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CHOPPER-CONTROLLED DISCHARGE LIFE CYCLING STUDIES ON LEAD-ACID BATTERIES

FINAL REPORT

by Joseph J. Kraml and Ernest P. Ames
TRW SPACE AND TECHNOLOGY GROUP

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LEWIS RESEARCH CENTER
21000 BROOKPARK ROAD
CLEVELAND, OHIO 44135

Contract No. DEN 3-88

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SPACE AND TECHNOLOGY GROUP
ONE SPACE PARK • REDONDO BEACH • CALIFORNIA 90278

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16. Abstract

A group of 108* state-of-the-art 6-volt lead-acid golf car batteries were tested in a program of daily charge/discharge cycling to failure points under various chopper-controlled pulsed dc and continuous current load conditions. The cycle life and failure modes were investigated as a function of depth of discharge, average current chopper frequency, and chopper duty cycle.

Approximately 69 percent of the test group had failed by the end of a 2-year period when testing was suspended. Test results show that battery life appears to be primarily and inversely related to depth of discharge and discharge current. Failure mode was characterized by a gradual capacity loss with consistent evidence of cell element aging. Chopper frequency and duty cycle seemed to be of little significance as life determining factors. The average mean life of the failed batteries was 467 cycles.

*Subsequently reduced to 107.

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FOREWORD

We wish to acknowledge the contribution to this study made by Dr. Joseph A. Orsino. As a nationally recognized authority and consultant in lead-acid battery technology, he provided valuable assistance in the preparation and performance of the failure analysis autopsy procedure used herein for identification of failure mechanisms.

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ILLUSTRATIONS

1. SUMMARY

The objective of this test program was to test to failure 108* EV-106 lead acid golf car batteries in a daily charge/discharge cycle program at various chopper-controlled and continuous current load conditions. The cycle life and failure modes of the battery were correlated with depth of discharge, average current, chopper frequency, and chopper duty cycle.

The testing was divided into three phases. The first phase consisted of the procurement and acceptance tests of the batteries. Physical examinations and discharge capacity tests were performed to verify conformance to manufacturer's specifications. The second and principal test phase consisted of the daily charge/discharge "life cycling" which provided the primary data. Batteries were arranged in series-connected groups of three units to form 36 test groups. Each test group was operated until all three batteries in the group had failed. In the third and final phase of testing, autopsies were performed upon selected failed test batteries for the purpose of failure analysis.

Life cycle testing of the batteries over a 2-year period produced a 69 percent failure of the test group. These results appeared to show that battery cycle life was primarily affected by, and inversely proportional to, the depth of discharge and the discharge current. Little difference in life was seen among the specimens operated at different chopper discharge frequencies and duty cycles. In addition, the continuous current (dc) discharge test articles had failure distributions similar to those subjected to chopper-controlled discharges. The mean number of cycles to failure of all failed batteries was 467.

The observed failure mode was characterized by a gradual capacity loss to the half-capacity failure point. Autopsies performed upon 23 test failures showed consistent evidence of cell element aging. Short circuits caused by metallic bridging across the plates at separator edges were found in every battery examined. Buckled positive plates and oxidized positive grids were found in all but two early battery failures. The presence of

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*Subsequently reduced to 107 (Section 4.2.5).

finely divided shedding over the entire surface of many of the positive plates suggested that excessive over-charging may have been applied.

Methods of charging and their effects were not investigated as part of this test. However, it was seer that considerable attention must be paid to this phase of battery operation in order to maintain performance while minimizing the damaging effects of excessive overcharge.

2. INTRODUCTION

A large amount of the petroleum now consumed by the United States is used as gasoline to power the internal combustion engines of automobiles and other mechanical equipment. As part of a national program to reduce the consumption of petroleum, electrically energized vehicles are being developed wherein electric storage batteries will be the mobile source of stored energy.

Currently available energy sources are the major limitation to more widespread usage of electric vehicles because of high operating cost and high weight penalty. Thus, major emphasis is being given to new types of energy sources having lower cost and weight. In the meantime, the lead-acid battery remains the most highly developed storage device on hand, and work is in progress to maximize the utilization of lead-acid batteries for electric vehicle applications.

One promising method of motor speed control for electric vehicles involves pulse modulation of the current from the battery, or so-called "chopper control." This method results in high efficiency in the control device. However, very little is known about the effects of pulsed discharge on lead-acid batteries and the overall cost-effectiveness of chopper-controlled drives cannot yet be determined.

Cataldo (Reference 8) found that pulse discharge of lead-acid batteries gave lower average output under all test conditions than that obtained on dc discharge, but that the average energy to a given cut-off voltage increased or decreased depending on the average current demand. In a more recent study, Dowgiallo (Reference 9) found that the particle size of some active materials in nonfailed batteries after pulse discharge testing was significantly greater than that in batteries after dc charging.

In neither of these studies were batteries systematically tested to failure, hence no life-expectancy data under pulsed load operating conditions have been available. The test program reported herein was therefore performed to provide preliminary data for cycle life of a state-of-the-art commercial lead-acid battery as a function of a number of operating variables. These were: depth of discharge, average current, chopper frequency, and chopper duty cycle.

3. EV-106 BATTERY LIFE TEST

3.1 TEST SCOPE

3.1.1 Purpose of Test

The objective of this test program was to gather cycle-life data by testing to failure a group of current production lead-acid golf car batteries in a daily charge/discharge cycle program at various chopper-controlled and continuous current load conditions. The cycle life and failure modes of the battery were investigated as a function of depth of discharge, frequency, duty cycle, and average current.

3.1.2 Specimen Tested

The battery selected for testing was the ESB type EV-106 6-volt lead-acid golf car battery. In order to obtain a consistent test sample, batteries were selected from the same production run and with consecutive serial numbers. The battery plate separators were of rubber construction.

3.1.3 Test Sequence

The Battery Life Test Program consisted of verifications, inspections, and tests as follows:

a) Screening and Acceptance Tests

b) Life Cycling Test

c) Autopsy and Failure Analysis

3.2 TEST CONDITIONS

3.2.1 Test Plan

The EV-106 lead-acid batteries which comprised this test were taken from the same lot of current production golf car batteries manufactured by ESB Incorporated (Exide). A preliminary examination and acceptance test was performed in which all batteries were weighed, their specific gravities measured, and their output discharge capacities measured. An additional eight spare batteries were procured for contingency purposes.

Upon completion of acceptance test, the life-cycling test was started. The batteries were connected in series-connected groups of three batteries, each group forming a test article, and 36 tests articles forming the complete test matrix. Each test article was assigned a specific set of discharge parameters for its operating mode in a daily program of discharge and recharge cycling. The assignments, shown in Table I, were various combinations of discharge currents, duty cycles, continuous or pulsed dc modes (chopper frequency), and depths of discharge in accordance with a Central Factorial Design experimental test plan.

The life, or number of cycles completed by each battery before failure, was examined as a function of the above parameters. The failure cycle was defined as that cycle in which a battery reached a cutoff or undervoltage before reaching the depth of discharge (DOD) specified in Appendix B, Table I. As each battery reached its failure cycle, it was removed from the test article and cycling was then resumed. This process was repeated until all three batteries in the test article had failed. (The failure criteria was subsequently redefined to cutoff before reaching one-half DOD. See Section 4.2.2, Test Parameter Changes.)

A destructive autopsy was performed upon the first battery to fail in each test article. The autopsy consisted of battery weighing, battery teardown, and detailed visual inspections of the separators, plates, and grids.

Testing was suspended when sufficient failures had occurred and further testing was not economically practical.

3.2.2 Test Facility

Two identical systems consisting of 18 test articles each were used to test a total of 36 test articles. Test operation control and data acquisition was provided by an Intel 80/10 Microcomputer Control System designed specifically for the test program. Generalized block diagrams of the test system and data system are shown in appendix Figures 1 and 2 (one of two systems shown for each).

The test bed was wholly contained in a single laboratory room with a maintained temperature environment of 22° ±2°C. Relative humidity conditions averaged less than 70 percent. Room air was continuously monitored for explosive concentration of hydrogen with an electronic hazardous gas detection system.

Batteries were installed on four wooden tables open to the room environment. Load banks, bus bars, and system cabling were contained on the tables. Protective enclosures and plexiglass shields enclosed the table arrays for personnel safety and convenience. System power supplies and computer control equipment were positioned separately at either end of the tables. Photographs of the physical test configuration and faciltiy are shown in Figures 3, 4, and 5 of Appendix C.

3.2.3 Test Equipment

Test sequencing was controlled by the microcomputer system to provide charge control, discharge control, and test data acquisition.

3.2.3.1 Charge Control System

The charge control system was designed to minimize the effects of the charge regime upon battery failure modes. Using the constant potential method, test articles were charged in parallel by connecting them to one of the three fixed dc "charge buses" through computer-controlled relays. Each charge bus was supplied by a separate dc power supply. The voltage level of each bus was set to a different fixed value corresponding to the level required for a one-, two- or three-battery test article. Test articles were recharged following their discharge cycle as soon as their electrolyte temperature, as measured by computer sensors, had returned to within 5°C of room ambient temperature. The latter was maintained at 22° ±2°C. The charging power supplies were sized to allow simultaneous charging of multiple test articles, as required. The system computer was programmed to terminate charging when the charge current, integrated as a function of time, was equal to the last discharge ampere-hour output plus an overcharge factor (initially 11 percent).

3.2.3.2 Discharge Control System

The discharge control system was designed to provide precise and selectable chopper frequency, duty cycle, and current load control for the test conditions tabulated in Table I. These variables and system equipment limitations dictated that only one test article in each system be discharged at any given time. Therefore, each test article was sequentially connected to the system discharge bus through computer-controlled contactors to an active high power load bank. Load chopper frequency, duty cycle, and current were maintained within ± 0.5 percent of nominal values. The system computer was programmed to terminate discharge when the time-integrated discharge current was equal to the specified depth of discharge (ampere-hour output) of Table I, or if any specific test article battery terminal output voltage reached an undervoltage cutoff value of 5.25 Vdc.

Figure 6 illustrates typical voltage (E) and peak current (Ip) waveforms for the chopper controlled pulsed dc discharge. Periodic examinations of all test article waveforms were performed to verify system performance to the test requirements.

3.2.3.3 Test Data

In addition to charge and discharge control, the microcomputer system provided all data acquisition (see Figure 2, one of two systems). Each of the data systems included a 100-channel data input scanner capable of reading 15 channels per second. Parametric data for the system scanner channels were assigned as follows:

Data	Number of Channels Assigned
1) Battery Voltage	54
2) Charge Current	18
3) Discharge Current	1
4) Electrolyte Temperatures	18
5) Battery Terminal Temperatures	6
6) Room Ambient Temperature	1
	98 Total

These data associated with each test article were scanned and checked against preset failure limits, every 6 minutes during charge, and every 20 seconds during discharge. For each scan operation, the following data information was calculated and updated:

1) Capacity input or output in ampere-hours (Ah), as determined by integration of charge or discharge current with respect to time

2) Power input or output in watts (W), as determined by the product of charge or discharge current and battery voltage

3) Energy input or output in watts-hours (Wh), as determined by integration of power input or output with respect to time.

All data was outputted on a test system printer terminal. Shown in Table II are sample real-time data provided for each test article. Table III is an example of the daily data summary provided for each test system (day 261 equals 17 September 1980).

3.3 TEST PERFORMANCE

3.3.1 Battery Procurement

The initial set of 108 EV-106 test batteries and eight spare batteries were received in March, 1979. When it was determined that the batteries were not all from the same production run, the shipment was returned to the vendor for a replacement set which did come from a single production run.

The second set of EV-106 batteries was received in July, 1979. This set proved to be unacceptable due to manufacturing and performance variations which became apparent during screening and acceptance tests.

A third and final set of EV-106 batteries with rubber separators was procured from the ESB facility in South Carolina late in August, 1979. Preliminary visual inspections and verifications were completed in August and functional acceptance testing commenced on 1 September 1979.

3.3.2 Acceptance and Cycling Tests

The two identical systems which made up the total test matrix of 108 batteries were identified as System I and System II. System I contained Test Articles 1 through 18 and System II contained Test Articles 19 through 36.

System 1 was configured and test-operated first in order to verify system operation. System II became operational approximately 2 weeks later.

Test system checkout and acceptance capacity discharge testing on Systems I and II was carried out during September, 1979. Testing time was lengthened considerably due to investigation of the low battery output capacity obtained and described in Section 4.1.2, Test Results.

Life cycle testing commenced on 2 October 1979 for System I batteries and on 15 October 1979 for System II batteries. Testing on both systems was ended 31 July 1981, the contractual expiration date for the technical effort.

3.3.3 Autopsy and Failure Analysis

A destructive autopsy analysis was performed upon each of 23 failed batteries removed from test. These were the first to fail in their respective test articles, except Autopsy Unit No. 22 (S/N 103), which was the second battery failure in Test Article 9. The autopsy consisted of battery weighing, battery teardown, and detailed visual inspections of the separators, plates, and grids. Reports were prepared for all batteries so examined.

A typical report is given in Appendix A, EV-106 Lead-Acid Battery Failure No. 16 (S/N 097).

4. TEST RESULTS AND DISCUSSION OF RESULTS

4.1 SCREENING AND ACCEPTANCE TESTS

As stated earlier, three separate sets of EV-106 batteries were sequentially procured for the test program before life cycling tests actually commenced with the third set of batteries. The first set of batteries was inspected, weighed, and measured for specific gravity. Battery weight averaged 63 pounds and specific gravity averaged 1.264. When it was discovered that the batteries were not all from the same production run, they were placed on a maintenance trickle charge to await return to the vendor.

A significant amount of acceptance testing was performed on the second set of batteries. Results of this testing brought to light certain deficiencies. These included the following:

a) Variations in electrolyte levels, ranging from the plate top to the bottom of the filler caps

b) Variations in specific gravities, ranging from 1200 to 1260, often in the same battery

c) Failure to respond to charging, with certain cells unable to display specific gravities greater than 1220

d) Discharge capacities ranging from 98 to 110 ampere-hours compared to the rated capacity of 132.5 ampere-hours.

The batteries were rejected and returned to the vendor.

The discussions that follow refer to the third and final set of batteries procured. These units became the test specimens for the life test program.

4.1.1 <u>Battery Weights and Specific Gravities</u>

Screening and acceptance tests of the third set of EV-106 batteries revealed that the units were of much greater uniformity than the second set. With only few exceptions, electrolyte levels were nominal. Conditions (b) and (c) mentioned in Section 4.1 were completely absent. The discharge capacity values shown in Condition (d) had improved by an average of 8 ampere hours.

The averages of the measured physical data were as follows:

Specific Gravity - 1.278

Battery Weight - 62.9 pounds

Water Required - 0 to 150 milliliters

Specific values are shown in Table IV.

4.1.2 Capacity Discharge Tests

The manufacturer's rated capacity of 132.5 ampere-hours at a 75-ampere rate was never realized during the standard acceptance test. Capacity values ranging from 118 to 106 ampere-hours were obtained over eight and nine successive discharge and charge cycles for an average value of 107 ampere-hours. Acting upon the manufacturer's recommendation to use an overcharge factor as high as 30 percent, increasing recharge input values of from 111 to 130 percent were tried but had little or no effect upon the output capacity. By mutual agreement with the NASA Program Manager, a recharge value of 125 percent was used for the capacity tests. A typical set of capacity values obtained for nine cycles using a 125 percent recharge factor is shown in Figure 7. Battery discharge cutoff voltage was 5.25 volts. Electrolyte specific gravity at the end of recharge averaged 1275 at an average temperature of 22°C. Specific capacity output values obtained for all batteries are shown in Table V. It can be noted from this data and Figure 7 that capacity output drops rapidly during the first three cycles and remains fairly constant for the remaining cycles.

The reasons for the diminished capacity values obtained compared to the rated value were not clearly defined by these tests. The cause appeared to be due to a combination of battery construction materials (rubber separators were used) and predischarge conditioning. The effect of the latter factor was demonstrated in a special test performed on Article 22 on 6 November 1979 after approximately six life cycles. Following the life cycle charge to 125 percent, the three test batteries were given a special 20-ampere continuous current discharge to an undervoltage limit of 3.9 volts/battery. The batteries were then charged to 125 percent and a standard 75-ampere continuous current discharge to an undervoltage limit of 5.25 volts/battery was performed. Capacity outputs obtained were 120, 120, and 116 ampere-hours compared to the original acceptance test capacity values of 107, 107, and 106 ampere-hours. Thus, the reconditioning performed by the 20-ampere discharge cycle improved the standard discharge capacity by an average of 11 percent.

4.1.3 Test Depths of Discharge (DOD)

Since the average measured capacity value for all batteries was only approximately 80 percent of the manufacturer's rated capacity value (106.5 versus 132.5 ampere-hour), the question of which value to use as the basis for calculating the operating depths of discharge became an important test consideration. By using the manufacturer's value of 132.5 to calculate the 25-, 50-, and 75-percent DOD, the actual depths would translate to 31-, 62-, and 93-percent DOD based upon the actual measured valued of 106.5.

Acting under agreement with the battery manufacturer and the NASA Program Manager, it was decided to proceed using the rated value (132.5) as base and perform the more severe test. Therefore, succeeding discussions referencing depths of discharge of 25, 50, and 75 percent should be interpreted as actual depths of 31, 62, and 93 percent, respectively. The references to 25-, 50-, and 75-percent depths of discharge have been retained to preserve continuity with their appearance as they occurred in the original contract Statement of Work and in succeeding reports and discussions during the course of testing.

4.2 LIFE CYCLE TEST

4.2.1 General

Life cycle testing was carried out to a contract end date which occurred before all test articles and/or batteries had reached their failure points as defined for the test. An average of 581 discharge/charge cycles were completed by the approximately 31 percent of the batteries still remaining in test when testing was stopped (31 July 1981). While completion of the tests to 100-percent failures would have been more desirable from a data standpoint in establishing completed group end points and average life, the number of failures was large enough to establish the general failure mode which could be expected for all batteries and to define failure trends in most cases.

Table VI summarizes the end-of-test cycling statistics.

4.2.2 Test Parameter Changes

Several changes were made to test control values during the performance period of the test. The parameters involved were Recharge Ratio (R/R), Specific Charge Voltage (V/Cell), and Battery Undervoltage Cutoff Value (Batt U/Vc). The initial contractually specified values, and final operating values were as follows:

	Initial	Final
Recharge Ratio	111 percent	120 percent
Specific Charge Voltage	2.38 volts	2.50 volts
Battery Undervoltage Cutoff	5.25 volts	3.90 volts

The increase in recharge ratio was necessary in order to bring the batteries up to consistent full-charge specific gravities under the constant-potential charge regime being employed. Ratios as high as 130 percent were tried, but use of the higher figures resulted in excessively long charge times for a 24 hour cycle period as well as subjecting the batteries to greater overcharge. By combining a higher specific charge voltage (2.50 volts/cell) with the 120 percent recharge ratio, a satisfactory combination of time and charge was obtained.

Test Article Nos. 8, 12, 16 (System I), and 23 and 32 (System II) reached undervoltage cutoff before their scheduled 75 percent discharge depth on the first life cycle discharge. All five of the referenced test articles were scheduled for a 75-percent depth of discharge at rates of 180 amperes or greater. All achieved from 80 to 85 percent of the scheduled depth of 98.5 ampere-hours. The battery undervoltage cutoff voltage was lowered from 5.25 to 3.90 volts to optimize battery performance within the scope of the tests. Similarly, failure determination was redefined from the original definition to consist of a three-part requirement:

Condition 1 - The cycle in which a battery reached the undervoltage cutoff point before reaching its scheduled depth-of-discharge.

Condition 2 - The cycle in which the battery reached cutoff point at one-half its scheduled depth-of-discharge.

Condition 3 - Repeat of Condition 2.

Arrival at Condition 3 constituted battery failure and removal from test.

The foregoing changes were made by direction of the NASA Project Manager under mutual agreement with the battery manufacturer. A chronological summary of the changes is given in Table VII.

4.2.3 Equalization Charging

Two equalization charges totaling 120 ampere-hours at a nominal 5-ampere rate were given to all test articles during November, 1979. These charges were performed to equalize the batteries when it appeared that test conditions had been stabilized. By January, 1980 it became evident from the declining and varying specific gravities being measured that a regular program of supplemental charging would be necessary (see Figure 7). Accordingly, a schedule of weekly 70 ampere-hour equalization charges for all test articles was implemented. The weekly charging operation was replaced with a biweekly charge schedule in April, 1980. This reduced frequency of performance of an equalization charge provided adequate specific gravities while allowing fewer interruptions and time lost from life cycling. In addition, the new schedule provided for multilevel proportional equalization charge inputs. In place of a single value input for all test articles, a 20, 40, and 60 ampere-hour charge input was given to the 25-, 50-, and 75-percent depth of discharge test articles respectively. This charge regime was continued for the remainder of the test.

Investigation of the effect of equalization charging upon battery life was not within the scope of this test. All battery groups received similar chargings and no nonequalized control groups existed for comparison purposes. However, the variations in capacity and power output of the undervoltage (UV) Test Articles, Nos. 8, 12, 16, 23, 32, and succeeding UV test articles could be observed. Generally, the average power output was seen to increase by about 5 percent while the ampere-hour output remained the same during the discharge cycle following equalization charge. This performance was by no means consistent for all test articles. It was more typical during the first 300 to 400 cycles of life, and often disappeared during the final 100 to 200 cycles. Many test articles displayed a drop in both average power and capacity outputs following equalization during the final cycles.

While data obtained was inconclusive, the testing did suggest that charging regimes could be a very significant factor in determining useful battery life and performance.

4.2.4 Specific Gravity Measurements and Water Replenishment

Specific gravity readings were taken weekly and were averaged monthly for reporting purposes. A chart of the postcharge monthly averages for all test articles from October 1979, through July 1981, is shown in Figure 8.

The average declined rapidly during the first months of life cycle testing from an initial 1.278 to 1.245 through January of 1980. The commencement of the weekly 70 ampere-hour equalization charge in January appeared to arrest the decline. The trend was fairly level through 1980, with a yearly average of 1.246. The average then rose slowly during the last 6 months of testing to finish at 1.260. The overall test specific gravity average was 1.254. All readings were taken at an electrolyte temperature of 20° to 23°C.

It was necessary to add water to the battery cells at 6 to 8 week intervals. An average of 200 milliliters per cell was given at each watering. The individual amounts required varied in direct proportion to the test units' depth of discharge and/or average discharge current.

4.2.5 Accidental Battery Damage

Battery S/N 074, Test Article 10, sustained a meltdown of the negative terminal on 19 April 1980 at Cycle No. 172 (Table VIII, Failure No. 75). The terminal and portions of the battery casetop were destroyed in the process. The accident was almost certainly caused by resistive heating due to poor contact at the battery cable terminal clamp. It was found that many test battery clamps had begun a loosening process at the clamp screws since start of test, apparently due to mechanical creep. A second torquing of all clamp screws was sufficient to correct the problem. Due to the significant test time accrued (172 cycles) no replacement battery was inserted in the test article. The failure was considered nonfunctional and no failure analysis was performed. It is listed in Table VIII for reference purposes.

The removal of Battery S/N 074 reduced the total battery test group number to 107 batteries and eliminated one battery from Test Article No. 10 (see Table I). The data presented in this report are based on a test complement of 107 batteries.

4.2.6 Test Failures

Battery life to failure conditions as a function of depth of discharge, average discharge current, discharge chopper frequency, (chopper-controlled pulsed dc and continuous current dc) and discharge chopper duty cycle was investigated. Seventy-four batteries failed in test and the mean number of cycles to failure was 467. The failures are summarized in Table VIII.

4.2.6.1 Premature Failures

Of the 74 battery failures, the first two failures were classified as premature failures or "infant mortalities." Due to the significant test time accrued, no replacements of these batteries were made.

The first failure, Battery S/N 091, Test Article 28, occurred on 28 January 1980 at Cycle No. 85 (Table 6, Failure No. 1). A capacity output loss, which started on 15 January 1980 rapidly progressed to the half-point final failure mode 2 weeks later. Autopsy revealed a penetrating crack in the separator between positive and negative Plate No. 9 in Cell No. 2, allowing a short circuit condition to develop. The separator fracture was assessed to be a manufacturing defect.

The second failure, Battery S/N 038, Test Article 36, occurred on 25 February 1980 at Cycle No. 110. (Table 6, Failure No. 2.) A similar 2-week decline in capacity output was again found to be due to a short circuit in Cell No. 2. In this case, the short was due to lead rundown from the positive terminal which enabled a rapid bridging to the negative plates to develop. Again, the failure was seen to have been induced by a manufacturing deficiency.

4.2.6.2 Cycle Life Versus Depth of Discharge

The most significant factor in determining battery life appeared to be the depth of discharge to which the batteries were subjected. Independent of the other parameter variables present for a given depth (frequency, duty cycle and current rate), the shallower discharged test batteries displayed lower percentages of failure and longer cycle life than their greater depth counterparts. Table IX illustrates these findings. As indicated earlier in Section 4.1.3, the test specification depths of discharge of 25, 50 and 75 percent listed in the table are actually DODs of 31, 62 and 93 percent respectively, if based on the actual (measured) battery capacity. It is interesting to note that the 75-percent DOD battery group (actually 93-percent DOD) displayed good comparative cycle life despite the very severe depth of discharge.

Although battery cycle life was seen to be inversely related to depth of discharge, the utilization of available battery capacity as measured by the total ampere-hours delivered during the life period appeared to be directly related to depth of discharge, with higher depths delivering greater total ampere-hour (and energy) outputs.

Figures 9 and 10 illustrate the above findings. Individual battery failure points and unfailed batteries' final cycle are depicted.

4.2.6.3 Cycle Life Versus Discharge Current

Test results tended to show that discharge current rates could be a significant factor in the determination of battery life, especially when considering the very low rates (20 to 60 amperes) versus the very high rates (180 amperes and above). The effect appears to be influenced by DOD.

Failure data is summarized in Table X. The discharge rate groups in Column 1 include both continuous (dc) and chopped current modes, except Groups 60, 140, and 220 which consisted of chopped modes only. Reference depth of discharge information is given in Columns 6, 7, and 8.

The data of Table X illustrates several discharge current rate characteristics. Containing only 50-percent DOD test batteries, discharge rate 20 sustained only 16.7-percent failure, while discharge 260 sustained 100-percent failure. In this case of extremes of rates, the discharge rate itself appeared to be the primary life-determining factor. Discharge rate 140, the median current group consisting of three test articles, displayed performance which was somewhat unique. With all its batteries operating under identical conditions of chopper frequency (500 Hz), chopper duty cycle (55 percent), and depth of discharge (50-percent DOD), the group sustained 100-percent failure at this moderate current.

If one neglects the premature failure of Battery No. 038 at 110 cycles, the failure band range would have been very small (468 to 555 cycles), with the first failure occurring much later in cycle life than in any other group, and the mean failure cycle number would have been Cycle 514.

4.2.6.4 Cycle Life Versus Discharge Chopper Frequency

The effect of discharge chopper frequency upon battery life appeared to be of no significance in itself. The failure data as a function of chopper frequency shown in Table XI shows little in the way of trends.

4.2.6.5 Cycle Life Versus Discharge Chopper Duty Cycle

As was the case with discharge frequency, the effect of discharge chopper duty cycle upon battery life was not readily discernable.

The data of Table XII lists the failures in relation to duty cycle.

4.2.6.6 Failure Mode

All of the life-cycling test failures were characterized by a single failure mode; a gradual decrease in output capacity to the half-capacity failure point. Occurring after several hundred cycles, this phenomenon was characteristic of electrode aging and end of useful battery life. Battery autopsy inspections supported the existence of a strong wearout factor. Consistent evidence of positive plate shedding, grid oxidation, existing and developing short circuits, and loss of grid material from the negative plates was found.

4.3 AUTOPSY AND FAILURE ANALYSIS

4.3.1 Reference Specimens

Failure analyses of test battery fatalities were accomplished through performance of a destructive autopsy or battery teardown upon each of the selected test-failed specimens. In order to provide a general basis for physical comparison, a baseline autopsy was performed upon two new battery specimens:

1) A dry, unactivated battery taken from production prior to final sealing and formation

2) A normal, wet and formed battery, S/N 111, taken from the test shipment.

Results of these examinations revealed the batteries to be constructed to good commercial standards with few irregularities. Major characteristics found are listed below:

1) Cell plates were in good alignment and their interplate distances equalized.

2) Terminal and cell interconnections were excellent; one small lead rundown from the positive terminal in one cell.

3) Approximately 5 percent of plate material (grid "biscuits") were missing in from 10 to 20 percent of the plates.

4) A few (two to three) separators in each battery had hairline cracks.

4.3.2 Test Failure Specimens

The 23 test batteries autopsied displayed remarkably consistent conditions as exemplified in the typical report for Battery Failure No. 16 given in the Appendix. This failure of Battery S/N 097 occurred at Cycle 410, which is within approximately 12 percent of the mean failure cycle number for all failed batteries.

The following conditions, with minor variations, were typical for all batteries examined:

a) Finely Divided Positive Plate Shedding. Characteristic of a battery after long service.

b) Short Circuits in One or More Cells. Evidenced in every battery examined; most frequently the result of "treeing" or metallic bridging across the plates. Less frequently, it was due to worn or cracked separators, or overflowing sediment chambers.

c) Buckled Positive Plates, Oxidized Grids. Characteristic of many charging cycles, or overcharge. It was felt that many batteries or cells received overcharge during the normal and equalization charge periods, merely because of the physical test configurations (series-connected cells and batteries). Numerous elements received charge, "whether they needed it or not."

d) Loss of Negative Plate Material. A possible consequence of continued charging when a cell element is short circuited.

5. SUMMARY OF RESULTS

Life cycling testing of 108* lead-acid golf car batteries over a 2-year period produced a 69-percent failure of the test group. Test performance results appeared to show that battery life was primarily affected by, and inversely proportional to, the depth of discharge and the discharge current. The observed failure mode was characterized by a gradual capacity loss to the half-capacity failure point. Autopsies performed upon 23 test failures showed consistent evidence of cell element aging. Short circuits were found in all batteries examined. Some indications of overcharging were also present. Chopper discharge frequency and duty cycle seemed to be of little significance as life determining factors. The continuous current (dc) discharge test articles had failure distributions similar to the chopper-controlled test specimens. The mean number of cycles to failure of all failed batteries was 467.

Methods of charging and their effects were not investigated as part of this test. However, it was determined that considerable attention must be paid to this phase of battery operation in order to maintain performance while minimizing charging time and overcharge.

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*Subsequently reduced to 107.

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APPENDIX A
EV-106 LEAD-ACID BATTERY FAILURE NO. 16 (S/N 097)
SAMPLE REPORT

TRW
SYSTEMS GROUP

INTEROFFICE CORRESPONDENCE

81.8725.2-053

TO: E. P. Ames
M2/1153

CC: Distribution

DATE: 11 February 81

SUBJECT: EV-106 Lead-Acid Battery Failure No. 16 (S/N 097)

FROM: L. P. Mack
BLDG M1 MAIL STA. 1406 EXT. 50776

Reference 1: "Chopper-Controlled Discharge Life Cycling Studies on Lead-Acid Batteries," Volume 1, Technical Proposal No. 34181.000 dated on August 26, 1978.

Reference 2: IOC No. 80.8725.2-075, "NASA Lewis Contract No. Den 3-88, Revision A of the Lead-Acid Battery Failure Analysis Procedure," L. P. Mack to E. P. Ames, dated March 12, 1980.

Reference 3: IOC No. 81.8725.2-052, "EV-106 Lead-Acid Battery Failure Analysis No. 15 (S/N 070)," L. P. Mack to E. P. Ames, dated February 11, 1981.

1. INTRODUCTION

A failed lead-acid battery, type EV-106, Test Article Number 024, Serial Number 097 was disassembled and examined. The battery had passed the nine-cycle acceptance tests. After acceptance, the battery was tested with a chopper-controlled discharge load for 410 cycles before it failed due to a loss in capacity. The battery had reached the undervoltage before it reached the one-half capacity output point for two cycles. The life test conditions for this battery were: chopper mode, an average current of 100A, a 87.5 percent duty cycle, a frequency of 500 Hz, and a depth-of-discharge (DOD) of 50 percent (Reference 1). The

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battery container, cell elements, sediment chambers, and cell components were then inspected in accordance with the lead-acid battery failure analysis procedure (Reference 2). The data generated by the visual inspection and selected physical tests of Battery S/N 097 were compared with data obtained from the autopsies of the baseline batteries and other failed batteries (e.g., Reference 3).

2. SUMMARY OF RESULTS

Failure of cells 1, 2, and 3 by the softening and the shedding of the positive plates in all three cells was the cause of failure of battery S/N 097. Several major failure symptoms had been observed in the cells. They are the "bridging" between positive and negative plates in Cell Nos. 2 and 3, and burnt oxides present in the positive plates from Cell Nos. 1, 2, and 3. All these failure characteristics are believed to originate from the breakdown of the positive plates. The inspection of the rest of the battery components from Battery S/N 097 revealed that they resembled those examined in Battery S/N 070 (with some minor exceptions).

3. RESULTS

The detailed results of the visual inspection of Battery S/N 097 are listed in the attached data sheets. Pre-teardown tests had indicated that Cell No. 2 had the lowest specific gravity (very significant), open circuit voltage and AC impedance readings among the three cells. The physical appearannce of the failed battery and its drained electrolyte was similar to that observed in failed Battery S/N 070. After the electrolyte had been completely drained from the battery, all three cell elements were removed from the battery container and examined individually.

Visual inspection of the element from Cell No. 1 revealed slight "mossing" on all sides. Figure 1 shows the "mossing" on the bottom surface of the element from Cell No. 1. However, no "bridging" was observed.

Visual inspection of the element from Cell No. 2 revealed very little, to almost no mossing or all surfaces, except for one of the side surfaces. Figure 2 shows the bottom surface of the cell element. Notice that very little "mossing" was observed. Figure 3 shows severe "mossing" on one of the side surfaces. Figure 4 shows negative active material contacting the top positive plate (P-1) on the side of the cell element shown in Figure 3. Figure 5 shows the side surface of the cell element after it was partly disassembled. Notice on the same figure the "bridging" between positive and negative plates.

Visual inspection of the element from Cell No. 3 revealed severe mossing at the bottom. "Bridging" between positive and negative plates was also observed on the bottom surface of the cell element on closer examination. Figure 6 shows negative active material ("moss") contacting the top positive plate. A few of the top plates and separators had been disassembled from the cell element to reveal more negative active material contacting another positive plate (P-3).

Visual inspection of the sediment chambers at the bottom of the empty battery container revealed the buildup but no overflow of oxides.

Visual inspection of the positive plates revealed characteristics also observed in Battery S/N 070 such as plate shedding, burnt oxides, grid oxidation and buckling. The active material loss from the positive plates of Cell Nos. 1 and 3 was very severe (to the extent of spalling). Only slight material loss occurred in the positive plates from Cell No. 2.

It is believed that Cell No. 2 was the first cell in battery S/N 097 that contained a short circuit. A shorted Cell 2 resulted in placing the charge-discharge burden on Cell Nos. 1 and 3, ultimately causing both cells to fail. This would explain the relative lack of plate shedding in Cell No. 2. Figure 8 shows spalling in one of the positive plates (P-5) from Cell No. 1 (top arrow). Part of the plate grid in Figure 8 was also observed to be slightly bent due to the severe grid oxidation (see bottom arrow). Figure 9 shows a plate (P-1) from Cell No. 1 where part of its grid disappeared near the plate tab. Inspection revealed that nearly all positive plates from Cell No. 1 had a small part of their grid disappearing near the plate tab. That part of the grid was believed to be completely oxidized into lead dioxide and had fallen out into the electrolyte.

Visual inspection of the separators revealed the usual amount of sulfate and lead dioxide deposition. This has also been observed in the separators from failed Battery S/N 070. One separator (SP-3) from Cell No. 1 was observed to have a crack extending nearly half its length. This cracked separator is shown in Figure 10. However, no short across the crack was evident.

Visual inspection of the negative plates revealed the usual amount of material loss and plate shrinkage. This has also been observed in the plates from failed Battery S/N 070. One negative plate (N-7) from Cell No. 3 had a small portion of it missing, as shown in Figure 11. Part of the grid also disappeared, as shown in the same figure.

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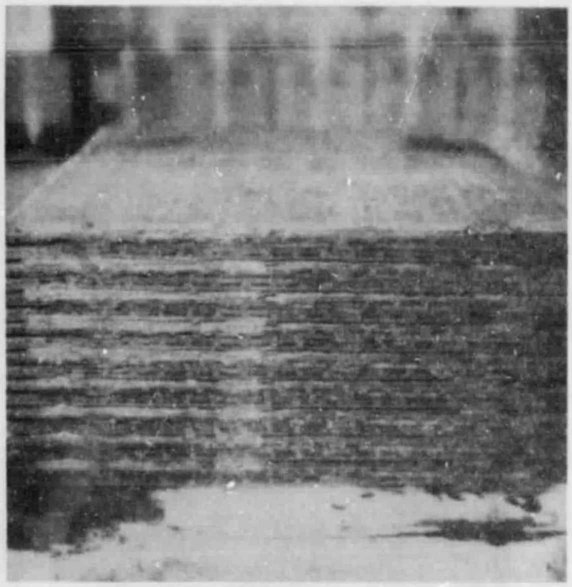

Figure 1. "Mossing" on the bottom surface of the element from cell No. 1.

Figure 2. Very little "mossing" on the bottom surface of the element from cell No. 2.

Figure 3. "Mossing" and "bridging" on one of the side surfaces of the element from cell No. 2.

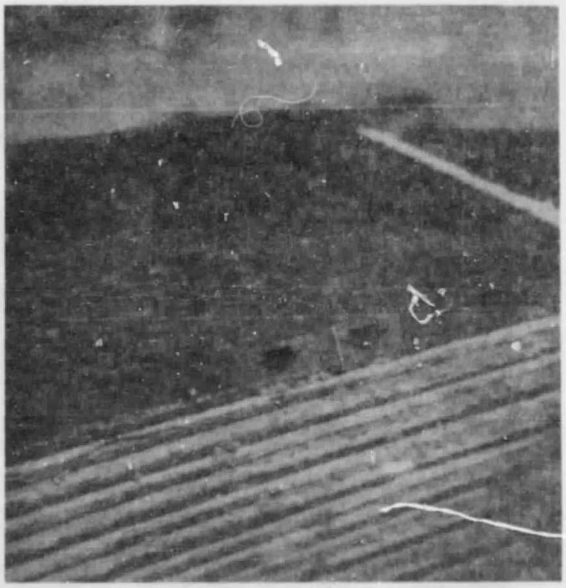

Figure 4. Negative active material beachheads on the positive plate (P-1) from cell No. 2.

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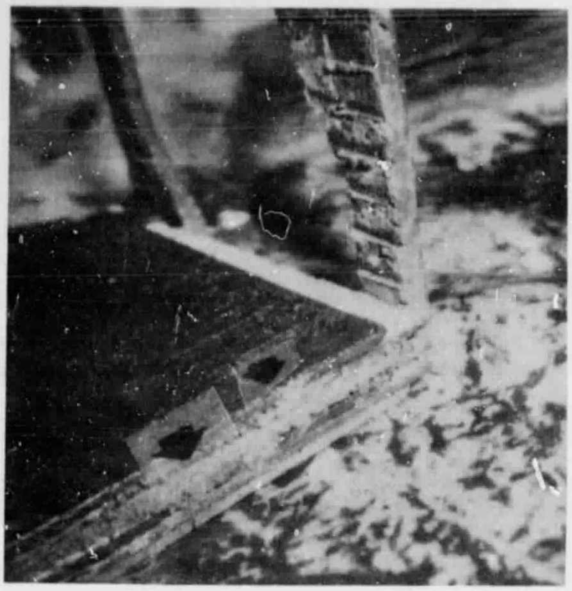

Figure 5. "Bridging" between positive and negative plates in cell No. 2.

Figure 6. "Bridging" between positive and negative plates in cell No. 3.

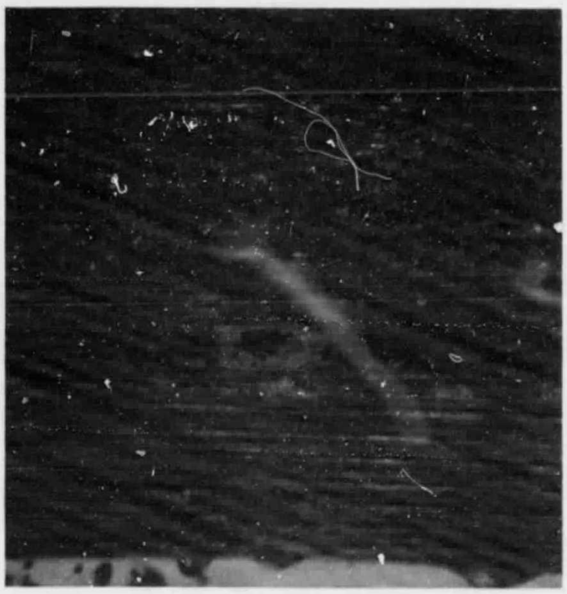

Figure 7. Top plates and separators removed to reveal more "bridging" in cell No. 3.

Figure 8. Spalling in plate (P-5) from cell No. 1.

Figure 9. Destruction of the positive grid near tab in cell No. 1.

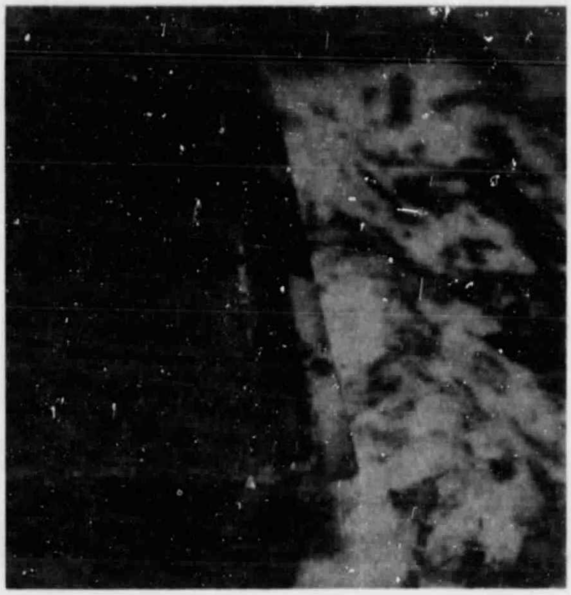

Figure 10. Cracked separator (SP-3) from cell No. 1.

Figure 11. Moderate-size hole near tab in negative plate (N-7) from cell No. 3.

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APPENDIX B

TABLES

Table I. Allocation of Batteries to Test Conditions in a Central Factorial Design Experiment

DOD (Percentage)	Discharge Current (Amperes) Average/Peak	Frequency (kHz)	Duty Cycle (Percentage)	Test Article	Battery Serial Numbers Bat 1	Bat 2	Bat 3
25	60/133	0.1	45	34	90	64	39
25	60/133	1.0	45	6	26	49	42
25	100/100	dc	dc	13	104	10	65
25	100/286	0.1	65	25	40	44	30
25	100/286	1.0	35	17	15	28	37
25	180/180	dc	dc	35	106	66	33
25	180/240	0.1	75	27	24	55	96
25	180/240	1.0	75	15	25	79	69
25	220/339	0.1	65	26	31	62	14
25	220/339	1.0	65	9	103	57	63
50	20/20	dc	dc	11	85	76	102
50	20/80	0.5	25	20	16	88	36
50	100/100	dc	dc	7	93	92	81
50	100/100	dc	dc	29	52	43	23
50	100/114	0.5	87.5	24	34	97	54
50	100/133	0.5	75	1	86	41	18
50	100/154	0.5	65	30	107	78	17
50	140/225	0.5	55	14	71	48	6
50	140/225	0.5	55	21	68	29	51
50	140/225	0.5	55	36	101	38	4
50	180/180	dc	dc	3	99	67	8
50	180/180	dc	dc	31	80	21	11
50	180/206	0.5	87.5	28	9	91	82
50	180/400	0.5	45	4	73	32	98
50	260/260	dc	dc	19	60	2	72
50	260/306	0.5	85	10	74	50	12
75	60/133	0.1	45	2	5	47	53
75	60/133	0.5	45	22	27	83	70
75	100/100	dc	dc	5	56	1	94
75	100/286	0.1	35	18	20	45	7
75	100/286	1.0	35	33	108	100	84
75	180/180	dc	dc	12	59	87	75
75	180/240	0.1	75	23	77	19	3
75	180/240	1.0	75	8	22	61	89
75	220/339	0.1	65	16	58	46	105
75	220/339	1.0	65	32	95	13	35

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Table II. Test Article 13 Real-Time Data (Day 261, 1980)

Time	Cycle No.	Operation	Battery No.	Volts	Amperes	Ampere-Hours	Watts	Watthours	Electrolyte	Temperature	
										Room	Terminal
				A. START DISCHARGE							
21:00:30	307	Open	104	6.343	0.0000	0.0000	0.0000	0.0000	23.8	21.2	000
			010	6.329	0.0000	0.0000	0.0000	0.0000			000
			065	6.320	0.0000	0.0000	0.0000	0.0000			
21:01:01	308	Discharge	104	5.885	-100.0	-0.0139	-588.7	-0.0818	23.7	21.2	000
			010	5.866	-100.0	-0.0139	-586.8	-0.0815			000
			065	5.869	-100.0	-0.0139	-587.1	-0.0815			
				B. END DISCHARGE							
21:20:59	308	Discharge	104	5.612	-100.0	-32.75	-561.4	-187.8	25.2	21.3	000
			010	5.583	-100.0	-32.75	-559.5	-187.1			000
			065	5.561	-100.0	-32.75	-556.3	-186.9			
				C. START CHARGE							
21:21:13	308	Open	104	6.120	0.0000	0.0000	0.0000	0.0000	25.4	21.3	000
			010	6.104	0.0000	0.0000	0.0000	0.0000			000
			065	6.092	0.0000	0.0000	0.0000	0.0000			
21:21:28	308	Charge	104	6.342	58.47	0.0000	370.8	0.0000	25.4	21.3	000
			010	6.333	58.47	0.0000	370.3	0.0000			000
			065	6.326	58.47	0.0000	369.9	0.0000			

Table III. Daily Summary Sheet for System I (Day 262, 1980)

DATA SUMMARY											
		END DISCHARGE				END CHARGE					
Article No.	Battery No.	Battery (volts)	Ampere Hour	Watt Hour	Temp. (C)	Battery (volts)	Ampere Hour	Watt Hour	Temp. (C)	Cycle No.
01	086	5.265	-65.54	-362.9	27.2	7.458	79.25	544.2	29.1	313
	041	5.321	-65.54	-366.2		7.583	79.25	549.6		
	018	5.388	-65.54	-366.4		7.621	79.25	547.1		
02	000	0.0010	-95.02	-1.171	31.4	0.0010	114.3	0.1382	26.9	306
	047	5.433	-95.02	-530.1		7.135	114.3	767.8		
	053	3.785	-95.02	-525.3		7.360	114.3	779.3		
03	099	4.374	-63.37	-337.3	28.5	7.513	76.61	521.1	27.6	305
	067	3.584	-63.37	-334.8		7.491	76.61	524.0		
	008	4.807	-63.37	-336.8		7.319	76.61	517.9		
04	073	4.897	-65.38	-314.0	33.3	7.504	78.74	542.7	30.7	310
	032	4.931	-65.38	-313.7		7.489	78.74	543.2		
	098	4.538	-65.38	-307.5		7.680	78.74	547.4		
05	056	5.305	-68.38	-385.6	28.0	7.466	82.72	570.0	30.9	308
	001	5.372	-68.38	-387.0		7.532	82.72	571.6		
	094	3.775	-68.38	-378.4		7.506	82.72	576.5		
06	026	5.776	-32.72	-187.1	24.6	7.680	39.75	281.4	27.1	310
	049	5.751	-32.72	-186.5		7.642	39.75	278.3		
	042	5.764	-32.72	-186.8		7.534	39.75	278.9		
07	093	5.368	-65.52	-371.6	27.9	7.435	79.26	550.6	31.5	307
	092	5.407	-65.52	-372.8		7.545	79.26	551.1		
	081	5.381	-65.52	-369.9		7.347	79.26	543.3		
08	022	4.855	-66.01	-343.2	31.0	7.466	80.15	550.7	33.4	306
	061	3.712	-66.01	-338.4		7.540	80.15	554.6		
	089	4.617	-66.01	-342.4		7.569	80.15	555.4		
09	103	5.165	-32.67	-165.2	27.2	7.813	39.37	270.7	29.3	309
	057	5.162	-32.67	-165.7		7.557	39.37	269.7		
	063	5.155	-32.67	-165.1		7.514	39.37	269.7		
10	000	0.0010	-65.18	-0.6122	33.3	0.0010	78.50	0.0912	29.8	309
	050	[illegible]	-65.18	-321.3		7.259	78.50	524.2		
	012	4.448	-65.18	-325.8		7.463	78.50	535.7		
11	085	5.935	-65.65	-399.5	24.6	7.934	78.81	547.4	28.5	307
	076	5.904	-65.65	-397.4		7.400	78.81	538.6		
	102	5.952	-65.65	-400.8		7.522	78.81	545.2		

Table III. Daily Summary Sheet for System I (Day 262, 1980) (Continued)

DATA SUMMARY											
		END DISCHARGE				END CHARGE					
Article No.	Battery No.	Battery (volts)	Ampere Hour	Watt Hour	Temp. (C)	Battery (volts)	Ampere Hour	Watt Hour	Temp. (C)	Cycle No.
12	059	3.704	-61.53	-323.2	29.2	7.541	74.57	517.6	30.7	307
	087	4.938	-61.53	-330.0		7.472	74.57	515.0		
	075	4.825	-61.53	-329.0		7.540	74.57	519.8		
13	104	5.612	-32.75	-187.8	25.2	7.708	39.43	276.4	28.6	308
	010	5.583	-32.75	-187.1		7.709	39.43	276.3		
	065	5.561	-32.75	-186.8		7.491	39.43	273.8		
14	071	5.174	-65.32	-342.4	30.6	7.547	79.13	546.7	32.6	309
	048	5.100	-65.32	-338.5		7.511	79.13	542.0		
	006	5.234	-65.32	-343.1		7.509	79.13	545.6		
15	025	5.319	-32.71	-175.6	25.9	7.720	39.31	276.8	28.7	309
	079	5.300	-32.71	-174.6		7.574	39.31	272.6		
	069	5.220	-32.71	-172.7		7.589	39.31	271.8		
16	058	3.850	-59.80	-289.2	33.1	7.535	72.42	501.1	28.6	308
	046	3.522	-59.80	-286.0		7.472	72.42	497.9		
	105	4.554	-59.80	-291.3		7.521	72.42	499.0		
17	015	5.603	-32.74	-175.1	27.0	7.675	39.46	276.4	29.0	309
	028	5.594	-32.74	-173.4		7.563	39.46	274.8		
	037	5.586	-32.74	-172.6		7.654	39.46	275.2		
18	020	5.191	-68.47	-353.7	32.9	7.383	82.77	564.5	27.9	309
	045	5.285	-68.47	-353.7		7.401	82.77	562.4		
	007	3.871	-68.47	-333.4		7.460	82.77	566.8		

Table III. Daily Summary Sheet for System I (Day 262, 1980) (Continued)

TIME SUMMARY				
	Discharge		Charge	
Article Number	Start Time	End Time	Start Time	End Time
01	261 08:00:00	261 08:39:34	261 09:59:32	261 16:20:22
02	261 08:42:00	261 10:17:18	261 12:10:29	261 20:06:04
03	261 15:01:00	261 15:22:24	261 15:23:04	261 20:13:12
04	261 10:22:00	261 10:44:06	261 12:54:04	261 15:49:19
05	261 15:25:00	261 16:06:17	261 18:24:11	261 21:09:31
06	261 10:46:00	261 11:19:01	261 11:19:18	261 13:04:33
07	261 16:26:00	261 17:05:34	261 20:05:32	261 23:10:47
08	261 11:21:00	261 11:43:18	261 14:13:59	261 16:49:14
09	261 11:56:00	261 12:05:12	261 12:05:30	261 14:41:02
10	261 12:07:00	261 12:22:23	261 19:12:21	262 00:12:36
11	261 17:07:00	261 20:23:46	261 20:24:02	262 01:24:17
12	261 20:26:00	261 20:46:47	262 00:28:59	262 02:54:14
13	261 21:01:00	261 21:20:55	261 21:21:28	261 22:56:43
14	261 12:25:00	261 12:53:20	261 14:43:18	261 17:28:33
15	261 12:56:00	261 13:07:11	261 13:07:28	261 14:52:43
16	261 13:09:00	261 13:25:38	261 17:36:02	261 21:26:10
17	261 13:38:00	261 13:57:55	261 13:58:13	261 15:38:28
18	261 14:00:00	261 14:41:21	261 18:19:11	261 22:34:26

Table IV. EV-106 Acceptance Test, Battery Specific Gravity, Weight, and Water Addition

Test Article	Battery S/N	Specific Gravities			Battery Weight	Water Added (CC)		
		Cell No. 1	Cell No. 2	Cell No. 3		Cell No. 1	Cell No. 2	Cell No. 3
1	086	1260	1262	1263	62.7	50	25	25
	041	1280	1280	1280	62.9	50	50	60
	018	1264	1268	1262	63.0	60	10	50
2	005	1280	1281	1281	62.9	35	45	75
	047	1282	1280	1282	63.1	10	0	75
	053	1270	1282	1272	63.4	65	50	75
3	099	1285	1281	1283	61.8	0	0	25
	067	1279	1280	1280	62.9	0	15	0
	008	1279	1280	1281	62.7	60	0	60
4	073	1282	1286	1282	62.9	50	35	105
	032	1282	1284	1283	62.8	85	05	50
	098	1285	1283	1278	62.9	0	20	65
5	056	1282	1284	1279	62.9	130	0	125
	001	1278	1280	1279	63.0	15	0	75
	094	1280	1277	1275	62.4	0	0	70
6	026	1278	1278	1277	63.2	10	0	65
	049	1280	1287	1283	62.5	70	55	85
	042	1286	1289	1287	63.0	50	35	115
7	093	1282	1279	1277	62.1	15	0	85
	092	1282	1283	1277	62.6	15	5	0
	081	1281	1281	1280	62.4	10	15	60
8	022	1283	1280	1288	63.2	0	0	95
	061	1282	1290	1285	63.4	0	0	60
	089	1280	1278	1277	61.9	5	0	50
9	103	1268	1268	1268	63.0	0	10	70
	057	1273	1270	1273	63.6	40	0	0
	063	1273	1273	1273	63.5	0	0	25
10	074	1288	1283	1281	62.9	70	0	105
	050	1278	1282	1285	61.8	50	65	85
	012	1279	1280	1278	63.5	0	0	70
11	085	1281	1280	1280	63.4	0	105	70
	076	1285	1279	1279	62.4	55	25	120
	102	1289	1289	1280	63.6	0	0	50
12	059	1285	1281	1283	63.3	0	30	20
	087	1279	1275	1280	61.7	60	0	30
	075	1279	1277	1282	63.4	45	0	55

Table IV. EV-106 Acceptance Test, Battery Specific Gravity, Weight, and Water Addition (Continued)

Test Article	Battery S/N	Specific Gravities			Battery Weight	Water Added (CC)		
		Cell No. 1	Cell No. 2	Cell No. 3		Cell No. 1	Cell No. 2	Cell No. 3
13	104	1281	1282	1277	63.8	0	0	100
	010	1279	1282	1278	62.8	40	0	85
	065	1280	1283	1282	62.8	75	40	60
14	071	1283	1283	1280	63.1	0	0	75
	048	1282	1278	1289	62.2	20	55	60
	006	1279	1283	1284	63.4	50	30	70
15	025	1278	1278	1268	63.8	0	0	25
	079	1282	1279	1279	63.0	0	0	60
	069	1282	1281	1285	63.0	35	0	100
16	058	1283	1280	1280	63.4	0	60	75
	046	1286	1281	1282	62.2	30	70	80
	105	1276	1280	1276	62.9	135	0	40
17	015	1282	1285	1286	63.4	65	40	0
	028	1275	1275	1274	63.1	60	0	75
	037	1280	1281	1279	63.4	85	40	50
18	020	1280	1285	1280	63.1	40	0	55
	045	1279	1277	1277	62.9	25	0	50
	007	1277	1278	1277	63.1	50	0	0
19	060	1285	1286	1283	63.5	80	45	20
	002	1276	1280	1279	62.8	75	75	50
	072	1279	1281	1279	62.7	75	75	75
20	016	1277	1275	1276	63.2	80	75	165
	088	1276	1278	1277	62.3	35	75	75
	036	1276	1280	1280	62.7	0	75	20
21	068	1278	1282	1272	62.4	95	10	65
	029	1281	1279	1280	63.6	10	60	0
	051	1280	1276	1276	62.1	75	100	100
22	027	1277	1275	1274	63.5	100	100	100
	083	1273	1279	1275	63.2	115	100	125
	070	1279	1279	1275	62.7	25	25	50
23	077	1280	1287	1282	63.7	130	123	85
	019	1281	1277	1279	63.2	125	85	150
	003	1276	1272	1270	62.5	130	100	135
24	034	1277	1282	1280	63.7	100	115	105
	097	1277	1277	1273	61.9	95	105	100
	054	1279	1280	1279	62.3	100	85	140

Table IV. EV-106 Acceptance Test, Battery Specific Gravity, Weight, and Water Addition (Continued)

Test Article	Battery S/N	Specific Gravities			Battery Weight	Water Added (CC)		
		Cell No. 1	Cell No. 2	Cell No. 3		Cell No. 1	Cell No. 2	Cell No. 3
25	040	1285	1285	1280	62.8	110	65	60
	044	1280	1283	1283	62.7	150	130	130
	030	1279	1278	1279	63.2	90	50	60
26	031	1280	1281	1283	62.4	140	150	75
	062	1279	1278	1278	63.3	125	120	120
	014	1276	1278	1275	62.5	130	125	85
27	024	1274	1275	1278	62.4	75	80	75
	055	1280	1281	1277	63.7	75	0	60
	096	1277	1276	1274	62.0	125	90	75
28	009	1280	1282	1276	63.3	130	100	135
	091	1275	1277	1273	62.1	75	100	140
	082	1281	1278	1279	61.9	105	70	75
29	052	1271	1275	1273	62.6	120	125	55
	023	1279	1276	1273	63.3	70	60	135
	043	1281	1276	1280	63.1	100	105	125
30	107	1285	1287	1288	62.8	115	70	135
	078	1277	1278	1277	61.4	125	100	90
	017	1266	1266	1267	63.4	100	75	120
31	080	1267	1262	1263	62.9	135	35	100
	021	1267	1270	1271	63.7	125	85	190
	011	1270	1268	1271	63.0	135	135	160
32	095	1270	1268	1267	62.5	135	125	100
	013	1272	1278	1272	63.1	85	85	160
	035	1280	1276	1276	62.9	130	110	100
33	108	1272	1272	1272	63.4	100	100	125
	100	1270	1274	1280	62.8	90	105	90
	084	1275	1275	1273	63.5	90	60	110
34	090	1271	1275	1270	62.0	120	110	110
	064	1281	1279	1276	63.3	80	80	105
	039	1275	1281	1276	62.7	90	80	60
35	106	1268	1266	1266	63.2	100	75	100
	066	1270	1281	1270	62.7	75	85	125
	033	1273	1274	1269	63.0	75	100	100
36	1[illegible]	1273	1277	1270	62.9	50	50	100
	0[illegible]	1279	1277	1277	63.1	45	65	105
	004	1280	1280	1280	62.9	50	50	60

Table V. EV-106 Acceptance Test, Discharge Capacities

Test Article	Battery S/N	Cycle 1	2	3	4	5	6	7	8	9	Average
1	086	113.9	110.0	106.2	104.4	103.8	105.0	102.5	104.3	N/A	106.26
	041	116.4	112.4	112.4	104.4	106.2	106.0	105.0	105.8	N/A	108.58
	018	113.9	110.0	106.2	104.4	105.0	105.5	103.8	104.4	N/A	106.64
2	005	115.0	110.0	109.9	106.3	105.0	106.3	103.8	104.5	N/A	107.60
	047	115.0	110.1	109.9	106.3	106.2	106.3	103.8	104.5	N/A	107.76
	053	115.0	110.0	108.7	106.3	105.0	106.0	103.8	104.5	N/A	107.41
3	099	114.0	106.2	106.2	106.3	102.5	103.7	104.3	103.8	N/A	105.88
	067	114.0	110.0	106.2	106.3	106.2	106.2	106.3	106.3	N/A	107.69
	008	114.0	106.2	106.2	106.3	103.8	103.7	104.3	103.8	N/A	106.04
4	073	115.0	112.5	110.0	107.4	103.8	104.0	102.5	104.0	N/A	107.40
	032	115.0	110.0	110.0	107.4	103.8	104.0	102.5	104.0	N/A	107.09
	098	115.0	110.0	106.2	107.4	103.8	104.0	102.5	104.0	N/A	106.61
5	056	115.0	112.0	108.0	107.3	105.0	106.0	102.5	104.0	N/A	107.48
	001	112.6	110.0	106.2	106.3	103.8	105.0	102.5	103.0	N/A	106.18
	094	118.8	113.0	108.0	108.3	106.2	106.3	105.0	105.0	N/A	108.83
6	026	115.0	112.4	110.5	108.7	106.2	106.3	106.9	106.0	N/A	109.00
	049	115.0	112.4	110.5	106.3	105.0	105.0	104.4	105.0	N/A	107.95
	042	118.8	112.4	110.5	106.8	105.0	105.0	104.4	104.5	N/A	108.43
7	093	112.6	112.5	110.0	106.5	105.0	105.0	104.5	103.8	N/A	107.49
	092	115.0	112.5	112.0	109.9	107.8	106.3	107.2	106.3	N/A	109.63
	081	112.6	112.5	110.0	104.5	103.8	105.0	103.3	102.5	N/A	106.78
8	022	112.6	111.0	106.2	105.1	103.8	105.0	104.3	104.9	N/A	106.61
	061	112.6	111.0	106.2	105.1	103.8	105.0	104.3	104.9	N/A	106.61
	089	109.0	108.0	106.2	104.1	102.5	105.0	103.3	103.3	N/A	105.11
9	103	112.5	111.0	108.0	112.4	106.3	106.3	105.8	103.8	N/A	108.26
	057	112.5	111.0	110.0	114.0	108.8	106.3	106.7	106.3	N/A	109.45
	063	118.7	112.0	110.0	114.0	108.0	106.3	106.5	106.3	N/A	110.33
10	074	113.1	110.0	108.0	103.7	101.3	101.3	102.0	100.0	N/A	104.93
	050	113.1	110.0	112.0	101.9	100.1	100.1	102.0	99.1	N/A	104.54
	012	113.1	110.0	108.0	104.8	105.1	104.2	103.8	103.6	N/A	106.58
11	085	114.9	112.5	106.2	109.2	106.3	106.3	106.0	106.3	N/A	108.46
	076	114.9	112.5	106.2	108.0	106.3	106.3	106.0	105.3	N/A	108.71
	102	114.9	112.5	106.2	109.2	116.3	106.3	106.0	106.3	N/A	109.[illegible]
12	059	112.5	112.5	106.2	107.0	105.0	105.0	105.0	104.3	N/A	107.19
	087	112.5	112.5	106.2	107.0	106.3	106.3	105.0	105.3	N/A	107.64
	075	115.0	112.5	106.2	107.0	105.0	105.0	105.0	104.3	N/A	107.50

Table V. EV-106 Acceptance, Test Discharge Capacities (Continued)

est ticle	Battery S/N	Cycle									Average
		1	2	3	4	5	6	7	8	9	
	104	113.7	108.0	106.2	107.3	105.0	105.0	103.8	103.9	N/A	106.61
13	010	112.4	108.0	106.2	105.3	102.5	102.5	102.5	102.9	N/A	105.29
	065	113.7	108.0	106.2	107.8	103.8	103.8	103.8	103.4	N/A	106.31
	071	114.9	106.2	106.2	105.1	104.3	103.9	102.6	102.6	N/A	105.73
14	048	112.4	106.2	106.2	101.1	97.5	98.1	94.7	97.3	N/A	101.69
	006	112.4	106.2	106.2	105.1	101.3	102.1	101.3	101.3	N/A	104.49
	025	112.4	106.2	106.2	107.3	106.3	106.6	106.3	106.0	N/A	107.16
15	079	116.2	112.5	112.5	110.6	108.8	108.3	107.5	106.0	N/A	110.30
	069	118.0	112.5	112.5	111.6	107.5	106.6	106.3	106.0	N/A	110.13
	058	112.5	106.2	110.0	109.6	106.3	106.3	106.3	105.0	N/A	107.78
16	046	112.5	106.2	110.0	107.8	103.8	104.3	102.6	104.5	N/A	106.46
	105	112.5	106.2	106.2	106.8	103.8	102.3	103.8	102.0	N/A	105.45
	015	118.7	112.5	110.0	110.0	107.8	106.9	106.9	106.3	N/A	109.89
17	028	118.7	106.2	110.0	106.5	106.3	105.4	105.7	105.0	N/A	108.10
	037	118.7	112.5	110.0	110.0	106.3	105.9	106.9	105.5	N/A	109.48
	020	118.7	112.4	110.0	107.5	106.3	106.3	105.0	106.0	N/A	109.03
18	045	116.0	112.4	110.0	106.3	106.3	103.8	104.0	105.0	N/A	107.98
	007	112.4	112.4	110.0	107.5	106.3	105.0	105.0	105.0	N/A	107.95
	060	113.4	111.4	106.3	108.7	104.2	104.3	105.0	104.9	105.0	107.02
19	002	114.6	111.4	106.3	108.3	104.2	103.9	105.0	104.4	103.8	106.88
	072	113.4	111.4	106.3	108.0	104.2	104.0	105.0	104.4	103.8	106.72
	016	112.2	106.3	106.3	108.5	102.5	104.3	103.8	103.3	103.8	105.67
20	088	113.5	106.3	106.3	109.3	102.5	105.3	105.0	103.3	103.8	106.14
	036	111.0	106.3	106.3	107.3	103.8	104.3	103.8	103.3	103.8	105.54
	068	112.6	106.3	108.0	109.2	105.2	105.3	106.3	104.8	105.0	106.97
21	029	112.6	111.3	108.5	111.6	106.5	107.3	107.5	106.9	107.5	108.86
	051	112.6	106.3	108.5	110.2	106.5	107.3	107.5	106.9	106.3	108.01
	027	112.6	108.0	106.3	106.7	103.9	104.9	105.0	105.0	105.0	106.38
22	083	112.6	108.0	106.3	106.3	106.3	106.7	106.3	106.3	106.3	107.22
	070	112.6	108.0	106.3	107.7	103.9	104.9	105.0	105.0	105.0	106.49
	077	118.8	108.0	105.0	107.9	105.3	106.3	105.0	105.8	106.3	107.60
23	019	112.6	107.5	105.0	107.9	105.3	105.0	105.0	105.0	106.3	106.62
	003	112.6	107.5	105.0	106.2	104.3	103.8	103.8	105.0	103.8	105.78
	034	118.8	107.0	106.3	107.0	107.5	107.5	107.5	106.5	107.5	108.40
24	097	118.8	106.3	106.3	107.0	105.2	105.0	106.3	106.0	106.3	107.47
	054	118.8	107.0	106.3	108.0	107.9	107.5	107.5	107.0	108.8	108.75

Table V. EV-106 Acceptance, Test Discharge Capacities (Continued)

Test Article	Battery S/N	Cycle									Average
		1	2	3	4	5	6	7	8	9	
	040	116.0	110.0	106.3	106.3	105.9	105.0	106.3	105.0	105.9	107.41
25	044	116.0	110.0	106.3	107.0	105.4	105.0	106.3	105.0	105.9	107.43
	030	116.0	110.0	106.3	107.0	105.9	106.3	106.3	105.0	105.9	107.63
	031	110.0	108.0	106.3	106.3	104.5	103.8	105.0	106.3	105.5	106.19
26	062	105.8	108.0	106.3	106.3	106.0	105.0	106.3	106.3	106.3	106.26
	014	105.8	108.0	106.3	106.3	103.3	101.3	104.0	106.3	103.8	105.01
	024	118.8	110.0	106.3	106.3	103.3	103.8	105.0	105.0	105.1	107.07
27	065	118.8	112.0	112.6	108.0	107.8	107.5	107.0	107.5	108.1	109.92
	096	112.5	108.0	106.3	105.0	102.3	102.5	105.0	105.0	104.1	105.63
	009	116.0	110.0	106.3	108.0	106.3	106.3	106.5	106.3	106.3	108.00
28	091	116.0	110.0	106.3	108.0	106.3	106.3	106.5	106.3	106.3	108.00
	082	116.0	110.0	106.3	108.0	106.3	106.3	106.5	106.3	106.3	108.00
	052	112.6	106.3	106.3	106.3	103.0	105.0	106.0	103.8	103.0	105.92
29	023	112.6	106.3	106.3	106.3	103.0	105.0	106.0	105.0	104.8	106.13
	043	112.6	106.3	106.3	106.3	103.0	103.8	105.5	103.8	103.0	105.73
	107	112.6	106.7	106.3	106.3	103.8	103.9	105.0	103.8	105.0	105.92
30	078	112.6	106.7	106.3	106.3	102.5	102.5	104.5	102.5	105.0	105.43
	017	112.6	106.7	106.3	106.3	102.5	103.8	104.0	103.8	105.0	105.67
	080	112.5	109.6	106.3	106.3	103.8	105.8	106.0	105.0	106.0	106.81
31	021	112.5	109.6	106.3	106.3	105.0	105.8	106.3	106.3	106.3	107.16
	011	112.5	109.6	106.3	106.3	105.0	105.8	106.3	106.3	106.0	107.12
	095	112.5	106.3	106.3	107.5	103.8	106.3	106.3	105.6	106.3	106.77
32	013	112.5	106.3	106.3	107.5	105.0	106.3	106.3	106.6	106.3	107.01
	035	115.0	112.6	112.5	111.4	106.3	106.3	106.3	107.6	106.3	109.37
	108	112.5	106.3	106.2	107.7	106.3	106.3	106.3	106.3	105.0	106.09
33	100	112.5	106.3	106.2	107.7	106.3	106.3	106.0	105.3	105.0	106.84
	084	115.0	112.6	112.5	110.7	106.3	108.8	106.3	109.0	108.8	110.02
	090	115.0	112.6	106.2	107.9	105.1	106.3	106.3	106.3	106.3	108.00
34	064	115.0	112.6	112.5	111.2	107.6	108.8	108.8	108.3	108.8	110.40
	039	115.0	112.6	106.2	108.9	106.3	106.3	106.3	106.8	107.5	108.43
	106	112.5	110.0	106.2	103.7	106.3	102.5	102.5	103.8	103.4	105.66
35	066	112.5	110.0	106.2	106.3	106.3	105.0	105.0	104.4	104.5	106.70
	033	112.5	110.0	106.2	107.3	106.3	106.3	106.3	104.9	105.0	107.30
	101	118.8	110.0	106.2	105.3	104.1	105.0	105.3	105.0	105.0	107.19
36	038	118.8	110.0	106.2	106.0	105.2	106.3	105.3	105.0	106.3	107.78
	004	118.8	110.0	106.2	107.4	106.3	107.5	105.3	105.0	106.3	108.09

Table VI. End of Test Cycling Summary

Test Article	Average Current	Depth of Discharge (percent)	Failure Cycle Number			Non-Failed Batteries	
			1st Battery	2nd Battery	3rd Battery	Batteries Left	Final Cycle No.
1	100	50	408	420	468	0	-
2	60	75	237	382	-	1	586
3	180 dc	50	371	375	407	0	-
4	180	50	370	414	455	0	-
5	100 dc	75	336	456	466	0	-
6	60	25	-	-	-	3	590
7	100 dc	50	472	502	-	1	585
8	180	75	345	382	472	0	-
9	220	25	484	554	-	1	589
10	260	50	172*	433	488	0	-
11	20 dc	50	-	-	-	3	589
12	180	75	359	382	453	0	-
13	100 dc	25	577	-	-	2	587
14	140	50	487	509	550	0	-
15	180	25	589	-	-	2	589
16	220	75	366	375	452	0	-
17	100	25	-	-	-	3	589
18	100	75	340	382	507	0	-
19	260 dc	50	408	415	502	0	-
20	20	50	438	-	-	2	573
21	140	50	468	508	544	0	-
22	60	75	407	446	499	0	-
23	180	75	363	449	479	0	-
24	100	50	410	468	-	1	575
25	100	25	-	-	-	3	576
26	220	25	543	557	-	1	574
27	180	25	557	-	-	2	574
28	180	50	85	467	510	0	-
29	100 dc	50	509	513	566	0	-
30	100	50	565	-	-	2	573
31	180 dc	50	417	495	513	0	-
32	220	75	273	402	404	0	-
33	100	75	371	408	487	0	-
34	60	25	-	-	-	3	572
35	180	25	-	-	-	3	572
36	140	50	110	492	549	0	-

*Accidental battery terminal destruction; removed from test.

Table VII. EV-106 Test Parameter Changes

Date	Parameter*				Remarks
	Recharge Ratio (percent)	V/Cell (volts)	U/Vc (volts)	Equalization Charge (ampere/hours)	
09/01/79	111	2.40	5.25	None	Initial Parameters
09/11/79	111	2.50	5.25	None	Raise V/Cell
09/18/79	130	2.50	5.25	None	One Cycle Each at Higher R/Rs
09/19/79	120	2.50	5.25	None	One Cycle Each at Higher R/Rs
09/20/79	125	2.50	5.25	None	New R/R
10/02/79	125	2.50	3.90	None	Start System I Life Test
10/09/79	125	2.53	3.90	None	Raise V/Cell
10/12/79	125	2.57	3.90	None	Raise V/Cell
10/15/79	125	2.57	3.90	None	Start System II Life Test
11/09/79	115	2.53	3.90	None	Lower R/R and V/Cell
11/21/79	115	2.53	3.90	90	First EQ Chg
11/28/79	115	2.53	3.90	30	EQ Chg Change
01/02/80	115	2.53	3.90	50	EQ Chg Change
01/02/80	115	2.53	3.90	70	FQ Chg Change
04/09/80	115	2.53	3.90	40 and 70	25, 50%, Depth of Discharge = 40 Ah 75%, Depth of Discharge = 70 Ah
04/10/80	120	2.53	3.90		Raise R/R
04/24/80	120	2.53	3.90	20-40-60	For 25, 50, 75% Depth of Discharge On Biweekly Schedule
09/23/80	115	2.50	3.90	20-40-60	Reduce R/R and V/Cell
10/06/80	120	2.50	3.90	20-40-60	Reduce R/R to 120%
10/15/80	120	2.50	3.90	20-30-40	New EQ Chg
11/26/80	120	2.50	3.90	30-40-50	Final EQ Chg
11/27/80	120	2.50	3.90	30-40-50	Final Parameters
To End of Test					

*R/R - Recharge Ratio
V/Cell - Specific Charge Voltage, volts/cell
U/Vc - Battery Undervoltage Cutoff
EQ Chg - Equalization Charge

Table VIII. EV-106 Life Test, Chronological Failure Summary

Failure Number	Date	Battery S/N	Test Article No.	Percent Depth of Discharge	Cycle No.	Autopsy	Remarks
1*	01/28/80	091	28	50	85	Yes	Cracked Separator
2*	02/25/80	038	36	50	110	Yes	Lead Rundown Positive Terminal
3	07/02/80	005	2	75	237	Yes	Ruptured Separator
4	08/24/80	095	32	75	273	Yes	Cracked Separator
5	10/18/80	094	5	75	336	Yes	Cell Nos. 2 and 3 Bridging Shorts
6	10/21/80	007	18	75	340	Yes	Cell No. 3 Bridging Short
7	10/30/80	061	8	75	345	Yes	Cell No. 3 Bridging Short
8	11/13/80	059	12	75	359	Yes	Cell Nos. 2 and 3 Bridging Shorts
9	11/19/80	058	16	75	366	Yes	Cell Nos. 1, 2 and 3 Bridging Shorts
10	11/21/80	098	4	50	370	Yes	Cell Nos. 1 and 3 Bridging Shorts
11	11/28/80	099	3	50	371	Yes	Cell Nos. 1, 2 and 3 Bridging Shorts
12	11/28/80	077	23	75	363	Yes	Cell Nos. 1, 2 and 3 Bridging Shorts
13	11/29/80	046	16	75	375	No	
14	12/02/80	067	3	50	375	No	
15	12/05/80	020	18	75	382	No	
16	12/07/80	075	12	75	382	No	
17	12/08/80	053	2	75	382	No	
18	12/08/80	089	8	75	382	No	
19	12/15/80	084	33	75	371	Yes	Cell Nos. 1, 2 and 3 Bridging Shorts
20	01/10/81	086	1	50	408	Yes	Cell Nos. 1, 2 and 3 Bridging Shorts
21	01/17/81	008	3	50	407	No	
22	01/20/81	073	4	50	414	No	
23	01/23/81	013	32	75	402	No	
24	01/25/81	035	32	75	404	No	
25	01/26/81	070	22	75	407	Yes	Cell Nos. 1, 2 and 3 Bridging Shorts
26	01/28/81	018	1	50	420	No	
27	01/30/81	097	24	50	410	Yes	Cell Nos. 1, 2 and 3 Bridging Shorts
28	02/05/81	002	19	50	408	Yes	Cell Nos. 1 and 3 Bridging Shorts
29	02/05/81	108	33	75	408	No	
30	02/08/81	011	31	50	417	Yes	Cell Nos. 2 and 3 Bridging Shorts
31	02/10/81	012	10	50	433	Yes	Cell Nos. 1 and 2 Bridging Shorts
32	02/12/81	060	19	50	415	No	
33	03/03/81	016	20	50	438	Yes	Cell Nos. 2 and 3 Bridging Shorts also Negative plates hard and dry
34	03/04/81	105	16	75	452	No	
35	03/05/81	032	4	50	455	No	
36	03/06/81	087	12	75	453	No	
37	03/06/81	056	5	75	456	No	
38	03/09/81	083	22	75	446	No	
39	03/12/81	003	23	75	449	No	
40	03/18/81	041	1	50	468	No	
41	03/22/81	001	5	75	466	No	
42	04/01/81	022	8	75	472	No	
43	04/02/81	092	7	50	472	No	
44	04/05/81	054	24	50	468	No	
45	04/05/81	082	28	50	467	No	

*Premature failures

Table VIII. EV-106 Life Test, Chronological Failure Summary (Continued)

Failure Number	Date	Battery S/N	Test Article No.	Percent Depth of Discharge	Cycle No.	Autopsy	Remarks
46	04/06/81	068	21	50	468	No	
47	04/10/81	057	9	25	484	Yes	Cell Nos. 1, 2 and 3 Bridging Shorts Cell Nos. 1 and 2 Cracked Separators
48	04/15/81	071	14	50	487	No	
49	04/15/81	050	10	50	488	No	
50	04/16/81	019	23	75	479	No	
51	05/03/81	004	36	50	492	No	
52	05/04/81	093	7	50	502	No	
53	05/04/81	100	33	75	487	No	
54	05/06/81	045	18	75	507	No	
55	05/06/81	110	31	50	495	No	
56	05/07/81	048	14	50	509	No	
57	05/07/81	027	22	75	499	No	
58	05/18/81	051	21	50	508	No	
59	05/20/81	072	19	50	502	No	
60	05/21/81	009	28	50	510	No	
61	05/25/81	021	31	50	513	No	
62	05/25/81	043	29	50	509	No	
63	05/30/81	023	29	50	513	No	
64	06/24/81	103	9	25	554	Yes	Cell Nos. 1, 2 and 3 Bridging Shorts
65	06/24/81	031	26	25	543	Yes	Cell Nos. 1, 2 and 3 Bridging Shorts
66	06/26/81	006	14	50	550	No	
67	06/26/81	029	21	50	544	No	
68	07/02/81	101	36	50	549	No	
69	07/13/81	109	26	25	557	No	
70	07/13/81	055	27	25	557	No	
71	07/20/81	104	13	25	577	No	
72	07/23/81	078	30	50	565	No	
73	07/29/81	052	29	50	566	No	
74	07/31/81	079	15	25	589	No	
75	04/18/81	074	10	50	172	No	Not a functional test failure; battery terminal accidently destroyed, No replacement.

Average number of cycles to failure (all battery failures) = 467

Table IX. Test Failures as a Function of Depth of Discharge

Depth of Discharge (percent)	Total Batteries Tested	Total Batteries Failed	Percent Failures	Mean Cycles to Failure
25	30	7	23.3	552
50	47	38*	80.8	457
75	30	29	96.7	403

*Includes two premature failures.

Table X. Test Failures as a Function of Average Discharge Current

Discharge Rate (amperes)	Total Batteries Tested	Total Batteries Failed	Percent Failures	Mean Cycles to Failure	Number of Batteries Per Depth of Discharge Test Group		
					25 Percent	50 Percent	75 Percent
20	6	1	16.7	438	0	6	0
60	12	4	33.3	434	6	3	3
100	33	21	63.6	460	9	15	9
140	9	9*	100.0	469	0	9	0
180	30	23*	76.7	426	9	12	9
220	12	10	83.3	441	6	0	6
260	5	5	100.0	449	0	5	0

*Includes one premature failure.

Table XI. Test Failures as a Function of Discharge Chopper Frequency

Discharge Chopper Frequency (Hz)	Total Batteries Tested	Total Batteries Failed	Percent Failures	Mean Cycles to Failure
(Constant dc)	30	21	70.0	452
[illegible]0	24	14	58.3	445
500	29	24*	82.8	442
1000	24	15	62.5	443

*Includes two premature failures.

Table XII. Test Failures as a Function of Discharge Chopper Duty Cycle

Duty Cycle (Percent)	Total Batteries Tested	Total Batteries Failed	Percent Failures	Mean Cycles to Failure
25	3	1	33.3	438
35	12	6	50.0	356
45	15	8	53.3	425
55	9	9*	100.0	466
65	15	11	73.3	470
75	15	11	73.3	449
85	8	7*	87.5	421
100	30	21	70.0	452

*Includes one premature failure.

APPENDIX C

ILLUSTRATIONS

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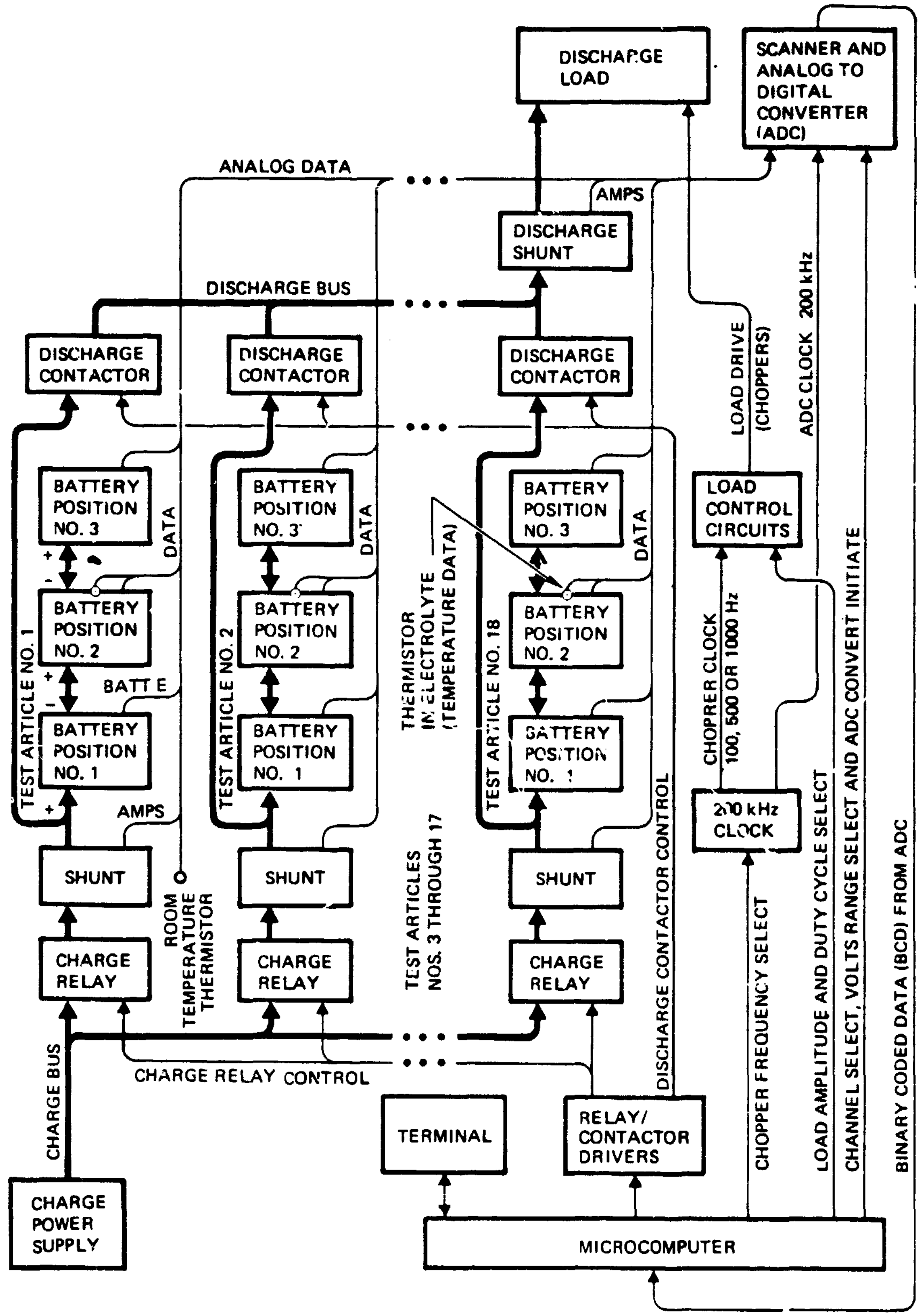

Figure 1. EV-106 Lead-Acid Battery Test System, Functional Block Diagram

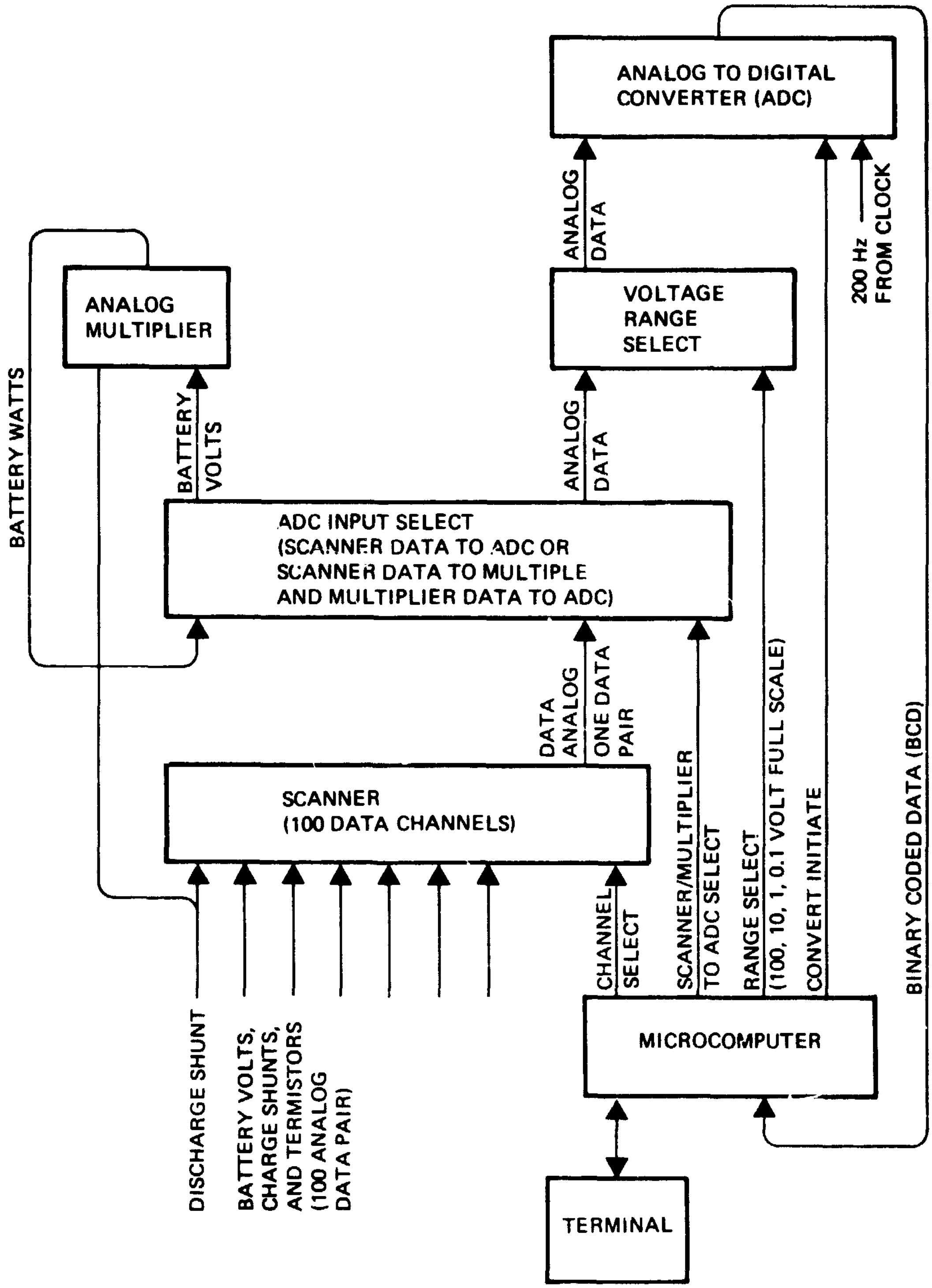

Figure 2. EV-106 Lead-Acid Battery Test, Data System Block Diagram

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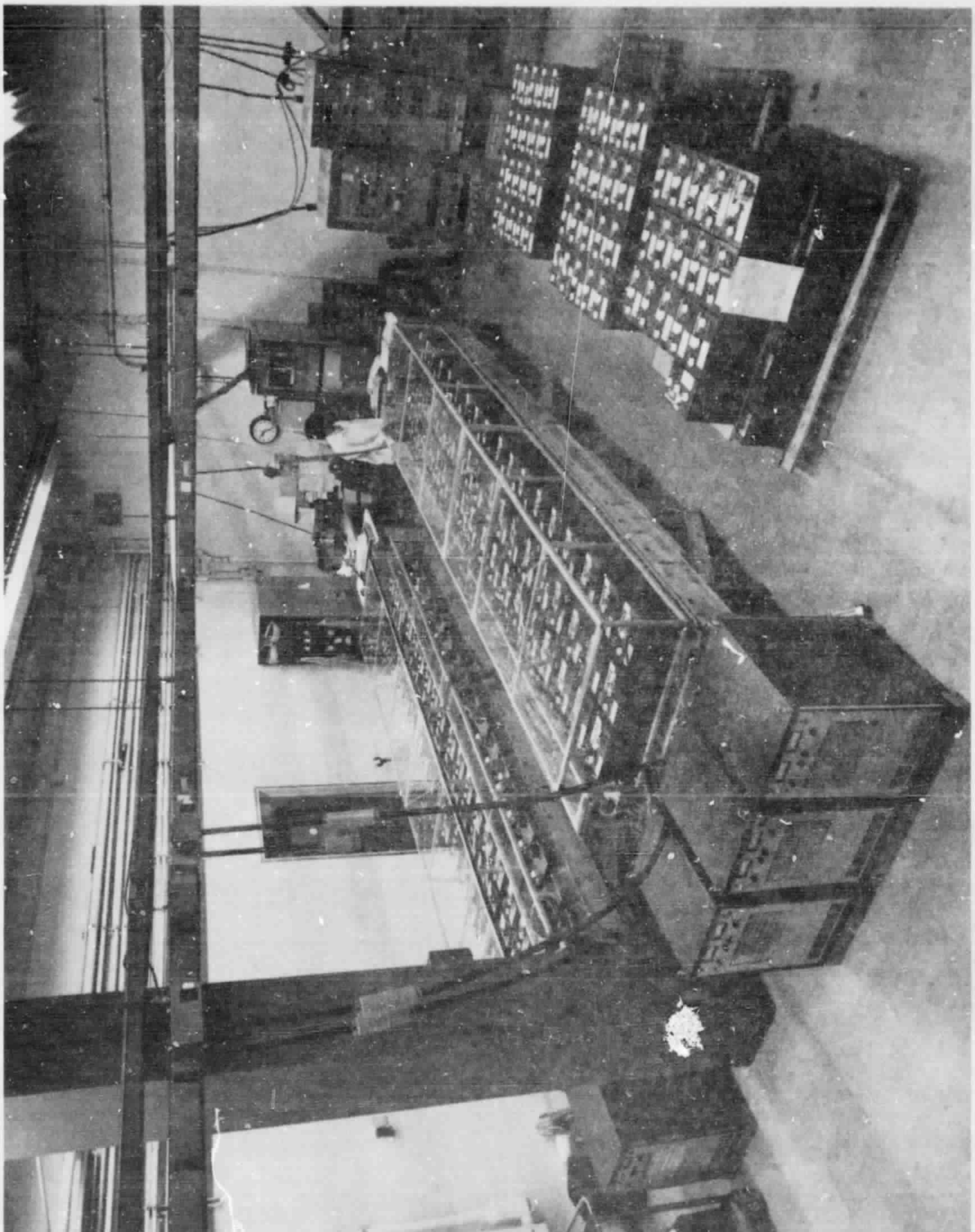

Figure 3. Test Facility, Overall View

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Figure 4. Test Data System, Microcomputer and Printer for System II

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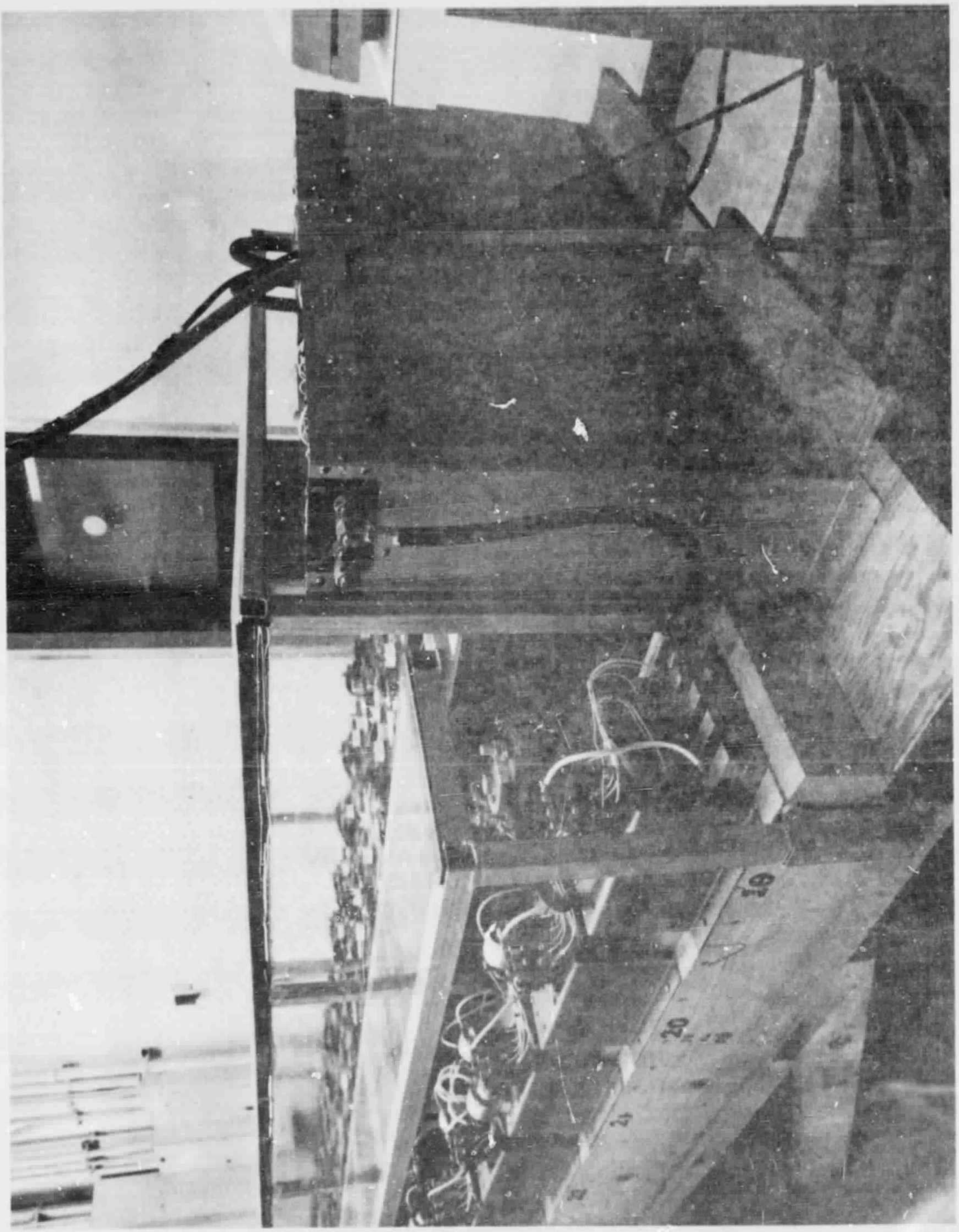

Figure 5. Test System II Load Banks and Control Elements for Test Articles 19 through 22

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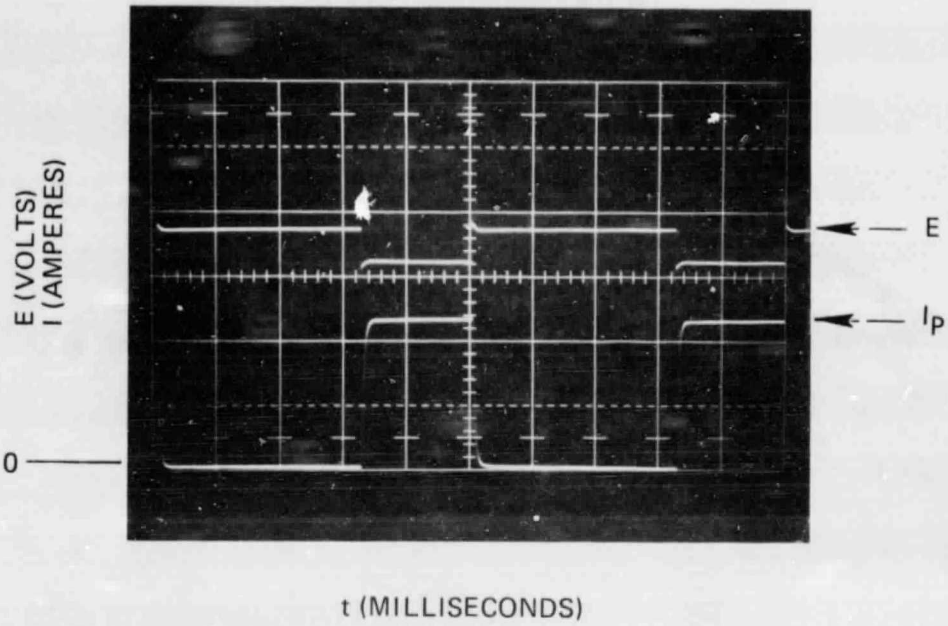

<u>SCALES:</u> E = 5V/DIV.
I = 125 AMP./DIV.
t = 0.4 MS/DIV.

<u>DISCHARGE PARAMETERS:</u>

AVERAGE CURRENT	= 100 AMP.
CHOPPER FREQUENCY	= 500 HZ
CHOPPER DUTY CYCLE	= 35%

Figure 6. Test Article 25 Discharge Current and Voltage Waveforms

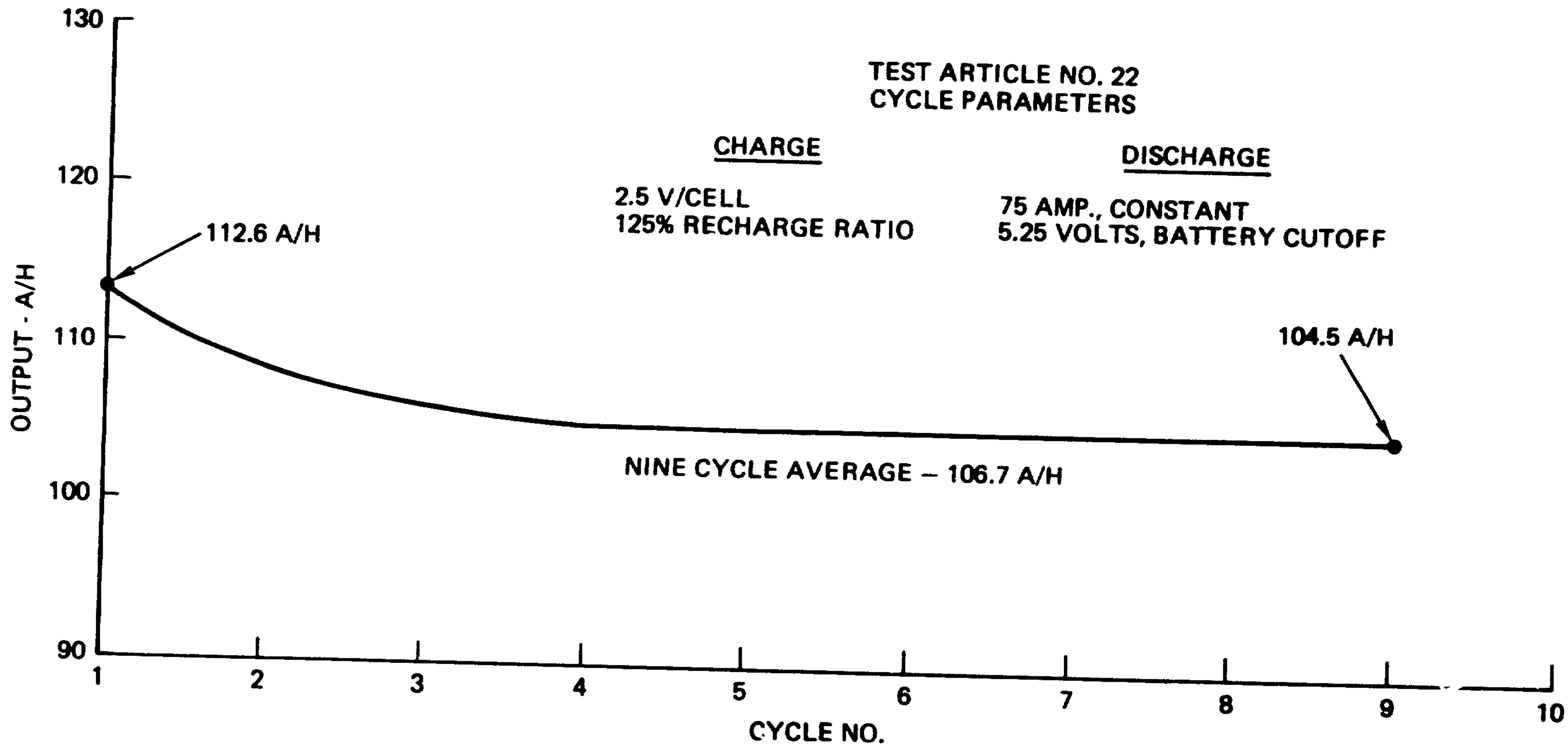

Figure 7. Acceptance Test, Capacity Discharge Output Typical for Nine Cycles

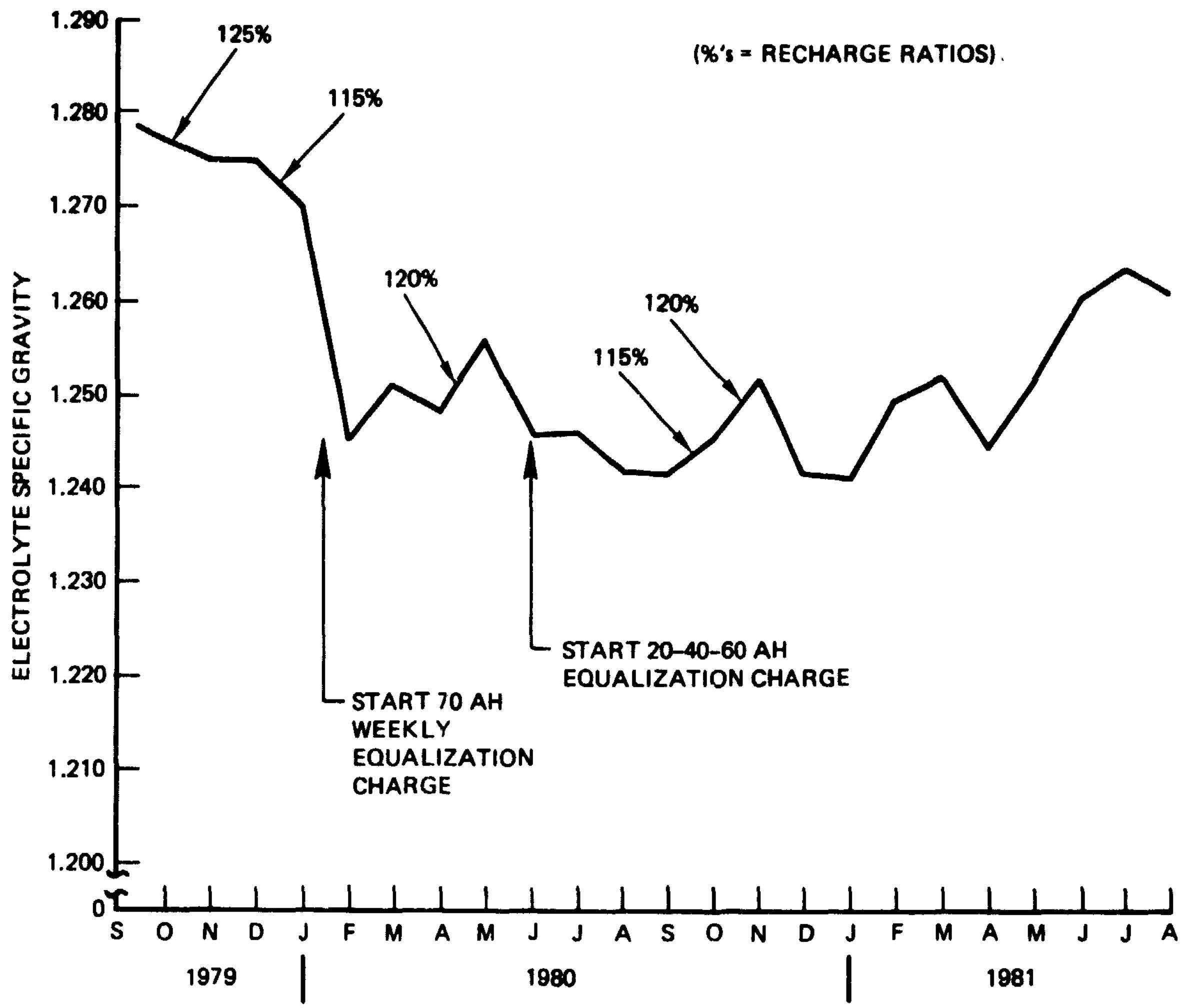

Figure 8. Specific Gravity Monthly Averages of all Test Batteries

TEST ARTICLE	DISCHARGE (AMPERES) AVE PEAK	FREQUENCY (KHz)	DOD (%)
34	60/133	0.1	25
6	60/133	1.0	25
13	100/100	dc	25
25	100/286	0.1	25
17	100/286	1.0	25
35	180/180	dc	25
27	180/240	0.1	25
15	180/240	1.0	25
26	220/339	0.1	25
9	220/339	1.0	25
11	20/20	dc	50
20	20/80	0.5	50
7	100/100	dc	50
29	100/100	dc	50
24	100/114	0.5	50
1	100/133	0.5	50
30	100/154	0.5	50
14	140/225	0.5	50
21	140/225	0.5	50
36	140/225	0.5	50
3	180/180	dc	50
31	180/180	dc	50
28	180/206	0.5	50
4	180/400	0.5	50
19	260/260	dc	50
10	260/306	0.5	50
2	60/133	0.1	75
22	60/133	0.5	75
5	100/100	dc	75
18	100/286	0.1	75
33	100/286	1.0	75
12	180/180	dc	75
23	180/240	0.1	75
8	180/240	1.0	75
16	220/339	0.1	75
32	220/339	1.0	75

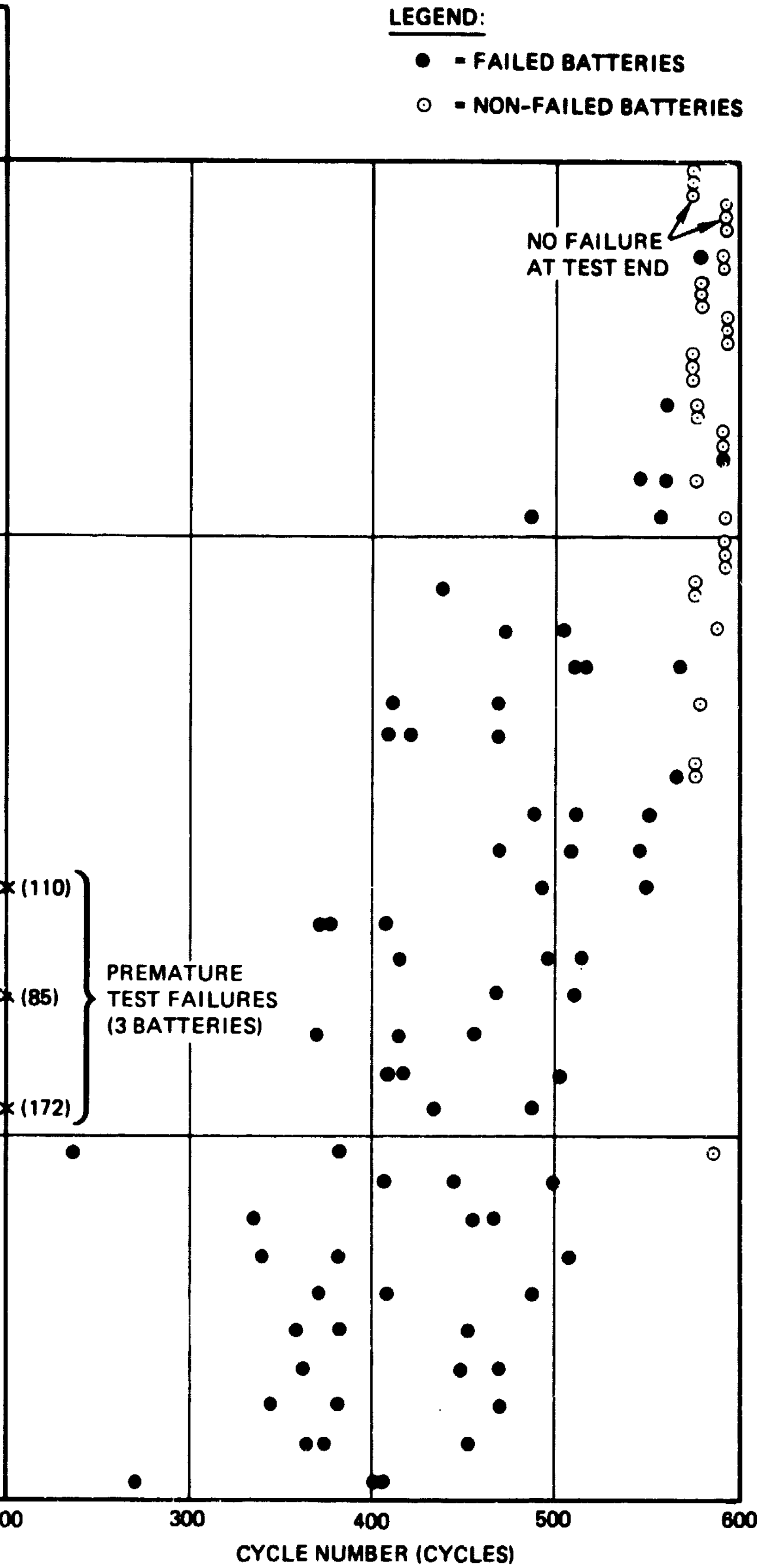

Figure 9. EV-106 Lead-Acid Battery Life Test, Charge/Discharge Cycles to Failure

TEST ARTICLE	DISCHARGE (AMPERES) AVE PEAK	FREQUENCY (KHz)	DOD (%)
34	60/133	0.1	25
6	60/133	1.0	25
13	100/100	dc	25
25	100/286	0.1	25
17	100/286	1.0	25
35	180/180	dc	25
27	180/240	0.1	25
15	180/240	1.0	25
26	220/339	0.1	25
9	220/339	1.0	25
11	20/20	dc	50
20	20/80	0.5	50
7	100/100	dc	50
29	100/100	dc	50
24	:00/114	0.5	50
1	100/133	0.5	50
30	100/154	0.5	50
14	140/225	0.5	50
21	140/225	0.5	50
36	140/225	0.5	50
3	180/180	dc	50
31	180/180	dc	50
28	180/206	0.5	50
4	180/400	0.5	50
19	260/260	dc	50
10	260/306	0.5	50
2	60/133	0.1	75
22	60/133	0.5	75
5	100/100	dc	75
18	100/286	0.1	75
33	100/286	1.0	75
12	180/180	dc	75
23	180/240	0.1	75
8	180/240	1.0	75
16	220/339	0.1	75
32	220/339	1.0	75

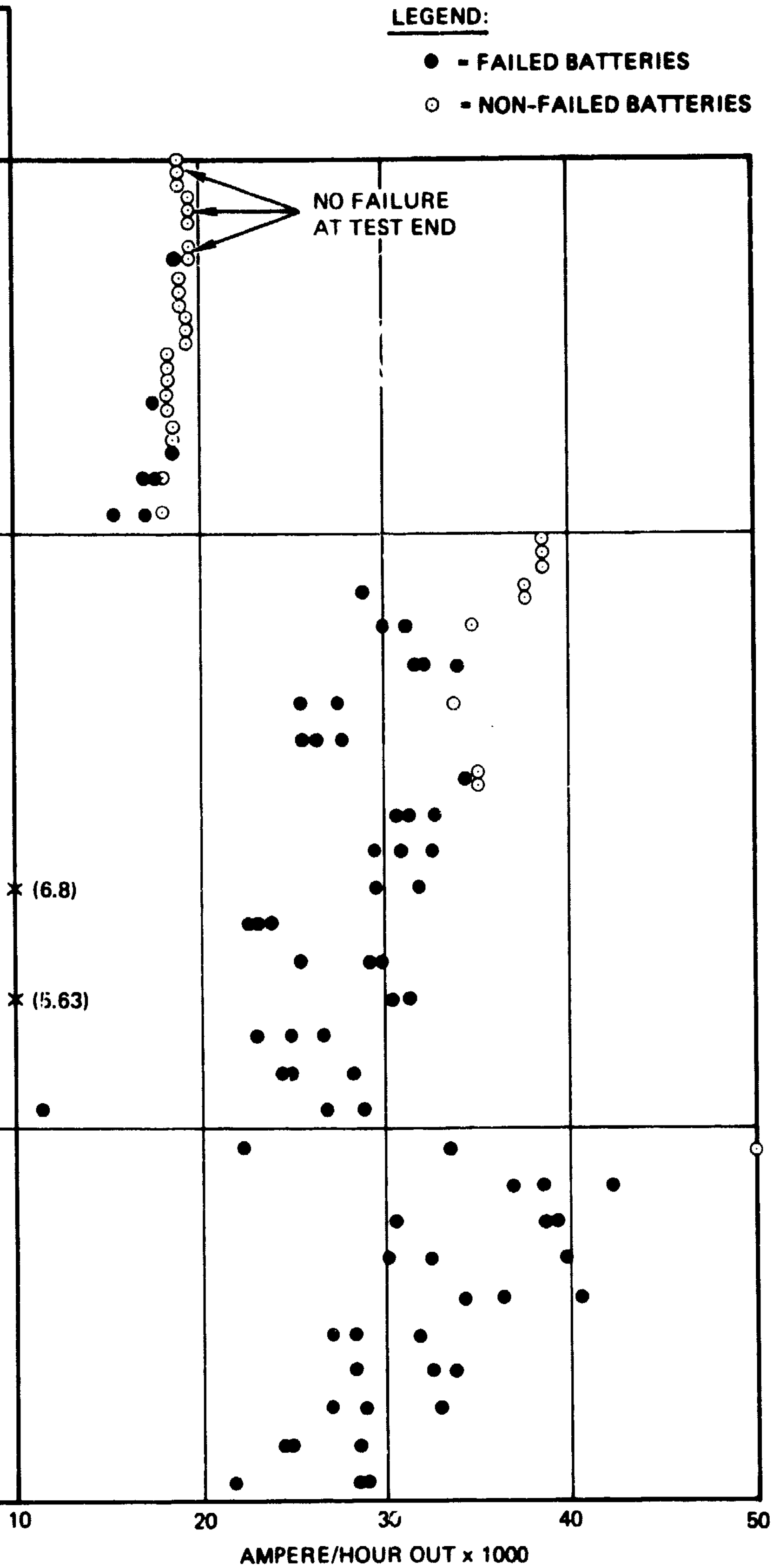

Figure 10. EV-106 Lead-Acid Battery Life Test, Ampere-Hours Out to Failure

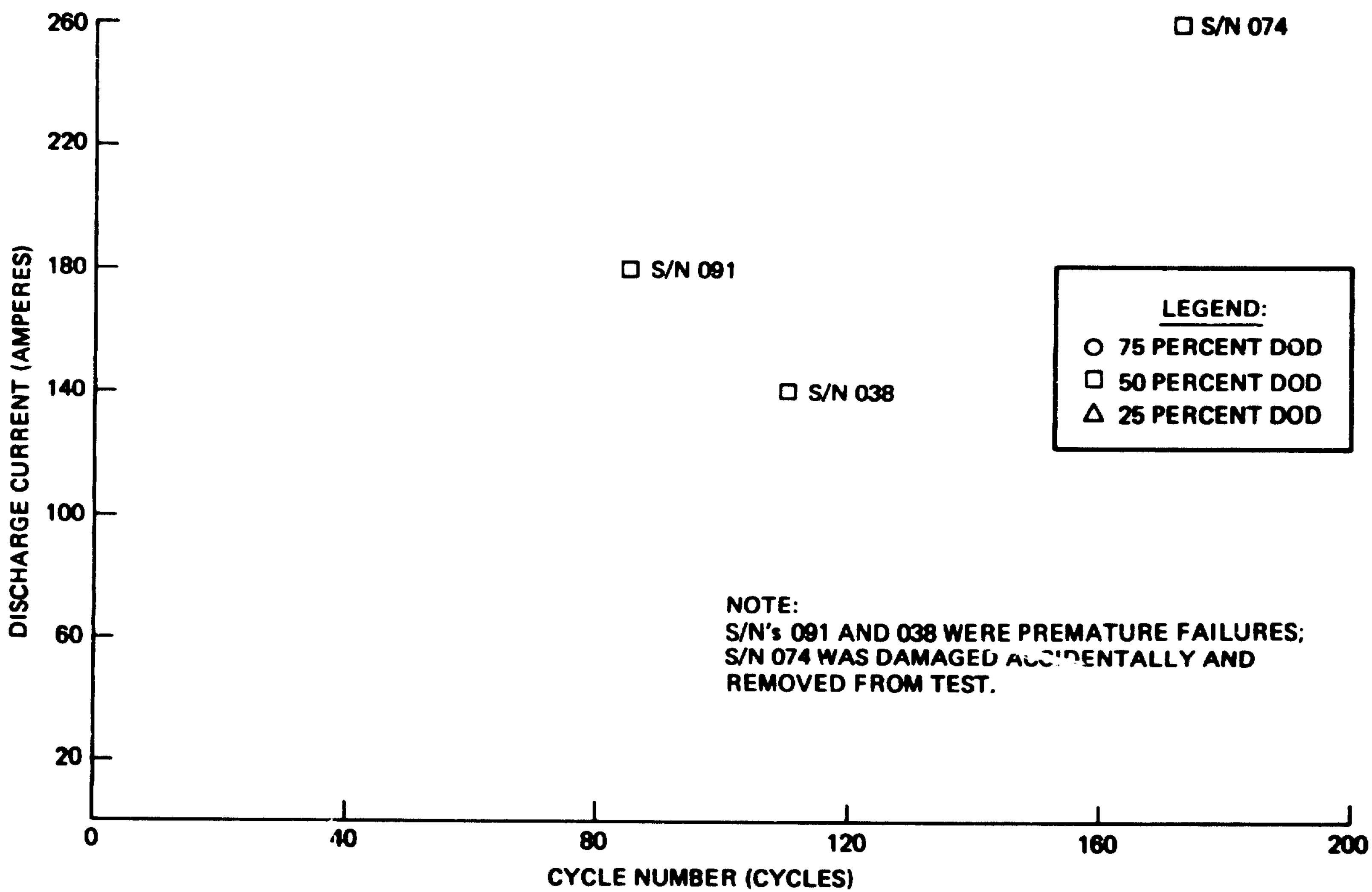

Figure 11. Failure Distribution, Cycle Life Versus Current/DOD

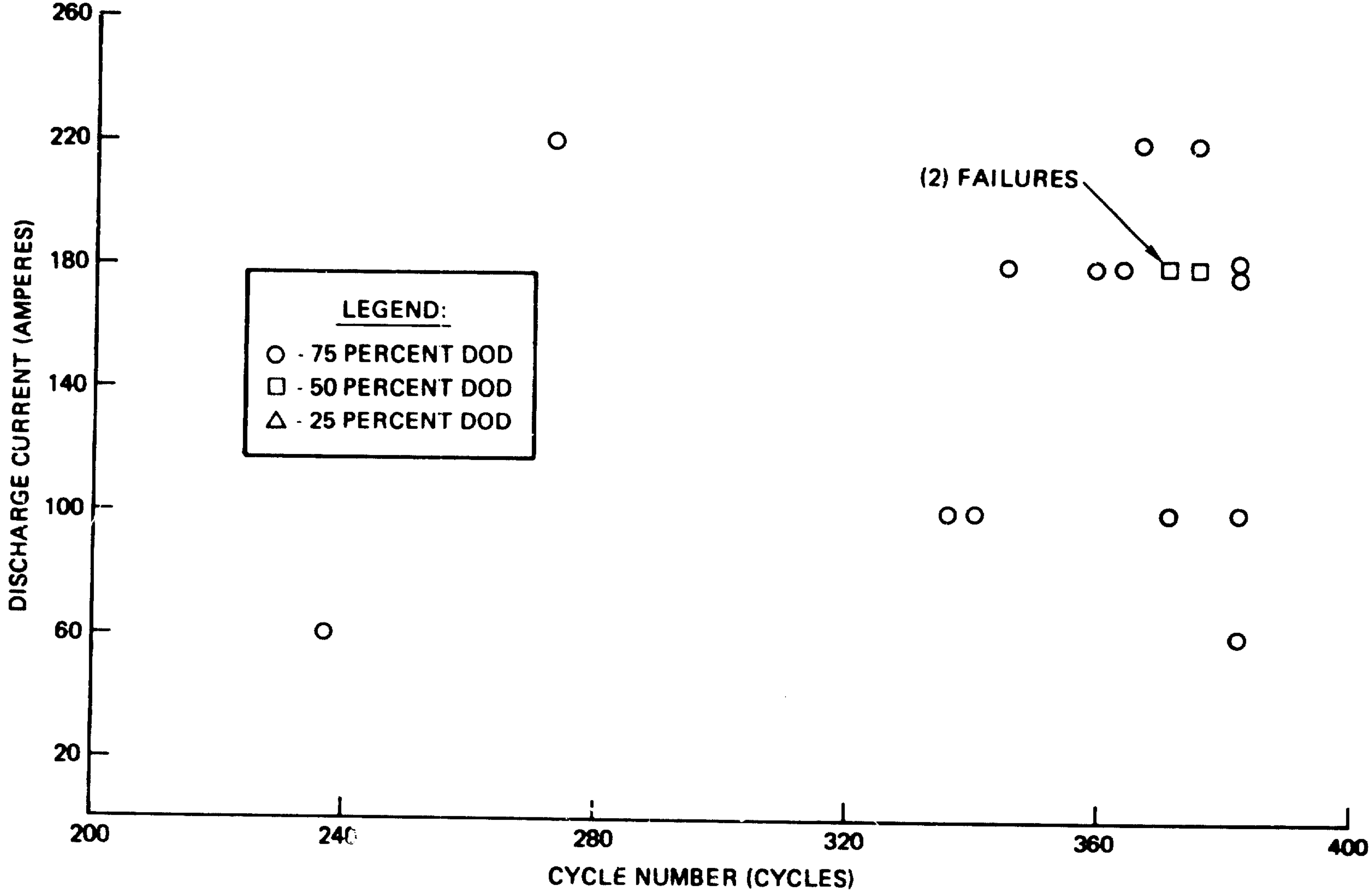

Figure 11. Failure Distribution, Cycle Life Versus Current/DOD (Continued)

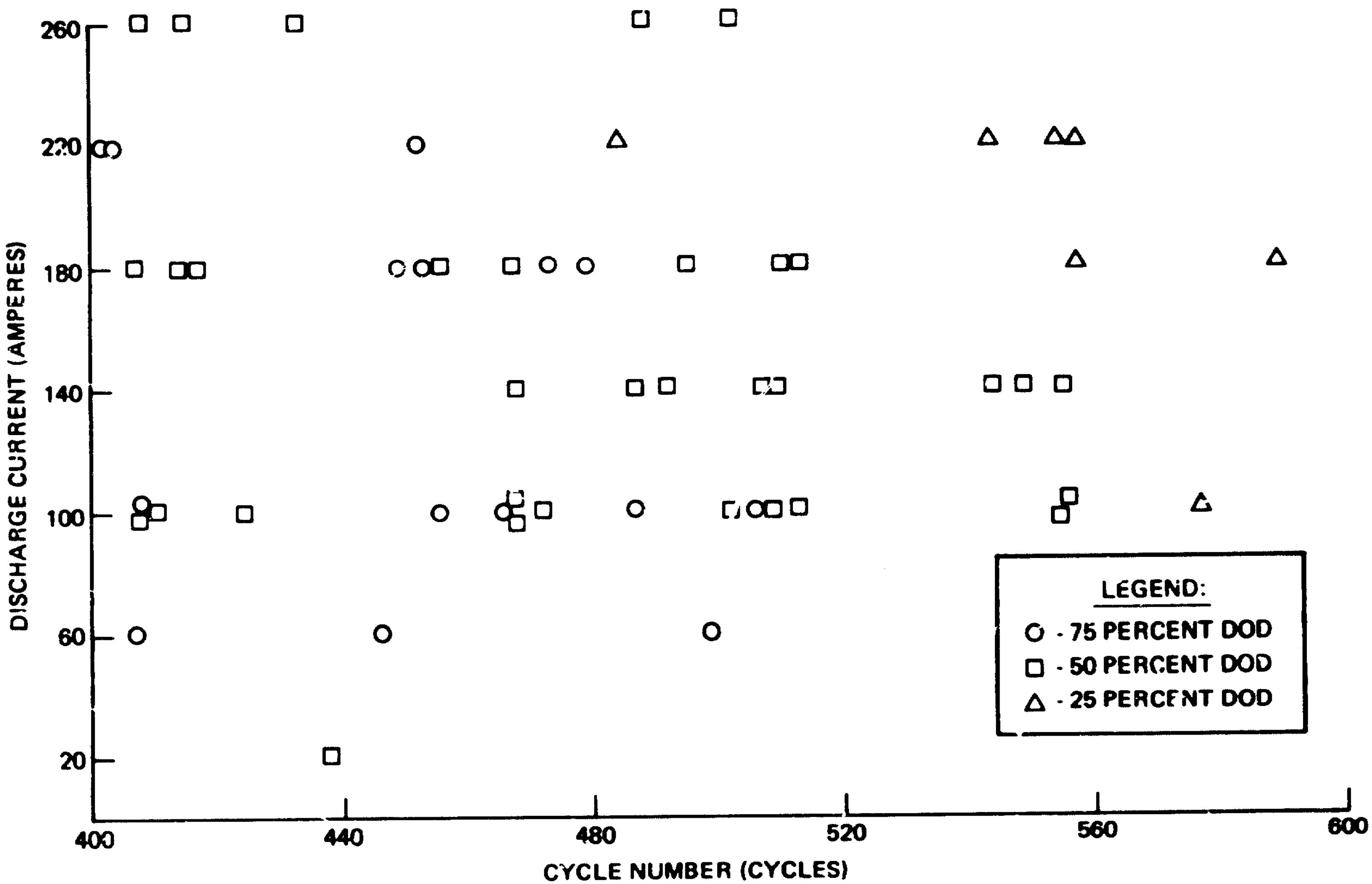

Figure 11. Failure Distribution, Cycle Life Versus Current/DOD (Continued)

REFERENCES

1. Karl V. Kordesch, "Batteries, Lead-Acid Batteries and Electric Vehicles," Vol. 2, Marcel Dekker, Inc., New York; 1977.

2. John M. Bozek and John J. Smithrick, "An Electric Vehicle Propulsion Systems Impact on Battery Performance - An Overview," DOE/NASA 1044-7, NASA TM-81515; May 1980.

3. John J. Smithrick, "Rapid, Efficient Charging of Lead-Acid and Nickel-Zinc Traction Cells," DOE/NASA/1011, 78/26, NASA TM-78901.

4. Eltra Corporation, "Annual Report for 1979 on Research, Development and Demonstration of Lead-Acid Batteries for Electric Vehicle Propulsion," ANL/OEPM-79-7, Argonne National Laboratory, Contract No. 31-109-38-4206; June 1980, pp. 9,72.

5. Gould Laboratories, "Final Report on State-of-the-Art Lead-Acid Vehicle Batteries," ANL-K77-3639-1 Argonne National Laboratory, Contract No. 31-109-38-3639; August 1977.

6. E. Willihnganz, "Charging Lead-Acid Storage Batteries," Presented at the Meeting of the Electrochemical Society, Cleveland; 1971.

7. W. Peukert, "Ueber die Abhangigkeit der Kapacitat von de Entaldestronstanke bei Bleiakkumulatoren," Elektrotech. Z., Heft 20; May 20, 1897, pp. 287-288.

8. Robert L. Cataldo, "Response of Lead-Acid Batteries to Chopper-Controlled Discharge," CONS/1044-1, NASA TM-73834; August 1978.

9. E. Dowgiallo, "Lead-Acid Battery Pulse Discharge Investigation," Final Report, DOE/CH/00128-1; April 1980.

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