

Nickel-Cadmium Cells for the Spacecraft Battery

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The storage battery for the Telstar satellite must undergo frequent charge-discharge cycles; in addition, it is subject to overcharge during a substantial portion of its life. Nickel-cadmium cells were chosen as best capable of satisfactory long-time operation under these conditions. A design and selection program was undertaken to ensure that Ni-Cd cores would meet objectives imposed by battery service conditions, and the cell enclosure was designed to minimize electrolyte leakage. Selection, qualification, and life tests indicated that a storage battery using the cell design would perform satisfactorily. To date, the only failures occurring during continuing life tests have been among cells subjected to 100 per cent discharge daily; this operation is far in excess of the expected duty cycle of satellite cells.

AUTHOR

I. BATTERY DESIGN OBJECTIVES

Since the peak power required during the communications experiment exceeds that available from the solar cells, the storage battery will undergo many charge-discharge cycles (to depths of discharge as great as 40 per cent of capacity) during the lifetime of the satellite. On the other hand, several times each year the satellite is in continuous sunlight for long periods, during which the daily average solar cell power exceeds the average power used during visible passes. Thus the battery will receive overcharge current for a substantial fraction of its life.

Design objectives for the storage battery thus include high overcharge capability and long cycle life; additionally, high recharge efficiency is of importance in minimizing electrical losses, and a nonfailing hermetic seal is required to prevent the loss of electrolyte. The nickel-cadmium storage cell, in principle, can meet these objectives. It has a theoretical capability of long cycle life; also, if there is an excess of capacity in the negative electrode of the cell, no hydrogen will be evolved during normal overcharge, and the oxygen which does form will recombine at moderate

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pressures so that the cell can be sealed. However, commercial sealed nickel-cadmium cells available at the beginning of the satellite program did not appear to meet all objectives. Most cells leaked, their electrical characteristics were not uniform, and there were no data to indicate a life expectancy adequate for the Telstar experiment.

II. CELL DEVELOPMENT PROGRAM

The sealed nickel-cadmium cells in the storage battery are the result of a development program intended to effect improvements in two general areas:

- (i) Production controls on active element manufacture
 - (a) Adequate excess capacity of negative electrode
 - (b) Individual cell electrode measurements before assembly.
- (ii) Container enclosure with high integrity
 - (a) Corrosion-resistant seal
 - (b) Improved welding techniques.

Activity in the first area of the above program was made effective through the cooperation of a nickel-cadmium battery manufacturer, who provided special active elements (cores) in accordance with detailed specifications presented below. For the second area, a special container was developed within Bell Laboratories, full advantage being taken of knowledge and processes resulting from experience in enclosing and sealing electron tubes. After assembly, the cells were subjected to a series of selection and qualification tests; on the basis of the results of electrical measurements made during these tests, satellite batteries were assembled of cells with well-matched characteristics.

III. ACTIVE ELEMENTS

Special active elements for nickel-cadmium cells, manufactured in accordance with the specifications in Table I, were purchased.

Cores were made according to these specifications in the research laboratory facilities of the battery manufacturer, with careful attention paid to each process used. The weight increase of plaques due to addition of active material was held within narrow limits; the edges of plates were treated to minimize the possibility of puncture of the separator. Positive and negative plates were assembled into cores, in pairs matched with respect to the results of open-cell capacity measurements. The quantity of electrolyte to be used was specified on the basis of core weight, which was closely controlled.

TABLE I—SPECIFICATIONS FOR F-SIZE CORES

Positive plate thickness:	0.0249 ± 0.0005 inch
Positive plaque porosity:	79.8 ± 0.4 per cent
Negative plate thickness:	0.0200 ± 0.0007 inch
Negative plaque porosity:	78.2 ± 0.6 per cent
Positive plate capacity in open cell test:	9.5 ampere hour minimum at approximately 1.35 ampere discharge rate after a charge of 700 milliamperes for 16 hours.
Ratio of the negative plate capacity to positive plate capacity:	greater than 1.5 for each cell.
Short-circuit test:	all cores to be tested for internal shorts by measuring the resistance between the positive and negative terminals, before the addition of electrolyte.
Separator:	Pellon (nylon) individual sheets to be visually examined for flaws.
Copper contamination:	no material or equipment, including welding tips, which contains copper to be used in any operation involved in preparing the cells.
Electrolyte:	the supplier to provide a recommendation with regard to the quantity and concentration of electrolyte to be added to the cells.
Axial length of core:	3.250 $\begin{matrix} +0.000 \\ -0.015 \end{matrix}$ inches.

IV. CELL CONTAINERS

With one exception, the requirements for the cell container and seal were comparable with the requirements for envelopes used to contain electron tubes. The exception was that the enclosure must be resistant to the potassium hydroxide electrolyte. In order to determine the effect that the electrolyte would have on structural materials, the reaction rates between potassium hydroxide and various metals and insulating materials were measured. Because of time limitations, the majority of these measurements were made at elevated temperatures in order to accelerate the reaction rates. A low reaction rate was observed between the electrolyte and components of the high-alumina ceramic, iron-nickel-cobalt alloy* sealing system, and this system was chosen for the insulator assembly. The remaining design parameters were selected so that the reaction would not cause failure during the time of the Telstar experiment. In addition to the insulator, the enclosure consisted of a cylindrical nickel can and a small nickel-iron alloy tube used for testing and filling purposes. The general appearance of the structure is shown in Fig. 1.

The seal was designed by the Laboratories and fabricated on contract at other locations. Details of the seal are shown in Fig. 2. In order to provide suitable stress balance in the seal and to minimize tolerance problems in fabrication, a configuration was chosen which allowed the metal member to surround conical segments of the ceramic on both the small diameter and the large diameter seal. The bond between the

* Common trade names for this alloy are Kovar and Rodar.

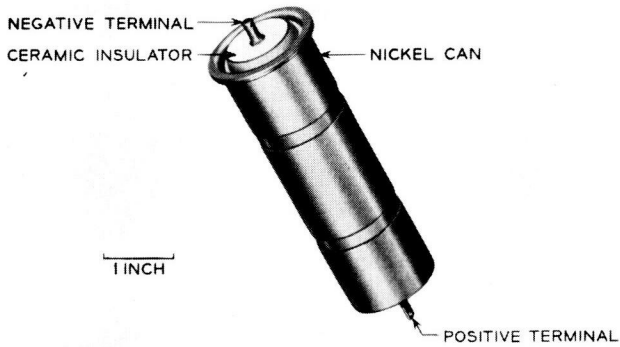


Fig. 1 — Nickel-cadmium cell for spacecraft battery.

ceramic and metal members was made by first metallizing the ceramic with a finely divided mixture of molybdenum and manganese sintered at 1525°C in a wet hydrogen atmosphere. The surfaces were then prepared for brazing by adding approximately 30 milligrams per square inch of electroplated nickel. A nickel-gold alloy requiring a brazing

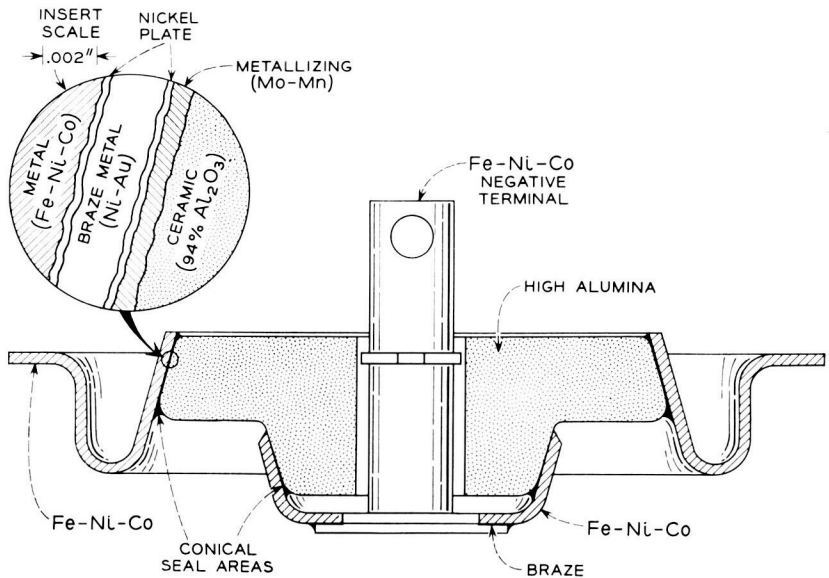


Fig. 2 — Details of ceramic seal.

temperature of approximately 1000°C was used to bond the metallized ceramic to the iron-nickel-cobalt alloy. An additional part later to serve as the negative terminal of the cell was attached to the smaller metal member at the time of the braze. The nickel-gold brazing alloy was chosen in order to avoid copper. Copper, common in other conventional brazing alloys, was considered to be an undesired electrolyte contaminant in cells designed for long life.

The remainder of the container consisted of a cylindrically drawn nickel shell having a flange at the open end with a cylindrical projection coined on the outer surface of the flange. The center of the closed end of the can was pierced to accommodate the tubulation. The tubing was attached to the can by means of a gold braze made in a resistance welder.

The sequence of assembly, as shown in Table II, was initiated by inserting the electrode assembly into the cylindrical can. Then the connector from the positive plate was spot welded to the can as shown in Fig. 3, and the negative connection from the assembly was spot welded to the center terminal of the insulator assembly. The insulator assembly was welded to the flange of the cylindrical can by a resistance weld, using the projection that had been previously formed. A resistance weld was chosen because it provided a positive means of attachment that could be accomplished with a minimum of deformation and with only local heating, thereby eliminating the use of temporary heat sinks and minimizing the chance of damage to the electrode assembly. This weld was performed using a 175-kva welder and a time setting of approximately 1/10 second. If more power had been available, a shorter time cycle would have

TABLE II—SEQUENCE OF ASSEMBLY

Preliminary assembly
(a) Fabricate seal assembly
(b) Fabricate can and tubulation assembly
(c) Fabricate electrode assembly
Insert electrode assembly in can and tubulation assembly
Spot weld electrode connectors to terminals
Projection weld seal assembly to flange of can and tubulation assembly
Add electrolyte through tubulation
Seal tubulation and form positive terminal
Compress can to contact electrode assembly
Charge and selection test

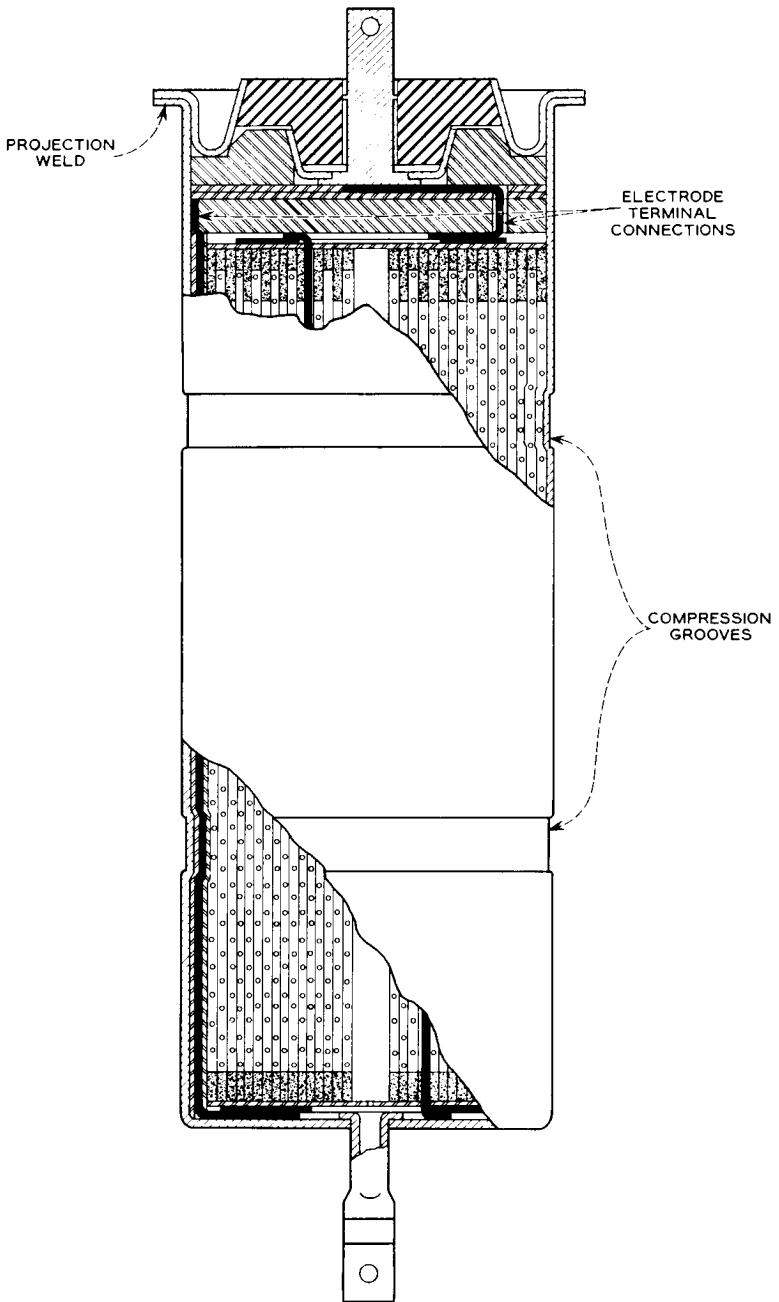


Fig. 3 — Section of completed cell.

been chosen. Cylindrical electrodes were mounted in a die set, and adequate pressure was used to prevent local expulsions.

Next, a carefully metered amount of electrolyte was inserted through the small diameter tubing using a needle type filler. The tubing had an integral gold-clad liner, which was wiped clean after application of electrolyte. Next, the tubing was squeezed flat and sealed by a resistance weld. Thus the final closure was accomplished. By shearing and drilling, the end of the tubulation was formed into a usable positive terminal. Radial compression was applied by a spinning operation to assure a snug fit of the core to the can. The snug fit was used to prevent core motion in the can during the vibration and acceleration of the launch period. Deformation resulting from the compression may be seen as two cylindrical grooves in Fig. 3.

The quality of all closure parts, of the welding operations, and the brazing operations, was evaluated by inspection of metallurgical sections made of sample assemblies. In addition, hydrostatic pressure tests were made to determine the strength of the welds. Each seal assembly and can and tubulation assembly was individually checked for leaks, using helium as a tracer gas and a mass spectrometer as a detector. Similarly, the complete assembly was checked for leaks before the electrolyte was added. The cells were finally sealed with a 50 per cent helium, 50 per cent oxygen atmosphere, with the expectation that tracer techniques could be used on the completed cell. However, after the electrolyte was added, the sensitivity of all types of tracer gas techniques proved to be erratic. It is hypothesized that this behavior is due either to a liquid or solid plug of the electrolyte, or to a compound containing electrolyte that prevented the flow of gas while selectively permitting a seepage of potassium hydroxide liquid. The most sensitive method for detecting leaks after seal-in proved to be the use of hydroxyl ion detectors on external surfaces adjacent to the seal. Tests on the completed container showed that no plastic deformation occurred for internal pressures below 500 pounds per square inch, and that rupture would occur only at appreciably higher pressures. In the event such pressures were generated, no provision was made to prevent destructive rupture.

In life tests of batteries similar to those installed in the satellite, evidence of leakage has been found on some cells. In all cases this leakage appeared to take place in the vicinity of the ceramic-to-metal seal. The design of this seal took into account actual rates of chemical reaction of alkali solutions with the materials used and, while corrosion was expected, the seals were designed so that failure was not anticipated in a two-year interval. Examination of sectional microphotographs of leaking

seals indicated that more rapid attack had taken place in this area than had been anticipated. It was observed that the thickness of the brazing material used in the ceramic-to-metal seal varied from the desired thickness of 2-3 mils to less than 1 mil and to greater than 6 mils. In addition, void areas were found where brazing material was present at both surfaces of the leaking seals. In some instances blisters were discovered between the metallizing and the plating. Leakage observed may have been due to a combination of the expected corrosion of the interface material coupled with fast creepage of electrolyte in void areas internal to the seal. As the voids appreciably reduced the seal length susceptible to corrosion, the time to failure was shorter than anticipated. The completed metal ceramic seals cannot be inspected for continuity of internal interfaces; hence, prevention of internal defects must be established by tolerance control and process inspection.

Experience indicated that when leaks did occur they were small. The dimensions of the material subject to attack were limited by the small circular area of the metal-ceramic interface adjacent to the void, and they were further diminished by the plugs of electrolyte. In most cases the appearance of a carbonate which forms when potassium hydroxide reacts with carbon dioxide in air has been so slight that leaks could not be detected by visual examination even though pH tests of the surface showed the presence of potassium hydroxide. Since the plugging effects observed in the leak-detection experience appeared to limit the flow of gases, it is believed that little gas has been lost from the leaking cells.

V. SELECTION TESTS

The following tests were performed on each completed cell, in the order shown:

(i) Capacity test — At an ambient temperature of 77°F, the cells were charged at 0.6 ampere for a period of 16 hours, then discharged at about the one-ampere rate. This cycle was repeated a minimum of 8 times. The end-of-charge voltage, cell temperature, and cell capacity were measured.

(ii) Continuous overcharge test — At an ambient temperature of 77°F the discharged cells were charged for a period of 64 hours at 0.6 ampere. The end-of-charge voltage and cell temperature were measured. The cells were then discharged and capacity was determined.

(iii) Self-discharge test — At an ambient temperature of 77°F the cells were again charged at 0.6 ampere for 16 hours. At the end of this period the cells were placed on open circuit for a period of 48 hours.

The cell voltage was measured continuously and the cell capacity determined by a discharge at the one-ampere rate.

(iv) Internal resistance test — At an ambient temperature of 77°F the cells were again charged at 0.6 ampere for 16 hours. Following this charge the cells were discharged at the one-ampere rate for 2 hours, after which a 2-ampere, 3-second pulse discharge was performed. The cell voltage was monitored on an oscilloscope to observe the instantaneous voltage change.

(v) Capacity test — Test (i) was repeated for two cycles at an ambient temperature of 30°F.

(vi) Vibration test — The cells were vibrated in the axial direction as shown in Table III. Total time for this test was 4.3 minutes.

(vii) Capacity test — Test (i) was repeated for 4 cycles at an ambient temperature of 77°F.

(viii) Leak test — All cells were tested for leakage using pH indicator paper, which was moistened with distilled water and rubbed over seal and weld.

(ix) Selection — For each test, distribution curves were plotted of the test variable (i.e., end-of-charge voltage, capacity, etc.) versus the number of cells. Only those cells which fell into a tight grouping around the variable mean were selected for satellite use.

VI. QUALIFICATION TESTS

A small sample of cells which passed the selection tests was given the following qualification tests, and then retested electrically:

(i) Vibration tests — Selected cells were subjected to 40g vibration in two planes between 5 and 2000 cps for 1.5 hours.

(ii) Acceleration tests — After vibration tests, the cells were subjected to 30-g acceleration in two planes for $\frac{1}{2}$ hour.

VII. CELL CHARACTERISTICS

Of 513 nickel-cadmium cells constructed and tested as described above, only two were found to be defective. One of these had an ob-

TABLE III

Frequency Range, cps	Test Duration, Seconds	Acceleration, g, 0 to Peak
7-25	30	1.5
25-60	40	14.0
60-2000	75	7.0
550-650	30	14.0

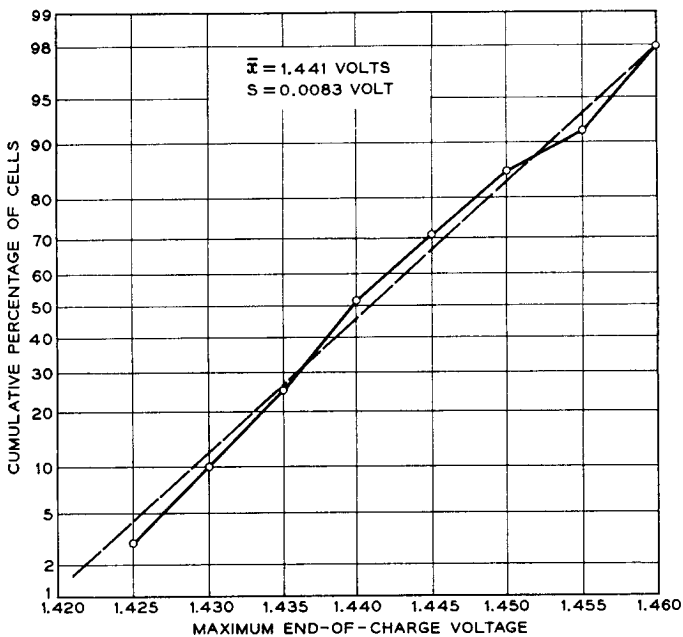


Fig. 4 — End-of-charge voltage distribution, 200 nickel-cadmium cells. Temperature 77°F, 0.6-ampere charge current.

viously cracked seal which caused a leak. The second developed a short circuit during the selection tests, and was considered to be the sole operational failure during selection testing. Only the 391 cells produced in the later stage of seal development were considered suitable for satellite batteries. The first 122 had seals of an earlier design which was considered to be less satisfactory.

Electrically, all cells (except the two noted above) showed adequate uniformity in the important measured quantities. The distribution charts showed normal distribution with satisfactory central values, which changed only slightly from test to test of the selection sequence. An example of a cumulative distribution chart for end-of-charge voltage of 200 cells is shown in Fig. 4. The ordinate scale on this figure is one for which a normal distribution plots a straight line.

A summary of the results of the electrical measurements of all cells at 77°F ambient temperature is as follows:

Capacity	6.2 ± 0.7 ampere hours
End-of-charge voltage at 0.6 ampere	1.45 ± 0.025 volts

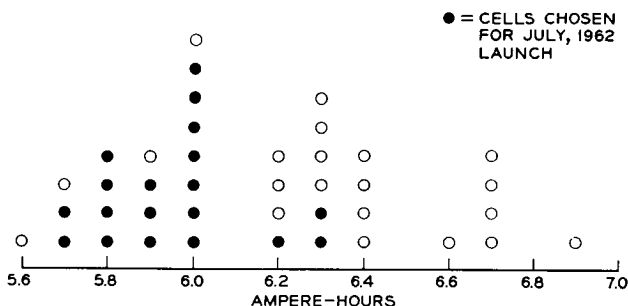


Fig. 5 — Capacity distribution, 40 nickel-cadmium cells.

Capacity loss on open circuit 0.8 ± 0.2 ampere hours (48 hours)

Internal resistance 28.0 ± 4.0 milliohms

Fig. 5 shows a typical chart of capacity measurements for the 40 cells from which the Telstar spacecraft battery was selected. The cells chosen for use were those whose capacities had the tightest grouping around a central value, while also showing reasonably tight grouping around central values of the other electrical quantities measured.

Fig. 6 presents what are commonly known as Tafel curves, for typical cells. These show the end-of-charge voltage as a function of overcharge current at various temperatures between -15°F and 120°F . The curve for 0°F has been extended to show the typical rapid rise of cell voltage which occurs when the overcharge current exceeds the safe value for the temperature at which the cell is operating. The limit to overcharge current is shown, for other temperatures, by the upper ends of the curves. Even at a temperature as low as 30°F the cells can accept the full output current of the solar cell power plant, although they never receive this full amount, nor are they expected to operate at this low temperature.

Ampere-hour charge efficiency of the cells is of general interest for two kinds of operation: (a) charging a completely discharged cell and (b) replacing a partial discharge removed from a fully charged cell. However, only the second of these operations is of importance to spacecraft operation, since the satellite's battery normally is only partially discharged. Representative data from significant efficiency measurements are presented in Table IV.

These data are believed to be descriptive of spacecraft battery performance. The sequence of measurement operations for each test was as follows:

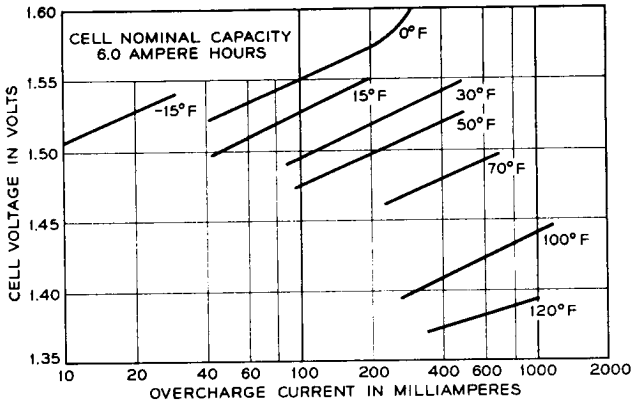


Fig. 6 — Nickel-cadmium cell Tafel characteristics.

- (a) Charge, then discharge, all cells to measure normal capacity
- (b) Charge all cells fully
- (c) Discharge all cells at 1 ampere for 2.5 hours
- (d) Recharge all cells at 0.200 ampere for time indicated
- (e) Repeat (c), (d) nine times
- (f) Discharge all cells to measure remaining capacity.

The above procedure divided capacity-measurement uncertainties among ten charge-discharge cycles, and resulted in efficiency data which had a spread of only a few per cent among all cells measured. Further, the procedure simulated (except for a difference in the time scale) a 2.5-ampere-hour discharge occurring during several successive orbits, followed by recharge during subsequent nonvisible orbits, at about the spacecraft's normal charge current.

The high efficiency noted in the 12-hour charge is actually an incremental efficiency; at the end of this charge-discharge sequence the battery was no longer fully charged. The lower efficiencies of the other tests reflect extra ampere-hours required to recharge the battery more

TABLE IV—AMPERE-HOUR CHARGE EFFICIENCY (REPLACING A PARTIAL DISCHARGE)

Test No.	Temp. °F	Charge, Amperes	Charge Time, Hours	Average Charge Efficiency
1	60	0.200	12	97%
2	60	0.200	14	88%
3	60	0.200	15	82%
4	60	0.200	16	77%

nearly completely. Full charge was obtained only after about 14 hours of recharge time. For this reason, a charge efficiency of 85 per cent is a conservative value to use in calculating the charge-discharge balance of the battery.

VIII. LIFE TESTS

At the time of launch of the Telstar satellite, many thousands of cell-hours of operation had been accumulated as a result of both selection tests of many cells and many experimental studies with a limited number of cells. However, the failure mechanisms of the spacecraft sealed nickel-cadmium cells are not yet known, so that significant life estimates will require data from operation over extended periods of time. Such data will be obtained from several batteries on life test.

One battery of 20 cells was placed on a simulated orbital cycle at room temperature in November, 1961. The cells of this battery had early seals, not used for satellites, but otherwise they were identical with those used for all models of the satellite, including that in orbit. This battery receives approximately 9 charge-discharge cycles per day, as shown in the load profile of Fig. 7. The three deep discharges represent use of the communications equipment during eclipse; the five shallow discharges represent subsequent eclipses when the beacon and telemetry constitute the loads on the power system.

A second battery of 22 cells with later, improved, seals was placed

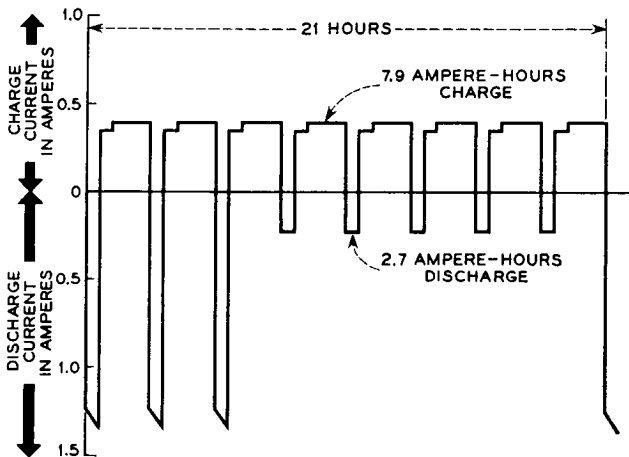


Fig. 7 — Load profile — simulated orbital cycle.

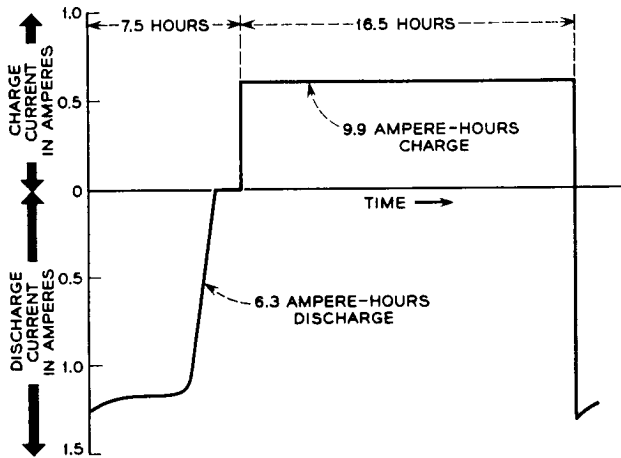


Fig. 8 — Load profile — accelerated life cycle.

on cycle test in April, 1962. This battery receives daily a complete discharge followed by a substantial overcharge, as shown in Fig. 8. This cycle was intended to provide an accelerated life test, and is identical to those of the selection tests; cells of this battery had received 22 selection-test cycles before being placed on life test.

During June, 1962, the battery on the simulated orbital cycle was removed from cycle test for measurements to answer questions raised during the spacecraft tests. Before being returned to the life test cycle all cells were examined for leaks, as had been done periodically since the life test was initiated. An indication of leakage of potassium hydroxide was found around the seals of 5 of the cells. Similar leak tests were made on the cells of the battery on accelerated life test, and two indications of leakage were found. These circumstances are summarized in Table V.

Both batteries were given several deep discharge cycles, after which several other indications of leak were found in cells on orbital life cycle,

TABLE V—JUNE, 1962, RESULTS

20 Cells, Orbital Life cycle		22 Cells, Accelerated Life Cycle
217	Test days	43
1753	Cycles	65
5	No. cells with indication of leak	2

TABLE VI

Group No.	Depth of Discharge	Charge Time, Hours	Discharge Time, Hours*
1	100%	16.5	7.5
2	75%	12	4
3	25%	4	1.5
4	Continuous overcharge at 0.6 ampere		

* Discharge through 1-ohm resistor.

and one other in a cell on the accelerated life cycle. Capacity measurements made during these discharges showed no loss of capacity from that measured on the cells during selection tests.

After the finding of indications of leakage in June, the battery on accelerated life cycle was divided into 4 cell groups, to determine, if possible, the effects of different modes of operation. These 4 groups were operated as shown by Table VI.

New cells previously subjected only to the selection test cycling were added to these groups as shown in Table VII.

In October, 1962, all the above cells were discharged to measure capacity. All yielded the capacity measured during their selection tests. The original cells had 6 months of operation, the new ones four months, all in addition to the selection tests. Eight of the original cells gave a positive indication to leak test, as did seven of the new cells. These seven were distributed among the four groups with no clear correlation between mode of operation and tendency to leak.

Most of the leaks discussed above have not resulted in visual evidence of the effect of potassium hydroxide reaching the open air. Thus the loss of electrolyte by these cells is quite small, although it is enough to cause a blue coloration of the indicator paper used in the leak test. As discussed in connection with the cell enclosure, it is believed that loss of evolved gas is also small.

In December, 1962, after more than one year of operation, all cells on

TABLE VII

Group No.	Depth of Discharge	Original Cells	New Cells	Total
1	100%	5	7	12
2	75%	5	5	10
3	25%	5	5	10
4	Continuous overcharge, 0.6 ampere	5	8	13

simulated orbital cycle, with their early seals, showed indications of leak. Less than half of the cells with later seals showed indications of leak. However, three of the cells in group 1 (Table VI) were found to have distorted seal assemblies, indicating that internal pressure had built up to dangerously high levels. End-of-charge voltages on these, as well as on several nondistorted cells of group 1, had risen to 1.5 volts. It has been determined that these cell failures were coincident with the evolution of hydrogen gas, although the cause of this evolution is not yet known.

Thus the first cell failures have occurred on the accelerated life cycle (100 per cent discharge daily). All cycle tests are being continued, and it is anticipated that useful data on both length of life and mechanism of failure will eventually be acquired. As yet, however, there are no significant data on which to estimate cell life in a satellite environment. Telemetry data from the satellite continued to show normal battery performance through January, 1963.