NICKEL-CADMIUM BATTERY CELL REVERSAL FROM RESISTIVE NETWORK EFFECTS

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ABSTRACT

During the individual cell short-down procedures often used for storing or reconditioning NiCd batteries, it is possible for significant reversal of the lowest capacity cells to occur. The reversal is caused by the finite resistance of the common current-carrying leads in the resistive network typically generated during short-down. A model is developed to evaluate the extent of such reversal in any specific battery, and the model is verified using data from short-down of a 4-cell, 3.5 Ah battery. Computer simulations of short-down on a variety of battery configurations indicate the desirability of controlling capacity imbalances due to cell configuration and battery management, limiting variability in the short-down resistors, minimizing lead resistances, and optimizing lead and battery configurations.

INTRODUCTION

Nickel-cadmium (NiCd) battery cells are often stored during extended periods of inactivity in a totally discharged state, usually with a shorting connector across the terminals of each cell. Much evidence points to this being the optimum storage mode, particularly at reduced temperature. In addition, a growing body of data also indicates that periodic total discharge of individual cells in a battery is an extremely useful way of reconditioning and balancing cell performance, and thus extending the operational life of a NiCd battery. For a battery of series-connected cells, the process of total discharge must generally be done for each cell independently, so that the lower capacity cells will not be series driven into reversal by the higher capacity cells. A particularly simple way to accomplish an independent discharge for each cell is merely to place a resistor (typically 1 ohm) across each cell and allow the cell to discharge for an extended period of time. For batteries this is often done by attaching a shorting resistor assembly to voltage sensing wires at a battery connector.

Typical battery short-down procedures involving discharge of more than one cell at a time do not provide for totally independent discharge of each cell. This situation arises simply because of the finite resistance in the current-carrying wires common to adjacent cells. The short-down procedure actually creates a resistive network in which coupling between adjacent cells must always exist as long as any lead resistance is present, as indicated in Fig. 1.

Because of the coupling effects of lead resistances, there is a distinct possibility that the lower capacity cells will be driven into reversal by the higher capacity cells, even when individual resistors are connected across each cell. The driving forces for such reversal should be generally minimized by maintaining capacity balance, minimum lead resistance, optimized cell configuration, and appropriate short-down procedures. In this report the network of Fig. 1 is analyzed as a function of cell characteristics, lead resistance, and shorting resistance. The extent of cell reversal that may realistically be expected is calculated for typical battery short-down configurations. Test data are also presented to support the model for a 4-cell NiCd battery consisting of 3.5 Ah "D" cells. Finally conclusions are provided to indicate how to minimize the possibility of cell reversal during individual cell short-down.

NETWORK ANALYSIS

For the network of Fig. 1, the cell currents I_n must be determined as a function of the cell voltages V_n, the shorting resistances S_n, and the lead resistances R_n. For each cell n, the application of Kirchhoff's laws shows that the current through the shorting resistor, I_n must equal the cell current. The voltage of each cell is equal to the sum of the voltage drops around each loop, i.e.,

$$V_n = I_n S_n + R_n(I_n - I_{n-1}) + R_{n+1}(I_n - I_{n+1}) \qquad (1)$$

which may be rearranged to

$$V_n = I_n(S_n + R_n + R_{n+1}) - I_{n+1}R_{n+1} - I_{n-1}R_n \qquad (2)$$

The relationships between voltage, current, and resistance are thus simply reduced to the equation

$$\underline{R}\ \underline{I} = \underline{V} \qquad (3)$$

where $\underline{R}$ is the n-by-n network resistance matrix with elements

$$r_{ij} = (S_i + R_i + R_{i+1})\delta_{ij} - R_j\delta_{i+1,j} - R_i\delta_{i-1,j} \qquad (4)$$

where δ_{ij} is the delta function. The diagonal term in Eq. 4 represents the discharge paths expected for ideal individual cell discharge. The off-diagonal terms represent the coupling of each cell through the network to other discharging cells. The current and voltage in Eq. (3) are both n-element column vectors with elements I_n and V_n, respectively. Equation (3) may be solved for either the cell voltages V_n if the currents I_n are known, or the currents may be determined if the voltages are known.

EXPERIMENTAL RESULTS

To evaluate how the analysis of the previous section can be applied to battery discharge, a 4-cell battery and resistance network were prepared having the values given in Table 1. The cells were 3.5 Ah NiCd "D" cells. The voltage and current of each cell was monitored as a function of time during the discharge through the resistors. The battery was typically charged for 16 h at C/10 following at least a 16-h short-down.

The first test involved charging cells 1 through 3 only, discharging these three cells for 2.5 h at 1 A, then resistively shorting down all four cells using the network defined in Table 1. The observed voltage behavior for the four cells is indicated in Fig. 2, where the points indicate the voltage calculated from Eq. (3) and the lines indicate the experimentally measured voltages. Cell 4, which is totally discharged, remains in reversal for about 2.5 h. The reversal current depends on the voltages of the other cells, but was as high as 94 ma (C/37) early in the reversal. The good agreement between the experimental data and the calculated points in Fig. 2 indicates that the network model of Fig. 1 can accurately describe the behavior of battery cells during individual cell short-down.

The second test involved connecting the shorting resistor to cell 4, 1 h before shorting down the other cells, thus creating about a 1 Ah lower capacity in cell 4. As indicated in Fig. 3, cell 4 was still driven into reversal for about 12 min with a maximum reversal rate of 92 ma. The third test was similar to the second test except that short-down was begun 1 h earlier on cell 3 rather than cell 4. The results are indicated in Fig. 4. The reversal rate was 172 mA at its maximum, about twice that of the previous test, presumably because during most of the reversal period the cells on each side of cell 3 had high voltages. In the third test the cell was in reversal for 32 min. These results suggest that during short-down the end cells in a series string have a much more benign environment with regard to reversal.

BATTERY SHORT-DOWN SIMULATIONS

The short-down of a battery containing n cells was simulated by a computer model. The inputs to this model consisted of shorting resistances, lead resistances, the capacity of each cell, and a current-voltage relationship as a function of residual capacity discharged from the depleted cell.

The current-voltage relationship that was used in the simulations was derived from short-down data for 3.5 Ah cells having 1 ohm short-down resistors, and is meant to provide only a representative current-voltage relationship during short-down. Each cell was assumed to have a constant voltage of 1.15 volts until its capacity was depleted, after which the voltage deceased linearly to 0.2 volts during the discharge of an additional 0.04 Ah. Thereafter each cell was assumed to have a voltage given by

$$V_n = 0.317 \times 10^{-5Q} - \Delta I(1.228 \times 10^{-1.226 \Delta I}) \qquad (5)$$

where Q is the residual capacity discharged in Ah. and ΔI is any discharge current in excess of that anticipated from the diagonal terms in Eqs. (3) and (4). Equation (5) was obtained empirically by fitting the voltage of one cell during short-down. When the voltage is negative, a voltage limitation of $V_n = -0.06 \log(I/0.00014)$ is used to give a reasonable asymptotic dependence for hydrogen evolution. While this model is only approximate, it provides a reasonable empirical representation of the short-down behavior with 1 ohm resistors, which can be used for evaluating trends in the short-down behavior.

The first computer simulation was for a 4-cell battery using the short-down parameters of Table 1, 3.5 Ah of capacity for cells 1 through 3, and 2.5 Ah for cell 4. The trends in the simulation should therefore be directly comparable to the data in Fig. 3. The results of the simulation, indicated in Fig. 5, clearly show the same features as the data in Fig. 3.

The second computer simulation was done for a 22-cell battery where 1 cell was assumed to have 1 Ah less capacity than the other 21 cells, and the position of the low-capacity cell was varied from one end to the middle of the cell string. All shorting resistors were 1 ohm and all lead resistances were 0.1 ohm. The results of this simulation, presented in Fig. 6, clearly show that the end cell should be subject to considerably less reversal than cells of equal capacity situated away from either end of the cell string.

A third simulation was done to determine the effect of varying the lead resistance on the cell reversal. An 11-cell battery was simulated, with the Ah in reversal during short-down plotted as a function of lead resistance in Fig. 7. The center cell was assigned 1 Ah less capacity than the other cells, so it is the cell being reversed in Fig. 7. All short-down resistances were 1.0 ohm. From the results in Fig. 7, approximately 0.025 ohm of lead resistance are required before reversal occurs under these conditions of simulation. The amount of reversal increases in a nearly linear fashion as the lead resistance is increased relative to the shorting resistance.

It is expected that the amount of cell reversal should increase as capacity imbalance increases. In Fig. 8 a fourth simulation is presented in which the capacity imbalance is varied and both the capacity and the time in reversal are plotted. This simulation is for an 11-cell battery whose center cell is low in capacity; shorting resistors are 1.0 ohm, and lead resistances are 0.1 ohm. Both capacity and time spent in reversal increase with increasing capacity imbalance. However, if the imbalance is near 2 Ah or higher, the low cell will stay in reversal long after the other cells are depleted, since it has been taken down far enough in capacity that even the low residual voltages present for the other cells can hold the low cell in reversal. The data in Fig. 8 clearly indicate the need to avoid conditions that can lead to large imbalances in capacity.

Capacity imbalances between the cells of a battery are generally controlled to less than 5% of the total capacity by cell matching procedures. However, extended periods of open-circuit stand, cycling, or other environmental considerations may temporarily create greater imbalances. If a normal distribution of cell capacities is assumed for an 11-cell battery, and these cells are arranged in order of increasing capacity in the battery, it was not possible to reverse any of the cells in a computer simulation where the total spread of capacities was allowed to go up to 1 Ah. This is because adjacent cells are never very different from each other in capacity. Adjacent cells would probably have to differ by 0,3 Ah or more to get reversal in this configuration. On the other hand, if the cell arrangement is changed so that high-capacity and low-capacity cells alternate without any change in the overall cell capacity distribution, extensive reversal becomes possible. This is simulated in Fig. 9, where the extent of reversal is plotted as a function of the Ah spread in an 11-cell battery, assuming a normal distribution of capacities. The cells alternate in capacity so that cells 2, 4, and 6 are the three lowest capacity cells. The results in Fig. 9 indicate that when capacity imbalances are possible, it is very likely that several cells can be driven into reversal simultaneously.

A final situation that can lead to significant imbalance in cell capacities in a battery is the effect of unmatched short-down resistors being used to take a battery down from a high state of charge. This effect causes some cells to discharge faster than others, so that large imbalances in capacity can exist when the first cell reaches depletion, even if all the cells were closely matched at the start of discharge. The effect is simulated in Fig. 10, where both the extent of reversal and the effective cell imbalance are plotted as functions of short-down resistor imbalance. The simulation started with a fully charged 3.5 Ah battery containing 11 cells, of which the center cell has an imbalanced short-down resistor. The initial capacity spread between high and low cell was 0.3 Ah and followed a normal distribution. The cells were arranged in an alternating high-low capacity arrangement. Fig. 10 indicates that a 15 to 20% imbalance in short down resistors can add 0.7 Ah to the imbalance between cells and can cause extensive reversal. The situation of imbalance due to variations in short-down resistors can be easily managed by either using matched resistors, or by discharging battery capacity as a series cell string until the lowest cell is depleted before the short-down resistors are connected.

CONCLUSIONS

The results presented here indicate that significant reversal of the lowest capacity cells can result from individual cell short-down of a NiCd battery. A model has been presented that provides a straightforward way to evaluate the risk of cell reversal for a particular battery or a particular short-down procedure. The consequences of cell reversal are likely to be (1) some hydrogen evolution, although not enough to overpressurize the cell; and (2) significant Cd reduction at the Ni electrode, possibly leading to Cd dendrite short-circuits. Such short-circuits, if formed, will be oxidized during recharge and are not expected to have any lasting impact on performance.

This report suggests a number of points that are important in minimizing the possibility of cell reversal, as follows:

1. Minimize capacity imbalances that may arise from uncontrolled battery handling or storage. This is particularly important during integration and test procedures.

2. Do not discharge battery capacity from a high state of charge by using individual cell short down. Discharge the battery as a series string of cells until the lowest capacity cell is depleted, then apply short-down resistors to individual cells.

3. Use 1%-tolerance resistors for short-down.

4. Minimize lead resistance relative to the resistance of the short-down resistors. Lead resistance includes that of leads internal to the battery assembly, plus that of any cable used to connect the battery to a breakout box where the short-down resistors are attached. The ultimate solution to minimize lead resistance is to attach the short-down resistors at the cell terminals, or to attach separate leads at

each cell terminal.

5. The arrangement of cells within a battery is critical. The optimum arrangement for minimizing the possibility of cell reversal is to order the series string of cells in terms of capacity, from high at one end to low at the other end. This procedure makes it difficult to reverse any cell in the string during short-down as long as the spread in cell capacities does not increase significantly beyond the initial spread typically allowed in NiCd batteries.

6. The end cells in the series-connected string are always less subject to reverse discharge during individual cell short down than the other cells in the battery.

Table 1. EXPERIMENTAL BATTERY NETWORK PARAMETERS FOR 4 CELLS CONNECTED IN SERIES (3.5 A h)

Lead Resistance, Ω	Shorting Resistance, Ω
$R_1 = 0.0721$	$S_1 = 1.045$
$R_2 = 0.0786$	$S_2 = 0.940$
$R_3 = 0.0878$	$S_3 = 0.991$
$R_4 = 0.0942$	$S_4 = 0.974$
$R_5 = 0.0879$	

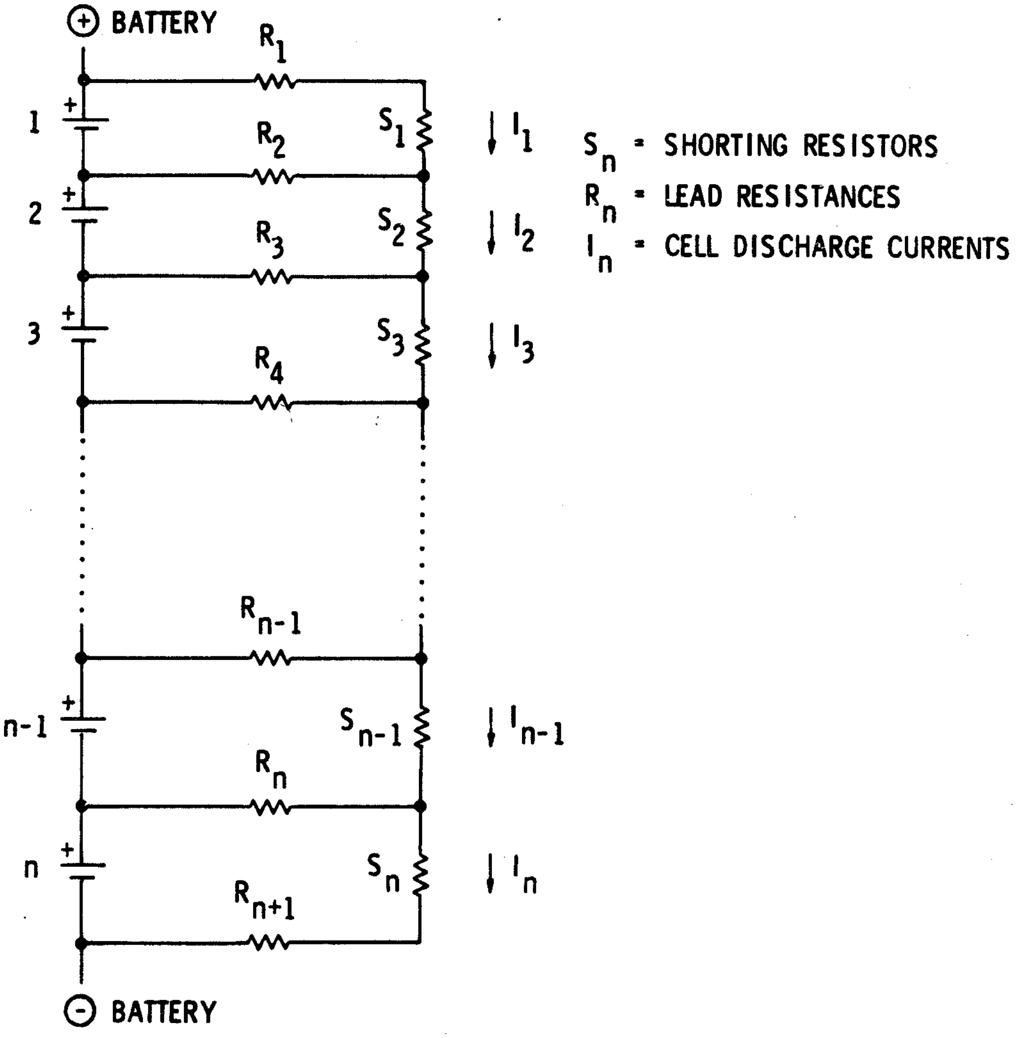

Figure 1. Resistive Network Created during Individual Cell Short-down of an N-Cell Battery

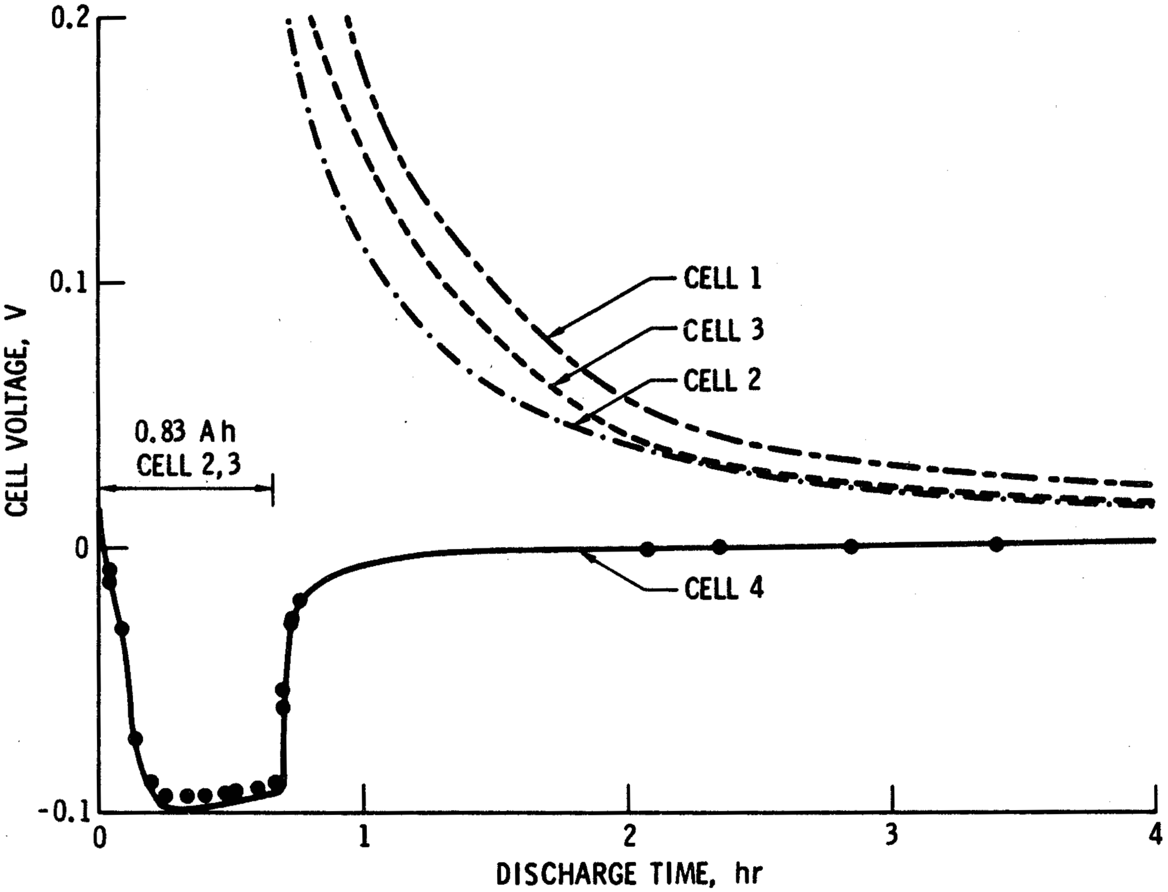

Figure 2. Short-down of a 4-Cell Battery; Cell 4 is Totally Discharged and Cells 1 Through 3 Have ∿1–A h Capacity

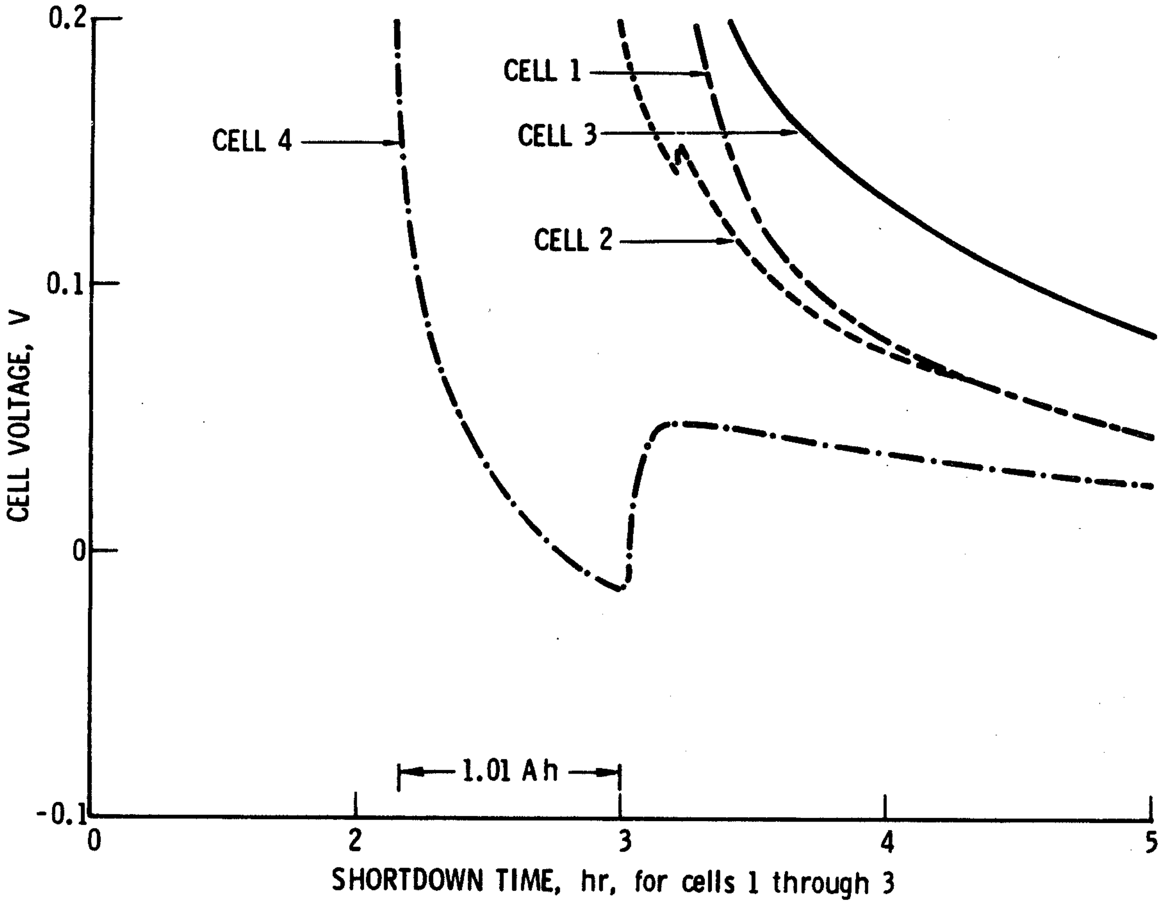

Figure 3. Short-down of a 4-Cell Battery; Cell 4 Discharge Started 1 hr Earlier Than Did That of the Other Cells

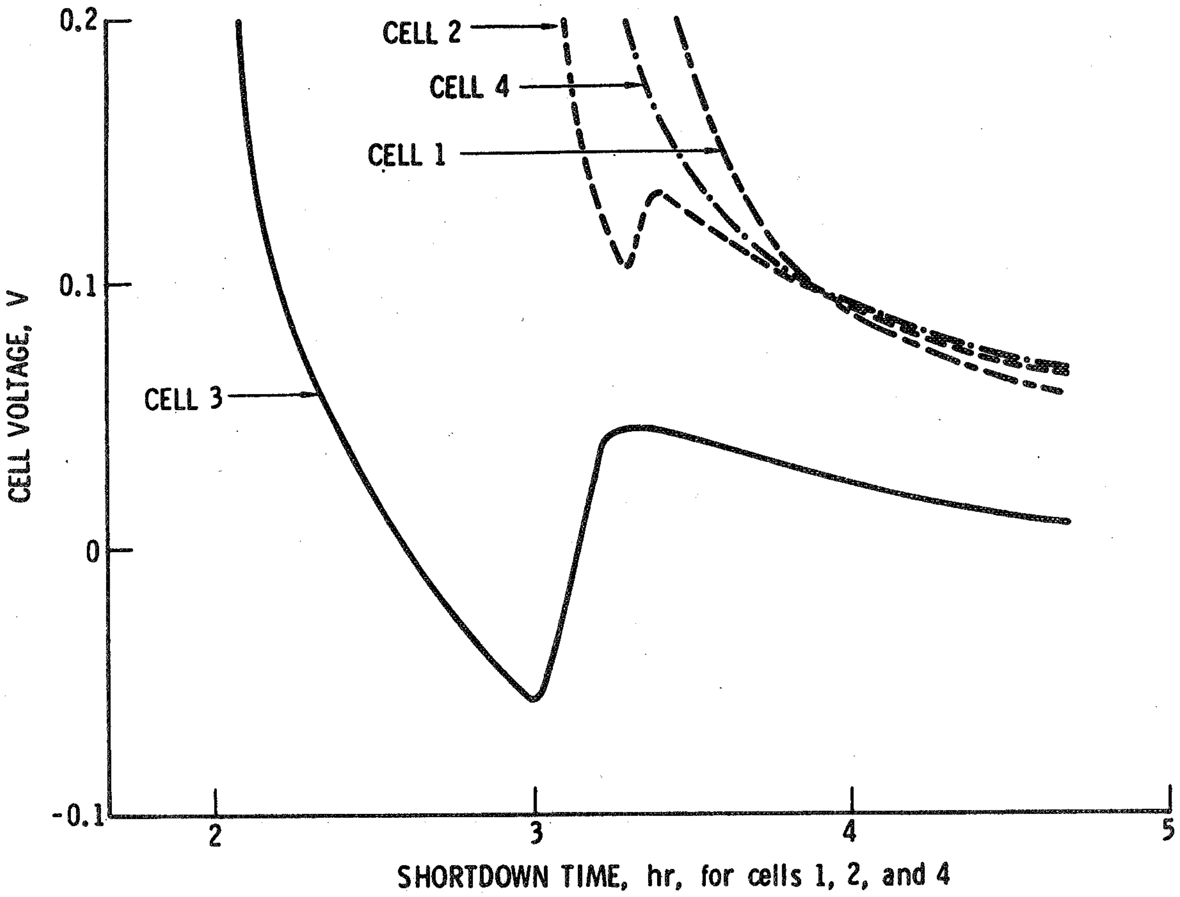

Figure 4. Short-down of a 4-Cell Battery; Cell 3 Discharge Started 1 hr Earlier Than Did That of the Other Cells

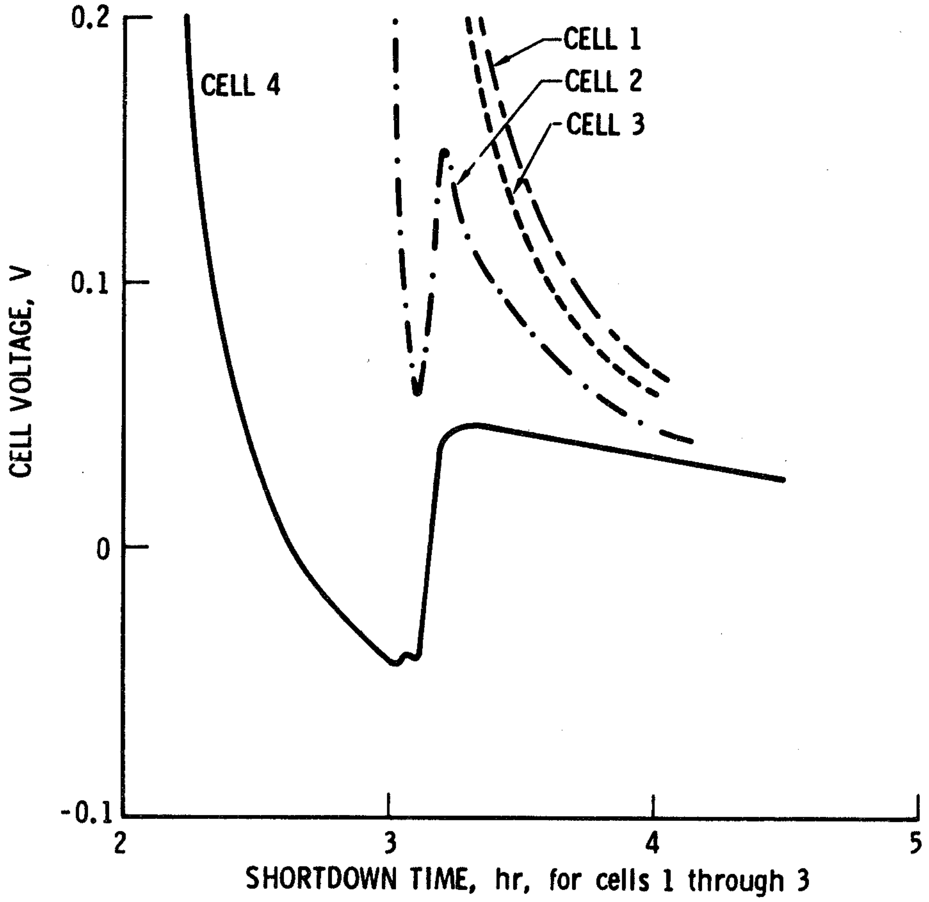

Figure 5. Short-down Simulation for a 4-Cell Battery, with 3.5 A h in Cells 1 Through 3, and 2.5 A h in Cell 4

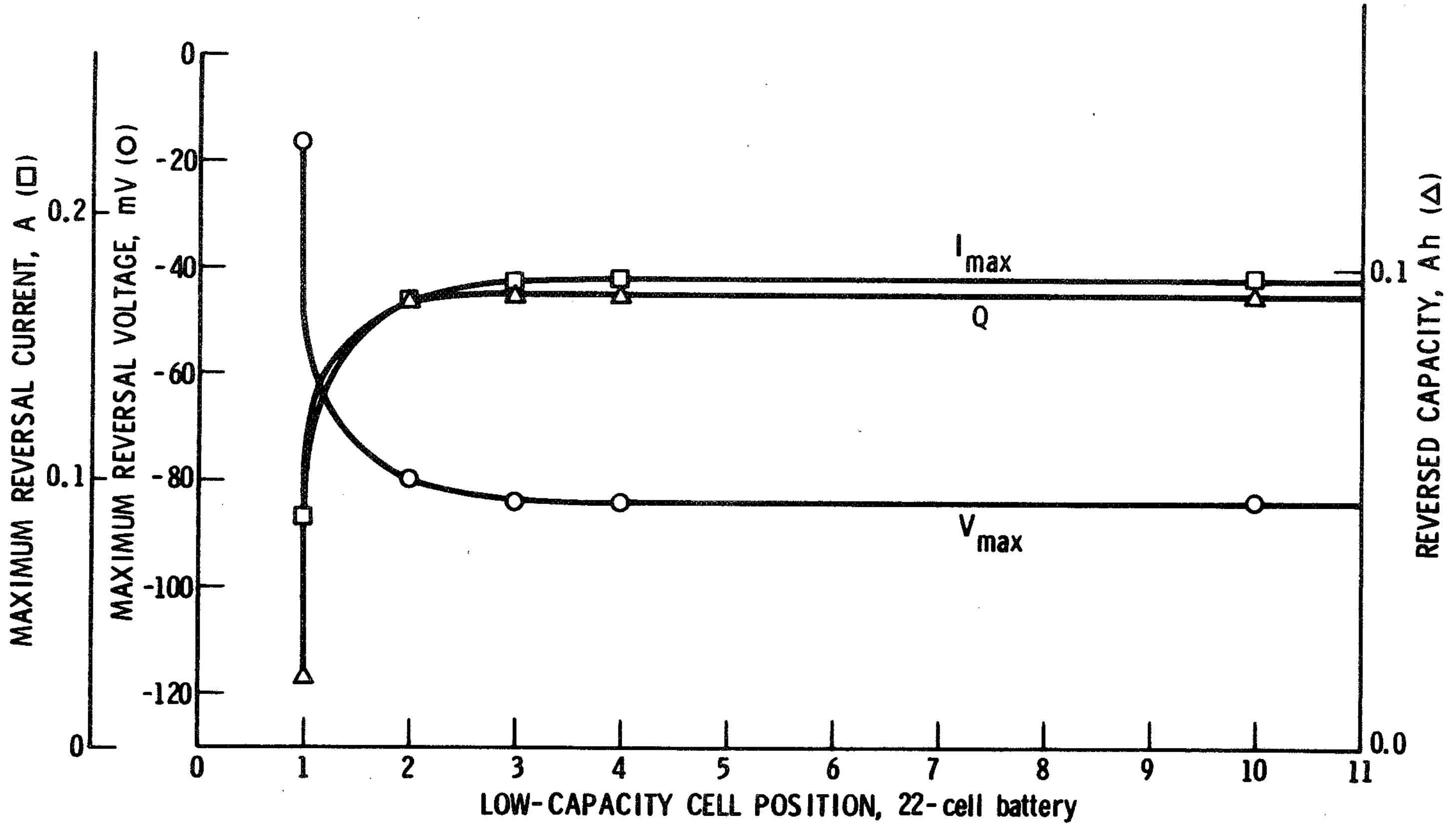

Figure 6. Dependence of the Extent of Reversal on Cell Position, for Capacity Imbalance = 1 A h, $R_n = 0.1\ \Omega$, and $S_n = 1.0\ \Omega$

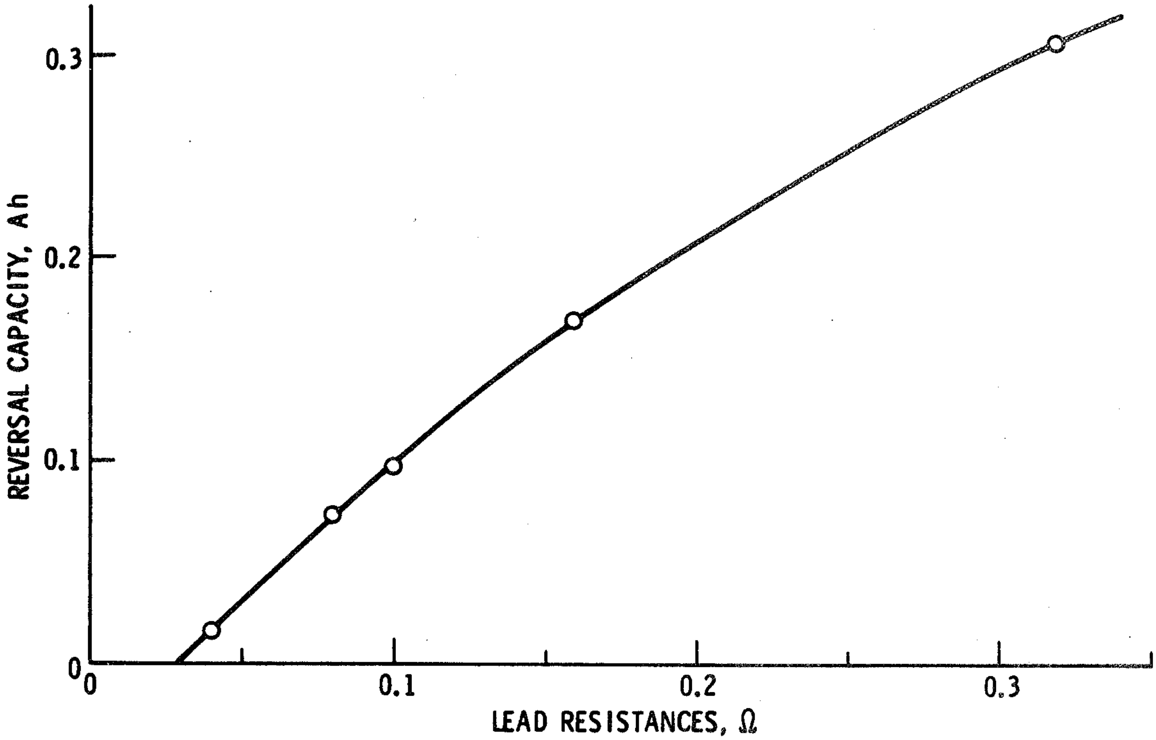

Figure 7. Extent of Reversal as a Function of Lead Resistance for the Center Cell of an 11-Cell Battery, for Capacity Imbalance = 1 A h and $S_n = 1.0\ \Omega$

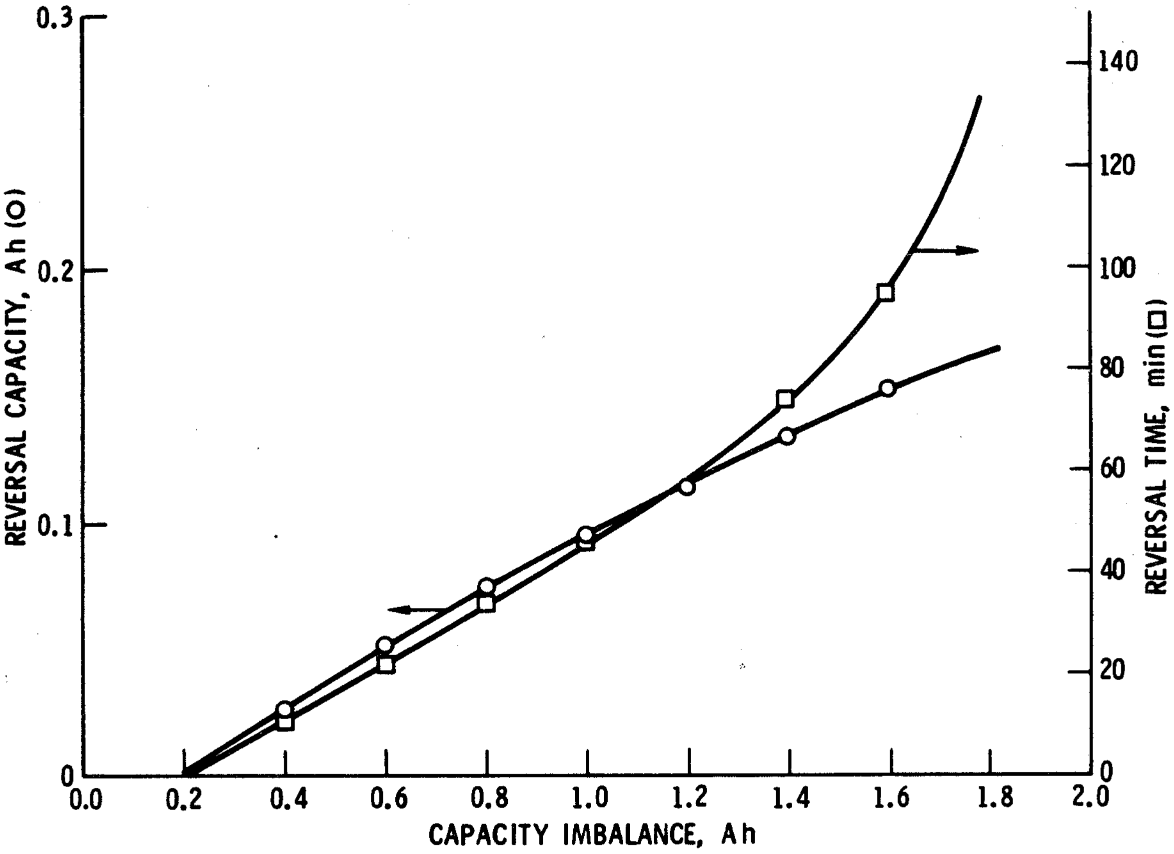

Figure 8. Extent of Reversal as a Function of Capacity Imbalance in the Center Cell of an 11-Cell Battery, for $S_n = 1.0\ \Omega$ and $R_n = 0.1\ \Omega$

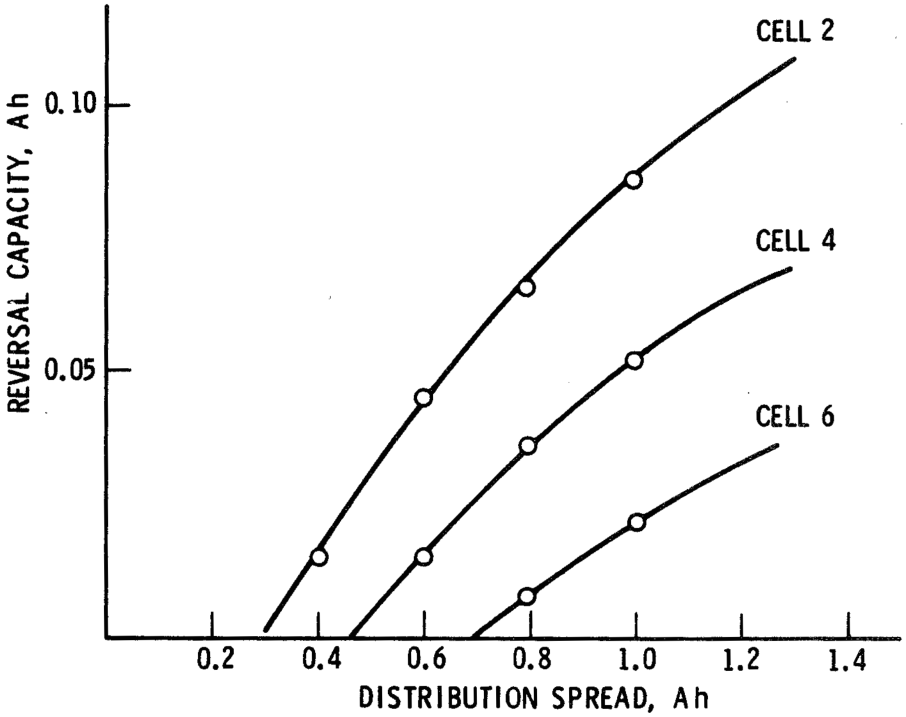

Figure 9. Extent of Reversal as a Function of Capacity Imbalance in an 11-Cell Battery Having Normal Capacity Distribution (High/Low Alternation of Cells), for $S_n = 1.0\ \Omega$ and $R_n = 0.1\ \Omega$

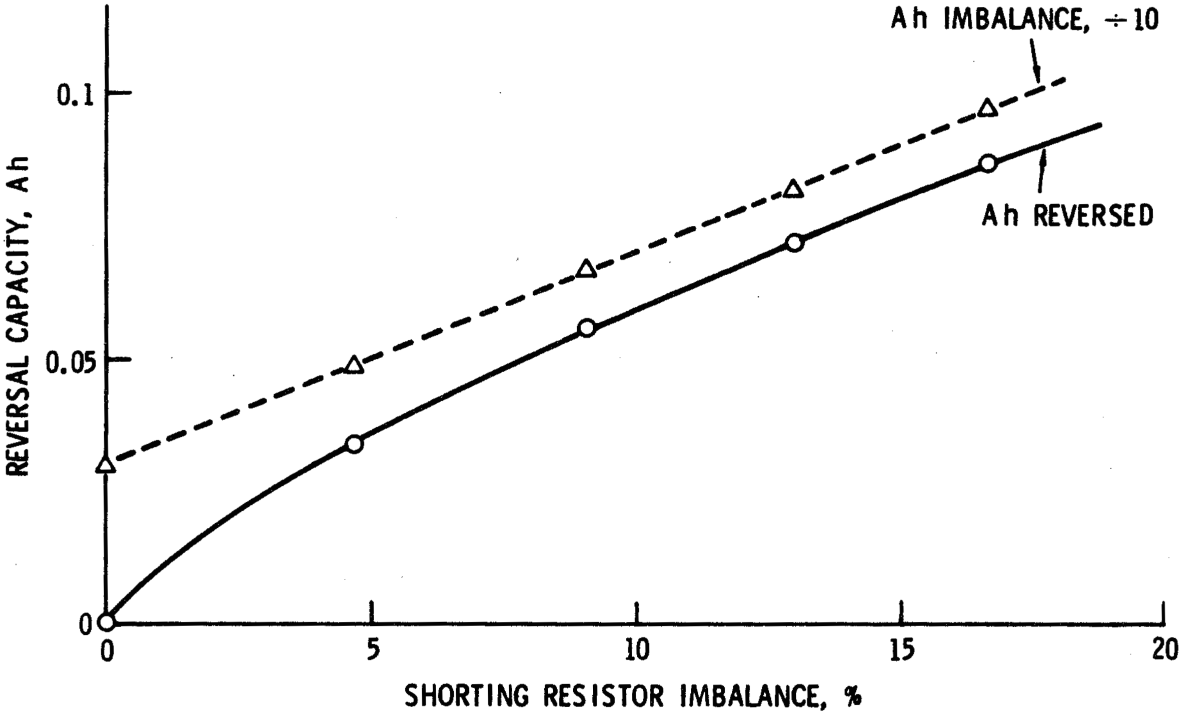

Figure 10. Short-down of Fully Charged Battery vs. Shorting-resistor Imbalance for Capacity Imbalance = 0.3 A h and R_n = 0.1 Ω