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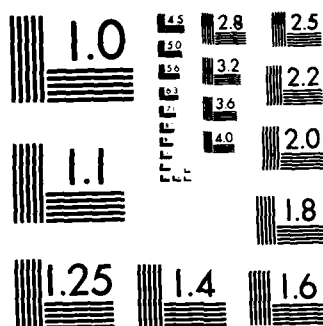
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**Results from Life Test in Progress
on Eagle-Picher Nickel Cadmium Cells**

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This report summarizes the results from low-earth-orbit life testing on Eagle-Picher nickel cadmium cells of nominal 50 Ah capacity that have been undergoing testing since 1983. As these cells have limited ability to withstand overcharge, a V-T charging scheme was adopted at the outset after careful determination of safe peak charge voltages at the two operating temperatures of 0 and 20°C. Of the original 30 cells put on life cycling under a complex load profile (10 cells each at 0°C/25% maximum depth-of-discharge (DOD), 0°C/40% maximum DOD, and 20°C/25% maximum DOD), both cell packs at 0°C were discontinued after less than 5000 cycles because of extensive internal shorting and/or serious loss of capacity. The 10 cell pack at 20°C has exceeded 15,000 cycles (in May 1987), with no evidence of voltage spreading or other serious decline in performance. The original V-T level selected for this pack has not required adjustment.					
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IN MEMORIAM

We note with regret the death of Charles Badcock, the primary author and motivating spirit behind this work. The absence of his leadership and encouragement is deeply felt by all of us.

1. INTRODUCTION

The objective of this battery testing is to determine appropriate charge voltage parameters for three groupings of ten 50 Ah nickel-cadmium (NiCd) cells prior to life testing and then to test the cells to failure in a simulated low earth orbit (LEO) scenario. This report discusses the successful completion of the charge voltage determination, as well as the completion of more than 15,000 LEO life cycles on some of the cells. The RSN 55-5 cells were manufactured by Eagle-Picher Industries. The cells were not designed to withstand overcharge, and this fact has necessitated certain precautions during charging. During the acceptance testing and characterization testing, anomalous behavior of some cells occurred, although the anomalies did not necessitate removal of any cells prior to the completion of characterization.

The actual life testing regime is designed to approximate a specific type of LEO operation containing a changing load with currents as high as 40 A for intervals of a few minutes. The test comprises 15 unique minor cycles per each major cycle of 22.5 h as shown in Fig. 1. Each 90-min minor cycle contains from one to three distinct discharge rates, and all but two of the minor cycles contain one or more charging rates as well. All of the charge profiles contain V-T levels, namely, charging at a constant current with a voltage limit, then continued charging at the constant voltage (temperature compensated). The duration of the charge sequence is, in every case, 59.54 min.

The 30 cells were divided into three groupings or packs of 10 cells each and were tested as shown in Table 1. Packs 1 and 2 (now discontinued) were maintained at 0°C during testing, and pack 3, which is still being tested, is maintained at 20°C. Groups 1 and 3 were subjected to a testing regime in which the maximum increase in DOD within a minor cycle is 15%, based on a nameplate capacity of 50 Ah. The average DOD achieved is 20% (all cycles); the maximum daily DOD is 25% nominal. For pack 2 the corresponding values were 20, 30, and 40%. Each of these packs has been independently treated in the characterization and life testing.

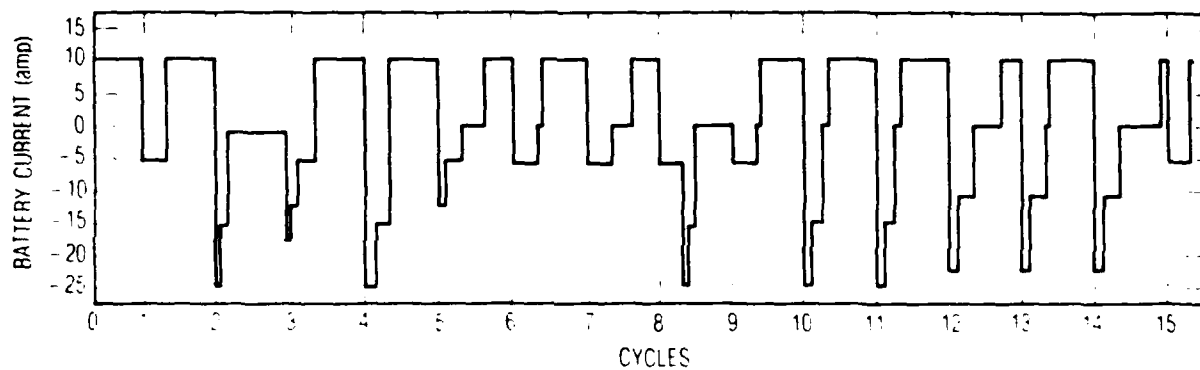


Fig. 1. Life Cycling Charge-Discharge Current Profiles (25% Maximum DOD Case). Note that charge is controlled to a current-limited constant voltage.

Table 1. Battery Power Settings over
the 15 Cycle Repeating Unit^a

Cycling time: 90 min

59.54 min charge

30.46 min discharge

Repeating unit elapsed time: 22.5 h (1350 min)

Tests 1 and 3 at 25% DOD max.; Test 2 at 40% DOD max.

^aA V-T charging regime was used, which causes the current to taper below the values shown once the battery voltage has achieved a temperature-dependent voltage set point.

II. ACCEPTANCE AND CHARACTERIZATION TESTING

The acceptance and characterization testing that is to be discussed encompasses the following elements:

- o Determine cell capacities.
- o Characterize cell performance during overcharge and/or determine the shape of the voltage "rollover" envelope.
- o Select the V-T parameters that will be utilized in the life testing that is to follow.

The objective of the first phase of testing was to subject the cells to acceptance testing, followed by a series of charge-discharge cycles with capacities determined on each discharge. In the early stages of the acceptance testing, some difficulty was encountered in causing the cells to perform as expected. The cells failed to sustain overcharge at greater-than-trickle charge rates and exceeded the required upper voltage limits, especially at lower test temperatures. Several cells exhibited higher than expected impedance characteristics, as well as poor charge acceptance. Repetitive cycling at low charge rates and constant current discharge to 0.5 V per cell corrected the difficulty. One cell failed two consecutive open circuit stand tests, indicating the presence of an internal short, but recovered and was retained in subsequent testing.

Prior to characterization testing, the cells were placed in three 10-cell packs that were matched closely in capacity, as shown in Table 2. The objectives were to determine if a low rate of overcharge could be withstood by the cells and to fix maximum allowable cell voltage levels during charge. The cells were successfully charged by the following regimes:

Cells Packs 1 and 2 (0°C)

25 A to 14.4 V limit (10 cell pack)
2.5 A (C/20) to 14.4 V
Charge at a constant 14.4 V for 15 h.

Cell Pack 3 (20°C)

25 A to 14.0 V limit (10 cell packs)
3.5 A (~ C/15) to 14.0 V
Charge at a constant 14.0 V for 15 h.

Table 2. Pack Average Data

Cell Pack	Mean Cell Capacity (Ah)	Standard Deviation
1	54.5	0.9
2	57.6	1.8
3	55.7	0.3

Sample V-T charge data are shown in Fig. 2, which is a composite of representative charge data taken during a series of charge/discharge cycles. The switchover from constant current to constant voltage is indicated, and certain cells are denoted by sequence number in pack for comparison. Allowable cell voltage maxima were set at 1.65 V at 0°C and 1.62 V at 20°C. Maximum cell voltages and durations of rollover* varied from one run to another in an apparently unpredictable manner.

*W. R. Scott and D. W. Rusta, Sealed-Cell Nickel-Cadmium Battery Application Manual, NASA Reference Publication 1052 (1979), pp. 80-81.

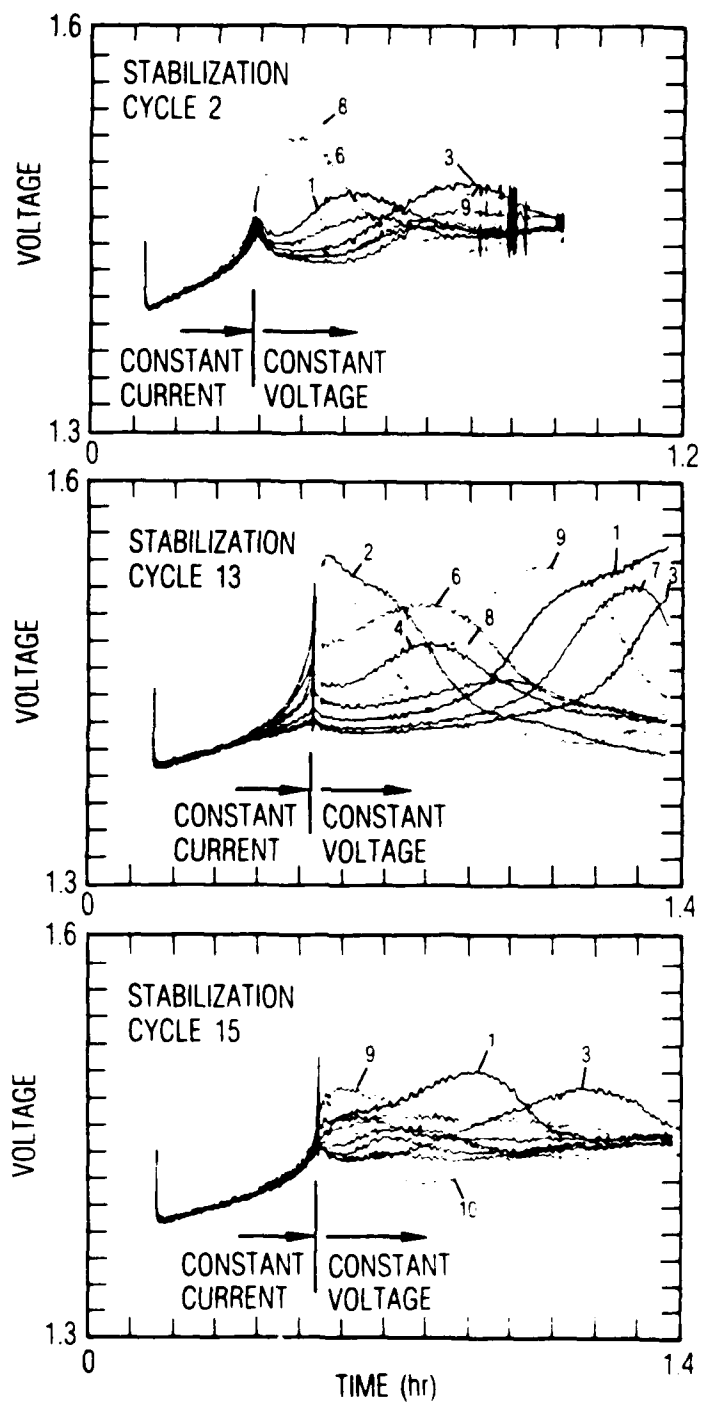


Fig. 2. Examples of Cell Voltage Rollover Profiles During Capacity Stabilization (Pack 1).

III. V-T PARAMETER DETERMINATION

Our objective was to determine the most appropriate set of V-T parameters for subsequent life testing. The parameter of interest is the battery or pack voltage set point, which enables the battery or pack to achieve a stable state of charge on cycling. During these tests the maximum allowable cell and pack voltage levels were increased as necessary.

The initial values of pack voltage (V_{batt}) and maximum allowable cell voltage (V_{cell}) were selected with the aid of data from G. Halpert*: 14.40 V and 1.56 V at 0°C and 14.00 V and 1.54 V at 20°C. These initial values were then refined to determine the values actually used in the life testing. The test to determine voltage levels consisted of two parts. First, the cells were charged for an extended period at rates from 2.5 to 3.5 A to achieve as full a state of charge as possible without harming the cells. Second, 15 cycles were performed, as follows: 30 A (C/1.67) discharge to 30% DOD, followed by constant current charge at C/25 to the voltage set point and continued constant voltage charge at the set point for 1 h. At each voltage limit the cycle-to-cycle changes in pack voltage at maximum DOD (lowest state of charge) and in charge return were monitored. Adequate levels for the V_{batt} set points were achieved when no significant change in either pack voltage or charge return occurred during the last few cycles. Adequate levels for max V_{cell} were simply those that enabled the cells to achieve 15 minor cycles without mishap (1.65 V at 0°C and 1.62 V at 20°C). No physical damage was externally evident when these voltages were approached by individual cells.

The values of V_{batt} at 14.60 V at 0°C and 14.15 V at 20°C (2.025 mV/°C temperature coefficient per cell) were used throughout the life test except for a lower value that was used in pack 1 between 2200 and 4400 cycles.

*G. Halpert, Simulated Orbital Testing of the General Electric Co. 26.5 Ampere-Hour Nickel-Cadmium Spacecraft Cells, NASA Technical Memorandum 82078 (September 1980).

IV. LIFE CYCLING

Calculated life testing profiles for the 25% maximum DOD case (packs 1 and 3) are given in Fig. 1. The profiles are identical for both the 25 and 40% maximum DOD case, except that all currents are 1.6 times greater in magnitude for the 40% profile. The profiles contain 15 minor cycles, which constitute the repeating unit, or major cycle. The rate of charge is limited by the simulated solar array output and is further limited because, for a portion of most of the periods of simulated insolation, the system load equals or exceeds the array output. Also, during two minor cycles in each major cycle, the batteries remain in discharge throughout the 90-min period.

Performance data for 14,000 simulated revolutions or cycles (5185 cycles total for cell groups 1 and 2) of life testing are summarized in Fig. 3. In Fig. 3a are plotted the ratios of ampere-hour in over ampere-hour out during a major cycle of 15 minor cycles, at differing points in the life cycling. Cell pack 2, at 0°C and 40% maximum DOD, exhibited the lowest ratios throughout its life (except for an unexplained dip around 2000 cycles). Pack 1, at 0°C and 25% maximum DOD, exhibited an increasing ampere-hour ratio and never appeared to stabilize. The decrease in the average upper voltage limit of pack 1 from 1.46 V/cell to 1.43 V/cell caused a transitory slowing in the rate of increase of the charge return (Fig. 3a) but did not halt it. Pack 3, at 20°C and 25% maximum DOD, was nearly constant until about 8000 cycles, with a ratio of about 1.09. In later cycling, pack 3 has continued to increase and currently (10 May 1987) is exceeding 1.13. We had expected that pack 1 would parallel the observed behavior of pack 2 and that both packs would exhibit higher efficiencies and lower charge returns than pack 3 operating at the higher temperature. The observed behavior of pack 1 (i.e., rapid increase) was anomalous almost from the start and presaged subsequent problems.

The averages of cell end-of-charge voltages (V_{eoc}) are plotted in Fig. 3b, and pack average minimum voltages (V_{min}) at the point of minimum state of charge within a major cycle are plotted in Fig. 3c. The average V_{eoc} is set by the voltage limit (the change in setting for pack 1 is shown between

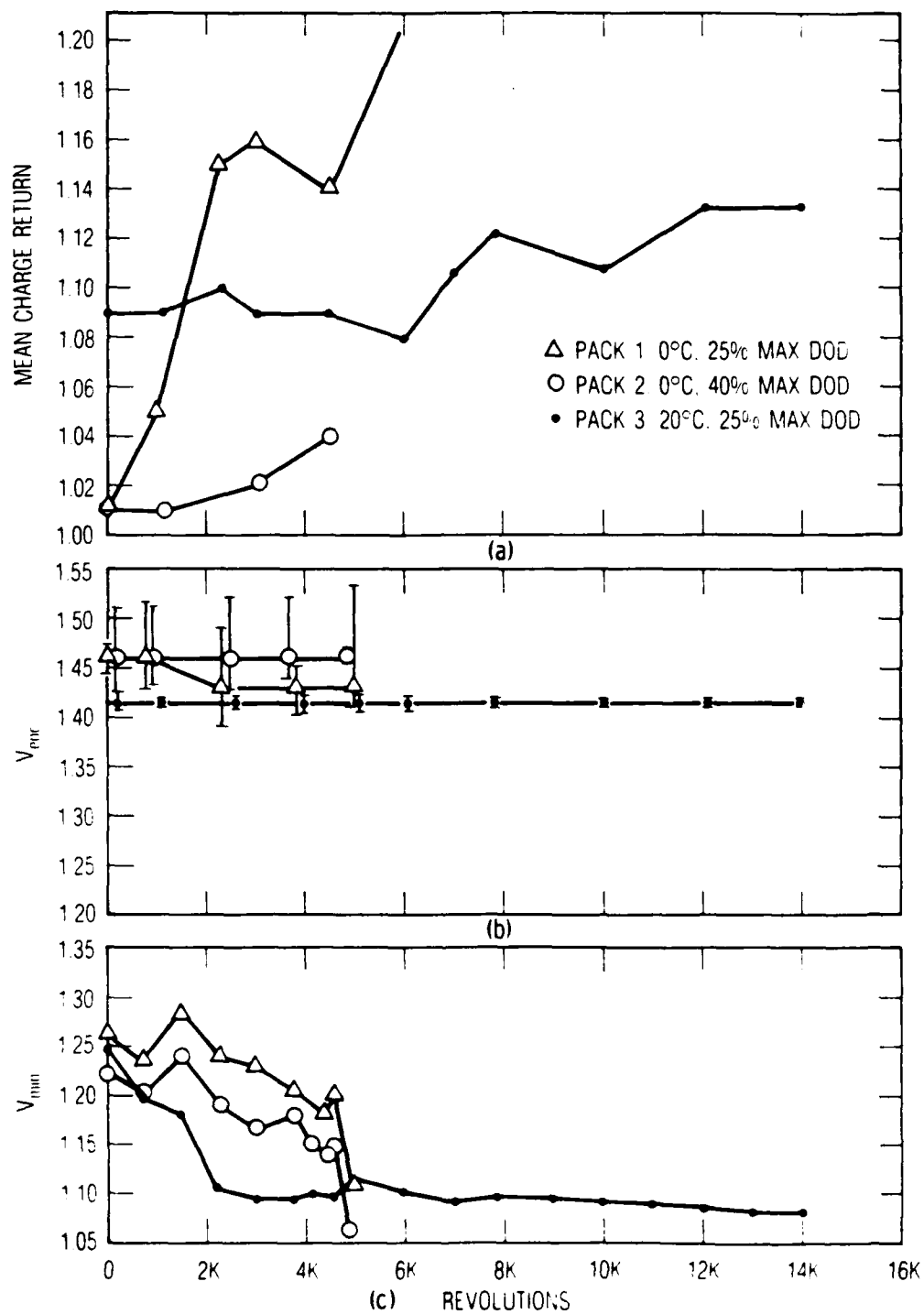


Fig. 3. Cycle Life Trends. (a) Mean charge return vs cycles; (b) end-of-charge voltage vs cycles; (c) cell minimum voltage vs cycles.

2200 and 4400 cycles). The spread in voltages is shown by bar lengths that indicate the range from lowest to highest cell within each pack. For packs 1 and 2, the V_{eoc} ranges are large. Such broad voltage spreads indicate that cell characteristics are not well matched in the 0°C tests. V_{min} (Fig. 3c) decreased during the first 4000 cycles for all packs, then became uncontrolled in packs 1 and 2 as cell failure occurred. The spread in pack 3 has actually narrowed during the course of life testing. In pack 3, a reasonably stable value of V_{min} of 1.08 V was in effect at 14,000 life cycles.

By 5185 cycles, 10 cells in packs 1 and 2 at 0°C either had failed outright or were performing unacceptably, and testing on packs 1 and 2 was discontinued. The causes and cycles to failure are summarized in Table 3. Six cells failed because of high impedance so that cell charging could not be accomplished within the charge control parameters of the test; these cells also continually went below the 1.0 V lower limit on discharge. In each case, cell removal was effected when the anomalous cell caused two consecutive test shutdowns because of excessively high cell voltage on charge (greater than 1.56 V at 0°C) or excessively low voltage on discharge (less than 1.0 V). When this anomalous impedance behavior first occurred, all the cells in the affected pack were subjected to reconditioning by discharging across individual cell resistors (~0.3 ohm) for 16 h, followed by recharging along a V-T with I_{max} of 3.5 A at 20° and 2.5 A at 0°. In all cases when this was done, an improvement in performance was noted; however, the improvement lasted only one or two minor cycles before the effects of high impedance were again evident. On the basis of these tests, we concluded that the increase in impedance is indicative of a permanent nonreversible deterioration in cell performance, possibly associated with component dryout. Four cells failed because of internal shorting. Attempts to "fuse" the short in one cell, using charge currents up to 20 A, failed. Pack 3, at a test temperature of 20°C, has had no cell failures over the course of life testing to date (more than 15,000 cycles on 10 May 1987). However, observations of cell voltages made recently during periods of equipment shutdown indicate the strong likelihood of internal shorting in some cells. To date the shorting has not affected the on-line performance of pack 3.

Several cells had demonstrated high impedance characteristics (i.e., high voltage on charge, low voltage on discharge) during acceptance testing. Repetitive cycling corrected the difficulty in most cases. No obvious correlation exists between these early outliers and cell failures that occurred during life testing.

Table 3. Cell Failure History

Cell S/N	Date Removed From Test	Cycle Life Achieved	Failure Mode
Pack 1 (0°C, 25% max. DOD)			
085	10/16/84	1700	HI ^a
037	11/6/84	1975	HI
001	11/19/84	2170	IS ^b
114	5/14/85	4600	IS
117	6/7/85	4875	HI
116	7/11/85 ^c	5185	IS
Pack 2 (0°C, 40% max. DOD)			
029	10/2/84	1550	HI
143	6/25/85	5020	IS
081	7/11/85 ^c	5185	HI
007	7/11/85 ^c	5185	HI

^aHigh impedance.

^bInternal shorting.

^cDiscontinuation of testing on packs 1 and 2.

The obvious correlation is with temperature, inasmuch as operation of these cells at 0°C using V/T charging was not successful. The electrical performance during testing suggests that some cells may have become negative limited during charge. This condition amplified small differences in charge efficiency and caused the large dispersions. The stresses caused by cells cycling near total discharge (those with lower efficiency) resulted in the shorting failures observed. This appeared to be complicated by a dry-out

condition that resulted in unacceptably high charge voltages and low discharge voltages. If the dry-out condition is not uniform, it also will cause dispersion in the cell packs. The superior performance of the cells tested at 20°C can be rationalized by high negative electrode utilization or availability, and the lower resistance of cells with marginal quantities or distributions of electrolyte.

V. DISCUSSION OF LIFE TEST RESULTS

We are somewhat surprised that the V-T parameters have not required adjustment over the course of life testing, even after 15,000 cycles at 20°C. Note that a large amount of acceptance testing and characterization was required for these packs, equivalent to 500 or more life test cycles; accordingly, any changes in cell characteristics that occurred during this prolonged "break-in" period were not observed in V-T testing. In a real-life situation, the cells would probably have received far less exercising prior to actual use.

Stability of the cells in pack 3 is evidenced by the selected battery calculated ampere-hour ratios, end-of-charge voltages, and minimum voltage data presented in Fig. 3. (Discussion of cell failure is contained in a succeeding paragraph.) After 2000 minor cycles, these parameters (taken at selected points in the 15 cycle sequence) became stable and changed little thereafter. Stability of battery parameters does not in itself indicate equivalent stability of individual cells, or that cells are well matched in characteristics as evidenced by the large cell voltage spreads that were observed in both of the 0°C packs.

Causes of cell failure are summarized in Table 3. No cells in pack 3 have shown significant deterioration. Adjustment of V-T parameters in tests 1 and 2 to counteract loss of charge acceptance because of increasing impedance would only have been viable for an increase in impedance of the entire pack. In the cases cited, the increases were due to individual cells within a pack. An unexpected correlation with temperature did exist, namely, that all weak and removed cells were at 0°C. The serial numbers of failed cells have been compared with cell performance data obtained during acceptance testing to determine if cell failure could have been predicted before actual use: no correlation was observed. Such an inversion from expected results* suggests

*W. R. Scott and D. W. Rusta, Sealed-Cell Nickel-Cadmium Battery Application Manual, NASA Reference Publication 1052 (1979), pp. 80-81.

that the cells have marginal construction parameters that dominate the normal failure mechanisms.

It appears that low temperature V-T charging (i.e., at 0°C) is not viable for these cells. Cell instability causes a significant spread in cell voltage on charge, resulting in differential aging and premature failure of some cells. The cell pack under test at 20°C has experienced no failures, which suggests that cell instability is less of a problem at higher temperatures. This conclusion is supported by the narrow spread of cell voltage observed on V-T charging at this temperature.

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