EVALUATION PROGRAM
for
SECONDARY SPACECRAFT CELLS

EVALUATION OF STORAGE METHODS,
OPEN CIRCUIT VERSUS CONTINUOUS TRICKLE CHARGE,
SONOTONE 3.5 AMPERE—HOUR SEALED NICKEL—CADMIUM
SECONDARY SPACECRAFT CELLS

prepared for
GODDARD SPACE FLIGHT CENTER
CONTRACT W11, 252B

QUALITY EVALUATION LABORATORY
NAD CRANE, INDIANA

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UNITED STATES NAVAL AMMUNITION DEPOT
CRANE, INDIANA

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EVALUATION OF STORAGE METHODS, OPEN CIRCUIT VERSUS CONTINUOUS TRICKLE CHARGE, SONOTONE 3.5 AMPERE-HOUR SEALED NICKEL-CADMIUM SECONDARY SPACECRAFT CELLS

QE/C 69-69 6 FEBRUARY 1969

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Enclosure (1)

REPORT BRIEF
EVALUATION OF STORAGE METHODS, OPEN CIRCUIT VERSUS CONTINUOUS TRICKLE CHARGE, SONOTONE 3.5 AMPERE-HOUR SEALED NICKEL-CADMIUM SECONDARY SPACECRAFT CELLS

Ref: (a) National Aeronautics and Space Administration Purchase Order Number W11,252B
(b) NASA ltr BRA/VBK/pad of 25 September 1961 w/BUWEPS first end FQ-1:WSK of 20 October 1961 to CO NAD Crane
(c) Preliminary Work Statement for Battery Evaluation Program of 25 August 1961
(d) NAD Crane Report QE/C 66-340 of 6 June 1966
(e) NAD Crane Report QE/C 67-471 of 4 August 1967

I. TEST ASSIGNMENT BRIEF

A. In compliance with references (a) and (b) evaluation of methods for storage of nickel-cadmium cells at room ambient conditions was begun according to the program outline of reference (c). The nickel-cadmium cells used for this test were 3.5 ampere-hour "D" cells manufactured by the Sonotone Corporation.

B. The object of these evaluation programs is to gather specific information concerning secondary spacecraft cells. Information concerning performance characteristics and limitations including cycle life under various electrical and environmental conditions will be of interest to power systems designers and users. Cell weaknesses, including causes of failure of designs, will be of interest to suppliers as a guide to product improvement.

C. The purpose of this 5-year test is to compare, after each successive 1-year storage period, the discharge and charge characteristics of charged cells on open circuit versus that of cells on continuous trickle charge.

D. Of the original 25 cells subjected to the acceptance tests, reported in reference (d), 20 were selected for this storage test. Following recharge, after completion of the acceptance tests, 10 cells were placed on open circuit stand and 10 were placed on continuous trickle charge at the c/100 rate.

E. Following completion of each year of storage, the cells were subjected to the tests of the standard acceptance test sequence. However, no cells were rejected or removed from the storage test on the basis of test data as applied to the acceptance tests prior to start of this storage test. These tests, after each year of storage, serve as a means of reporting the condition of the cells as the test continues and aids in the selection of a cell of lower capacity of each storage method for analysis at the end of each yearly storage period.

1. Data of the acceptance test sequence following completion of the first 1-year storage period is contained in reference (e).

2. Data of the acceptance test sequence following completion of the second 1-year storage period is contained in this report, summarized with that taken before start of the storage test, reference (d), and that following the first 1-year storage period, reference (e).

3. Following removal of one cell of each storage method after each 1-year storage period, the remainder of the cells were recharged and shelved for the following 1-year storage period.

II. CONCLUSIONS

A. The results of the first 2 years of this storage test tend to show that:

1. The initial capacities of charged cells following the first and second 1-year open circuit storage periods are unreliable. They varied from zero to 62 percent of the average initial capacity before start of the storage test.

2. The initial capacities of charged cells following the first and second 1-year trickle charge storage periods are reliable. They averaged 78 and 75 percent respectively of the average initial capacities before start of the storage test.

3. Conversely, the second and third discharge capacities of cells following successive yearly open circuit storage periods are reliable, and averaged considerably higher than the capacities of cells following successive yearly trickle charge storage periods.

B. The ceramic seals of these cells, manufactured by Sonotone Corporation, remain satisfactory after 2 years of the storage test as evidenced by no leakers out of the 18 cells on test.

EVALUATION OF STORAGE METHODS, OPEN CIRCUIT VERSUS CONTINUOUS TRICKLE CHARGE, SONOTONE 3.5 AMPERE-HOUR SEALED NICKEL-CADMIUM SECONDARY SPACECRAFT CELLS

I. INTRODUCTION

A. On 5 June 1968, tests of the acceptance test sequence were begun on 18 cells following the second 1-year storage period.

II. TEST CONDITIONS

A. All tests were performed at an ambient temperature between 23° C and 27° C at existing relative humidity and atmospheric pressure, and consisted of the following:

1. Phenolphthalein Leak Test.
2. Capacity Test.
3. Cell Short Test.
4. Immersion Seal Test.
5. Overcharge Test.
6. Internal Resistance Test.
7. Immersion Seal Test.
8. Visual Postmortem.

B. All charging and discharging were done at constant current (±5 percent). Cells were charged in series but discharged individually.

III. CELL IDENTIFICATION AND DESCRIPTION

A. The cells were identified by the manufacturer's serial numbers which were from A-2491 to A-2564 although not consecutively.

B. The 3.5 ampere-hour "D" cell is cylindrical with an average diameter of 1.306 inches and an average overall length of 2.387 inches including the positive terminal. The average weight was 158.8 grams. Figure 1 is a photograph of a Sonotone Corporation 3.5 ampere-hour "D" cell.

C. The cell container or can, and the cell cover are made of stainless steel. A stainless steel tab, welded to the cover, serves as a contact for the negative terminal. The positive terminal is a solder type extension of the positive plate tab, through the center of the cover. The positive terminal is insulated from the "negative" cover by a ceramic seal. Two crimp rings, about 1/32 inch deep, located about 9/16 inch from each end of the cell, were crimped after assembly to hold the element snugly in the can to withstand vibration.

D. These 18 cells, rated by the manufacturer at 3.5 ampere-hours, have completed two 1-year storage periods at 25° C. Nine of the cells have been on open circuit stand during the last year in the charged state. The other nine cells have been on continuous overcharge during the last year at the c/100 rate (35 milliamperes).

IV. TEST PROCEDURE AND RESULTS

A. Phenolphthalein Leak Test:

1. The phenolphthalein leak test is a determination of the condition of the welds and ceramic seals prior to any electrical tests. This test was performed with a phenolphthalein spray indicator solution of one-half of one percent concentration.

2. There were no signs of leakage of any of the cells subjected to the leak test.

B. Capacity Test:

1. Upon receipt, the cells were subjected to the acceptance tests which included three capacity checks. The capacity test is a determination of the cell capacity at the c/2 discharge rate, where c is the manufacturer's rated capacity, to a cutoff voltage of 1.00 volt per cell.

a. The discharge of each of the three original capacity checks followed a 1-hour open circuit period after a 16-hour charge at the c/10 rate.

b. For the series of three capacity checks following each 1-year period of the respective storage method, the first consisted of an immediate discharge to 1.00 volt per cell at the c/2 rate. The second and third capacity discharge checks followed a 1-hour open circuit period after a 16-hour charge at the c/10 rate.

2. Open Circuit Storage Test:

a. The capacities of the first capacity check of the 10 cells picked for the 1-year open circuit storage periods averaged 3.90 ampere-hours. This was used as 100 percent capacity for the start of the test. All following capacities or averages thereof are plotted on the graphs as percentages of the initial average capacity. Following recharges, the second and third capacity checks averaged 3.80 and 3.61 ampere-hours for 97.5 and 92.5 percent respectively of the first capacity test.

b. Following the first 1-year open circuit stand (1967, reference (e)), the 10 cells were discharged to 1.00 volt per cell at the c/2 rate. This first of three capacity checks ranged from 0.02 to 2.37 ampere-hours for an average of 1.62 ampere-hours, or 41.5 percent of the initial capacity. The capacities of the second and third capacity checks following recharges averaged 3.54 and 3.30 ampere-hours respectively for about 91 and 85 percent of the initial capacity at the start of the test.

c. Following the second 1-year stand (1968), the nine cells (one cell removed for postmortem analysis after first 1-year of storage tests) were discharged to 1.00 volt per cell at the c/2 rate. This first of three capacity checks resulted in capacities ranging from 0.0 to 2.31 ampere-hours for an average of 1.20 or approximately 31 percent of the initial capacity. The capacities of the second and third capacity checks, following recharges, averaged 3.12 and 2.99 ampere-hours respectively for approximately 80 and 75.4 percent of the initial capacity. However, by considering cell A-2495 as having failed by the end of the second 1-year open circuit stand, the averages of the second and third capacity checks following recharges, were both approximately 82 percent of the initial capacity.

d. This shows that the initial capacities of charged cells left on 1-year open circuit stands at 25° C are unreliable. However, the capacities of these cells, following recharges after the first 1-year open circuit stand are 100 percent reliable; and those following the second 1-year open circuit stand are 89 percent reliable since one of the nine cells failed during the second 1-year stand.

e. The capacity test data of charged cells on successive 1-year open circuit storage periods is given in Table I and shown graphically in Figure 2.

3. Trickle Charge Storage Test:

a. The capacities of the first capacity check of the 10 cells picked for the 1-year trickle charge storage periods averaged 3.92 ampere-hours. This was used as 100 percent capacity for the start of the test. All following capacities or averages thereof are plotted on the graphs as percentages of the initial average capacity. Following recharges, the second and third capacity checks averaged

3.81 and 3.59 ampere-hours for 97.2 and 91.6 percent respectively of the first capacity test.

b. Following a 1-hour open circuit period after completion of the first 1-year trickle charge storage period at a charge rate of c/100 (1967, reference (e)), the 10 cells were discharged to 1.00 volt per cell at the c/2 rate. The first of the three capacity checks ranged from 2.33 to 3.73 ampere-hours for an average of 3.06 ampere-hours or 78 percent of the initial capacity. The capacities of both the second and third capacity checks following recharges averaged 2.45 ampere-hours for 63 percent of the initial capacity at the start of the test.

c. Following a 1-hour open circuit period after completion of the second 1-year trickle charge storage period at a charge rate of c/100, the nine cells (one cell removed for postmortem analysis after first 1-year of storage tests) were discharged to 1.00 volt per cell at the c/2 rate. The first of the three capacity checks ranged from 2.28 to 3.29 ampere-hours for an average of 2.92 ampere-hours or about 75 percent of the initial capacity at the start of the test. The capacities of the second and third capacity checks, following recharges averaged 2.59 and 2.85 ampere-hours respectively for about 66 and 73 percent of the initial capacity at the start of the test.

d. This shows that the initial capacities of charged cells left on yearly trickle charge storage periods at the c/100 charge rate are reliable. However, while the capacities of these cells following recharges after the yearly trickle charge storage periods are reliable (average above 63 percent of the initial capacity at start of test), the average capacities are below those of cells following recharges after the yearly open circuit storage periods.

e. The capacity test data of charged cells on successive 1-year trickle charge storage periods is given in Table I and shown graphically in Figure 3.

C. Cell Short Test:

1. The cell short test is a means of detecting slight shorting conditions which may exist in a cell because of imperfections in the insulating materials, or damage to element in handling or assembly; or which may develop in cells due to deterioration of the insulation materials during service life.

2. Following completion of the third capacity discharge test, prior to the start of each yearly storage period, each individual cell was loaded with a resistor of value giving a c/1 to c/5 discharge rate. Each cell was allowed to stand 16 hours with the resistor acting as a

shorting device. At the end of 16 hours, the resistors were removed and the cells allowed to stand on open circuit for 24 hours. Under the regular acceptance test procedure used prior to start of the first 1-year storage period, any cell whose voltage did not recover to a minimum of 1.15 was rejected. However due to the nature of this series of successive 1-year storage periods, cells with recovery voltages less than 1.15 after each yearly storage period are not rejected or removed from succeeding tests.

3. The recovery voltages for the cells, prior to the start of the storage test, ranged from 1.21 to 1.24 volts for an average of 1.22 volts per cell.

4. The recovery voltages for the cells after the first 1-year period under either storage method averaged 1.21 volts per cell.

5. Following the second 1-year open circuit storage period, the open circuit voltage of each of two cells failed to recover significantly above zero volt. However, the recovery voltage of cells following the second 1-year trickel charge storage period averaged 1.21 volts.

6. The recovery voltages values following the cell short test are given in Table II.

D. Immersion Seal Test:

1. The immersion seal test is a means of detecting leakage of a seal or weld. The test was performed before and after the overcharge test during the acceptance test sequence prior to start of each 1-year storage period to determine the presence and cause of leaks.

2. The cells were placed under water in a bell jar container. A vacuum of 20 inches of mercury was held for 3 minutes. Tests are to be discontinued on cells discharging a steady stream of bubbles.

3. None of the cells leaked following the tests of the second 1-year storage period.

E. Overcharge Test:

1. The overcharge tests were performed to determine the steady state voltage at specified rates. The test specified a series of three successive constant current charges at the c/20, c/10 and c/5 rates in order. The charge at each rate was for a minimum of 48 hours or until the increase of the on-charge voltage was less than 10 millivolts per day. Upon completion of 48 hours of charge at each

of the lower rates, the charge rate was increased to the next higher specified rate. These tests were performed prior to start of the storage test, and after each successive yearly storage period under each storage method.

2. The cells were monitored hourly throughout the overcharge test. Under regular acceptance testing, the test procedure requires that charging be discontinued on cells which exceed 1.50 volts, the maximum specified on-charge voltage. However, for this test, charging of a few cells was discontinued when their on-charge voltages exceeded the revised voltage limit of 1.55 but none were rejected or removed from the test.

a. During the overcharge test prior to the first 1-year storage period, charging was discontinued on two of the 20 cells when the voltage exceeded 1.55 volts after 10 hours at the c/5 rate.

b. During the overcharge test after the first 1-year storage periods:

(1) Only one of the open circuit stored cells exceeded 1.55 volts at the c/10 rate. It was removed from the charging circuit after 7 hours of charge, and was not subjected to overcharging at the c/5 rate.

(2) The highest on-charge cell voltage reached by trickle charge stored cells was 1.42 while charging at the c/5 rate.

c. During the overcharge test after the second 1-year storage periods:

(1) Only two of the open circuit stored cells exceeded 1.55 volts for a few hours. The cells were allowed to continue the overcharge sequence and did not exceed 1.55 volts at either the c/10 or c/5 charge rates.

(2) The highest on-charge cell voltage reached by trickle charge stored cells was 1.50 while charging at the c/5 rate.

3. The average on-charge voltages during the overcharge periods of the cells stored under each of the storage methods are shown graphically in Figure 4. This graph indicates that:

a. Under either method of storage, the average of the on-charge cell voltages are higher during the overcharge period before start of the storage test than during the overcharge periods following either of the two 1-year storage periods.

b. Under the open circuit storage method, the average of the on-charge cell voltages during the overcharge periods following each 1-year storage period was less than that of the previous year.

c. Under the trickle charge storage method, the average of the on-charge cell voltages during the overcharge periods following the first 1-year storage period was considerably less than that prior to start of the trickle charge storage; whereas the average of the on-charge cell voltages following the second 1-year storage period was only slightly less than that prior to start of the trickle charge storage period.

F. Internal Resistance Test:

1. This test was performed to determine the internal resistance of the cells.

2. At the completion of the overcharge test; the cells were returned to the c/20 charging rate and given a short pulse (5-10 seconds) at the c/1 charge rate. The cell voltages, V_1, immediately prior to the pulse; and V_2, 5 milliseconds after the initiation of the pulse were read on a CEC high-speed oscillograph recorder (28.8 inches of tape per second). The internal resistance of the cell in ohms was calculated according to the following formula:

$$R = \frac{V_2 - V_1}{I_c - I_c/20}$$

V_1 and V_2 are in volts (read to the nearest 0.01 volt); I_c and $I_c/20$ are in amperes (read to the nearest 0.001 ampere).

3. The internal resistance value for each cell is shown in Table III. Due to the number of significant figures in the voltage measurements, the error in the resistance values is very large (on the order of 10 milliohms). Therefore, it is difficult to obtain any meaningful results for comparative purposes from the resistance data.

G. Visual Postmortem:

1. Following completion of tests after the second 1-year storage period, cell A-2526 from the open circuit portion and cell A-2559 from the c/100 overcharge portion of the 1-year test were opened.

a. The cell subjected to the open circuit test had the following visual characteristics:

(1) The separator material was considerably less pliable than normal with considerable migrated active material on the side adjacent to the positive plate. The heaviest migration was under the scoring area.

(2) The positive plate had normal flexibility with no visible loss of active material.

b. The cell subjected to the c/100 trickle charge test had the following visual characteristics:

(1) The separator material was very pliable with very little migration on any portion of the separator.

(2) The positive plate was less flexible than normal and had little visible loss of active material.

2. For purposes of comparison, the following information on the postmortem of cells A-2536 and A-2564 following completion of tests after the first 1-year storage period is given.

a. Cell A-2536, subjected to the open circuit test had the following visual characteristics:

(1) The separator material was considerably less pliable than normal with considerable migration against the positive plate. The heaviest migration was under the scoring area.

(2) The positive plate was less flexible than normal and had little visible loss of active material.

(3) The negative plate had normal flexibility but had a discoloration on approximately 1/3 of the plate length starting at the center of the core.

b. Cell A-2564, subjected to the c/100 trickle charge test had the following visual characteristics:

(1) The separator material was very pliable with very little migration on any portion of the separator.

(2) The positive plate had normal flexibility with no visible loss of active material.

(3) The negative plate had normal flexibility with no visible discoloration.

TABLE I
CAPACITY TESTS

	Cell Number	Before Storage Periods Ampere-Hours			After First 1-Year Storage Period Ampere-Hours			After Second 1-Year Storage Period Ampere-Hours		
		1st	2nd	3rd	Without Charge 1st	After Recharge 2nd	After Recharge 3rd	Without Charge 1st	After Recharge 2nd	After Recharge 3rd
1-YEAR OPEN CIRCUIT STANDS	A-2491 ●	4.34	4.29	4.11	2.01	3.90	3.55	1.54	3.50	3.50
	A-2492 □	4.06	4.15	4.03	0.02	2.73	3.68	0.00	3.70	3.64
	A-2493 △	3.64	3.50	3.33	2.13	3.46	3.29	1.84	3.24	3.22
	A-2494 ▽	4.11	4.06	3.94	2.33	3.71	3.58	1.79	3.26	3.32
	A-2495 ○	2.98	2.80	2.58	0.02	2.33	2.22	0.04	1.83	0.74
	A-2498 ×	3.69	3.37	3.17	1.72	3.71	3.26	2.31	3.76	3.36
	A-2503 ◇	4.29	4.17	3.80	2.01	3.70	3.26	0.00	2.97	2.80
	A-2508 ♡	3.89	3.97	3.80	2.37	3.42	3.23	1.70	3.10	3.01
	A-2526 ⊕	4.15	4.06	3.97	2.28	4.03	3.85	1.61	2.71	3.36
	A-2536	3.82	3.64	3.36	1.31	3.38	3.06	--	--	--
	AVERAGE	3.90	3.80	3.61	1.62	3.54	3.30	1.20	3.12	2.99
	PERCENT	100.0	97.5	92.5	41.5	90.8	84.6	30.7	80.0	76.8
1-YEAR OVERCHARGE PERIODS AT c/100	A-2540 ●	3.99	3.99	3.99	3.24	2.75	2.83	3.12	2.97	3.10
	A-2542 □	4.17	4.15	3.89	2.65	2.21	2.45	3.18	2.93	3.03
	A-2544 △	3.99	3.82	3.73	3.20	2.61	2.59	2.28	2.31	2.33
	A-2545 ▽	3.78	3.50	3.25	2.97	2.21	2.18	3.21	2.86	2.76
	A-2546 ○	4.41	4.20	3.80	2.83	2.43	2.51	2.98	2.93	3.03
	A-2547 ×	3.50	3.20	2.92	2.33	1.75	1.77	2.28	2.02	2.06
	A-2548 ◇	3.81	3.75	3.47	3.38	2.71	2.47	2.76	1.68	2.84
	A-2557 ♡	3.76	3.80	3.54	3.73	2.89	2.85	3.21	3.15	3.29
	A-2559 ⊕	3.76	3.90	3.76	3.73	2.85	2.74	3.29	2.42	3.18
	A-2564	4.03	3.82	3.59	2.53	2.14	2.15	--	--	--
	AVERAGE	3.92	3.81	3.59	3.06	2.45	2.45	2.92	2.59	2.85
	PERCENT	100.0	97.2	91.6	78.0	62.5	62.5	74.5	66.5	72.7

TABLE II
CELL SHORT TEST
RECOVERY VOLTAGES

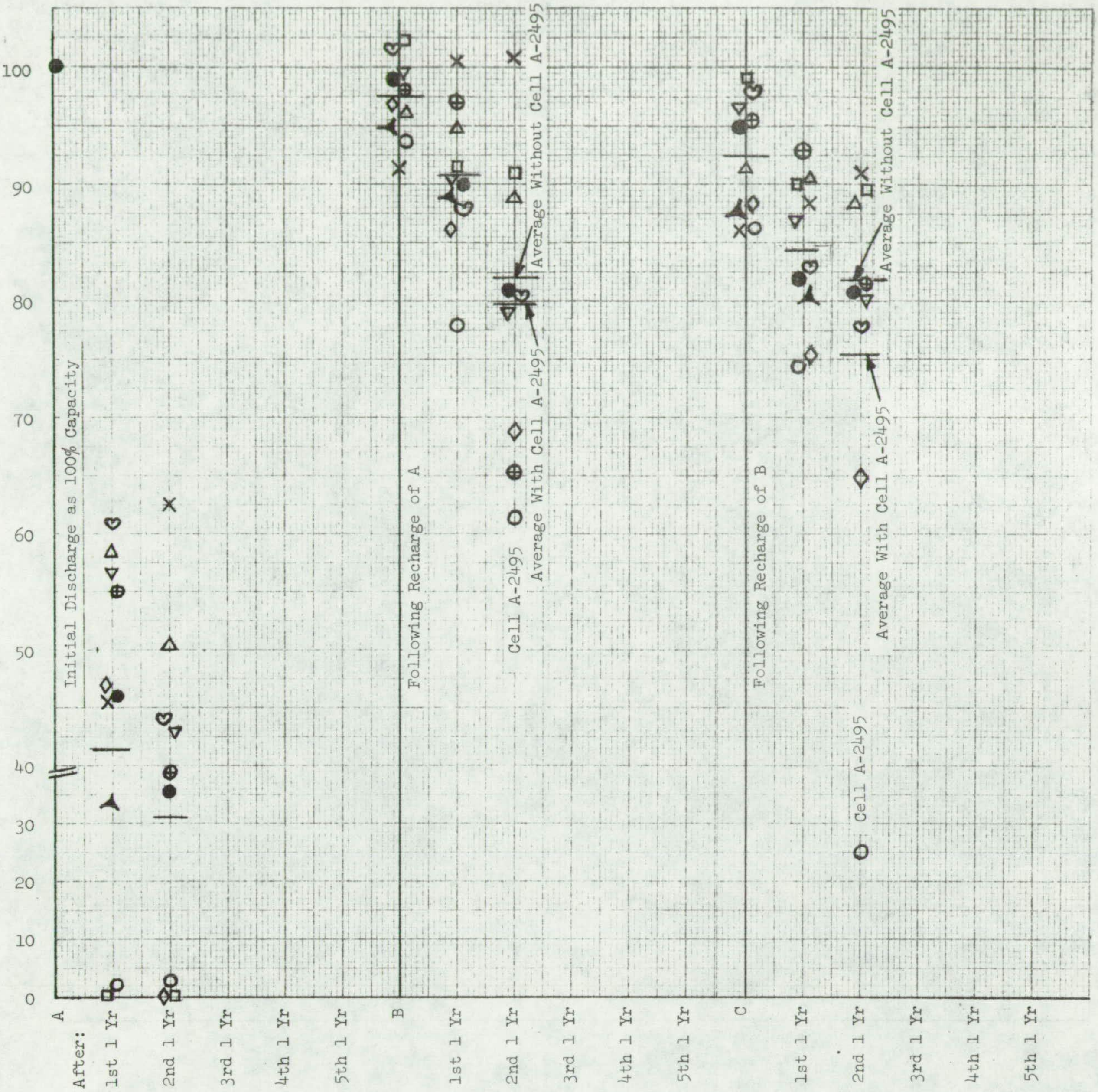
Cell Number	Before Storage Test	After First 1-Year Storage Test	After Second 1-Year Storage Test
A-2491	1.21	1.20	1.20
A-2492	1.23	1.21	0.02
A-2493	1.23	1.21	1.21
A-2494	1.22	1.22	1.21
A-2495	1.22	1.20	1.19
A-2498	1.22	1.22	1.20
A-2503	1.22	1.21	1.22
A-2508	1.22	1.21	0.00
A-2526	1.22	1.20	*
A-2536	1.23	1.22	--
AVERAGE	1.22	1.21	
A-2540	1.23	1.20	1.21
A-2542	1.22	1.19	1.21
A-2544	1.22	1.22	1.20
A-2545	1.22	1.22	1.23
A-2546	1.23	1.19	1.20
A-2547	1.22	1.23	1.24
A-2548	1.24	1.22	1.23
A-2557	1.22	1.21	1.21
A-2559	1.21	1.21	1.22
A-2564	1.23	1.23	--
AVERAGE	1.22	1.21	1.217

* Missed in error

TABLE III
INTERNAL RESISTANCE (Milliohms)

Cell Number	Before Storage Test	After First 1-Year Storage Test	After Second 1-Year Storage Test
A-2491	6.02	12.03	12.04
A-2492	9.02	12.03	12.04
A-2493	15.03	18.04	15.05
A-2494	6.02	15.03	12.04
A-2495	6.02	18.04	21.07
A-2498	6.02	18.04	6.02
A-2503	9.02	15.03	15.05
A-2508	9.02	12.03	9.03
A-2526	3.01	12.03	6.02
A-2536	3.01	12.03	---
AVERAGE	7.22	14.43	12.04
A-2540	6.02	15.03	6.02
A-2542	3.01	15.03	12.04
A-2544	6.02	15.03	15.05
A-2545	6.02	18.04	9.03
A-2546	3.01	15.03	12.04
A-2547	6.02	21.05	21.07
A-2548	6.02	15.03	9.03
A-2557	6.02	15.03	15.05
A-2559	3.01	18.04	9.03
A-2564	3.01	15.03	---
AVERAGE	4.81	16.23	12.04

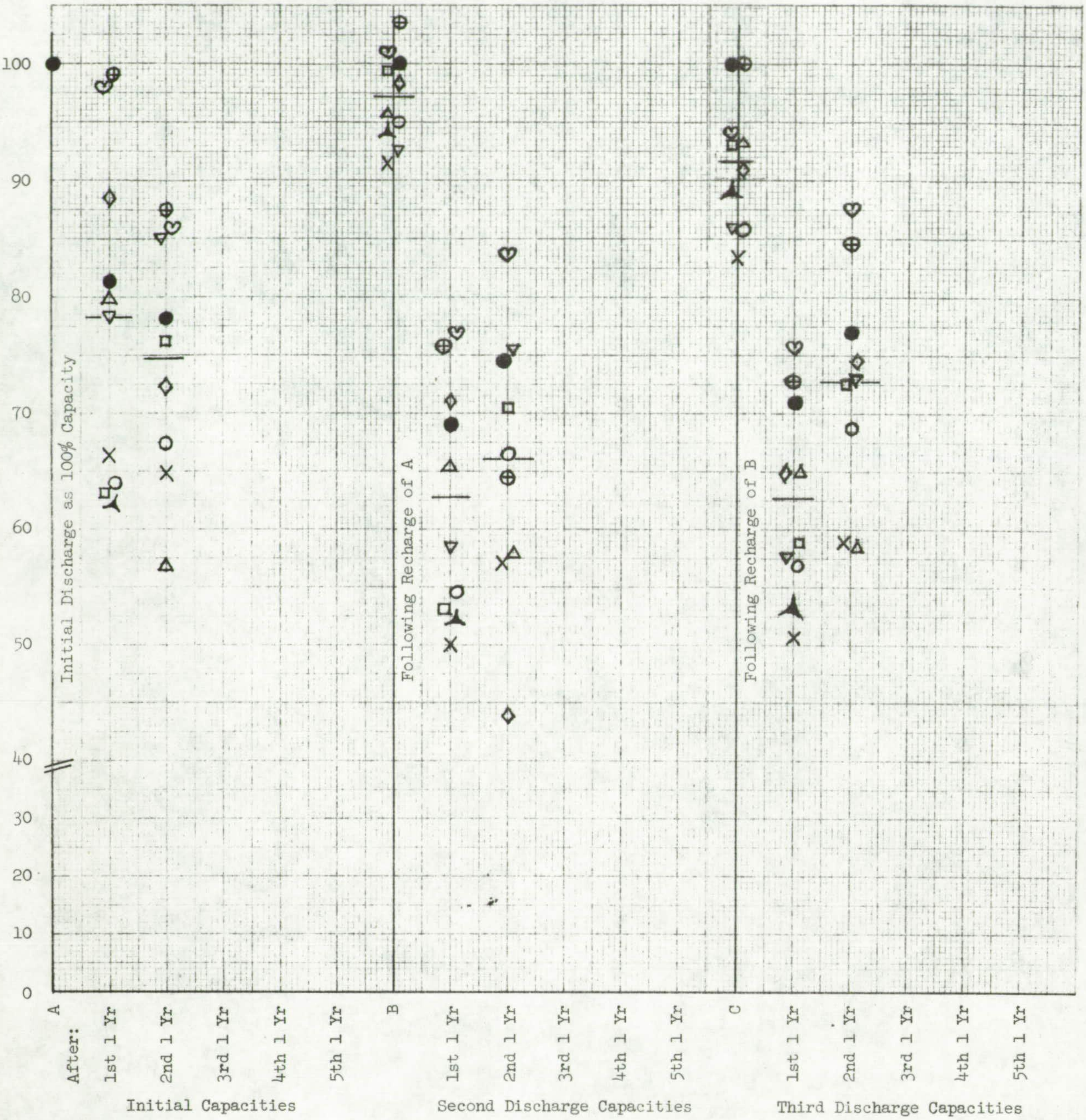
FIGURE 1



OPEN CIRCUIT STORAGE TEST AT 25° ± 2° C

INITIAL AND TWO REPEAT CAPACITY TESTS AFTER EACH YEAR OF OPEN CIRCUIT STORAGE
(Each capacity test shown as percentage of initial discharge.)

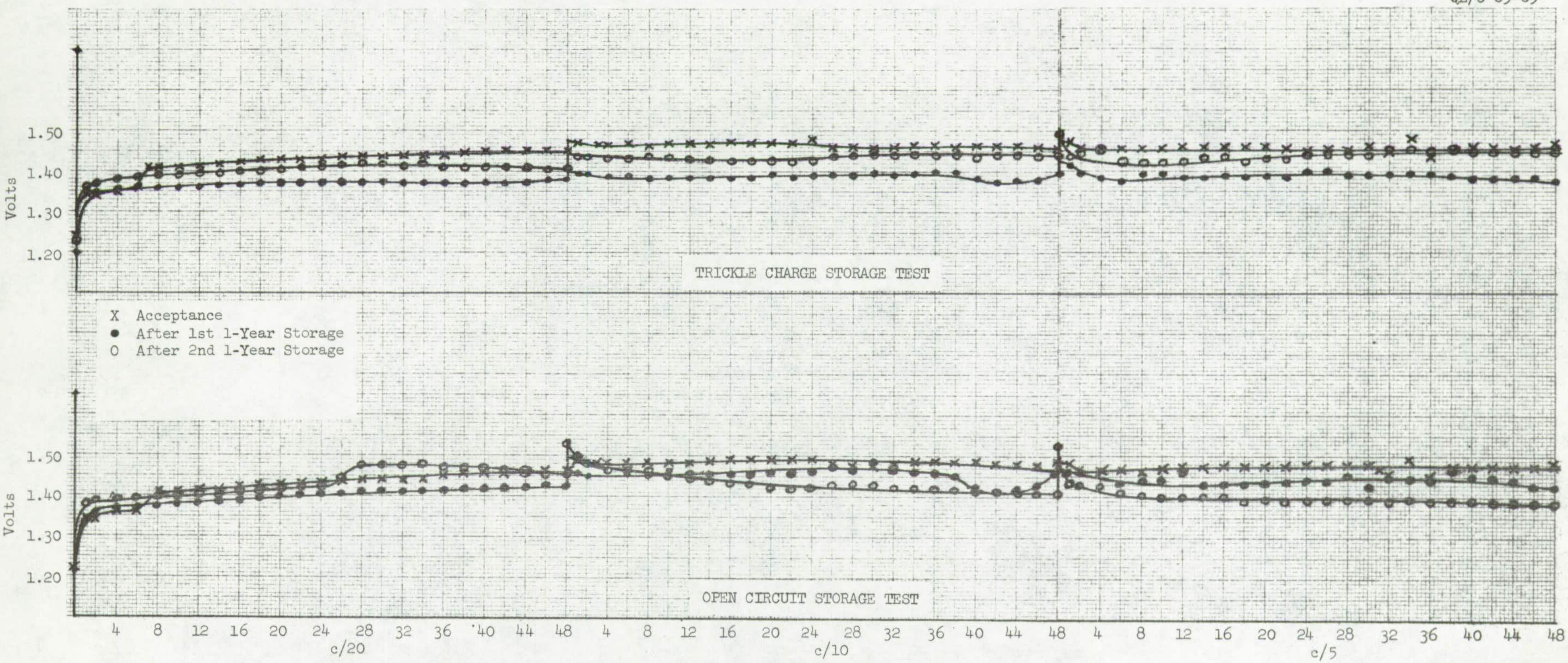
FIGURE 2



TRICKLE CHARGE STORAGE TEST AT 25° ± 2° C

INITIAL AND TWO REPEAT CAPACITY TESTS AFTER EACH YEAR OF TRICKLE CHARGE STORAGE
(Each capacity test shown as percentage of initial discharge.)

FIGURE 3



OVERCHARGE VOLTAGES (AVERAGE) VERSUS TIME AT c/20, c/10 AND c/5

FIGURE 4

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