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REPORT DAC-60525-F

DEVELOPMENT AND TESTING OF A FIVE-AH SILVER CADMIUM CELL

FINAL REPORT COVERING PERIOD
7 JULY 1967 THROUGH 6 APRIL 1969

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY

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Contract NAS 3-10925

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ABSTRACT

Task I of this program was devoted to the design of a 5 Ah silver-cadmium cell using purchased cadmium electrodes and Astropower inorganic separator 3420-09. All other components and techniques used were identical to those used on a concurrent program (NAS 3-10924) related to a 5 Ah silver-zinc cell.

Task II consisted of an evaluation of the selected design on a 40% depth-of-discharge, 1.5-hour cycling period, regime at 25°C. Several groups of five cells with minor variations were tested. The 40% KOH concentration appeared to establish a capability of at least 4700 such cycles.

Task III covered the evaluation of the cells using 30% and 40% KOH on various cycling regimes conducted at 25°C and 100°C. Pressure and gas analysis data were obtained on some cells.

ACKNOWLEDGEMENT

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Special acknowledgement is also given to Messrs. G. Boehm, L. Lante, and D. Mathias for their assistance in the compilation and evaluation of test data.

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Section 1
INTRODUCTION

The silver-cadmium secondary cell has a cycle life limited by the deterioration of the conventional separators used to date, caused by the concurrent attack of strong alkali electrolyte and soluble silver.

The problem may be alleviated with the use of a nonoxidizable inorganic separator.

The development of a 5 Ah silver-cadmium cell could be accomplished quite readily in view of the great amount of work already done on the 5 Ah silver-zinc cell of a concurrent program (NAS 3-10924). Case, cover, hardware, electrode tooling, valve, sealing techniques, and assembly methods remained constant. Cadmium electrodes of the sintered porous nickel plaque type were purchased. The separator was the rigid inorganic slab 3420-09 used in the silver-zinc cell. The present program consisted of the design, fabrication and testing of 5 Ah silver-cadmium cells sealed with 40 psig-pressure relief valves and incorporating the inorganic separator. This would provide the information desired to confirm the feasibility of this approach for obtaining a long cycle life secondary cell.

Section 2
SUMMARY

The effort under this program was directed toward evaluating the operating characteristics of a sealed silver-cadmium secondary cell using an inorganic separator.

A large number of multiplate cells were fabricated and evaluated at 25°C and 100°C over a series of various cycling regimes of different periods and depths of discharge.

After selecting a particular silver-cadmium cell design, several groups of cells were fabricated and cycled on the 40% depth-of-discharge, 1.5-hour cycling period regime at 25°C to quickly evaluate their electrical characteristics and cycle life. It was established that the high KOH concentration was definitely preferable and 40% KOH was selected because of the large number of cycles obtained with this concentration at the time of the selection. (However, one group using 45% KOH showed very good uniformity but was discontinued at cycle 3095 because of the termination of the program; all other cells of the program were already filled with 40% KOH.)

The last task consisted of evaluating the selected cell design on various regimes at 25°C and 100°C.

On wet stand at 25°C, the cells using 40% KOH retained 62% of their original capacity after approximately 5 months.

The coulombic efficiency was established at various depths of discharge ranging from 25% to 100%, at 25°C and 100°C, with 30% and 45% KOH concentration. It was in the range of 90 to 95% in any combination of variables.

Cycling at 100% depth, one cycle a day (24-hour period), the best cells reached approximately 160 cycles with 40% KOH.

Cycling at 40% depth, 1.5-hour cycling period, the cells are capable of exceeding 4700 cycles.

Section 3
TASK I: CELL DESIGN

The objective of this program was to build and test 5 Ah silver-cadmium cells with construction features, case, cover, hardware, and inorganic separators used under Contract NAS 3-10924, "Development and Testing of 5 Ah Ag-Zn Cell."*

The cadmium electrodes are to be purchased. Silver electrodes are to be fabricated by standard methods in use in our laboratory.

In order to establish the optimum cell design with these constraints, parametric evaluation of the characteristics of each electrode was in order.

3.1 CADMIUM ELECTRODE

3.1.1 First Samples

A few cadmium electrodes of the sintered porous nickel type (impregnated with cadmium hydroxide) were acquired. Although larger than the desired size to fit in the molded 5-Ah case used in the Ag-Zn contract NAS 3-10924, they were evaluated for their specific capacity.

Five plates were tested as follows: After measuring their physical characteristics (Table I), they were charged and discharged against solid nickel sheet counterelectrodes without separators in 31% KOH. Varying the charging time from 5 hours to 9 hours, the capacity output leveled off at 2.30 Ah with a minimum of 2.80 Ah input, thus yielding an efficiency of 83 to 84% at the selected rate of charge and discharge, which was 20 mA/cm^2 (Table II).

Figure 1 shows a linear relationship between output and charging time; the slope is a measure of the efficiency which is constant (84%) up to the point where the excess charge is not useful and the output levels off.

Using corrected area (active) and corrected weight, we find the following conservative design parameters.

* Himy, A., "Development and Testing of a Five Ah Silver-Zinc Cell," NASA Final Report CR-72551, May 1969.

TABLE I

0.031" THICK CADMIUM ELECTRODE MECHANICAL CHARACTERISTICS

Plate	Total Area	Corrected Area (active)	Total Weight	Corrected Weight (without tab)
1	8.80 in^2	8.35 in^2	16.58 g	15.94 g
2	8.72 in^2	8.27 in^2	16.92 g	16.28 g
3	8.85 in^2	8.40 in^2	16.79 g	16.10 g
4	8.97 in^2	8.52 in^2	16.52 g	15.88 g
5	8.85 in^2	8.40 in^2	16.92 g	16.28 g
Avg.	8.84 in^2	8.39 in^2	16.74 g	16.10 g

TABLE II

0.031" THICK CADMIUM ELECTRODE ELECTRICAL CHARACTERISTICS

Charging Time:* (Hours)		5	7	8	9
Input*	(Ah)	1.75	2.45	2.80	3.15
Output: Plate	1	1.28		2.32	2.39
(Ah_o)	2	1.46	1.92		2.39
	3	1.60	2.13		2.30
	4	1.62	1.92		
	5	1.40	2.01		2.33
Average		1.47	2.01	2.32	2.35
Efficiency		84%	82%	83%	74%

* Fixed charge at 0.350 A constant current.

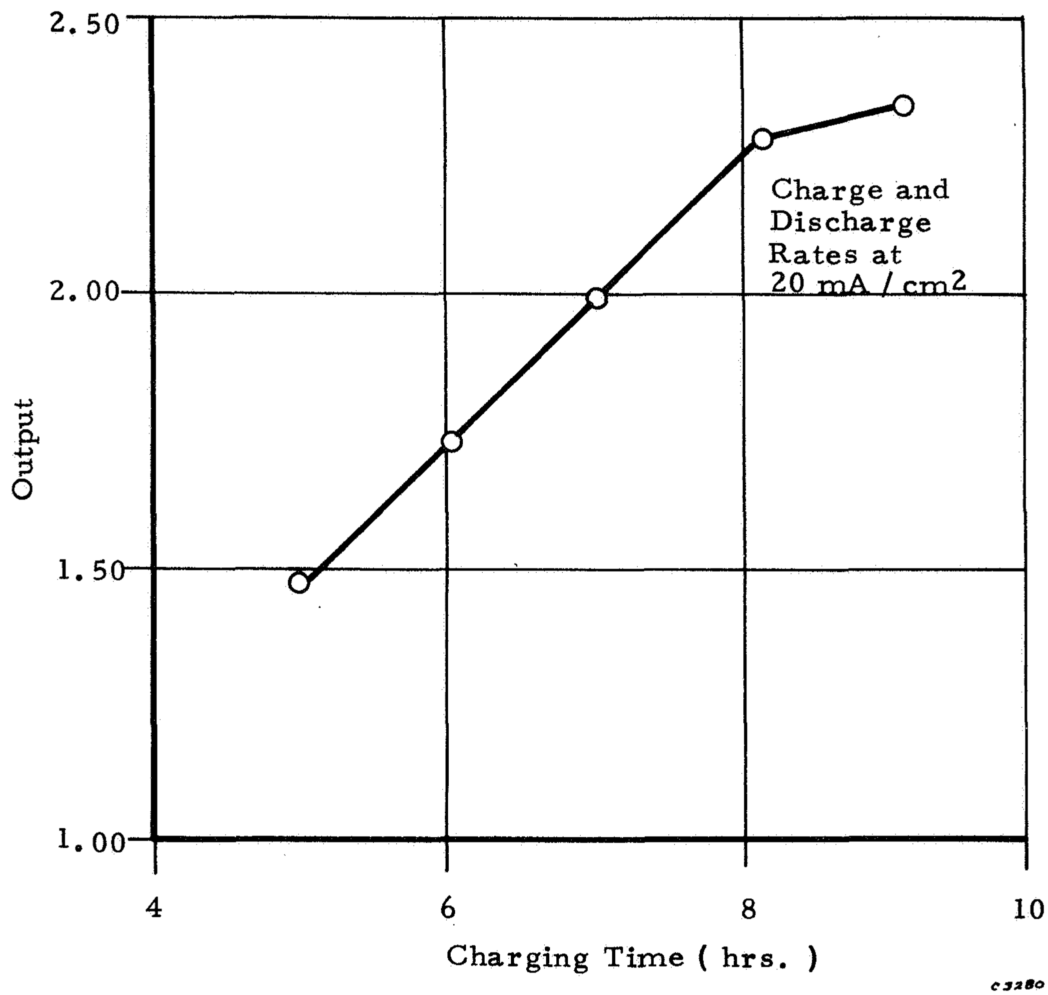


Figure 1. Charge Efficiency of the Cadmium Electrode (2.97" x 2.97" x 0.031")

Output:	2.30 Ah
Area:	8.4 in.^{2}
Thickness:	31 mils
Weight:	16.1 g
Specific Capacities:	0.088 Ah/in.^{2} - mil of electrode 0.143 Ah/g of electrode

Using approximately 2" x 1.9" x 0.022" cadmium electrodes in this program would result in a total capacity of 0.75 Ah per electrode. However, the active area facing the silver plate is 1.6" x 1.6" = 2.5 in.^{2}, giving only a 0.50-Ah plate.

Two test cells using one positive (0.010-inch thick and 2.5 g of silver) and two Cd electrodes were quickly evaluated while waiting for the smaller size Cd electrodes on order. The Cd electrodes, originally 2.97" x 2.97", were cut down to 1.93" x 2.0" to fit the 5-Ah cell case and to conform to the desired cell pack.

The results are reported in Figure 2 (discharge curves at various rates) and Figure 3 (voltage and capacity as a function of rate). These data indicate that the Cd plates limit the cell capacity on charge and on discharge.

3.1.2 Regular Cadmium Electrode

Cadmium electrodes of the proper size (0.022" thick) were ordered for maximum multiplate cell design flexibility. As received, their dimensions were 1.93" x 2.20". They were cut down to 1.93" x 1.95", and nickel wires were spot-welded to their tabs.

Five test cells, using one positive electrode and two negative electrodes, were cycled at various discharge rates to establish their electrical characteristics for cell design information. Data are reported in Table III. The capacity, still Cd limited, does not exceed 0.8 Ah, even after substantial overcharge. This is clearly evidenced by the discharge of the first design of a multiplate cell using six positives (0.010" thick and 2.5 g of silver each) and seven negatives (see Paragraph 3.3.1). The total output of this multiplate

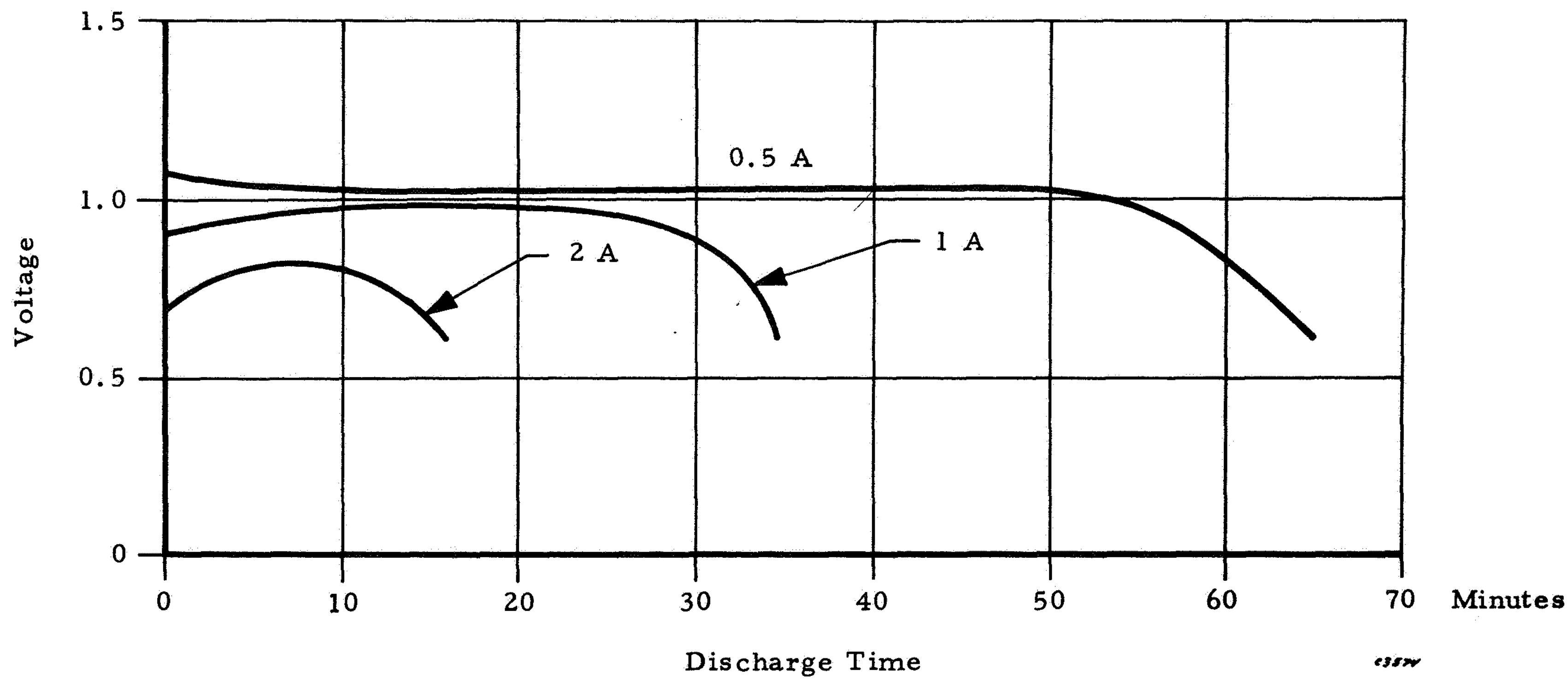


Figure 2. Typical Discharges of Test Cell ($1^+/2^-$) with 0.031" Cd Electrode

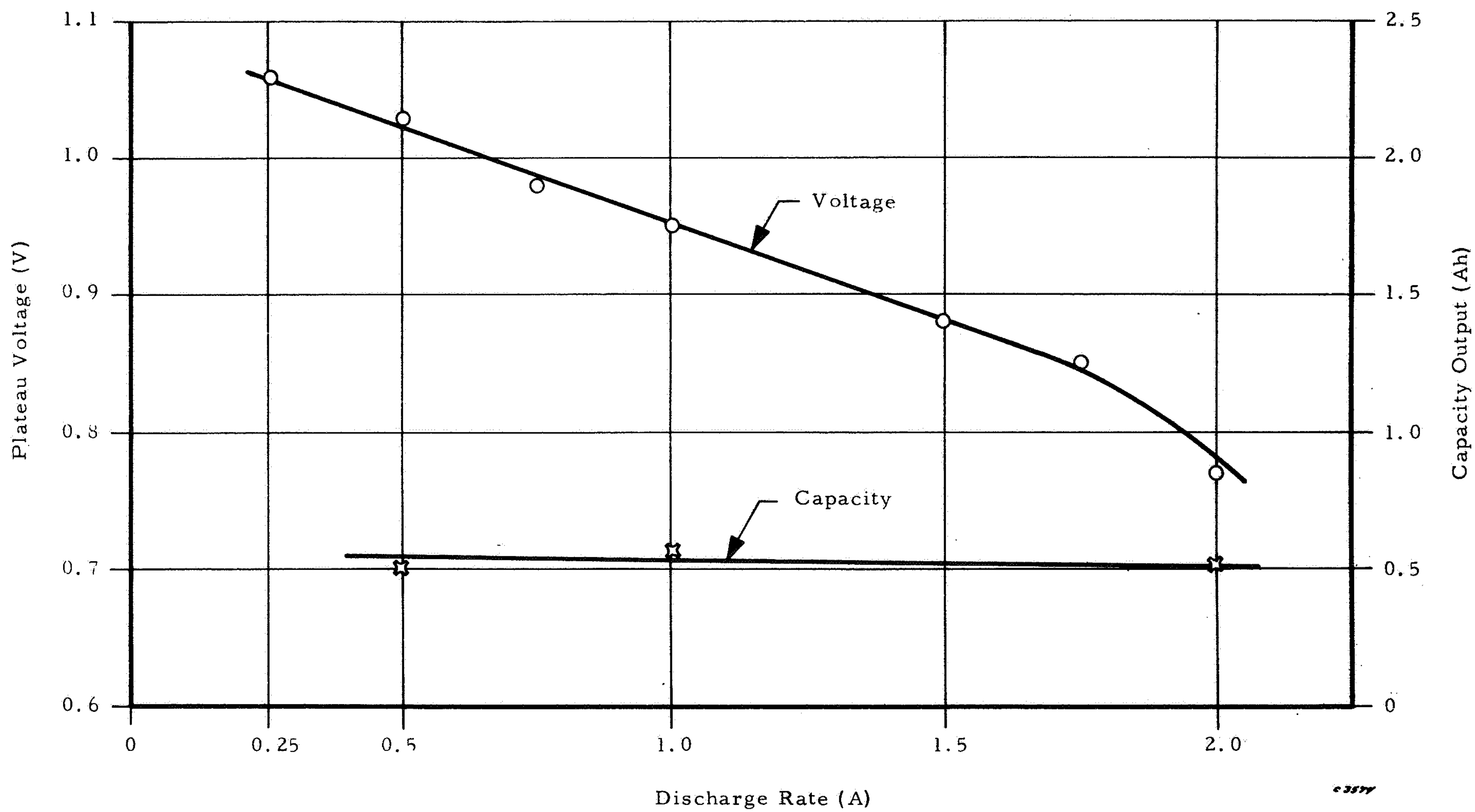


Figure 3. Characteristics of Test Cell ($1^+ / 2^-$) (0.031" Cd Electrode)

TABLE III

SINGLE ELECTRODE TEST CELLS ($1^+/2^-$) (0.022" Cd ELECTRODES)

Charge: 100 mA to 1.70 V

Cycle	1	2	3	4	5	6
Rate (Amp.)	0.5	0.5	0.5	1.0	2.0	0.5
Capacity (Ah)						
Cell CL-4-1	0.68	*	0.75	0.65	0.27	0.80
CL-4-2	0.71	*	0.75	0.65	0.40	0.81
CL-4-3	0.73	*	0.75	0.68	0.37	0.81
CL-4-4	0.63	*	0.50	—	0.37	0.75
CL-4-5	0.63	*	0.60	0.60	—	0.75
Average	0.68	*	0.67	0.63	0.33	0.78
Plateau Voltage (Volts)						
Cell CL-4-1	1.01	1.00	1.00	0.94	0.64	0.92
CL-4-2	1.01	1.02	1.00	0.96	0.68	0.98
CL-4-3	1.01	1.00	1.00	0.94	0.67	0.98
CL-4-4	1.00	1.00	1.00	—	0.64	0.92
CL-4-5	0.98	0.99	1.00	0.94	—	0.98
Average	1.00	1.00	1.00	0.95	0.66	0.96

*Polarization data obtained on this cycle.

cell was only 3 Ah while the available capacity of the total silver is at least 5 Ah, if we consider a conservative silver utilization of 3 g/Ah. The discharge curve reported in Figure 4 shows a long slope between 0.90 V and 0.60 V, which is an indication of lack of Cd active material.

Polarization data of the test cells are given in Table IV.

In order to determine the maximum capability of the Cd electrodes in optimum conditions, preliminary cells were built using one Cd electrode and two solid nickel counterelectrodes in free electrolyte (flooded condition). Data reported in Table V establishes a value of 0.5 Ah as a design parameter for a total area of 3.65 in.^{2}.

3.1.3 Effect of Charging

Eight test cells were built and cycled at different charging rates in an attempt to maximize the capacity if an optimum charging rate can be found. The data reported in Table VI show no further improvement over the 0.5 Ah average capacity obtained previously. After completing the capacity and polarization tests, the cells were placed on automatic cycling at the 1/2-hour discharge, 1-hour charge, 40% depth of discharge regime.

3.1.4 Automatic Cycling

Assuming an actual capacity of 0.6 Ah, the automatic cycling selected was done at 40% depth and 1.5-hour cycling period:

Discharge: 0.500 A for 1/2 hour
Charge: 0.275 A for 1 hour

Several single electrode test cells were thus cycled. Figure 5 shows cycling curves at various cycles. Some cells were discontinued at regular intervals for examining the cell components. One cell was opened at cycle 209, one at 417 and one at 600. All components were in good condition. The remaining cells were left cycling up to cycle 1373 when they were purposely discontinued so that cycling panels could be made available for a larger number of multiplate cells being concurrently evaluated (Paragraph 3.3 and Section 4). After

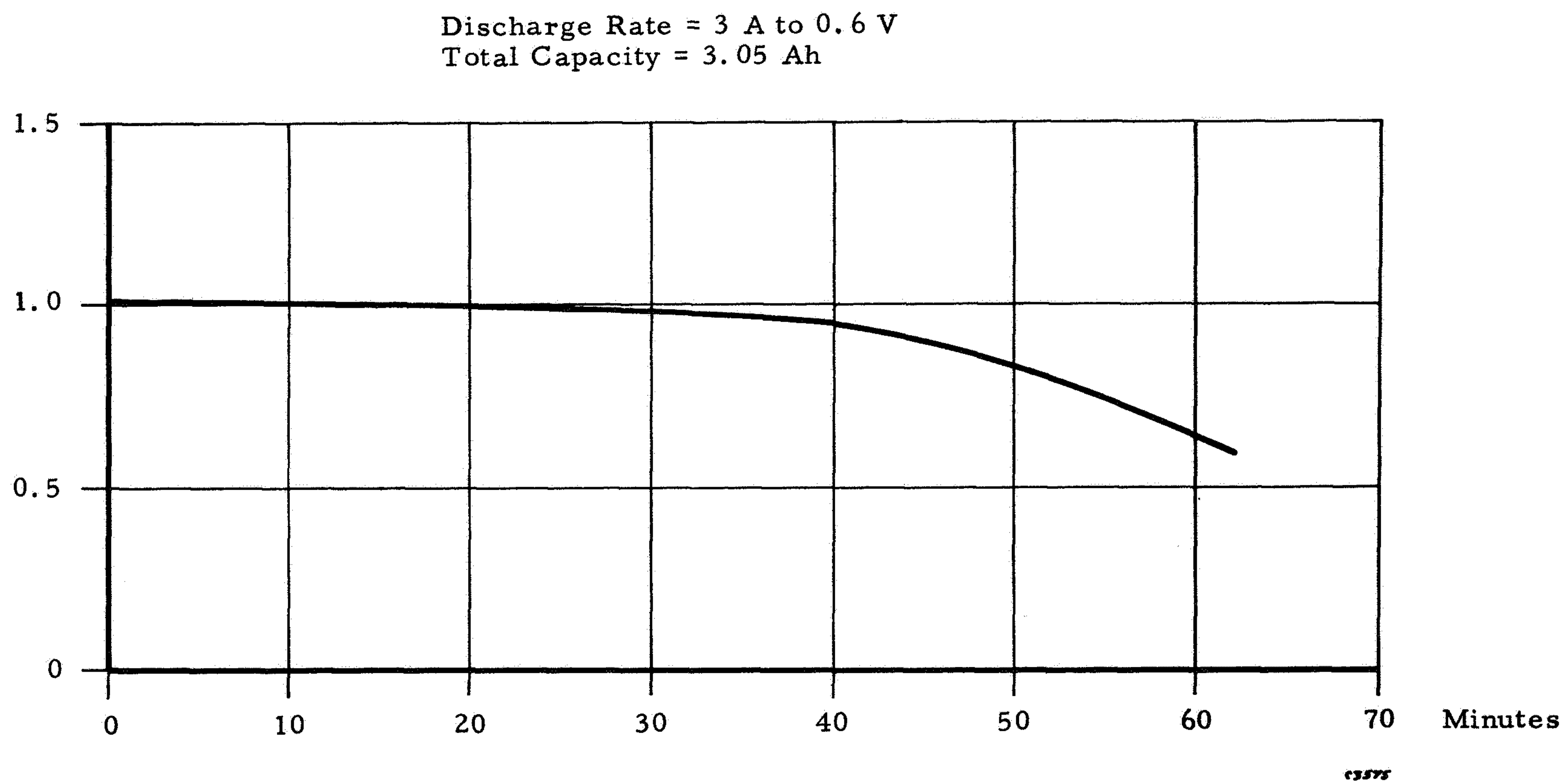


Figure 4. First Model of Multiplate Ag-Cd Cell ($6^+/7^-$)

TABLE IV

POLARIZATION DATA ON TEST CELLS
USING 0.022" Cd ELECTRODES

Rate (A)		0.25	0.50	0.75	1.00	1.50	1.75	2.00
Current Density (mA/cm^2)		7.50	15.0	22.5	30.0	45.0	52.5	60.0
Plateau Voltages (Volts)								
Cell	CL-4-1	1.06	1.00	0.95	0.91	0.84	0.83	0.79
	CL-4-2	1.07	1.00	0.96	0.93	0.89	0.88	0.85
	CL-4-3	1.07	1.00	0.95	0.91	0.83	0.79	0.76
	CL-4-4	1.05	1.00	0.95	0.92	0.88	0.86	0.81
	CL-4-5	1.04	0.99	0.92	0.89	0.82	0.78	0.70
Average		1.06	1.00	0.95	0.91	0.85	0.83	0.78

TABLE V

CAPACITY OF CADMIUM ELECTRODES
(1.93" x 1.90" x 0.022")

Charge: 100 mA to 1.60 V
Discharge: 0.5 A to break.

Cell No.	Cycle 1	Cycle 2	Cycle 3
CL-8-1	0.56 Ah	0.47 Ah	0.50 Ah
CL-8-2	0.59	0.49	0.55
CL-8-3	0.59	0.50	0.55
CL-8-4	0.62	0.52	0.58
CL-8-5	0.56	0.47	0.52
Average	0.58 Ah	0.49 Ah	0.54 Ah

Average over 3 cycles: 0.54 Ah
Mean deviation: ± 0.04 Ah

TABLE VI

EFFECT OF CHARGING RATE ON CADMIUM ELECTRODE (0.022" THICK)

	CL Test Cell Series (2 Cells Per Variation)			
Charging Rate	100 mA	150 mA	200 mA	250 mA
	Capacity Output Average			
Discharge Rate				
0.5 A	0.48 Ah	0.42 Ah	0.47 Ah	0.55 Ah
1.0 A	0.44	0.31	0.34	0.44
2.0 A	0.45	*	*	0.40
	Voltage Average			
0.25 A	1.10 V	1.10 V	1.08 V	1.15 V
0.50 A	0.95	0.96	1.08	0.98
0.75 A	0.87	0.89	0.91	0.93
1.00 A	0.80	0.83	0.85	0.87
1.25 A	0.75	0.77	0.83	0.87
1.50 A	0.74	0.77	0.77	0.78

*Tests invalid

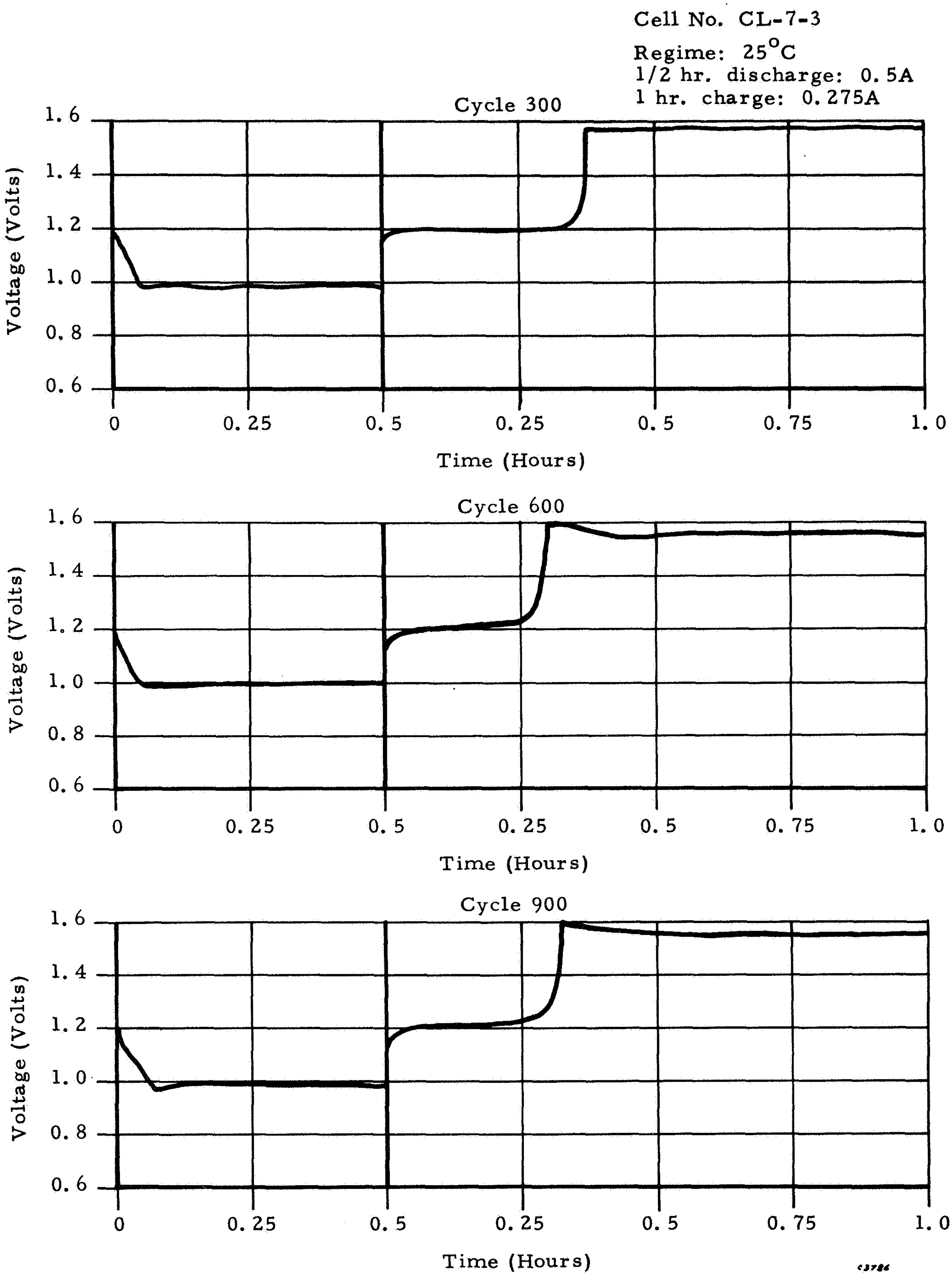


Figure 5. Single Electrode Ag-Cd Cell (0.6Ah)

a certain period on stand, they were put back on cycling in order to accumulate more cycles ahead of the multiplate cells so as to anticipate the failure mode. Their cycle life ranged from 1625 to 2125 cycles after failing to meet their cycling capacity requirement. All cells, except one, were disassembled and no immediate cause of failure could be traced. An attempt was made to revive the remaining cell (cycle 2125), by flushing it with 45% KOH solution so as to try to raise its actual KOH concentration.

The capacity checked first was 0.38 Ah. After reconditioning, the OCV was good over 16 hours (1.40 V), but the capacity was not significantly higher (0.42 Ah). Put back on automatic cycling, it increased to 2492 cycles before failure; the cell could not reach the upper plateau on charge. Upon disassembly, silver penetration appeared to be the cause of failure. Heavy carbonation of the electrolyte also may have been an important factor.

3.2 SILVER ELECTRODE

In order to design a properly balanced cell, the total silver capacity must be smaller than the total cadmium capacity by at least 20%. Keeping the size constant (1.6" x 1.6") similar to previously used electrodes, the thickness and amount of silver can be reduced to the acceptable level required by the silver-cadmium cell design.

A series of electrodes of various thicknesses (down to 0.007") and weights were made and evaluated for capacity to determine their silver utilization.

Table VII shows that although denser than the usual electrode used in the Ag-Zn cell (control coded CL-4-5), the silver utilization is still acceptable around 3 g/Ah. Manufacturing silver plates of good performance at any thickness down to 0.007" does not present any problem.

In order to establish the performance of the silver plate enclosed in a wafer, as is done in the multiplate cell, plates with varied amounts of silver were charged, then discharged against excess zinc to ascertain the full use of silver in the wafer configuration.

TABLE VII

THIN SILVER PLATE CHARACTERISTICS

Plate	Silver Weight	Thickness	Silver Utilization
CL-2-5	4.5 g	22 mils	2.35 g/Ah
CL-2-1	3.0 g	13 mils	2.80 g/Ah
CL-2-2	2.5 g	10 mils	2.80 g/Ah
CL-2-3	2.0 g	9 mils	3.16 g/Ah
CL-2-4	1.5 g	7 mils	3.30 g/Ah

Outputs of two plates in excess electrolyte average the following:

Type	Silver	Output
1	2.5 g (control)	0.75 Ah
2	3.0 g	0.90 Ah
3	3.5 g	1.00 Ah

The multiplate cell Design #2 (see Paragraph 3.3.1) has five positives of Type 1, equivalent to 5 x 0.75 Ah = 3.75 Ah. The cell capacity being 3.7 to 3.9 Ah on the first cycle (with overcharge) shows that the silver is fully used in the multiplate cell.

Type 2 plate, above, shows that the equivalent capacity in a multiplate cell should be 0.9 x 5 = 4.5 Ah. However, in a cell so designed and reported in Paragraph 3.3.2, the extra silver did not bring any additional capacity, giving essentially the same output of 3.5 Ah, as cells using less silver.

3.3 MULTIPLATE CELL DESIGN

Several cell designs were successively tried in an attempt to raise the cadmium to silver ratio. The selected cadmium electrode (22 mil thick) was kept constant. It yields a maximum of 0.54 Ah for the desired area. The silver can give the same output in a thickness of 9 mils. Consequently, the conventional arrangement of alternating polarities on a one-to-one basis may not result in an efficient use of the available internal case space as the increased number of plates entails an increased number of plates, and, therefore, an increased inert-to-active material ratio. Besides, to obtain excess cadmium to silver ratio, the silver plates must be made thinner, and present fabrication techniques prevent such an approach. Consequently, other electrode configurations were considered.

3.3.1 Attempted Designs

A summary of the electrode pack configurations successively tried is presented here in symbolic form. They are explained in the next paragraphs.

Design	Configuration	Number of Cd Plaques
No. 1	$6^{+}w/7^{-}$	7s = 7p
No. 2	$5w^{+}/6^{-}$	4d + 2s = 10p
No. 3	$4w^{+}/5^{-}$	3t + 2d = 13p
No. 4	$4^{+}/5^{-}w$	5d = 10p

Legend:
p = Cd plaque
s = single plaque electrode
d = double plaque electrode
t = triple plaque electrode
w = wafer construction (electrode encapsulated)

3.3.1.1 Design No. 1

The first design consisted of six positive electrodes (0.010" thick and 2.50 g of Ag each) and seven cadmium electrodes. Data are as follows:

Cycle	Rate	Capacity	Drain at 2 A	Total Capacity
1	3 A	3.05 Ah	0.0 Ah	3.05 Ah
2	3 A	3.05 Ah	0.0 Ah	3.10 Ah
3	3 A	3.20 Ah	0.0 Ah	3.20 Ah
4	6 A	2.20 Ah	0.7 Ah	2.90 Ah
5	12 A	1.40 Ah	1.1 Ah	2.50 Ah

Voltage vs rate is given in Figure 6. The discharge shown in Figure 4 was clearly cadmium limiting.

3.3.1.2 Design No. 2

In an effort to raise the cell design capacity, the number of electrodes was reduced, but the number of cadmium electrodes was increased by using a multiple of the present cadmium plaque to make one working negative electrode. Thus, Design No. 2 consisted of five silver positives and six negatives consisting of four double cadmium plaques for the center electrodes and two single plaques for the end electrodes, which brings the total of cadmium plaques to ten, instead of seven as in Design No. 1.

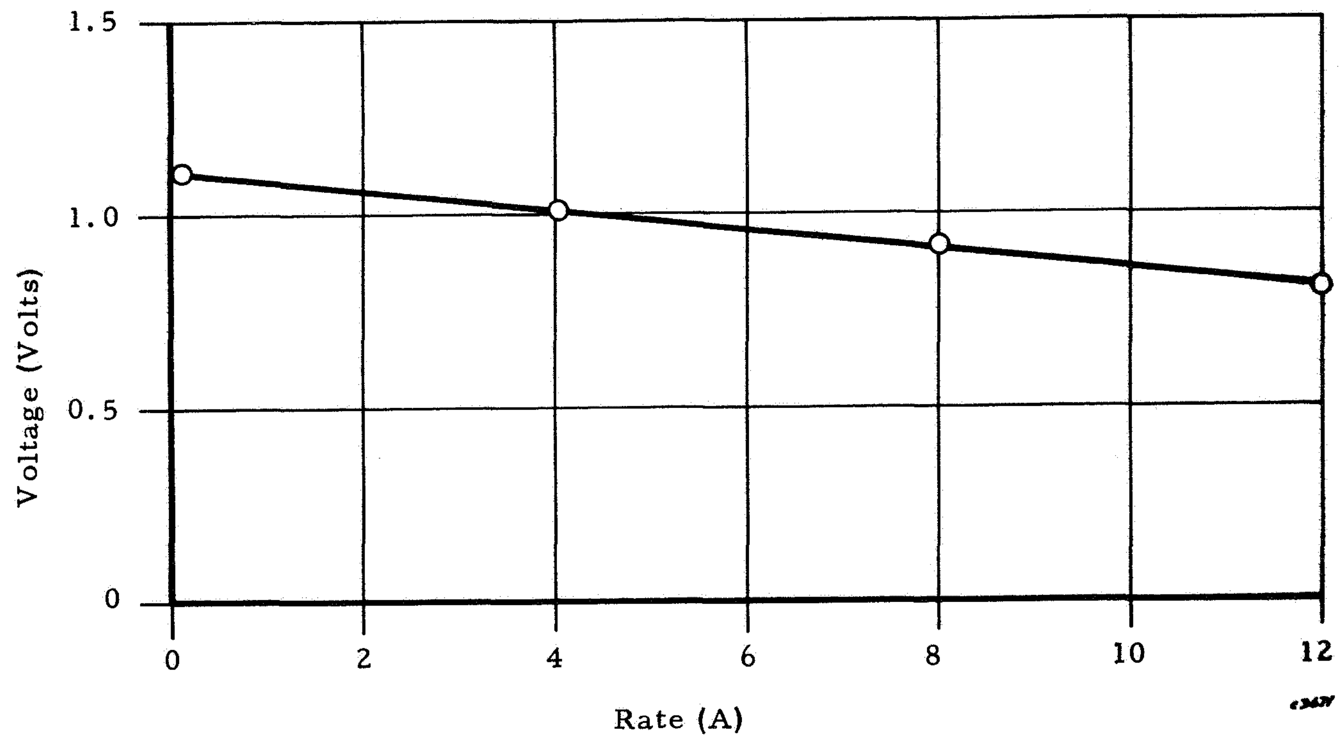


Figure 6. Polarization Curve
Cell CL-5, Design #1, $6\overset{+}{w}/7^{-}p$
(7 plaques)

Cycle	Depth	Output at 2 A to 0.6 V
1	100%	3.8 Ah
2	100%	3.7 Ah
3-400	40%	Automatic cycling
401	100%	3.7 Ah
402-405	40%	Discontinued

Figure 7 shows that the discharge is still cadmium limiting.

3.3.1.3 Design No. 3

Another design used four positives and five negatives consisting of three triple cadmium plaques and two double cadmium plaques, which brings the total of cadmium plaques to 13. Even so, the output was in the same range. Data are as follows:

Cycle	Depth	Output at 2 A to 0.6 V
1	100%	3.7 Ah
2	100%	3.5 Ah
3-400	40%	Automatic cycling
401	100%	3.8 Ah
402-562	40%	Automatic cycling
563	100%	3.5 Ah
564-750	40%	Automatic cycling
750		Discontinued

The discharge in Figure 8 seemed to be less cadmium limiting.

Design No. 3A had the same electrode pack configuration with slightly shortened cadmium plates for ease of construction. Data are as follows:

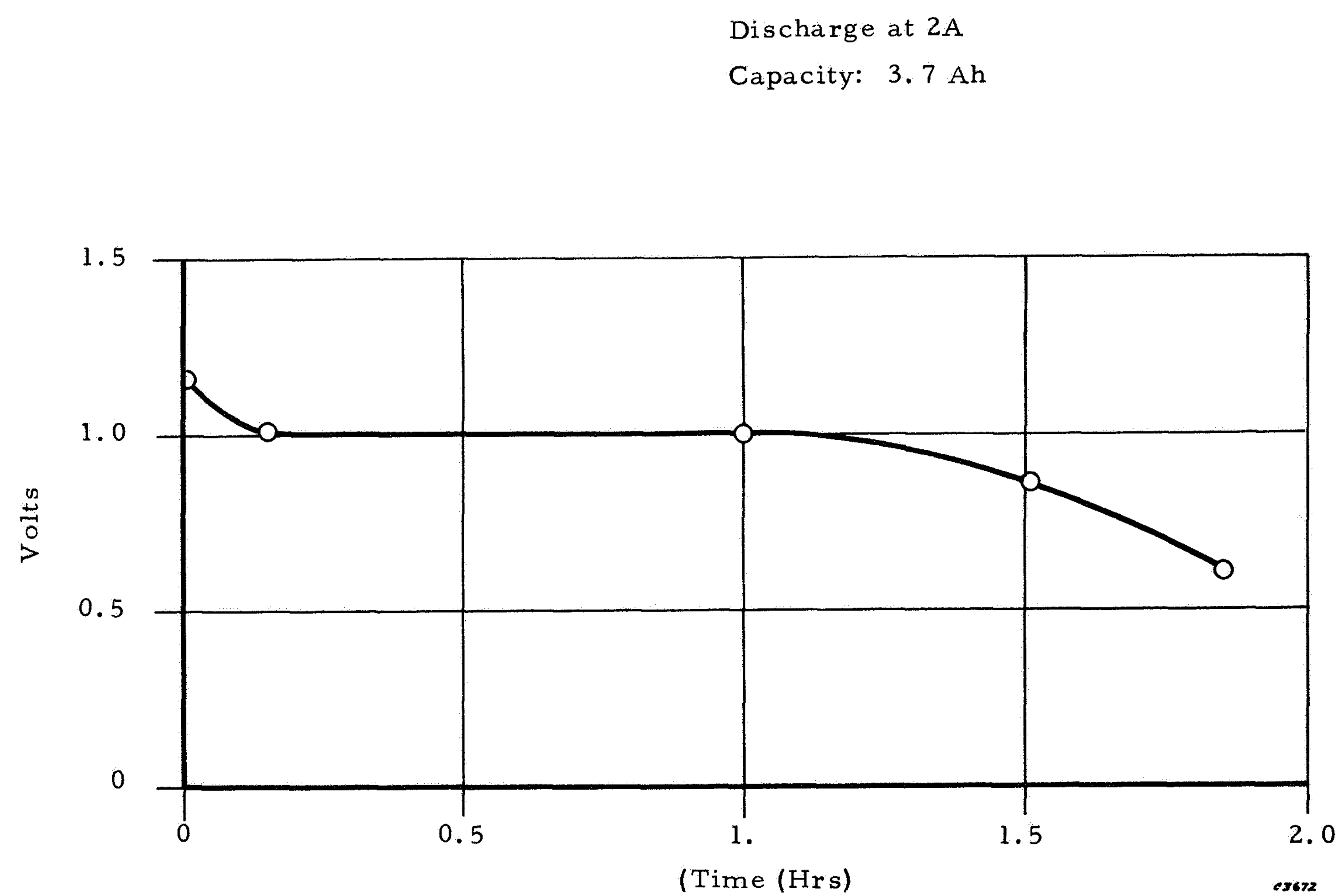


Figure 7. Design #2: $5^{+}w/6^{-}$
(4d + 2s = 10p)

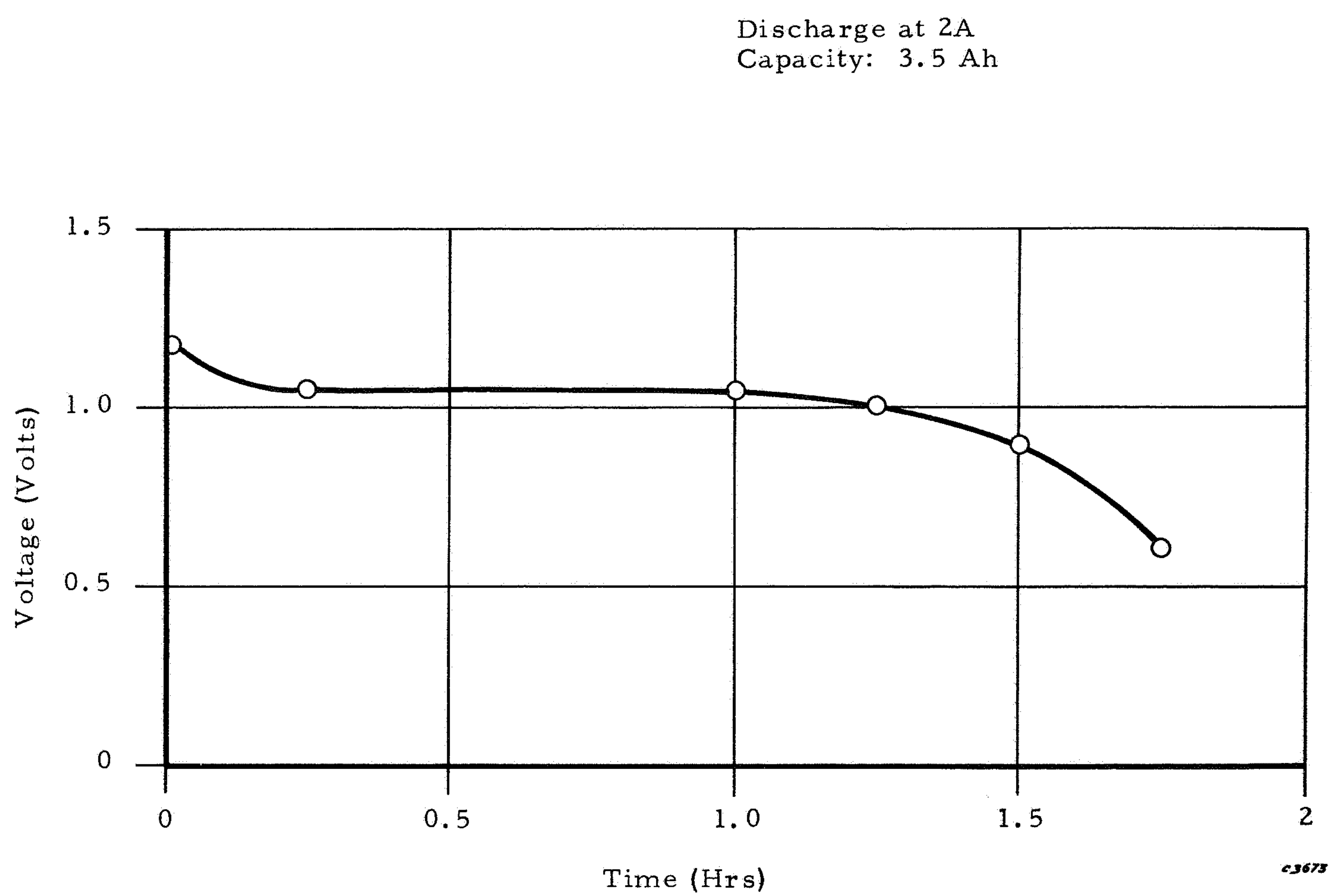


Figure 8. Design #3: $4^{+}w/5^{-}$
(3t + 2d = 13p)

Cycle	Depth	Output at 2 A to 6.0 V
1	100%	4.0 Ah
2	100%	3.2 Ah
3-130	40%	Automatic cycling
131	100%	3.9 Ah
132-292	40%	Automatic cycling
293	100%	3.5 Ah
294-775	40%	Automatic cycling
776	—	Discontinued

Some automatic cycling curves are shown in Figure 9.

3.3.1.4 Design No. 4

One single attempt was made with encapsulated cadmium plates ($4^+/5^-$w). Data are as follows:

Cycle	Depth	Output at 2 A to 0.6 V
1	100%	4.0 Ah
2	100%	3.2 Ah
3-130	40%	Automatic cycling
131	100%	3.5 Ah
132-292	40%	Automatic cycling
293	100%	3.5 Ah
294-600	40%	Automatic cycling
601	—	Discontinued

As discussed in Paragraph 3.3.3, this design was not pursued as the recombination rate of oxygen by cadmium plates was considerably reduced as expected.

3.3.2 Design with More Silver

In an attempt to raise the capacity of the silver-cadmium cell in the present case configuration, one cell was built after Design No. 2, with some extra

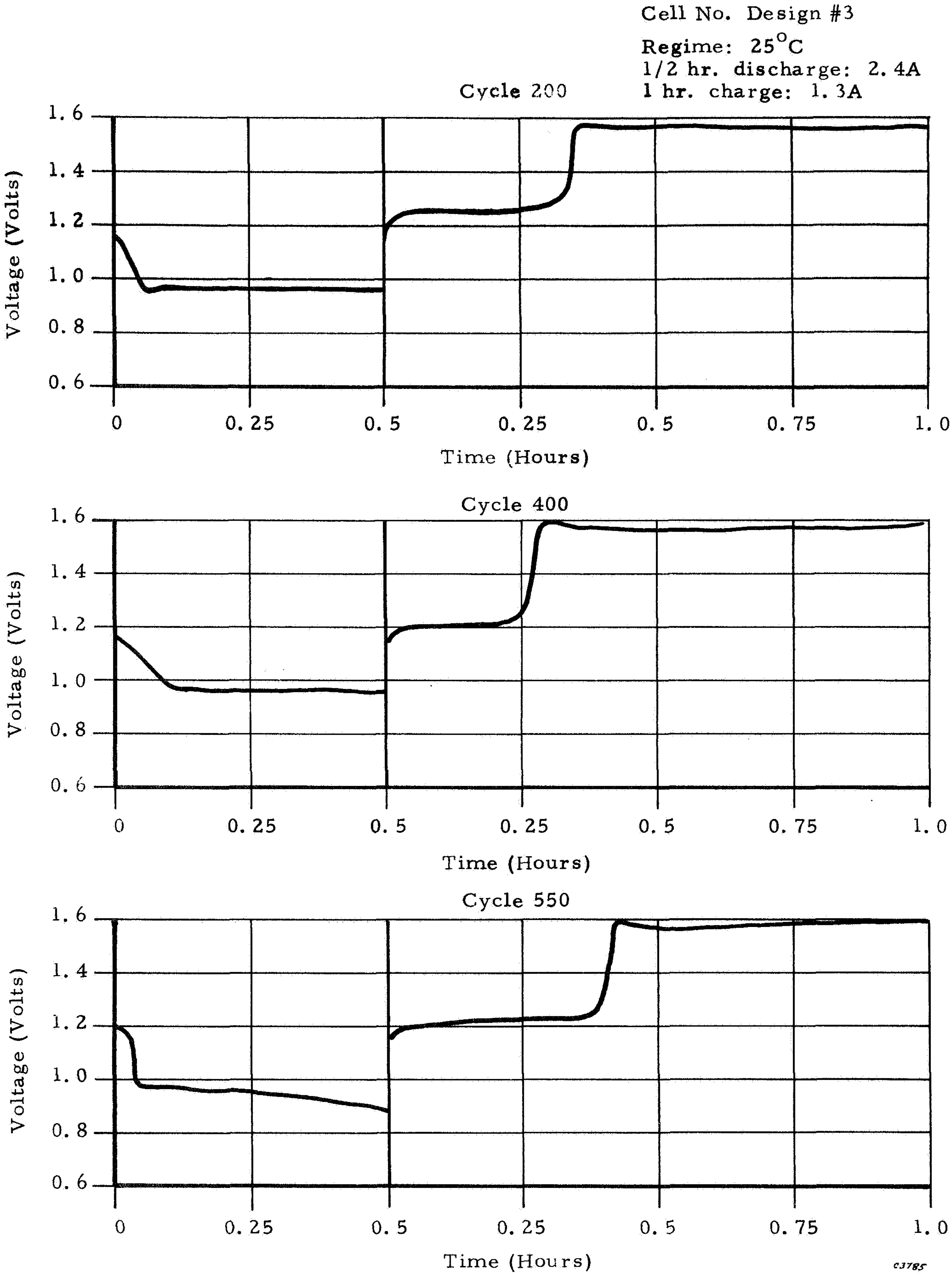


Figure 9. Multiplate Silver-Cadmium Cell (3Ah Nominal)

silver allowed by the space (about 2.5 g more, which is equivalent to about 1 Ah practical).

The data given in Table VIII show that the capacity is still in the same range and therefore is limited by the cadmium capacity available. The cell was put on the same automatic cycling regime (40% depth, 1.5-hr cycling period) until it reached 440 cycles. At this point it became difficult to hold the charging voltage limit and the cycling balance. Because the voltage limit is usually maintained relatively low (1.56 V) to avoid hydrogen gassing at the cadmium on charge, the capacity input was not sufficient to balance the output. On the other hand, raising the voltage limit led to hydrogen evolution long before the available silver was fully charged. This cell model was immediately discontinued. The cell was disassembled; all components were in good condition.

3.3.3 Recombination Rate

3.3.3.1 Cells

In order to help select the version of the multiplate cell design to be tested in the next task, the four cells of Design Nos. 2, 3, 3A, and 4 were fitted with pressure gauges and 40 psi pressure relief valves to monitor the pressure build-up on charge and the pressure decay rate. This was to determine their relative merit for gas recombination. After charge and overcharge, the pressure was built up to 15 psig and the cells were left on stand. The pressure decay rate curve in Figure 10 shows that Design Nos 3 and 3A, having the maximum number of Cd plaques, exhibit the fastest recombination, although No. 2 is not too far behind.

Another test was to evacuate the cells down to 29" Hg after discharge, then charge the cells only to the point where gassing starts (noted by pressure build-up) without reaching hydrogen evolution (by monitoring the charging and voltage and stopping the charge before reaching 1.60-1.65V).

The capacities were as follows:

TABLE VIII

CAPACITY OF CELL DESIGN #2A WITH MORE SILVER (CL-16-1)

Cycle	Input	End Voltage	Output
1	4.0 Ah	1.66 V	3.3 Ah
2	5.1 Ah	1.80 V	4.0 Ah
3	3.5 Ah	1.66 V	3.1 Ah
4	4.0 Ah	1.71 V	3.5 Ah

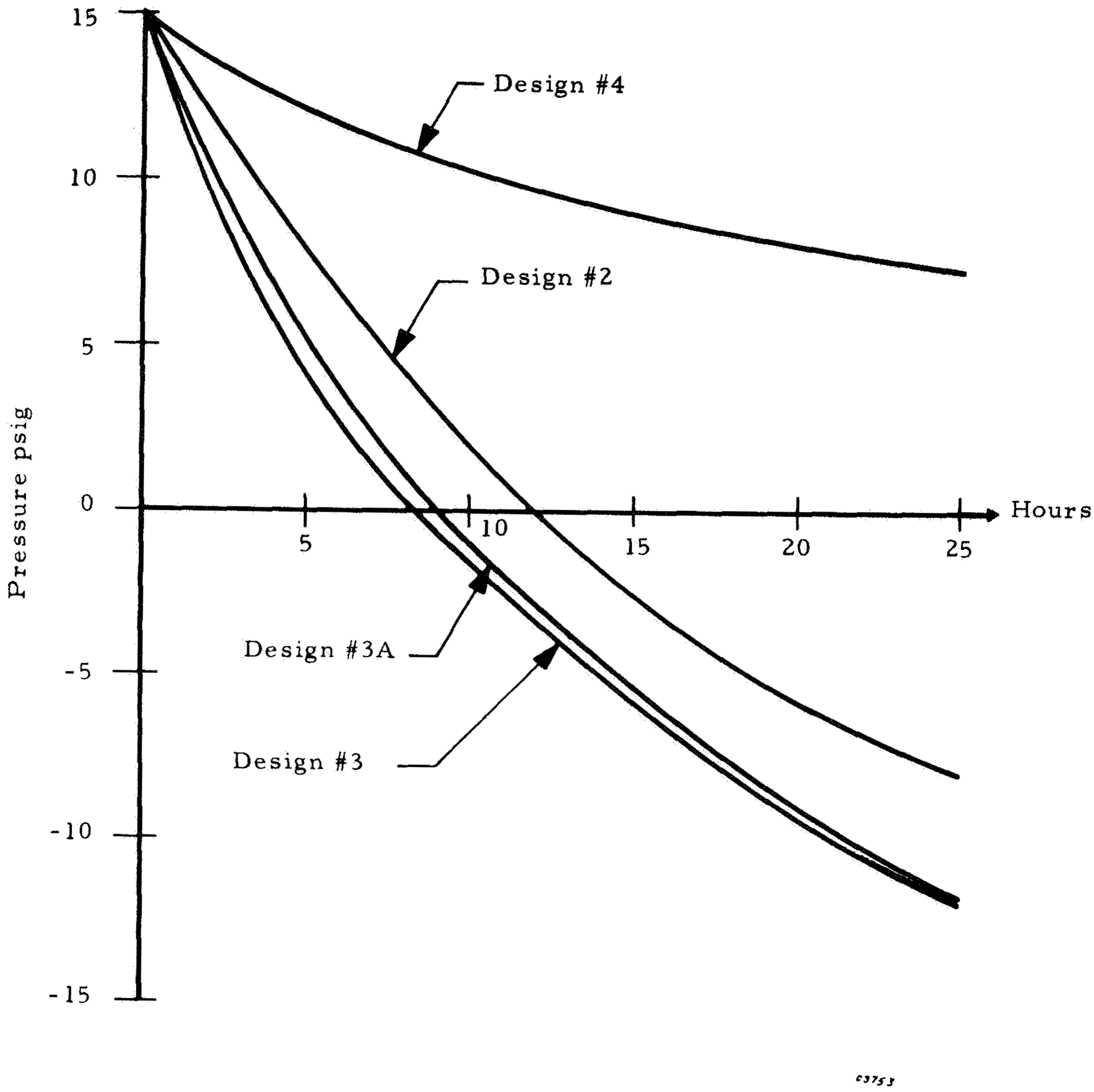


Figure 10. Pressure Decay in Ag-Cd Multiplate Cells

Design No. 3 — 3.40 Ah

Design No. 3A — 3.60 Ah

Design No. 4 — 3.20 Ah

Afterward, the cells were placed on automatic cycling with a voltage limit set at 1.57 V/cell to avoid any gassing (oxygen only, if any) and subsequent pressure build-up. Within one day, all No. 3 designs (which started at 0 psig) dropped to about -28" Hg whereas No. 4 took two days to drop to -9".

3.3.3.2 KOH Concentration

In order to select the KOH concentration with respect to recombination rate of oxygen with the Cd electrodes, pressure decay rate tests were run on Cd plaques charged, soaked in different KOH concentrations (30 and 40%), then sealed in bombs flushed with oxygen and pressurized to 20 psig. Data reported in Table IX and Figure 11 show faster recombination rate with 30% rather than 40% KOH as expected. The end pressure is the same (after 24 hours).

Calculations on bomb volume and pressure drops show that the end pressure after 24 hours is equivalent to a recombination of oxygen by 70% of the cadmium present in the sintered plaque.

In a multiplate cell containing 10 cadmium plaques in a restricted free volume, the pressure would drop to -10" Hg, approximately.

Although the total recombination is as good with 30% as with 40%, the rate is certainly greater in 30%. A fast recombination is desirable for cells on continuous cycling which subjects them to occasional overcharge. The 30% KOH electrolyte was therefore kept on subsequent cell testing.

TABLE IX

PRESSURE DECAY (psig) DUE TO CADMIUM PLATES SOAKED IN DIFFERENT KOH CONCENTRATIONS

Time (Hour)	30%					40% KOH				
	Plate				Average (psig)	Plate				Average (psig)
	#1	#2	#3	#4		#1	#2	#3	#4	
0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
1	17.5	16.0	17.0	15.0	16.4	18.0	19.5	18.5	19.0	18.8
2	17.0	16.0	17.0	15.0	16.3	18.0	19.0	18.0	18.5	18.4
4	17.0	16.0	17.0	15.0	16.3	17.0	18.0	17.5	18.0	17.6
6	17.0	16.0	17.0	15.0	16.3	16.5	18.0	17.5	17.5	17.4
24	16.5	16.0	16.5	15.0	16.0	15.0	16.5	16.0	16.0	15.9

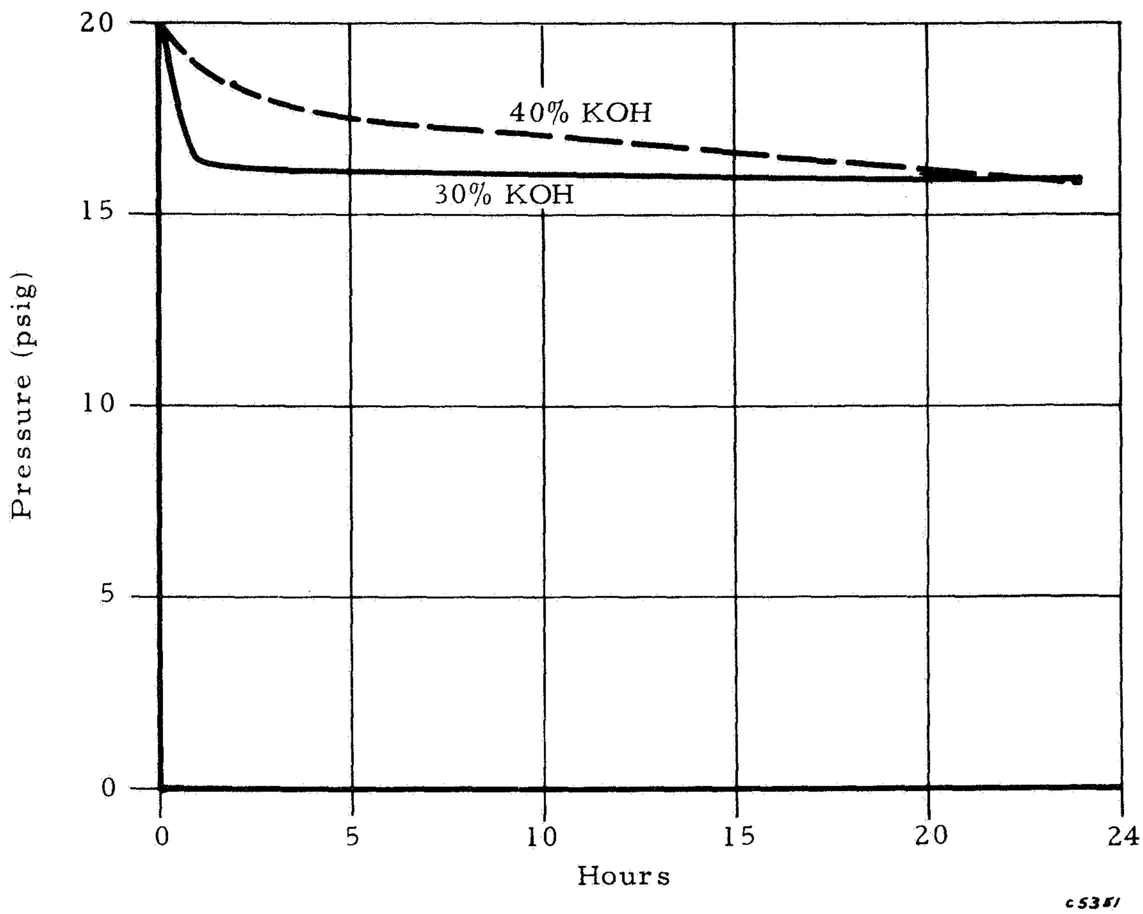


Figure 11. Pressure Decay of Cd Plates in Oxygen Atmosphere (Soaked in Different KOH Concentrations)

Section 4
TASK II – CELL DESIGN DEFINITION

The cell design selected (No. 2A) is Design No. 2 with the following variations:

a. Teflon collars were placed on positive wafers.

b. 40 psig pressure relief valves were used.

c. 30% KOH concentration was temporarily retained in preference to 40%.

The electrode pack configuration is five encapsulated positives and six negatives, consisting of ten cadmium plaques. The total mass of silver is 12.5 g. The cells averaged 3.5 Ah original capacity. After formation and sometimes a few cycles, cells of Task II were tested in groups started at different times on the following regime:

Cycling Period:	90 minutes
Depth:	40% depth of discharge based on average original capacity (3.5 Ah)
Discharge:	2.8 A for 1/2 hour
Charge:	1.55 A to 1.7 A for 1 hour

4.1 GROUP NO. 1

Ten cells were fabricated in this group. On formation (Cycle 1), the cells were purposely overcharged with an input of 6.1 Ah to 1.7 volts. The output averaged 3.8 Ah. Cycle 2 gives the stabilized capacity, meaning that the input was controlled to the point of incipient gassing and slightly higher. The inputs and the outputs were about 3.6 Ah and very close. Table X shows data concerning Cycles 1 and 2. Figure 12 is a typical discharge (Cycle 2).

The work statement required that the cells be removed from test after 200 cycles, disassembled, and examined. However, after reaching 208 cycles, only two cells were discontinued and opened. All components appeared satisfactory. The other eight were kept cycling and reached 500 cycles without failure or adjustment. The voltage at end of discharge is shown at the beginning of their cycling and at cycle 500, in Table XI. Automatic cycling curves are shown in Figure 13.

TABLE X

TEST DATA OF CELLS OF DESIGN #2A

(Group No. 1)

Cell	Cycle 1		Cycle 2			
	Input to 1.70 V	Output to 0.6 V	Input to 1.65 V	Input to 1.60 V	Output to 0.6 V	Plateau Voltage at 2 A
CL-15-1	6.1 Ah	3.7 Ah	3.70 Ah	3.45 Ah	3.55 Ah	1.04 V
CL-15-2	6.1 Ah	3.8	3.70 Ah	3.45 Ah	3.50	1.03 V
CL-15-3	6.1 Ah	3.7	3.70 Ah	3.45 Ah	3.45	1.03
CL-15-4	6.1 Ah	3.8	3.70 Ah	3.45 Ah	3.60	1.03
CL-15-5	6.1 Ah	3.8	3.70 Ah	3.45 Ah	3.50	1.03
CL-15-6	6.1 Ah	3.7	3.70 Ah	3.45 Ah	3.50	1.03
CL-15-7	6.1 Ah	3.9	3.70 Ah	3.45 Ah	3.70	1.03
CL-15-8	6.1 Ah	3.9	3.70 Ah	3.45 Ah	3.70	1.03
CL-15-9	6.1 Ah	3.9	3.70 Ah	3.45 Ah	3.65	1.03
CL-15-10	6.1 Ah	3.9	3.70 Ah	3.45 Ah	3.65	1.03
Average	6.1 Ah	3.8 Ah	3.70 Ah	3.45 Ah	3.58 Ah	1.03 V

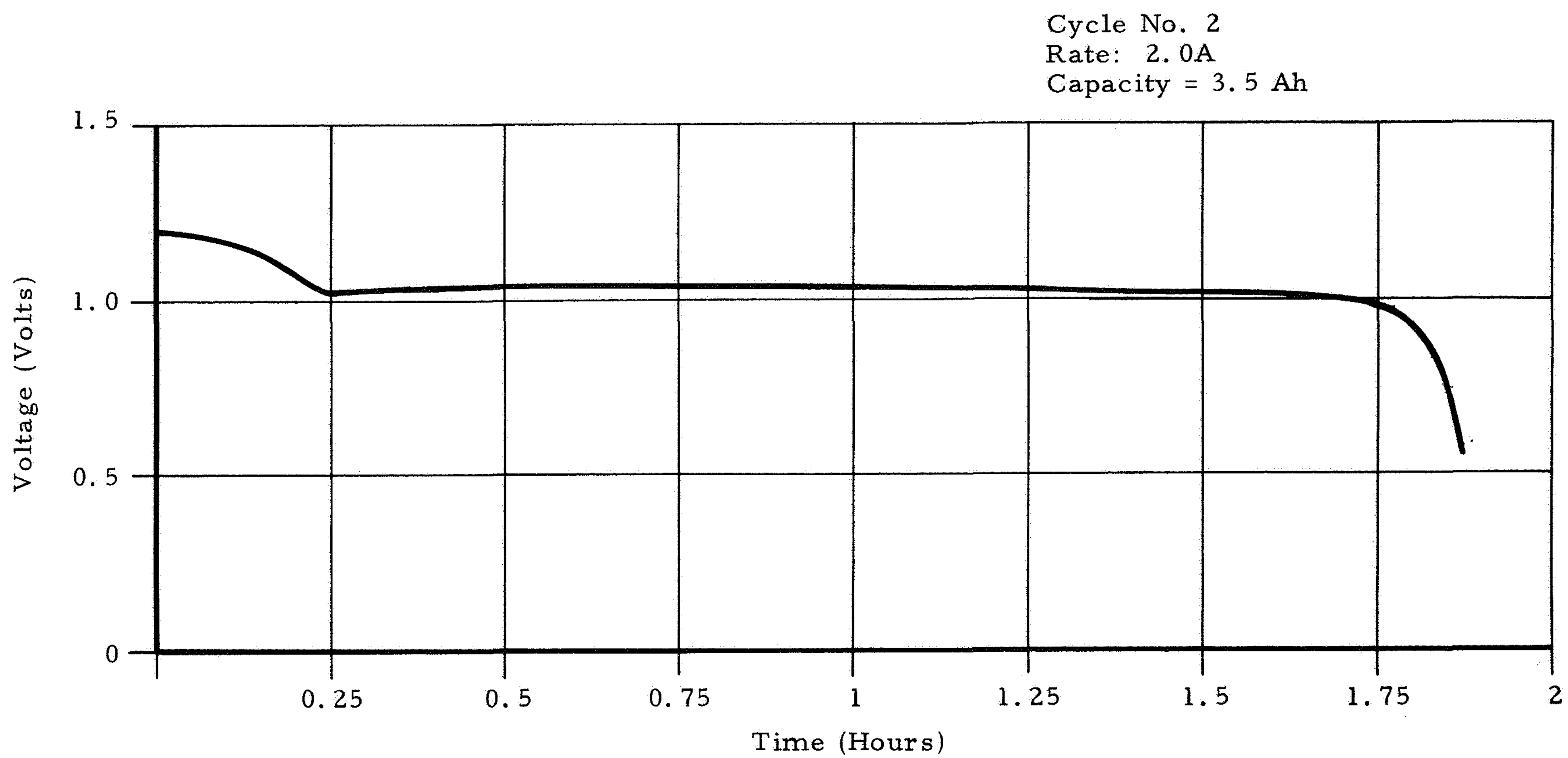


Figure 12. Typical Discharge of Ag-Cd Cell Design #2A

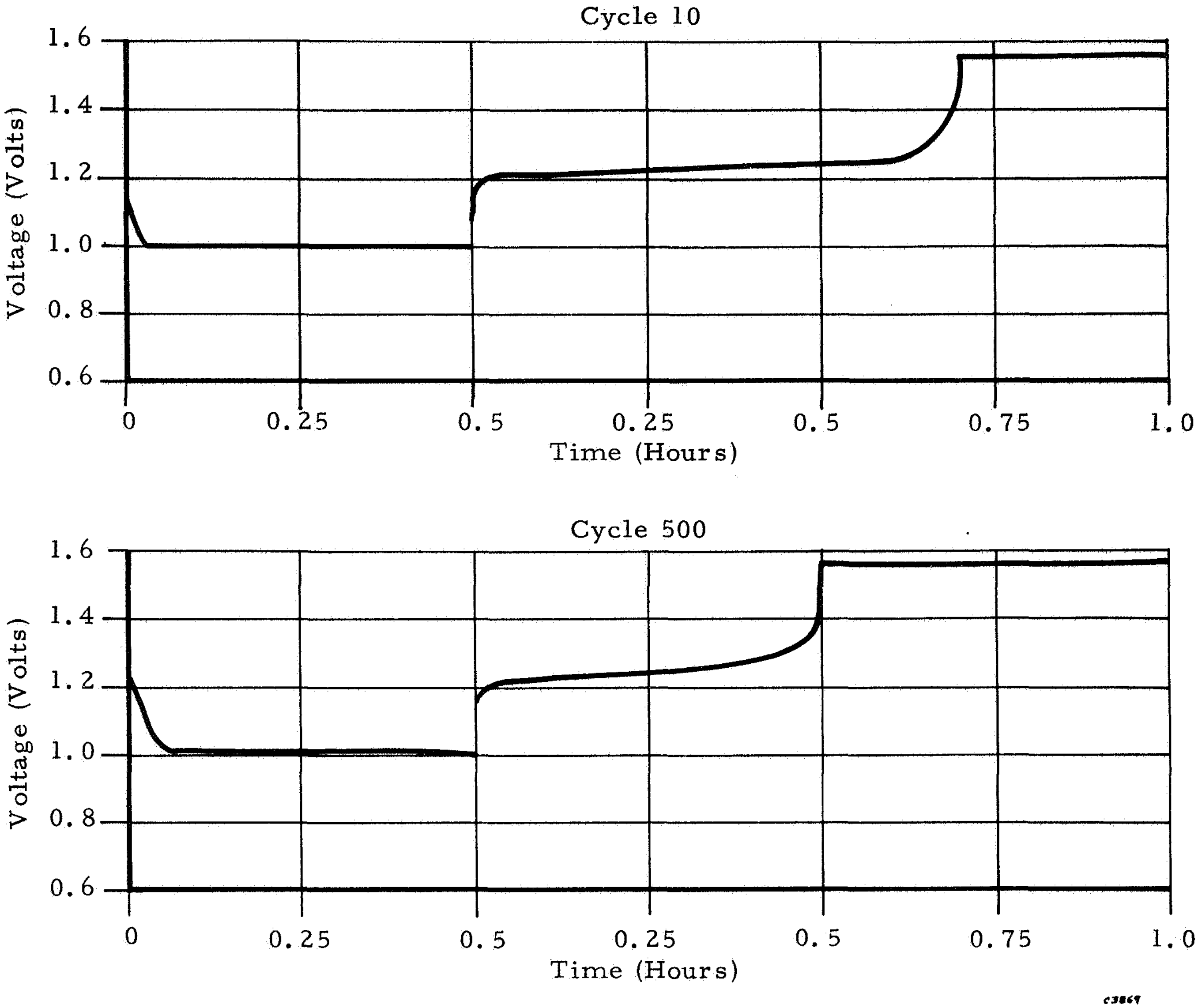
TABLE XI

VOLTAGE AT END OF DISCHARGE

(Rate: 2.8A)

Cell No.	Cycles 1 - 10	Cycles 500
CL-15-1	1.0 V	1.02 V
CL-15-2	1.0	1.00
CL-15-3	1.0	1.01
CL-15-4	1.0	1.01
CL-15-5	1.0	1.00
CL-15-6	1.0	0.98
CL-15-7	1.0	1.00
CL-15-8	1.0	1.00
CL-15-9	1.0	*
CL-15-10	0.98	*
Average	1.0 V	1.0 V

* Discontinued at cycle 208 for dissection and examination.



Cell No. CL-15-1
Regime:
1/2 hr Discharge: 2.8 A
1 hr Charge: 1.55 A

Figure 13. Automatic Cycling of 3.50 Ah Ag-Cd Cell of Group #1

Two of these cells were equipped with pressure gauges. The pressures were, respectively, 2 psig and -14" Hg vacuum, at the beginning. Pressure was monitored through two more cycles to confirm oxygen recombination data (Table XII). On cycle 3, the cells were allowed to gas to 15 psig end pressure. After stand, the pressure dropped to -10" of Hg. A pressure decay rate curve is shown in Figure 14.

One cell, CL-15-6, showed signs of failure after 706 cycles. It was discontinued and opened. One wafer had one cracked separator, the crack running vertically in the center. No immediate explanation was attempted at this time as the phenomenon may have been a deficiency resulting from cell construction, separator fabrication, or stress during cycling.

At cycle 835, the remaining cells showed signs of imbalance in the group and difficulty in maintaining a uniform end-of-charge voltage on each cell. It was decided to discontinue two cells and to open them for examination. Cells CL-15-2 and CL-15-8 were chosen because they showed signs of OCV loss on charged stand. After removing the cover and separating the electrode leads, closer examination of the individual plate OCV's showed imbalance between plates within the same cell. All components were intact, no cracks could be detected in all separators.

The imbalance of plates was attributed to the difference in charge acceptance caused by the uneven wetting of the negative interseparator due to poorly distributed contact pressure between the negative electrode and the positive electrode separator wafer. This is best illustrated in Figure 15 showing how the construction using Teflon tape around the edges of the wafer creates a gap that the Pellon interseparator does not fill uniformly, nor does necessarily the electrolyte after prolonged cycling.

This is evidence by the uneven pattern of matching streaks shown on Figure 16, representing a picture of the components of an element (silver electrode, interseparator and cadmium electrode).

To circumvent this difficulty, the cells of later groups were built with an extra piece of Pellon filling the gap.

TABLE XII

PRESSURE DATA ON CELLS OF DESIGN #2A

Cell	Charge			Stand		Discharge
	Input (Ah)	End Voltage (V)	End Pressure (psig)	End Pressure After 19 Hours	End Pressure After 48 Hours	Output (Ah)
Cycle 3						
CL-15-1	3.60	1.66	+15	-2" Hg	-14" Hg	3.60
CL-15-2	3.74	1.70	+15	-2"	-10"	3.60
Cycle 4						
CL-15-1	3.3	1.60	-14" Hg			3.20
CL-15-2	3.3	1.61	-10"			3.20

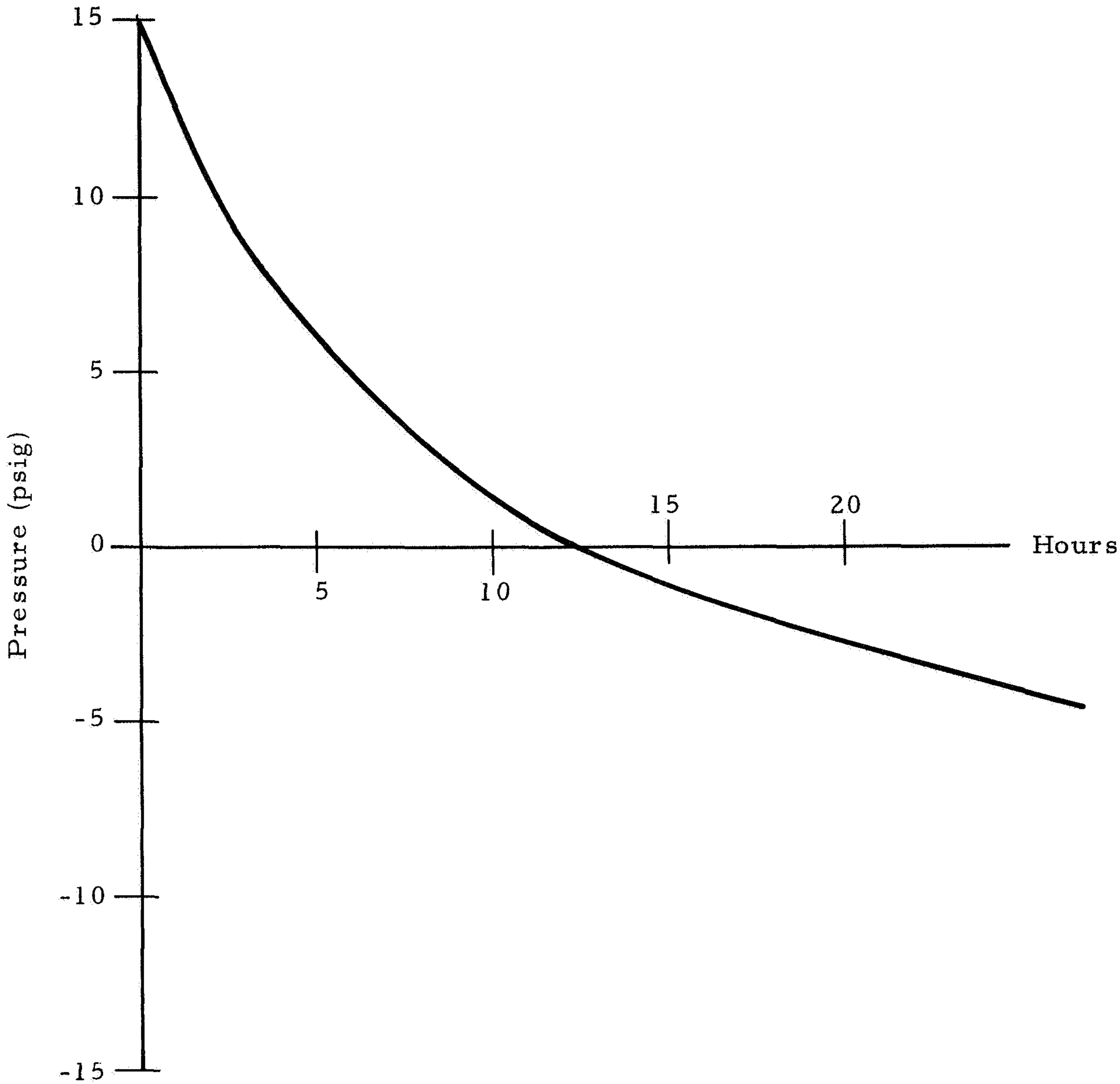


Figure 14. Pressure Decay in Ag-Cd Cells
No. CL-15-1 and CL-15-2
Design #2A

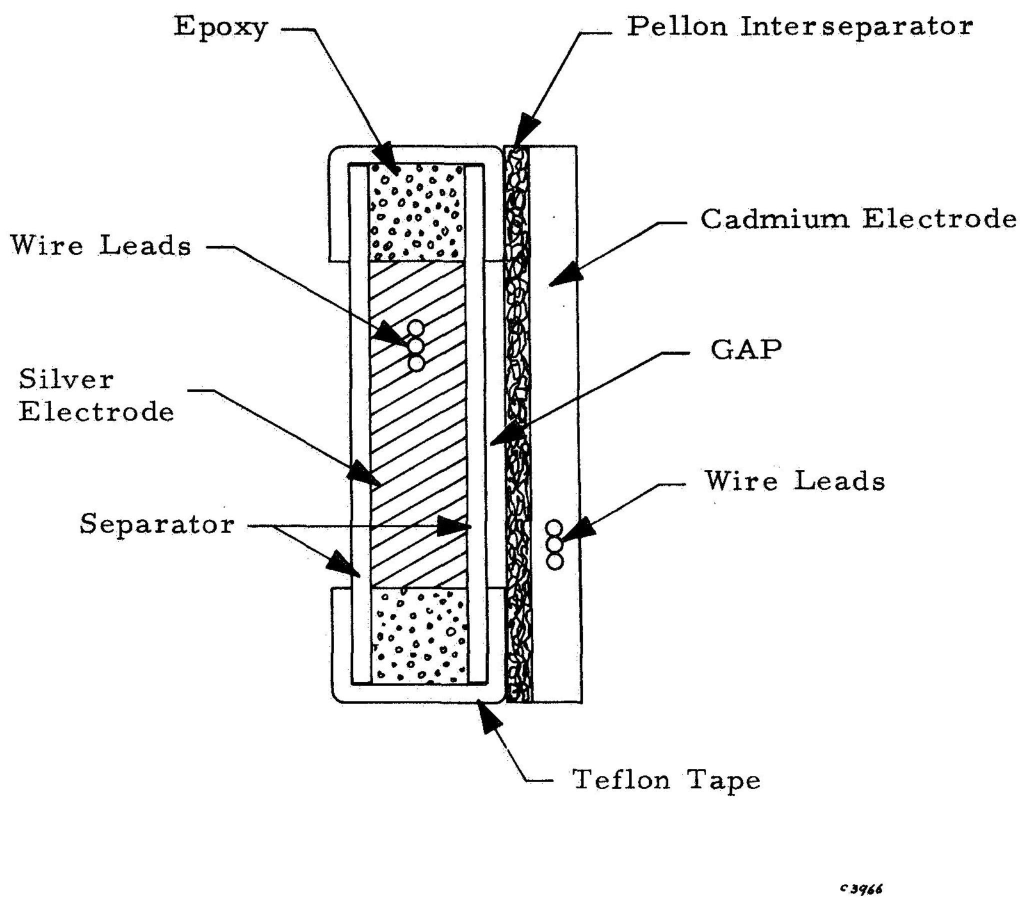
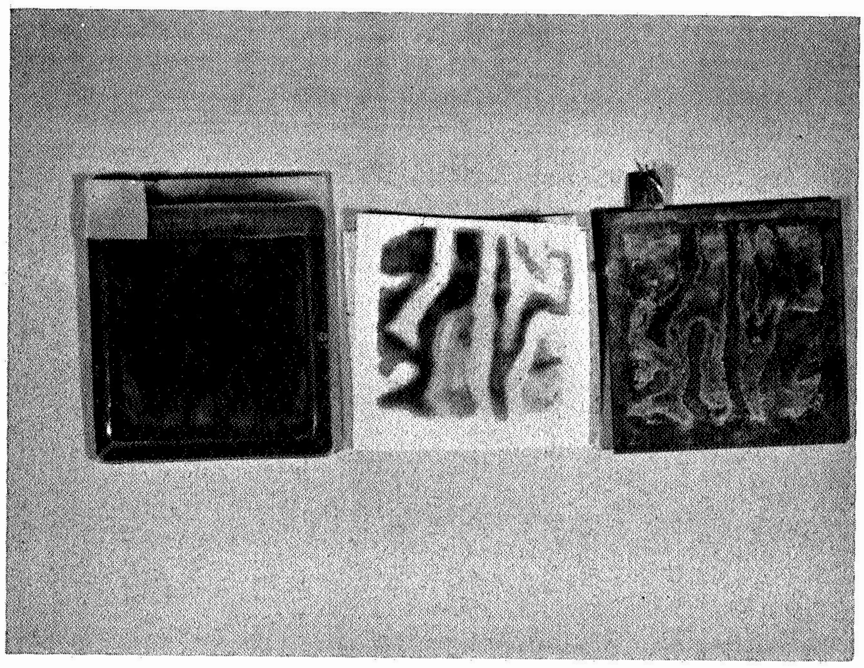


Figure 15. Top Cross-Section of One Ag-Cd Element



C3965

Figure 16. Positive Wafer, Pellon Interseparator, and Cadmium Electrode (Left to Right)

Another balancing was attempted on the remainder of the cells of this group (group No. 1) and the cells were put back on cycling, at cycle 836. At cycle 848, imbalance started again: Some cells were overcharged, while others were undercharged (Figure 17). Cell CL-15-1, which was provided with a pressure gauge, went from 0 to 40 psig in 16 hours. All cells were stopped except the cell with the pressure gauge. After releasing the pressure and the sealing, this cell was left cycling as above, maintaining its voltage limit to 1.56 V. At cycle 850, the pressure was -4" Hg. At cycle 900, it dropped to -22" Hg. However, the charge current had to be raised to 1.80 A to maintain a sufficient input for uninterrupted cycling.

At cycle 1046, signs of weakness on discharge imposed a new readjustment of the charge current up to 2.0 A, and an increase of the limiting voltage to 1.60 V. The cell began to cycle successfully again. The pressure did not build up. After a few days, it was decided to determine how high the voltage could be increased without building excessive pressure. Raising the voltage to 1.62 V caused the pressure to stabilize at +5 psig and remain constant. The stabilization pressure P_s was reached at an end-of-charge current of 400 mA. Some cycling characteristics are shown in Figures 18 and 19. The last cells of the group failed after 1207 cycles and 1531 cycles. Cell CL-15-1, discontinued after 1207 cycles, had three cracked separators; the other cells had all their components in good condition, but the separators had some dark stains extending through them which appear to be selected sites of silver penetration.

All cycling data are summarized and compared with other groups later in Table XXXII.

4.2 GROUP NOS. 2 AND 3

Shortly after Group No. 1, two groups (Nos. 2 and 3) of 5 cells each, were built and formed. Tables XIII and XIV give their formation capacities. They were cycled separately on the same test regime (40% depth). They ran into the same imbalance as Group No. 1. The same comments as for Group No. 1 hold true for these two groups.

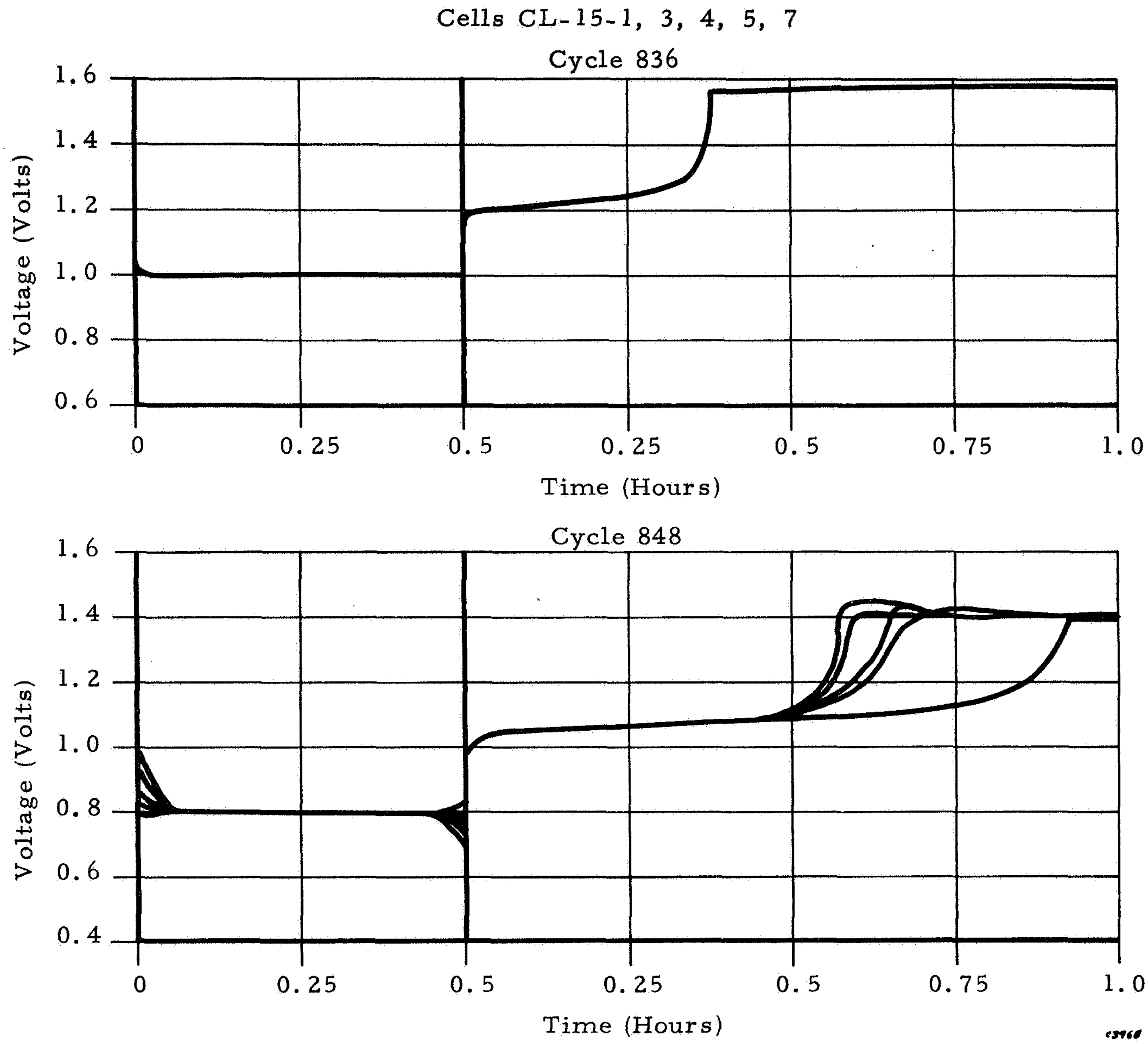


Figure 17. Group #1: Imbalance of Cells Previously Balanced at Cycle 836

Regime: Discharge = 2.8 A for 1/2 hr
Charge = 1.55 A for 1 hr

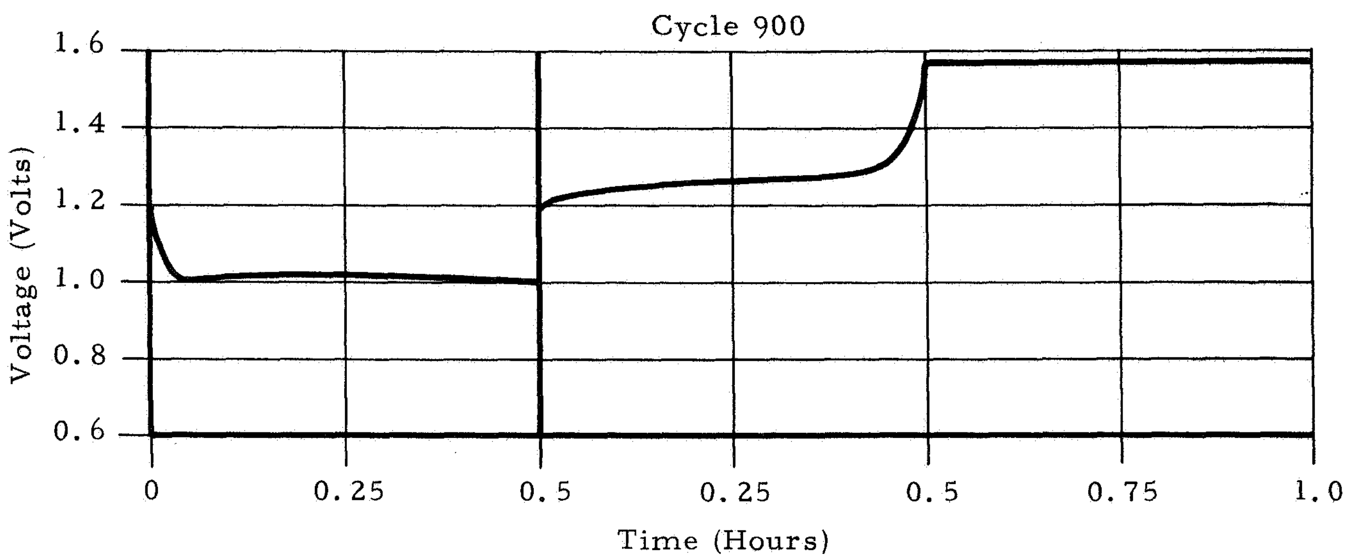


Figure 18. Group #1: Cell CL-15-1 Cycling Alone

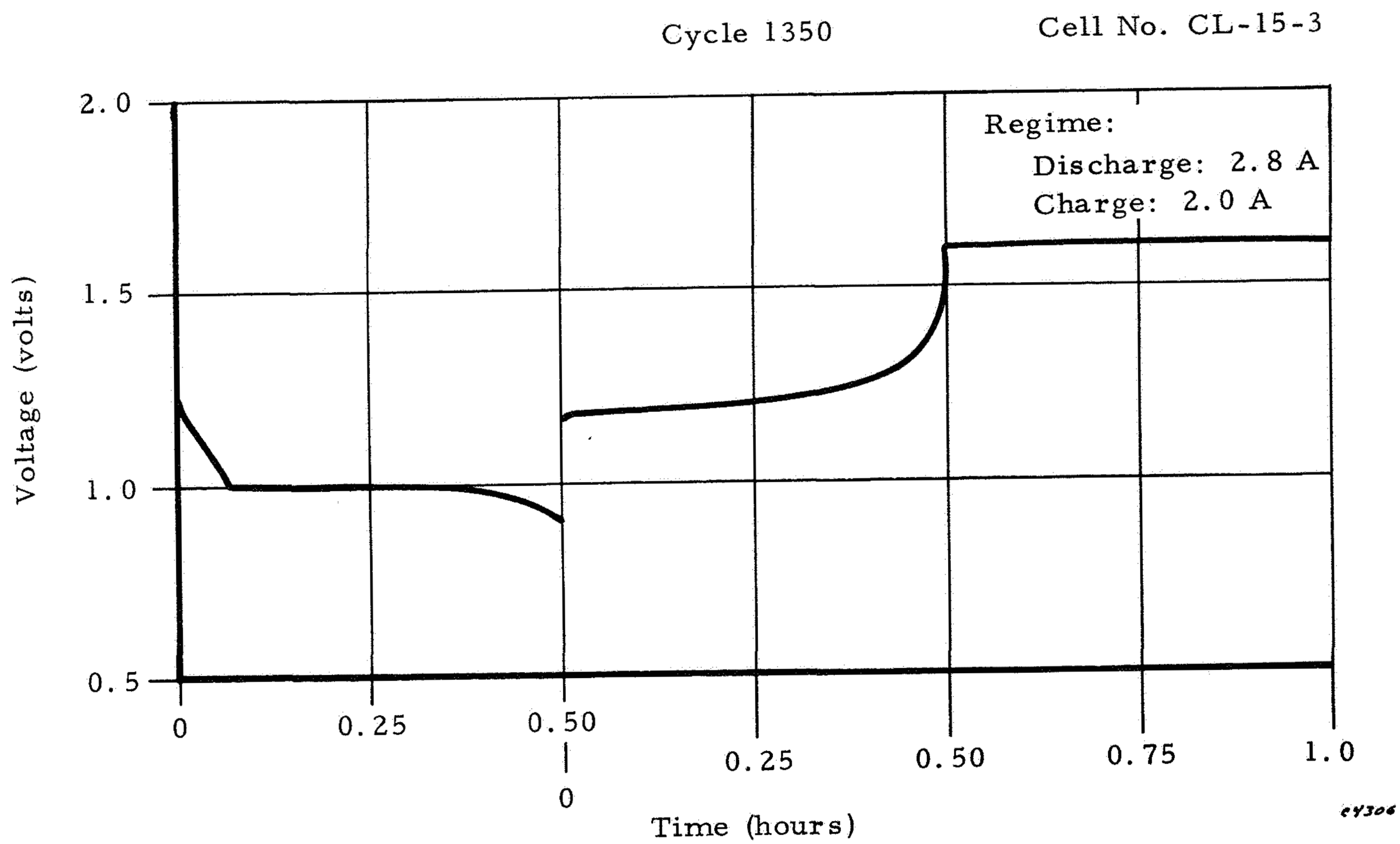


Figure 19. Group #1 Cycling Curve

TABLE XIII

FORMATION OF SILVER-CADMIUM CELLS
OF GROUP #2

Cell No.	Cycle 1 Input	Cycle 1 Output
CL-20-1	7.0 Ah	3.70 Ah
CL-20-2	7.0 Ah	3.70 Ah
CL-20-3	7.0 Ah	3.60 Ah
CL-20-4	7.0 Ah	3.60 Ah
CL-20-5	7.0 Ah	3.80 Ah
Average	7.0 Ah	3.68 Ah

TABLE XIV

FORMATION OF Ag-Cd CELLS OF GROUP #3

Cell No.	Cycle 1	
	Input	Output
CL-22-1	6.3 Ah	3.50 Ah
CL-22-2	6.3 Ah	3.50 Ah
CL-22-3	6.3 Ah	3.80 Ah
CL-22-4	6.3 Ah	3.50 Ah
CL-22-5	6.3 Ah	3.50 Ah
Average	6.3 Ah	3.56 Ah

Two cells of Group No. 2 were stopped after 300 cycles. Their capacities were 3.8 Ah and 3.6 Ah and their components were intact. Figures 20 to 24 show the variations in cycling characteristics.

Two cells of Group No. 3 were stopped after 209 cycles. Their capacities were 3.5 Ah and 3.1 Ah and their components were intact. Figures 25 to 32 show the variations in cycling characteristics. One cell of Group No. 3, CL-22-4, reached 5664 cycles. Electrolyte addition was 2 cm^3 only.

In cells of both groups, the uneven pattern of streaks was observed on all negative interseprators when the cells were opened.

Cycling data are presented in Table XXXII for comparison with other groups.

4.3 GROUP NOS. 4 AND 5

These are groups of five cells each using an extra piece of Pellon to fill the gap described in Paragraph 4.1.

Data on formation presented respectively in Tables XV and XVI, show no significant difference in capacity or voltage.

In both groups, the uniformity was relatively good. To quantify the uniformity value, a study of the cycling curves at various times was made to include percentage of the peroxide voltage portion on discharge (p%), the end voltage on discharge (V_e), the percentage of the monoxide voltage portion on charge and the final voltage on charge (V_f).

This method establishes a basis for studying the degree of variation between cells of the same group at a given cycle, between different cycles of the same cell, and between cells of different groups.

However, after a large number of cycles, the imbalance set in and cells had to be cycled individually.

Group No. 4 data are presented in Tables XVII to XX and Figures 33 to 36. Group No. 5 data are presented in Tables XXI to XXIII and Figures 37 and 38. Cycling data are presented in Table XXXII for comparison with other groups.

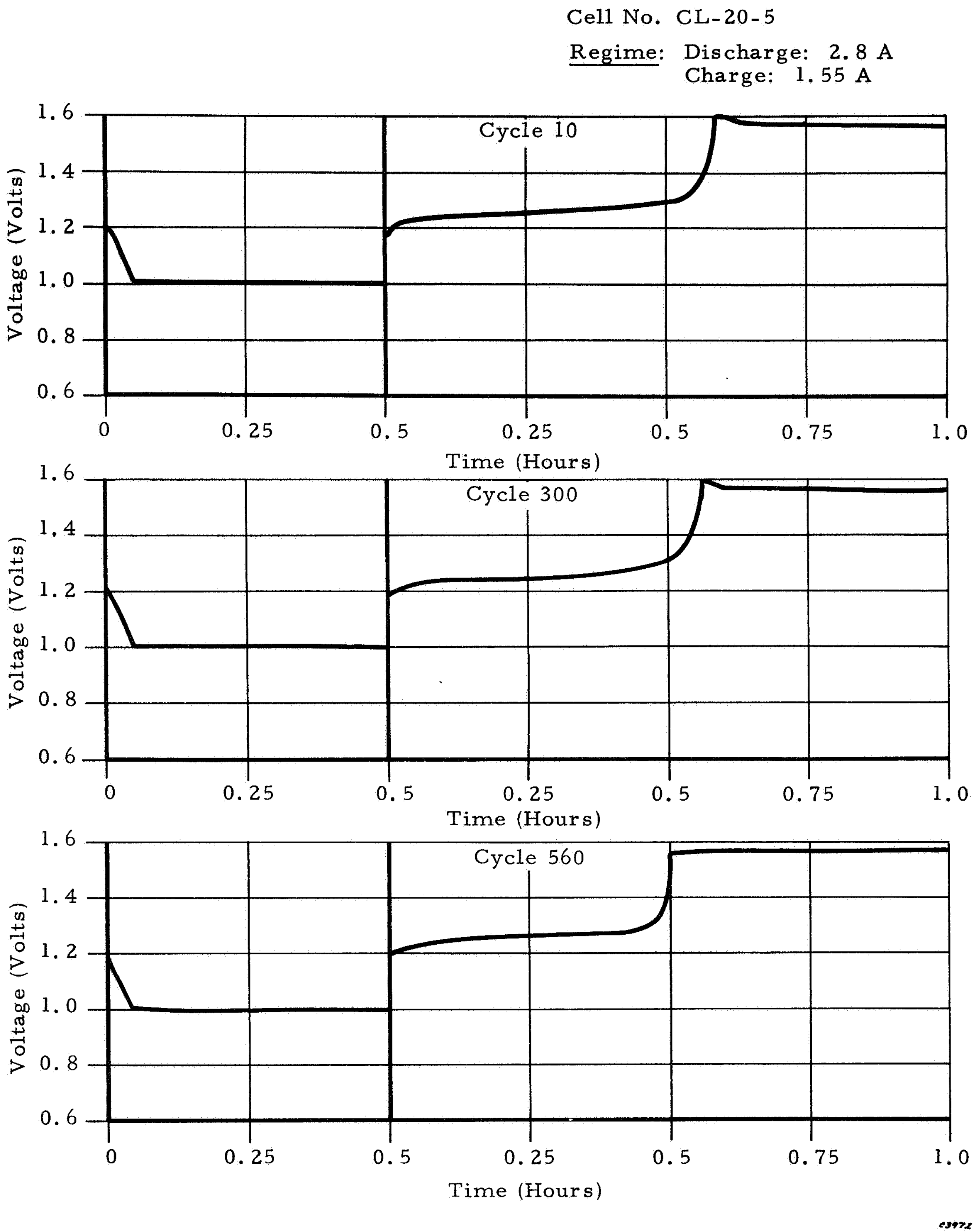
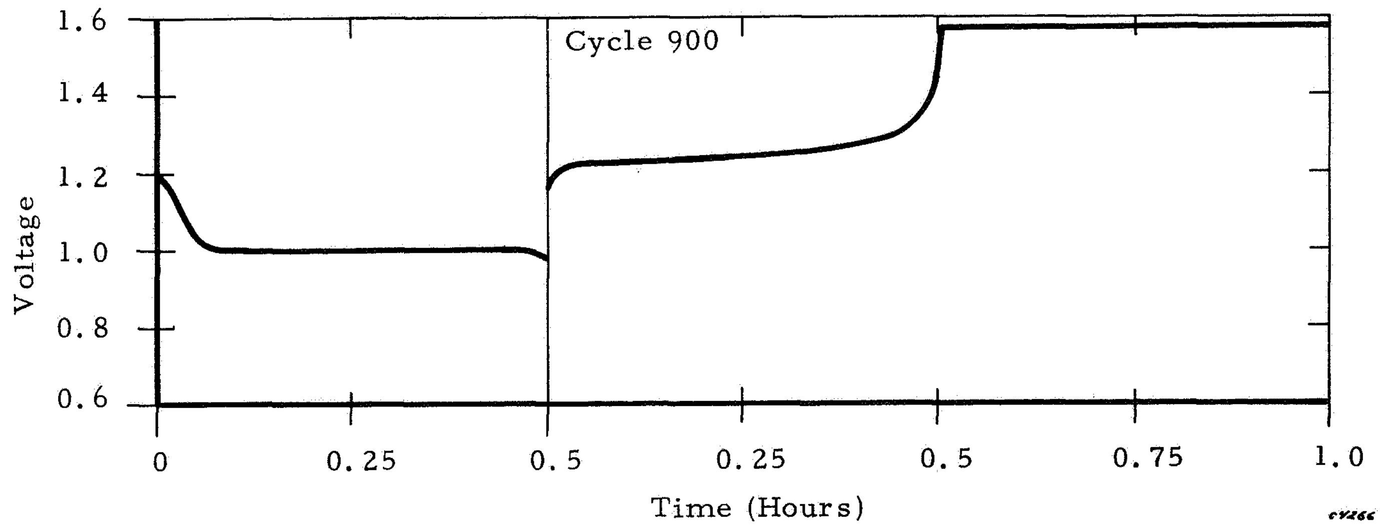


Figure 20. Cycling Curves of Group #2



Regime: Discharge = 2.8 A
Charge = 1.55 A

Figure 21. Group 2 Cell Cycling Curves

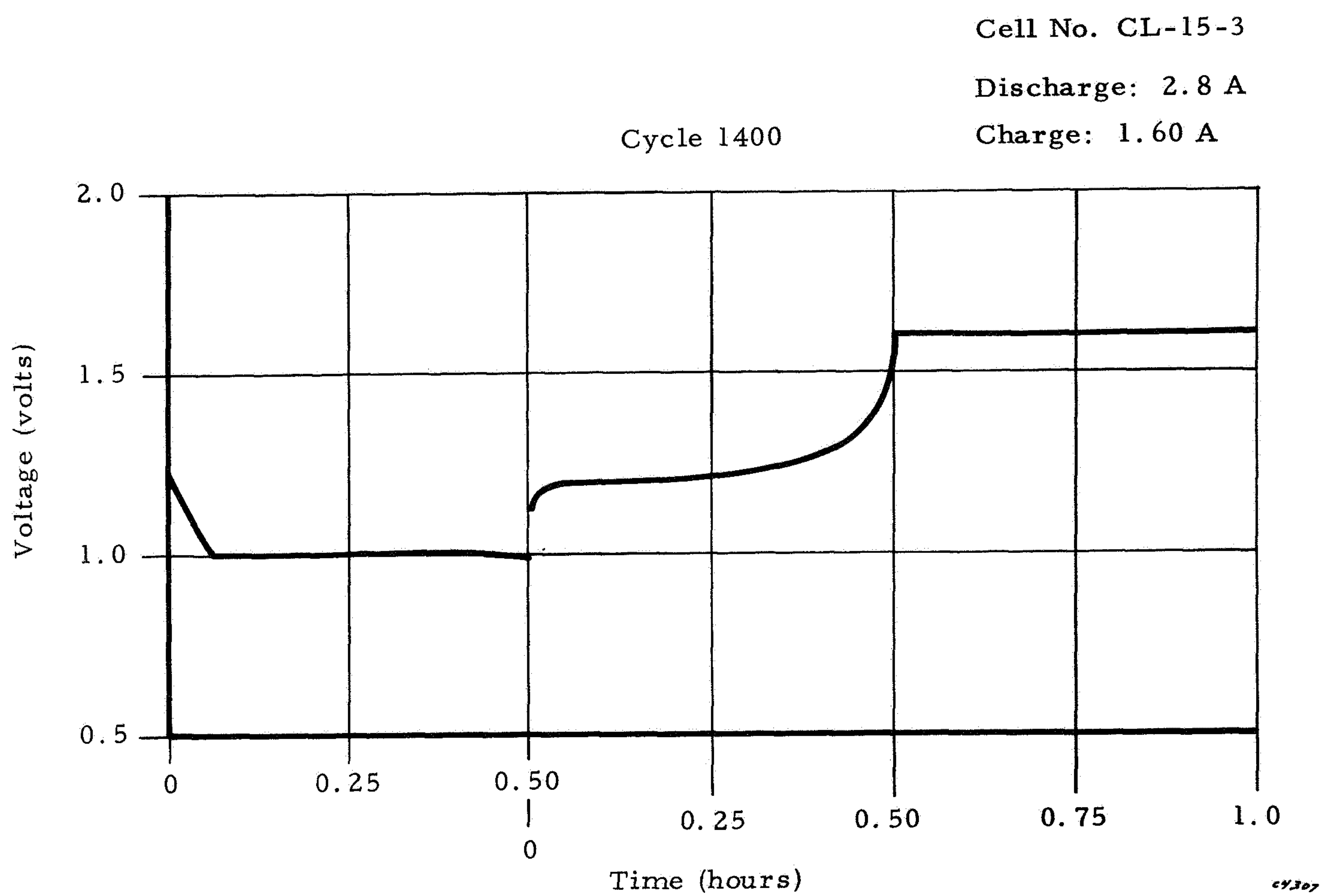


Figure 22. Group #2 Cycling Curve

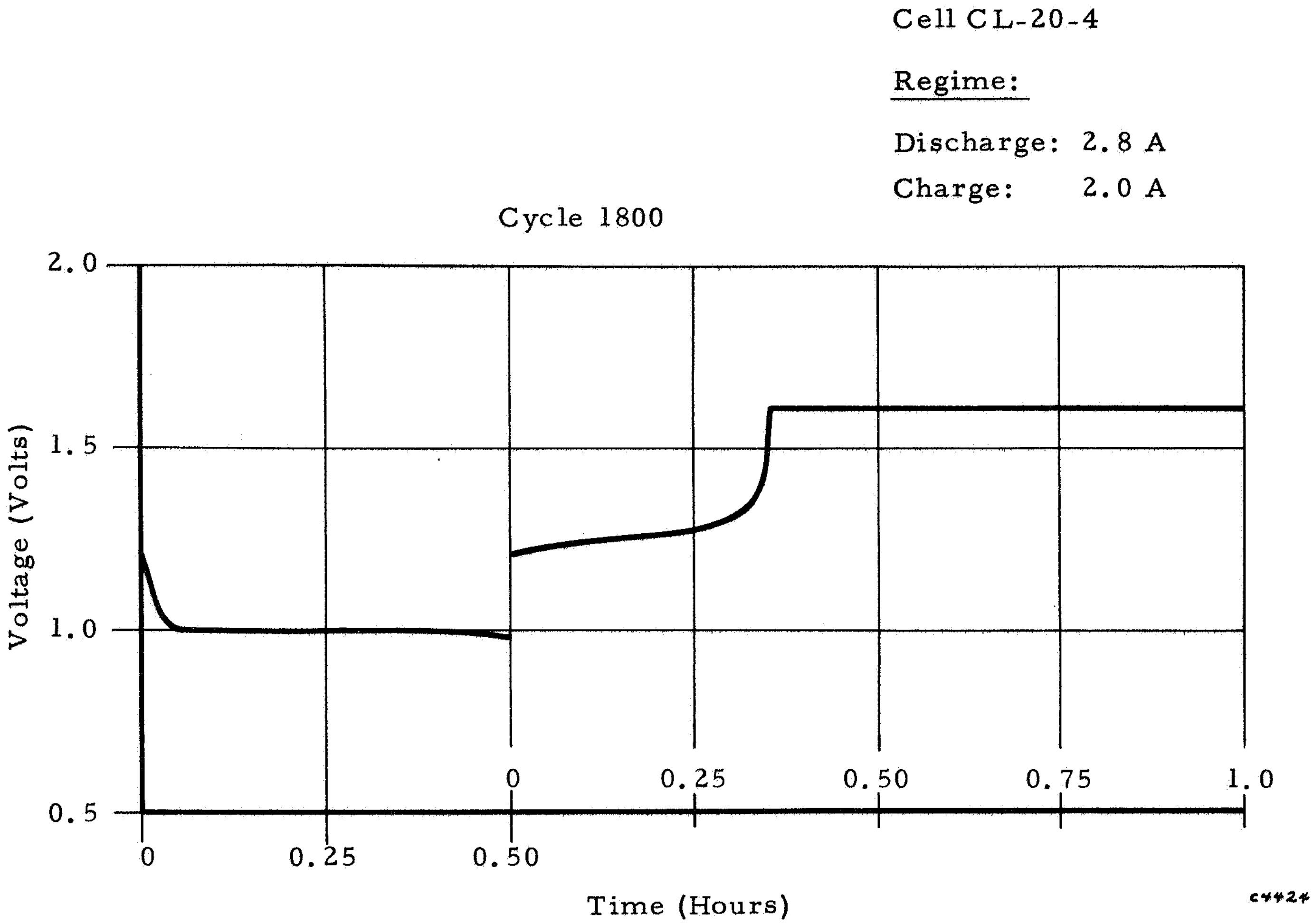


Figure 23. Group #2 Cycling Curves

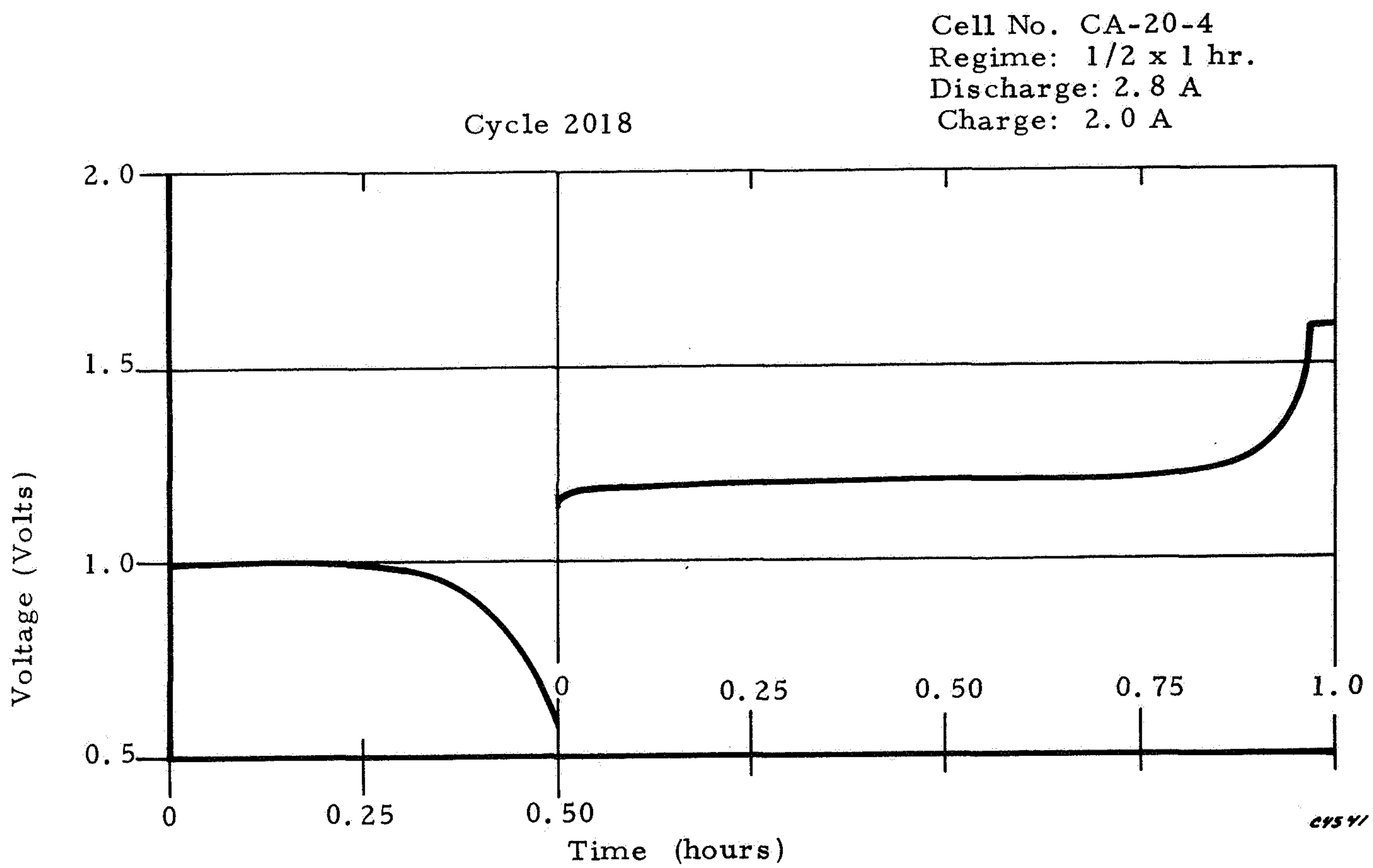
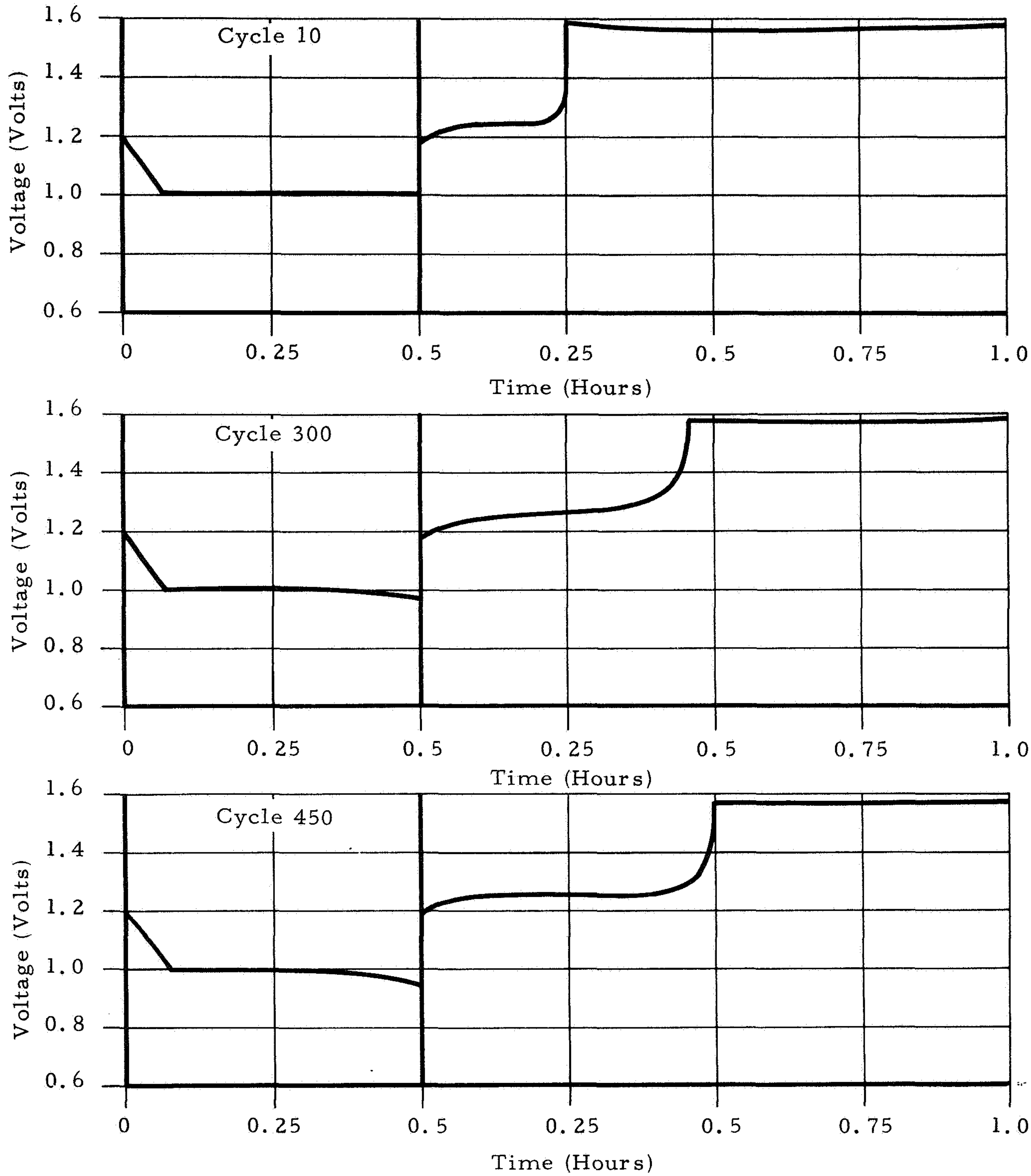
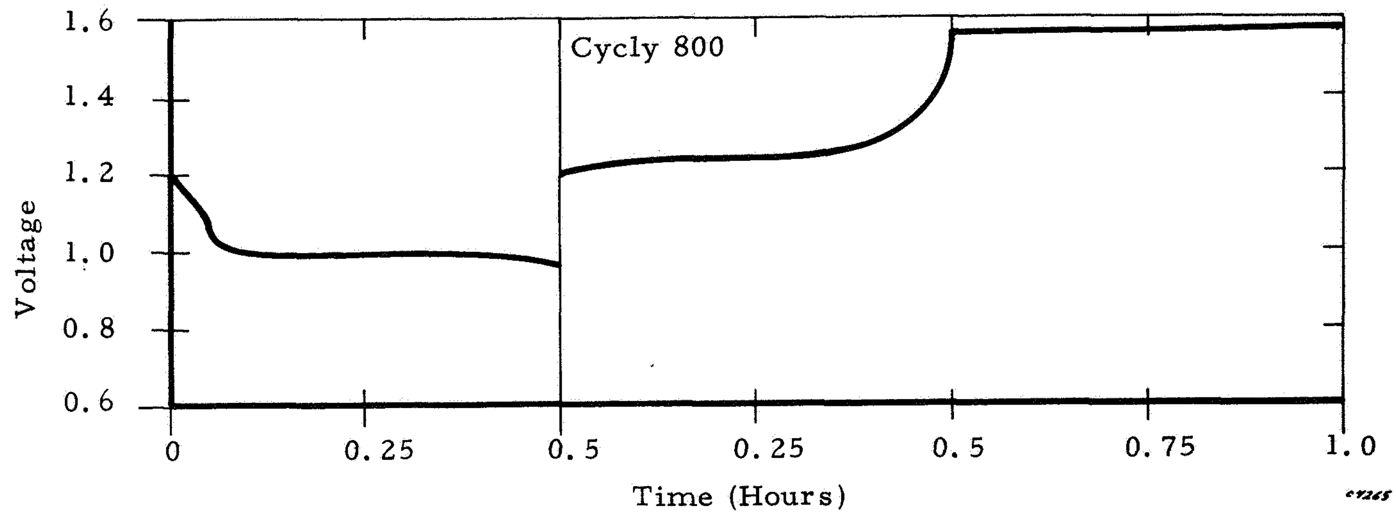


Figure 24. Group No. 2 Cycling Curves



Cell No. CL-22-1
Regime: Discharge: 2.8 A
Charge: 1.55 A

Figure 25. Cycling Curves of Group #3



Regime: Discharge = 2.8 A
Charge = 1.55 A

Figure 26. Group 3 Cell Cycling Curve

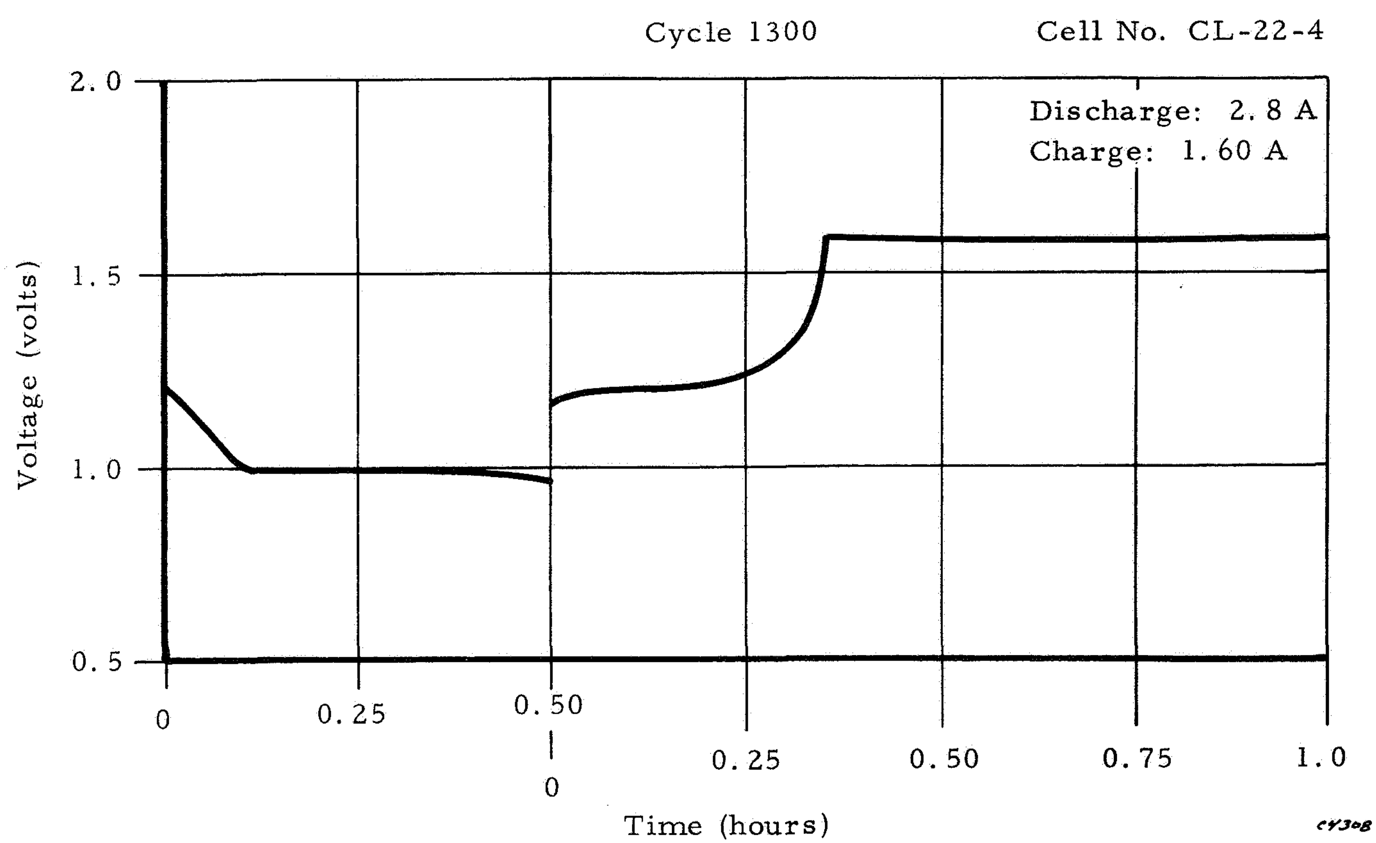


Figure 27. Group #3 Cycling Curve

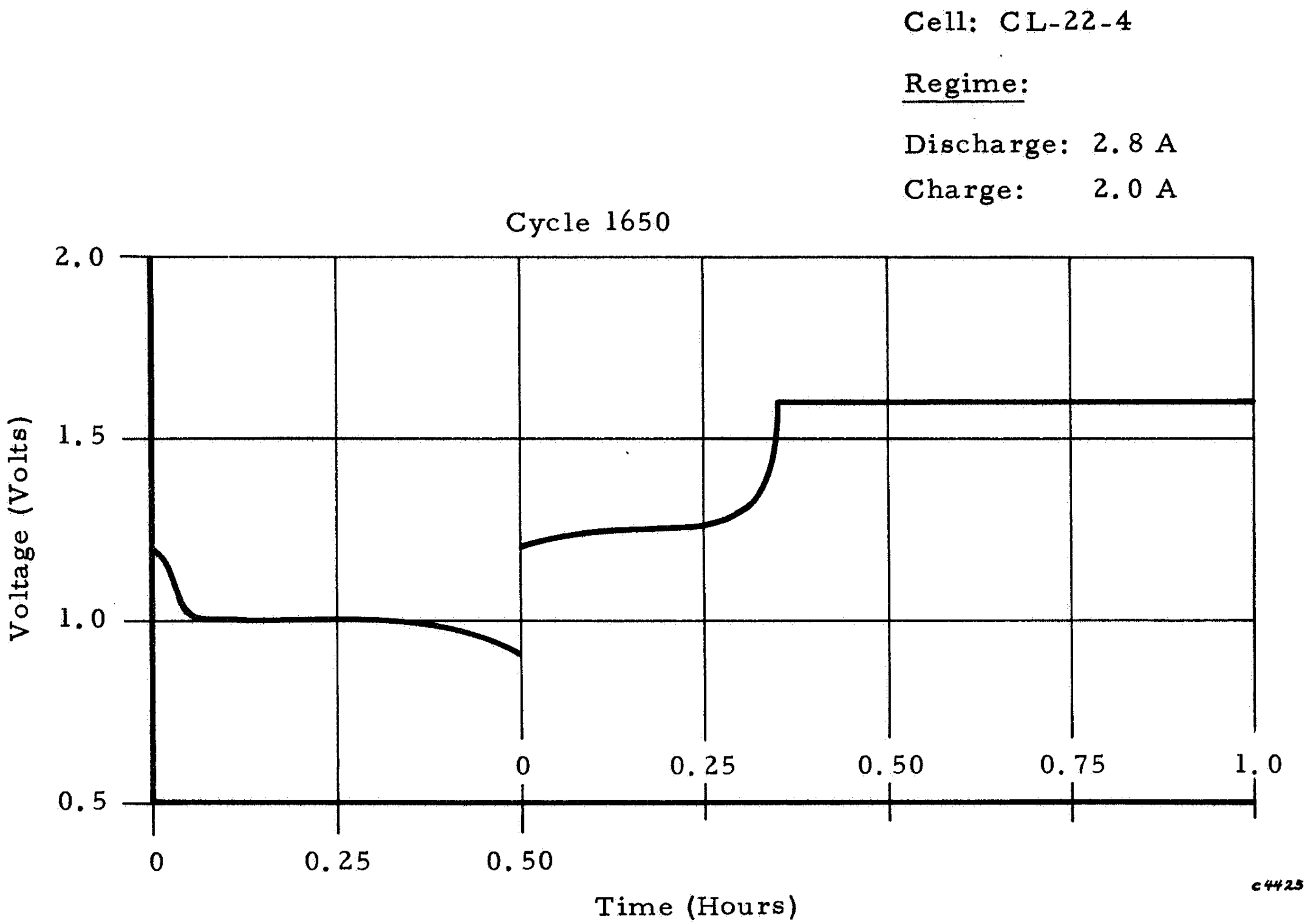


Figure 28. Group #3 Cycling Curves

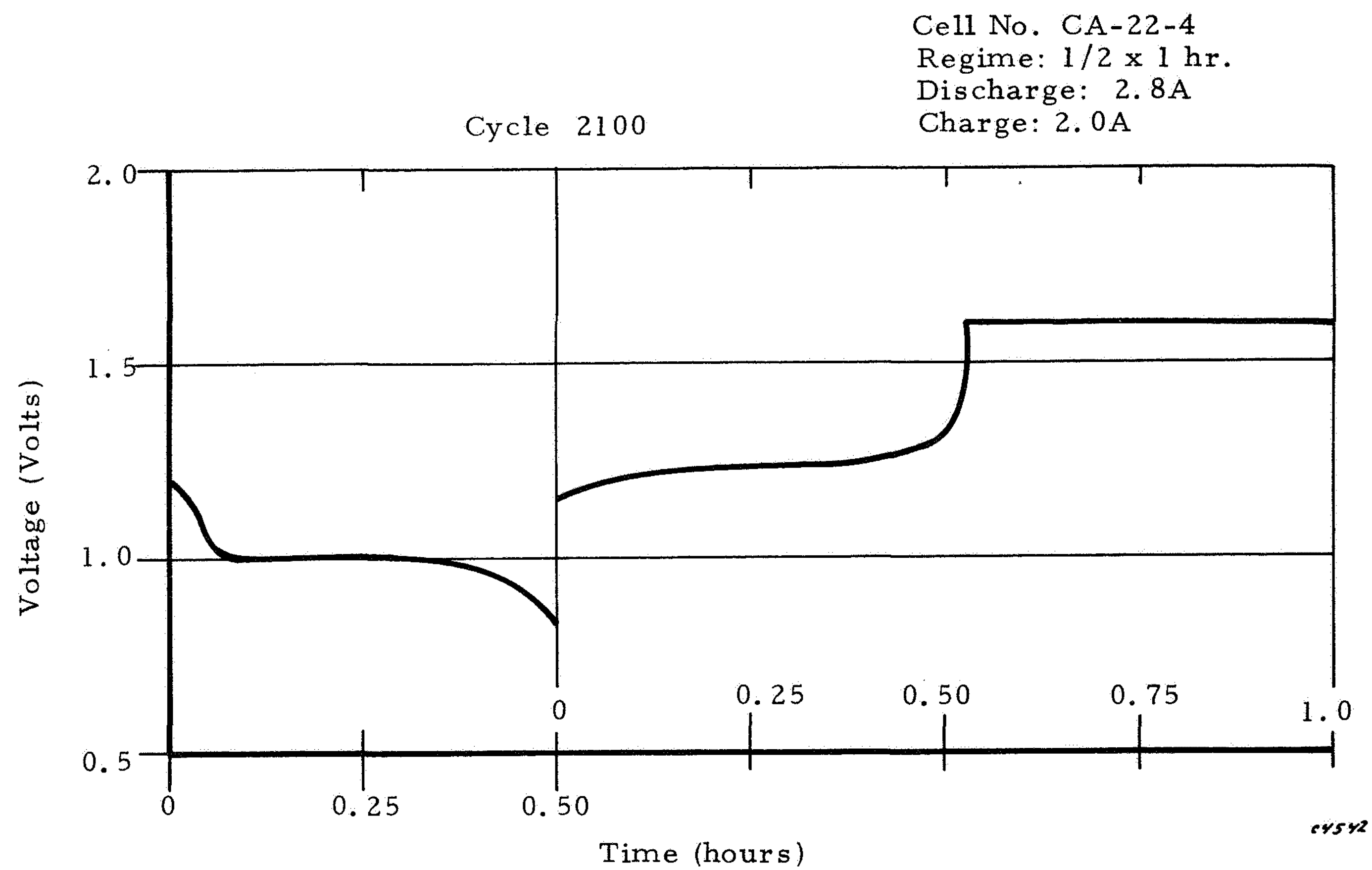


Figure 29. Group No. 3 Cycling Curves

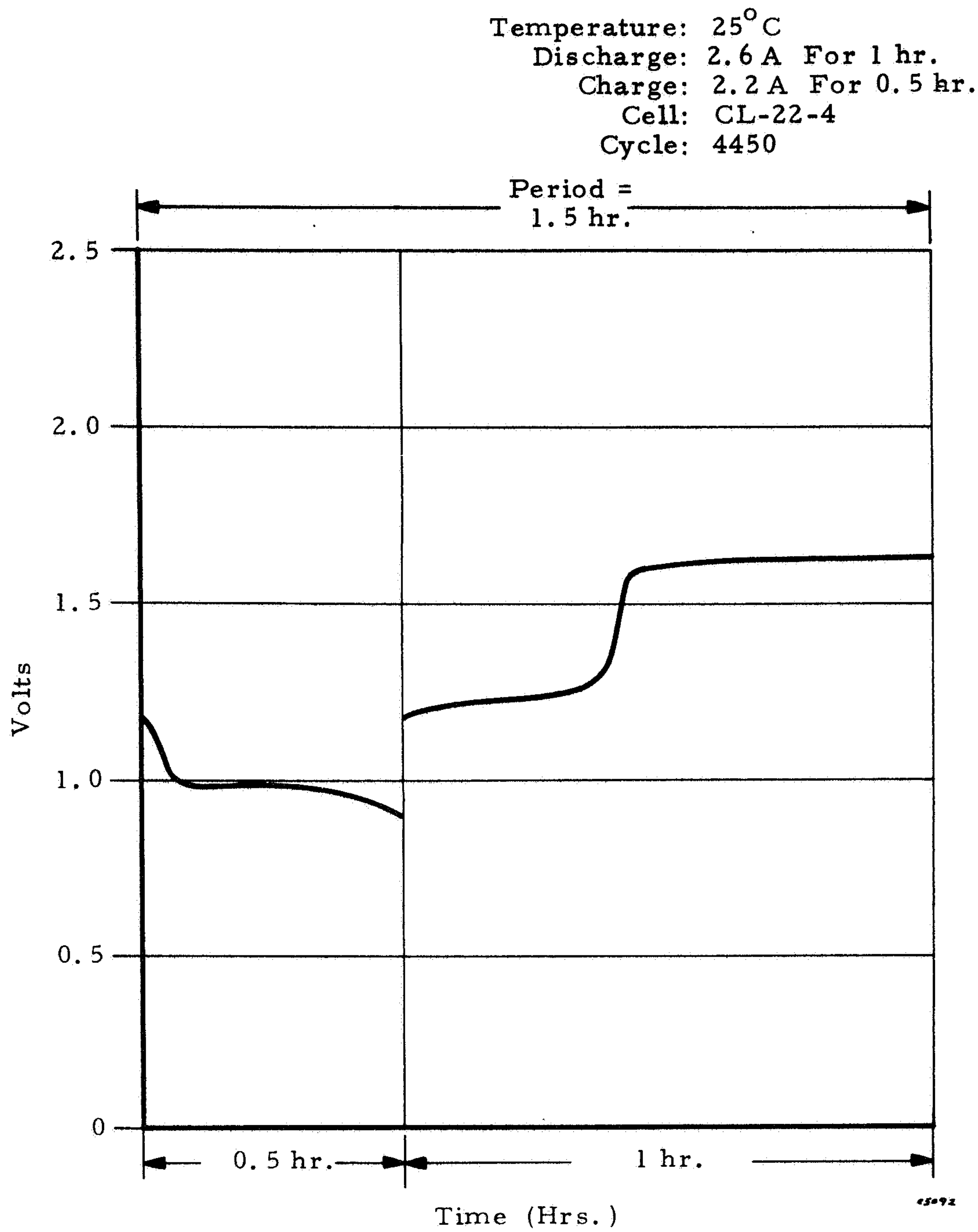


Figure 30. Cycling Curves - Task II, Group 3 (40% Depth)

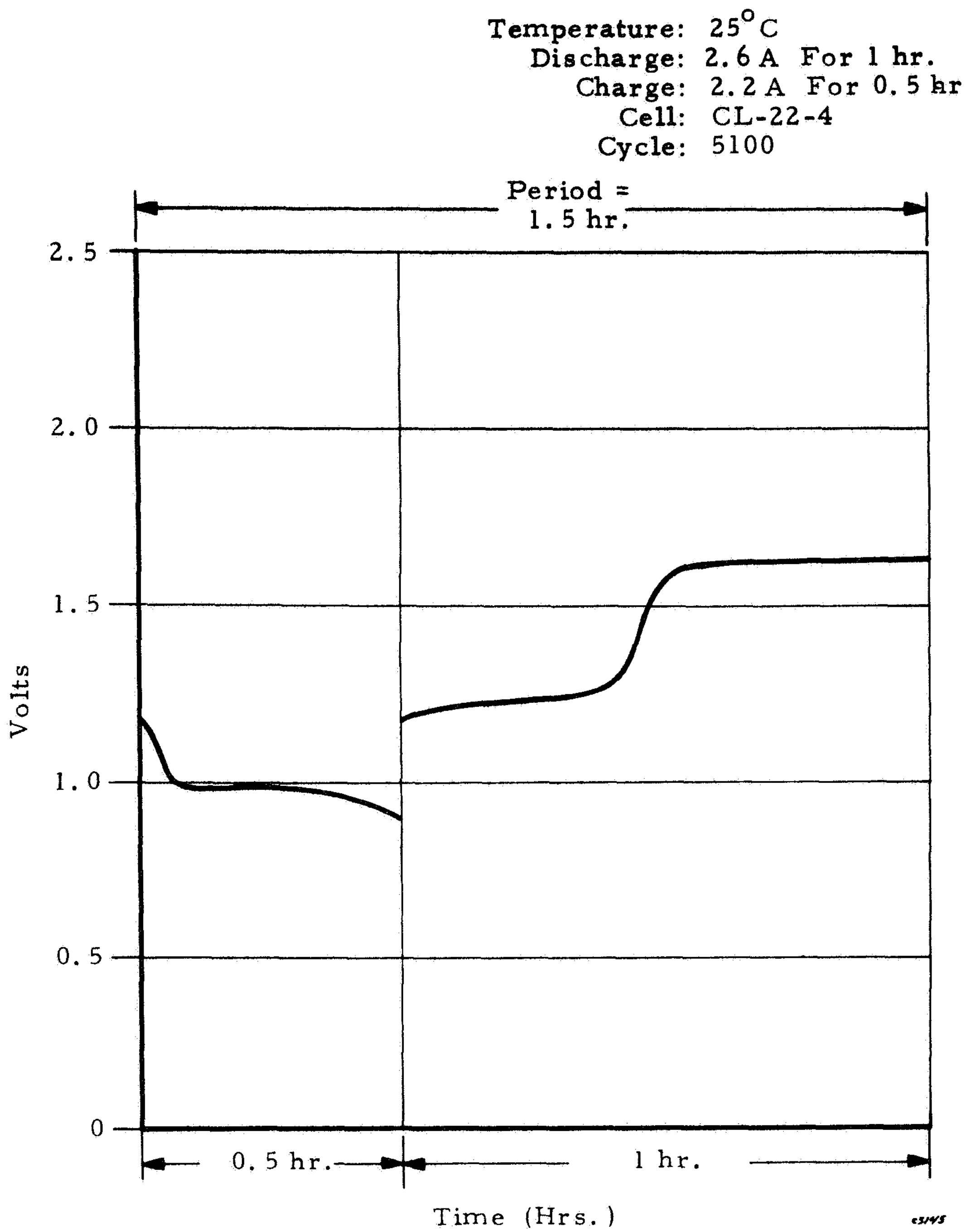


Figure 31. Cycling Curves — Task II, Group 3 (40% Depth)

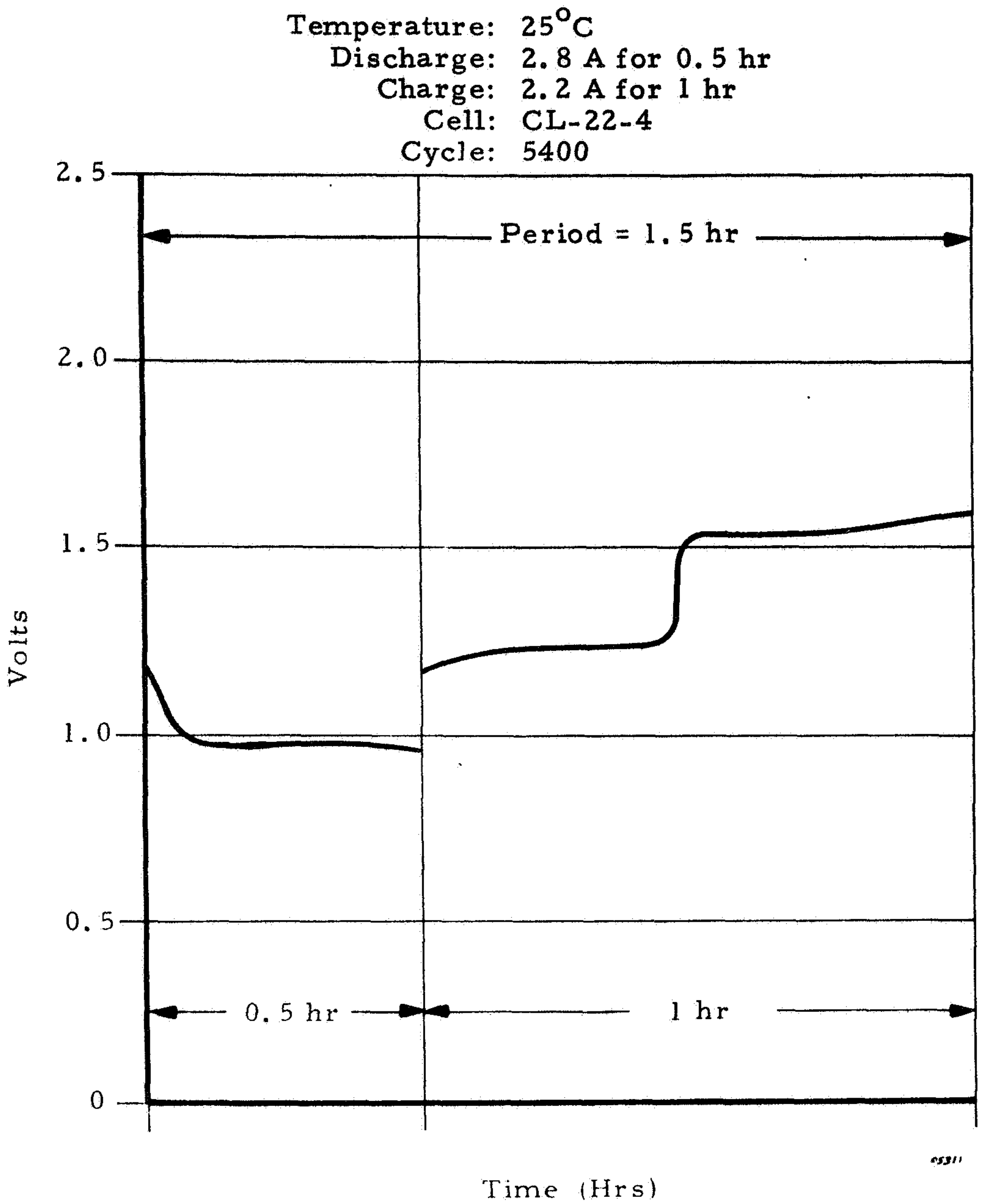


Figure 32. Cycling Curves - Task II, Group 3 (40% Depth)

TABLE XV

GROUP #4: FORMATION OF Ag-Cd CELLS (2A to 0.6V)

Input: 5.0 Ah

Cell No.	Output	Plateau Voltage
CL-23-1	3.60 Ah	0.98 V
CL-23-2	3.50 Ah	1.02 V
CL-23-3	3.50 Ah	1.0 V
CL-23-4	2.40 Ah	1.0 V
CL-23-5	3.40 Ah	1.0 V
Average	3.50 Ah	1.0 V

TABLE XVI

GROUP #5: FORMATION OF Ag-Cd CELLS (2A to 0.6V)

Input: 5.9 Ah

Cell No.	Output	Plateau Voltage
CL-24-1	3.50 Ah	1.0 V
CL-24-2	3.50 Ah	1.0 V
CL-24-3	3.60 Ah	1.0 V
CL-24-4	3.50 Ah	1.0 V
CL-24-5	3.70 Ah	1.0 V
Average	3.55 Ah	1.0 V

TABLE XVII

UNIFORMITY STUDY

Group: No. 4

Regime: Discharge: 2.8 A for 0.5 hr

Charge: 1.7 A for 1.0 hr

Voltage Limit: 1.60 V/cell

Temperature: 25°C

Cycle 1-10

Cell Number		1	2	3	4	5	Avg
Charge	m%	35	35	35	35	35	35
(OC = 1.5%)	V_f	1.56	1.56	1.56	1.56	1.56	1.56
Discharge	p%	10	10	10	10	10	10
	V_p	1.04	1.04	1.04	1.04	1.04	1.04
	V_e	1.02	1.02	1.02	1.01	1.02	1.02
Electrolyte Addition	Cum. Amt (cc)	0	0	0	0	0	0

Cycle 300

Charge	m%	41	41	41	41	41	41
(OC = 1.7%)	V_f	1.57	1.57	1.57	1.57	1.58	1.57
Discharge	p%	19	19	19	19	19	19
	V_p	1.02	1.02	1.02	1.02	1.02	1.02
	V_e	1.00	0.98	1.00	0.99	0.99	0.99
Electrolyte Addition	Cum. Amt (cc)	0	0	0	0	0	0

TABLE XVIII

UNIFORMITY STUDY

Group: No. 4

Regime: Discharge: 2.8 A for 0.5 hr

Charge: 1.70 A for 1.0 hr

Voltage Limit: 1.60 V/cell

Temperature: 25°C

Cycle 600

Cell Number		1	2	3	4	5	Avg
Charge	m%	47	47	47	47	47	47
(OC = 3.8%)	V_f	1.59	1.58	1.58	1.57	1.58	1.58
Discharge	p%	19	19	19	19	19	19
	V_p	1.02	1.02	1.02	1.02	1.02	1.02
	V_e	0.98	0.97	0.97	0.95	0.98	0.97
Electrolyte Addition	Cum. Amt (cc)	0	0	0	0	0	0

Cycle 900

Charge	m%	44	44	44	44	44	44
(OC = 1.2%)	V_f	1.58	1.58	1.58	1.58	1.58	1.58
Discharge	p%	16	16	16	16	16	16
	V_p	1.01	1.01	1.01	1.00	1.00	1.01
	V_e	0.97	0.97	0.97	0.98	0.96	0.97
Electrolyte Addition	Cum. Amt (cc)	0	0	0	0	0	0

TABLE XIX

UNIFORMITY STUDY

Group: #4

Regime: Discharge: 2.8 A for 0.5 hr

Charge: 1.7 A for 1.0 hr

Voltage Limit: 1.60 V/cell

Temperature: 25°C

Cycle 1200

Cell Number		1	2	3	4	5	Avg.
Charge	m%	56	57	57	57	57	57
(OC = -8.5%)	V_f	1.57	1.57	1.57	1.57	1.57	1.57
Discharge	p%	8	8	8	8	8	8
	V_p	1.01	1.01	1.01	1.01	1.01	1.01
	V_e	0.92	0.90	0.92	0.92	0.89	0.91
Electrolyte Addition	Cum. Amt (cc)	0	0	0	0	0	0

TABLE XX

UNIFORMITY STUDY

Group: 4

Regime: Discharge: 2.8 A for 0.5 hr

Charge: 1.6 A for 1.0 hr *

Voltage Limit: 1.68 V/cell*

Temperature: 25°C

Cycle 1500

Cell Number		1	2	3	4	5	Avg.
Charge	m%	58	58	61	72	58	61
(OC = 4.1%)	V_f	1.67	1.80	1.70	1.58	1.66	1.68
Discharge	p%	14	14	14	14	14	14
	V_p	1.00	0.87	0.98	1.02	1.00	0.99
	V_e	0.99	0.95	0.90	0.81	0.94	0.90
Electrolyte Addition	Cum. Amt (cc)	0	0	0	1.5	0	

Cycle 1800

				(f)	(f)	(c)	
Charge	m%	59	56	---	---	---	58
(OC = 4%)	V_f	1.66	1.72	---	---	---	1.69
Discharge	p%	8	8	---	---	---	8
	V_p	1.00	0.97	---	---	---	0.99
	V_e	0.88	0.89	---	---	---	0.89
Electrolyte Addition	Cum. Amt (cc)	4.0	7.0	---	---	---	5.5

* NOTE: Different charge currents and V limits were tried in order to keep the cells cycling. Under present conditions, set at cycle 1474; the cells are operating but getting out of balance.

(f)=cells 3, and 4 failed at cycle 1569, 1501.
(c)=cell 5 removed at cycle 1717 for capacity check.

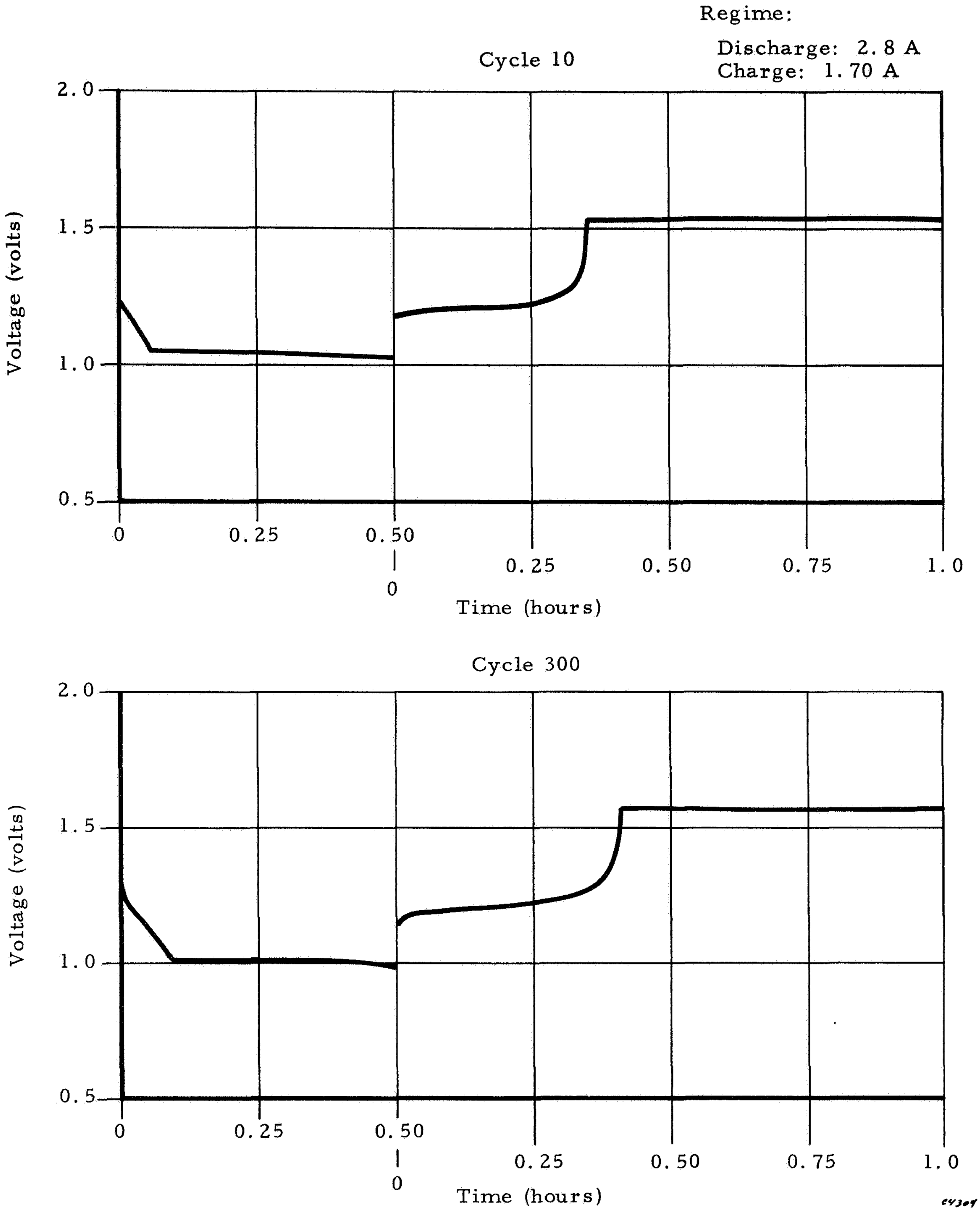


Figure 33. Group #4 Cycling Curve

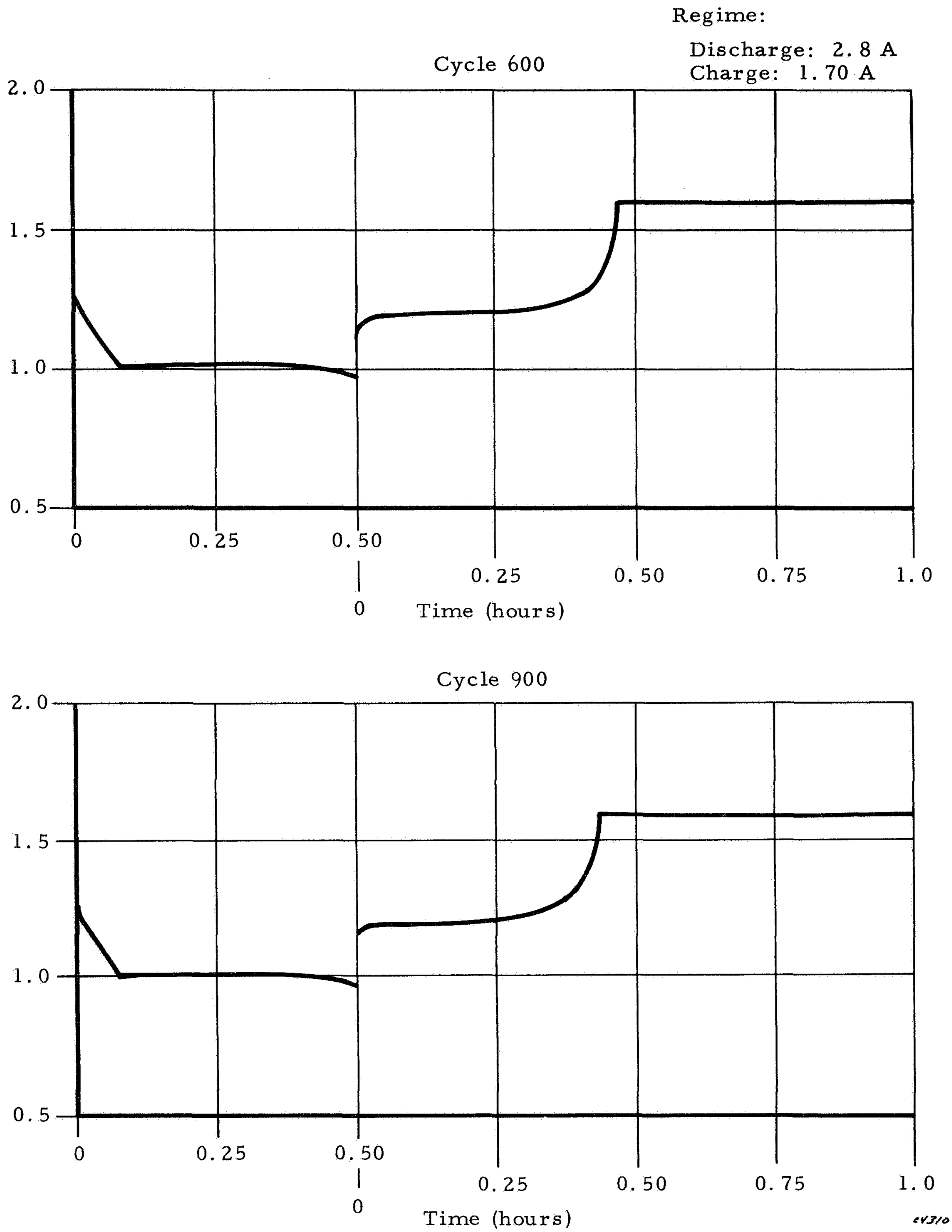


Figure 34. Group #4 Cycling Curves

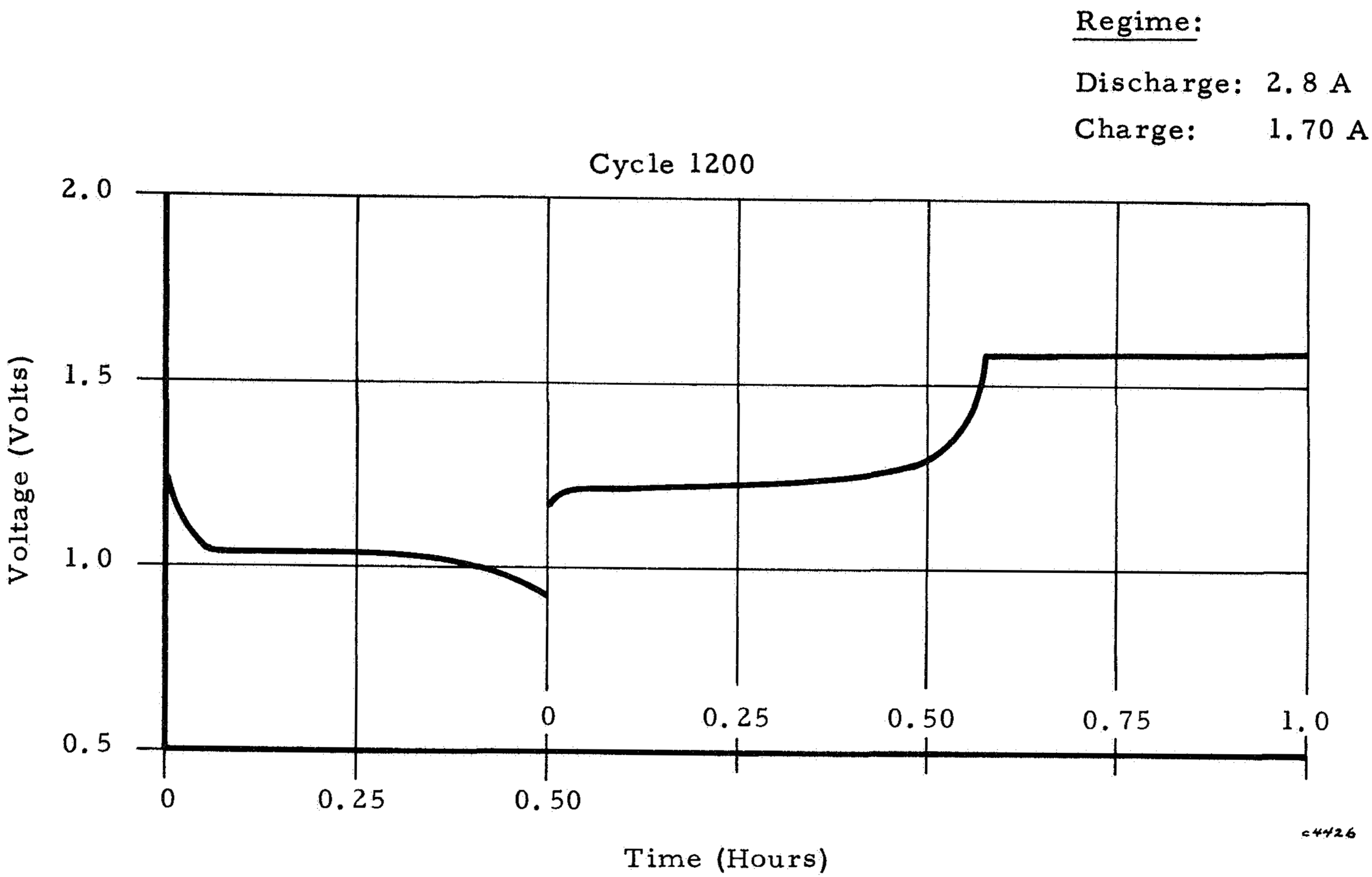


Figure 35. Group #4 Cycling Curves

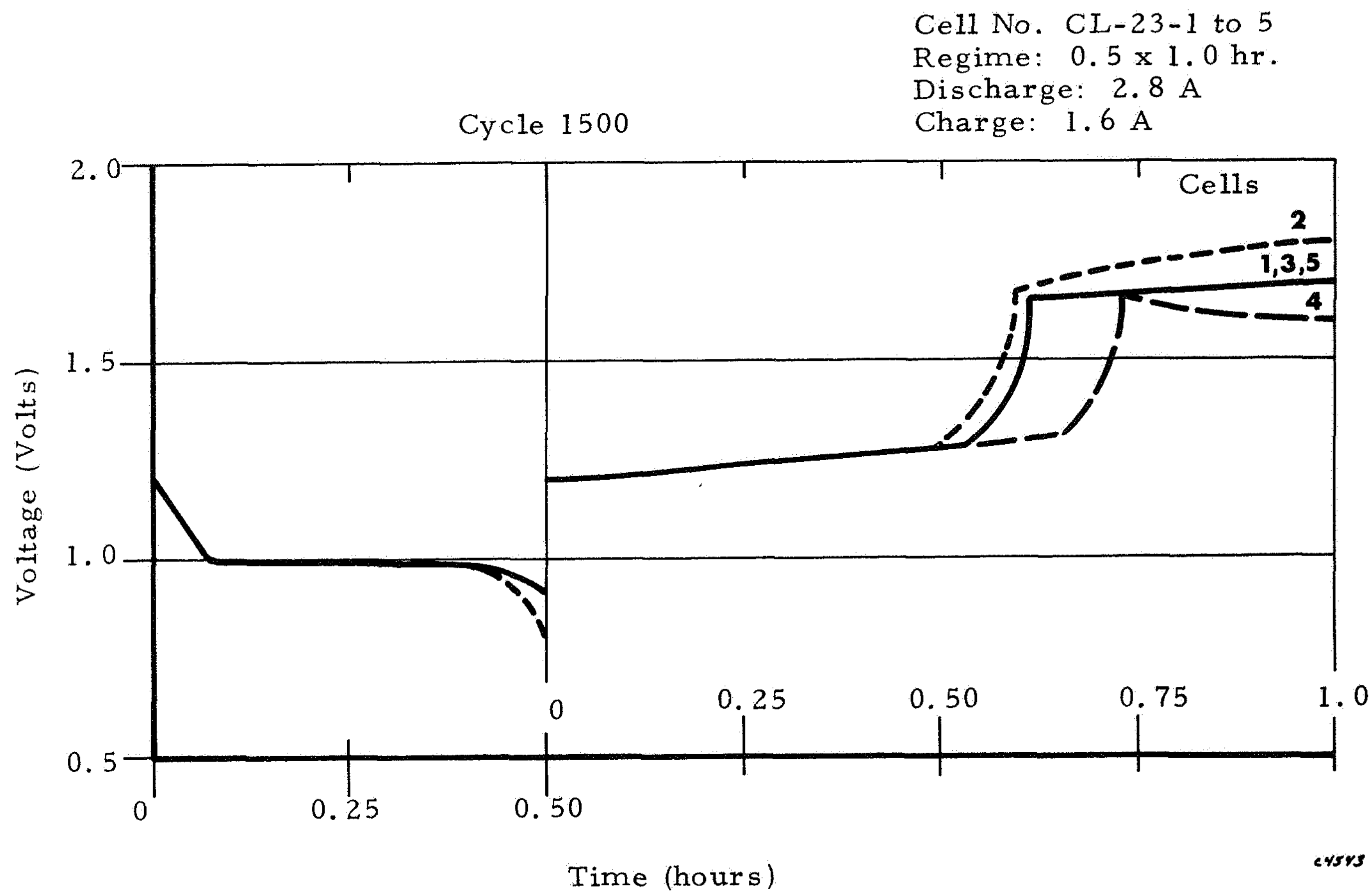


Figure 36. Group 4 Cycling Curves

TABLE XXI

UNIFORMITY STUDY

Group: No. 5

Regime: Discharge: 2.8 A for 0.5 hr

Charge: 1.7 A for 1.0 hr

Voltage Limit: 1.60 V/cell

Temperature: 25°C

Cycle 1-10

Cell Number		1	2	3	4	5	Avg
Charge	m%	47	47	47	47	47	47
(OC = 4.9%)	V_f	1.56	1.56	1.56	1.56	1.56	1.56
Discharge	p%	12	12	12	12	12	12
	V_p	1.03	1.02	1.02	1.03	1.02	1.02
	V_e	1.03	1.00	0.94	1.03	1.02	1.01
Electrolyte Addition	Cum. Amt (cc)	0	0	0	0	0	0

Cycle 300

Charge	m%	45	45	45	45	43	45
(OC = 2%)	V_f	1.56	1.57	1.57	1.58	1.57	1.57
Discharge	p%	14	14	14	14	14	14
	V_p	1.02	1.02	1.01	1.01	1.02	1.02
	V_e	0.98	0.95	0.94	0.97	0.96	0.96
Electrolyte Addition	Cum. Amt (cc)	0	0	0	0	0	0

TABLE XXII

UNIFORMITY STUDY

Group: No. 5

Regime: Discharge: 2.8 A for 0.5 hr

Charge: 1.70 A for 1 hr

Voltage Limit: 1.60 V/cell

Temperature: 25°C

Cycle 600

Cell Number		1	2	3	4	5	Avg
Charge	m%	44	44	44	44	44	44
(OC = -3.7%)	V_f	1.65	1.57	1.59	1.60	1.58	1.60
Discharge	p%	14	14	14	14	14	14
	V_p	1.01	1.00	0.99	0.99	1.00	1.00
	V_e	0.98	0.98	0.98	0.91	0.97	0.97
Electrolyte Addition	Cum. Amt (cc)	0	0	0	0	0	0

TABLE XXIII

UNIFORMITY STUDY

Group: #5

Regime: Discharge: 2.8 A for 0.5 hr

Charge:* 1.70 A for 1.0 hr

Voltage Limit: 1.60 V/cell

Temperature: 25°C

Cycle 900

Cell Number		1	2	3	4	5	Avg.
Charge	m%	53	52	53	62	52	54
(OC = 0%)	V_f	1.65	1.60	1.59	1.58	1.63	1.61
Discharge	p%	9	9	9	9	9	9
	V_p	0.97	1.00	0.99	1.00	0.98	0.99
	V_e	0.82	0.82	0.82	0.82	0.81	0.82
Electrolyte Addition	Cum. Amt (cc)	0	0	0	0	0	0

Cycle 1200

Charge	m%	49	44	49	**	44	47
(OC = 5%)	V_f	1.65	1.58	1.56	---	1.60	1.60
Discharge	p%	10	10	10	---	10	10
	V_p	0.98	1.01	1.00	---	1.00	1.00
	V_e	0.83	0.93	0.90	---	0.90	0.89
Electrolyte Addition	Cum. Amt (cc)	0	0	0	---	0	0

*Note: Charge current was increased to 2.0 A at cycle 1160.

**Cell No. 4 was stopped at cycle 968 because of frequent failures.

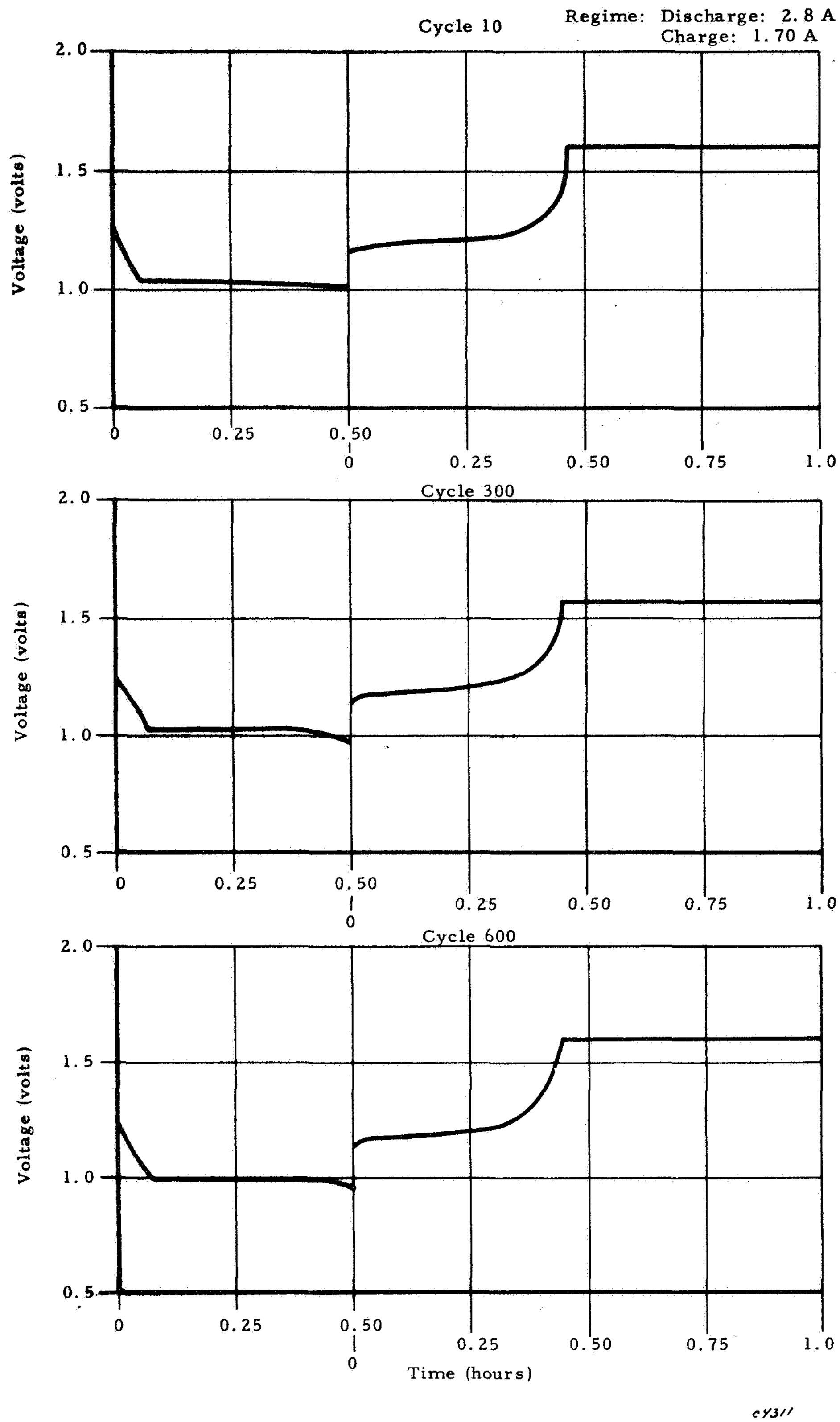


Figure 37. Group #5 Cycling Curves

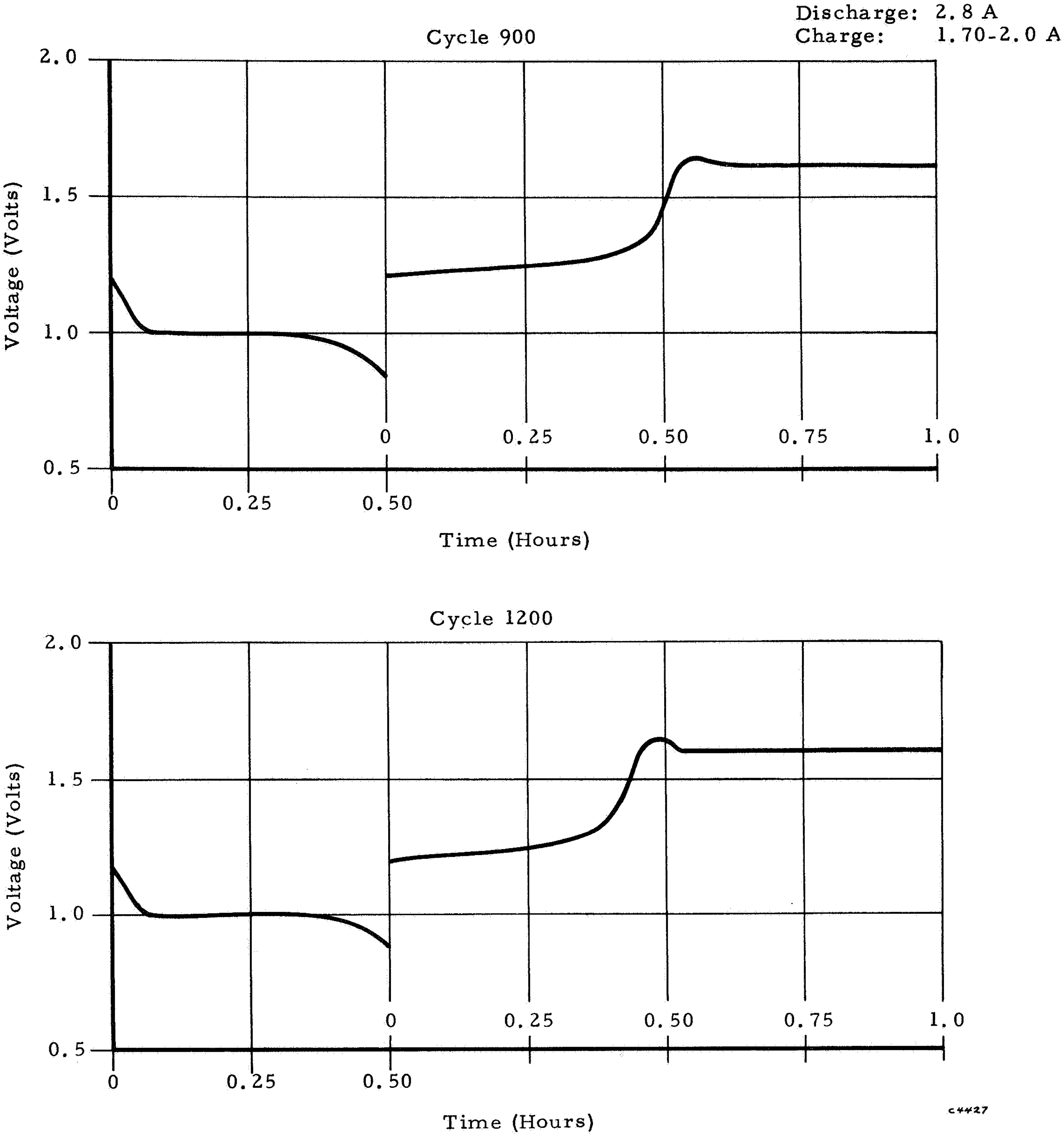


Figure 38. Group #5 Cycling Curves

4.4 GROUP NO. 6

In order to determine the effect of KOH concentration on the cycle life, two cells out of five in this group were filled with 40% KOH instead of 30%. Formation data are given in Table XXIV. Cycling data are reported in Tables XXV and XXVI and Figures 39 through 41. A clear difference appears at an early stage in the two sub-groups. Cycling data are presented in Table XXXII for comparison purposes. One cell with 40% KOH reached 4327 cycles. Only 0.5 cc of electrolyte was added to this cell.

4.5 GROUP NO. 7

In view of the promising results of Group No. 6, a new group of five cells using 40% KOH was put on test. Formation capacities and plateau voltages are given in Table XXVII. It is significant that their capacity reached 4.0 Ah uniformly. This is due to the higher KOH concentration as shown and discussed in Paragraph 4.7. A typical discharge curve is shown in Figure 42. The cells cycles uniformly up to 3500 cycles. One cell, CL-27-2, failed at cycle 3512; upon dissection, all components appeared in good condition, but the separators showed heavy silver penetration in some spots. The other four cells reached about 4700 cycles at the end of the program when their cycling was discontinued. Figure 43 shows typical cycling curves. The cells were submitted to an OCV and capacity check. Table XXVIII gives their condition at that time. All showed definite signs of low current leakage as indicated by their OCV drop. One cell, CL-27-5, had still 4.5 Ah and a relatively good OCV after 4758 cycles. Electrolyte addition amounted to 3 cm^3 after 4700 cycles.

4.6 GROUP NO. 8

Another group of five cells was filled with 45% KOH. The capacity on formation was higher than before. The average was 4.4 Ah (Table XXIX). Here again the five cells cycled uniformly without maintenance and reached 3095 cycles at the end of the program when their cycling was discontinued. Figure 44 shows typical cycling curves. The cells were submitted to an OCV and capacity check. Their capacities, shown in Table XXX, are remarkably good and uniform (5 Ah average). No electrolyte addition was made at any time on the cells of this group.

TABLE XXIV

FORMATION DATA OF GROUP #6

KOH Concentration	Cell Number	Capacity
30%	CL-26-1	3.50 Ah
	CL-26-2	3.50 Ah
	CL-26-3	3.50 Ah
	Average	3.50 Ah
40%	CL-26-4	3.60 Ah
	CL-26-5	3.66 Ah
	Average	3.63 Ah

TABLE XXV

UNIFORMITY STUDY

Group: No. 6

Regime: Discharge: 2.8 A for 0.5 hr

Charge: 1.55 A for 1.0 hr

Voltage Limit: 1.60 V/cell

Temperature: 25°C

Cycle 1-10

Cell Number		1	2	3	Avg	4	5	Avg
		30% KOH				40% KOH		
Charge	m%	38	38	38	38	31	31	31
(OC = 0.9%)	V_f	1.57	1.57	1.57	1.57	1.56	1.56	1.56
Discharge	p%	12	12	12	12	12	12	12
	V_p	1.03	1.02	1.02	1.02	1.04	1.04	1.04
	V_e	1.01	1.01	1.01	1.01	1.03	1.03	1.03
Electrolyte Addition	Cum. Amt (cc)	0	0	0	0	0	0	0

Cycle 300

Charge	m%	36	36	36	36	30	30	30
(OC = 4.7%)	V_f	1.58	1.59	1.58	1.58	1.55	1.55	1.55
Discharge	p%	22	22	22	22	22	22	22
	V_p	1.02	1.02	1.02	1.02	1.04	1.04	1.04
	V_e	0.99	0.97	0.99	1.02	1.02	1.02	1.02
Electrolyte Addition	Cum. Amt (cc)	0	0	0	0	0	0	0

TABLE XXVI

UNIFORMITY STUDY

Group: #6

Regime: Discharge: 2.8 A for 0.5 hr

Charge: 1.55 A for 1.0 hr

Voltage Limit: 1.60 V/cell

Temperature: 25°C

Cycle 684*

Cell Number		1	2	3	Avg.	4	5	Avg.
		30% KOH				40% KOH		
Charge 30% (OC = -1%) 40% (OC = 2.5%)	m%	46	46	46	46	34	34	34
	V_f	1.61	1.60	1.59	1.60	1.58	1.62	1.60
Discharge	p%	20	20	20	20	23	23	23
	V_p	1.00	0.99	1.00	1.00	1.02	1.02	1.02
	V_e	0.99	0.97	0.99	0.98	1.00	1.00	1.00
Electrolyte Addition	Cum. Amt (cc)	0	0.5	0	0.2	0	0	0

*Data at cycle 650 not valid because of failure of power supply.

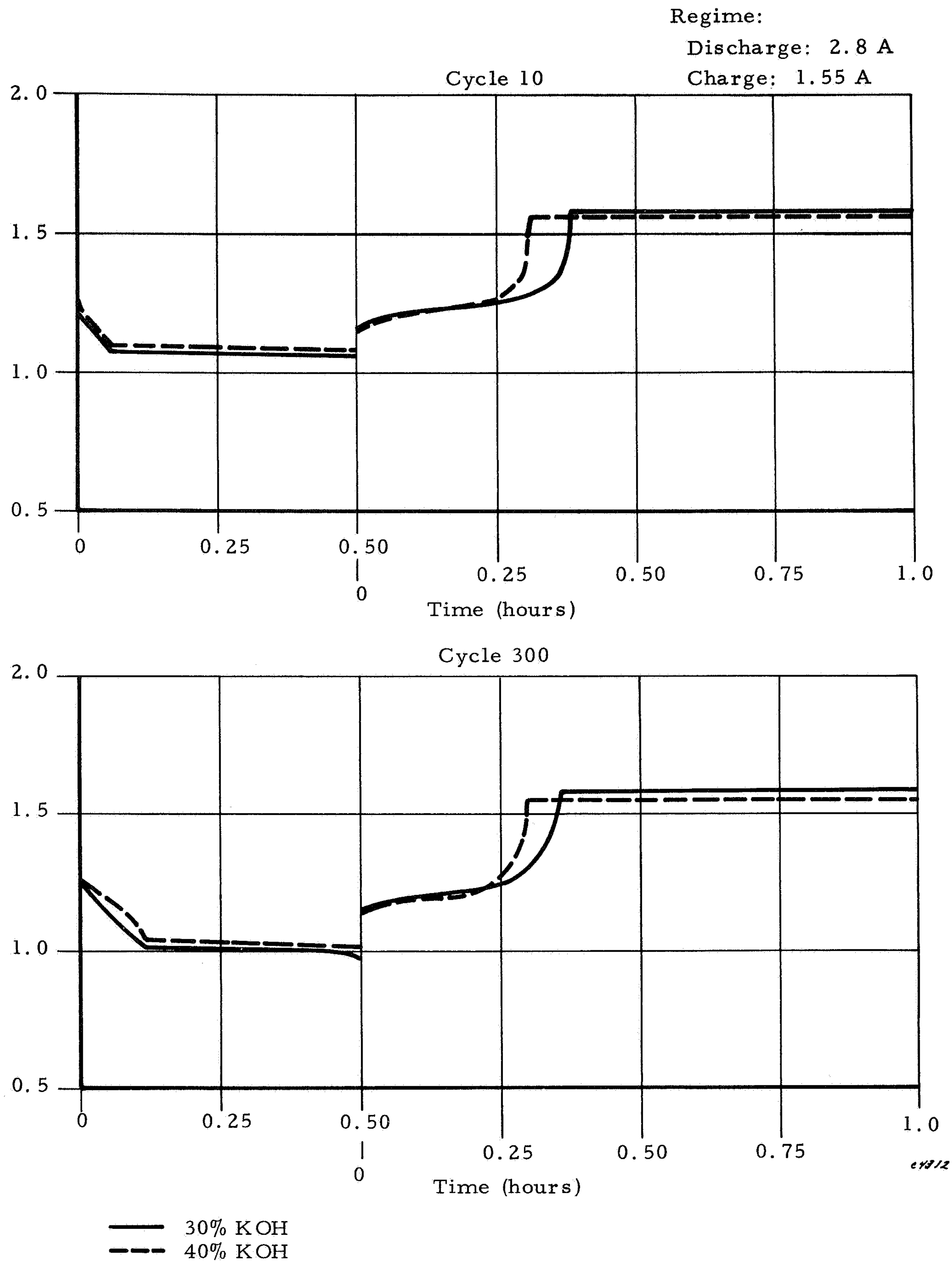
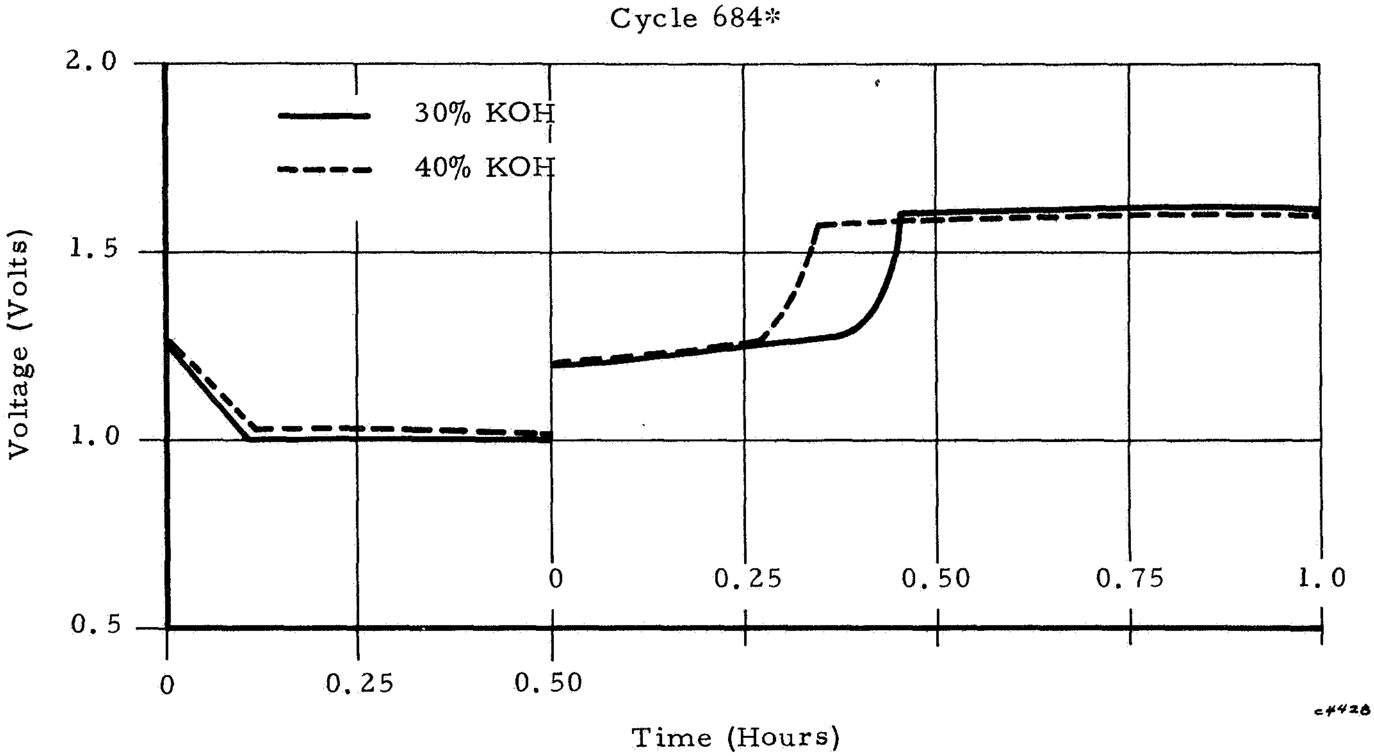


Figure 39. Group #6 Cycling Curves

Regime:

Discharge: 2.8 A

Charge: 1.55 A



* Cycle 600 data not reported because of power supply failure.

Figure 40. Group #6 Cycling Curves

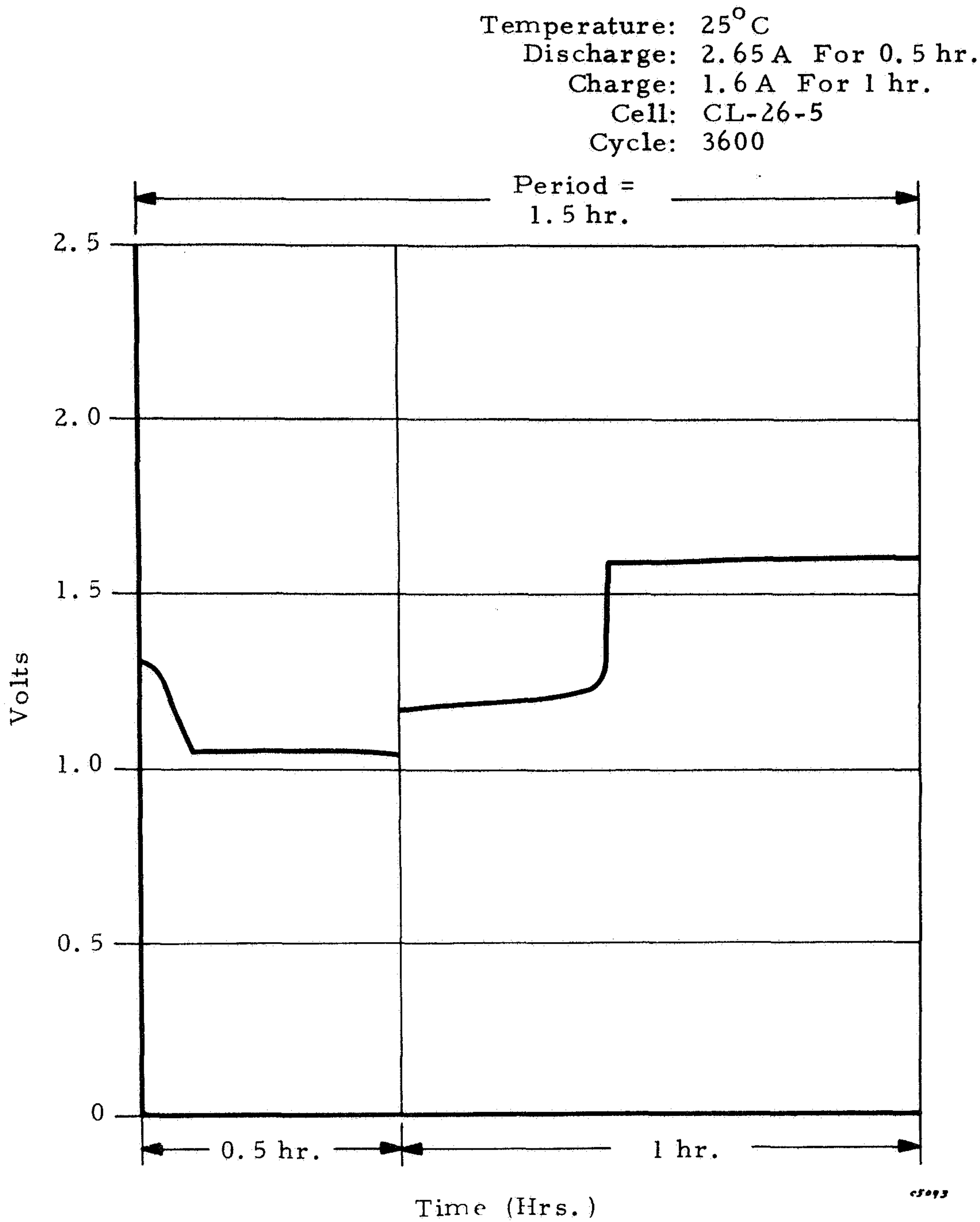


Figure 41. Cycling Curves - Task II, Group 6 (40% Depth)

TABLE XXVII

GROUP 7: FORMATION DATA OF CELLS USING 40% KOH

(Discharge at 1.0 A to 0.6 V)

Cells	Output	Plateau Voltage
CL-27-1	4.0 Ah	1.06 V
CL-27-2	4.0	1.06
CL-27-3	4.0	1.06
CL-27-4	4.0	1.06
CL-27-5	4.0	1.06
Average	4.0 Ah	1.06 V

TABLE XXVIII

OCV AND CAPACITY CHECK OF TASK II CELLS (40% KOH)

(Still cycling at the end of the program)

Cell No.	Cycle No.	OCV (hrs on stand)	Capacity (Ah)
CL-27-1	4630	1.23 V (5 hrs)	3.7
CL-27-3	4758	1.10 V (3 hrs)	3.1
CL-27-4	4758	1.09 V (3 hrs)	1.9
CL-27-5	4758	1.39 V (6 hrs)	4.5

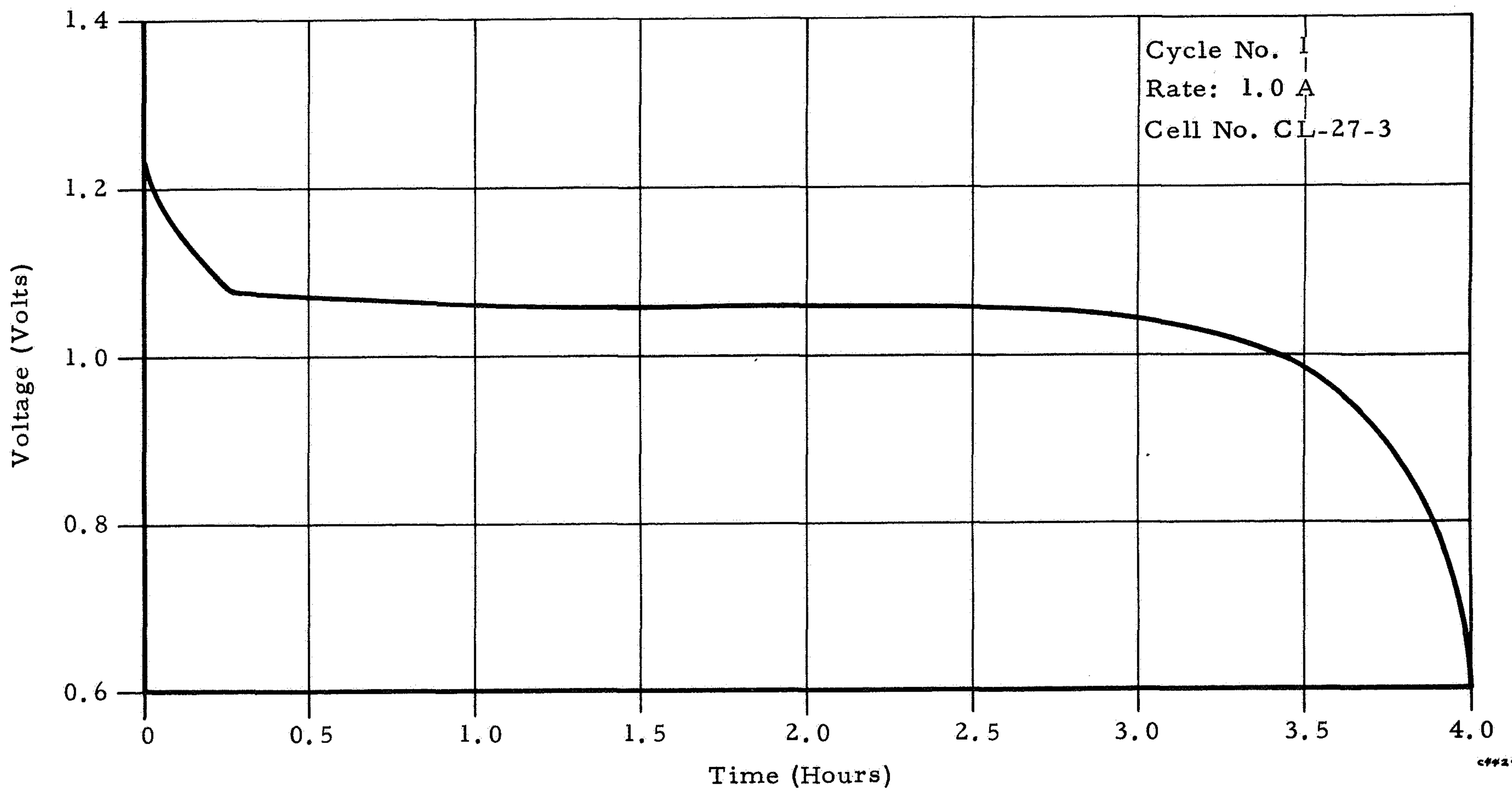


Figure 42. Group 7: Ag-Cd Cell With 40% KOH

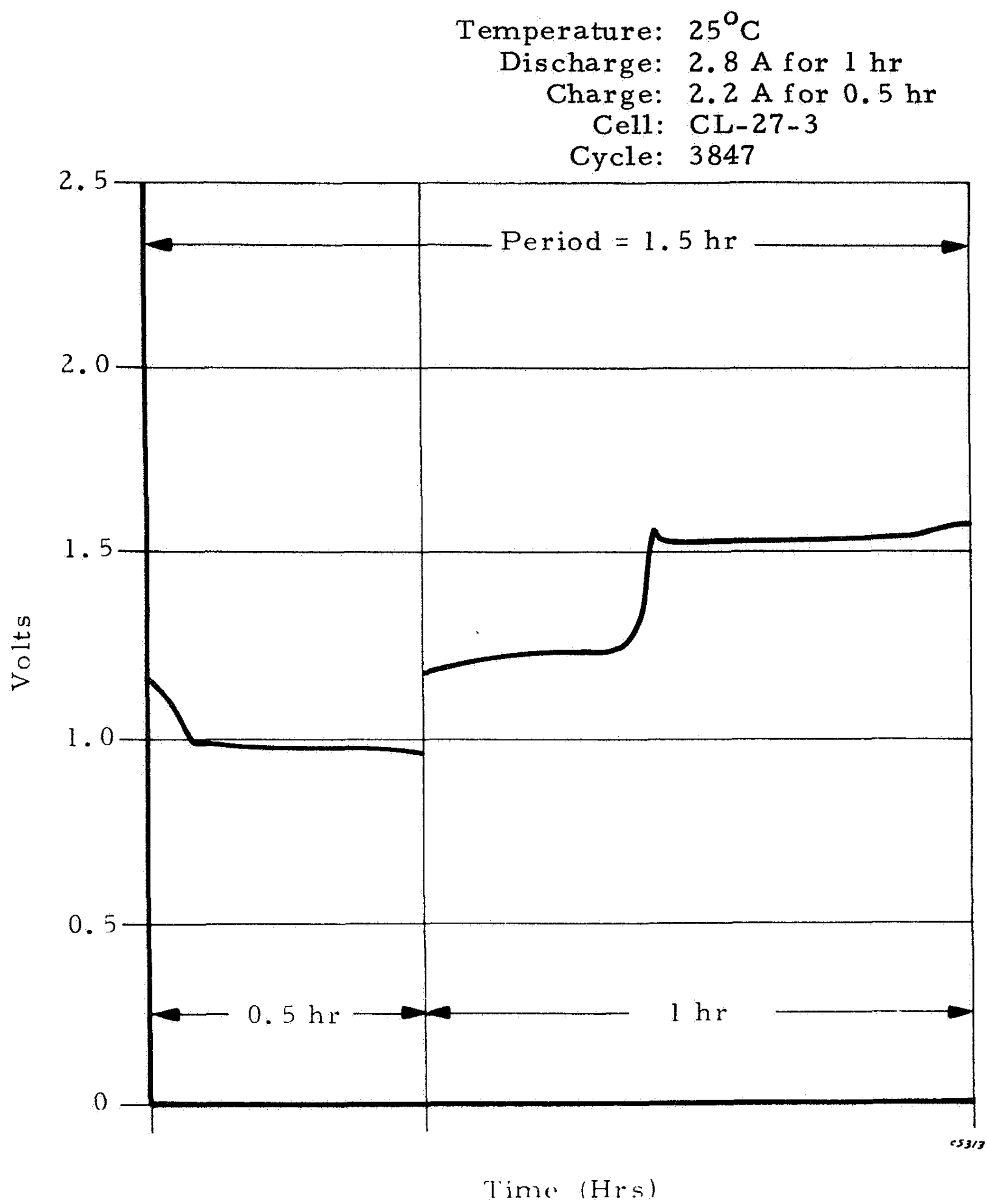


Figure 43. Cycling Curves - Task II, Group 7 (40% Depth)

TABLE XXIX

GROUP 8: FORMATION DATA OF CELLS USING 45% KOH

(Discharge at 1 A to 0.6 V)

Cell No.	Output (Ah)	Plateau Voltage (V)
CL-48-1	3.9	1.05
CL-48-2	4.7	1.05
CL-48-3	4.7	1.06
CL-48-4	4.5	1.05
CL-48-5	4.2	1.05
Average	4.4	1.05

TABLE XXX

OCV AND CAPACITY CHECK OF TASK II CELLS (45% KOH)

(Still cycling at the end of the program)

Cell No.	Cycle No.	OCV (hrs on stand)	Capacity (Ah)
CL-48-1	3095	1.41 V (5 hrs)	4.9
CL-48-2	3095	1.38 V (5 hrs)	5.1
CL-48-3	3095	1.39 V (5 hrs)	5.1
CL-48-4	3095	1.41 V (5 hrs)	5.1
CL-48-5	3095	1.41 V (5 hrs)	5.1

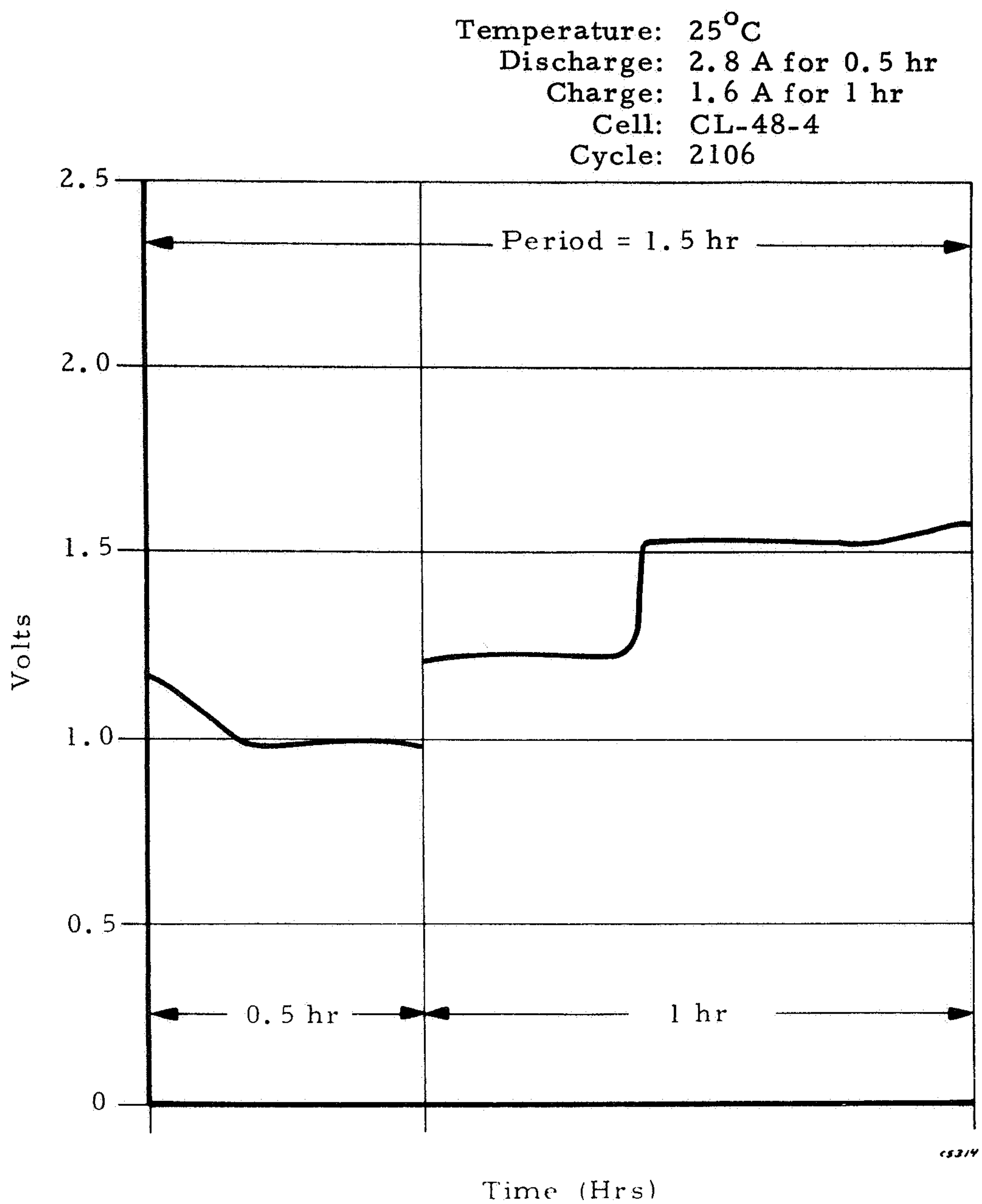


Figure 44. Cycling Curves - Task II, Group #8 (40% Depth)

At the time of the review of the performance data of Task II cells with the NASA Project Manager, the data on 40% and 45% KOH cells were not available when approval to proceed with Task III cells was granted. However, during the course of Task III, the KOH concentration was changed to 40% when more data became available. The 45% KOH appears also of great interest because of the remarkable uniformity of cycling, capacity and voltage, at least up to the time when the cells were discontinued.

4.7 COMMENTS

Increased capacity was noticed in all silver-cadmium cells fabricated lately. As reported previously, the raise in KOH concentration is definitely one factor that, however, was not enough to account for capacities up to 4.8 Ah obtained after the end of August. A new shipment of sintered cadmium electrodes had been received in August and the new electrodes (supposedly identical to the ones of the previous shipment) were used in the fabrication of cells, starting with the series CL-38, CL-39, CL-48, and CL-49. The capacity of the cells of these series show an average capacity of 4.5 Ah. On previous tests using first shipment cadmium electrodes, the use of 40% KOH concentration raised the capacity, but not over 4 Ah, as shown in series CL-26, CL-27, CL-32, and CL-33, where cells using 30% and 40% KOH were compared. Table XXXI presents a summary of capacities of all relevant cells and brings out the striking differences caused by KOH concentration or cadmium electrodes.

4.8 FAILURE ANALYSIS

Cycling data of all groups of cells of Task II are summarized in Table XXXII for comparison purposes. It appears strikingly that the selected type of silver-cadmium cell can more than double its cycling capability when it uses 40 to 45% KOH in lieu of 30% KOH.

The failures of cells can be categorized as follows:

a. At the beginning of the program, a few cells had cracked separators, but this proved to be a minor construction deficiency as it completely disappeared from all subsequent cells. All components, electrodes, separators and seals were in good condition.

TABLE XXXI

CAPACITY VARIATIONS CAUSED BY Cd ELECTRODES AND KOH CONCENTRATION

(Average Capacity of 5 or 10 Cells at Cycle 1)

Cd Electrode Shipment	Series of Cells	KOH		
		30%	40%	45%
First	CL-26	3.5 Ah	3.7 Ah	
	CL-27		4.0 Ah	
	CL-32	3.8 Ah	4.3 Ah	
	CL-33	3.2 Ah	3.6 Ah	
Second	CL-38		4.6 Ah	
	CL-39		4.6 Ah	
	CL-48			4.4 Ah
	CL-49		4.2 Ah	4.5 Ah
	40 cells		4.8 Ah	

TABLE XXXII

SUMMARY OF CYCLING DATA OF ALL TASK II CELLS

30% KOH			40% KOH			45% KOH		
Group No.	Cell No.	Cycles	Group No.	Cell No.	Cycles	Group No.	Cell No.	Cycles
1	CL-15-1	1208	6	CL-26-4	3625	8	CL-48-1	3095 *
1	CL-15-2	835 (A)	6	CL-26-5	4327	8	CL-48-2	3095 *
1	CL-15-3	1531				8	CL-48-3	3095 *
1	CL-15-4	880	7	CL-27-1	4630 *	8	CL-48-4	3095 *
1	CL-15-5	868	7	CL-27-2	3512	8	CL-48-5	3095 *
1	CL-15-6	707	7	CL-27-3	4758 *			
1	CL-15-7	835 (A)	7	CL-27-4	4758 *			
1	CL-15-8	835 (A)	7	CL-27-5	4758 *			
1	CL-15-9	208 (A)						
1	CL-15-10	208 (A)						
2	CL-20-1	301 (A)						
2	CL-20-2	301 (A)						
2	CL-20-3	1185						
2	CL-20-4	2019						
2	CL-20-5	1185						
3	CL-22-1	1309 (A)						
3	CL-22-2	2109						
3	CL-22-3	209 (A)						
3	CL-22-4	5664						
3	CL-22-5	209 (A)						
4	CL-23-1	1847						
4	CL-23-2	2507						
4	CL-23-3	1569						
4	CL-23-4	1501						
4	CL-23-5	2150						
5	CL-24-1	1590						
5	CL-24-2	1658						
5	CL-24-3	1955						
5	CL-24-4	968						
5	CL-24-5	2166						
6	CL-26-1	1291						
6	CL-26-2	1623						
6	CL-26-3	1335						

(A) = Stopped for examination
* = Still capable of cycling

b. The main contributing cause of failure was the low rate current leakage through the separators resulting from the slowly progressing silver penetration, enhanced by the low KOH concentration in most of the cells of this task.

c. This occurred in varying degrees in different cells of the same group, which caused severe imbalance between cells, resulting in different amounts of overcharge and water loss. This situation was particularly severe in cells of the first three groups where uniformity of wetting was lacking.

d. After the construction deficiency was corrected (Groups 4 to 8), the increased cycle-life was mainly due to the change to higher KOH concentration. Uniformity was improved, electrolyte loss was practically nil (actually no addition in cells with 45%) and silver penetration was drastically reduced.

e. However, a quantitative analysis of the separators in different cells showed unexpected amounts of nickel in addition to the usual silver and cadmium contents. Table XXXIII gives on two cells cycled under the same conditions 8 times more nickel in cell CL-22-4 (5664 cycles) than in cell CL-26-1 (1291 cycles). This unexpected metal may well be contributing to the slow short since it can easily be trapped in the micropores of the inorganic separator, whereas this may not occur in a Ni-Cd cell because of the large pores of the separator material (Pellon). The analytical detection of the three metals was done independently by an outside laboratory, Metallurgical Service Laboratories. Copies of the analyses can be found in Appendix B.

TABLE XXXIII

ANALYSIS OF SEPARATORS FROM FAILED SILVER CADMIUM CELLS

Cell No.	Cycling Temp (^{o}C)	Total Cycles at Temp	Total Wet Life* (days)	Area of Piece Analyzed (in^2)	Detected Metal Content of Separator					
					Silver		Cadmium		Nickel	
					(mg)	(mg/in^2)	(mg)	(mg/in^2)	(mg)	(mg/in^2)
CL-35-2	100	2[a]	30	0.56	0.60	1.08	0	0	1.81	3.24
CL-26-1	25	1291[b]	115	0.62	0.30	0.48	0.77	1.24	1.33	2.14
CL-22-4	25	5664[b]	377	1.95	4.40	2.30	1.00	0.50	32.9	16.9

* Total time before cell was opened. Includes stand at 25^{o}C.

(a) 75% depth, 24-hr cycling period.

(b) 40% depth, 1.5-hr cycling period.

Section 5

TASK III: CELL TESTING

After approval of the review of performance of Task II cells (only cells with 30% KOH had sufficient cycling data at that time), the selected cell design was used exclusively throughout this task, with 30% KOH electrolyte, changed to 40% later on during the course of the program.

5.1 TEST NO. 1 — WET STAND AT 25°C

Ten cells using 30% KOH were charged, discharged once, recharged and put on charged stand (CL-30 series).

The OCV of six cells dropped to 1.11 volts after 60 to 70 days (Table XXXIV). It was decided to discharge all the cells before the 90-day scheduled stand to determine the comparative capacity retention of good and low OCV cells. The average capacity retention (residual vs original capacity) of good OCV cells was 80%, whereas the low OCV cells averaged 58% (stand ranging from 60 to 71 days). The cells were recharged and put back on a second stand in increments of 3 months, regardless of their OCV drop.

Since higher KOH concentrations up to 45% are beneficial, six new cells were placed on charged wet stand at 25°C: four cells with 40% KOH and two cells with 45% KOH (Test No. 1A). Formation capacities are given in Table XXXV.

Two cells with 40% KOH were discharged after 108 days, two other cells after 140 days, and the last two cells after 160 days.

The capacity retention percentage is definitely better than that of cells using 30% KOH. Table XXXVI draws a comparison between the different groups of cells. Figure 45 gives the capacity retention percentage vs time, for all cells using high KOH concentration.

5.2 TEST NO. 2 — WET STAND AT 100°C

Ten cells, CL-31 series, were scheduled for this test. Six cells were inadvertently charged in reverse. However, the test was pursued in order to get

TABLE XXXIV

TEST #1 - WET STAND AT 25°C

(CL-30 Series)

Cell No.	Original Capacity	Days on Stand	Final OCV	Residual Capacity	Capacity Retention (%)
1	3.4 Ah	71	1.39 V	2.8 Ah	82
2	3.6	71	1.38	3.2	89
3	3.6	71	1.36	2.6	72
4	3.3	71	1.15	2.4	73
5	3.5	73	1.11	2.2	63
6	3.4	71	1.11	2.0	59
7	3.4	71	1.38	2.6	76
8	3.5	60	1.11	1.9	54
9	3.2	60	1.11	1.8	56
10	3.4	71	1.11	1.5	44

TABLE XXXV

FORMATION CAPACITY OF CL-49 SERIES CELLS

Test #1A: Charged Wet Stand at 25°C

Cell No.	Electrolyte	Output (Ah)	Average
CL-49-1	40%	3.9	4.2 Ah
CL-49-2	40%	4.5	
CL-49-3	40%	4.5	
CL-49-4	40%	3.9	
CL-49-5	45%	4.6	4.5 Ah
CL-49-6	45%	4.5	

TABLE XXXVI

WET STAND AT 25°C

%KOH	Cells	Original Capacity	Days on Stand	OCV (V)	Residual Capacity	Capacity Loss Total%	Capacity Loss % per Day
30%	Average of 10 cells	3.4 Ah	69	1.22 V	2.3 Ah	33%	0.48%
40%	CL-49-1	3.9 Ah	108	1.39 V	3.2 Ah		
	CL-49-2	4.5 Ah	108	1.40 V	3.0 Ah		
	Average	4.2 Ah	108	1.39 V	3.1 Ah	26%	0.24%
	CL-49-3	4.5 Ah	146	1.38 V	2.55 Ah		
	CL-49-4	3.9 Ah	146	1.39 V	2.65 Ah		
	Average	4.2 Ah	146	1.39 V	2.60 Ah	38%	0.26%
45%	CL-49-5	4.6 Ah	160	1.35 V	2.60 Ah		
	CL-49-6	4.5 Ah	160	1.34 V	2.65 Ah		
	Average	4.5 Ah	160	1.34 V	2.60 Ah	42%	0.26%

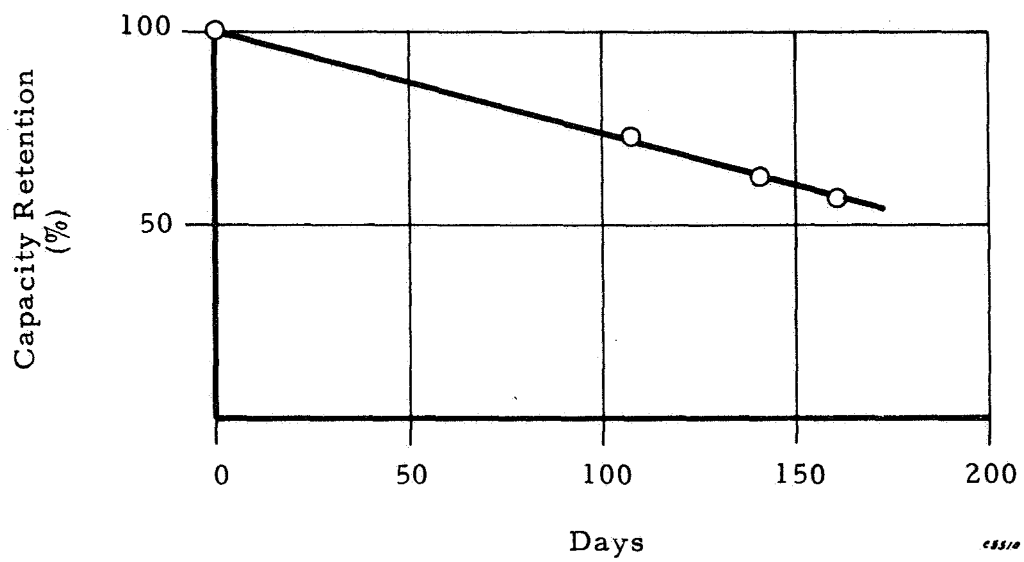


Figure 45. Capacity Retention on Charged Stand at 25°C

some useful information with provision to repeat the test on new cells to remove all doubts. The results of this test over 96 hours at $100^{\circ}C$ are shown in Table XXXVII and Figure 46.

The capacity loss and OCV degradation result from the thermal decomposition of AgO to Ag_2O. The test data show that approximately 60% of the original capacity is still retained after exposure at $100^{\circ}C$ for 24 hours and after 48 hours, although the OCV dropped to 1.12 V in less than 16 hours.

This test was repeated on 10 new cells (Series CL-31A). Table XXXVIII and Figure 47 give the test results that are similar to the first test. The capacity drops to zero after 120 hours exposure at $100^{\circ}C$, but is recoverable up to 70% with a normal charge to 1.60 V cut-off voltage.

5.3 TEST NO. 3 — ELECTRICAL CHARACTERIZATION

Fifteen cells, ten cells using 30% KOH and five cells using 40% KOH, were tested on various depths of discharge ranging from 25% to 100% at 25° and $100^{\circ}C$ consecutively. All discharges were run at the 8-hour rate (0.440 A) and the charges were set constantly at 0.250 A to 1.60 V accurately for coulombic efficiency determination. Table XXXIX and Figures 48 and 49 show the performance of the cells.

5.4 TEST NO. 4 — CYCLING AT 100% DEPTH, $25^{\circ}C$, ONE CYCLE PER DAY (24 HOUR PERIOD)

Fifteen cells, 10 cells with 30% KOH and five cells with 40% KOH, were cycled at $25^{\circ}C$ on the following regime, one cycle per day:

Discharge:	2.9 A to 0.6 V (about 1.2 hours)
Charge:	0.180 A for about 22.8 hours, voltage limited to 1.65 V/cell average.

This regime insures a total discharge of the capacity of the cell within 1.2 hours as required.

Out of ten original cells using 30% KOH, one cell failed at 110 cycles, and another at 120 cycles. The other cells showed signs of OCV failure after

TABLE XXXVII

TEST #2 (CL-31 SERIES)
CAPACITY RETENTION AFTER EXPOSURE AT 100°C

Cell No.	Original Capacity	Time at 100°C (hrs)	Final OCV	Residual Capacity	Capacity After Recharge(25°C)
CL-31-1*	2.8 Ah	8	1.38 V	2.5 Ah	2.8 Ah
CL-31-2	3.6 Ah		1.21 V	2.6 Ah	2.9 Ah
CL-31-3*	2.9 Ah	16	1.11 V	2.6 Ah	2.8 Ah
CL-31-4*	2.7 Ah		1.10 V	2.5 Ah	2.8 Ah
CL-31-5*	3.0 Ah	24	1.12 V	2.4 Ah	2.9 Ah
CL-31-6*	2.9 Ah		1.11 V	2.0 Ah	2.8 Ah
CL-31-7	3.5 Ah	48	1.10 V	1.9 Ah	2.8 Ah
CL-31-8	3.4 Ah		1.08 V	2.0 Ah	2.9 Ah
CL-31-9	3.6 Ah	96	1.11 V	0.7 Ah	2.8 Ah
CL-31-10*	3.0 Ah		1.11 V	0.3 Ah	2.7 Ah

*Cells inadvertently charged in reverse for 16 hours before taking corrective action.

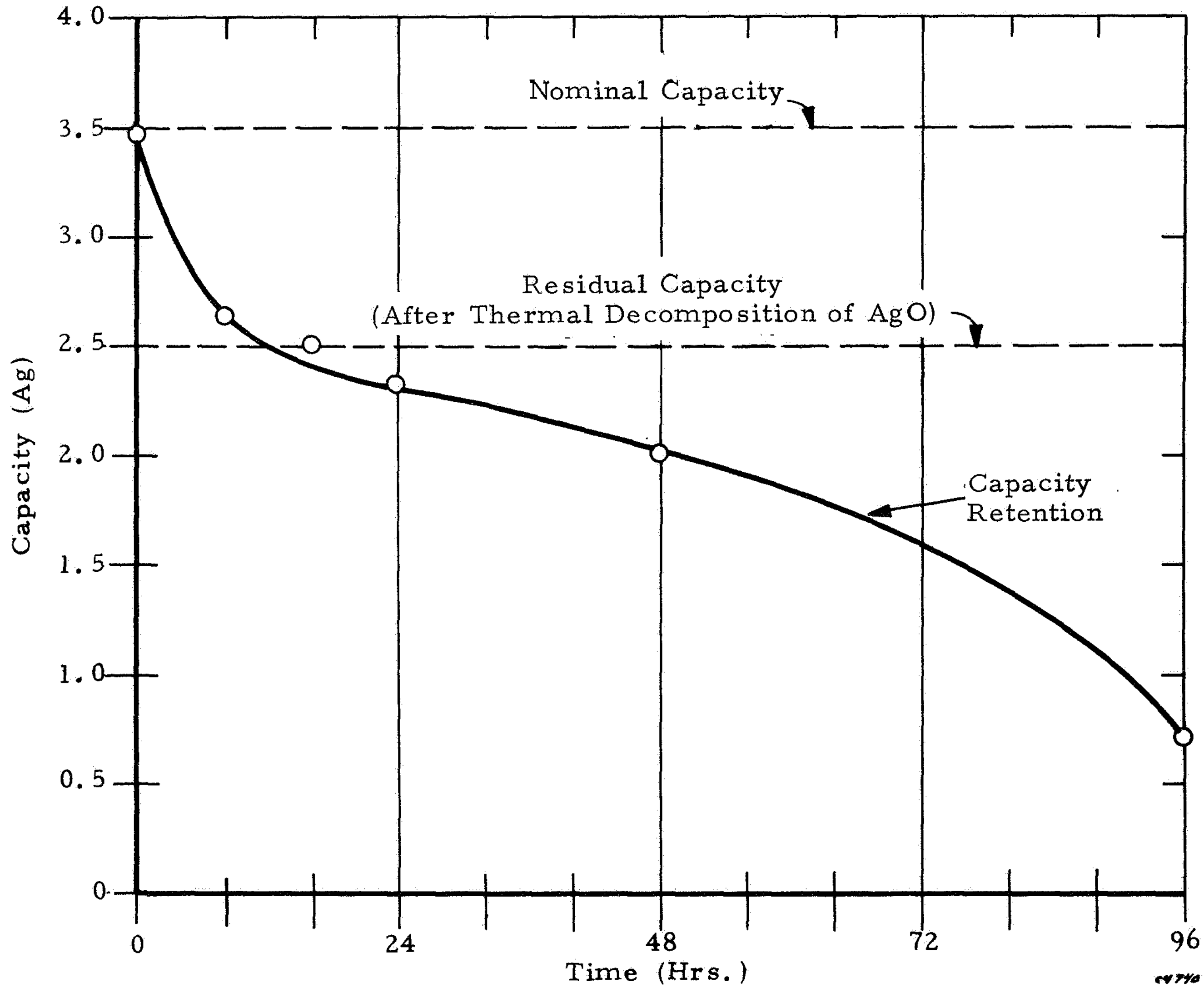


Figure 46. Test #3: Capacity Retention at 100°C.
(Ag-Cd CL-3 Design)

TABLE XXXVIII

TEST #2 A (CL-31 A SERIES)
CAPACITY RETENTION AFTER EXPOSURE AT 100°C

Cell No.	Original Capacity	Time at 100°C (hrs)	Final OCV	Residual Capacity	Capacity After Recharge (25°C)
CL-31-3A	3.95 Ah	16	1.10 V	2.4 Ah	2.5 Ah
-4A	3.95		1.10	2.4	2.5
Average:	3.95 Ah		1.10 V	2.4 Ah	2.5 Ah
CL-31-5A	3.75 Ah	24	1.10 V	2.20 Ah	2.6 Ah
-6A	3.95		1.10	2.3	2.6
Average:	3.85 Ah		1.10 V	2.25 Ah	2.6 Ah
CL-31-7A	3.90 Ah	48	1.10 V	1.80 Ah	2.5 Ah
-8A	4.00		1.10	2.00	2.5
Average:	3.95 Ah		1.10 V	1.90 Ah	2.5 Ah
CL-31-9A	3.40 Ah	96	1.10 V	0.90 Ah	2.3 Ah
-10A	3.80		1.10	1.40	2.3
Average:	3.60 Ah		1.10 V	1.15 Ah	2.3 Ah
CL-31-2A	3.80 Ah	125	0.93 V	0	1.75 Ah
CL-31-1A	3.70 Ah	149	0.86 V	0	1.75 Ah

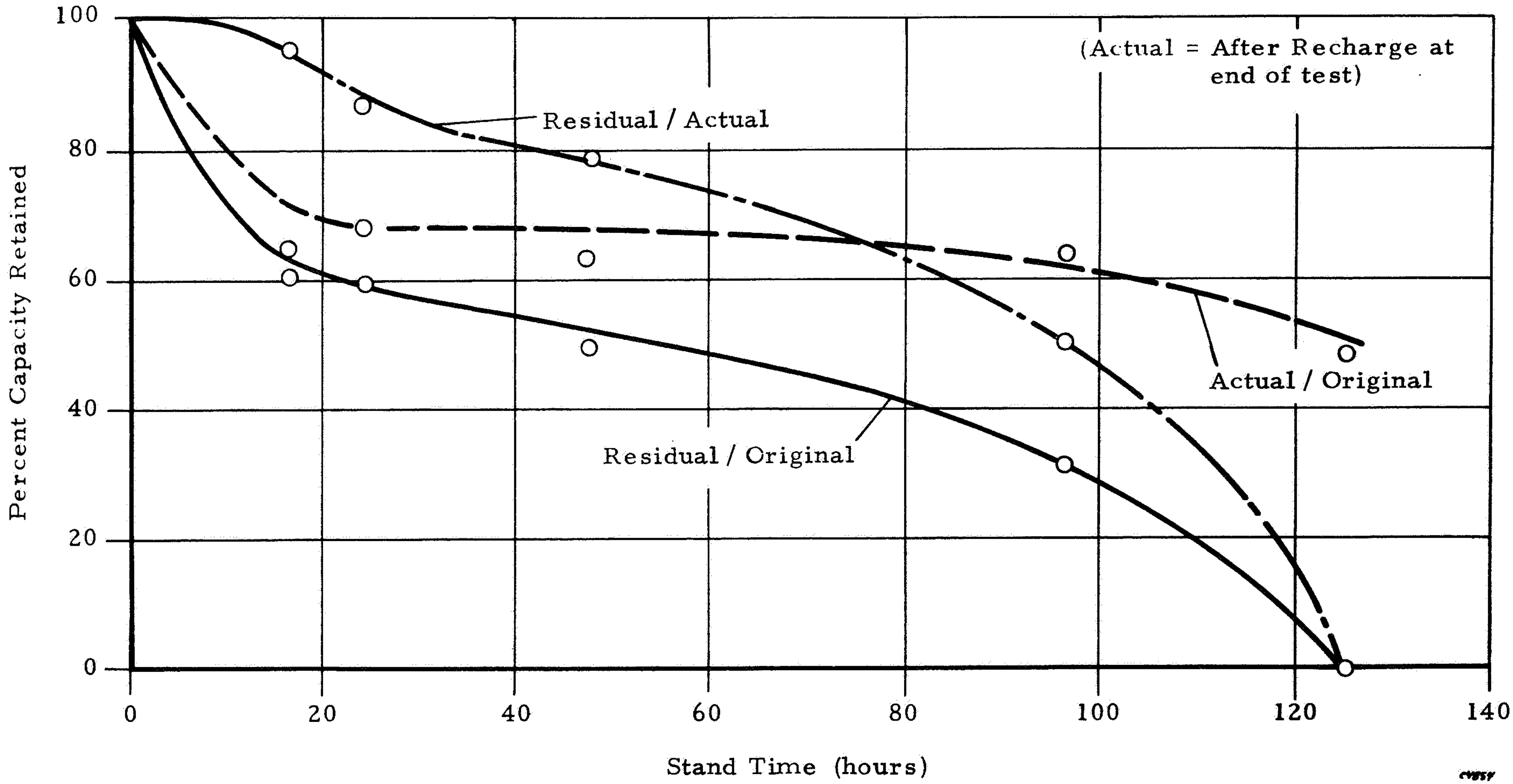


Figure 47. Ag-Cd Cells. CL-31A. (Test 2A)
Wet Stand Tests at 100°C. (Repeat)

TABLE XXXIX

TASK III, TEST #3, ELECTRICAL CHARACTERIZATION AVERAGES OF 10 CELLS WITH 30% KOH AND 5 CELLS WITH 40% KOH

Cycle No.	Temp (°C)	Depth of Discharge (%)	Output (Ah)	KOH (%)	Input to 1.60 V (Ah)	Efficiency (%)
1	25	25	0.88	30	1.09	81
				40	1.06	83
2	25	40	1.40	30	1.47	96
				40	1.44	98
3	25	60	2.10	30	2.15	98
				40	2.10	96
4	25	75	2.62	30	2.64	99
				40	2.73	97
5	25	100	3.12	30	3.38	92
			3.77	40	3.77	100
6	100	25	0.88	30	0.94	83
				40	0.96	92
7	100	40	1.40	30	1.41	99
				40	1.68	84
8	100	60	2.10	30	2.11	99
				40	2.33	91
9	100	75	2.49*	30	2.73	91
			2.64	30	2.69	98
10	100	100	2.52	30	2.63	96
			3.02	40	3.02	100

*Voltage dropped to 0.6 V before 75% of the nominal output.

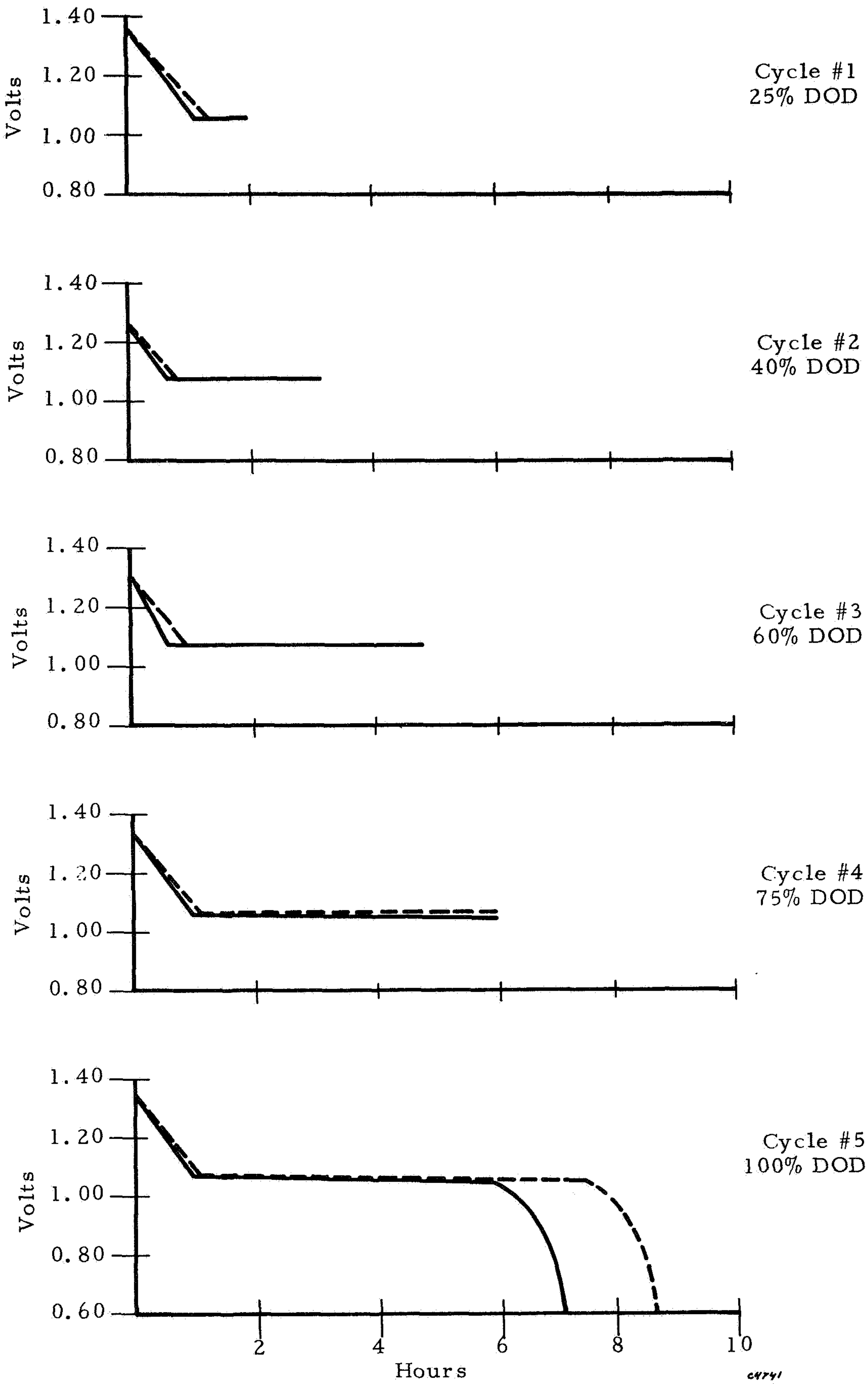


Figure 48. Task III, Test 3, Electrical Characterization at 25°C Cycling Curves. (Solid Lines Represent 30% KOH Cells, Broken Lines 40% KOH Cells.)

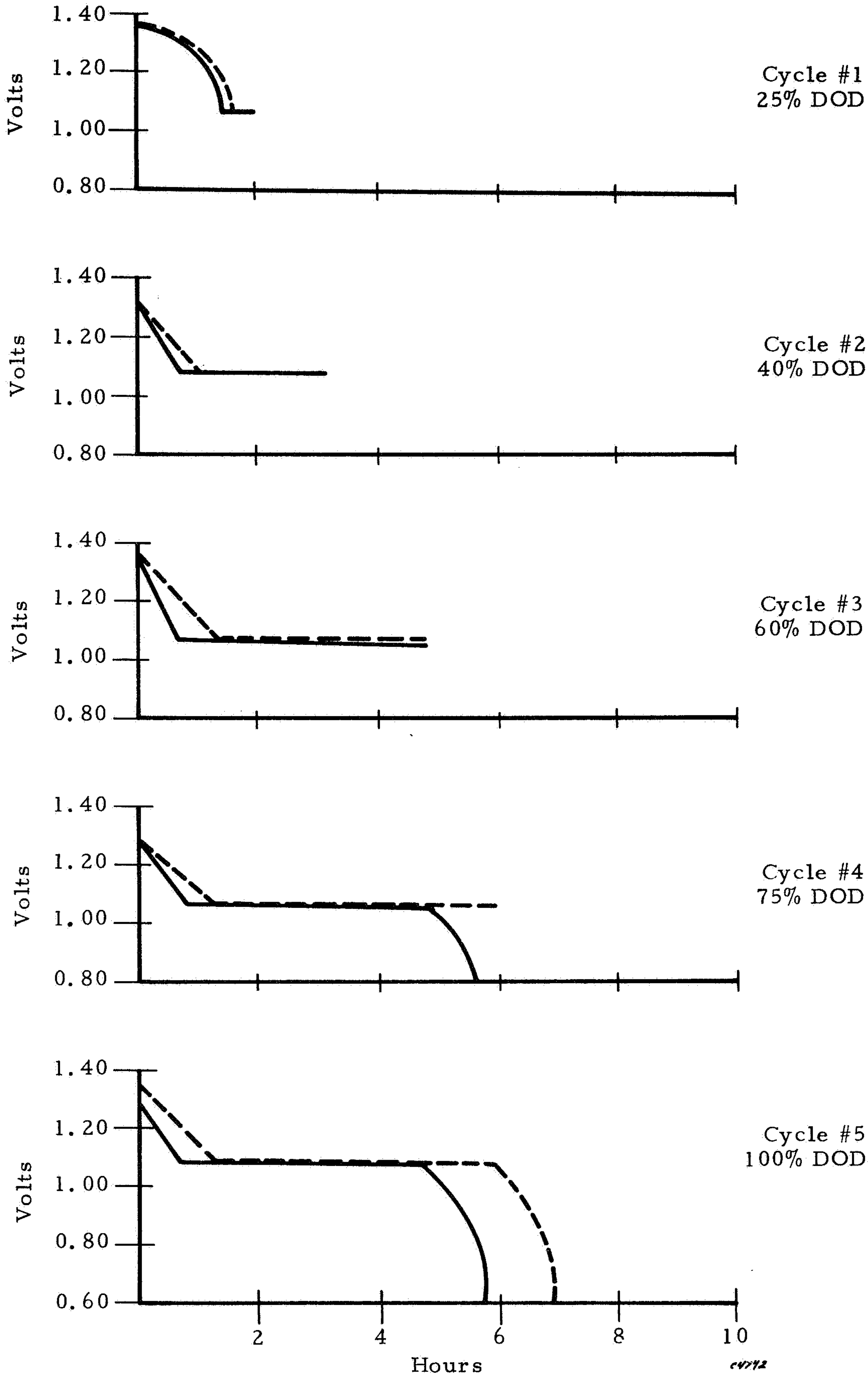


Figure 49. Task III, Test 3, Electrical Characterization at 100°C Cycling Curves. (Solid Lines Represent 30% KOH Cells, Broken Lines 40% KOH Cells.)

cycle 125 and were discontinued at cycle 133. The cells using 40% KOH showed OCV failures at cycle 143. Their slow shorts were of the order of 20 mA (average) as demonstrated by the OCV decay and 50% capacity loss over 72 hours stand. If discharged within a few hours after end of charge, the cells still yielded about 3 Ah. The cells were discontinued at cycle 163.

Here again the cells with 40% KOH electrolyte outperformed the cells with 30% KOH, in cycle life and in output. Data are presented in Table XL. The electrolyte addition was also remarkably lower in cells using 40% KOH. Only 2 cm^3 were added on the average of five cells over their total cycle life compared to 20 cm^3 average in 10 cells using 30% KOH. On a cycle-basis, the cells with 40% KOH used 0.01 cm^3/cycle compared to 0.18 cm^3/cycle in cells with 30% KOH.

The failure mode of all cells was general silver penetration, but silver build-up was noticed at local sites.

5.5 TEST NO. 5 – CYCLING AT 75% DEPTH, 25°C, 24-HOUR PERIOD

Five cells using 30% KOH were cycled on the following regime at 25°C:

Discharge:	2.2 A for 1.2 hours
Charge:	0.130 A for 22.8 hours, voltage limit set at 1.65 V/cell average

Typical cycling curves are shown in Figures 50, 51, and 52.

The cells reached about 200 cycles on this regime, and the mode of failure was loss of OCV caused by silver penetration. Two cells still cycling at the end of the program were OCV- and capacity-checked; after charge, they held 1.38 V after 5 hours, and delivered 3.7 Ah and 2.7 Ah respectively. Individual cell data are presented in Table XLI and later in Table LI.

5.6 TEST NO. 6 – CYCLING AT 75% DEPTH, 100°C, 24-HOUR PERIOD

The regime was the same as above, except that the temperature was 100°C. After a few days, it became difficult to cycle them when series-connected. It

TABLE XL

TASK III – TEST NO. 4 – CYCLING AT 100% DEPTH, 25°C

Cycle No.	30% KOH		40% KOH	
	No. of Cells	Average Output	No. of Cells	Average Output
1	10	3.18 Ah	5	3.61 Ah
3	10	3.40 Ah	5	3.37 Ah
9	10	3.13 Ah	5	2.95 Ah
24	10	2.66 Ah	5	2.69 Ah
36	10	2.70 Ah	5	2.77 Ah
50	10	2.72 Ah	5	2.82 Ah
60	10	2.58 Ah	5	2.82 Ah
71	10	2.62 Ah	5	2.94 Ah
79	10	2.65 Ah	5	2.81 Ah
90	10	2.58 Ah	5	3.02 Ah
104	10	2.64 Ah	5	3.03 Ah
110	9	2.84 Ah	5	3.09 Ah
115	9	2.28 Ah	5	2.47 Ah
120	8	2.55 Ah	5	3.07 Ah
125	8	2.19 Ah	5	3.16 Ah
127	4*	2.05 Ah	5	3.10 Ah
128	1*	1.25 Ah	5	2.92 Ah
130	2*	1.30 Ah	5	3.11 Ah
132	2*	2.20 Ah	5	3.11 Ah
134	DISCONTINUED		5	2.56 Ah
138			5	3.30 Ah
140			5	3.08 Ah
142			5	3.20 Ah
143			5*	1.45 Ah+
147			5	3.04 Ah
149			5	3.0 Ah
156			5	3.1 Ah
157			4*	2.6 Ah
158			3*	2.6 Ah
160			3*	2.6 Ah
162			2*	2.4 Ah
163			DISCONTINUED	

* Several cells lost their OCV after a relatively long stand.

+ When the cells were on charged stand for 72 hours, the OCV's dropped to 1.10 V - 1.27 V and about 50% of the capacity was lost.

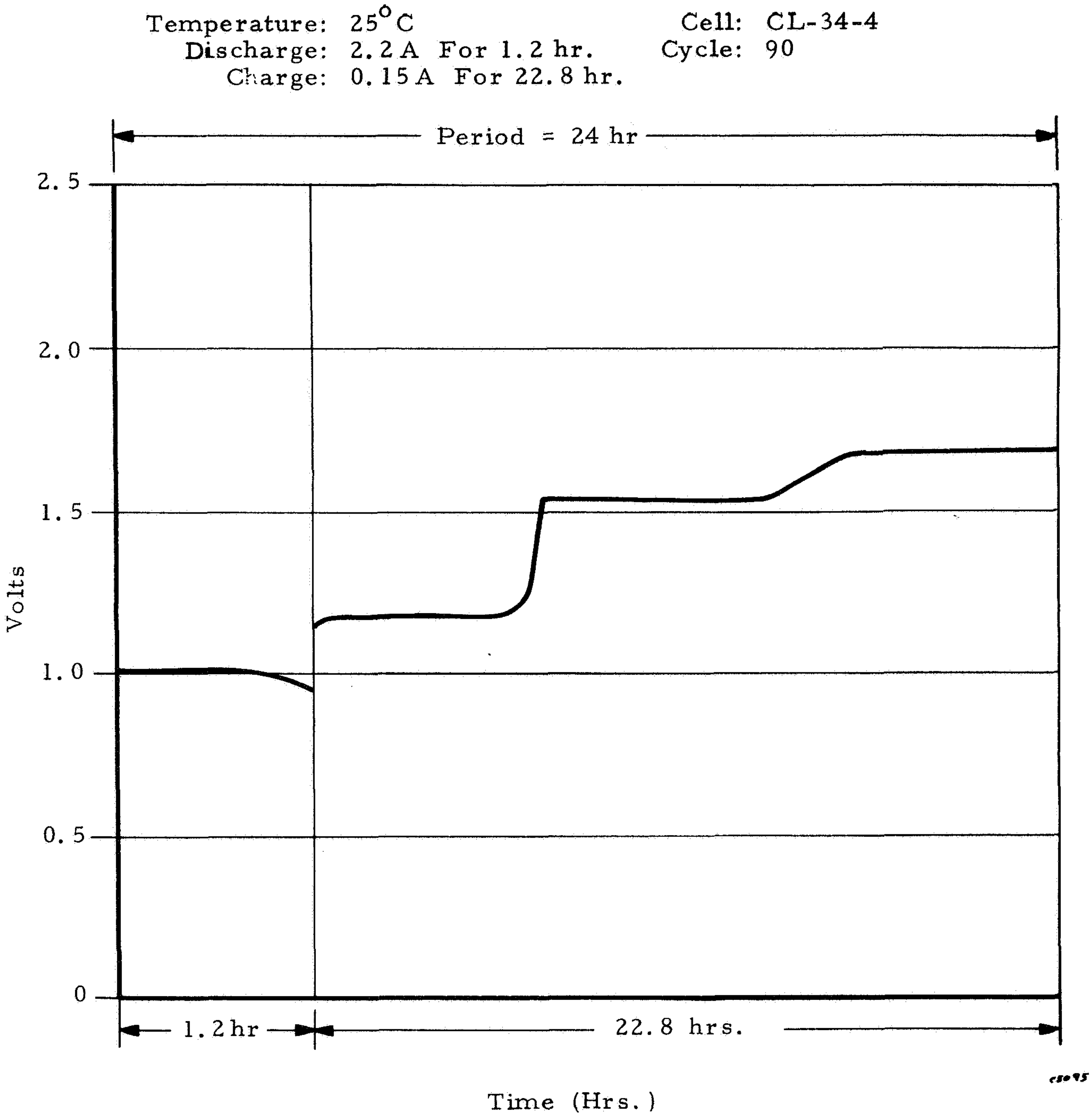


Figure 50. Cycling Curves - Task III, Test 5 (75% Depth)

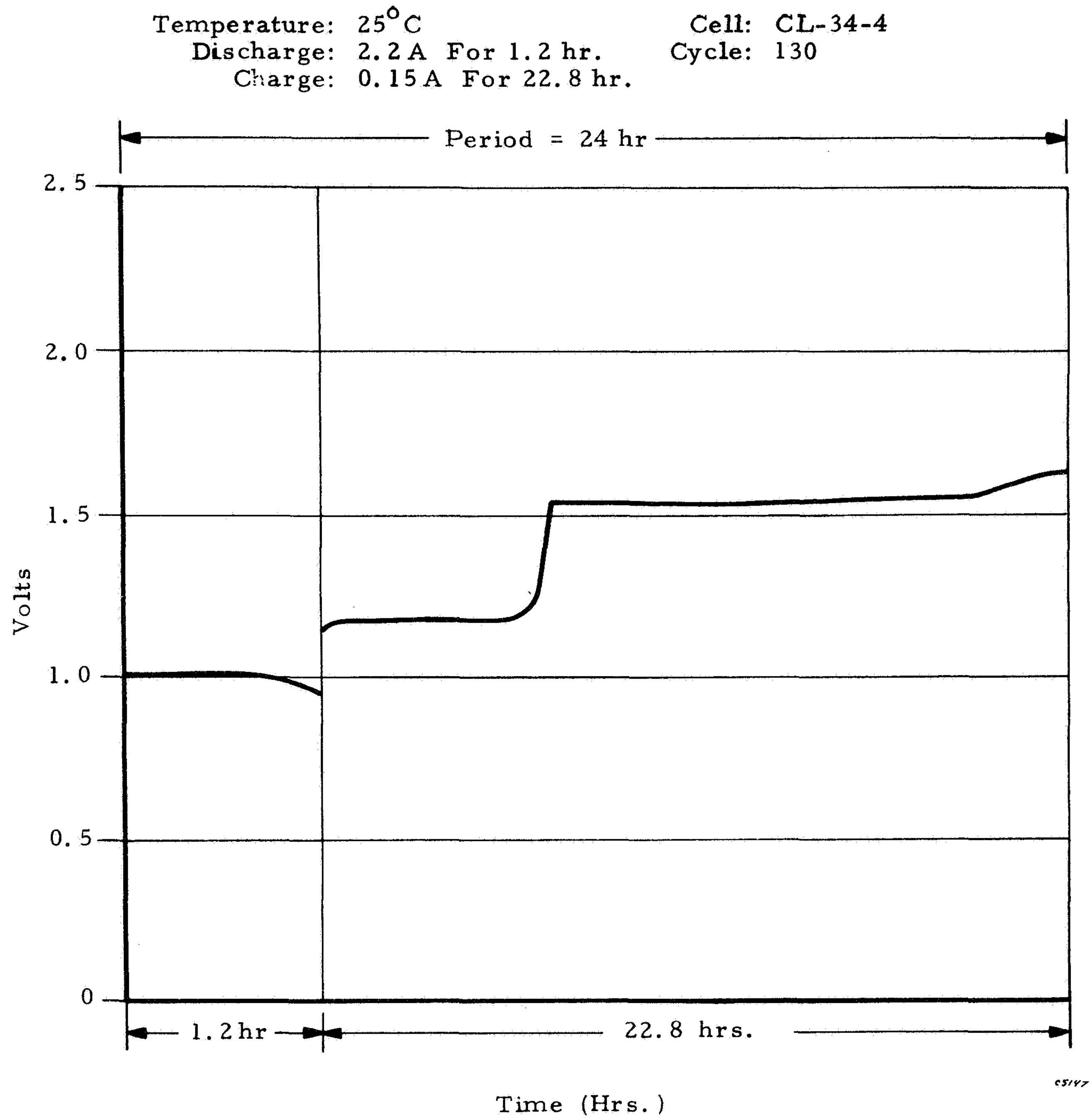


Figure 51. Cycling Curves - Task III, Test 5 (75% Depth)

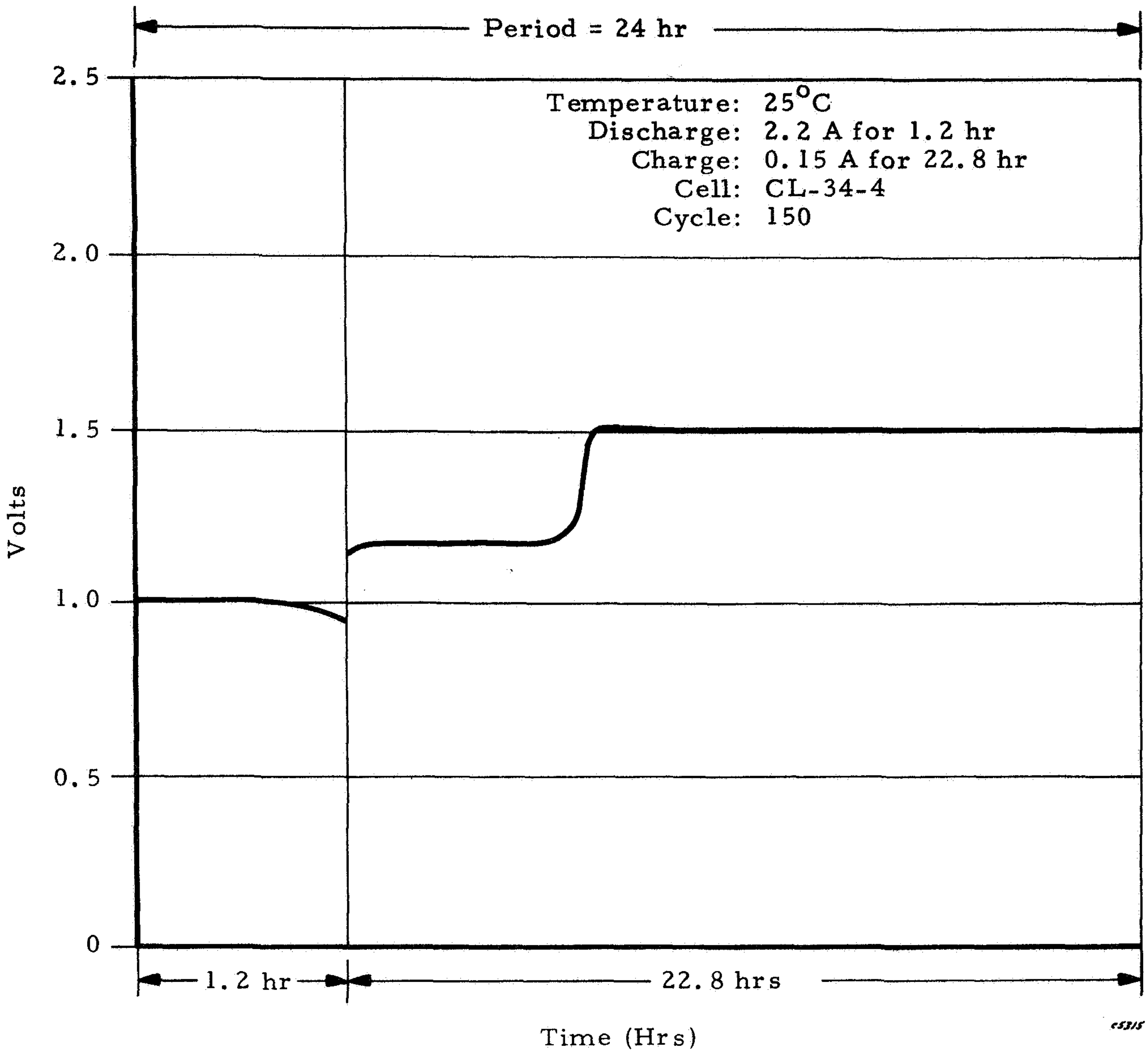


Figure 52. Cycling Curves - Task III, Test 5 (75% Depth)

TABLE XLI

TASK III – CYCLING DATA I.

Test No.	Regime Temp.	Depth	Period	Cell No.	Cycles	Average
5	25°C	75%	24 hrs.	CL-34-1 CL-34-2 CL-34-3 CL-34-4 CL-34-5	214 + 210 214 + 198 178	202 +
6	100°C	75%	24 hrs.	CL-35-1 CL-35-2 CL-35-3 CL-35-4 CL-35-5	25 48 77 32 76	51
9	25°C	75%	8 hrs.	CL-38-1 CL-38-2 CL-38-3 CL-38-4 CL-38-5	251 428 + 286 428 + 428 +	364 +
8	100°C	75%	8 hrs.	CL-37-1 CL-37-2 CL-37-3 CL-37-4 CL-37-5	38 22 42 25 124	50
7	25°C	40%	8 hrs.	CL-36-1 CL-36-2 CL-36-3 CL-36-4 CL-36-5	118 400 218 333 394	292
10	100°C	40%	8 hrs.	CL-39-1 CL-39-2 CL-39-3 CL-39-4 CL-39-5	221 * 221 275 224	235

* Catastrophic failure at Cycle 8.

+ Still cycling at the end of the program.

was decided to determine first the cycling conditions of one cell at a time. The difficulty of cycling at 100°C stems from the poor coulombic efficiency on charge, enhanced by the fact that the cell is exposed to 100°C for a long time on charge (22.8 hours), which will cause an excessive self-discharge. Consequently, the charge current had to be raised substantially. The current was raised to 0.5 A while maintaining a voltage limit of 1.50 volts per cell.

Heavy silver penetration and fast drying out were the primary causes of failure of the cells. Cycling data, which are erratic, are presented in Table XLI.

5.7 TEST NO. 7 – CYCLING AT 40% DEPTH, 25°C, 8-HOUR PERIOD

Five cells using 30% KOH were cycled on the following regime:

Discharge:	1.40 A for 1 hour
Charge:	0.25 A for 7 hours

They reached about 300 cycles (see Table XLI). Typical cycling curves are shown in Figures 53, 54, and 55. Silver penetration was the cause of failure.

5.8 TEST NO. 8 – CYCLING AT 75% DEPTH, 100°C, 8-HOUR PERIOD

Five cells using 30% KOH were put on the following regime:

Temperature:	100°C
Discharge:	2.60 A for 1 hour
Charge:	0.410 A for 7 hours

Their formation capacities averaged 3.5 Ah. Four cells failed between 25 and 42 cycles; the one cell left cycled by itself up to 124 cycles. Data are presented in Table XLI. Failure analysis of the cells showed that silver penetration was the main culprit. It was particularly severe at 100°C.

5.9 TEST NO. 9 – CYCLING AT 75% DEPTH, 25°C, 8-HOUR PERIOD

The cells used on this test were filled with 40% KOH electrolyte. Their capacities were remarkably higher, in the range of 4.6 Ah (Table XLII).

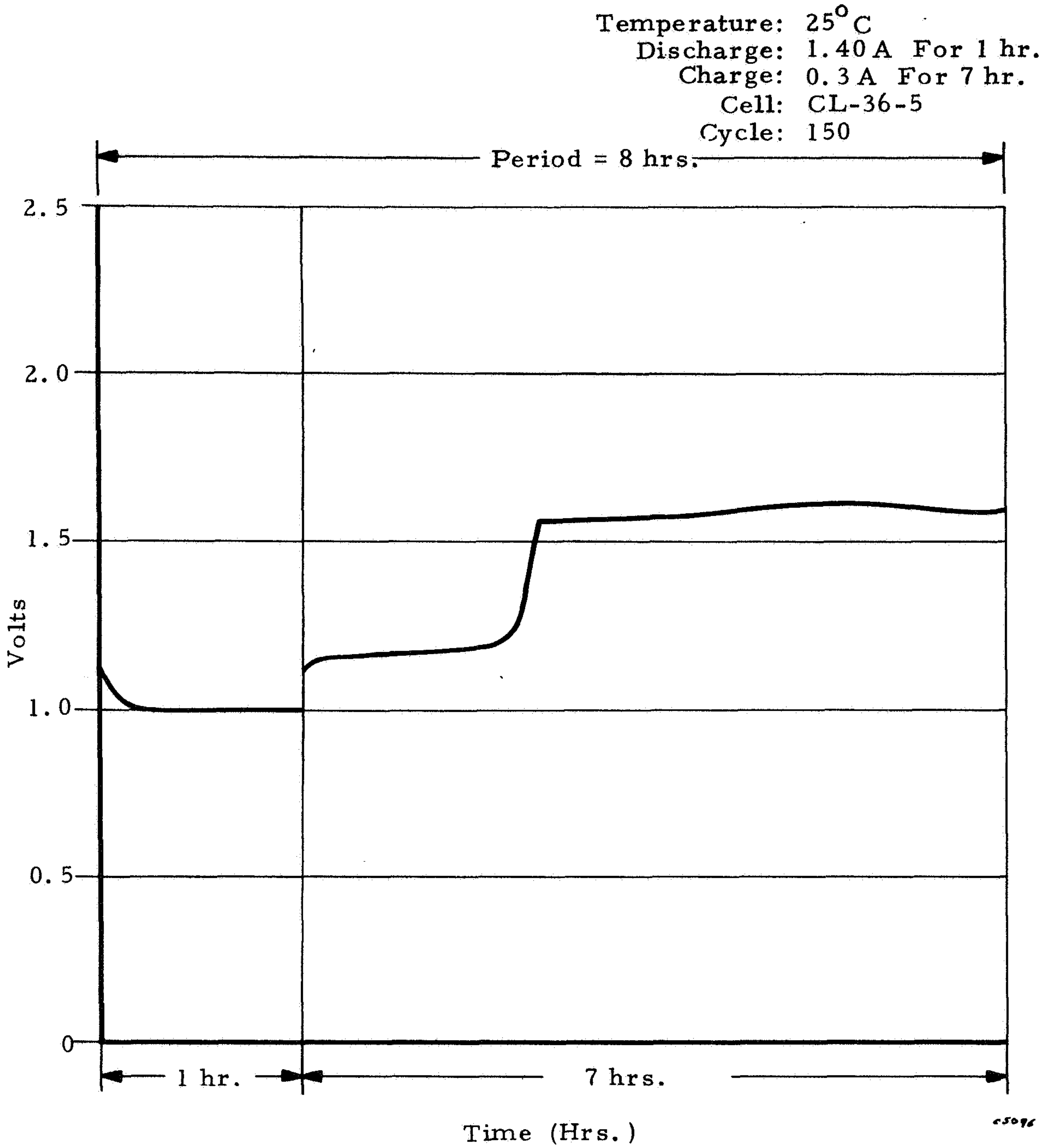


Figure 53. Cycling Curves - Task III, Test 7 (40% Depth)

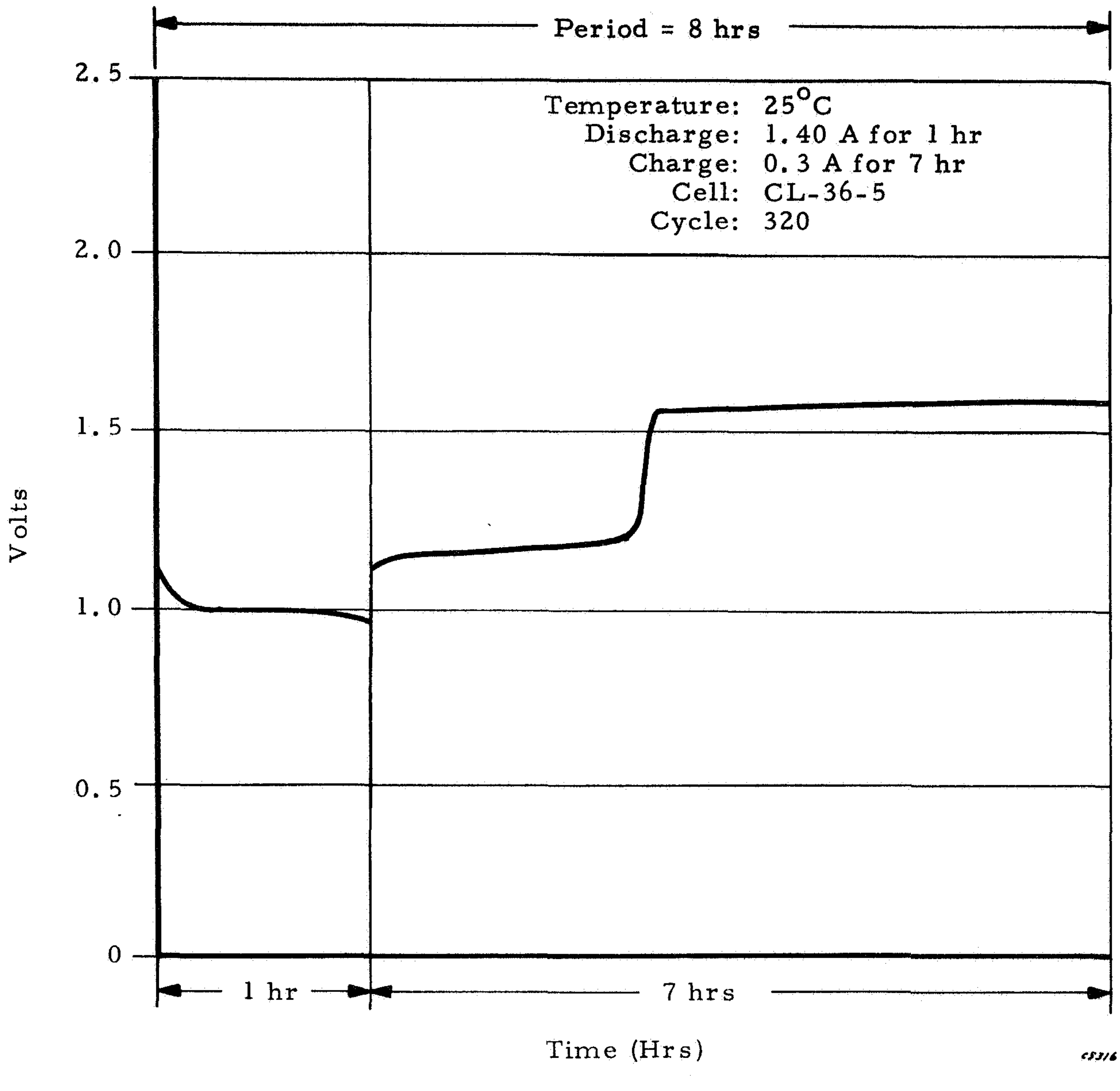


Figure 54. Cycling Curves - Task III, Test 7 (40% Depth)

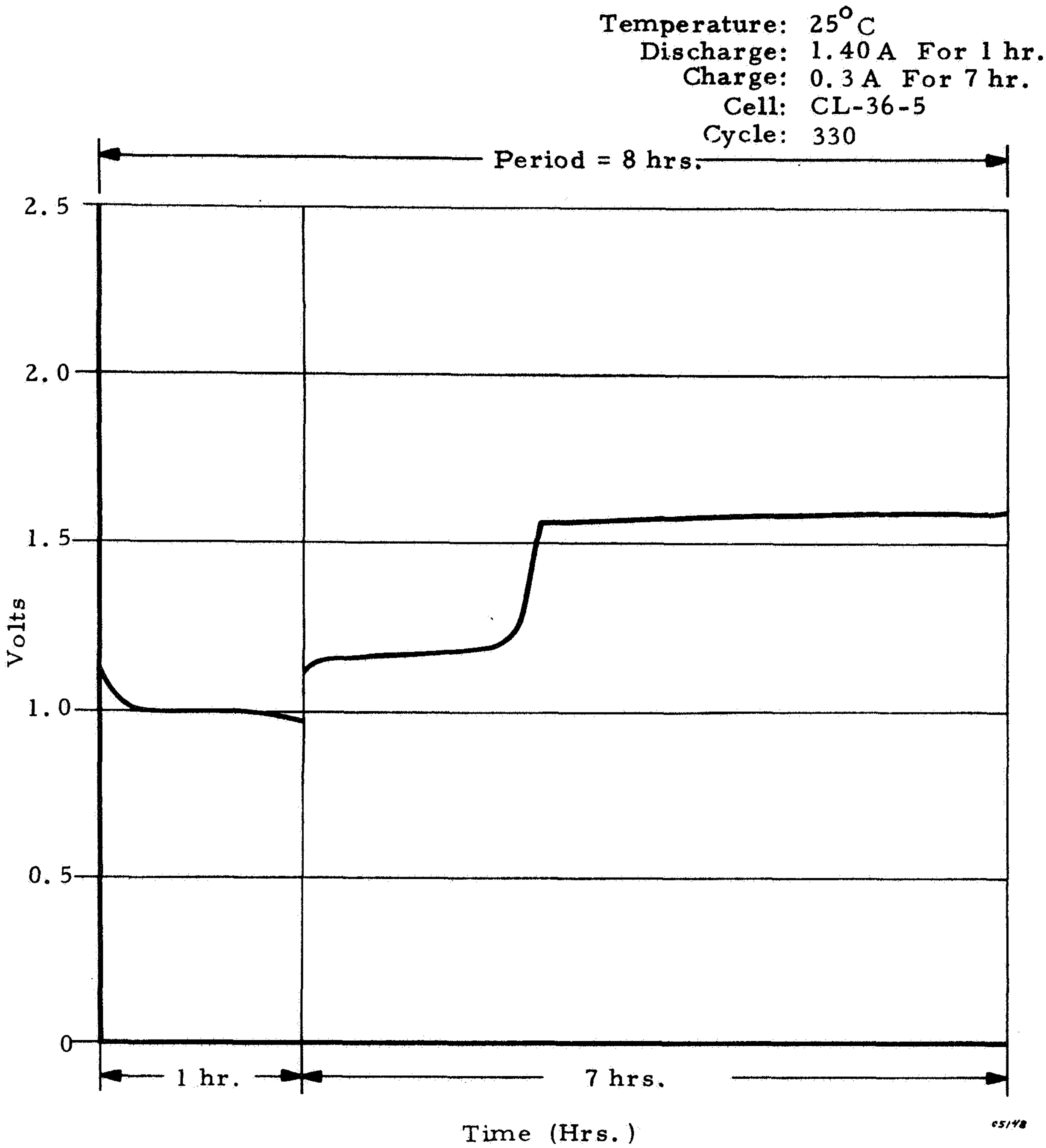


Figure 55. Cycling Curves — Task III, Test 7 (40% Depth)

TABLE XLII

FORMATION CAPACITY OF CL-38 SERIES CELLS

Test #9 (25°C, 40% Depth, 1 Hr x 7 Hr)

Cell No.	Output
CL-38-1	4.7 Ah
CL-38-2	4.7
CL-38-3	4.4
CL-38-4	4.6
CL-38-5	4.6
Average	4.6 Ah

They were placed on the same regime as above, except at 25°C. Cycling data are presented in Table XLI. Cycling curves are shown in Figures 56, 57, and 58. Failure of two cells was again due to silver penetration, but three cells were still cycling at the end of the program, after reaching 428 cycles. Their capacities were 4.9 Ah (see Table LI).

5.10 TEST NO. 10 – CYCLING AT 40% DEPTH, 100°C, 8-HOUR PERIOD

All cells from this point on used 40% KOH electrolyte, as it appeared that silver penetration was remarkably delayed. The five cells marked for this test have their formation capacities presented in Table XLIII. They average 4.6 Ah. The cycling regime was as follows:

Discharge: 1.40 A for 1 hour

Charge: 0.50 A for 7 hours, with a voltage limited to 1.50 V, only.

The cells cycled better than before and reached about 235 cycles. Data are presented in Table XLI. Cycling curves are shown in Figures 59, 60, and 61. Failure analysis on one cell showed a catastrophic failure at cycle 8; examination revealed one cracked separator, possibly due to some stress introduced during fabrication. The other four cells showed the usual silver penetration.

5.11 TESTS NO. 11 AND 15 – CYCLING AT 40% DEPTH, 25°C, 1-5-HOUR PERIOD

Ten cells were cycled in two groups concurrently; one group (Test No. 15) being fitted with pressure gauges and fittings for gas sampling and gas collection beyond the 40 psig relief valve. Their original capacities are shown respectively in Tables XLIV and XLV.

They were placed on the following regime:

Discharge: 2.80 A for 1/2 hour

Charge: 1.60 A for 1 hour

The voltage limit originally set at 1.6 V/cell average proved to be too high as some cells reached relative high pressures (35 psig). The valves opening only at 40 psig, no gas was released.

Temperature: 25°C
Discharge: 2.6 A For 1 hr.
Charge: 0.45 A For 7 hr.

Cell: CL-38-5
Cycle: 100

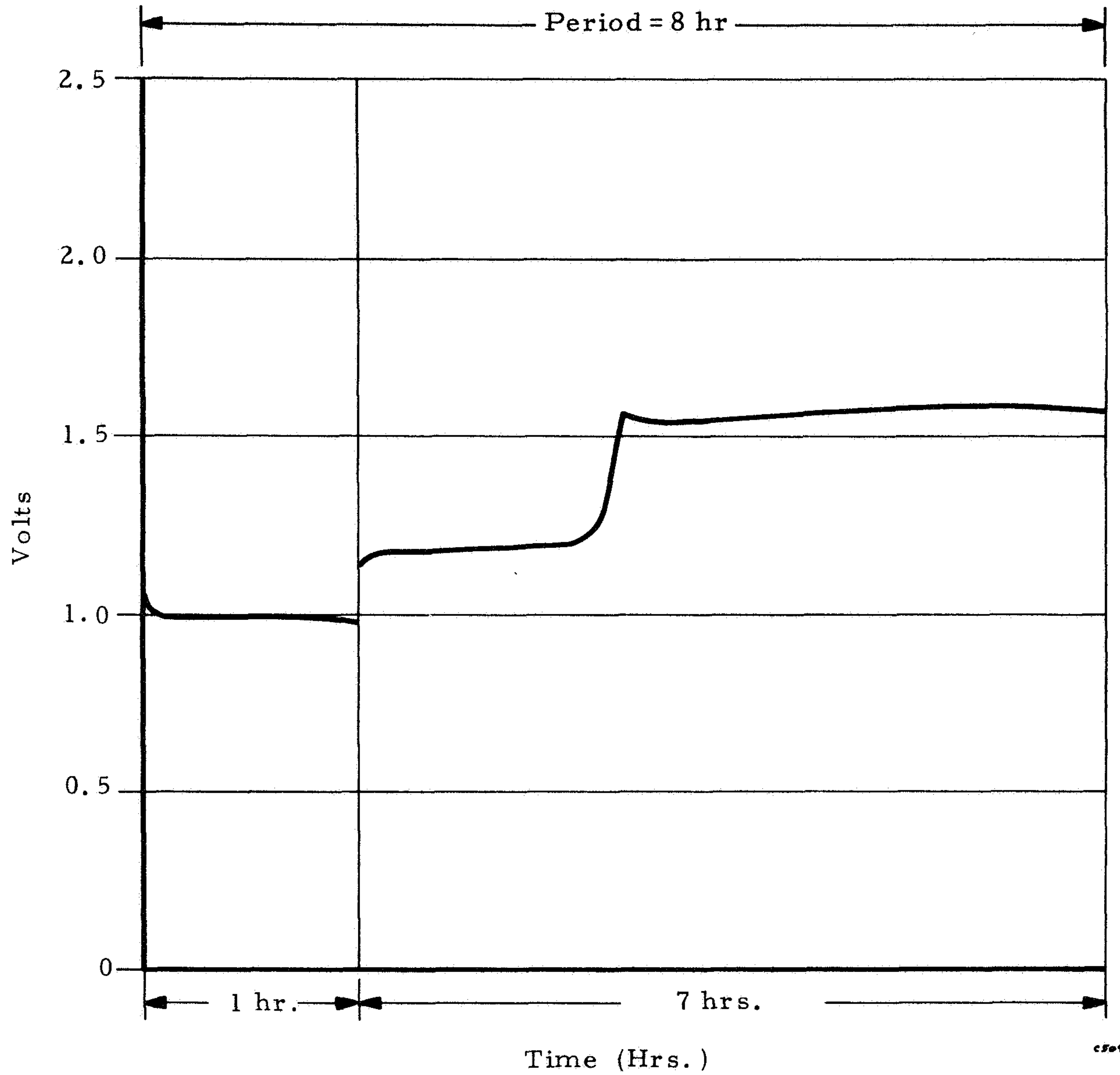


Figure 56. Cycling Curves - Task III, Test 9 (75% Depth)

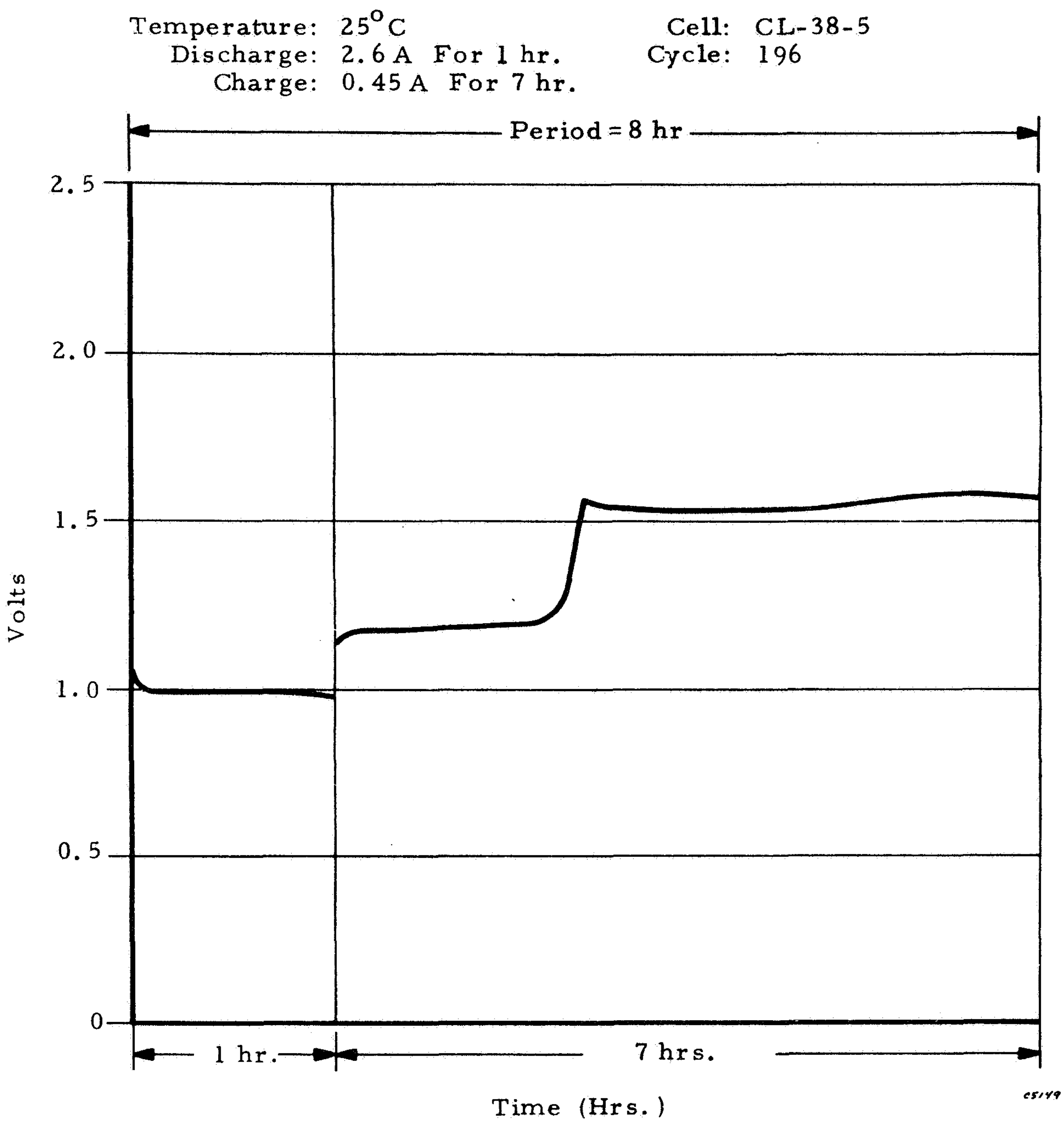


Figure 57. Cycling Curves - Task III, Test 9 (75% Depth)

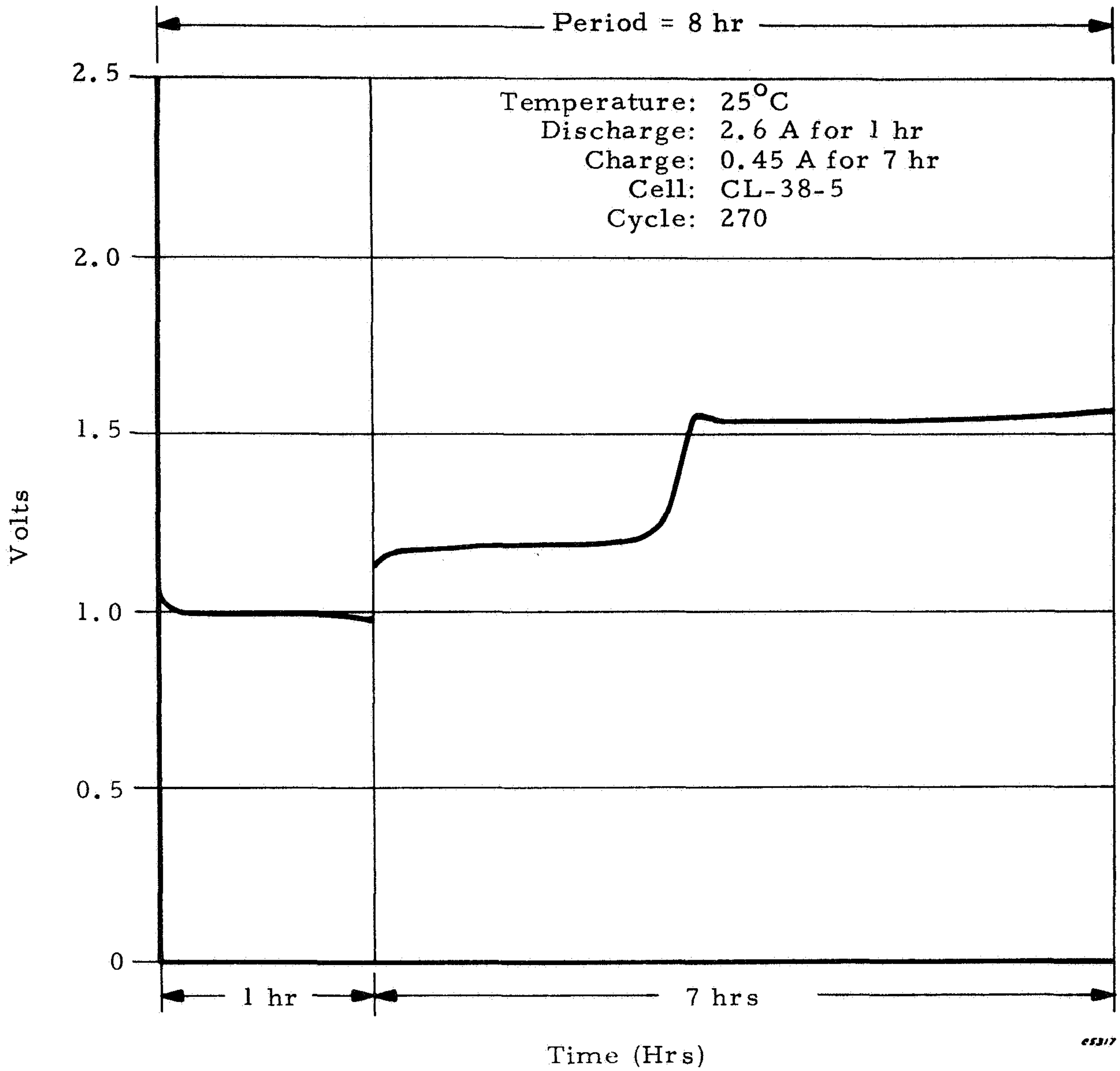


Figure 58. Cycling Curves - Task III, Test 9 (75% Depth)

TABLE XLIII

FORMATION CAPACITY OF
CL-39 SERIES CELLS

Test #10 (100°C, 40% Depth, 1 hr x 7 hr)

Cell Number	Output
CL-39-1	4.8 Ah
CL-39-2	4.5
CL-39-3	4.4
CL-39-4	4.6
CL-39-5	4.5
Average	4.6 Ah

TABLE XLIV

FORMATION CAPACITY OF CELLS FOR
TEST NO. 11, 25°C, 40% DEPTH,
1.5-HOUR PERIOD

Cell Number	Output
CL-49-1	5.0 Ah
CL-40-2	5.1
CL-40-3	4.9
CL-40-4	4.7
CL-40-5	4.8
Average	4.9 Ah

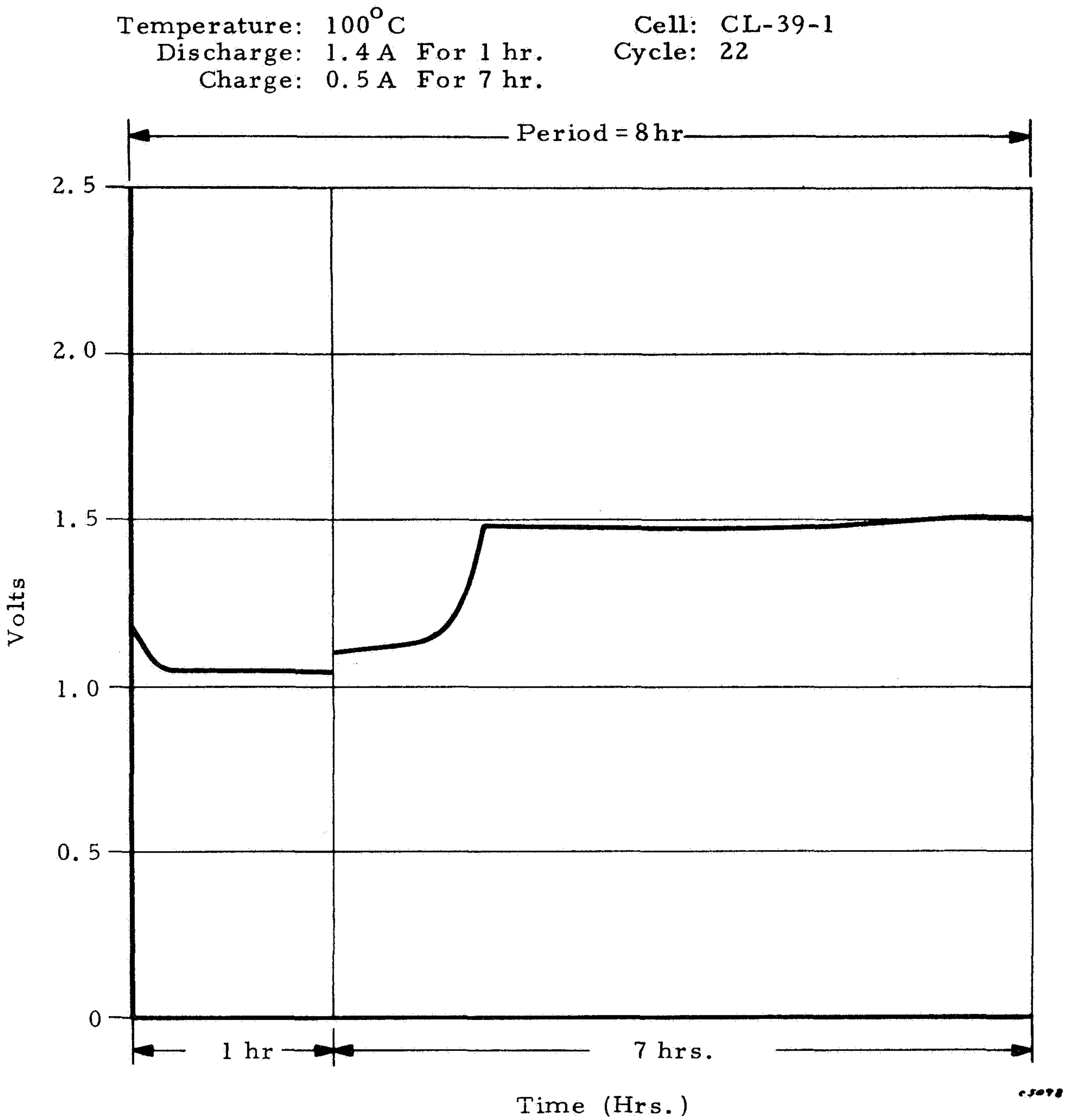


Figure 59. Cycling Curves - Task III, Test 10 (40% Depth)

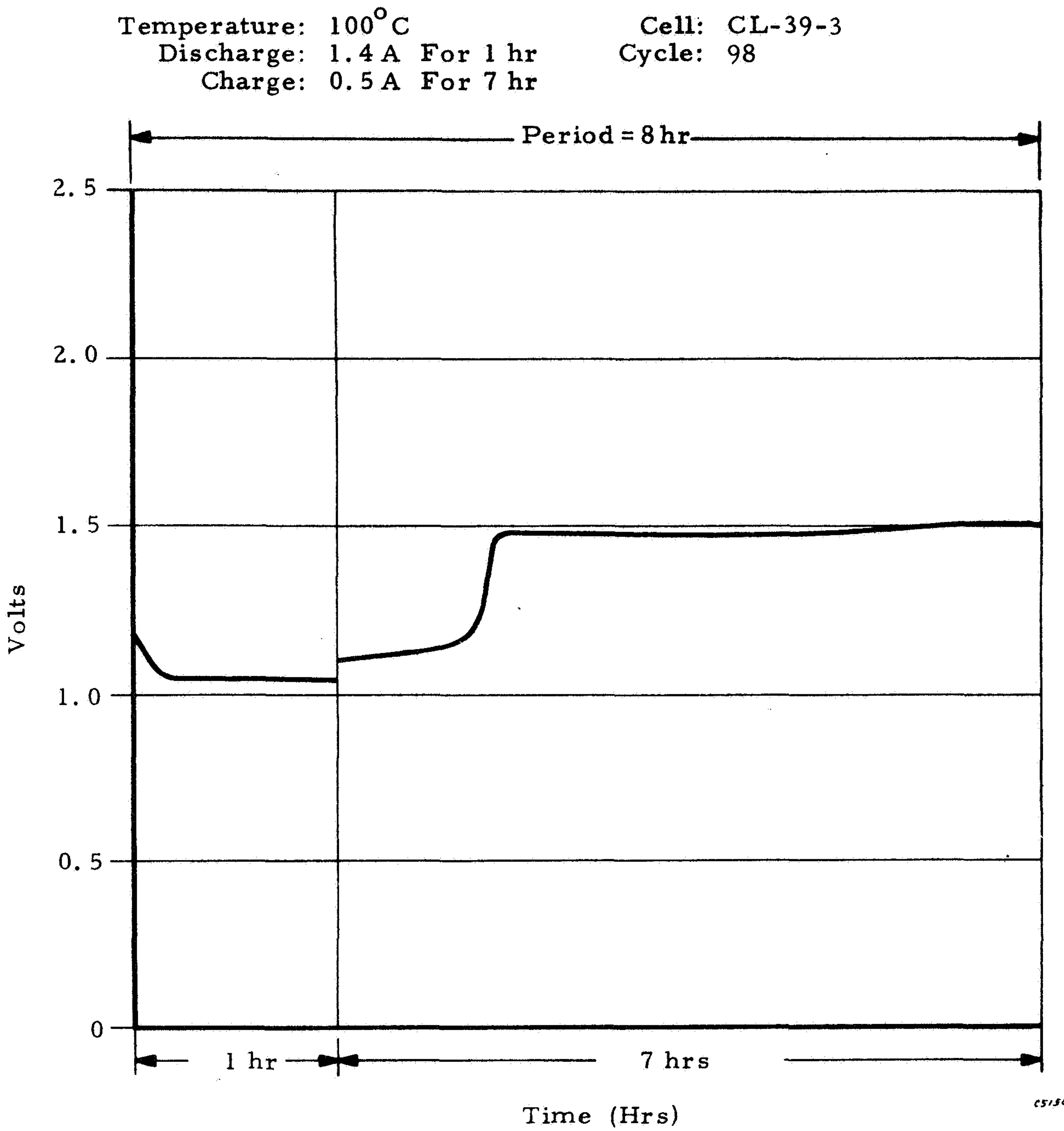


Figure 60. Cycling Curves – Task III, Test 10 (40% Depth)

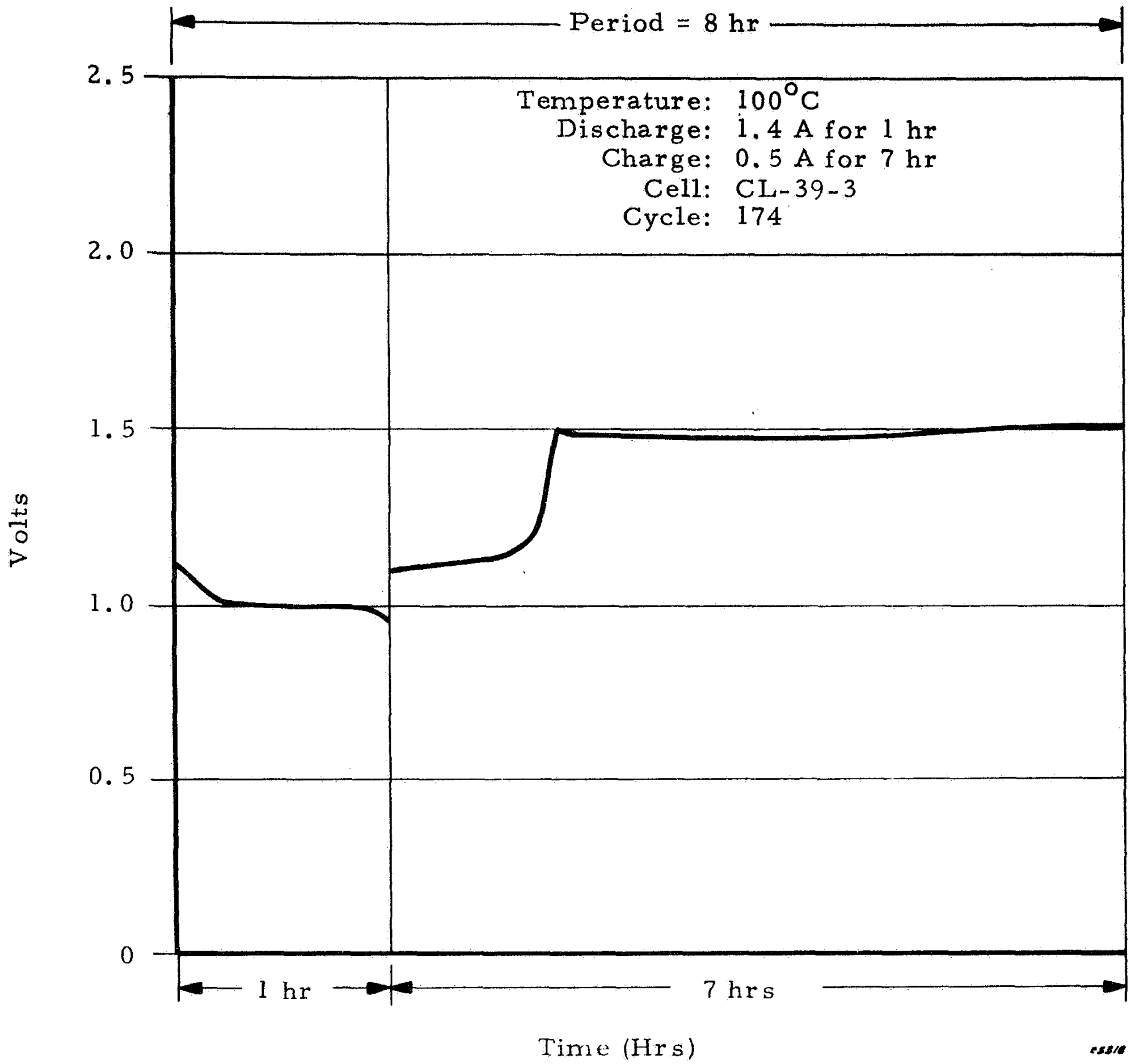


Figure 61. Cycling Curves - Task III, Test 10 (40% Depth)

TABLE XLV

FORMATION CAPACITY OF CELLS FOR TEST NO. 15

25°C, 40% Depth, 1.5-hr period
Gassing Measurements

Cell Number	Output
CL-44-1	4.7 Ah
CL-44-2	4.8
CL-44-3	4.8
CL-44-4	4.9
CL-44-5	4.7
Average	4.8 Ah

The voltage limit was then cut down to 1.56 V/cell at cycle 318, which led to a substantial decrease in pressure caused by the cessation of gas evolution coupled with the recombination of the oxygen present in the cells. Some typical cycling curves are given in Figures 62, 63, and 64. Gassing data are presented in Table XLVI as a function of cycling history. The cells were still cycling at the end of the program after reaching about 2000 cycles. No electrolyte addition was ever made. They were OCV- and capacity-checked. Data are presented in Tables XLVII and LI.

5.12 TESTS NO. 13 AND 17 – CYCLING AT 20% DEPTH, 25°C, 1.5-HOUR PERIOD

Ten cells were cycled in two groups concurrently; one group (Test No. 17) being fitted with pressure gauges and fittings for gas sampling and gas collection beyond the 40 psig relief valve. Their original capacities are shown in Tables XLVIII and IL.

They were placed on the following regime:

Discharge:	1.40 A for 1/2 hour
Charge:	0.8 A for 1 hour

The high voltage limit (1.60 V/cell) originally set caused quasi-immediate overcharge to a point where imbalance of end-of-charge voltages set in and gas was released from three cells. At cycle 251, the voltage limit was reduced to 1.53 V/cell, which led here again to a drastic pressure reduction, a more uniform end-of-charge voltage and a complete cessation of gas venting. Typical cycling curves are shown in Figures 65, 66, and 67. Gassing data are presented in Table L as a function of cycling history. The cells were still cycling at the end of the program after reaching about 2000 cycles. No electrolyte addition was ever made. They were OCV- and capacity-checked. Data are presented in Table LI.

5.13 TESTS NO. 12 AND 16 – CYCLING AT 40% DEPTH, 100°C, 1.5-HOUR PERIOD

The same tests as described in Paragraph 5.11 were repeated at 100°C. The capacities of the five cells of Test No. 12 are given in Table LII and those of

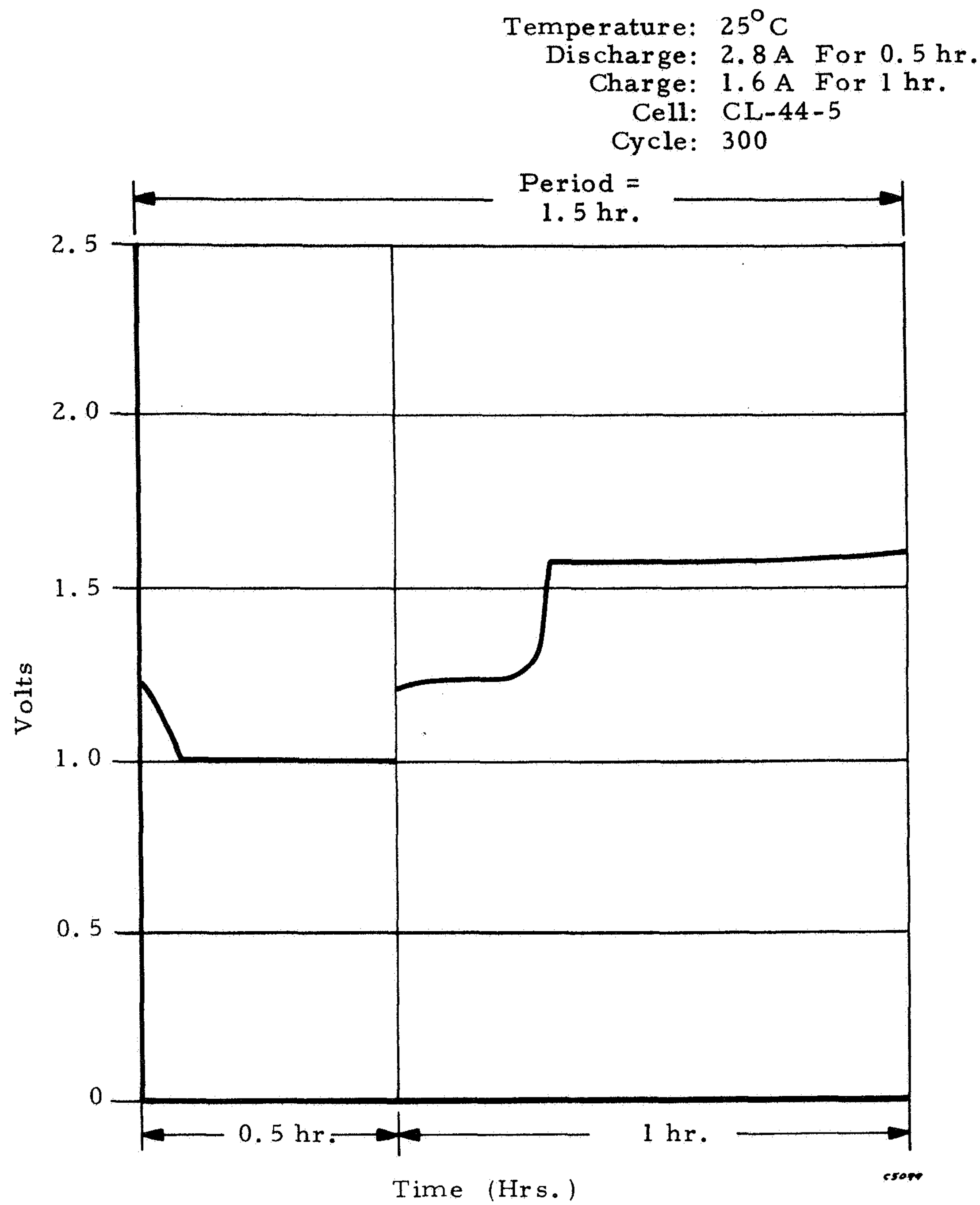


Figure 62. Cycling Curves - Task III, Test 15 (40% Depth)

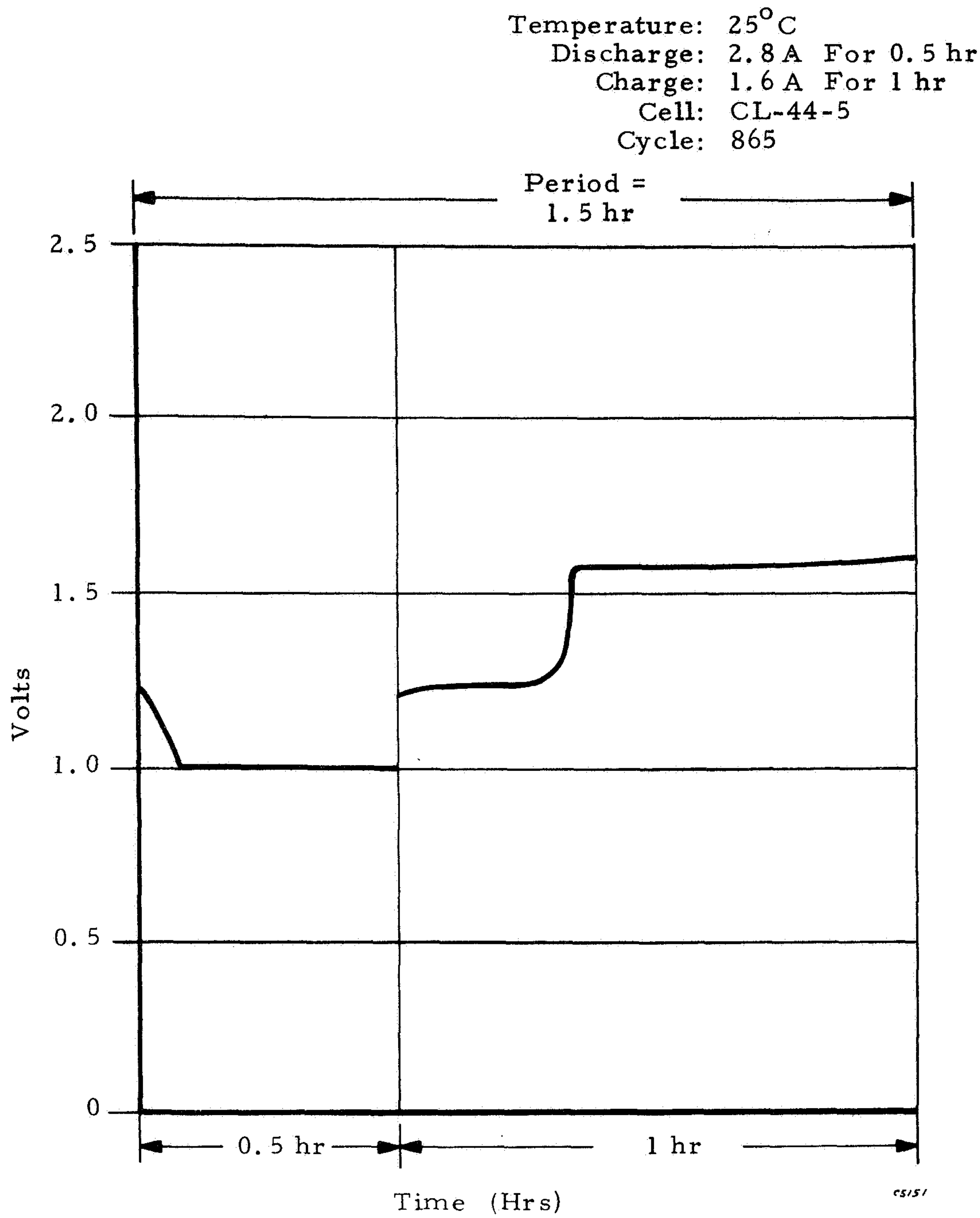


Figure 63. Cycling Curves - Task III, Test 15 (40% Depth)

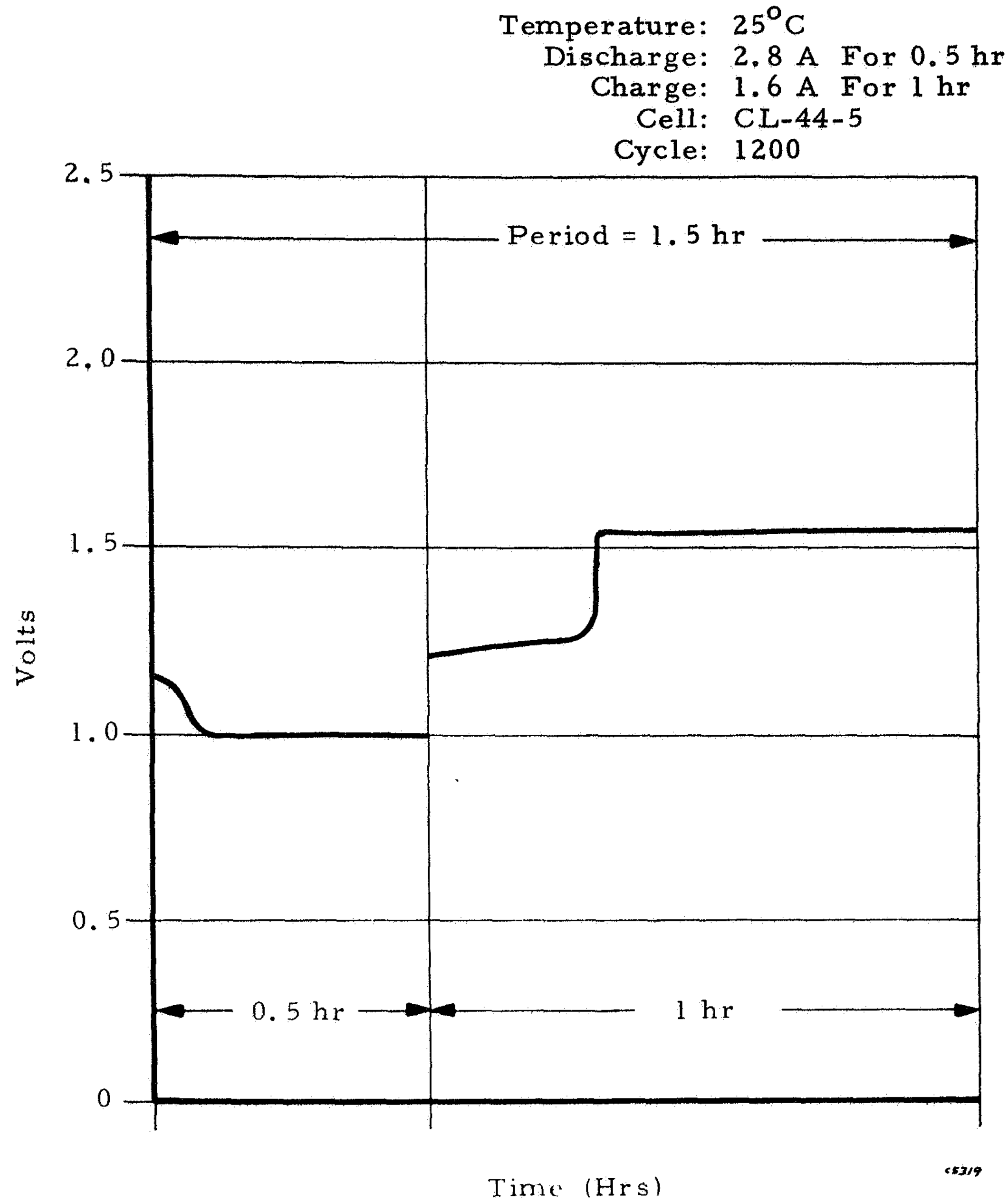


Figure 64. Cycling Curves — Task III, Test 15 (40% Depth)

TABLE XLVI

GASSING MEASUREMENTS FOR CL-44 CELLS (TEST NO. 15)
40% DEPTH, 1.5 HOUR PERIOD, 25°C

Cycle No.	Pressure (psig)	Accumulated Vented Gas (cc)	End-of-Charge Voltage* (V)	Gas Analysis (Coverage)		
				H_2 %	O_2 %	N_2 %
107	0 to 33	0	1.57 to 1.63	0	79.5	20.5
204	0 to 35	0	1.55 to 1.64	0	74.5	25.5
299	0 to 31	0	1.57 to 1.62	—	—	—
412	-5 to 0	0	1.56	—	—	—
466	-5 to 0	0	1.56	—	—	—
556	-5 to 0	0	1.56	—	—	—
655	-6 to 0	0	1.54	—	—	—
765	-5 to 0	0	1.56	—	—	—
957	-5 to 0	0	1.54 to 1.58	—	—	—
1198	-5 to 0	0	1.54 to 1.58	—	—	—
1601	-4 to 0	0	1.52 to 1.62	—	—	—

* Voltage limit originally set at 1.60 V/cell average was cut down to 1.56 V/cell at cycle 318 to reduce pressure and balance end-of-charge voltages.

Note: When the cells are below atmosphere pressure, attempts to run gas analysis fail as the gas sample removed is immediately polluted with large amount of air during the transfer to the gas chromatograph.

TABLE XLVII

CELLS CYCLED AT 25°C AND 1.5-HR. PERIOD

(Cells Still Cycling at the End of the Program at 25°C)

Test No.	Regime: Depth of Discharge (%)	Regime: Period (hrs)	Cell No.	Cycles	Status
11	40%	1.5	CL-40-1	2098	OK
			CL-40-2	2098	OK
			CL-40-3	2098	OK
			CL-40-4	1827	OK
			CL-40-5	2098	OK
15 (g)	40%	1.5	CL-44-1	2098	OK
			CL-44-2	2050	OK
			CL-44-3	2098	OK
			CL-44-4	2098	OK
			CL-44-5	2098	OK
13	20%	1.5	CL-42-1	2098	OK
			CL-42-2	2098	OK
			CL-42-3	2098	OK
			CL-42-4	1938	OK
			CL-42-5	2050	OK
17 (g)	20%	1.5	CL-46-1	1760	OK
			CL-46-2	2016	OK
			CL-46-3	1100	OK
			CL-46-4	2016	OK
			CL-46-5	2016	OK

(g) = Group of cells set up for gassing measurements.

TABLE XLVIII

FORMATION CAPACITY OF CELLS FOR TEST NO. 13, 25°C, 20% DEPTH, 1.5-HOUR PERIOD

Cell Number	Output
CL-42-1	4.8 Ah
CL-42-2	5.1
CL-42-3	4.7
CL-42-4	4.7
CL-42-5	4.7
Average	4.8 Ah

TABLE IL

FORMATION CAPACITY OF CELLS FOR TEST NO. 17

25°C, 20% Depth, 1.5-hr period
Gassing Measurements

Cell Number	Output
CL-46-1	4.6 Ah
CL-46-2	5.1
CL-46-3	4.8
CL-46-4	4.7
CL-46-5	4.9
Average	4.8 Ah

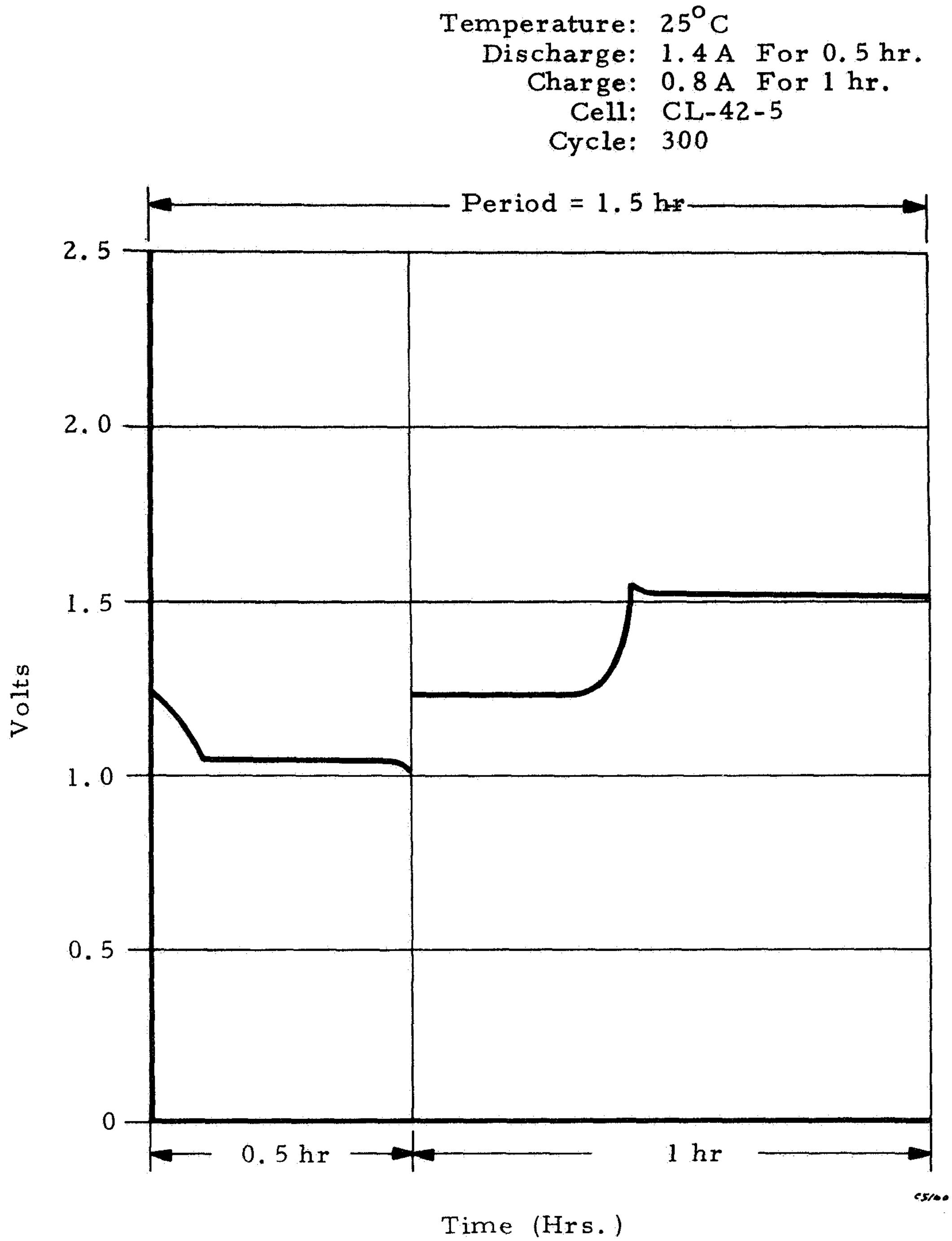


Figure 65. Cycling Curves - Task III, Test 13 (20% Depth)

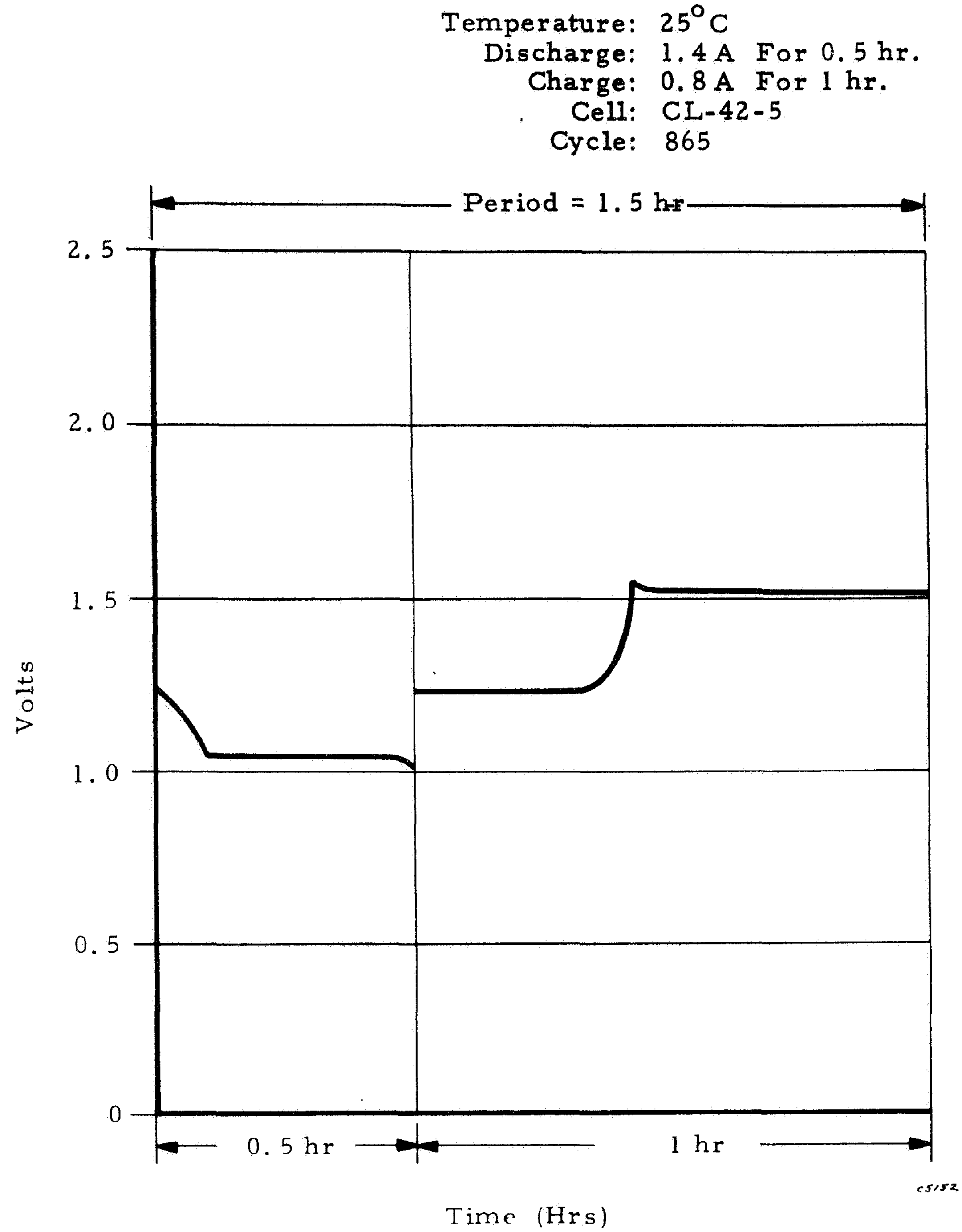


Figure 66. Cycling Curves - Task III, Test 13 (20% Depth)

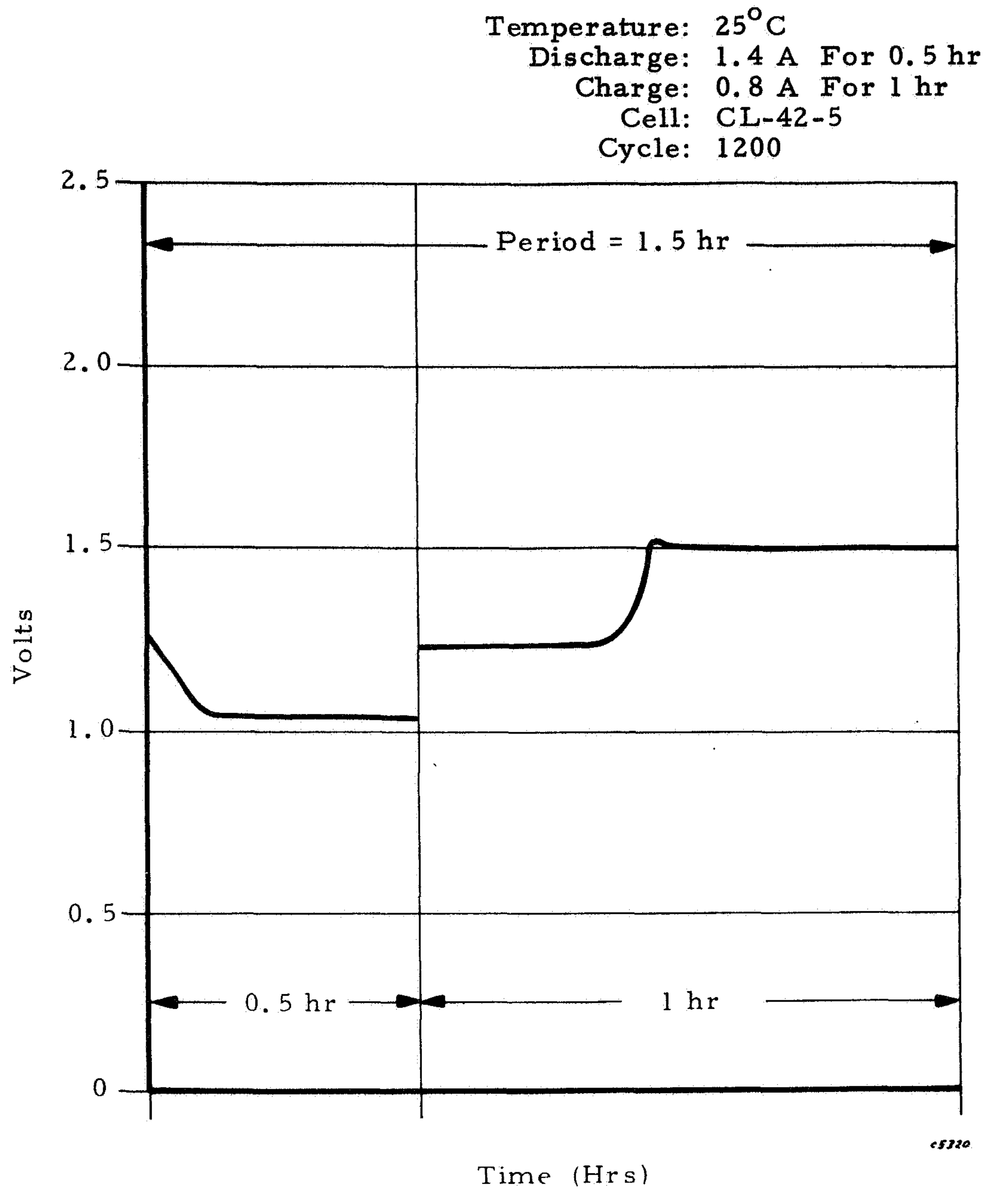


Figure 67. Cycling Curves – Task III, Test 13 (20% Depth)

TABLE L

GASSING MEASUREMENTS FOR CL-46 CELLS (TEST NO. 17) 20% DEPTH, 1.5 HOUR PERIOD, 25°C

Cycle No.	Pressure (psig)	Accumulated Vented Gas (cc)	End-of-Charge Voltage* (V)	Gas Analysis (Coverage)		
				H_2 %	O_2 %	N_2 %
107(1)	9 to 42	0 to 68	1.54 to 1.66	0	62.4	37.6
204(2)	19 to 42	0 to 278	1.53 to 1.68	19	67.0	14.0
299(3)	-4 to 7	0	1.51 to 1.52	—	—	—
412	-9 to -2	0	1.50 to 1.53	—	—	—
444	-9 to -2	0	1.53	—	—	—
556	-9 to -2	0	1.49 to 1.53	—	—	—
655	-9 to -1	0	1.49 to 1.53	—	—	—
765	-8 to -1	0	1.49 to 1.53	—	—	—
958	-5 to 12*	0	1.49 to 1.55	0.8*	64.6*	34.1*
1196	-5 to 0	0	1.51 to 1.52	—	—	—
1583	-20 to 8	0	1.48 to 1.63	—	—	—

(1) One overcharged cell (42 psig, 1.66 V, 46% H_2, 29% O_2, 25% N_2) was not counted in the average.

(2) Two cells were overcharged.

(3) Voltage limit originally set at 1.60 V/cell average was cut down to 1.53 V/cell at cycle 251. Three cells which were overcharged released only a total of 29 cc, 68 cc, 324 cc, respectively, before ending gas evolution. After the voltage reduction, no cell gassed.

* Two cells in series were overcharged: gas analysis noted is for cell of lowest pressure; highest pressure cell gave 12.9% H_2, 55.6% O_2, 30.9% N_2.

Note: When the cells were below atmosphere pressure, attempts to run gas analysis failed as the gas sample removed was immediately polluted with large amount of air during the transfer to the gas chromatograph.

TABLE LI

OCV AND CAPACITY CHECK OF TASK III CELLS

(Still cycling at the end of the program)

Test No.	Cell No.	OCV (hrs on stand)	Capacity
5	CL-34-1	1.38 V (5 hrs)	3.7 Ah
	CL-34-3	1.38 V (5 hrs)	2.7 Ah
9	CL-38-2	1.42 V (5 hrs)	4.8 Ah
	CL-38-4	1.39 V (5 hrs)	4.9 Ah
	CL-38-5	1.42 V (5 hrs)	4.9 Ah
11	CL-40-1	1.38 V (5 hrs)	4.1 Ah
	CL-40-2	1.38 V (5 hrs)	3.7 Ah
	CL-40-3	1.38 V (5 hrs)	4.7 Ah
	CL-40-4	1.38 V (5 hrs)	4.7 Ah
	CL-40-5	1.39 V (5 hrs)	3.7 Ah
13	CL-42-1	1.38 V (5 hrs)	3.6 Ah
	CL-42-2	1.38 V (5 hrs)	3.8 Ah
	CL-42-3	1.38 V (5 hrs)	3.0 Ah
	CL-42-4	1.38 V (5 hrs)	2.7 Ah
	CL-42-5	1.39 V (5 hrs)	2.7 Ah
15	CL-44-1	1.38 V (5 hrs)	3.5 Ah
	CL-44-2	1.35 V (5 hrs)	3.7 Ah
	CL-44-3	1.37 V (5 hrs)	3.6 Ah
	CL-44-4	1.35 V (5 hrs)	1.7 Ah
	CL-45-5	1.26 V (5 hrs)	3.6 Ah
17	CL-46-1	1.42 V (5 hrs)	4.0 Ah
	CL-46-2	1.37 V (5 hrs)	3.6 Ah
	CL-46-3	1.38 V (5 hrs)	2.8 Ah
	CL-46-4	1.36 V (5 hrs)	3.2 Ah
	CL-46-5	1.38 V (5 hrs)	3.1 Ah

TABLE LII

FORMATION CAPACITY OF CELLS FOR TEST NO. 12

$100^{o}C$, 40% Depth, 1.5-hr period

Cell Number	Output
CL-41-1	5.0 Ah
CL-41-2	4.9
CL-41-3	4.9
CL-41-4	4.7
CL-41-5	4.8
Average	4.8 Ah

Test No. 16 are given in Table LIII. Gassing and cycling data are presented in Tables LIV and LV, respectively. No electrolyte addition was ever made. Failure of cells was due to the same severe silver penetration.

5.14 TESTS NO. 14 AND 18 – CYCLING AT 20% DEPTH, 100°C, 1.5-HOUR PERIOD

The same tests as described in Paragraph 5.12 were repeated at 100°C. The capacities of the five cells of Test No. 14 are given in Tables LVI and LVII, respectively. A typical cycling curve is shown in Figure 68. Gassing and cycling data are presented in Tables LVIII and LV. It is interesting to note that hydrogen is absent and oxygen content is very low. This is due to the fact that the end charging voltage is relatively low and mainly that whatever oxygen is evolved or formerly present was recombined quite rapidly at 100°C by the cadmium electrodes. Two cells were discontinued at cycle 176 and 205 because the cases cracked and electrolyte leaked out. The other cells presented the same symptoms of silver penetration.

TABLE LIII

FORMATION CAPACITY OF CELLS FOR TEST NO. 16

$100^{o}C$, 40% Depth, 1.5-hr. Period
Gassing Measurements

Cell No.	Output
CL-45-1	5.0 Ah
CL-45-2	4.9 Ah
CL-45-3	4.8 Ah
CL-45-4	5.0 Ah
CL-45-5	4.9 Ah
Average	4.9 Ah

TABLE LIV

GASSING MEASUREMENTS FOR CL-45 CELLS (TEST NO. 16)

40% Depth, 1.5-hr. Period, 100°C

Cycle No.	Pressure (psig)	Accumulated Vented Gas (cc)	End-of-Charge Voltage (V)	Gas Analysis (Average)		
				H_2 (%)	O_2 (%)	N_2 (%)
32	2 to 23	0	1.49 to 1.50		16.2	81.8
147	2 to 27	0	1.50 to 1.54		39	61

TABLE LV

CELLS CYCLED AT 100°C AND 1.5-HR. PERIOD

Test No.	Depth of Discharge	Cell No.	Cycles	Average
12	40%	CL-41-1	229	
		CL-41-2	202	
		CL-41-3	213	
		CL-41-4	167	
		CL-41-5	202	173
16 (g)	40%	CL-45-1	140	
		CL-45-2	98	
		CL-45-3	108	
		CL-45-4	173	
		CL-45-5	194	
14	20%	CL-43-1	765	
		CL-43-2	605	
		CL-43-3	555	
		CL-43-4	239	
		CL-43-5	533	508
18	20%	CL-47-1	404	
		CL-47-2	176*	
		CL-47-3	522	
		CL-47-4	205*	
		CL-47-5	444	

Note: * Polysulfone case cracked, electrolyte leaked, test discontinued.

(g) Group of cells set up for gassing measurements.

TABLE LVI

FORMATION CAPACITY OF CELLS FOR TEST NO. 14

$100^{o}C$, 20% Depth, 1.5-hr. Period

Cell No.	Output
CL-43-1	4.95 Ah
CL-43-2	4.70 Ah
CL-43-3	4.70 Ah
CL-43-4	4.90 Ah
CL-43-5	4.70 Ah
Average	4.80 Ah

TABLE LVII

FORMATION CAPACITY OF CELLS FOR TEST NO. 18

$100^{\circ}C$, 20% Depth, 1.5-hr. Period
Gassing Measurements

Cell No.	Output
CL-47-1	4.90 Ah
CL-47-2	4.70 Ah
CL-47-3	4.75 Ah
CL-47-4	4.85 Ah
CL-47-5	4.75 Ah
Average	4.80 Ah

TABLE LVIII

GASSING MEASUREMENTS FOR CL-47 CELLS (TEST NO. 18)

20% Depth, 1.5-hr. Period, $100^{\circ}C$

Cycle No.	Pressure (psig)	Accumulated Vented Gas (cc)	End-of-Charge Voltage (V)	Gas Analysis (Average)		
				H_2 (%)	O_2 (%)	N_2 (%)
133	7 to 28	0	1.47 to 1.51	0	1.9	98.1
256	14 to 22	0	1.49 to 1.50	0	2.5	97.5

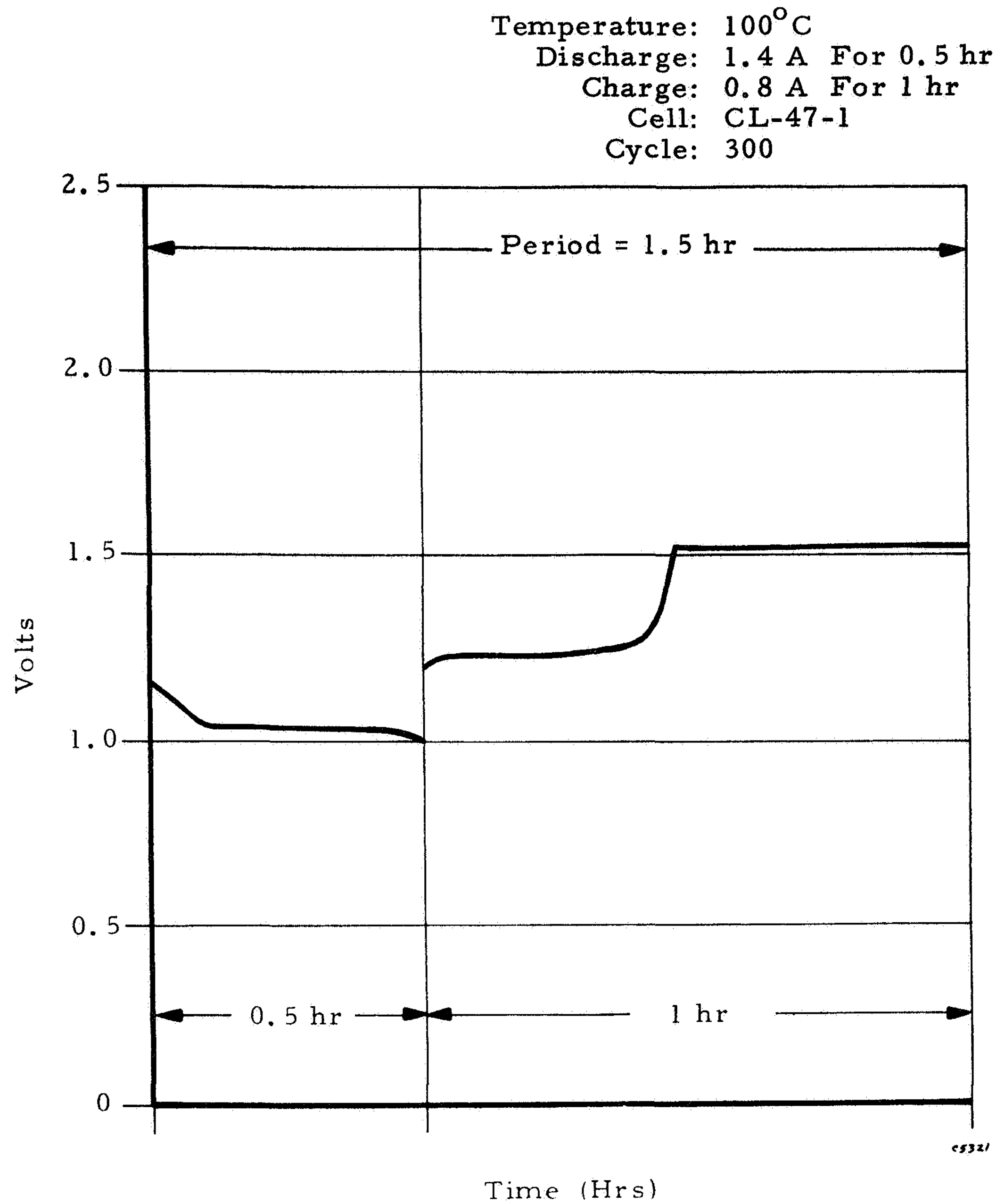


Figure 68. Cycling Curves — Task III, Test 18 (20% Depth)

Section 6
CONCLUSION

A 5 Ah silver-cadmium cell using the Astropower inorganic separator 3420-09 and purchased cadmium electrodes was electrically evaluated on various regimes. The cell is capable of cycling up to $100^{\circ}C$. At the 40% depth of discharge at $25^{\circ}C$, it can exceed 5000 cycles with a possibility of improvement when 45 % KOH is used. Figures 69 and 70 show a graphical summary of the cycling results at $25^{\circ}C$.

The main mode of failure is silver penetration in all instances, especially at $100^{\circ}C$, which enhances the phenomenon regardless of the cycling period to a point where cycling data are very often of the same order of magnitude.

Since the inorganic separator is inert to the silver attack, an obvious solution to the slowing down of the silver penetration is to further restrict the pore size, without changing the water absorption of the separator. This problem is more procedural than compositional.

It appears, therefore, that an inorganic separator is the solution to long cycle life, long wet life, nonmagnetic secondary cells.

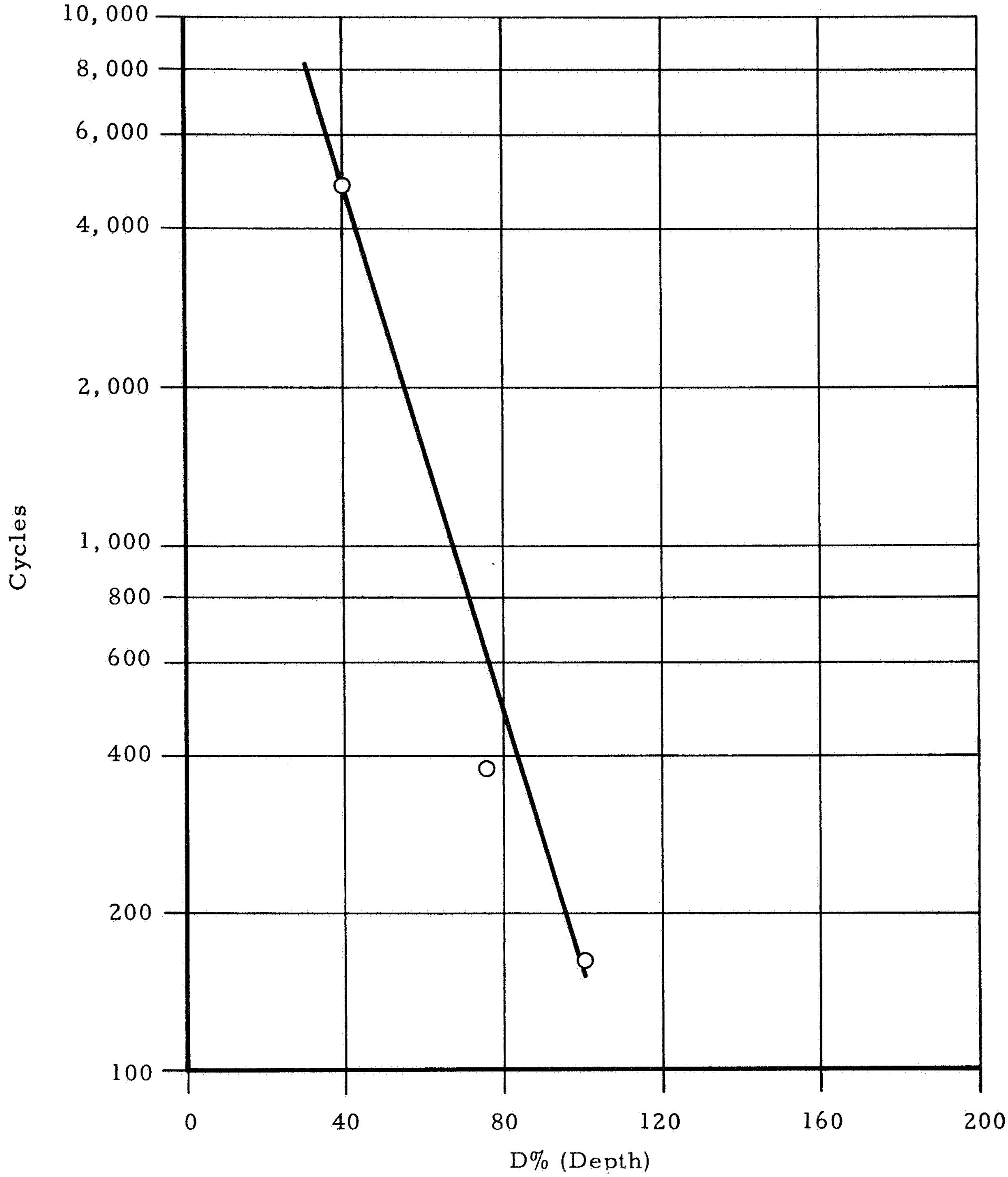


Figure 69. Cycles vs. Depth of Discharge at 25°C

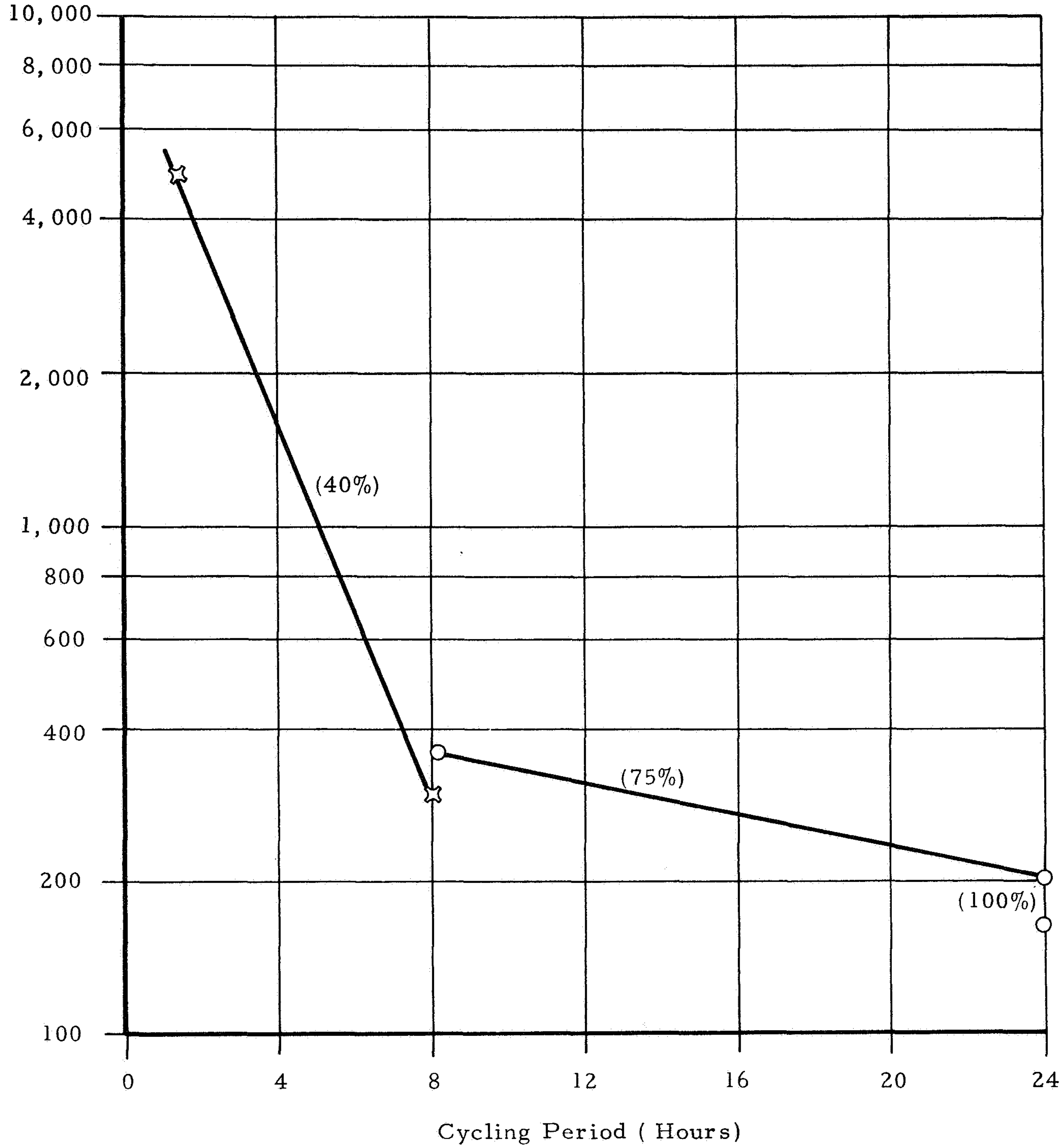


Figure 70. Cycles vs. Cycling Period at 25°C (Depth-of-Discharge as Indicated in Parentheses)

APPENDIX A

CELL SPECIFICATIONS OF THE 5 AH SILVER-CADMIUM CELL CL-3

(Using Sintered Nickel Plaques)

Appendix A

CELL SPECIFICATIONS OF THE 5 AH SILVER-CADMIUM CELL CL-3

(Using Sintered Nickel Plaques)

Electrode Pack Configurations: 5 positives, 6 negatives

Positives:	Dimensions:	1.6" x 1.6" x 0.013"
	Silver Weight:	2.5 g
	Interseparator:	1 Pellon 2506 K layer
Negatives:	Dimensions:	1.93" x 1.95" x 0.022"
	Type:	Sintered nickel plaque (Cd impregnated)
	Construction:	Each electrode consists of 2 plaques welded at their tabs, except the 2 end electrodes which consist of 1 plaque each.
	Interseparator:	2 Pellon 2506 K layers
Separator:	Inorganic:	Rigid 3420-09
	Thickness:	25 mils
	Absorption:	10%
Assembly:	Positive electrode sandwiched between two oversized rigid separators forming a compartment sealed on 3 edges and open at the top.	
Electrolyte:	22 cm^3 of 40% KOH	
Case and Cover:	Polysulfone P-1700	
Other:	40 psig pressure relief valve	
Dimensions: (plastic only)	3" h x 2.28" w x 1.04" t	
Weight: (with electrolyte)	245 g	

APPENDIX B

SEPARATOR ANALYSES

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LOS ANGELES
SAN DIEGO
OAKLAND
SAN JOSE

DATE: 8-26-66

P.O. No. PN-667688
P/S# SM20489-8

Shipper No.

Lab. No. 88329-1

Specification:

Material: OL-3420-09

TO: DOUGLAS AIRCRAFT COMPANY, INC.
2121 Campus Dirve
Newport Beach, California
Attn: Mr. K. Thomas

We submit the following report of chemical analysis:

Cd-------- .77 Milligrams

Ni-------- 1.33 Milligrams

Ag-------- .30 Milligrams

WT. = .552 g + 0.62 in^2 = AREA

CL-26-1 1291 ~ 115 days @ 25°C

Cd— 1.24 mg/in^2
Ni— 2.14 "
Ag— 0.48 "

METALLURGICAL SERVICE LABORATORIES

Penny Fridger, Mgr. Chem. Sect.

METALLURGICAL SERVICE LABORATORIES
division of
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SAN DIEGO
OAKLAND
SAN JOSE

DATE: 9-20-68

P.O. No. 8N-667834

P/S# SM32819-8

~~Shipper No.~~

TO: DOUGLAS AIRCRAFT COMPANY
2121 Campus Drive
Newport Beach, California
Attn: Receiving

Lab. No. 98289

Specification: OL-3420-09

Material:

We submit the following report of chemical analysis:

Ag--------	0.60 ~~%~~ mg
Cd--------	*
Ni--------	1.81 ~~%~~ mg

area = 0.56 in^2

*Not detected

SEPARATOR FROM CL-35-2 1 CYCLE AT 100°C 30 days wet li
SANDED + WASHED ON BOTH SIDES

Ag – 1.07 mg/in^2
Cd – 0 "
Ni – 3.24 mg/in^2

METALLURGICAL SERVICE LABORATORIES

Poppy Bridger, Mgr. Chem. Sect.

TESTING ENGINEERS, INCORPORATED
METALLURGICAL DIVISION
11008 S. NORWALK BLVD., SANTA FE SPRINGS, CALIF. 90670
(213) 723-8541 & 941-3291

LOS ANGELES
SAN DIEGO
OAKLAND
SAN JOSE

DATE: 4-1-69

P.O. No. 9N-668743

Shipper No. SM589-9

Lab. No. 39305

Specification:

Material: OL-3420-09

TO: MCDONNELL DOUGLAS CORPORATION
2121 Campus Drive
Newport Beach, California
Attn: Receiving

We submit the following report of chemical analysis:

Heat# CL-22-4

Ag------	4.4 mg.	2.3 mg/in^2
Cd------	1.0 mg.	0.5 mg/in^2
Ni------	32.9 mg.	17.0 mg/in^2

5664 ~ at R.T.
377 days wet life
area = 1.95 in^2

TESTING ENGINEERS, INC.
METALLURGICAL DIVISION

F. E. Dupas

F. E. Dupas, Supvr, Chem. Se

APPENDIX C

DELIVERY OF 30 CELLS
DESIGN: AC-3

Appendix C
DELIVERY OF 30 CELLS
DESIGN: AC-3

At the end of the technical performance period, the program was extended to include fabrication and delivery of 30 silver-cadmium cells of 5 Ah capacity, using a nonmagnetic Astropower cadmium electrode and the same inorganic separator.

The cells were fabricated and cycled five times before delivery.

The outputs are presented in Table C-I. After two cycles where the cells were charged to 1.70 V cut-off voltage, half of the cells were charged to 1.70 V and the other half to 1.80 V. An increase in capacity of approximately 1 Ah was observed. The last two cycles were done to 1.80 V cut-off. The capacity stabilized around 7 Ah. It is recommended to use a charging rate of 0.250 A to a cut-off voltage of 1.75 volts.

The cell specifications are given in Table C-II.

TABLE C-I

OUTPUTS OF ASTROPOWER SILVER-CADMIUM CELLS

(Discharge At 1 A to 0.6 V)

Cell No.	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5
Charge at 0.3 A to →	1.70 V	1.70 V	1.70 V (except *)	1.80 V	1.80 V or 7 Ah input
1	5.50 Ah	5.43 Ah	5.30 Ah *	7.10 Ah	6.90 Ah
2	5.22 Ah	5.25 Ah	5.05 Ah *	6.80 Ah	7.00 Ah
3	5.37 Ah	5.55 Ah	5.10 Ah *	6.45 Ah	6.90 Ah
4	5.15 Ah	5.13 Ah	5.10 Ah *	6.05 Ah	6.90 Ah
5	5.75 Ah	5.65 Ah	5.30 Ah *	6.45 Ah	6.90 Ah
6	5.29 Ah	5.30 Ah	5.00 Ah *	6.35 Ah	6.80 Ah
7	5.52 Ah	5.52 Ah	5.40 Ah *	7.10 Ah	6.95 Ah
8	5.52 Ah	5.30 Ah	5.00 Ah *	6.10 Ah	6.95 Ah
9	5.19 Ah	5.13 Ah	5.00 Ah *	6.05 Ah	6.80 Ah
10	5.75 Ah	5.50 Ah	5.20 Ah *	7.10 Ah	6.90 Ah
11	5.75 Ah	5.50 Ah	5.20 Ah *	7.10 Ah	6.90 Ah
12	5.65 Ah	5.50 Ah	5.00 Ah *	6.50 Ah	6.90 Ah
13	5.52 Ah	5.50 Ah	5.25 Ah *	6.90 Ah	7.00 Ah
14	5.74 Ah	5.45 Ah	5.15 Ah *	7.10 Ah	6.95 Ah
15	5.62 Ah	5.58 Ah	5.25 Ah *	6.10 Ah	6.90 Ah
16	5.75 Ah	5.30 Ah	7.15 Ah	6.90 Ah	6.85 Ah
17	5.75 Ah	5.20 Ah	6.50 Ah	6.18 Ah	6.95 Ah
18	5.82 Ah	5.45 Ah	6.45 Ah	6.63 Ah	7.00 Ah
19	5.90 Ah	5.35 Ah	6.35 Ah	6.65 Ah	6.95 Ah
20	5.85 Ah	5.45 Ah	6.45 Ah	6.70 Ah	7.05 Ah
21	5.70 Ah	5.40 Ah	6.30 Ah	6.23 Ah	7.00 Ah
22	5.60 Ah	5.35 Ah	6.50 Ah	6.75 Ah	7.00 Ah
23	5.93 Ah	5.40 Ah	6.45 Ah	6.65 Ah	7.00 Ah
24	5.80 Ah	5.45 Ah	6.40 Ah	6.63 Ah	7.00 Ah
25	5.60 Ah	5.20 Ah	6.30 Ah	6.10 Ah	6.95 Ah
26	5.80 Ah	5.45 Ah	6.30 Ah	6.30 Ah	7.05 Ah
27	5.25 Ah	5.05 Ah	6.00 Ah	6.00 Ah	6.75 Ah
28	5.60 Ah	5.25 Ah	6.40 Ah	6.50 Ah	6.85 Ah
29	5.68 Ah	5.25 Ah	6.25 Ah	6.38 Ah	6.90 Ah
30	5.65 Ah	5.15 Ah	6.15 Ah	6.18 Ah	6.85 Ah
Average	5.60 Ah	5.35 Ah	6.40 Ah (*) not included	6.53 Ah	6.92 Ah

TABLE C-II

CELL SPECIFICATIONS OF THE 5 AH SILVER-CADMIUM CELL AC-3 (USING ASTROPOWER Cd ELECTRODE)

Electrode Pack Configuration: 5 positives, 4 negatives

Positives:	Dimensions:	1.75" w x 1.60" x 0.024"
	Silver Weight:	5.3 g
	Interseparator:	2506 K Pellon
Negatives:	Dimensions:	1.90" w x 2.10" h x 0.070" (KT included)
	Active Material (94% CdO 1234 Baker):	8.9 g
	Interseparator:	KT paper
Separator:	Inorganic:	3420-09 rigid
	Thickness:	25 mils
	Absorption:	10%
	Grid:	Silver 5 Ag-38-1/0 Distex
Assembly:	Positive electrode encapsulated between two oversized rigid separators forming a compartment sealed on 3 edges and open at the top.	
Electrolyte:	26.5 cm^3 of 40% KOH	
Case and Cover:	Polysulfone P-1700	
Others:	40 psig pressure relief valve	
Dimensions (plastic only):	3" h x 2.28" w x 1.04" t	
Weight (with electrolyte):	260 g	

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