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OVERCHARGE CONTROL
OF NICKEL-CADMIUM
SPACECRAFT BATTERIES USING THE
AUXILIARY ELECTRODE SIGNAL

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SUMMARY

The auxiliary electrode is a flight-qualified charge-control device that signals the onset of overcharge within a sealed nickel-cadmium cell. Being in intimate association with the electrochemical process of the nickel-cadmium cell, it provides a unique method for overcharge control. Qualification of the 20-ampere-hour cell with auxiliary electrode for the OAO spacecraft has shown that no compensation of the electrode signal is required for the temperatures, charge rates and depths of discharges experienced by the batteries on this spacecraft.

A study of the effectiveness of charge-control signals from 100 to 500 millivolts with 47-ohm impedance between the auxiliary and negative electrode established a 250- to 300-millivolt range as an optimum control level. Characteristics observed with this control level include less than one-atmosphere cell pressures and 1-watt or less thermal dissipation from overcharge. Results of this study have shown that optimum performance obtained with this control level can be achieved only when the battery ampere-hour capacity is not maximized by overcharge.

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Floyd E. Ford*

INTRODUCTION

Spacecraft with large power systems of over 200 watts, requiring larger ampere-hour capacity for the sealed nickel-cadmium spacecraft batteries, are becoming more in demand. As the capacity requirements are increased, the problems associated with heat and pressure from overcharge become more complex. Overdesign, as used in small power systems, is no longer practical for these large systems. A charge-control technique that minimizes overcharge is more than desirable; it is necessary.

Signal-electrode (also referred to as third or auxiliary electrode) charge control of nickel-cadmium batteries offers to a power system designer some unique advantages over previous methods. Being in intimate association with the electrochemical process of the cell, the signal electrode signals the onset of oxygen pressure within a cell and provides a voltage that is linearly related to pressure over a limited region. This signal voltage can provide a unique

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method for overcharge control. Use of a selected number of the signal-electrode-type cells in each battery provides signals that can be used to maintain the capacity of the battery above the rated value and optimize overcharge.

APPROACH

There are practically no data available on the 20-ampere-hour signal-electrode cell except what are supplied by the manufacturer when the cells are purchased. The author has found such data of little value in establishing signal levels for charge control. One objective of this paper is to generate parametric data on the 20-ampere-hour nickel-cadmium cell and the signal-electrode characteristics operating in this cell. The information should provide the following data:

1. Optimum load resistance R_L between signal and cadmium electrode.

2. Signal-electrode voltage, for charge control, that gives the most desirable cell characteristics.

3. Temperature variable associated with signal electrode and effects on cell operation.

4. Optimizing performance of cell with signal-electrode control. Parameters to include ampere-hour capacity, cell pressure, thermal heat from overcharge, and signal-voltage compatibility with system.

SIGNAL-ELECTRODE LOAD RESISTOR

To evaluate the effect of various load resistances R_L on signal-electrode performance, a technique for accurately controlling the ampere-hour recharge was used. The exact recharge of 100 percent after a 15-percent depth of discharge was controlled by an electronic ampere-hour integrator (Reference 1). Additional recharge to compensate for the inefficiency was accomplished by switching to an appropriate trickle rate for the remainder of the sunlight period. Data on percent return were derived by Sizemore (Reference 2) and were used as a minimum for this test. These were 107, 115, and 124 percent at 0°C, 25°C, and 40°C, respectively.

Figure 1 illustrates the results of this test at the three temperatures, for four different values of R_L. The negative slopes of the constant-resistance curves at 100-percent recharge indicate the sensitivity of the signal electrode and cell to temperature. At first sight, it would seem that temperature compensation of the signal electrode is required. However, in view of the overcharge requirements of the nickel-cadmium cell in conjunction with these data, it is clear that the decreasing signal voltage with temperature will provide an increasing overcharge with temperature. All resistance values tested showed similar trends; the greater resistances giving greater slopes.

Another factor for consideration is the signal voltage obtained with the various resistances. A plot of signal-electrode voltage (at constant pressure)

against log of resistance (Figure 2) shows two asymptotes, one at zero voltage (the short-circuit current of the signal electrode) and the other at 0.8 volt (the open-circuit voltage of the signal electrode). The greatest sensitivity of signal voltage to resistance occurs between 10 and 100 ohms.

Two other factors to be considered in selecting a load resistance for the signal electrode are (1) influence of resistance on internal cell pressure and (2) change in signal level with cycle life (at constant pressure). During test, a change in resistance from 100 to 1 ohm produced less than 15-percent change in internal pressure and a corresponding 90-percent reduction in signal voltage. The effects of low resistance values on pressure were more noticeable as the average internal cell pressure increased; i.e., the higher the ambient internal pressure, the more effect the low values of resistance had in reducing the pressure. It was concluded that for pressures of interest (10 to 20 lbs/in^2 absolute) the small pressure decrease obtained with low resistance was not worth the sacrifice in signal voltage.

An increase in sensitivity of the signal electrode to oxygen pressure was observed during work on contract NAS 5 10241, Reference 3. The effect of this on cell operation is that less overcharge is experienced on cycling with increase in signal sensitivity. Figure 3 illustrates the signal voltage for 47-ohm resistance for two constant-pressure conditions over 150 cycles of operation on a 90-minute orbit. A decrease in sensitivity is observed during this cyclic

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period. This change was always observed when a new test series was initiated on the same test cells. A decrease in signal level implies that a slight increase overcharge would occur with cycling. A gradual increase of internal pressure would occur during initial cycling with the fixed signal voltage. Life tests have shown that the signal voltage stabilizes and that the percentage return remains fairly consistent from cycle to cycle.

In consideration of the factors that influence the selection of a load resistance, a 47-ohm resistor was selected for further investigation of the signal electrode and cell characteristics. Figure 4 shows data obtained from simulated cycling of a near-earth orbit (90 minutes) with 260-mv signal-electrode control voltage. The percentage increase of overcharge with increasing temperature demonstrates the self-compensating characteristics of the signal electrode when controlling cell operation over a wide temperature range. Life tests of signal-electrode cells are currently being conducted at NAD, Crane (Reference 4). The characteristics exhibited in Figure 4 are being verified in life test. The change in sensitivity with cycle life has not been enough to alter the overcharge of the test packs appreciably since life tests were initiated.

SIGNAL-ELECTRODE DEPENDENCY ON BATTERY CURRENT

A characteristic of the signal-electrode voltage that is evident on practically all published cycling data is an abrupt signal-voltage change when the battery current is switched from charge to discharge or vice versa. This change

in signal electrode with change in cell (or battery) current is due to a common resistance of the two electrodes. Figure 5 illustrates the change in signal-electrode voltage due to change in battery (or cell) current. The slope of this curve is independent of the magnitude of current change and has a value of approximately one-half the cell resistance.

Figure 6 shows an equivalent circuit of the 20-ampere-hour nickel-cadmium cell with signal electrode. The signal electrode is represented by a voltage generator V_q with an internal impedance R_q in series. Cell resistance is shown associated with the positive and negative electrodes and called R_{CP} and R_{CN}, respectively. A signal voltage at R_L is measured with respect to the negative cell potential. Any voltage generated across R_{CN} due to cell current will be reflected across R_L. If the voltage of V_q is constant (constant pressure) and R_q is assumed less than R_L, the change in voltage across R_{CN} due to battery current will be seen across R_L.

SIGNAL-ELECTRODE VOLTAGE

To determine the magnitude of signal voltage for charge control across the 47-ohm resistor R_L, it is necessary to establish the relationship between signal voltage and cell's ampere-hour capacity. The temperature relationships of these two parameters are important considerations in selecting a signal-voltage control level for operation temperature range. Ideally, once the signal-voltage magnitude is determined, the battery could always be recharged to this

voltage and then stop the charge for the remaining sunlight period. No additional charge would be required or desired for the battery. By definition, a fully charged battery would have that ampere-hour capacity obtained when recharged to the signal-voltage cutoff.

A series of charge/discharge tests were conducted to establish the ampere-hour capacity that could be obtained at various signal-electrode voltages. Ampere-hour capacities were determined at C/2* discharges to 1.0 volt/cell after charging (1) C/10 for 16 hours, (2) C/2 charge to 100-mv signal level, (3) C/2 charge to 300-mv signal level, and (4) C/2 charge to 500-mv signal level. Five test cells were used, with one as the control cell. This cell was representative of the average capacity of the five cells.

Test parameters recorded included cell voltage, signal-electrode voltage, cell pressure, pack current, and temperature rise in center of pack above ambient. Each cell was heat-sinked to ensure adequate heat removal. Figure 7 shows the typical test pack configuration used when cell tests were conducted on the 20-ampere-hour cell. Note that the thermocouple is located in the center of the pack between cell number 3 and 4. Each cell was equipped with a pressure transducer for recording pressure.

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*C is rated capacity of cell and denotes the capacity at the 2-hour rate.

Figure 8 presents the ampere-hour capacity in percent of rated capacity for the three signal voltages used for control. An obvious trend in the data is the divergence of the input and output capacity with increase in signal-electrode voltage. As the signal voltage is increased, more overcharge is required to reach it. The discharge capacity does not increase in the same proportion as does the charge input capacity. For cyclic operation, more cyclic overcharge would clearly be required to reach the higher signal-electrode voltage levels.

Figure 9 shows the ampere-hours obtained from the C/2 discharge with temperature as the independent variable. The ampere-hours gained by increasing the signal voltage from 300 to 500 millivolts is approximately 4 percent at 25°C, 12.5 percent at 40°C, and 10 percent at 0°C. The condition for diminishing return of ampere-hours with increase signal-electrode voltage is evident. More capacity can be realized at the higher signal voltages but the capacity again is not enough to justify the higher overcharge conditions it requires.

Observing the transfer characteristic (signal voltage vs pressure) of this device at the various temperatures is basic to understanding the signal electrode; in particular, its limitations for charge control. Figure 10 shows a typical transfer characteristic of a 20-ampere-hour signal-electrode cell. A linear response is obtained over a limited region of pressure and provides the most desirable operating region. Overcharge can be directly related to cell pressure by the signal voltage. Unfortunately, the signal voltage varies from

cell to cell (at same pressure); but the greatest variation of signal voltage is due to unbalance in cell capacity among a group of cells. In general, the lower-capacity cell will provide the largest signal-electrode voltage. Exceptions to this rule are found and are usually attributed to a very sensitive signal electrode.

An obvious precaution that must be exercised in selecting a signal-voltage level for control is evident at $0^{\circ}C$. At this temperature, a signal voltage above 500 millivolts would not be obtained and the results could be disastrous to the battery since charging would not be terminated.

A probable explanation for nonlinearity in the curve at higher pressures is the signal-electrode material which is surface-dependent and can only respond to a given amount of oxygen molecules. Once the surface is saturated, additional oxygen molecules have very little effect on the signal voltage being generated.

SIGNAL-ELECTRODE VOLTAGE DECAY RATE

One problem associated with signal-electrode charge control in near-earth orbits (90 to 100 minutes) is that the signal voltage in some cases may not decay sufficiently during the shadow period below the threshold level used for charge control. This causes a premature fully charged signal at the beginning of sunlight. Several factors influence the decay rate and two of these are shown in Figure 11. Decay rates were determined over a 10-minute

interval, 10 minutes after the C/2 discharge was initiated. The best conditions for fastest decay rate are high temperature and high overcharge; neither of these are compatible with desirable operating conditions and long-life requirements for nickel-cadmium batteries.

THERMAL OUTPUT DURING OVERCHARGE

Figure 11 shows thermal data measured on a 20-ampere-hour nickel-cadmium cell with signal electrode (Reference 5). These are data for a typical near-earth orbit at a 25-percent depth of discharge, with cell voltage, signal-electrode voltage, and thermal output shown as time-dependent variables. The percentage return is approximately 106, with a corresponding heat from overcharge of 0.7 watt. A 290-mv signal-electrode voltage represents the end of charge-signal voltage. Heat generated during discharge produced 3.9 watts peak. Integration of the area under the heat curve gives approximately 140 watt-minutes from discharge and 5 watt-minutes from overcharge. The heat from overcharge is insignificant when compared to the total orbital average dissipated by the cell. There was no cell capacity degradation during operation under these conditions.

OPTIMUM SIGNAL-VOLTAGE RANGE

From the data shown, there is evidently an optimum signal-voltage range for charge control. The range of this voltage is centered at 300 mv with an approximate variation of ±50 mv. With 300 mv, the highest pressure for data

shown was 17 lbs/in^2 absolute and the worst-case capacity at 40°C is 80 percent of rated ampere-hour capacity; heat output from overcharge is less than 1 watt at 25°C. The magnitude of these parameters will vary from cell to cell; however, values shown are typical for near-earth orbit regime. Restricting the upper-temperature operation of the battery to 30°C provides a condition where the ampere-hour capacity is always greater than rated capacity with a fixed signal-electrode control voltage. For life requirements on the present generation of spacecraft this is not an additional restriction; it is one imposed by the limitation of the nickel-cadmium cell itself, not by the signal electrode.

One additional comment on overcharge is that the percentage return on a cyclic basis, to return to a fixed signal-electrode voltage, increases as the signal voltage is increased. The state of overcharge is therefore increased with signal-electrode voltage. The important fact is that greater deliverable capacity demands greater heat generation and pressure build-up within each cell.

Crane data are available (Reference 4) on life tests of 6-, 12-, and 20-ampere-hour signal-electrode cells, using two concepts of charge control. The 20-ampere-hour signal electrode has only recently entered the test program. During these life tests, signal electrodes of all cells in a test pack are or-gated to the control circuit. The highest signal-electrode voltage controls the test

pack. With only a few exceptions, the signal electrode that controls at the beginning continues to control throughout the life test.

CONCLUSIONS

The ability to control overcharge of nickel-cadmium batteries by the signal electrode while obtaining optimum performance on the battery has been demonstrated. Emphasis is placed on the fact that optimum performance of nickel-cadmium batteries can be achieved only when the ampere-hour capacity is not maximized by overcharge. Using a selected number of signal-electrode-type cells in each battery provides a signal voltage that can be used to maintain the capacity of the battery and optimize overcharge. The immediate benefits of signal-electrode charge control are evident from the data presented. Long-term gains are now being determined in special designed life test. A statement by Dr. Carson (Reference 6) "the knowledge that cycle life is adversely affected by overcharging leads one to the conclusion that the charge-control design should minimize the rate and duration of overcharge to the fullest extent possible for the application," states the need for overcharge control. The signal electrode is a device that fills this need for nickel-cadmium batteries.

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2. K. O. Sizemore, "Use of the Absorption Hydrogen Electrode and the Oxygen Fuel-Cell Electrode in Nickel-Cadmium Cells," NASA Report X-716-66-83, April 1966

3. S. Lerner, "Final Report for Characterization of Recombination and Control Electrodes for Nickel-Cadmium Cells," Gulton Industries, Inc., NAS 5 10241

4. D. E. Mains, "Fourth Annual Report of Cycle Life Test," Report QE/C 68-138 U. S. Navy Ammunition Depot, Quality Evaluation Laboratory (Crane, Ind.)

5. G. D. Mitchell and R. T. Foley, "Fifth Progress Report for Research into Fundamental Phenomena Associated with Spacecraft Electro-chemical Devices - Calorimetry of Nickel Cadmium Cells," American University (Washington, D. C.) NAS 5-10105

6. W. N. Carson, Jr., "A Study of Nickel-Cadmium Spacecraft Battery Charge Control Methods," General Electric Company, NASA 5-9193
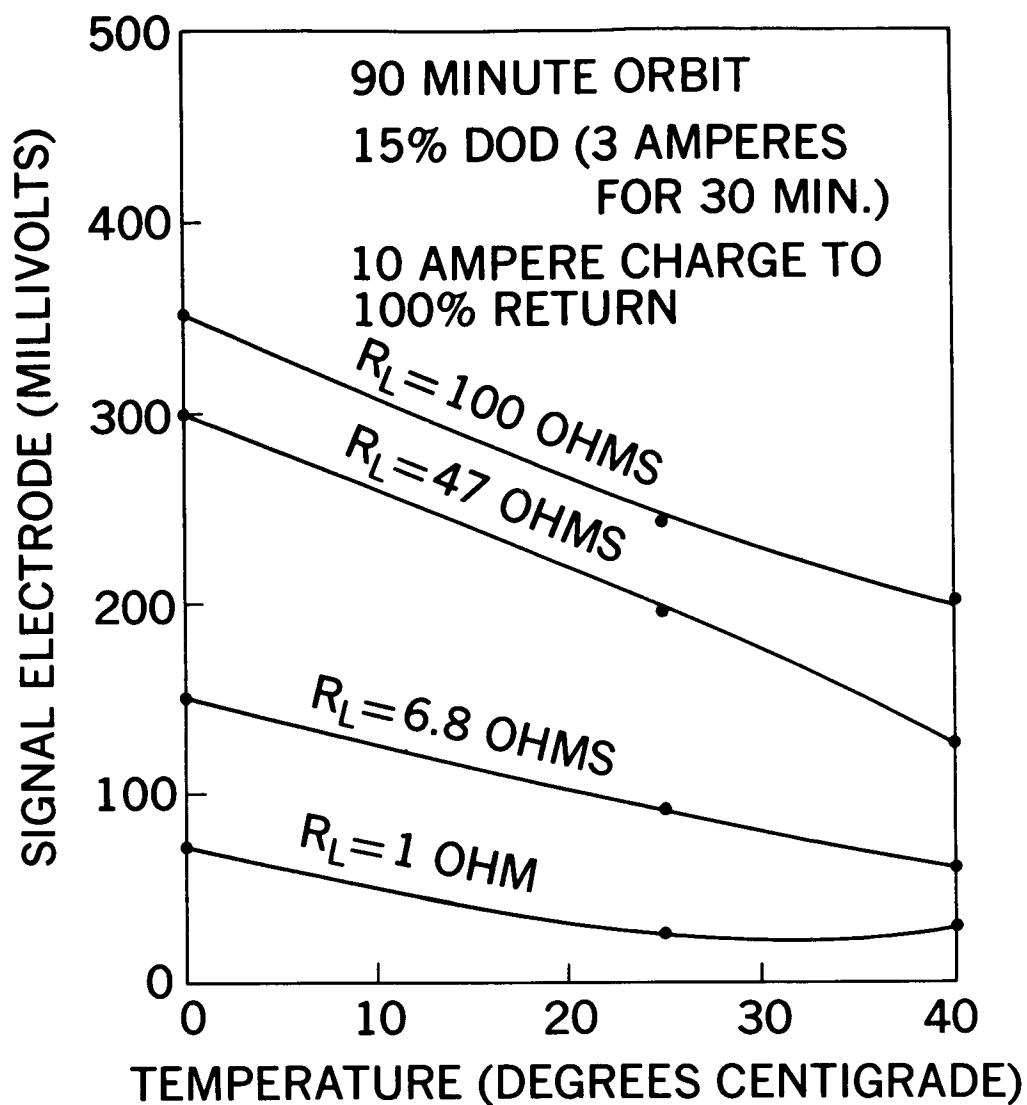
Figure 1. Signal Electrode Characteristics at 100 Percent Recharge
on the 20 Ampere-Hour Nickel-Cadmium Cell
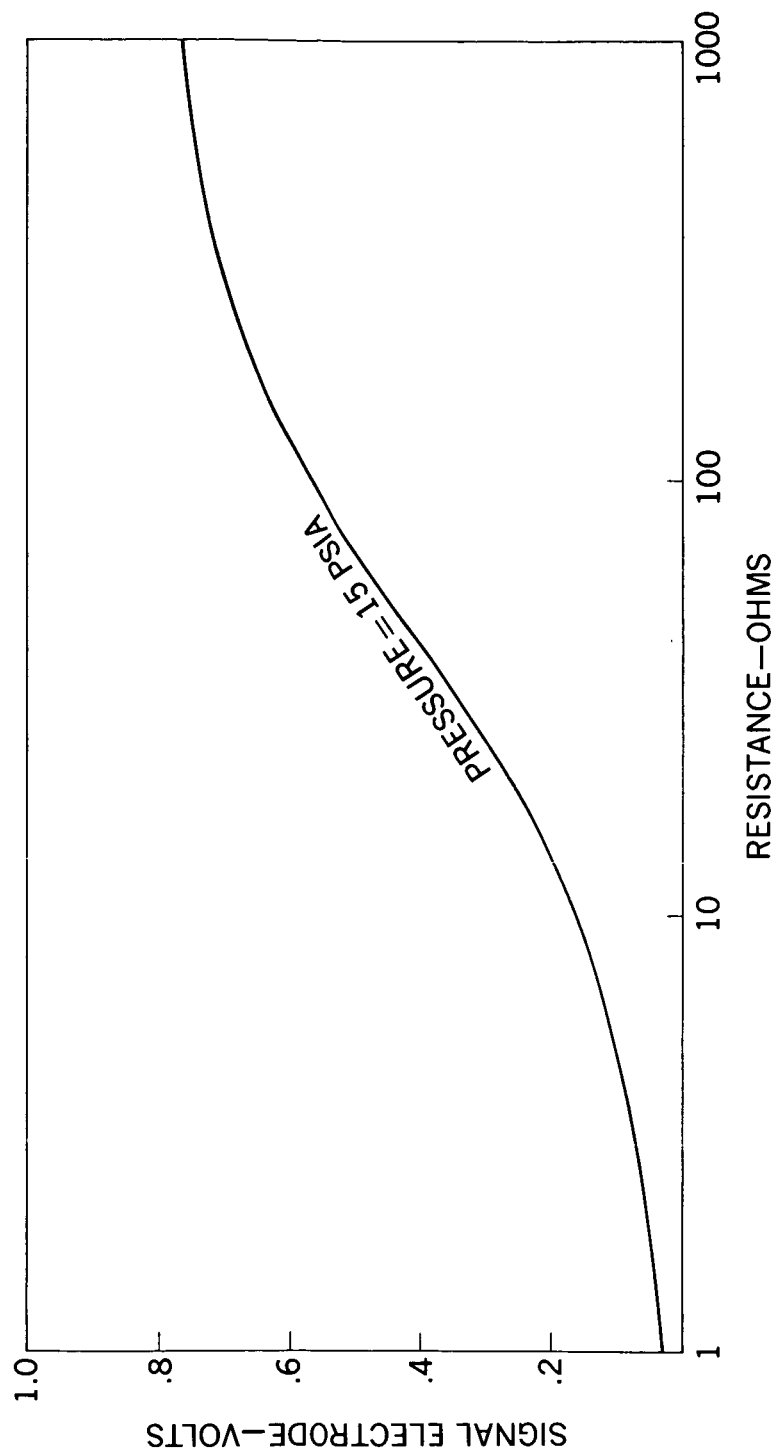
Figure 2. Signal Electrode Voltage for Various Signal to Cadmium Loads on Cell No. 3, 25°C Temperature
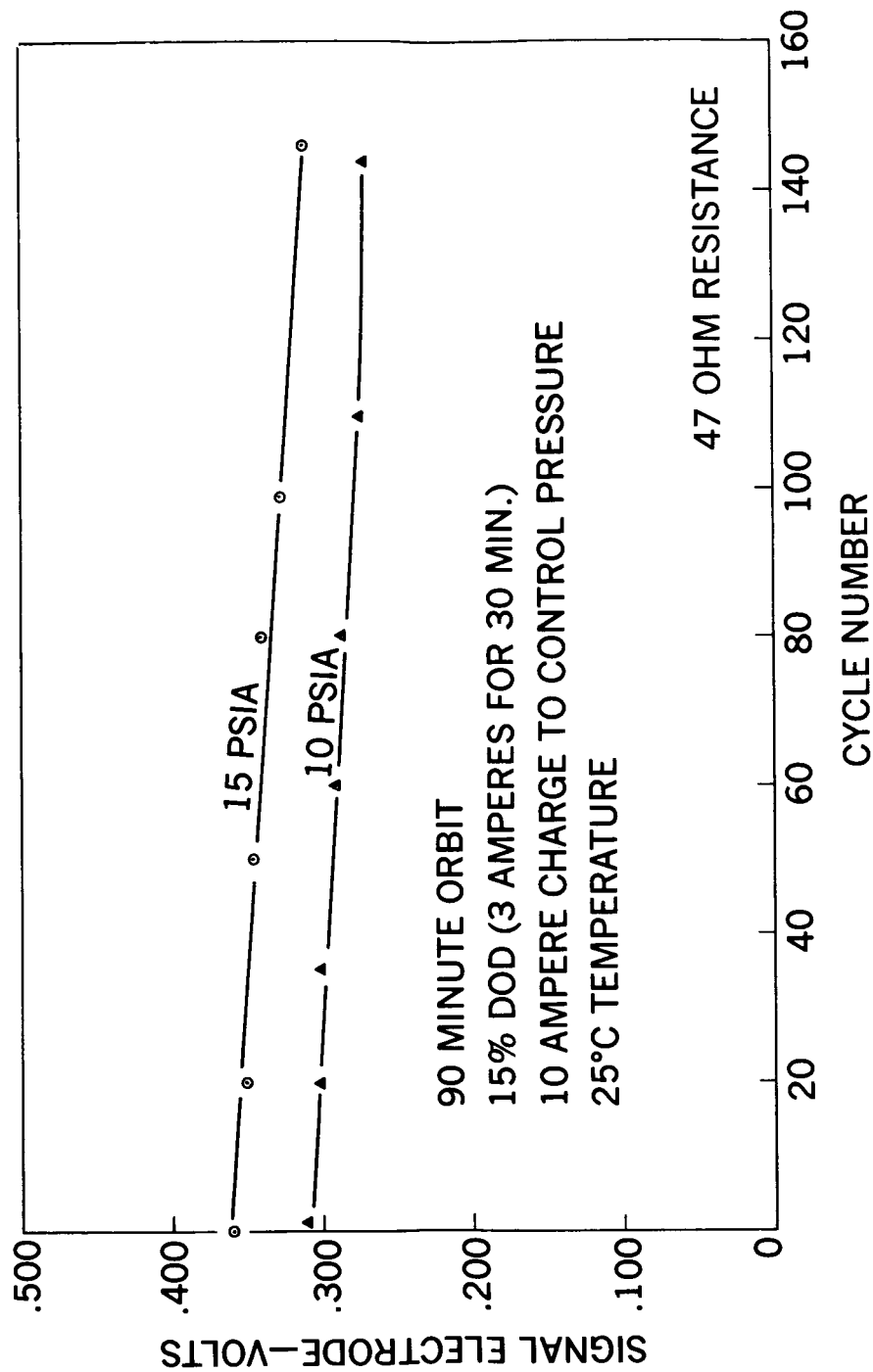
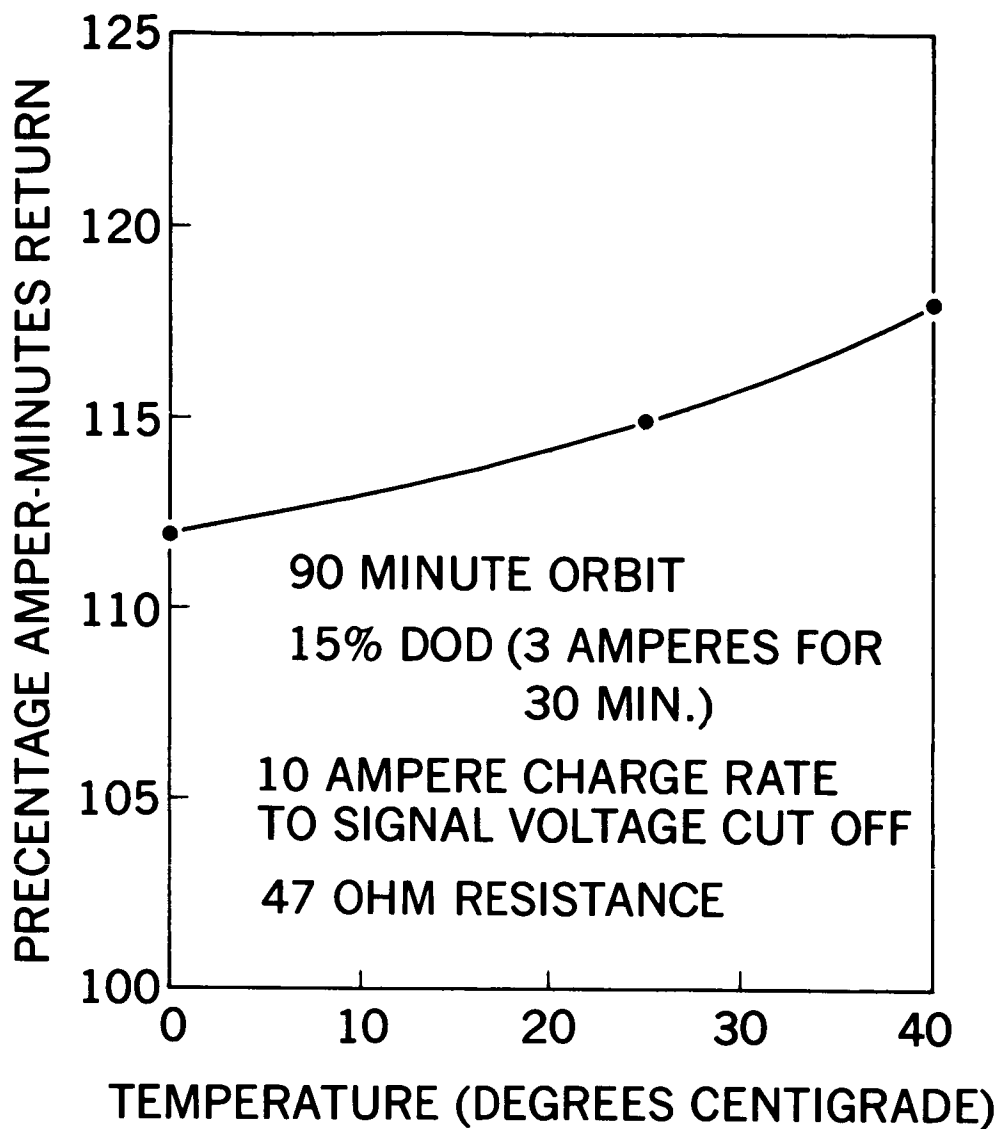Figure 3. Change in Sensitivity of Signal Electrode Voltage with Cycling

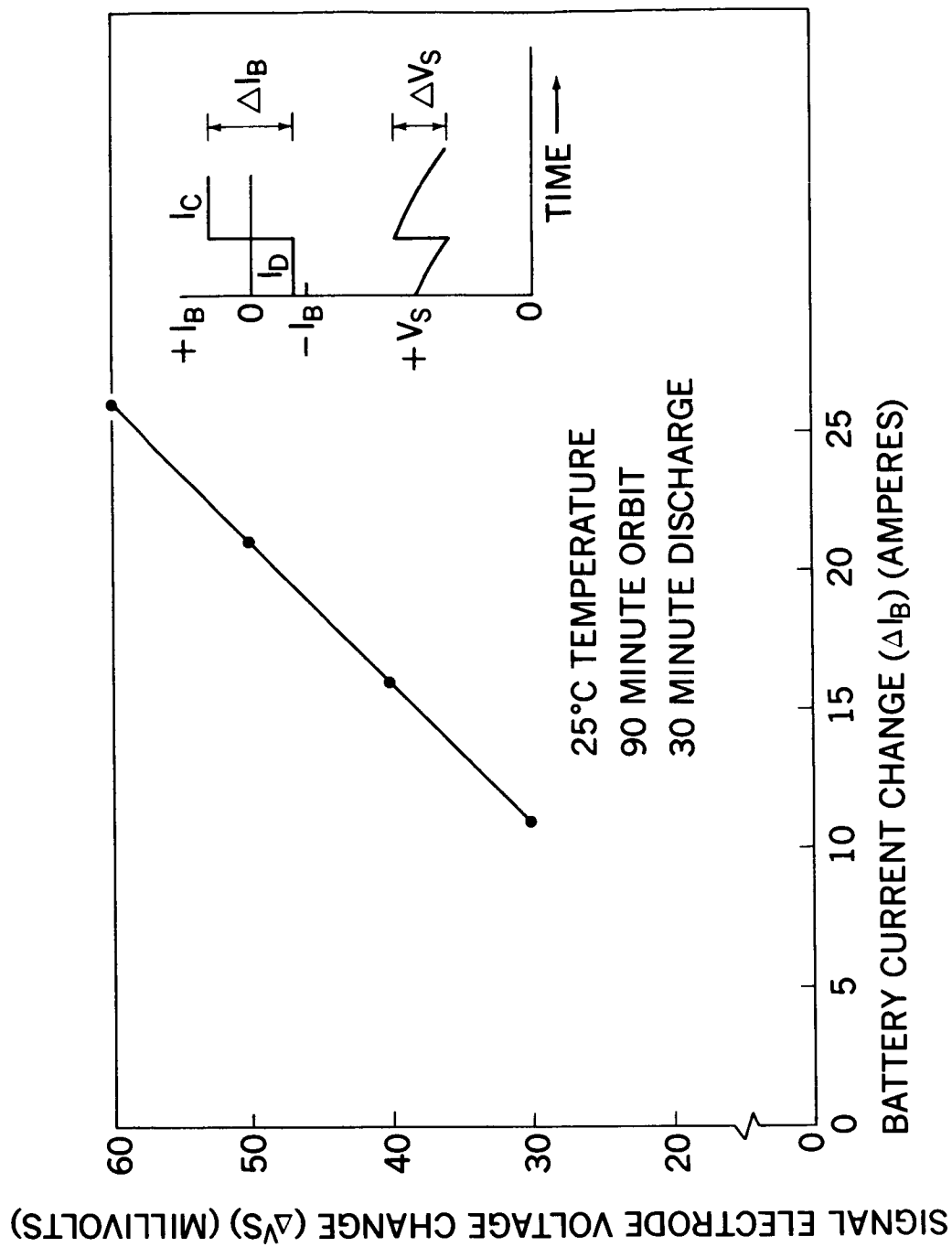Figure 4. Percentage Recharge for Signal Voltage of 260-Millivolt Control

Figure 5. Signal Electrode Sensitivity to Battery Current Change
(47 OHM Load Resistance)

R_{CP}: RESISTANCE OF POSITIVE ELECTRODE

R_{CN}: RESISTANCE OF NEGATIVE ELECTRODE

R_q: INTERNAL SIGNAL ELECTRODE

R_L: EXTERNAL SIGNAL ELECTRODE LOAD

V_q: VOLTAGE GENERATOR OF SIGNAL ELECTRODE

E_C: CELL POTENTIAL
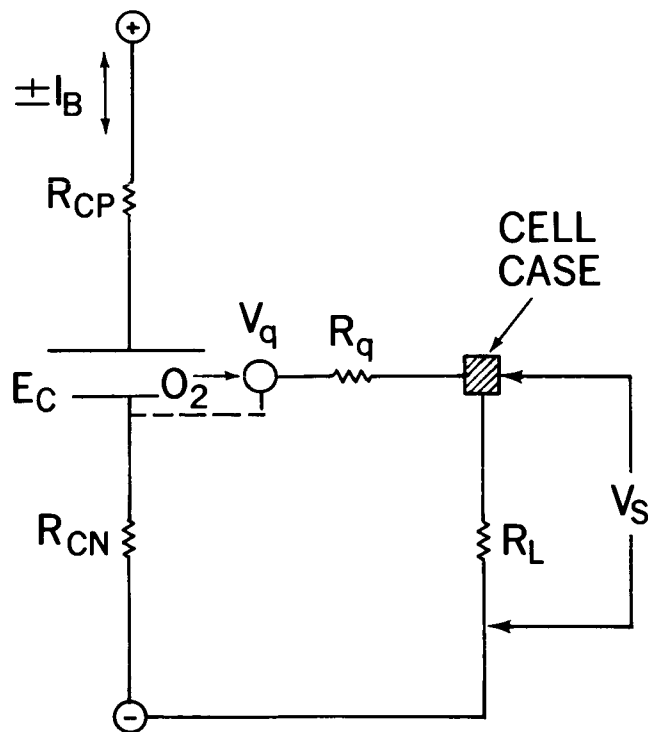
Figure 6. Equivalent Circuit of Nickel-Cadmium Cell with Signal-Electrode
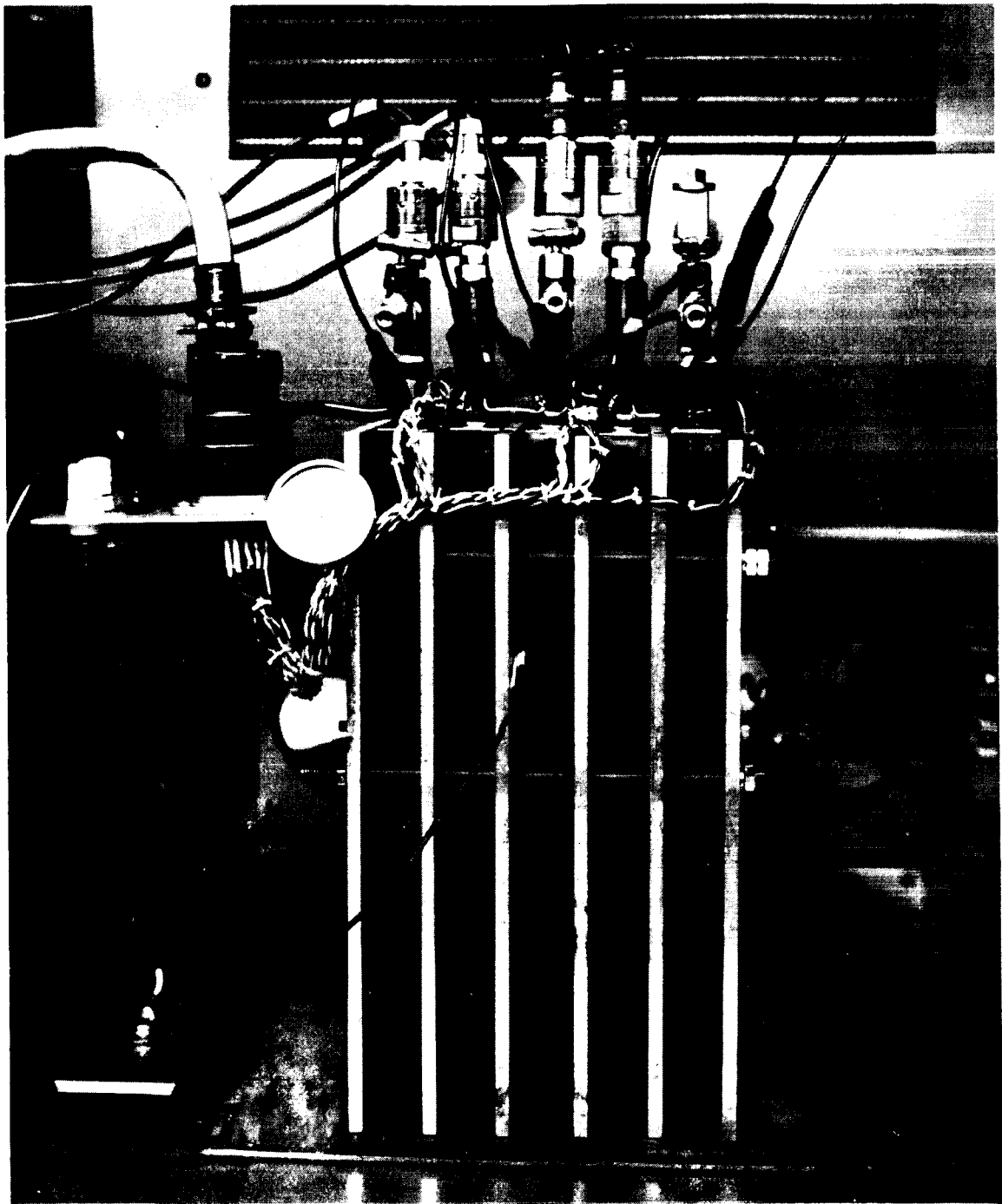
Figure 7. Typical Test Pack Configuration for Studying Cell
Characteristics
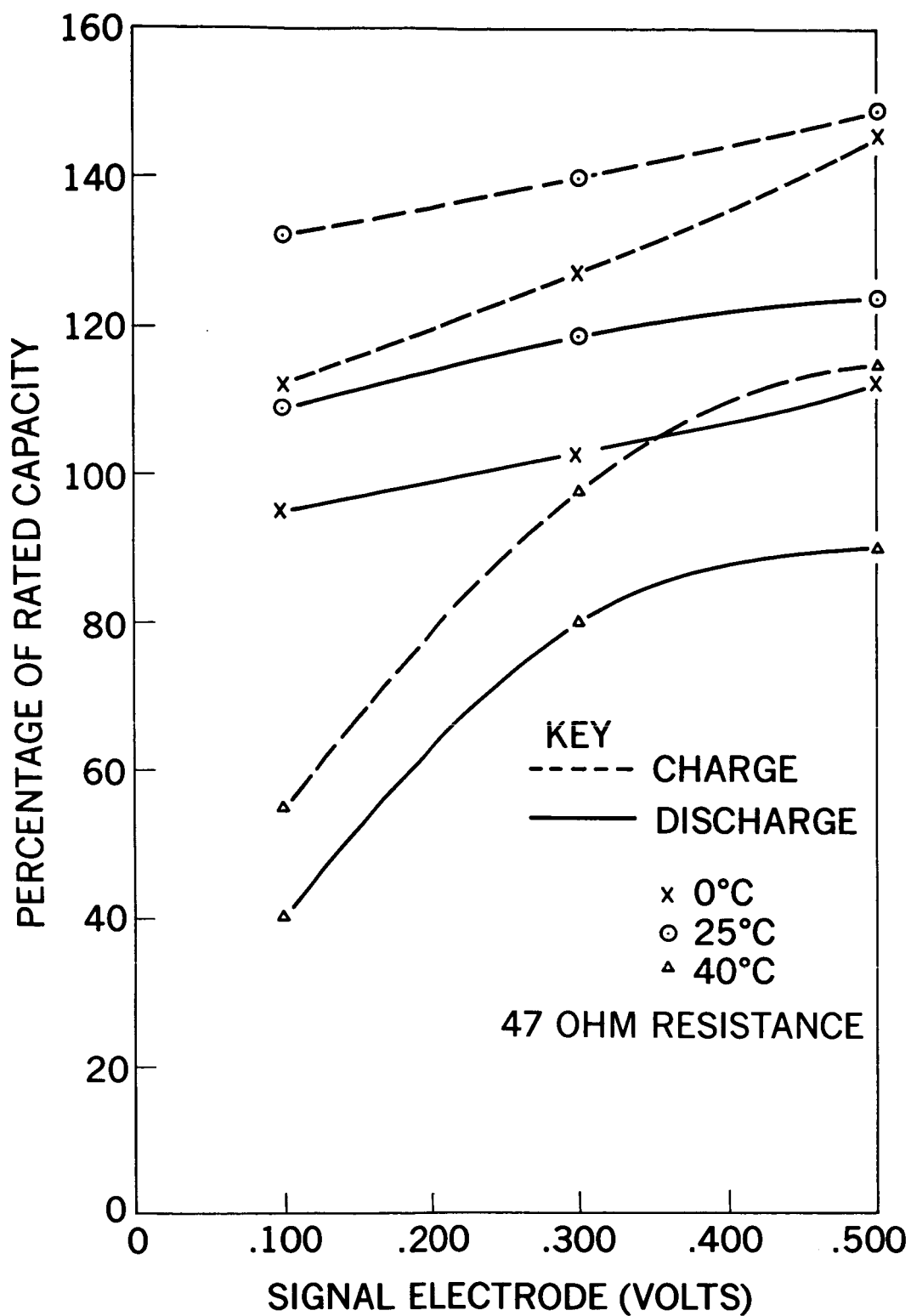
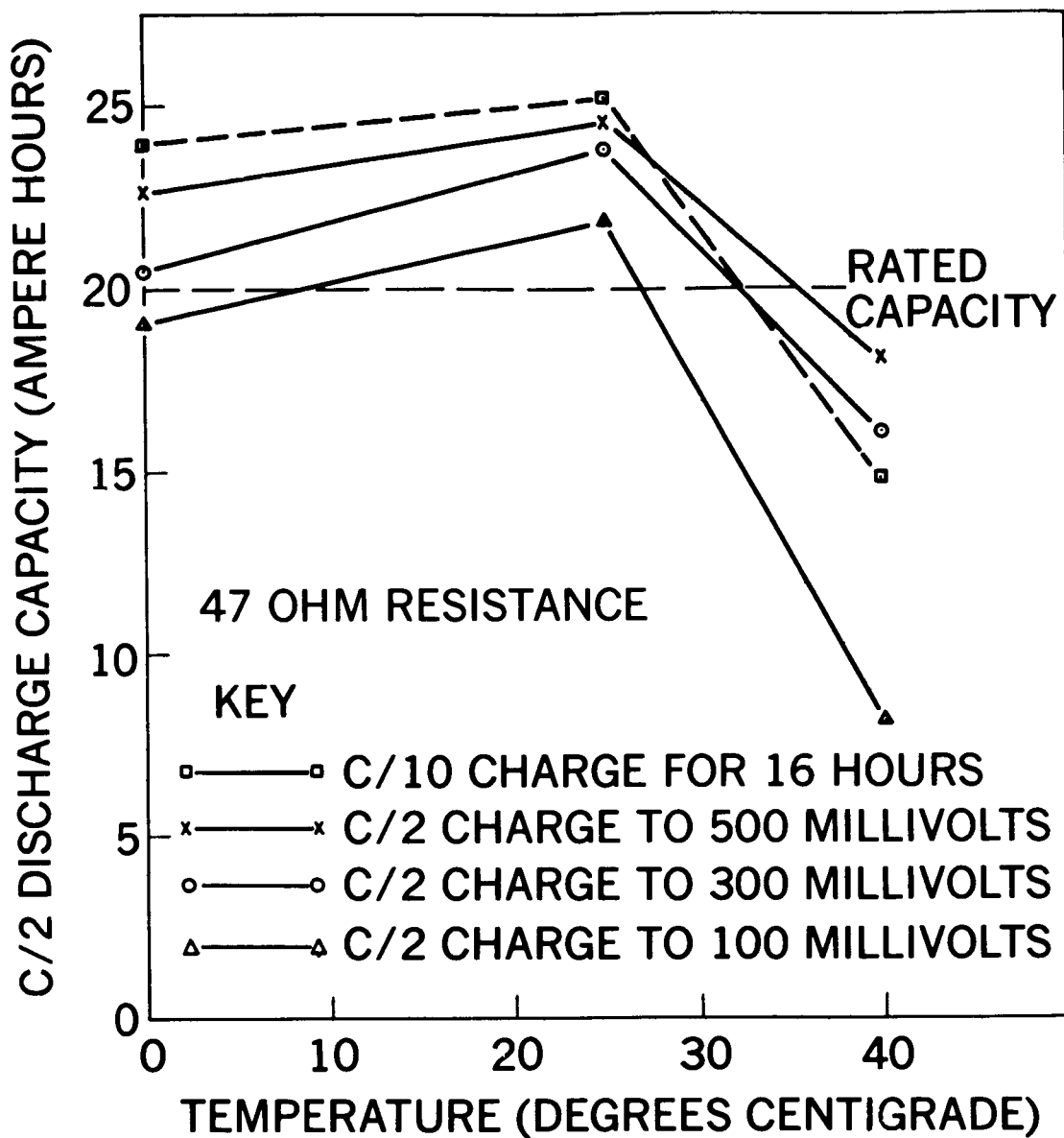Figure 8. Percentage of Rated Capacity Obtained for Various
Signal Electrode Voltage Levels
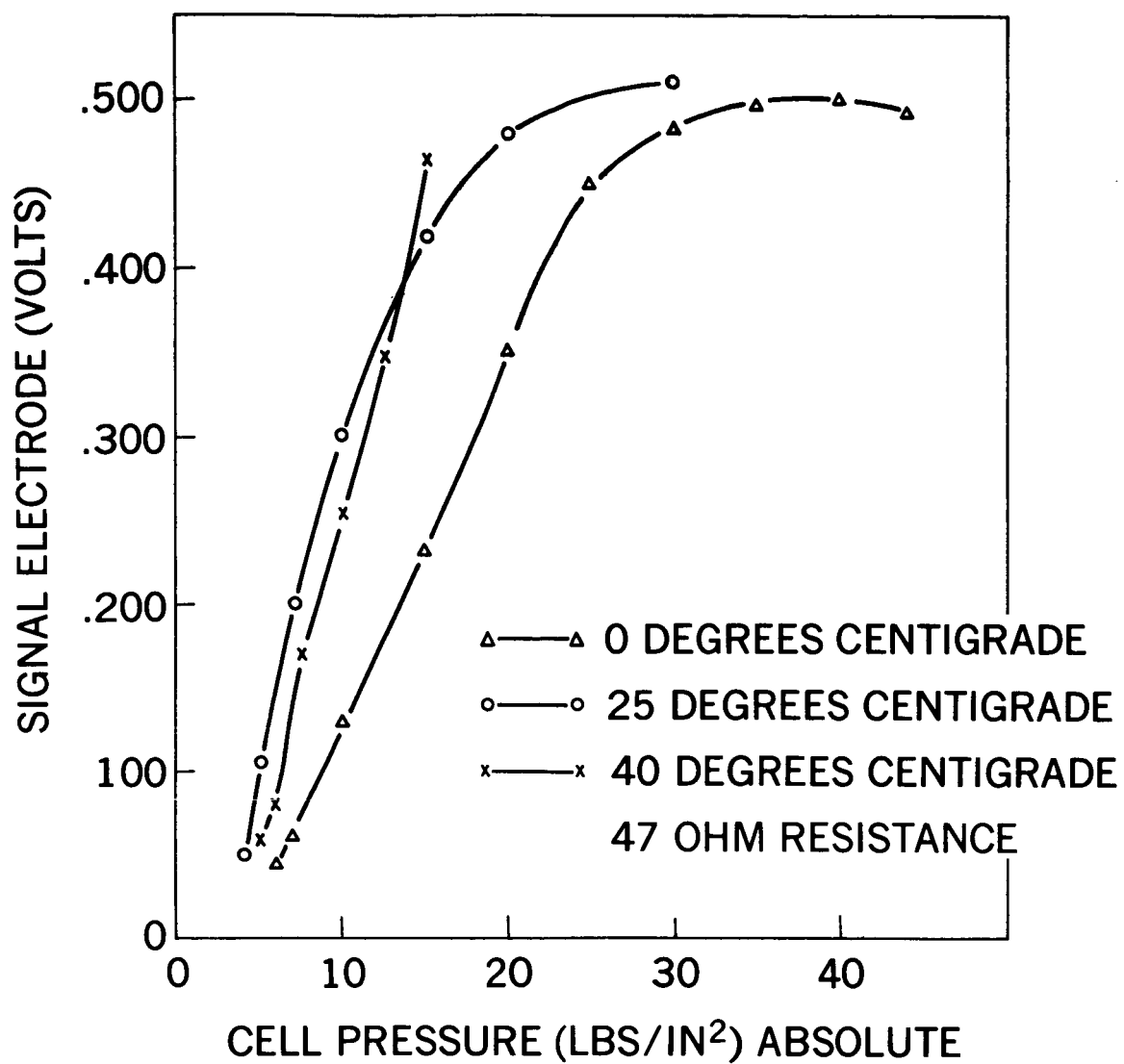
Figure 9. Ampere-Hour Capacity for C/2 Discharge

Figure 10. Transfer Characteristics of a Typical Signal Electrode

x——x C/2 CHARGE TO 500 MILLVOLTS

o——o C/2 CHARGE TO 300 MILLIVOLTS

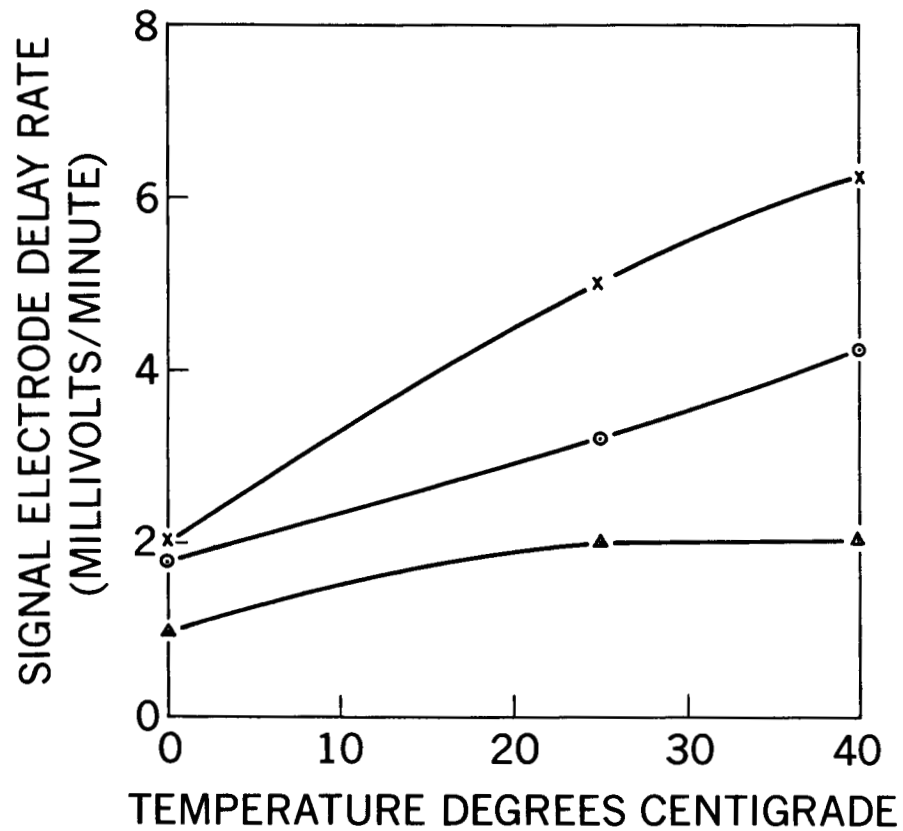▲——▲ C/2 CHARGE TO 100 MILLIVOLTS

47 OHM RESISTANCE

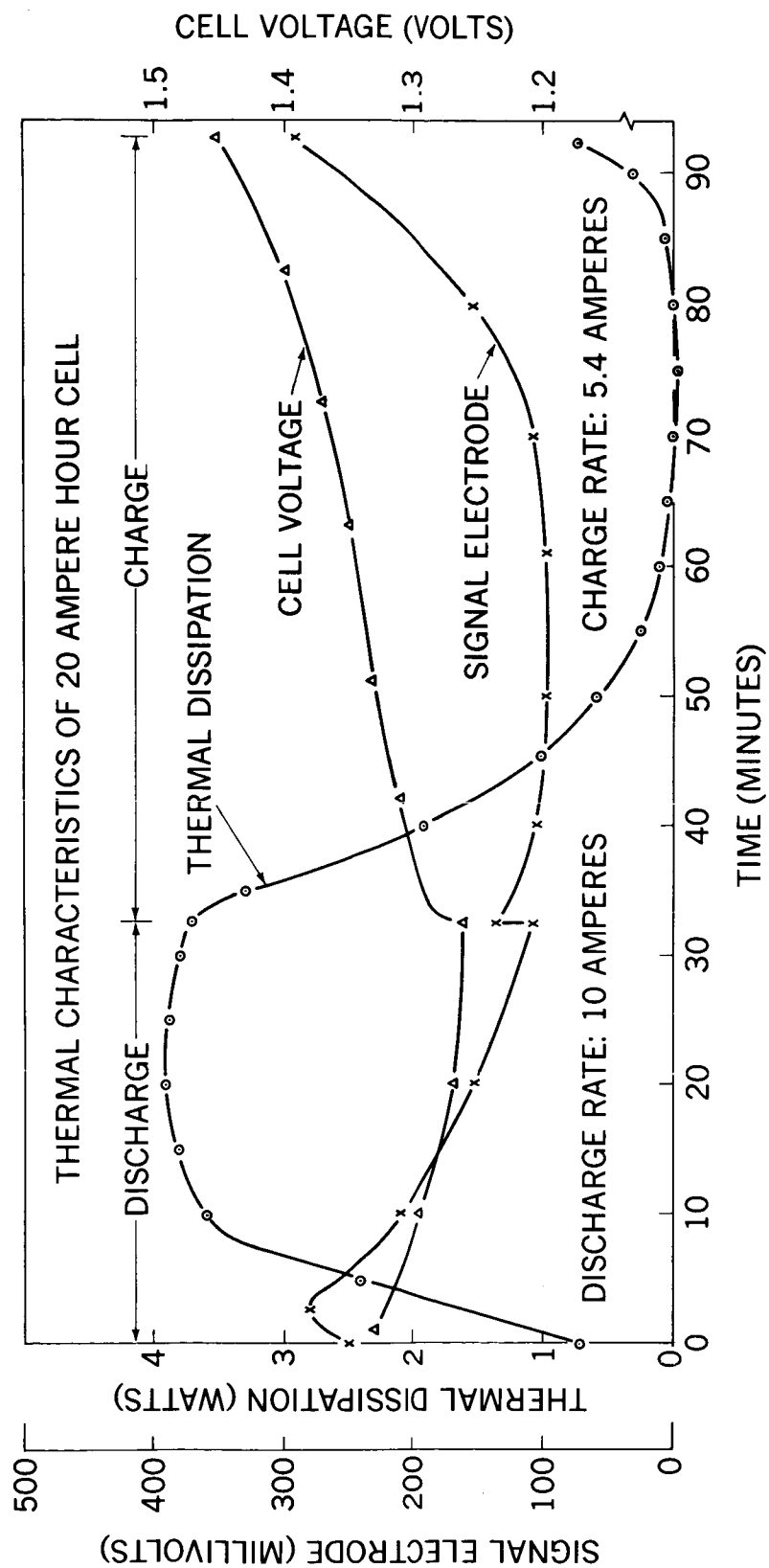Figure 11.   Signal Electrode Voltage Decay Rate during C/2 Discharge

Figure 12. Thermal Characteristics of 20 Ampere-Hour Nickel-Cadmium Cell with Signal Electrode