.1	88.1	60.5
28-3	181.4	251.8	70.4	48.7	32-3	180.7	251.4	70.7	48.6

6. Automatic Cycling

Test cells of Experiment #1 were placed on the automatic cycling regime. The charge and discharge rates were in accordance with the cell's corresponding factors and levels. Cells were cycled at two temperatures, 0°C and 25°C. The cycling orbit was: 58 minutes charge and 36 minutes discharge, for a total of 94 minutes.

End of charge and discharge voltages of each cell were recorded automatically by digital voltmeter. Test cells which failed to accept full charge and reversed on discharge, or whose voltage fell below 0.6 V, were removed from cycling. All cells removed were given full capacity charge-discharge cycles to determine loss of capacity.

Tables XIII and XIV give the cycle at which cells were removed from cycling and post-cycle capacities. All cells were positive limiting on their post-cycle capacity discharge. Table XV lists the cycle life of Groups 12, 2, 5, 10, 11 and 16 to 0.9 V.

Tables XVI and XVII give the average cycle life for each group of cells, including the test conditions and construction factors for that cell group at 0°C and 25°C respectively. It can be seen from these tables that, at both temperatures, the longest cycle life was obtained at 40% depth of discharge with teflonated cadmium hydroxide negative electrodes, at a cell balance ratio of 1.5:1. In both cases, the separator was silver treated fibrous sausage casing (FSC) and the absorber was fuel cell asbestos. At room temperature, longer cycle life was obtained with an electrolyte volume of 25% of electrode stack height, while at 0°C, longer cycle life was obtained with the electrolyte level at 75% of electrode stack height.

At both test temperatures, the use of RAI2291 as a separator lead to severely decreased cycle life.

TABLE XIII. - CYCLE DATA OF Ag/Cd TEST CELLS AT 0°C

TEST CELL NO.	CELL REMOVED ON CYCLE NO.		POST CYCLE CAPACITIES		REMARKS
			POSITIVE (Ah)	NEGATIVE (Ah)	
1-1		16	4.3 *	5.7 *	
1-2		90	4.2	7.5	
1-3		16	4.2	6.3	
4-1	3		5.4	5.9	
4-2	3		4.9	5.9	
4-3	3		5.2	6.0	
9-1		3	4.2 *	4.8 *	* These cells reversed on discharge and developed a crack in the seal due to excess gas pressure.
9-2		36	4.9	6.2	
9-3		16	5.0	5.5	
12-1	476		4.2	8.2	
12-2	153		5.0	8.7	
12-3	905		4.3	7.9	
6-1		16	5.9	7.1	
6-2		16	5.1 *	6.4 *	
6-3		16	4.9 *	5.9 *	
7-1	3		3.7	4.9	
7-2	3		4.3	5.9	
7-3	3		4.7	6.1	
14-1		3	4.7	6.1	
14-2		16	4.1	5.9	
14-3		3	4.5	5.8	
15-1	24		4.0 *	6.4 *	
15-2	16		3.5	7.5	
15-3	16		4.0 *	7.4 *	
21-1		20	5.6	6.0	
21-2		16	4.2 *	4.5 *	
21-3		16	5.0	5.8	
24-1	3		6.2	7.1	
24-2	3		6.0	7.2	
24-3	3		6.1	7.4	
29-1		3	4.6	7.7	
29-2		3	4.6	7.1	
29-3		3	5.5	8.2	
32-1	41		5.3	6.5	
32-2	16		5.4	6.5	
32-3	20		5.0	6.7	
18-1		165	5.4	6.1	
18-2		20	4.0 *	5.3 *	
18-3		16	4.3 *	4.9 *	
19-1	3		5.4	6.6	
19-2	3		5.9	6.7	
19-3	3		5.2	6.9	
26-1		3	5.8	8.0	
26-2		3	5.3	8.0	
26-3		16	6.0	7.9	
27-1	44		3.9 *	5.6 *	
27-2	44		5.7	7.3	
27-3	44		3.9 *	5.9 *	

TABLE XIV. - CYCLING DATA OF Ag/Cd TEST CELLS AT 25°C

TEST CELL NO.	CELL REMOVED ON CYCLE NO.		POST CYCLE CAPACITIES		REMARKS
			POSITIVE (Ah)	NEGATIVE (Ah)	
5-1	86		4.0 *	5.4 *	* These cells reversed on discharge and developed a crack in the seal due to excess gas pressure.
5-2	16		4.7 *	5.3 *	
5-3	1055		2.5	4.5	
8-1		36	5.1	6.1	
8-2		86	4.7	6.1	
8-3		36	4.5 *	4.7 *	
13-1	16		4.8 *	5.8 *	
13-2	3		3.5	4.6	
13-3	3		3.7	4.7	
16-1		260	3.1 *	6.2 *	
16-2		102	3.9 *	6.5 *	
16-3		395	3.2	4.9	
2-1	738		3.6	5.0	
2-2	1055		3.1	5.9	
2-3	1055		2.4	5.2	
3-1		35	5.1	6.5	
3-2		90	4.8 *	5.2 *	
3-3		73	4.0	5.6	
10-1	768		2.8	4.4	
10-2	16		4.6	5.2	
10-3	16		4.0	5.6	
11-1		186	1.4 *	6.3 *	
11-2		365	2.4	4.1	
11-3		186	1.9 *	6.1 *	
17-1	186		4.7	7.8	
17-2	20		5.0	6.8	
17-3	102		4.0	7.7	
20-1		16	5.0	6.0	
20-2		16	4.6	5.4	
20-3		16	5.2	6.0	
25-1	36		4.1	5.2	
25-2	36		4.7	5.5	
25-3	3		4.5	6.0	
28-1		186	5.1	5.9	
28-2		41	4.9	5.7	
28-3		41	4.2	5.6	
22-1	40		5.3 *	7.4 *	
22-2	102		4.8	6.8	
22-3	86		5.4	6.5	
23-1		16	5.4	6.0	
23-2		16	5.1	5.8	
23-3		36	5.0	5.5	
30-1	86		4.8	5.4	
30-2	41		4.3 *	5.6 *	
30-3	71		4.9	5.3	
31-1		166	3.9 *	6.4 *	
31-2		41	3.6 *	6.4 *	
31-9		165	4.3 *	6.2 *	

TABLE XV. - CYCLE LIFE DATA OF Ag/Cd TEST CELLS TO 0.9 VOLT

TEST CELL NO.	TEST TEMPERATURE	NO. CYCLES TO 0.9V	NO. CYCLES TO 0.6V
12-1	0°C	466	476
12-2	0°C	20	153
12-3	0°C	862	905
2-1	25°C	650	738
2-2	25°C	1055	1055
2-3	25°C	1055	1055
5-1	25°C	56	86
5-2	25°C	3	16
5-3	25°C	1000	1055
10-1	25°C	703	768
10-2	25°C	12	16
10-3	25°C	8	16
11-1	25°C	182	186
11-2	25°C	260	365
11-3	25°C	182	186
16-1	25°C	185	260
16-2	25°C	62	102
16-3	25°C	324	395

TABLE XVI. - AVERAGE GROUP CYCLE LIFE & TEST FACTORS AT 0°C

CELL GROUP	AVERAGE LIFE (Cycles)	DOD (1)	AUXILIARY (2)	SEPARATOR (3)	VOL. KOH (4)	ABSORBER (5)	Cd TYPE (6)	CELL BALANCE	CHARGE RATE (A)
1	41	40%	None	Cello	25%	KT	S	1.3:1	4.25
4	3	40%	AB-6	RAI	75%	FCA	S	1.3:1	4.25
6	16	40%	None	Cello	25%	KT	S	1.5:1	5.25
7	3	40%	AB-6	RAI	75%	FCA	S	1.5:1	5.25
9	18	40%	AB-6	RAI	25%	KT	T	1.5:1	4.25
12	511	40%	None	Cello	75%	FCA	T	1.5:1	4.25
14	7	40%	AB-6	RAI	25%	KT	T	1.3:1	5.25
15	19	40%	None	Cello	75%	FCA	T	1.3:1	5.25
18	67	60%	AB-6	Cello	25%	FCA	S	1.3:1	5.25
19	3	60%	None	RAI	75%	KT	S	1.3:1	5.25
21	17	60%	AB-6	Cello	25%	FCA	S	1.5:1	4.25
24	3	60%	None	RAI	75%	KT	S	1.5:1	4.25
26	7	60%	None	RAI	25%	FCA	T	1.5:1	5.25
27	44	60%	AB-6	Cello	75%	KT	T	1.5:1	5.25
29	3	60%	None	RAI	25%	FCA	T	1.3:1	4.25
32	26	60%	AB-6	Cello	75%	KT	T	1.3:1	4.25

(1) Depth of Discharge
(2) Auxiliary AB-6 Fuel Cell Electrode
(3) Separator - Cellulose or RAI2291
(4) Volume KOH - 25 or 75% of plate height
(5) Absorber - KT paper or Fuel Cell Asbestos
(6) Cadmium Electrode Type
S = Standard
T = Teflonated $Cd(OH)_2$

TABLE XVII - AVERAGE GROUP CYCLE LIFE & TEST FACTORS AT 25°C

CELL GROUP	AVERAGE LIFE (Cycles)	DOD (1)	AUXILIARY (2)	SEPARATOR (3)	VOL.KOH (4)	ABSORBER (5)	Cd TYPE (6)	CELL BALANCE	CHARGE RATE (A)
2	949	40%	AB-6	Cello	25%	FCA	T	1.5:1	5.25
3	66	40%	None	RAI	75%	KT	T	1.5:1	5.25
5	386	40%	AB-6	Cello	25%	FCA	T	1.3:1	4.25
8	53	40%	None	RAI	75%	KT	T	1.3:1	4.25
10	267	40%	None	RAI	25%	FCA	S	1.3:1	5.25
11	246	40%	AB-6	Cello	75%	KT	S	1.3:1	5.25
13	7	40%	None	RAI	25%	FCA	S	1.5:1	4.25
16	252	40%	AB-6	Cello	75%	KT	S	1.5:1	4.25
17	103	60%	None	Cello	25%	KT	T	1.5:1	4.25
20	16	60%	AB-6	RAI	75%	FCA	T	1.5:1	4.25
22	76	60%	None	Cello	25%	KT	T	1.3:1	5.25
23	23	60%	AB-6	RAI	75%	FCA	T	1.3:1	5.25
25	25	60%	AB-6	RAI	25%	KT	S	1.3:1	4.25
28	89	60%	None	Cello	75%	FCA	S	1.3:1	4.25
30	66	60%	AB-6	RAI	25%	KT	S	1.5:1	5.25
31	124	60%	None	Cello	75%	FCA	S	1.5:1	5.25

(1) Depth of Discharge
(2) Auxiliary AB-6 Fuel Cell Electrode
(3) Separator - Cellulose or RAI2291
(4) Volume KOH - 25 or 75% of plate height
(5) Absorber - KT paper or Fuel Cell Asbestos
(6) Cadmium Electrode Type
S = Standard
T = Teflonated $Cd(OH)_2$

D. EXPERIMENT II-A - TEST CELLS WITH INORGANIC SEPARATORS

1. Scope

One of the requirements of this program was the fabrication of silver-cadmium test cells with inorganic separators, for delivery to NASA/Lewis Research Center. These cells were fabricated, assembled, and shipped dry for testing and evaluation by Lewis Research Center.

As a preliminary step, prior to fabricating the 96 cell lot, twelve (12) representative test cells were constructed and tested to ascertain performance under the cycling regime.

2. Cell Construction

The 12 cells were fabricated in three groups of four (4) cells. Each group of four cells contained a different type of inorganic separator. Within each group of four cells, 2 cells were constructed with KT paper as the absorber and 2 were constructed with 0.007" non-woven nylon as the absorber. The construction factors and cell identification numbers are shown in Table XVIII.

The positive electrode of each cell was 3.25 inches wide x 2.63 inches high and .025 inches thick, and contained 14.7 grams of silver (7.35 Ah theoretical capacity). The reduction in size from 3.5 inches wide x 3.0 inches in height was necessitated by the size of the inorganic separator and the fixed dimensions of the cell case.

The negative electrodes were of the teflonated cadmium hydroxide type. The cell was fabricated with a Cd:Ag cell balance ratio of 1.3:1. The electrolyte was 40% aqueous solution of potassium hydroxide.

3. Formation

The cells were filled with 40% KOH to above the top of the separators and allowed to soak for 72 hours. At the end of the 72 hour stand, the cells were placed in a vacuum chamber and evacuated to 27" Hg to remove any entrapped gases. The cells were then refilled with electrolyte and formed.

The formation procedure consisted of three charge-discharge cycles. Each cycle consisted of a 14 mA/cm^2 (1.5 A) charge (without diodes) for 24 hours, followed by a 18 mA/cm^2 (2.0 A) discharge to -1.5 V. Three formation cycles were required to develop full positive capacity. This was apparently due to the difficulty in wetting the positive electrodes through the heavy inorganic separators.

Table XIX gives the capacities for both positive and negative electrodes for each of the three formation cycles.

TABLE XVIII - CONSTRUCTION FACTORS FOR EXPERIMENT II-A TEST CELLS

CELL NO.	SEPARATOR TYPE	ABSORBER POS. ELECTRODE	ABSORBER NEG. ELECTRODE
572	Flexible - 3420-25	*	KT Paper
573	" "	*	KT Paper
574	" "	*	0.007" Non-Woven Nylon
575	" "	*	0.007" Non-Woven Nylon
647	Flexible - 3420-09	*	KT Paper
648	" "	*	KT Paper
649	" "	*	0.007" Non-Woven Nylon
650	" "	*	0.007" Non-Woven Nylon
722	Rigid - 3420-09	KT Paper	KT Paper
723	" "	KT Paper	KT Paper
724	" "	0.007" Non-woven Nylon	0.007" Non-Woven Nylon
725	" "	0.007" Non-woven Nylon	0.007" Non-Woven Nylon

* On cells 572-650, the absorber on the positive electrode is an integral part of the flexible separator.

TABLE XIX. - FORMATION CAPACITIES FOR CELLS WITH CERAMIC SEPARATORS

SEPARATOR TYPE	CELL NO.	CYCLE 1		CYCLE 2		CYCLE 3	
		POS. CAP. (Ah)	NEG. CAP. (Ah)	POS. CAP. (Ah)	NEG. CAP. (Ah)	POS. CAP. (Ah)	NEG. CAP. (Ah)
Flexible 3420-25	572	2.8	6.4	3.9	8.3	4.0	8.0
	573	3.3	10.1	4.2	9.6	4.0	9.4
	574	2.1	8.6	3.2	9.4	4.0	9.2
	575	2.3	8.0	3.3	8.7	4.0	9.1
Flexible 3420-09	647	3.4	8.1	4.1	7.4	4.3	8.1
	648	3.3	4.7	3.8	9.2	4.1	9.9
	649	2.5	8.5	3.5	7.7	4.1	8.4
	650	2.5	10.9	3.5	9.8	4.1	9.4
Rigid 3420-09	722	4.5	10.4	4.9	9.2	5.5	9.7
	723	3.8	10.3	4.3	9.2	4.9	9.4
	724	3.2	10.3	4.5	7.5	4.5	8.8
	725	3.1	10.4	4.8	9.3	4.9	8.6

The average positive capacity on the best cycles of the cells with rigid 3420-09 separators was 4.95 Ah. The average capacity for the flexible separators was 4.0 Ah for the 3420-25, and 4.15 Ah for the 3420-09 material.

Since all the electrodes were prepared from one lot of material and selected at random, it would appear that the rigid material allows better wetting of the electrodes than the flexible material.

4. Automatic Cycling

After formation, diode sets were assembled on the cells and the cells were charged at 41 mA/cm^2 (4.5 A) for 24 hours. At the conclusion of charge, the electrolyte level of each cell was adjusted to three-quarters of the electrode stack height. The cells were assembled with pressure gauges and placed on a cycling regime.

The 40% depth of discharge cycling regime consisted of a 25 mA/cm^2 (2.7 A) discharge for 35 minutes and a 41 mA/cm^2 (4.5 A) charge for 55 minutes at 25°C.

During the cycling, the cells were continuously monitored and complete charge-discharge curves were obtained for each cycle.

Typical charge-discharge curves for each group of cells are shown in Figures 21 through 24. The discharge curves indicate that cells with KT absorbers have a lower end-of-discharge voltage than cells with non-woven nylon absorbers. In all cases, the voltage level was greater than 0.9 V at 30 minutes of discharge. This is even true for the cycle in which the cells fell below the cutoff voltage.

The cells were continued on cycle until the end-of-discharge voltage fell below 0.7 volts.

Table XX gives the cycle at which each cell was removed from cycling.

TABLE XX. - CYCLE LIFE OF CELLS

CELL NO.	ABSORBER MATERIAL	SEPARATOR	CYCLE REMOVED	CYCLE LIFE TO 0.9V
572	KT	Flexible 3420-25	374	297
573	KT	" "	489	407
574	0.007" Nylon	" "	1100	707
575	0.007" Nylon	" "	659	506
647	KT	Flexible 3420-09	443	407
648	KT	" "	523	489
649	0.007" Nylon	" "	1271	761
650	0.007" Nylon	" "	2170	1450
722	KT	Rigid 3420-09	410	297
723	KT	" "	630	489
724	0.007" Nylon	" "	1530	890
725	0.007" Nylon	" "	1530	1100

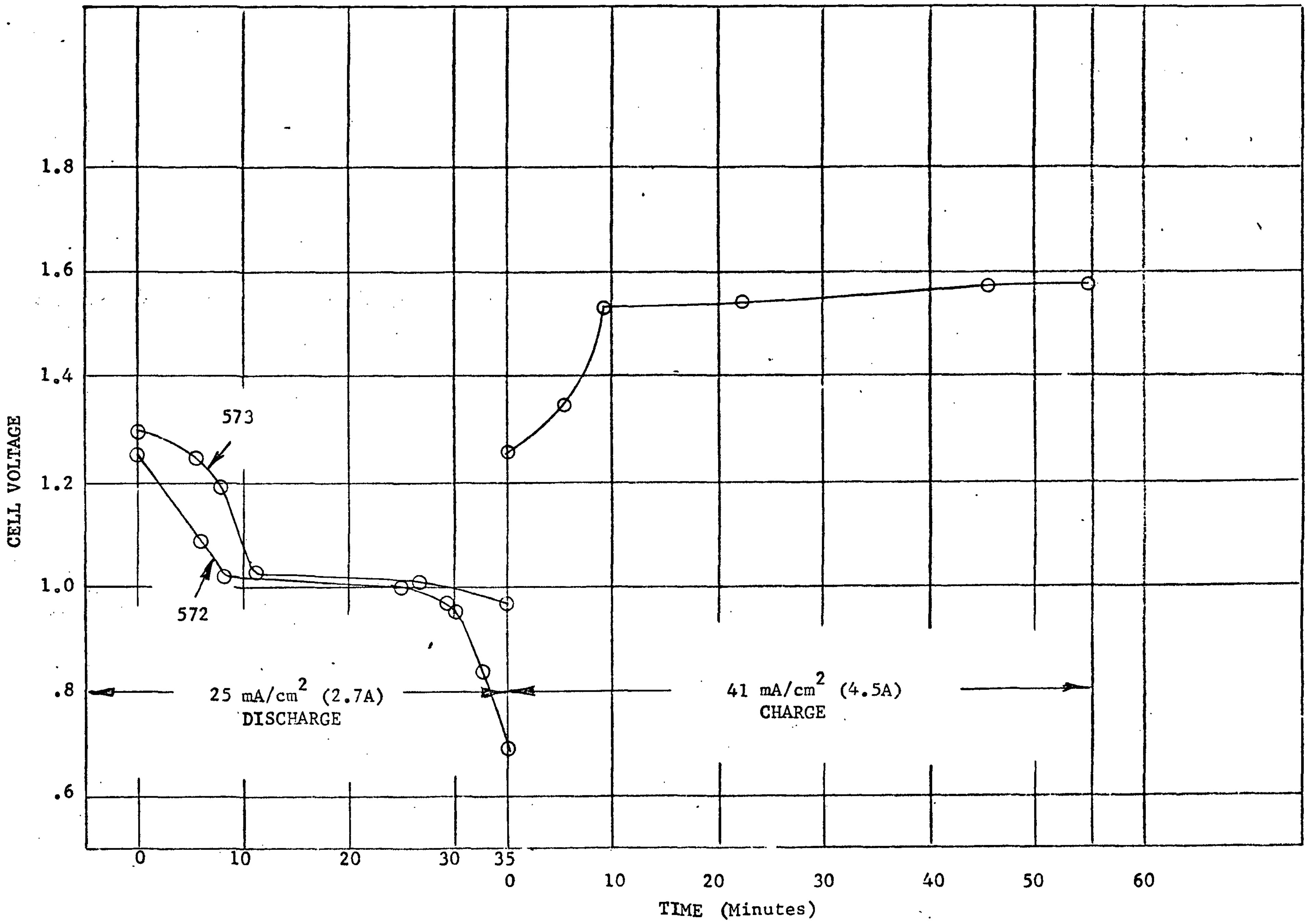


FIGURE 21. TYPICAL CHARGE-DISCHARGE CURVE OF A SILVER-CADMIUM CELL ON 90 MINUTE ORBIT FLEXIBLE SEPARATOR 3420-25, KT ABSORBER

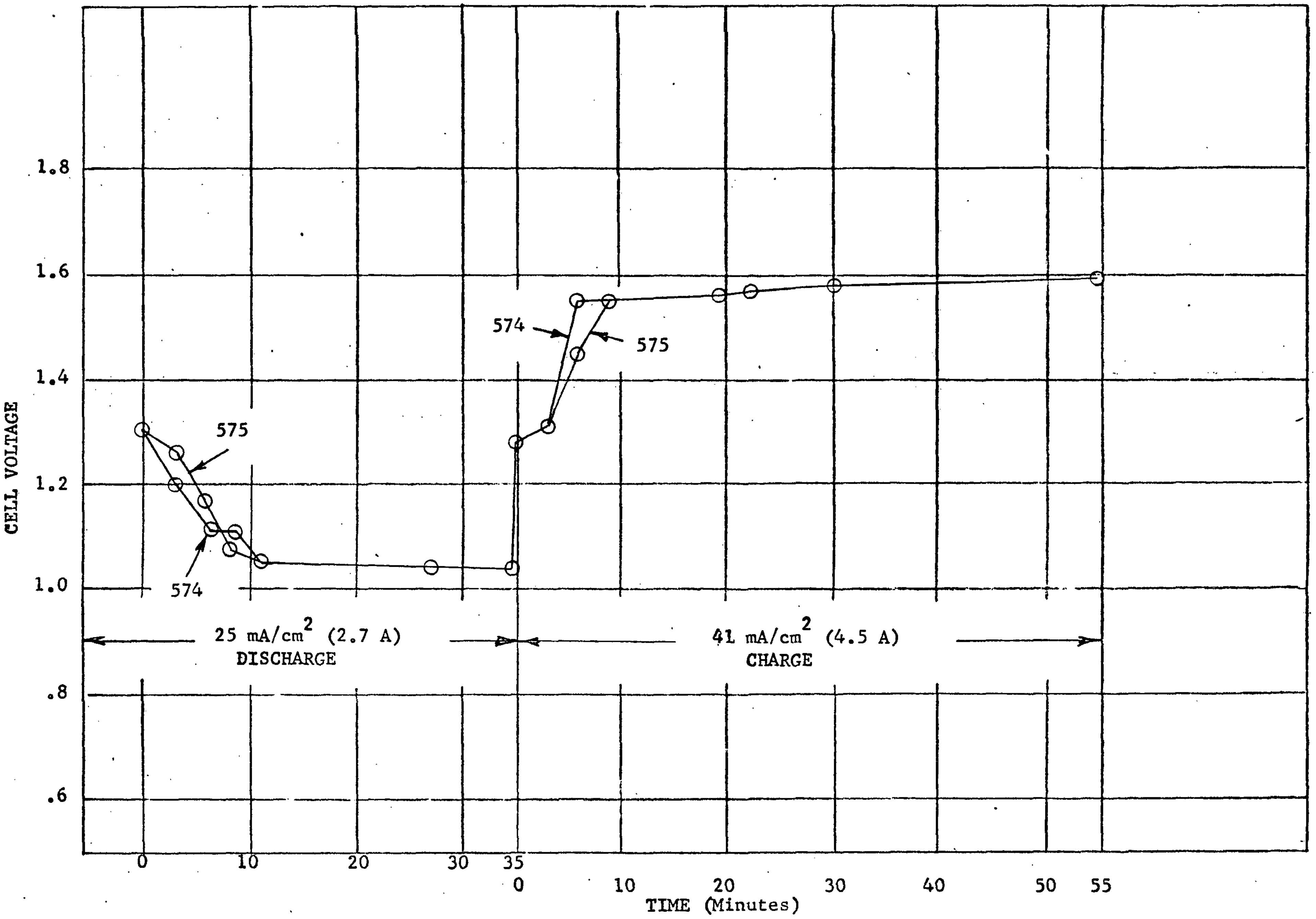


FIGURE 22. TYPICAL CHARGE-DISCHARGE CURVE OF A SILVER-CADMIUM CELL ON 90 MINUTE CYCLE ORBIT FLEXIBLE SEPARATOR 3420-25, NON-WOVEN NYLON ABSORBER

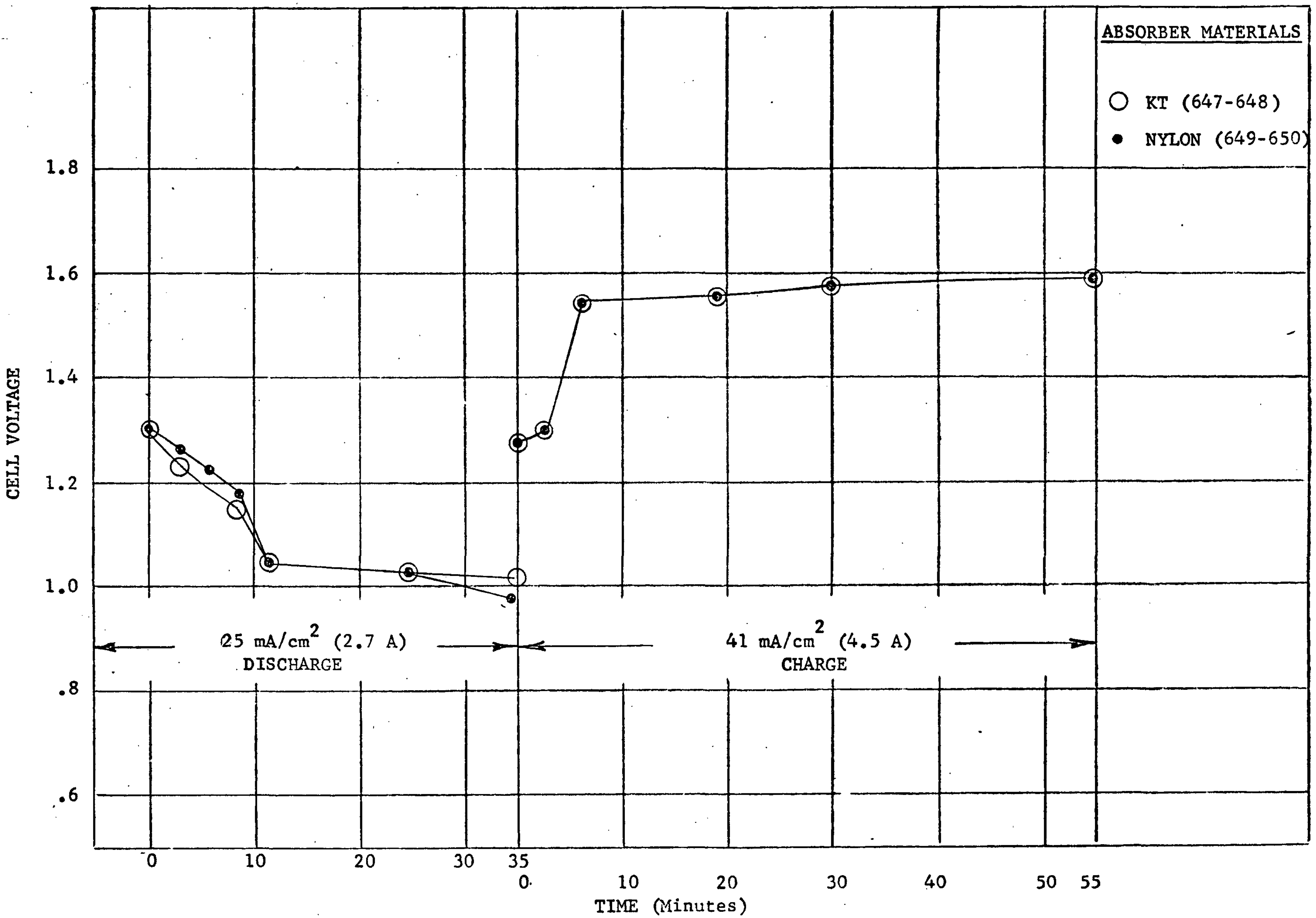


FIGURE 23. TYPICAL CHARGE-DISCHARGE CURVE OF A SILVER-CADMIUM CELL ON 90 MINUTE CYCLE ORBIT - FLEXIBLE SEPARATOR 3420-09

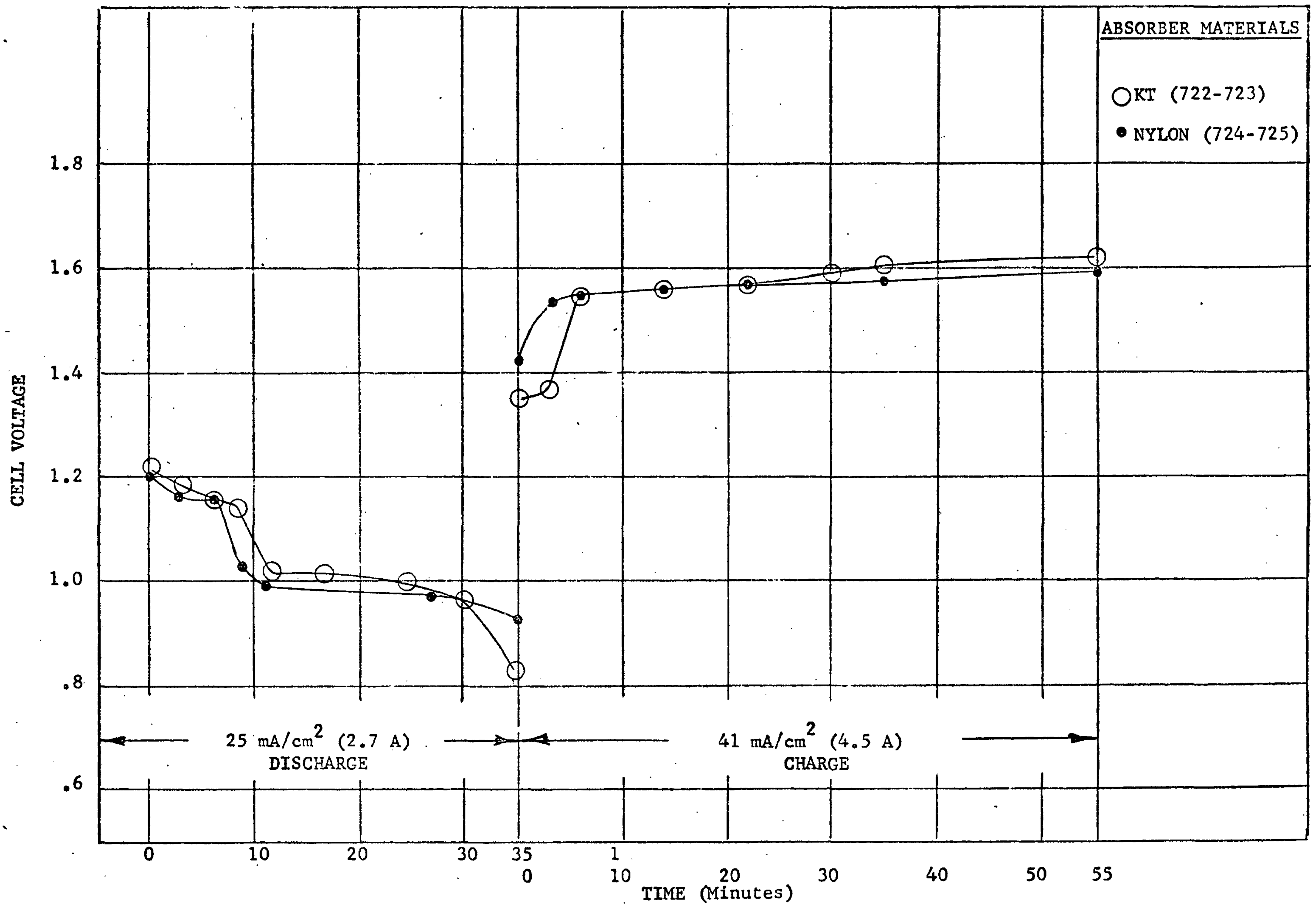


FIGURE 24. TYPICAL CHARGE-DISCHARGE CURVE OF A SILVER-CADMIUM CELL ON 90 MINUTE CYCLE ORBIT - RIGID ASTROSET SEPARATOR 3420-09

Table XXI lists the average cycle life for all the cells and for each subgroup.

TABLE XXI - AVERAGE CYCLE LIFE TO 0.7 V

GROUP	AVG. CYCLE LIFE
All Cells (12)	927 (cycles)
Cells with Flexible 3420-25 Separator (4)	656
Cells with Flexible 3420-09 Separator (4)	1077
Cells with Rigid 3420-09 Separator (4)	1025
Cells with Flexible 3420-25 & KT (2)	432
Cells with Flexible 3420-25 & .007 Nylon (2)	880
Cells with Flexible 3420-09 & KT (2)	483
Cells with Flexible 3420-09 & .007 Nylon (2)	1721
Cells with Rigid 3420-09 & KT (2)	520
Cells with Rigid 3420-09 & .007 Nylon (2)	1530
All cells with KT absorber (6)	478
All cells with .007 Nylon absorber (6)	1377

The data in Table XXI shows that there is little difference in cycle life between cells fabricated with either the flexible or rigid 3420-09 separators. However, in all cases, and independent of the separator, the cycle life of cells with non-woven nylon absorbers was 2-3 times greater than cells with KT absorbers. The discharge current density for the cells with inorganic separators was 20% greater than for cells with organic separators, at the same depth of discharge.

5. Post Cycle Analysis

After each cell was removed from the cycling regime, it was flooded with 40% KOH, charged (diodes removed) in the vented condition at 14 mA/cm^2 (1.5 A) for 24 hours, and discharged at 18 mA/cm^2 (2.0 A) to minus 1.5 V. The total capacity of the electrodes, as well as the limiting electrode, was determined for each cell. Table XXII gives the post cycle capacity data for each cell.

TABLE XXII - POST CYCLE CAPACITIES

CELL	SEPARATOR		ABSORBER	NO. CYCLES	POS. CAP.	NEG. CAP.
572	Flexible	3420-25	KT Paper	374	4.2 Ah	7.1 Ah
573	"	"	KT Paper	489	4.1	7.3
574	"	"	0.007 Nylon	1100	2.1	1.0
575	"	"	0.007 Nylon	659	3.4	1.2
647	Flexible	3420-09	KT paper	443	4.2	7.1
648	"	"	KT paper	523	4.3	7.7
649	"	"	0.007 Nylon	1271	3.7	1.8
650	"	"	0.007 Nylon	2170	4.2	2.2
722	Rigid	3420-09	KT paper	410	5.6	4.3
723	"	"	KT Paper	630	4.5	5.2
724	"	"	0.007 Nylon	1530	1.0	3.5
725	"	"	0.007 Nylon	1530	4.0	3.4

Post mortem examinations of the cells with non-woven nylon absorbers were conducted. Cells removed from cycling with KT paper absorbers were delivered to Lewis Research Center for further testing and evaluation.

The six cells with nylon absorbers (Nos. 574, 575, 649, 650, 724 and 725) were opened and the electrode stack removed. Examination showed heavy silver migration through the flexible inorganic separators and the nylon absorbers. The large amount of silver penetration may have accounted for the low post-cycling capacities of these cells. Almost no silver migration was found on the two cells with the rigid inorganic separator. However, Cell #724, which gave only 1.0 Ah of positive capacity on post-cycle analysis, was found to have cracked separator plates which may have provided a direct path for silver migration to the negative electrodes.

The negative electrodes from all six cells showed no signs of blistering or cracking. They showed good adhesion to the substrate, and no tendencies towards shape change such as slumping.

The positive electrodes also showed no signs of physical deterioration.

VI. EXPERIMENT II - CELLS WITH INORGANIC SEPARATORS

A. SCOPE

Ninety-six (96) silver-cadmium cells were to be fabricated and delivered in the dry condition to NASA/Lewis Research Center.

The cells were divided into 3 groups of 32 cells. Each group of 32 cells contained a different type of inorganic separator, which was supplied by Astropower Division of McDonnell-Douglas Corp. The three types of separator materials were designated by Astropower as:

1. 3420-09 Rigid
2. 3420-09 Flexible
3. 3420-25 Flexible

The absorber material for the positive electrodes encapsulated in the rigid separator was 0.020 inch KT paper, rolled down to a thickness of 0.012 to 0.014 inches. For cells with flexible separators, the absorber material was made an integral part of that separator.

The absorbers for the negative electrodes were made into bags by rolling down 0.020 inch KT paper and cementing the edges with an epoxy compound.

B. POSITIVE ELECTRODES

1. Substrate Size

Because the inorganic separators were of the same size as the organic separators, the silver electrodes were cut down in size to allow for a cementing border around the edges and still fit in the plastic cases. The size of the silver electrodes was reduced to 3.25 inches wide by 2.63 inches high from 3.5 inches wide by 3.0 inches high, as used in the organic separator cells. The sizes of all inorganic separators were 3.7" wide by 3.1" high.

2. Electrode Fabrication

Two hundred (200) positive silver electrodes, measuring 3.25" wide by 2.63" high by .025" thick, and containing 14.7 grams of silver (7.35 Ah theoretical capacity) were fabricated by the "lost wax" sintering process. The electrode density was 4.2 gms/cc.

One hundred, fifty (150) of these electrodes, which were pre-numbered, were delivered to Astropower Division for encapsulation in the flexible inorganic separators.

The electrode-separator assemblies were then divided into two groups of 75 electrodes, each group with a different type of separator. One group was designated as having separator type 3420-09 and the other group designated as 3420-25.

Thirty-two (32) of the remaining silver electrodes were placed in absorber bags of rolled KT paper and encapsulated in the rigid Astroset (3420-09) separator.

C. NEGATIVE ELECTRODES

The negative electrodes used in these cells were of the teflonated cadmium hydroxide type. The electrode dimensions were 3.5" wide by 3.0 inches high, by .036 inch thick. The amount of active material on each electrode was adjusted to yield a Cd to Ag ratio of 1.5:1.

Two hundred fifty (250) electrodes were fabricated and serially numbered. The weight and average thickness of each electrode was recorded. Each electrode was placed in an absorber bag fabricated from rolled down (12-24 mil) KT paper, and sealed in a plastic bag until it was fabricated into an electrode cell stack.

D. Cell Assembly

1. Randomization of Electrodes

In order to insure randomization of electrodes within a given group of 32 cells, the following procedure was used:

A beaker was filled with numbered chips corresponding to the numbers of the 250 negative electrodes. A second beaker was filled with numbered chips representing the 75 positive electrodes with flexible separator 3420-09. One chip representing a positive electrode was drawn, along with two chips representing negative electrodes. These three electrodes were then used as one cell stack assembly. The cell was then designated by the number of the positive electrode. The selection procedure continued until 32 individual positive electrodes were matched with negative electrodes.

This procedure was repeated for positive electrodes with flexible separator 3420-25 and for positive electrodes with rigid separators.

2. Electrode Stack Assembly

The three electrodes for each cell were placed in a welding fixture and the terminals (silver plated nickel) were resistance welded to the electrode tabs. Prior to welding the terminals to the electrodes, a number of test pieces were welded in order to determine the welding schedule which yielded a reliable electrode-to-terminal bond.

After welding the terminals to the electrodes, cell covers were assembled to the terminals. The exposed terminals and tab areas of the cell stacks were covered with an epoxy coating to minimize the possibility of shorting.

3. Final Assembly

The electrode stack to cover assemblies were inserted into the cell cases. Polyethylene shims were added until a sliding fit between the electrode assembly and the case was achieved. The case and cover were then sealed with an epoxy compound, and allowed to cure, at room temperature, for 24 hours while being held in a special locating fixture which applied uniform clamping pressure on all four sides of the joint.

After completion of the sealing operation, each cell was equipped with a pressure gauge and assembled between two plastic plates acting as a restraining jacket. The cells were pressurized to 40 psig and placed in a water bath to determine leakage.

The pressure jackets and gauges were removed, the cells weighed, the fill hole sealed with a #10 shipping screw, and the cells packed and shipped to NASA.

Table XXIII gives the cell number, electrode randomization and dry weight of all cells shipped. The cell number equals the positive number.

TABLE XXIII - ELECTRODE RANDOMIZATION & DRY CELL WEIGHT

FLEXIBLE ASTROSET #3420-09				FLEXIBLE ASTROSET #3420-25			
CELL	NEGATIVE	NEGATIVE	WEIGHT	CELL	NEGATIVE	NEGATIVE	WEIGHT
577	493	532	198.7	501	505	545	196.8
578	454	576	199.5	514	425	527	198.3
580	413	514	195.5	516	446	521	197.1
581	433	434	199.4	517	416	504	197.1
585	456	570	197.1	518	417	467	200.0
587	507	589	196.4	519	489	552	193.0
592	412	464	197.4	520	492	581	196.4
593	458	496	197.5	523	578	598	195.0
594	436	448	196.3	524	404	415	197.1
595	451	559	197.6	528	447	574	199.3
598	548	577	195.5	529	411	463	197.8
599	438	500	199.5	531	414	494	197.7
600	441	569	196.9	532	444	539	198.3
613	476	588	200.2	534	445	536	197.8
614	478	584	195.1	539	474	480	196.1
615	540	565	198.4	540	572	575	197.1
616	484	517	197.7	542	486	511	197.6
619	432	537	194.7	545	418	596	200.0
620	524	585	197.4	547	573	582	197.3
622	450	567	195.0	549	481	472	195.8
624	503	522	194.4	550	443	566	198.1
628	452	502	196.2	552	402	431	197.4
629	485	525	198.9	554	422	453	197.2
630	476	542	197.9	556	449	568	198.9
631	523	525	193.5	557	490	579	196.8
633	497	555	198.3	558	435	437	198.5
634	468	471	198.7	561	429	535	197.5
637	457	534	196.0	563	426	495	199.0
638	442	506	195.2	565	516	591	196.5
642	401	586	198.3	566	408	410	199.9
645	409	510	195.5	567	546	595	200.0
646	470	528	195.7	571	519	553	197.2

continued......

TABLE XXIII - Continued

	RIGID ASTROSET #3420-09		
CELL	NEGATIVE	NEGATIVE	WEIGHT
651	563	580	213.3
652	469	598	214.4
653	479	533	208.5
654	475	513	207.5
655	498	515	213.5
656	460	564	214.2
657	406	550	215.6
658	509	547	213.6
659	466	571	212.9
660	488	520	209.5
661	423	430	210.5
662	424	544	215.5
663	461	483	216.0
664	473	551	216.6
665	455	541	215.5
666	440	477	211.6
667	427	531	211.7
668	491	558	215.0
669	428	487	207.0
670	419	439	212.6
671	554	583	206.3
672	561	592	208.3
673	529	594	208.7
674	512	593	212.4
675	421	459	213.1
676	562	600	208.7
677	462	556	209.6
678	560	597	212.3
679	499	557	207.9
680	482	549	210.4
681	501	599	208.6
682	403	465	208.3

VII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Silver-cadmium cells constructed from non-magnetic, sintered silver electrodes and pressed cadmium electrodes, with a variety of separators, have been assembled into sealed cells. An evaluation of the experimental results leads to the following conclusions:

1. Sealed silver-cadmium cells with silver treated cellulosic barriers and inorganic separators were cycled on short orbits (94 minutes) at 40% (20 mA/cm^2) depth-of-discharge, and two temperatures, 0°C and 25°C. Cells yielded as many as 905 cycles at 0°C and 1055 cycles at 25°C.

   A 4 Ah cell with two silver treated cellulosic barriers and an organic (non-woven nylon) separator gave more than 4500 cycles at 60% (30 mA/cm^2) depth-of-discharge, both at 25°C. The orbit was 35 minutes of discharge and 55 minutes of charge.

   The total number of cycles, under the same test conditions, was found to vary with the separator-absorber system.

2. The teflonated cadmium hydroxide electrode proved to be a "non-fading" type, when manufactured in accordance with the process specifications given in the Appendix. The electrodes' reliability was established over a wide range of current densities and number of cycles (over 7000).

   Cells constructed with teflonated cadmium electrodes showed good oxygen recombination properties. Test cells with cellulosic barriers have cycled in a partial vacuum for over 7000 cycles, and retained their capacity and physical integrity.

   Charkey (Contract No. NAS 5-9106) reported similar improved qualities of "teflon bound-fibrous cadmium electrodes" on a 35% depth-of-discharge cycle orbit.

3. Cellulosic separator materials, such as silver treated fibrous sausage casing, make good barriers in cells subjected to high rates of charge and discharge at high depths. The use of such barriers will be limited by a relatively short cell life (calendar time) and elevated temperatures.

4. Barriers made from irradiated polyethylene, such as RAI2291, do not appear to be suited for use in silver-cadmium cells subjected to high rate, deep cycling regimes. The material increases cell impedance and interferes with the diffusion of oxygen to the cadmium electrode.

5. The use of 45% KOH as the electrolyte for silver-cadmium cells subjected to high rate deep cycles is not recommended. Under this regime, the use of concentrated electrolyte (45% KOH) leads to shortened cycle life.

6. Thick inorganic absorber materials, such as potassium titanate (KT) and fuel cell asbestos, have shown to have shorter cycle life by a factor of 2 to 3 over non-woven nylon when used in silver-cadmium cells with inorganic separators and cycled on high rate, short orbit regimes.

7. Cells with Astroset 3420-09 rigid separators showed very little sign of silver migration when compared with Astroset 3420-09 and 3420-25 flexible separators. The flexible separators showed signs of heavy silver penetration. Cells with rigid separators, however, operated at reduced voltage levels.

B. RECOMMENDATIONS

1. Cells constructed with three electrodes (two negatives and one positive) do not normally behave in the same manner as cells constructed from multi-electrode stacks. This is due to the fact that the two-negative electrodes are "end electrodes". We recommend the construction of full sized cells with the desired Cd to Ag ratio separator system and teflonated electrodes, and subject these cells to the same orbit cycles and depth-of-discharge as the three-plate cells.

2. Investigate electrode configuration to optimize high rate performance and thermal characteristics.

APPENDIX A

MANUFACTURING PROCESSES

PRESSED TEFLONATED CADMIUM HYDROXIDE NEGATIVE ELECTRODES

AND

SINTERED SILVER ELECTRODES

I. INTRODUCTION

This part of the Final Report deals with the description of processes and techniques utilized under this program, for the manufacture of silver-cadmium electrodes.

Appendix "A" gives the processes which were utilized in the manufacture of pressed teflonated cadmium-hydroxide negative electrodes, and sintered silver electrodes by the "lost wax" process.

Sketches and flow charts are included where possible and practicable.

The order in which some manufacturing steps are listed may be modified to suit available equipment and tooling.

Appendix "B" shows Failure Analysis Reports, NASA Form 51221.

II. THE SILVER ELECTRODE

1.0 Preparation of Silver Wax Mix

1.1 Weigh out a convenient lot of silver powder, Handy & Harman Silpowder 150.

1.2 Add paraffin wax, 5% by weight of silver powder (5 gms wax per 100 gms of silver).

1.3 Place the mixture in an oven at 120°F for 30 to 45 minutes, until the wax melts and coats all the silver particles.

1.4 Remove coated powder from the oven and allow to cool to room temperature.

1.5 Break up lumps of the entire mix and pass through an 80 mesh sieve.

1.6 Weigh out the sieved mix, in half quantities 9.45 gms., and store in plastic closed dishes. (Two dishes required per electrode, 18.9 gms total silver powder mix per each electrode.)

2.0 Pressing Electrodes

2.1 Spread half quantity in the bottom of a smooth steel mold and spread out evenly, using a doctor blade or leveler.

2.2 Place silver substrate (Figure 3 of main report) on top of the spread out silver powder mix.

2.3 Add second half of mix to top and smooth out with doctor blade or leveler.

2.4 Close top of mold, and press down at 141 Kg/cm^2 of electrode area -- approximate electrode thickness 0.025 inch.

Note: The pressures were calculated to bring the electrode particles to a desired density. The pressure of 141 Kg/cm^2 produced a density of 4.2 gms/cc of electrode. This pressure may vary from one size to another, with the thickness of electrodes and type of equipment used.

2.5 Remove silver electrode from the mold.

3.0 Sintering

3.1 Place pressed electrodes into a sintering furnace and sinter at 1300°F for 10 minutes.

Note: Sintering time and temperature may vary depending on the type of furnace. During sintering, the wax particles will volatize.

3.2 Spot check porosity and thickness of sintered electrodes. Small adjustments in the sintering parameters may be required to obtain the desired porosity. An average porosity of 47% (using alcohol as the liquid medium to check porosity) was obtained on this program.

3.3 Store electrodes in sealed plastic bags or use in cell assemblies.

III. THE PRESSED TEFLONATED CADMIUM ELECTRODE

1.0 Raw Material Specifications

The following raw materials are used in the fabrication of pressed teflonated cadmium electrodes.

1.1 Battery Grade Cadmium Nitrate solution per Gulton Dwg. No. A-551-13119 (Figure 1A).

1.2 Solvay mercury cell process potassium hydroxide per Gulton Dwg. No. A-5374 (Figure 2A).

1.3 Silver powder, Handy & Harman Silpowder 150.

1.4 Teflon emulsion - Dupont type P-30.

1.5 Silver substrates - expanded metal 99.9% fine silver (See Figure 3 of main report).

2.0 Preparation of Cadmium Hydroxide [$Cd(OH)_2$]

2.1 Obtain a needed quantity of cadmium nitrate [$Cd(NO_3)_2$] per Para. 1.1 and maintain at a concentration of 8.26N.

2.2 Obtain a needed quantity of potassium hydroxide (KOH) per Para. 1.2 and maintain at a concentration of 8.07N.

2.3 To a given amount of the cadmium nitrate [$Cd(NO_3)_2$] solution, add a quantity of potassium hydroxide (KOH) solution, 2% in excess of the stoichiometric amount.

CHEMICAL PURITY SPECIFICATIONS

BATTERY GRADE CADMIUM NITRATE PURIFIED 85% SOLUTION - APPROX.

Clear, colorless solution, free from suspended matter or sediment

Specific Gravity: 1.90 at 120°F

Maximum Limits of Impurities on the Following:

Chloride	(Cl)	0.004%
Sulfate	(SO_4)	0.005%
Arsenic	(As)	0.001%
Copper	(Cu)	0.005%
Iron	(Fe)	0.002%
Lead	(Pb)	0.005%
Zinc	(Zn)	0.05%
Ammonia		0.01%
Free Acid Content, HNO_3		0.05% Min. 0.15% Max.
Total other impurities		0.01%

Note: Above limits of impurities are on a a crystal basis as $Cd(NO_3)_2 \cdot 4H_2O$.

Gulton Drawing No.
A-551-13119

Figure -1A-

SPECIFICATION, POTASSIUM HYDROXIDE

(FOR ELECTROLYTE)

This material shall be Solvay Mercury Cell Process Potassium Hydroxide, Premium Grade, 45% liquor having the following analysis:

KOH	45 - 46%
K_2CO_3	0.06% Max.
KCl	0.005% Max.
NaO	0.10% Max.
Fe	4 PPM Max.
Hg	1 PPM Max.
Turbidity	5 PPM Max.
$KClO_3$	None
Ni	None
Color, White, Min,	98.0

Gulton Drawing No.
A-5374

Figure -2A-

2.4 Wash the precipitate of cadmium hydroxide Cd $(OH)_2$ with deionized or distilled water. Filter the solution to remove the supernatant fluid containing the excess (KOH).

2.5 Continue washing until the filtrate is neutral.

2.6 Dry the precipitate in an oven maintained at 70°C for 16 hours minimum.

2.7 Remove precipitate Cd $(OH)_2$ from the oven, cool to room temperature and grind into a powder small enough to pass through an 80 mesh screen.

2.8 Take sample of each lot and analyze for purity, as described below.

3.0 Purity Analysis of Cadmium Hydroxide - Cd $(OH)_2$

3.1 Weigh out a convenient amount of Cd $(OH)_2$ from each lot.

3.2 Dry the test lot in an oven maintained at 275°C for 24 hours.
Note: This procedure converts the cadmium hydroxide to cadmium oxide and removes any moisture.

3.3 Remove the cadmium oxide from the oven and dry in a dessicator until it reaches room temperature.

3.4 Dissolve an accurately weighed amount of CdO in dilute nitric acid.

3.5 Precipitate cadmium hydroxide by adding an excess of 5% KOH.

3.6 Add solid potassium cyanide (KCN) until the precipitate redissolves.

3.7 The cadmium metal is then determined by electroplating onto a platinum cathode.

3.8 Convert the amount of cadmium metal, plated out, back into cadmium oxide (by calculation).

3.9 The calculation should yield a purity of 99.5% minimum, of the original CdO taken.

4.0 Preparation of Electrode Mix

4.1 Weigh out a convenient lot of prepared cadmium hydroxide.

4.2 Add 5% by weight of silver powder Handy & Harman "Silpowder 150"

4.3 Add 5% by weight of DuPont P-30 Teflon emulsion.
Note: To every 100 gms of $Cd(OH)_2$ add 5 gms. of silver plus 5 gms. of Teflon emulsion.

4.4 Add a small amount of distilled or deionized water and blend the mix thoroughly into a paste.

4.5 Dry the paste at 70°C for 24 hours.

4.6 Place dried paste into oven maintained at 275°C and keep for 20 minutes.

4.7 Remove paste from oven and allow to cool to room temperature.

4.8 Grind teflonated cadmium mix into a powder to pass an 80 mesh screen.

5.0 Pressing Negative Electrodes

5.1 Weigh out the negative mix in plastic dishes, half quantity, 10 gms per electrode (two dishes required per electrode, 20 gms).

5.2 Spread half quantity in the bottom of a smooth steel mold and spread out evenly, using a doctor blade or leveler.

5.3 Place silver substrate (Figure 3 of main report) on top of the spread out cadmium mix.

5.4 Add second half of mix to top and spread out with doctor blade or leveler.

5.5 Close top of mold and press at 1000 Kg/cm^2 of electrode area, for 10.5 in^2 electrode.

Note: The pressures were calculated to bring the electrode to a desired thickness and density. The pressure of 1000 Kg/cm^2 produced electrodes with thickness of 0.036 average, and an "active material" density of 3.2 gms/cc.

5.6 Remove pressed electrode from the mold and trim excess cadmium mix from tab area and sides, if needed.

5.7 Measure thickness and weight of each electrode. Record weight and thickness data.

5.8 Store pressed electrodes in sealed plastic bags or use in cell assembly.

6.0 Flow Chart

Figure 3A is a Process Flow Chart for teflonated cadmium electrodes.

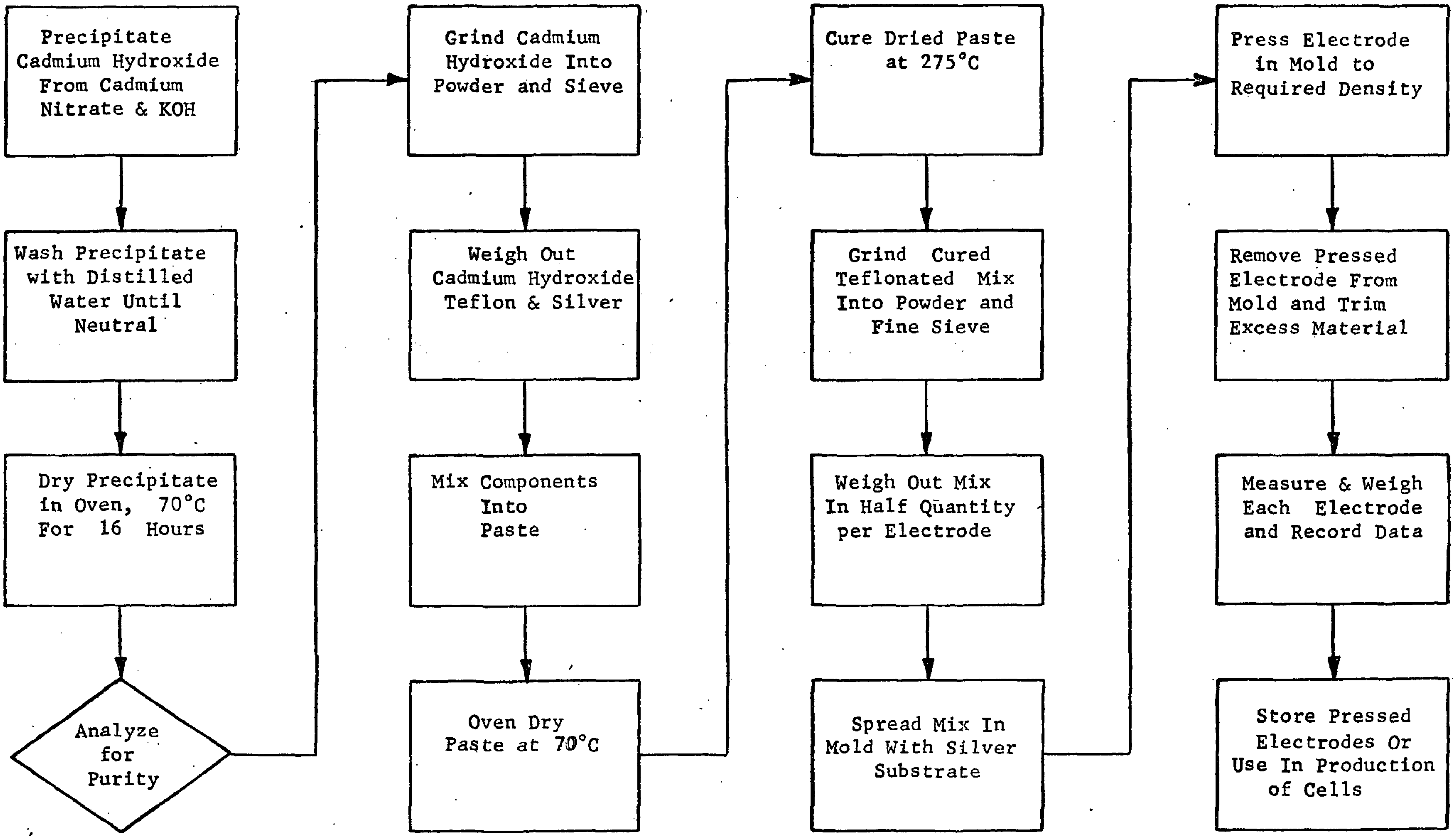


FIGURE 3A. PROCESS FLOW CHART FOR TEFLONATED CADMIUM ELECTRODES

APPENDIX B

FAILURE ANALYSIS REPORTS

(NASA Form 51221)

FAILURE ANALYSIS REPORT

NASA Contract No. NAS 3-13233

Date: 6/28/71 Report No.

Cell Identification

Lot No. Cell No. 572 Test No. IIA

Test Conditions

Cycle Period 1.5 hrs. Temp. 25 °C
Charge .92 hrs., 4.5 amps. Discharge .59 hrs., 2.7 amps.

Failure Conditions

Cycles to Failure 374 Date
Cause of Failure
End of discharge voltage, last cycle < 0.7V

External Inspection

a. Leakage None
b. OCV 1 hr. after test 1.1
c. Initial weight gms
Final weight gms
Weight change gms
d. Phenolphthalein test
e. Case inspection Good
f. Residual capacity -- AH

Internal Inspection- N/A

a. Active material in case
b. Pack wetness: free KOH / ; moist ;dry
c. Migrated active material
d. Terminals
Plate tabs
e. Negative Pack Capacity: As failed --- AH
After recharge 7.1 AH
Positive Pack Capacity: As failed --- AH
After recharge 4.2 AH
f. No. of plates: positive 1 ; negatives 2

FAILURE ANALYSIS REPORT

NASA Contract No. NAS-3-13233

Date: 6/28/71

Report No.

Cell Identification

Lot No.

Cell No. 573

Test No. IIA

Test Conditions

Cycle Period 1.5 hrs.

Temp. 25 °C

Charge .92 hrs., 4.5 amps.

Discharge .59 hrs., 2.7 amps.

Failure Conditions

Cycles to Failure 489

Date

Cause of Failure

End of discharge voltage, last cycle < 0.7V

External Inspection

a. Leakage None

b. OCV 1 hr. after test 1.1

c. Initial weight ____ gms

Final weight ____ gms

Weight change ____ gms

d. Phenolphthalein test

e. Case inspection Good

f. Residual capacity --- AH

Internal Inspection - N/A

a. Active material in case

b. Pack wetness: free KOH / ; moist ____ ;dry

c. Migrated active material

d. Terminals

Plate tabs

e. Negative Pack Capacity: As failed --- AH

After recharge 7.3 AH

Positive Pack Capacity: As failed --- AH

After recharge 4.1 AH

f. No. of plates: positive 1 ; negatives 2

FAILURE ANALYSIS REPORT

NASA Contract No. NAS3-13233

Date: 6/28/71
Report No. ____

Cell Identification
Lot No. ____
Cell No. 574
Test No. IIA

Test Conditions
Cycle Period 1.5 hrs.
Temp. 25 °C
Charge .92 hrs., 4.5 amps.
Discharge .59 hrs., 2.7 amps.

Failure Conditions
Cycles to Failure 1100
Date ____
Cause of Failure ____
End of discharge voltage, last cycle < 0.7

External Inspection
a. Leakage None
b. OCV 1 hr. after test 1.1
c. Initial weight ____ gms
Final weight ____ gms
Weight change ____ gms
d. Phenolphthalein test ____
e. Case inspection Good
f. Residual capacity --- AH

Internal Inspection
a. Active material in case None
b. Pack wetness: free KOH / ; moist ____ ;dry ____
c. Migrated active material Heavy
d. Terminals Clean
Plate tabs Clean
e. Negative Pack Capacity: As failed --- AH
After recharge 1.0 AH
Positive Pack Capacity: As failed --- AH
After recharge 2.1 AH
f. No. of plates: positive 1 ; negatives 2

SEPARATOR INSPECTION
From top (+) terminal on left

Polarity

PLATE NO.	TYPE	TYPE	CONDITION	CONDITION
1 (-)	Nylon	--	Good	--
2 (+)	--	Flexible 3420-25	--	Good
3 (-)	Nylon	--	Good	

Remarks:

Heavy silver penetration of all separator and absorber materials

PLATE INSPECTION
From top, (+) terminal on left

Polarity

PLATE NO.	CONDITION
1 (-)	Excellent
2 (+)	Excellent
3 (-)	Excellent

Remarks:

FAILURE ANALYSIS REPORT

NASA Contract No. NAS 3-13233

Date: 6-28-71 Report No.

Cell Identification

Lot No. Cell No. 575 Test No. II-A

Test Conditions

Cycle Period 1.5 hrs. Temp. 25 °C

Charge .92 hrs., 4.5 amps. Discharge .59 hrs., 2.7 amps.

Failure Conditions

Cycles to Failure 575 Date

Cause of Failure

End of discharge voltage, last cycle < 0.7 volt

External Inspection

a. Leakage Case to cover leak

b. OCV 1 hr. after test 1.1

c. Initial weight gms

Final weight gms

Weight change gms

d. Phenolphthalein test

e. Case inspection Good

f. Residual capacity -- AH

Internal Inspection

a. Active material in case None

b. Pack wetness: free KOH / ; moist ;dry

c. Migrated active material Heavy

d. Terminals Clean

Plate tabs Clean

e. Negative Pack Capacity: As failed -- AH

After recharge 1.2 AH

Positive Pack Capacity: As failed -- AH

After recharge 3.4 AH

f. No. of plates: positive 1 ; negatives 2

SEPARATOR INSPECTION
From top (+) terminal on left

Polarity

PLATE NO.	TYPE	TYPE	CONDITION	CONDITION
1 (-)	Nylon		Good	
2 (+)		Flexible 3420-25		Good
3 (-)	Nylon		Good	

Remarks:

Heavy silver migration through both separator and absorber

PLATE INSPECTION
From top, (+) terminal on left

Polarity

PLATE NO.	CONDITION
1 (-)	Excellent
2 (+)	Excellent
3 (-)	Excellent

Remarks:

FAILURE ANALYSIS REPORT

NASA Contract No. NAS 3-13233

Date: 6-28-71 Report No.________

Cell Identification

Lot No.________ Cell No. 647 Test No. II-A

Test Conditions

Cycle Period 1.5 hrs. Temp. 25 °C

Charge .92 hrs., 4.5 amps. Discharge .59 hrs., 2.7 amps.

Failure Conditions

Cycles to Failure 443 Date________

Cause of Failure________

End of discharge voltage, last cycle < 0.7 volts

External Inspection

a. Leakage None

b. OCV 1 hr. after test 1.1

c. Initial weight________gms

Final weight________gms

Weight change________gms

d. Phenolphthalein test________

e. Case inspection Good

f. Residual capacity________AH

Internal Inspection N/A

a. Active material in case________

b. Pack wetness: free KOH / ; moist________;dry________

c. Migrated active material________

d. Terminals________

Plate tabs________

e. Negative Pack Capacity: As failed -- AH

After recharge 7.1 AH

Positive Pack Capacity: As failed -- AH

After recharge 4.2 AH

f. No. of plates: positive 1 ; negatives 2

FAILURE ANALYSIS REPORT

NASA Contract No. NAS 3-13233

Date: 6-28-71 Report No.

Cell Identification

Lot No. Cell No. 648 Test No. II-A

Test Conditions

Cycle Period 1.5 hrs. Temp. 25 °C
Charge .92 hrs., 4.5 amps. Discharge 5.9 hrs., 2.7 amps.

Failure Conditions

Cycles to Failure 523 Date
Cause of Failure
End of discharge voltage, last cycle < 0.7 volt

External Inspection

a. Leakage None
b. OCV 1 hr. after test 1.1
c. Initial weight gms
Final weight gms
Weight change gms
d. Phenolphthalein test
e. Case inspection Good
f. Residual capacity AH

Internal Inspection N/A

a. Active material in case
b. Pack wetness: free KOH / ; moist ;dry
c. Migrated active material
d. Terminals
Plate tabs
e. Negative Pack Capacity: As failed -- AH
After recharge 7.7 AH
Positive Pack Capacity: As failed -- AH
After recharge 4.3 AH
f. No. of plates: positive 1 ; negatives 2

FAILURE ANALYSIS REPORT

NASA Contract No. NAS 3-13233

Date: 6-28-71 Report No.______

Cell Identification
Lot No.______ Cell No. 649 Test No. II-A

Test Conditions
Cycle Period 1.5 hrs. Temp. 25 °C
Charge .92 hrs., 4.5 amps. Discharge .59 hrs., 2.7 amps.

Failure Conditions
Cycles to Failure 1271 Date______
Cause of Failure______
End of discharge voltage, last cycle $\leq$ 0.7 V

External Inspection
a. Leakage None
b. OCV 1 hr. after test 1.1
c. Initial weight______gms
Final weight______gms
Weight change______gms
d. Phenolphthalein test______
e. Case inspection______
f. Residual capacity______AH

Internal Inspection
a. Active material in case None
b. Pack wetness: free KOH / ; moist______;dry______
c. Migrated active material Heavy
d. Terminals Clean
Plate tabs Clean
e. Negative Pack Capacity: As failed -- AH
After recharge 1.8 AH
Positive Pack Capacity: As failed -- AH
After recharge 3.7 AH
f. No. of plates: positive 1 ; negatives 2

SEPARATOR INSPECTION
From top (+) terminal on left

Polarity

PLATE NO.	TYPE	TYPE	CONDITION	CONDITION
1(-)	Nylon		Good	
2(+)		Flexible 3420-09		Good
3(-)	Nylon		Good	

Remarks:

Heavy silver migration through separators and absorbers

PLATE INSPECTION
From top, (+) terminal on left

Polarity

PLATE NO.	CONDITION
1 (-)	Excellent
2 (+)	Excellent
3 (-)	Excellent

Remarks:

FAILURE ANALYSIS REPORT

NASA Contract No. NAS 3-13233

Date: 6-28-71 Report No.

Cell Identification

Lot No. Cell No. 650 Test No. II-A

Test Conditions

Cycle Period 1.5 hrs. Temp. 25 °C

Charge .92 hrs., 4.5 amps. Discharge .59 hrs., 2.7 amps.

Failure Conditions

Cycles to Failure 2170 Date

Cause of Failure

End of discharge voltage, last cycle < 0.7 V

External Inspection

a. Leakage None

b. OCV 1 hr. after test 1.1

c. Initial weight gms

Final weight gms

Weight change gms

d. Phenolphthalein test

e. Case inspection Good

f. Residual capacity AH

Internal Inspection

a. Active material in case None

b. Pack wetness: free KOH / ; moist ;dry

c. Migrated active material Heavy

d. Terminals Clean

Plate tabs Clean

e. Negative Pack Capacity: As failed -- AH

After recharge 2.2 AH

Positive Pack Capacity: As failed -- AH

After recharge 4.2 AH

f. No. of plates: positive 1 ; negatives 2

SEPARATOR INSPECTION
From top (+) terminal on left

Polarity

PLATE NO.	TYPE	TYPE	CONDITION	CONDITION
1 (-)	Nylon		Good	
2 (+)		Flexible 3420-09		Good
3 (-)	Nylon		Good	

Remarks:

Heavy silver migration through separators and absorbers

PLATE INSPECTION
From top, (   ) terminal on left

Polarity

PLATE NO.	CONDITION
1 (-)	Excellent
2 (+)	Excellent
3 (-)	Excellent

Remarks:

FAILURE ANALYSIS REPORT

NASA Contract No. NAS -13233

Date: 6-28-71
Report No. ____

Cell Identification
Lot No. ____
Cell No. 722
Test No. II-A

Test Conditions
Cycle Period 1.5 hrs.
Temp. 25 °C
Charge .92 hrs., 4.5 amps.
Discharge .59 hrs., 2.7 amps.

Failure Conditions
Cycles to Failure 410
Date ____
Cause of Failure ____
End of discharge voltage, last cycle < 0.7 V

External Inspection
- a. Leakage None
- b. OCV 1 hr. after test 1.1
- c. Initial weight ____ gms
  - Final weight ____ gms
  - Weight change ____ gms
- d. Phenolphthalein test ____
- e. Case inspection Good
- f. Residual capacity ____ AH

Internal Inspection N/A
- a. Active material in case ____
- b. Pack wetness: free KOH / ; moist ____ ; dry ____
- c. Migrated active material ____
- d. Terminals ____
  - Plate tabs ____
- e. Negative Pack Capacity: As failed -- AH
  - After recharge 4.3 AH
  - Positive Pack Capacity: As failed -- AH
  - After recharge 5.6 AH
- f. No. of plates: positive 1 ; negatives 2

FAILURE ANALYSIS REPORT

NASA Contract No. NAS 3-13233

Date: 6-28-71 Report No.

Cell Identification
Lot No. Cell No. 723 Test No. II-A

Test Conditions
Cycle Period 1.5 hrs. Temp. 25 °C
Charge .92 hrs., 4.5 amps. Discharge .59 hrs., 2.7 amps.

Failure Conditions
Cycles to Failure 630 Date
Cause of Failure
End of discharge voltage, last cycle < 0.7 V

External Inspection
a. Leakage None
b. OCV 1 hr. after test 1.1
c. Initial weight gms
Final weight gms
Weight change gms
d. Phenolphthalein test
e. Case inspection Good
f. Residual capacity AH

Internal Inspection N/A
a. Active material in case
b. Pack wetness: free KOH / ; moist ;dry
c. Migrated active material
d. Terminals
Plate tabs
e. Negative Pack Capacity: As failed -- AH
After recharge 5.2 AH
Positive Pack Capacity: As failed -- AH
After recharge 4.5 AH
f. No. of plates: positive 1 ; negatives 2

FAILURE ANALYSIS REPORT

NASA Contract No. NAS 3-13233

Date: 6-28-71 Report No.

Cell Identification

Lot No. Cell No. 724 Test No. II-A

Test Conditions

Cycle Period 1.5 hrs. Temp. 25 °C

Charge .92 hrs., 4.5 amps. Discharge .59 hrs., 2.7 amps.

Failure Conditions

Cycles to Failure 1530 Date

Cause of Failure

End of discharge voltage, last cycle < 0.7 V

External Inspection

a. Leakage None

b. OCV 1 hr. after test 1.1

c. Initial weight gms

Final weight gms

Weight change gms

d. Phenolphthalein test

e. Case inspection Good

f. Residual capacity AH

Internal Inspection

a. Active material in case None

b. Pack wetness: free KOH / ; moist ;dry

c. Migrated active material Minimal

d. Terminals Clean

Plate tabs Clean

e. Negative Pack Capacity: As failed -- AH

After recharge 3.5 AH

Positive Pack Capacity: As failed -- AH

After recharge 1.0 AH

f. No. of plates: positive 1 ; negatives 2

SEPARATOR INSPECTION
From top (+) terminal on left

Polarity

PLATE NO.	TYPE	TYPE	CONDITION	CONDITION
1 (-)	Nylon		Good	
2 (+)	Nylon	3420-09 Rigid	Good	Cracked
3 (-)	Nylon		Good	

Remarks:

Very little silver migration

PLATE INSPECTION
From top, (+) terminal on left

Polarity

PLATE NO.	CONDITION
1 (-)	Excellent
2 (+)	Excellent
3 (-)	Excellent

Remarks:

FAILURE ANALYSIS REPORT

NASA Contract No. NAS 3-13233

Date: 6-28-71 Report No.________

Cell Identification

Lot No.______ Cell No. 725 Test No. II-A

Test Conditions

Cycle Period 1.5 hrs. Temp. 25 °C

Charge .92 hrs., 4.5 amps. Discharge .59 hrs., 2.7 amps.

Failure Conditions

Cycles to Failure 1530 Date______

Cause of Failure______

End of discharge voltage, last cycle < 0.7 V

External Inspection

a. Leakage None

b. OCV 1 hr. after test 1.1

c. Initial weight______gms

Final weight______gms

Weight change______gms

d. Phenolphthalein test______

e. Case inspection Good

f. Residual capacity______AH

Internal Inspection

a. Active material in case None

b. Pack wetness: free KOH ✓; moist______;dry______

c. Migrated active material Minimal

d. Terminals Clean

Plate tabs Clean

e. Negative Pack Capacity: As failed -- AH

After recharge 3.4 AH

Positive Pack Capacity: As failed -- AH

After recharge 4.0 AH

f. No. of plates: positive 1; negatives 2

SEPARATOR INSPECTION
From top (+) terminal on left

Polarity

PLATE NO.	TYPE	TYPE	CONDITION	CONDITION
1 (-)	Nylon		Good	
2 (+)	Nylon	3420-09 Rigid	Good	Good
3 (-)	Nylon		Good	

Remarks: Minimal silver migration

PLATE INSPECTION
From top (+) terminal on left

Polarity

PLATE NO.	CONDITION
1 (-)	Excellent
2 (+)	Excellent
3 (-)	Excellent

Remarks:

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