HERMETICALLY SEALED NICKEL-CADMIUM BATTERIES FOR THE ORBITING ASTRONOMICAL OBSERVATORY SATELLITE

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Abstract

A report is presented on the design considerations and the testing of the battery for this large NASA satellite scheduled to be orbited in 1964. The construction of the cells and batteries is described. The electrical, thermal and mechanical aspects of the battery are delineated. Life cycle testing is reported along with the reliability assessment based on the life test data.

I. Introduction

The Orbiting Astronomical Observatory is a NASA Scientific Satellite under the prime auspices of Grumman Aircraft Engineering Corporation. It will provide at a distance of 500 miles from the earth a stationary observation platform to permit scientists to explore the universe unimpeded by the earth's atmosphere. The period of the orbit is 101 minutes.

Among the main subsystems of the Orbiting Astronomical Observatory is the electric power supply. It uses solar cells as the primary converter, inverters, regulators, and hermetically sealed nickel-cadmium storage batteries.

In May 1961, GAEC entered into a program with Gulton Industries to design, develop, and qualify the storage battery for the Orbiting Astronomical Observatory.

Presented at the ARS Space Power Systems Conference, Santa Monica, Calif., September 25-28, 1962. Many people have contributed to the program described herein. In particular, Jay Wartell, Project Engineer, Gulton Industries, has made a significant contribution.

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II. Development of the Orbiting Astronomical Observatory Storage Battery

The following is an outline of the program to provide the Orbiting Astronomical Observatory storage battery: 1) design study for cells and batteries, 2) development testing, 3) prototype fabrication, 4) qualification testing, 5) life cycling, and 6) fabrication and acceptance testing of flight batteries.

The hermetically sealed nickel-cadmium cell is the VO-20 HS size which is rated at 20 amp-hr. It contains carefully selected and inspected sintered plate electrodes, an hermetic ceramic-to-metal seal, a nonwoven nylon separator, a steel container, and welded closures, the amount of electrolyte, the type of separator, and the configuration of the electrode assembly, an overcharge capability has been built into the cells such that when the cells are fully charged, the normal internal operating pressure will not exceed 50 psi during C/10 overcharge. The design of the cell included a material evaluation to select materials for the cell and the hermetic seal which were resistant to the strong caustic oxidizing environment inside the cell. In addition, the effects of trace contaminants of these materials on the kinetics of the nickel and cadmium electrodes were studied to insure no change of cell characteristics due to minor corrosion and/or deterioration during cell life. Separators were screened carefully for both electrical and mechanical performance, and nylon separators are used. Cell case alloys and welds were studied for stress corrosion effects and 304 stainless steel was selected for the cell case. The mechanical design of the hermetic ceramic-to-metal seal is such as to withstand the thermal and mechanical stresses caused by cell fabrication and subsequent use. The hermetic seal has a leakage rate of less than 2×10^{-6} cc/sec of helium at 1 atm.

Because of the expected battery temperature variation in orbit of 35°F to 110°F, electrical development and qualification tests are being run between 5°F and 134°F. During the course of cell development testing, the following electrical information was collected: 1) charge-discharge characteristics at various temperatures, 2) cycle life characteristics, 3) overcharge characteristics, 4) limiting voltage and current values for sealed cell and battery operation as a function of temperature, and 5) self discharge.

Table 2 shows a comparison of the capacities of cells at different temperatures. Five cells in series were used for each test.

Note that low rate charging at low temperatures results in higher capacity. The values are above the nominal 20 amp-hr. At charge currents of 7 and 15 amp, no advantage accrues to low temperature operation, and in fact, at a 15 amp charge rate the resulting capacity is low at 40°F. In addition, at lowered temperatures care must be exercised during charge not to exceed the voltage level at which hydrogen will be generated internally, causing cell pressure to rise.

Figure 1 shows the discharge characteristics of VO-20 HS-B cells at 90°F for various rates of discharge.

Figure 2 shows the discharge characteristics of the VO-20 HS-B as a function of temperature. As shown previously in Table 1, very little difference in capacity is noted between 90° and 40° after about a 10 amp charge. The voltage level of the colder discharge is lower, however, due to the higher internal resistance of the cell. At 21°F the initial discharge voltage is higher because a higher potential is achieved during cold charge, but at a 10 amp charge rate, no permanent advantage to subsequent capacity is attained. At 134°F the self discharge causes reduced voltage and reduced capacity as compared to 90°F.

The charge characteristics of groups of 10 cells are shown in Figs. 3 and 4. In Fig. 3, at 90°, note that during the 2 amp charge, there is a slight peak in voltage after which the cell voltage levels off to the steady state overcharge value that is depicted in Fig. 5.

At the 7 amp and 15 amp charge rates, the cells are being charged at rates beyond their steady state overcharge capability, and the charge therefore was stopped before cell voltages reached a steady value, if indeed they would have at all. Note that the maximum spread between cell voltages occurs at the end of charge, and this must be considered duly if control by voltage is contemplated.

As shown in Fig. 4, charge at low temperature accentuates high current affects. The 2 amp charge had begun to level off while the 7 amp and 15 amp charges were terminated. Note the increased voltage spreads for these two charges.

Figure 5 shows the steady state overcharge voltage characteristic of the VO-20 HS cell. At elevated temperatures the slope of the voltage vs log current line decreases.

As part of the qualification program for the Orbiting Astronomical Observatory cells, life tests are being run at temperatures between 5°F and 110°F. A 36% depth of discharge is reached and the cycle period is 101 minutes. Figures 6-8 summarize life cycle tests still in progress. Groups of 5 cells are running in each case. At 48°F and at 90°F the results are extremely uniform. At 48°F there is a larger spread in voltage during the course of the cycle as compared to 90°F. At 110°F the early several hundred cycles were erratic until the recharge current was adjusted properly to adequately recharge the batteries. The end of discharge voltage continued to be nonuniform but the average discharge voltage was fairly stable at slightly above 1.2.

It has been observed and previously reported[1] that during continuous cycling at room temperature, hermetically sealed nickel-cadmium cells exhibit a memory effect such that after a few hundred cycles they appear to assume a capacity close to the depth to which they are being cycled. For example, cells which are being continuously cycled in a 70% depth of capacity routine will if completely discharged to 1.0 v. deliver no more than 70% of capacity. A subsequent charge at C/10 for 24 to 48 hr. returns the cell to full capacity which can be observed if the cell is immediately given another capacity check. Gradually, however, the cell capacity out of cycle retreated to slightly more than the cycling value. At very shallow depths such as 10%, about 25% of capacity remains available.

This phenomenon again has been observed in the Orbiting Astronomical Observatory tests at 90°F and 110°F but at 48°F the memory effect was not observed and the cells retained their full nominal capacity even though operating in the 36% depth routine. The data in Table 2 show this effect.

The electrical design of the Orbiting Astronomical Observatory battery package consists of three strings of 22 cells each. One string will operate the equipment while the two redundant strings are available as standby batteries that increase the reliability of the total battery package. The operating battery is, on the average, cycled to a depth of 36% and if its voltage falls below 22.0 v, one of the standby batteries is switched into operation. The average cycle routine consists of a 101 minute orbit with 36 minutes of discharge and 65 minutes of recharge. In some cycles, 85 minutes of continuous sunlight are encountered. Standby batteries are kept fully charged by an intermittent trickle. Each battery string has its own charge control regulator, and, during sunlight intervals, as the operating string becomes charged, solar array current is diverted to the standby strings. Battery selection also can be accomplished by ground command.

Since the charge control regulator depends on cell voltage sensing for its control function, it must have built into it a temperature compensated value for the control voltage. During cell development tests there was determined for individual cells a value of voltage at any temperature between 5°F and 120°F which was never to be exceeded for safe operation of the sealed cells. Since a battery of 22 cells will not have all its cells at the same voltage at the same time during charge, and since, as shown in Figs. 3 and 4, there is a spread in voltage between cells, it was necessary to determine a maximum "battery voltage" curve. Tests run on batteries yielded data on voltage spreads, and the curve of Fig. 9 was developed. When the battery voltage reaches the indicated value during charge, no cell will be at a voltage level where hydrogen will be generated internally.

Another piece of information, which was of interest, is the self discharge of these cells. The data are shown plotted in Fig. 10. In all probability, self discharge will not be a significant factor during normal Orbiting Astronomical Observatory operation.

For the mechanical design of the battery, thermal considerations dictated the geometry of the package. In order to provide the necessary thermal coupling to keep all cells, both operating and standby, at approximately the same temperatures, to keep the temperature of the heat sink uniform, and to assure sufficient area for waste heat rejection from the heat sink by radiation, a configuration was designed consisting of two (2) battery assembly packs, each containing three (3) half batteries in good thermal contact. The configuration is shown in Fig. 11. The total battery package has a capability of 11.1 watt hours per pound and 1.4 watt hours per cubic inch.

With the thermal information obtained in testing individual cells, it was possible to analyze battery configurations analytically. Calculations indicated that an assembly pack in which cells were layered two per level, side by side, to a height of 17 layers (using one dummy cell for a total of 34 cell units) would meet the thermal requirements. Adjacent layers have their terminals rotated 90° so that any one face of the pack has all the terminals and intercell connectors of only one half battery. The fourth side of the assembly is the heat sink surface.

To test the thermal design, a prototype of a 10 cell section of the Orbiting Astronomical Observatory battery was constructed, placed in a vacuum of 7×10^{-5} mm of mercury, put through a routine consisting of 3 hr of charge, 16 hr on overcharge, and then fully discharged. Tests were run with heat sink temperature of $10^{o}F$, $60^{o}F$, $80^{o}F$, and $130^{o}F$, and in all tests the maximum thermal gradient from the heat sink to the skin of the cell being charged never exceed $13^{o}F$. This compares favorably with the calculated gradient of $12.9^{o}F$.

Transient thermal tests were performed to see what response the prototype battery had with respect to a decreasing or increasing heat sink temperature. In the first test, the average battery temperature and the heat sink temperature were at $84^{o}F$. The heat sink temperature then was reduced to $0^{o}F$ as the battery was placed on charge. It was observed that the average temperature of the prototype battery decreased $30^{o}F$ for the 5 hr run.

In the second test the average battery temperature and the heat sink temperature were at $40^{o}F$. The heat sink temperature was increased to $130^{o}F$ as the battery was placed on charge. It was seen that the average battery temperature increased $65^{o}F$ during the 5 hr run.

The analytical results and their verification by experimentation indicate that the design of the Orbiting Astronomical Observatory battery is satisfactory for it to function under the thermal conditions it will see in space. The passive temperature control design assures that the battery will remain between $35^{o}F$ and $110^{o}F$.

III. Reliability Assessment of The Orbiting Astronomical Observatory Battery Package

As of June 26, 1962, three early prototype cells had each survived 3905 cycles at $48^{o}F$. Cycle data for the cells on the life cycle part of the qualification test are given in Table 3. Estimates of cell life given below include the prototype cells and cells tested at $48^{o}F$ and $90^{o}F$.

When it is assumed that the number of cycles to failure follows a exponential distribution and data are pooled from the prototype and qualification tests, then, the estimates of mean number of cycles to failure are: 1) for a cell, 22990 cycles, 2) for a battery, 1045 cycles, and 3) for the power package, 3135 cycles.

Using the assumption of a Gaussian distribution, with standard deviation 1% of the mean, the probability that the power package will survive more than 7000 cycles is in excess of 0.999999. If it is assumed that the standard deviation is 10% of the mean, the probability that the power package will exceed 7000 cycles is greater than 0.99.

IV. Conclusion

A carefully worked out program has been in progress to provide reliable sealed cells and to provide a satisfactory battery design for the Orbiting Astronomical Observatory satellite. The cells have been tested and qualified both technically and mechanically, and are at present undergoing life tests. An ingenious battery design has been achieved to minimize weight and maximize transfer of waste heat to a radiating heat sink. Electrical and environmental tests of the battery package indicate an adequate design, and battery prototypes are being readied for the formal qualification testing. Life cycling of cells to date indicates a probability in excess of 99% that the battery will perform its function for the prescribed 7000 cycles.

References

[1] "Nickle-cadium batteries," Aeronaut. Sys. Div. TDR-62-67,Wright Patterson Air Force Base, Ohio(April 1,1962).

Table 1 Comparison of Capacities After Similar Charges At Different Temperatures

I_a after 2 amp charge and overcharge and 20 amp discharge

Cell no.	388B	389B	390B	391B	392B	Avg	Range
40°F	23.0	24.3	22.7	21.7	25.0	23.3	3.3
90°F	20.0	20.7	17.8	16.3	19.0	18.8	4.4
Difference	3.0	3.6	4.9	5.4	6.0	4.4	3.0

I_b after 2 amp charge and overcharge and 10 amp discharge

Cell no.	393B	394B	395B	396B	397B	Avg	Range
40°F	23.5	25.7	23.8	21.7	25.2	24.0	4.0
90°F	20.7	20.3	18.8	19.8	20.8	20.1	2.0
Difference	2.8	5.4	5.0	1.9	4.4	3.9	3.5

II_a after 7 amp charge for 25 amp-hr and 20 amp discharge

Cell no.	388B	389B	390B	391B	392B	Avg	Range
40°F	21.4	20.0	18.3	19.9	20.0	19.9	3.1
90°F	20.3	20.4	18.3	17.7	20.1	19.4	2.7
Difference	1.1	-0.4	0	2.2	-0.1	0.6	2.6

II_b after 7 amp charge for 25 amp-hr and 10 amp discharge

Cell no.	393B	394B	395B	396B	397B	Avg	Range
40°F	20.3	20.8	19.4	18.4	21.6	20.1	3.2
90°F	20.2	20.8	19.3	19.7	20.9	20.2	1.5
Difference	0.1	0	0.1	-1.3	0.7	-0.1	2.0

Table 1 Continued

III_a after 15 amp charge and 20 amp discharge

Cell no.	393B	389B	390B	391B	392B	Avg
40°F	19.7	18.0	18.7	18.3	17.3	18.4
90°F	21.3	20.7	20.7	18	18	19.9
Difference						-1.5

III_b after 15 amp charge and 10 amp discharge

Cell no.	393B	394B	395B	396B	397B	Avg
40°F	18.8	19.6	17.7	17.5	20.0	18.7
90°F	18.8	19.3	20.3	18.8	19.8	19.5
Difference						-0.8

Table 2 Cycling Capacity of VO-20 HS Cell

	48°F	90°F	
Cycle No.	Out of Cycle Capacity	Out of Cycle Capacity	Capacity After Recharge at 10 amp
100	20.0	12.8	...
200	20.8	7.5	10.7
300	21.5	7.5	11.3
400	21.5	7.2	9.0
500	21.5	7.3	13.3
600	22.3	10.7	11.2
			Capacity After Recharge at 2 amp
700	22.8	10.8	17.5
800	20.0	6.7	21.0
900	22.3	13.3	19.2
1000	22.3	13.5	19.7
1200	22.8	16.0	21.7
1500	23.6	19.5	20.0
1800	23.7	13.7	20.3
2000	...	...	...

Table 3 Cycle Life Data

No. of cells	Temp. °F	No. of cycles/cell
5	90°	1194
5	48°	1061
4	110°	1144
4	5°	215

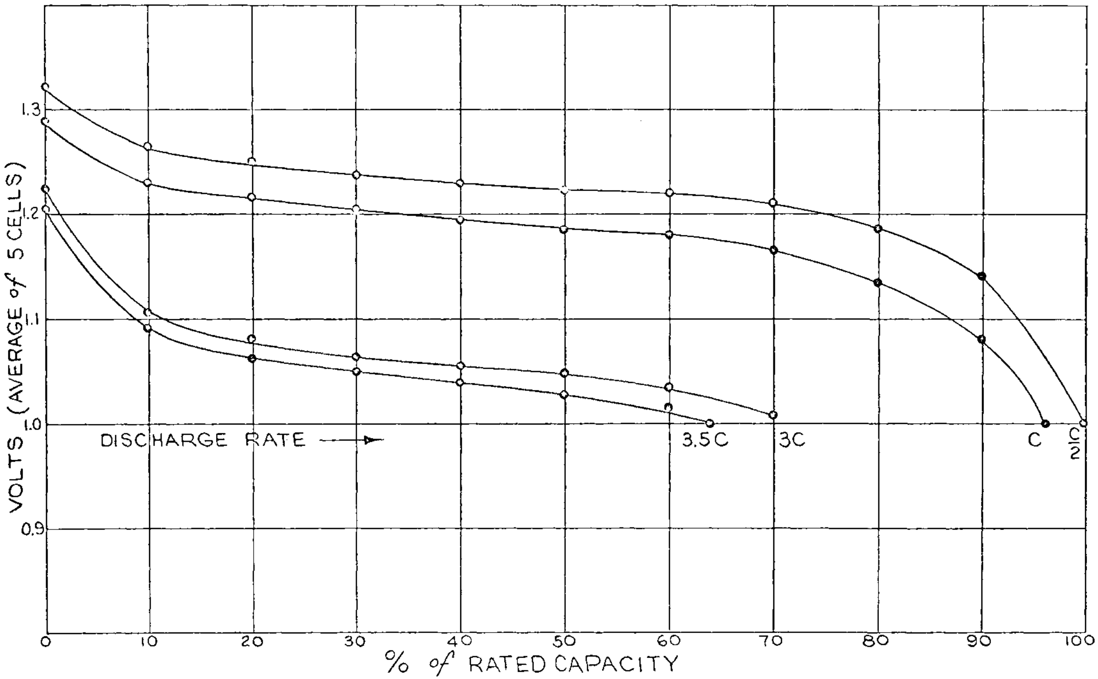

Fig. 1 Discharge characteristics of VO-20 HS-B hermetically sealed nickel-cadmium cells at 90°F

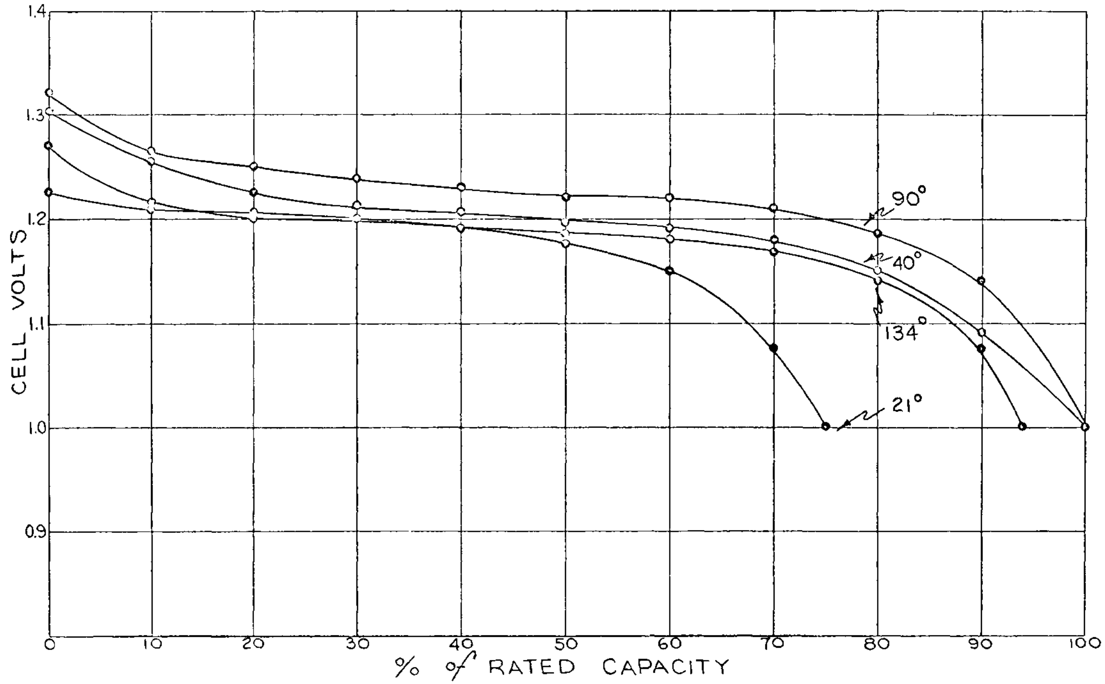

Fig. 2 Discharge characteristics of VO-20 HS-B hermetically sealed nickel-cadmium cells at C/2 rate at various temperatures after 10 amp charge and 8 hr stand

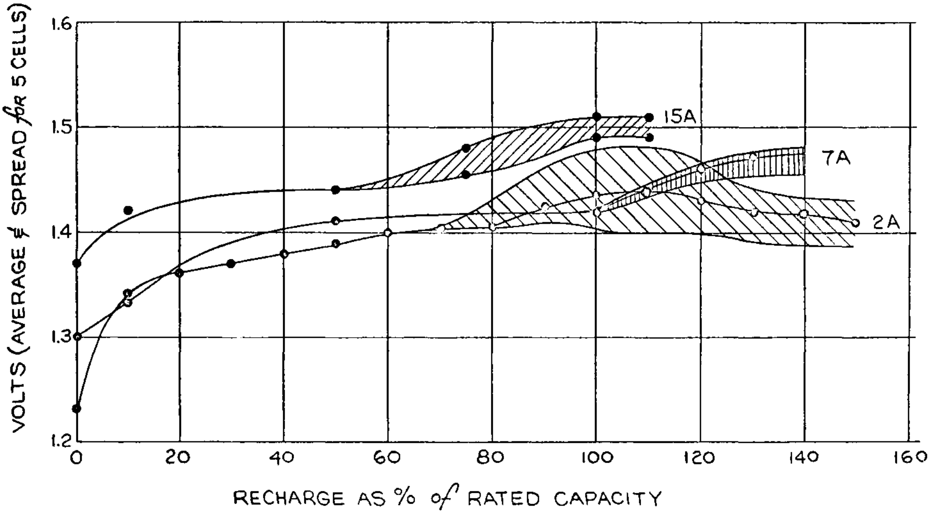

Fig. 3 Charge characteristics of VO-20 HS-B hermetically sealed nickel-cadmium cells at 90°F

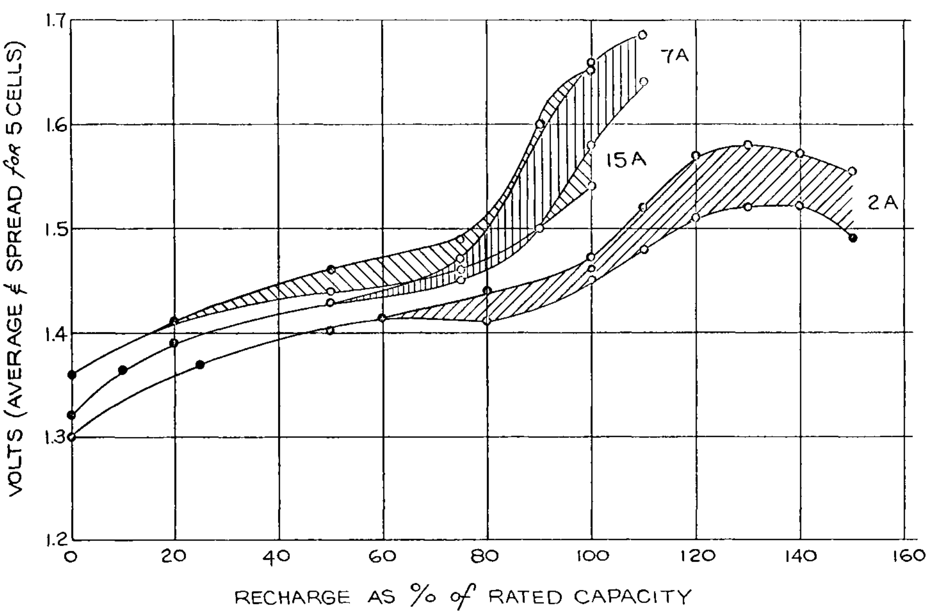

Fig. 4 Charge characteristics of VO-20 HS-B hermetically sealed nickel-cadmium cells at 40°F

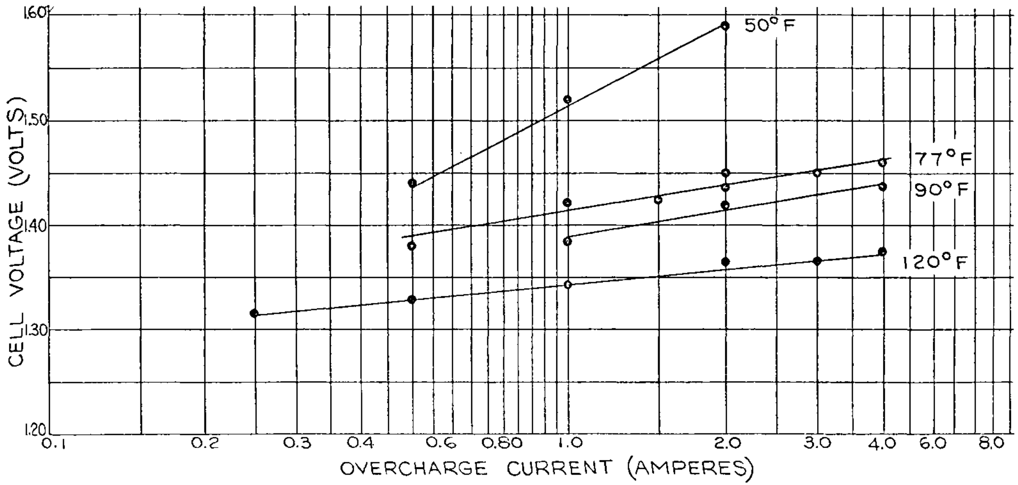

Fig. 5 Overcharge voltage characteristics of VO-20 HS-B hermetically sealed nickel-cadmium cells

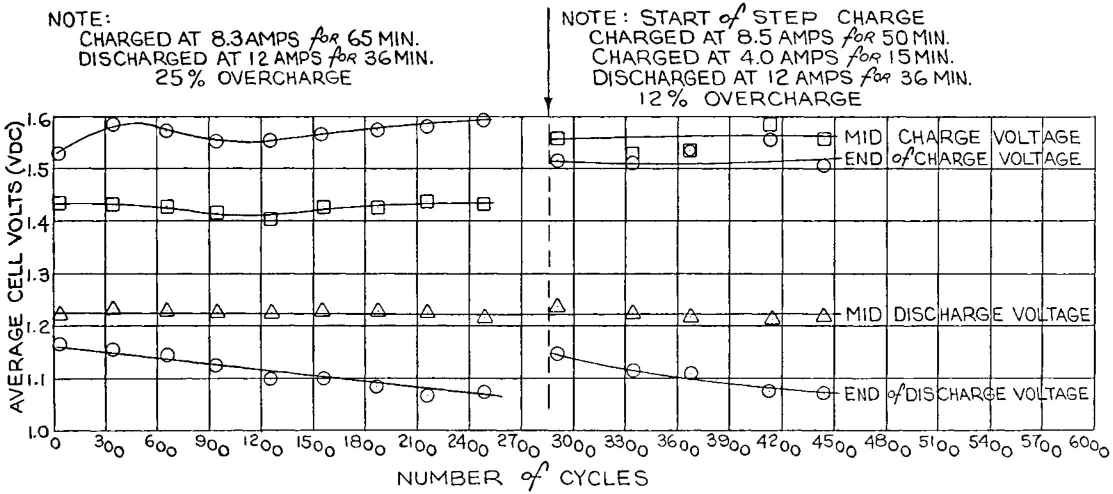

Fig. 6 Orbiting Astronomical Observatory Qualification test. Life cycling data at 48°F

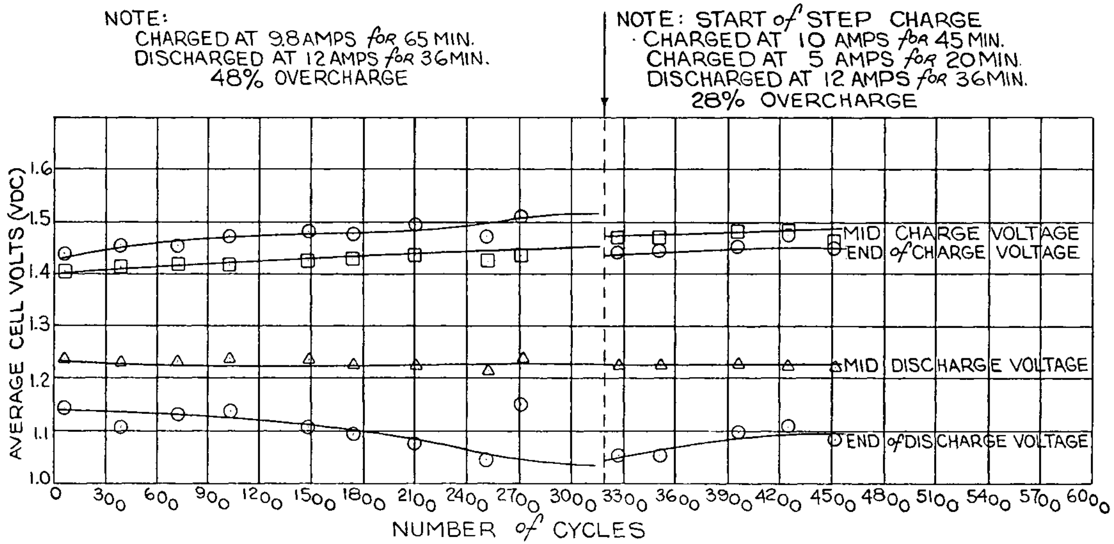

Fig. 7 Orbiting Astronomical Observatory Qualification test.
Life cycling data at 90°F

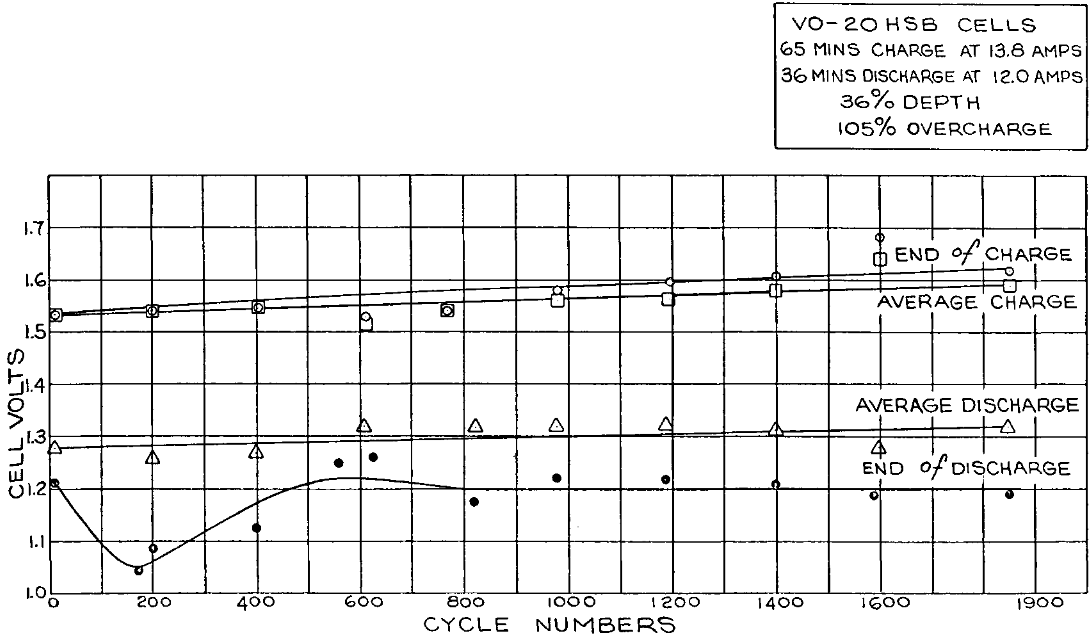

Fig. 8 Orbiting Astronomical Observatory Qualification test. Life cycling data at 110°F.

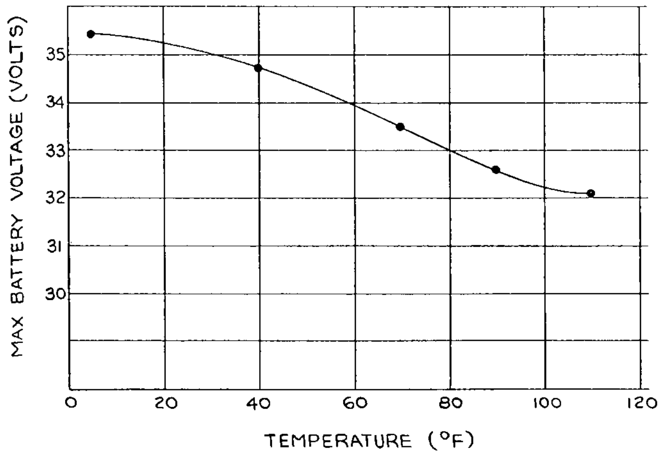

Fig. 9 Maximum limiting charge voltage for a battery of 22 VO-20 HS-B hermetically sealed nickel-cadmium cells

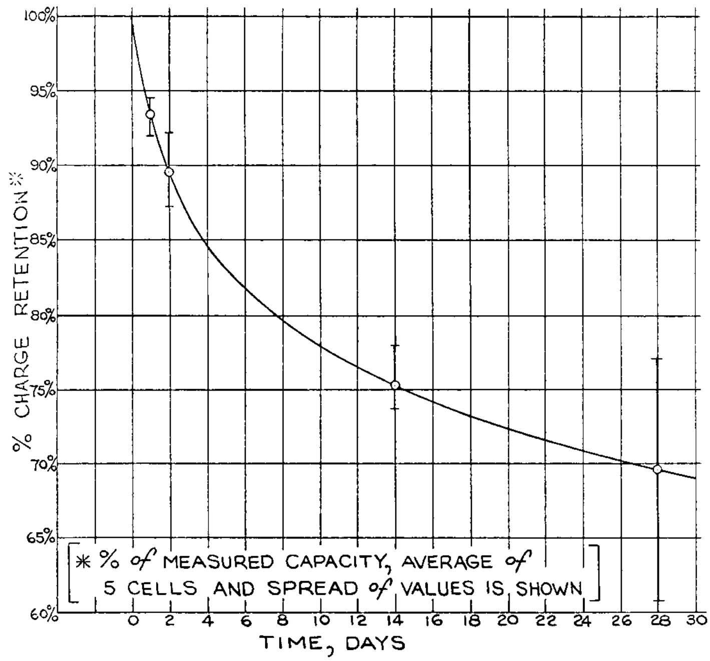

Fig. 10 Charge retention of VO-20 HS-B hermetically sealed nickel-cadmium cells at 90°F

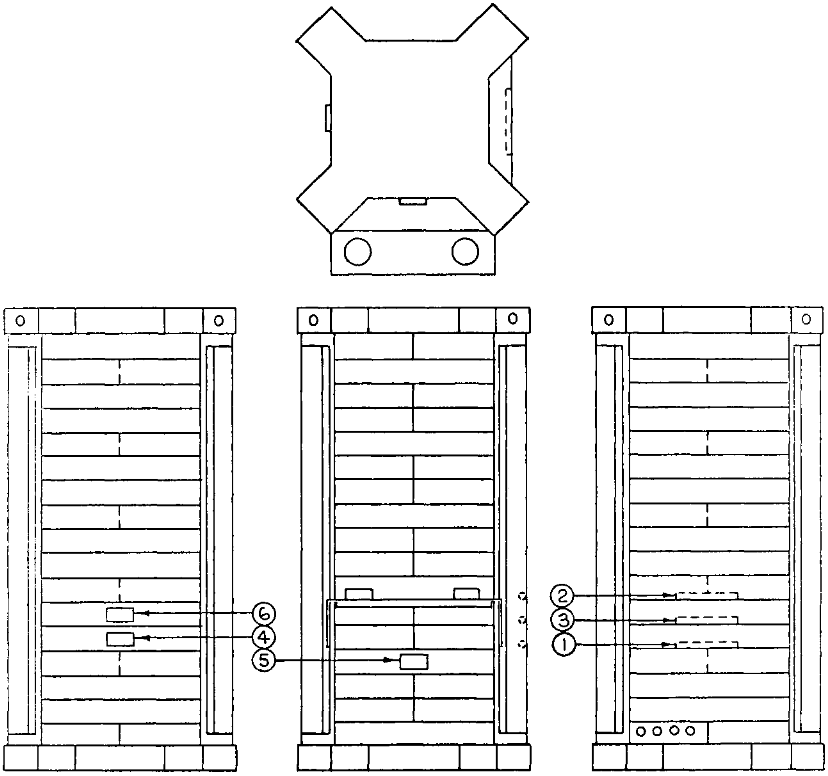

Fig. 11 Orbiting Astronomical Observatory battery assembly. The numbered items are temperature sensing devices.