FABRICATION & TESTING OF NEGATIVE-LIMITED SEALED NICKEL-CADMIUM CELLS

Report No. 752-015

Final Report

1 July 1974 to 28 February 1975

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Prepared by D.J. Gordy

Approved by C.J. Menard

31 March 1975

Jet Propulsion Laboratory

Contract No. 953680

JPL - 953680

Gould Inc., Gould Laboratories
Energy Research
Mendota Heights, Minnesota

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ABSTRACT

Based on technology developed on a preceding program 100 each 20 Ah and 3 Ah negative limited nickel-cadmium cells were fabricated and assembled in hermetically sealed stainless steel containers. A portion of these were delivered directly to Jet Propulsion Laboratory and the remainder were subjected to special tests and then delivered to the Laboratory.

The cells were purposely designed and shown to exhibit a desired large voltage rise signal, in excess of 250 mA, at the end of each charge period. This built-in voltage characteristic is quite attractive for charge control purposes in that conventional sealed nickel-cadmium cells exhibit little or no such detectable signal at the end of charge. Other attractive features were that the negative limited cells exhibit lower self discharge rates than conventional sealed nickel-cadmium cells and do not require overcharge as do these cells. It was shown that the negative limited cells are capable of operating at charge and discharge rates up to 5C and can deliver at least 1000 cycles on a 30-minute regime at 25% DOD.

The cells were found to be not entirely gas free as was intended at the start of the program. Extent of the gassing was not deemed critical or detrimental however in view of the observed operating pressures which were in the range of 7 to 20 psig for most test conditions as well as the fact that the cells were operated in the flooded conditions and therefore contained very little internal void volume. A yet to be explained result was that the cells were found to exhibit somewhat higher capacity loss rates during cycling than conventional sealed nickel-cadmium cells. When this latter problem is resolved the negative limited cells should constitute a significant advance in the state-of-the-art of sealed nickel-cadmium cell technology.

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I. INTRODUCTION

The concept of a negative limited nickel-cadmium cell is quite interesting in that it could be made to operate in a markedly different and improved manner than the conventional and popular positive limited, sealed nickel-cadmium cell. First, unlike the conventional cell, the negative limited version could be so constructed that it would exhibit a strong and positive signal at the end of charge. This signal would greatly simplify the charge control problems that are normally associated with the conventional cell. Next the negative limited cell could be made to operate with little or no internal gassing as opposed to the conventional cells which are designed to accommodate and operate with appreciable amounts of internal gassing and pressure. This non-gassing feature would avoid the ever present threat of catastrophic failure which can occur in conventional sealed cells due to development of excessive internal pressures. The non-gassing feature would also minimize the electrolyte loss rate through possible small leakage paths and thereby delay failure by drying out. In addition to the above, the negative limited cell, unlike the conventional cell, could be made to operate without overcharge which would tend to increase efficiency as well as reduce internal heat generation which is known to be deleterious to life. Finally the negative limited cell could be operated in the electrolyte 'flooded' condition as opposed to the electrolyte 'starved' condition which is required in conventional cells. Operation in the 'flooded' condition has the advantage of providing greater electrode utilization and hence capacity and reducing internal resistance and thereby providing higher rate capability.

Gould Inc. has in the past, under subcontract to JPL, conducted work which was directed at development of such a negative limited, non-gassing cell.[1,2] Approach involved incorporation of three changes in the design of conventional nickel-cadmium cells. These were:

1. Change the ratio of positive to negative active material in the cells so that the cells become negative-limited.
2. Use a grid material for the cadmium electrode that has a high over-potential for the hydrogen evolution reaction so that the onset of hydrogen gassing would be signaled by a relatively large voltage step.
3. Incorporation of a miniature electronic charge control device that will be used externally to each cell to end the charge using the voltage step as a signal.

During work on parts 1 and 2[1,2] the concept of a negative-limited 'non-gassing' nickel-cadmium battery was demonstrated by constructing and testing practical size experimental cells of approximately 25 Ah capacity. Thirty cells were constructed and tested[2] for 500 cycles using an accelerated regime approximating a 90-minute orbit period. Three groups of 10 cells each were tested at 0°, 25°, and 40°C. The test program clearly showed that the negative-limited nickel-cadmium cell was a very promising avenue leading to a practical, long-lived secondary cell.

The technology developed in the above-referenced program was applied in the present work, which consisted of the following tasks:

- Cell design and hardware fabrication
- Component and cell construction
- Cell testing

One-hundred each, 3 Ah and 20 Ah cells were fabricated and tested on this program. Fifty-two cells of each size were delivered to JPL. The remaining 48 cells underwent varying tests including a 1000-cycle life test. The fabrication of these 200 cells and the related testing is the subject of this report.

II. EXPERIMENTAL

A. Cell Design and Hardware Fabrication

1. Cell Design

The first task undertaken was to establish the physical dimensions necessary to produce a 20 Ah and a 3 Ah cell. Calculations were performed using data acquired in an earlier study,[1,2] and the number of electrodes required and the area of each was established. The numerical values are given in Table 1. The cadmium electrodes are identical to the ones employed in an earlier study.[1,2] The nickel electrode employed in this work was increased in thickness from 50 to 65 mils while maintaining the same loading per cu. inch in order to increase the positive/negative active material ratio. The separator thickness was also increased from 10 to 18 mils in an effort to improve the overall separation and perhaps improve electrolyte distribution.

TABLE 1. Component Dimensions for Negative-Limited Sealed Nickel-Cadmium Cells

Type	No.	H (In.)	W (In.)	T (In.)	Loading (g/In.^{3})
		3 Ah Size Cell			
Nickel Electrode	7	2.25	1.75	0.065	31.6
Cadmium Electrode	6	2.25	1.75	0.015	60.7
Pellon	14	2.50	2.00	0.018	–
		20 Ah Size Cell			
Nickel Electrode	9	5.50	3.50	0.065	31.6
Cadmium Electrode	8	5.50	3.50	0.015	60.7
Pellon	18	5.75	3.75	0.018	–

From the above information the cell case and cover sizes were finalized. The covers were designed to have two ceramic-to-metal seals. The terminal stud of the cadmium electrode was silver plated. Provisions were made for attaching Trerice pressure gauges (tubes and sockets fabricated from 316 stainless steel) and a rupture disc safety device to the fill tube. All cell hardware and connecting test fixtures were chosen to be stainless steel. Provisions were also made to seal the fill tube, in the absence of the pressure test and safety attachments, to aid in storage and shipment of the cells. This seal consisted of a Swag-Lok type, stainless steel tubing cap. Detailed engineering drawings for the cell cover and case are shown in Appendix I.

2. Hardware Fabrication

Stainless steel cans and covers were fabricated in the required sizes to accommodate the cell components. The total number of cell cases fabricated was 150 of each size (20 Ah and 3 Ah) while 115 covers with ceramic seals were constructed for each size cell. The covers were produced from type 304L stainless steel via a draw and punch operation. These components were then provided with two ceramic-to-metal seals by Ceramaseal Corp. The cell cans were of a folded design made by cutting and bending the raw stock and completing the closure by welding the seam on both sides and the ends and length of the bottoms. These components were fabricated by Sauciers Metal Fabricating. Compound pressure gauges (tubes and sockets made from 316 stainless steel) were provided by H.O. Trerice Co. while the rest of the fittings necessary to complete the external test connections were of 316 stainless steel Swag-Lok type connectors furnished by Minnesota Valve and Fitting. The safety device was a rupture disc type provided by Fike.

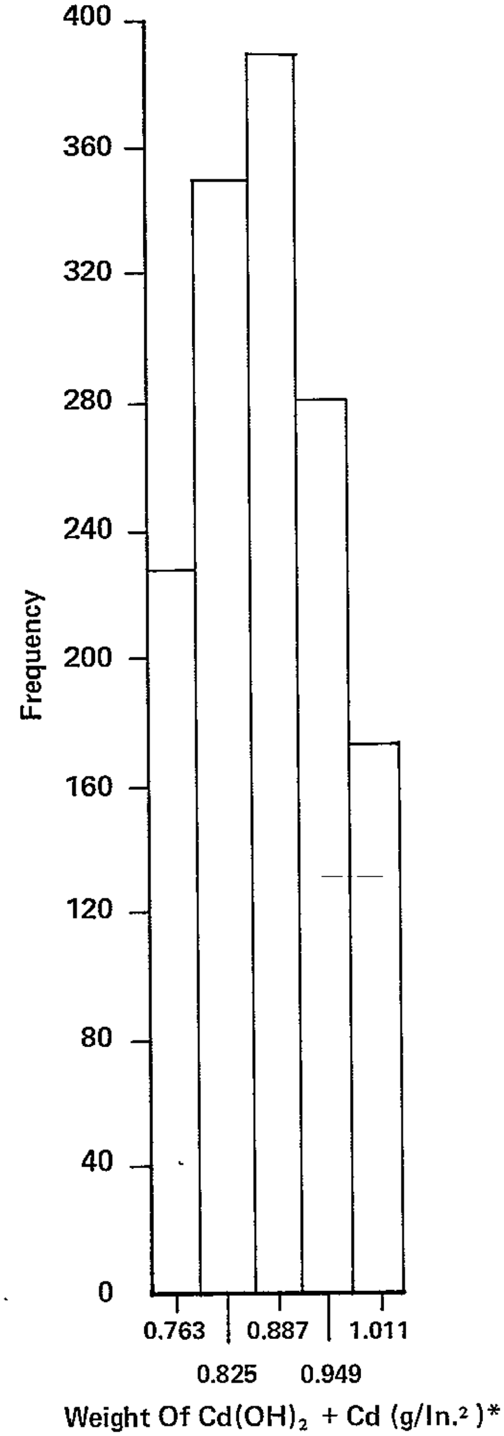
B. Electrode Fabrication

1. Cadmium Electrodes

Electrodeposited cadmium electrodes, which earlier work[1,2] indicated were best suited for use in negative-limited cells, were prepared and screened prior to cell construction.

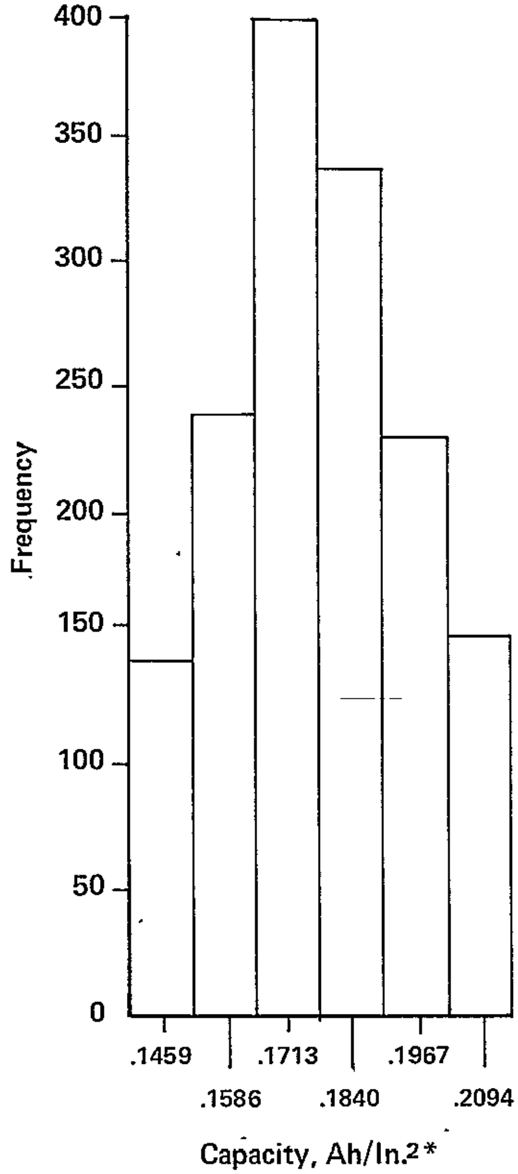
Electrodes were prepared using a laboratory version of a proprietary production process whereby the cadmium active mass is deposited on a 5 Ag 7-4/0 expanded silver support (Exmet Corp.) to which silver tabs have been welded to serve as the electrode current collectors. The finished electrodes are 2.25 x 1.75 in. and 5.50 x 3.50 in. in size for the 3 Ah and 20 Ah size cells, respectively. The electrode thickness varies from 0.014 to 0.016 in. and the average $Cd(OH)_2$ + Cd loading was 0.89 g/in.^{2}. Electrical formation steps associated with the manufacturing process were employed to screen the electrode capacities to assure that electrodes of closely balanced capacities were assembled into cells. In addition to these steps, all electrodes were subjected to careful visual examination to eliminate those with physical defects.

The total number of electrodes prepared was 1,892. After examination for physical defects this number was reduced to 1,742. Further elimination was accomplished using weight gains and formation capacities together as criteria for selection of cell components. The final number of electrodes judged suitable for cell construction was determined to be 1,452. Figure 1 shows a frequency distribution based on electrode weight gains (g/in.^{2}), while Figure 2 gives a frequency distribution based on electrode capacity (Ah/in.^{2}). These distributions were based on the 1,452 electrodes judged suitable for cell construction.



*Range = Given Value ± 0.031 g/in.^{2}

Figure 1. Loading Distribution For Selected Cadmium Electrodes (Sample Size Is 1452; Required Number For Cell Build Was 1400)



*Range = Given Value ± 0.00635

Figure 2. Capacity Distribution For Selected Cadmium Electrodes (Sample Size Is 1452; Required Number For Cell Build Was 1400)

2. Nickel Electrode

Nickel electrodes were identical to those described previously with the exception of thickness.[1,2] Inco type 287 nickel powder was first dired in a vacuum oven for one hour at 210°C. After removal from the oven, the powder was allowed to cool in a dry room (RH $<$ 5%). The powder was then placed in a set of standard sieves and processed on a Ro-Tap shaker for 15 minutes. The fraction of the powder less than 37μ (1.04 g/cc on the Scott Densiometer) was stored in the dry room until needed for fabrication.

Nickel plaques were then prepared from the above mentioned powder. These plaques were prepared by sprinkling the nickel powder into a 6 x 12 in. mold containing a previously annealed 20 x 20 mesh, 7-mil wire, woven nickel screen. The excess powder was then struck off and removed from the mold prior to sintering. Sintering was performed in a vacuum furnace at a pressure of less than 100 microns of mercury. Sintering time was 30 minutes at a temperature of 1675°F.

Plaques, thusly prepared, were first marked to the appropriate sizes for the electrodes used in the 20 Ah and 3 Ah size cells. Then these electrodes were coined and current collectors were welded on at the appropriate locations. The thickness of these plaques prior to impregnation was 62.6 mils with a standard deviation of 0.8 mils. Total sample size was 480 plaques.

These plaques were then impregnated with active mass using one of Gould's private processes. The final loading was 1.915 ± 0.062 g/cc based on weight gain after formation. After final weighing and calculating the weight gain, the plaques were cut into individual electrodes and screened using weight gain, thickness, and physical inspection as criteria.

The electrodes prepared in this way were shown to be extremely uniform.[1,2] For the purpose of the present work it was deemed sufficient to screen only the electrode weights and thicknesses to assure the desired level of uniformity. Formed electrodes were also carefully inspected for physical defects such as blisters, pitting, and cracking. Selected samples were used for nitrate analysis with the results giving an average NO_3^- content after formation of 0.147 ± 0.036 percent by weight.

C. Cell Assembly and Preparation

1. Component Testing

Prior to cell assembly, a sufficient quantity of each size (20 Ah and 3 Ah) cell cans were subjected to leak testing using a Veeco Model MS17 helium leak detector. All cans selected for the cell build showed an actual leak rate no exceeding 1×10^{-8} standard cc/sec He. The criteria for selection was a leak rate not to exceed 1×10^{-8} standard cc/sec He.

All exterior cell hardware (gauges, safety device, and connectors) were assembled and tested on the Veeco leak detector. Again, the criteria for acceptance was set at 1×10^{-8} standard cc/sec He, as the maximum tolerable leak rate.

2. Cell Assembly

Each cell was constructed using the total number of components given in Table 1. The electrodes were selected to be as closely matched as possible. The electrode bundles were constructed using 18 mil pellon separator between each electrode and a final wrap of the same separator around the entire pack both vertically and horizontally. In addition, 36 mils (two layers) of separator were placed along each edge (both sides and the bottom) of the cell pack to provide extra insulation from the metal cell can. Terminal connections were made via spot welding of the tab bundle to the terminal post of the cover assembly and then the cases were welded in place. All cells were then subjected to 100% leak testing again and those that failed to pass the minimum requirement of 1×10^{-8} standard cc/sec of He were rewelded and subjected to a second 100% testing. After final leak testing, these cells were maintained in the dry state until they were prepared for their "conditioning" cycles.

3. Cell Preparation

After passing the final leak test during the assembly portion of the program, each cell was filled (flooded) with $30 \pm 0.1\%$ KOH and subjected to two preparatory cycles. These cycles consisted of charging the cells in the vented state at the C/12.5 rate for 16 hours and discharging them at the C/8 rate to 0.0V. By conditioning the cells in this manner a discharge reserve is placed on the nickel electrode. This amounts to approximately 8 Ah for the 20 Ah size cell and 0.7 Ah for the 3 Ah size cell. Also, the first charge allows the cell to expel any excess electrolyte that may be displaced by any changes in electrode and/or separator mass. The capacities measured during the second discharge of this conditioning routine are recorded and referred to as "formation" capacities. Data relating to the performance of the 100, 20 Ah size cells were:

• Average "Formation" Capacity	22.10 Ah
• Standard Deviation	2.06 Ah
• Mean Deviation from the Mean	1.59 Ah
• Sample Variance	4.26 Ah^2
• Sample Size	1.00×10^2
• Bowley Skewness	1.85×10^{-2}

Data relating to the performance of the 100, 3 Ah size cells were:

• Average "Formation" Capacity	3.36 Ah
• Standard Deviation	0.28 Ah
• Mean Deviation from the Mean	0.22 Ah
• Sample Variance	7.63×10^{-2} Ah^2
• Sample Size	1.00×10^{2}
• Bowley Skewness	2.59×10^{-1}

After the cells completed these conditioning cycles they were sealed and held until they could be given their preliminary testing. All cycling was performed at 25 ± 0.5°C. See Tables 2 and 3 for results on individual cells from the "formation" cycling.

D. Test Program

All 200 cells were subjected to testing as stated in item 1 below. After these tests, 52 of each size were shipped to Jet Propulsion Laboratory and the remaining 48 of each were tested at Gould. Of the remaining 96 cells (48 of each), 40 of these (20 of each size) were subjected to testing as stated in items 2 and 3. Forty additional cells of this 96 were subjected to testing as stated in item 4, eight of the 20 Ah size tested as stated in item 5.

1. Capacity Matching

All cells fabricated were cycled 30 times to 25% depth-of-discharge. All charges were constant current and were terminated when a 1.750V cell voltage was reached. All charges in this work were performed in this way unless otherwise specified. These initial tests were performed at the 1C rates. At these rates and the 25% DOD this regime enabled the logging of 48 cycles per day; *i.e.*, 15 minute charge at 1C rate and 15 minute discharge at 1C rate – 30 minute total turnaround per cycle. After the 30th discharge the cells were charged at C/12.5 and discharged to 0.0V at C/8, for the following three cycles. The capacities were measured on all three of these cycles. The mean capacity of the 33rd discharge was determined and 52 cells from each group closest to the median were delivered to Jet Propulsion Laboratory. The remaining 96 cells remained at Gould for further testing. Also, the cell internal pressure was monitored three times daily during these initial 33 cycles. All tests were performed at 25°C.

TABLE 2. "Formation Capacity" & Preliminary Test
Capacity For 20 Ah Size Cells

Cell Numbers	Capacity on 33rd Discharge, Ah	"Formation Capacity," Ah
97-001	20.12	22.74
97-002	22.36	22.74
97-003	22.09	22.21
97-004	18.97	23.14
97-005	19.69	22.34
97-006	22.55	22.64
97-007	22.12	22.71
97-008	20.96	22.90
97-009	22.19	22.68
97-010	14.92	23.38
97-011	21.06	22.63
97-012	21.03	21.47
97-013	20.99	21.36
97-014	21.34	22.69
97-015	20.96	21.29
97-016	19.22	16.95
97-017	20.94	22.04
97-018	18.99	22.03
97-019	20.68	21.71
97-020	20.03	21.41
97-021	18.55	21.72
97-022	20.79	25.42
97-023	20.19	24.98
97-024	20.69	25.23
97-025	20.69	25.47
97-026	20.63	25.50
97-027	21.56	24.87
97-028	19.73	25.58
97-029	21.66	25.59
97-030	20.53	25.07
97-031	17.09	19.00
97-032	16.51	19.54
97-033	17.99	19.08
97-034	19.29	19.21
97-035	19.08	19.75
97-036	17.36	19.48
97-037	17.98	19.55
97-038	16.84	19.56

TABLE 2. (Cont'd)

Cell Numbers	Capacity on 33rd Discharge, Ah	"Formation Capacity," Ah
97-039	16.21	19.57
97-040	18.58	18.97
97-041†	22.10	25.43
97-042†	21.88	26.90
97-043	23.21	25.43
97-044	25.75	25.33
97-045†	19.59	25.33
97-046†	19.04	24.45
97-047	18.73	26.13
97-048	18.15	21.59
97-049†	20.00	26.34
97-050†	21.14	25.28
97-051†	19.31	19.80
97-052†	19.11	21.70
97-053†	21.91	24.91
97-054†	20.15	21.68
97-055†	22.16	22.56
97-056†	22.17	22.68
97-057	22.38	23.01
97-058†	21.09	22.16
97-059†	22.12	22.14
97-060	26.23	23.06
97-061	22.78	21.11
97-062†	19.52	20.37
97-063†	20.87	21.99
97-064	20.78	23.01
97-065*	26.47	24.16
97-066	22.27	21.17
97-067*	27.10	22.26
97-068	25.47	23.02
97-069*	14.19	20.05
97-070	15.96	20.97
97-071	16.43	20.88
97-072	15.43	20.71
97-073	17.27	20.74
97-074	16.74	21.24
97-075	16.74	20.92

TABLE 2. (Cont'd)

Cell Numbers	Capacity on 33rd Discharge, Ah	"Formation Capacity," Ah
97-076*	14.24	19.83
97-077	17.14	21.57
97-078/	19.61	21.68
97-079	18.56	19.52
97-080/	19.38	20.21
97-081/	19.88	21.93
97-082/	19.89	21.11
97-083/	19.62	21.03
97-084/	20.27	21.19
97-085	17.92	20.12
97-086/	20.17	21.68
97-087	17.14	20.56
97-088	18.75	22.07
97-089	16.53	21.97
97-090	18.56	21.74
97-091	17.14	21.35
97-092	17.09	22.13
97-093	16.17	21.92
97-094	16.03	21.39
97-095	18.47	21.14
97-096	23.49	20.82
97-097/	21.83	22.80
97-098	24.35	23.56
97-099/	21.41	20.67
97-100	18.18	17.43
97-101	22.33	23.54
97-102	23.77	23.16
97-103	23.83	22.71
97-104	17.68	17.51

/Selected for initial delivery to Jet Propulsion Laboratory

*Discarded values for statistical calculations

TABLE 3. "Formation Capacity" & Preliminary Test Capacity For 3 Ah Size Cells

Cell Number	Capacity on 33rd Discharge, Ah	"Formation Capacity", Ah
97-201	3.45	3.39
97-202*	3.25	3.43
97-203*	3.15	3.42
97-204	3.29	3.27
97-205*	3.12	3.42
97-206*	2.90	3.40
97-207*	3.09	3.68
97-208	3.14	3.39
97-209	2.10	3.43
97-210	2.35	3.46
97-211	2.26	3.45
97-212	2.35	3.64
97-213*	2.45	3.51
97-214	2.23	3.45
97-215*	2.49	3.54
97-216	2.28	3.48
97-217	2.37	3.52
97-218	2.26	3.41
97-219	2.25	3.46
97-220*	2.58	3.44
97-221*	2.65	3.07
97-222*	2.97	3.49
97-223*	2.91	3.66
97-224*	2.73	3.55
97-225	2.39	3.64
97-226	2.31	3.34
97-227*	2.51	3.59
97-228*	3.12	3.47
97-229*	3.01	3.43
97-230*	2.64	3.16
97-231*	3.15	3.66
97-232	2.26	3.51
97-233	2.19	3.51
97-234	1.93	3.53
97-235	2.00	3.55
97-236	2.00	3.55
97-237	2.05	3.56

TABLE 3. (Cont'd)

Cell Number	Capacity on 33rd Discharge, Ah	"Formation Capacity", Ah
97-238*	3.14	3.50
97-239	2.21	3.61
97-240	1.98	3.49
97-241	2.06	3.37
97-242	No Cell	
97-243	No Cell	
97-244	No Cell	
97-245	No Cell	
97-246	1.89	3.39
97-247	1.99	3.36
97-248	No Cell	
97-249	2.04	3.22
97-250	2.23	3.26
97-251*	2.72	3.19
97-252	1.95	3.22
97-253	2.23	3.28
97-254	2.07	3.25
97-255	No Cell	
97-256	No Cell	
97-257	No Cell	
97-258*	3.11	3.00
97-259*	3.13	2.87
97-260*	2.60	2.97
97-261	2.82	2.80
97-262*	3.03	3.14
97-263*	2.92	3.00
97-264*	2.90	3.05
97-265*	2.66	2.85
97-266*	2.92	3.07
97-267	2.29	3.85
97-268*	2.85	3.68
97-269*	3.09	3.91
97-270*	3.19	3.87
97-271	3.32	3.87
97-272*	3.23	3.81
97-273*	2.98	3.85
97-274*	2.95	3.82
97-275	3.37	3.88

TABLE 3. (Cont'd)

Cell Number	Capacity on 33rd Discharge, Ah	"Formation Capacity", Ah
97-276	No Cell	
97-277*	2.49	3.17
97-278*	2.85	3.00
97-279	2.34	2.81
97-280	2.28	2.67
97-281	2.31	2.77
97-282*	2.61	3.27
97-283*	2.57	3.28
97-284*	2.89	3.41
97-285*	2.55	3.15
97-286*	2.67	3.26
97-287*	3.24	3.36
97-288*	2.66	3.05
97-289*	2.79	3.17
97-290	2.88	3.46
97-291*	3.21	3.61
97-292*	2.71	3.53
97-293	3.44	3.81
97-294	No Cell	
97-295	1.95	3.11
97-296	1.89	3.31
97-297	2.04	3.02
97-298	2.06	3.43
97-299	2.03	3.29
97-300	2.01	3.21
97-301	2.05	3.41
97-302	1.83	3.19
97-303*	2.67	3.00
97-304*	3.19	3.52
97-305*	3.21	3.09
97-306	2.39	2.90
97-307	3.29	3.20
97-308*	3.21	3.15
97-309*	3.12	3.31
97-310*	3.22	3.42

*Selected for initial delivery to Jet Propulsion Laboratory

2. Charge-Discharge Characterization

Forty cells, of the remaining 96 cells, consisting of four groups of 10 cells each (20 cells of the 20 Ah size and 20 cells of the 3 Ah size) were tested at 0° and 25°C. The first 15 cycles (cycles 34-49) at these temperatures were to 100% depth-of-discharge using various charge and discharge rate pairs to aid in the evaluation of rate performance. The tests performed are given in Table 4. The testing of groups larger than 10 cells each was not necessary from a statistical point of view. Cell capacities were measured on each of the above cycles and curves were developed for each temperature.

TABLE 4. Rate Characterization & Life Test Regime

Cycle No.	Charge Rate	Discharge Rate	Depth-of-Discharge, %
34	C/10	C/10	100
35	C/10	C/2	100
36	C/10	C	100
37	C/10	5C	100
38	C/2	C/10	100
39	C/2	C/2	100
40	C/2	C	100
41	C/2	5C	100
42	C	C/10	100
43	C	C/2	100
44	C	C	100
45	C	5C	100
46	5C	C/10	100
47	5C	C/2	100
48	5C	C	100
49	5C	5C	100
50-99	C	C	25
100	C/10	C/10	100
101-199	C	C	25
200	C/10	C/10	100
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.		.	.
901-999	C	C	25
1000	C/10	C/10	100

3. Life Tests

All of the 40 cells mentioned above (para. 2), were subjected to life tests using the regime set forth for cycles 50 to 1000 in Table 4. The tests consisted of four groups of 10 cells each (20 cells each of the 20 Ah and 3 Ah sizes) which were tested at 0° and 25°C (one group for each size at each temperature). Cell charge and discharge voltages and cell pressures were measured on all capacity measurement cycles. Additional internal cell pressure measurements were made on a daily basis. Criteria for failure during this cycling was either a capacity measurement less than 40% of rated and/or a pressure reading in excess of 44 psig.

4. Stand (Open Circuit) Test

It was not known what effects repeated stands and/or storage would have on this type of cell design. Therefore, we tested 10 cells from each size (20 Ah and 3 Ah) at 25° and 50°C to determine the effect of open-circuit stand in the charged state. The cells were allowed to stand on open circuit at their respective temperatures for two months. Five cells from each group at each temperature were discharge checked after one month and the remaining five cells of each group were discharge checked at the end of two months. This approach gave three points of reference in respect to self-discharge at these two temperature points. The cell voltages and pressures were measured throughout the test.

5. Higher Cutoff for Charge Voltage

In order to offset fade (loss of capacity) experiences in earlier work[1,2], it was deemed worthwhile to explore the possibility of raising cutoff voltage. Accordingly, we cycle-tested 8, 20 Ah size cells using a 1.85 volt cell charge cutoff as opposed to the 1.75 volt cutoff. The cycling was conducted at the C charge and discharge rates with a 25% depth-of-discharge. Capacity checks were made every 100 cycles and the cell pressures were monitored three times daily. This test was conducted at 25°C.

III. RESULTS AND DISCUSSION

A. Preliminary Testing to Select Initial Delivery Cells

Preliminary testing to select the initial delivery cells was conducted at 25°C and the cycle regime consisted of 33 cycles. The first 30 cycles were at the 1C charge and discharge rates. The depth-of-discharge was 25% of the rated capacity. The final three cycles were to 100% depth-of-discharge and were conducted at the C/12.5 charge rate and the C/8 discharge rate. All charges were terminated at a cell potential of 1.750 volts. Capacity measurements made during the last three cycles, along with pressure data, were used to match and select the initial delivery items.

1. Preliminary Tests – 20 Ah Size Cells

One-hundred and four of the 20 Ah size cells were subjected to the preliminary cycling and completed the necessary cycles without a cell failure. The internal cell pressure was monitored at least three times daily and the mean operating pressure was determined to be 10.74 psig with a standard error of the mean of 0.273 psig. The sample size was 622.

During these initial cycles, it was observed that the cell pressure rose to its maximum during the first four to eight cycles and then maintained a stable reading for the remainder of the 30 cycles. During the three capacity test cycles, a slight decrease in pressure was noted for all cells. On open circuit stand after testing, the above-mentioned pressures fell to zero and then into a vacuum; maximum time to obtain a vacuum was approximately 120 hours.

Evaluation of the performance data on these cells (33rd discharge capacity measurement) produced the following results:

• Mean Capacity	19.95 Ah
• Standard Deviation	2.35 Ah
• Mean Deviation from the Mean	1.89 Ah
• Sample Variance	5.55 Ah^2
• Sample Size	1.00×10^2
• Bowley Skewness	4.21×10^{-2}

The results (capacities) for individual cells, along with the "formation" capacity data are given in Table 2.

Based on the above generated.statistics, 52 cells with capacities closest to the sample median were selected and shipped to Jet Propulsion Laboratory. The average capacity of the 52 cells selected for delivery was 20.64 Ah and the standard error of the mean for this group was 0.135 Ah. The average operating pressure of this group of cells was 10.8 psig. The mean operating pressure was measured over the first 33 cycles of operation.

2. Preliminary Tests – 3 Ah Size Cell

One-hundred of the 3 Ah size cells were subjected to the preliminary cycling and completed the required cycles with no cell failures. The internal cell pressure was monitored three times daily without regard to cell status (on charge or on discharge). The mean operating pressure for these cells over the first 33 cycles was 7.27 psig with a standard error of the mean of 0.243 psig.

During these initial cycles, it was noted, as with the 20 Ah size cells, that the cell internal pressure rose to its maximum during the first four to eight cycles and then maintained a relatively stable reading for the remainder of the 30 cycles. During the three capacity test cycles (cycles 31 to 33), a slight decrease in pressure was noted for all cells tested. Also, as with the 20 Ah size cells, it was observed that on open circuit stand the cell internal pressure fell to a negative value in less than 120 hours.

Evaluation of the performance data on these cells (33rd discharge capacity measurement) produced the following statistical values:

• Mean Capacity	2.64 Ah
• Standard Deviation	4.74×10^{-1} Ah
• Mean Deviation from the Mean	4.13×10^{-1} Ah
• Sample Variance	2.25×10^{-1} Ah^2
• Sample Size	1.00×10^{2}
• Bowley Skewness	5.75×10^{-2}

The results of testing (capacities) for individual cells, along with the respective "formation" capacity data are given in Table 3.

Based on the above statistics, 52 of the 3 Ah size cells with capacities closest to the sample median were selected and shipped to the Jet Propulsion Laboratory. The average capacity of the 52 cells selected for delivery was 2.900 Ah and the standard error of this mean was 0.034 Ah. The average operating pressure of this group of cells over the first 33 cycles was 7.29 psig with a standard error for the mean of 0.891 psig.

B. Charge and Discharge Rate Characterization

Evaluation of cell capacity performance utilizing different pairs of charge and discharge rates was carried out on four groups of 10 cells each (one group for each size at 0°C and one group of each size cell at 25°C). The rate pairs (charge and discharge) are given in Table 4 for cycles 34 through 49. To aid in evaluation of the data collected, a "base" capacity was defined as that capacity delivered by a group of cells charged at their respective temperatures at the C/10 rate and discharged at their respective temperatures at the C/10 rate.

1. Evaluation of Performance of 20 Ah Size Cells

Two groups of 10 cells each (one group at 0°C and one at 25°C) were tested using the rate pairs for charge and discharge given in Table 4 for cycles 34 to 49. The capacity measured for cycle 34 at each temperature was used as the "base" capacity and assigned a value of 100% output. Capacities measured on the remaining 14 cycles were then expressed as a percent of this "base" value and a family of curves was plotted for each temperature. Figure 3 is the plot for results measured at 0°C and Figure 4 gives the results measured at 25°C. These figures show the change in percentage output for each of four different charge rates as the discharge rate is increased. As can also be seen in these figures, the percentage output varies (decreases) as the charge rate increases and the discharge rate is held constant. Another item of interest seen from these figures is that at both 0° and 25°C when the 5C charge rate was coupled with the 5C discharge rate there is noted to be an increase in performance. It is speculated that this phenomena may be attributed either to internal temperatures and/or changes in active material structure both of which are dependent on rates.

2. Evaluation of Performance of 3 Ah Size Cells

Two groups of 10 cells each (one group at 0°C and one group at 25°C) were tested using the charge and discharge rate pairs listed in Table 4 for cycles 34 to 49. The average capacity measured for cycle 34 at each temperature was used as the "base" capacity for each group and assigned a value of 100% output. Average capacities measured on the remaining 14 cycles were then expressed as a percentage of this "base" value and a family of curves was plotted for each test temperature. Figure 5 is the plot of results measured at 0°C and Figure 6 represents the test results measured at 25°C. As in the results for the 20 Ah size cells, we again see the change in cell output for a given charge rate as the discharge rate is varied. Also, it is evident that a systematic decrease in output is experienced as the charge rate is varied and the discharge held constant. Again, we experience the same change in performance at both temperatures when the 5C charge and 5C discharge are coupled together as was noted during testing of the 20 Ah size cells.

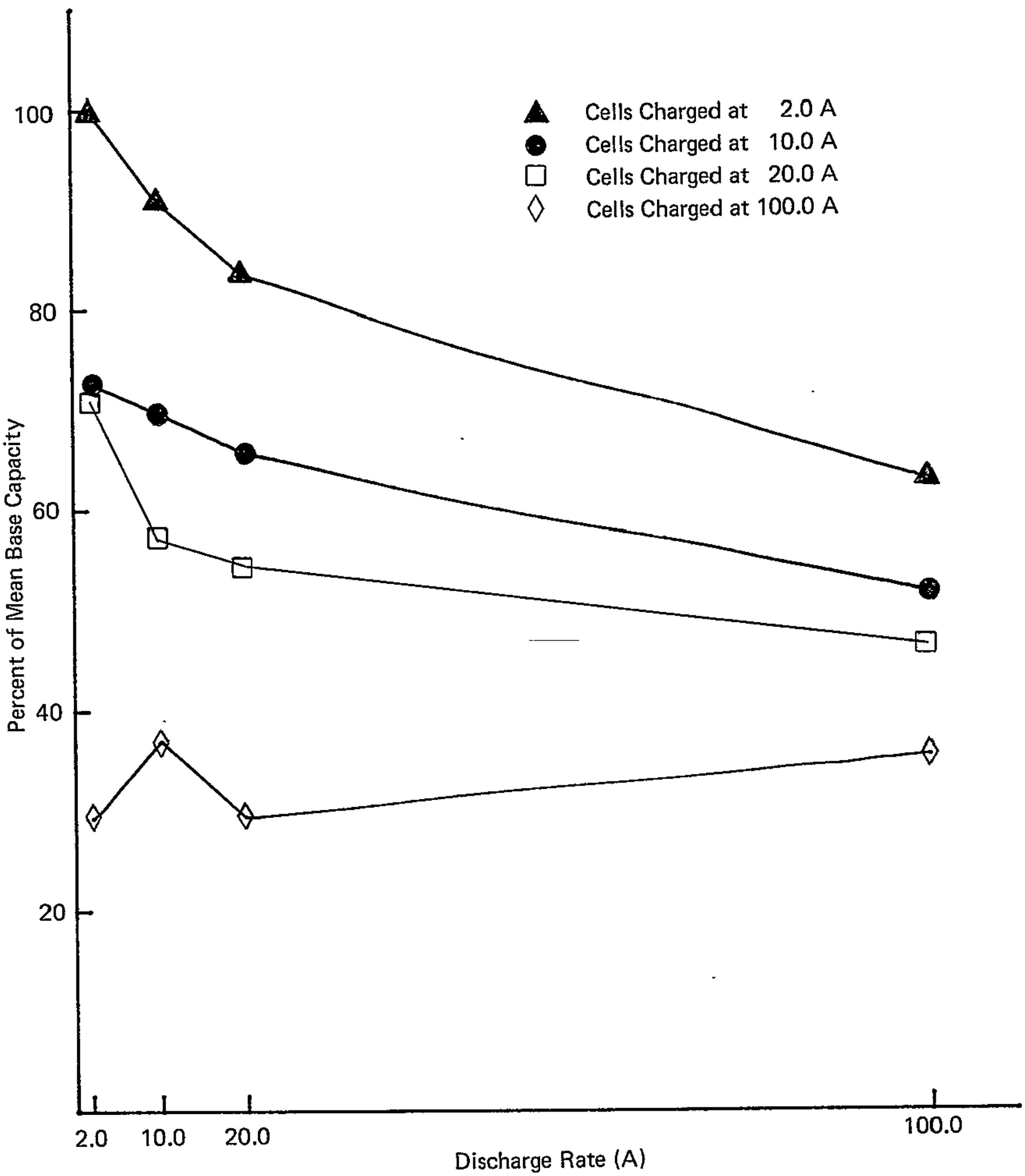


FIGURE 3. Charge and Discharge Rate Characterization For 20 Ah Size Cells Tested at 0°C

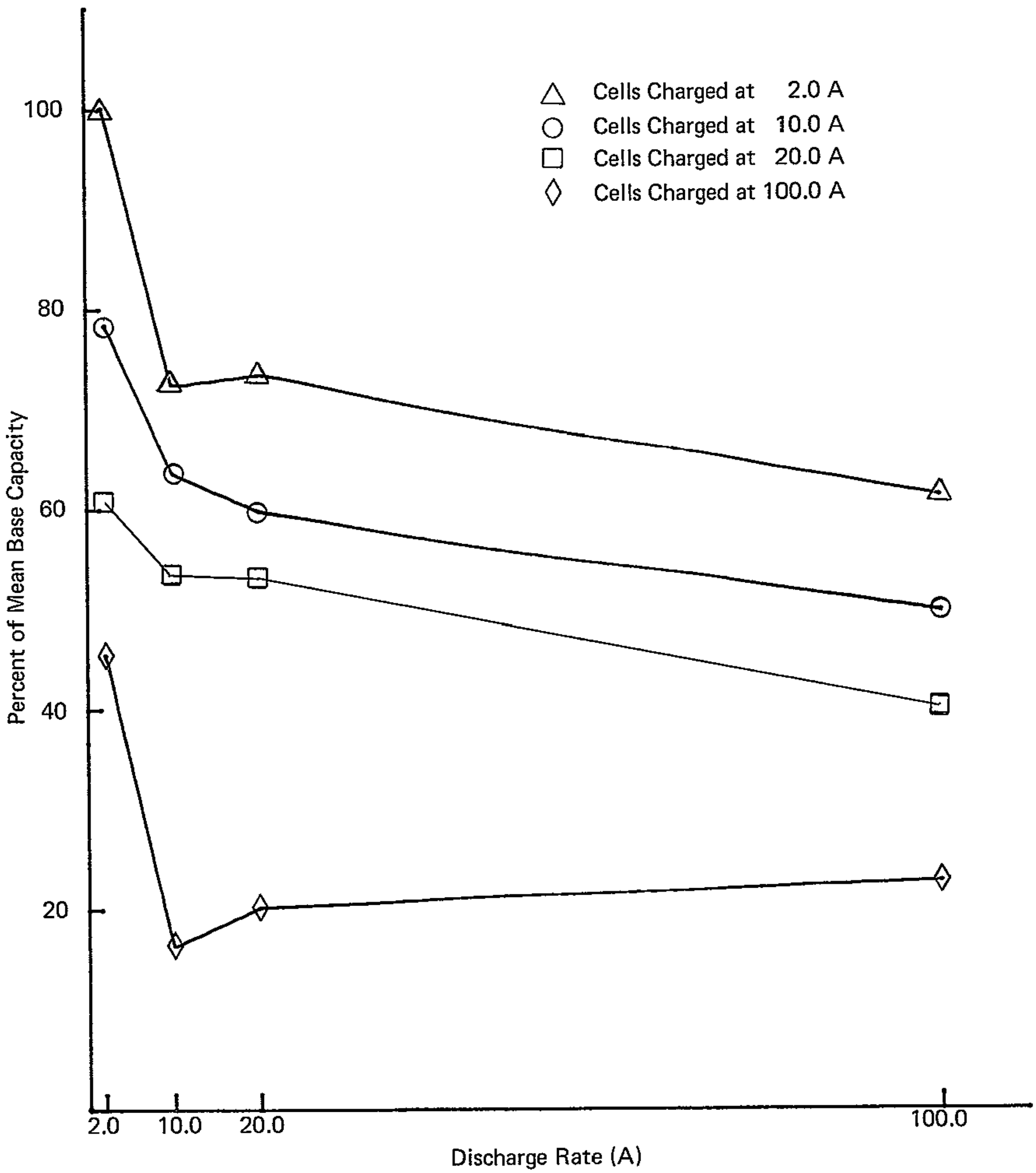


FIGURE 4. Charge and Discharge Rate Characterization For 20 Ah Size Cells Tested at 25°C

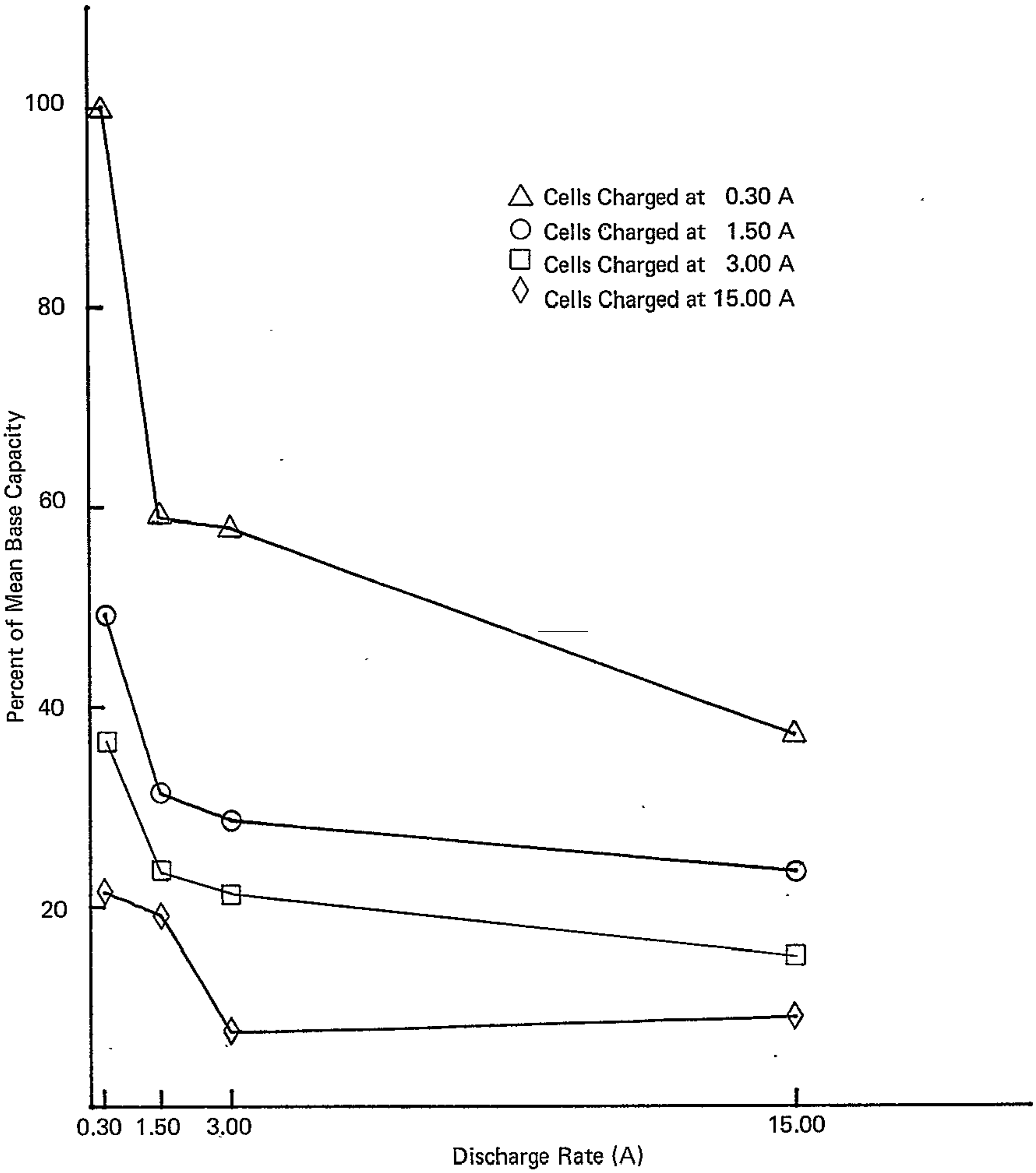


FIGURE 5. Charge and Discharge Rate Characterization For 3 Ah Size Cells Tested at 0°C

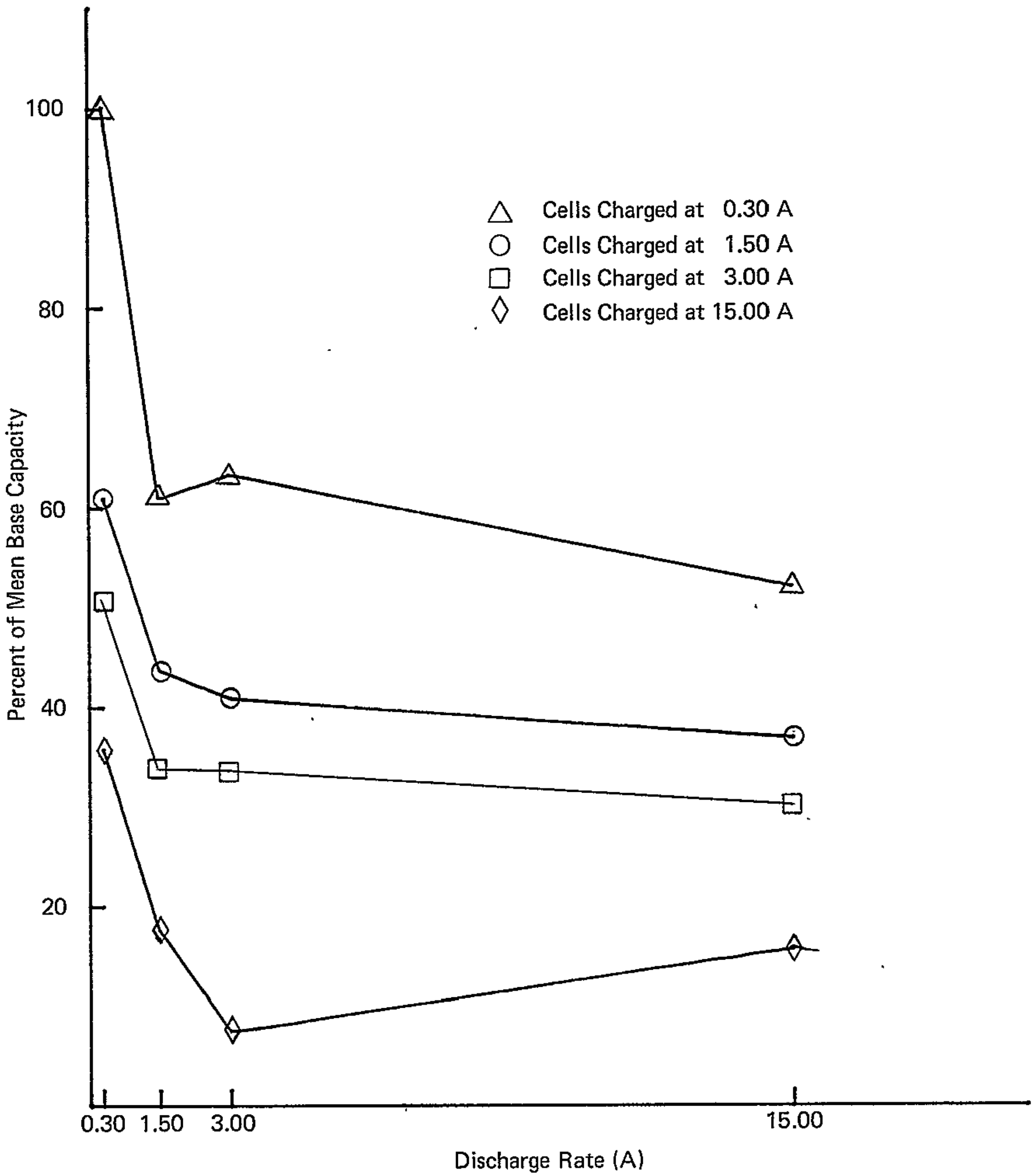


FIGURE 6. Charge and Discharge Rate Characterization For 3 Ah Size Cells Tested at 25°C

C. 1000 Cycle Performance Testing

The 40 cells (20 of each size) used in the rate performance testing were cycled an additional 951 cycles (total number of cycles equal to 1000) at their respective test temperatures. Cell cycling was carried out as per Table 4, cycles 50 through 1000. The charge rates were 1C for auto cycling and C/10 for capacity check cycles. The charge cutoff potential was 1.750 volts. The discharge rates were 1C for 15 minutes during auto cycling and C/10 to 0.0 volt for capacity checks. Capacity measurements were performed every 100 cycles and cell internal pressures were read three times daily during normal working days.

1. 20 Ah Size Cells – Cycle Performance at 0°C

The average cell capacities and the standard error of the mean are given in Table 5 for the 10, 20 Ah cells tested at 0°C. Figure 7 shows these results plotted as test points and the standard error of the mean is shown as error bars.

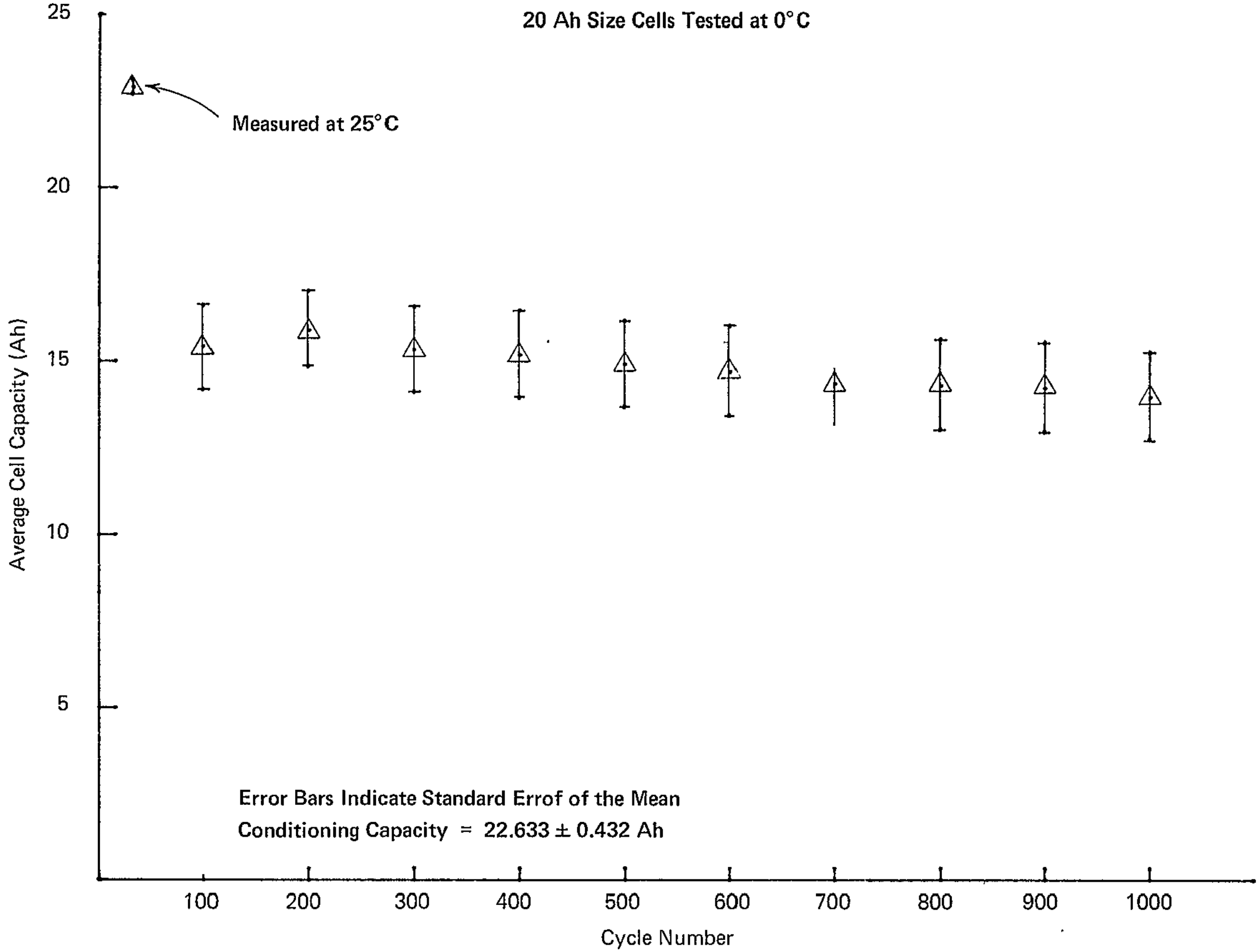
TABLE 5. Average Cell Capacity for 20 Ah Size Cells Tested at 0°C

Cycle No.	Mean Capacity, Ah	Standard Error Of The Mean
33	22.897	0.197
100	15.359	1.234
200	15.898	1.107
300	15.314	1.237
400	15.177	1.268
500	14.900	1.252
600	14.704	1.314
700	14.371	1.328
800	14.309	1.315
900	14.237	1.294
1000	13.981	1.273

These capacities were determined with a 2.0 amp charge to 1.750 volts and a 2.0 amp discharge to 0.0 volt. After 1000 accelerated cycles, this group of cells had an average capacity of 13.891 ± 1.273 Ah, the larger part of the capacity degradation occurring within the first 100 cycles. It was further noted that after the first 100 cycles the nickel electrode, which initially had discharge reserve capacity built in, was the limiting electrode during cell discharge.

Throughout all of these tests the cells exhibited a sharp voltage rise at the end of each charge period. Typical charge voltage profiles were similar to those given previously.[2]

FIGURE 7. Variation of Mean Cell Capacity With Cycle Number
20 Ah Size Cells Tested at 0°C



The average cell pressure, again of the 10 cells, is shown in Figure 8. The error bars indicate the standard error of the mean for the given average. The initial negative internal pressure was due to oxygen recombination in the cell during stand on open circuit. The oxygen was introduced to the system during the cell construction and conditioning which were performed while the cells were in the vented condition. The cell pressure increased gradually to the 7 psig range over the first 100 cycles where it tended to remain for the balance of the 1000 test cycles. It should be noted, that although the 7 psig operating pressure of this system exceeds the optimum goal of zero that this is still a very small value for operation of a sealed nickel-cadmium cell which is flooded with electrolyte.

A slight periodic variation in the internal cell pressure was noted. This variation was related to the capacity check cycles and was attributed to the longer period of time between charges allowing for greater oxygen recombination within the system. Appendix II will list the mean operating pressures and corresponding standard error that were recorded during the above cycling.

This group of cells completed the test program without a cell failure due to either low capacity or high pressure.

2. 20 Ah Size – Cycle Performance at 25°C

The mean cell capacities and the associated standard error of the mean are given in Table 6 for the 10, 20 Ah size cells tested at 25°C. Figure 9 shows these results plotted as capacity vs cycle number with the standard error given as error bars.

TABLE 6. Average Cell Capacity for 20 Ah Size Cells Tested at 25°C

Cycle No.	Mean Capacity, Ah	Standard Error Of The Mean
33	18.634	0.076
100	17.911	1.134
200	13.384	0.728
300	12.163	0.764
400	11.228	0.684
500	11.753	0.923
600	10.410	0.604
700	11.242	0.847
800	10.710	0.788
900	10.635	0.829
1000	10.448	0.844

FIGURE 8. Average Cell Pressure as a Function of Cycle Number
20 Ah Size Cells Tested at 0°C

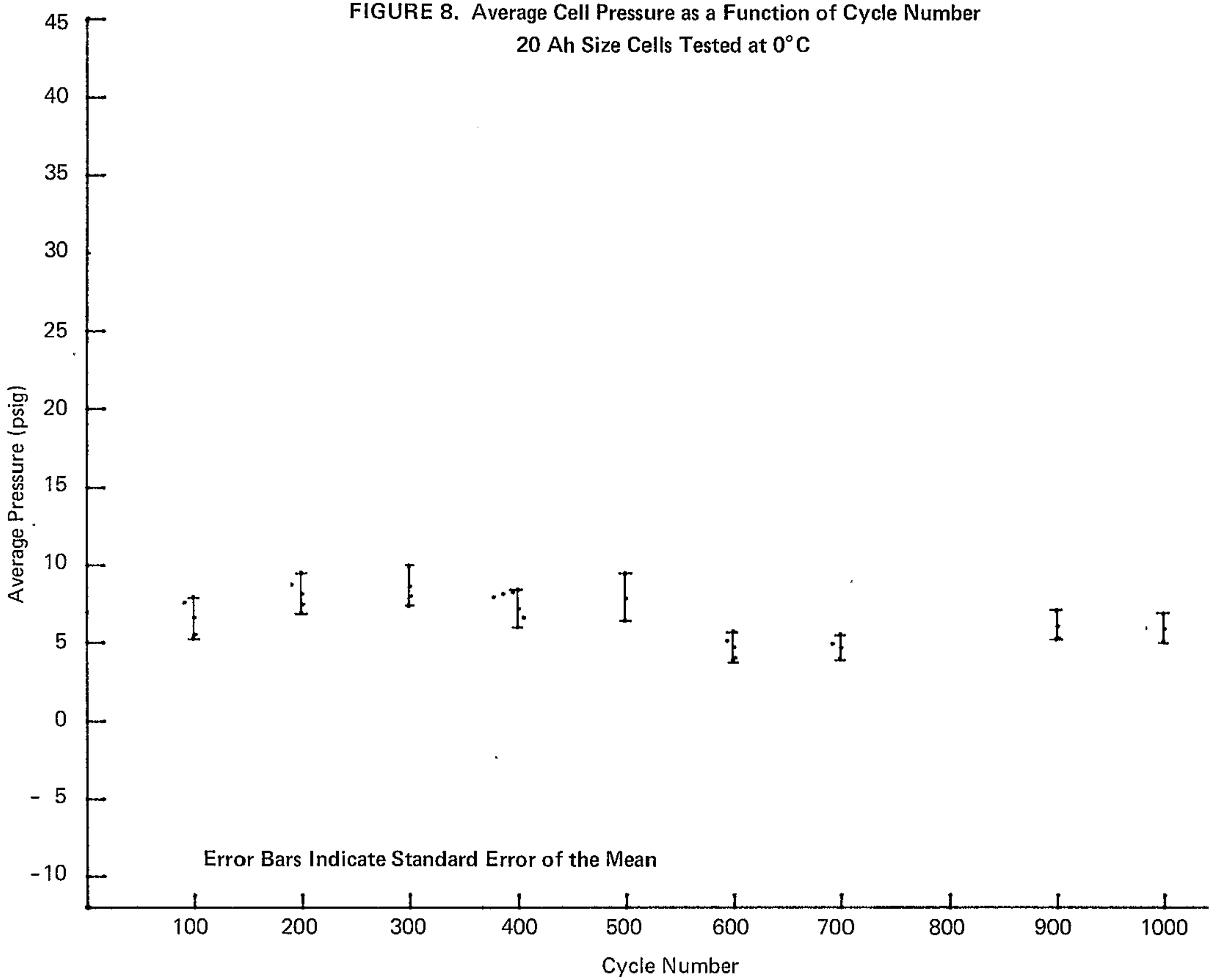
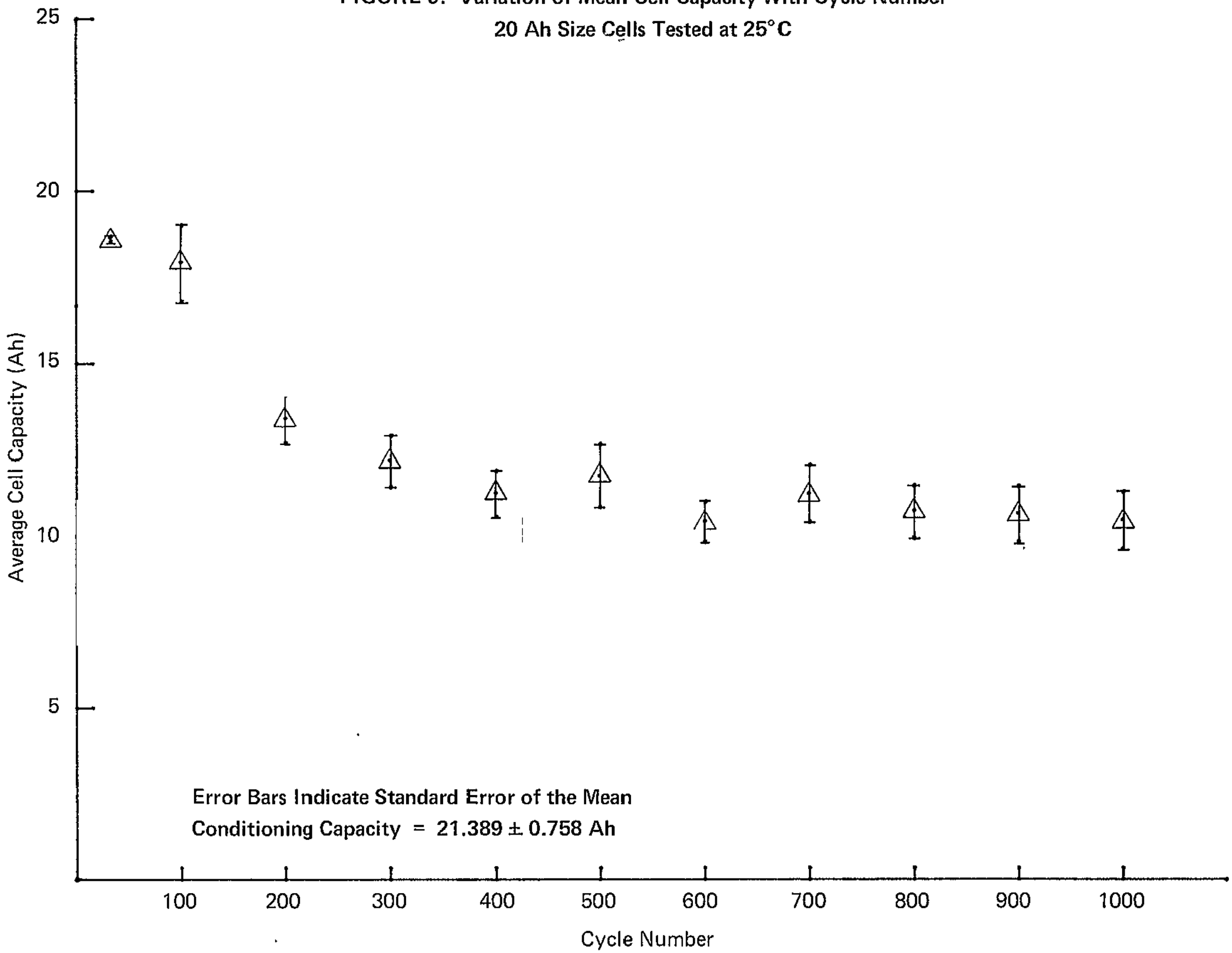


FIGURE 9. Variation of Mean Cell Capacity With Cycle Number
20 Ah Size Cells Tested at 25°C



These capacities were determined with a 2.0 amp charge to 1.750 volts and a 2.0 amp discharge to 0.0 volt. After 1000 cycles of accelerated testing, this group of cells had an average capacity of 10.448 ± 0.844 Ah, the larger part of the capacity loss occurring within the first 200 cycles. It was further noted that after the first 100 cycles the nickel electrode of some of the cells, which initially had a discharge reserve capacity in them, were the limiting electrodes during cell discharge and after the first 200 cycles the nickel electrodes were the limiting factor for all 10 cells being tested.

The average cell pressure, again of the 10 cells, is shown as a function of cycle number in Figure 10. The error bars indicate the standard error of the mean for the given value. Unlike the group of cells tested at 0°C, the initial cell pressure was in most cases several psig higher and positive in sign. Also, more variation in the experimental points is evident and a more rapid and higher plane of operating pressure was noted. Again it must be remembered that the results presented here are for a sealed and flooded cell.

As with the cells tested at 0°C, a slight periodic variation in the internal pressure of the cells was noted. Again, this variation appears related to the change in rates at the capacity check cycles. Appendix III will list the mean pressure and standard errors recorded during this test.

Of the 10 cells tested, six completed the 1000 cycles. One cell shorted and three cells were removed due to low capacities (less than 40% of rated). No cells were removed due to excessive pressure. Voltage profiles during charge were as given previously.[2]

3. 3 Ah Size Cells – Cycle Performance at 0°C

The average cell capacities along with their associated standard error of the mean are given in Table 7 for the 10,3 Ah size cells tested at 0°C. Figure 11 shows these values plotted vs cycle number along with the standard error of the mean as the error bars.

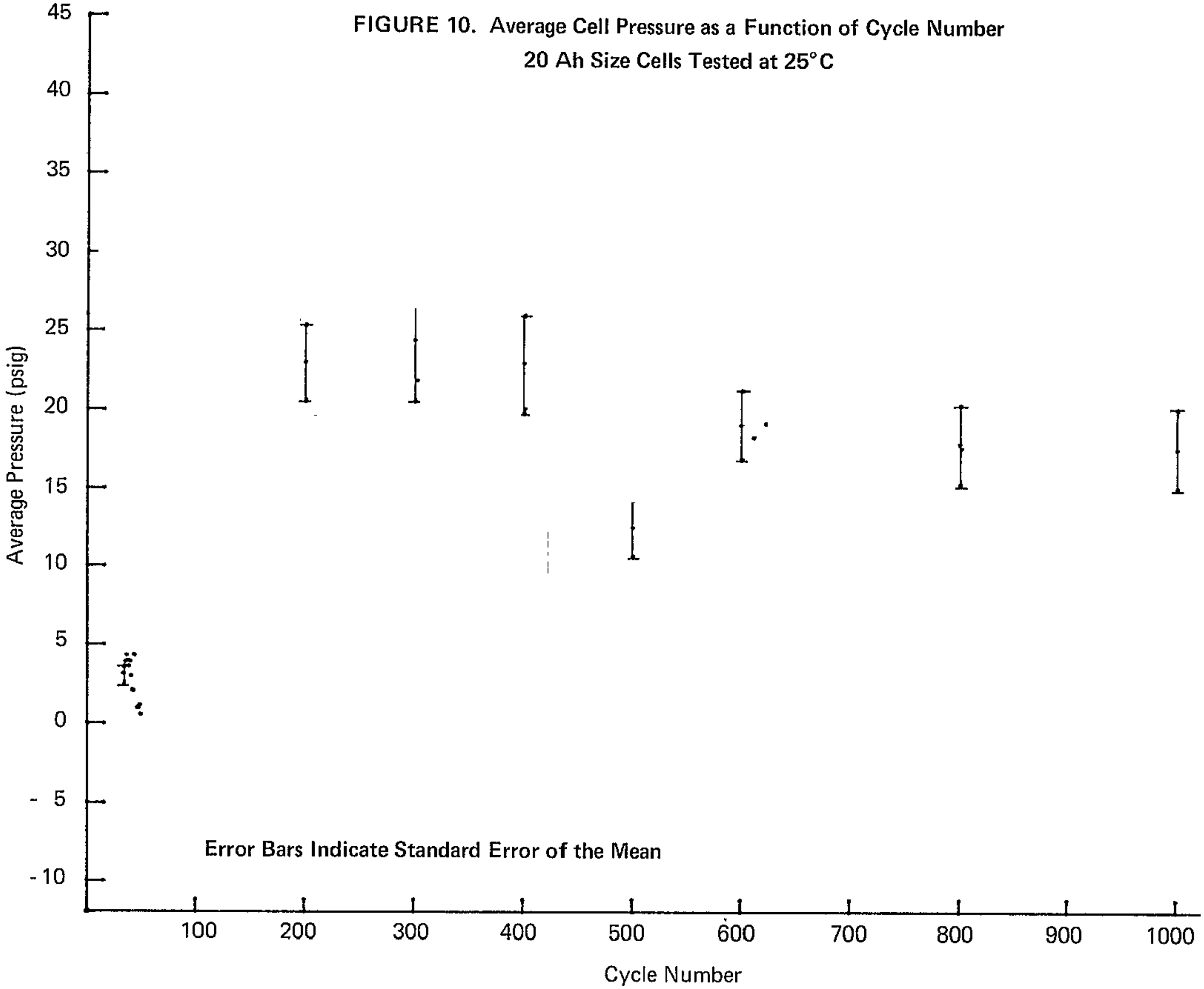


FIGURE 10. Average Cell Pressure as a Function of Cycle Number
20 Ah Size Cells Tested at 25°C

FIGURE 11. Variation of Mean Cell Capacity With Cycle Number
3 Ah Size Cells Tested at 0°C

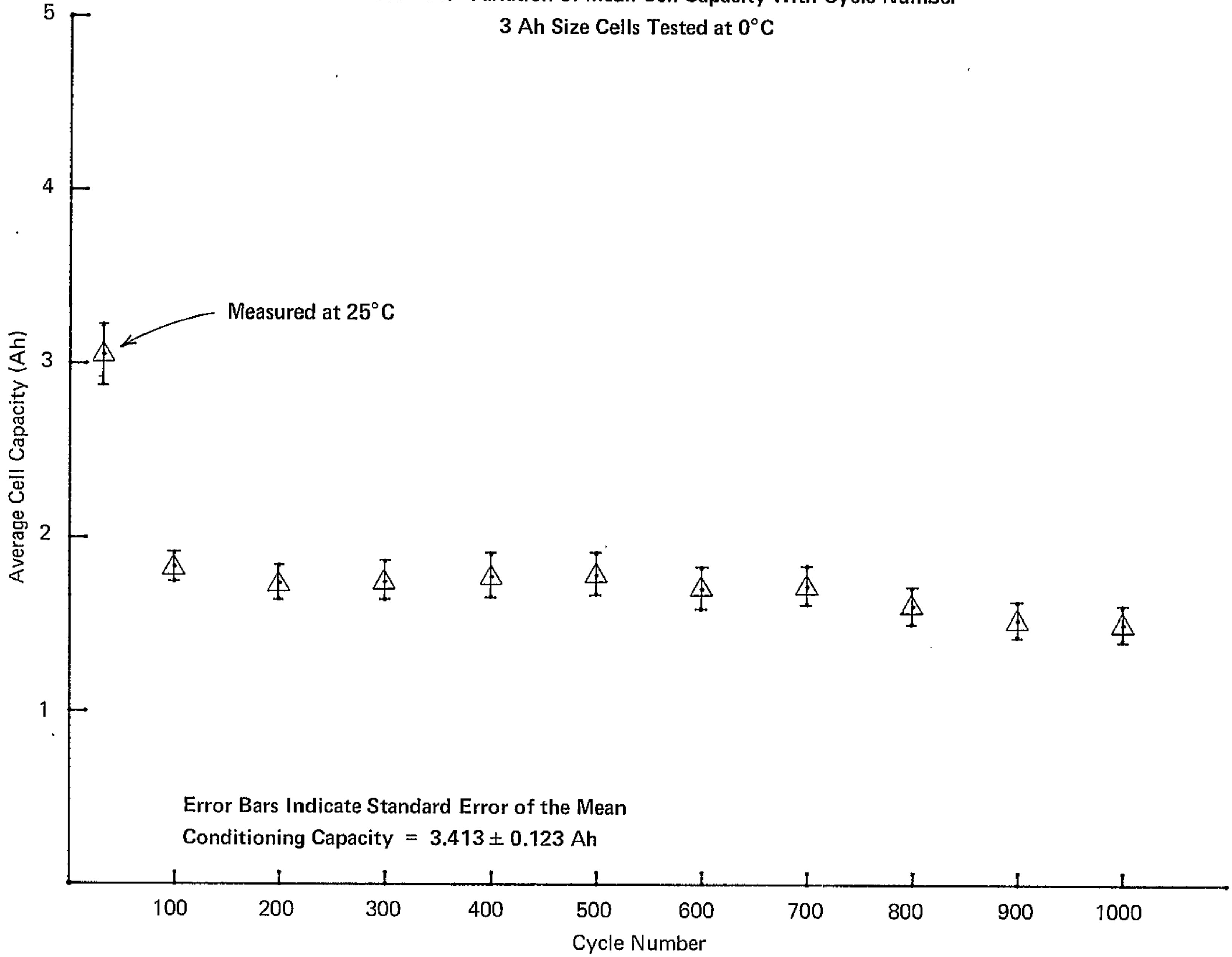


TABLE 7. Average Cell Capacity for 3 Ah Size Cells Tested at 0°C

Cycle No.	Mean Capacity, Ah	Standard Error Of The Mean
33	3.045	0.171
100	1.822	0.087
200	1.735	0.100
300	1.746	0.115
400	1.777	0.127
500	1.787	0.123
600	1.703	0.121
700	1.722	0.111
800	1.604	0.103
900	1.525	0.101
100	1.504	0.099

These capacities were determined with a 0.30 amp charge to 1.750 volts and a 0.30 amp discharge to 0.0 volt. As already noted with the 20 Ah size cells tested at 0°C the bulk of the capacity loss occurs within the first 100 cycles. Again, as noted on the larger size cells, the nickel electrode is the limiting factor during cell discharge after the first 200 cycles.

The average cell pressures as a function of cycle number for the 10 cells tested at 0°C are given in Figure 12. The error bars indicate the standard error of the mean for the appropriate average. As was the case for the 20 Ah size cells, the average cell pressure started negative, rose slowly over the first 200 cycles, and then maintained approximately a 7 psig value for the remainder of the 1000 cycles. Also, as with previous groups of cells, a periodic variation in pressure was noted to correspond with the capacity check cycles. Appendix IX will contain the average cell pressures and the standard error of the mean for each reading set recorded.

All 10 of the above cells completed the 1000 cycles without failure for any reason. Voltage profiles during charge were as given previously.[2]

4. 3 Ah Size Cells – Cycle Performance at 25°C

The average capacities along with the appropriate standard error of the mean are given in Table 8 and plotted in Figure 13 for the 10 cells of the 3 Ah size cycled at 25°C. These capacities were determined with a 0.30 amp charge to 1.750 volts and a 0.30 amp discharge to 0.0 volt. As already noted from the test results for the 20 Ah size at 25°C, the trends in capacity loss and cell pressure behavior are similar. Figure 14 gives the plot of average cell pressure as a function of cycle number, while the data from which this plot was derived will be found in Appendix V. The discontinuity in the curve at about cycle 600 was caused by a power failure which allowed the cells to stay on open circuit for 42 hours prior to being restarted on auto cycling.

FIGURE 12. Average Cell Pressure as a Function of Cycle Number
3 Ah Size Cells Tested at 0°C

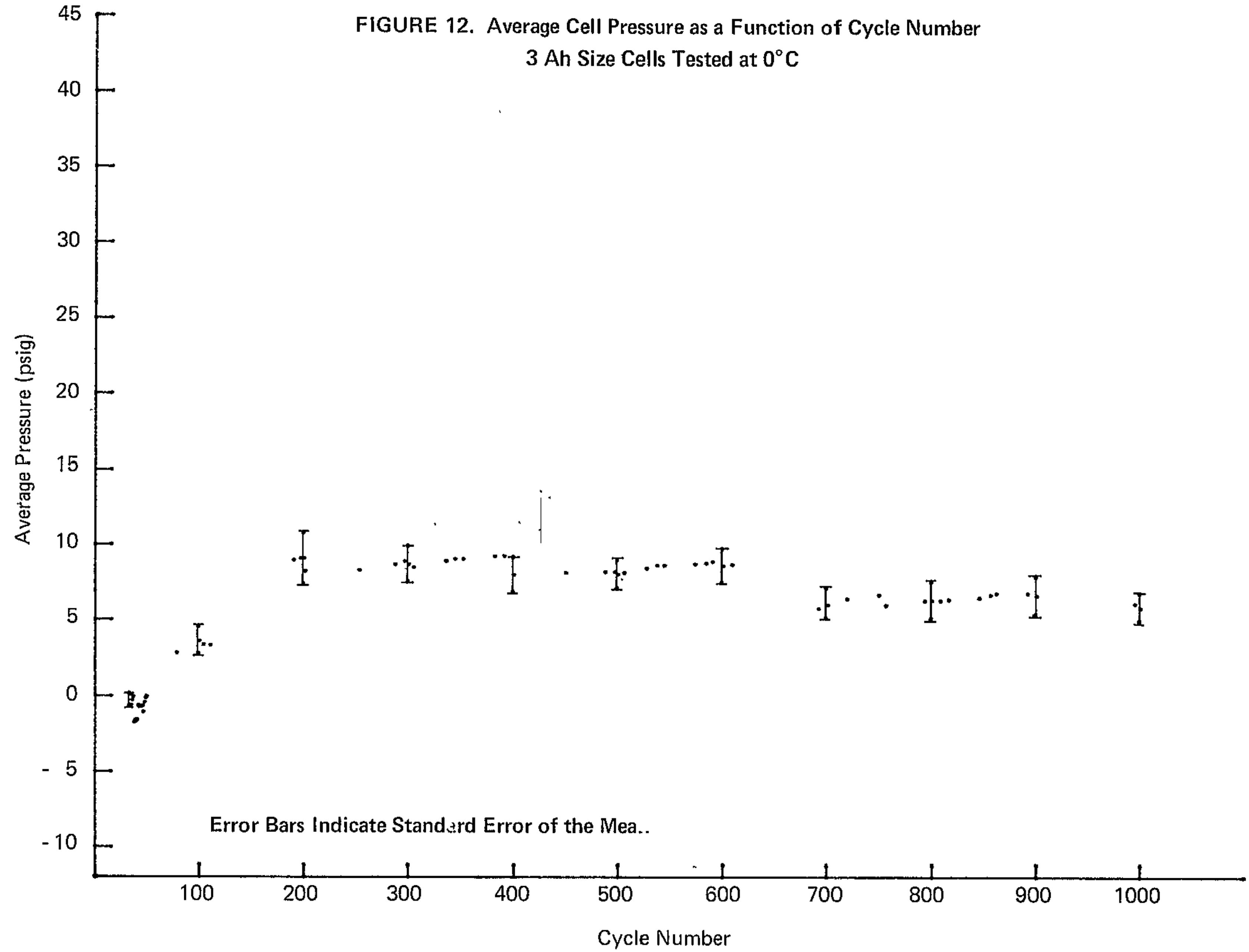


FIGURE 13. Variation of Mean Cell Capacity With Cycle Number
3 Ah Size Cells Tested at 25°C

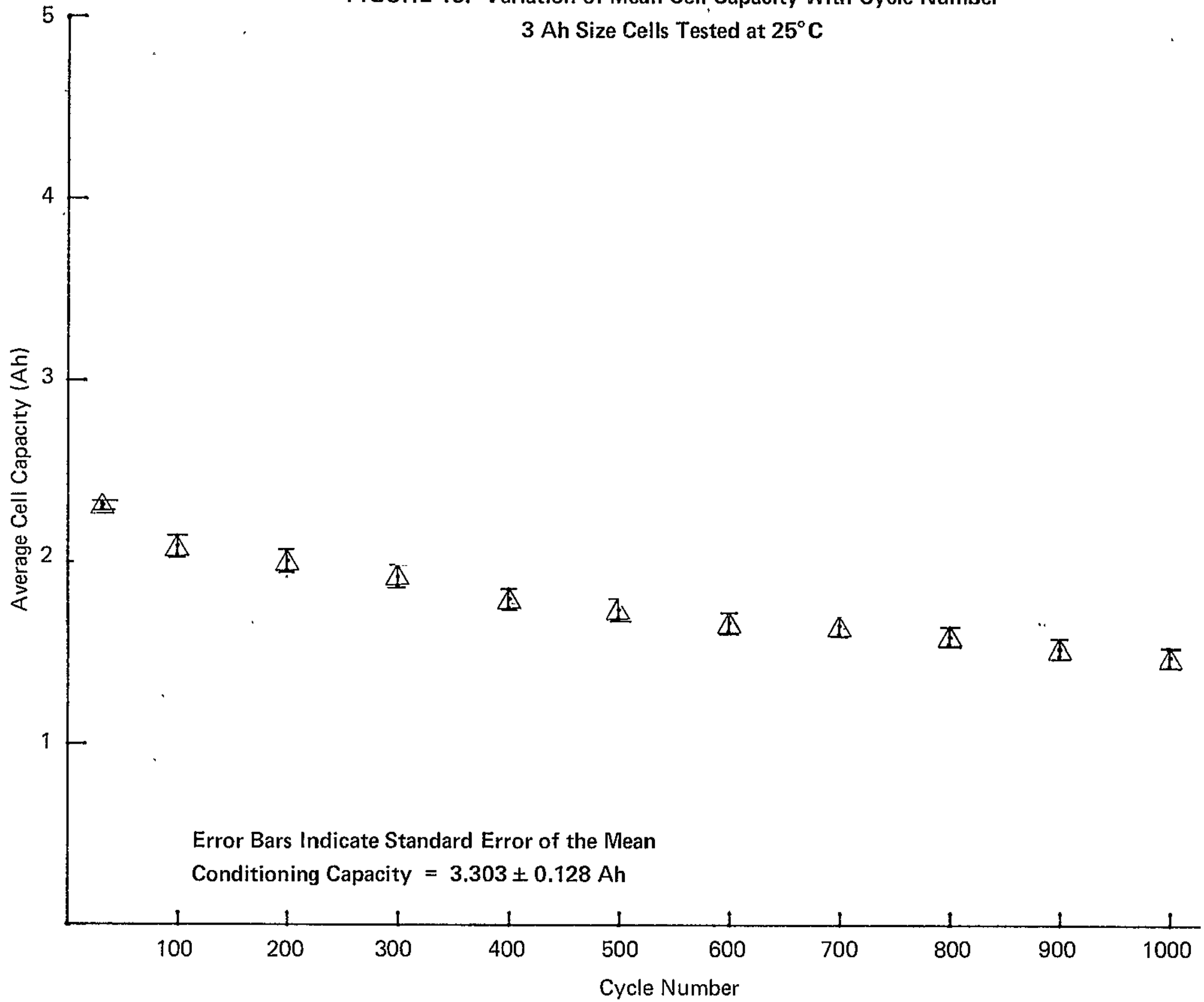
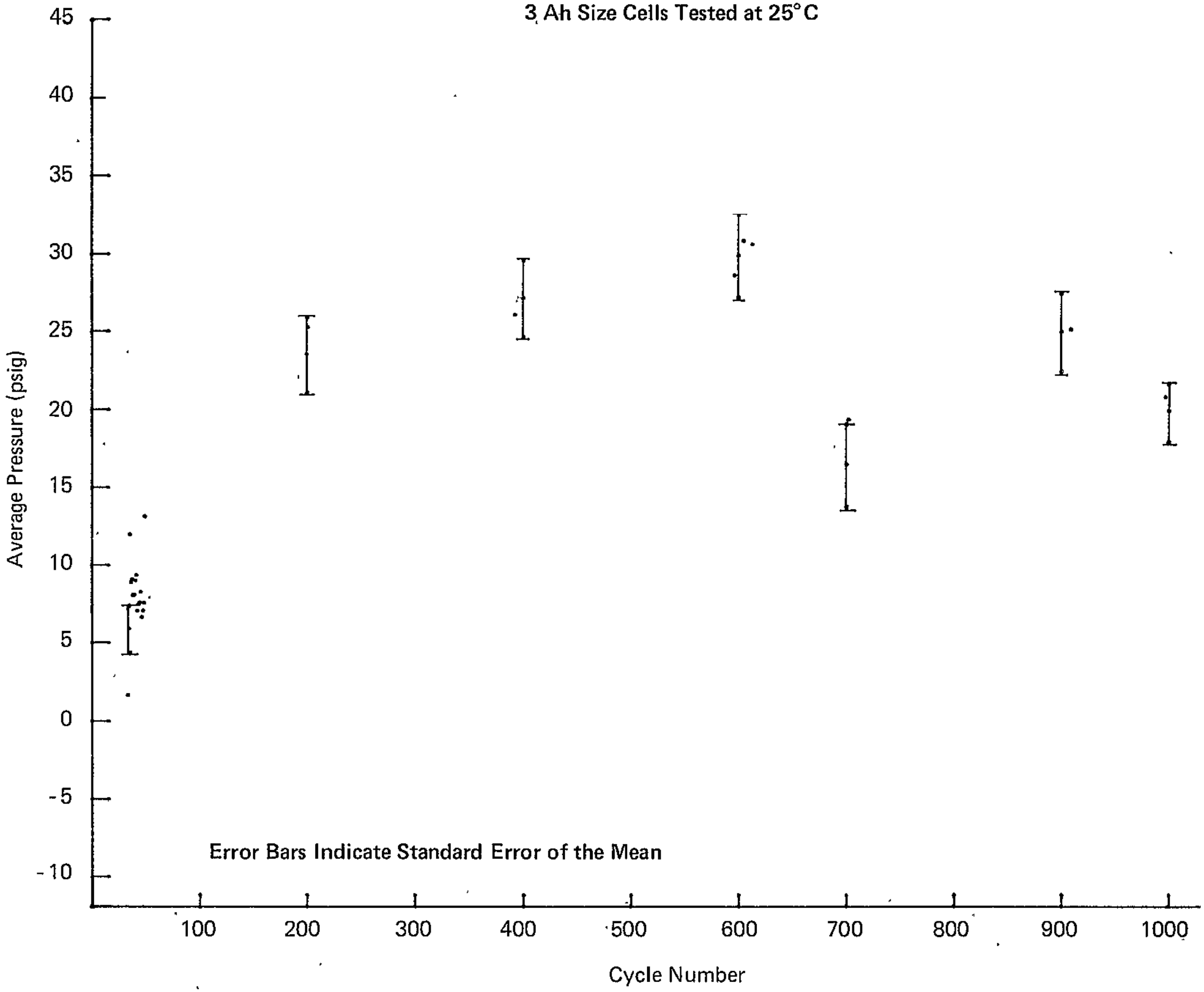


FIGURE 14. Average Cell Pressure as a Function of Cycle Number
3 Ah Size Cells Tested at 25°C



All 10 cells tested at 25°C completed the 1000 cycles without failure. Voltage profiles during charge were as given previously.[2]

TABLE 8. Average Cell Capacity for 3 Ah Size Cells Tested at 25°C

Cycle No.	Mean Capacity, Ah	Standard Error Of The Mean
33	2.311	0.013
100	2.086	0.055
200	2.005	0.055
300	1.918	0.058
400	1.797	0.052
500	1.736	0.051
600	1.664	0.052
700	1.651	0.053
800	1.589	0.047
900	1.526	0.046
1000	1.479	0.049

D. Open-Circuit Stand Charge Retention

Ten cells from each size (20 Ah and 3 Ah) were tested at 25° and 50°C to determine the rate of capacity loss while on open-circuit stand in the charged state. These cells were charged at their respective C/10 rates to 1.750 volts cutoff potential. They were then discharged at their respective C/10 rate to 0 0 volt and this capacity measurement was then used as the starting value for the stand comparison. They were then charged again at the C/10 rate to 1.750 volts and placed in their appropriate temperature storage conditions.

1. Performance at 25°C

Twenty cells were tested at 25°C, 10 of each size (20 Ah and 3 Ah). After being allowed to stand for 30 days at 25°C, five cells of each size were removed from the test chamber and were discharged at the C/10 rate to measure their capacities. The results for the 3 Ah size showed that they had retained an average of 73.82% of their original capacity. The results for the five 20 Ah size cells stored under identical conditions showed that they had retained 82.86% of their original capacity.

During the above-mentioned discharges, and the discharges to establish the starting capacity for these cells, the voltages for each half cell were monitored to determine which electrode was controlling the cell discharge. On the initial cycle, the cell potential and the cadmium electrode potentials both reached 0.0 volt at the same time. After 30 days on open circuit four out of five of the 20 Ah size cells and all of the five 3 Ah size cells showed that the nickel electrode was the controlling electrode during cell discharge.

After an additional 30 days (60 days total) the remaining five cells of each size were discharged and their mean capacities were compared to their starting capacities. The results for the 3 Ah size showed a retention of 66.96% of their original capacity while the 20 Ah size showed a retention of 81.6% of their original capacities, Figure 15 shows the results of these tests plotted as percent cell capacity retained vs days on stand. Also, a straight line fit (least squares) is plotted for each set of data. The observed loss rates are somewhat less than for conventional sealed nickel-cadmium cells and appreciably less than for vented nickel-cadmium cells.[3,4]

2. *Performance at 50°C*

Ten of the 20 Ah size cells and 10 of the 3 Ah size cells were placed in test chambers at 50°C and allowed to stand on open circuit in the charged state. Due to accidental damage to the temperature controls of one chamber the results for the 20 Ah size cells were lost. These cells were subjected to temperatures in excess of 250°C for an unknown length of time. Further testing of this group was not carried out.

After 30 days stand at 50°C, five of the 3 Ah size cells were removed from storage and allowed to stand at 25°C for 16 hours. They were then discharged at 0.30 amp and their average capacities were compared with their starting capacities. The results indicate that these cells had retained 32.40% of their original capacity. As was noted with the 25°C test results, the nickel electrode was the controlling electrode on all five cells during discharge.

After an additional 30 days (60 days total) the remaining five cells were discharge checked. The results showed that these cells had retained 11.17% of their starting capacity. Figure 16 shows the results of these stand tests plotted as percent capacity remaining vs days on open circuit stand at 50°C. Also, a least squares line fit is given for the results. The coefficient of determination for the fit was 0.9574.

E. Cell Performance Using a 1.850 Volt Charge Cutoff Potential

It was thought that one possible way of off-setting the capacity fade experienced during cycle testing would be to raise the cell charge cutoff potential and allow the cell to receive more input current. To test this possibility, eight of the 20 Ah size cells were cycled at 25°C using a 1.850 volt charge cutoff potential. The charge was at the 20.0 amp rate to 1.850 volts and the discharge was at 20.0 amps for 15 minutes. Every 100 cycles, the capacity was checked using a 2.0 amp charge to 1.850 volts and a 2.0 amp discharge to 0.0 volt. The cell internal pressure was monitored three times daily and the test was carried on for 300 cycles.

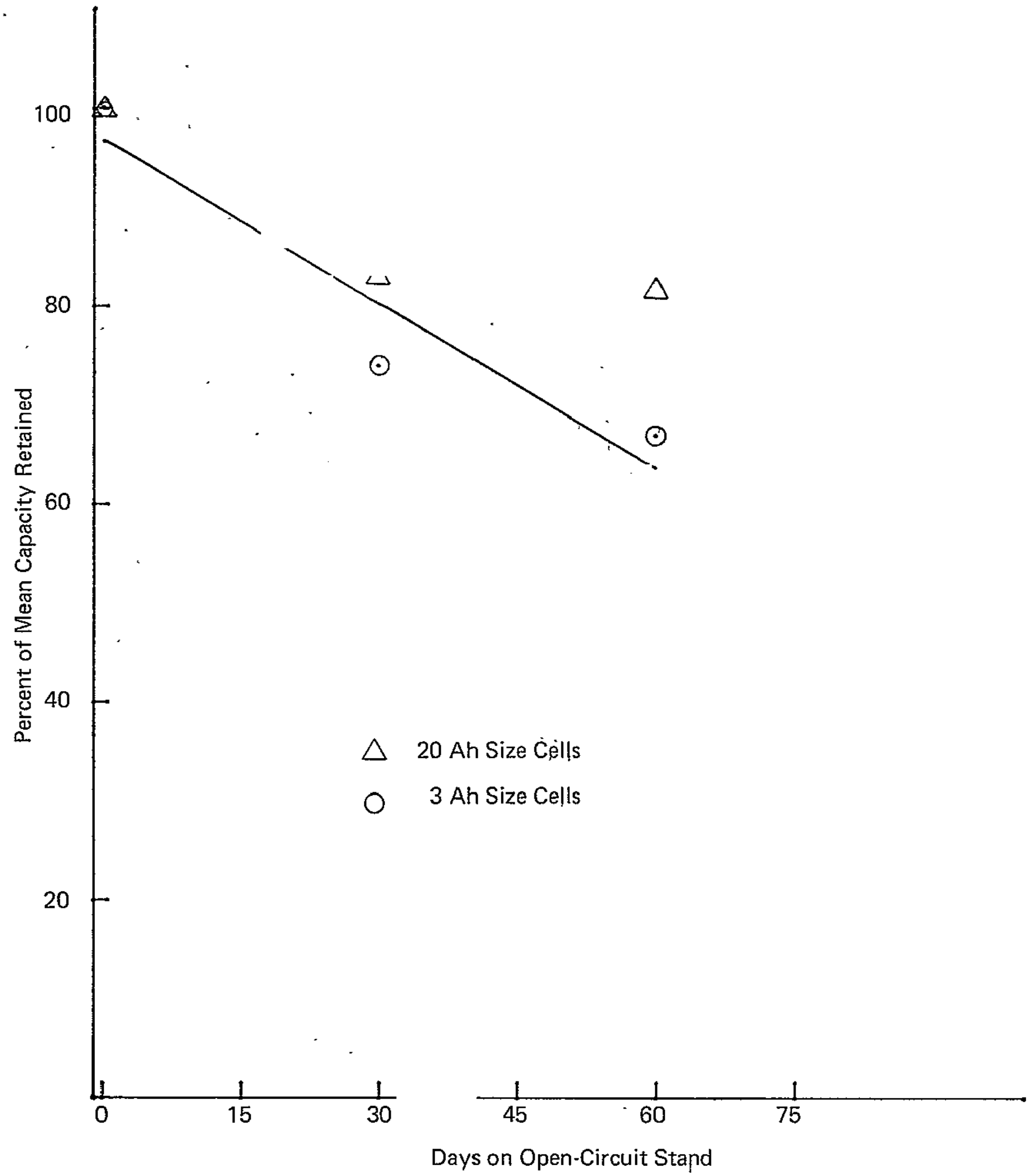


FIGURE 15. Percent of Cell Capacity Retained After Standing on Open-Circuit at 25°C

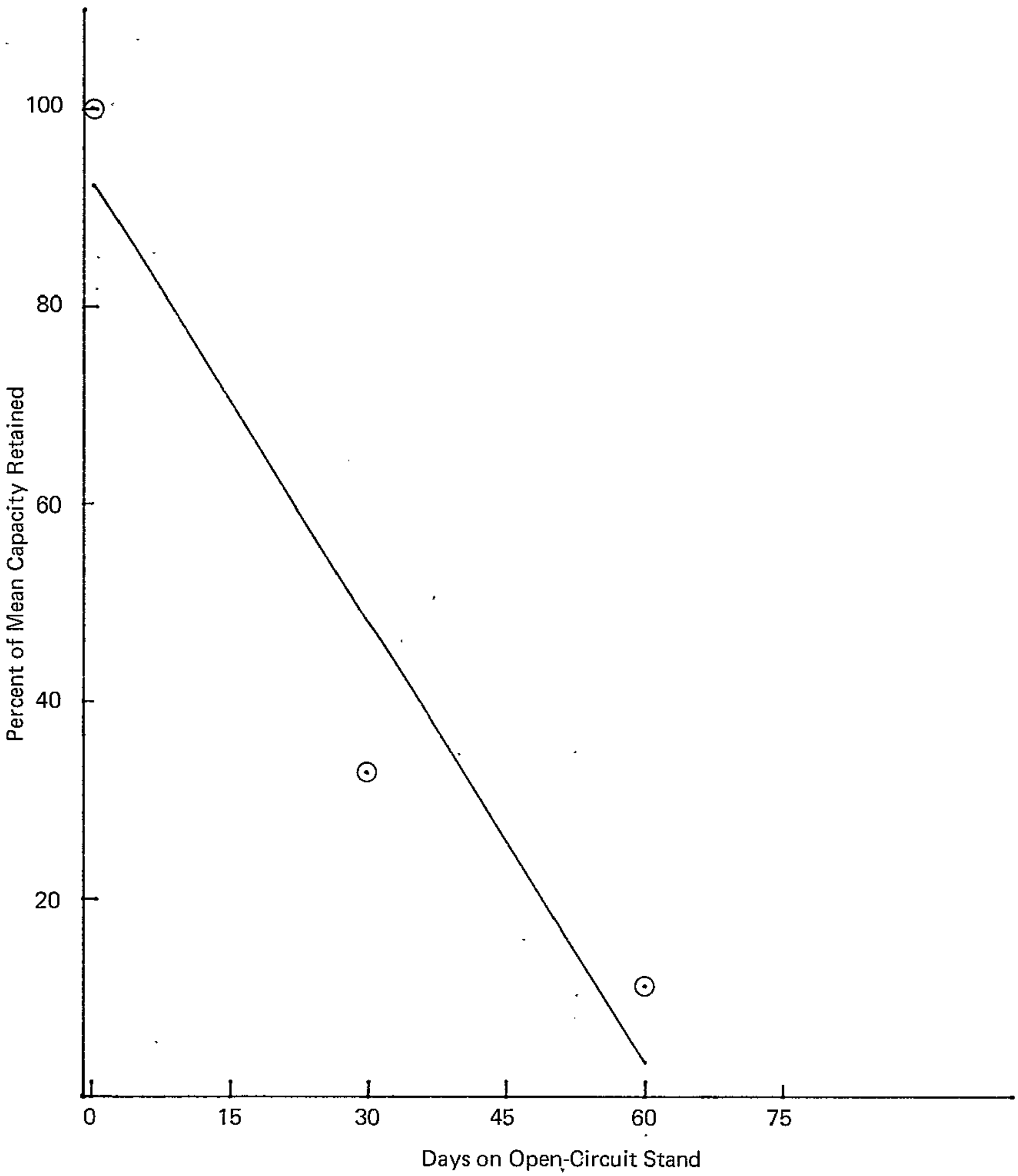
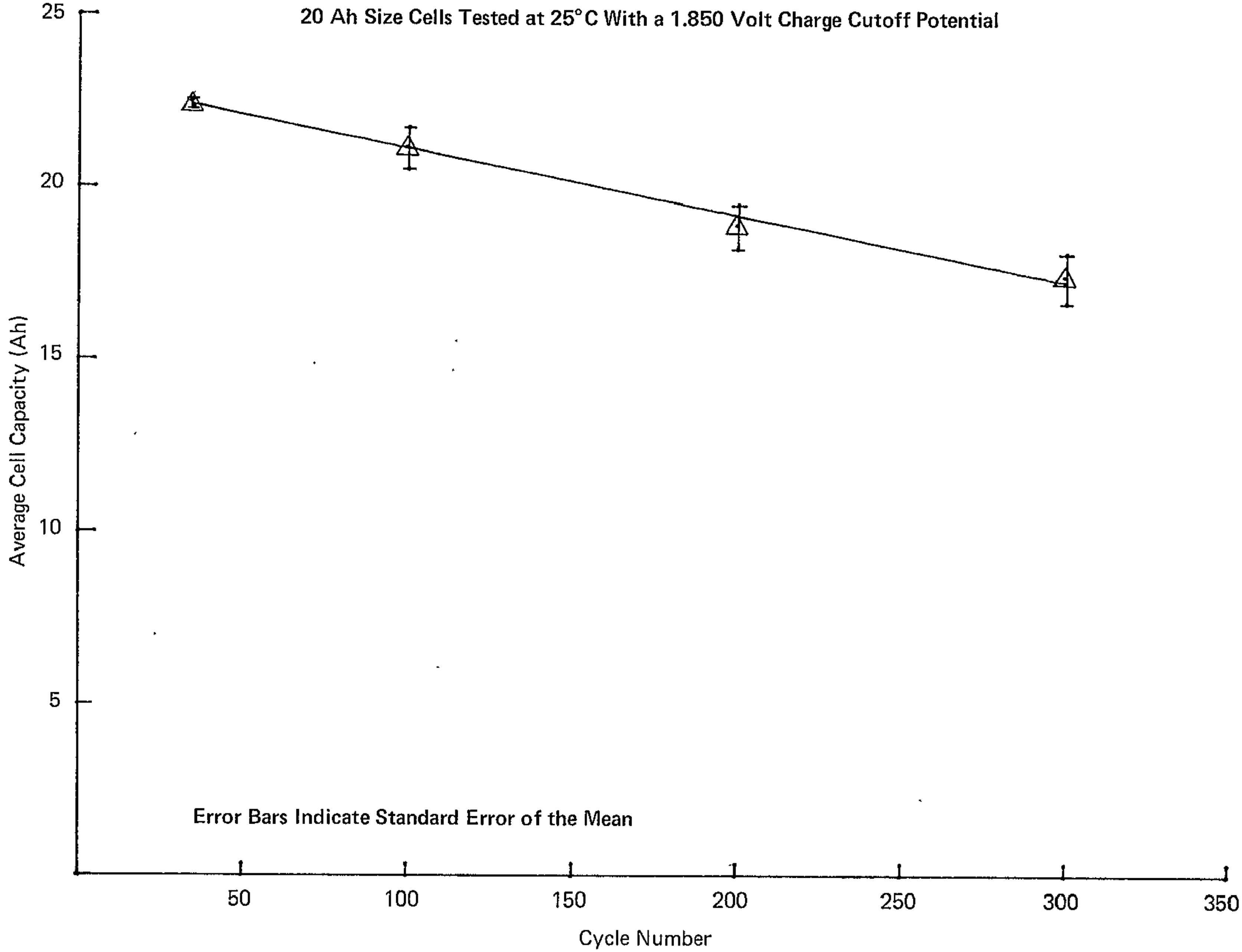


FIGURE 16. Capacity Retention Vs Days on Open-Circuit Stand For 3 Ah Size Cells at 50°C

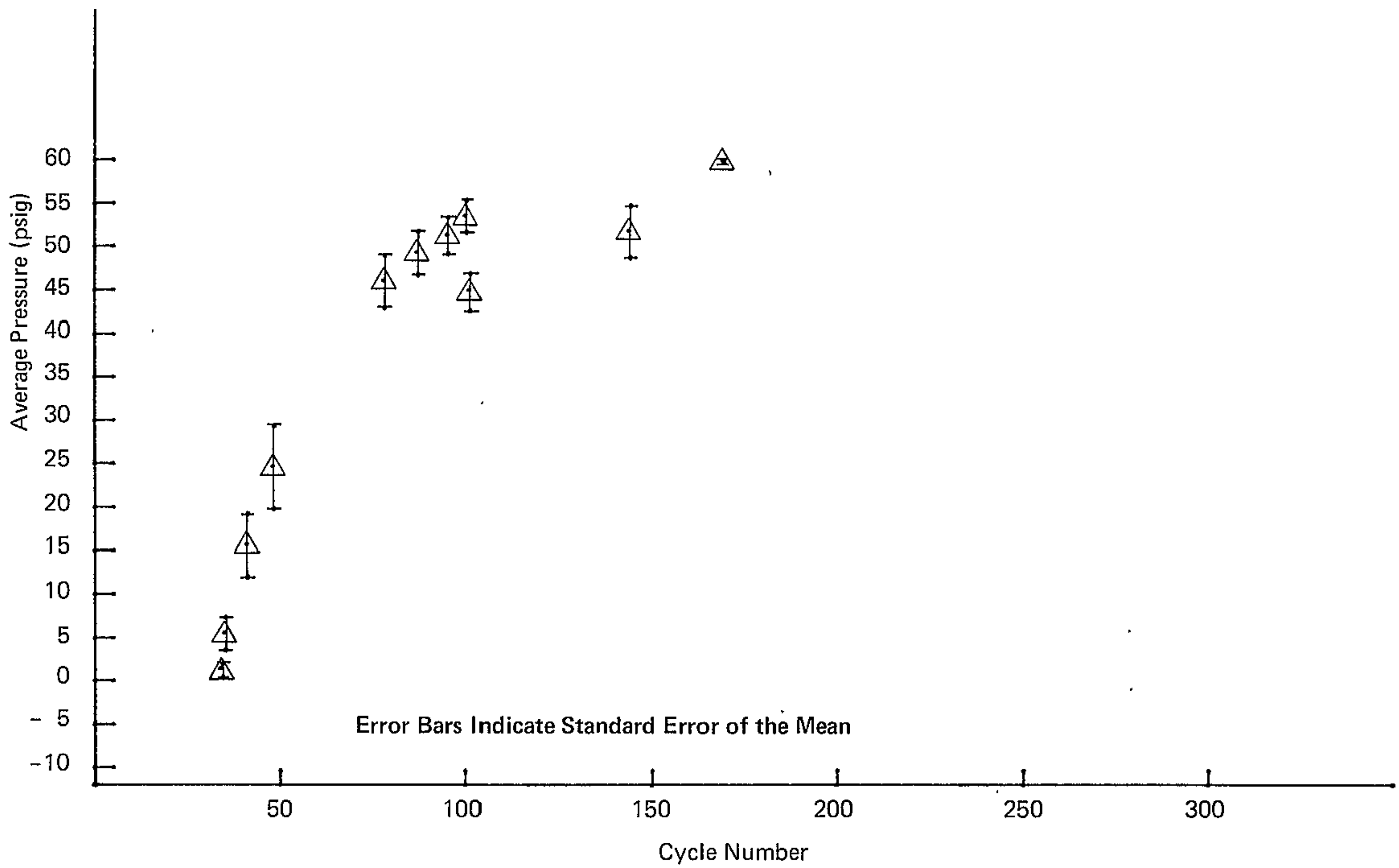
Figure 17 shows how the capacity exhibited a continual decrease as the number of cycles increased. The higher cutoff potential did not seem to affect this decline in anyway. However, from Figure 18 we can see that the change in cutoff potential to 1.850 volts was very detrimental to the cell pressure. The average cell pressure slowly rose over the first 150 cycles until it reached a maximum reading of 60 psig (limits of the gauge). With continued cycling, the pressure continued to rise, as was indicated by rupturing of several safety discs (rating of 100 psig) between cycles 250 and 300.

FIGURE 17. Variation of Mean Cell Capacity With Cycle Number
20 Ah Size Cells Tested at 25°C With a 1.850 Volt Charge Cutoff Potential



100

FIGURE 18. Variations in Average Cell Pressure as a Function of Cycle Number
20 Ah Size Cells Tested at 25°C With a 1.850 Volt Charge Cutoff Potential



IV. CONCLUSIONS

The objective of this program was to fabricate, test, and deliver "hardware type" (hermetically sealed in stainless steel containers) negative-limited nickel-cadmium cells based on prior negative-limited nickel-cadmium technology developed on an earlier program. The objective was met in full by fabricating 200 such cells, conducting characterization tests on all and special tests on a portion of these, and delivering the cells to JPL as specified in the contract.

An ultimate judgement on the merits of these cells (especially life, reliability, and ease of operation as a battery) is to be determined by JPL's subsequent test and evaluation. Based on results obtained to date, however, some comments can be made regarding this subject. These comments are, with a few exceptions, quite positive in nature as indicated below.

1. The cells were successfully packaged and hermetically sealed in stainless steel containers in a similar manner to conventional sealed nickel-cadmium cells.
2. The cells exhibit the sharp voltage-rise signal at the state of full charge. Magnitude of the signal is much greater than in conventional sealed nickel-cadmium cells. These characteristics should therefore facilitate development of simplified and reliable charge control circuits.
3. The cells exhibit somewhat lower self-discharge rates than conventional sealed nickel-cadmium cells and much lower self-discharge rates than vented nickel-cadmium cells.
4. The cells do not require overcharge as do conventional sealed nickel-cadmium cells.
5. The cells are capable of operating at charge and discharge rates of at least 5C and can deliver at least 1000 cycles on a 30-minute regime at 25% DOD.
6. The cells appear to exhibit a somewhat higher capacity degradation rate than conventional sealed nickel-cadmium during the course of rapid cycling. The rate of degradation was found to be a function of the number of cycles. During the first 100 to 200 cycles the rate is quite rapid and is believed to be associated with degradation of the positive electrodes. Thereafter the rate is much less (although comparable to, or perhaps somewhat higher than, that of conventional sealed nickel-cadmium cells) and is associated with degradation of the negative electrodes. The degradation rate cannot be diminished by raising the cutoff voltage beyond 1.75 volts.

7. The cells are not entirely 'gas-free' as was intended at the start of the program. Extent of the gassing is, however, quite small considering the moderate observed pressures of about 7 to 20 psig and the fact that the cells are operated in the flooded condition with very little void volume.

At the present state of development it would appear that the negative-limited cell may serve well in missions requiring limited cycle-life capability. Due to capacity degradation the cells would not, however, appear ready at this point for general purpose applications including those with extensive cycle life requirements. The key to improved performance would appear to reside in modifications and improvements in the positive electrodes. Also, consistent with the goal of a very long cycle-life capability, further modifications and improvements in the negative electrode would seem necessary. When such improvements are realized the negative-limited cell will constitute a significant advance in the state-of-the-art of sealed nickel-cadmium cell technology.

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E. Luksha, D.J. Gordy, and C.J. Menard, "Non-Gassing Nickel-Cadmium Battery Electrodes and Cells", Report No. 712-122-4, Prepared for Jet Propulsion Laboratory, Contract No. 953184.

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3. S.U. Falk and A.J. Salkind, Alkaline Storage Batteries, p. 403, John Wiley and Sons, Inc. New York, NY (1969).

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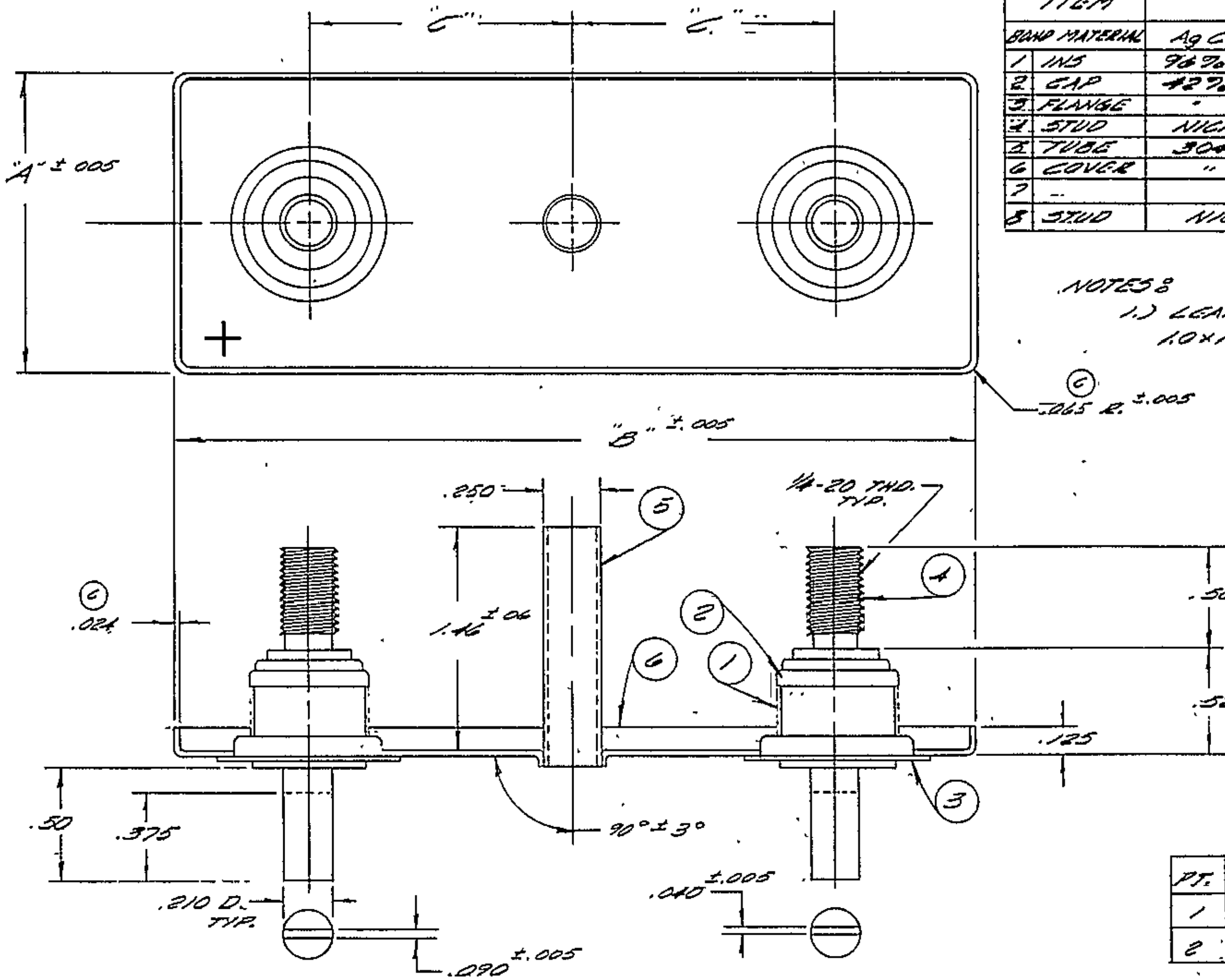
APPENDIX I.

Mechanical Drawings of Hardware Required For
Negative-Limited Sealed Nickel-Cadmium Cells –
20 Ah and 3 Ah Sizes

ITEM		DESCRIPTION	QTY	DRAWING
BOND MATERIAL		Ag Cu Pd & Ag Cu In, Au Cu		
1	INS	96% MIN ALUMINA	1	
2	CAP	42% NIFE	1	
3	FLANGE	" "	1	
4	STUD	NICKEL 200	1	
5	TUBE	304 L STN. STL	1	
6	COVER	" " " "	1	
7	--			
8	STUD	NICKEL 200	1	

NOTES:

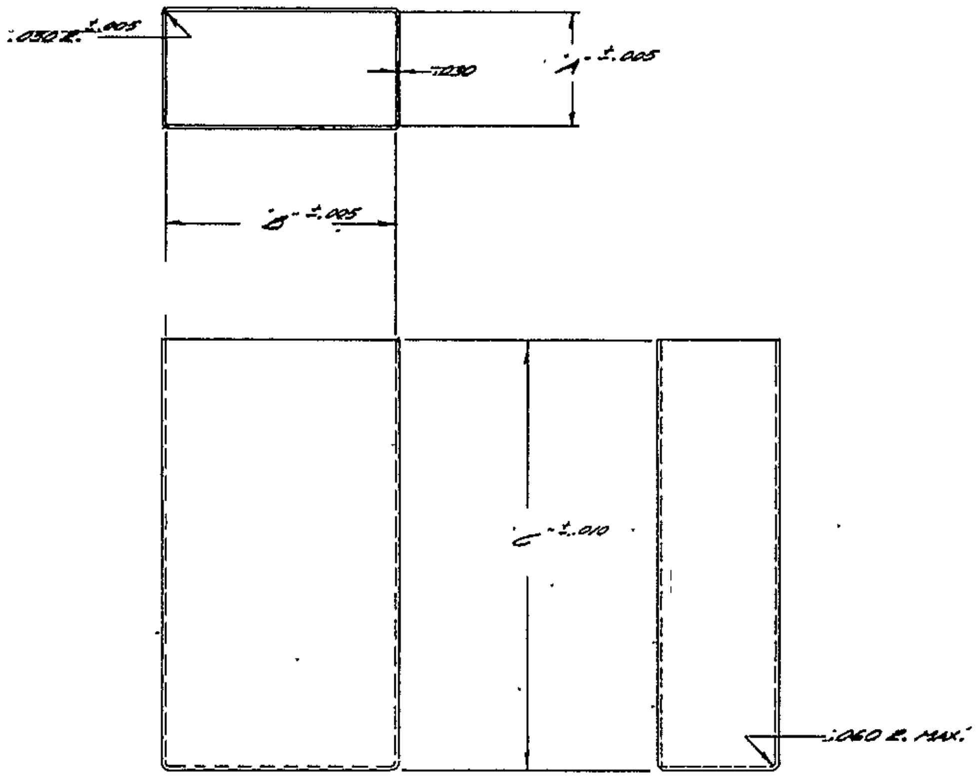
1.) LEAK RATE NOT TO EXCEED 1.0×10^{-8} STD. ATM. CC/SEC. - He



PT.	A ±.005	B ±.005	C ±.03
1	1.390	3.750	1.15
2	.964	2.	.58

Stainless Steel Cover and Ceramic Seal Assembly

PT.	"A"	"B"	"C"
1	1.390	3.750	6.90
2	.964	2.250	3.65



NOTES:

1.) LEAK RATE NOT TO EXCEED 1.0×10^{-8} STD. ATM. CC/SEC.-He

2.) WELDS NOT TO BE GROUND OR POLISHED

3.) MAT'L: #304 L STAINLESS STEEL

Stainless Steel Cell Case

APPENDIX II.

Mean Internal Cell Pressure and Standard Error of the Mean
For Negative-Limited Sealed Nickel-Cadmium Cells –
20 Ah Size Tested at 0° C

Cycle No.	Mean Pressure, psig	Standard Error Of The Mean
34	-0.918	0.216
35	-0.147	0.367
36	-0.250	0.608
37	-0.240	0.658
38	-0.155	0.428
39	1.400	0.916
40	0.900	0.909
41	1.550	1.211
42	2.600	1.684
43	1.475	1.533
44	3.150	2.137
45	4.000	1.915
46	4.750	2.892
47	1.925	0.921
48	3.300	1.058
49	4.900	1.309
50	0.250	1.028
54	1.150	1.176
80	6.400	1.950
91	7.600	2.130
100	6.550	1.324
101	5.500	1.682
139	7.700	2.251
183	8.750	2.473
190	8.750	2.395
200	8.116	1.321
201	7.450	2.413
209	7.550	2.394
217	7.750	2.520
247	8.350	2.601
256	8.650	2.588
264	8.900	2.456
294	9.400	2.423
300	8.583	1.305
301	7.950	2.408
339	7.750	2.489
377	7.950	2.404
386	8.150	2.403

Cycle No.	Mean Pressure, psig	Standard Error Of The Mean
395	8.250	2.315
400	7.116	1.222
405	6.550	2.153
439	7.400	2.403
500	7.850	1.547
506	2.850	1.429
514	3.950	2.039
545	4.450	1.992
564	4.900	1.978
594	5.150	1.939
600	4,683	0.968
601	4.000	1.824
643	4.350	1.846
652	4.600	1,837
660	4.750	1.874
692	4.950	1.870
700	4.637	0.815
730	5.000	1.805
740	5.100	1.874
747	5.100	1.814
777	5.200	1.810
786	5.450	1.815
794	5.200	1.713
800	5.250	1.130
801	4.700	1.396
851	5.650	1.770
862	5.800	1.756
869	6.000	1.770
900	6.083	0.950
901	5,250	1.631
931	5.700	1.801
942	5.850	1.810
949	5.800	1.748
982	5.950	1.795
1000	5.866	0.955

APPENDIX III.

Mean Internal Cell Pressure and Standard Error of the Mean
For Negative-Limited Sealed Nickel-Cadmium Cells –
20 Ah Size Tested at 25°C

Cycle No.	Mean Pressure, psig	Standard Error Of The Mean
34	3.060	0.575
35	6.016	0.875
36	3.875	0.797
37	4.350	0.924
38	3.900	0.900
39	3.575	0.912
40	3.950	0.952
41	2.950	1.225
42	2.050	0.425
43	2.000	0.449
44	4.350	1.359
45	7.625	1.607
46	7.875	1.631
47	0.900	0.428
48	0.950	0.607
49	1.150	0.605
50	0.500	0.500
61	9.000	2.211
99	8.800	2.430
100	12.600	2.604
101	11.400	2.339
140	26.500	5.398
148	27.800	5.699
156	28.700	5.918
185	29.950	6.177
193	25.550	5.465
200	22.937	2.438
203	19.050	4.447
210	19.550	4.399
217	20.300	4.434
246	21.800	4.680
255	21.333	5.254
266	23.100	5.012
300	24.400	3.837
302	21.750	5.200
338	22.700	5.202
345	22.700	5.219
355	22.800	5.242

Cycle No.	Mean Pressure, psig	Standard Error On The Mean
386	22.850	5.364
391	23.100	5.414
400	22.875	3.124
401	20.000	4.633
442	15.400	4.204
476	17.300	4,926
500	12.446	1.847
506	15.111	3.501
513	15.777	3.573
521	16.777	3.774
551	18.555	4.150
600	19.083	2.188
611	18.222	4.310
622	19.222	4.569
651	19.888	4.791
660	20.111	4.959
690	20.222	4,991
700	20.388	3.411
702	19.777	4.719
710	19.666	4.772
717	19.888	4.834
758	20:111	4.950
774	20.222	5.103
800	17.814	2.574
801	17.555	4.400
832	18.555	4.634
844	18.444	4 696
849	18.222	4.680
880	18.222	4.855
889	18.000	5.047
900	17.740	2.602
901	17.000	4.447
934	17.888	4.553
952	17.778	4.672
961	17.778	4,752
985	16.778	4.612
1000	17.592	2.574

APPENDIX IV.

Mean Internal Cell Pressure and Standard Error of the Mean
For Negative-Limited Sealed Nickel-Cadmium Cells –
3 Ah Size Tested at 0°C

Cycle No.	Mean Pressure, psig	Standard Error Of The Mean
34	0.000	0.383
35	-0.700	0.442
36	-0.325	0.394
37	-0.050	0.616
38	-1.830	0.462
39	-1.630	0.463
40	-1.767	0.459
41	-1.600	0.392
42	-0.650	0.614
43	-0.790	0.633
44	-0.690	0.633
45	-0.740	0.610
46	-0.740	0.610
47	-1.140	0.558
48	-0.450	0.786
49	-0 150	0.966
50	-0.050	0.880
79	2.800	1.220
100	3.583	0.918
104	3.300	1.590
111	3.250	0.771
142	6.450	1.330
150	7.050	1.469
158	7.700	1.667
190	9.000	1.738
197	9.100	1.754
200	9.050	1.706
201	8.200	1.678
253	8.300	1.764
288	8.700	1.732
297	8.900	1.772
300	8.650	1.222
305	8.450	1.748
336	8.950	1.817
344	9.050	1.850
352	9.050	1.850
382	9.250	1.872
391	9.250	1.793
400	7.950	1.183

Cycle No.	Mean Pressure, psig	Standard Error Of The Mean
450	8.150	1.757
488	8.200	1.779
497	8.200	1.786
500	8.000	0.982
506	8.150	1.825
527	8.450	1.865
537	8.650	1.946
544	8.650	1.963
574	8.750	2.083
584	8.800	2.059
590	8.900	2.057
600	8.550	1.153
609	8.700	2.092
692	5.750	1.785
700	6.067	1.032
701	6.000	1.831
719	6.450	1.877
749	6.700	1.919
756	5.950	1.808
793	6.350	1.882
800	6.275	1.276
808	6.300	1.868
816	6.400	1.892
845	6.500	1.922
856	6.700	1.938
862	6.800	1.970
892	6.800	1.993
900	6.575	1.303
910	6.200	1.836
942	6.100	1.772
995	6.100	1.748
1000	5.800	0.975

APPENDIX V.

Mean Internal Cell Pressure and Standard Error of the Mean For Negative-Limited Sealed Nickel-Cadmium Cells — 3 Ah Size Tested at 25° C

Cycle No.	Mean Pressure, psig	Standard Error Of The Mean
34	1.600	0.581
35	5.950	1.542
36	12.000	2.347
37	8,850	1.983
38	9.100	2.218
39	8.000	2.097
40	8.100	2.172
41	9.050	2.199
42	9.350	2.317
43	7.000	2.133
44	7.500	2.207
45	7.600	2.186
46	8.300	2.265
47	6.600	2.034
48	7.100	2.121
49	7.600	2.088
50	13.200	2,550
79	16.300	2.816
100	14.000	1.576
103	18.700	3.303
117	18.900	3.271
147	21.000	3.405
157	21.900	3.475
164	22.800	3.479
175	21.300	3.522
183	21.400	3.429
191	21.100	3.535
200	23.600	2.429
201	25.300	3.809
254	25.300	3.690
287	26.600	3.742
297	27.000	3.754
300	27.750	2 605
305	25.900	3.802
336	26.100	3.585
344	26.000	3.593
353	26.200	3.536
383	26.000	3.393
392	26.100	3.325
400	27.200	2.504

Cycle No.	Mean Pressure, psig	Standard Error Of The Mean
449	27.000	3.568
487	27.100	3.557
496	27.000	3.527
500	30.067	2.180
510	31.100	4.034
539	29.900	3.851
549	29.400	3.936
557	29.100	3.877
587	28.600	3.787
597	28.600	3.787
600	29.950	2.720
605	30.900	4.089
613	30.600	4.020
623	10.800	2.649
628	10.400	2.548
636	10.350	2.497
666	11.400	2.257
675	11.800	2.318
683	12.350	2.246
696	10.900	2.137
700	16.500	2.689
702	19.400	3.011
753	19.000	2.970
785	18.850	2.917
795	18.750	2.892
800	20.525	2.191
808	24.000	3.534
820	23.500	3.590
851	21.950	3.409
862	21.450	3.390
868	21.350	3.309
897	20.600	3.294
900	25.050	2.542
909	25.200	3.904
942	23.350	3.748
997	20.800	3.492
1000	19.900	1.931