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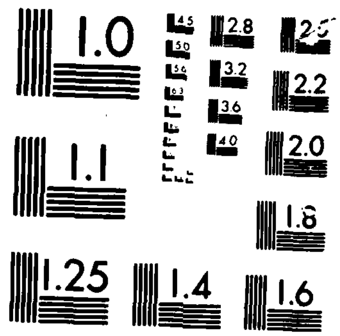

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AFWAL-TR-85-2104

AIRCRAFT BATTERY STATE OF CHARGE AND CHARGE CONTROL SYSTEM

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3 Great Pasture Road
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February 1986

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This Interim Report describes work done by Energy Research Corporation (ERC) in developing an aircraft battery state of charge and charge control system. The basis for this system developed by ERC is a nickel-oxygen (NiO_2) "Pilot" cell (0.374 Ah). This pilot cell is cycled in tandem with a nickel-cadmium battery. The oxygen pressure of the pilot cell is utilized to determine and control the state of charge of the nickel-cadmium battery. The NiO_2 pilot cell baseline performance was determined during this period. The effect of using different nickel electrodes (ERC, SAFT, MARATHON) was also performed.

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1.0 INTRODUCTION

The start date for contract No. F33615-84-C-2435, Aircraft Battery State of Charge and Charge Control System, was July 1, 1984. A kickoff meeting was held at ERC on July 10, 1984 with Dick Marsh representing the Air Force, following which development work was started. Personnel were assigned and a separate area established for the fabrication and testing of Ni-O_2 pilot cells. Test equipment required to characterize pilot cells were obtained and design and building of cycling equipment for testing of cells was done in-house.

Detailed technical data is regularly being submitted to Air Force Wright Aeronautical Laboratories, Aero Propulsion Laboratory, WPAFB through monthly letter reports. This interim report summarizes the work performed during the first 12-month period.

2.0 PROGRAM STATUS OVERVIEW

During the first 12 months, efforts were directed towards obtaining data on the baseline characteristics of the pilot cell. All the sub-tasks except temperature effects were completed. Originally, we planned to characterize the pilot cells first for their charge-discharge dependency on temperature and then extend the studies to aircraft batteries. The first series of experiments were designed to obtain data on performance characteristics at ambient temperatures. Completion of these tests took longer time than originally anticipated. Accordingly, we plan to commence experiments to study the effects of temperature on cell performance in September 1985. We intend to study the temperature dependence of the Ni-O_2 cells and the aircraft cells simultaneously.

Ni-O_2 cells were fabricated with ERC roll-bonded electrodes and tested at various C-rates, both on charge and on discharge. The cells were also subjected to life cycle tests and the single electrode potentials were monitored during testing to identify the failure mechanisms.

During this phase, aircraft cells from Saft and Marathon were purchased and tested for their performance characteristics. One cell of each type was cut open and pilot cells were fabricated using these electrodes. The pilot cells thus constructed with commerical aircraft electrodes were also tested to identify their performance characteristics.

As planned, an aircraft battery system study was initiated during this time period to understand the electrical interfaces and battery/cell parameters. An electronic tracking cycler was designed and built; using this cycler, a 13-cell Saft battery stack was alternately charged and discharged in conjunction with a pilot cell containing an identical nickel electrode. In addition, tests were designed to charge the battery to various states of charge between 10% and 100% and experimentally determine the delivered capacities. The data obtained in the series of tests will form the basis for designing other cyclers to be used to measure state of charge and to monitor tracking accuracies.

Cycling tests were interrupted periodically to measure the variations in pressure and state of charge in case of pilot cells and fuel gauge respectively.

Work on Phase II, System Life and Stability, was started in July 1985. Investigation of temperature effects (carried over from Phase I) will also be performed during Phase II. An aircraft battery from the third manufacturer will be purchased and tested. Pilot cells will be fabricated with identical electrodes and performance characteristics evaluated both separately and in tandem operation with the main battery.

3.0 EXPERIMENTAL RESULTS

3.1 Ni-O_2 CELL DESIGN

The nickel-oxygen test cells employed a three-electrode configuration utilizing one electrode for oxygen evolution and a different electrode for oxygen consumption. This concept divides the functions and eliminates problems encountered in conventional two-electrode systems, in which catalysts that function well during oxygen consumption tend to oxidize or dissolve when subjected to evolution.

The normal specifications for the nickel electrodes are as follows:

Electrode Size	1.26 x 1.00 x .070 inch
Active Material	2.53 gms
Theoretical Capacity	.440 Ah
Nominal Capacity	.374 Ah

Depending on the active material content, the area of the electrode is varied to obtain the required capacity. A sketch of the cell design is shown in Figure 1.

3.2 Ni-O_2 CELL TESTS

Using the three-electrode concept, the nickel electrode of the pilot cell is charged against the platinum gas electrode and discharged against the nickel screen. The potentials and pressure are monitored during the tests.

The electrodes are first housed in a test fixture and fully charged, with the end of charge being indicated by the leveling out of the pressure profile. The cell is then discharged to 100% depth and the delivered capacity calculated. The procedure is repeated until the nickel electrode is stabilized and reproducible

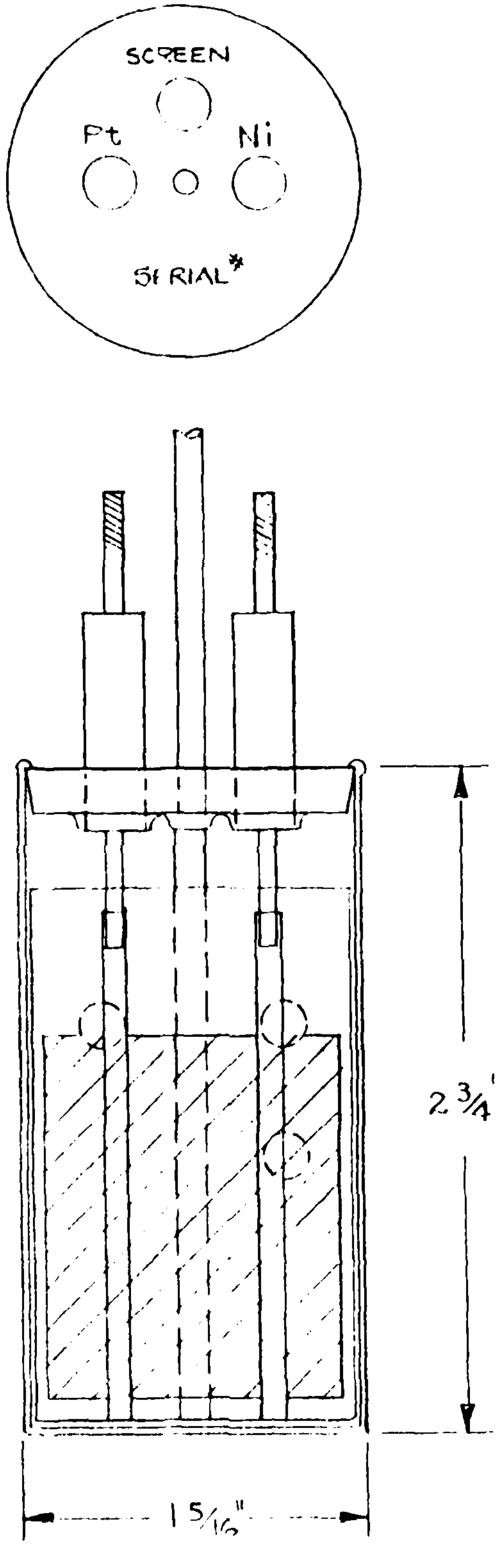


FIGURE 1 Ni - O_2 Pilot Cell

results are obtained. This procedure qualifies the system, after which the electrode assembly is removed from the test fixture and assembled in a stainless steel can. Ziegler seals and welding of the cover ensure a leak-proof construction; then a pressure gauge is screwed on top. The cell is now ready to undergo characterization tests.

3.3 CELL CHARACTERIZATION

The test matrix for characterization of cells is shown in Table 1. The cell was charged and discharged at different C-rates and different depths of discharge. Table 2 shows the test results of Cell #1.

Some problems were encountered with the first cell fabricated after 22 cycles. This cell was cycled manually to evaluate the relationship among charge, discharge and depth of discharge.

The charging of the cell on cycle No. 23 was normal, but when the cell was discharged at 200 mA, the actual delivered capacity of the cell was .232 Ah, less than the expected value of .280 Ah. The cycle was repeated, and the capacity delivered was only .200 Ah. The loss in capacity could be due to a leak in the system and/or shorting of the cell. The cell was dissected and a postmortem examination was carried out. The cell case was carefully cut open and the cell components examined.

The electrode assembly looked clean, and no evidence of shorts was noticeable. The electrodes and separator did not exhibit any damage, defects or discoloration, and the current lead welds were clean.

The only abnormality was the accumulation of a few cc's of a brown liquid in the bottom of the cell. We theorized that if

TABLE 1

CELL TEST MATRIX

Cell No.:	1	2
Test Temperature	Ambient	Ambient
Test Mode	Manual	Automatic
Charge Current, mA	50, 100, 150	100
Time	Current Dependent	4 hrs
Overcharge	25 to 67%	10%
Discharge Current	50, 100, 150, 200	100
Time	Current Dependent	3½ hrs
Depth	100%	94%

TABLE 2: CELL PERFORMANCE AT DIFFERENT DEPTHS OF DISCHARGES

CYCLE	CHARGE				DISCHARGE				
No.	I (mA)	AH	V (volts)	P (psig)	I (mA)	AH	V (volts)	P (psig)	DOD (%)
1	100	.450	.617	60	100	.358	- .915	88	100
2	100	.400	.617	56	200	.367	- .100	87	100
3	100	.625	.615	50	200	.383	-1.035	82	100
4	100	.376	.599	50	200	.376	-1.000	80	100
5	100	.475	.599	50	200	.383	-1.000	82	100
6	50	.488	.525	50	100	.405	- .965	85	100
7	150	.487	.642	50	150	.375	- .954	84	100
8	150	.450	.652	50	100	.400	- .950	85	100
9	150	.450	.646	50	200	.400	-	87	100
10	50	.500	.544	51	50	.413	-1.050	84	100
11	50	.325	.514	60	50	.280	- .826	82	75
12	50	.342	.526	59	100	.280	-1.061	62	75
*13	50	.308	-	59	200	.823	-1.440	84	75
14	50	.310	.511	63	200	.240	-1.540	82	75

*Excessive discharge by mistake.

TABLE 2: CELL PERFORMANCE AT DIFFERENT DEPTHS OF DISCHARGE (continued)

	CHARGE				DISCHARGE				
CYCLE NO.	I (mA)	AH	V	P (psig)	I (mA)	AH	V	P (psig)	DOD %
15	100	.195	.595	56	50	.168	-.780	78	45
16	"	.176	.608	54	100	.163	-.909	76	44
17	"	.185	-	53	200	.170	-1.090	78	45
18	150	.180	.620	54	50	.185	-	76	49%
19	"	.188	-	52	100	.175	-	74	47%
20	"	.180	-	64	200	.170	-	84	45%

TABLE 2 (continued)

CELL PERFORMANCE AT DIFFERENT DOD

CYCLE NO.	MODE	I (mA)	AH	V	P (psig)	DOD (%)
21	Charge	100	.300	+.550	58	-
	Discharge	50	.283	-.820	80	75%
22	Charge	100	.300	+.584	50	-
	Discharge	100	.283	-.801	72	75%
23	Charge	100	.300	+.588	50	-
	Discharge	200	.234	-1.051	68	63%
24	Charge	100	.317	+.588	50	-
	Discharge	200	.200	-.948	63	53%

a recombination of gases had taken place resulting in the production of water, the water could have leached out some of the active materials from the positive electrode and settled at the bottom of the cell.

To investigate the performance of the electrodes, the same electrode assembly from the cell was housed in a test fixture and fully charged. It was then discharged at 200 mA and a delivered capacity of .350 Ah was obtained, indicating that the electrodes were still capable of delivering 94% of the nominal capacity.

3.4 *LIFE CYCLE TESTS*

Tests cells were next subjected to life cycle tests. Automatic cyclers with adjustable current and time settings were designed and built. Cycling of the cells commenced, charging, and discharging cells alternately at constant current and fixed times; voltage and pressure profiles were monitored at regular intervals. Cycling was interrupted periodically to monitor variations in pressure with changes in ambient temperature on an open-circuit stand. This ensured that the cells did not leak or exhibit electrochemical decay due to self-discharge on the stand.

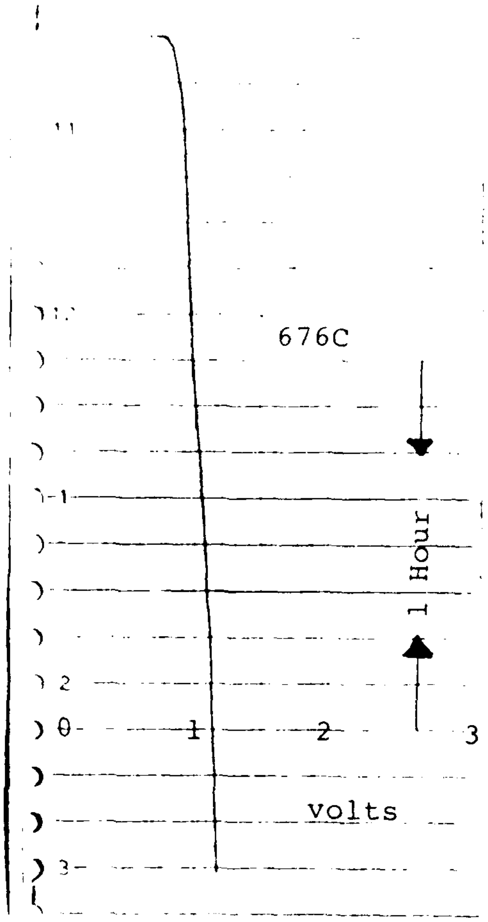
Cells fabricated both with ERC roll-bonded and sintered nickel aircraft nickel electrodes were tested. In addition, a special cell was assembled in a test fixture incorporating a cadmium reference electrode. This experiment was done to monitor the performance of the nickel and gas electrodes separately so that it would be possible to identify which electrode fails first. This data would prove important in the design of improved cells and in predicting their performance without having to undergo extensive testing.

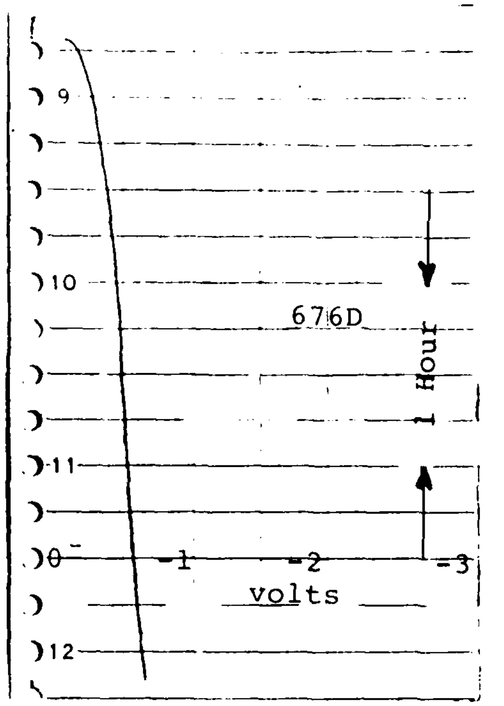
Life cycle tests commenced with one cell from the first batch. This cell was fabricated with ERC roll-bonded nickel electrode. The cycling regime was set at 4-1/2 and 3-1/2 hours for charge and discharge modes, respectively, and the current was kept constant at 100 mA in both cases. After 677 cycles the cell did not exhibit any deterioration in performance. To accelerate the testing, the cycling regime was changed from cycle No. 678 such that the number of cycles per time period was doubled. By increasing the current by a factor of 2 and reducing the cycle time by half, the ampere hours were maintained the same. The old and new regimes were as follows:

Cycle No.	1-677	from 678
Charge - hours	4.50	2.25
mA	100	200
Ah	.450	.450
Discharge - hours	3.50	1.75
mA	100	200
Ah	.350	.350
No. of cycles/day	3	6

The voltage profiles of the old and new regimes are shown in Figure 2. As expected, the potentials increased in the new regime, owing to the higher operating current, and the change in pressure was not affected. This is shown in Figures 3 and 4.

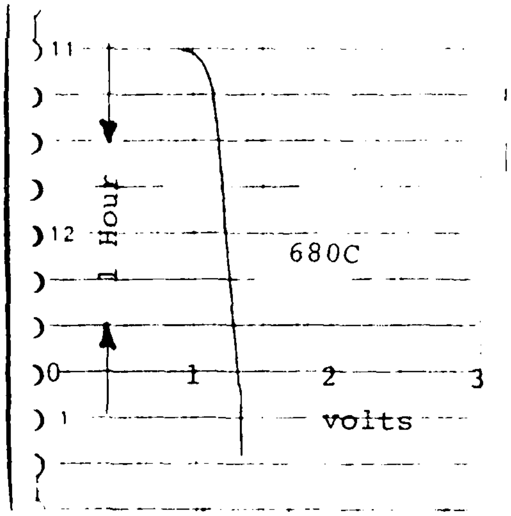
After the cycling regime was changed, the cell underwent another 200 cycles before failure. The voltage profile for cycle No.

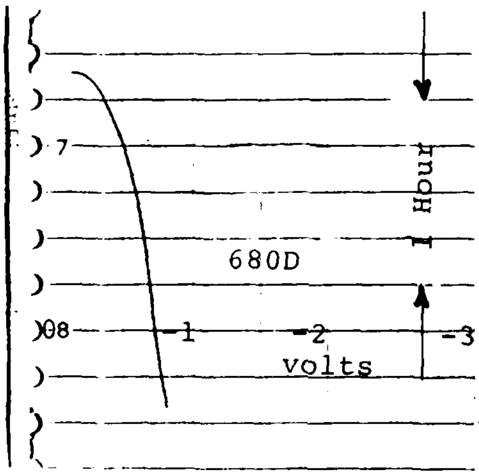




<u>OLD REGIME</u>

Charge: 4½ hrs @ 100 mA
Discharge: 3½ hrs @ 100 mA





Charge, Ni/Pt

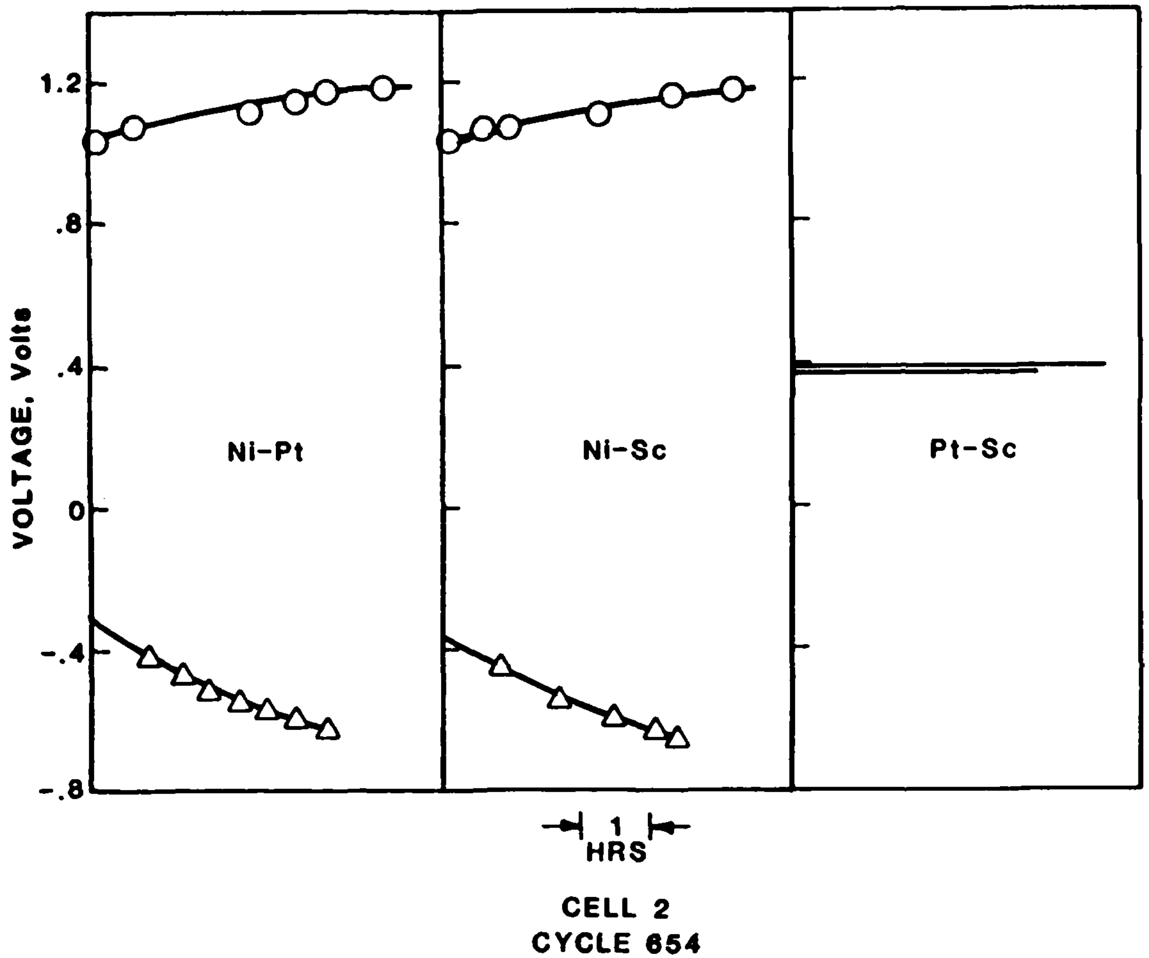
Discharge, Ni/Screen

<u>NEW REGIME</u>

CHARGE: 2¼ hrs @ 200 mA
DISCHARGE: 1-¾ hrs @ 200 mA

<u>FIGURE 2</u>

VOLTAGE PROFILE OF CELL NO. 2



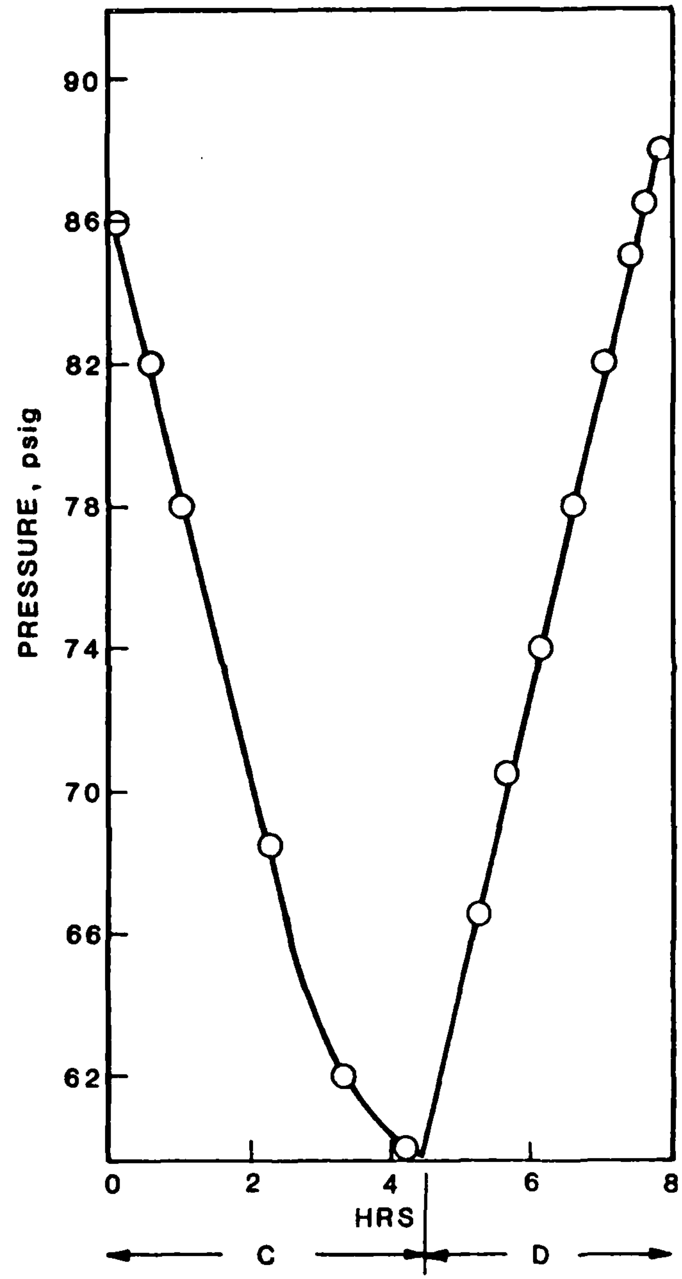


FIGURE 3: CELL PERFORMANCE IN OLD CYCLING REGIME

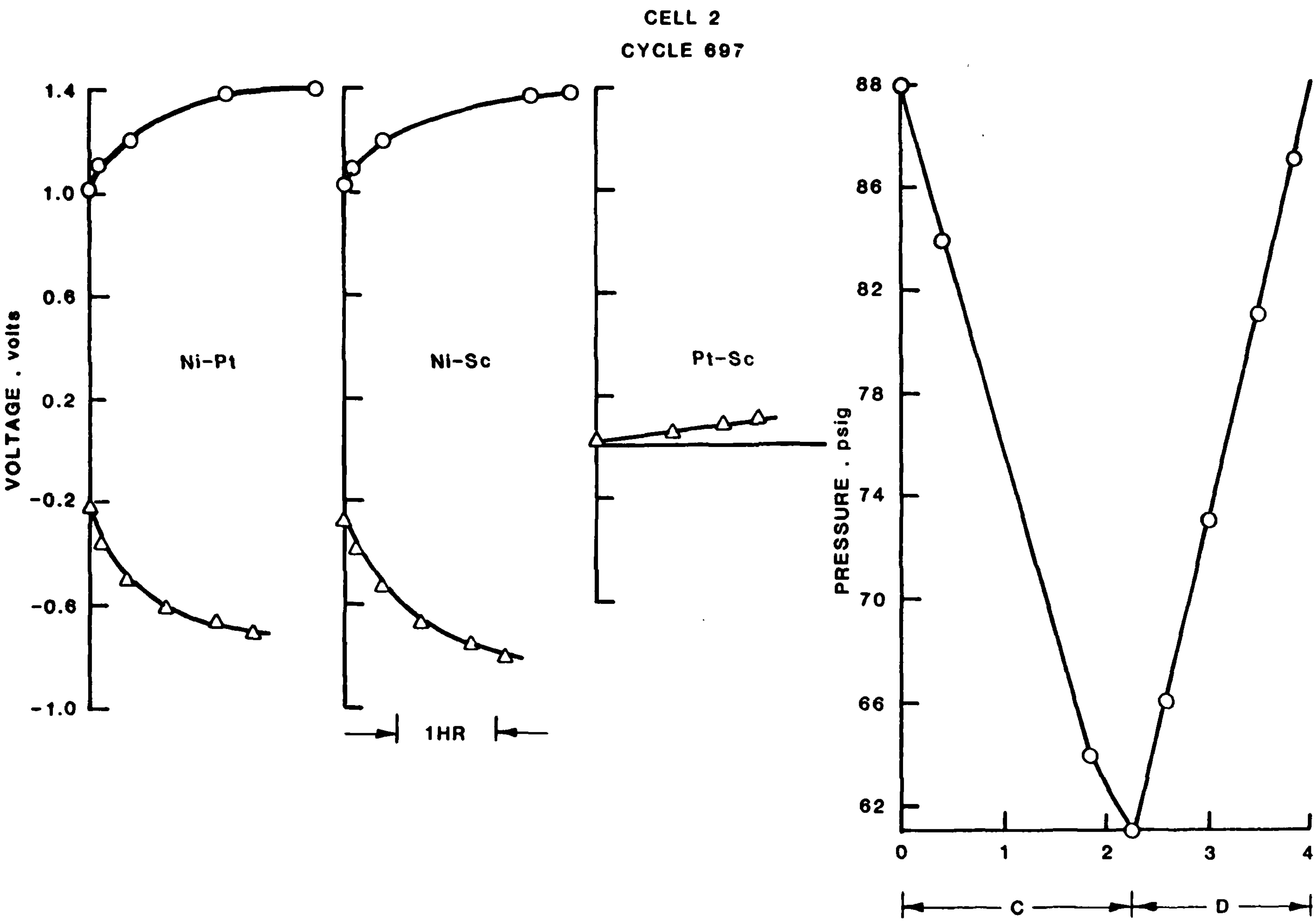
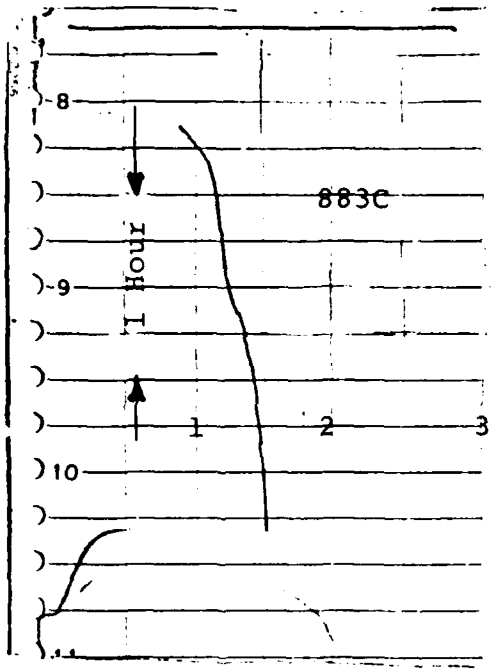
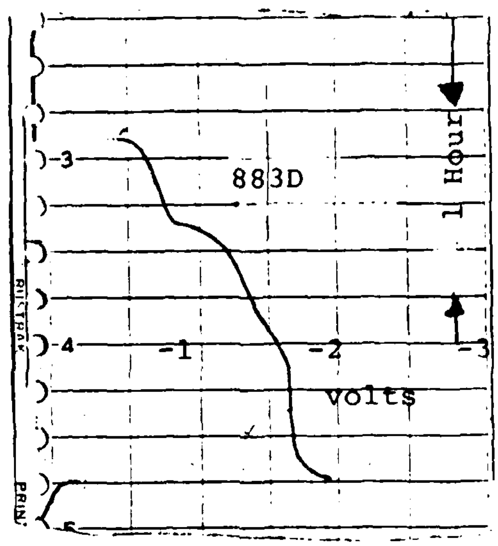


FIGURE 4: CELL PERFORMANCE IN THE NEW CYCLING REGIME



Charge - Ni-Pt



Discharge, Ni-Screen

FIGURE 5: VOLTAGE PROFILE - CELL NO. 2, CYCLE NO. 883

883 is presented in Figure 5. Deterioration in performance is indicated by the erratic profile and the high values of potentials. In spite of this, the cell continued to exhibit excellent linearity in pressure. (See Figure 6)

The test was discontinued and the cell was cut open. Postmortem showed that the integral structure of the electrode assembly remained intact. However, brownish colored liquid and brown deposits on the case were noticeable. The average values of voltage and pressure on cycling, and the standard deviation, are summarized in Table 3.

Initial test results indicate that the cells can be subjected to continuous charge-discharge cycles for extended periods; e.g., cell No. 2 was cycled over 800 times in the last 7 months and was still capable of delivering the required capacity. Having established the baseline data, we started work on further characterization of the performance of individual cells.

Cell No. 26 was built using ERC rolled nickel. The nominal capacity of the cell is 450 mAh. The first series of tests were directed towards investigating the dependence of charge efficiency on the amount of overcharge. Both charge and discharge currents were kept constant at 100 mA and the cell was charged between 0 and 100% over its nominal capacity. For each overcharge, the cell was discharged to 100% depth and the delivered capacity was calculated. As to be expected, the delivered capacities increased with the amount of overcharge but at a lower magnitude. Next, the cell was charged at 200 mA and the amount of charge was varied between 0 and 100% over the nominal capacity. Again, the cell was discharged to 100% depth and the delivered capacities were calculated. Test results for currents of 100 and 200 mA are summarized in Table 4.

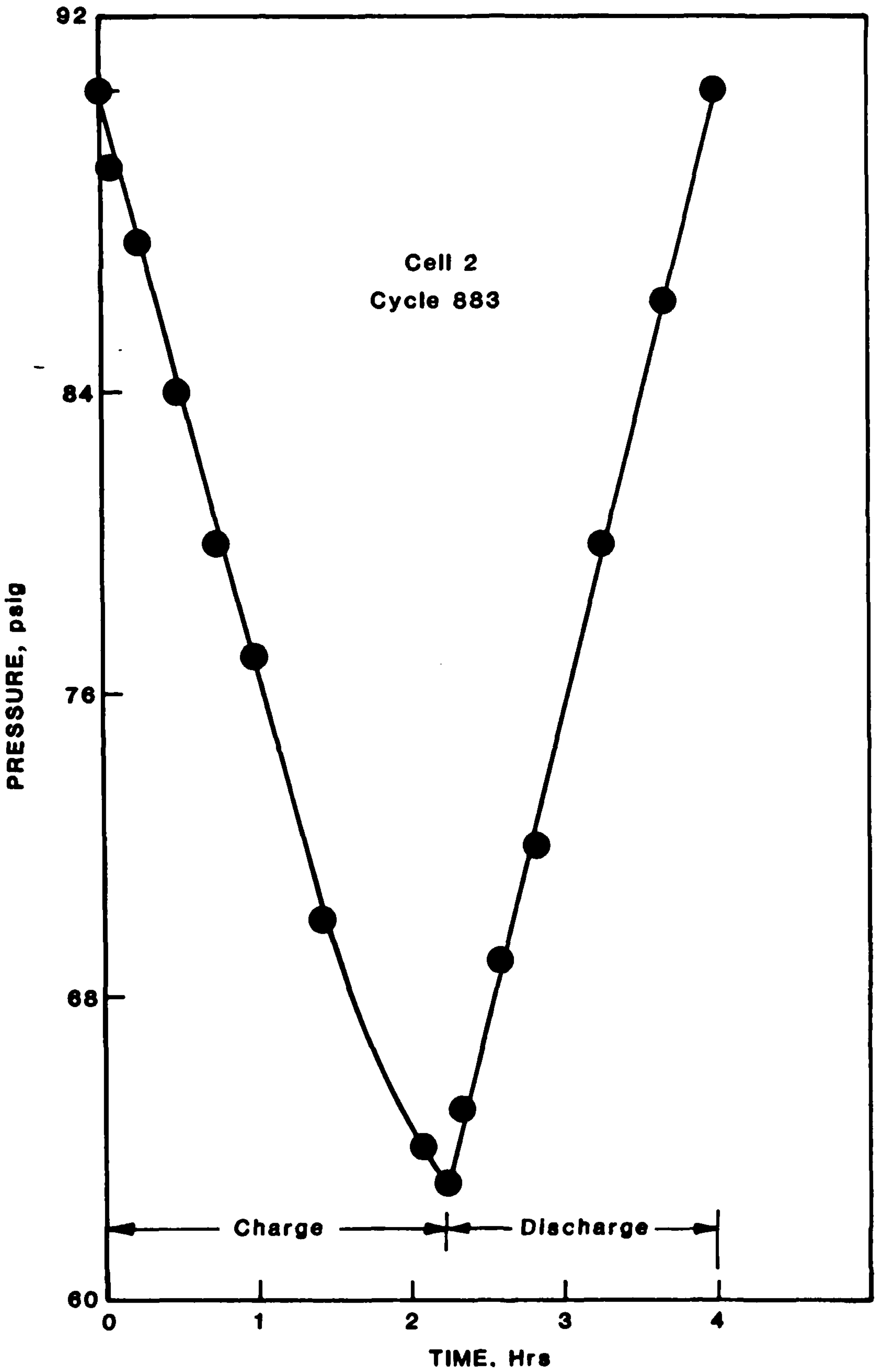


FIGURE 6: PRESSURE PROFILE-CELL NO.2, CYCLE NO. 883

TABLE 3

CELL PARAMETERS ON LIFE CYCLE

Cell No.:	2		
Ni Positive:	ERC roll-bonded		
Cycle No.:	1-677 from 678		
Cycle Time:	6.75 hours	4.00 hours	
Charge:	4.50 hours	2.25 hours	
Discharge:	2.25 hours	1.75 hours	

	CHARGE			DISCHARGE		
CYCLE NO.	V, Ni-Pt Avg.	V, Ni-Pt End	ΔP	V, Ni-Sc. Avg.	V, Ni-Sc. End	ΔP
342	.553	-	23	-	-	23
405	.683	-	25	- .617	-	24
450	.939	-	24	- .616	-	24
545	1.217	1.140	25	- .576	- .650	21
597	1.145	1.187	27	- .625	- .683	28
654	1.110	1.176	26	- .565	- .646	21
$\bar{x}$	.941	1.1677	24.8	- .600	- .660	23.5
σ	.2696	.0246	1.4720	.0273	.0203	2.5884
697	1.229	1.350	28	- .609	- .800	29
883	1.199	1.500	29	-1.296	-1.950	30

TABLE 4

EFFECT OF OVERCHARGE ON DELIVERED CAPACITY

		CHARGE						DISCHARGE					
S.NO.	CYCLE NO.	t Hrs.	I mA	Ah	END V	END P	OVER-CHARGE %	t hrs	I mA	Ah	END V	END P	DEL'D/ NOM. %
1	8	4.50	100	.450	.562	23	0	4.50	100	.450	-1.000	63	100
2	2	4.75	"	.475	.611	20	6	"	"	"	-1.010	60	"
3	3	5.30	"	.530	.611	19	18	4.58	"	.458	-1.000	61	102
4	5	6.40	"	.640	.605	19¼	42	5.00	"	.500	-1.000	62	111
5	10	7.90	"	.790	.595	16½	76	5.33	"	.533	-1.000	64	118
6	11	9.00	"	.900	.594	16	100	5.50	"	.550	-1.000	65½	122
7	9	2.33	200	.466	.605	23	4	2.00	200	.400	-1.000	60	89
8	4	2.40	"	.480	.653	20	7	"	"	"	-1.000	56	"
9	6	2.75	"	.550	.657	19¼	22	2.25	"	.450	-1.000	59	100
10	7	3.20	"	.640	.670	17	42	2.42	"	.484	-1.070	62	108
11	12	3.95	"	.790	.680	16	76	2.50	"	.500	-1.090	61½	111
12	13	4.50	"	.900	.670	14	100	2.58	"	.516	-1.090	62½	115

CELL NO. 26 - NOMINAL CAPACITY .450 Ah - 100% DOD

The second part of the tests consisted of evaluating the dependency of the delivered capacity on the rate of discharge. For each charge cycle, the current and the amount of overcharge were maintained constant at 100 mA and 20% over nominal, respectively. The discharge currents were varied between 50 and 900 mA (0.1 C to 2.0 C rates) and delivered capacities were calculated. The ratio of delivered to nominal capacity was found to be 1.28 at 50 mA and 0.84 at 900 mA. The other parameters are summarized in Table 5.

The voltage profiles on discharge at the different rates are shown in Figures 7, 8 and 9. Figure 10 shows the variations in delivered capacities with discharge currents.

The planned tests for characterizing the pilot cell containing ERC roll-bonded nickel elecrode were thus completed and the baseline data were established. Life testing of the cell on alternate charge/discharge modes was started in the following regime:

Charge:	2-1/4 hrs. @ 225 mA, .506 Ah
Discharge:	1-3/4 hrs. @ 225 mA, .394 Ah
Nominal Capacity:	.450 Ah
Overcharge per Cycle:	12% over nominal capacity
	28% over delivered capacity
Depth of Discharge:	88% of nominal capacity
Charge/Discharge Rates:	C/2

This cell was tested for cycle life at a higher operating current of 225 mA. Though the cell functioned normally, the potentials during discharge were high because of the higher current density and depth of discharge. The current was accordingly reduced to 150 mA which resulted in more acceptable values of operating parameters.

TABLE 5

DISCHARGE PERFORMANCE - DISCHARGE CURRENT VS. DELIVERED CAPACITY

CYCLE NO.	RATE	I mA	t hrs	VOLTS		END P	CUTOFF VOLTS	CAP. AH	EFF. %
				END	PLATEAU				
15	0.1C	50	11.58	-1.056	-.745	64	-1.0	.576	128
3	0.2C	100	4.58	-1.000	-.819	61	-1.1	.470	104
20	0.3C	150	3.50	-1.280	-.835	68	-1.2	.468	104
6	0.4C	200	2.25	-1.000	-.937	59	-1.1	.470	104
19	0.6C	250	2.07	-2.000	-1.080	68	-1.2	.454	101
14	0.8C	350	1.33	-1.232	-1.060	59	-1.2	.455	101
18	1.0C	450	1.20	-1.600	-1.096	68	-1.4	.420	93
16	1.5C	675	0.67	-1.654	-1.281	64	-1.4	.420	93
17	2.0C	900	0.58	-2.000	-1.294	64	-1.6	.378	84

CELL #26 - NOMINAL CAPACITY .450 Ah - DOD 100%

CHARGE PER CYCLE - 5.4 hrs @ 100 mA, .54 Ah, 20% OVERCHARGE

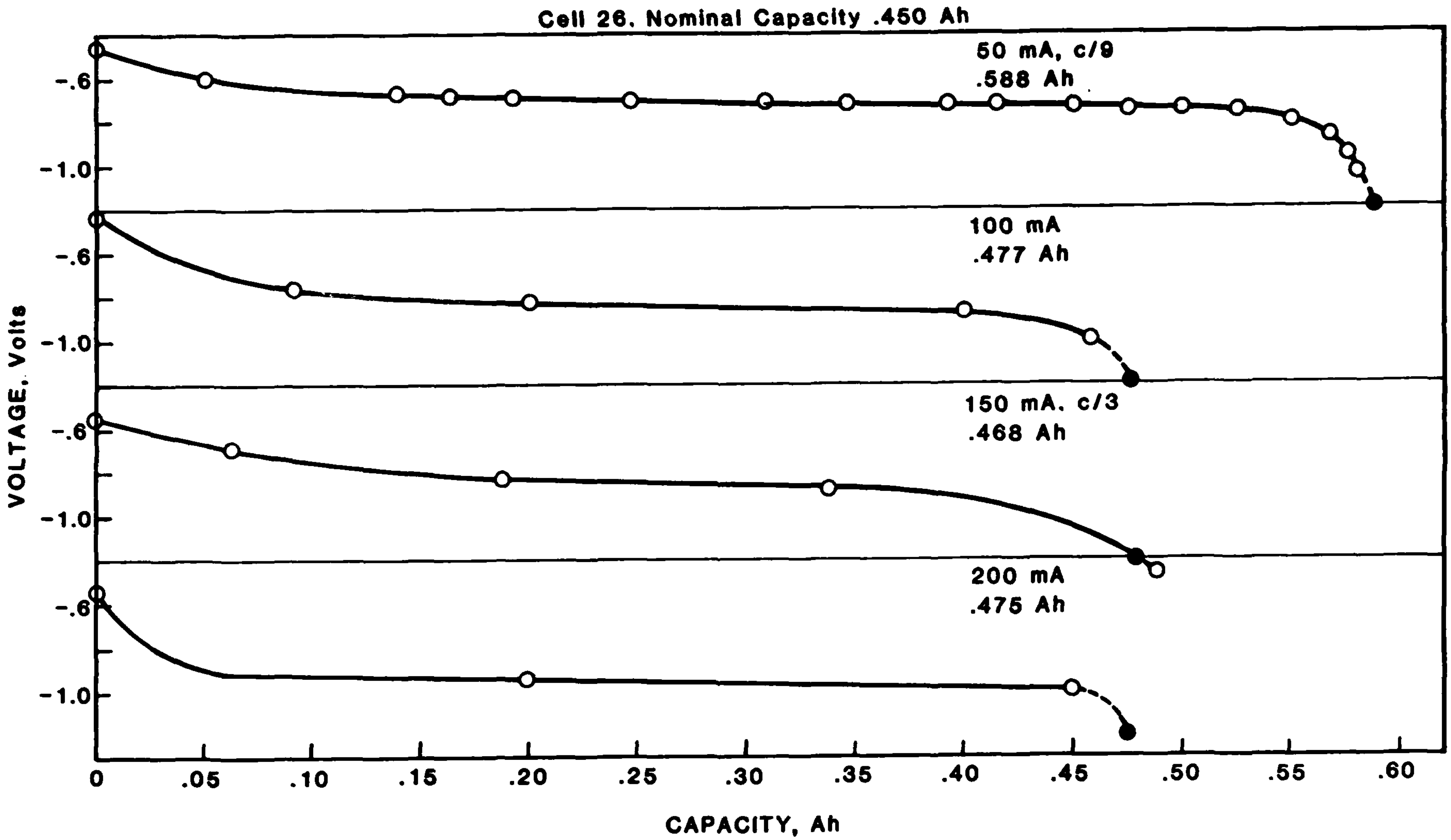


FIGURE 7: DISCHARGE PERFORMANCE OF CELL 26-50, 100, 150, 200 mA

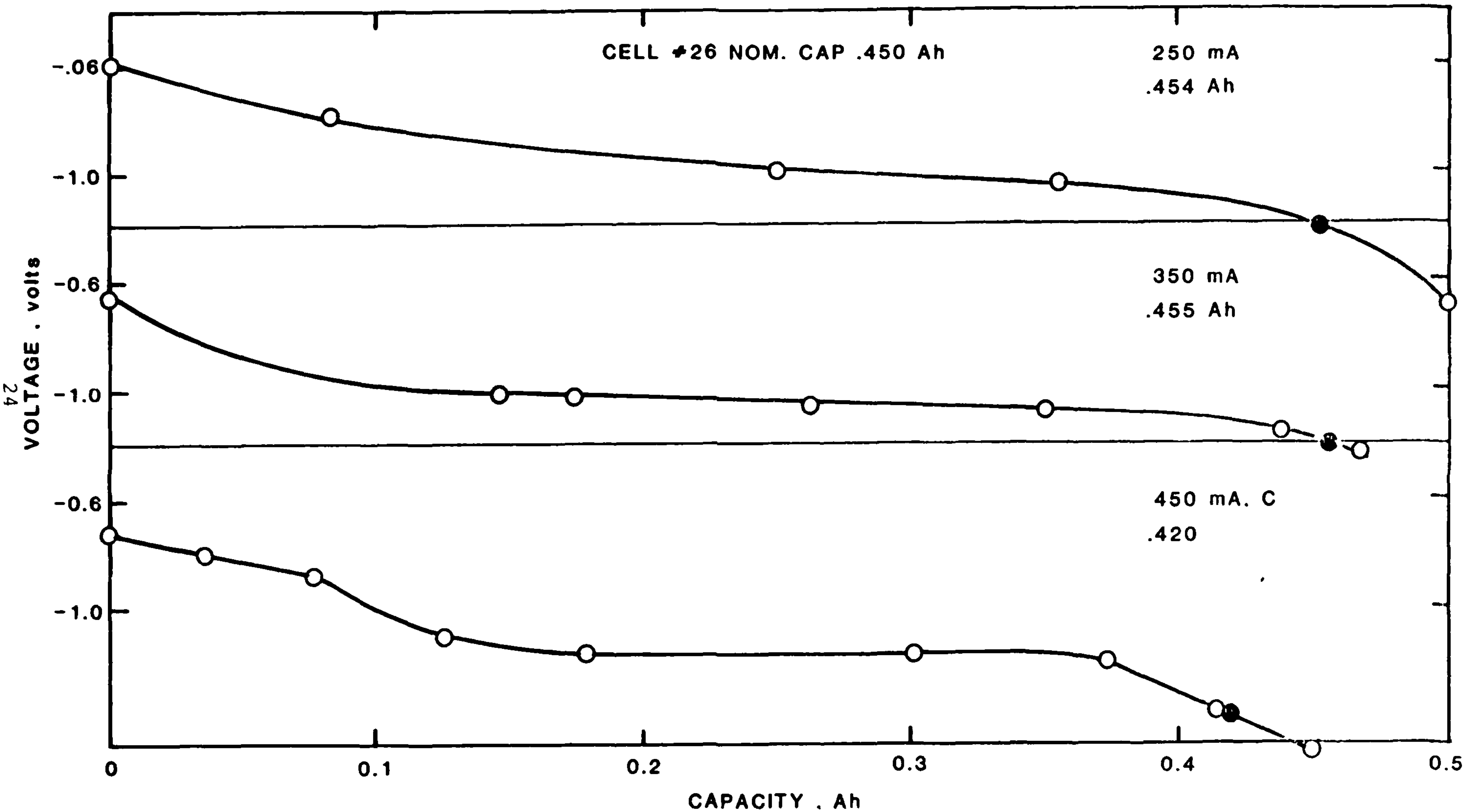


FIGURE 8: DISCHARGE PERFORMANCE OF CELL #26 - 250, 350, 450 mA

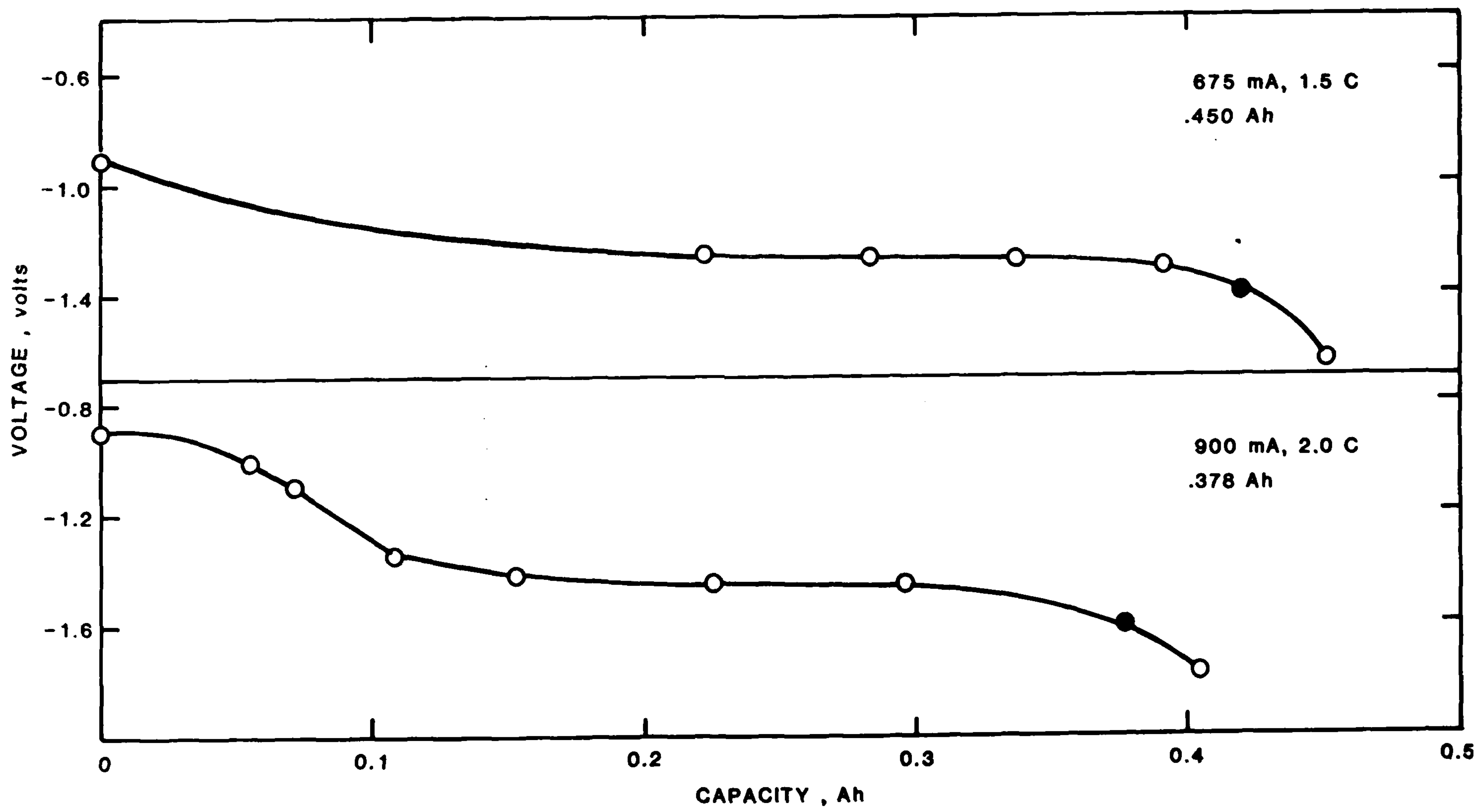


FIGURE 9: DISCHARGE PERFORMANCE OF CELL #26, 675, 900 mA

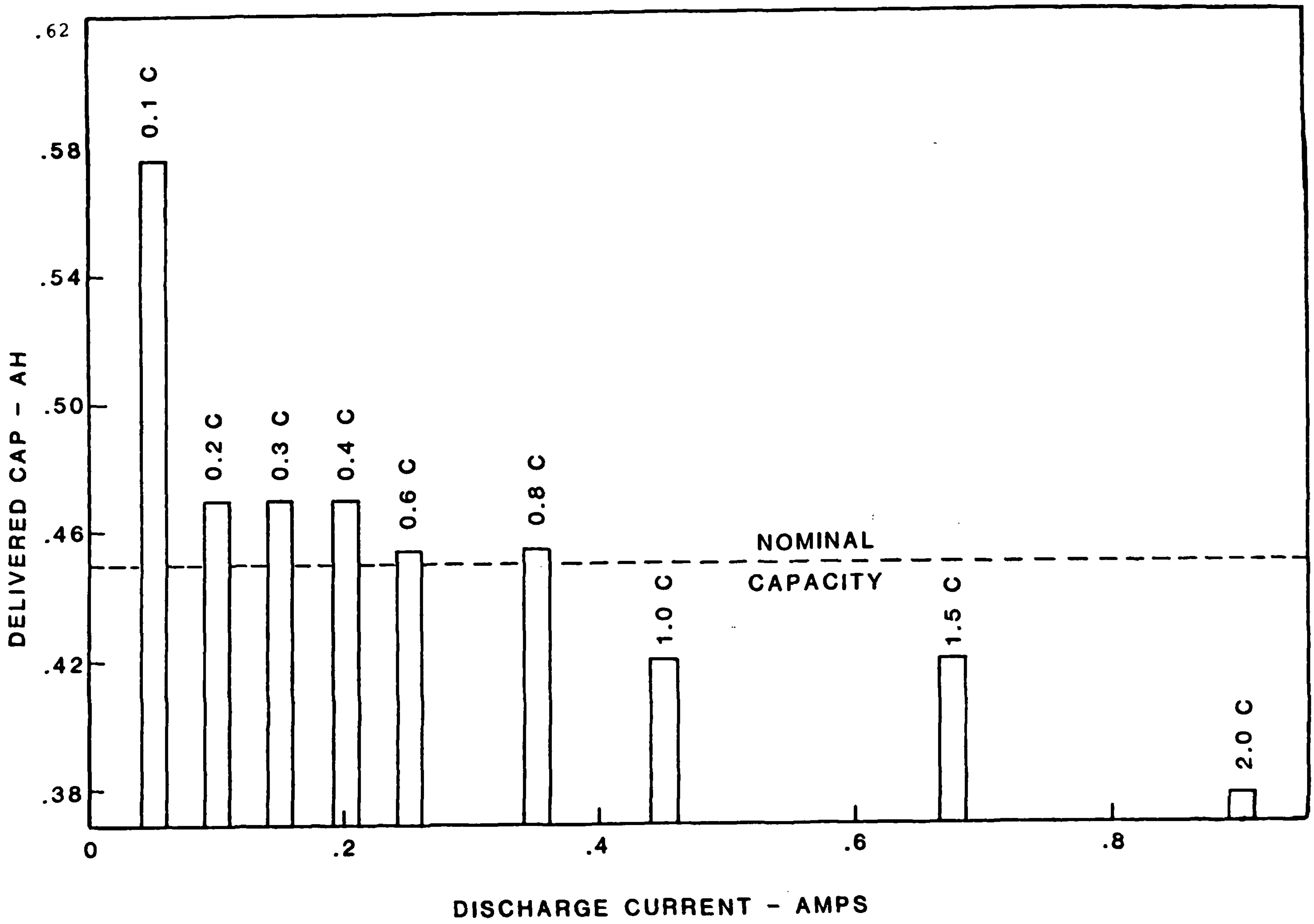


FIGURE 10: EFFECT OF DISCHARGE CURRENT ON DELIVERED CAPACITY - CELL #26

The voltage and pressure profiles for cycles 493 are shown in Figure 11. The high polarization of nickel on discharge seems to indicate deterioration of the nickel electrode. Currently, cycling is being continued and the cell is being monitored to check for stabilization or failure.

Summary of the life cycle data and statistical analysis for standard deviation are given in Table 6.

3.5 SINGLE ELECTRODE POTENTIALS

In keeping with the work plan, cell No. 25 was built in a test fixture. In addition to the three electrodes, the assembly was designed to accommodate a cadmium wire to be used as a reference electrode to monitor the potential of each working electrode.

After undergoing a conditioning cycle, the cell was charged for 5 hours at a current of 100 mA followed by discharge at the same current and a capacity of .292 Ah was delivered. The potentials of nickel and platinum electrodes were monitored against each other and also against screen and the cadmium reference wire.

The values of the cell voltage and the single electrode potentials of the fresh cell are shown in Figure 12. The test plan was to subject the cell to continuous charge/discharge cycles and monitor the potentials of individual electrodes at regular intervals. Abnormal changes in voltage would indicate cell failure and also identify which of the electrode(s) exhibit a deterioration with time.

The cell had undergone over 650 charge/discharge cycles and except for a slight increase in the nickel electrode potential over a period of 6 months, performance characteristics are very similar to that at the beginning of life tests. The voltage and pressure

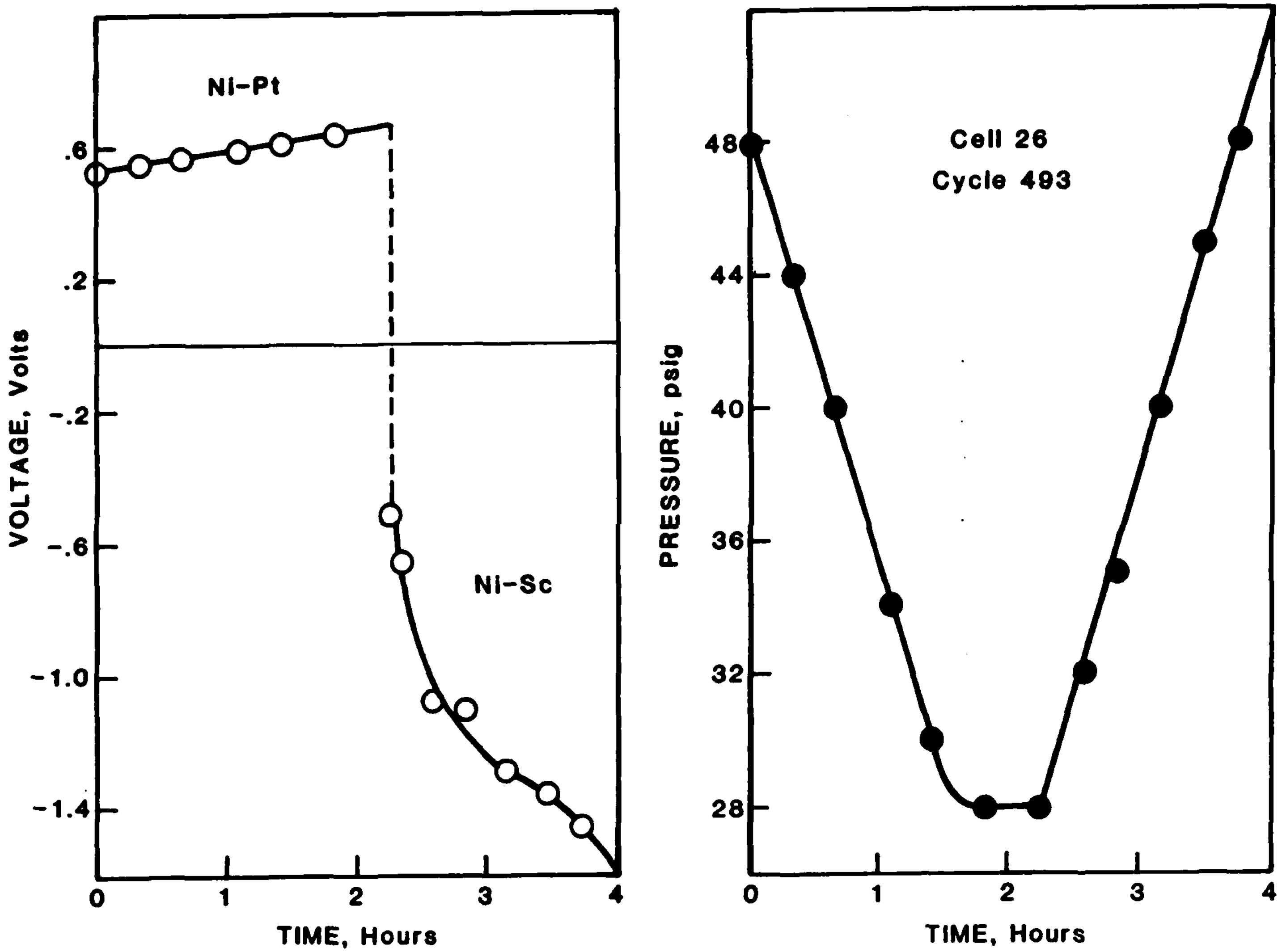


FIGURE 11: VOLTAGE & PRESSURE PROFILES-CELL 26, CYCLE 493

TABLE 6

CELL PARAMETERS ON LIFE CYCLE

Cell No.: 26
Ni Positive: ERC roll-bonded

Cycle Time: 4 hours
Charge: 2-1/4 hours
Discharge: 1-3/4 hours

CYCLE NO.	I mA	CHARGE V, Ni-Pt Avg.	CHARGE V, Ni-Pt End	ΔP	DISCHARGE V, Ni-Sc. Avg.	DISCHARGE V, Ni-Sc. End	ΔP
5	225	.614	.716	34	- .836	-1.025	35
29	225	.600	.700	33	- .763	- .985	34
132	225	.693	.720	33	- .872	-1.110	34
$\bar{x}$		.636	.712	33.3	- .824	-1.040	34.3
σ		.0501	.0106	.5774	.0555	.0638	.5774
245	150	.589	.660	22	- .866	-1.150	26
324	150	.609	.660	23	- .862	-1.100	22
493	150	.606	.660	22	-1.251	-1.590	22
$\bar{x}$		.601	.660	22.3	- .993	-1.280	23.2
σ		.0108	0	.1119	.2234	.2696	2.309

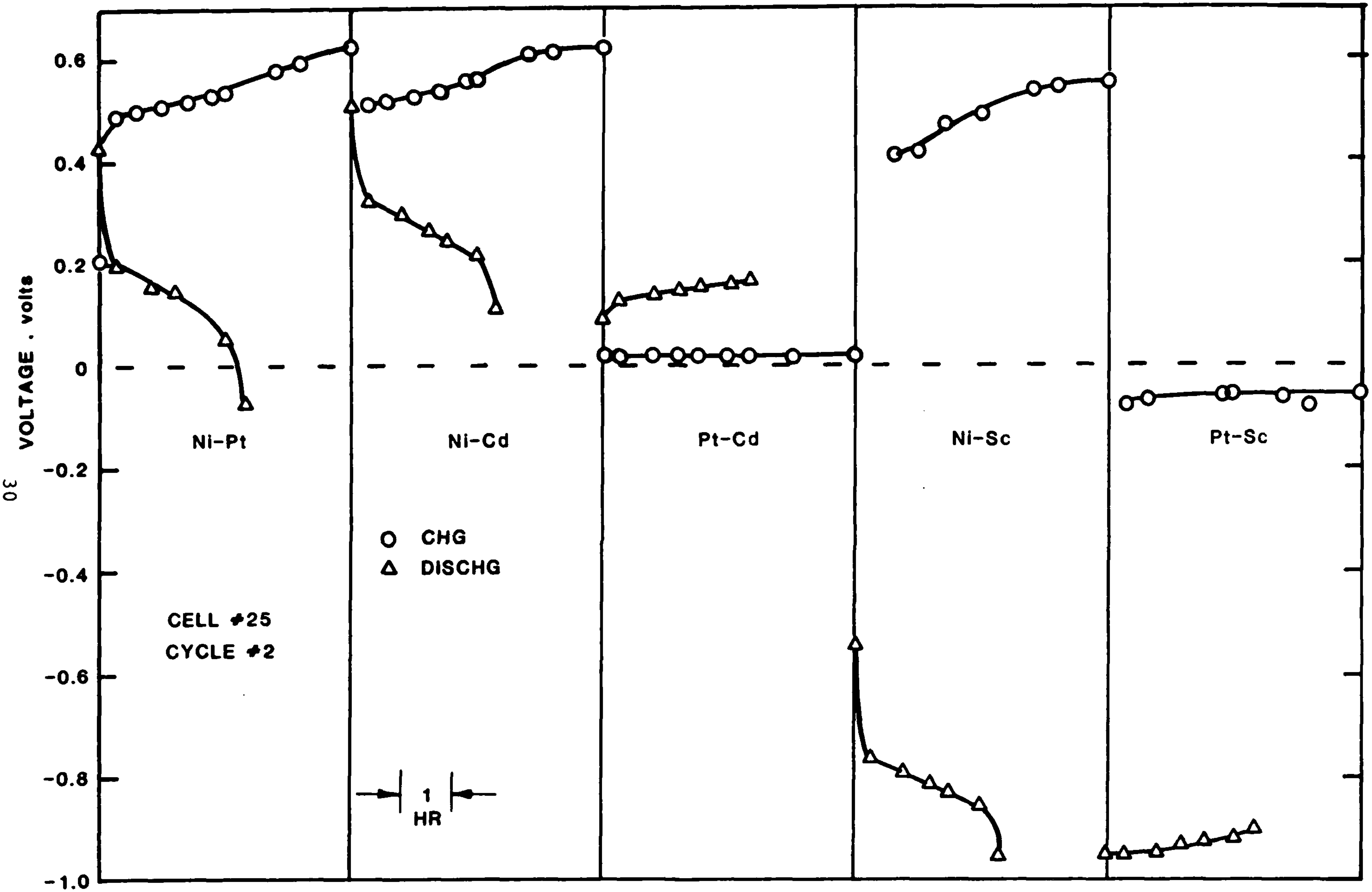


FIGURE 12: SINGLE ELECTRODE POTENTIALS

profiles for cycle No. 624 are given in Figure 13.

The performance characteristics of the cell on cycling are summarized in Table 7.

3.6 SINTERED NICKEL PILOT CELL

Having completed characterization of ERC roll-bonded nickel electrodes, work was started in evaluating the performance of a nickel-oxygen cell containing sintered nickel electrode. Small sections were cut from the positive plate of a commercial Saft aircraft cell and assembled with counter electrodes in a test fixture. After confirming performance in the fixture the electrode assembly was transferred to the standard container and the cell sealed to form a leak-proof system. The cell design was the same as before, employing a three-electrode configuration.

Prior to starting life cycle tests, characterization and performance verification of this cell was carried out. The procedure was the same as that used to verify the performance of cell #26 containing ERC roll-bonded nickel. From the test data, summarized in Tables 8 anbd 9, it can readily be seen that the cell's performance was excellent and it satisfied the requirements for monitoring and controlling the main battery.

The cell was tested manually 10 times before starting routine life cycle tests. The test regime is given below.

Charge	3-1/2 hours @ 100 mA
Discharge	2-1/2 hours @ 100 mA
DOD	83%
Overcharge	40%

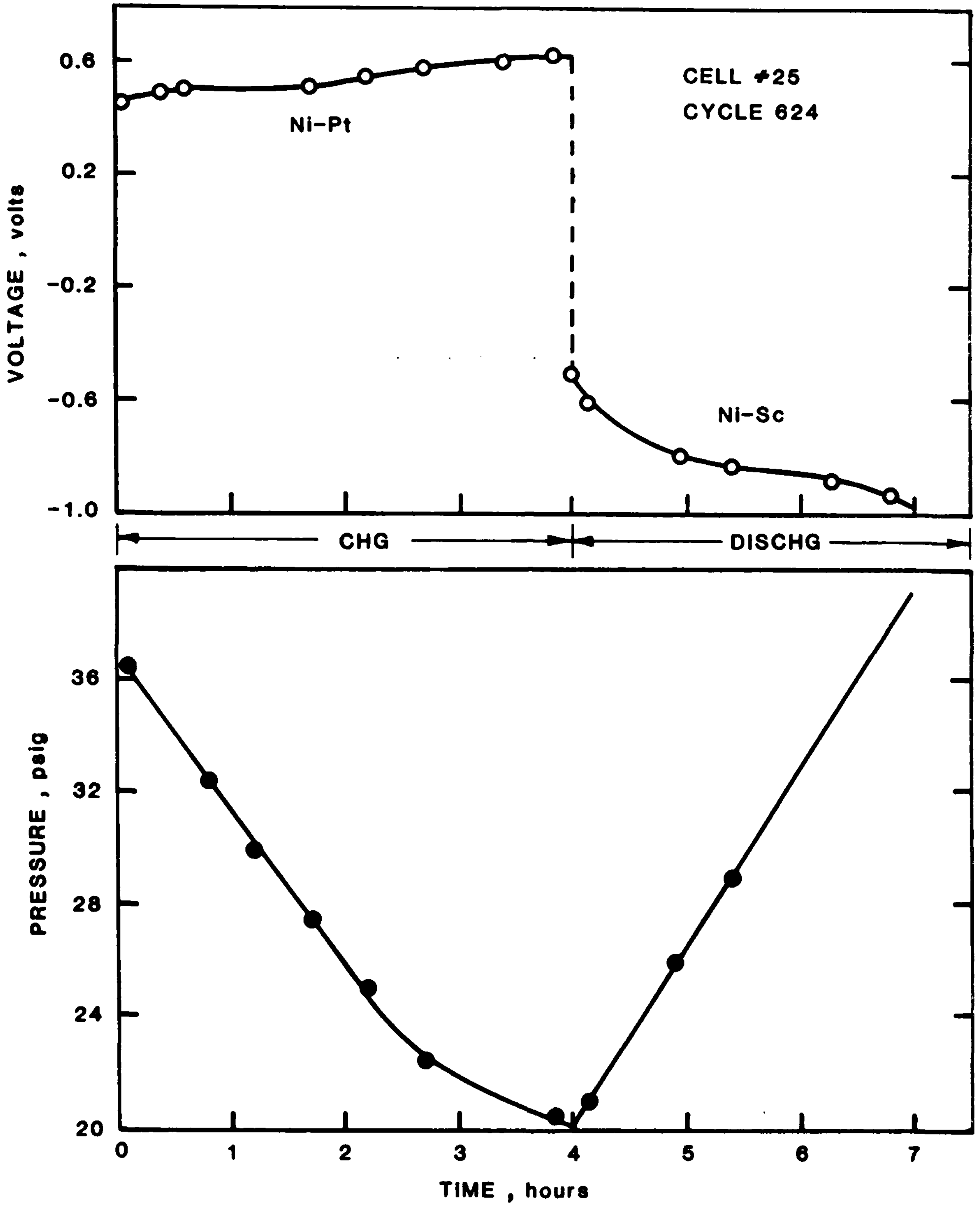


FIGURE 13: PRESSURE PROFILE - CELL 25, CYCLE 624

TABLE 7

CELL PARAMETERS ON LIFE CYCLE

Cell No.: 25 (with reference electrode)
Ni Positive: ERC roll-bonded

Cycle Time: 7.0 hours
Charge: 4.0 hours
Discharge: 3.0 hours
Current: 100 mA

	CHARGE				DISCHARGE			END VOLTS	
	Average Voltage				Average Voltage			Charge	D'chrge
CYCLE NO.	Ni-Pt	Ni-Cd	Pt-Cd	ΔP	Ni-Sc	Ni-Cd	ΔP	Ni-Pt	Ni-Sc
2	.542	.565	.022	20	-.831	.246	23	.601	-.954
50	.518	.532	.021	16	-.766	.278	18	.614	-.800
113	.516	.554	.037	16	-.789	.287	16	.640	-.890
175	.520	.551	.030	15	-.790	.305	15	.635	-.901
234	.540	.568	.029	16	-.736	.347	16	.618	-.835
273	.523	.547	.024	18	-.732	.335	18	.618	-.807
381	.483	.533	.025	-	-.794	.298	-	.610	-.823
457	.564	-	-	-	-	-	-	.625	-.850
500	.501	.517	.014	16	-.790	.282	17	.620	-.885
548	.511	.554	.017	17	-.774	.290	17	.610	-.910
623	.547	.557	.012	18	-.804	.254	19	.620	-.960
$\bar{x}$	.524	.548	.023	16.9	-.781	.292	17.7	.619	-.874
σ	.0228	.0160	7.6659	1.5366	.0300	.0316	2.3452	.0112	.0556

TABLE 8

EFFECT OF OVERCHARGE ON DELIVERED CAPACITY - CELL NO. 27

CELL #27 - SAFT SINTERED Ni - NOM CAP .360 AH

Overcharge vs. Delivered Capacity @ 100% DOD, c/3 rate

CYCLE #	MODE	I mA	t hours	AH	VOLTS end	VOLTS plateau	P start	P end	ΔP	OVERCHARGE %	% DELIVERED/NOMINAL
3-14-85	Chg	120	3.00	.360	.589	.512	60	30	30	0	-
2	Dischg	120	2.69	.323	-1.000	-.782	30	60	30	-	89
3-18-85	C	120	3.75	.450	.680	.584	44	13	31	25	-
4	D	120	2.75	.330	-1.005	-.826	13	43	30	-	92
3-19-85	C	120	4.50	.540	.688	.651	43	10	33	50	-
5	D	120	2.92	.350	-1.000	-.839	10	43	33	-	97
3-20-85	C	120	5.25	.630	.690	.660	43	9	34	75	-
6	D	120	3.00	.360	-1.036	-.893	9	45	36	-	100
3-21-85	C	120	6.00	.720	.709	.680	45	11	34	100	-
7	D	120	3.00	.360	.814	-.814	11	45	34	-	100

TABLE 9

EFFECT OF DISCHARGE CURRENT ON DELIVERED CAPACITY - CELL NO. 27

CELL NO 27 - SAFT SINTERED Ni - NOM CAP : .360 AH

Discharge Performance - 100% DOD

Charge Per Cycle - 3.75 hours @ 120 mA, .450 AH, 25% Overcharge

CYCLE NO	RATE	I mA	t Hours	VOLTS End	VOLTS Plateau	P Start	P End	ΔP	VOLTS Cut-Off	CAP AH	% Ah EFF.**
3-26-85 10	c/9	40	9.81	-1.000	-.684	13	48	35	-1.000	.392	109
3-22-85 8	c/6	60	6.38	-1.000	-.733	12	46	34	-1.000	.382	106
3-18-85 4	c/3	120	2.75	-1.005	-.826	13	43	30	-1.000	.330	92 *
3-28-85 12	c/2	180	2.00	-1.144	-.848	13	47	34	-1.000	.360	100
3-29-85 13	c	360	.94	-1.238	-.913	13	47	34	-1.000	.338	94
3-27-85 11	1.5c	540	.59	-1.290	-.963	14	47	33	-1.100	.321	89
3-25-85 9	2.0c	720	.44	-1.400	-.986	12	46	34	-1.100	.315	88

*CYCLE 4, c/3 rate, not fully discharged as indicated by ΔP
**Based on nominal capacity

To date, the cell has undergone over 800 cycles and the performance is satisfactory. The voltage and pressure profiles for cycle No. 838 are shown in Figure 14 and the data on cycling are summarized in Table 10.

The statistical analysis of the data for roll-bonded electrodes are compared with that of sintered electrodes in Table 11. With respect to voltage, the roll-bonded electrodes obviously exhibit a better value of departure from norm compared with the sintered electrode. However, the reverse is true in case of change in pressure. Cells using sintered nickel electrodes show a lesser variation of change in pressure than the roll-bonded electrode. Note, however, that the order of magnitude of the differences are small and both types of cells show more than adequate consistency to be used to track the main battery's state of charge.

3.7 LINEARITY OF PRESSURE

The cells that are being cycled are monitored at regular intervals and the presssure profiles analyzed. In order to investigate the stability of the linear relationship with time, from the data of cell NO. 25 (ERC nickel), a plot of pressure against time was made. This is shown in Figure 15 (the top portion for cycles 1 through 260) after which the pressure at the end of discharge was reduced.

The bottom portion of Figure 8 shows the pressure profile for cycles 261 through 460. The results show that the values of ΔP and slope are independent of the absolute values of pressure and that the linearity does not change with time. The minor fluctuations are attributable to variations in the temperature of

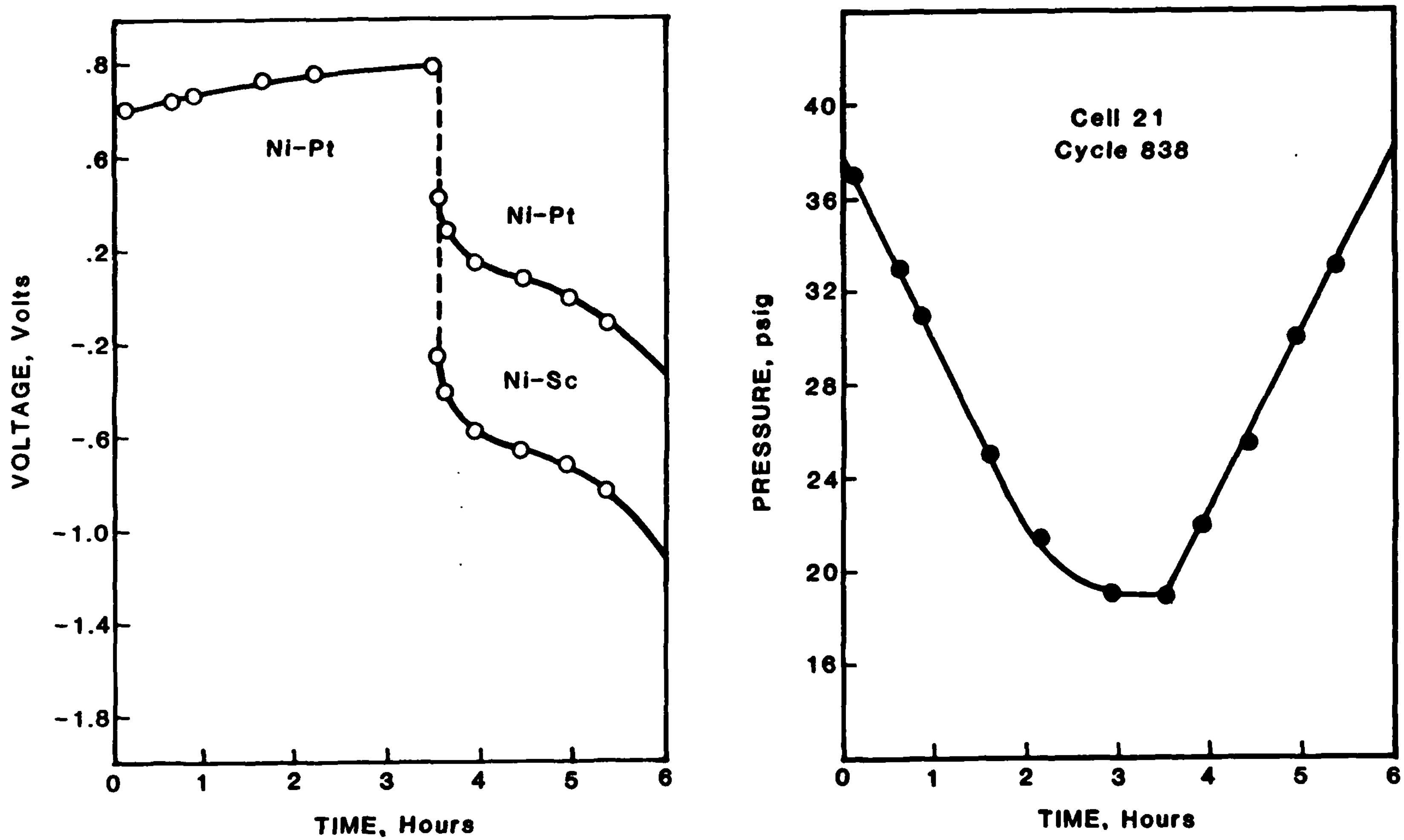


FIGURE 14: PRESSURE PROFILE-CELL 21, CYCLE 838

TABLE 10

CELL PARAMETERS ON LIFE CYCLE

Cell No. 21
Ni Positive: Sintered, Saft

Cycle Time: 6 Hours
Charge: 3-1/2 hours
Discharge: 2-1/2 hours
Current: 100 mA

CYCLE NO.	CHARGE V, Ni-Pt Avg.	CHARGE V, Ni-Pt End	ΔP	DISCHARGE V, Ni-Sc. Avg.	DISCHARGE V, Ni-Sc. End	ΔP
47	.716	.853	19	-.736	-	19
100	.768	.850	18	-.692	- .825	18
192	.725	.850	17	-.759	- .900	17
265	.830	.935	19	-.690	-	19
334	.845	.960	19	-.708	- .880	19
404	.894	.970	19	-.623	-1.480	19
562	.898	1.025	-	-.709	-2.050	-
697	.931	.900	19	-.605	-2.050	21
750	.967	1.050	-	-.970	-2.050	-
838	.924	1.000	19	-.638	-2.050	19
$\bar{x}$	.850	.939	18.6	-.713	-1.535	18.9
	.0886	.0742	.7440	.1028	.5856	1.1260

TABLE 11

COMPARISON OF STATISTICAL DATA

TYPE		ROLL-BONDED			SINTERED
CELL NO.		2	26	25	21
CHARGE					
V avg.	$\bar{x}$	.941	.601	.524	.850
	σ	.2696	.0108	.0228	.0886
ΔP	$\bar{x}$	24.8	22.3	16.9	18.6
	σ	1.4720	.5774	1.5366	.7440
DISCHARGE					
V avg.	$\bar{x}$	-.600	-.824	-.781	-.713
	σ	.0273	.0555	.0300	.1028
ΔP	$\bar{x}$	23.5	23.2	17.7	18.9
	σ	2.5884	.5774	2.3452	1.1260

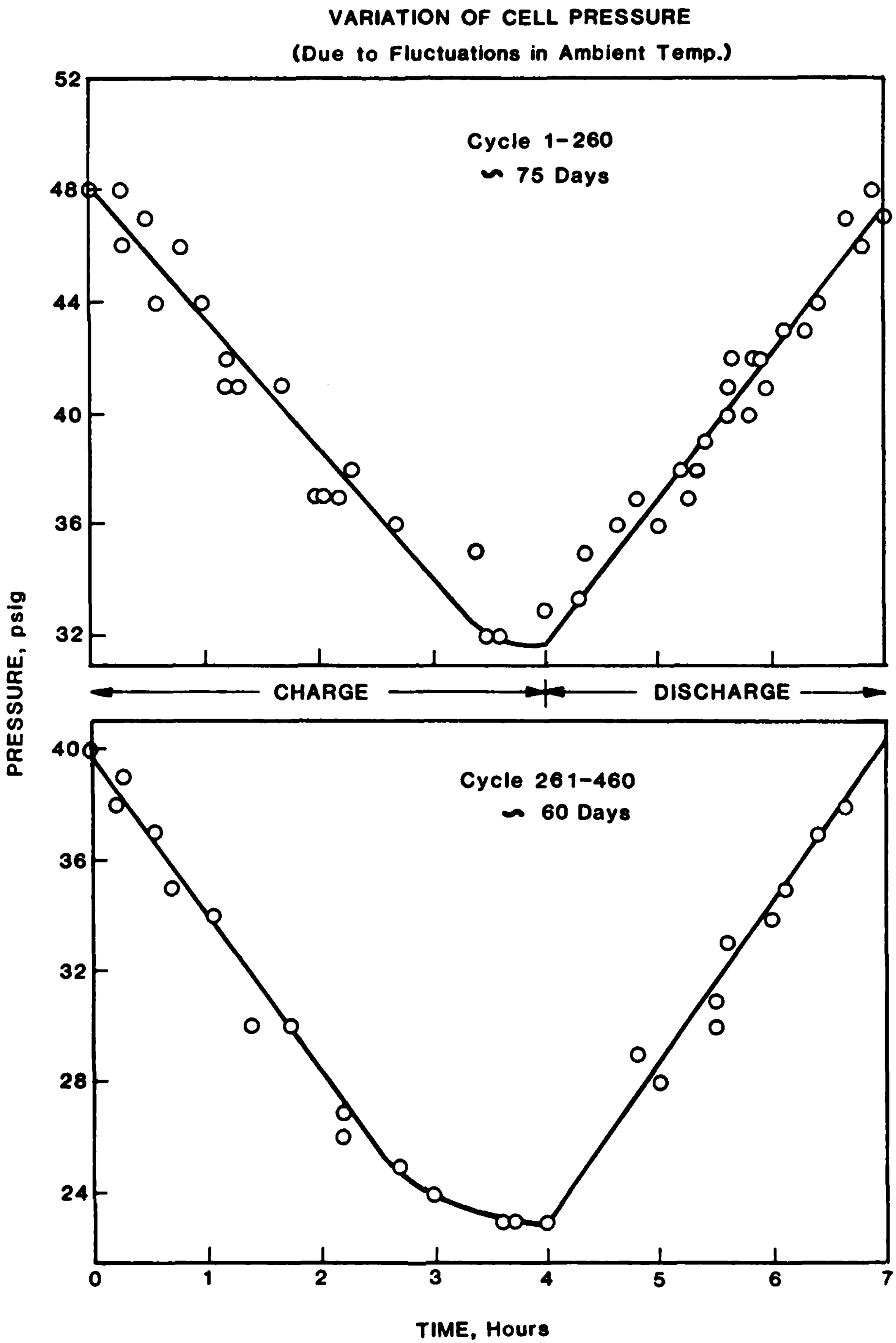


FIGURE 15: OVERALL PRESSURE PROFILE-ERC Ni

the surroundings. A similar plot for cell No. 21 containing sintered nickel electrode is shown in Figure 16.

3.8 COMMERCIAL AIRCRAFT BATTERIES

One cell each from Saft and Marathon (nominal capacity 12 Ah) were discharged at 6 Amps (C/2 rate), immediately after charging. The discharge was repeated with the cells allowed to stand overnight after charging. The delivered capacity in the first case was 26.5 and 17.5 Ah for Marathon and Saft respectively. The capacity values were reduced by 15 and 20% when discharged after overnight stand. The discharge characteristics of the cells are shown in Figure 17.

The cells were also discharged as per MIL-Spec DOD-C-85050 (AS), 4.7.2.7, duty cycle test. No problems were encountered with the high currents and the test results are summarized in Table 12.

After completing tests of single cells, 16 cells each manufactured by Saft and Marathon were assembled to constitute battery stacks. The batteries were also subjected to MIL-Spec-DOD-C-85050 (AS), 4.7.2.7 duty cycle test and the results are shown in Table 13.

A carbon pile resistor was used for these tests. Its magnitude, as measured by means of a shunt, was different from that specified in the Mil-Specs and the resistance value of 16-cell tests was not consistent with that for single cells. Furthermore, as discovered later, some of the aircraft cells were defective and had to be removed. These are the apparent reasons that the voltage values of the batteries (Table 13) are not consistent with those of single cells (Table 12).

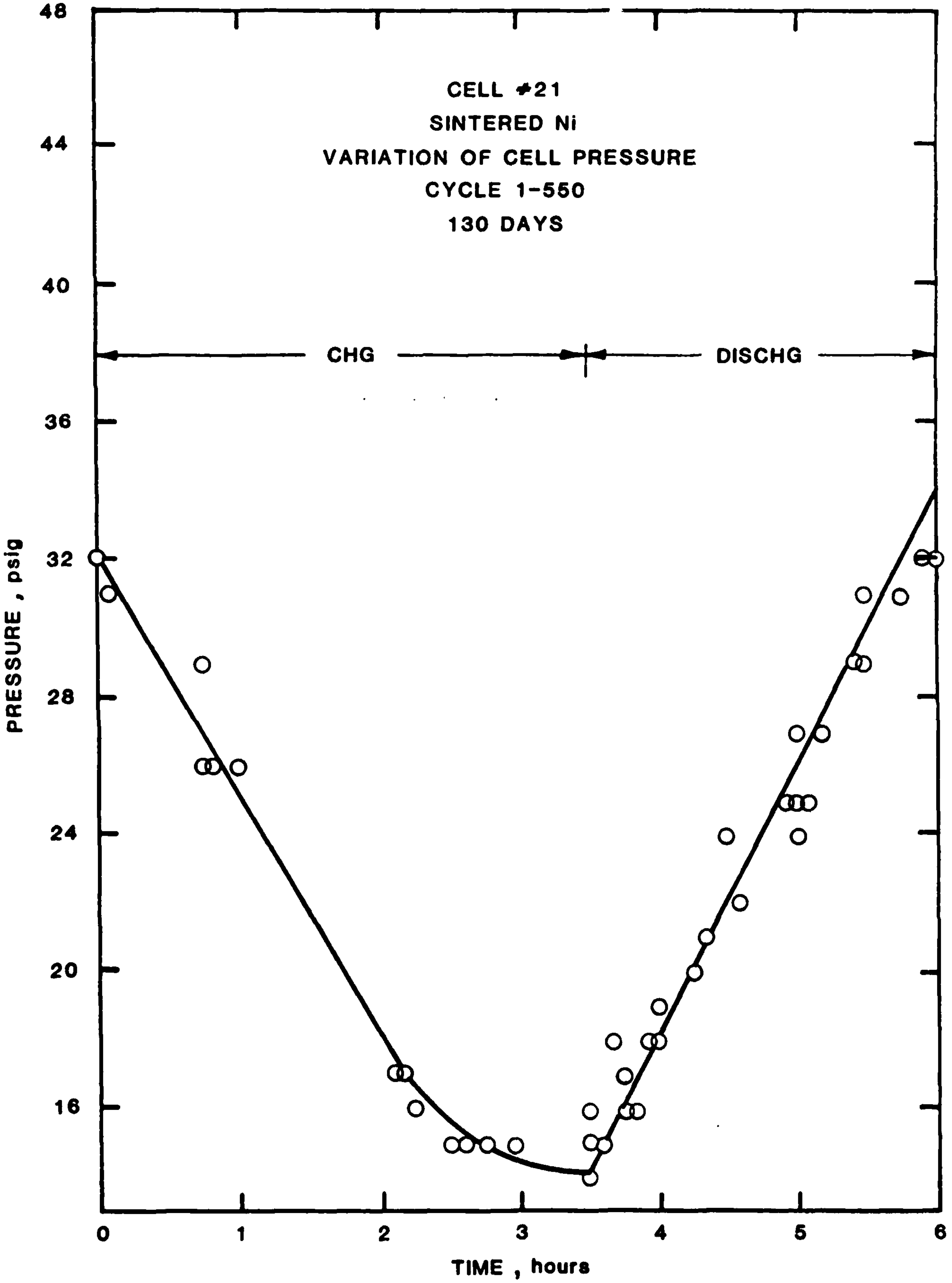


FIGURE 16: OVERALL PRESSURE PROFILE - SINTERED Ni

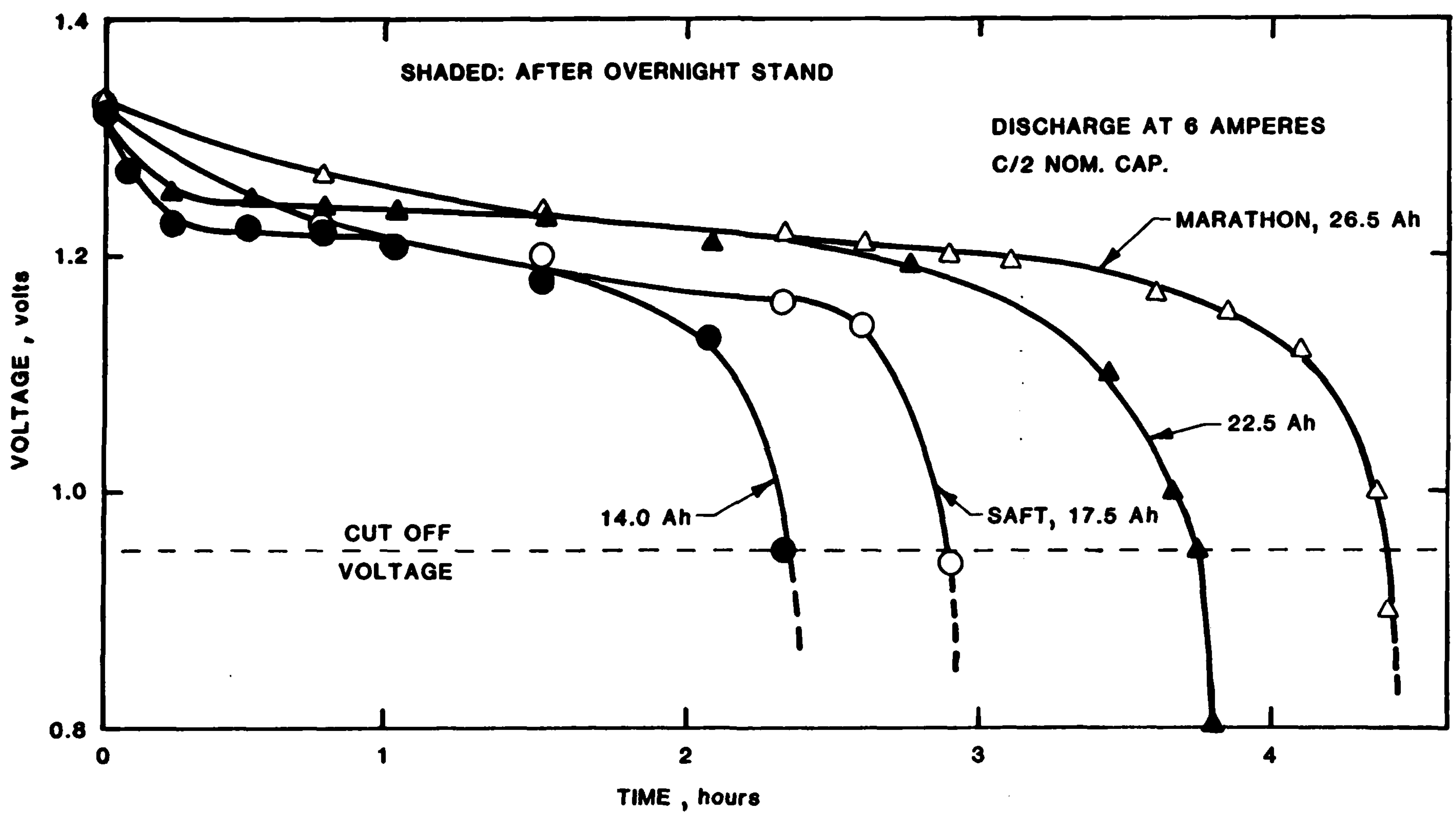


FIGURE 17: DISCHARGE PERFORMANCE OF AIRCRAFT CELLS

TABLE 12

DUTY CYCLE TEST ON AIRCRAFT CELLS

CELL TYPE	CYCLE NO.	MODE →→→	OCV	DISCHG		OCV		DISCHG	
		SECS.→→→	0	0	20	0	260	0	20
SAFT	1	V(volts)	-	.62	.54	1.22	1.27	.59	.49
		I(amps)	0	324	282	0	0	318	252
	2	V	1.35	.67	.61	1.30	1.32	.64	.59
		I	0	378	330	0	0	366	330
MARATHON	1	V	1.34	.49	.46	1.33	1.39	.49	.45
		I	0	468	420	0	0	468	396

TABLE 13

DUTY CYCLE TEST ON AIRCRAFT BATTERIES

BATTERY TYPE	CYCLE NO.	MODE →→→	OCV	DISCHARGE		OCV		DISCHARGE	
		SECS. →→→	0	0	20	0	260	0	20
Marathon	1	V(volts)	22.4	7.5	6.3	20.1	21.0	6.9	6.0
		I(amps)	0	522	462	0	0	522	450
	2	V	21.7	7.7	6.5	20.3	-	6.9	6.1
		I	0	522	466	0	0	528	450
Saft	1	V	22.1	12.7	10.8	20.5	21.1	12.1	10.4
		I	0	360	318	0	0	342	323
	2	V	22.0	13.5	11.6	19.8	20.9	13.2	10.8
		I	0	324	312	0	0	336	312

3.9 BATTERY TRACKING SYSTEM

In accordance with the work plan, preliminary design and tests were initiated towards state of charge indicator/controller system study. An experimental electronic cycler was designed and built to determine the tracking characteristics of the $Ni-O_2$ cell when operated in tandem with the main battery.

The cycler consists essentially of a constant-current power supply to provide the power source, a cycling unit with provisions to vary cycling times and current and a fuel gauge which converts the pressure of the $Ni-O_2$ cell into percent state of charge.

Cell No. 27 was housed in the fuel gauge for the first series of evaluation tests. The cycling equipment was first calibrated with one Saft aircraft cell, and the calibration curve is shown in Figure 18. Next, a battery stack of 16 Saft aircraft cells connected in series was cycled in conjunction with the same $Ni-O_2$ cell No. 27 and a typical profile of current, voltage and state of charge is shown in Figure 19. After about 10 cycles, the experiment had to be discontinued because:

- Three of the Saft cells had shorted out.
- Capacity obtained by discharging one cell did not truly represent capacity of stack possibly because of variations between cells.
- Preset parameters of cycler were out of phase with characteristics of the pilot cell.

In view of these factors, we decided to repeat the experiment. Another pilot cell, No. 28, was built, again using a section of nickel electrode cut out from a Saft cell. This cell and the Saft battery stack of 13 cells were first tested separately to identify their characteristics and the following capacities were obtained.

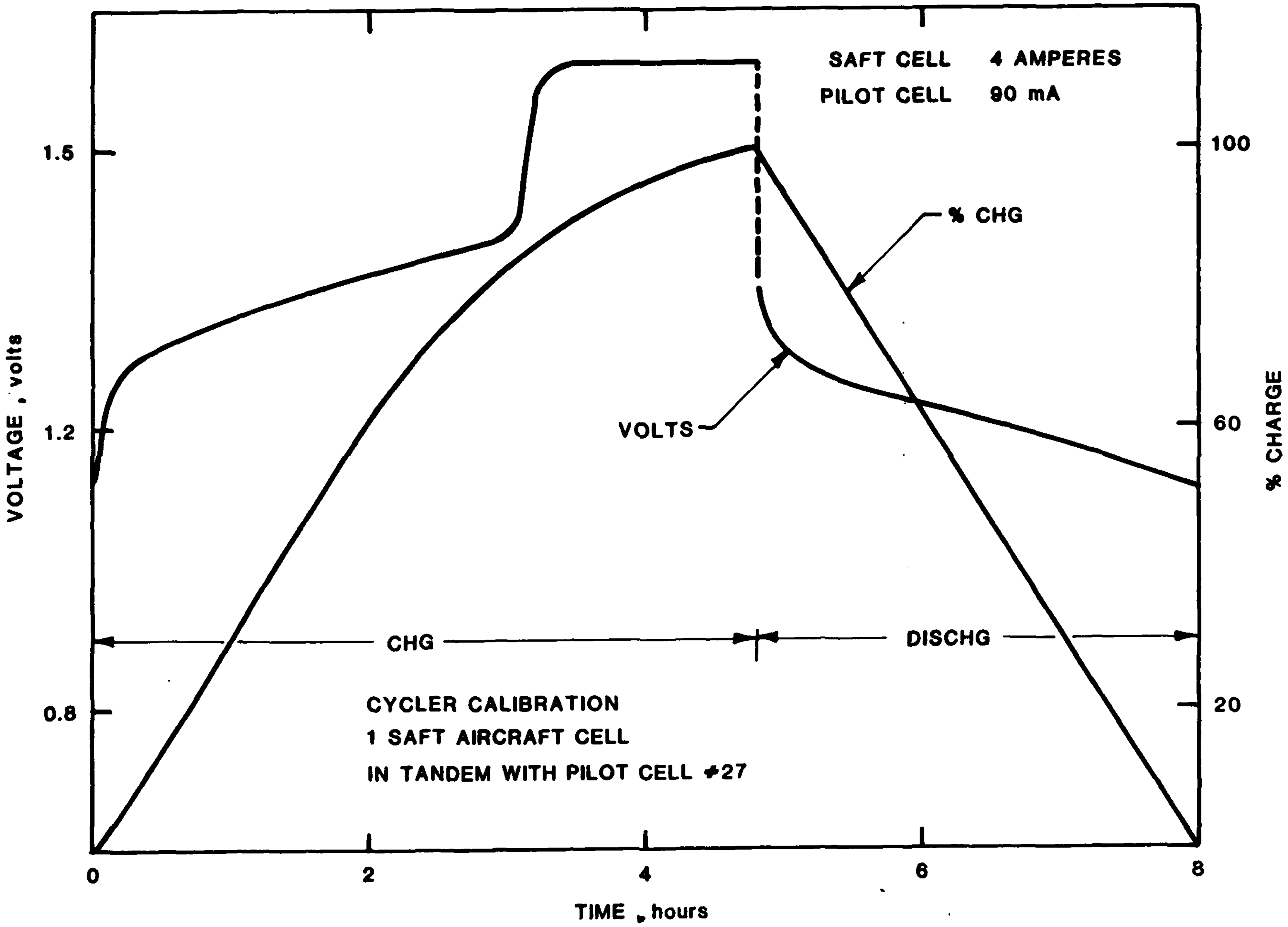


FIGURE 18: CALIBRATION OF TRACKING CYCLER

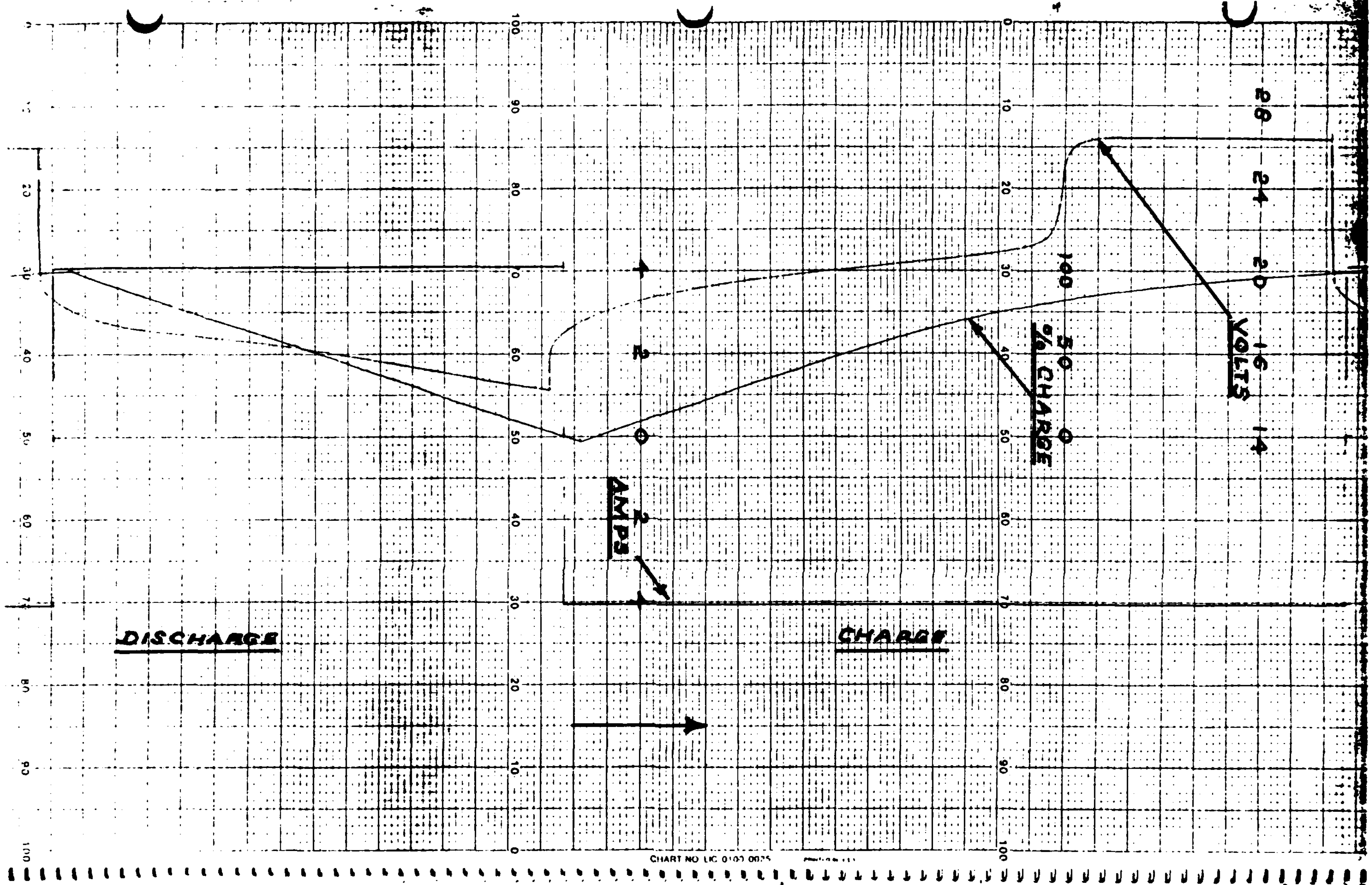


FIGURE 19: PERFORMANCE OF 16-CELL SAFT BATTERY

SAFT		PILOT CELL	
End V	Ah	End V	Ah
13.0	16.9	- .8	.221
12.0	17.4	- .9	.237
11.0	17.6	-1.0	.258

The performance characteristics of the two are shown in Figure 20. Based on these data, operating parameters of the tracking cycler were modified. The design specifications are given in Table 14.

The battery and pilot cell were connected to the tracking cycler such that operation of the pilot cell was in tandem with the battery. The cycler was also equipped with a provision to cut off the charge current when the fuel gauge reading (% charge) exceeded 100%.

Cycling of the system was started and the first 5 cycles were utilized to fine-tune system parameters after which cycling was continued in the automatic operating mode. About 25 cycles have been completed to date and the system is functioning well. A typical charge-discharge cycle is shown in Figure 21.

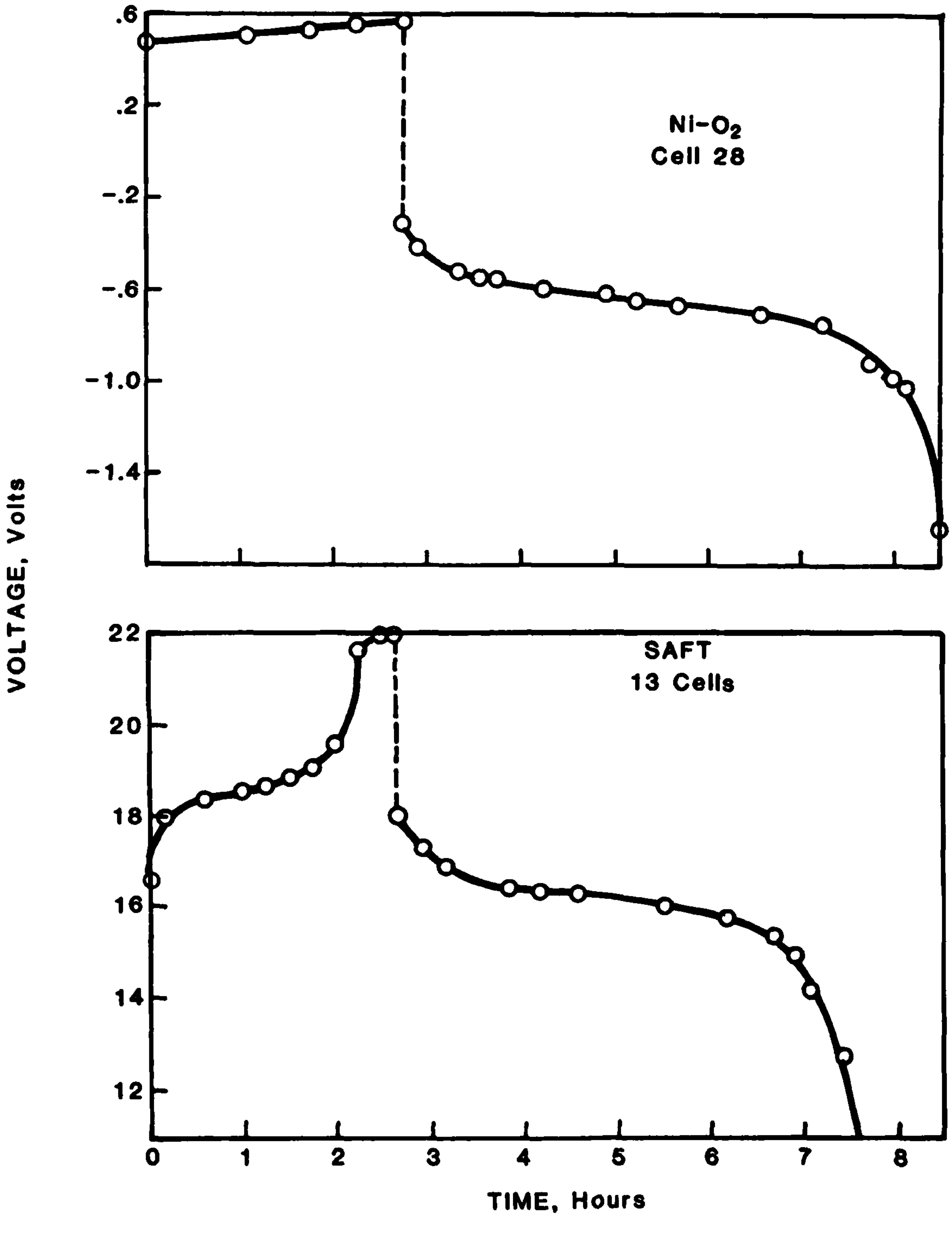


FIGURE 20: PERFORMANCE CHARACTERISTICS OF BATTERY AND PILOT CELL

TABLE 14

TRACKING CYCLER SPECIFICATIONS

	SAFT	$Ni-O_2$
From graph, total time to end of discharge	7.45 hrs	7.55 hours
Charge time	2.65	2.75
Discharge time	4.80	4.80
Discharge current	3.6A	46 mA
Actual delivered capacity	17.28 Ah	.221 Ah
Discharge		
DOD	75%	75%
Capacity to be removed	12.95 Ah	.166 Ah
I	3.6 A	46 mA
t	3.6 hours	3.6 hours
Charge		
Overcharge	11%	11%
Capacity to be put in	14.39 Ah	.184 Ah
I	3.6 A	46 mA
t	4.0 hours	4.0 hours
i.e. cycler to be calibrated to,		
Charge	4.0 hours @ 3.6 A	4.0 hours @ 46 mA
Discharge	3.6 hours @ 3.6A	3.6 hours @ 46 mA

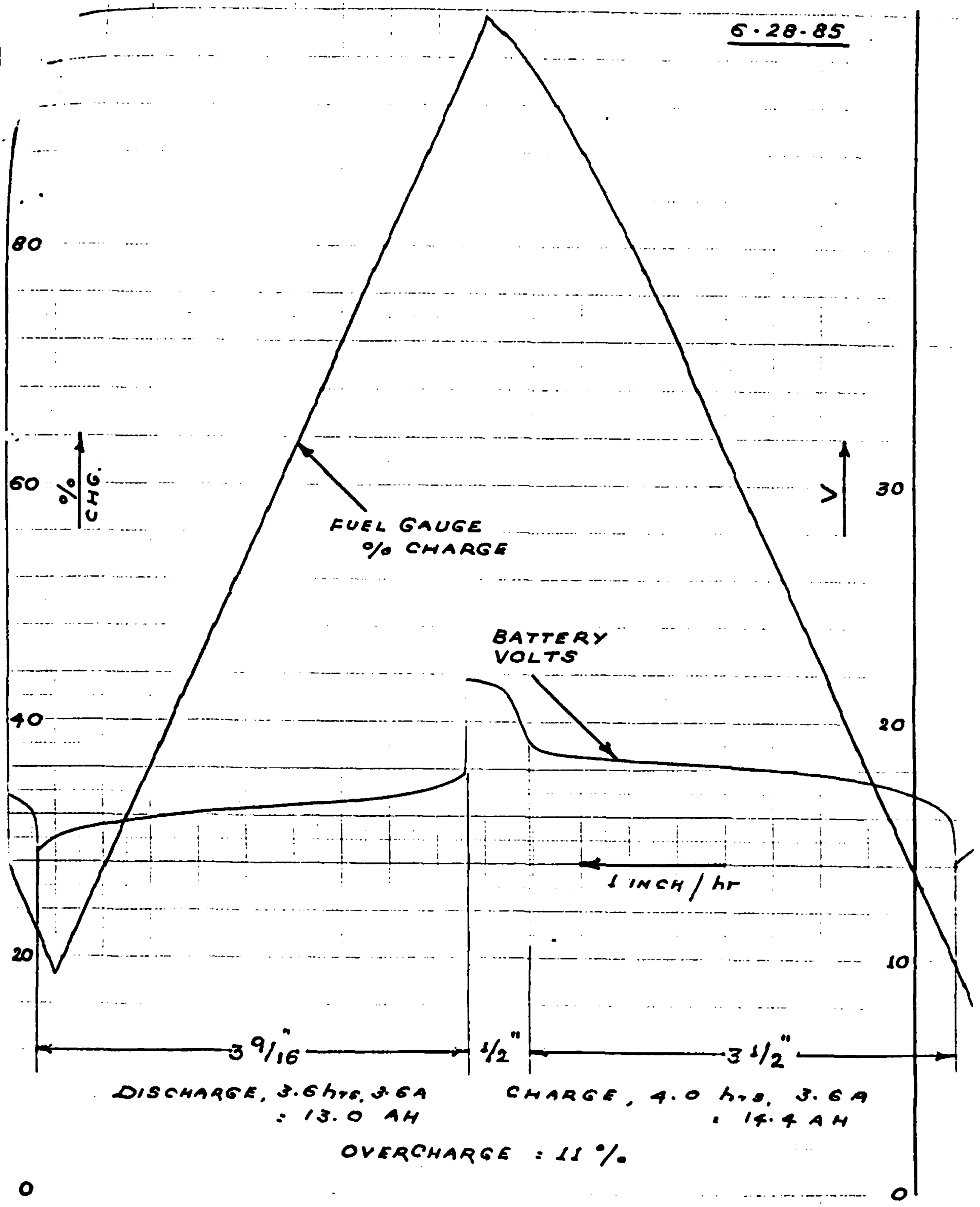


FIGURE 21: OPERATION OF PILOT CELL IN TANDEM WITH SAFT BATTERY

4.0 SUMMARY AND CONCLUSIONS

The major objective of work performed during this phase was to characterize the performance of metal gas cells containing different types of positive electrodes. Nickel electrodes of the roll-bonded (ERC) and sintered (Saft and Marathon) types were tested for charge/discharge rate effects, effects of over-charge/over-discharge, and linearity of pressure. The test results proved that the performance characteristics of the nickel-oxygen cells are more than adequate and will be capable of tracking the state of charge of the main battery.

Special tests were also conducted to monitor the potentials of each working electrode separately both during charge and discharge. This enabled a better understanding of the performance of each individual electrode and identify which electrode deteriorated first and causes cell failure. This information is valuable in predicting estimates of life and improving performance of the nickel-oxygen cell.

Having established this, selected representative cells were subjected to continuous cycling tests on alternate charge-discharge regimes to obtain data on cell life. The results indicate that the cells can sustain continuous cycling for extended time periods and retain their stability to give the required, reliable and reproducible parameters.

Commercial aircraft cells (Saft and Marathon) were purchased and their characteristics were also evaluated.

The aircraft cells and nickel-oxygen cells fabricated with electrodes used in aircraft cells were thus qualified and found to be acceptable. The next subtask of aircraft battery system study was started as planned. An electronic cycling system was designed and built and tests were started. Initial experiments were designed to understand the electrical interfaces that would be required, tracking capabilities of the pilot cell and critical areas that need more detailed investigation.

Since the developmental efforts and investigations of this phase took longer than orginally planned, work on temperature effects were not done as scheduled. It is now proposed to carry this over to the next phase. In the interest of time, this study will be performed simultaneously on the nickel-oxygen cell, aircraft battery and integrated system.

In the next 12 months efforts will be devoted to the study of system life and stability under Phase II.

The results of Phase I will be analyzed and new prototype cells utilizing advanced components and construction techniques will be manufactured. Brassboard electronic circuits will also be constructed. The integrated systems will be placed on one or more charge/discharge cycle regimes for at least 9 months in order to determine system life and stability characteristics. The system tests will be conducted essentially at the brassboard level.

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