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USE OF THE ADSORPTION HYDROGEN ELECTRODE AND THE OXYGEN FUEL-CELL ELECTRODE IN NICKEL-CADMIUM CELLS

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GODDARD SPACE FLIGHT CENTER
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ABSTRACT

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The characteristics of two types of auxiliary electrodes are investigated. The essentially linear response of the adsorption hydrogen's electrode voltage as a function of oxygen pressure and its stability in potassium hydroxide electrolyte makes it an ideal electrode for charge control. Although the oxygen fuel-cell electrode is a very good gas recombination electrode and better by a factor of 20 over the adsorption hydrogen electrode, it is difficult to use as a charge-control electrode because of its high sensitivity to oxygen pressure.

Author

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INTRODUCTION

One of the most difficult problems associated with sealed spacecraft batteries is rises in internal pressure. This condition is present whenever some cells in a battery approach full charge and, with the continuation of charging, could result in excessive pressure buildup.

In a properly designed sealed nickel-cadmium cell, oxygen evolves from the positive (nickel) electrode under this condition, but the negative (cadmium) electrode is capable of recombining some of this evolved oxygen. However, the recombination rate of the cadmium electrode is sufficient to maintain the cell at a safe pressure level only when the cell is overcharged at a rate of C/10. For most spacecraft applications, the energy removed from a battery must be replaced in a minimum amount of time. Usually this necessitates charging the battery at a high rate (greater than C/10) until full charge is achieved. Thus, a means must be provided to detect the end-of-charge condition among the cells of a battery, and to subsequently limit further charging current to levels that will not cause significant gas evolution.

Previously attempted charge-control methods have included the use of batteries much larger than actually required for the spacecraft power system, so that the normal charging current would not be great enough to cause a dangerous level of outgassing during moderate overcharge. This method, of course, has resulted in overweight batteries.

Various charge-state detection systems have been devised employing electronic and electrochemical combinations of cell-voltage monitors, temperature sensors, and ampere-hour integrators. These complicated and often unreliable devices used in spacecraft to control the charging of nickel-cadmium (Ni-Cd) batteries may soon be replaced with auxiliary electrodes that sense the oxygen evolved when a cell approaches full charge.

The auxiliary electrode approach for charge control eliminates the need for overweight batteries and offers a straightforward method of control by developing a voltage signal in the presence of evolved oxygen which can be used to detect the completion of charge and thus to regulate a simple control circuit that will limit the charging current for the remainder of the charge period.

Two types of auxiliary electrodes have been developed: the adsorption hydrogen electrode (which for this report shall be called electrode A) and the oxy gen fuel-cell electrode (electrode B). When in use, both types are connected externally to the cadmium-electrode terminal through a resistance whose value depends upon the performance characteristics desired. The chemical and electrochemical reactions for these electrodes are as follows.

- Electrode A (ref. 1)
  1. Cathodic reduction of water to form adsorbed hydrogen: $4H_2O + 4e^- \rightarrow 4H + 4\,OH^-$
  2. Reaction of adsorbed hydrogen with O_2 to form water: $4H + O_2 \rightarrow 2\,H_2O$
  3. Net reaction: $O_2 + 2\,H_2O + 4\,e^- \rightarrow 4\,OH^-$
- Electrode B (ref. 2)

  Cathodic reaction of water with O_2 to form hydroxyl: $O_2 + 2\,H_2O + 4e^- \rightarrow 4\,OH^-$

In the past year, two battery manufacturers have incorporated these types of electrode separately into their sealed Ni-Cd spacecraft cells.

Emphasis is placed on electrode A in this report because of its early availability and because of the large amount of data accumulated at GSFC.

Tests performed at Goddard have shown the auxiliary electrode to be feasible for use in spacecraft for earth-orbiting missions. Long-term life testing is being performed for GSFC at the Naval Ammunition Depot Quality Evaluation Laboratory, Crane, Indiana. These two test programs were designed to answer some of the following questions regarding the use of auxiliary electrodes as a charge-control device:

1. Based on a comparison between the two currently available types of auxiliary electrodes, which type appears to be more effective as a charge-control element?
2. Is the response of the auxiliary electrode voltage to oxygen pressure stable throughout the life cycle of a cell?
3. What is the temperature dependence of the auxiliary electrode; how does this affect the percent recharge of the battery?
4. What percent recharge is needed to maintain the state-of-charge of the cells in a battery?

5. What external auxiliary electrode resistance and threshold voltage should be used for effective charge control?

6. What type of charge-control circuit is best suited for use with a battery system using auxiliary electrode cells.

7. Does the cell, whose auxiliary electrode voltage signal first limits recharge during the battery's early life, continue to act as the controlling cell after many cycles?

8. Is it necessary to have an auxiliary electrode in every cell of a battery subject to this type of charge control?

TEST PROCEDURE

The data presented here were taken primarily from tests of five-cell batteries, each cell of which contained an auxiliary electrode. During cycling, the orbital regime was 90 minutes: 30 minutes of constant current discharge followed by 60 minutes of charge. The charge and discharge current rates were the same. During the charge period, this rate was sustained from 30 to 40 minutes, depending upon the percent recharge desired, and was followed by a 20- to 30-minute trickle charge or an open-circuit condition to complete the period. The depths of discharge were 25 percent and 40 percent, at temperatures of 0°C, 25°C, and 40°C.

Seven principal tests of at least 600 cycles each were conducted on a battery of five 6-ampere-hour cells equipped with electrode A. Additional tests were performed on a battery of five 12-ampere-hour cells equipped with electrode B (about 2000 cycles), and a battery of three 12-ampere-hour cells equipped with both types of electrodes (about 750 cycles).

Immediately before and after each test, two capacity checks were made. Each cell was discharged to 0.5 volt, shorted overnight, and then charged at C/10 for 16 hours. Capacity was then measured during a C/2 discharge to 1.0 volt.

APPARATUS

Instrumentation

A copper-constantan thermocoupl_ was installed between the second and third cells of each battery, and every cell was equipped with a piezo-resistive pressure transducer. Throughout the tests, a multichannel recorder logged battery temperature and current, as well as individual cell voltages, pressures, and auxiliary electrode voltages. The ampere-hours in and out of the battery were monitored with an accuracy of better than 1 percent by a solid-state ampere-hour integrator coupled to a printer. At the end of each charge or discharge period, the printer automatically recorded the ampere-hours as measured by the integrator.

Charge-Control Circuit

Figure 1 shows a block diagram of the charge-control circuit. This solid-state device is designed to monitor the control-electrode potential of each of the cells in a series battery while they are being charged. When the signal from any one of the cells rises above a pre-set value, the circuit reduces the charge current to zero (or to a predetermined trickle charge) by changing the conductance of the series transistor.

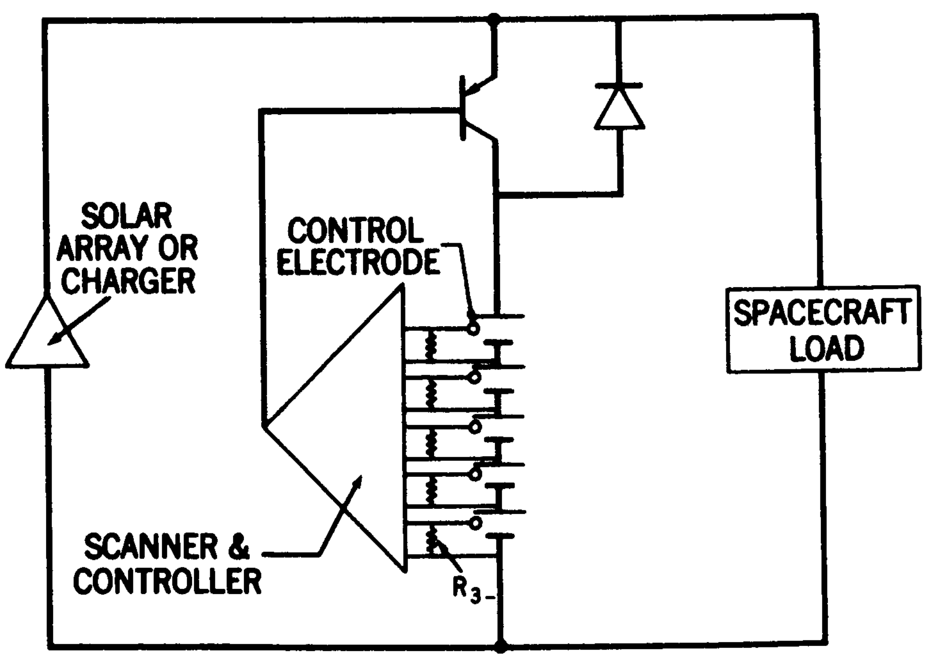

Figure 1–Series Auxiliary Electrode Control Circuit for a Ni-Cd Battery

ADSORPTION HYDROGEN ELECTRODE (ELECTRODE A)

Results of Test A-101

This test was made using five 6-ampere-hour Ni-Cd cells with type A electrodes. All auxiliary electrodes were connected to the scanner, and the first to reach the threshold level would control the charge to the battery. The depth of discharge for this test was 40 percent; the temperature was 25°C; the percent recharge was 110 percent. Figure 2 shows a typical early cycle curve.

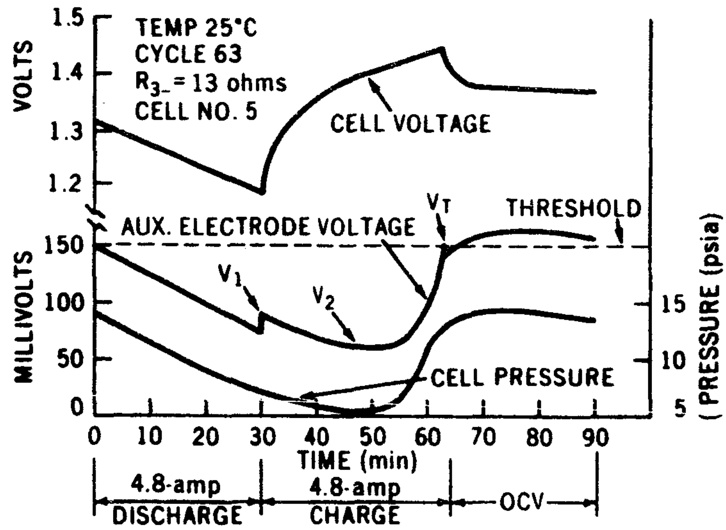

Figure 2–Typical Early Cycle Curve, Test A-101 (6-amp-hr Ni-Cd cell with auxiliary electrode A, 40% depth of discharge, 110% recharge)

The threshold (or level of auxiliary electrode voltage at which the charge rate was reduced or stopped) was chosen to be 150 millivolts (mv) because this voltage is a good working level for the solid-state scanner. The resistance value across each cell was adjusted to 13 ohms to give a battery recharge of 110 percent. As an example of how the percent recharge can be varied, it might be noted that by reducing the auxiliary electrode resistance to 6.8 ohms, the percent recharge would be increased to about 115 percent. Conversely, increasing the auxiliary electrode resistance to 22 ohms would decrease the percent recharge to about 103 percent. The above variations were characteristic of cells 1, 3, 4, and 5.

The signal voltages of the five auxiliary electrodes for a given pressure and resistance were very close, within ±5 mv. However, the pressure level variation among the cells at the end of charge was as great as 10 psia, causing the auxiliary electrode in the higher pressure cell to give a higher signal. Cell 2 was a high-pressure cell – 10 psia higher at the end of charge than cells 1, 3, 4, and 5. Therefore, it was necessary to reduce the auxiliary electrode resistance for this cell to 6.8 ohms to make its signal level compatible with those of cells 1, 3, 4, and 5.

The higher pressure level of cell 2 might suggest that it is a low-capacity cell and would therefore exhibit the lowest end-of-discharge voltage on a capacity check. Throughout the 5000 cycles of operation, however, cell 2 had an average pressure level 10 psia above that of the remaining four cells. Whenever a capacity check was made, it was noted that cell 4, one of the average pressure cells, had the lowest end-of-discharge voltage.

Referring again to Figure 2, three auxiliary electrode voltage levels are noted: V_1 is the voltage level of the auxiliary electrode at the beginning of charge; V_2 is the lowest voltage level during charge; and V_T is the threshold voltage, or the level at which charge current is terminated or reduced. Note in this figure the level of V_T compared to V_1, and V_2, and also the large pressure variation during charge. During early cycling the pressure decay during discharge is very good. Likewise, the auxiliary electrode voltage decay is very good. However, after 400 cycles the pressure decay during the discharge period lessened to such an extent that V_1 is equal to V_T. This condition is illustrated in Figure 3. The pressure decay stabilized at the level shown and remained for the life of the cell.

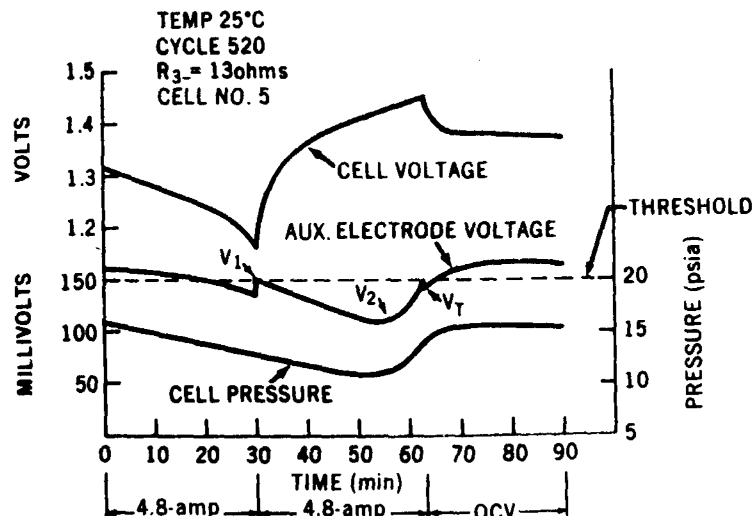

Figure 3–Life-Cycle Curve after 400 Cycles, Test A-101 (6-amp-hr Ni-Cd cell with auxiliary electrode A, 40% depth of discharge, 110% recharge)

The two factors that contribute to oxygen pressure reduction within the cells are the gas recombination rates of the cadmium and auxiliary electrodes. Comparison of the auxiliary electrode voltages to pressure in Figures 1 and 2 indicates that the auxiliary electrodes have not lost sensitivity. In both cases the threshold voltage was 150 mv and the pressure at threshold was 14 psia. Therefore, the decrease in gas recombination of the cell must be attributed to the cadmium electrode.

Results of Test A-106

This test was conducted on the same cells used in test A-101 (6-amp-hr Ni-Cd cells with type A electrodes). The battery was subjected to a temperature of 25°C, a depth-of-discharge of 25 percent, an average percent recharge of 115 percent, and a trickle charge of 150 milliamps (ma) during the rest period. Cycle time was 90 minutes, and the test lasted 780 cycles. At the completion of this test a capacity check yielded 3.8 amp-hr.

The purpose of this test was to determine the behavior of auxiliary electrodes under the influence of external resistances varying from 0.5 to 510 ohms. If the resistances had been varied while the auxiliary electrodes were connected to the scanner (which was set for a threshold of 170 mv), the percent recharge of the battery would have varied as well. To avoid this variance, all auxiliary electrodes except that of cell 5 were disconnected from the scanner. With a fixed external resistance of 6.8 ohms and a threshold voltage of 170 mv, cell 5 was used to control and maintain the battery at 115 percent recharge. The external resistance of the auxiliary electrodes on the other four cells could then be varied freely without affecting the percent recharge of the battery.

Figure 4 shows the parameters of cell 5 (the controlling cell) as functions of cycle number. In the top line, the end-of-discharge voltage is plotted against cycle number. The next line down is a plot of the maximum pressure during each cycle occurring during the trickle charge. The pressure of the cell at threshold voltage is shown in the next line, followed by a line representing the minimum pressure during the cycle. The bottom plot relates the percent recharge to the cycle number throughout the test. During this test, electrode A maintained the percent recharge of the battery at a nearly constant 115 percent, and the pressure level at threshold was maintained at an average pressure level of 19 psia. These two steady parameters strongly indicate that the sensitivity of electrode A is very stable.

Figure 5 shows the relationship between cell pressure and auxiliary electrode resistance for cell 3. Three pressure curves, representing maximum, threshold, and minimum pressure for a cycle, are plotted as a function of

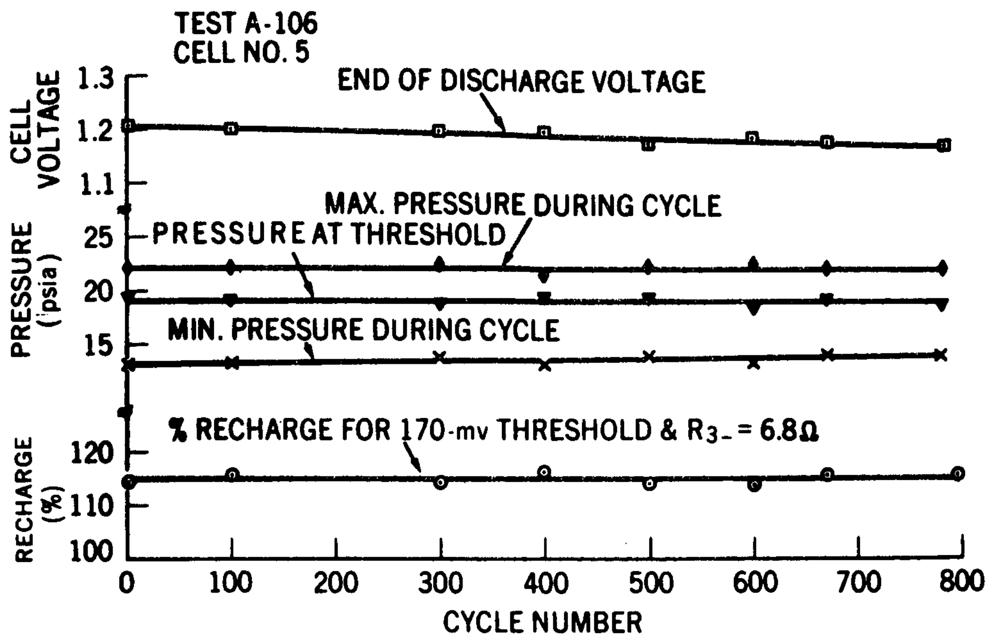

Figure 4–Six-Amp-Hr Ni-Cd Cell with Auxiliary Electrode A for Control

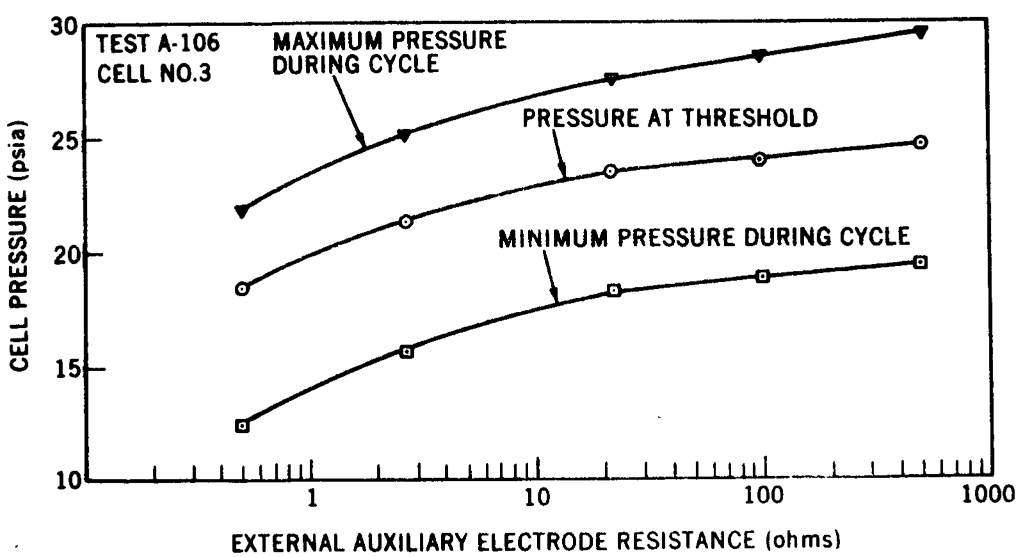

Figure 5–Pressure-Level Variation during Cycle as a Function of Auxiliary Electrode Resistance

external auxiliary electrode resistance. For each curve five points representing resistance values of 0.5, 2.7, 22, 100, and 510 ohms are noted. For cells 1 through 4 the resistance values of the auxiliary electrodes were changed using the above resistance values in intervals of 150 cycles. From these cycles the data in the figure was plotted. As might be expected, the average pressure in the cell was reduced by the lower auxiliary electrode resistance because the auxiliary electrode is recombining more of the oxygen gas. For example, the maximum cell pressure during a cycle for cell 3 was 29.5 psia for 510 ohms. This pressure was reduced to 22.0 psia by using a 0.5-ohm resistance.

Figure 6 shows a plot of auxiliary electrode power at threshold, at the ratio V_T/V_2, and at the ratio V_T/V_1 as a function of auxiliary electrode resistance. The small change in auxiliary electrode voltage between the beginning of charge and at threshold was not appreciably increased by the use of a low external resistance as indicated by the lower line in the figure. Note that, for all resistance values from 0.5 to 510 ohms, V_T/V_1 is less than 1.0. Therefore, there will always be a few minutes delay in the commencement of charge due to the high auxiliary electrode signal. However, the ratio of V_T/V_2 (where V_2 is the lowest auxiliary signal during charge) is substantially improved by the use of a low external resistance. As a by-product of this test, the maximum power point at the threshold voltage was found to occur at an auxiliary electrode resistance of about 7 ohms.

V_T = Threshold voltage
V_1 = Auxiliary electrode voltage beginning of charge
V_2 = Auxiliary electrode voltage at lowest point during charge

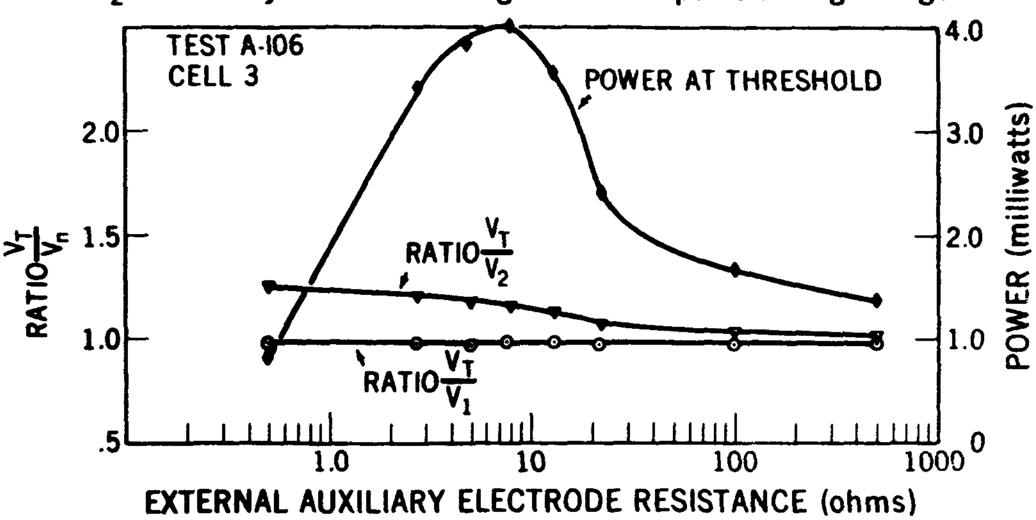

Figure 6–Auxiliary Electrode Voltage Variations and Power Dissipation as a Function of Resistance

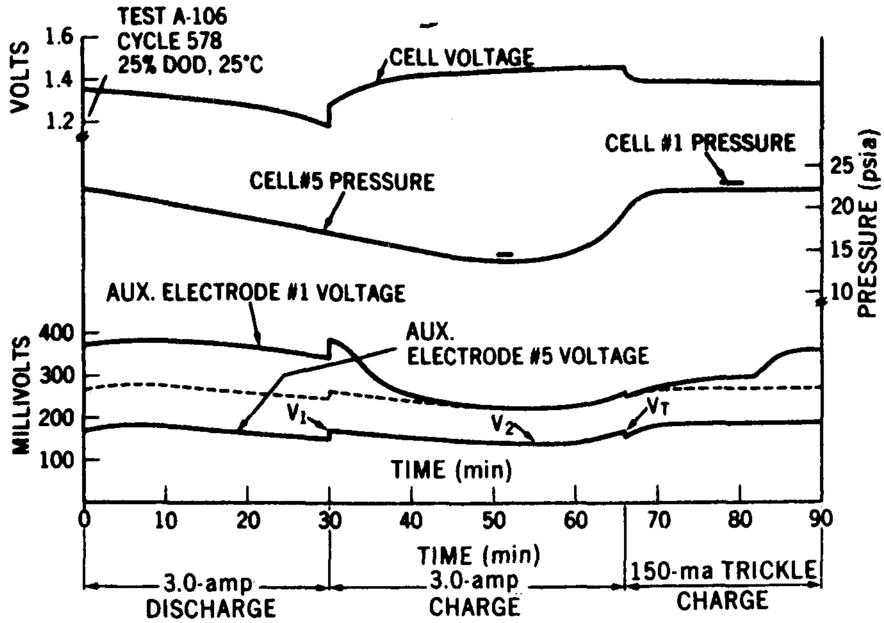

Figure 7–Anomalous Behavior of Auxiliary Electrode A for External Resistance of 22 ohms (cells 1, 2, 3, 4; cell 5 controlling; 150-mv threshold, R_3 =6.8 ohms)

Figure 7 shows a typical cycle for this test and illustrates cell voltage, cell pressure, and auxiliary electrode voltages for cells 1 and 5 as a function of time. As noted before, the auxiliary electrode in cell 5 controlled the charge with a threshold voltage of 170 mv and a resistance of 6.8 ohms. The auxiliary resistance for cell 1 was 22 ohms, the voltage of its auxiliary electrode was monitored and, as mentioned before, its output was disconnected from the scanner. For the first few cycles the auxiliary voltage of cell 1 gave an output represented by the dotted line in Figure 7. But after a few cycles, the voltage gave an output represented by the solid line. The auxiliary electrode appears to gain sensitivity towards the end of the trickle charge period and to remain at this level until part way through the charge period. This unusual behavior of the auxiliary electrode was experienced during portions of the tests made using both the 13 and 22-ohms resistances. This characteristic was noted in all cells tested. In some it occurred near the beginning of the trickle charge, rather than toward the middle.

Sensitivity Shift of Electrode A

One of the most important questions regarding the use of an auxiliary electrode in Ni-Cd cells is the long-term stability of its output voltage at a given oxygen pressure.

Cycling tests of cells having type A auxiliary electrodes indicate that the sensitivity of the electrodes increases during the first 2 months of testing and stabilizes thereafter. This increased sensitivity causes the percent recharge of the battery to decrease. This behavior was noted at GSFC and at Crane.

Figure 8 shows the sensitivity shift of electrode A after 5000 cycles. Cell pressure in psia is plotted versus auxiliary electrode voltage in millivolts for an auxiliary electrode resistance of 6.8 ohms. The curve on thé left represents auxiliary electrode response at beginning of life; the curve on the right represents response after 5000 cycles. The horizontal dotted lines represent the average cell pressure at the threshold voltage for three recharges: 102 percent, 110 percent, and 115 percent. The effect of auxiliary electrode shift in sensitivity can be determined from the information shown in Figure 8. If the threshold voltage is held constant at 150 millivolts (the vertical dotted line), sensitivity shift will cause the recharge of the cell to decrease from a 115 percent recharge to a 110 percent recharge.

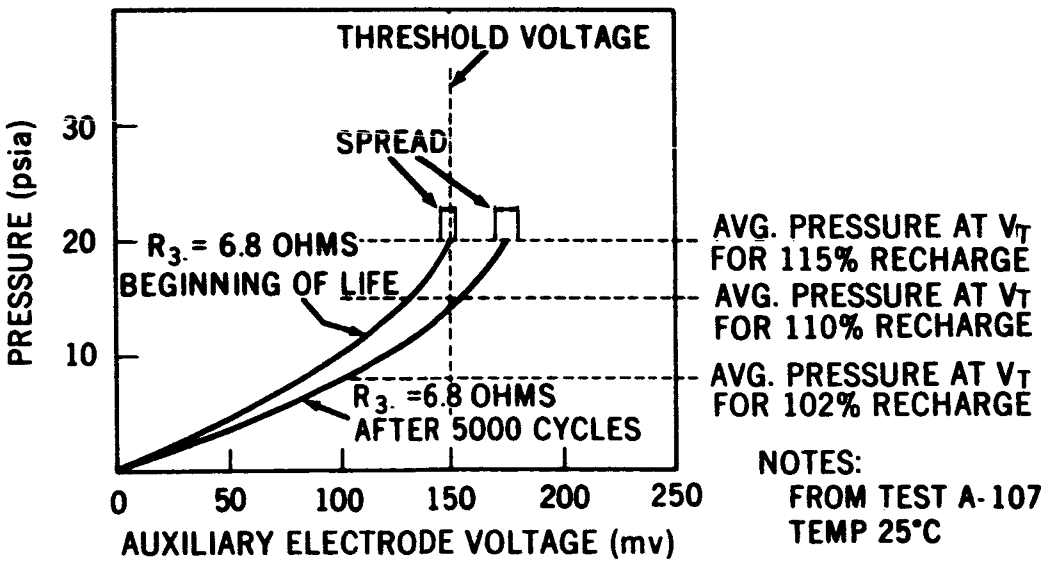

Figure 8–Auxiliary Electrode A Sensitivity Shift as a Function of Life
(Resistance = 6.8 ohms)

Figure 9 shows the sensitivity shift during cell life when the auxiliary electrode resistance was adjusted for 13 ohms. This shift was much greater and compares with the unusual behavior noted in Figure 7 for resistance values between 13 and 22 ohms.

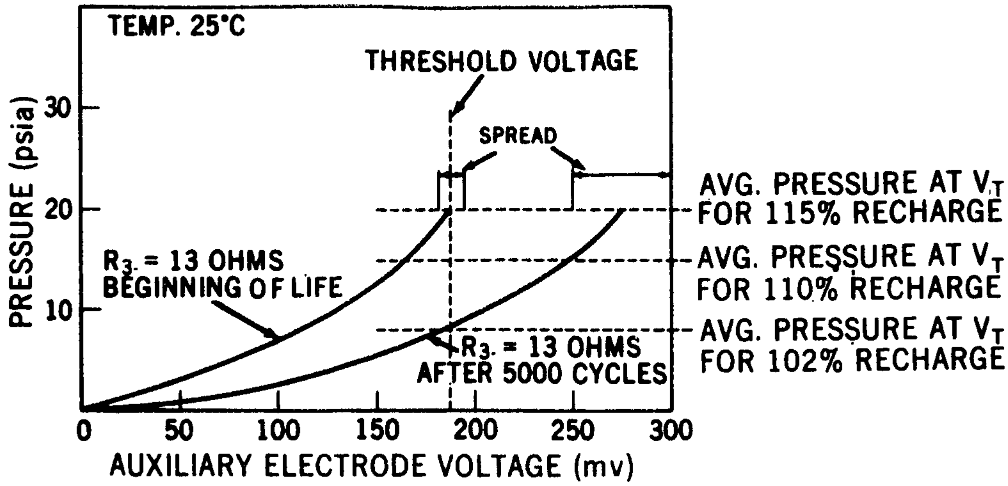

Figure 9–Auxiliary Electrode A Sensitivity Shift as a Function of Life (resistance = 13 ohms)

Response of Electrode A as a Function of Temperature

Figure 10 shows the auxiliary electrode voltage as a function of pressure for temperatures of 0°C, 25°C, and 40°C. The auxiliary electrode resistance for these temperatures was 6.8 ohms. For a given cell pressure and auxiliary electrode resistance, electrode signal voltage increased with increase in temperature. As an example, consider a cell pressure of 28 psia (upper dotted line). At this pressure level the auxiliary electrode developed a signal of 150 mv at 0°C, 175 mv at 25°C, and 200 mv at 40°C.

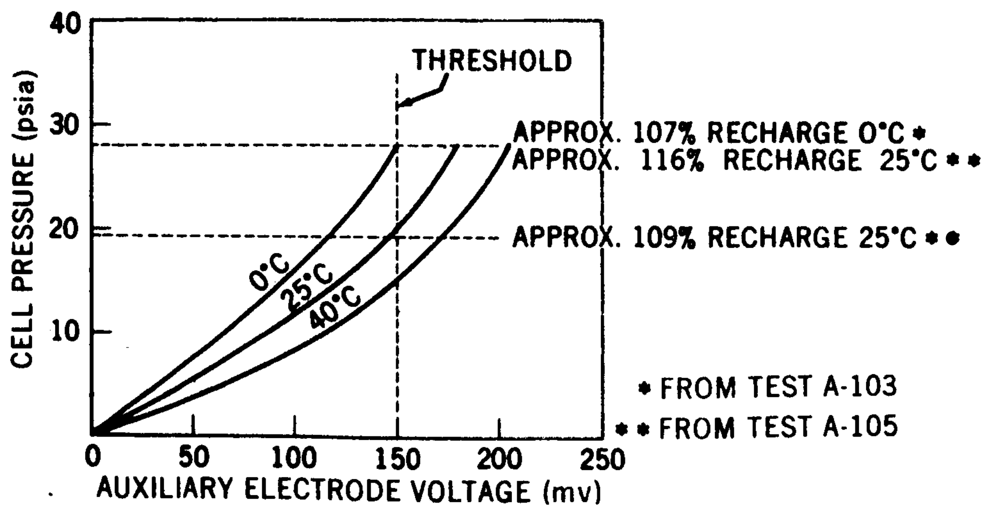

Figure 10–Auxiliary Electrode A Sensitivity as a Function of Temperature (R_3 = 6.8 ohms)

Cycling tests have shown that the minimum percent recharge needed to maintain state of charge of the battery at 0°C, 25°C, and 40°C is 107, 115, and 124 percent respectively. It so happened that the average end-of-charge pressure for the above prescribed conditions was the same (28 psia). If the battery is to be operated over the temperature range of 0°C to 40°C, the auxiliary electrode threshold voltage for a resistance of 6.8 ohms would have to be adjusted from 150 mv at 0°C to 175 mv at 25°C and to 200 mv at 40°C.

If, however, the threshold voltage were held constant at 150 mv between 0°C and 25°C, the percent recharge would only increase from 107 to 109 percent as shown by the intersection of the vertical line with the two horizontal lines and the 0°C and 25°C curves in Figure 10.

OXYGEN FUEL-CELL ELECTRODE (ELECTRODE B)

Test B-102 was conducted on a battery consisting of five 12-amp-hr Ni-Cd cells containing the oxygen fuel-cell electrode for control. The parameters for this test were 25 percent depth-of-discharge at a temperature of 25°C, on a 90-minute orbit regime for 1950 cycles. The threshold voltage was 400 mv; the auxiliary electrode resistance was 1.2 ohms.

The voltage signal produced by this electrode is extremely sensitive to oxygen pressure. In fact, the onset of oxygen evolution produces an accelerated voltage which prematurely signals the charge controller to stop charge before the battery has attained the fully charged state. Therefore, the needed percent recharge must be attained by employing a 500-ma trickel charge.

Figure 11 shows electrode B's voltage response of cell 1 for cycles 94 and 490 as well as the cell's pressure and voltage. Early in life (cycle 94) the auxiliary electrode demonstrated a large voltage excursion from beginning of charge to end of charge. However, after many cycles (cycle No. 490), the voltage excursion is substantially reduced, indicating that the electrode is partially saturated with oxygen gas. Note also that the average cell pressure has increased from cycle 94 to cycle 490.

Figure 12 shows various end-point parameters for cell 1 as a function of cycle number. Some of these parameters are end-of-discharge cell voltage, cell pressure at auxiliary electrode voltage threshold, the ratio of threshold voltage to beginning of charge voltage, and battery percent recharge per cycle. As shown in Figure 12, the percent recharge of the battery increased from an initial value of 113 percent to a final value of 124 percent, and the pressure level at the 400-mv threshold increased from an initial value of 2 psia to a final value of 10 psia. The increase in both percent recharge and pressure level indicates

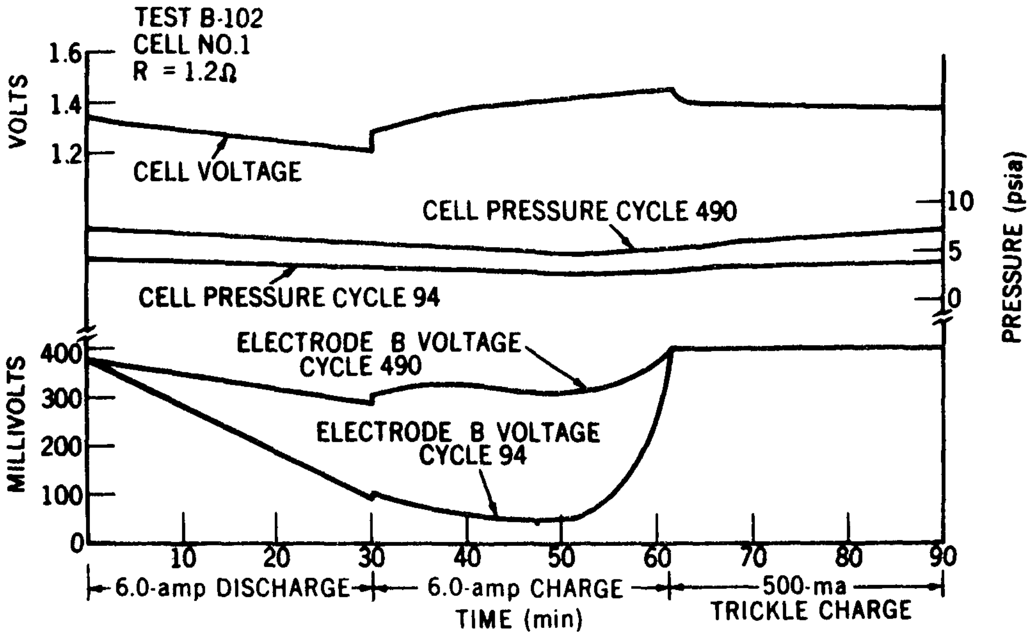

Figure 11–Twelve-Amp-Hr Ni-Cd Battery with Axuiliary Electrode B for control (25% depth of discharge, 25° C, 90-min. cycle, 400-mv threshold)

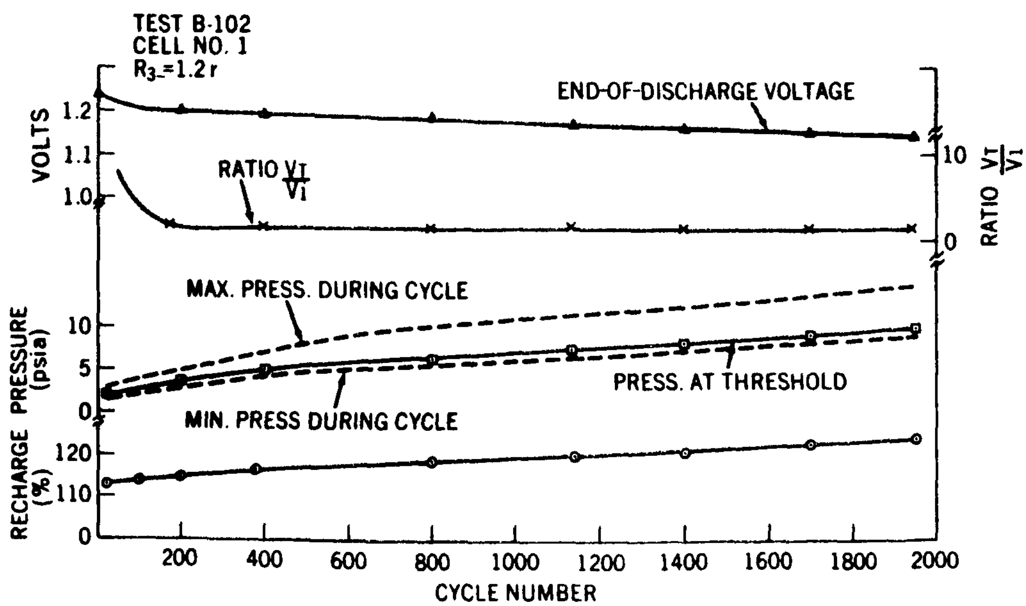

Figure 12–Twelve-Amp-Hr Ni-Cd Battery with Auxiliary Electrode B for control, End Point Parameters (25% depth of discharge, 25°C, 90-min. cycle, 400-mv threshold)

a sensitivity loss in the auxiliary electrode. During this test the auxiliary electrode of cell 1 controlled the battery for the 1950 cycles.

COMPARISON OF ELECTRODE A AND ELECTRODE B IN THE SAME CELL

So that the relative behavior of electrodes A and B could be studied in the same environment, three cells were constructed using SAFT 12-ampere-hour Ni-Cd stacks. Electrodes A and B were added to the stacks. These electrodes have a surface area of 7/8 by 2-3/4 inches and employ pellon as an absorber of electrolyte.

Three tests of 250 cycles each were conducted. All tests were conducted at 25°C and at a 25 percent depth-of-discharge on a 90-minute cycle.

Test AB-101

In this test each cell had electrode A (the adsorption hydrogen electrode), as a controlling element connected through a 13-ohm resistance to a scanner set for a threshold voltage of 100 mv. Electrode B (the oxygen fuel cell electrode), was disconnected from the scanner, but was connected to the cadmium electrode through a resistance of 1.2 ohms (1.2 ohms being a good resistance to use when using this electrode as a control electrode). In this way electrode B was used as a scavenger or gas recombination electrode.

In Figure 13, the cell voltage, auxiliary electrode voltages of electrodes A and B, and cell pressure are plotted as a function of time for cycle 224. From this graph an excellent comparison of the two electrodes can be obtained. A fairly linear relationship exists between the voltage of electrode A and the cell pressure. Electrode A being used for charge control, the percent recharge of battery can be easily adjusted from 100 percent to 140 percent by adjusting the resistance or the threshold voltage level, or both, of the auxiliary electrode. However, the voltage response of electrode B is not a linear function of cell pressure, but increases sharply between 90 percent and 100 percent recharge and then levels off as the electrode becomes saturated with oxygen. Because of this saturation, it is not possible to select a threshold voltage for this electrode which will permit a recharge greater than 100 percent. The highest threshold voltage which can be chosen for electrode B is 400 mv, because above that level the electrode becomes saturated. Note that varying the auxiliary electrode resistance does not avoid this saturation effect.

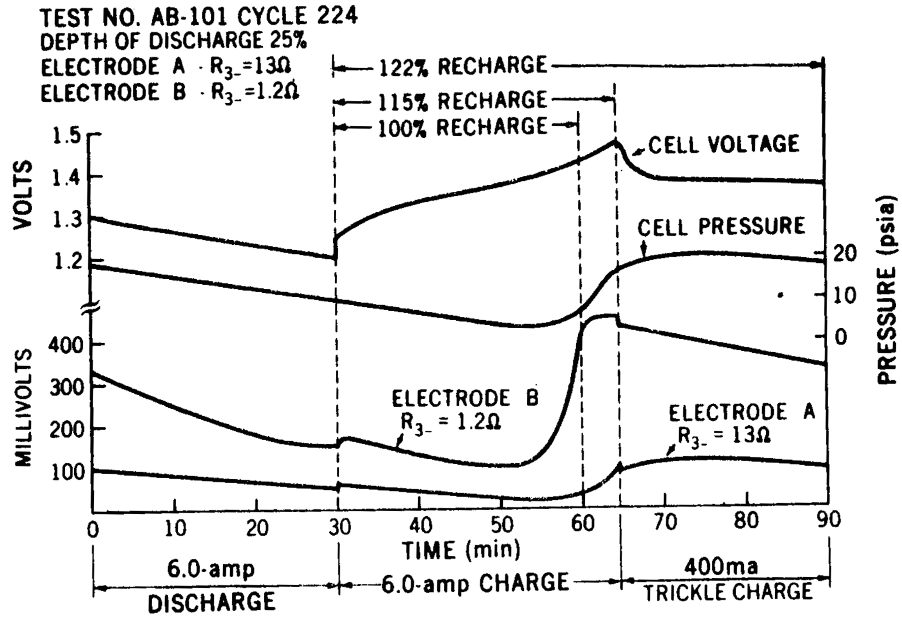

Figure 13–Comparison of Auxiliary Electrode Behavior During Cycle with Electrode A Controlling (12-Amp-Hr Ni-Cd cell, 25°C)

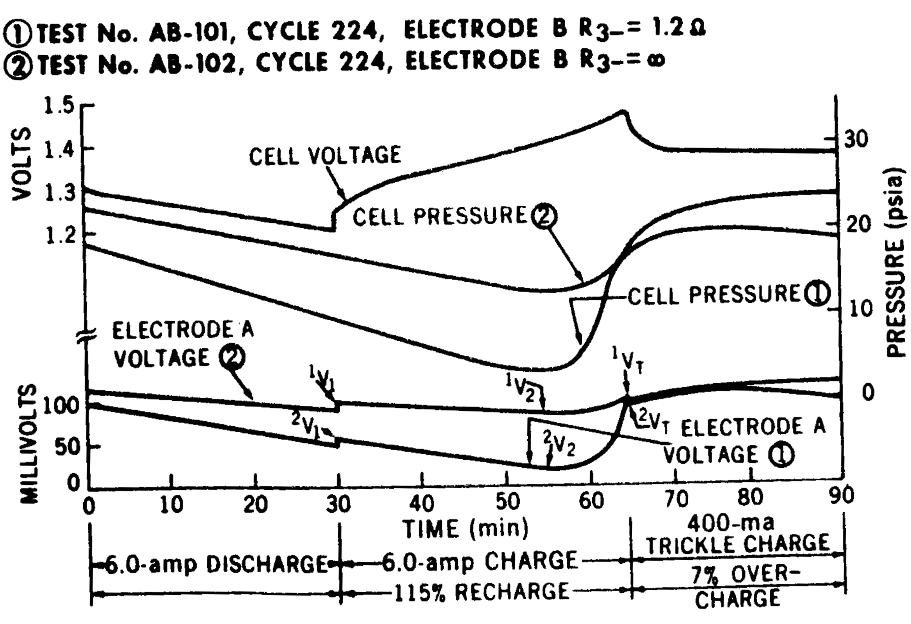

Figure 14–Comparison of Cell Behavior with Electrode A Controlling and with Electrode B Connected and Disconnected (12-Amp-Hr, Ni-Cd cell with two auxiliary electrodes, 25°C, 25% depth of discharge)

Test AB-102

This test was similar to the test AB-101 except that the oxygen fuel-cell was disconnected from the cadmium electrode, thereby eliminating its ability to recombine oxygen gas. From these two tests the cell pressure variations and the effect on voltage response of electrode A can be compared with electrode B connected and disconnected as a gas recombination electrode.

This comparison is well illustrated in Figure 14, which shows a typical cycle taken from each test plotted against the same time axis. The top pressure curve and the top electrode curve (electrode A) were taken from test AB-102, cycle 224, and illustrate their respective behavior without the aid of a gas recombination electrode. Notice that the auxiliary electrode voltage at the beginning of charge is equal to the threshold voltage (100 mv). Also observe that cell pressure for this test at beginning of charge and at threshold is 17 psia. The bottom pressure curve and the bottom auxiliary electrode curve (electrode A) were taken from test AB-101, cycle 224, and show their relative behavior with the aid of a gas recombination electrode. Notice that auxiliary electrode voltage at the beginning of charge has been suppressed from 100 mv to 50 mv and that the cell pressure has dropped from 17 psia to 10 psia. Thus, by the use of electrode B for gas recombination, the voltage variation of electrode A for charge control has been greatly improved. The high beginning-of-charge voltage signal of electrode A, which caused a charging delay of 5 minutes or more noted in other tests, is eliminated by the addition of a gas recombination electrode.

Test AB-103

This test was conducted to show the behavior of a cell when the oxygen fuel-cell electrode (electrode B) was used for charge control. Electrode A was disconnected from the scanner, but its voltage across a 13-ohm resistor was monitored. The threshold voltage of electrode B was set for 400 mv and its resistance was 1.2 ohms. Notice in Figure 15 that electrode B reaches the 400-mv threshold at about 100 percent recharge. This is in agreement with test B-101.

CONCLUSIONS

The essentially linear response of the adsorption hydrogen electrode's (electrode A) voltage as a function of oxygen pressure makes it an ideal electrode for charge control. This characteristic enables the percent recharge of the battery to be adjusted from 90 percent to 140 percent. However, a critically small voltage difference is noted between the end-of-charge and the beginning-of-charge. This condition can be substantially improved by the addition of a scavenger, or

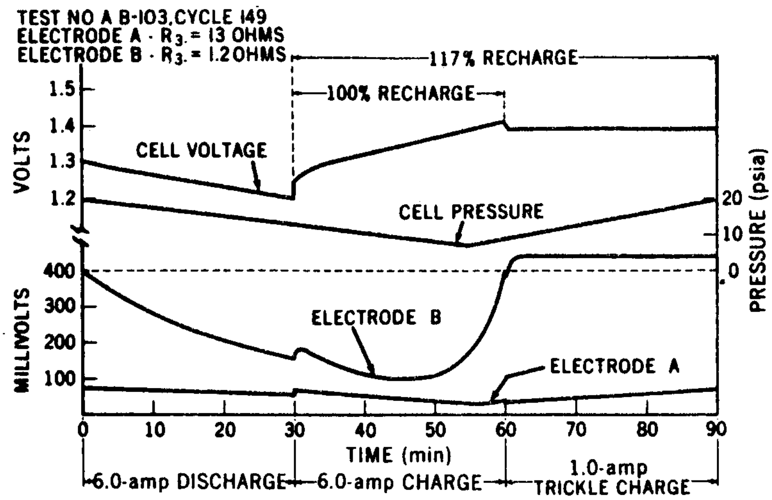

Figure 15—Comparison of Auxiliary Electrode Behavior During Cycle with Electrode B controlling (12-amp-hr Ni-Cd cell with two auxiliary electrodes, 25°C, 25% depth of discharge)

gas recombination electrode, to aid the cadmium electrode in removing oxygen pressure during discharge.

The oxygen fuel-cell electrode (electrode B) is a very good gas recombination electrode and better by a factor of 20 over the adsorption hydrogen electrode. But when electrode B is used for charge control, it is difficult to put into the cell the desired percent recharge because of its high sensitivity to oxygen pressure. In fact, the onset of oxygen evolution produces an accelerated trip voltage which prematurely signals the charge controller before the battery has attained the fully charged state. A large voltage variation between the end-of-charge and the beginning-of-charge is noted early in life for this electrode, but this variation decreases substantially after several hundred cycles.

A slight increase in sensitivity of the adsorption hydrogen electrode has been noted over a 9-month period. The greatest shift takes place during the first 2 months of operation and stabilizes thereafter. The sensitivity shift for auxiliary electrode resistance of 6.8 ohms will decrease percent recharge by 5 percent. However, an auxiliary resistance of 13 ohms will decrease the percent recharge by 10 percent. Also, anomalous auxiliary electrode behavior is experienced when using resistance values of 13 and 22 ohms.

In contrast to the adsorption hydrogen electrode, the oxygen fuel-cell electrode looses sensitivity. The sensitivity loss caused the percent recharge to increase by 10 percent over a 4-month period.

To maintain the state-of-charge of the battery when using the adsorption hydrogen electrode over the temperature range of 0°C to 40°C, the threshold voltage of the electronic scanner would have to be adjusted to 150 mv at 0°C, 175 mv at 25°C, and 200 mv at 40°C for an auxiliary resistance of 6.8 ohms to compensate for the temperature dependence of the auxiliary electrode.

Cycling tests show that the minimum percent recharge needed to maintain state-of-charge of the battery at 0°C, 25°C, and 40°C is 107, 115, and 124 percent, respectively.

A resistance value of 6.8 ohms appears to be the most effective of those tried for charge control with the adsorption hydrogen electrode when the following parameters are optimized: signal voltage level, cell pressure level, V_T/V_2 ratio, and avoidance of the anomalous auxiliary electrode region between 13 and 22 ohms.

In all tests conducted at GSFC and Crane (reference 3), the first cell to do the controlling remained the controller. This result indicates that it is not necessary to have an auxiliary electrode control from every cell. For reliability it may be necessary to have two or three auxiliary electrodes capable of controlling in a 10-cell battery. The remaining cells should have auxiliary electrodes and should be shorted to the cadmium to ensure a low-pressure-level relationship.

REFERENCES

1. Seigar, H. N., Shair, R. C., and Ritterman, P. F., "The Adhydrode in Charge Control," Proceedings of the 18th Annual Power Sources Conference, May 1964.

2. Carson, Dr. W. N., Jr., "Use of Electrodes in Sealed Nickel-Cadmium Cells," General Electric Final Report No. 63GL113, July 1963.

3. Phone conversation with Hugh Shultz and D. Mains of Naval Ammunition Report, Crane, Indiana.

APPENDIX A

Specifications for Adsorption Hydrogen Electrode 6-Amp-Hr Cells

AUXILIARY ELECTRODE

- Number of auxiliary electrodes used per cell: one
- Dimensions:

Length	20.55	cm
Width	1.79	cm
Thickness	0.066	cm

- Location of auxiliary electrode in the cell: edge of the plate pack on two sides and the bottom
- Internal impedence of auxiliary electrode with respect to cadmium electrode: approximately 7 ohms
- Type of electrolyte wicking used for auxiliary electrode: pellon

NICKEL-CADMIUM ELECTRODES

Nickel Plate

- Number of plates per cell: 9
- Dimensions:

Length	5.51 cm
Width	4.80 cm
Thickness	.084 cm (per plate)

- Weight (dry): 72 gm for 9 plates
- Weight of active material: 33.3 gm for 9 plates

Cadmium Plate

- Number of Plates per cell: 10
- Dimensions:

Length	5.51 cm
Width	4.80 cm
Thickness	0.76 (per plate)

- Weight (dry): 81 gm for 10 plate
- Weight of active material: 39.0 gm for 10 plates

APPENDIX B

Specifications for Oxygen Fuel-Cell Electrode
12-Amp-Hr Cells

AUXILIARY ELECTRODE

- Number of auxiliary electrodes used per cell: one
- Dimensions:

Length	6.35	cm
Width	2.22	cm
Thickness	0.0381	cm

- Location of auxiliary electrode in the cell: edge of the plate pack on one side
- Internal impedence of auxiliary electrode with respect to cadmium electrode: approximately 60 milliohms
- Type of electrolyte wicking used for auxiliary electrode: pellon

NICKEL-CADMIUM ELECTRODES

Nickel Plate

- Number of plates per cell: 12
- Dimensions:

Length	6.0	cm
Width	7.0	cm
Thickness	0.091	cm (per plate)

- Weight (dry): 150 gm for 12 plates
- Weight of active material: 68 gm for 12 plates

Cadmium Plate

- Number of plates per cell: 13
- Dimensions:

Length	6.0	cm
Width	7.0	cm
Thickness	0.079	cm (per plate)

- Weight (dry): 164 gm for 13 plates
- Weight of active material: 86 gm for 13 plates