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NICKEL-CADMIUM BATTERY TEST PROJECT— RELATIONSHIP BETWEEN OPERATION, LIFE, AND FAILURE MECHANISM

Volume II. Battery Test Results

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ABSTRACT

This program was designed to establish optimum methods for operating nickel-cadmium batteries in order to substantially increase their cycling life. Fifteen batteries containing aerospace-type cells were operated under related, but different, cycling schemes to determine the effects of rapid charging, rapid discharging, charge termination, and other factors on the life of a nickel-cadmium battery. The computerized test automatically monitored and recorded the many parameters that characterize the operation of a cell. These included capacity, watt-hours, current efficiency, energy efficiency, voltage, and pressure. The parameters were analyzed as a function of cycle life. The results have led to a set of seven relationships between operation and cycle life. It is suggested that these be considered when designing a battery system for long life.

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VOLUME II. BATTERY TEST RESULTS

INTRODUCTION

The useful lifetime of a spacecraft can be limited by any of various factors, but most often is fixed by the failure of some critical component or subsystem; it is not uncommon for this failing subsystem to be the battery. Extending the life expectancy of space batteries can, therefore, lead to a significant decrease in the cost of the space effort by increasing spacecraft lifetimes.

There is a two-step approach that can be used to study the factors that are essential to extending battery life. The first step entails an empirical (or "black box") study of the relationships between the life of a cell and the manner in which it is operated. Such a study seeks to identify those processes —rapid charging, rapid discharging, deep discharge, overcharge, etc.— which are injurious to the cell and thus tend to limit battery life. With this knowledge, it would then be possible to operate the battery in such a way as to minimize the effects of those processes. The second step is to identify and characterize the degradation processes which lead to cell failure and then to take appropriate steps to curtail or eliminate the problem. This second step is a materials problem.

These two steps were combined in a single program, the Nickel-Cadmium Battery Test Project. The first phase was devoted to cycling 15 batteries in such a way as to reveal the previously mentioned relationships between mode of operation and cell life. The second phase covered a materials study of the failed or degraded cells.

This paper is the second volume in a series of four on the combined study. The first volume has been published (by Martin Marietta Corporation). The contents of Volumes I and II are outlined in the following paragraphs.

Volume I describes (Reference 1) the various battery cycling modes, i.e., the "experimental design," and details the procedures and instrumentation involved during the various phases of the project—acceptance testing of the cells, cycling of the batteries, and analytical studies of the cells tested.

The present volume—Volume II—gives the results of the cell acceptance tests and battery life testing. It describes the operating conditions for all batteries, the parameters measured during the life cycling test, and the relationships between operation and life as revealed by the test program. Volume II is divided into the following sections:

- Acceptance Tests—a description of the initial tests on the cells as supplied by the manufacturer

- Battery Test Description—a discussion of the overall test program from the standpoint of plan, operation, and measured parameters

- Battery Output Comparisons—a discussion of the parameters, including cycle life, capacity, energy efficiency, voltage, and pressure; and of comparisons made between the batteries and of the trends in the parameters which were the result of the battery cycling experience

- Relationships Between Operation and Life—a series of seven suggestions, based on the cycling test data and the trends in the parameters, to optimize battery operation and to increase life.

The title of the forthcoming Volume III is "Analysis of the Cells and Their Components." The analysis was performed on five cells from each test battery. A test battery was considered to have failed when five (or more) of its ten cells had reached any one of the following three limits: (1) a discharge voltage of less than 1.0v before completion of the normal discharge half-cycle, (2) a voltage in excess of 1.50v during the normal charge half-cycle, or (3) a loss of more than 75% of its initial capacity. As soon as battery failure occurred, the test was terminated, and the five remaining cells were subjected to a series of other tests to determine the factors affecting degradation. Three cells were tested to determine changes in electrical characteristics—capacity, overcharge tolerance, electrode imbalance, etc. The other two cells were opened, and the various components thoroughly examined—visually, chemically, and physically—to establish what changes had taken place. The results are presented in Volume III.

An additional report, entitled "Computer Program for Analyzing Battery Performance Data," which was an outgrowth of this program, has been published (Reference 2). It contains a description and procedures for a set of five computer routines for abstracting and presenting battery test data.*

ACCEPTANCE TESTS

Before battery assembly, the individual cells were subjected to a series of acceptance tests. These tests served as a means of: (1) certifying that the cells met the manufacturer's specification; (2) comparing cell capacities, end-of-charge voltages, pressures, and internal resistance; and (3) selecting cells to assure that the test batteries were comprised of relatively uniform cells. The results of the acceptance tests are found in Appendix A. When the acceptance tests were completed, limits of acceptability were established. The cells that were within the limits were utilized in the test; the others, many of which were never used in the test program, were allowed to stand on open circuit. At a later date when Batteries 13 and 14 were established, some of the cells were given another acceptance test and installed as part of one or the other of these new batteries.

BATTERY TEST DESCRIPTION

The test cells for this study were 6-ampere-hour, VO-6HS nickel-cadmium cells supplied by Gulton Industries. They were tested at the Baltimore Division of the Aerospace Group, Martin Marietta Corporation. The cells were matched and assembled into slots in individual battery test racks. Most of the batteries contained cells that were matched statistically on the basis of the acceptance test data, the exceptions being Batteries 13 and 14. The manufacturer data and acceptance test data for each cell in its battery position are listed in Appendix B.

Each battery contained ten 6-ampere-hour hermetically sealed, aerospace-type nickel-cadmium cells with a ceramic-metal seal on one terminal and with the other terminal welded directly to the can. Each cell consisted of nine (9) nickel-hydroxide-filled positive electrodes of the sintered-nickel type interspersed among ten (10) sintered-nickel cadmium-hydroxide-filled negative electrodes. These plates were manufactured by the Société des Accumulateurs Fixes et de Traction (SAFT) process, and ceramic-metal seal was made by means of a silver braze material inside the cell. Some cells (three to five per battery) were equipped with pressure

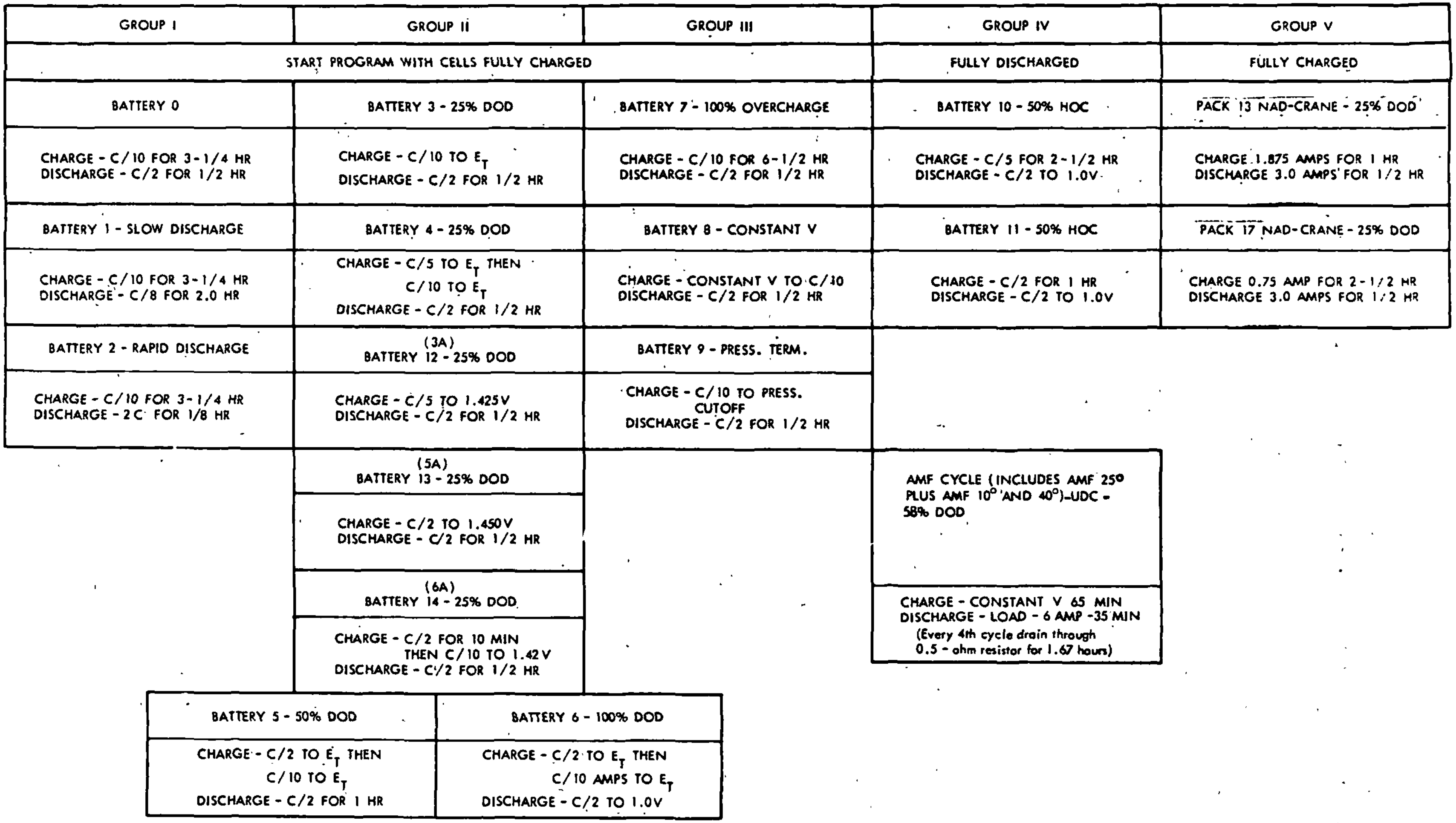
*This report is not designated as a numbered volume.

gauges, and others (one per battery) had a 0-250 psia pressure transducer connected to the fill tube. The remaining cells were sealed at the pinch tube.

All cells were operated at 25°C in a circulating-air temperature cabinet in which the temperature was calibrated at various positions to assure a maximum deviation of ±1°C. Each cell was constrained at the sides by a coated steel plate to prevent bulging. Two problems were noted during the early stages of the test. First, some of the cells were concave, and therefore the center of the coated plate was restrained only when there was pressure within the cell. This problem was alleviated by placing small spacers (shims) between the cell wall and the coated plate. The second problem involved possible leaks in the ceramic seal; it was solved by potting the seal with an epoxy compound.

The overall battery test program is shown in Figure 1. It can be seen from the arrangement of the various operational modes that the intent of the program was to isolate variables. Thus the three batteries in Group I were operated in such a way as to hold constant all variables except discharge rate and thereby determine the effect of this variable on performance and life. The test was divided into groups according to the type of operating variable being studied. The variable in Group I was the rate of discharge; in Group II, the type and rate of charge. In Group III, the variables were charge termination and effect of constant-potential charging; in Group IV, the variable was the effect of charge rate during the period prior to the gassing. A second principle of the program was to operate one battery as the "control" battery and compare the operation of all other batteries to it. Battery 0 served as the control battery.

Group V comprises the cycling schemes used in the battery cycling tests at the Naval Ammunition Depot (NAD), Crane, Indiana (GSFC Contract W11,-252B). These tests used the same type of cells from the same manufacturing era as those in Groups I-IV. All batteries in the Martin Marietta test and Packs 13 and 17 at Crane can be compared with Battery 0, which had the same rate, depth, and/or type of charge or discharge. For the most part, the depth of discharge employed was 25%. In Group IV and in two instances in Group II, the depth of discharge was greater. One operating cycle in Figure 1 is called the AMF-UDC (upside-down cycle)—58% depth of discharge. This was an unusual cycle in which three batteries, operated at 10°C, 25°C, and 40°C at AMF in Alexandria, Virginia, were drained every fourth cycle to balance the cells in the discharged condition, instead of in the charged condition by overcharging as in the normal instance. This cycle is included because the cells came from the same manufacturing lot and were of the type



KEY: C refers to the average cell capacity, not nominal capacity. The C/10 rate is therefore 0.63 amp. E_T is the end-of-charge voltage of Battery 0.

DOD = depth of discharge.
HOC = height of charge.

Figure 1. Battery Test Program (6-ampere-hour cells at 25° C)

used in the Martin Marietta battery test program. Similar logic was used in the listing of batteries in Group V.

In attempting to isolate variables, it is imperative that at least one parameter be held constant. The problem arises that, if the charge or discharge rate is changed, either the time or ampere-hours is affected. For this test, depth of discharge was chosen as the basis for comparison and, in most instances, the cells were discharged for 1/2 hour to a depth of discharge of 25%. Other questions arose concerning the voltage and current limits. In most instances, the voltage and current limits were chosen to correspond to those of Battery 0 (the control battery). For example, the low constant-current voltage (1.425v) of Battery 8 was derived from the average end-of-charge voltage of the cells in Battery 0 after a constant-current (C/10) charge. This C/10 charge also governed the charge termination (I = C/10) of Battery 8. The term "C" normally refers to the nominal cell capacity, which in this case would have been 6 ampere-hours, and therefore the C/10 rate would be equivalent to 0.6 ampere. However, for this test "C" refers to the average actual capacity of the cells; hence the C/10 rate was actually 0.63 ampere. The depth of discharge when using the nominal cell capacity was therefore actually 26.25%. Packs 13 and 17 from the Crane test had charge and discharge rates as shown in Figure 1, which resulted in a depth of discharge of 25%, based on the nominal capacity.

The battery test was controlled and monitored by an IBM 1710 process computer which scanned the data and recorded them onto punched cards when preset limits were reached. The purpose in using a computer is obvious when one considers (1) the need for 24-hours-per-day operation, monitoring, control, data acquisition, and recording; (2) the ability of the computer to contain fail-safe devices for emergencies; and (3) the fact that the desired accuracy and validity of data acquisition are beyond the limit of human ability employed in conjunction with manually operated equipment. As a result of automated testing, 0.5 million IBM cards containing battery test data were recorded and later transferred to four magnetic storage tapes by means of a series of computer programs.

The battery test was started with Battery 0, which was given a 16-hour charge prior to cycle 1 discharge. The other batteries, except 10 and 11, were charged the same way before their operation in the prescribed operating mode. Batteries 10 and 11 were started in the test program with their cells completely discharged and then given a cycle 1 charge to initiate the testing. Batteries 0-9 and 12-15, and Packs 13 and 17 from NAD-Crane, were always balanced by overcharging for the desired time or to the desired limit.

Batteries 10 and 11 and the AMF-UDC batteries were always discharged to failure in order to balance the cells.

BATTERY OUTPUT COMPARISONS

Battery performance during the cycling test is discussed in this section in terms of measured or calculated parameters recorded automatically by the on-line computer. Certain parameters, i.e., voltage and pressure, were recorded during the half-cycle (charge or discharge) process. Others, i.e., capacity and efficiency, were recorded upon completion of the half-cycle when a compilation or integration of the data was required. For purposes of discussion and ease of computer data reduction, the parameters are divided into the following subsections:

- Cycle life
- Duration, ampere-hours, and watt-hours
- Current efficiency, energy efficiency, and E/I ratio
- Voltage
- Pressure
- Depth of discharge and periodic draining—AMF battery test

In each subsection, the variables are discussed in terms of trends exhibited by the battery during the test and comparison of the trends between the various batteries and battery groups. For general interest, the values for many of the measured or calculated parameters averaged over the entire cycle life for each battery are given in Table 1. The values are separated into six sets of parameters for charge and the same six sets of parameters for discharge. Two additional sets listed in the "Charge" table are energy efficiency-current efficiency and number of cycles included in the averaging. This table serves as a general summary of the many variables observed and recorded during the test program.

Cycle Life

The criterion used most often to describe battery life is the number of charge-discharge cycles in which a battery performs within specified limits. Usually, the limits are applied to each cell in the battery, and the term

Table 1

Average Value of Endcard Variables

CHARGE

Set	Parameters	Battery Number											
		0	1	2	4	12	13	14	7	8	9	10	11
1	Time duration	3.25	3.23	3.23	1.69	1.29	0.511	1.967	6.482	0.950	2.880	2.497	0.980
2	Amp-minutes	123.8	122.6	122.8	108.3	97.7	97.2	100.5	246.2	104.5	109.6	189.5	186.4
	Amp-hours	2.06	2.04	2.05	1.80	1.63	1.62	1.68	4.10	1.74	1.83	3.16	3.11
3	Watt-minutes	169.7	168.3	167.7	148.2	133.0	133.9	136.5	343.8	144.2	141.5	264.3	263.7
	Watt-hours	2.83	2.80	2.80	2.47	2.22	2.23	2.28	5.730	2.403	2.492	4.404	4.394
4	Avg. current	0.634	0.633	0.634	1.070	1.262	3.17	0.852	0.633	1.855	0.634	1.265	3.169
	Min. current	0.615	0.620	0.677	0.63	1.233	3.14	6.30	0.625	0.628	0.624	1.246	3.145
	Max. current	0.636	0.635	0.633	1.267	1.266	3.17	3.17	0.636	4.000	0.637	1.269	3.173
5	Avg. power	0.869	0.869	0.866	1.463	1.719	4.36	1.157	0.884	2.560	0.865	1.763	4.483
	Min. power	0.733	0.746	0.794	0.889	1.500	3.87	0.838	0.767	0.890	0.745	1.520	3.992
	Max. power	0.906	0.908	0.908	1.80	1.801	4.55	4.302	0.910	5.464	0.908	1.851	4.702
7	Energy efficiency	69.6	72.0	67.3	80.5	89.9	90.3	88.49	34.6	82.8	80.0	80.3	85.2
	Current efficiency	76.3	77.4	77.4	87.7	96.8	97.5	94.8	38.6	90.8	86.8	90.3	96.7
6	Avg. E/Avg. I	2.16	2.17	2.16	1.28	1.08	0.43	1.594	2.20	0.752	2.15	1.102	0.446
8	Beginning Cycle	4	2	2	27	1	1	875	2	2	2	1	16
	End Cycle	3094	2990	2563	5603	2688	4396	2538	2215	8529	3457	3039	6140
No. of Cycles included in averaging		2489	2546	2203	5180	2509	4122	1592	1824	8127	3157	3551	5641

Table 1 (Continued)

Average Value of Endcard Variables

DISCHARGE

Set	Parameters	Battery Number											
		0	1	2	4	12	13	14	7	8	9	10	11
1	Time duration	0.498	1.998	0.125	0.50	0.500	0.503	0.503	0.502	0.500	0.501	0.902	0.951
2	Amp-minutes Amp-hours	94.5 1.575	94.94 1.582	95.00 1.583	94.78 1.580	94.68 1.578	95.46 1.591	95.27 1.588	95.30 1.588	94.83 1.580	95.07 1.584	171.2 2.854	180.4 3.007
3	Watt-minutes Watt-hours	118.2 1.970	121.2 2.020	113.0 1.883	119.1 1.985	119.8 1.996	120.9 2.016	120.7 2.011	119.1 1.985	119.3 1.988	119.3 1.989	212.4 3.540	224.8 3.747
4	Avg. current Min. current Max. current	3.162 3.088 3.168	0.792 0.781 0.792	12.70 12.58 12.72	3.162 3.153 3.171	3.154 3.149 3.154	3.161 3.52 3.164	3.160 3.155 3.164	3.165 3.152 3.170	3.163 3.153 3.184	3.164 3.156 3.182	3.164 3.141 3.172	3.160 3.137 3.166
5	Avg. power Min. power Max. power	3.955 3.501 4.269	1.011 0.920 1.098	15.09 13.89 16.26	3.973 3.583 4.282	3.144 3.166 3.990	4.004 3.567 4.304	4.002 3.780 4.256	3.957 3.734 4.241	3.979 3.545 4.316	3.972 3.592 4.292	3.925 3.167 4.350	3.938 3.178 4.369
6	Avg. E/Avg. I	0.395	1.611	0.093	0.397	0.401	0.400	0.400	0.394	0.397	0.396	0.392	0.394

"battery failure" depends on how many individual cells have exceeded the preset limits (failed). For a battery test such as this, the objective was to obtain a large enough sampling of failed cells to represent the effects of operation on the battery. A battery was considered failed when five of its ten cells had lost more than 75% of its 6-ampere-hour capacity, or had an end-of-charge voltage exceeding 1.50v, or fell below a discharge voltage of 1.0v before completion of the normal discharge half-cycle.

The numbers of cycles and days of operation before battery failure or test termination are listed in Table 2. Fifteen of the batteries listed are those tested in this program while the other five were being tested at AMF, Alexandria, Virginia, or NAD, Crane, Indiana. Of the 20 listed, 13 failed because of degradation accompanying cycling before termination of the test program. The test was terminated when it was decided that additional cycling could not produce results having a significant effect on the program objectives. Cell failures in this program were of three types—degradative, catastrophic, and manufacturing-lot dissimilarities. The degradative (long-term) type was the most important in that these failures gave the greatest insight into the influence of operating factors on battery life. This type is used in establishing relationships between operation and life appearing later in this report. The catastrophic type of failure included cells that leaked or shorted prematurely. The third type of failure was caused by the unusual behavior of those cells that were equipped with pressure transducers. One cell of this type was installed in each of the first 11 original batteries. These cells were delivered later than the other cells and exhibited abnormal acceptance-test characteristics. They were returned to the manufacturer for adjustment by a long low-rate overcharge and then later returned to Martin Marietta for testing. Because of this treatment, because many of these cells failed prematurely, and because their mode of failure was high end-of-charge voltage (unlike that of most of their neighbors), it was decided that failure of these cells should be disregarded.

A number of features of Table 2 deserve special mention. As a first item, Battery 8 registered 10,218 cycles during the test program and was terminated, when the program ended, with only three cells having failed. This battery was operated in a manner conducive to long cycle life. This statement is supported and discussed below. Second, three batteries were terminated prematurely for specific reasons. (a) Battery 3 was terminated soon after the start of the test because its operating cycle closely approximated that of Battery 0. The cells from Battery 3 were allowed to stand on open circuit for two years, after which time they were given another acceptance test and cycled as Battery 12. (b) Battery 5 failed after only 568 cycles. This failure is attributed to the fact that Battery 5 was charged using two-step current operation (C/2–C/10)

Table 2

Cycling Test Results

Battery	Cycles	Days	No. of Cells Failed
0	3,065	479	5
1	3,928*	860*	1
2	2,072	370	5
3	—	—	-
4	5,418	551	5
5	568	117	5
6	320	75	5
7	2,837	830	5
8	10,218*	940*	3
9	4,582*	760*	2
10	3,834	558	5
11	5,793	480	5
12	3,863*	390*	2
13	5,976*	390*	0
14	2,323*	363*	0
AMF 10°	6,613	557	5
AMF 25°	5,870	513	5
AMF 40°	2,332	260	5
Pack 13 (Crane)	3,598	225	5
Pack 17 (Crane)	2,449	306	5

* Testing terminated before failure of as many as five cells.

and both steps were terminated at E_T, which was dependent on the charge voltage of Battery 0. (E_T is defined as the average end-of-charge voltage of the cells in Battery 0 on a given cycle.) Battery 0, on the other hand, was charged using only a C/10 charge rate. The E_T for Battery 0 was not high enough for Battery 5 to achieve a full state of charge. The problem was aggravated by the fact that the depth of discharge of Battery 5 was 50%.
(c) The charge mode for Battery 6 was like that of Battery 5, and it is presumed that both batteries failed for the same reason. Batteries 3, 5, and 6 were not considered in deriving the relationships appearing in this report.

Third, it is of interest to compare the cycle life of Battery 7 (2,837 cycles) with that of Battery 8 (10,218) while at the same time comparing the number of days of operation of Battery 7 (830) with that of Battery 8 (940). The great difference in cycle life in spite of a similarity in the number of operating days results from the fact that the operating cycle of Battery 7 took 7 hours, while that of Battery 8 was approximately 1-1/2 hours. This comparison is significant because it confirms the fact that many times a short cycle life does not necessarily mean inferior performance. For comparison, the batteries are listed in order of decreasing cycle life and decreasing number of days of operation in Table 3.

It should not be concluded from the data in Table 3 that nickel-cadmium batteries are now generally capable of operating for periods ranging from 1 to 3 years. It should be emphasized that the cycle life and days of operation listed are based upon the criterion of five cell failures or, in some instances, upon deliberate termination of the test. Flight batteries, on the contrary, often fail with the failure of the first cell and almost invariably do so with the failure of the second. Table 4 was compiled to illustrate the randomness and tendency to early failure of the cells used in this test program. It shows that ten batteries had a first cell failure within a 6-month period and that six of the ten had a second failure within the same period. Only one battery was completely operational after 1 year, although five batteries operated a full year without a second cell failure.

A histogram of the batteries on a cycle basis is given in Figures 2 and 3, affording a better overall picture of the randomness and rate of failure for all the batteries. The position in the battery of each cell failure is indicated (by cell number), and the number of cycles to failure for each can be approximated from the scale.

Table 3

Comparison of Batteries in Order of Decreasing Cycle Life and Days of Operation

In Order of Decreasing Cycle Life		In Order of Decreasing Number of Days	
Battery	Cycles	Battery	Days
8	10,218*	8	940*
AMF 10°	6,613	1	860*
13	5,976*	7	830
AMF 25°	5,870	9	760*
11	5,793	10	558
4	5,418	AMF 10°	557
9	4,582*	4	551
12	3,863*	AMF 25°	513
1	3,928*	11	480
10	3,834	0	479
Pack 13 (Crane)	3,598	13	390*
0	3,065	12	390*
7	2,837	2	370
Pack 17 (Crane)	2,449	14	363*
AMF 40°	2,332	Pack 17 (Crane)	306
14	2,323*	AMF 40°	260
2	2,072	Pack 13 (Crane)	225
5	568	5	117
6	320	6	75

* Testing terminated before failure of as many as five cells.

Table 4

Compilation of First and Second Cell Failures*

Battery	First Failure		Second Failure	
	Cycles	Days	Cycles	Days
0	666	142	1,899	295
1	1,580	379	>3,928	> 942
2	1,316	185	1,500	211
3	—	—	—	—
4	2,098	201	2,267	217
5	281	41	290	92
6	193	39	320	64
7	1,058	308	2,200	640
8	3,563	341	3,823	366
9	2,386	358	3,323	497
10	1,388	202	1,456	212
11	2,080	173	2,698	224
12	536	38	2,434	172
13	> 5,976	>249	>5,976	>249
14	> 2,323	>232	>2,323	>232
AMF 10°	1,368	95	5,597	388
AMF 25°	1,033	72	3,865	268
AMF 40°	1,991	138	2,026	140
Pack 13 (Crane)	308	19	502	32
Pack 17 (Crane)	721	45	721	45

* Excludes cell 9 for each battery in the test program.

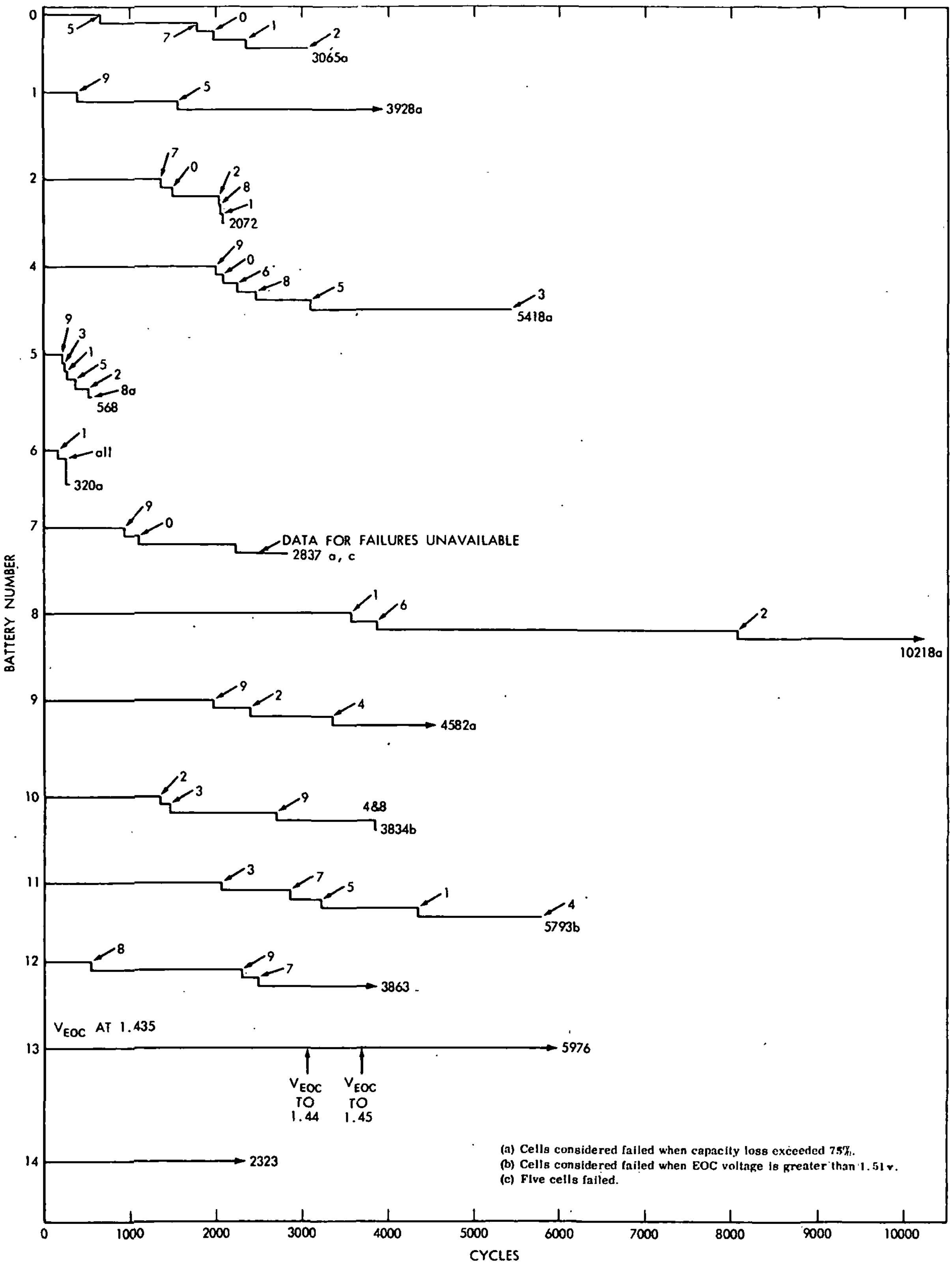


Figure 2. Histogram of Batteries Tested at Martin Marietta

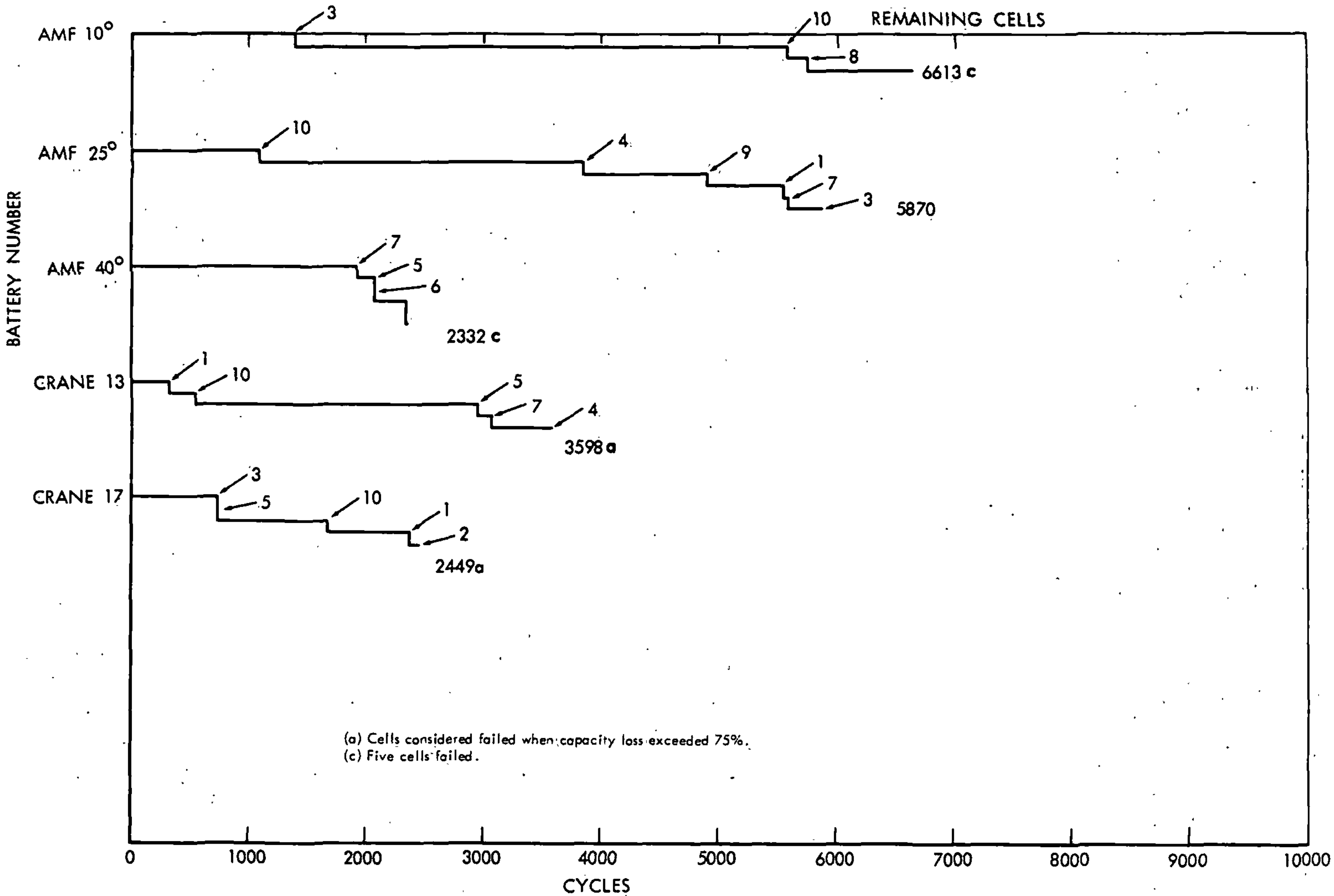


Figure 3. Histogram of Batteries Tested at AMF and NAD-Crane

Duration, Ampere-Hours, and Watt-Hours

This subsection is concerned with three derived quantities which were calculated and recorded by the computer at the end of each half-cycle. These quantities are: (1) the duration of the half-cycle, (2) the ampere-hours passed, and (3) the watt-hours of energy involved. These three parameters are similar in that they are all functions involving time as a variable, in the following integrals:

$$\text{Duration} = T = \int dt,$$

$$\text{Ampere-hours} = A = \int i dt,$$

and

$$\text{Watt-hours} = W = \int V_{avg} \; i dt,$$

where t is time, i is current, and V_{avg} is the average voltage of the working cells. These values, three for charge and three for discharge, are plotted versus cycle number in Appendix C. The data for every 25th cycle are plotted for all batteries in the test program with the exception of Batteries 3, 5, and 6, which were discounted for reasons discussed earlier.

The trends in the three variables during the cycling test as exhibited in Appendix C are given in Table 5. A horizontal arrow ($\longrightarrow$) denotes a constant-level output for the parameter during the cycling life of the battery. Where a level trend is indicated, only the average value of the parameter taken over the entire cycle life is given. Vertical arrows ($\uparrow$ or $\downarrow$) indicate upward or downward trends in output during cycling. In addition to the average value of the parameter, the upper and lower limits are given. An irregular trend is denoted by "I" where the parameter showed no distinct trend. For cases when more than one trend could be assigned to a parameter, a multiple trend is given, as in the case of Battery 9 charge duration.

Most batteries were operated (Figure 1) in a constant-current-for-a-fixed-time mode on charge and/or discharge. Those in Group I were of this type. This is reflected in their level time-duration and ampere-hour parameters (Table 5). For the watt-hour parameter, however, a downward trend is noted. This is because the average voltage is included in the calculation. The decreasing trend in watt-hours for Batteries 0 and 2 on discharge reflects a degradation in the discharge voltage level. This was indicative of the loss in overall capacity of the cells during the cycling test, in which they lost 75% of their 6-ampere-hour capacity. The cause of this

Table 5

Trends in Time-Integral Parameters

Group and Battery No.	Charge Duration (Hours)			Discharge Duration			Ampere-Hours (Charge)			Ampere-Hours (Discharge)			Watt-Hours (Charge)			Watt-Hours (Discharge)		
	Trend	Range	Avg	Trend	Range	Avg	Trend	Range	Avg	Trend	Range	Avg	Trend	Range	Avg	Trend	Range	Avg
Group I																		
0	→		3.25	→		0.50	→		2.06	→		1.58	→		2.83	↓	2.03-1.93	1.97
1	→		3.23	→		2.00	→		2.04	→		1.58	→		2.80	→		2.02
2	→		3.23	→		0.13	→		2.05	→		1.58	→		2.80	↓	1.93-1.83	1.88
Group II																		
4	I	1.47-1.93	1.69	→		0.50	I	1.68-1.93	1.80	→		1.58	I	1.33-2.33	2.47	→		1.99
12	→		1.29	→		0.50	→		1.63	→		1.58	↓	2.27-2.17	2.22	↓	2.03-1.43	2.00
13	→		0.51	→		0.50	→		1.62	→		1.59	→		2.23	→		2.02
14	→		1.97	→		0.50	→		1.68	→		1.59	→		2.28	→		2.01
Group III																		
7	→		6.48	→		0.50	→		4.10	→		1.59	→		5.73	→		1.99
8	I	0.83-1.20	0.95	→		0.50	I	1.67-2.00	1.74	→		1.58	I	2.00-2.67	2.40	→		1.99
9	→ I →	2.80 2.63-2.93 3.00	2.88	→		0.50	→ I →	1.67-1.87	1.83	→		1.58	→ I →	2.40 2.27-2.60 2.60	2.49	→		1.99
Group IV																		
10	→		2.50	↓ ↑	0.95-0.85 0.85-0.95	0.90	→		3.16	↓ ↑		2.85	→		4.40	↓ ↑	3.80-3.35 3.35-3.65	3.54
11	→		0.98	→		0.95	→		3.11	→		3.00	→		4.39	→		3.75

loss is related to the charge rate of C/10 combined with a C/2 discharge rate. This is discussed below.

The batteries in Group II were all discharged (Figure 1) using the same constant-current-fixed-time discharge procedure as with the Group I batteries. However, two types of charge operation were utilized: (a) a single-step operation which for both Batteries 12 and 13 included voltage limit termination, and (b) a two-step operation which for Battery 4 included a voltage termination for both steps and for Battery 14 included a time termination of the first step and voltage termination of the second. This operation of Battery 4 resulted in an irregular charge-time duration which further affected the ampere-hour and watt-hour parameters. The Battery 12 watt-hour parameters decreased for both charge and discharge. Note (Table 5) the smaller average ampere-hour values for charge of the Group II batteries as compared with the Group I batteries. Yet the Group II batteries operated for a much longer cycle life than the Group I batteries. The charge rate has a profound effect on cycle life. (See the next section, "Relationships Between Operation and Life.")

In Group III, Battery 7 was operated in a constant-current-fixed-time mode for charge; Battery 8 was operated in a constant-potential charge mode which was terminated when the current dropped to the C/10 level. Battery 9 operated in a constant-current mode and was terminated by a pressure limit in one cell of the battery. All three were discharged in the same manner as Group I and Group II. The watt-hour values of Battery 7, which was charged exactly twice as long as Battery 0, were level for charge and discharge throughout the test. Both the current termination of Battery 8 and the pressure termination of Battery 9 produced irregular values of charge duration which affected the other two parameters as well. The Battery 9 data can be described in terms of three distinct periods (see Appendix C). During the first period (cycles 1-1,300), during which time the pressure transducer cell satisfactorily terminated the charge, the parameters were level. During the second period (cycles 1,300-2,000), the charge-duration parameter was irregular and was indicative of the problems in the pressure transducer cell. In the third period (cycles 2,000-3,500), the pressure transducer cell was removed from test, and the battery was charged for a fixed time (3.0 hours), corresponding to the previously established pressure limit. The level parameters reflect the results of this third period of operation.

In Group IV, Batteries 10 and 11 were charged and discharged at a constant current. The charge was terminated after a fixed time, and the discharge was terminated at a 1.0v limit. Also the unusual operation comprised a 50% charge from the completely discharged condition ("height of charge" as compared to "depth of discharge"). Battery 10 discharge parameters exhibit two periods, the first of which was the result of the initially planned operational mode (cycles 1-1,750). The second trend of the parameters during discharge (cycles 1,750-end) reflects a change in charge operation in which the voltage limit of 1.50, which already had been reached before the end of charge, was extended to 1.51 on cycle 2,950 and then to 1.52 on cycle 3,100. The problem of high end-of-charge voltage was evident in all cells in this battery. Battery 11 behaved similarly but only after longer operation. In this instance the charge time was reduced slightly (see Appendix C, page C-23) instead of increasing the charge voltage limit. The high end-of-charge voltage for these two batteries was accompanied by high pressures at the end of charge. This behavior was unexpected, since the cells were never charged for more than 3 ampere-hours after discharge to 1.0v per cell.

Current Efficiency, Energy Efficiency, and E/I Ratio

Current efficiency and energy efficiency were calculated and recorded only at the end of each complete cycle. They are defined in the usual terms as follows:

$$\text{Current efficiency} = \frac{\text{Ampere-hours discharge}}{\text{Ampere-hours charge}}$$

and

$$\text{Energy efficiency} = \frac{\text{Watt-hours discharge}}{\text{Watt-hours charge}} .$$

Because the watt-hours and ampere-hours were available for each half-cycle, it was decided that another derived quantity would be computed and recorded. This quantity is referred to as the "E/I Ratio" and is defined as follows:

$$\text{E/I Ratio} = \frac{\text{Watt-hours/Ampere-hours}}{\text{Average current}} .$$

The term "watt-hours" refers to the total watt-hours for the battery divided by the number of cells. The E/I ratio is thus the time-weighted battery voltage divided by the product of number of cells and the time-weighted average current.

This information was recorded in the hope that a study of cycle-to-cycle changes in this ratio would provide some insight into the rate at which a battery is degrading, or that an early indicator of ultimate life might be discovered. A cursory study of the results has attained neither of these objectives. These data, accurate to a few parts per thousand, are available on magnetic tape to anyone who wishes to make additional studies.

Trends in the three parameters discussed in this subsection—current efficiency, energy efficiency, and E/I ratio— are given in Table 6 and are presented graphically in Appendix D.

In Table 6, the following items are significant. For the Group I batteries, it can be seen that current efficiencies are constant over the life of all three batteries. This is of course a consequence of fixed-current, fixed-time operation. The energy efficiency of Battery 1 (C/8 discharge) was also essentially constant. The energy efficiencies of Batteries 0 and 2, however (C/2 and 2C discharge), decreased with life. This decrease was a consequence of a cycle-to-cycle decrease in the discharge voltage which was large enough to more than compensate for a simultaneous but smaller decrease in the charge voltage.

A puzzling problem can be found by comparing the marked irregularity of the energy and current efficiencies of Battery 4 and Battery 8 with the corresponding efficiencies of Batteries 12, 13, and 14 (Table 6 and Appendix D). It can be seen in Appendix D that there were relatively large fluctuations in the current efficiency and energy efficiency of Batteries 4 and 8 and that these efficiencies were essentially constant in Batteries 12, 13, and 14. This marked dissimilarity is not to be expected, in view of the similarity of the charge-discharge patterns of these batteries. This relationship is paralleled by a dissimilarity in the charge E/I ratios of these two groups. Batteries 4 and 8 were characterized by an ascending value of E/I on charge, while the value of this ratio was constant for Batteries 12, 13, and 14.

There is no reason to believe that this anomaly was caused by a weakness in the equipment, and attempts to explain these results in terms of electrochemical phenomena have not been successful. In short, the reason for these differences is not known.

The current efficiency values for the batteries in Group II were quite high (87.7% to 97.5%), which is equivalent to a 1.14 to 1.03 charge-to-discharge ratio. The energy efficiencies were correspondingly high (80.5% to 90.3%). Note that these high efficiencies were accompanied by relatively high values for cycle life. Compare, for example (Figure 2), the lives of Group II batteries with those in Group I.

The irregularity in the current efficiency and energy efficiency of Battery 9 (Appendix D and Table 6) was undoubtedly associated in some way with the fact that charge termination depended on the pressure of one of the cells. Note that this irregularity disappeared after this cell failed and time-termination of the charge process was adopted.

Table 6

Trends in Current Efficiency, Energy Efficiency, and E/I Ratio

Group and Battery No.	Current Efficiency			Energy Efficiency			Avg E/Avg I Ratio						No. of Cycles	No. of Cells Failed
							Charge			Discharge				
	Trend	Range	Avg	Trend	Range	Avg	Trend	Range	Avg	Trend	Range	Avg		
Group I														
0	→		76.3	↓	72-68	69.6	→		2.16	→		0.40	3,065	5
1	→		77.4	→		72.0	→		2.17	→		1.61	3,928*	1
2	→		77.4	↓	70-66	67.3	→		2.16	→		0.93	2,072	5
Group II														
4	I	96-78	87.7	I	84-72	80.5	↑	1.20-1.38	1.28	→		0.40	5,418	5
12	→		96.8	→		89.9	→		1.08	→		0.40	3,863*	2
13	↓	100-90	97.5	↓	92-88	90.3	→		0.43	→		0.40	5,976*	0
14	→		94.8	→		88.4	→		1.59	→		0.40	2,323*	0
Group III														
7	→		34.6	→		38.6	→		2.20	→		0.39	2,837**	5
8	I	94-78	90.8	I	88-70	82.8	↑	0.54-0.84	0.75	→		0.40	10,218*	3
9	{ I →	94-84 84 }	86.8	{ I →	88-78 76 }	80.0	→		2.15	→		0.40	4,582	2
Group IV														
10	{ ↓ ↑	98-86 86-94 }	90.3	{ ↓ ↑	90-76 76-84 }	80.3	→		1.10	→		0.39	3,834	4
11	→		96.7	→		85.2	→		0.45	→		0.39	5,793	5

Legend:

↑ Upward trend

↓ Downward trend

→ Level trend

I Irregular (difficult to recognize a trend)

* Removed from the test prior to failure

** Unusual failure of last three cells

The Group IV batteries, numbers 10 and 11, were discharged to 1.0v per cell on each cycle and then given a charge corresponding to 50% of capacity. Both of these batteries exhibited a decreasing trend in both current efficiency and energy efficiency followed by an increasing trend in these parameters. These changes were less marked for Battery 11. For Battery 10, the voltages of the cells were approaching 1.50v per cell before 3 ampere-hours was returned. The end-of-charge voltage limit for Battery 10 was raised to 1.51v per cell and then to 1.52v. It is interesting to note that the watt-hour values did not increase significantly, but the efficiencies increased because ampere-hours of discharge increased slightly. Although Battery 11 followed the same format, the results were not as pronounced and indicated that the C/2 charge rate was more efficient than the C/5 (Battery 10) rate.

The E/I ratios increased only for Batteries 4 and 8. This is interesting, since both batteries exhibited quite irregular trends in watt-hours and ampere-hours. In no case did the E/I ratio decrease.

Voltage

The voltage of the 10 cells in each battery was monitored by the computer during every cycle. However, voltage data were punched onto cards for permanent record only at a preset cycle number (every 250) or when the watt-hour value had changed by 2% from the previously stored value. This was done automatically by the computer in its capacity as a processor and data acquisition system. The voltage was taken at constant intervals during the charge and discharge cycles, but there were no voltage and current data specifically taken at the very beginning and end of charge or discharge—an error which should be corrected in future cycling tests.

The voltage on charge and discharge for every 500th cycle is plotted vs ampere-hours for each of the battery groups in Appendix E. These data are summarized in Table 7, in which the range of voltage for cells 1 to 5 is given at 1.0-ampere-hour input, end of charge, 0.75-ampere-hour of output, and end of discharge. It is significant that the voltage range at 1.0 ampere-hours of charge appears to be higher for all those batteries which exhibited larger cycle life, e.g., 1.39 to 1.40v for Batteries 12, 13, 8, and 9 as compared to 1.37 to 1.38v for Batteries 0, 2, and 7. Similarly, the voltage range for these same longer-life batteries is higher at 0.75 ampere-hour of discharge (1.27 to 1.28v) than is true with the shorter-lived batteries (1.17 to 1.26v).

These observations cannot be completely explained in terms of obvious reasons such as charge-to-discharge ratios. It seems very probable, however,

Table 7

Voltage Range of Five Cells Chosen at Random (volts)

Approx. Cycle	Battery 0					Battery 1					Battery 2				
	Charge		Discharge		No. of Random Cells Failed	Charge		Discharge		No. of Random Cells Failed	Charge		Discharge		No. of Random Cells Failed
	At 1.0 Amp-H	Final	At 0.75 Amp-H	Final		At 1.0 Amp-H	Final	At 0.75 Amp-H	Final		At 1.0 Amp-H	Final	At 0.75 Amp-H	Final	
100	1.37-8	1.43-4	1.27-8	1.21	0	1.37-8	1.43-4	1.29	1.23	0	1.38	1.43-5	1.18-20	1.12-4	0
500	1.37	1.41-3	1.26	1.18-12	0	1.37	1.42-3	1.28-9	1.21-2	0	1.37	1.43-5	1.18-20	1.11-4	0
1000	1.36-8	1.41-3	1.26	1.16-1.18	1	1.36-9	1.43-4	1.28	1.16-21	0	1.37-8	1.43-5	1.19-20	1.11-4	0
1500	1.37-8	1.41-3	1.25-6	1.08-1.17	1	1.38-40	1.42-4	1.28	1.13-7	0	1.36-8	1.43-4	1.17-20	1.09-10	0
2000	1.39-1.40	1.42-3	1.25-6	1.10-5	1	1.39-40	1.42-4	1.27-8	1.15-8	1	1.37-8	1.44-6	1.18-9	1.05	2
2500	1.37-8	1.43-4	1.24-6	1.09-1.12	2	1.38-40	1.42-4	1.27-8	1.11-6	1	1.37	1.42-4	1.16-9	1.03-5	2
3000	1.36-7	1.41-2	1.25	1.13-1.17	2	1.38-40	1.42-4	1.27-8	1.11-8	1					

Approx. Cycle	Battery 4					Battery 12					Battery 13					Battery 14				
	Charge		Discharge		No. of Random Cells Failed	Charge		Discharge		No. of Random Cells Failed	Charge		Discharge		No. of Random Cells Failed	Charge		Discharge		No. of Random Cells Failed
	At 1.0 Amp-H	Final	At 0.75 Amp-H	Final		At 1.0 Amp-H	Final	At 0.75 Amp-H	Final		At 1.0 Amp-H	Final	At 0.75 Amp-H	Final		At 1.0 Amp-H	Final	At 0.75 Amp-H	Final	
100	1.38-9	1.43-4	1.27-8	1.22	0	1.36-9	1.41-3	1.27	1.21	0	1.39	1.43-4	1.27-9	1.22	0					
500	1.37-8	1.41-2	1.36-7	1.20	0	1.38	1.42-3	1.27-8	1.20-1	0	1.39-40	1.43-4	1.28	1.19-20	0	1.38-9	1.41	1.27	1.20	0
1000	1.37-8	1.42-3	1.25	1.19-20	0	1.38	1.42-3	1.27-8	1.18-9	0	1.40	1.43-4	1.28-9	1.22	0	1.39	1.41	1.26-7	1.19-21	0
1500	1.37-9	1.42-3	1.26-7	1.15-9	0	1.38-9	1.42-3	1.27	1.17-9	0	1.40	1.43-4	1.27-8	1.14-8	0	1.39	1.41	1.26-7	1.16-20	0
2000	1.38-9	1.42-3	1.26	1.15-9	0	1.38-9	1.42-3	1.27	1.14-8	0	1.40-1	1.43-4	1.27-8	1.14-6	0					
2500	1.37-8	1.40-1	1.26	1.03-15	0	1.38-9	1.42-3	1.26-7	1.12-7	0	1.40-1	1.43-4	1.27-8	1.08-12	0					
3000	1.38-40	1.41-2	1.26-7	1.07-14	0						1.40-1	1.43-4	1.27	1.06-10	0					
3500*	1.38-9	1.40-1	1.26-7	1.11-5	1						1.41-2	1.44	1.27	1.02-8	0					
4000**	1.39-40	1.42-3	1.25-6	1.07-1.12	1						1.42	1.45	1.27-8	1.14-6	0					
4500	1.40-1	1.42-3	1.25-6	1.07-10	1						1.42	1.45	1.27-8	1.15-6	0					
5000	1.40-1	1.42-3	1.25-6	1.05-15	1															
5500	1.40-1	1.42-3	1.25-6	1.06-11	1															

Table 7 (Continued)

Voltage Range of Five Cells Chosen at Random (volts)

Approx. Cycle	Battery 7					Battery 8					Battery 9				
	Charge		Discharge		No. of Random Cells Failed	Charge		Discharge		No. of Random Cells Failed	Charge		Discharge		No. of Random Cells Failed
	At 1.0 Amp-H	Final	At 0.75 Amp-H	Final		At 1.0 Amp-H	Final	At 0.75 Amp-H	Final		At 1.0 Amp-H	Final	At 0.75 Amp-H	Final	
100	1.37	1.42-3	1.25-6	1.18-20	0	1.40-1	1.43-4	1.28	1.22-3	0	1.36-7	1.41-4	1.27-8	1.21-2	0
500					0	1.39-40	1.42-3	1.28	1.21	0	1.37	1.41-3	1.26-7	1.19-20	0
1000	1.37	1.43-4	1.24-5	1.18-20	0	1.39-40	1.42-3	1.28	1.20-1	0	1.37	1.41-3	1.26-7	1.18-20	0
1500	1.37-8	1.42-4	1.24-7	1.18-21	0	1.39-40	1.42-3	1.27-8	1.18-20	0	1.37-8	1.41-2	1.25-8	1.11-8	0
2000	1.37-8	1.43-5	1.24-6	1.16-9	0	1.38	1.41-2	1.27	1.13-8	0	1.36-9	1.39-42	1.22-6	1.13-7	0
2500						1.39-40	1.41-2	1.26-7	1.12-8	0	1.38-9	1.43	1.26	1.03-6	1
3000						1.38-40	1.40-2	1.26-7	1.03-16	0	1.38-9	1.42-3	1.25-6	1.07-15	1
3500						1.39-40	1.40-4	1.26-7	1.09-17	1	1.38-9	1.42-3	1.26	1.07-12	2
4000						1.40	1.41-2	1.26-7	1.09-14	1					
4500						1.40	1.42	1.24	1.13-4	1					
5000						1.40	1.42	1.26	1.09-11	1					
5500						1.40-1	1.42-3	1.26-7	1.14	1					
6000						1.40-1	1.41-2	1.26	1.10-3	1					
6500						1.39-41	1.41-2	1.25-7	1.15-7	1					
7000						1.40-1	1.41-2	1.26-7	1.15-9	1					
7500						1.40-1	1.41-2	1.26	1.16-7	1					
8000						1.40-1	1.41-2	1.25-6	1.07-9	1					
8500						1.40-1	1.42-3	1.26-7	1.17-8	2					

Approx. cycle	Battery 10				Battery 11			
	Charge		Dischg.	No. of Random Cells Failed	Charge		Dischg.	No. of Random Cells Failed
	At 1.6 Amp-H	Final	At 1.6 Amp-H		At 1.6 Amp-H	Final	At 1.6 Amp-H	
100	1.39	1.42-3	1.25-6	0	1.40-1	1.44-5	1.25-6	0
500	1.40	1.44-6	1.24-5	0	1.41-2	1.45-7	1.25-6	0
1000	1.41-2	1.45-8	1.23-4	0	1.42	1.47-8	1.25	0
1500	1.40-1	1.45-7	1.23-4	2	1.42	1.98-9	1.25	0
2000	1.40	1.44-7	1.24	2	1.42	1.98-50	1.24-5	0
2500	1.40-1	1.44-8	1.23-4	2	1.42-3	1.47-9	1.24-5	1
3000	1.40-1	1.45-8	1.24	2	1.42-3	1.45-50	1.25	1
3500	1.40-1	1.45-8	1.24	2	1.42	1.46-9	1.25	2
4000	1.40	1.46-7	1.24-5	2	1.42	1.47-50	1.25	2
4500					1.42	1.46-51	1.25	3
5000					1.41-2	1.45-9	1.23-4	3
5500					1.41-2	1.46-50	1.24	3
6000					1.42-3	1.48-9	1.24-5	4

that these voltage differences are related to the differences in the amount of gassing and overcharge as discussed below.

It seems probable that additional information could be derived from the large amount of voltage data generated during the test program. However, such studies are best conducted using statistical techniques. These have not been attempted by the authors.

Pressure

At least four of the ten cells in each battery were equipped with pressure gauges (except Battery 14, in which three cells were so equipped), and one cell in most batteries was equipped with a pressure transducer (none in Battery 14). Pressure measurements were made by visual inspection during a complete cycle at least once per month. These were tabulated and stored in log books. The pressure transducer output was fed into the computer so that, on every cycle in which voltage was recorded, pressure data were recorded also.

The pressure gauge data have been reduced and are presented in Appendix F. The minimum and maximum pressures are given at intervals of approximately 250 cycles. The difference between these two values (ΔP), averaged over the life of the battery, is given in Table 8.

It can be seen in Table 8 that the average ΔP for Battery 1 was greater than that of either of the other two batteries in Group I. The difference—10.4 psi vs 8.4 psi—is probably significant, but the authors can offer no clear explanation for the fact that a lower discharge rate is found to be associated with a larger pressure change.

A more fruitful comparison can be made between Battery 0 and Battery 9. The cycling regime for these two batteries was the same except that the former received more overcharge—2.06 ampere-hours of charge vs 1.83 ampere-hours of charge (see Table 1). This difference brought about a very significant difference in the respective average ΔP values (see Table 8) and, more importantly, in the cycle life of these two batteries. Five cells of Battery 0 failed after 3,065 cycles, but only two cells of Battery 9 failed (excluding cell 9) after 4,582 cycles.

Another interesting relationship is disclosed in Table 9, which lists the various batteries in ascending order of average ΔP. It can be seen that (except for batteries marked "*") there is an inverse relation between this variable and the cycle life given in the third column. "No. of Cells Failed" (fourth column) should be taken into account in making this comparison.

Table 8

Average Pressure Changes

Cell No.	Battery No.											
	0	1	2	4	12	13	14	7	8	9	10	11
0	7.3	11.4	8.7	4.1	1.0	0.9	1.0	14.6	2.3	3.7	6.9	2.7
1	5.0	11.7	9.7	3.4	0.9	0.7	1.3	18.2	1.9	2.8	8.3	2.2
2	8.4	12.4	8.8	3.6	1.4	0.3	1.3	22.3	1.9	2.4	7.6	3.0
3	9.8	10.0	7.3	2.9	0.4	0.3		13.4	2.3	2.0	6.9	2.8
4	10.1	9.9	8.2	3.7	1.1	0.0		15.8	3.2	2.0	6.0	2.6
5	8.3	9.6	8.4	4.1	0.6			18.5	3.6	3.9		4.6
6		8.0		3.0	0.5			21.0	2.1	3.8		3.6
7				2.9	0.6					4.2		4.4
8					0.5					1.4		
9												
Average	8.2	10.4	8.5	3.5	0.8	0.4	1.2	17.7	2.5	2.9	7.1	3.2

Table 9

Comparison of Battery Life and Average ΔP

Battery	ΔP (psi)	No. of Cycles	No. of Cells Failed**
13*	0.4	5,976	0
12*	0.8	3,863	2
14*	1.2	2,323	0
8*	2.5	10,218	3
9*	2.9	4,582	2
11	3.2	5,793	5
4	3.5	5,418	5
10	7.1	3,834	5
0	8.2	3,065	5
2	8.5	2,072	5
1*	10.4	3,928	1
7	17.7	2,837	5

* Removed from line prior to failure.

** Cell 9 of all batteries excluded.

Battery 1, the only battery discharged at a low rate (C/8), is an obvious exception. Apparently this slow discharge had a deleterious effect on the ability of the negative to recombine oxygen without adversely affecting life.

It should be noted that Batteries 10 and 11 exhibited a significant ΔP. This was somewhat unexpected, since these batteries were charged for only 3 ampere-hours and discharged to 1.0v—a 50% height-of-charge cycle contrasted with a 50% depth-of-discharge cycle. The ΔP values for these two batteries were 0 during early cycle life, as expected. However, after a few hundred cycles, it appeared that gas was being generated near the end of the 50% charge. The ΔP increased during the first 1,000 to 1,300 cycles, then leveled off. The two batteries were ultimately removed from test when the cells failed by having an end-of-charge voltage greater than 1.52v (the only batteries in which the cells failed in this mode). Note that Battery 11 had a lower ΔP than Battery 10, even though it was charged at the higher rate (C/2 as compared with C/5). This was probably caused by the fact that the nickel electrode is more efficient at the higher charge rate.

Depth of Discharge and Periodic Draining—AMF Battery Test

All batteries in the battery test project were operated at 25% depth of discharge with the exception of Batteries 5 and 6, which failed prematurely, and Batteries 10 and 11, which were operated using the "height of charge" operational procedure (see Figure 1).

The so-called AMF study of the "Upside-Down Cycle" points to the possibility of a significant increase in depth of discharge without a prohibitive decrease in battery life. Since this program has not been described previously, it is reported briefly here.

Three batteries were involved, each containing 10 cells and each operated at a different temperature. These were 10°, 25°, and 40°C. A 65-35 cycle (65 minutes of charge, 35 minutes of discharge—simulating the conditions of an earth orbit) was used with a discharge rate of 6 amperes, which corresponds to a 58% depth of discharge. A "taper" charge was used, i.e., constant voltage with a 6-ampere current limit. Each of the three batteries was operated with a different voltage limit to compensate for temperature, and each such limit was adjusted upward several times during the life of a battery whenever there was evidence of "fading."

The cycle used was unconventional in that the cells in a given battery were equalized with respect to their charge condition not by overcharging, as is the usual practice, but by complete discharging of the cells. This was accomplished during every fifth 100-minute "orbital" period by discontinuing the usual cycling pattern at the end of discharge and connecting across each cell a 0.5-ohm resistor. These resistors were left in place for 100 minutes, at the end of which time they were removed and the battery was put on charge. In short, the complete charge-discharge pattern consisted of four "working" cycles followed by a "bleed" period. The operation was of course automated by means of relays, stepping switches, etc. The results of this program are presented in Figure 3.

RELATIONSHIPS BETWEEN OPERATION AND LIFE

The data and observations given above seem to support the following conclusions:

1. Rapid charging tends to increase cycle life.
2. Excessive overcharging tends to decrease cycle life.
3. High discharge rates tend to decrease cycle life.

These are discussed below together with relationships involving temperature, depth of discharge, and open-circuit stand derived from this program and the other tests cited.

Effect of Rapid Charging on Life

The first conclusion above is supported by a wealth of evidence, most of which is summarized in Table 10.

a) The most conclusive evidence comes from a comparison of Batteries 12 and 13 of Group B. Note that the former had had three cell failures at 3,863 cycles, while the latter had had none after 5,976 cycles.

b) The test results obtained at NAD-Crane (Packs 13 and 17, Group A) support the same conclusion.

c) A comparison of Group A of Table 10 with Groups B and D also points to the beneficial effect of rapid charging.

d) Batteries 4 and 14 (Group C) can be compared by consulting Figure 2. Note that after 2,323 cycles Battery 4 had experienced three failures and Battery 14 had experienced none.

Table 10

Effect of Charge Current

Battery	Type of Charge	Current	Charge Terminated by	Hours	Amp-Hrs	Voltage	Cycles	Days	No. of Cells Failed
GROUP A - DEPTH OF DISCHARGE 25% (C/2 for 1/2 hour)									
0	Constant current	0.63	Time	3.25	2.04		3,065		5
Pack 17 (NAD-Crane)	Constant current	0.75	Time	2.5	1.875		2,449		5
Pack 13 (NAD-Crane)	Constant current	1.875	Time	1.0	1.875		3,598		5
GROUP B - DEPTH OF DISCHARGE 25% (C/2 for 1/2 hour)									
12	Constant current	1.25	Volts			1.425	3,863*		3
13	Constant current	3.15	Volts			1.45	5,976*		0
GROUP C - TWO-STEP CHARGE - 25% DOD (C/2 for 1/2 hour)									
4	Constant current	1.25 0.63	Volts Volts			1.425 1.423	5,418		5
14	Constant current	3.15 0.63	Time Volts	0.17		1.420	2,323*		0
GROUP D - DISCHARGED TO 1.0v EVERY CYCLE - 50% DOD (C/2 for 1/2 hour)									
10	Constant current	1.25	Time	2.5	3.12		3,834		5
11	Constant current	3.15	Time	1.0	3.15		5,793		5
GROUP E - CONSTANT POTENTIAL - 25% DOD (C/2 for 1/2 hour)									
8	Constant voltage	Variable	Current = 0.63 amp		6 amp current limit		10,218*		3

* Testing terminated before failure of as many as five cells.

e) The data in Group D of Table 10 clearly point to the beneficial effect of rapid charge.

f) Battery 8 (Group E) was charged at constant voltage with a current limit of 6 amperes. Thus its charge rate, at least at the beginning of charge, was the greatest of any of the batteries. Its cycle life was also the greatest.

Effect of Overcharge

The effect of overcharge on the life of a sealed nickel-cadmium cell has long been a controversial topic. Unfortunately, the results of this investigation are not such that they will settle the issue; but they are of some interest.

The pertinent data were obtained from Batteries 0, 7, and 9, and are given in Table 11. These three batteries were all discharged in the same manner and were all charged at C/10. A comparison of the results obtained from Batteries 0 and 9 indicates that overcharge is very deleterious, a relatively small decrease in the amount of overcharge causing a very significant increase in life.

The data from Batteries 0 and 7, on the other hand, indicate that a deliberately excessive amount of overcharge had little or no effect. However, the latter conclusion is clouded by the fact that there is considerable evidence to indicate that the last three cell failures in Battery 7 were caused either by human error or by a malfunction of the apparatus. If this is the fact, it must be concluded that a large excess of overcharge may be beneficial.

It is conceivable that this last conclusion and that derived from a comparison of Batteries 0 and 9 are both correct. If so, it must be concluded that there is an amount of overcharge (e.g., Battery 0) that, all other things being equal, tends to a minimum life expectancy for the cell. Either a lesser amount of overcharge (e.g., Battery 9) or a greatly increased amount of overcharge (e.g., Battery 7) has the effect of increasing life.

Battery 8 is included in Table 11 in order to present additional evidence that a minimum amount of overcharge (and high efficiency) is conducive to long life provided that the other variables such as charge rate and discharge rate are similarly optimized.

Effect of Discharge Rate

It is the consensus of experimenters and designers that the life of a battery is increased by lowering the rate of discharge. The data presented in Table 12 show clearly that this is true.

Table 11

Effect of Overcharge
(6-ampere-hour cells, 25% depth of discharge, 25°C)

Battery No.	Rate	Charge Terminated by	Percentage of Recharge (%)	Current Efficiency (%)	Cycles to Failure	No. of Cells Failed
7	C/10	Time	267	38	2,837	5
0**	C/10	Time	133	75	3,065	5
9**	C/10	Pressure of one cell	~120	83	4,582*	2
8	Constant potential (1.425v)	I = C/10	~111	~90	10,218*	3

* Test terminated prior to battery failure.

** Battery 0 was charged only 0.2 amp-hr (avg) more than Battery 9.

Table 12

Effect of Rate of Discharge
(6-ampere-hour cells, 25% depth of discharge)

Battery	Discharge Rate	Cycles	No. of Cells Failed
0	C/2	3,065	5
1	C/8	3,928*	1
2	2C	2,072	5

*Test terminated before battery failure.

Effect of Depth of Discharge

It is widely known that battery life varies inversely with depth of discharge. Batteries 4, 5, and 6 were included in this study to increase our knowledge of this relationship. Unfortunately, the charge mode adopted for Batteries 5 and 6 was such that they failed prematurely because of insufficient charging. This was discussed under "Cycle Life," above.

Effect of Periodic Complete Discharge

The only batteries subjected to periodic complete discharge were the AMF test batteries. The procedure used to operate these batteries also included discharge at the relatively rapid C rate and to 58% depth of discharge—both detrimental to cell life—and charge at a constant potential (rapid charge) and with a minimum of overcharge—both beneficial to nickel-cadmium cell life. These conditions are discussed in the above paragraphs.

The effect of periodic complete discharge cannot be easily evaluated, because no batteries in the test program were operated in the same manner as the AMF batteries but without periodic discharge. However, very approximate estimates can be made using the results of other test programs.* Taking a conservative approach, these results lead to the conclusion that the cycle life of the 40° battery was almost doubled and that of the 10° and 25° batteries was more than doubled.

*Numerous documents are available giving test results obtained at the Naval Ammunition Depot, Crane, Indiana (GSFC Contract W11,252B).

Considering that the detrimental discharge procedure balanced to some extent the beneficial charge procedure, the extraordinary life of these batteries must be ascribable to periodic complete discharge.

For a practical operating spacecraft system using this procedure, a significant increase in life or a significant weight saving, or some combination of both, could be obtained. However, the price would be a substantial increase in the complexity of the battery control circuitry. It was the consensus of spacecraft power system designers that such an increase in complexity was —particularly because of reliability considerations — too high a price to pay, and it was decided to abandon the idea.

Effect of Temperature

It is generally recognized that high operating temperatures shorten cell life and that the optimum temperature is between room temperature and the ice point. The results below, obtained from the AMF program, confirm this view.

Temperature	Cycles to 5th Cell Failure
10° C	6,613
25° C	5,870
40° C	2,332

Effect of Long-Term, Open-Circuit Stand

The cycling of Batteries 12, 13, and 14 commenced 18 months after Battery 0 was started. The cells of Battery 12 were the same cells as those of Battery 3, which had been terminated after 128 cycles. Those cells remained in the 25% discharged condition at room temperature for approximately two years before conditioning and acceptance testing for use in Battery 12; the cells of Batteries 13 and 14 were cells which had been given acceptance testing but which had not been previously employed in the test. These cells were also stored on open circuit at room temperature before testing. There is nothing about the performance of these batteries (Figure 2) to indicate that a year or two of storage had a significant effect on cycle life.

SUMMARY

The effects discussed in the preceding section have been translated into suggestions for optimum operational methods. (Items 4 and 5 are based on the results of the AMF battery test.) These suggestions, then, are guidelines that the battery engineer or power systems designer should follow in order to attain optimum battery life:

1. Rapid charging, i.e., high current during the pregassing period of charge; modified constant-potential operation is desirable.

2. Maximum current efficiency, i.e., a minimum of overcharge, achieved by maintaining low end-of-charge voltage or by a pressure signal.

3. Minimum rate of discharge.

4. Minimum depth of discharge.

5. Operating temperature below 25° C, preferably closer to 10° C.

6. Long-term, open-circuit stand is not necessarily detrimental to cycle life.

7. Periodic complete discharge probably lengthens the life of a battery.

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APPENDIX A

ACCEPTANCE TEST DATA

Each of the tables A-1 through A-4 contains the following acceptance test information for all of the nickel-cadmium cells that were given that particular test (both accepts and rejects): measured values of ampere-hour capacity, terminal charging voltages, capacity test pressure readings, and internal resistance measurements. Figure A-1 is a histogram of capacity distribution, and Figure A-2 presents a plot of normal vs "overvoltage" cell charge-characteristics. Figure A-3 is a histogram of capacity test final pressure distribution. Figure A-4 is a plot of capacity test sampling of pressure characteristics, and Figure A-5 is a histogram of internal resistance distribution in milliohms.

Table A-1
Measured Capacity Values

Mfr. cell serial no.	Test cell no.	Ampere-hour capacity	Mfr. cell serial no.	Test cell no.	Ampere-hour capacity
2869	001	5.943	3117	037	6.257
2874	002	6.104	3153	038	6.239
2858	003	6.213	3110	039	5.956
2854	004	6.170	2867	040	6.327
2852	005	6.301	3155	041	6.187
2887	006	6.253	3154	042	6.148
2870	007	6.248	2862	043	6.060
2884	008	6.484	3114	044	6.030
2851	009	6.178	2873	F045L	6.069
2853	010	6.344	3141	046	6.279
3145	011	6.218	3125	047	6.418
2863	F012L	6.235	3148	049	6.266
2856	F013G	6.419	3162	050	5.969
2882	014	6.322	3156	051	5.960
3129	015	6.480	3116	052	6.549
3142	016	6.580	2861	053	6.410
3151	017	6.322	3112	054	6.248
3149	018	6.606	2876	F055L	6.440
2872	019	6.296	3144	056	6.143
3130	020	6.497	3113	057	6.423
2871	021	6.209	2850	F058L	6.222
3124	022	6.868	3108	059	6.418
2865	023	6.589	3160	060	6.117
3120	024	6.418	2881	062	6.440
2886	025	6.113	3158	063	6.279
3131	026	6.453	2831	064	6.209
2878	027	6.453	2848	065	6.301
2888	028	6.414	2866	066	6.113
3109	029	6.052	3123	067	6.248
3139	030	6.279	2826	068	6.432
2879	031	6.327	3127	F069S	6.619
3159	032	6.056	2825	070	6.174
2860	033	6.484	2838	071	6.182
3118	034	6.384	3164	072	6.331
3128	035	5.995	2836	073	6.235
3126	036	6.152	2877	074	6.584

Table A-1
Measured Capacity Values (Continued)

Mfr. cell serial no.	Test cell no.	Ampere-hour capacity	Mfr. cell serial no.	Test cell no.	Ampere-hour capacity
2829	075	6.104	2898	195	6.318
2839	F076L	6.196	2931	196	6.650
3165	078	6.602	2926	197	6.152
2841	079	6.349	2929	198	6.269
3143	080	6.135	2896	200	6.423
3121	082	6.785	2891	201	6.794
3166	085	6.436	2927	202	5.991
2846	086	6.475	2902	203	6.528
2842	088	6.519	2904	F204S	6.205
2828	089	6.397	2911	205	6.143
2855	090	6.401	2895	206	6.340
3161	091	6.130	2924	207	5.855
2845	092	6.174	2907	208	6.515
2837	093	6.231	2934	209	6.065
2827	094	6.405	2928	210	6.004
2830	095	6.314	2922	211	6.235
3132	096	6.331	2930	212	6.506
2880	097	6.462	2932	213	6.366
3111	098	6.794	2914	214	6.475
3150	099	6.370	2935	215	6.100
3115	100	6.672	2910	216	6.349
2868	102	6.056	2890	217	6.646
2840	103	6.274	2906	218	6.480
2883	F104L	6.135	2900	219	6.833
2835	105	6.183	2923	F220S	6.405
3119	106	6.523	2912	221	6.471
3458	107	6.392	2901	222	7.012
2849	108	6.148	2892	223	6.842
2832	109	6.239	2905	224	6.353
2883	110	6.392	2899	225	6.375
2847	111	6.488	2920	226	6.060
3457	F112G	6.646	2916	227	6.445
3122	115	6.510	2908	228	6.309
2834	120	6.558	2909	229	6.549
2894	193	6.506	2893	230	6.654
2925	194	6.715	2919	231	6.287

Legend:
F-Failed cell S-Shorted cell L-Caustic leak G-Blocked pressure gauge

Table A-2
Terminal Charging Voltages

Chg	Test Cell No.									
	01	02	03	04	05	06	07	08	09	10
1	1.46	1.44	1.44	1.45	1.45	1.44	1.46	1.44	1.45	1.45
2	1.42	1.42	1.43	1.41	1.42	1.42	1.42	1.42	1.41	1.42
3	1.42	1.41	1.41	1.42	1.42	1.41	1.42	1.41	1.41	1.42
Chg	Test Cell No.									
	11	F12L	F13G	14	15	16	17	18	19	20
1	1.43	1.44	1.44	1.43	1.44	1.44	1.43	1.44	1.44	1.43
2	1.41	1.42	1.42	1.40	1.43	1.42	1.41	1.42	1.42	1.41
3	1.42	1.42	1.40	1.41	1.42	1.41	1.42	1.42	1.40	1.43
Chg	Test Cell No.									
	21	22	23	24	25	26	27	28	29	30
1	1.43	1.45	1.45	1.43	1.43	1.45	1.44	1.43	1.45	1.44
2	1.42	1.43	1.41	1.43	1.40	1.41	1.42	1.42	1.41	1.43
3	1.42	1.43	1.40	1.42	1.40	1.41	1.42	1.41	1.41	1.43
Chg	Test Cell No.									
	31	32	33	34	35	36	37	38	39	40
1	1.44	1.44	1.44	1.44	1.45	1.45	1.44	1.44	1.45	1.44
2	1.42	1.41	1.42	1.44	1.41	1.43	1.43	1.41	1.43	1.43
3	1.41	1.40	1.42	1.43	1.41	1.43	1.43	1.40	1.43	1.41
Chg	Test Cell No.									
	41	42	43	44	F45L	46	47	F48X	49	50
1	1.45	1.45	1.45	1.45	1.45	1.46	1.46	–	1.45	1.45
2	1.43	1.43	1.43	1.43	1.43	1.44	1.44	–	1.43	1.42
3	1.43	1.42	1.42	1.43	1.42	1.42	1.42	–	1.43	1.42
Chg	Test Cell No.									
	51	52	53	54	F55L	56	57	F58L	59	60
1	1.43	1.43	1.44	1.44	1.43	1.45	1.44	1.43	1.45	1.44
2	1.41	1.43	1.42	1.41	1.42	1.42	1.41	1.43	1.44	1.41
3	1.40	1.43	1.41	1.41	1.41	1.42	1.41	1.42	1.43	1.40

Table A-2
Terminal Charging Voltages (Continued)

Chg	Test Cell No.									
	F61X	62	63	64	65	66	67	68	F69S	70
1	–	1.43	1.43	1.43	1.42	1.44	1.44	1.43	1.43	1.43
2	–	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.45	1.43
3	–	1.42	1.42	1.42	1.42	1.43	1.43	1.42	1.45	1.42

Chg	Test Cell No.									
	71	72	73	74	75	F76LS	F77X	78	79	80
1	1.45	1.46	1.44	1.44	1.45	1.45	–	1.45	1.45	1.46
2	1.43	1.44	1.42	1.43	1.42	1.43	–	1.43	1.42	1.43
3	1.42	1.43	1.42	1.42	1.42	1.42	–	1.43	1.42	1.42

Chg	Test Cell No.									
	F81X	82	F83X	F84L	85	86	F87S	88	89	90
1	–	1.45	–	1.46	1.44	1.45	1.45	1.44	1.44	1.45
2	–	1.44	–	1.43	1.43	1.44	1.43	1.43	1.43	1.44
3	–	1.43	–	1.44	1.43	1.43	1.43	1.42	1.42	1.43

Chg	Test Cell No.									
	91	92	93	94	95	96	97	98	99	100
1	1.45	1.45	1.45	1.45	1.45	1.46	1.45	1.45	1.44	1.45
2	1.42	1.42	1.42	1.41	1.42	1.44	1.42	1.42	1.43	1.42
3	1.43	1.42	1.42	1.42	1.42	1.43	1.42	1.43	1.42	1.43

Chg	Test Cell No.									
	F101X	102	103F	104L	105	106	107	108	109	110
1	–	1.45	1.44	1.44	1.44	1.45	1.44	1.44	1.44	1.44
2	–	1.43	1.42	1.42	1.42	1.43	1.42	1.43	1.42	1.43
3	–	1.43	1.42	1.41	1.42	1.43	1.42	1.42	1.42	1.43

Chg	Test Cell No.									
	111	F112G	F113X	F114X	115	F116X	F117X	F118X	F119X	120
1	1.44	1.44	–	–	1.45	–	–	–	–	1.44
2	1.42	1.43	–	–	1.43	–	–	–	–	1.43
3	1.42	1.42	–	–	1.43	–	–	–	–	1.42

Table A-2
Terminal Charging Voltages (Continued)

Chg	Test Cell No.									
	F121X through F192X									
Chg	193	194	195	196	197	198	F199T	200		
1	1.44	1.45	1.44	1.45	1.44	1.45	—	1.45		
2	1.42	1.43	1.42	1.43	1.42	1.43	—	1.43		
3	1.42	1.42	1.42	1.42	1.42	1.42	—	1.42		
Chg	201	202	203	F204S	205	206	207	208	209	210
1	1.45	1.45	1.45	1.45	1.45	1.45	1.44	1.45	1.45	1.44
2	1.43	1.43	1.42	1.43	1.42	1.43	1.42	1.43	1.43	1.42
3	1.43	1.42	1.42	1.43	1.42	1.42	1.42	1.42	1.42	1.42
Chg	211	212	213	214	215	216	217	218	219	F220S
1	1.45	1.45	1.45	1.44	1.45	1.45	1.45	1.45	1.45	1.45
2	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43
3	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42
Chg	221	222	223	224	225	226	227	228	229	230
1	1.45	1.45	1.45	1.45	1.44	1.46	1.45	1.45	1.45	1.45
2	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43
3	1.42	1.42	1.42	1.42	1.42	1.42	1.43	1.42	1.42	1.42
Chg	231									
1	1.45									
2	1.43									
3	1.42									

Legend:

F-Failed cell
S-Shorted cell
X-Overvoltage on charge

L-Caustic leak
T-Malformed terminal
G-Blocked gauge

Table A-3
Typical Capacity Test Pressure Data

Cell numbers 001 to 010										
001	002	003	004	005	006	007	008	009	010	Time
+04	-10	+00	+01	+00	+01	-01	-11	+00	-00	Chg 1 Term
+09	-08	+03	+05	+04	+07	+05	-09	+04	+03	Chg 2 Term
-18	-25	-19	-18	-24	-22	-20	-30	-30	-20	10-1
-18	-24	-18	-16	-21	-20	-20	-25	-20	-20	10-2
-17	-22	-16	-16	-20	-20	-20	-25	-20	-20	10-3
-16	-22	-17	-16	-19	-18	-18	-22	-18	-18	10-4
-15	-21	-16	-16	-19	-18	-18	-21	-18	-18	11-1
-15	-20	-16	-15	-20	-16	-16	-17	-17	-20	11-2
-14	-14	-15	-15	-20	-16	-16	-20	-16	-20	11-3
-14	-14	-16	-15	-18	-15	-15	-20	-15	-18	11-4
-10	-18	-13	-12	-16	-14	-15	-19	-15	-15	12-1
-10	-16	-14	-10	-15	-12	-15	-20	-15	-15	12-2
-07	-16	-14	-15	-15	-10	-14	-20	-17	-15	12-3
-04	-15	-10	-08	-15	-09	-12	-18	-10	-14	12-4
+00	-15	-10	-05	-15	-07	-10	-17	-10	-10	13-1
+03	-10	-05	-03	-10	-05	-07	-15	-05	-10	13-2
+00	-10	+03	-05	-05	-03	-05	-15	-03	-05	13-3
+06	-10	+00	-05	-02	+00	-04	-15	+00	-05	13-4
+06	-06	+00	-03	-05	+01	+00	-12	+01	-05	14-1
+08	-05	+01	+00	-03	+03	-01	-10	+03	+00	14-2
+09	-05	+03	+00	+00	+03	+02	-10	+03	-03	14-3
+09	-02	-03	+03	+03	+03	+03	-07	+06	+03	14-4
+09	-01	+01	+01	+00	+06	+03	-05	+06	+00	15-1
+09	+00	+03	+03	+03	+06	+03	-05	+06	+03	15-2
+09	+00	+06	+06	+03	+07	+03	-02	+06	+03	15-3
+09	+00	+06	+06	+03	+07	+05	-01	+06	+03	15-4
+10	+00	+04	+06	+04	+08	+05	-03	+05	+04	16-1
+11	+00	+05	+05	+04	+08	+05	-02	+05	+04	16-2
+11	+00	+05	+05	+04	+08	+05	-01	+06	+04	16-3
+11	+00	+05	+05	+04	+08	+06	-01	+06	+04	Chg 3 term

Cell numbers 011 to 020										
011	F012L	F013G	014	015	016	017	018	019	020	Time
+00	+01	-25	-09	+01	-05	+00	+02	+03	+00	Chg 1 term
+03	+05	-25	-05	+03	+00	+02	+04	+06	+00	Chg 2 term
+04	+06	-25	-01	+03	+02	+03	+05	+08	+01	Chg 3 term

Table A-3
Typical Capacity Test Pressure Data (Continued)

Cell numbers 021 to 030

021	022	023	024	025	026	027	028	029	030	Time
-02	+03	-09	+02	+01	+03	-09	-05	+13	+00	Chg 1 term
+01	+13	+00	+05	+03	+05	-04	+00	+16	+02	Chg 2 term
+02	+14	+00	+06	+04	+05	-01	+01	+17	+03	Chg 3 term

Cell numbers 031 to 040

031	032	033	034	035	036	037	038	039	040	Time
-07	+03	-09	+03	+15	+15	+06	+00	+08	-03	Chg 1 term
-05	+06	-05	+06	+22	+21	+08	+01	+13	+03	Chg 2 term
-01	+09	-05	+06	+24	+22	+12	+02	+15	+04	Chg 3 term

Cell numbers 041 to 050

041	042	043	044	F045L	046	047	F048L	049	050	Time
+05	+02	-05	+11	-05	-05	+05	—	+00	-05	Chg 1 term
+07	+09	+01	+15	+01	+01	+09	—	+01	+00	Chg 2 term
+08	+10	+02	+17	+02	+02	+10	—	+03	+02	Chg 3 term

Cell numbers 051 to 060

051	052	053	054	F055L	056	057	F058L	059	060	Time
+01	+01	-06	+07	-10	+00	+01	-08	+06	+00	Chg 1 term
+04	+04	+01	+12	-05	+03	+04	+04	+11	+01	Chg 2 term
+04	+05	+02	+15	+00	+02	+04	+07	+12	+02	Chg 3 term

Cell numbers 061 to 070

F061X	062	063	064	065	066	067	068	F069S	070	Time
-12	-20	-12	-26	-25	-20	-17	-22	-25	-15	Chg 1 term
+08	+06	+12	+06	+03	+19	+16	+05	+02	+06	Chg 2 term
—	+12	+15	+12	+05	+26	+18	+10	+03	+08	Chg 3 term

Cell numbers 071 to 080

071	072	073	074	075	F076L	F077X	078	079	080	Time
-20	-15	-17	-20	-20	-22	+02	-17	-20	-05	Chg 1 term
—	+13	+07	+04	+06	+03	—	+04	+05	+17	Chg 2 term
—	+15	+08	+06	+09	+04	—	+05	+06	+19	Chg 3 term

Table A-3
Typical Capacity Test Pressure Data (Continued)

Cell numbers 081 to 090										
F081X	082	F083X	F084L	085	086	F087S	088	089	090	Time
—	+12	—	—	+04	+05	—	-07	+02	+12	Chg 1 term
—	+20	—	—	+09	+09	—	+03	+10	+20	Chg 2 term
—	+24	—	—	+12	+13	—	+06	+13	+22	Chg 3 term
Cell numbers 091 to 100										
091	092	093	094	095	096	097	098	099	100	Time
+15	+12	-06	+02	+00	+13	+06	-05	+04	-04	Chg 1 term
—	—	—	—	—	—	—	—	—	—	Chg 2 term
+27	+16	+01	+07	+04	+25	+13	+02	+07	+02	Chg 3 term
Cell numbers 101 to 110										
F101X	102	103	F104L	105	106	107	108	109	110	Time
—	+16	-10	+00	+00	+02	+03	+00	+04	+05	Chg 1 term
—	+26	+02	+05	+03	+07	+04	+02	+12	+09	Chg 2 term
—	+28	+03	+06	+03	+09	+05	+03	+12	+09	Chg 3 term
Cell numbers 111 to 120										
111	F112G	F113X	F114X	115	F116X	F117X	F118X	F119X	120	Time
-15	-30	—	—	+00	—	—	—	—	-12	Chg 1 term
-07	-30	—	—	+06	—	—	—	—	-04	Chg 2 term
-01	-30	—	—	+14	—	—	—	—	+05	Chg 3 term
All remaining cells either failed acceptance tests or were not equipped with pressure gages.										

Legend:

F-Failed cell
S-Internal short
X-Overvoltage
L-Caustic leak
G-Blocked gauge

"-" values in in. of Hg
"+" values in psia

Table A-4
Internal Resistance Measurements

Cell no.	001	002	003	004	005	006	007	008	009	010
Int. res.	3.5*	3.5	3.7	3.5	3.7	3.7	4.0	3.7	3.9	3.9
Cell no.	011	F012L	F013G	014	015	016	017	018	019	020
Int. res.	3.9	3.7	4.2	4.0	3.9	3.7	4.2	3.7	4.2	3.7
Cell no.	021	022	023	024	025	026	027	028	029	030
Int. res.	3.5	3.5	3.7	3.3	3.7	3.7	3.5	3.7	3.7	4.0
Cell no.	031	032	033	034	035	036	037	038	039	040
Int. res.	3.5	3.3	3.7	3.9	4.9	4.2	3.5	4.2	3.7	3.7
Cell no.	041	042	043	044	F045	046	047	F048	049	050
Int. res.	3.9	4.6	4.4	3.9	3.9	4.2	3.7	—	3.7	3.5
Cell no.	051	052	053	054	F055L	056	057	F058L	059	060
Int. res.	3.9	3.9	4.2	3.9	3.9	3.9	3.5	4.2	4.0	3.7
Cell no.	F061X	062	063	064	065	066	067	068	F069S	070
Int. res.	—	4.7	4.7	3.9	3.5	4.0	3.9	3.7	3.7	3.9
Cell no.	071	072	073	074	075	F076L	F077X	078	079	080
Int. res.	3.9	4.0	3.9	4.7	4.9	4.2	—	3.9	4.2	4.2
Cell no.	F081	082	F083	F084	085	086	F087	088	089	090
Int. res.	4.4	3.7	4.4	3.9	4.4	4.2	—	4.2	4.4	4.2
Cell no.	091	092	093	094	095	096	097	098	099	100
Int. res.	3.9	4.6	4.9	4.0	4.4	3.9	4.7	4.6	4.4	4.6
Cell no.	F101X	102	103	F104L	105	106	107	108	109	110
Int. res.	—	4.6	4.9	4.0	3.9	4.6	4.4	3.9	4.2	3.9
Cell no.	111	F112G	F113X	F114X	115	F116X	F117X	F118X	F119X	120
Int. res.	3.9	3.7	4.0	3.9	3.9	4.0	—	—	—	3.9
Cell no.	F131X	F132X	F133X	F134X	F135X	F136X	F137X	F138X	F139X	F140X
Int. res.	4.6	4.0	4.9	4.6	—	4.6	3.9	3.7	4.4	3.7
Cell no.	F121X through F192X failed acceptance test.									
Cell no.	193	194	195	196	197	198	F199T	200		
Int. res.	3.7	3.9	3.7	3.9	4.0	3.9	—	4.0		

* All internal resistance values in milliohms.

Table A-4
Internal Resistance Measurements (Continued)

Cell no. Int. res.	201 3.9	202 3.7	203 3.9	F204 —	205 4.2	206 4.2	207 4.6	208 3.7	209 4.4	210 5.1
Cell no. Int. res.	211 4.2	212 3.9	213 3.7	214 3.3	215 3.5	216 3.7	217 3.5	218 3.7	219 3.3	F220 —
Cell no. Int. res.	221 4.7	222 3.9	223 3.7	224 3.9	225 4.4	226 4.2	227 3.9	228 3.9	229 3.9	230 3.7
Cell no. Int. res.	231 3.5	F232X —	F233X —	F234X —	F235X —	F236X —	F237X —	F238X —	F239X —	F240X —

Legend: F-Failed cell
S-Internal short
X-Overvoltage
G-Blocked gauge
L-Caustic leak
T-Malformed terminal

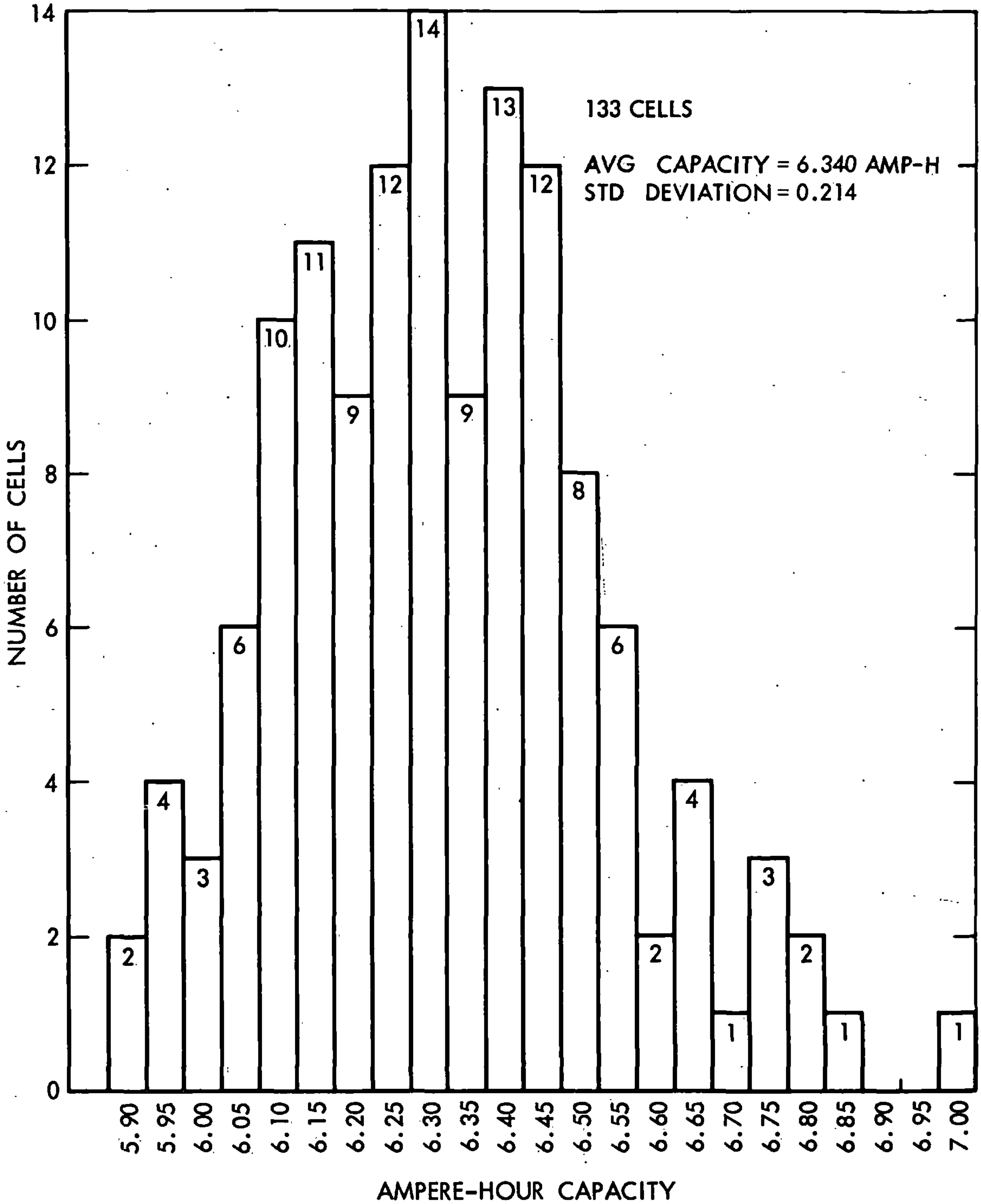


Figure A-1. Capacity Distribution, Nickel-Cadmium Cell Acceptance Tests, September 1963

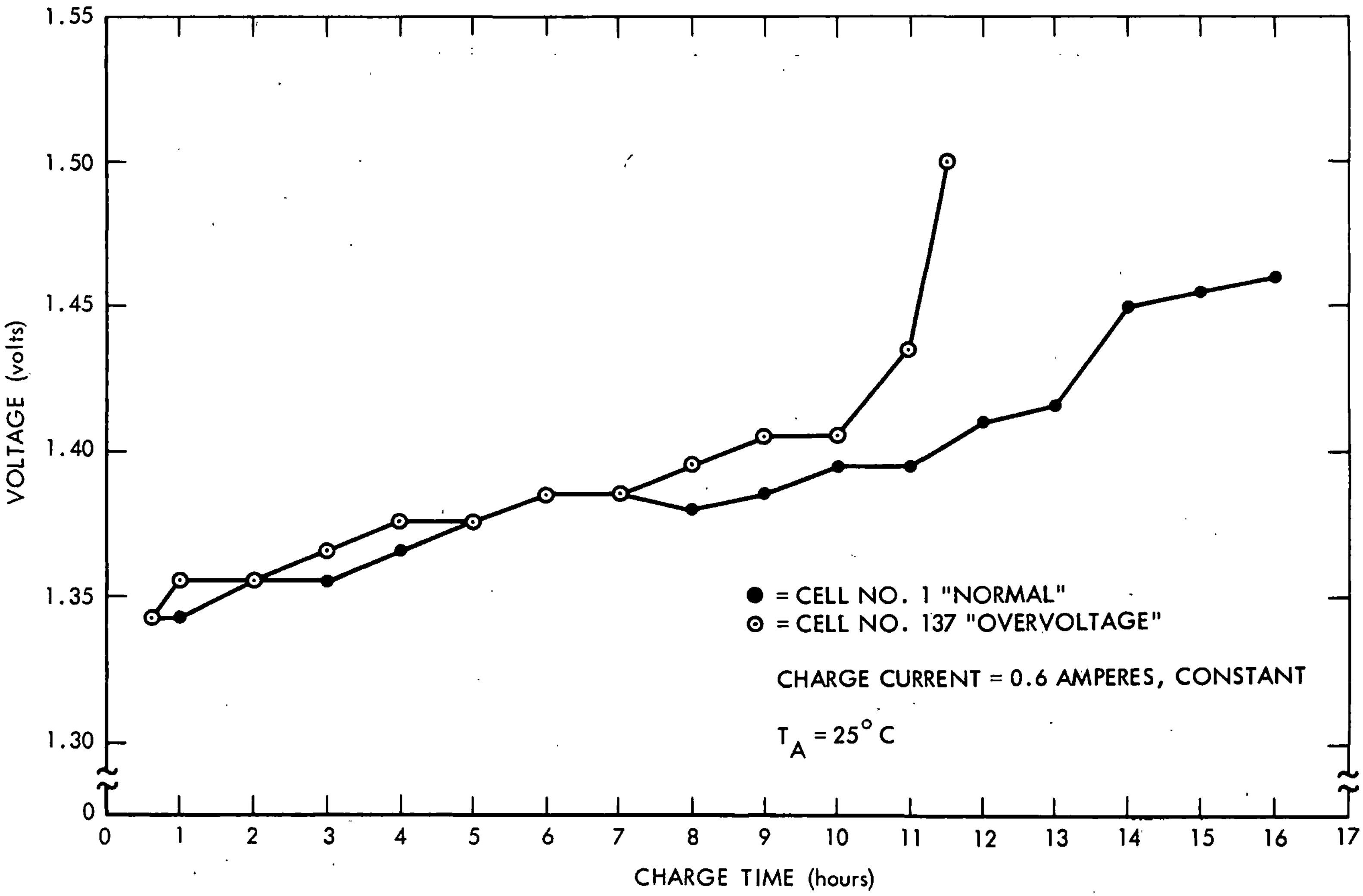


Figure A-2. Normal vs "Overvoltage" Cell, Charge Characteristics, Nickel-Cadmium Cell Acceptance Tests, September 1963

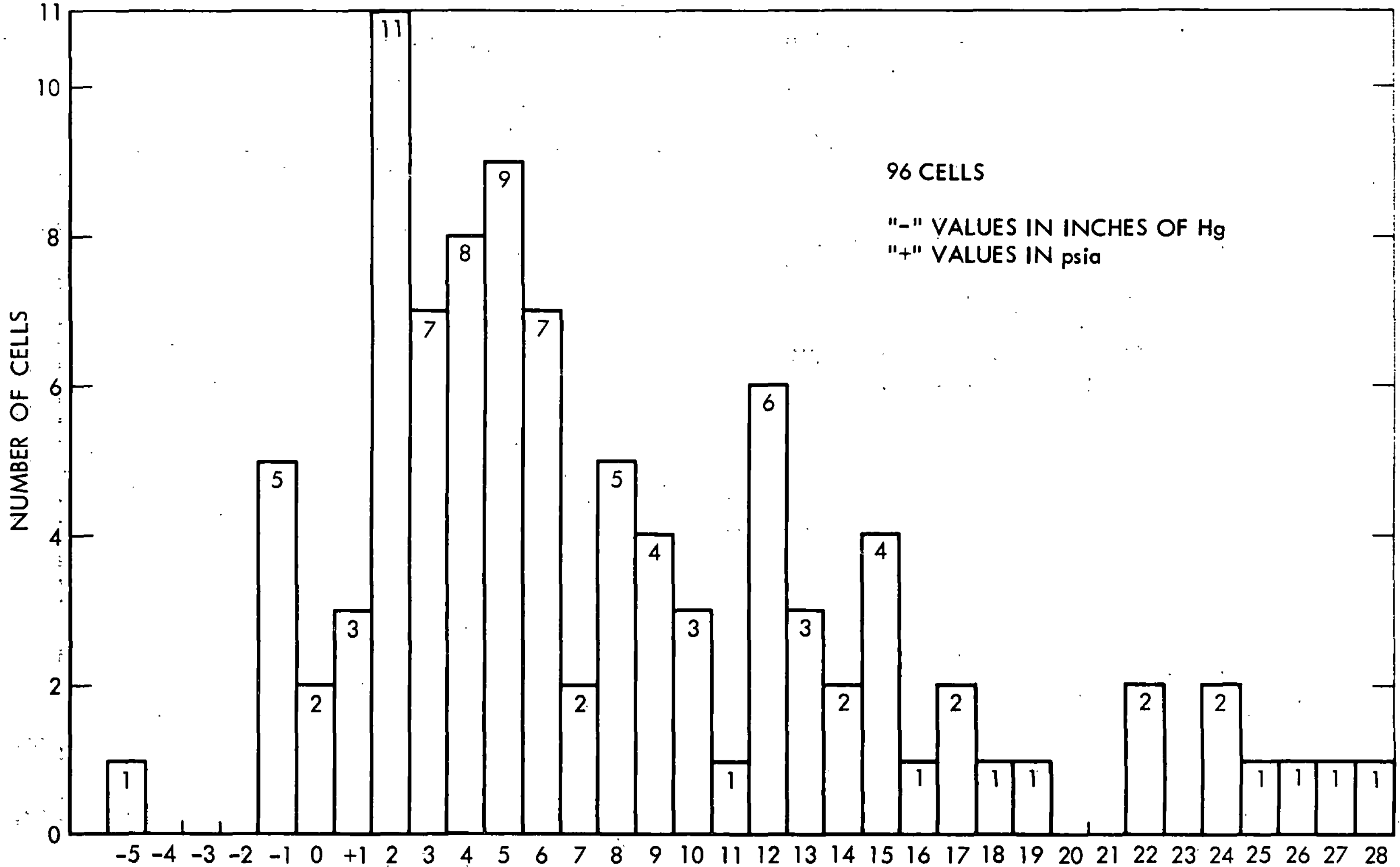


Figure A-3. Capacity Test, Final Pressure Distribution, Charge No. 3, Nickel-Cadmium Cell Acceptance Tests, September 1963

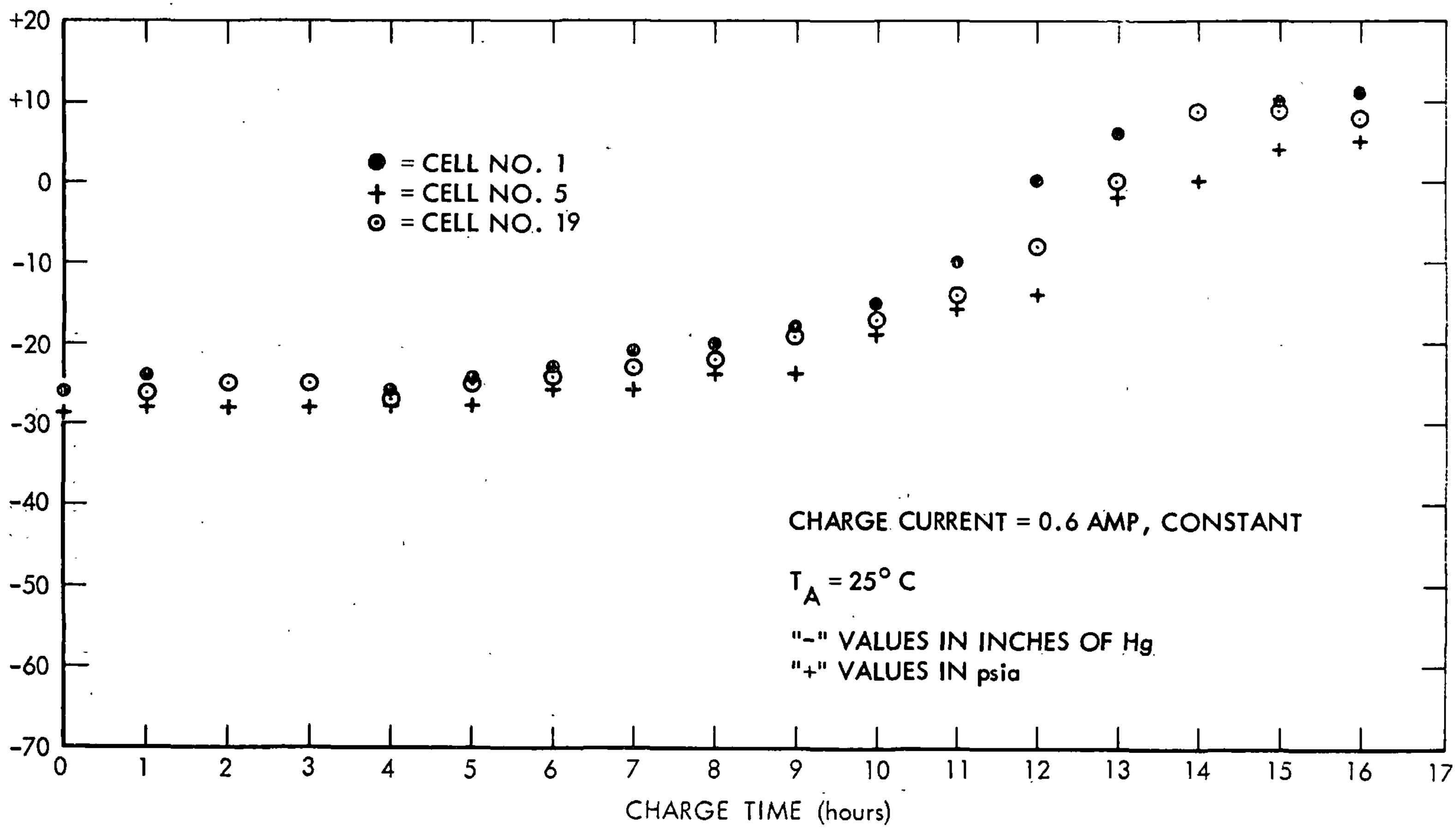


Figure A-4. Capacity Test, Sampling of Pressure Characteristics, Nickel-Cadmium Cell Acceptance Tests, September 1963

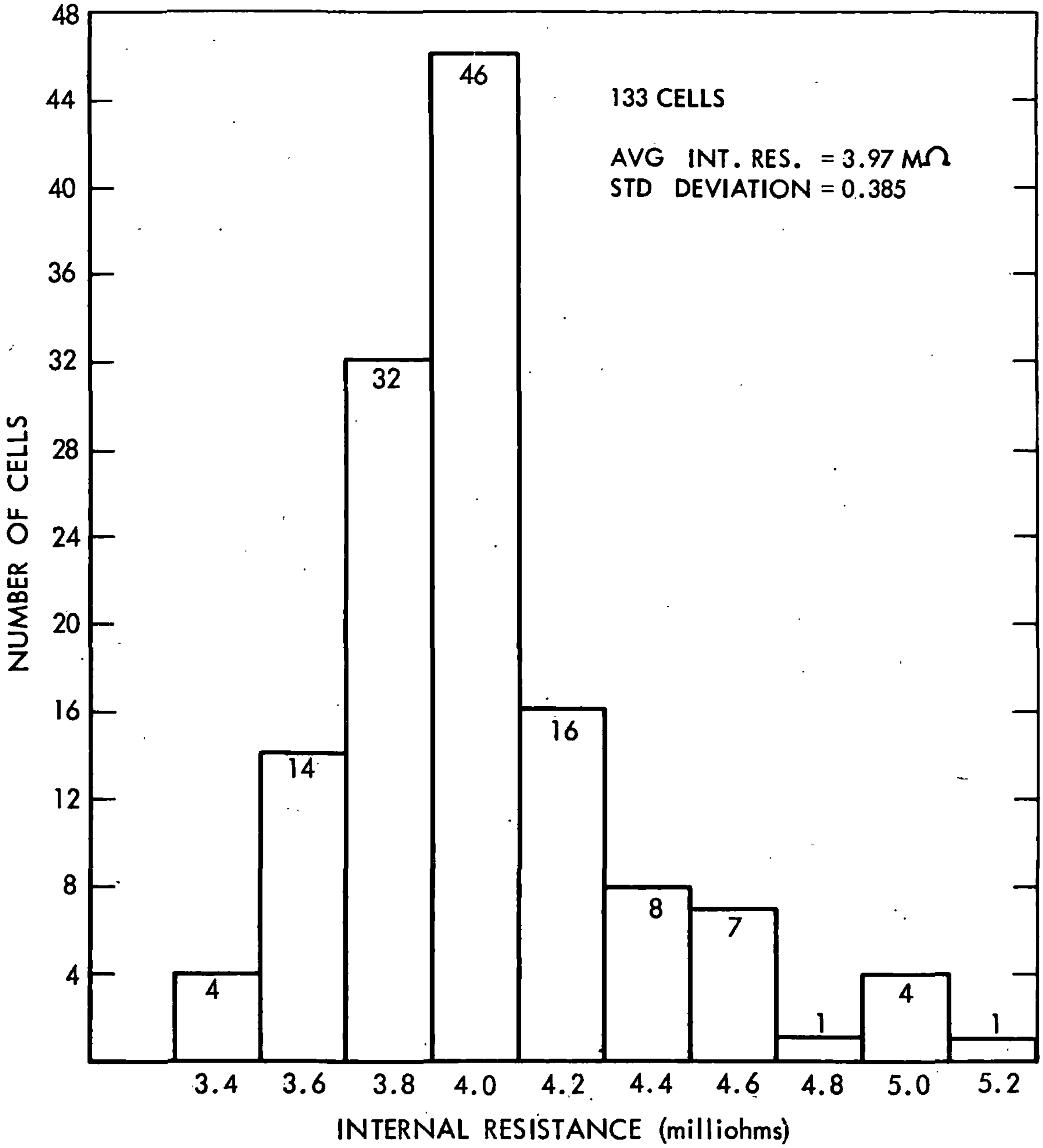


Figure A-5. Internal Resistance Distribution, Nickel-Cadmium Cell Acceptance Tests, September 1963

APPENDIX B

MANUFACTURER DATA AND ACCEPTANCE TEST DATA FOR CELLS IN TEST

Table B-1
Battery 0 Cell Data (Chg. 3.25 hr at C/10, dischg. 0.5 hr at C/2)

Cell No.	Martin Marietta No.	Gulton No.	Manufacturer Data: Overcharge Volts	Manufacturer Data: Overcharge Press.	Manufacturer Data: Capacity (amp-h)	Manufacturer Data: Short Test (v)	Acceptance Tests: Meas. Capacity (amp-h)	Acceptance Tests: Term. Volt. Chg.*	Acceptance Tests: Term. Press. Chg.*	Acceptance Tests: Intern. Resist. (milli-ohms)	Shipping Group	Off
0	41	3155	1.40	10	6.50	1.18	6.187	1.45 1.45 1.43	5 7 8	3.9	8	1986
1	49	3148	1.40	5	6.80	1.18	6.266	1.45 1.43 1.43	0 1 3	3.7	8	2349
2	59	3108	1.40	15	6.65	1.20	6.418	1.45 1.44 1.43	6 11 12	4.0	8	Cell C 3065
3	64	2831	1.41	11	6.35	1.20	6.209	1.43 1.43 1.42	-13 16 12	3.9	4	Cell D
4	89	2828	1.41	5	6.20	1.19	6.397	1.44 1.43 1.42	2 10 13	4.4	4	Cell E
5	91	3161	1.40	10	6.60	1.19	6.130	1.45 1.42 1.43	15 - 27	3.9	8	666
6	208	2907	1.41	2	7.00	1.18	6.515	1.45 1.43 1.42	-	3.7	6	Cell A
7	210	2928	1.41	15	6.25	1.20	6.004	1.44 1.42 1.42	-	5.1	6	1899
8	213	2932	1.41	12	6.45	1.20	6.366	1.45 1.43 1.42	-	3.7	6	Cell B
9	241	4796	1.42	17	6.15	1.20	5.790	1.45 1.43 1.43	1	3.9	11	35
						Avg. Std. Dev.	6.228 .205					
						Cell 241 Rerun	6.450	1.45	48			

Failure of cells 0, 1, 2, 5, and 7 was from capacity loss greater than 75%; failure of cell 9 was from voltage on charge greater than 1.50v.
* For test cycles 1, 2, and 3, respectively.

Table B-2

Battery 1 Cell Data (Chg. 3.25 hr at C/10, dischg. 200 hr at C/8)

Cell No.	Martin Marietta No.	Gulton No.	Manufacturer Data: Overcharge Volts	Overcharge Press.	Capacity (amp-h)	Short Test (v)	Acceptance Tests: Meas. Capacity (amp-h)	Term. Volt. Chg.*	Term. Press. Chg.*	Intern. Resist. (milliohms)	Shipping Group	Off
0	17	3151	1.40	6	6.80	1.19	6.322	1.43 1.41 1.42	0 2 3	4.2	8	Cell E
1	19	2872	1.41	8	6.20	1.19	6.296	1.44 1.42 1.40	3 6 8	4.2	5	Cell C
2	27	2878	1.41	4	6.60	1.18	6.453	1.44 1.42 1.42	-4.5 -2 - .5	3.5	5	
3	60	3160	1.41	2	6.70	1.19	6.117	1.44 1.41 1.40	0 1 2	3.7	8	Cell D
4	63	3158	1.41	3	6.75	1.19	6.279	1.43 1.43 1.42	-6 12 15	4.7	8	
5	88	2842	1.41	3	6.35	1.19	6.519	1.44 1.43 1.42	-3.5 -1.5 6	4.2	4	1580
6	100	3115	1.41	7	6.75	1.21	6.672	1.45 1.42 1.43	-2 0 4	4.6	8	
7	218	2906	1.41	11	6.75	1.18	6.480	1.45 1.43 1.42		3.7	6	Cell A
8	227	2916	1.41	19	6.75	1.18	6.445	1.45 1.43 1.43		3.9	6	Cell B
9	252	4778	1.42	-20	6.40	1.20	5.808	1.46 1.43 1.43	10 35 43	4.2	11	399
						Avg. Std. Dev.	6.339 0.229					

Failure of cell 5 was from capacity loss greater than 75%; failure of cell 9 was from voltage on charge greater than 1.50v.

* For test cycles 1, 2, and 3 respectively.

Table B-3
Battery 2 Cell Data (Chg. 3.25 hr at C/10, dischg. 1/8 hr at 2C)

Cell No.	Martin Marietta No.	Gulton No.	Manufacturer Data: Overcharge Volts	Manufacturer Data: Overcharge Press.	Manufacturer Data: Capacity (amp-h)	Manufacturer Data: Short Test (v)	Acceptance Tests: Meas. Capacity (amp-h)	Acceptance Tests: Term. Volt. Chg.*	Acceptance Tests: Term. Press. Chg.*	Acceptance Tests: Intern. Resist. (milli-ohms)	Shipping Group	Off
0	3	2858	1.42	6	6.25	1.19	6.213	1.44 1.43 1.41	0 3 5	3.7	5	1500
1	9	2851	1.42	7	6.30	1.19	6.178	1.45 1.41 1.41	0 4 6	3.9	5	Cell C 2072
2	29	3109	1.40	15	6.30	1.20	6.052	1.45 1.41 1.41	13 16 17	3.7	8	2011
3	31	2879	1.41	4	6.35	1.18	6.327	1.44 1.42 1.41	-3.5 -2.5 -12	3.5	5	Cell D
4	34	3118	1.41	10	6.65	1.20	6.384	1.44 1.44 1.43	3 6 6	3.9	8	Cell A
5	68	2826	1.41	4	6.50	1.19	6.432	1.43 1.43 1.42	-11 5 10	3.7	4	2396
6	193	2894	1.42	0	6.45	1.18	6.506	1.44 1.42 1.42		3.7	5	Cell B
7	198	2929	1.41	19	6.20	1.21	6.269	1.45 1.43 1.42		3.9	6	1316
8	229	2909	1.41	5	6.85	1.19	6.549	1.45 1.43 1.42		3.9	6	2057
9	244	4790	1.42	26	6.85	1.20	6.402	1.45 1.44 1.43	20 33 35	3.7	11	Cell E 2566
						Avg. Std. Dev.	6.332 0.147					
						Cell 244 Rerun	6.960	1.45	25			

Failure of cells 0, 1, 2, 5, 7, and 8 was from capacity loss greater than 75%; failure of cell 9 was from end-of-charge voltage greater than 1.50v.
* For test cycles 1, 2, and 3 respectively.

Table B-4 (see also Table B-13)
Battery 3 Cell Data (Chg. to E_T at C/10, disch. 0.5 hr at C/2)

Cell No.	Martin Marietta No.	Gulton No.	Manufacturer Data: Overcharge Volts	Manufacturer Data: Overcharge Press.	Manufacturer Data: Capacity (amp-h)	Manufacturer Data: Short Test (v)	Acceptance Tests: Meas. Capacity (amp-h)	Acceptance Tests: Term. Volt. Chg.*	Acceptance Tests: Term. Press. Chg.*	Acceptance Tests: Intern. Resist. (milli-ohms)	Shipping Group	Off
0	5	2852	1.41	7	6.35	1.19	6.301	1.45 1.42 1.42	0 4 4	3.7	5	
1	11	3145	1.40	7	6.90	1.17	6.218	1.43 1.41 1.42	0 3 4	3.9	8	Cell A
2	21	2871	1.41	10	6.25	1.18	6.209	1.43 1.42 1.42	-1 1 2	3.5	5	
3	54	3112	1.40	16	6.55	1.20	6.248	1.44 1.41 1.41	7 12 15	3.9	8	
4	75	2829	1.41	8	6.20	1.19	6.104	1.45 1.42 1.42	-10 6 9	4.9	4	Cell B
5	96	3132	1.40	17	6.45	1.20	6.331	1.46 1.44 1.43	13 - 25	3.9	8	550
6	102	2868	1.41	10	6.20	1.18	6.056	1.45 1.43 1.43	16 26 28	4.6	5	
7	108	2849	1.41	6	6.20	1.19	6.148	1.44 1.43 1.42	0 2 3	3.9	4	2480
8	231	2919	1.41	24	6.45	1.19	6.287	1.45 1.43 1.42		3.5	6	
9	243	4807	1.42	6	6.55	1.20	5.633	1.45 1.42 1.42	25 35 50	3.7	11	2280
						Avg. Std.Dev.	6.153 0.193					
						Cell 243 Rerun	6.250	1.44	36			

Failure of cells 5,7, and 9 was from capacity loss greater than 75%.
* For test cycles 1,2, and 3 respectively.

Table B-5

Battery 4 Cell Data (Chg. to E_T at C/5 and to E_T at C/10, dischg. 0.5 hr at C/2)

Cell No.	Martin Marietta No.	Gulton No.	Manufacturer Data: Overcharge Volts	Manufacturer Data: Overcharge Press.	Manufacturer Data: Capacity (amp-h)	Manufacturer Data: Short Test (v)	Acceptance Tests: Meas. Capacity (amp-h)	Acceptance Tests: Term. Volt. Chg.*	Acceptance Tests: Term. Press. Chg.*	Acceptance Tests: Intern. Resist. (milli-ohms)	Shipping Group	Off
0	7	2870	1.41	5	6.40	1.19	6.248	1.46 1.42 1.42	-5 5 6	4.0	5	Cell E 2098
1	20	3130	1.41	12	6.70	1.21	6.497	1.43 1.41 1.43	0 0 1	3.7	8	Cell A
2	23	2865	1.42	5	6.40	1.19	6.589	1.45 1.41 1.40	-4.5 0 0	3.7	5	Cell B
3	46	3141	1.41	6	7.00	1.18	6.279	1.46 1.44 1.42	-2.5 1 2	4.2	8	5599
4	52	3116	1.41	15	6.70	1.20	6.549	1.43 1.43 1.43	1 4 5	3.9	8	Cell C
5	72	3164	1.41	5	6.80	1.19	6.331	1.46 1.44 1.43	-7.5 13 15	4.0	8	Cell D 3078
6	92	2845	1.42	14	6.25	1.19	6.174	1.45 1.42 1.42	12 - 16	4.6	4	2267
7	93	2837	1.42	4	6.45	1.19	6.231	1.45 1.42 1.42	-3 - 1	4.9	4	4655
8	228	2908	1.41	13	6.65	1.19	6.309	1.45 1.43 1.42		3.9	6	2459
9	251	4789	1.43	23	6.15	1.20	6.169	1.46 1.45 1.45	24 29 32	3.9	11	2002
						Avg. Std. Dev.	6.338 0.147					
						Cell 251 Rerun	6.610	1.48	18			

Failure of cells 0, 3, 5, 6, 7, and 8 was from capacity loss greater than 75%; failure of cell 9 was from end-of-charge voltage greater than 1.50v.

* For test cycles 1, 2, and 3 respectively.

Table B-6

Battery 5 Cell Data (Chg. to E_T at C/2 and to E_T at C/10, dischg. 1 hr at C/2)

Cell No.	Martin Marietta No.	Gulton No.	Manufacturer Data: Overcharge Volts	Manufacturer Data: Overcharge Press.	Manufacturer Data: Capacity (amp-h)	Manufacturer Data: Short Test (v)	Acceptance Tests: Meas. Capacity (amp-h)	Acceptance Tests: Term. Volt. Chg.*	Acceptance Tests: Term. Press. Chg.*	Intern. Resist. (milli-ohms)	Shipping Group	Off
0	2	2874	1.41	4	6.35	1.18	6.104	1.44 1.42 1.41	-5 -4 0	3.5	5	577
1	6	2887	1.41	7	6.55	1.19	6.253	1.44 1.42 1.41	1 7 8	3.7	5	290
2	30	3139	1.41	12	6.80	1.18	6.279	1.44 1.43 1.43	0 2 3	4.0	8	551
3	32	3159	1.40	9	6.45	1.19	6.056	1.44 1.41 1.40	3 6 9	3.3	8	281
4	42	3154	1.41	6	6.70	1.19	6.148	1.45 1.43 1.42	2 9 10	4.6	8	483
5	73	2836	1.41	7	6.30	1.19	6.235	1.44 1.42 1.42	-8.5 7 8	3.9	4	381
6	95	2830	1.41	2	6.30	1.19	6.314	1.45 1.42 1.42	0 - 4	4.4	4	584
7	206	2895	1.41	4	6.45	1.19	6.340	1.45 1.43 1.42		4.2	6	585
8	214	2914	1.41	5	6.80	1.18	6.475	1.44 1.43 1.42		3.3	6	568
9	248	4768	1.42	15	6.20	1.20	5.567	1.45 1.42 1.42	20 40 48	3.9	11	226
						Avg. Std. Dev.	6.177 0.234					
						Cell 248 Rerun	6.175	1.45	46			

All cells failed from capacity loss greater than 75%.
* For test cycles 1, 2, and 3 respectively.

Table B-7

Battery 6 Cell Data (Chg. to E_T at C/2 and to E_T at C/10, dischg. at C/2 to 1.0v)

Cell No.	Martin Marietta No.	Gulton No.	Manufacturer Data: Overcharge Volts	Manufacturer Data: Overcharge Press.	Manufacturer Data: Capacity (amp-h)	Manufacturer Data: Short Test (v)	Acceptance Tests: Meas. Capacity (amp-h)	Acceptance Tests: Term. Volt. Chg.*	Acceptance Tests: Term. Press. Chg.*	Acceptance Tests: Intern. Resist. (milli-ohms)	Shipping Group	Off
0	16	3142	1.41	7	6.95	1.19	6.580	1.44 1.42 1.41	-2.5 0 2	3.7	8	780
1	53	2861	1.41	6	6.30	1.19	6.410	1.44 1.42 1.41	-3 1 2	4.2	5	193
2	70	2825	1.41	7	6.15	1.19	6.174	1.43 1.43 1.42	-7.5 6 8	3.9	4	557
3	78	3165	1.41	5	7.00	1.19	6.602	1.45 1.43 1.43	-10 5 6	3.9	8	780
4	109	2832	1.41	17	6.20	1.19	6.239	1.44 1.42 1.42	4 12 12	4.2	4	780
5	111	2847	1.41	4	6.35	1.19	6.488	1.44 1.42 1.42	-7.5 -3.5 -0.5	3.9	4	642
6	195	2898	1.41	10	6.25	1.19	6.318	1.44 1.42 1.42	—	3.7	6	780
7	200	2896	1.41	5	6.45	1.18	6.423	1.45 1.43 1.42	—	4.0	6	780
8	216	2910	1.41	7	6.75	1.18	6.349	1.45 1.43 1.42	—	3.7	6	780
9	247	4787	1.42	6	6.35	1.20	6.175	1.45 1.43 1.42	11 11 10	4.0	11	57
						Avg. Std. Dev.	6.375 0.146					
						Cell 247 Rerun	6.700	1.48	6			

All cells failed from capacity loss greater than 75%.

* For test cycles 1, 2, and 3, respectively.

Table B-8
Battery 7 Cell Data (Chg. 6.5 hr at C/10, dischg. 0.5 hr at C/2)

Cell No.	Martin Marietta No.	Gulton No.	Manufacturer Data: Overcharge Volts	Overcharge Press.	Capacity (amp-h)	Short Test (v)	Acceptance Tests: Meas. Capacity (amp-h)	Term. Volt. Chg.*	Term. Press. Chg.*	Intern. Resist. (milli-ohms)	Shipping Group	Off
0	4	2854	1.42	9	6.35	1.19	6.170	1.45 1.41 1.42	1 5 5	3.5	5	1058
1	37	3117	1.41	16	6.55	1.20	6.257	1.44 1.43 1.43	6 8 12	3.5	8	
2	44	3114	1.40	12	6.40	1.20	6.030	1.45 1.43 1.43	11 15 17	3.9	8	
3	47	3125	1.41	11	6.80	1.20	6.418	1.46 1.44 1.42	5 9 10	3.7	8	Cell C
4	71	2838	1.41	3	6.25	1.19	6.235	1.45 1.43 1.42	-10	4.2	4	
5	110	2883	1.41	6	6.70	1.18	6.392	1.44 1.43 1.43	5 9 9	3.9	5	Cell D
6	120	2834	1.41	7	6.40	1.20	6.558	1.44 1.43 1.42	-6 -2 -5	3.9	4	Cell E
7	211	2922	1.42	30	6.50	1.19	6.235	1.45 1.43 1.42		4.2	16	Cell A
8	224	2905	1.41	6	6.60	1.19	6.353	1.45 1.43 1.42		3.0	6	Cell B
9	250	4784	1.42	5	6.50	1.20	5.751	1.45 1.43 1.42	15 24 28	3.7	11	942
						Avg. Std.Dev.	6.234 0.215					
						Cell 250 Rerun	6.400	1.44	36			

Cell 0 failed from capacity loss greater than 75%; cell 9 failed from end-of-charge voltage greater than 1.50v.
* For test cycles 1, 2, and 3 respectively.

Table B-9
Battery 8 Cell Data (Chg. to E_T at C/10, dischg. 0.5 hr at C/2)

Cell No.	Martin Marietta No.	Gulton No.	Manufacturer Data: Overcharge Volts	Manufacturer Data: Overcharge Press.	Manufacturer Data: Capacity (amp-h)	Manufacturer Data: Short Test (v)	Acceptance Tests: Meas. Capacity (amp-h)	Acceptance Tests: Term. Volt. Chg.*	Acceptance Tests: Term. Press. Chg.*	Acceptance Tests: Intern. Resist. (milli-ohms)	Shipping Group	Off
0	10	2853	1.42	9	6.40	1.19	6.344	1.45 1.42 1.42	0 3 4	3.9	5	
1	18	3149	1.40	6	7.20	1.19	6.606	1.44 1.42 1.42	2 4 5	3.7	8	3563
2	57	3113	1.41	10	6.65	1.20	6.423	1.44 1.41 1.42	1 4 4	3.5	8	Cell B-1
3	86	2846	1.41	8	6.30	1.19	6.475	1.45 1.44 1.43	5 9 13	4.2	4	
4	94	2827	1.41	4	6.45	1.19	6.405	1.45 1.41 1.42	2 - 7	4.0	4	
5	97	2880	1.41	6	6.50	1.18	6.462	1.45 1.42 1.42	6 - 13	4.7	5	
6	197	2926	1.42	28	6.35	1.20	6.152	1.44 1.42 1.42		4.0	6	3823 Cell A-2
7	205	2911	1.41	8	6.50	1.18	6.143	1.45 1.42 1.42		4.2	6	Cell A-1
8	225	2899	1.40	2	6.45	1.19	6.375	1.44 1.43 1.42		4.4	6	Cell B-2
9	246	4780	1.42	20	6.40	1.20	6.140	1.44 1.42 1.41	0 7 11	4.4	11	
						Avg. Std. Dev.	6.352 0.151					
						Cell 246 Rerun	6.500	1.44	11			

Cells 1 and 6 failed from capacity loss greater than 75%.
* For test cycles 1, 2, and 3 respectively.

Table B-10

Battery 9 Cell Data (Chg. to P_T at C/10, dischg. 0.5 hr at C/10)

Cell No.	Martin Marietta No.	Gulton No.	Manufacturer Data				Acceptance Tests				Shipping Group	Off
			Overcharge		Capacity (amp-h)	Short Test (v)	Meas. Capacity (amp-h)	Term. Volt. Chg.*	Term. Press. Chg.*	Intern. Resist. (milli-ohms)		
			Volts	Press.								
0	15	3129	1.41	15	6.60	1.20	6.480	1.44 1.43 1.42	1 3 5	3.9	8	Cell A
1	24	3120	1.41	12	6.65	1.20	6.418	1.43 1.43 1.42	2 5 6	3.3	8	Cell D
2	36	3126	1.40	15	6.45	1.20	6.152	1.45 1.43 1.43	15 21 22	4.2	8	2386
3	56	3144	1.40	6	6.70	1.19	6.143	1.45 1.42 1.42	0 3 2	3.9	8	3323
4	67	3123	1.40	11	6.40	1.20	6.248	1.44 1.43 1.43	-8.5 16 18	3.9	8	
5	79	2841	1.41	6	6.40	1.19	6.349	1.45 1.42 1.42	-10 5 6	4.2	4	Cell C
6	90	2855	1.41	0	6.30	1.19	6.401	1.45 1.44 1.43	12 20 22	4.2	5	Cell B
7	99	3150	1.41	5	6.65	1.18	6.370	1.44 1.43 1.42	4 - 7	4.4	8	
8	217	2890	1.41	5	6.70	1.18	6.646	1.45 1.43 1.42		3.5	6	
9	245	4813	1.420	0	6.45	1.20	6.087	1.44 1.42 1.41	0 8 10	3.5	11	1976
						Avg. Std. Dev.	6.329 0.164					
						Cell 245 Rerun	6.500	1.44	15			

Cells 2, 3, and 9 failed from capacity loss greater than 75%.

* For test cycles 1, 2, and 3 respectively.

Table B-11
Battery 10 Cell Data (Chg. 2.5 hr at C/10, dischg. at C/2 to 1.0v)

Cell No.	Martin Marietta No.	Gulton No.	Manufacturer Data: Overcharge Volts	Manufacturer Data: Overcharge Press.	Manufacturer Data: Capacity (amp-h)	Manufacturer Data: Short Test (v)	Acceptance Tests: Meas. Capacity (amp-h)	Acceptance Tests: Term. Volt. Chg.*	Acceptance Tests: Term. Press. Chg.*	Acceptance Tests: Intern. Resist. (milli-ohms)	Shipping Group	Off
0	28	2888	1.41	5	6.75	1.18	6.414	1.43 1.42 1.41	-2.5 0 1	3.7	5	Cell C
1	40	2867	1.41	9	6.30	1.19	6.327	1.44 1.43 1.41	-1.5 3 4	3.7	5	Cell E
2	85	3166	1.40	0	6.75	1.19	6.436	1.44 1.43 1.43	4 9 12	4.4	8	1388
3	105	2835	1.41	9	6.40	1.19	6.183	1.44 1.42 1.42	0 3 3	3.9	4	1456
4	107	3458	1.41	0	6.80	1.20	6.392	1.44 1.42 1.42	3 4 5	4.4	10	3537
5	209	2934	1.41	5	6.15	1.20	6.065	1.45 1.43 1.42		4.4	6	Cell D
6	212	2930	1.41	15	6.30	1.20	6.506	1.45 1.43 1.42		3.9	6	Cell A
7	215	2935	1.41	21	6.40	1.20	6.100	1.45 1.43 1.42		3.5	6	Cell B
8	221	2912	1.41	10	6.60	1.18	6.471	1.45 1.43 1.42		4.7	6	3537
9	249	4770	1.42	7	6.85	1.20	6.485	1.49 1.49 1.47	5 50 24	4.2	11	2698
						Avg. Std. Dev.	6.339 0.155					
						Cell 249 Rerun	6.465	1.50	—			

Cells 2, 4, 8, and 9 failed from end-of-charge voltage greater than 1.51v; cell 3 was internally shorted.
* For test cycles 1, 2, and 3 respectively.

Table B-12
Battery 11 Cell Data (Chg. 1 hr at C/2, dischg. at C/2 to 1.0v)

Cell No.	Martin Marietta No.	Gulton No.	Manufacturer Data				Acceptance Tests				Shipping Group	Off
			Overcharge		Capacity (amp-h)	Short Test (v)	Meas. Capacity (amp-h)	Term. Volt. Chg.*	Term. Press. Chg.*	Intern. Resist. (milli-ohms)		
			Volts	Press.								
0	14	2882	1.41	0	6.50	1.18	6.322	1.43 1.40 1.41	-4.5 -2.5 -.5	4.0	5	Cell C
1	26	3131	1.41	9	6.70	1.20	6.453	1.45 1.41 1.41	-3 5 5	3.7	8	4356
2	33	2860	1.41	6	6.45	1.18	6.484	1.44 1.42 1.42	-4.5 -2.5 -2.5	3.7	5	Cell D
3	62	2881	1.41	5	6.50	1.18	6.440	1.43 1.43 1.42	-10 6 12	4.7	5	3855
4	8	2884	1.41	4	6.70	1.19	6.484	1.44 1.42 1.41	-5.5 -4.5 -.5	3.7	5	5643
5	38	3153	1.41	3	6.90	1.19	6.239	1.44 1.41 1.40	0 1 2	4.2	8	Cell B
6	80	3143	1.41	6	6.55	1.18	6.135	1.46 1.43 1.42	-2.5 17 19	4.2	8	5650
7	115	3122	1.40	13	6.55	1.20	6.510	1.45 1.43 1.43	0 6 14	3.9	8	3850
8	203	2902	1.41	5	6.75	1.19	6.528	1.45 1.42 1.42	-	3.9	6	Cell A
9	242	4812	1.42	3	6.60	1.20	6.000	1.41 1.46 1.46	0 0 0	3.5	11	

Cells 1, 3, 4, 6, and 7 failed from end-of-charge voltage greater than 1.51v.
* For test cycles 1, 2, and 3 respectively.

Table B-13 (see also Table B-4)
Battery 12 (formerly Battery 3) Cell Data (Acceptance Test Reruns)

Cell No.	Martin Marietta No.	Acceptance Test Rerun (9-1-64)					Acceptance Test Rerun (1-19-65)				
		Capacity Cycle 1	Capacity Cycle 2	Capacity Cycle 3	Capacity Cycle 4	Intern. Resist. (milli-ohms)	Capacity Cycle 1	Capacity Cycle 2	Capacity Cycle 3	Final Press. (psi)*	EOC Volts*
0	5	6.965	6.803	6.725	6.838	3.9	7.052	6.443	6.912	6 10 10	1.490 1.469 1.464
1	11	7.183	6.986	6.899	6.995	4.0	7.248	7.205	7.183	5 12 11	1.501 1.479 1.470
2	21	6.812	6.694	6.624	6.681	4.4	6.965	6.781	6.773	2 7 7	1.482 1.464 1.461
3	54	6.877	6.746	6.698	6.764	4.2	6.877	6.746	6.703	6 10 10	1.485 1.466 1.463
4	75	6.786	6.624	6.511	6.620	2.8	6.986	6.899	6.855	4 8 9	1.490 1.469 1.465
5	96	6.855	6.790	6.751	6.773	3.0	6.965	6.965	6.947	10 16 15	1.503 1.489 1.497
6	102	6.729	6.598	6.528	6.559	3.0	7.083	6.777	6.764	6 11 12	1.477 1.463 1.461
7	108	6.580	6.375	6.224	6.436	3.9	6.637	6.463	6.397	7 8 13	1.472 1.453 1.450
8	231	7.061	6.869	6.725	6.860	2.8	7.167	7.074	6.995	- - -	1.482 1.456 1.451
9	243						6.921	6.711	6.620	14 20 20	1.472 1.453 1.446
	Avg. Std. Dev.	6.872 0.170	6.720 0.187	6.632 0.170	6.725 0.168						

* For cycles 1, 2, and 3 respectively.

Table B-14 (see also Table B-15)
Battery 13 Cell Data (Chg. to 1.450v at C/2, dischg. 0.5 hr at C/2)

Cell No.	Martin Marietta No.	Gulton No.	Manufacturer Data: Overcharge Volts	Manufacturer Data: Overcharge Press.	Manufacturer Data: Capacity (amp-h)	Manufacturer Data: Short Test (v)	Original Acceptance Tests: Meas. Capacity (amp-h)	Original Acceptance Tests: Term. Volt. Chg.*	Original Acceptance Tests: Term. Press. Chg.*	Original Acceptance Tests: Intern. Resist. (milli-ohms)	Shipping Group	Reason for Not Being Used in Original Battery
0	12	2863	1.41	0	6.25	1.18	6.235	1.44 1.42 1.42	1 5 6	3.7	5	Leak
1	22	3124	1.40	15	7.10	1.21	6.868	1.45 1.43 1.43	3 13 14	3.5	8	High cap.dev.
2	35	3128	1.40	12	6.35	1.20	5.995	1.45 1.41 1.41	15 22 24	4.9	8	Low cap.dev.
3	39	3110	1.40	9	6.30	1.20	5.956	1.45 1.43 1.43	8 13 15	3.7	8	Low cap.dev.
4	43	2862	1.41	5	6.30	1.19	6.060	1.45 1.43 1.42	-2.5 1 2	4.4	5	Passed A. T.
5	50	3162	1.41	5	6.60	1.19	5.969	1.45 1.42 1.42	-2.5 0 2	3.5	8	Low cap.dev.
6	51	3156	1.41	6	6.50	1.18	5.960	1.43 1.41 1.40	1 4 4	3.9	8	Low cap.dev.
7	202	2927	1.41	20	6.20	1.21	5.991	1.45 1.43 1.42	-	3.7	6	Low cap.dev.
8	207	2924	1.41	9	6.10	1.19	5.855	1.44 1.42 1.42	-	4.6	6	Low cap.dev.
9	226	2920	1.41	23	6.30	1.20	6.060	1.46 1.43 1.42	-	4.2	6	Passed A. T.

* For test cycles 1, 2, and 3 respectively.

Table B-15 (see also Table B-14)
Battery 13 Cell Data (Acceptance Test Rerun)

Cell No.	Martin Marietta No.	Capacity Cycle 1	Capacity Cycle 2	Capacity Cycle 3	Term. Press.*	Term. Volt.*
0	12	6.703	6.681	6.576	4 7 7	1.467 1.457 1.450
1	22	6.746	7.118	6.148	1 14 15	1.50 1.449 1.490
2	35	6.629	6.615	6.558	5 9 10	1.463 1.453 1.448
3	39	6.703	6.725	6.655	2 4 5	1.492 1.473 1.468
4	43	7.008	6.987	6.947	1 4 3	1.468 1.457 1.452
5	50	6.550	6.484	6.462	6 7 7	1.458 1.456 1.442
6	51	6.572	6.550	6.480	3 5 4	1.453 1.444 1.440
7	202	6.899	6.790	6.615	-	1.454 1.438 1.435
8	207	6.812	6.768	6.667	-	1.458 1.442 1.433
9	226	6.943	6.921	6.794	-	1.459 1.445 1.441

* For cycles 1, 2, and 3 respectively.

Table B-16 (see also Table B-17)
Battery 14 Cell Data
(Chg. 10 min at C/2, then to 1.42v at C/10; dischg. 0.5 hr. at C/2)

Cell No.	Martin Marietta No.	Gulton No.	Manufacturer Data				Acceptance Tests				Shipping Group	Reason for Not Being Used in Original Battery
			Overcharge		Capacity (amp-h)	Short Test (v)	Meas. Capacity (amp-h)	Term. Volt. Chg.**	Term. Press. Chg.**	Intern. Resist. (milli-ohms)		
			Volts	Press.								
0	25	2886	1.41	5	6.25	1.18	6.113	1.43 1.40 1.40	1 3 4	3.7	5	Passed A. T.
1	74	2887	1.41	4	6.65	1.18	6.584	1.44 1.43 1.42	-10 6 9	4.7	5	Passed A. T.
2	82	3121	1.41	12	6.70	1.20	6.785	1.45 1.44 1.43	12 20 24	3.7	8	High cap.dev.
3	98	3111	1.42	11	6.95	1.21	6.794	1.45 1.42 1.43	-2.5 - 2	4.6	8	High cap.dev.
4	194	2925	1.41	16	6.65	1.18	6.715	1.45 1.43 1.42	-	3.9	6	High cap.dev.
5	196	2931	1.41	32	6.60	1.20	6.650	1.45 1.43 1.42	-	3.9	6	Passed A. T.
6	201	2891	1.41	6	6.95	1.18	6.794	1.45 1.43 1.43	-	3.9	6	High cap.dev.
7	219	2900	1.41	14	7.10	1.19	6.833	1.45 1.43 1.42	-	3.3	6	High cap.dev.
8	222	2901	1.41	5	7.30	1.19	7.012	1.45 1.43 1.42	-	3.9	6	High cap.dev.
9	223	2892	1.41	5	6.80	1.18	6.892	1.45 1.43 1.42	-	3.7	6	High cap.dev.

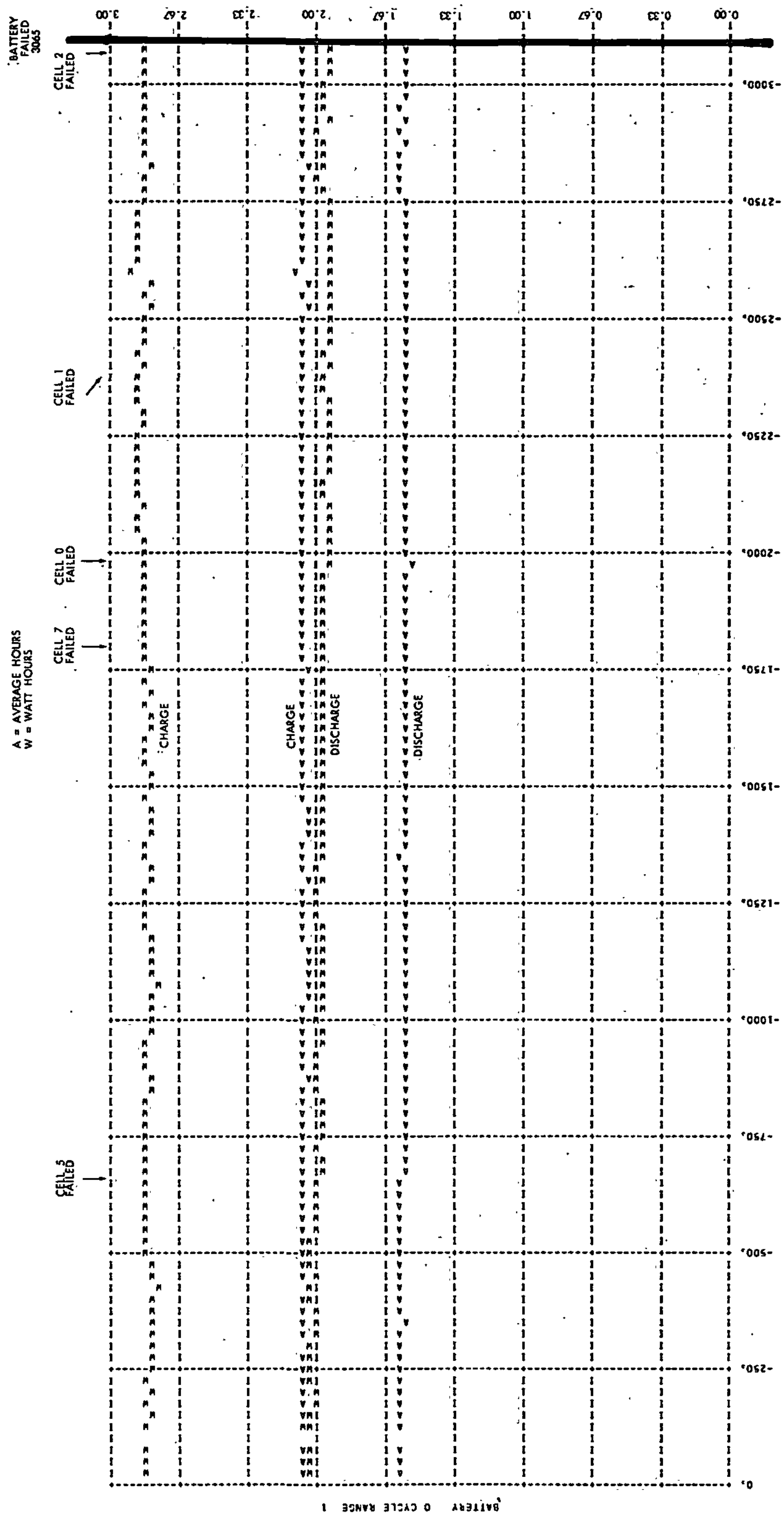
* For test cycles 1, 2, and 3 respectively.

Table B-17 (see also Table B-16)
Battery 14 Cell Data (Acceptance Test Reruns)

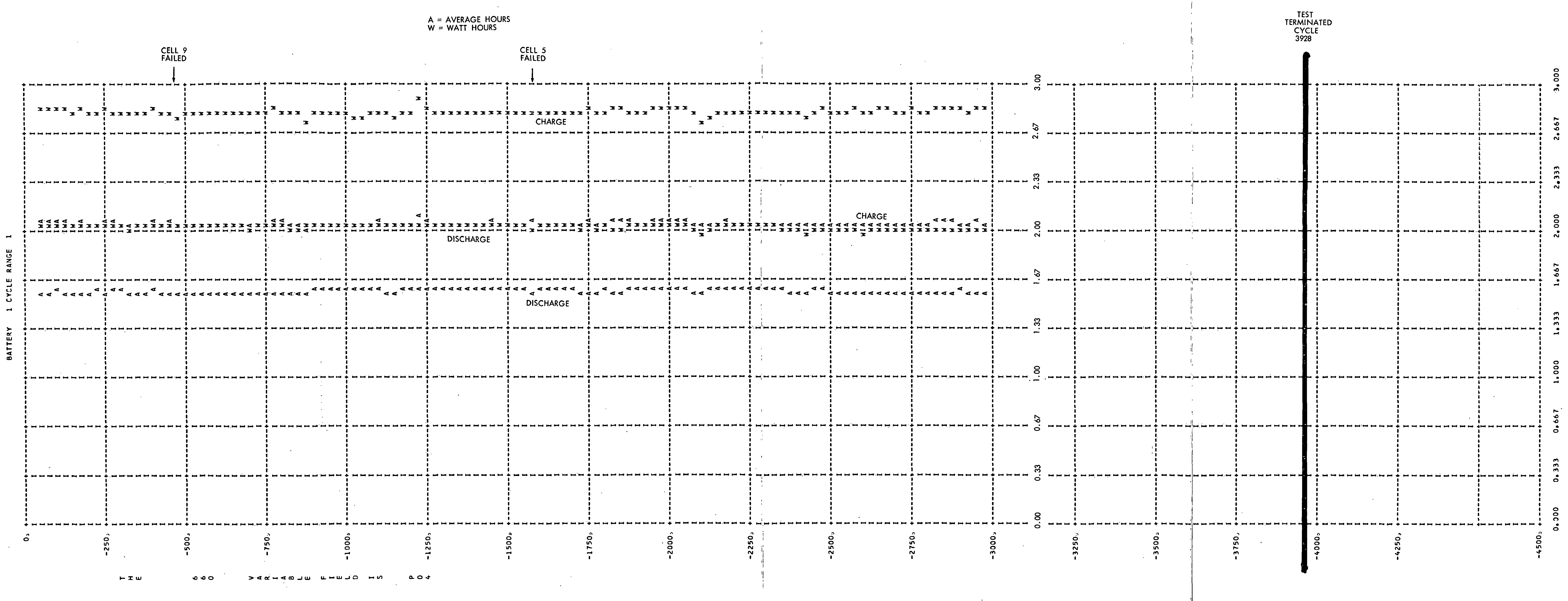
Gulton No.	Acceptance Test Rerun (10-26-64)						Acceptance Test Rerun (12-6-64)			
	Position	Capacity Cycle 1	Capacity Cycle 2	Capacity Cycle 3	Short Test (v)	Intern. Resist. (milli-ohms)	Capacity Cycle 1	Capacity Cycle 2	Term. Volt.*	Press.*
25	1	6.834	6.777	6.724	1.162	4.4	6.599	6.586	1.45 1.43	2 3
74		7.117	7.074	7.030	1.181	4.0	6.932	6.889	1.46 1.46	3 3
82	2	6.965	6.938	6.890	1.182	3.9	6.816	6.794	1.45 1.45	5 6
98		7.008	7.030	7.030	1.184	4.0	6.872	6.899	1.49 1.48	6 7
194		7.183	7.078	7.008	1.172	4.0	6.937	6.833	1.44 1.44	
196	3	7.052	6.938	6.877	1.174	4.4	6.846	6.764	1.45 1.44	
201	4	7.445	7.456	7.384	1.172	3.9	7.236	7.227	1.46 1.44	
219	5	7.270	7.183	7.131	1.176	4.0	7.032	6.967	1.45 1.44	
222	6	7.358	7.292	7.270	1.177	3.9	7.180	7.149	1.46 1.44	
223	7	7.205	7.117	7.069	1.178	4.0	7.019	6.963	1.47 1.45	
Avg. Std Dev.		7.144 0.164								

APPENDIX C

VALUES OF AMPERE-HOURS AND WATT-HOURS VERSUS CYCLE NUMBER


BATTERY FAILED 3065
CELL 2 FAILED
CELL 1 FAILED
CELL 0 FAILED
CELL 7 FAILED
CELL 5 FAILED
A = AVERAGE HOURS
W = WATT HOURS
CHARGE
DISCHARGE
CHARGE
DISCHARGE
3.00
2.67
2.33
2.00
1.67
1.33
1.00
0.67
0.33
0.00
0.
250.
500.
750.
1000.
1250.
1500.
1750.
2000.
2250.
2500.
2750.
3000.
BATTERY 0 CYCLE RANGE 1

3090



A = AVERAGE HOURS
W = WATT HOURS
CELL 9 FAILED
CELL 5 FAILED
TEST TERMINATED CYCLE 3928
CHARGE
DISCHARGE
CHARGE
DISCHARGE
BATTERY 1 CYCLE RANGE 1
0.00
0.33
0.67
1.00
1.33
1.67
2.00
2.33
2.67
3.00
0,
-250,
-500,
-750,
-1000,
-1250,
-1500,
-1750,
-2000,
-2250,
-2500,
-2750,
-3000,
-3250,
-3500,
-3750,
-4000,
-4250,
-4500,

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C-4

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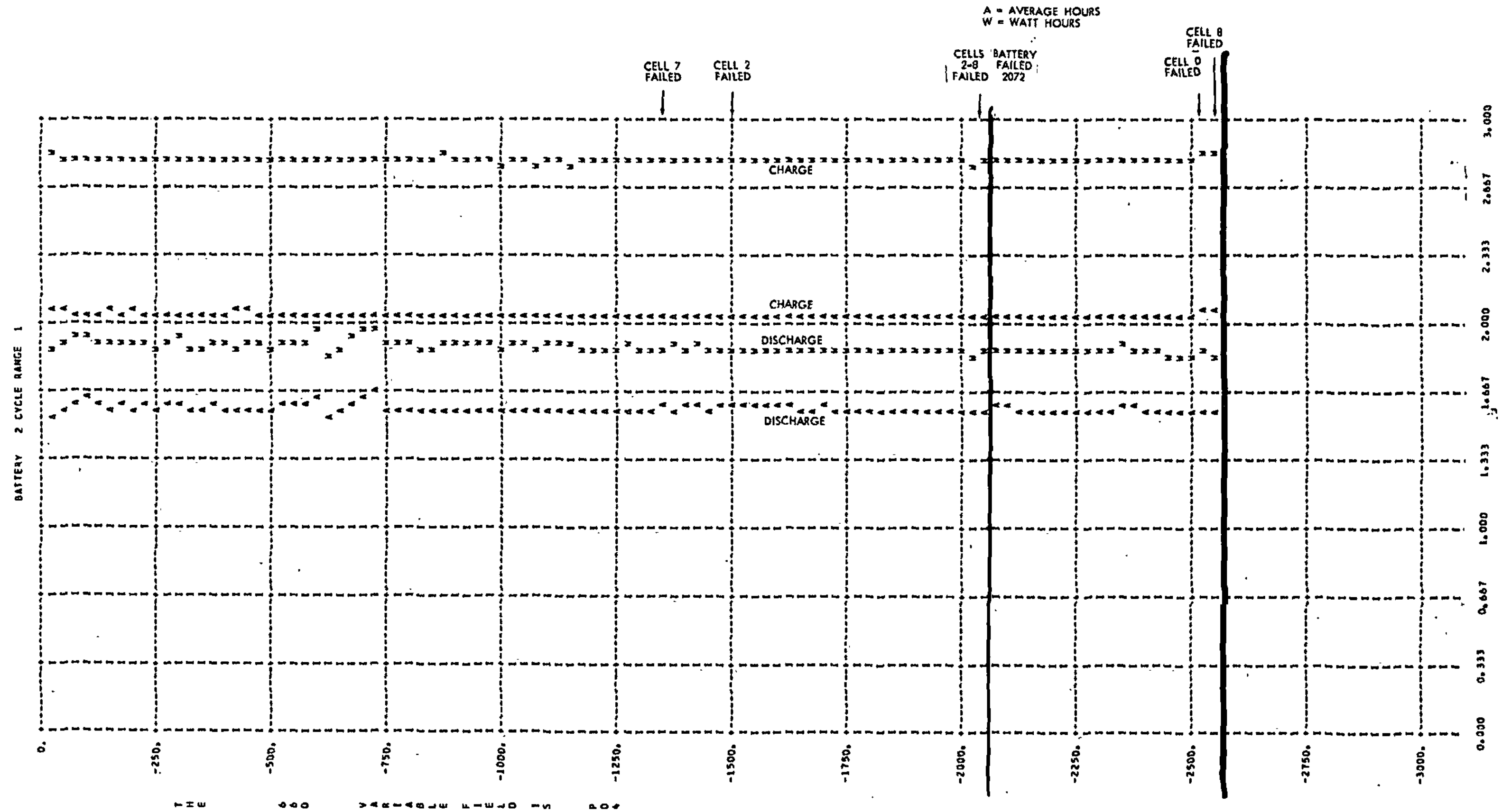

A = AVERAGE HOURS
W = WATT HOURS
CELL 7 FAILED
CELL 2 FAILED
CELLS 2-8 FAILED
BATTERY FAILED 2072
CELL 0 FAILED
CELL 8 FAILED
CHARGE
CHARGE
DISCHARGE
DISCHARGE
BATTERY 2 CYCLE RANGE 1
0.000
0.333
0.667
1.000
1.333
1.667
2.000
2.333
2.667
3.000
0.
250.
500.
750.
1000.
1250.
1500.
1750.
2000.
2250.
2500.
2750.
3000.

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C-6

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T = TIME (HOURS)
A = AMPERE HOURS
W = WATT HOURS
CELL 0 FAILED
CELL 6 FAILED
CELL 8 FAILED
CELL 5 FAILED
ALL CELLS ON LINE EXCEPT #9
CELL 6 FAILED
BATTERY FAILED 5418
CELL 3 FAILED
CELLS 0-12 FAILED
CHARGE
DISCHARGE
CHARGE
DISCHARGE
CHARGE
DISCHARGE
BATTERY 4 CYCLE RANGE 1
POLT P02A P03W

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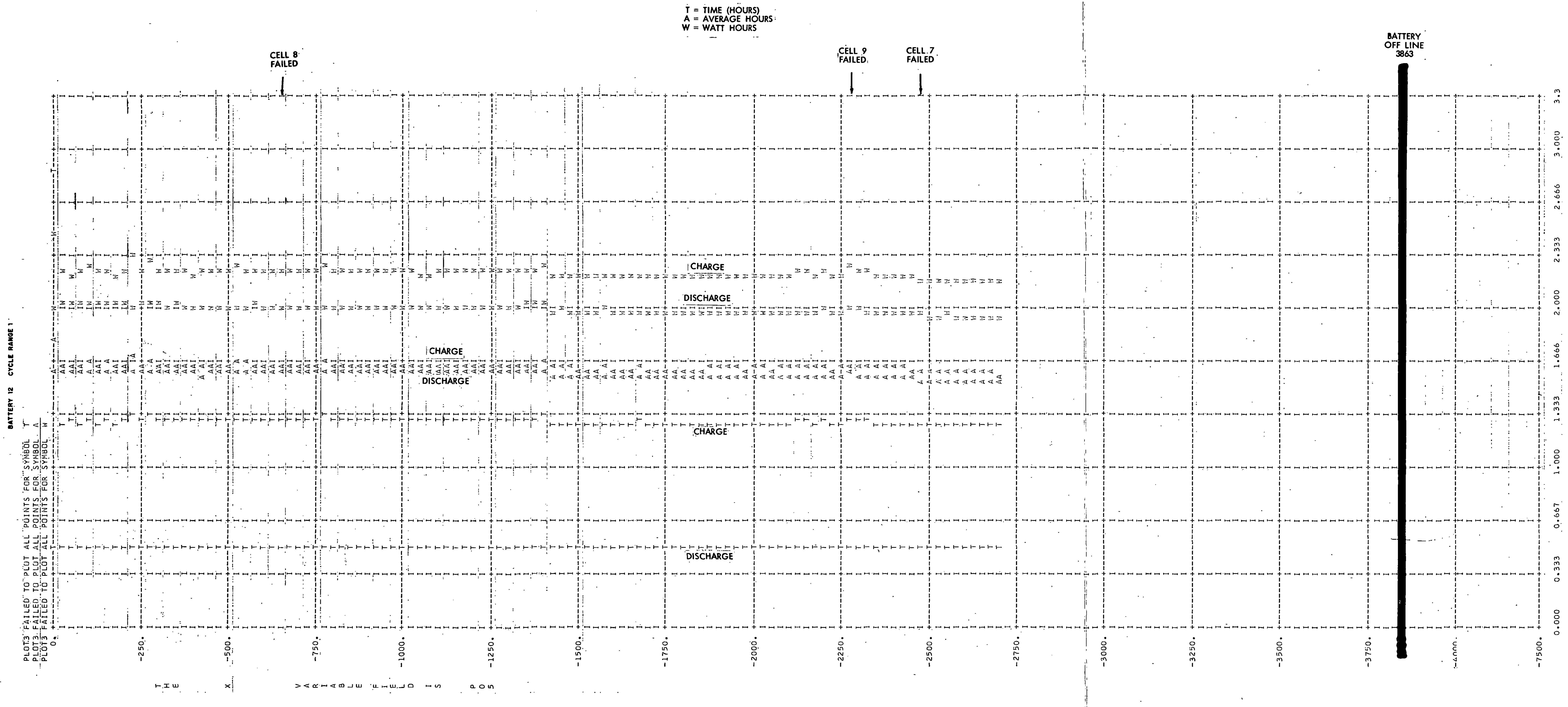
C-8


T = TIME (HOURS)
A = AVERAGE HOURS
W = WATT HOURS
CELL 8 FAILED
CELL 9 FAILED
CELL 7 FAILED
BATTERY OFF LINE 3863
CHARGE
DISCHARGE
CHARGE
DISCHARGE
CHARGE
DISCHARGE
BATTERY 12 CYCLE RANGE 1
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL T
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL A
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL W
0.000
0.333
0.667
1.000
1.333
1.666
2.000
2.333
2.666
3.000
3.3
P01T P02A P03W
0.
-250.
-500.
-750.
-1000.
-1250.
-1500.
-1750.
-2000.
-2250.
-2500.
-2750.
-3000.
-3250.
-3500.
-3750.
-7500.
THE X VARIABLE FIELD IS POS

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T = TIME (HOURS)
A = AMPERE HOURS
W = WATT HOURS
VEOC = 1.435
VEOC = 1.44
VEOC = 1.45
BATTERY OFF LINE 5976
BATTERY 13 CYCLE RANGE 1
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL T
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL A
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL W
CHARGE
DISCHARGE
CHARGE
DISCHARGE
CHARGE
DISCHARGE
0.
-250.
-500.
-750.
-1000.
-1250.
-1500.
-1750.
-2000.
-2250.
-2500.
-2750.
-3000.
-3250.
-3500.
-3750.
-4000.
-4250.
-4500.
-4750.
-5000.
-5250.
-5500.
-5750.
-6000.
-7500.
0.000
0.333
0.667
1.000
1.333
1.666
2.000
2.333
2.666
3.000

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C-12

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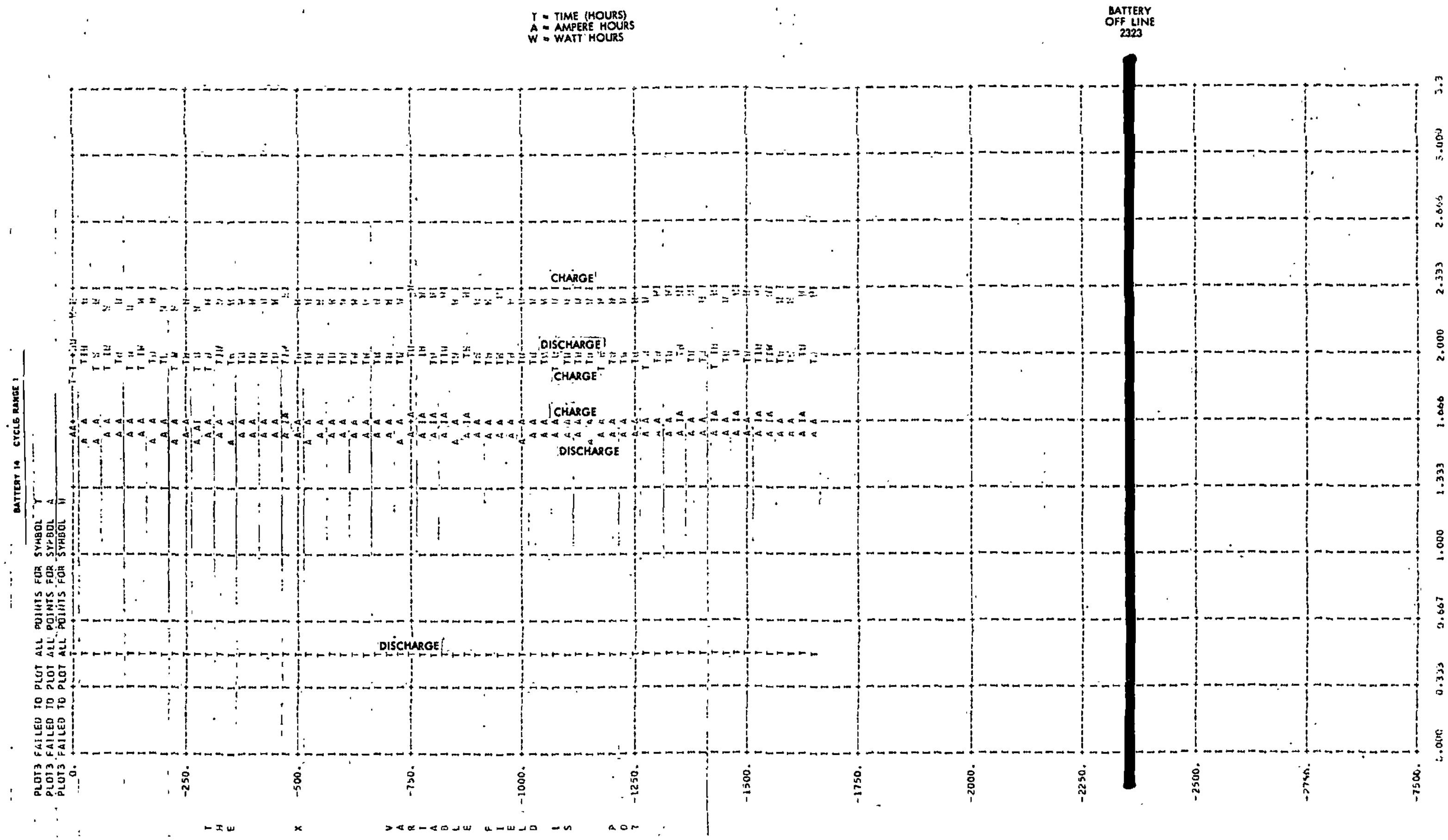
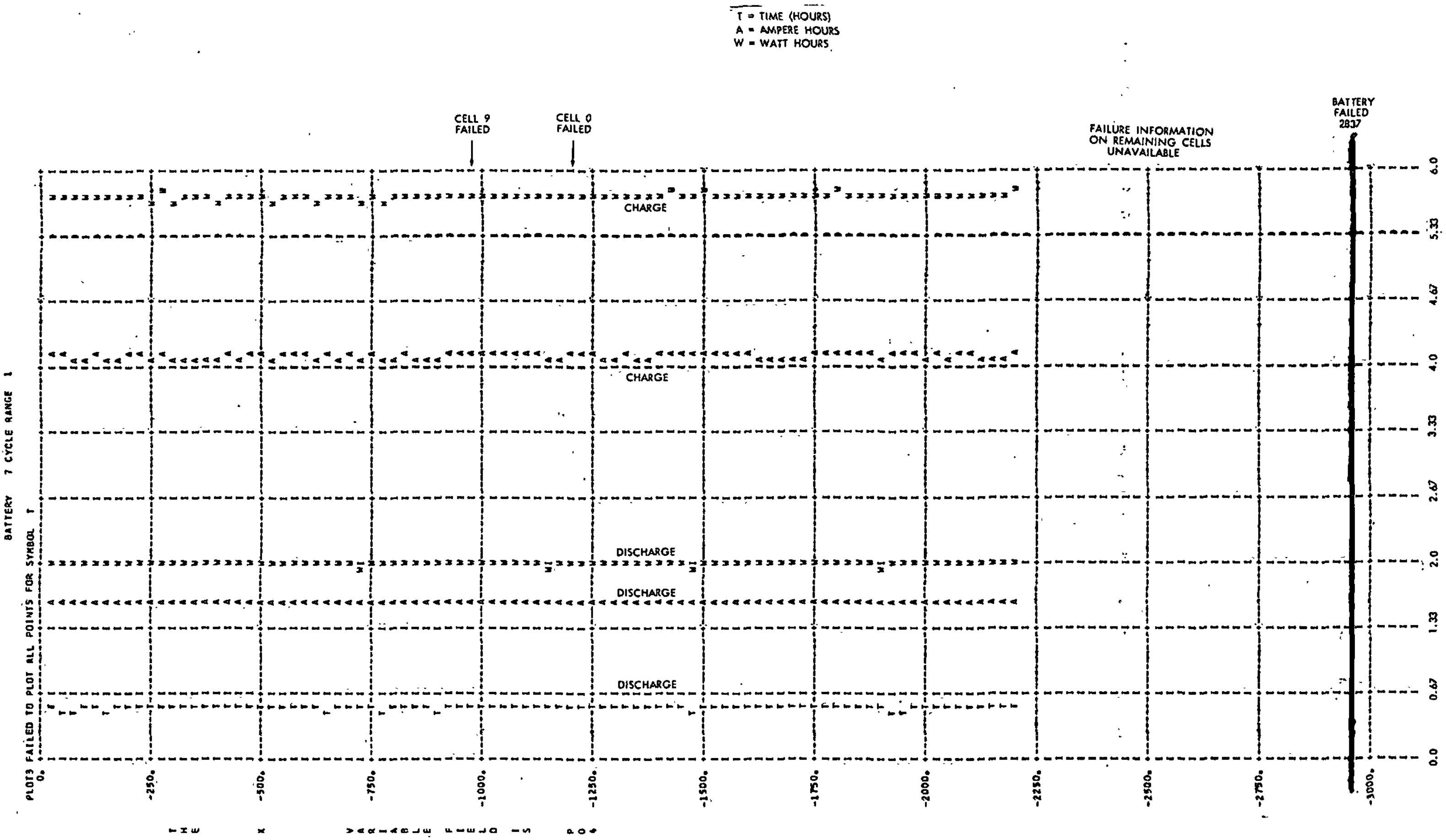
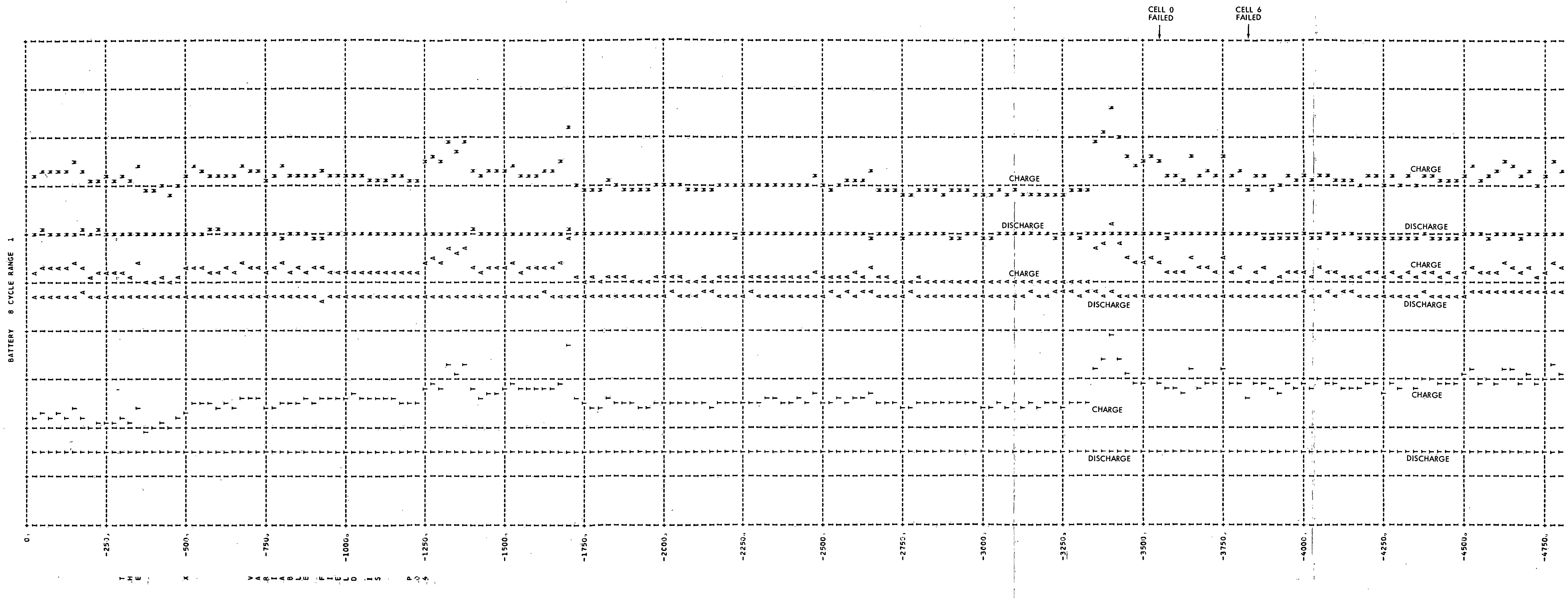


T = TIME (HOURS)
A = AMPERE HOURS
W = WATT HOURS
BATTERY OFF LINE 2323
BATTERY 14 CYCLE RANGE 1
PLOTS FAILED TO PLOT ALL POINTS FOR SYMBOL T
PLOTS FAILED TO PLOT ALL POINTS FOR SYMBOL A
PLOTS FAILED TO PLOT ALL POINTS FOR SYMBOL W
CHARGE
DISCHARGE
CHARGE
CHARGE
DISCHARGE
DISCHARGE
0.
-250.
-500.
-750.
-1000.
-1250.
-1500.
-1750.
-2000.
-2250.
-2500.
-2750.
-3000.
0.000
0.333
0.667
1.000
1.333
1.666
2.000
2.333
2.666
3.000
3.3



T = TIME (HOURS)
A = AMPERE HOURS
W = WATT HOURS
CELL 9 FAILED
CELL 0 FAILED
FAILURE INFORMATION ON REMAINING CELLS UNAVAILABLE
BATTERY FAILED 2837
CHARGE
CHARGE
DISCHARGE
DISCHARGE
DISCHARGE
BATTERY 7 CYCLE RANGE 1
PLOTS FAILED TO PLOT ALL POINTS FOR SYMBOL T
THE X VARIABLE FIELD IS POS
6.0
5.33
4.67
4.0
3.33
2.67
2.0
1.33
0.67
0.0
0.
-250.
-500.
-750.
-1000.
-1250.
-1500.
-1750.
-2000.
-2250.
-2500.
-2750.
-3000.


CELL 0
FAILED
CELL 6
FAILED
BATTERY 8 CYCLE RANGE 1
CHARGE
DISCHARGE
CHARGE
DISCHARGE
CHARGE
DISCHARGE
CHARGE
DISCHARGE
CHARGE
DISCHARGE
CHARGE
DISCHARGE
0.
-250.
-500.
-750.
-1000.
-1250.
-1500.
-1750.
-2000.
-2250.
-2500.
-2750.
-3000.
-3250.
-3500.
-3750.
-4000.
-4250.
-4500.
-4750.
THE X VARIABLE FIELD IS

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page 16

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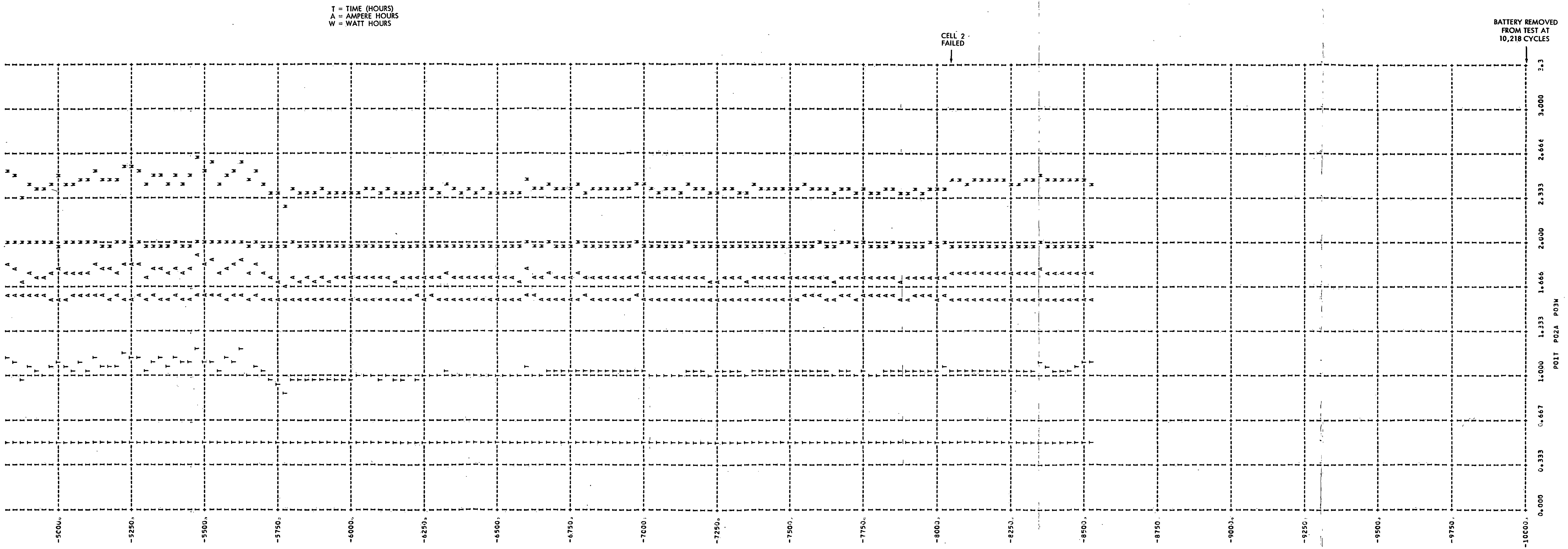

T = TIME (HOURS)
A = AMPERE HOURS
W = WATT HOURS
CELL 2
FAILED
BATTERY REMOVED
FROM TEST AT
10,218 CYCLES

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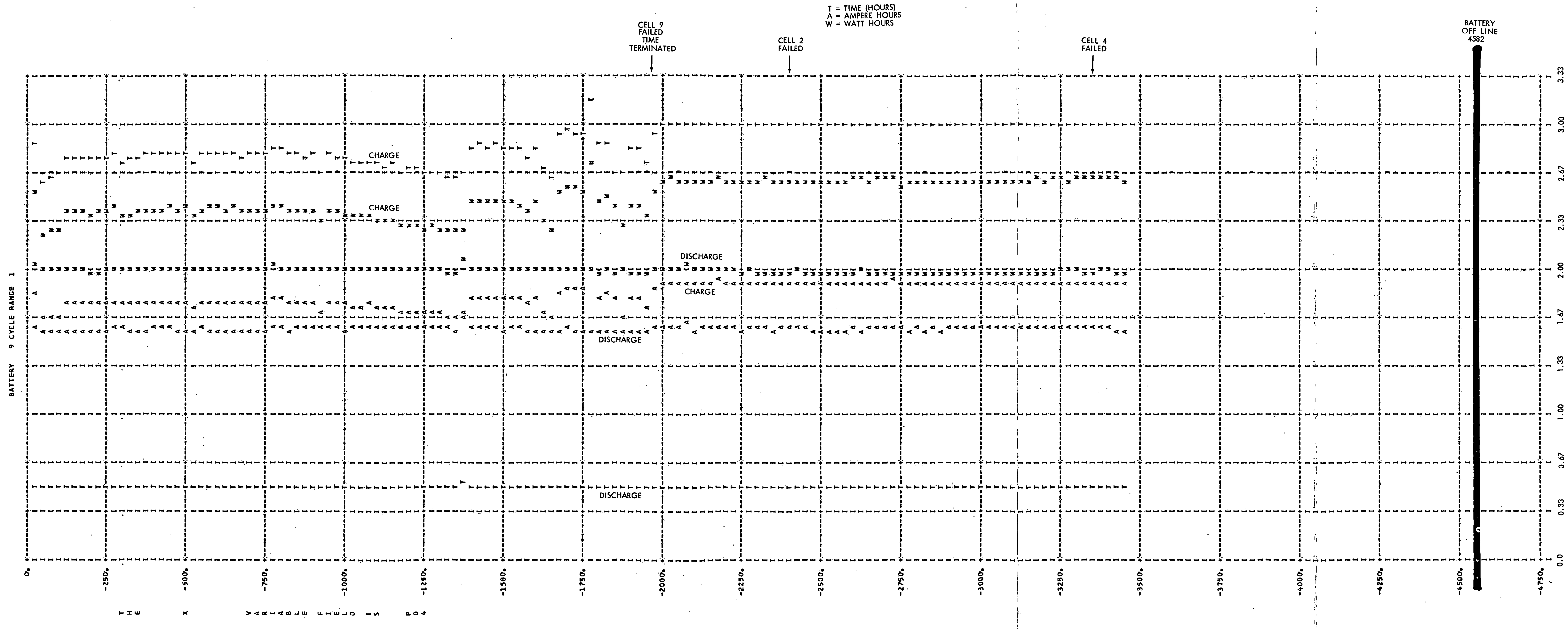

T = TIME (HOURS)
A = AMPERE HOURS
W = WATT HOURS
CELL 9 FAILED TIME TERMINATED
CELL 2 FAILED
CELL 4 FAILED
BATTERY OFF LINE 4582
BATTERY 9 CYCLE RANGE 1
CHARGE
CHARGE
DISCHARGE
CHARGE
DISCHARGE
DISCHARGE
3.33
3.00
2.67
2.33
2.00
1.67
1.33
1.00
0.67
0.33
0.0
0.
250.
500.
750.
1000.
1250.
1500.
1750.
2000.
2250.
2500.
2750.
3000.
3250.
3500.
3750.
4000.
4250.
4500.
4750.
THE X VARIABLE FIELD IS PO4

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C-20

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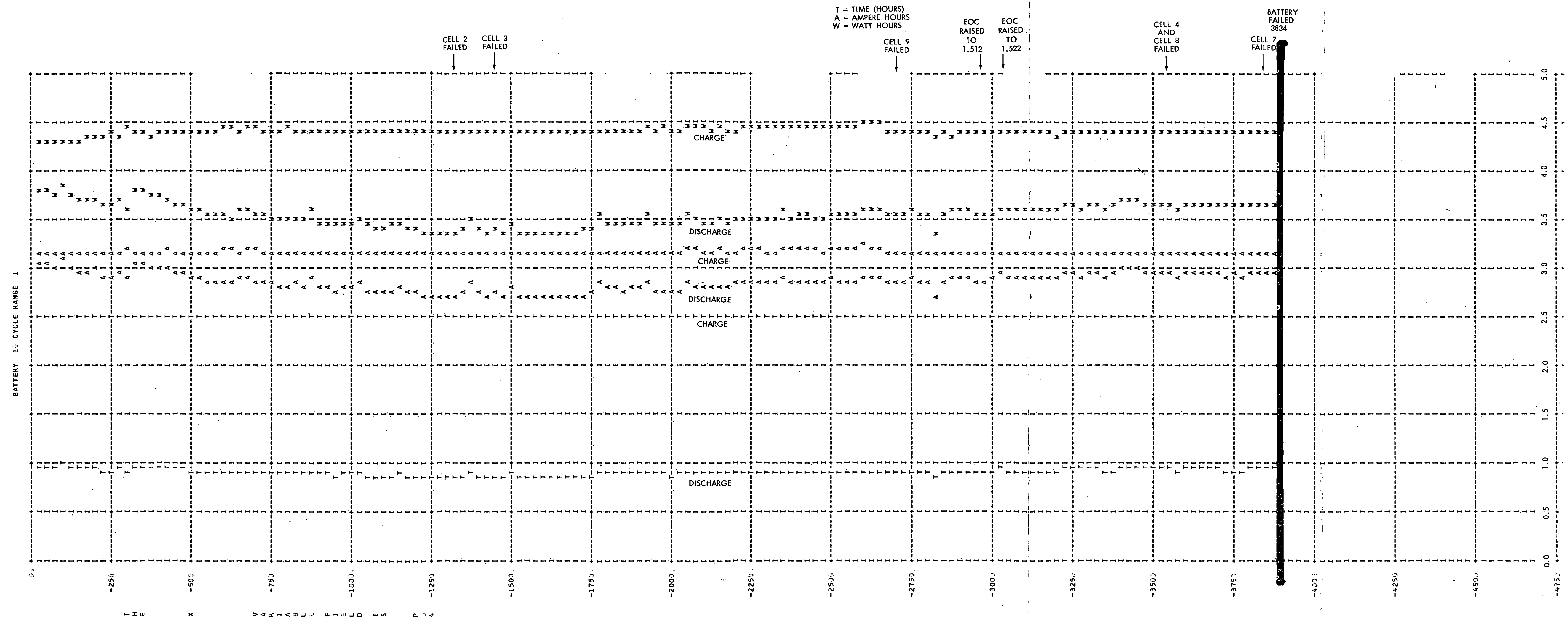

T = TIME (HOURS)
A = AMPERE HOURS
W = WATT HOURS
CELL 2 FAILED
CELL 3 FAILED
CELL 9 FAILED
EOC RAISED TO 1.512
EOC RAISED TO 1.522
CELL 4 AND CELL 8 FAILED
CELL 7 FAILED
BATTERY FAILED 3834
CHARGE
DISCHARGE
CHARGE
DISCHARGE
CHARGE
DISCHARGE
BATTERY 15 CYCLE RANGE 1

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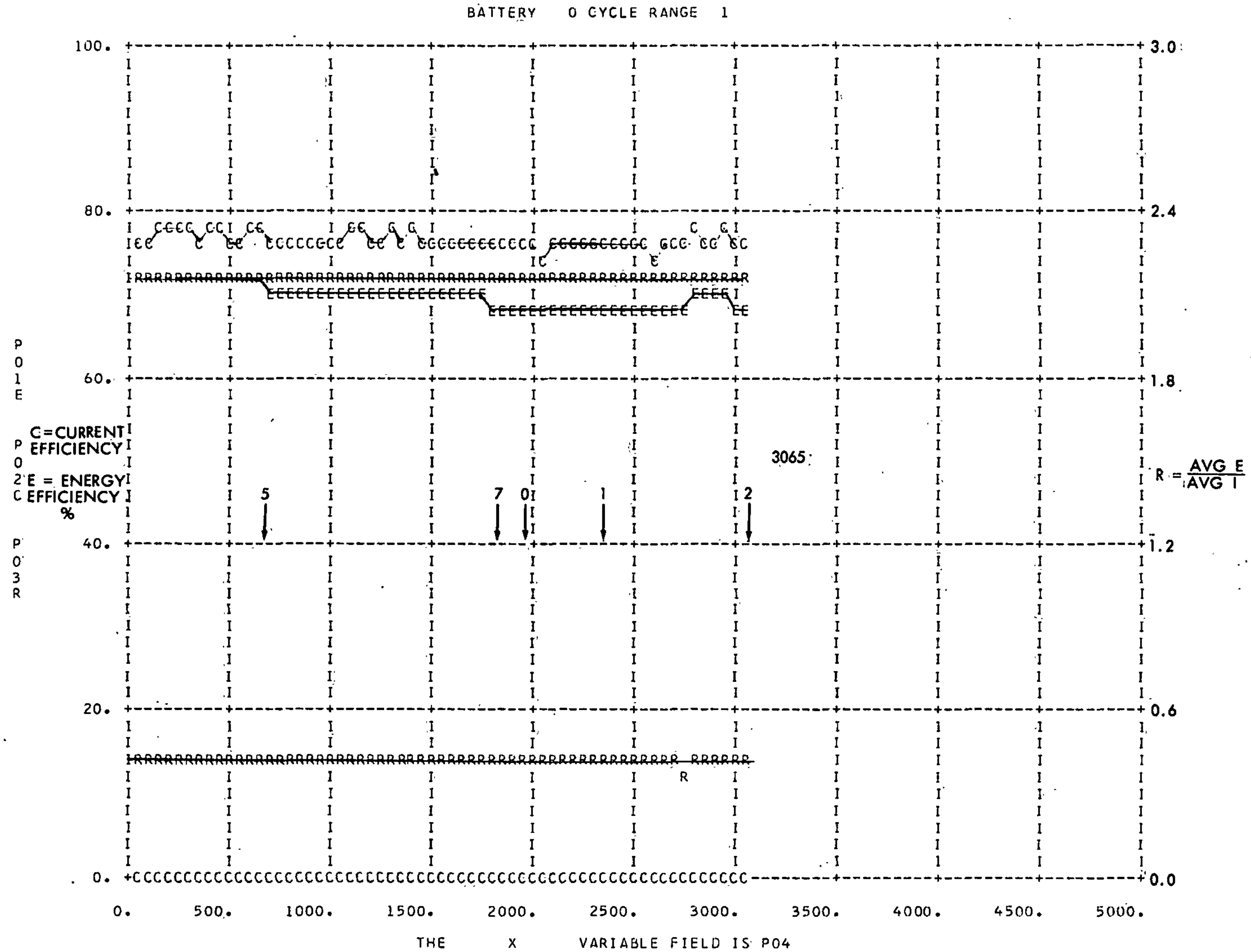
T = TIME (HOURS)
A = AMPERE HOURS
W = WATT HOURS
CELL 3 FAILED
CELL 7 FAILED
CELL 5 FAILED
CELL 1 FAILED
CHARGED TIME REDUCED BECAUSE HIGH EOC VOLTAGE
CELL 4 FAILED
BATTERY FAILED 5793
CHARGE
DISCHARGE
CHARGE
DISCHARGE
CHARGE
DISCHARGE
BATTERY 11 CYCLE RANGE 1
TIME X VARIABLE FIELD IS P 4

APPENDIX D

TRENDS IN CURRENT EFFICIENCY, ENERGY EFFICIENCY, AND E/I RATIO



BATTERY 0 CYCLE RANGE 1
100.
80.
60.
40.
20.
0.
3.0
2.4
1.8
1.2
0.6
0.0
P 0 1 E
P 0 2 C
P 0 3 R
C=CURRENT EFFICIENCY
E = ENERGY EFFICIENCY
%
5
7
0
1
2
3065
R = AVG E / AVG I
0.
500.
1000.
1500.
2000.
2500.
3000.
3500.
4000.
4500.
5000.
THE X VARIABLE FIELD IS P04

Figure 4a

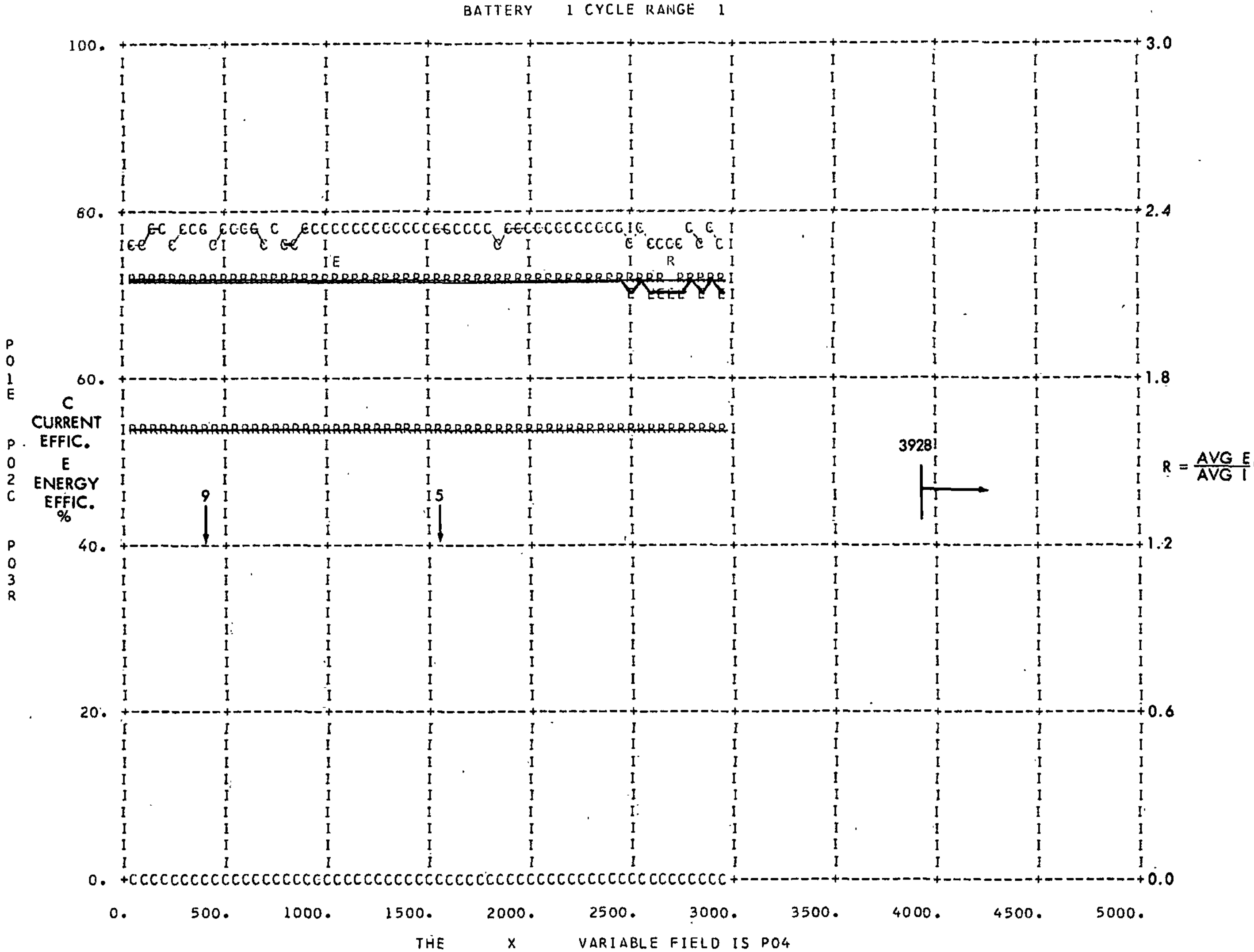

BATTERY 1 CYCLE RANGE 1
100.
80.
60.
40.
20.
0.
3.0
2.4
1.8
1.2
0.6
0.0
P01E
C CURRENT EFFIC.
P02C
E ENERGY EFFIC. %
P03R
9
15
3928
R = AVG E / AVG I
0.
500.
1000.
1500.
2000.
2500.
3000.
3500.
4000.
4500.
5000.
THE X VARIABLE FIELD IS P04

Figure 4b

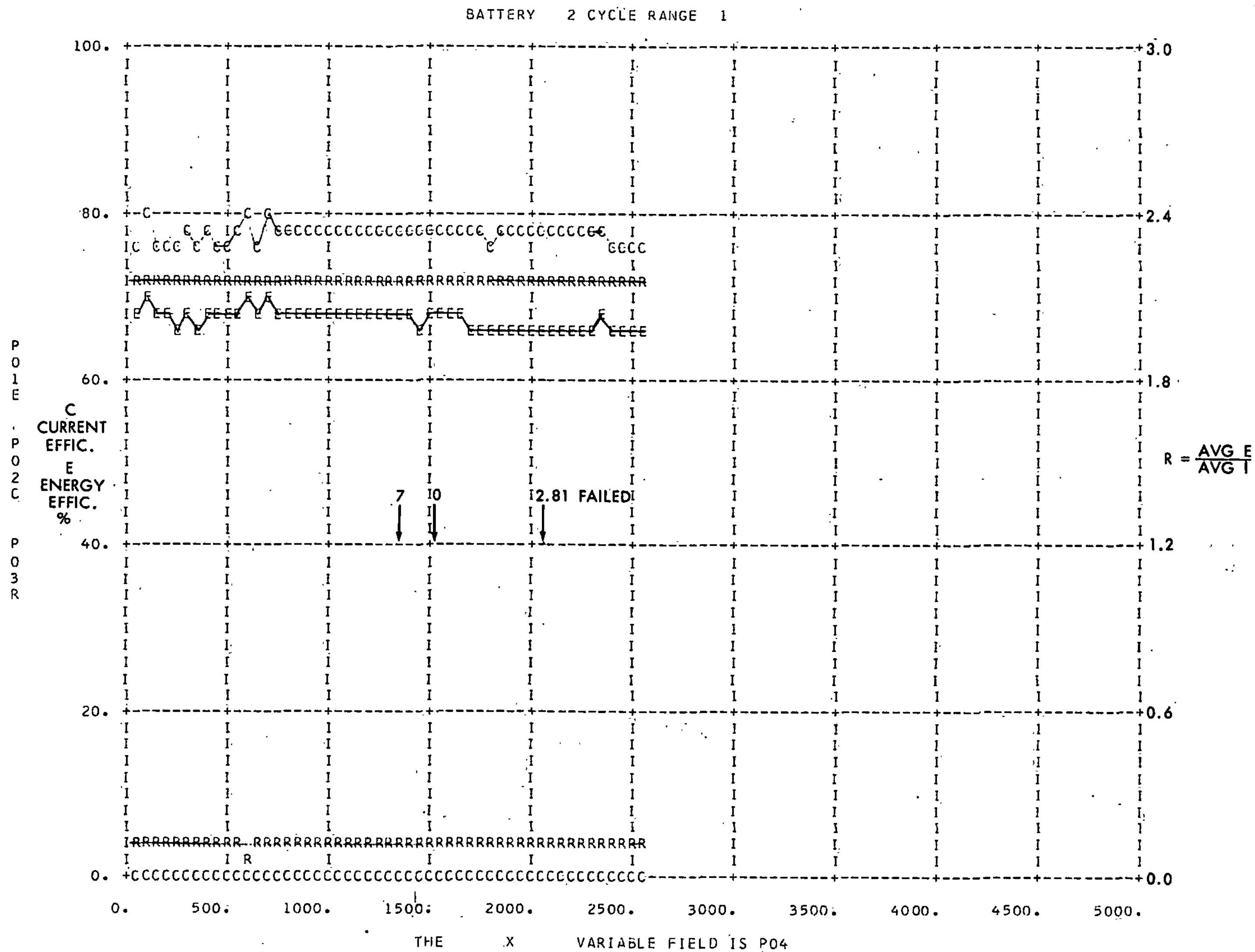

BATTERY 2 CYCLE RANGE 1
100.
80.
60.
40.
20.
0.
3.0
2.4
1.8
1.2
0.6
0.0
P01E . P02C P03R
C CURRENT EFFIC.
E ENERGY EFFIC. %
R = AVG E / AVG I
7
10
2.81 FAILED
0. 500. 1000. 1500. 2000. 2500. 3000. 3500. 4000. 4500. 5000.
THE X VARIABLE FIELD IS P04

Figure 4c

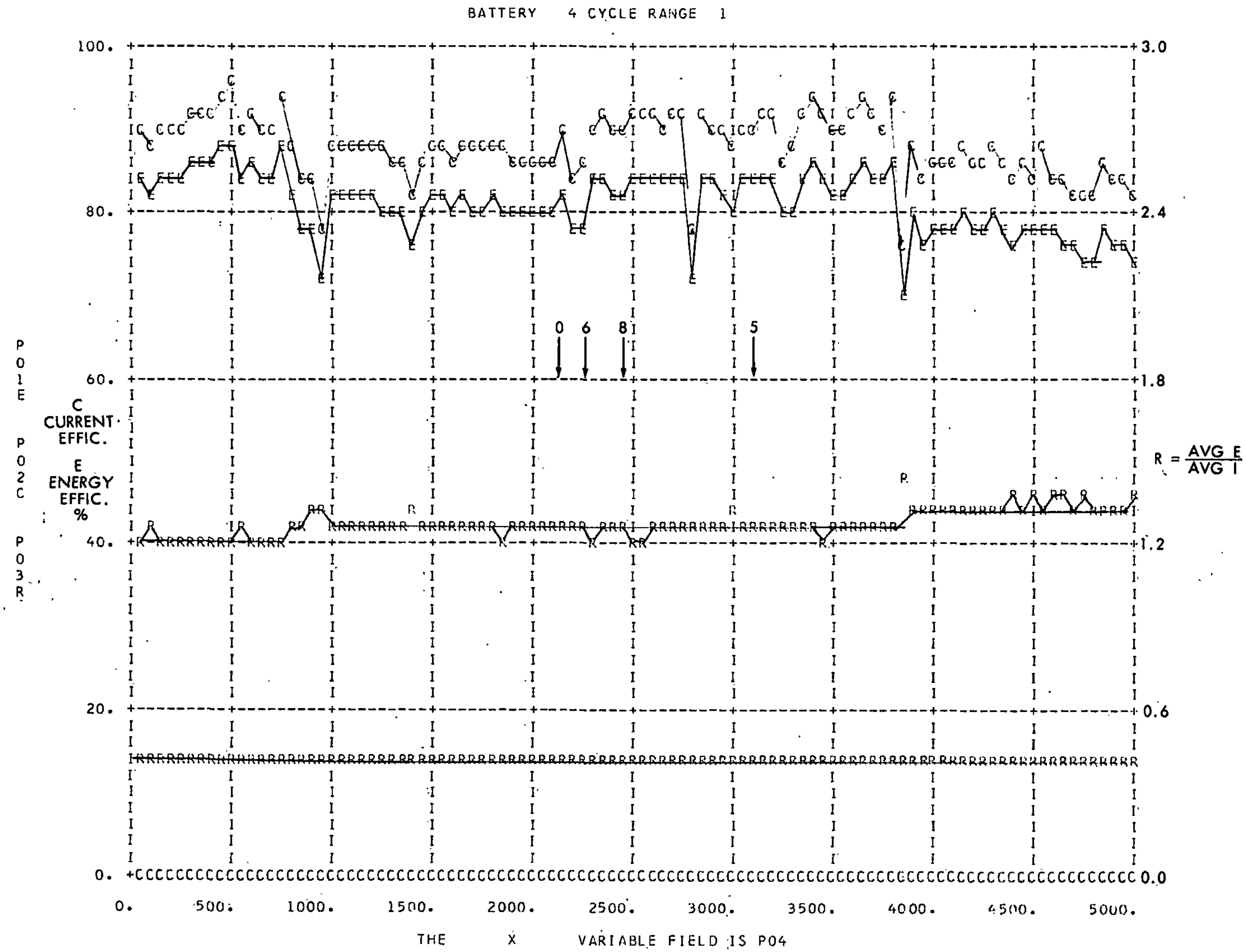

BATTERY 4 CYCLE RANGE 1
100.
80.
60.
40.
20.
0.
3.0
2.4
1.8
1.2
0.6
0.0
P01E
P02C
P03R
C CURRENT EFFIC.
E ENERGY EFFIC. %
R = AVG E / AVG I
0 6 8 5
0. 500. 1000. 1500. 2000. 2500. 3000. 3500. 4000. 4500. 5000.
THE X VARIABLE FIELD IS P04

Figure 4d

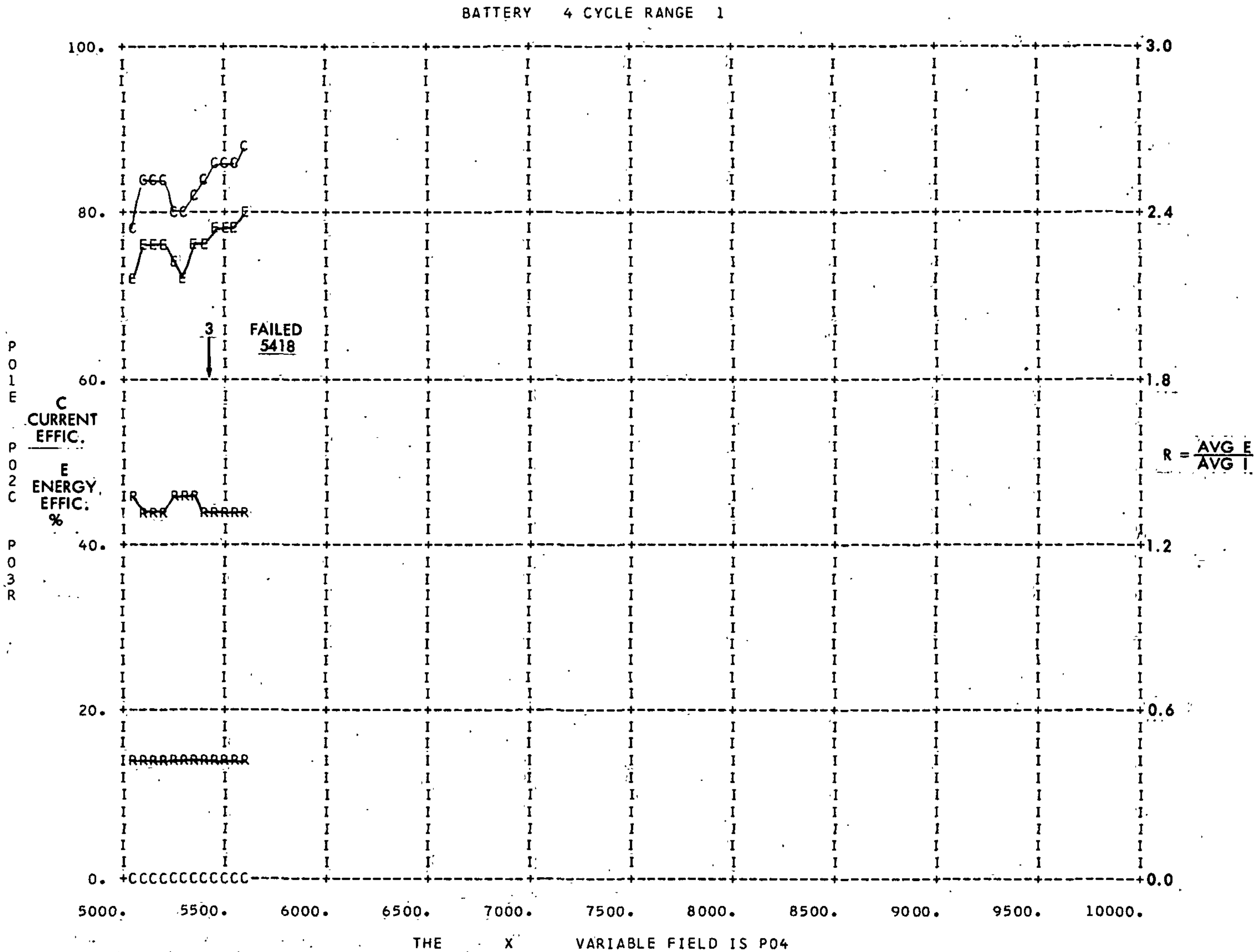


Figure 4d (Continued)

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL E
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL C
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL R

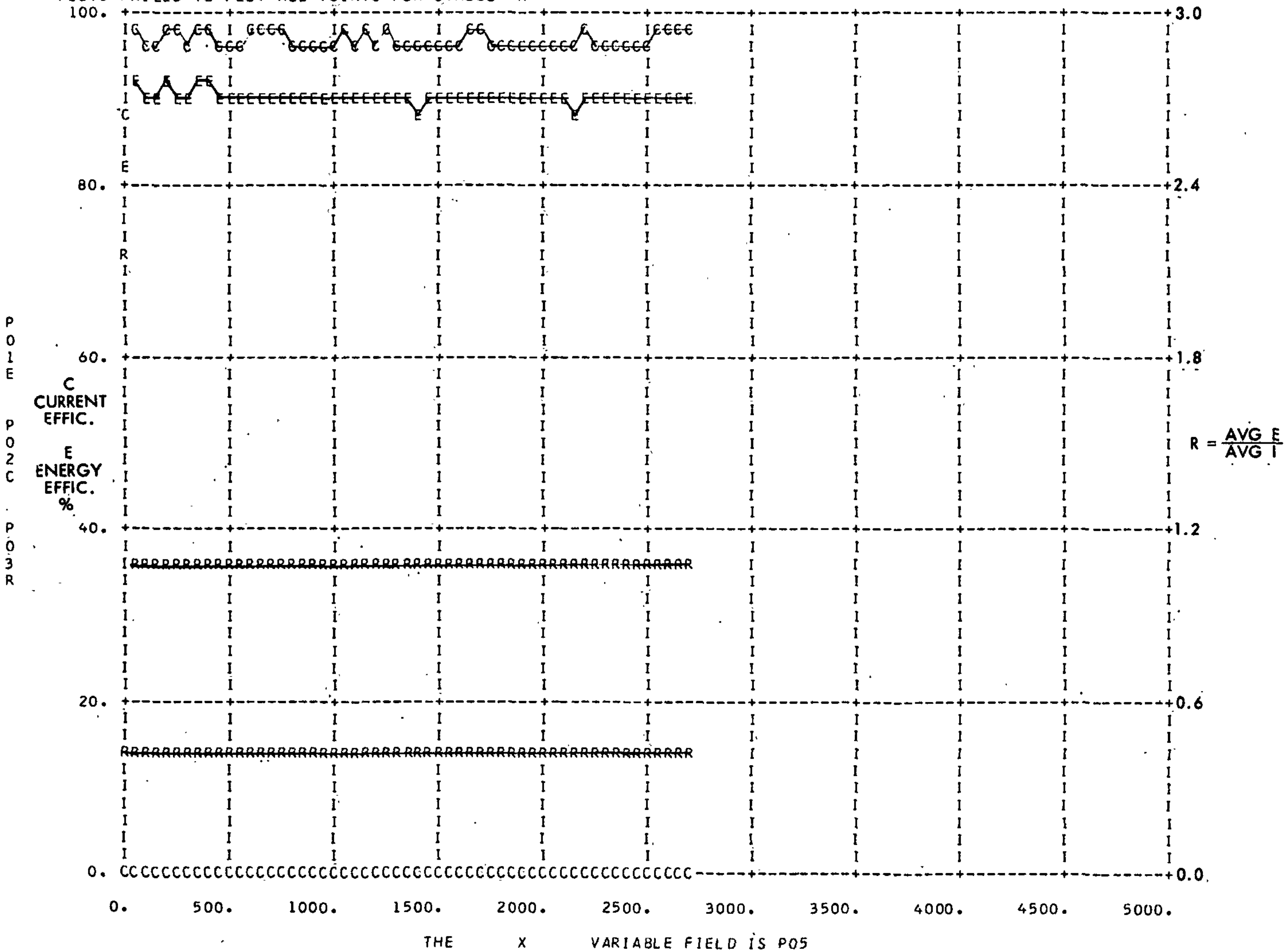


Figure 4e

BATTERY 13 CYCLE RANGE 1

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL E
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL C
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL R

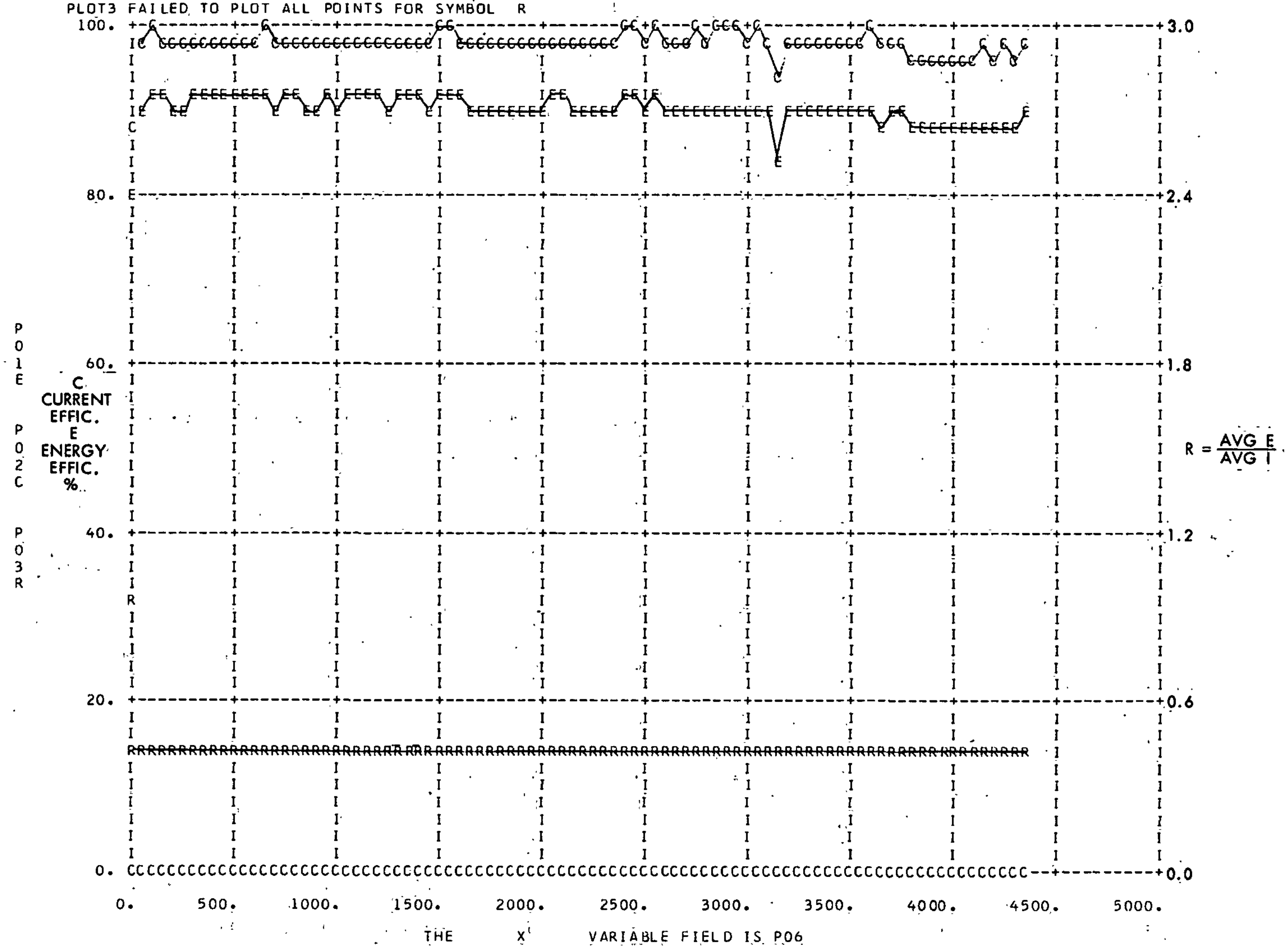


Figure 4f

BATTERY 14 CYCLE RANGE 1

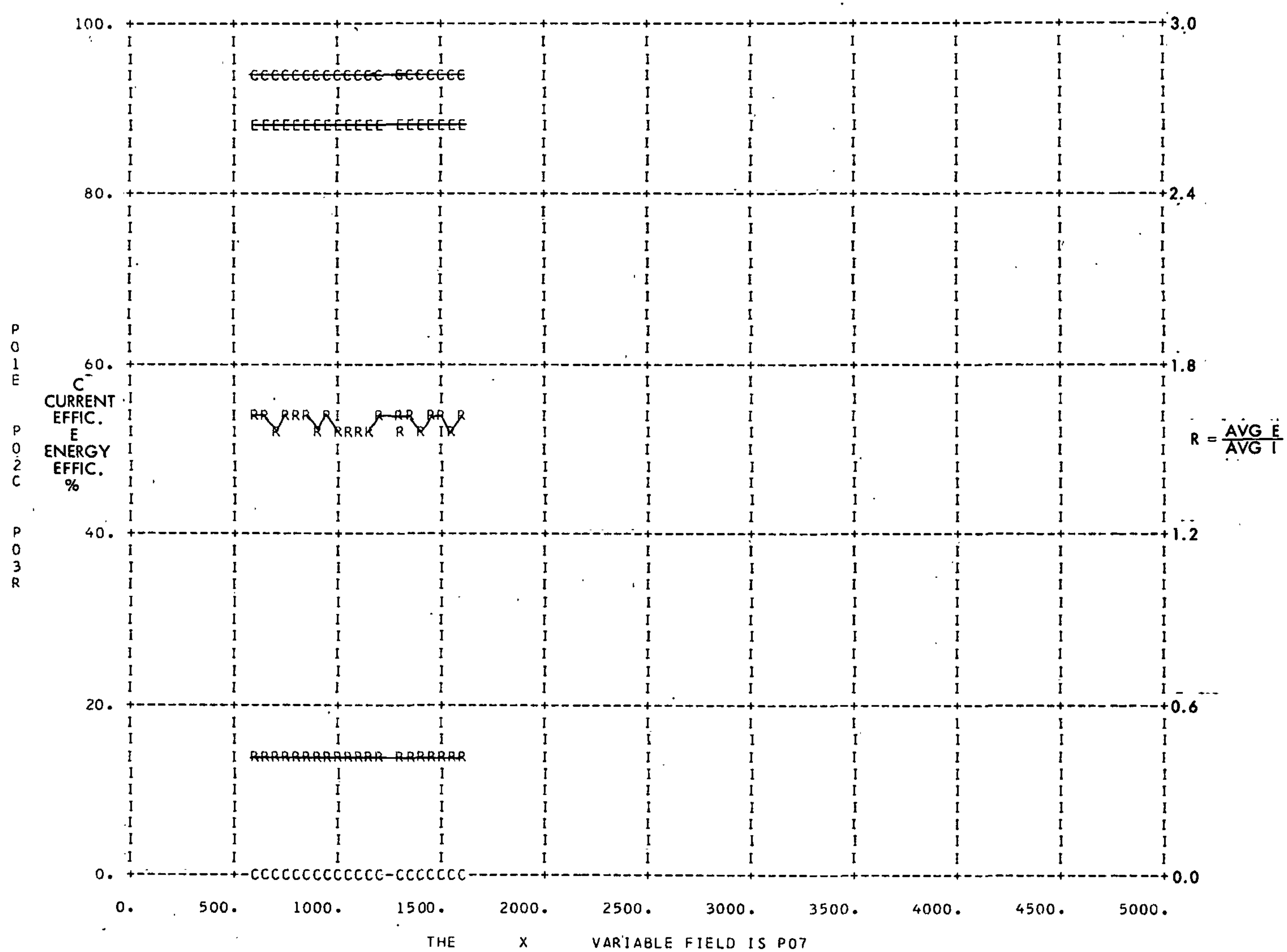


Figure 4g

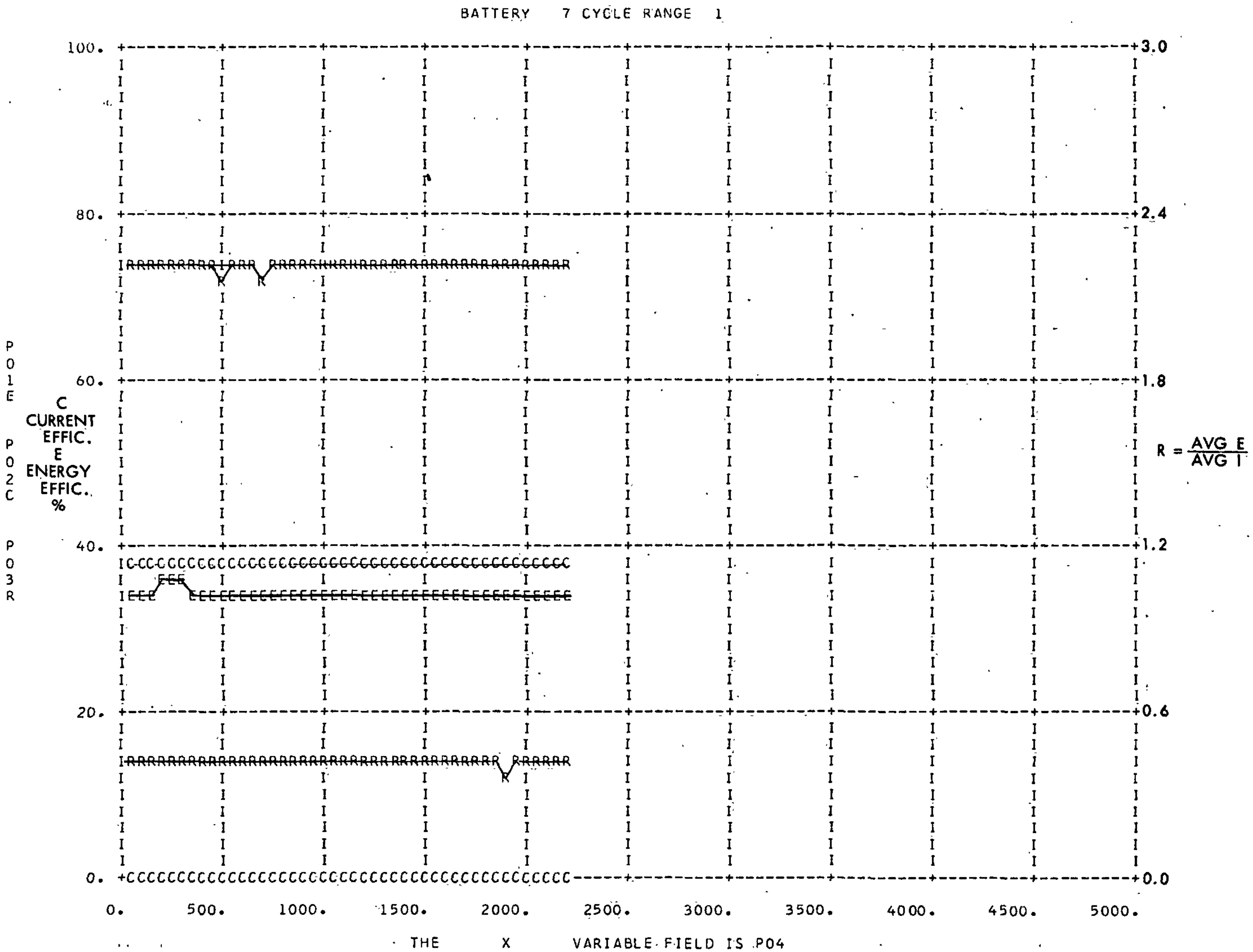

BATTERY 7 CYCLE RANGE 1
100.
80.
60.
40.
20.
0.
3.0
2.4
1.8
1.2
0.6
0.0
P01E
P02C
P03R
C
CURRENT
EFFIC.
E
ENERGY
EFFIC.
%
R = AVG E / AVG I
0.
500.
1000.
1500.
2000.
2500.
3000.
3500.
4000.
4500.
5000.
THE X VARIABLE FIELD IS P04

Figure 4h

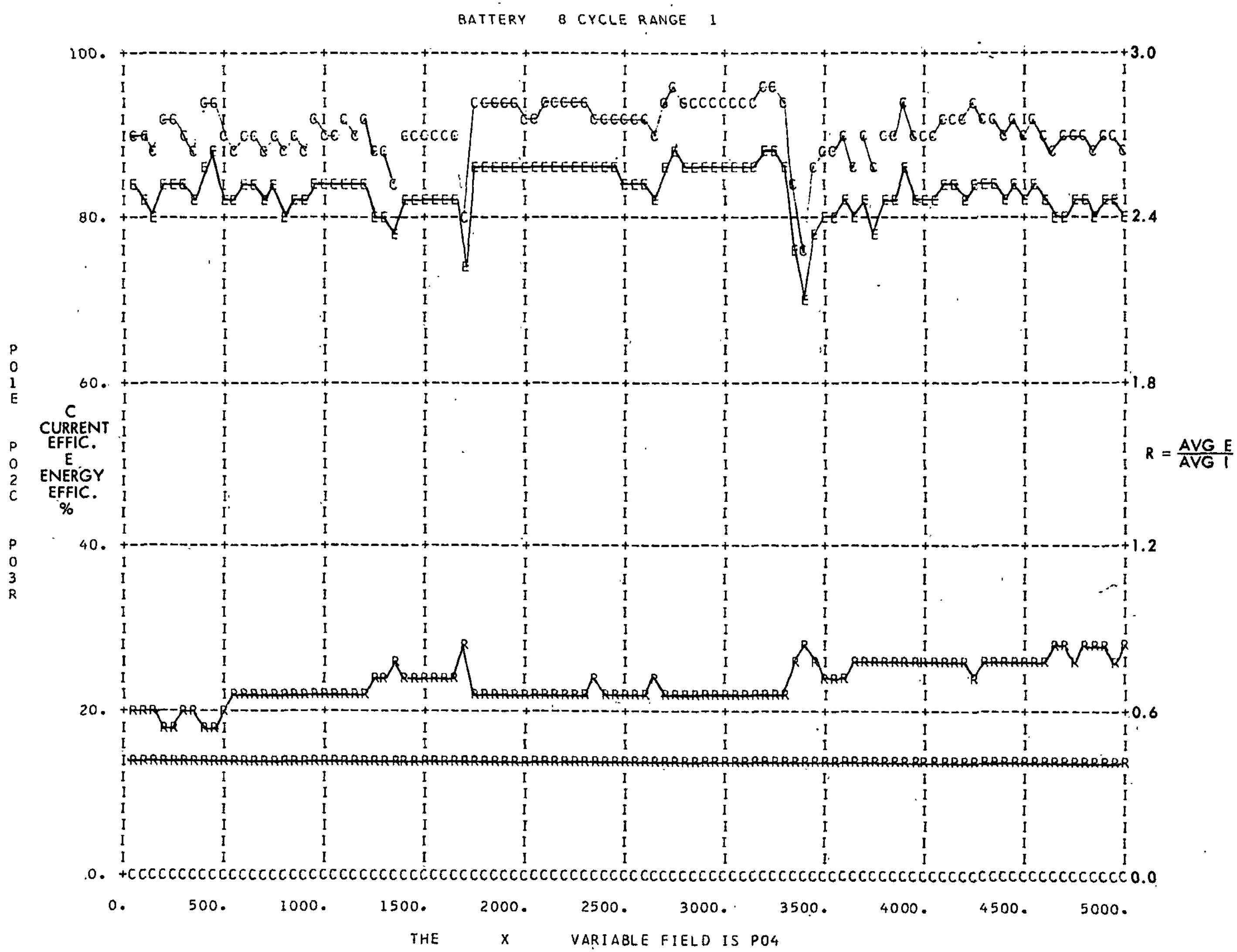

BATTERY 8 CYCLE RANGE 1
100.
80.
60.
40.
20.
.0.
3.0
2.4
1.8
1.2
0.6
0.0
P01E P02C P03R
C CURRENT EFFIC.
E ENERGY EFFIC. %
R = AVG E / AVG I
0. 500. 1000. 1500. 2000. 2500. 3000. 3500. 4000. 4500. 5000.
THE X VARIABLE FIELD IS P04

Figure 4i

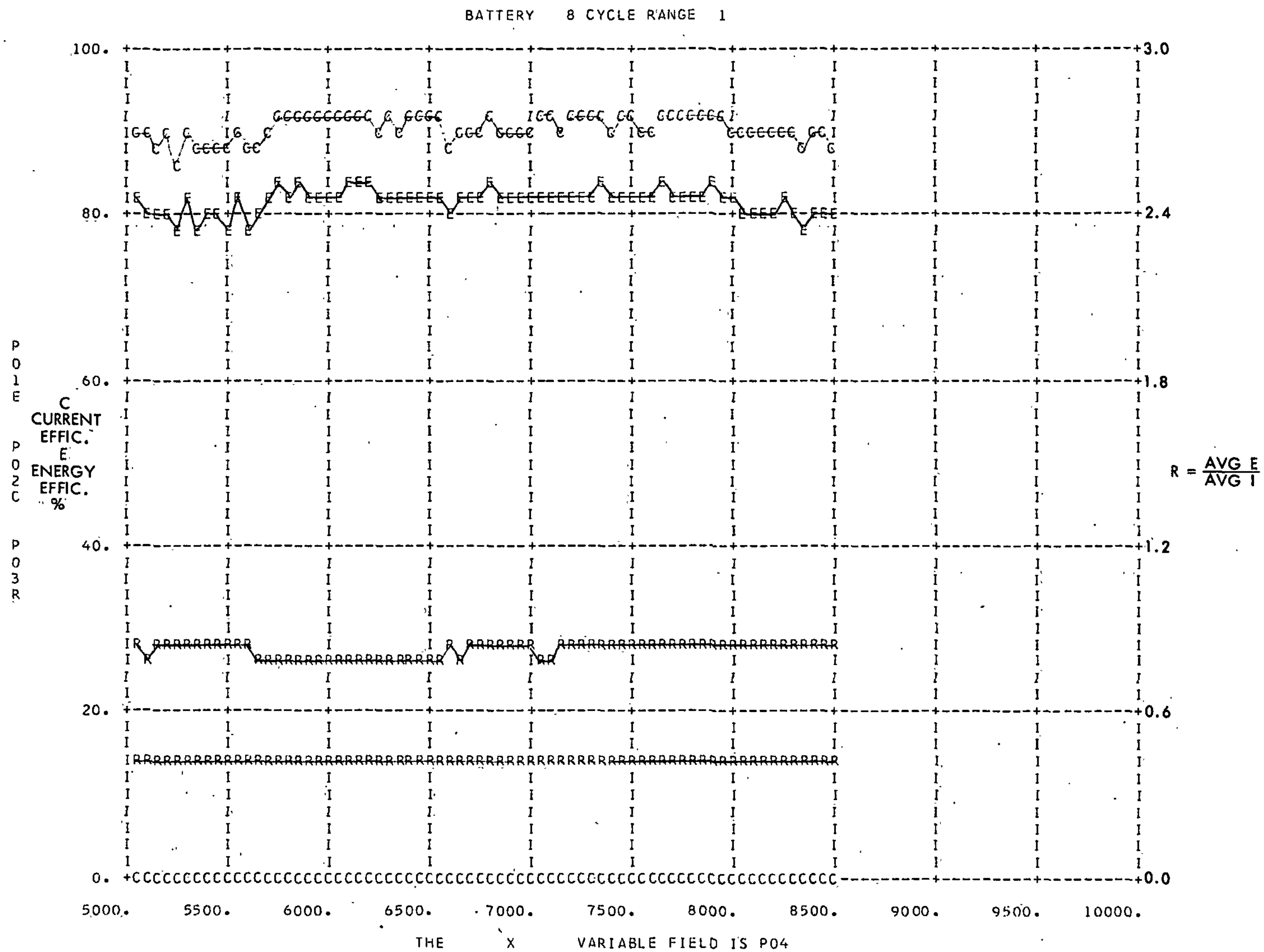


Figure 4i (Continued)

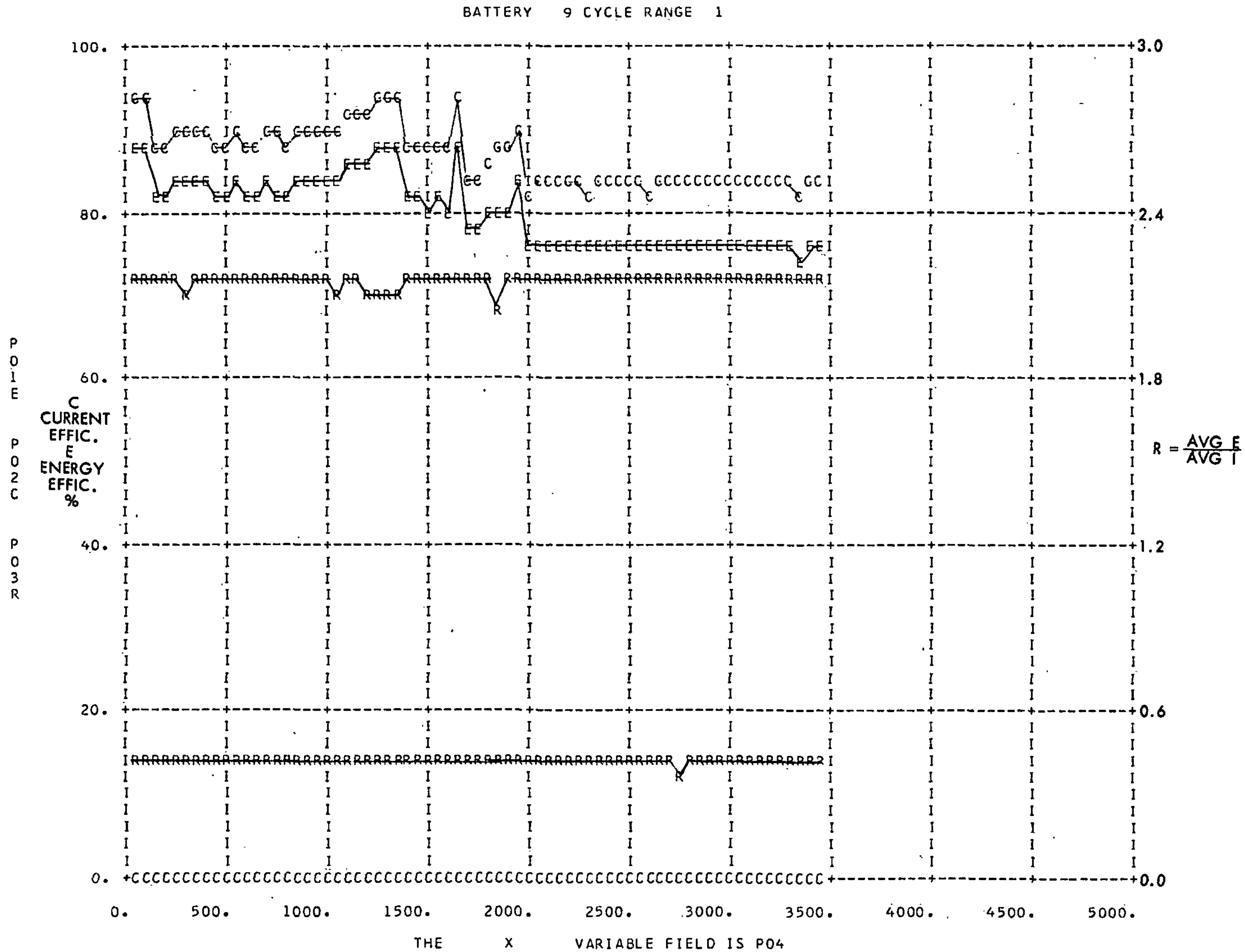
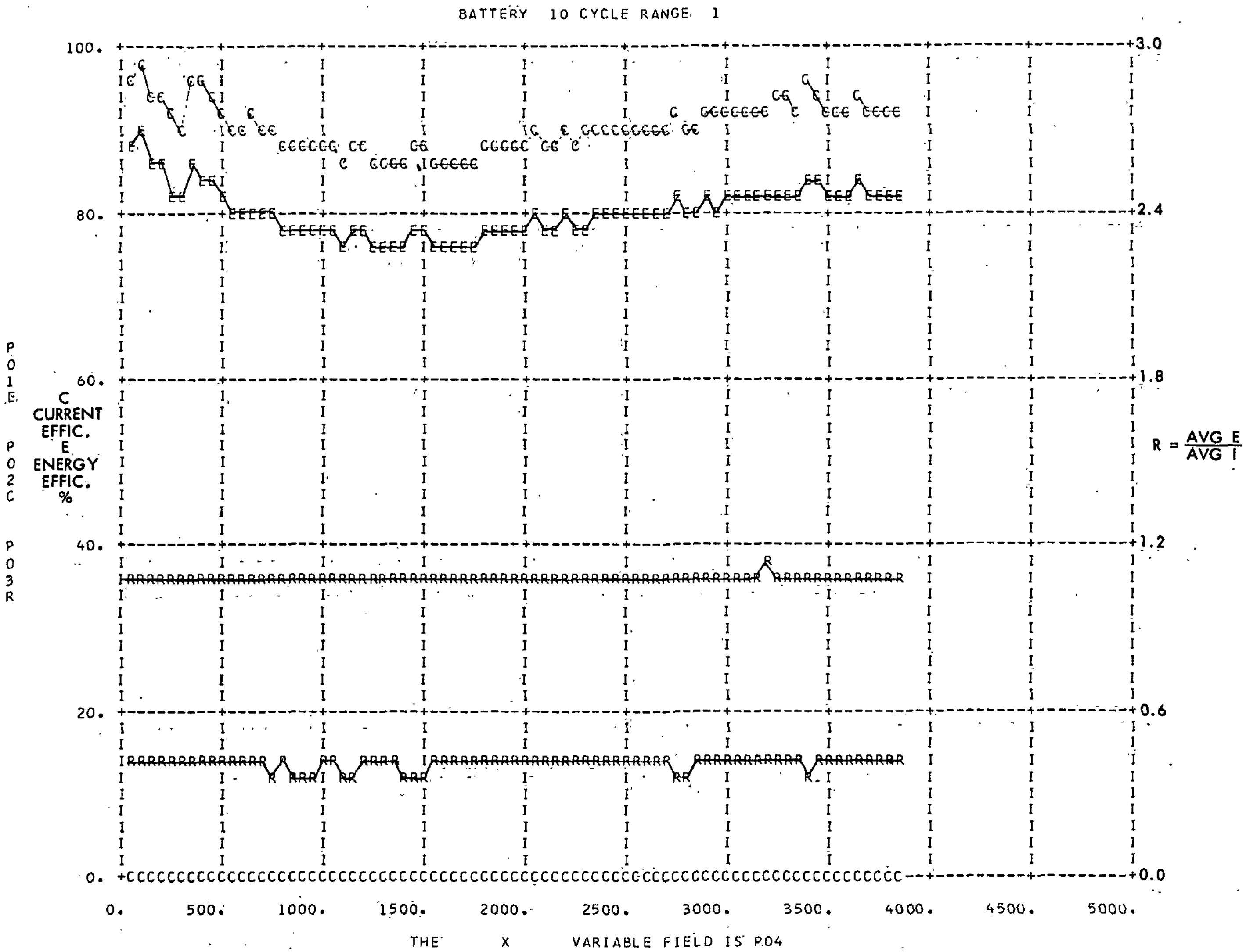

BATTERY 9 CYCLE RANGE 1
100.
80.
60.
40.
20.
0.
3.0
2.4
1.8
1.2
0.6
0.0
P01E
P02C
P03R
C
CURRENT
EFFIC.
E
ENERGY
EFFIC.
%
R = AVG E / AVG I
0.
500.
1000.
1500.
2000.
2500.
3000.
3500.
4000.
4500.
5000.
THE X VARIABLE FIELD IS P04

Figure 4j



BATTERY 10 CYCLE RANGE 1
100.
80.
60.
40.
20.
0.
3.0
2.4
1.8
1.2
0.6
0.0
P01E
P02C
P03R
C CURRENT EFFIC.
E ENERGY EFFIC. %
R = AVG E / AVG I
0.
500.
1000.
1500.
2000.
2500.
3000.
3500.
4000.
4500.
5000.
THE X VARIABLE FIELD IS P04

Figure 4k

BATTERY 11 CYCLE RANGE 1

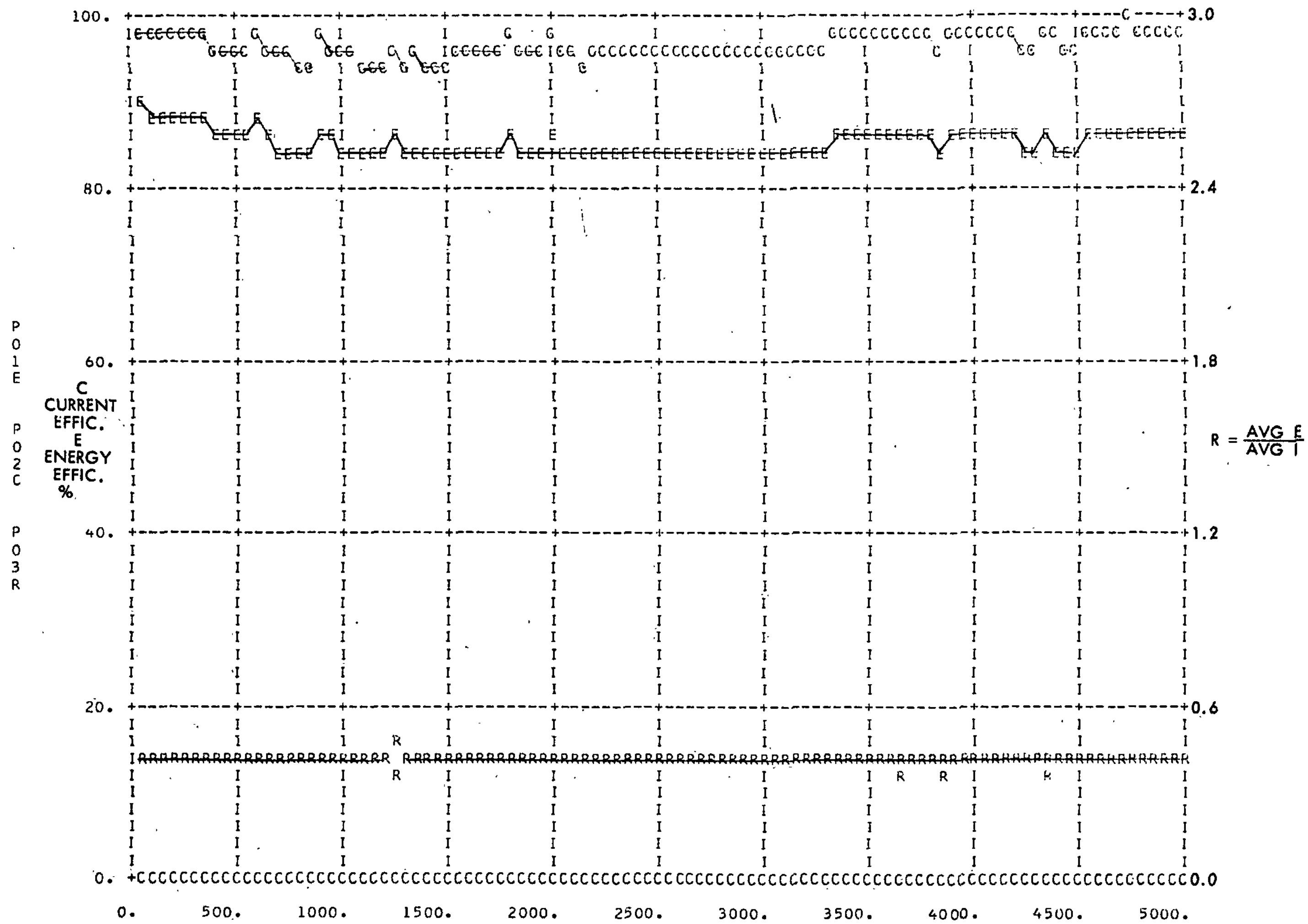


Figure 42

BATTERY 11 CYCLE RANGE 1

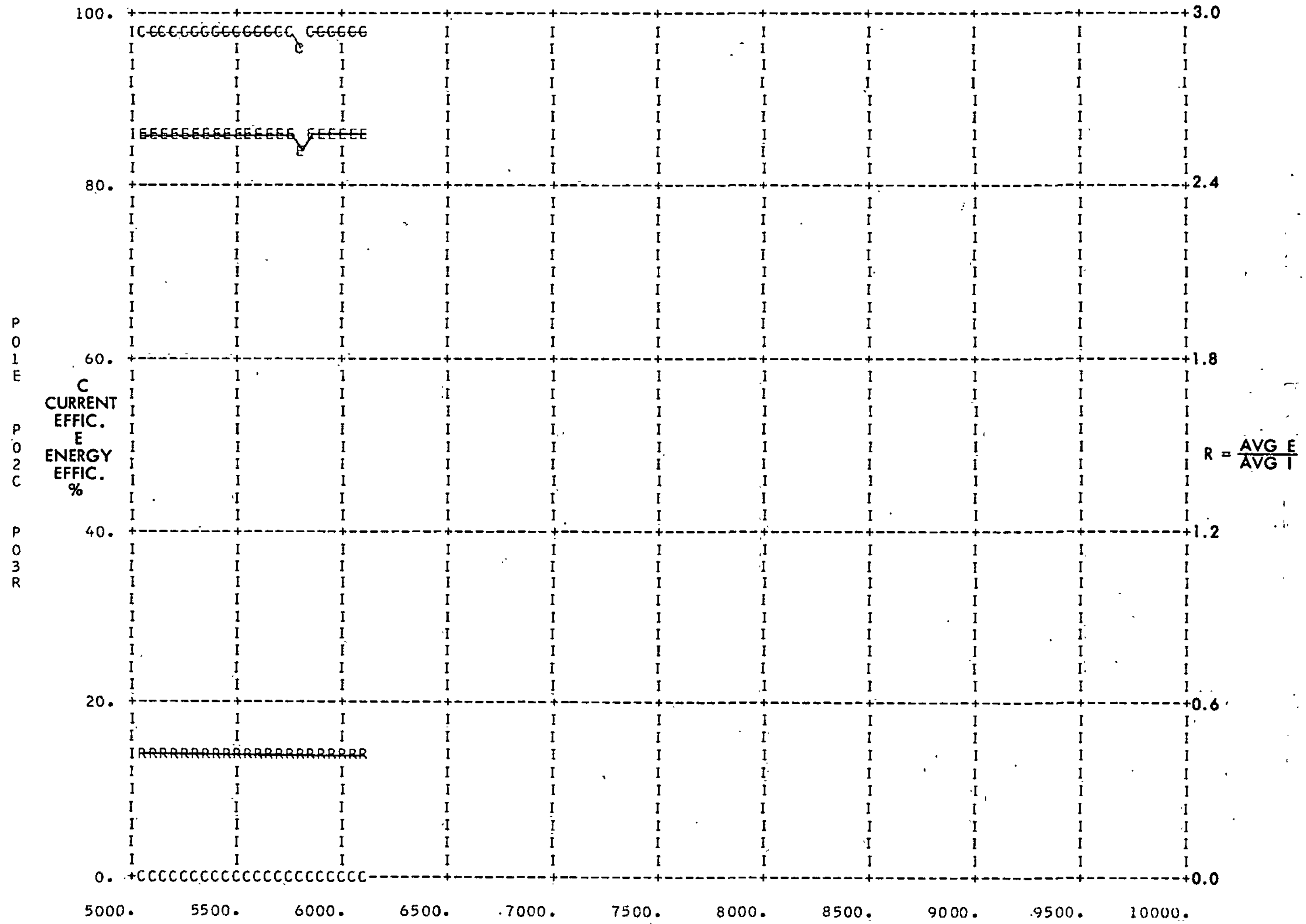


Figure 4ℓ (Continued)

APPENDIX E

COMPUTER PLOTS OF CHARGE AND DISCHARGE VOLTAGE FOR EVERY 500 CYCLES VERSUS AMPERE-HOURS

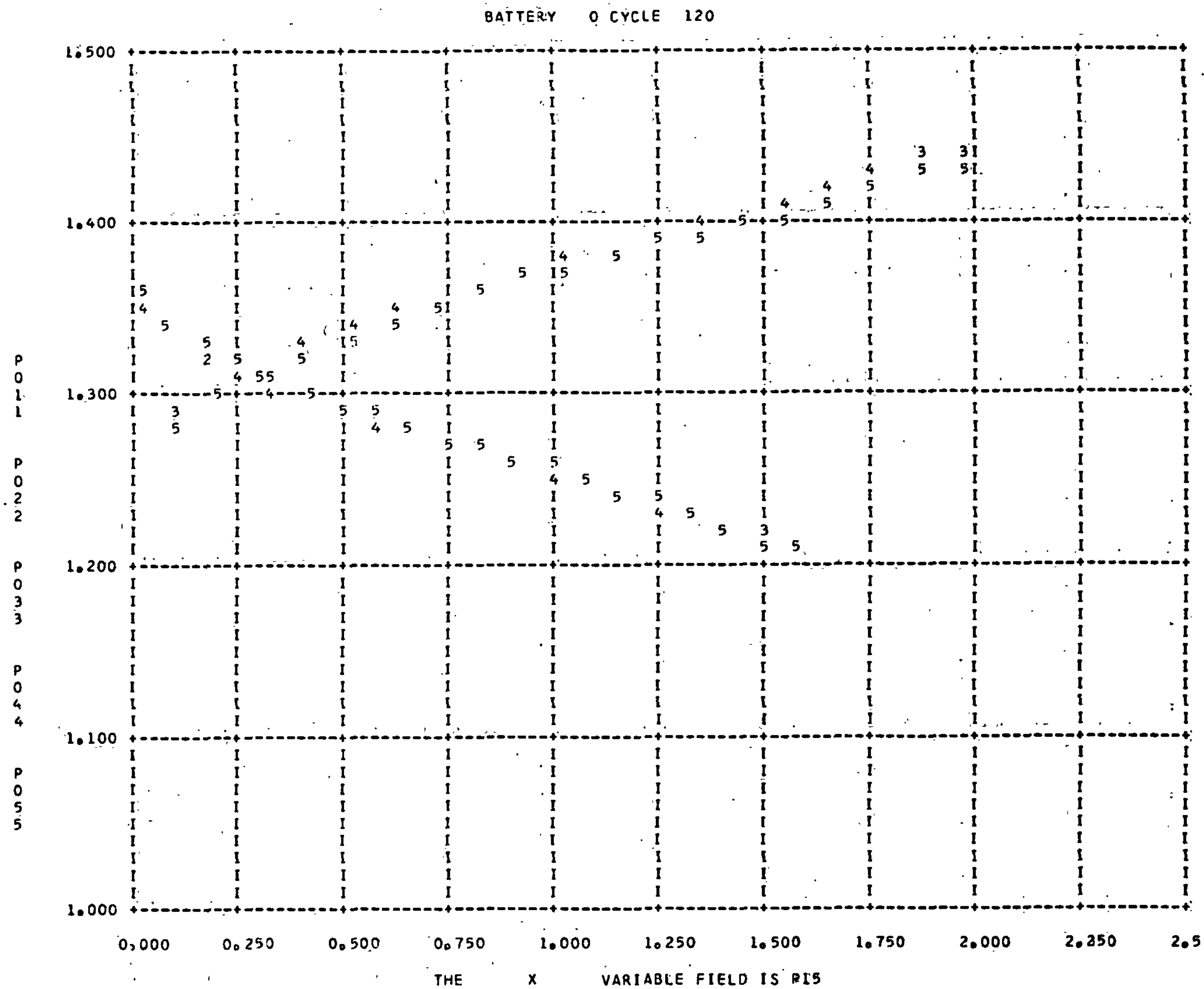

BATTERY 0 CYCLE 120
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS RI5

Figure 5aa

BATTERY 0 CYCLE 498

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 5

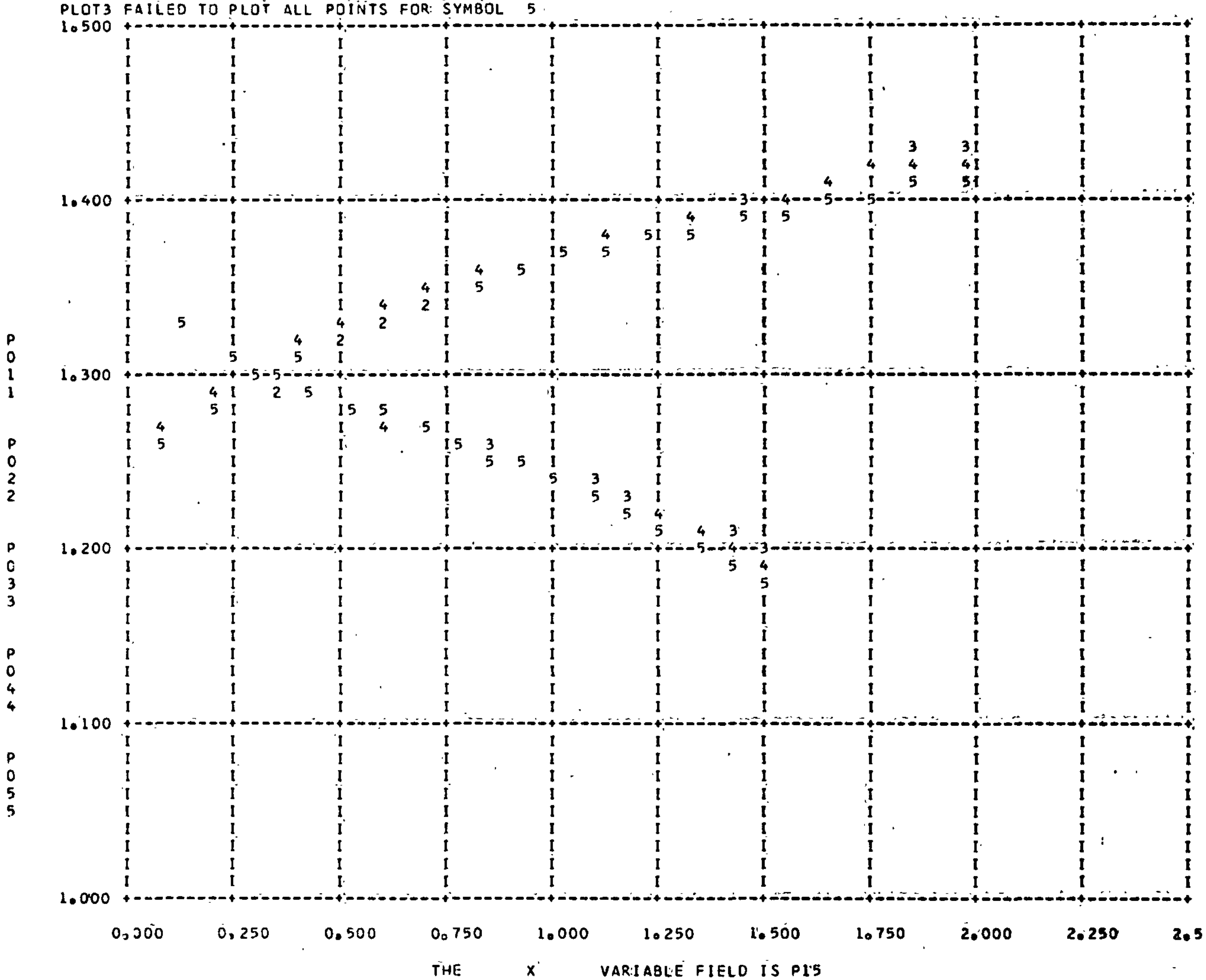


Figure 5ab

E-3

BATTERY 0 CYCLE 1020

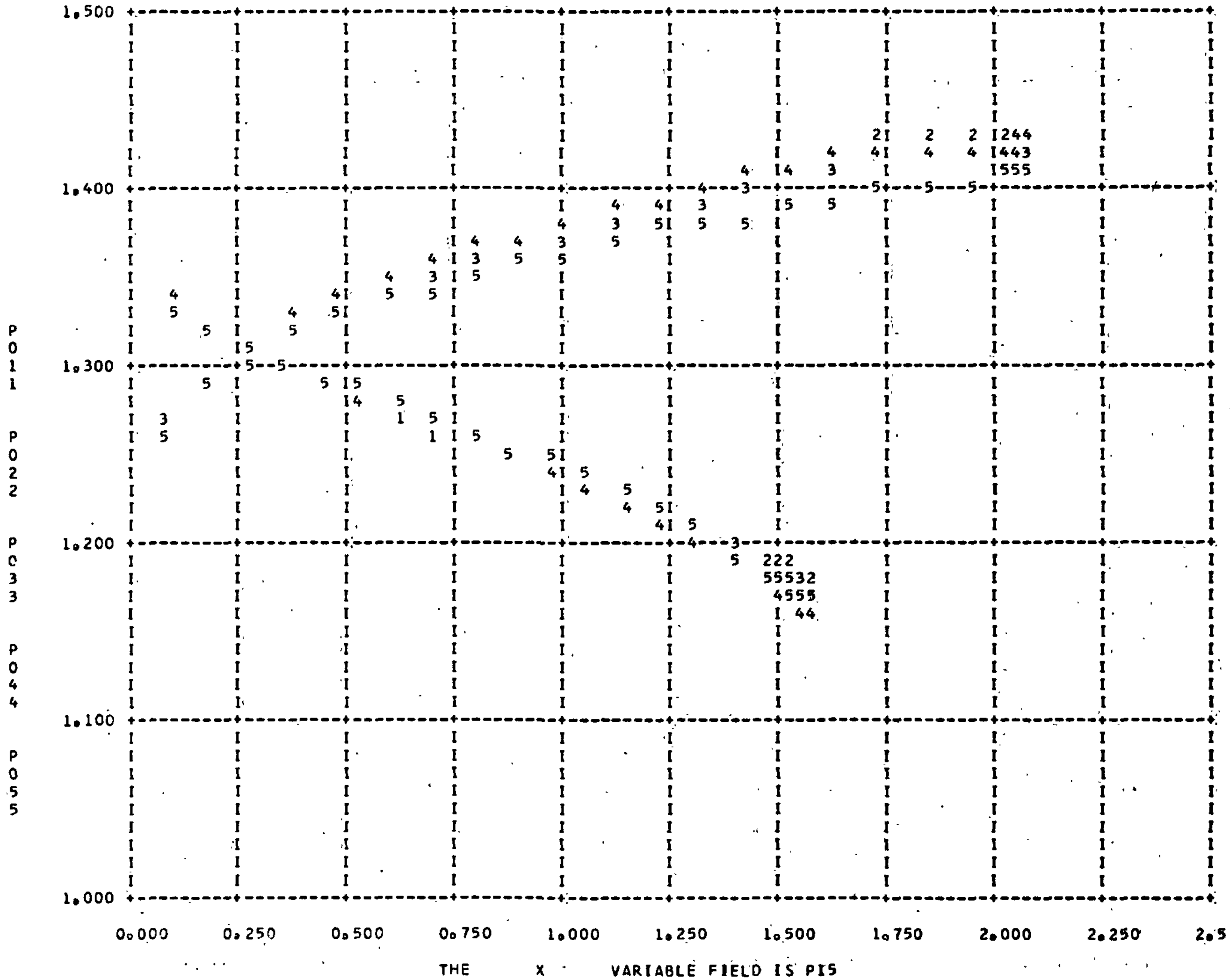
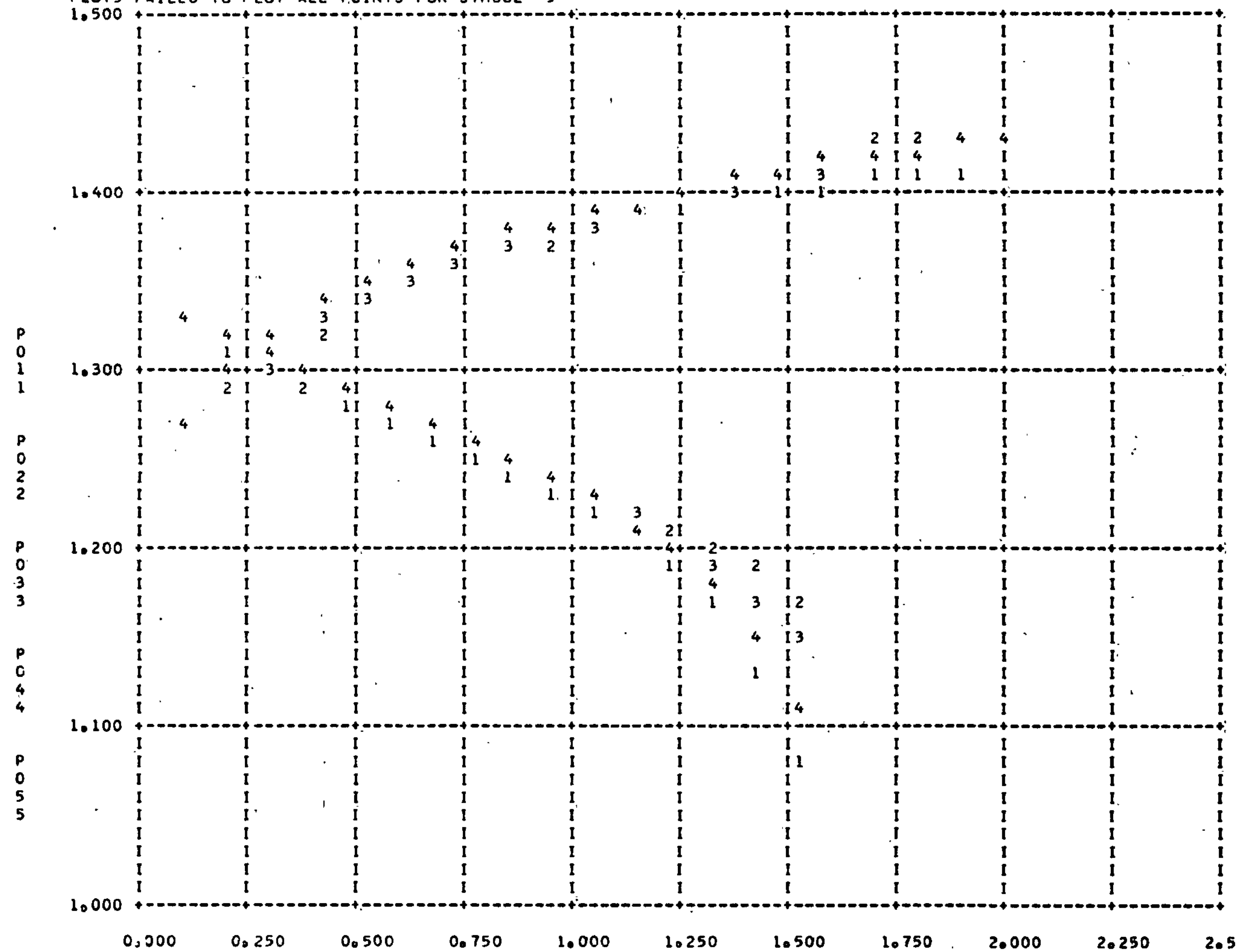


Figure 5ac

BATTERY 0 CYCLE 1519

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 5

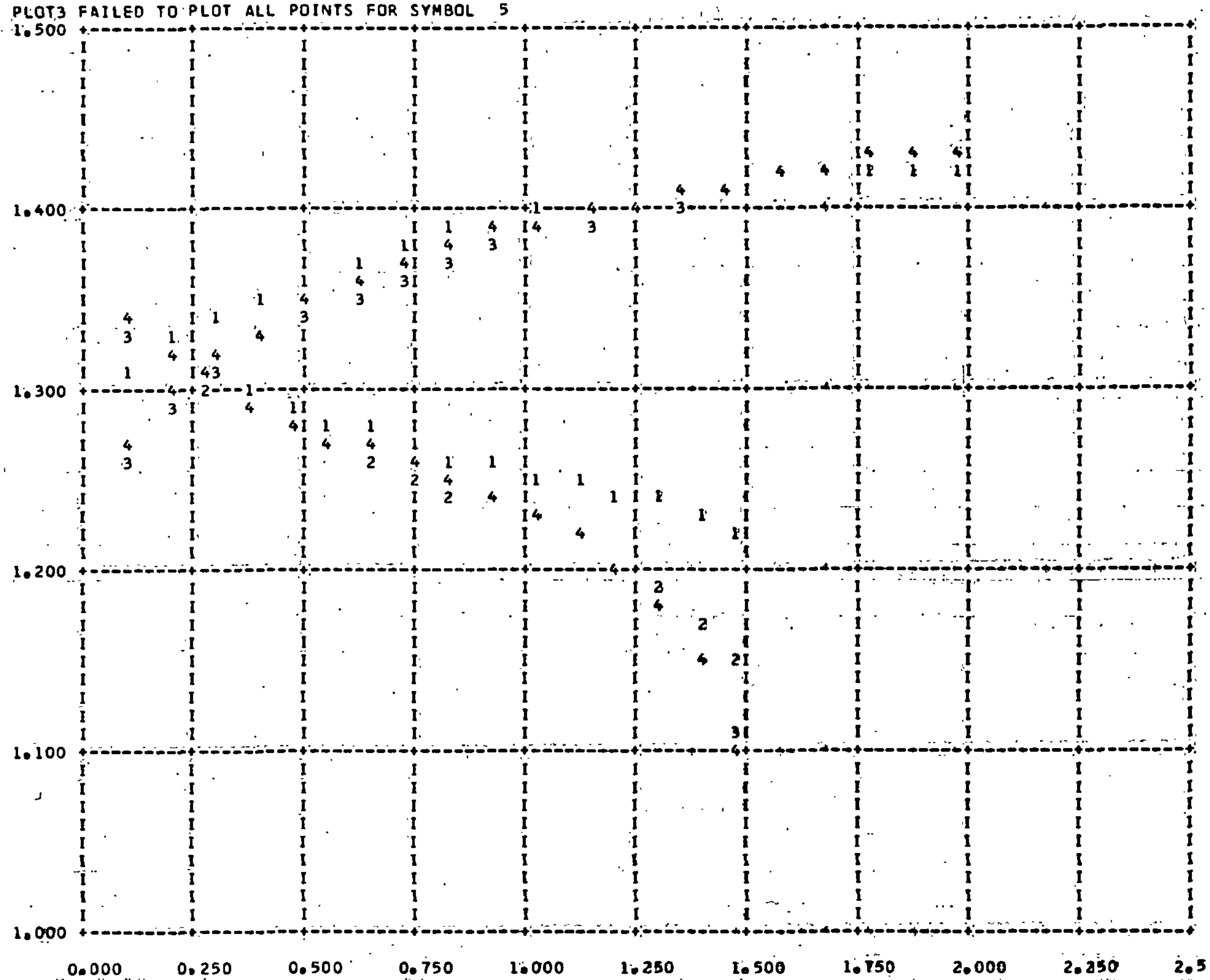


THE X VARIABLE FIELD IS P15

Figure 5ad

BATTERY 0 CYCLE 2079

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 5



THE X VARIABLE FIELD IS RIS

Figure 5ae

BATTERY 0 CYCLE 2536

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 1
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 5

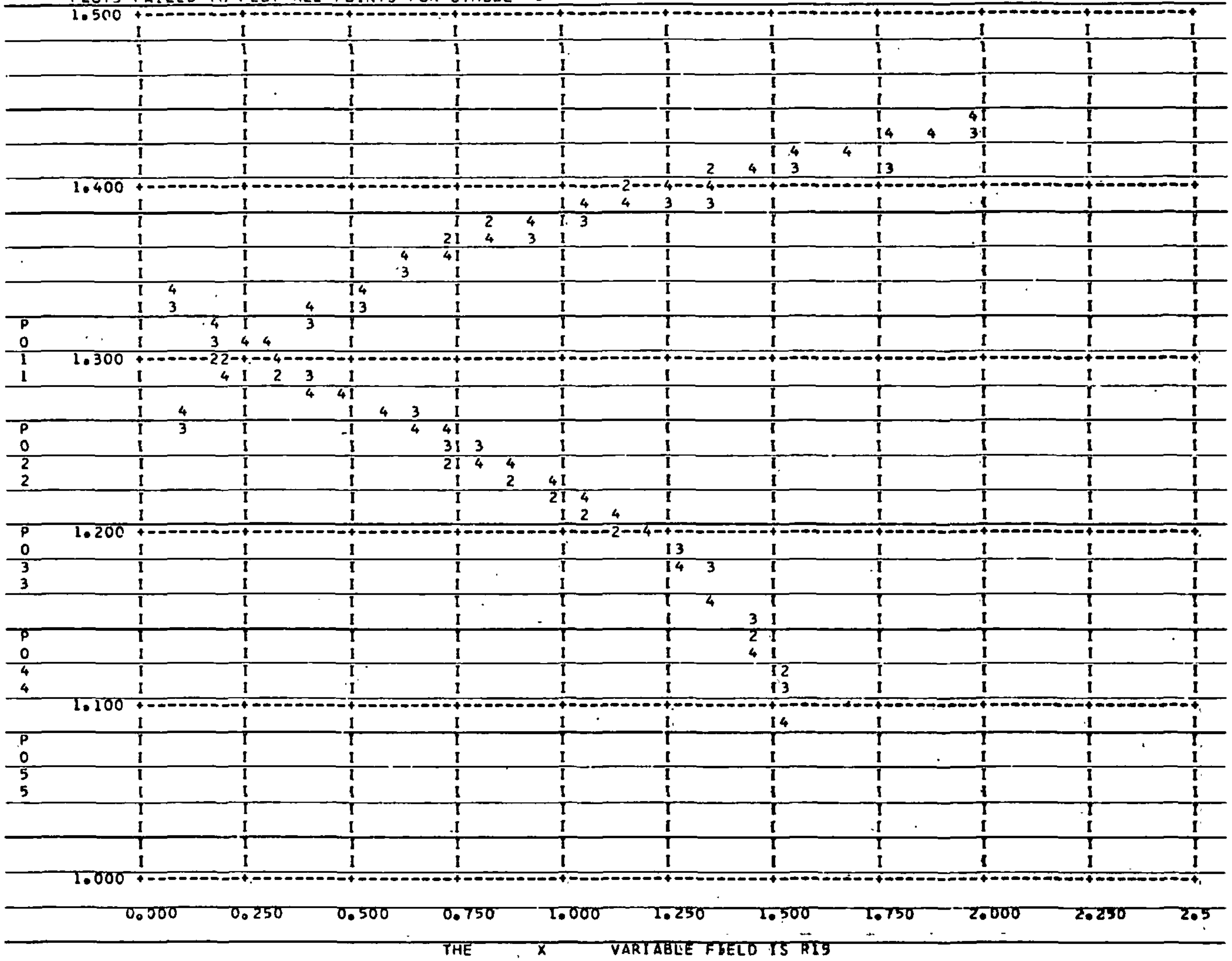


Figure 5af

BATTERY 0 CYCLE 3062

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 1
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 5

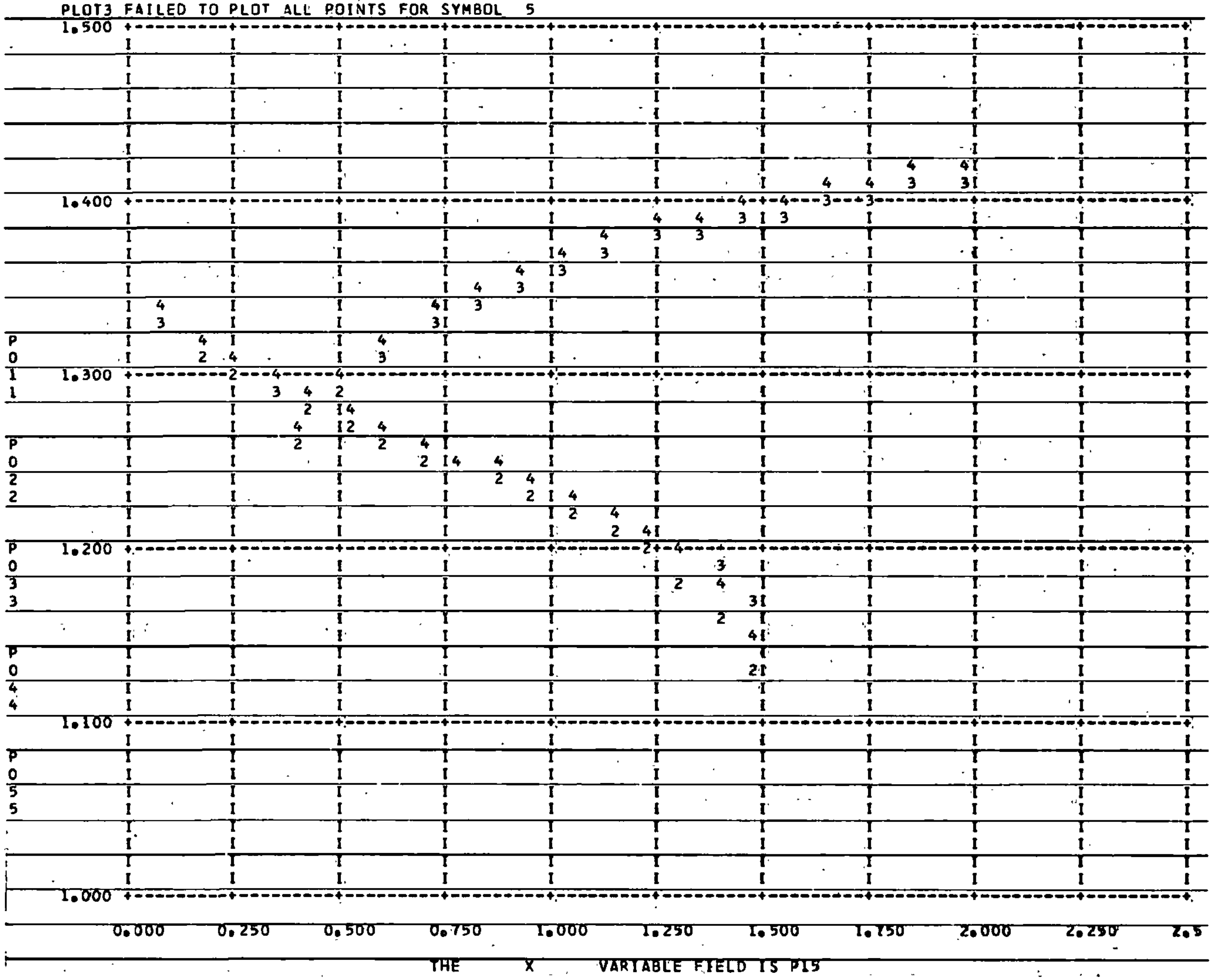


Figure 5ag

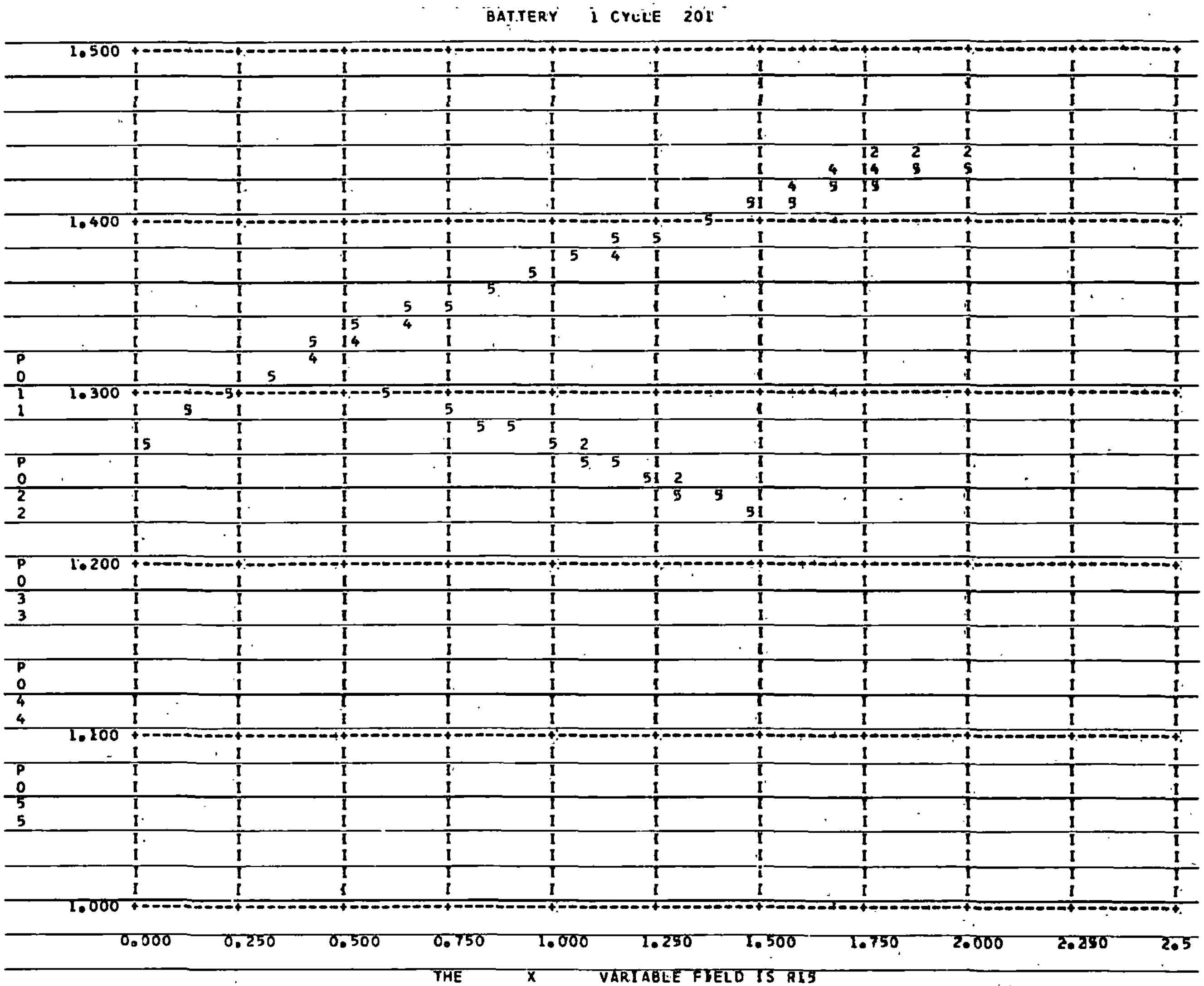

BATTERY 1 CYCLE 201
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS R15

Figure 5ba

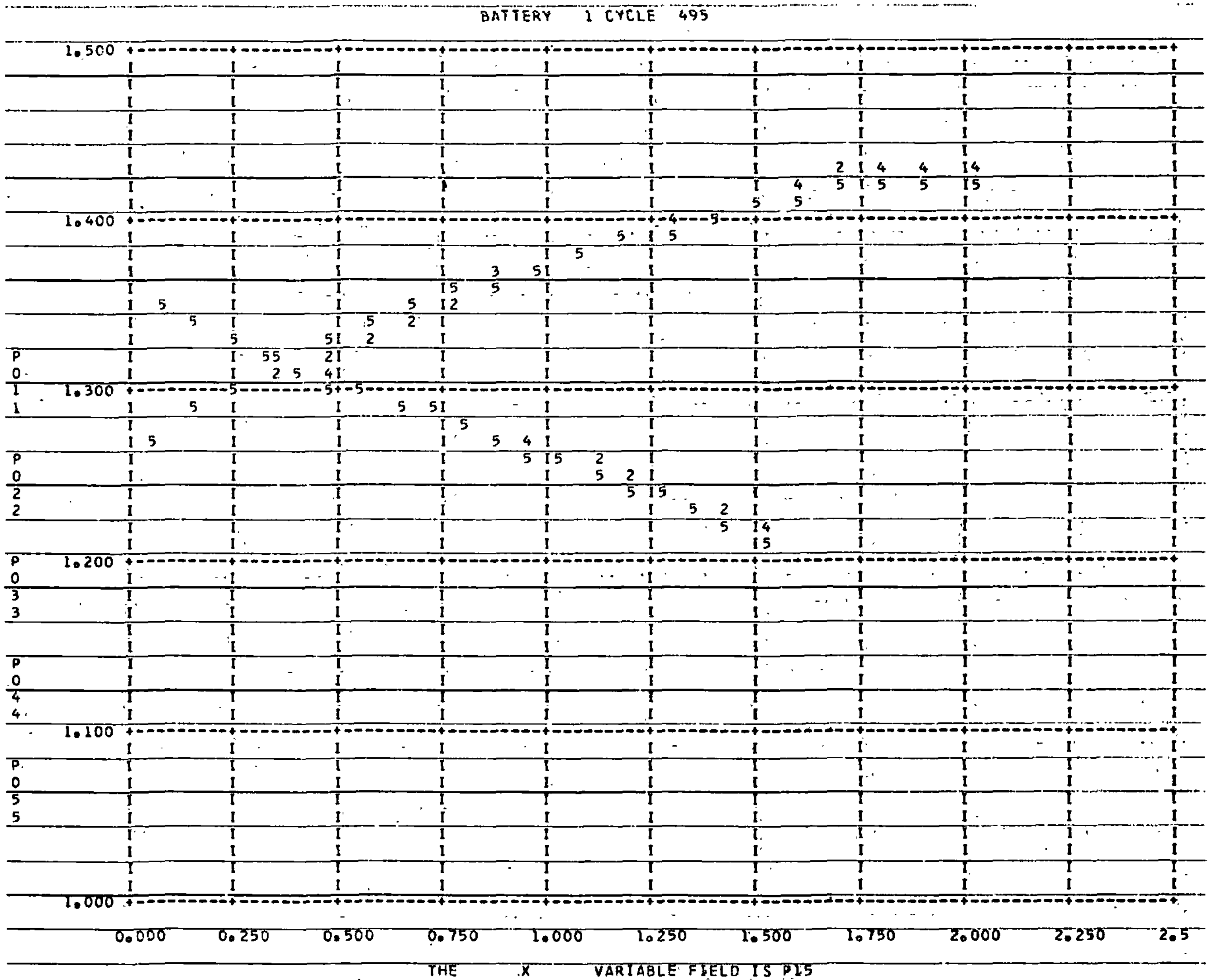

BATTERY 1 CYCLE 495
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS P15

Figure 5bb

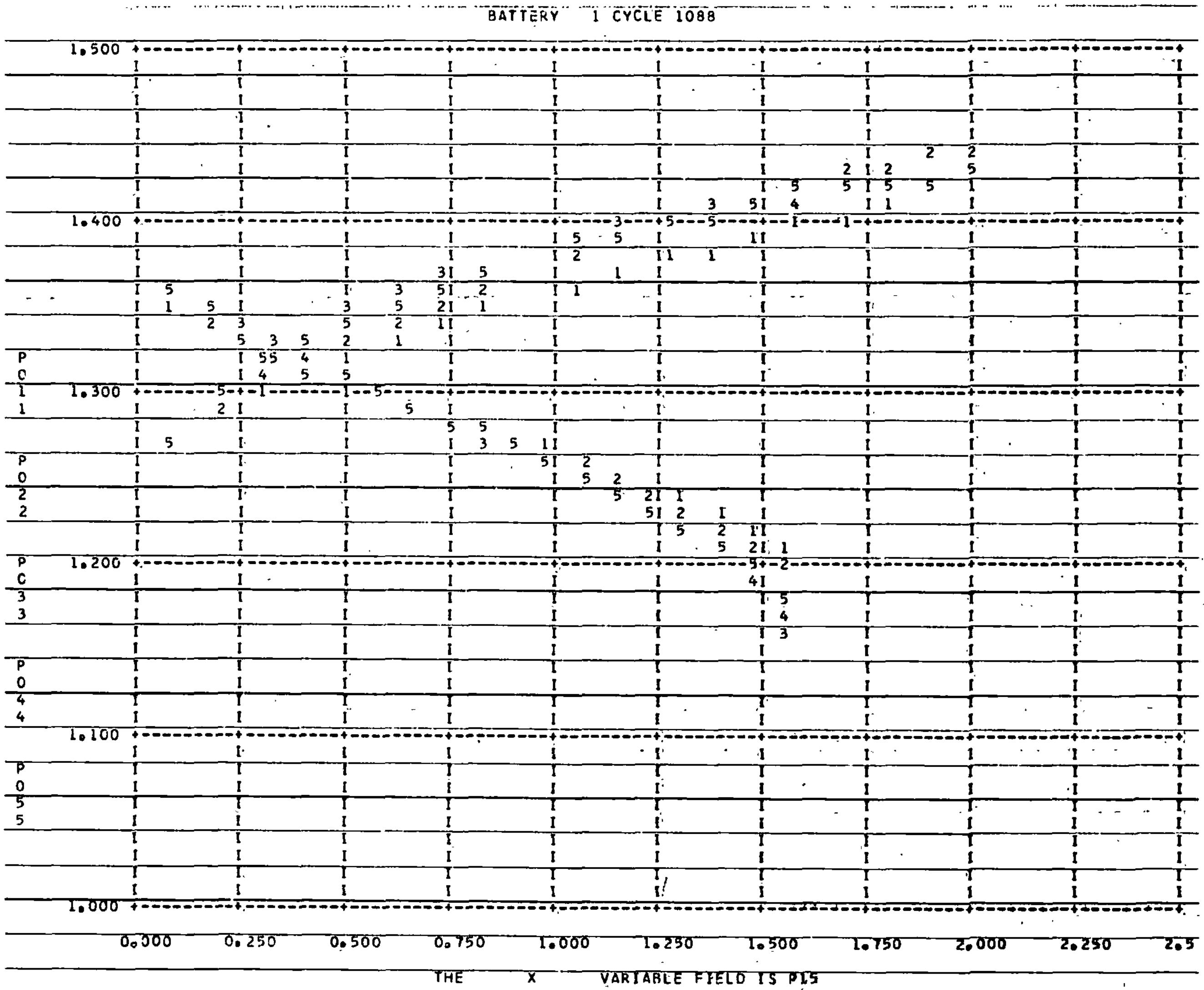

BATTERY 1 CYCLE 1088
1.500
1.400
1.300
1.200
1.100
1.000
P
0
1
1
P
0
2
2
P
C
3
3
P
0
4
4
P
0
5
5
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS P15

Figure 5bc

BATTERY 1 CYCLE 1689

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 5

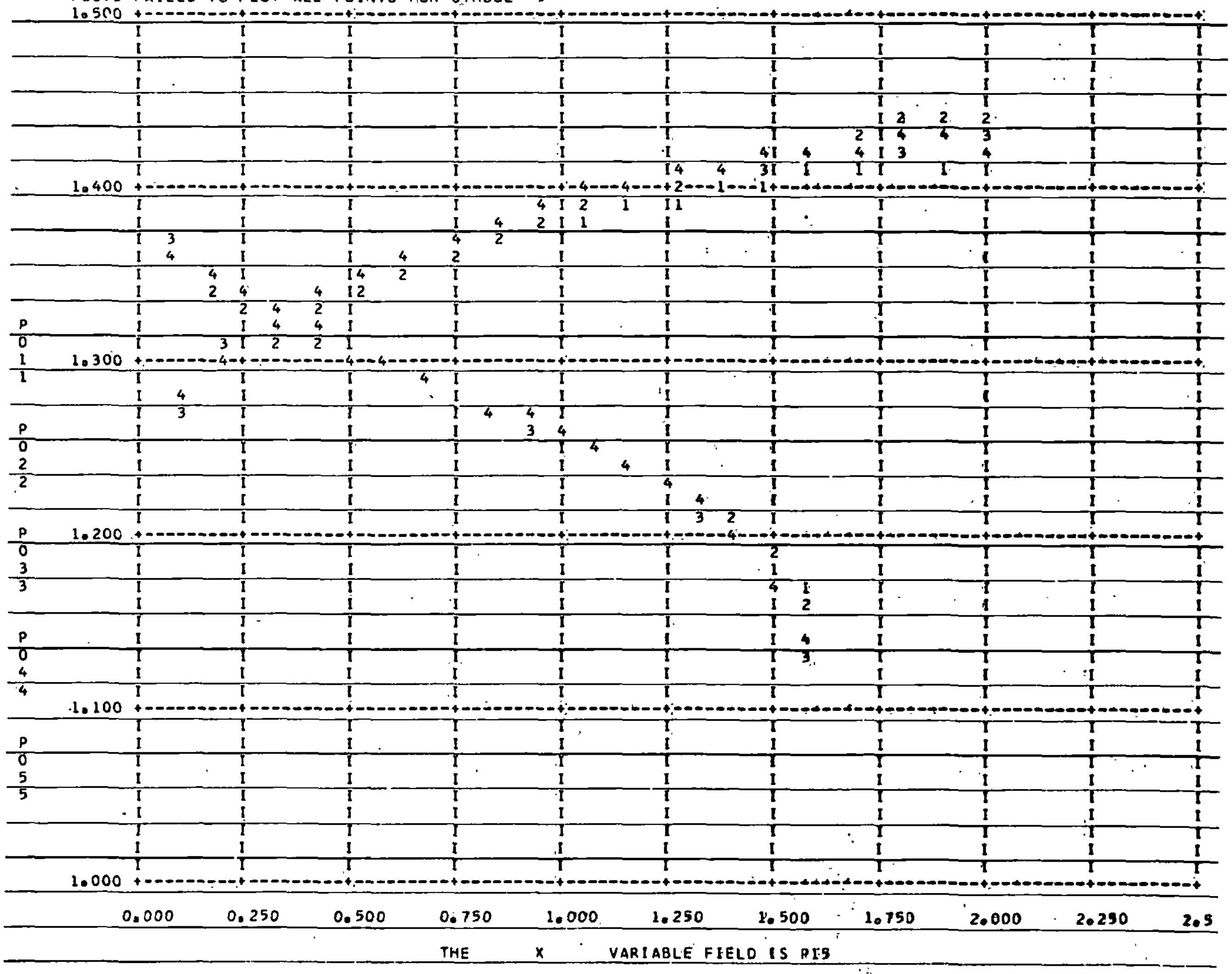


Figure 5bd

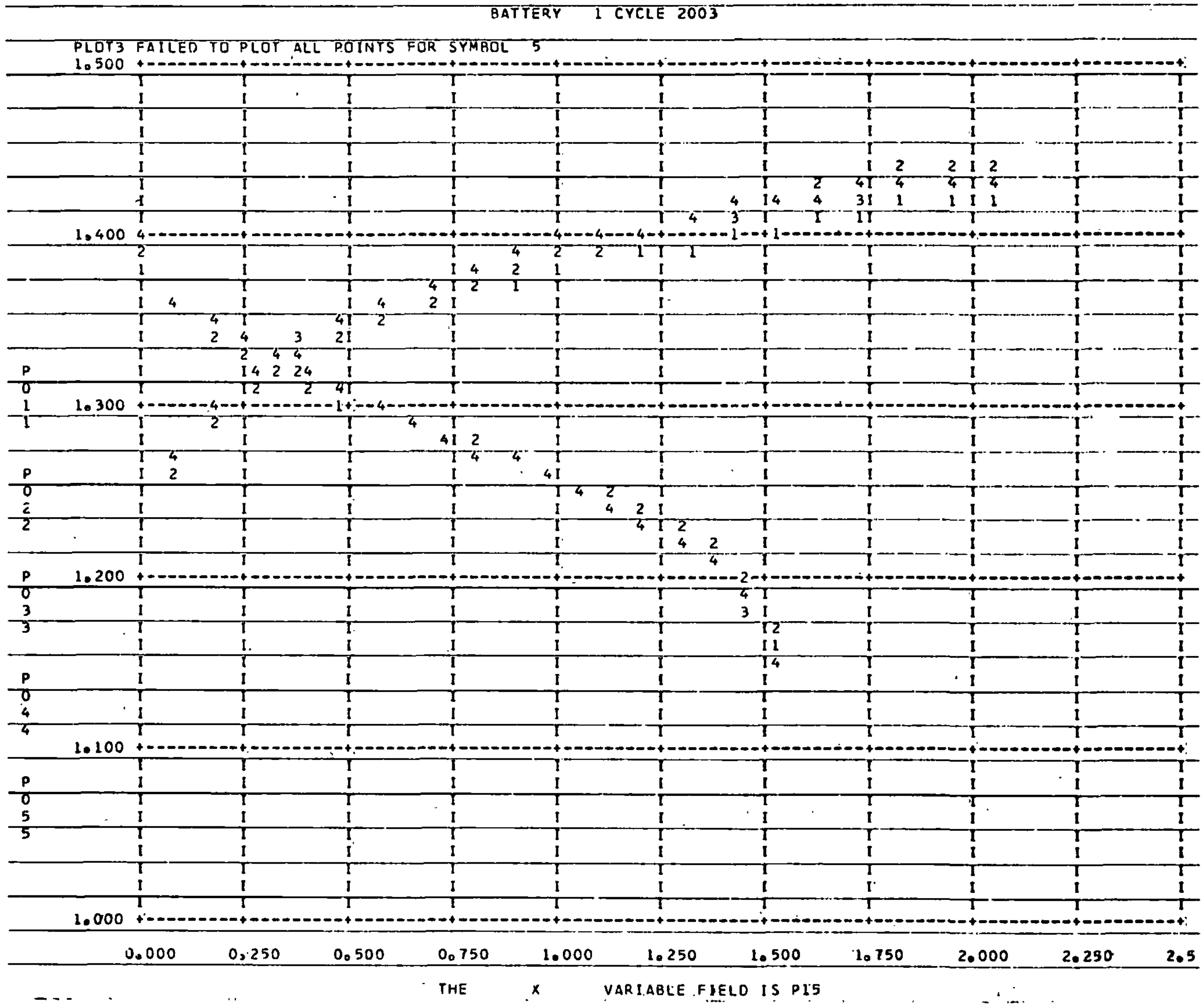

BATTERY 1 CYCLE 2003
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 5
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS P15

Figure 5be

BATTERY 1 CYCLE 2460

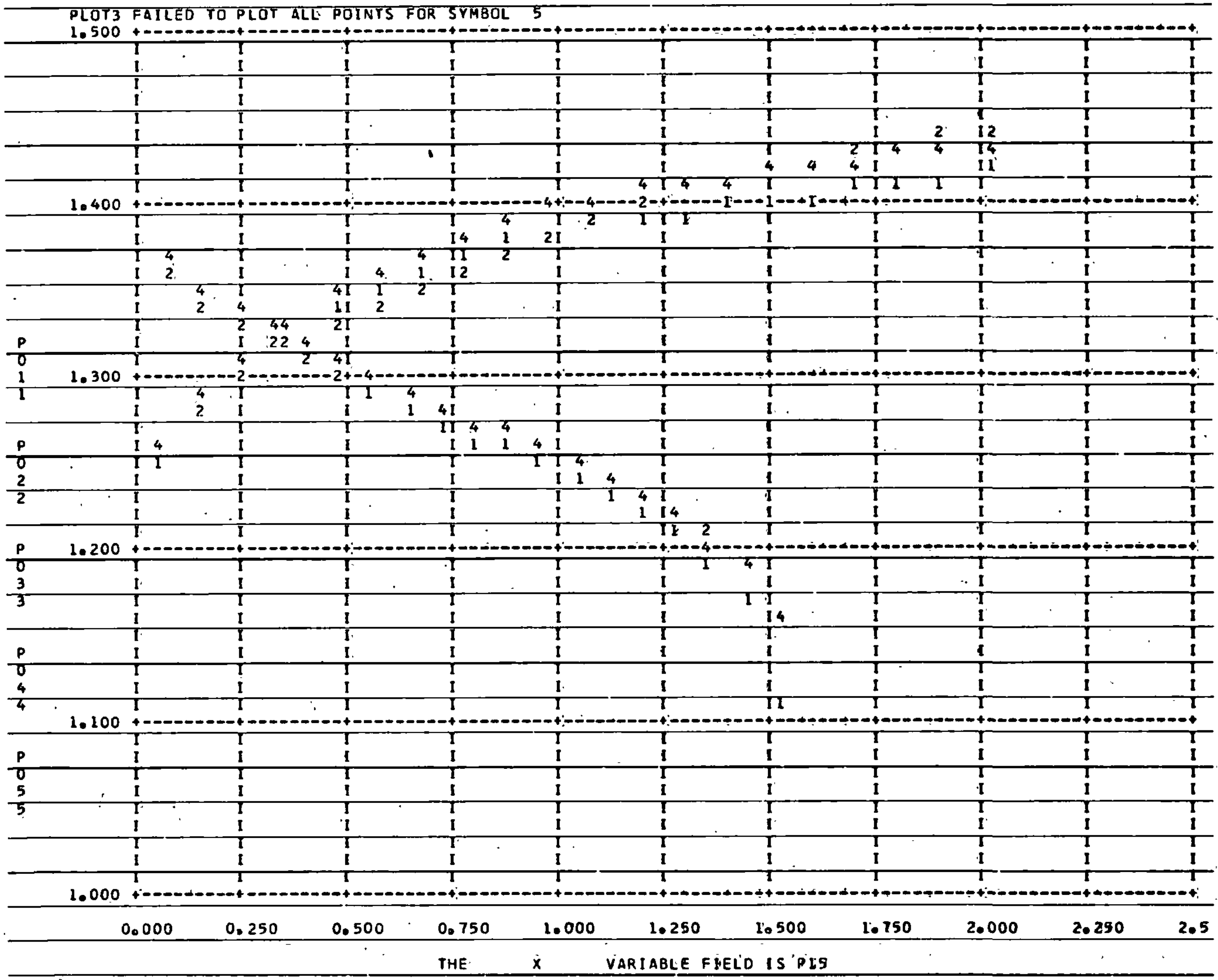


Figure 5bf

BATTERY 1 CYCLE 2961

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 5

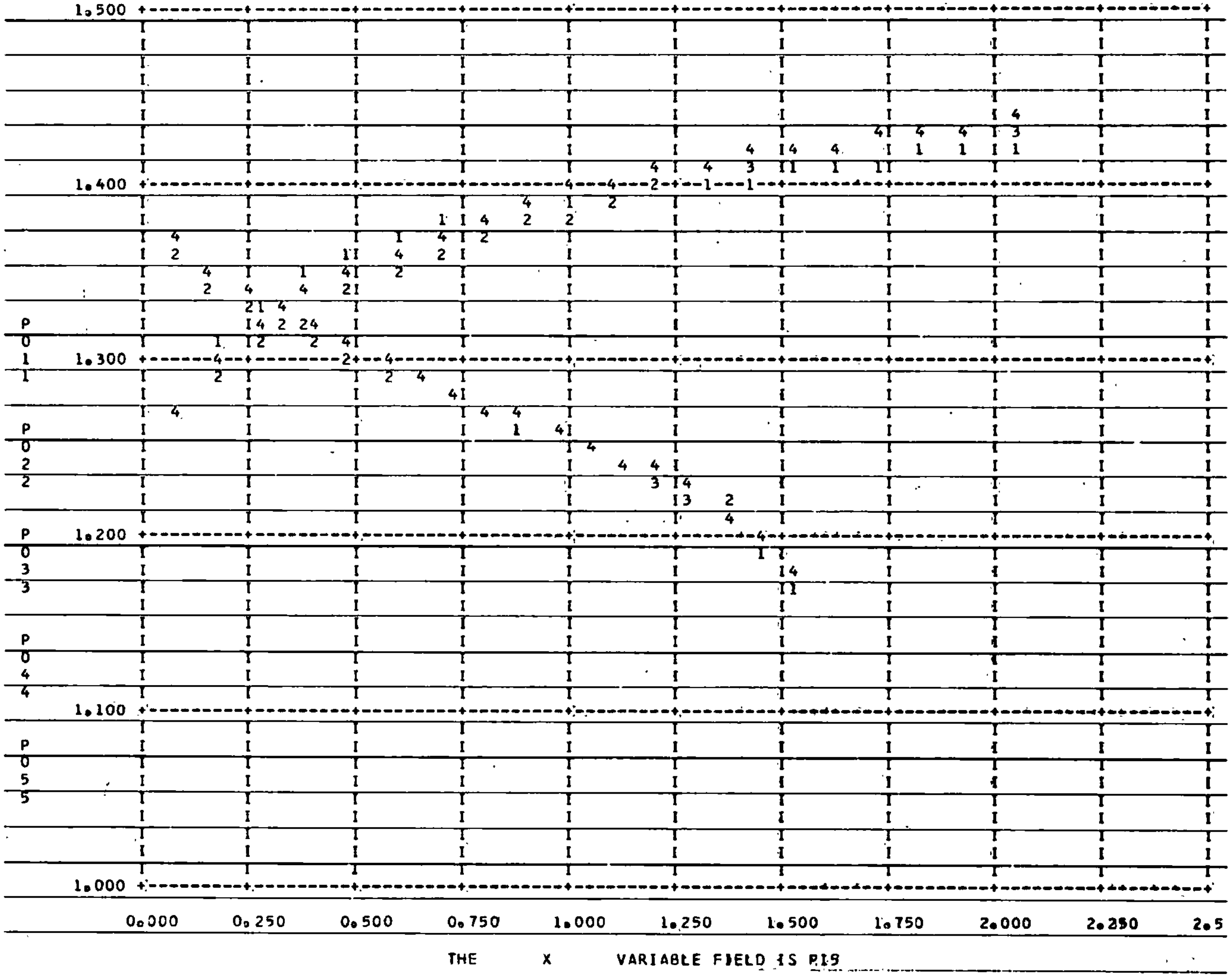


Figure 5bg

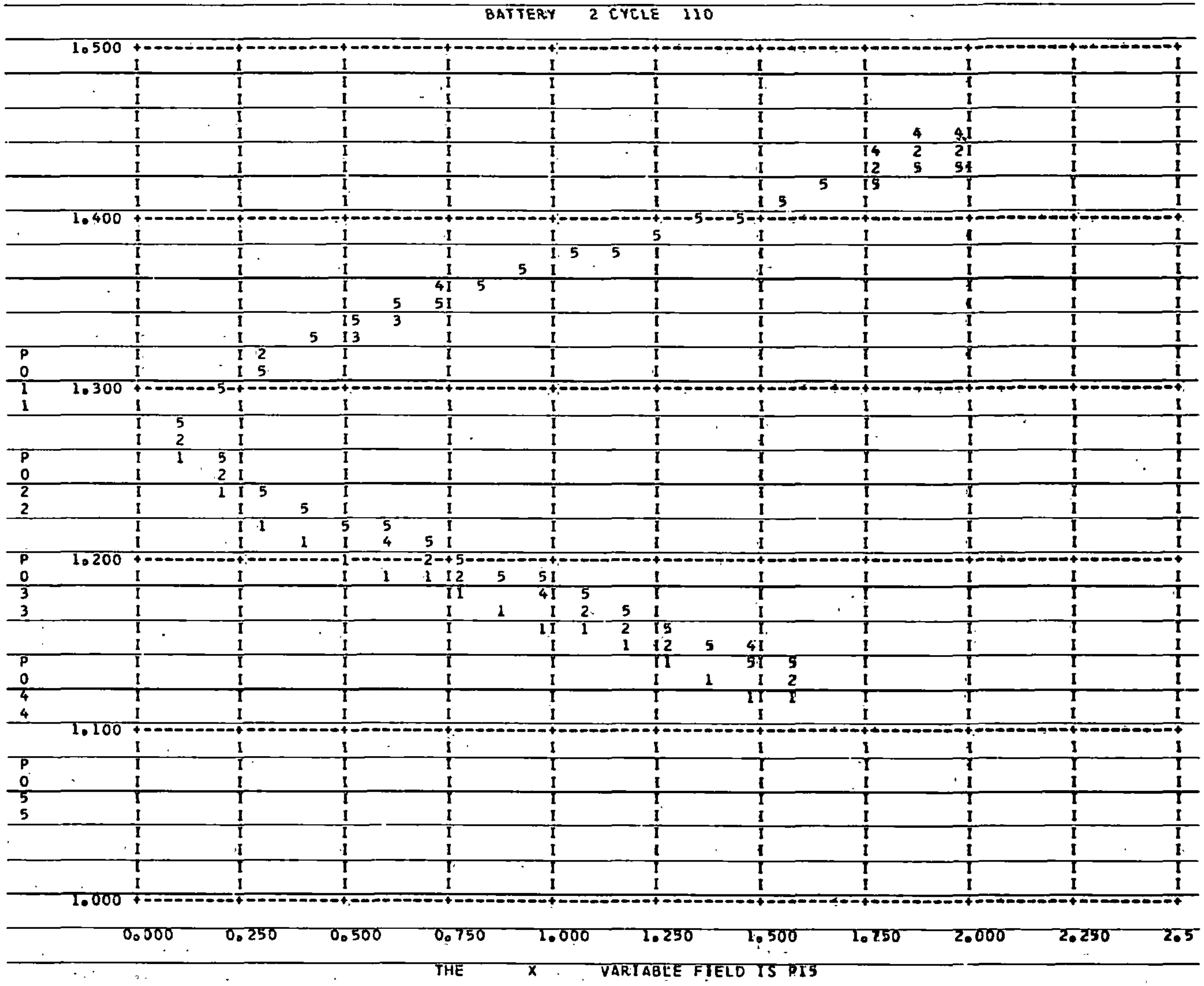

BATTERY 2 CYCLE 110
1.500
1.400
1.300
1.200
1.100
1.000
P
0
1
1
P
0
2
2
P
0
3
3
P
0
4
4
P
0
5
5
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS PIS

Figure 5ca

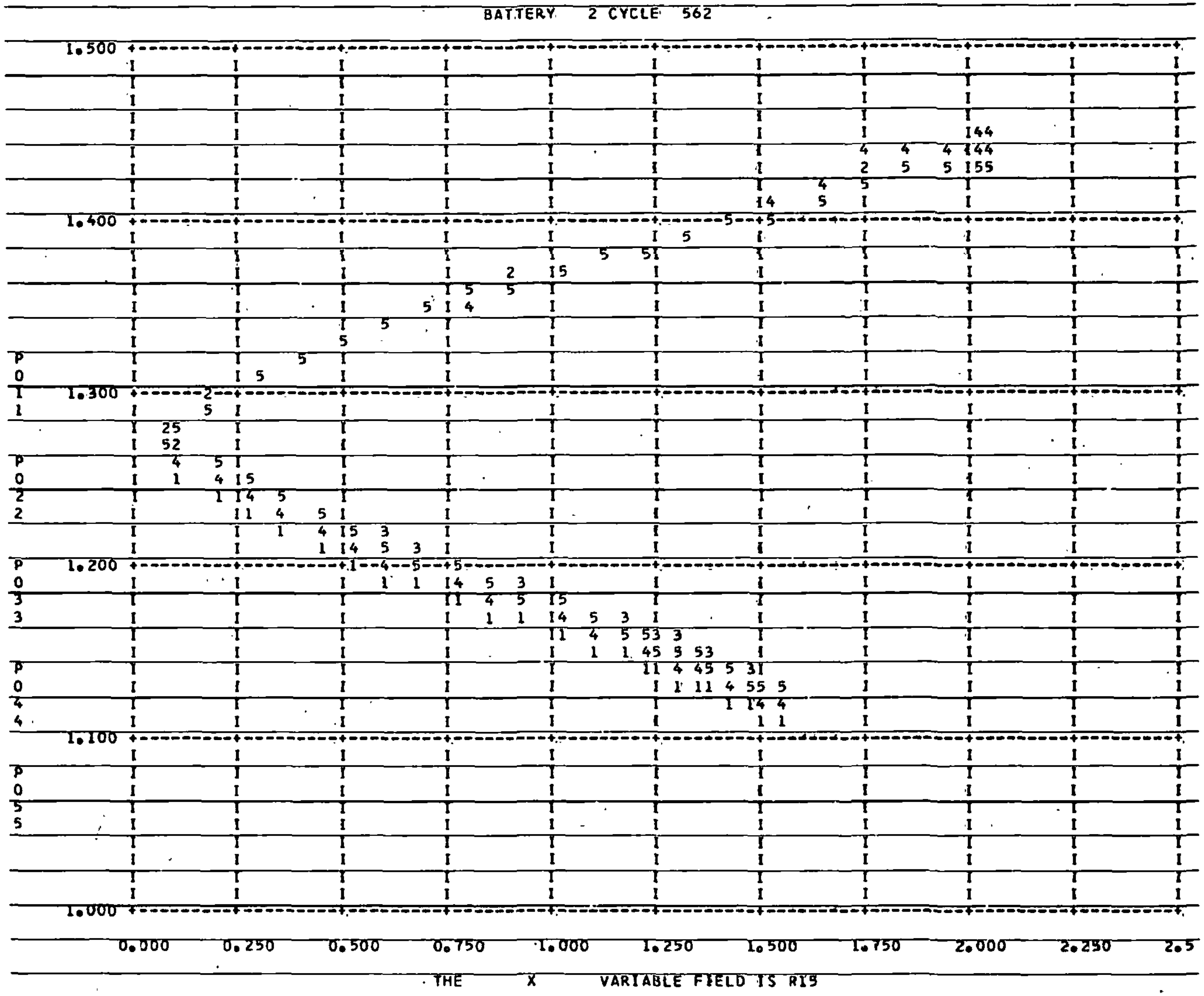

BATTERY 2 CYCLE 562
1.500
1.400
1.300
1.200
1.100
1.000
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS RIS

Figure 5cb

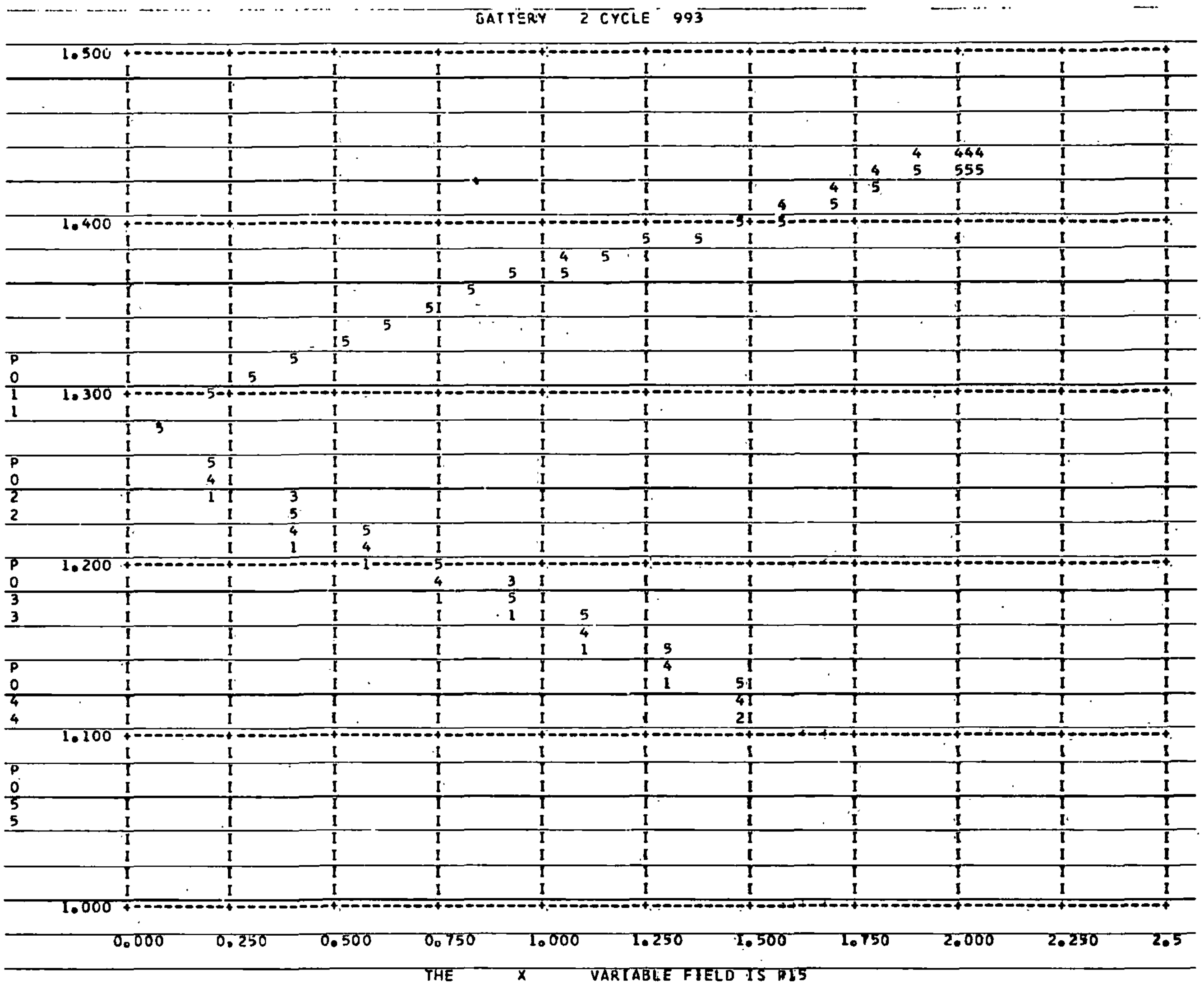

BATTERY 2 CYCLE 993
1.500
1.400
1.300
1.200
1.100
1.000
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS R15
P
0
1
1
P
0
2
2
P
0
3
3
P
0
4
4
P
0
5
5

Figure 5cc

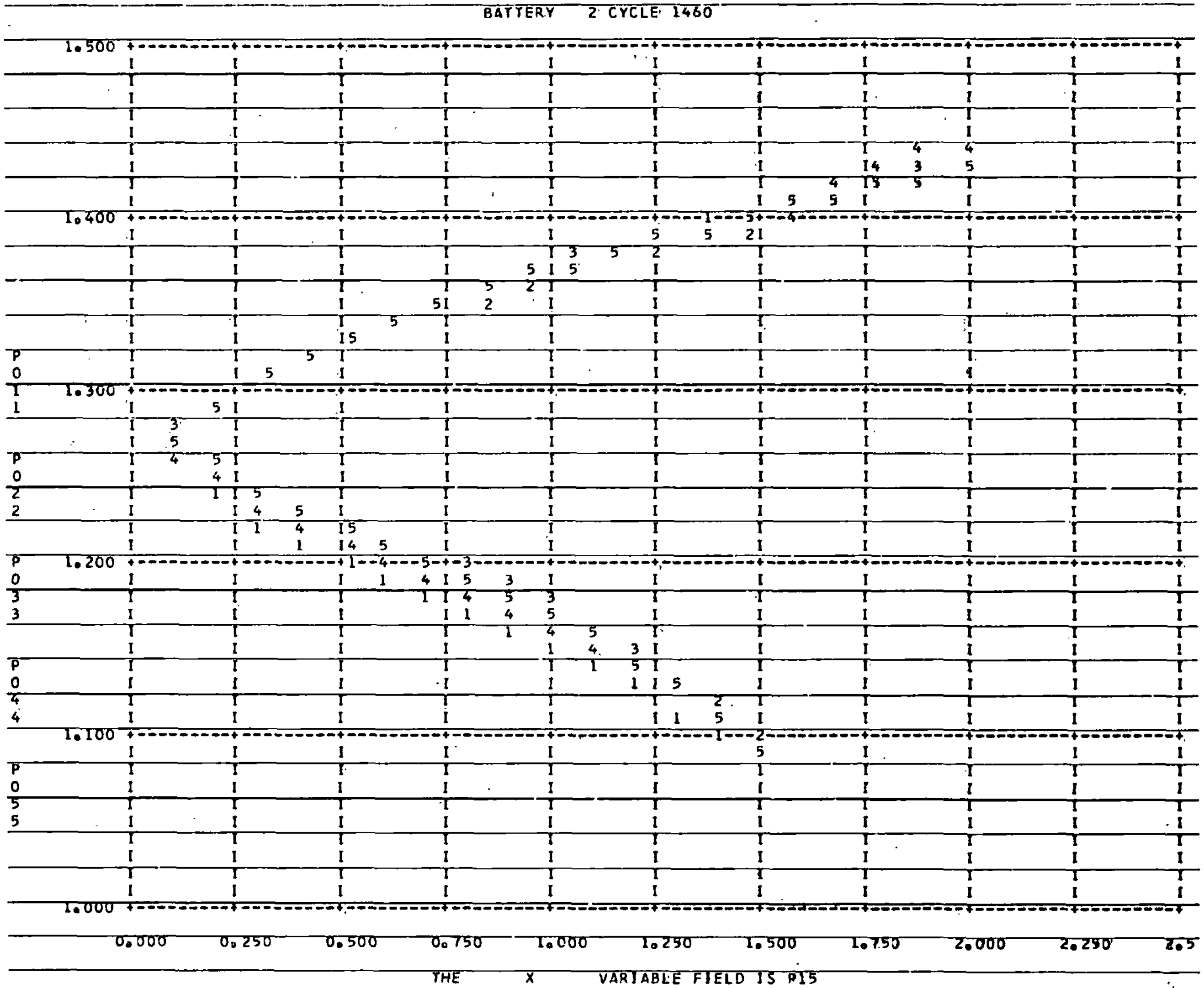

BATTERY 2 CYCLE 1460
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
THE X VARIABLE FIELD IS P15

Figure 5cd

BATTERY 2 CYCLE 2147

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 1
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 2

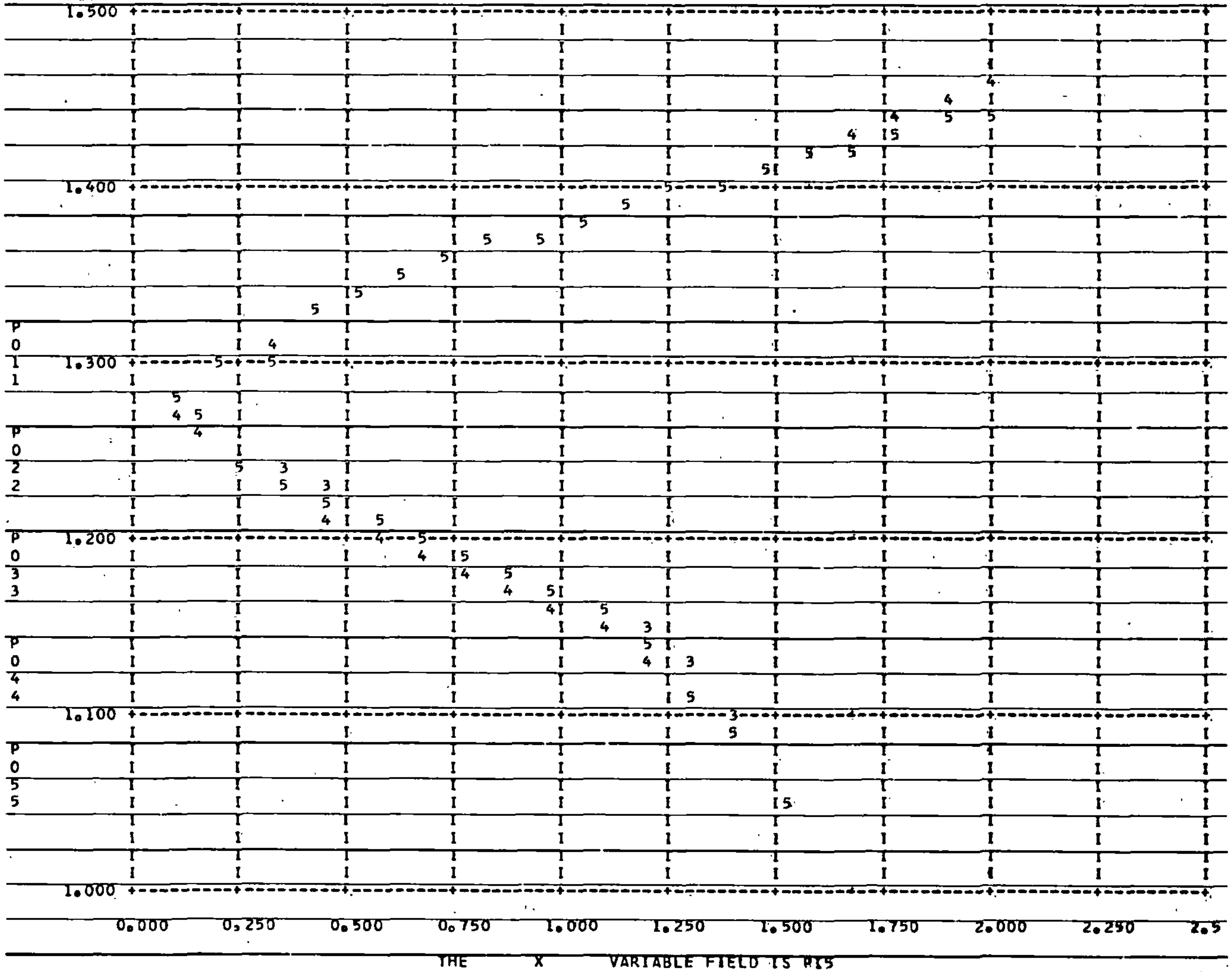


Figure 5ce

BATTERY 2 CYCLE 2538

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 2
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 5

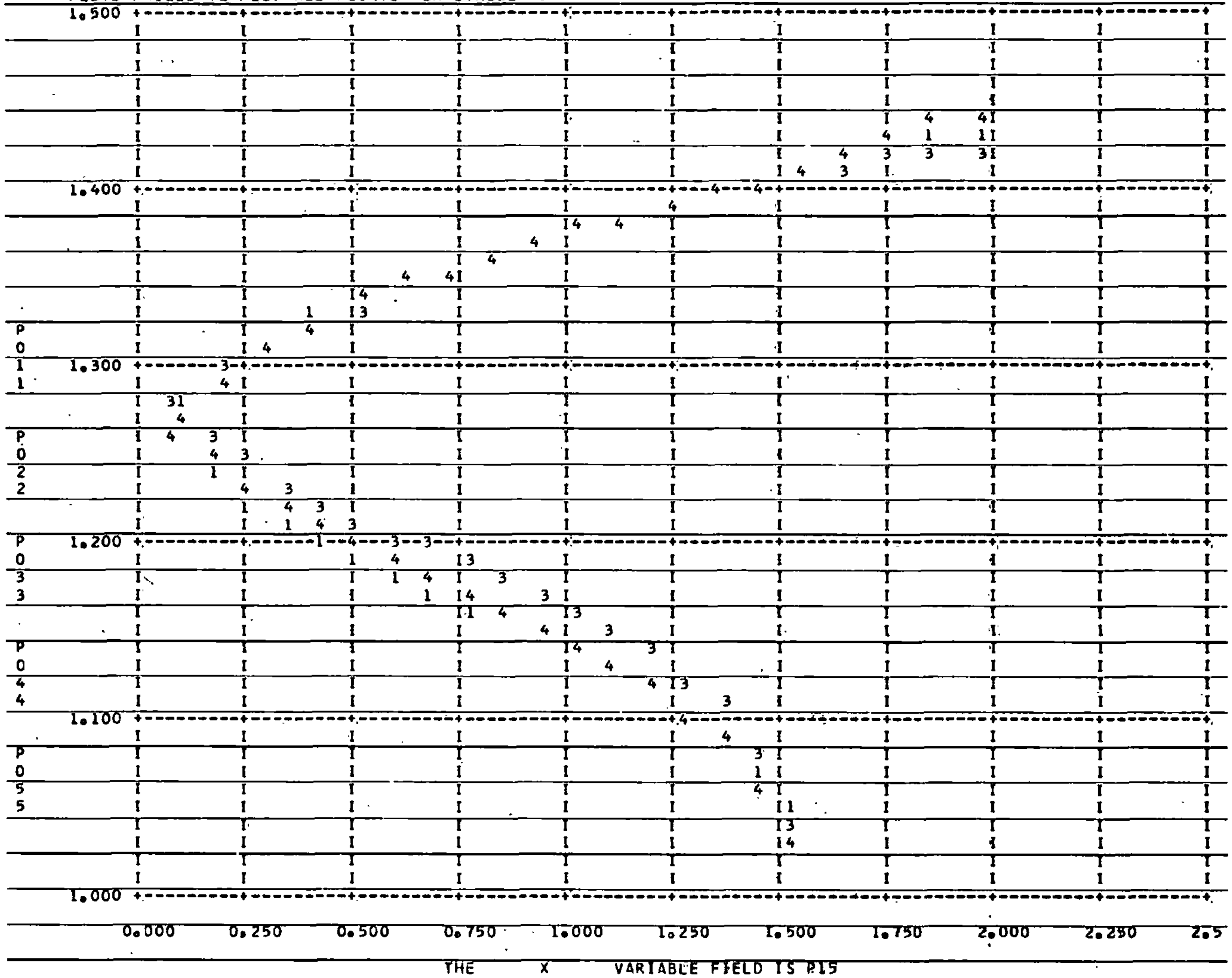


Figure 5cf

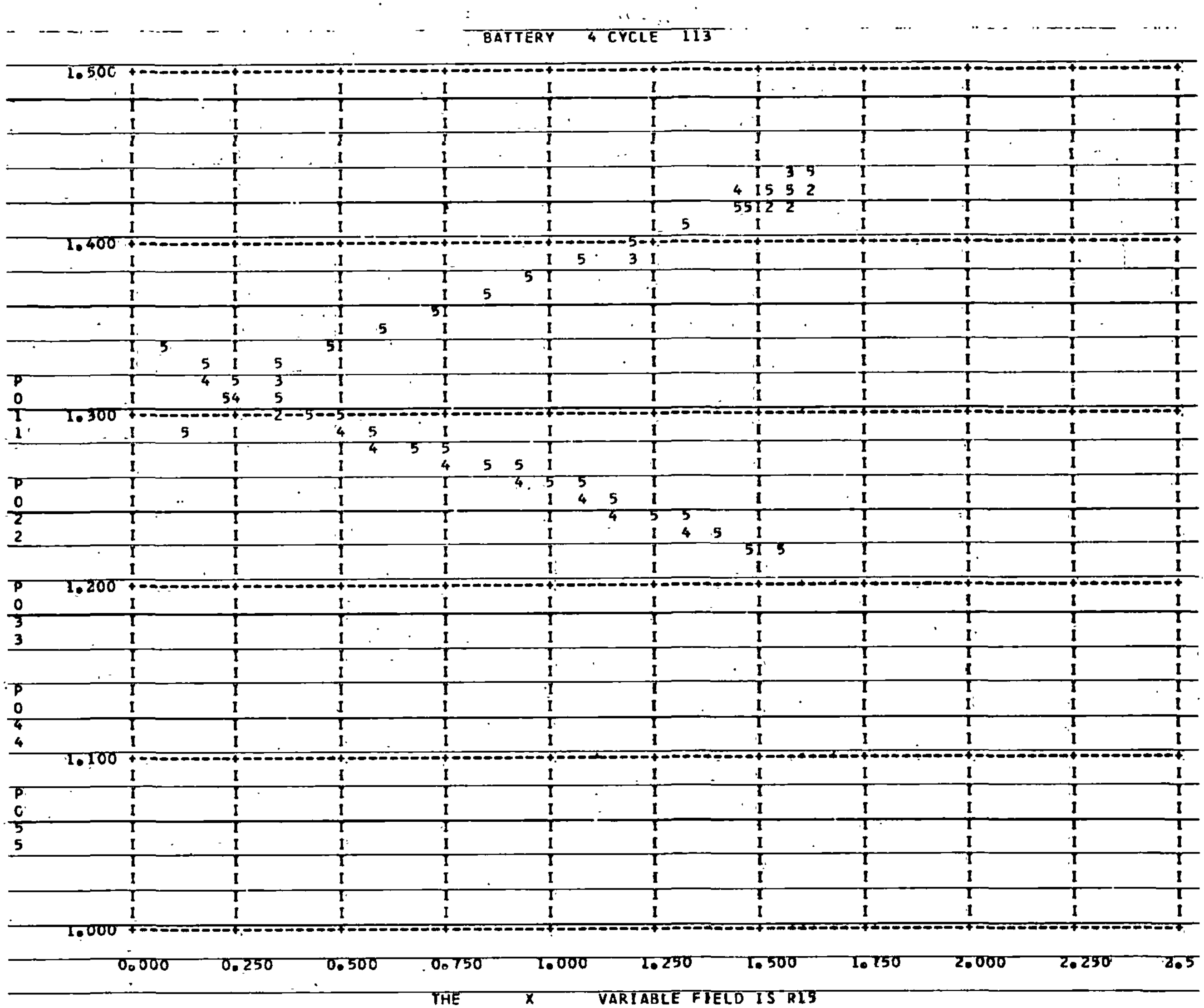


Figure 5da

E-22

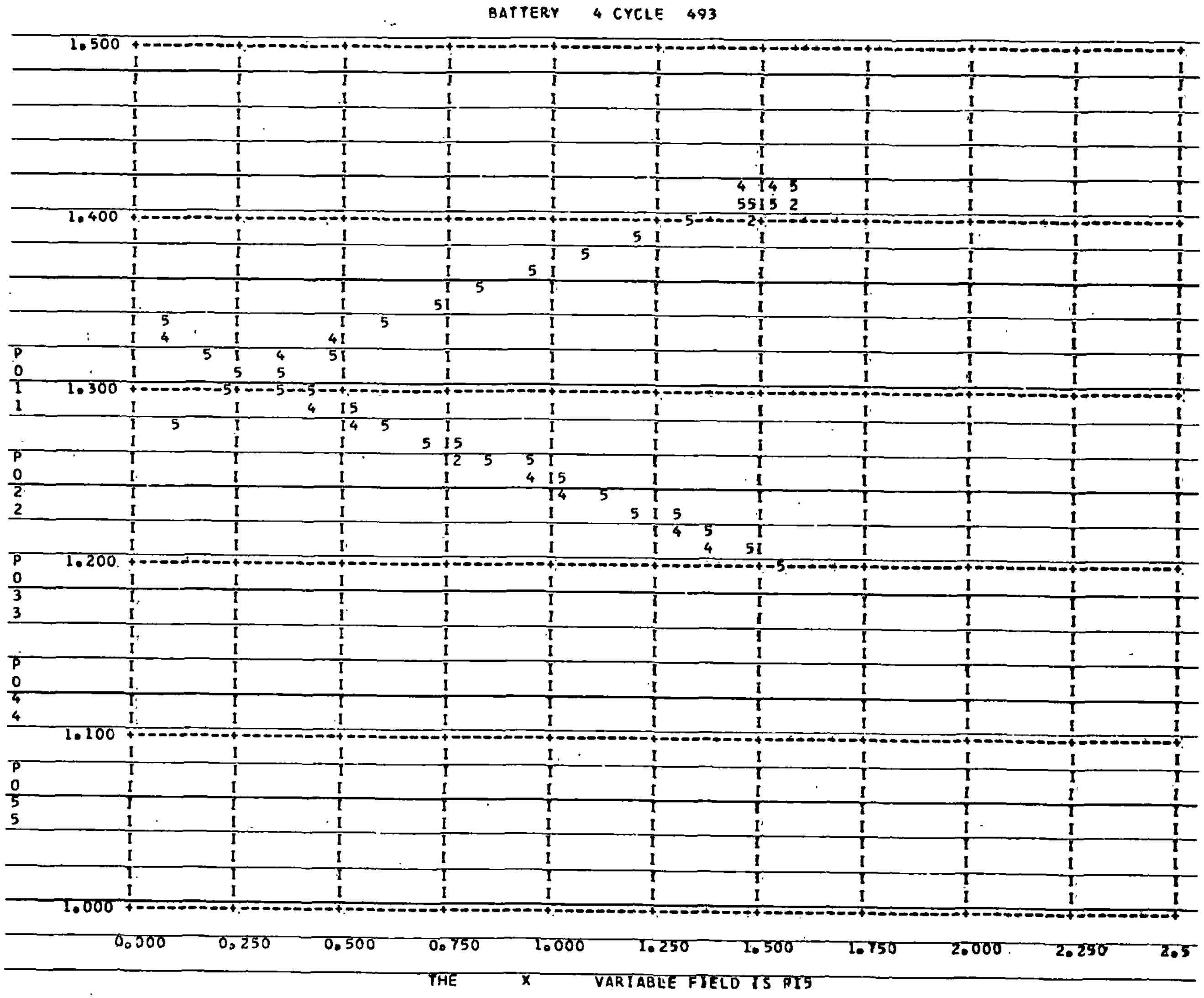

BATTERY 4 CYCLE 493
1.500
1.400
1.300
1.200
1.100
1.000
P
O
1
1
P
O
2
2
P
O
3
3
P
O
4
4
P
O
5
5
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS PI5

Figure 5db

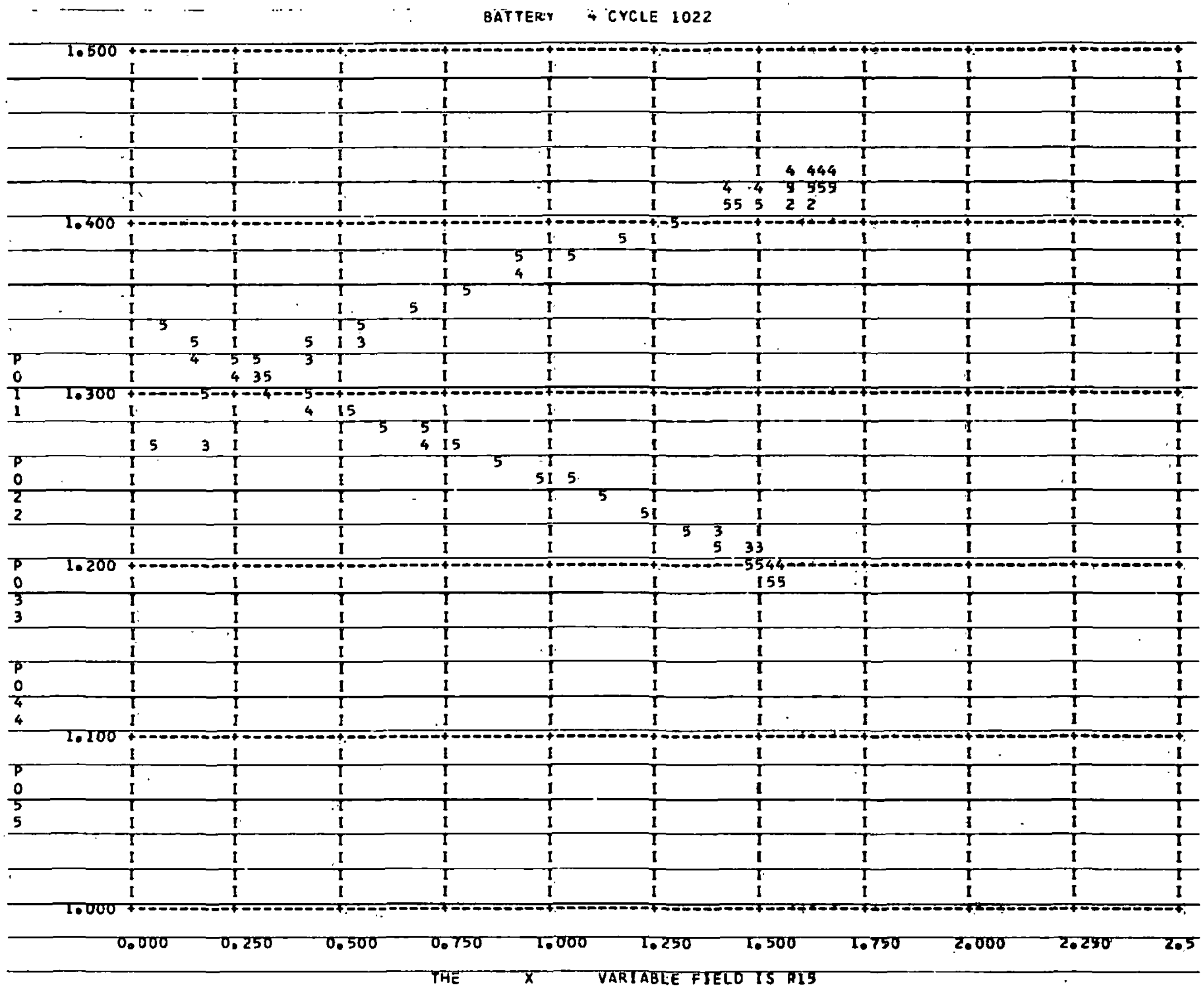

BATTERY 4 CYCLE 1022
1.500
1.400
1.300
1.200
1.100
1.000
P O 1 1
P O 2 2
P O 3 3
P O 4 4
P O 5 5
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS R15

Figure 5dc

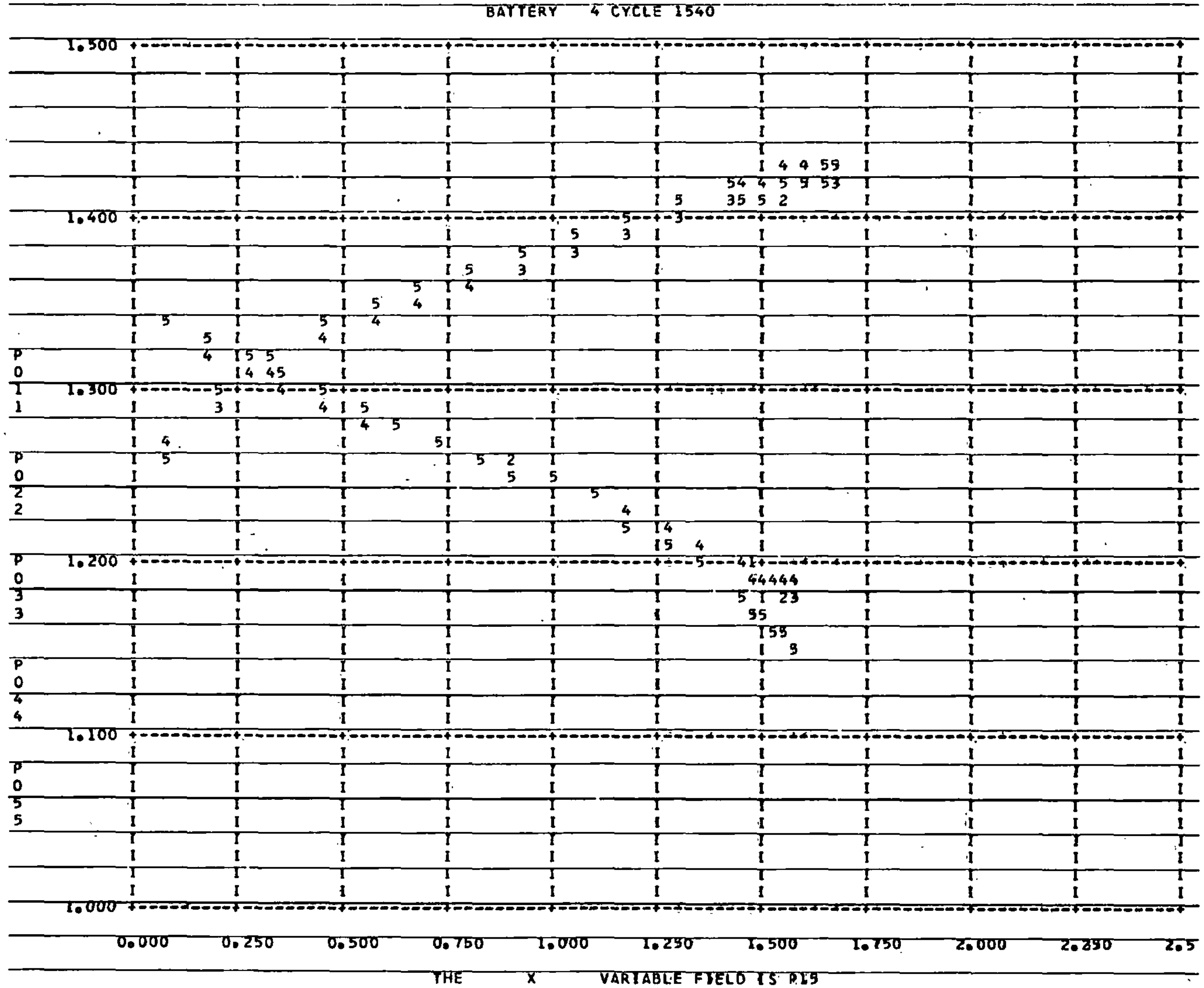

BATTERY 4 CYCLE 1540
1.500
1.400
1.300
1.200
1.100
1.000
P
O
1
1
P
O
2
2
P
O
3
3
P
O
4
4
P
O
5
5
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS R15

Figure 5dd

BATTERY 4 CYCLE 2021

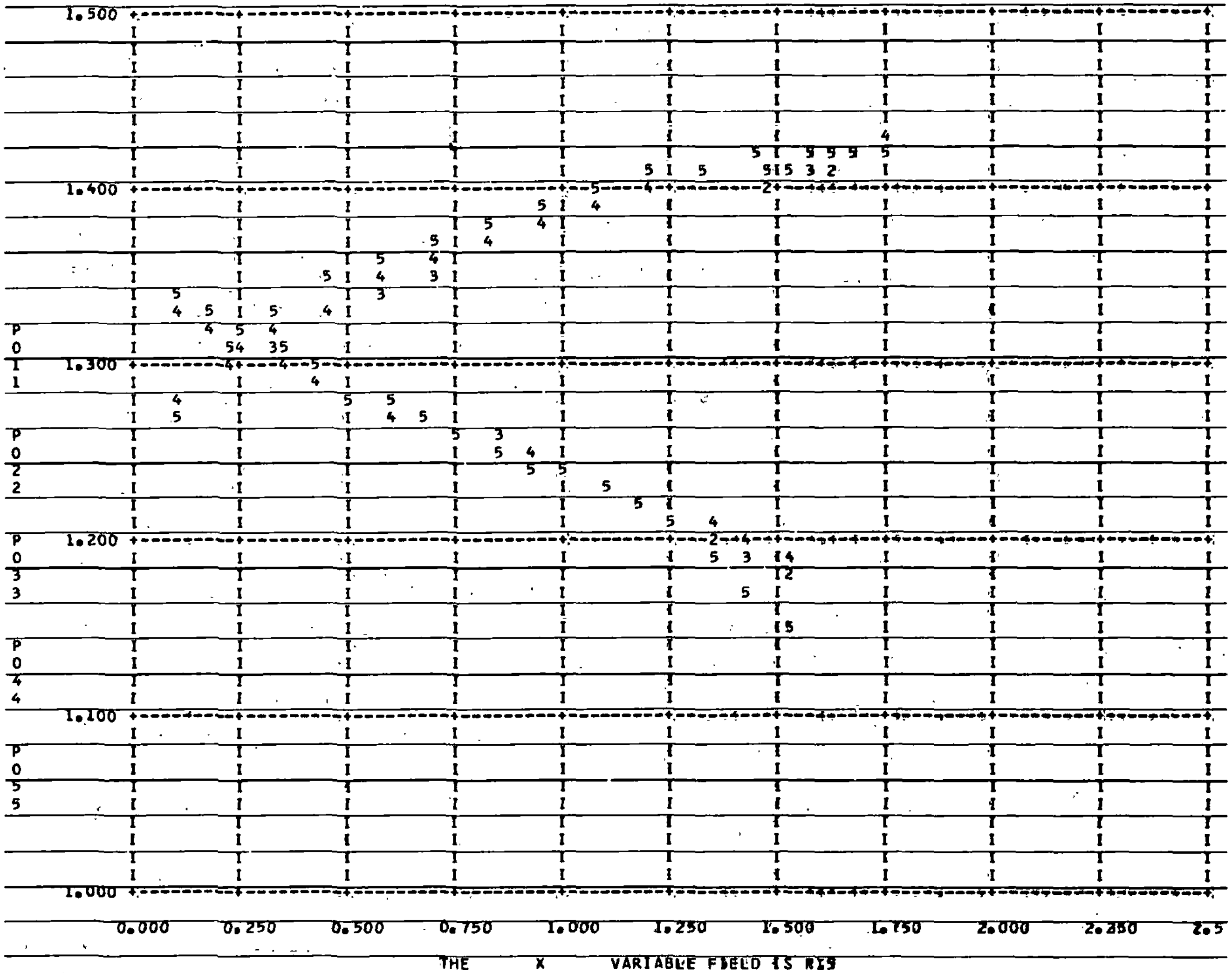


Figure 5de

BATTERY 4 CYCLE 2564

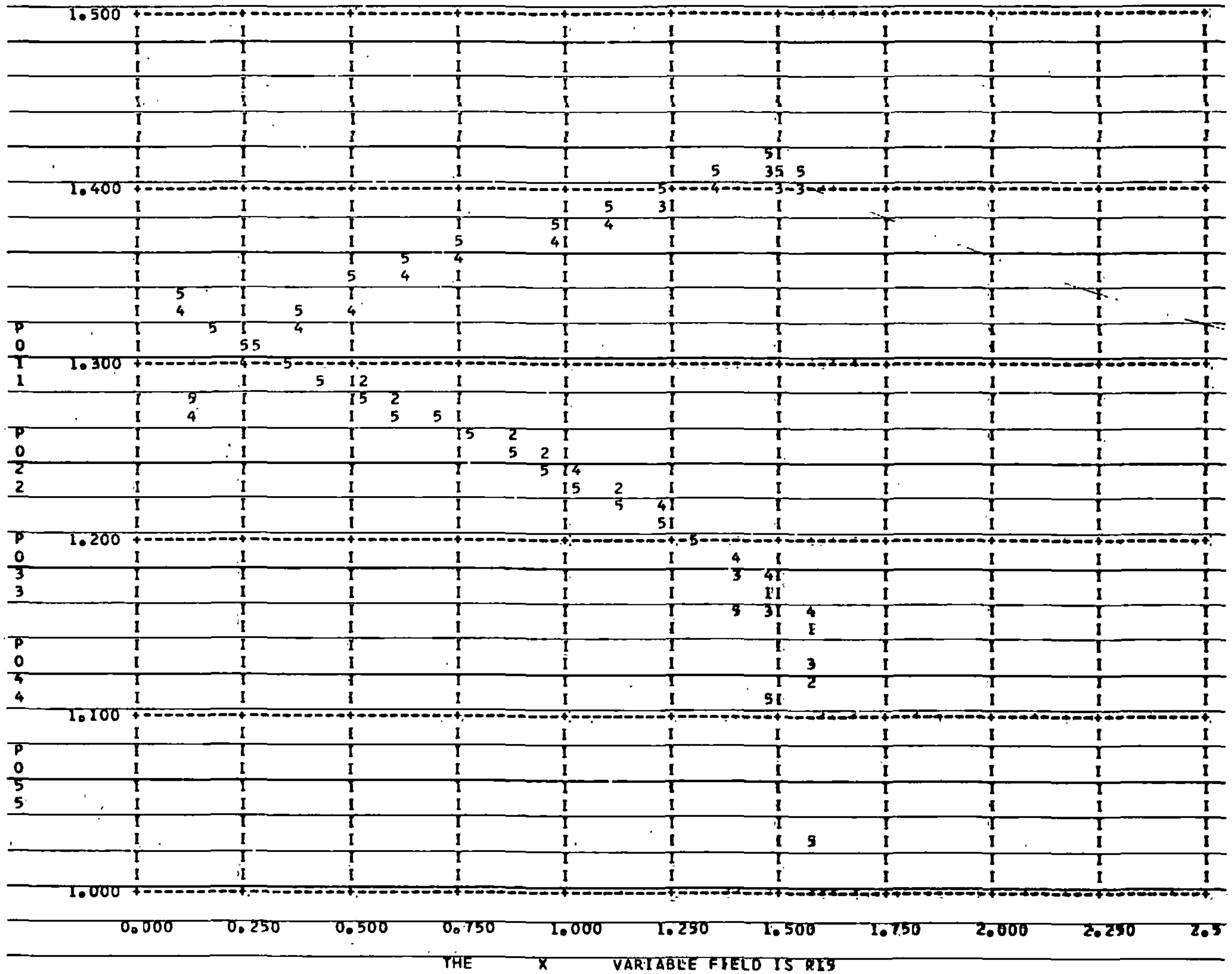


Figure 5df

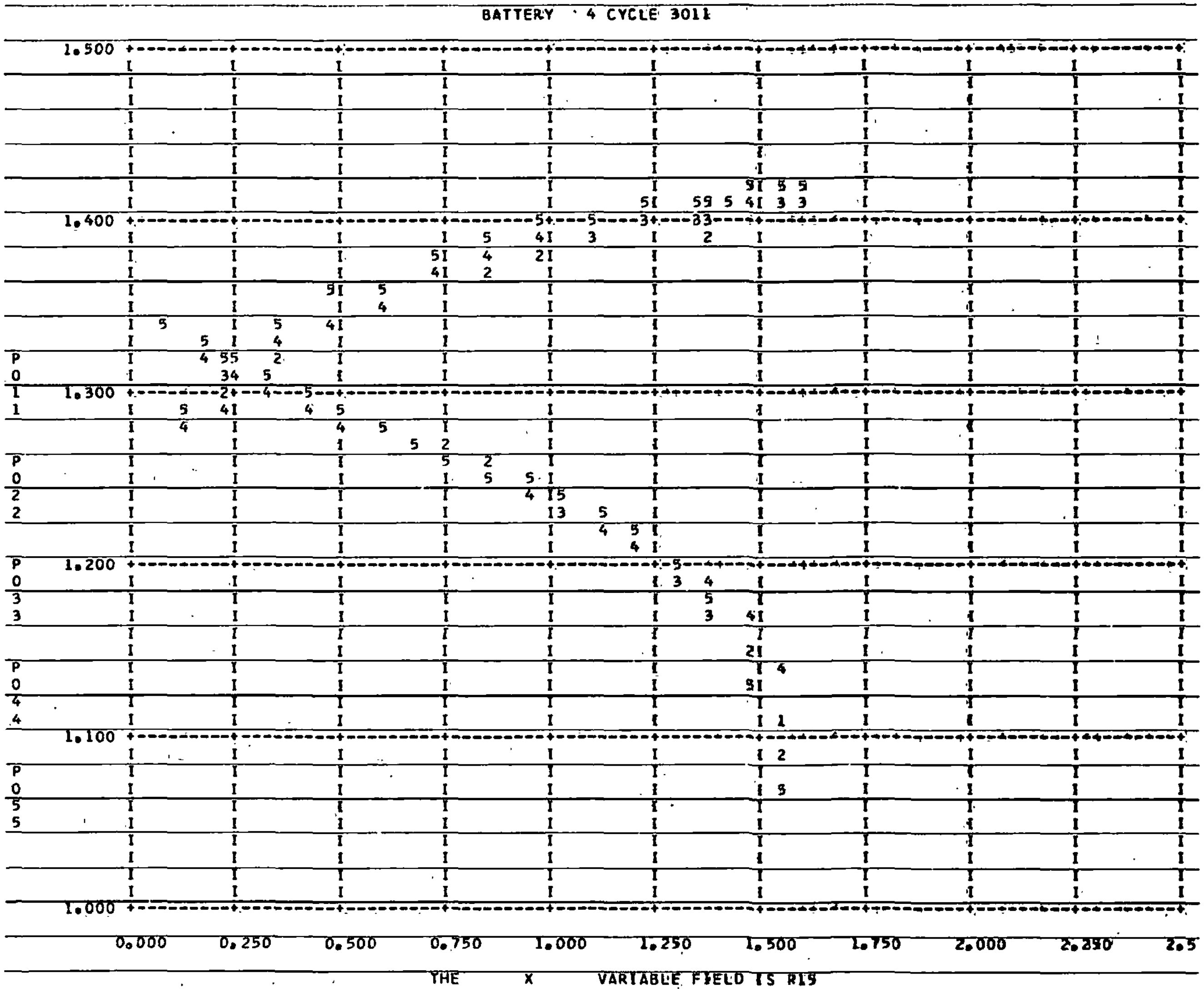

BATTERY 4 CYCLE 3011
1.500
1.400
1.300
1.200
1.100
1.000
P
0
1
1
P
0
2
2
P
0
3
3
P
0
4
4
P
0
5
5
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS RIS

Figure 5dg

BATTERY 4 CYCLE 3560

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 5

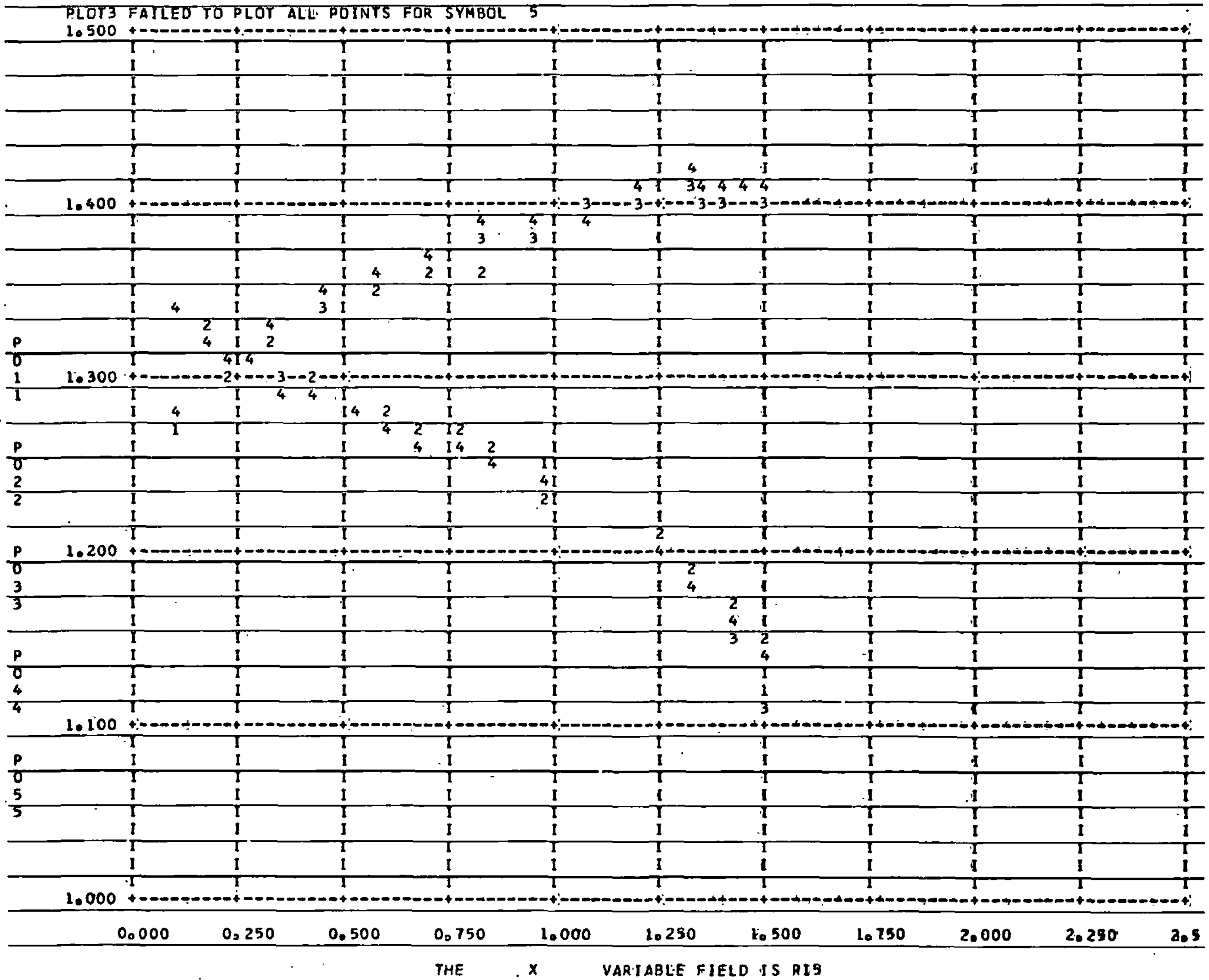


Figure 5dh

BATTERY 4 CYCLE 4032

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 5

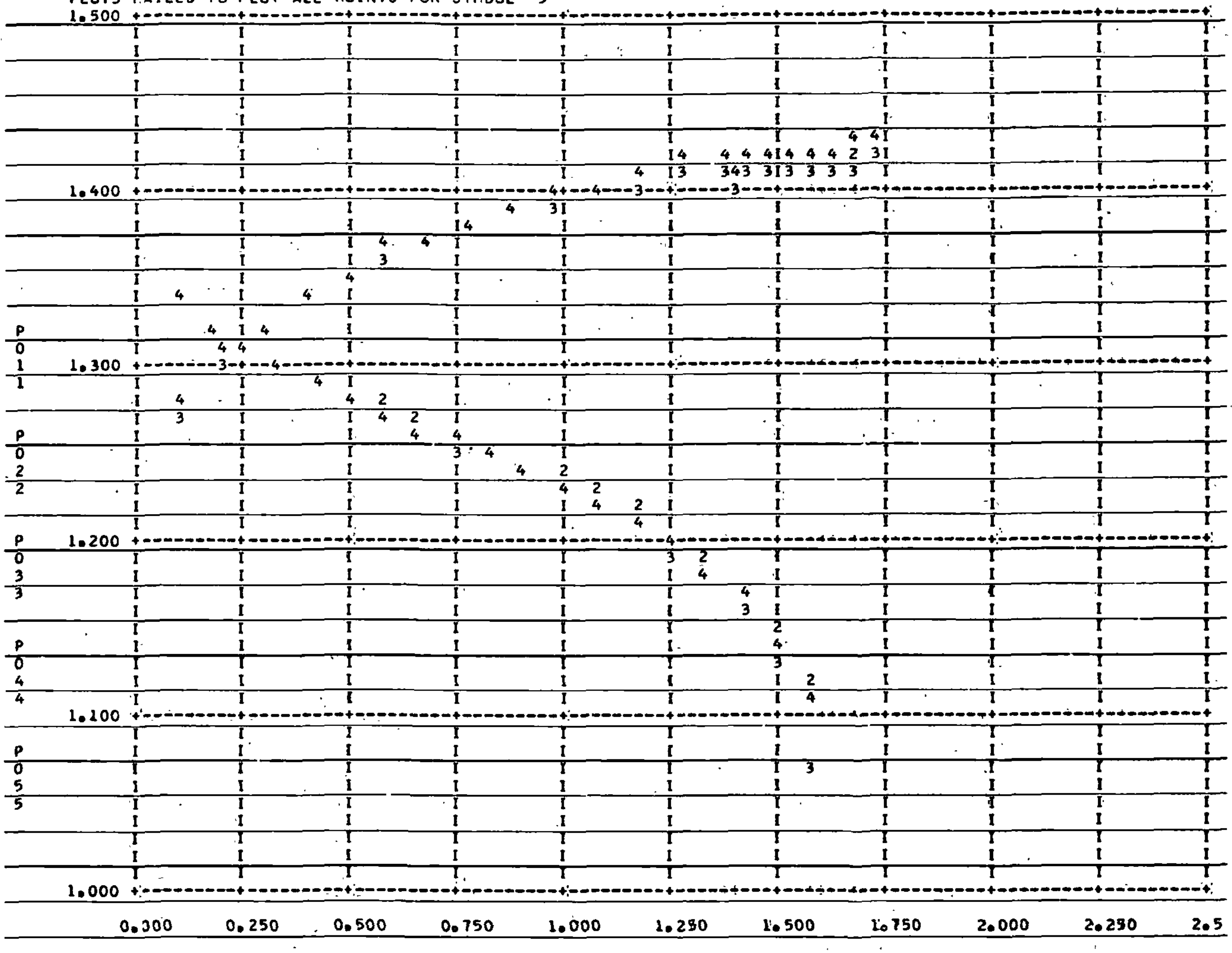
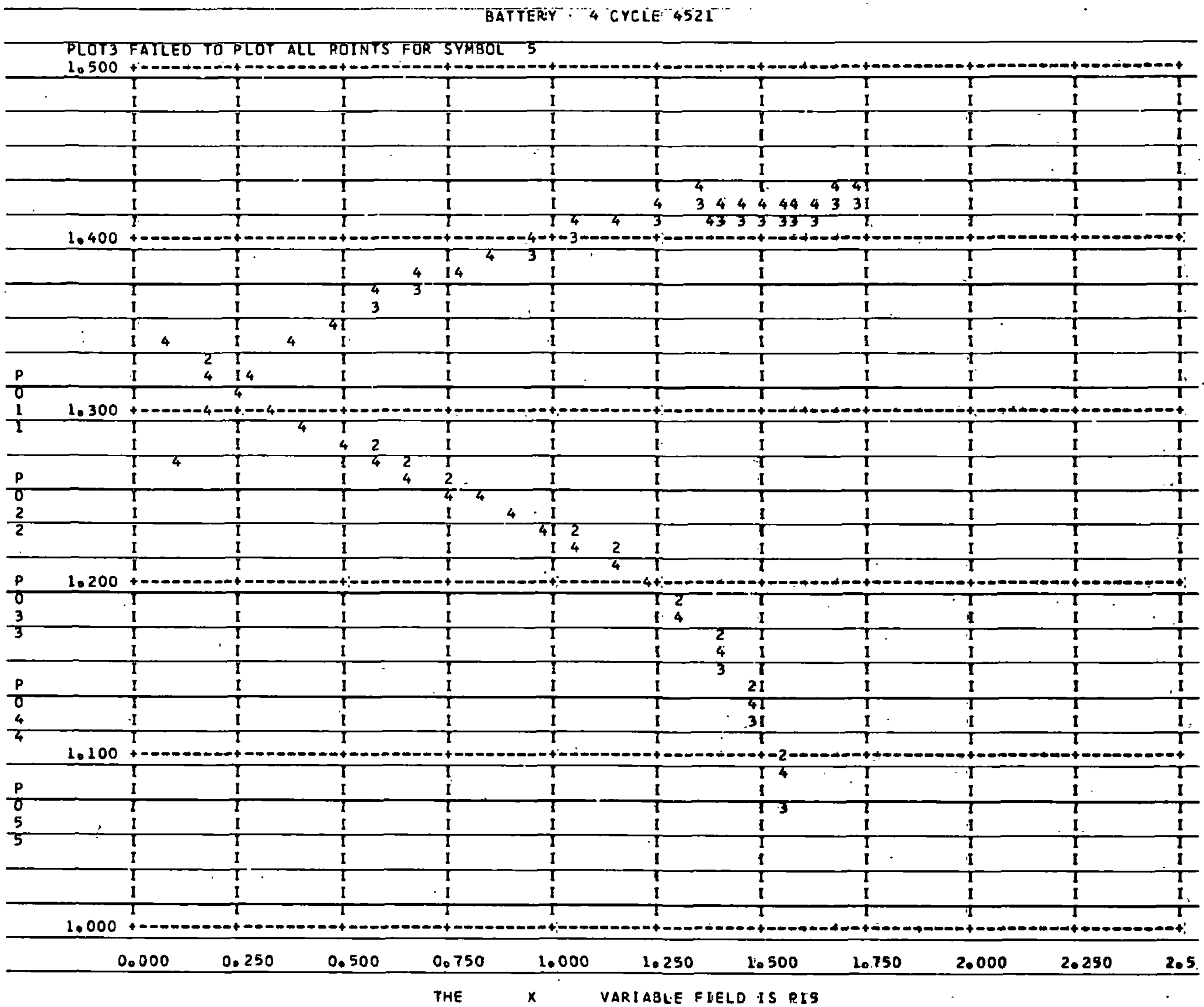


Figure 5di



BATTERY 4 CYCLE 4521
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 5
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS RIS

Figure 5dj

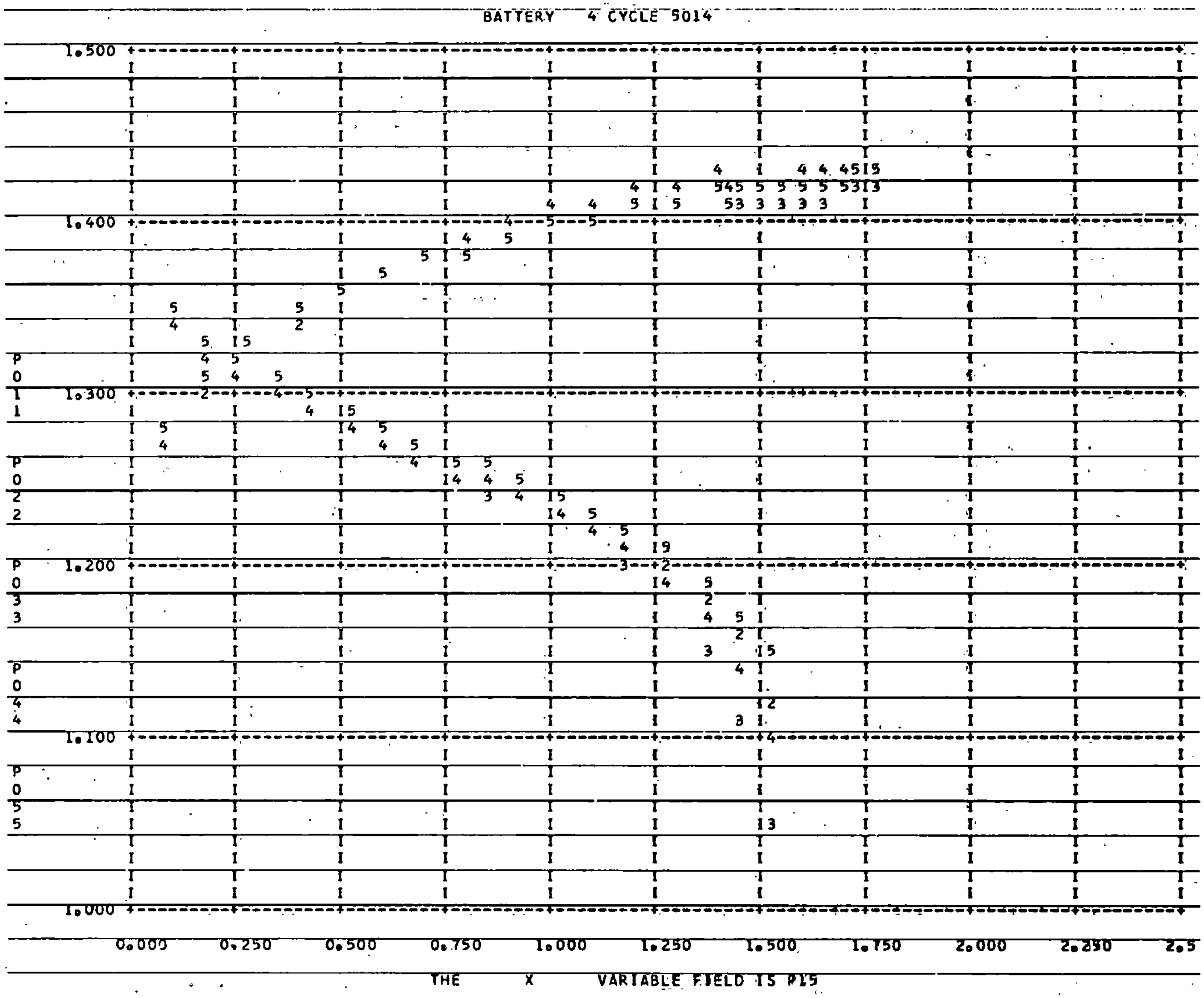
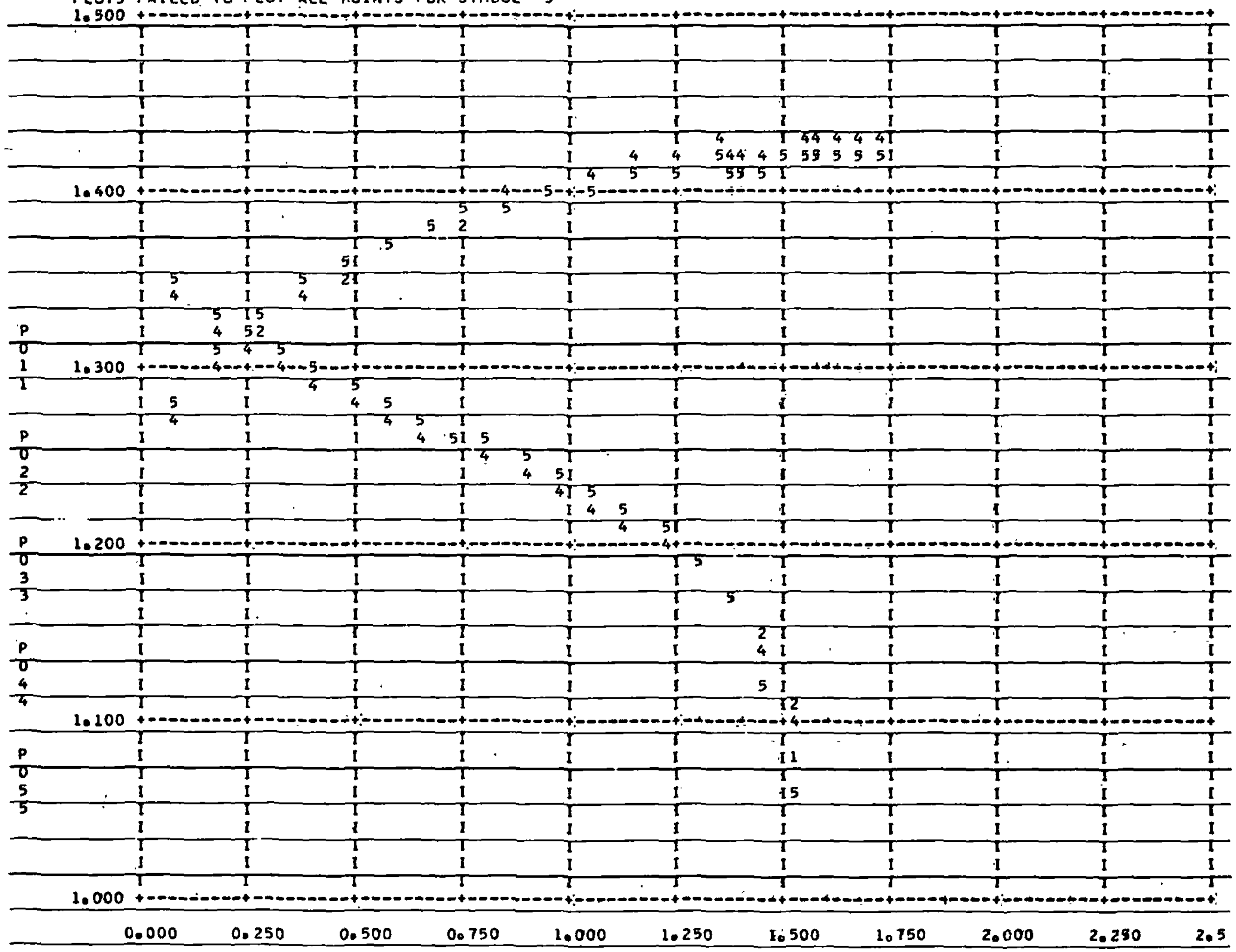

BATTERY 4 CYCLE 5014
1.500
1.400
1.300
1.200
1.100
1.000
P
0
1
1
P
0
2
2
P
0
3
3
P
0
4
4
P
0
5
5
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS P15

Figure 5dk

BATTERY 4 CYCLE 5510

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 3



THE X VARIABLE FIELD IS PI9

Figure 5dl

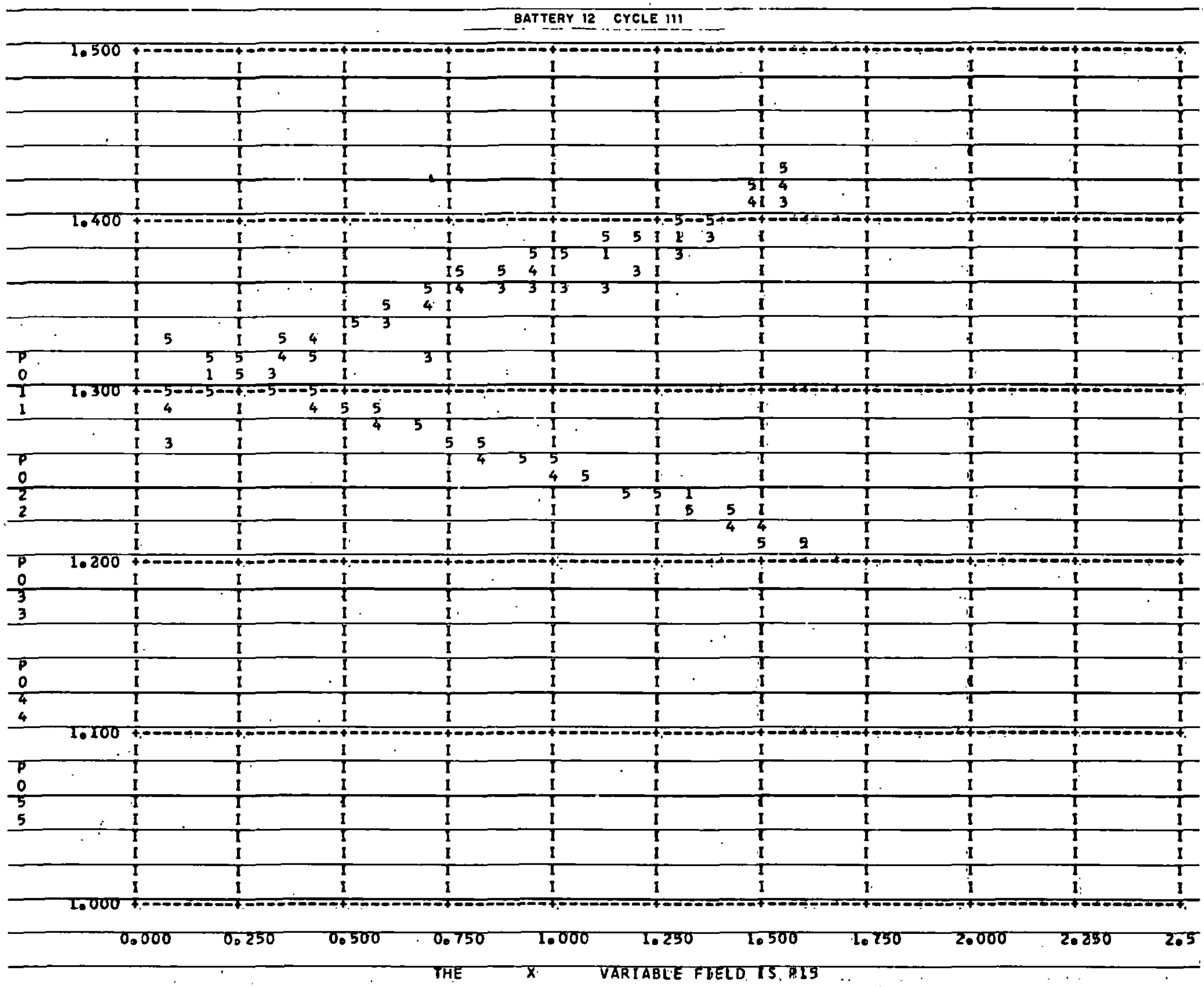

BATTERY 12 CYCLE 111
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS R15

Figure 5ea

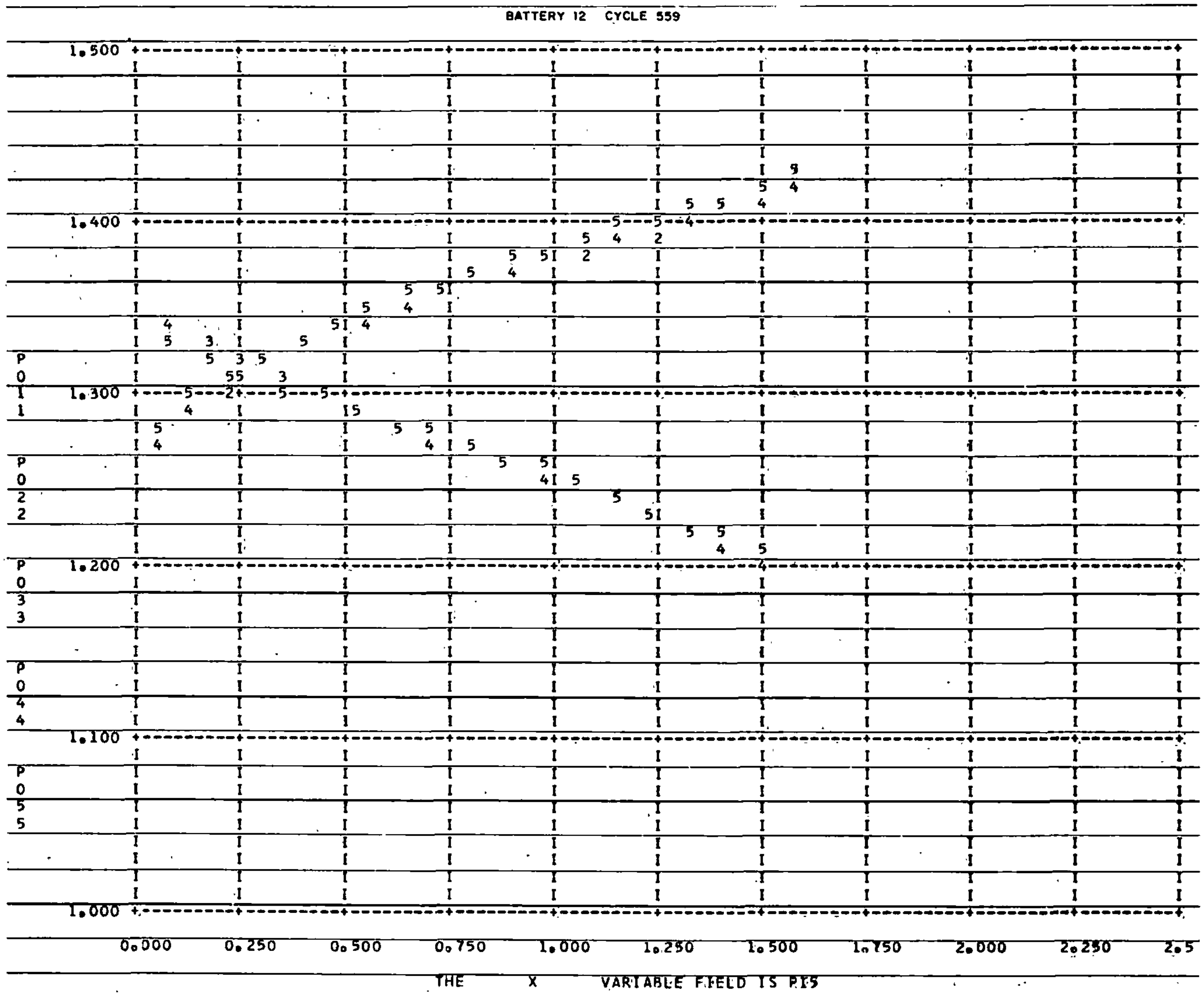

BATTERY 12 CYCLE 559
1.500
1.400
1.300
1.200
1.100
1.000
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS PTS
P011
P022
P033
P044
P055

Figure 5eb

BATTERY 12 CYCLE 1007

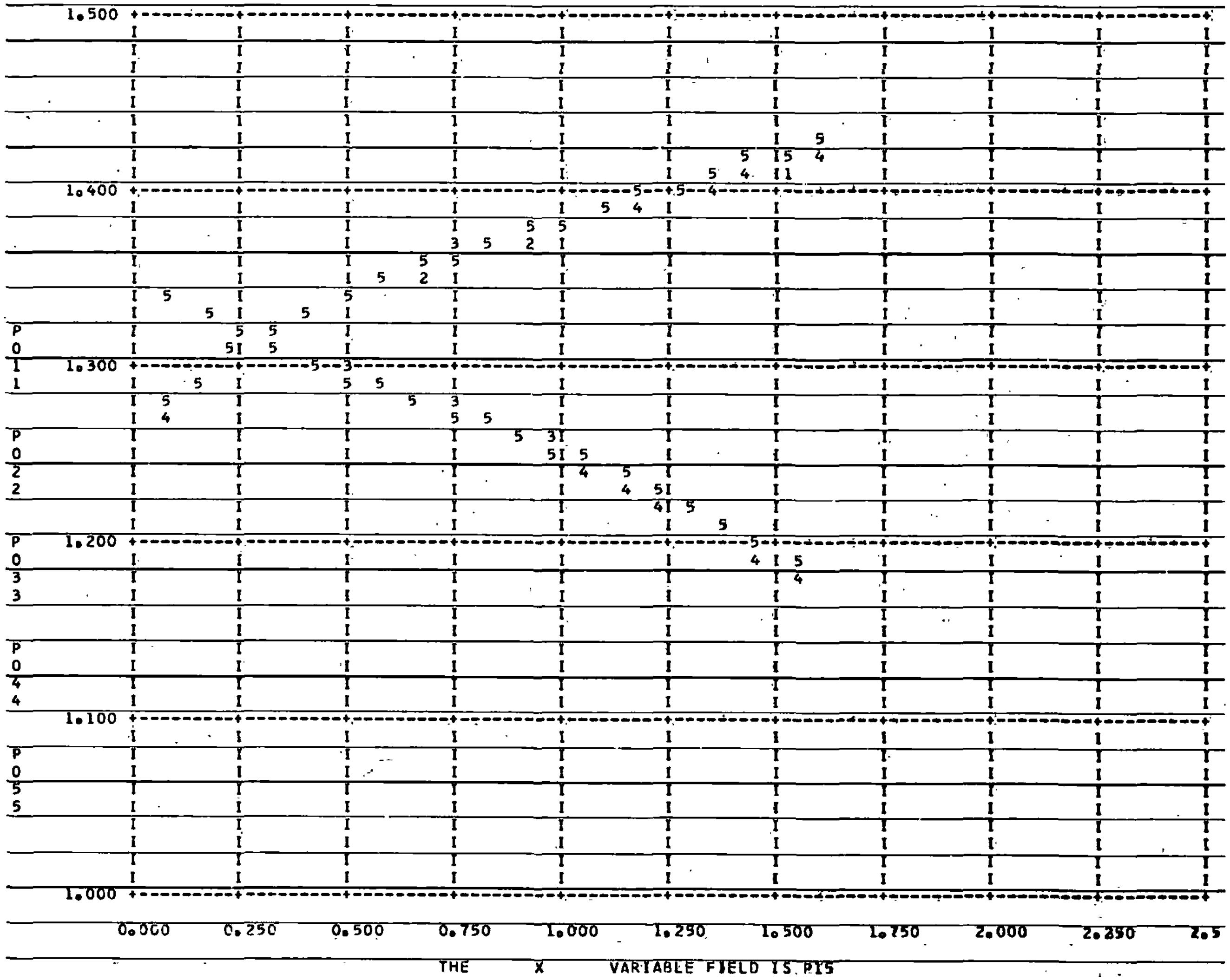


Figure 5ec

BATTERY 12 CYCLE 1455

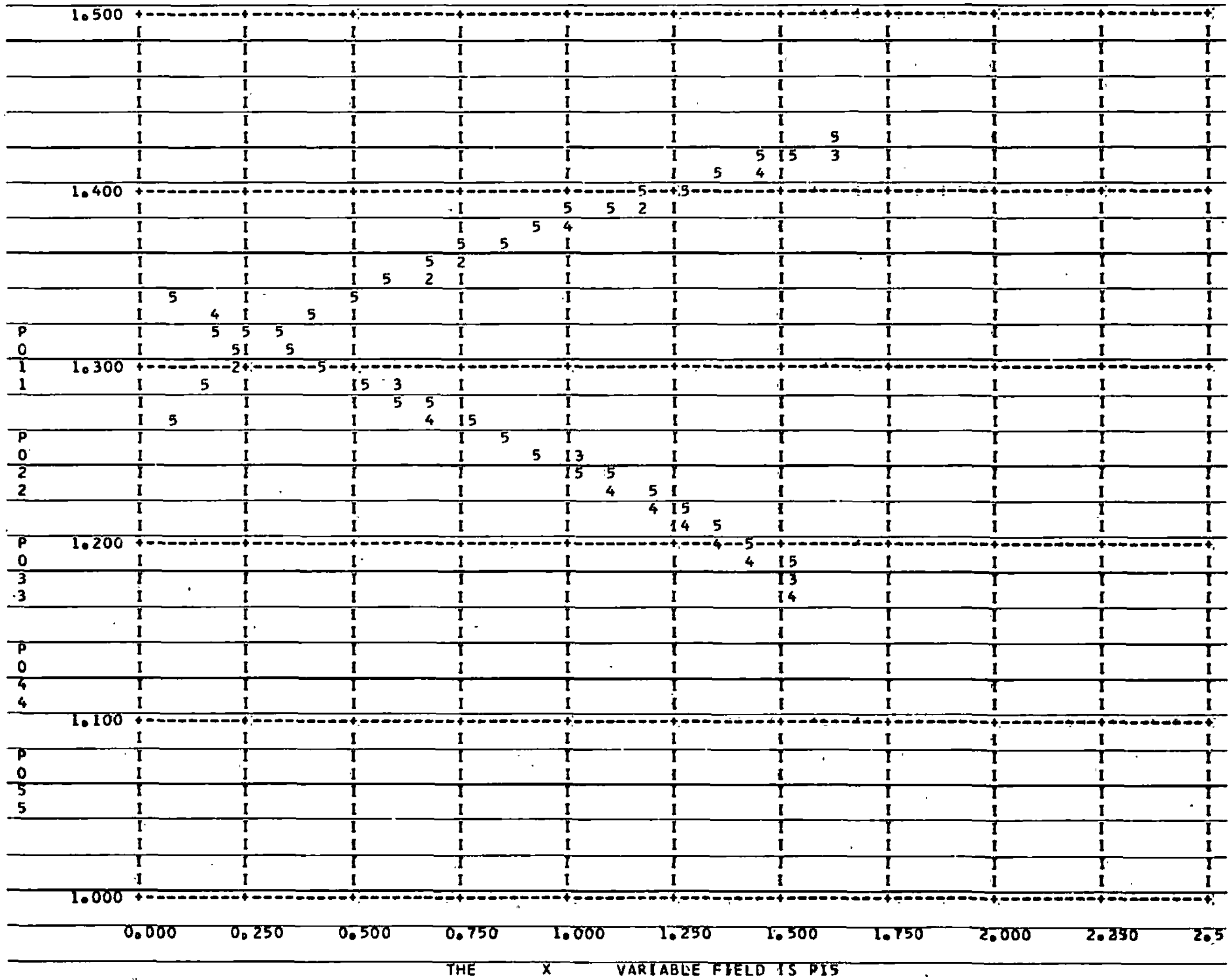
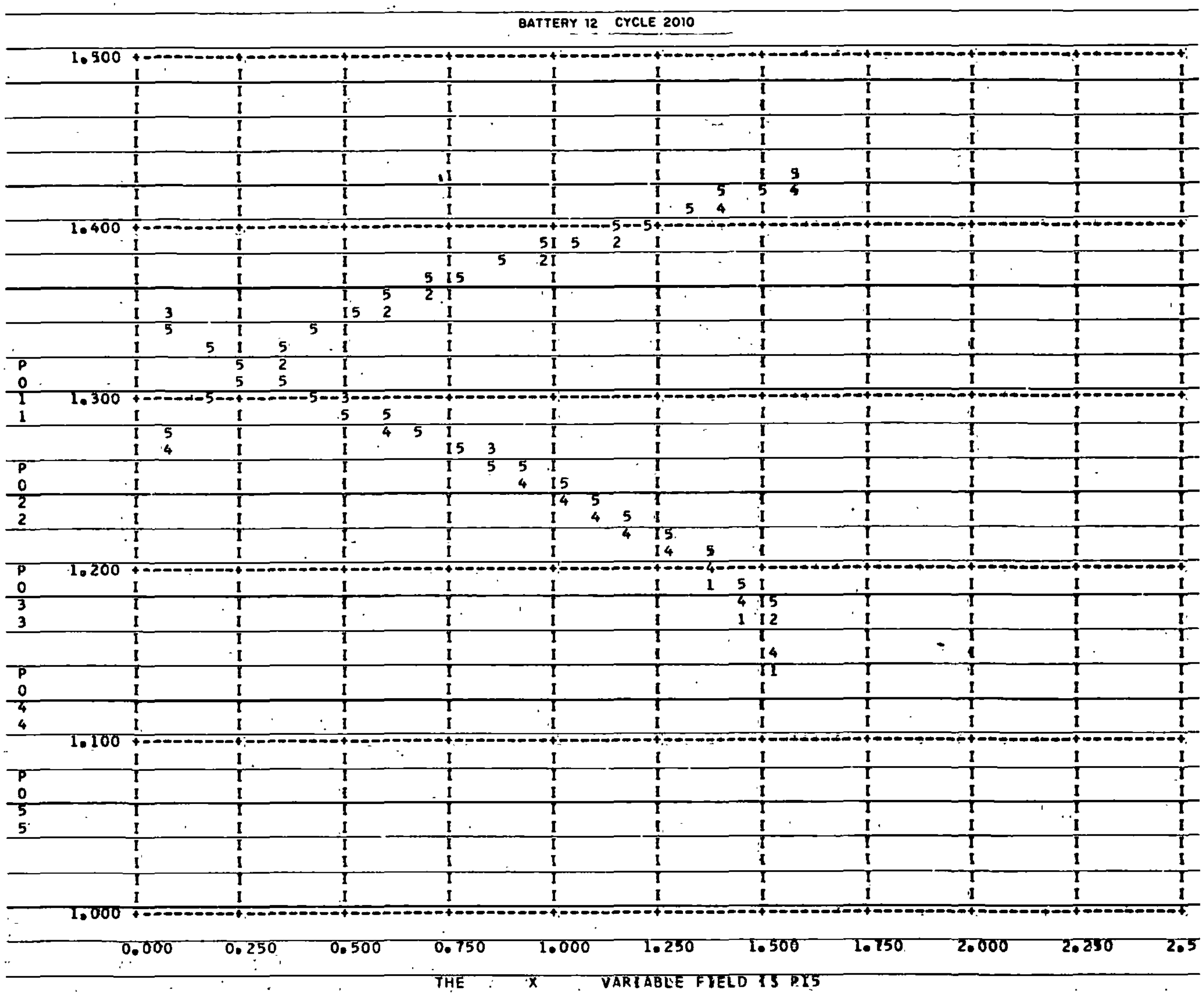


Figure 5ed



BATTERY 12 CYCLE 2010
1.500
1.400
1.300
1.200
1.100
1.000
P O I 1
P O 2 2
P O 3 3
P O 4 4
P O 5 5
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS PI5

Figure 5ee

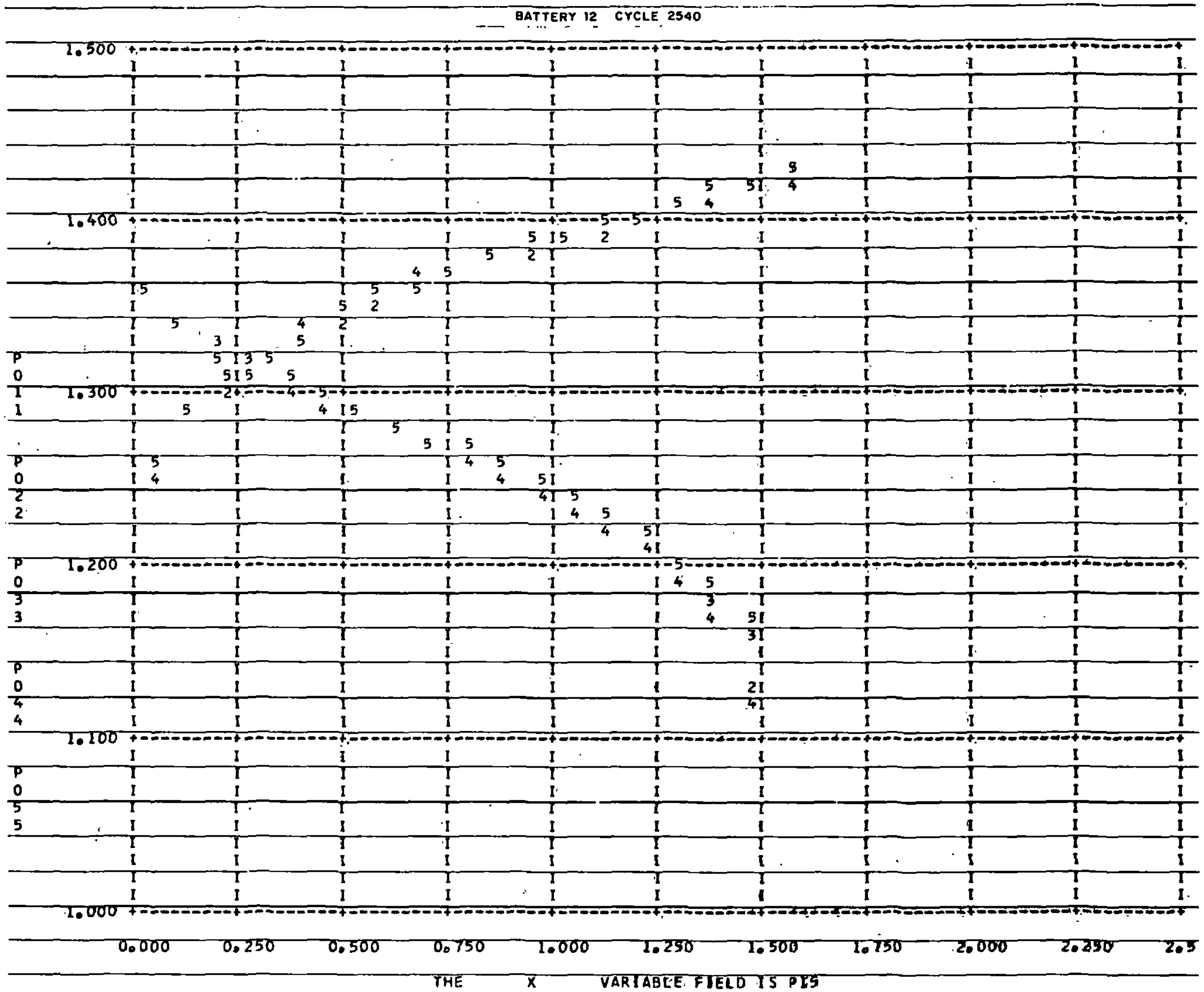
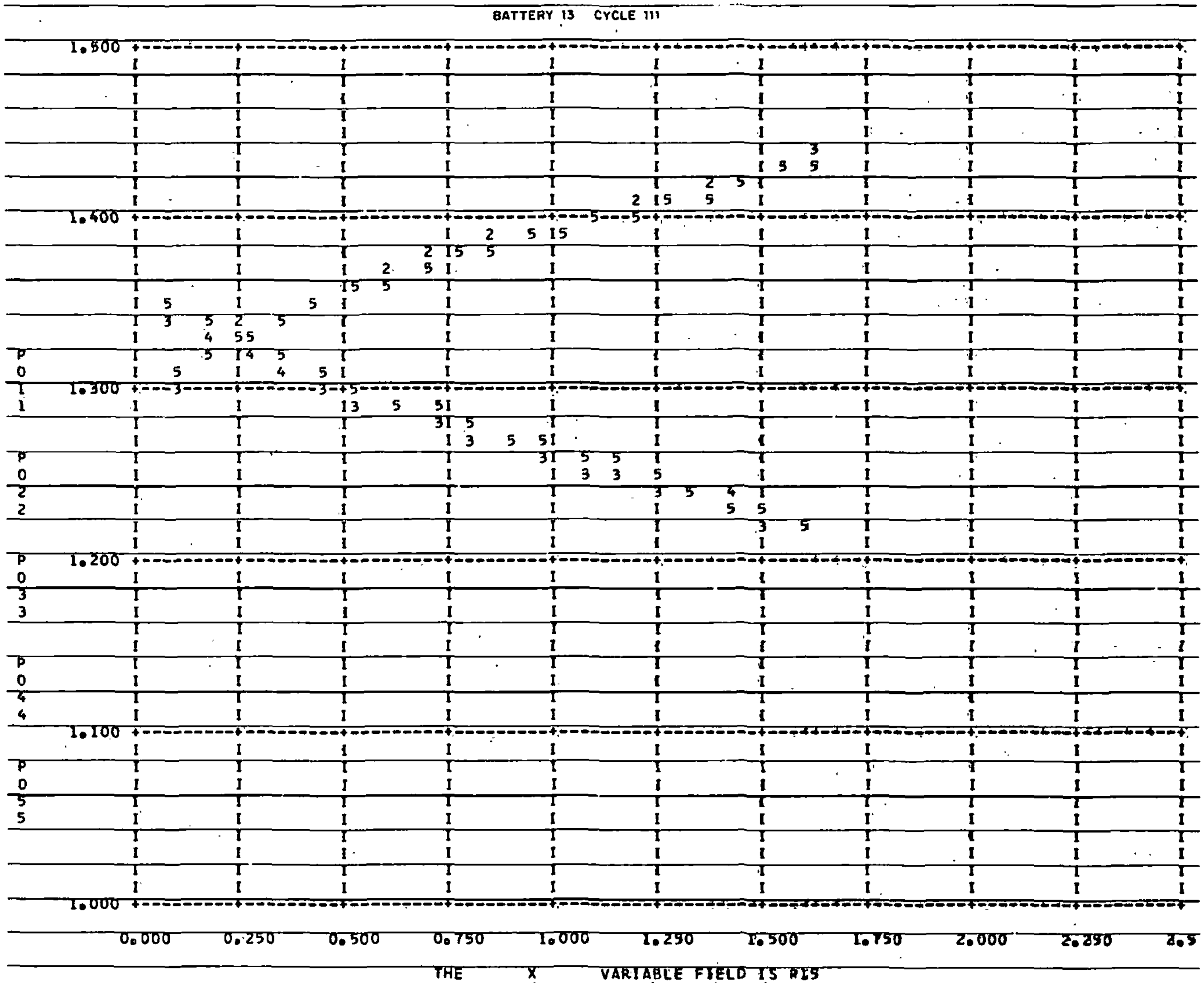
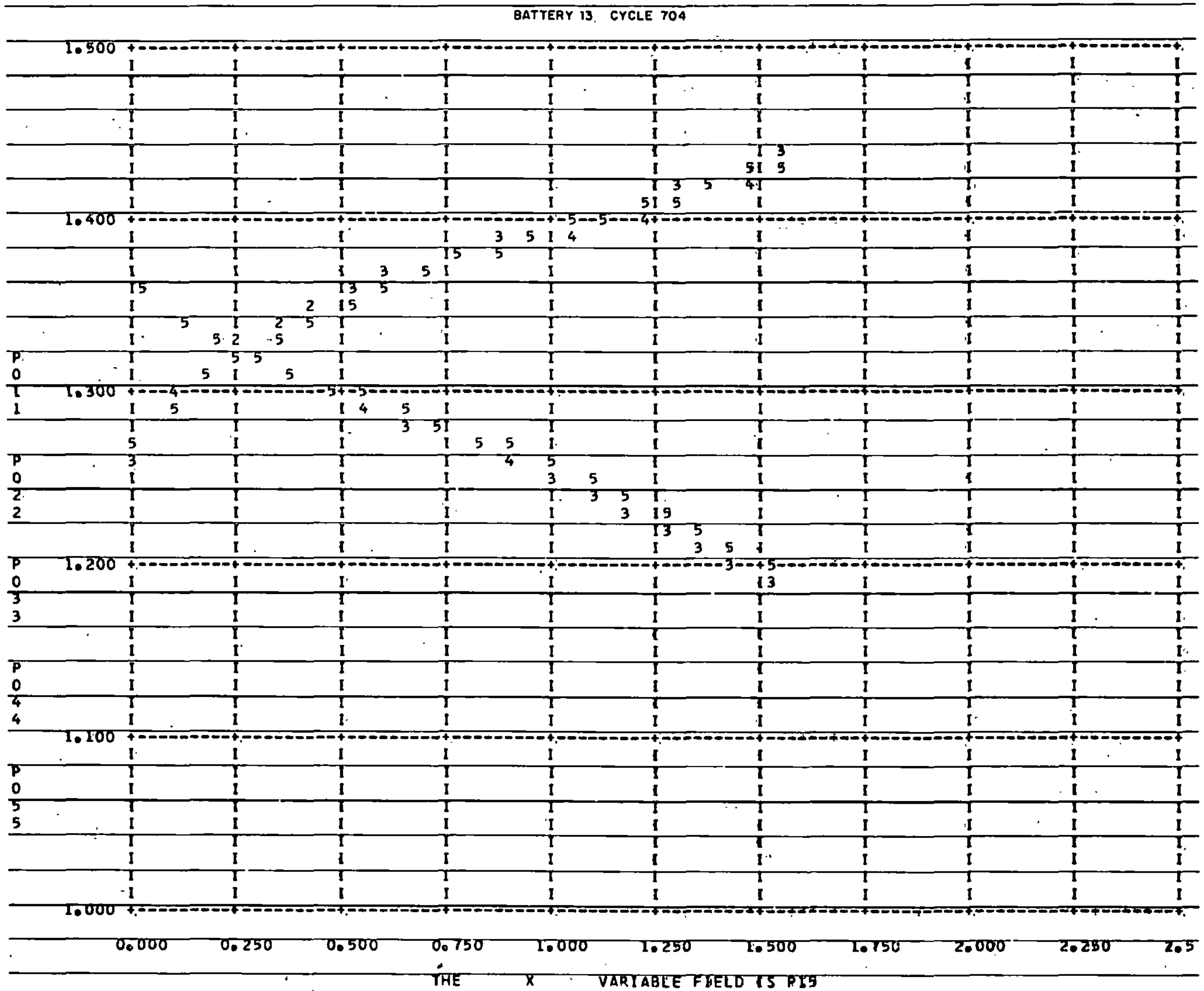

BATTERY 12 CYCLE 2540
1.500
1.400
1.300
1.200
1.100
1.000
P
0
1
1
P
0
2
2
P
0
3
3
P
0
4
4
P
0
5
5
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS PIS

Figure 5ef



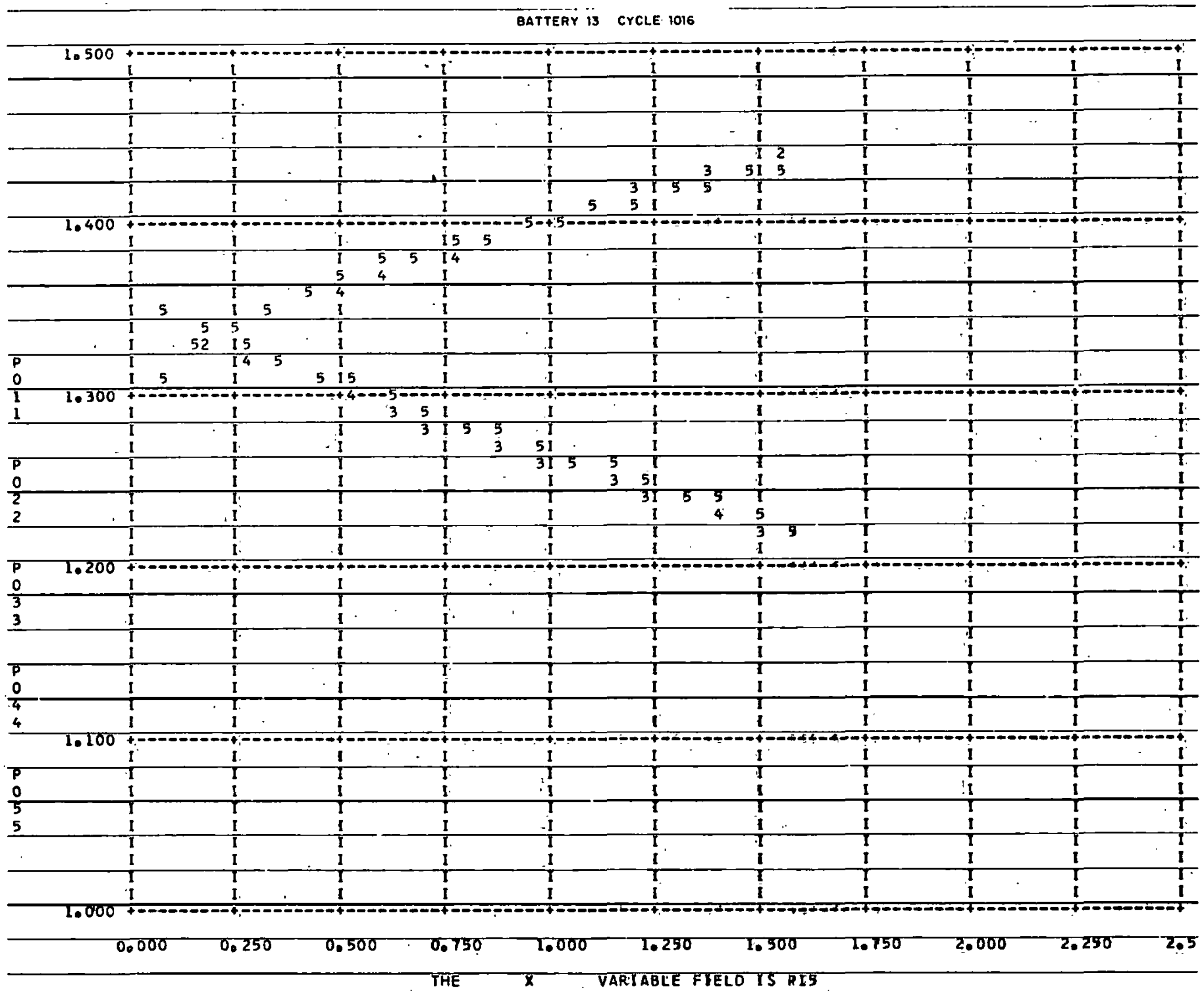
BATTERY 13 CYCLE 111
1.500
1.400
1.300
1.200
1.100
1.000
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
THE X VARIABLE FIELD IS RIS
P O I 1
P O 2 2
P O 3 3
P O 4 4
P O 5 5

Figure 5fa



BATTERY 13 CYCLE 704
1.500
1.400
1.300
1.200
1.100
1.000
P
0
1
1
P
0
2
2
P
0
3
3
P
0
4
4
P
0
5
5
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS PIS

Figure 5fb



BATTERY 13 CYCLE 1016
1.500
1.400
1.300
1.200
1.100
1.000
P
0
1
1
P
0
2
2
P
0
3
3
P
0
4
4
P
0
5
5
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS RIS

Figure 5fc

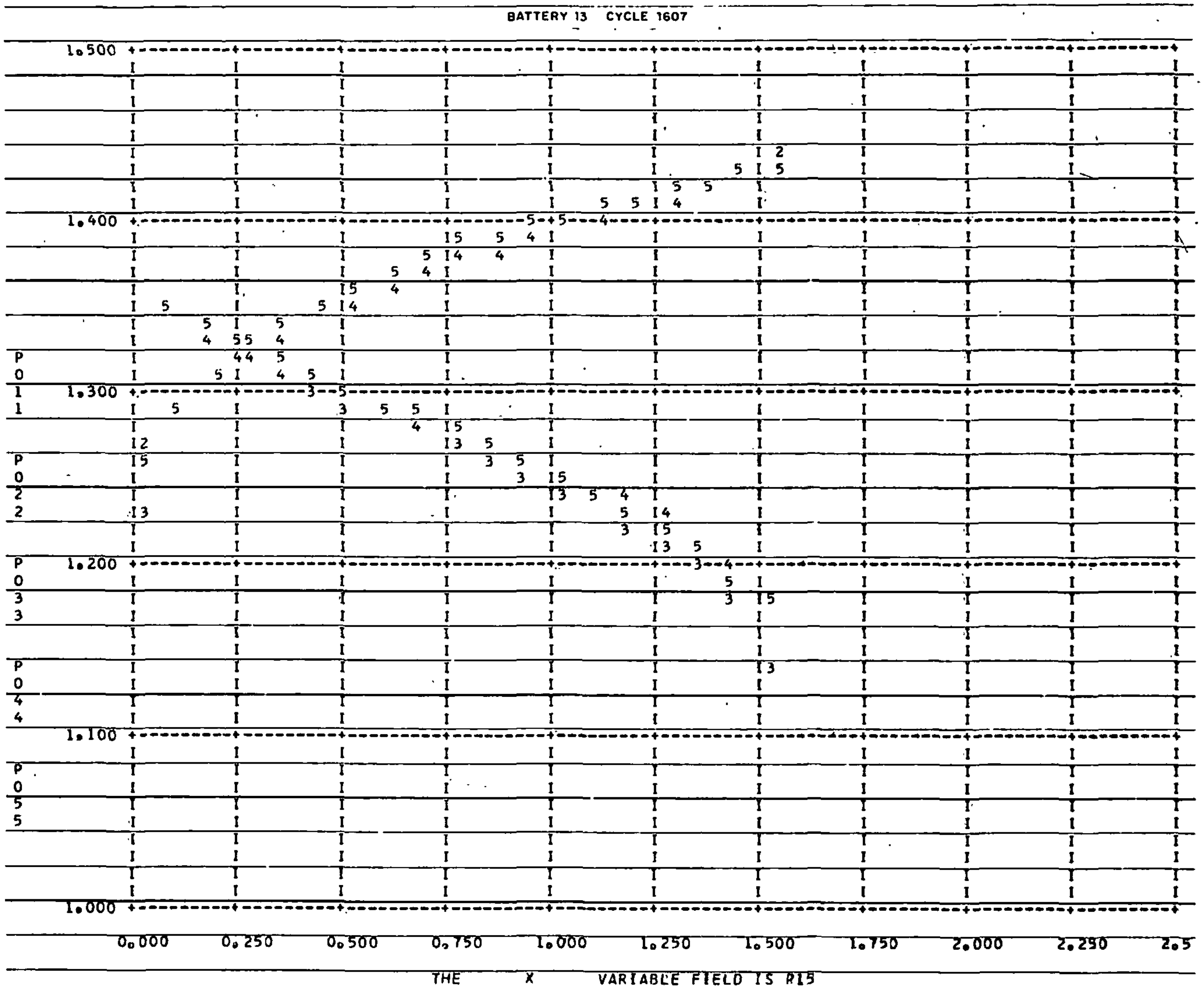

BATTERY 13 CYCLE 1607
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000 0.250 0.500 0.750 1.000 1.250 1.500 1.750 2.000 2.250 2.5
THE X VARIABLE FIELD IS R15

Figure 5fd

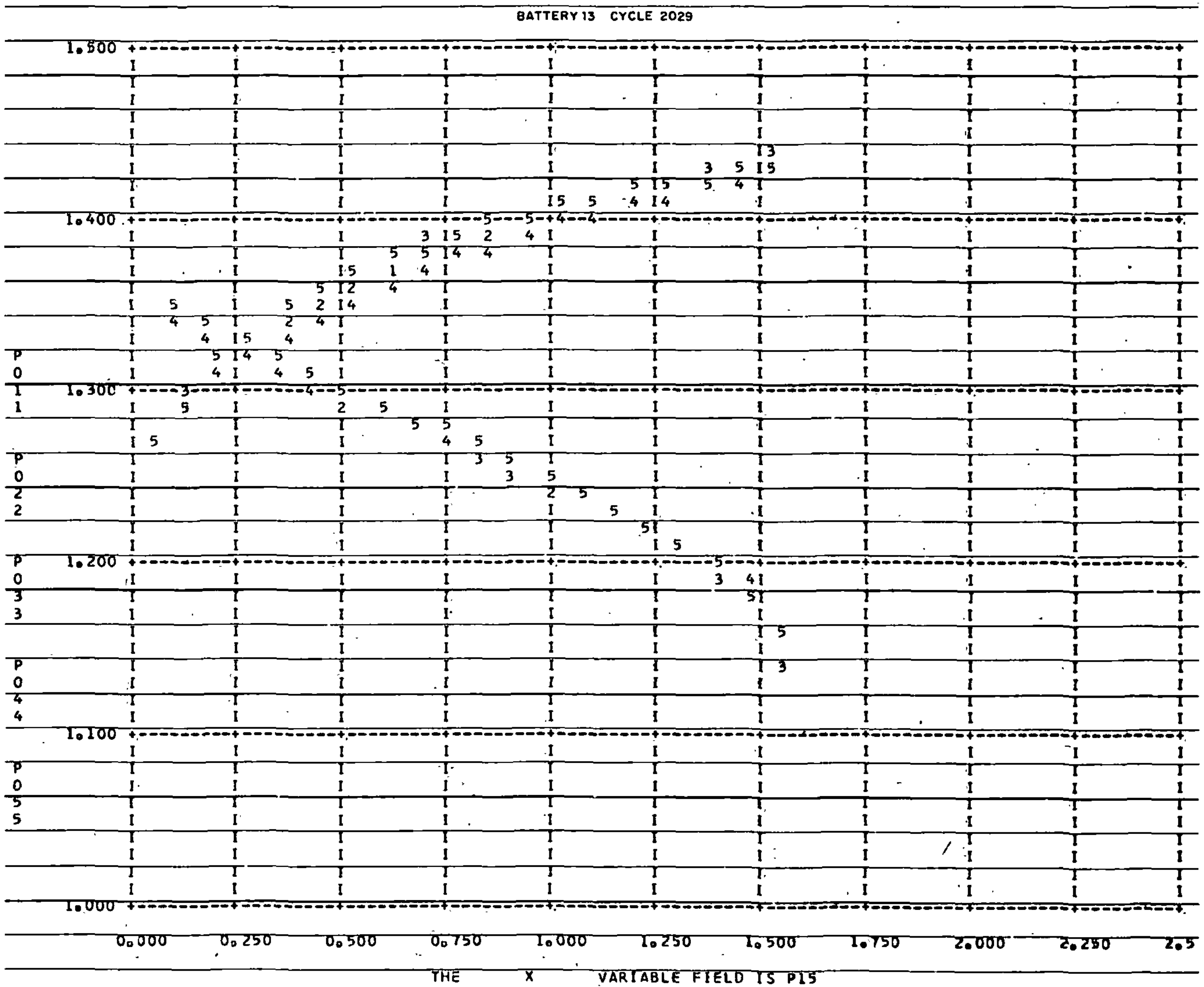

BATTERY 13 CYCLE 2029
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS P15

Figure 5fe

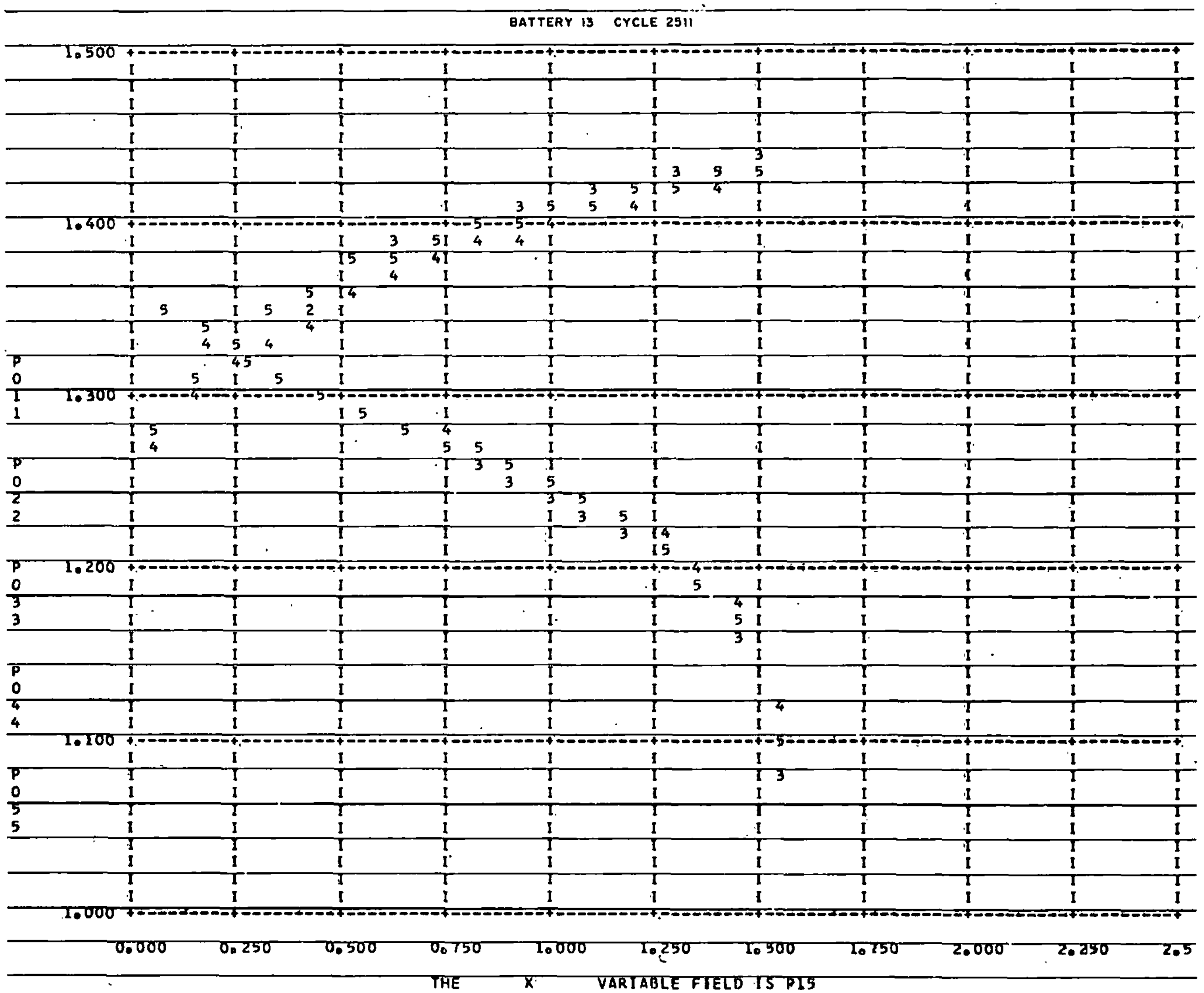
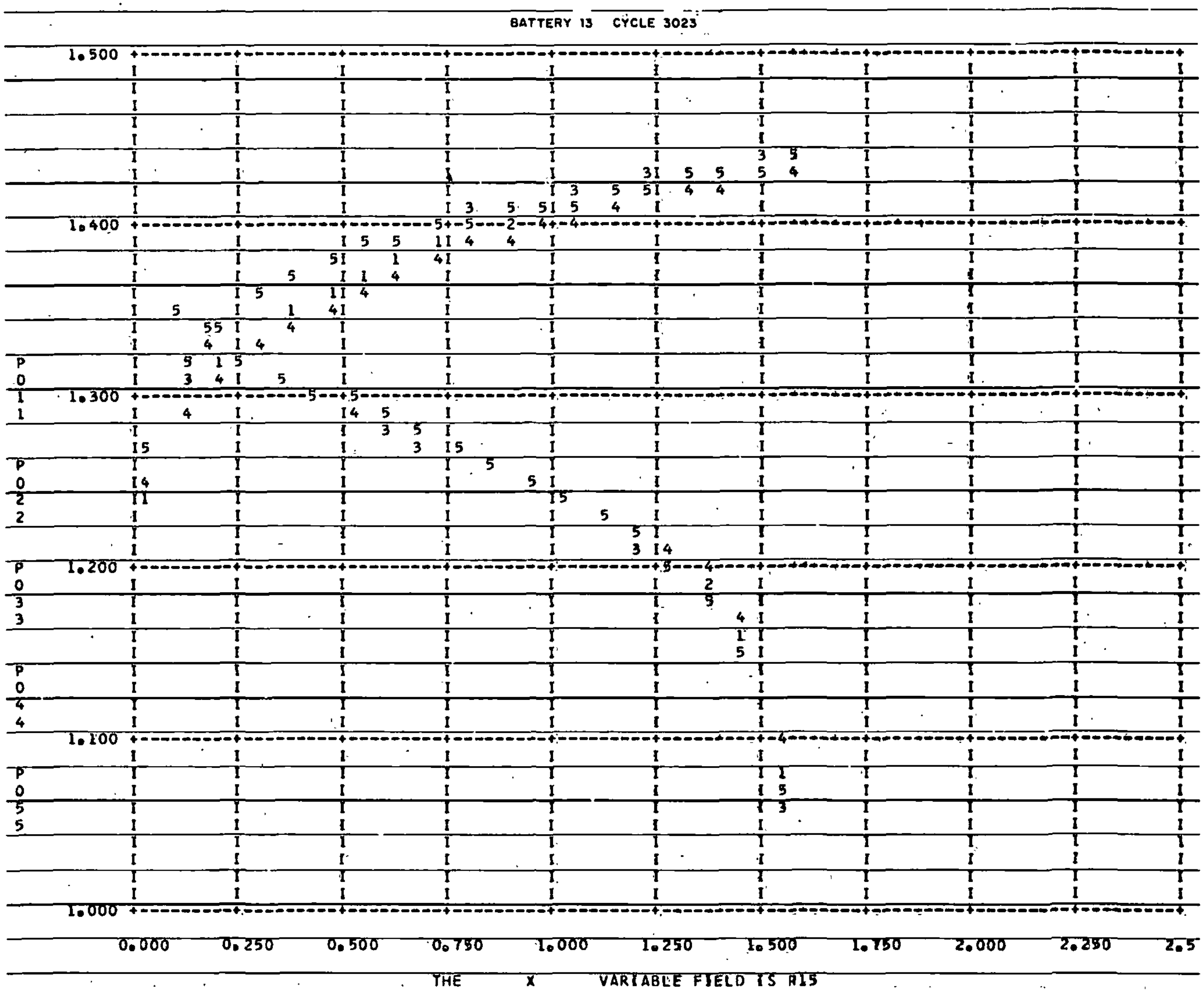
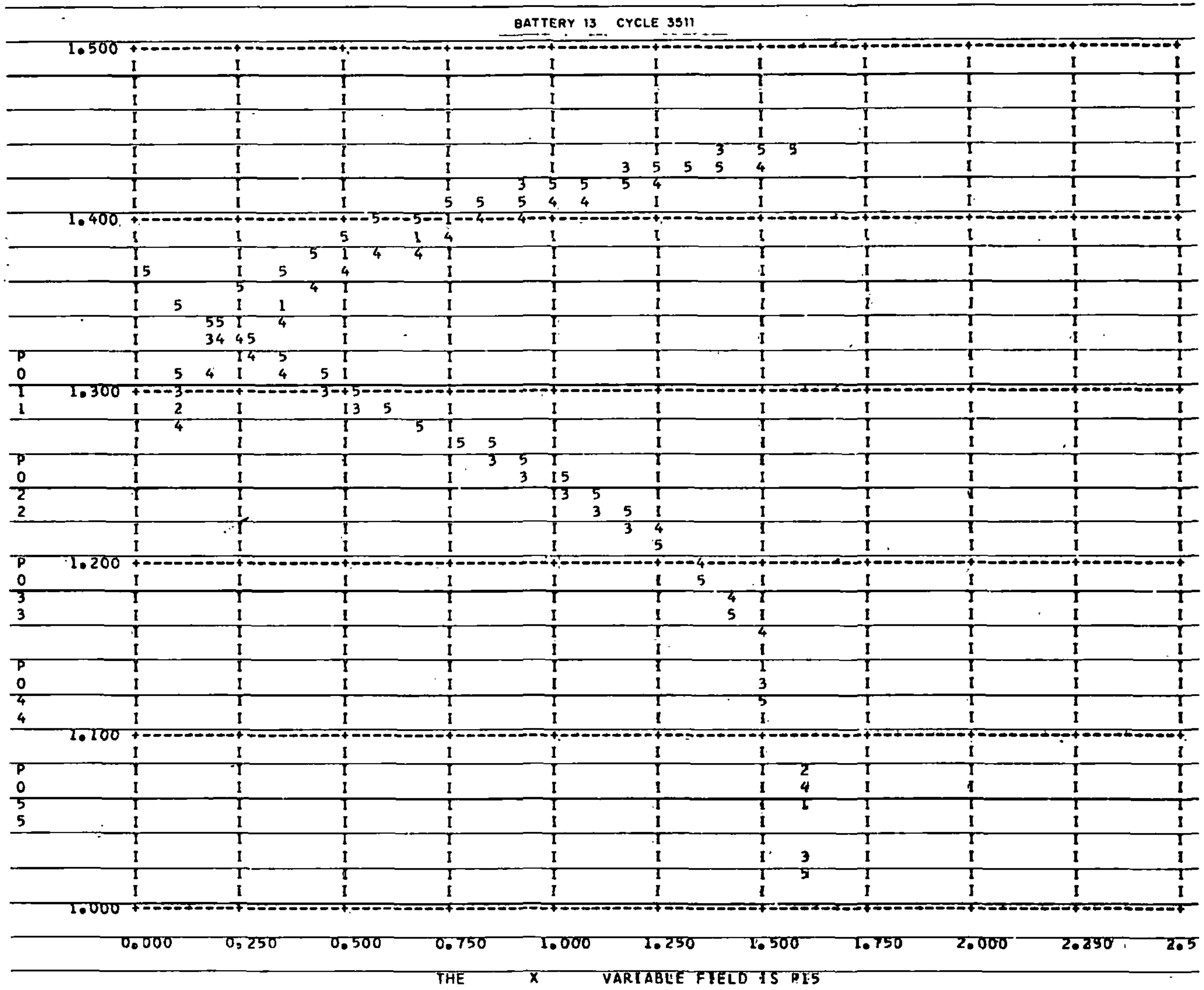

BATTERY 13 CYCLE 2511
1.500
1.400
1.300
1.200
1.100
1.000
P
0
1
1
P
0
2
2
P
0
3
3
P
0
4
4
P
0
5
5
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS P15

Figure 5ff



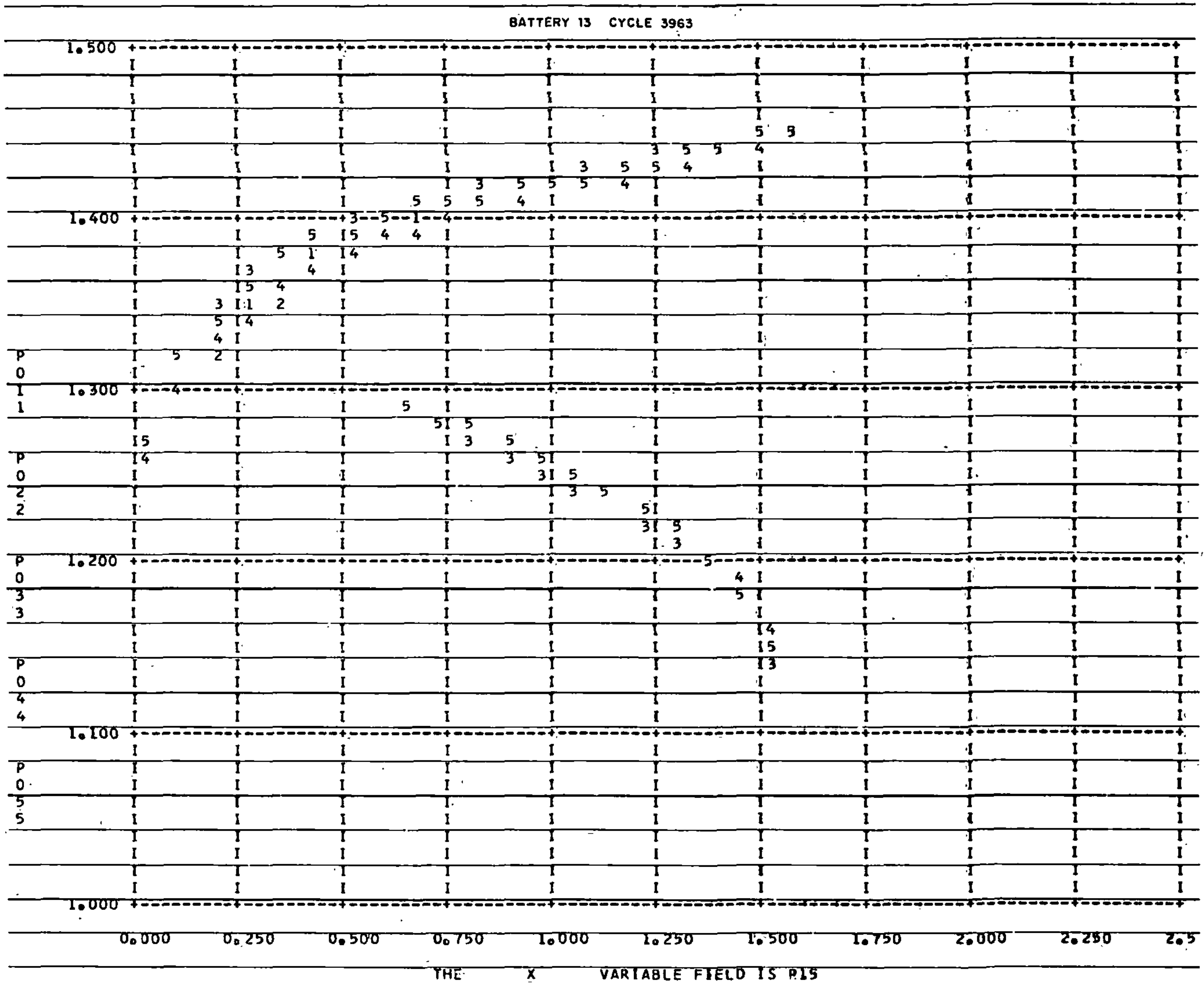
BATTERY 13 CYCLE 3023
1.500
1.400
1.300
1.200
1.100
1.000
P
O
1
1
P
O
2
2
P
O
3
3
P
O
4
4
P
O
5
5
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS R15

Figure 5fg



BATTERY 13 CYCLE 3511
1.500
1.400
1.300
1.200
1.100
1.000
P01
P02
P03
P04
P05
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS PI5

Figure 5fh



BATTERY 13 CYCLE 3963
1.500
1.400
1.300
1.200
1.100
1.000
P O 1 1
P O 2 2
P O 3 3
P O 4 4
P O 5 5
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS P15

Figure 5fi

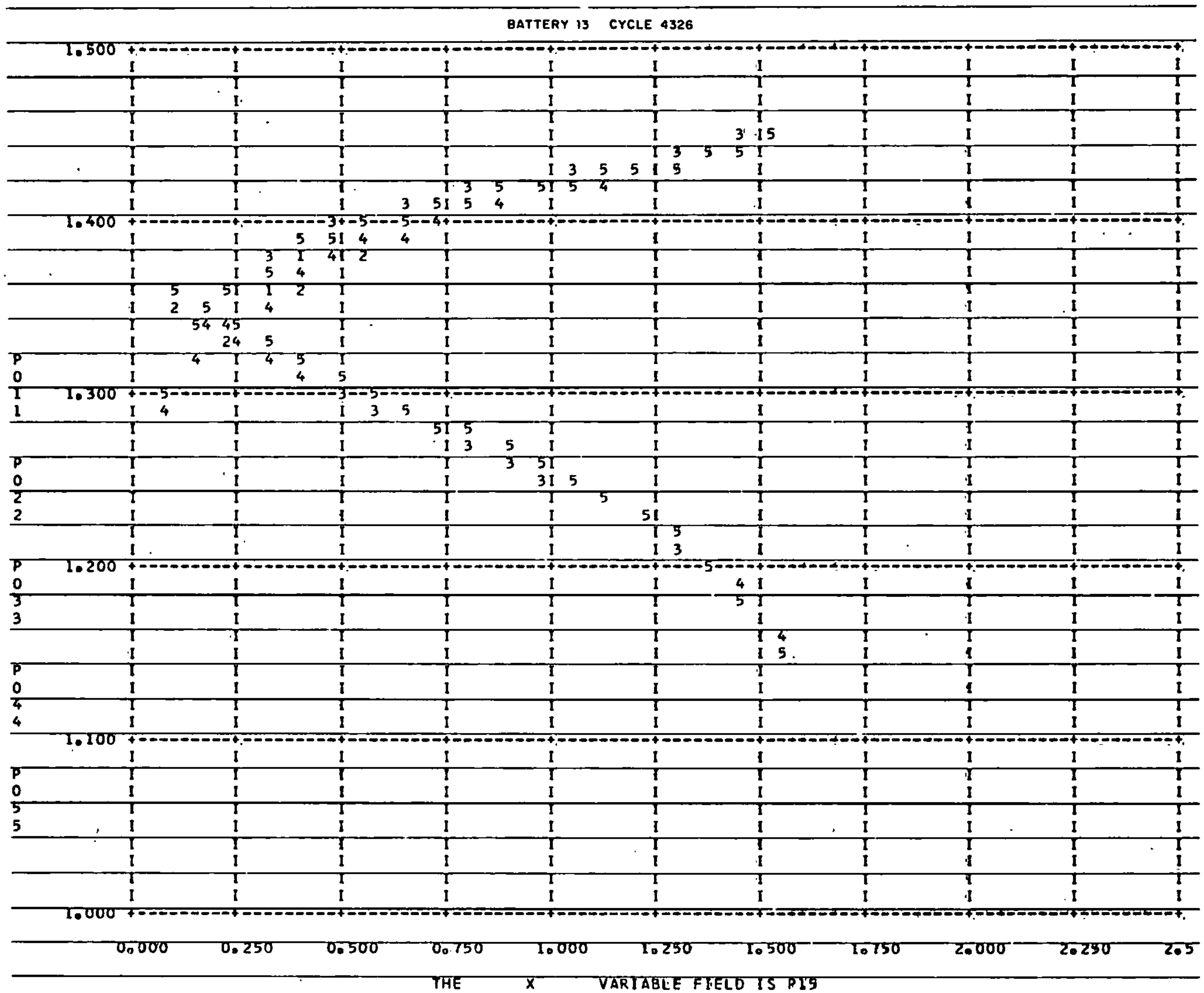

BATTERY 13 CYCLE 4326
1.500
1.400
1.300
1.200
1.100
1.000
POT1
POT2
POT3
POT4
POT5
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS P19

Figure 5fj

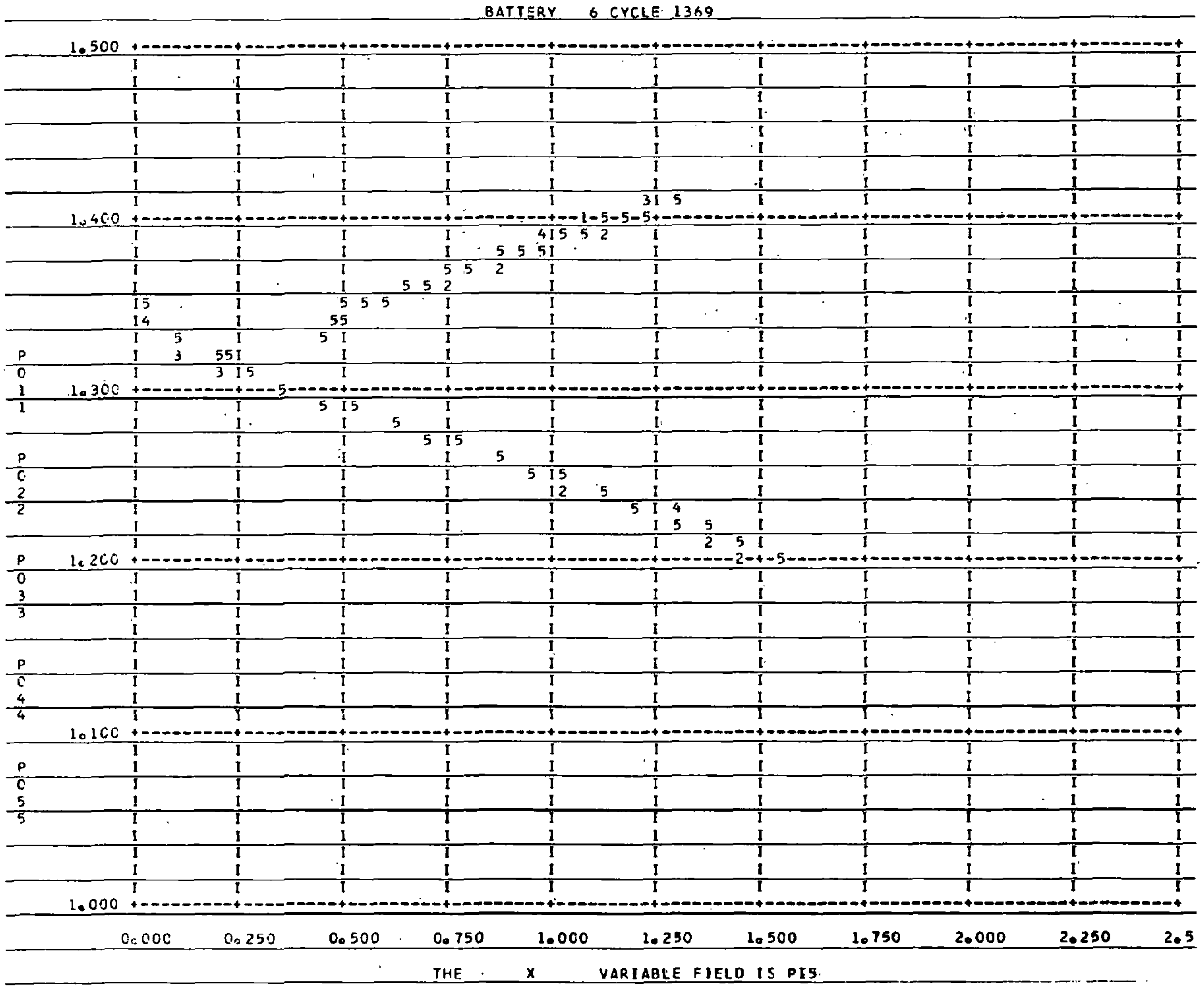

BATTERY 6 CYCLE 1369
1.500
1.400
1.300
1.200
1.100
1.000
P
0
1
1
P
0
2
2
P
0
3
3
P
0
4
4
P
0
5
5
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS PI5

Figure 5ga

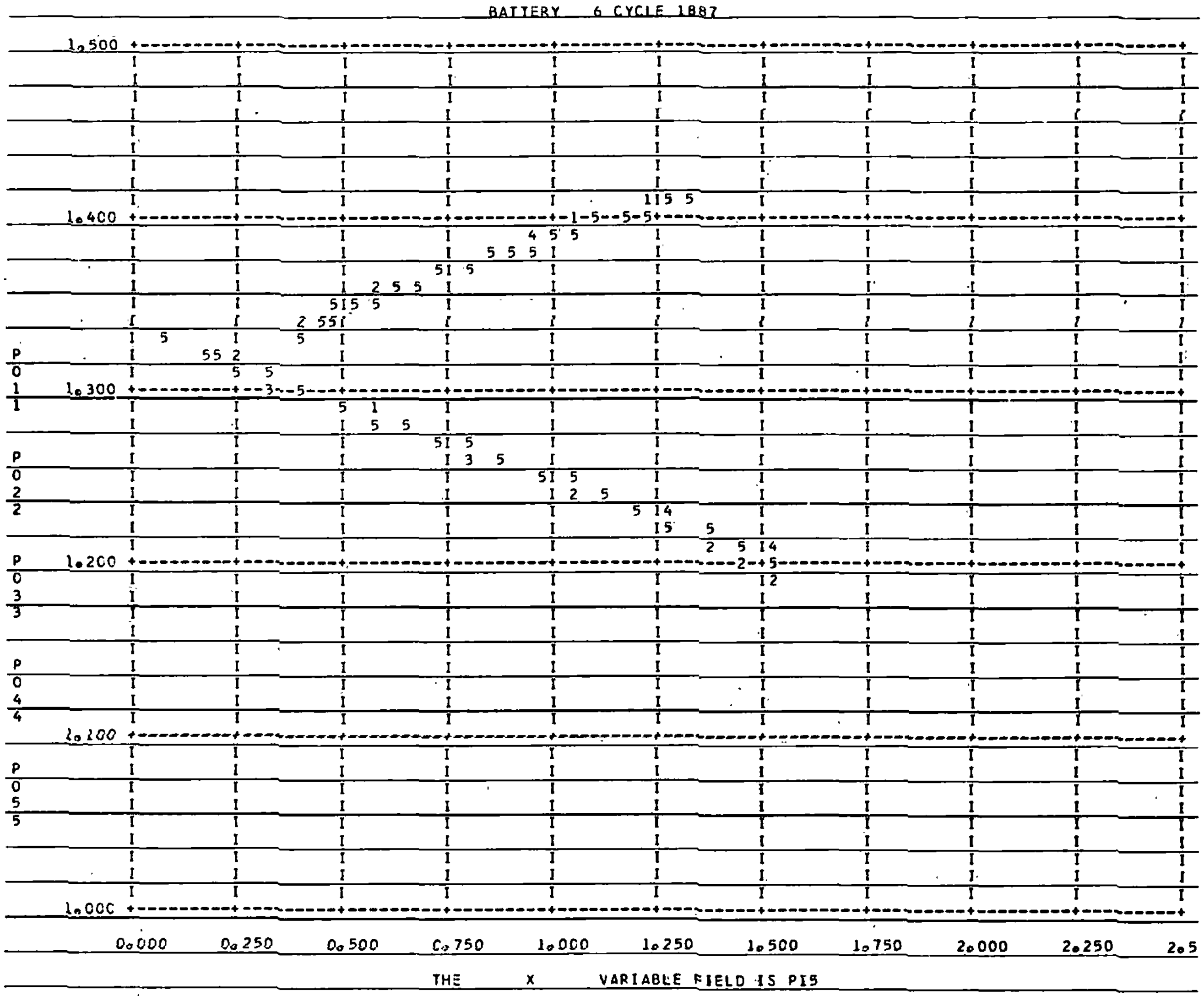
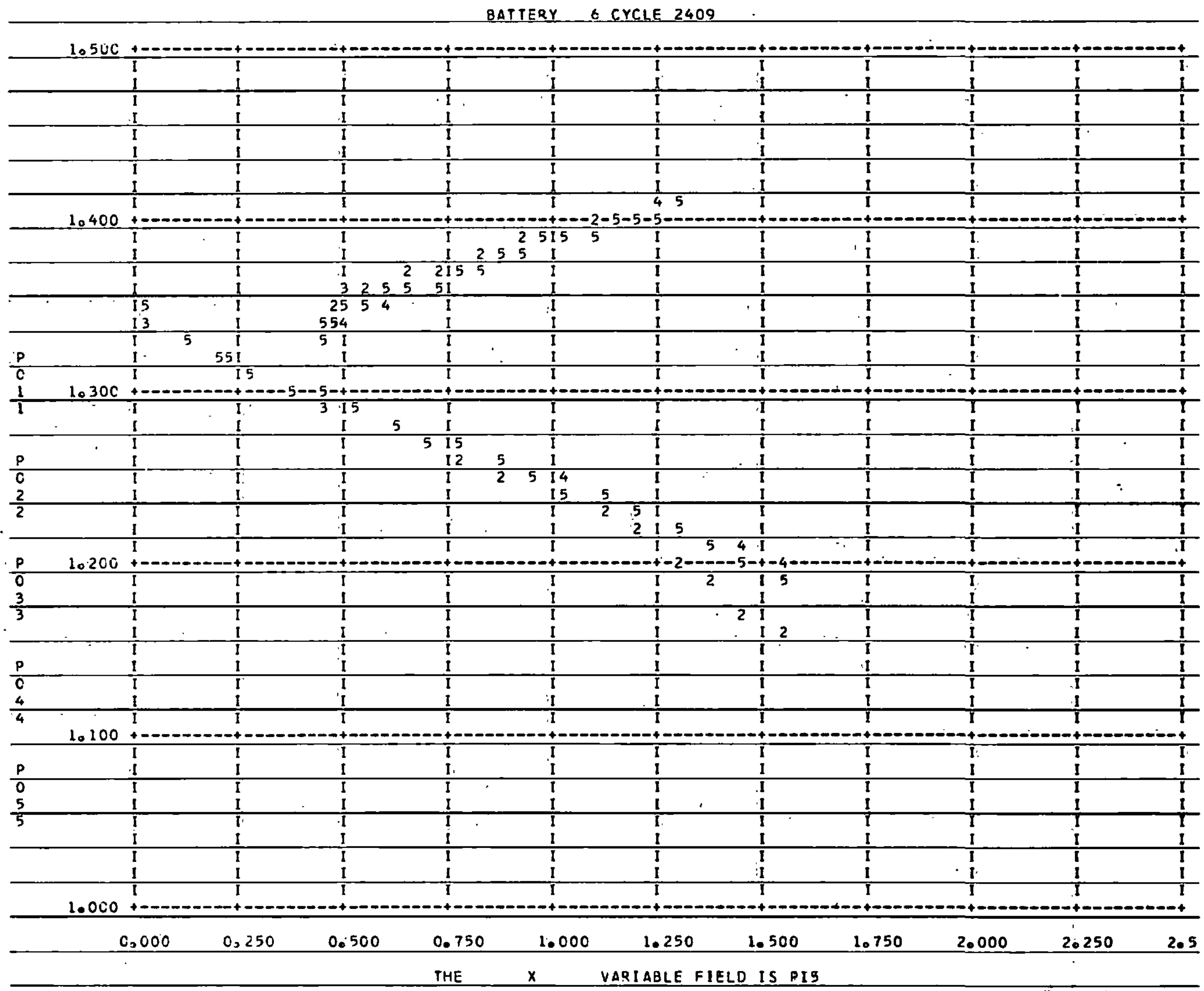

BATTERY 6 CYCLE 1887
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS PI5

Figure 5gb



BATTERY 6 CYCLE 2409
1.500
1.400
1.300
1.200
1.100
1.000
P O 1 1
P O 2 2
P O 3 3
P O 4 4
P O 5 5
0.000 0.250 0.500 0.750 1.000 1.250 1.500 1.750 2.000 2.250 2.5
THE X VARIABLE FIELD IS PIS

Figure 5gc

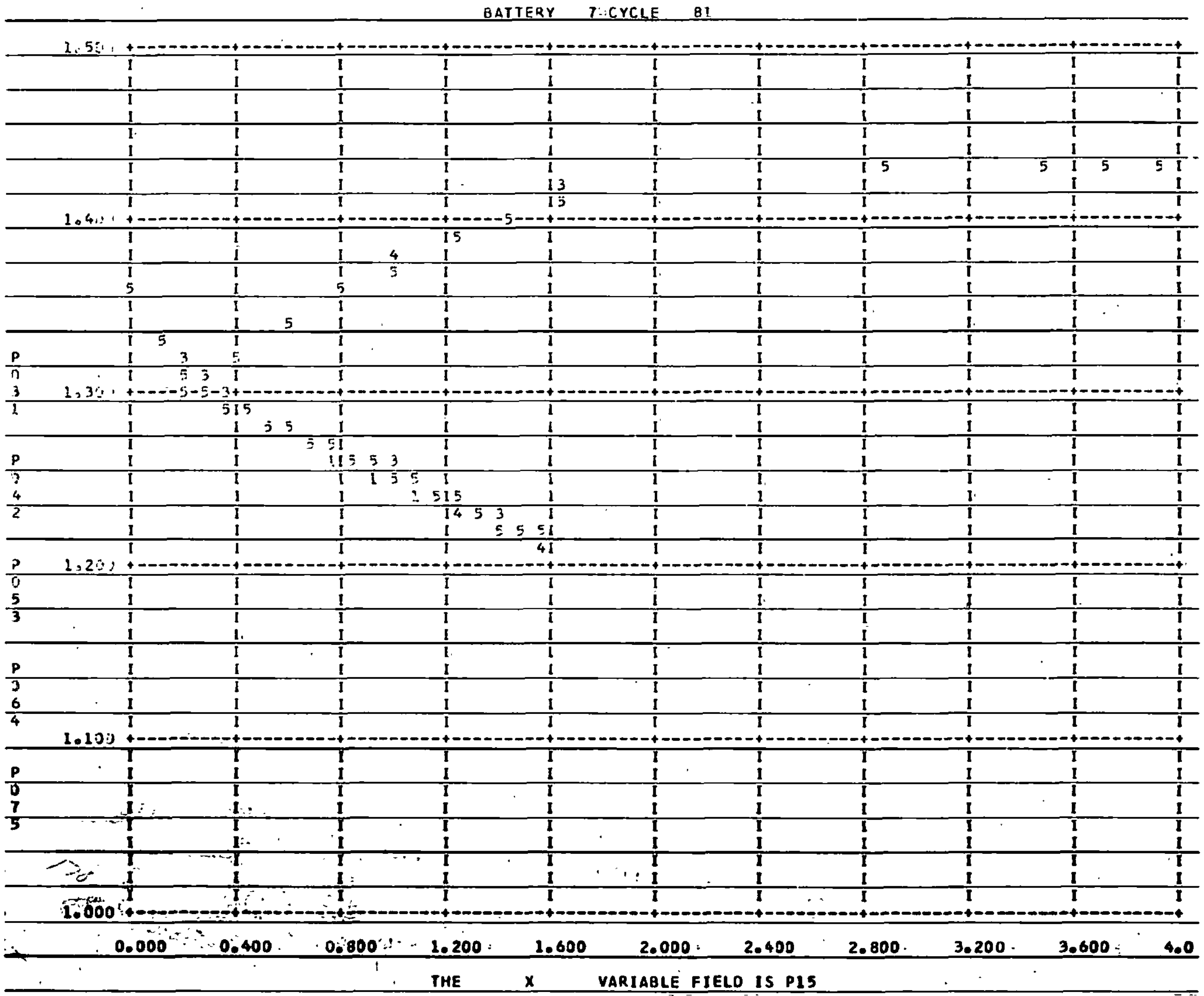

BATTERY 7 CYCLE 81
1.500
1.400
1.300
1.200
1.100
1.000
0.000
0.400
0.800
1.200
1.600
2.000
2.400
2.800
3.200
3.600
4.0
THE X VARIABLE FIELD IS P15
P031
P242
P053
P364
P075

Figure 5ha

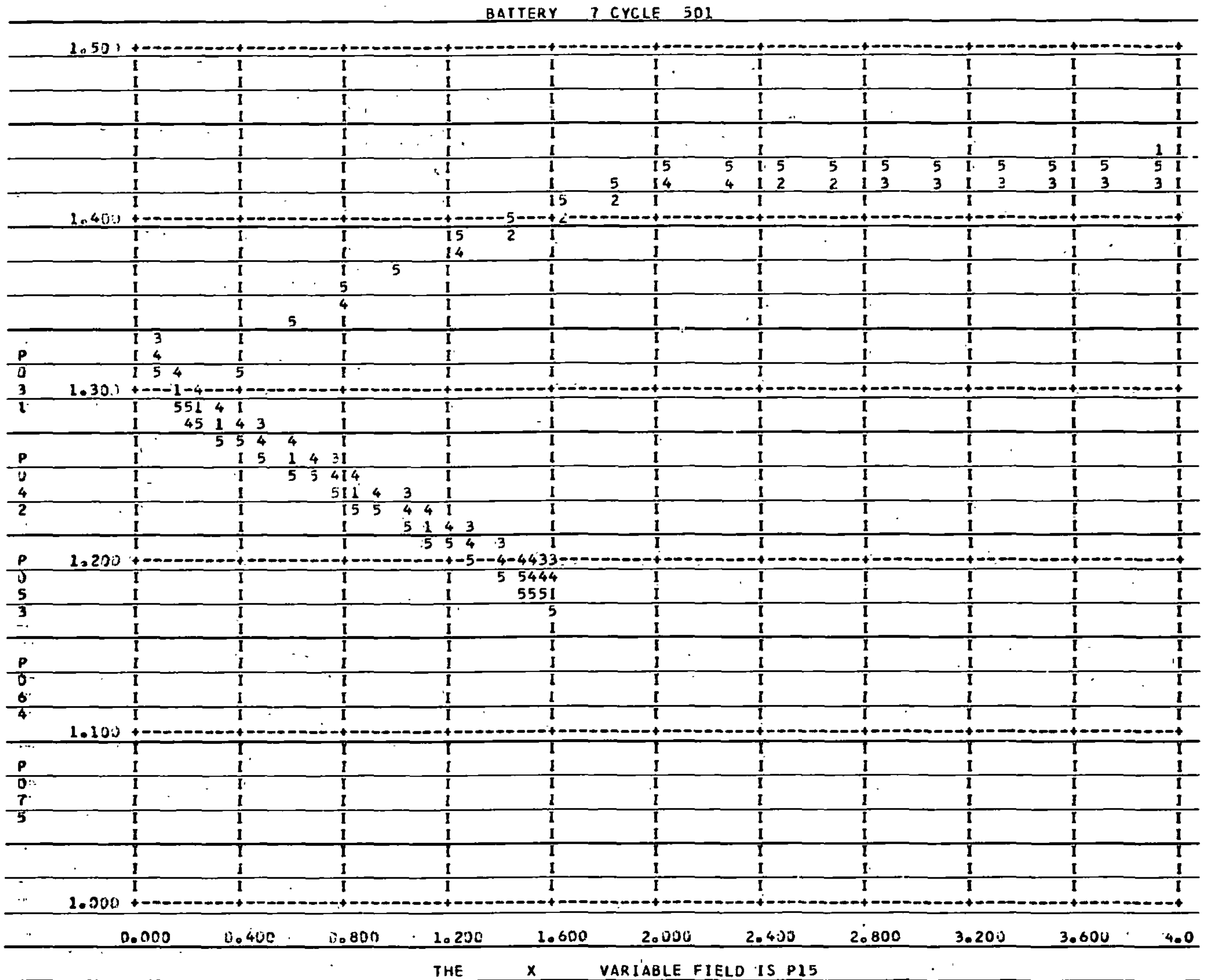

BATTERY 7 CYCLE 501
1.500
1.400
1.300
1.200
1.100
1.000
P031
P042
P053
P064
P075
0.000
0.400
0.800
1.200
1.600
2.000
2.400
2.800
3.200
3.600
4.0
THE X VARIABLE FIELD IS P15

Figure 5hb

BATTERY 7 CYCLE 936

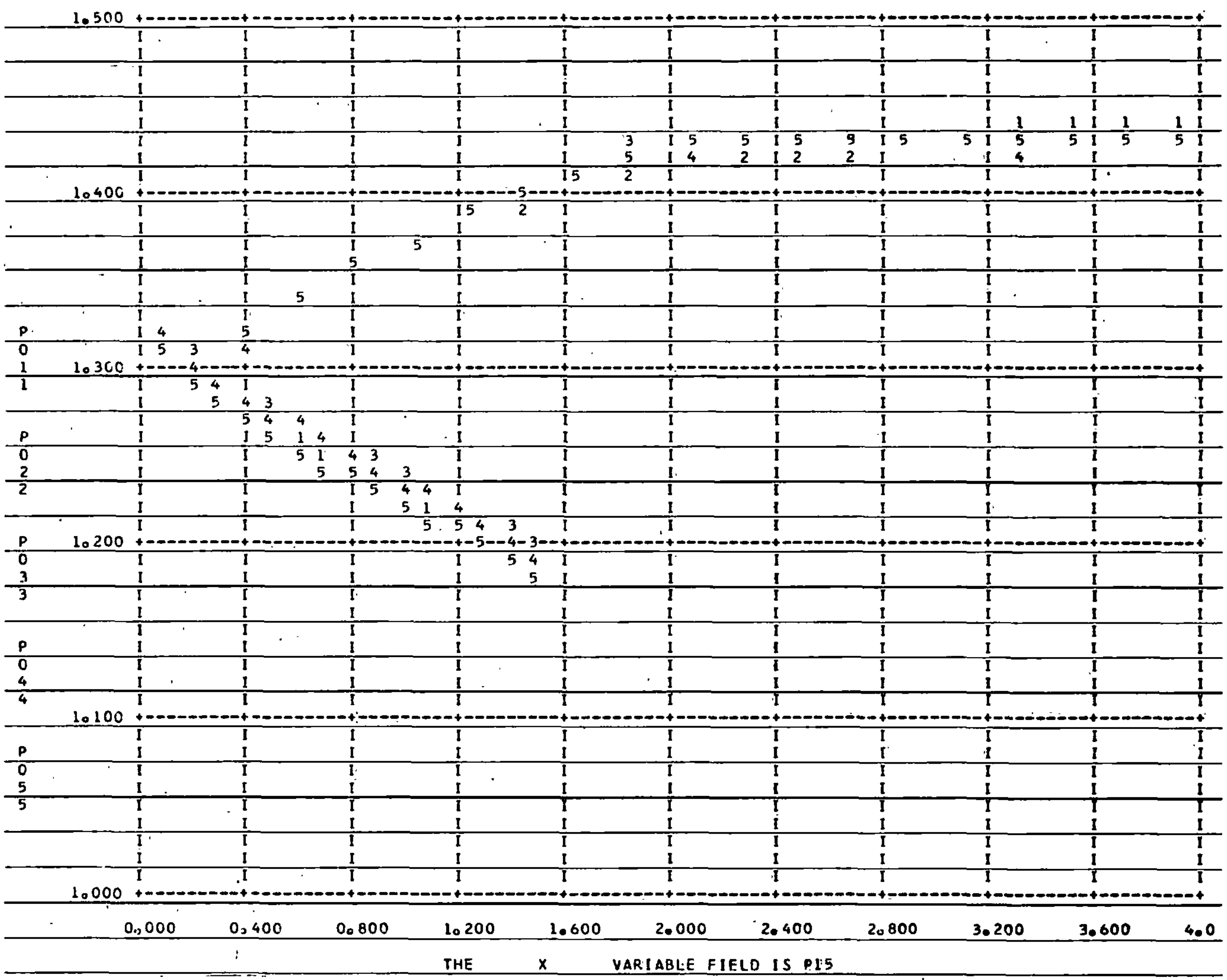


Figure 5hc

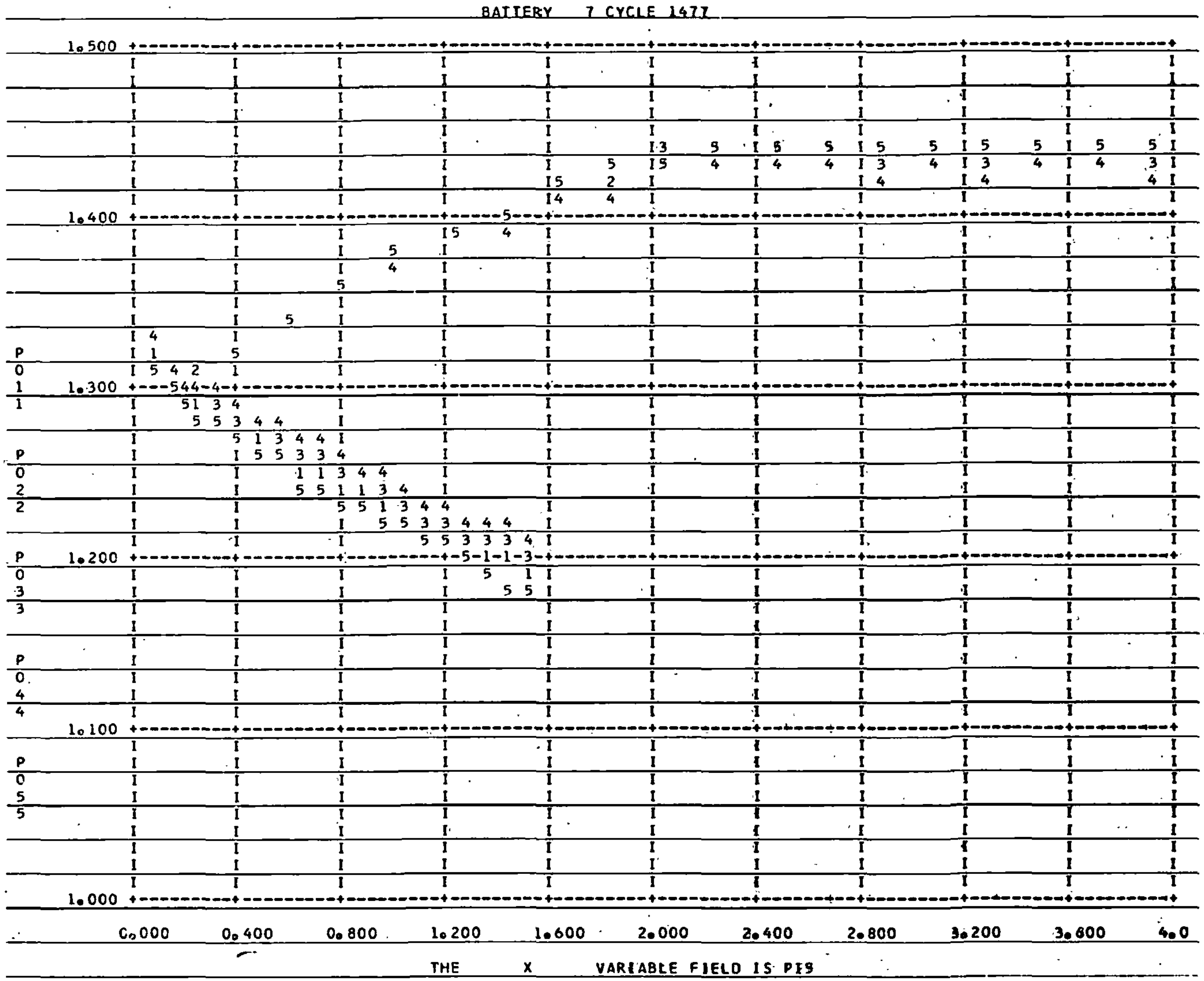

BATTERY 7 CYCLE 1477
1.500
1.400
1.300
1.200
1.100
1.000
P
0
1
1
P
0
2
2
P
0
3
3
P
0.
4
4
P
0
5
5
0.000
0.400
0.800
1.200
1.600
2.000
2.400
2.800
3.200
3.600
4.0
THE X VARIABLE FIELD IS PIS

Figure 5hd

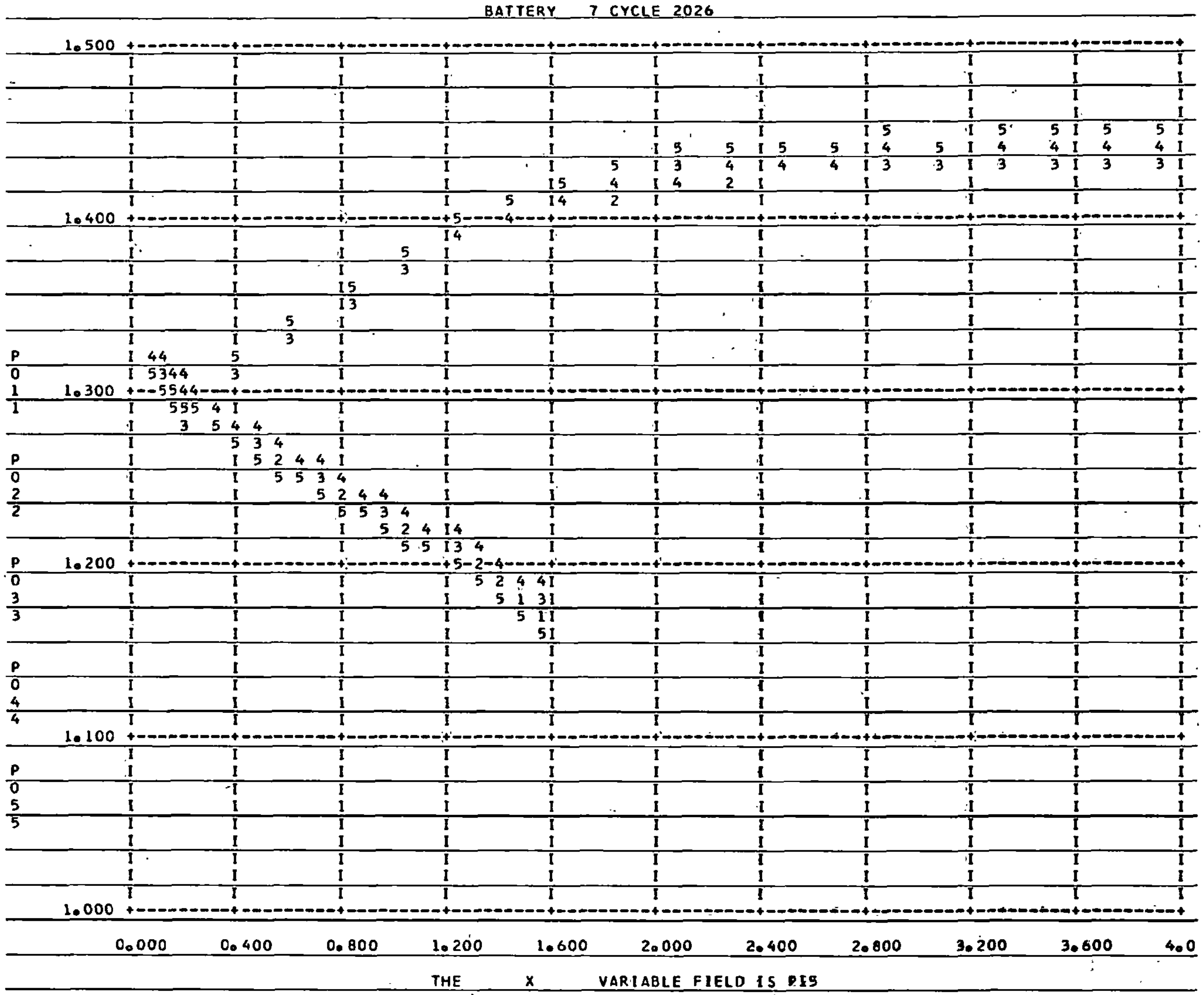

BATTERY 7 CYCLE 2026
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000
0.400
0.800
1.200
1.600
2.000
2.400
2.800
3.200
3.600
4.0
THE X VARIABLE FIELD IS PIS

Figure 5he

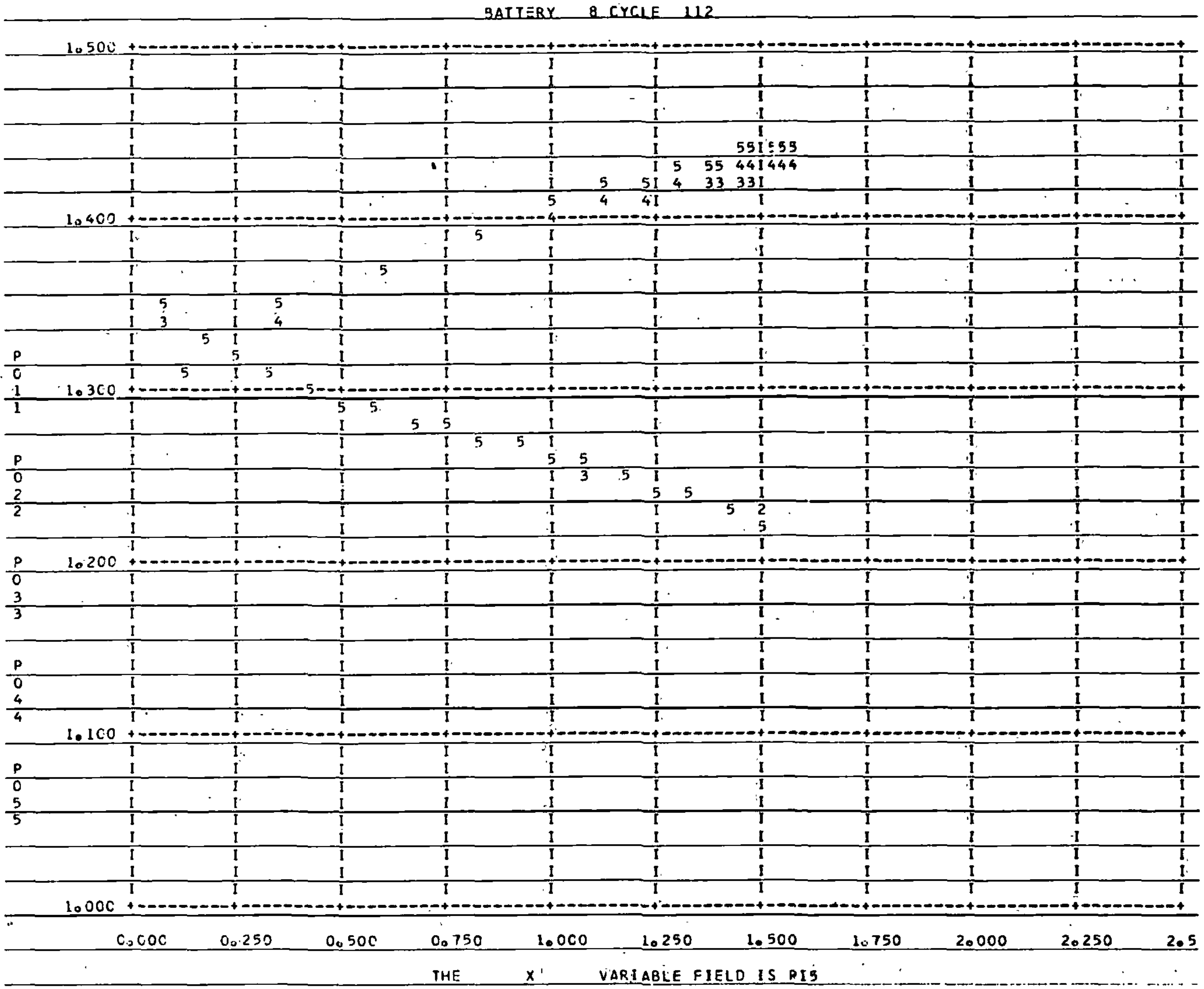

BATTERY 8 CYCLE 112
1.500
1.400
1.300
1.200
1.100
1.000
P 0 1 1
P 0 2 2
P 0 3 3
P 0 4 4
P 0 5 5
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X' VARIABLE FIELD IS RIS

Figure 5ia

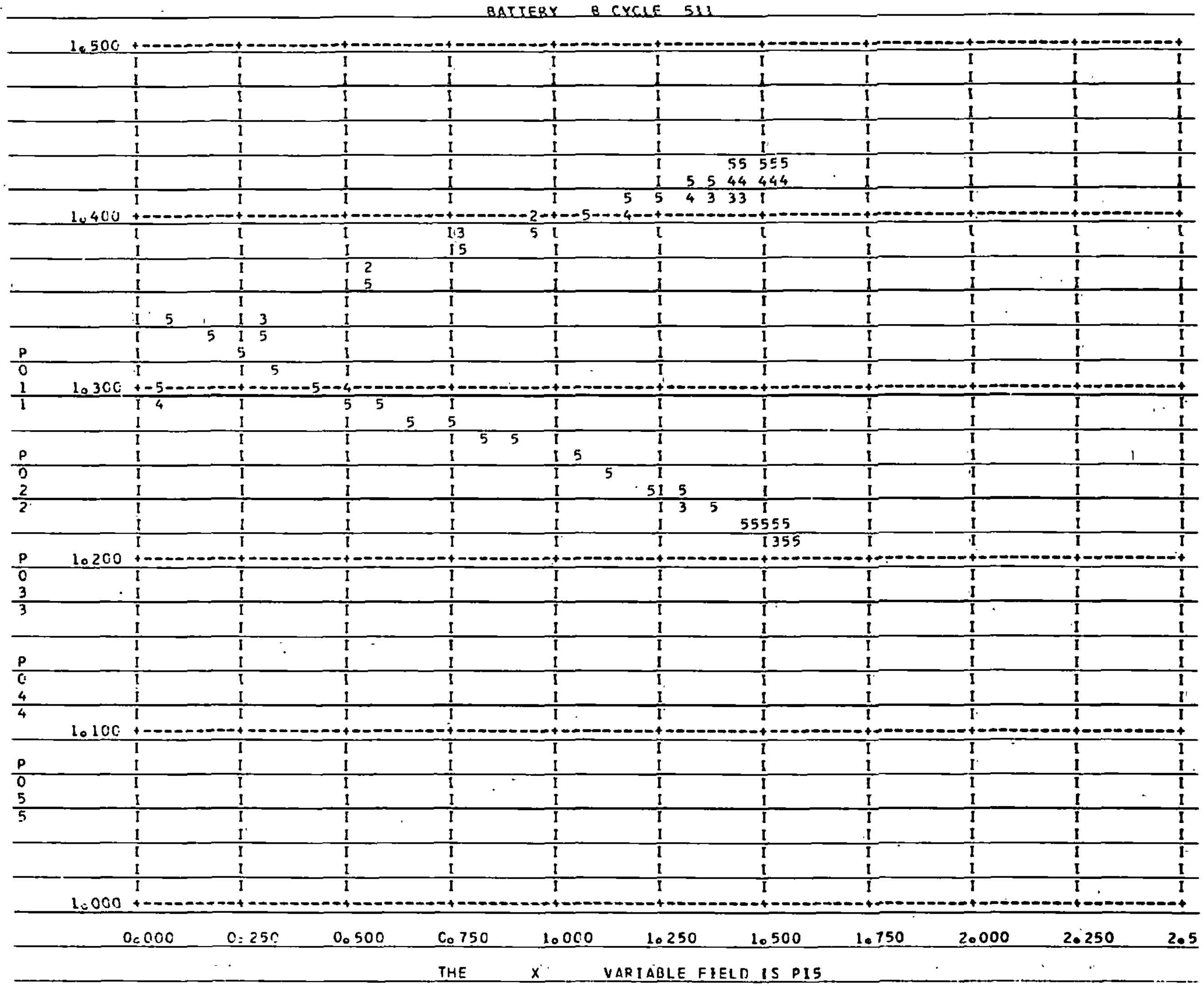

BATTERY B CYCLE 511
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS PI5

Figure 5ib.

BATTERY 8 CYCLE 1021

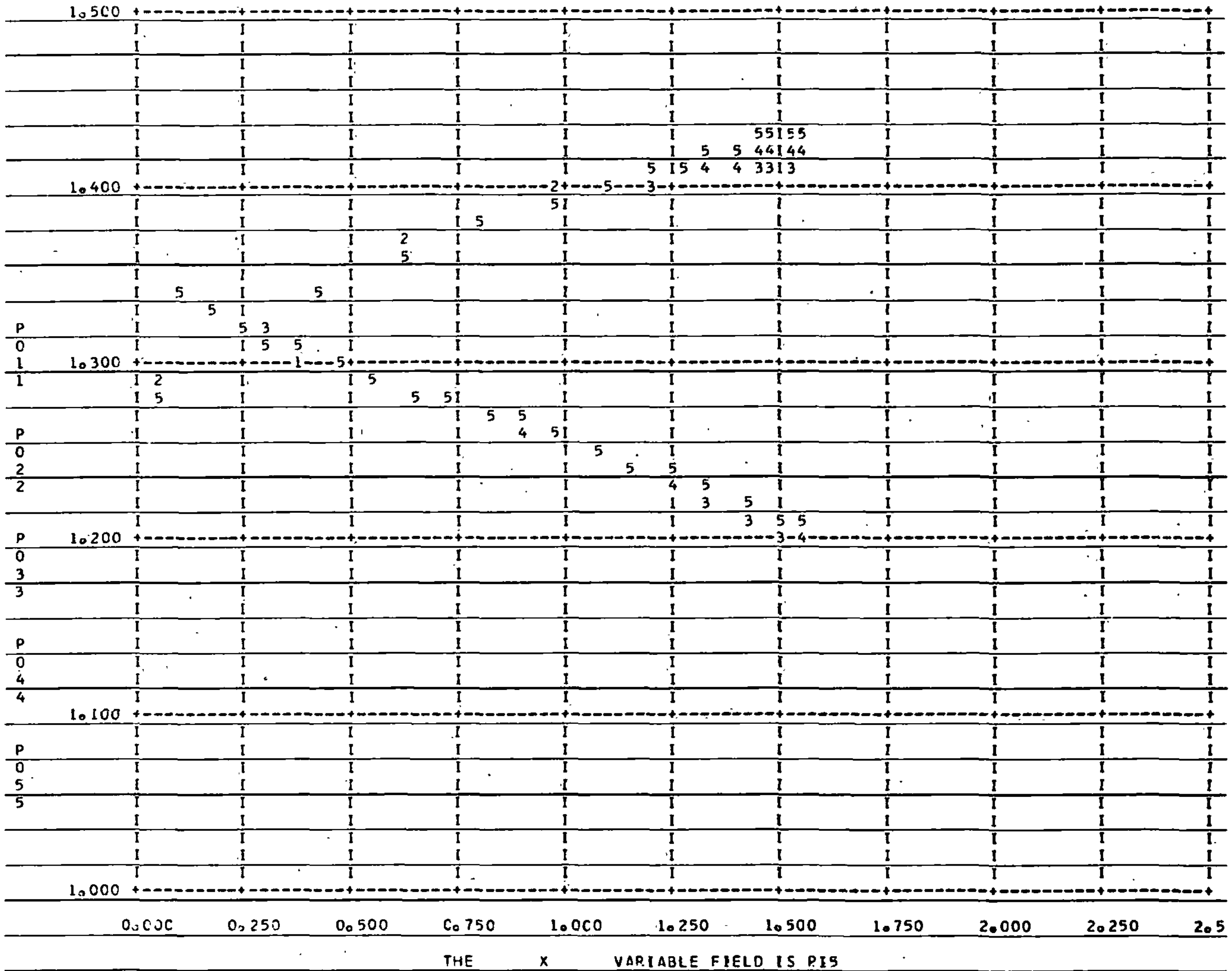


Figure 5ic

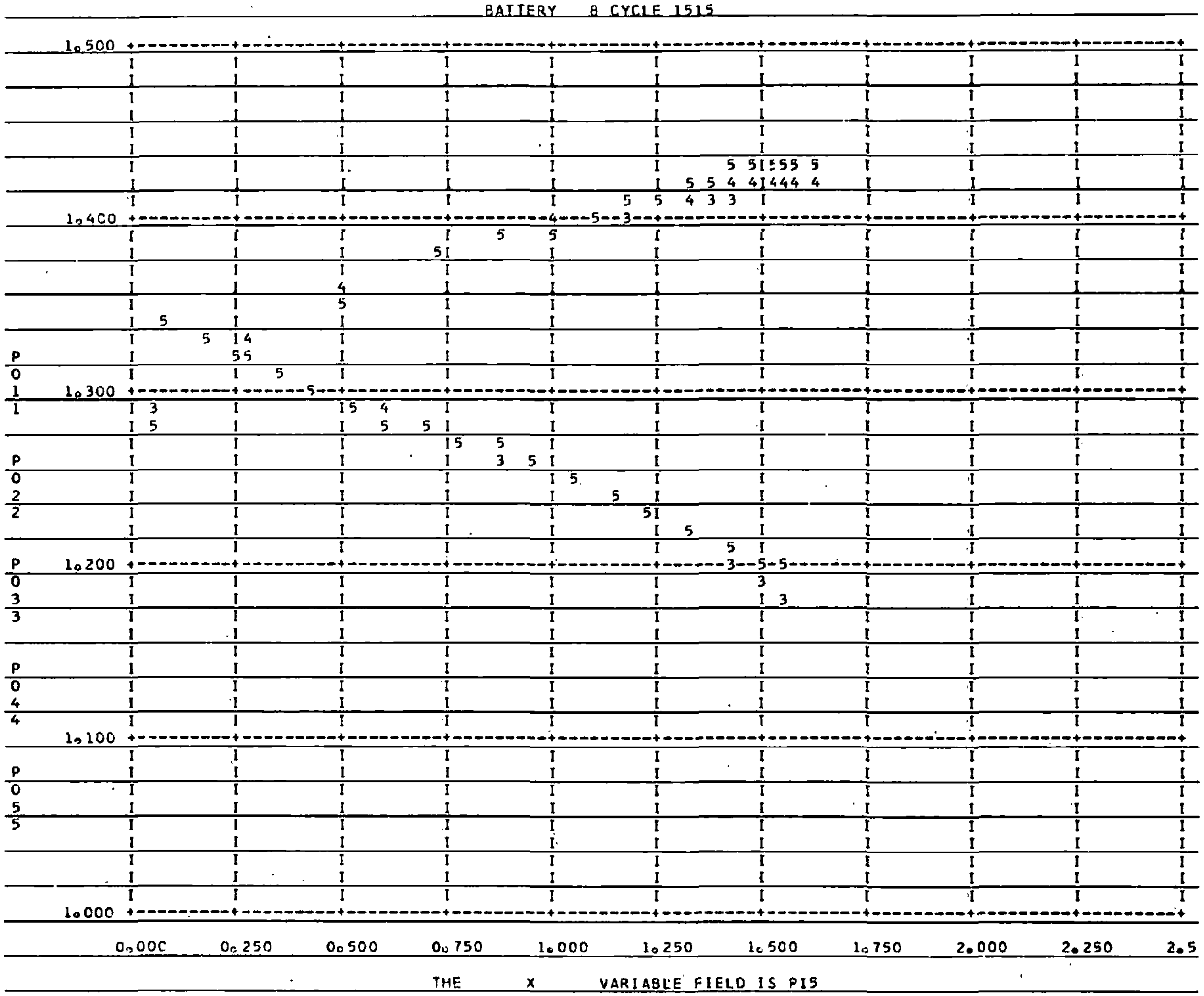

BATTERY 8 CYCLE 1515
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS PI5

Figure 5id

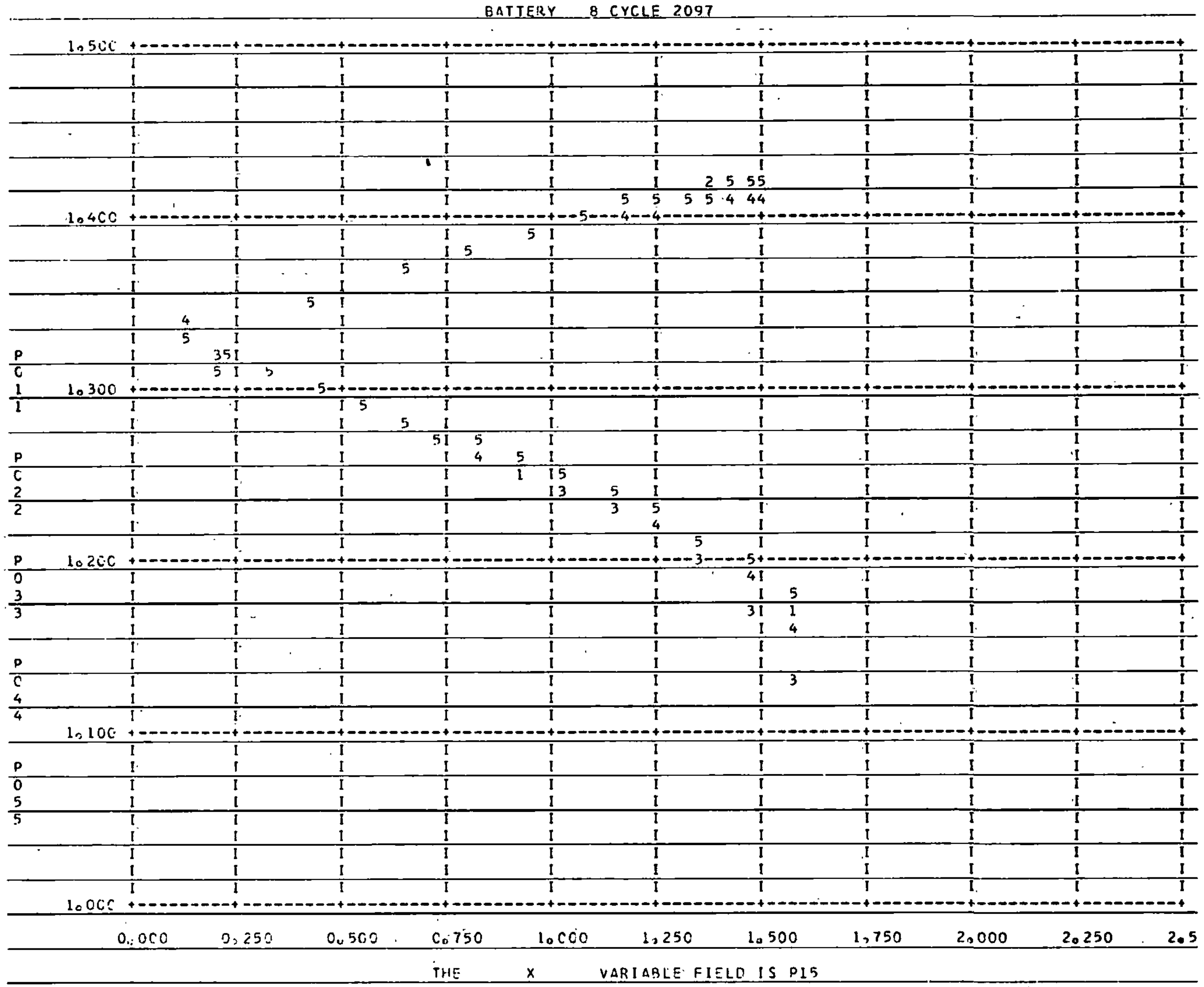

BATTERY 8 CYCLE 2097
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS P15

Figure 5ie

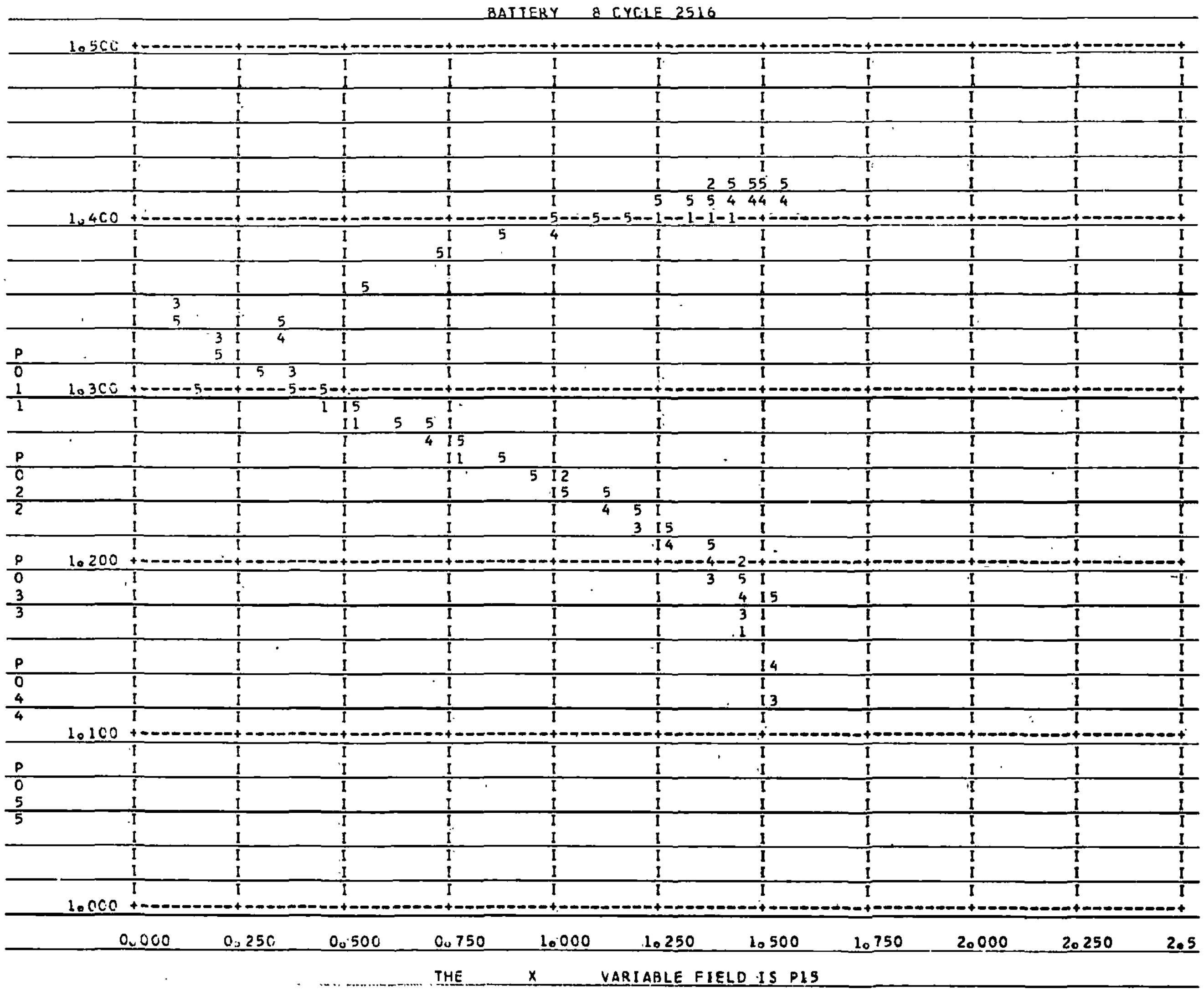

BATTERY 8 CYCLE 2516
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS P15

Figure 5if

BATTERY 8 CYCLE 3019

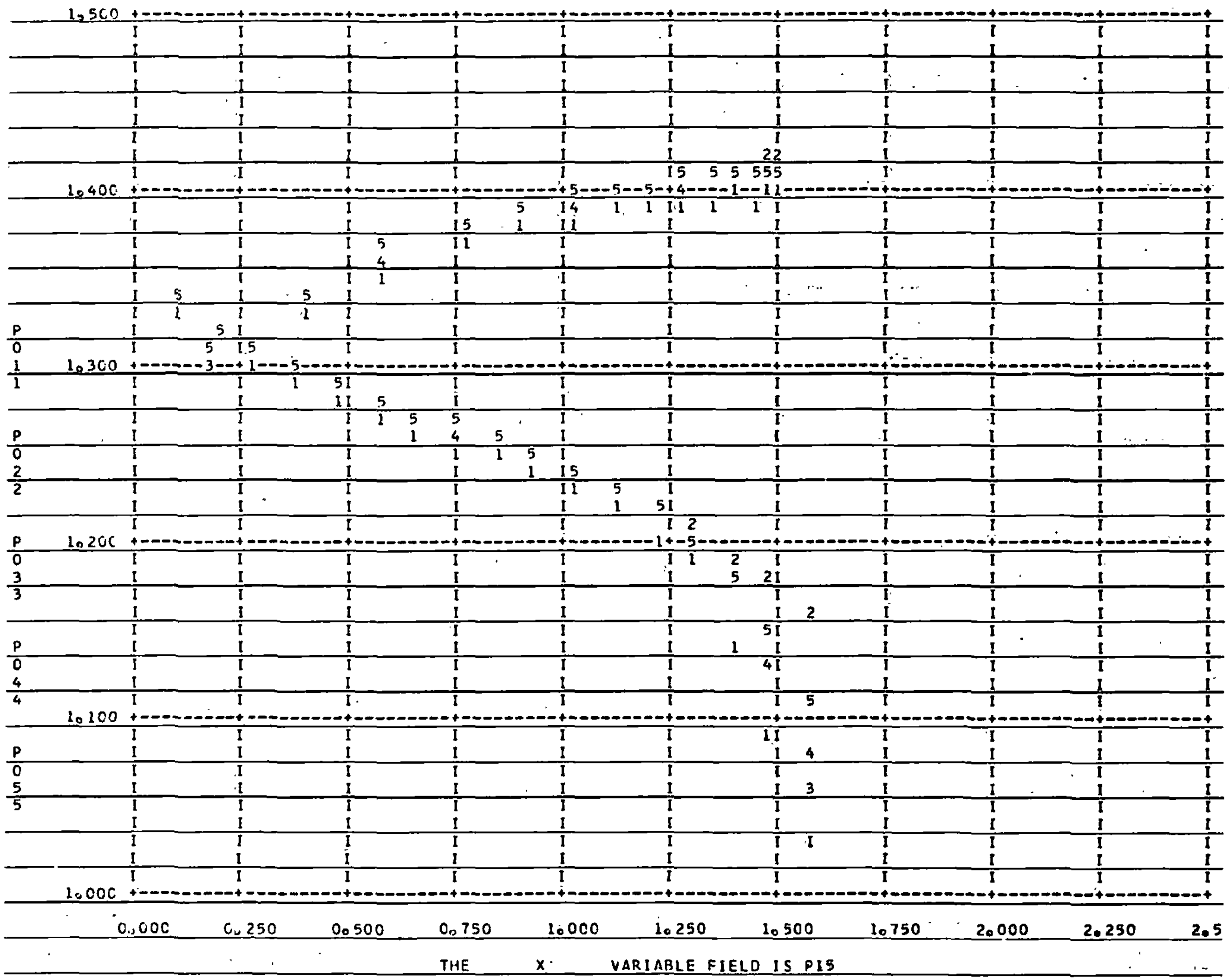


Figure 5ig

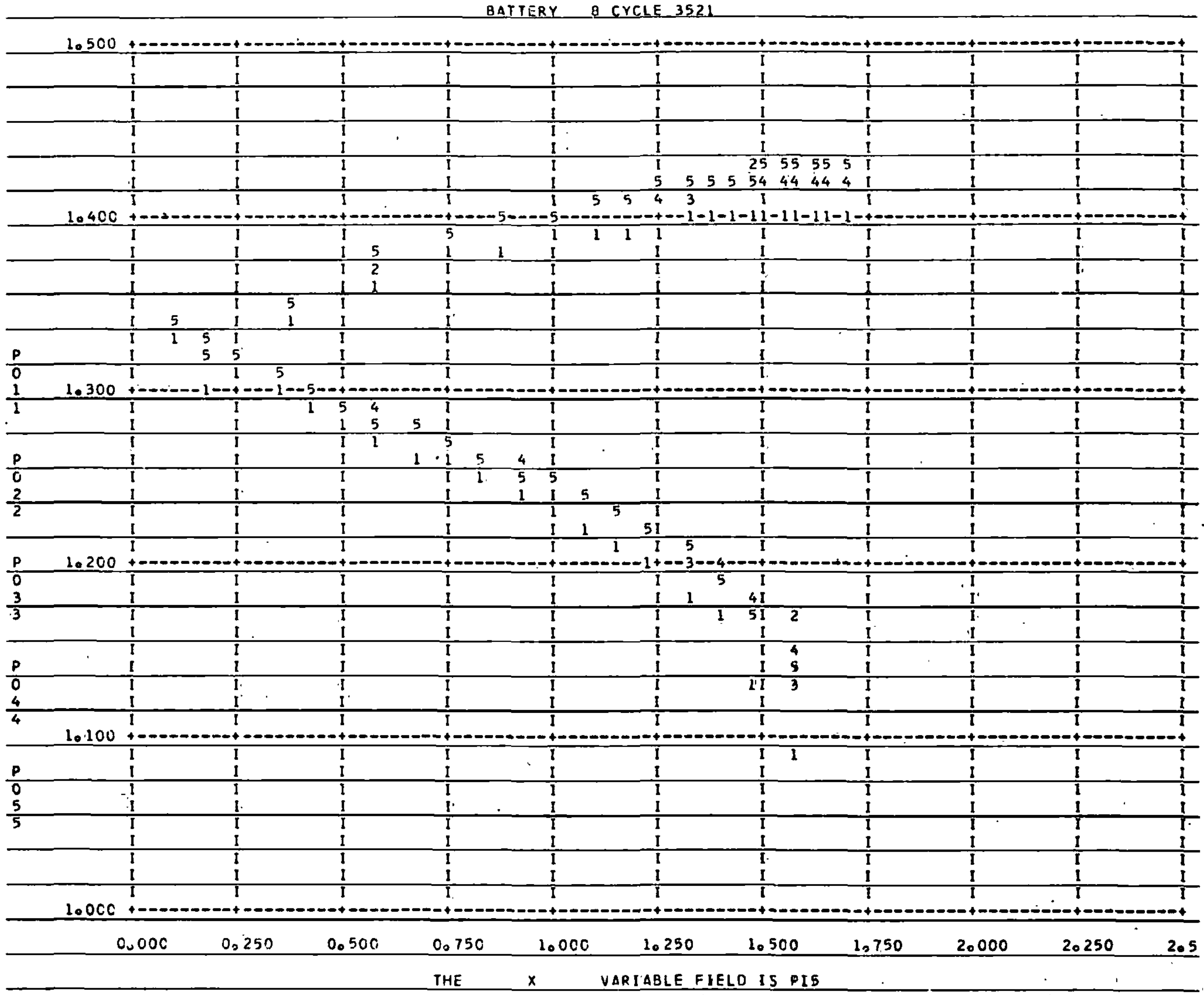

BATTERY 8 CYCLE 3521
1.500
1.400
1.300
1.200
1.100
1.000
P 011
P 022
P 033
P 044
P 055
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS PIS

Figure 5ih

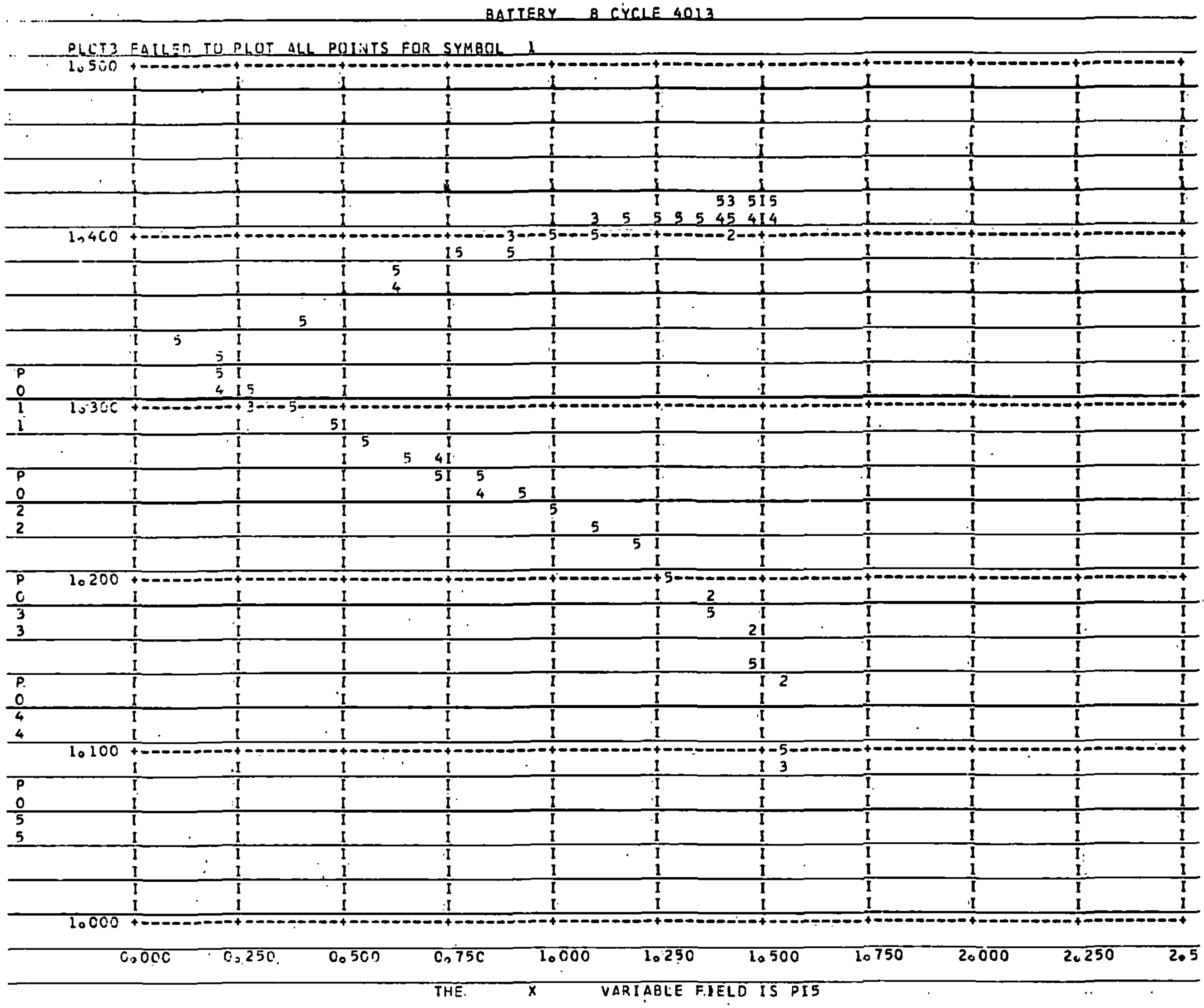

BATTERY B CYCLE 4013
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 1
1.500
1.400
1.300
1.200
1.100
1.000
P O 1 1
P O 2 2
P O 3 3
P O 4 4
P O 5 5
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS PI5

Figure 5ii

BATTERY 8 CYCLE 4511

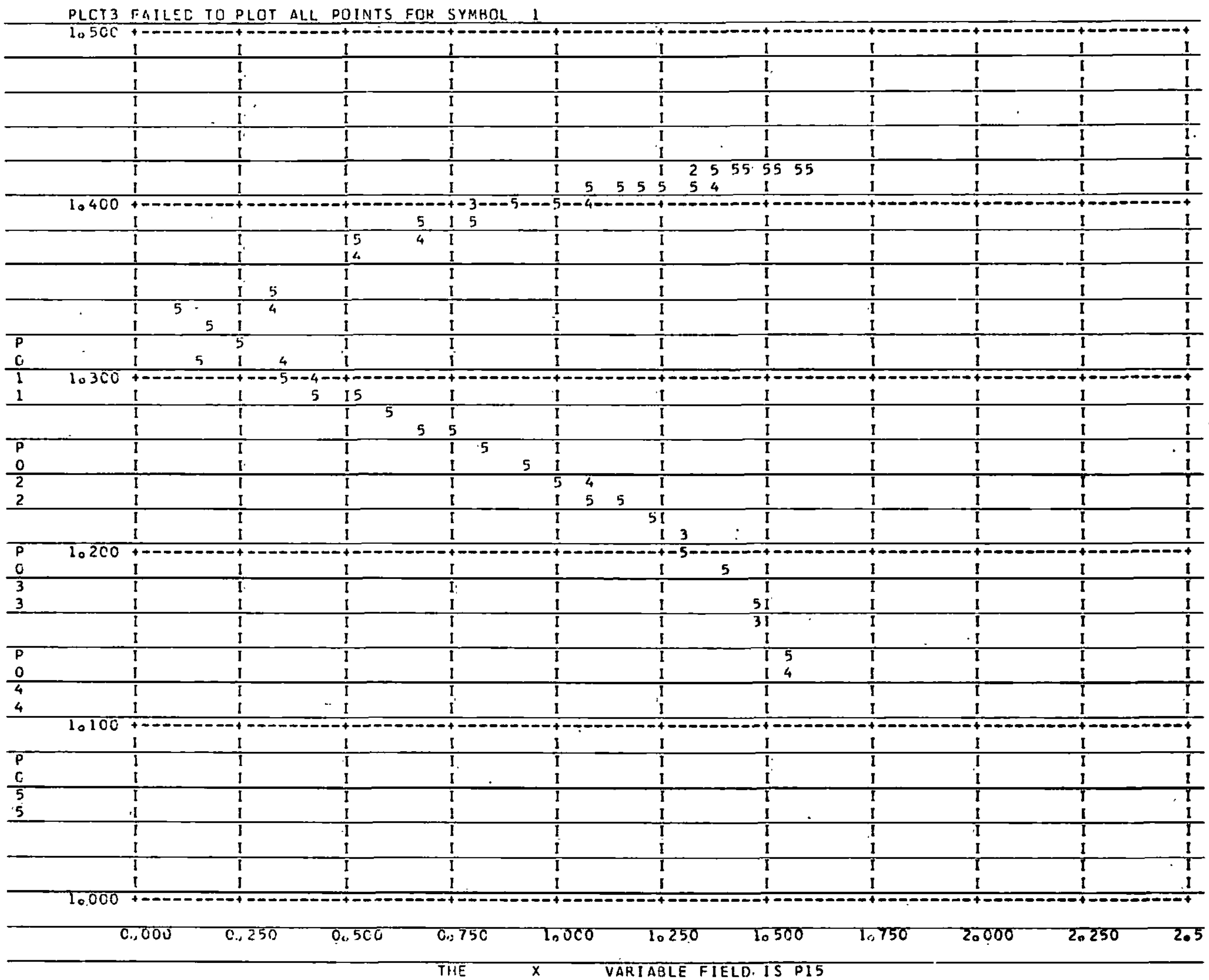


Figure 5ij

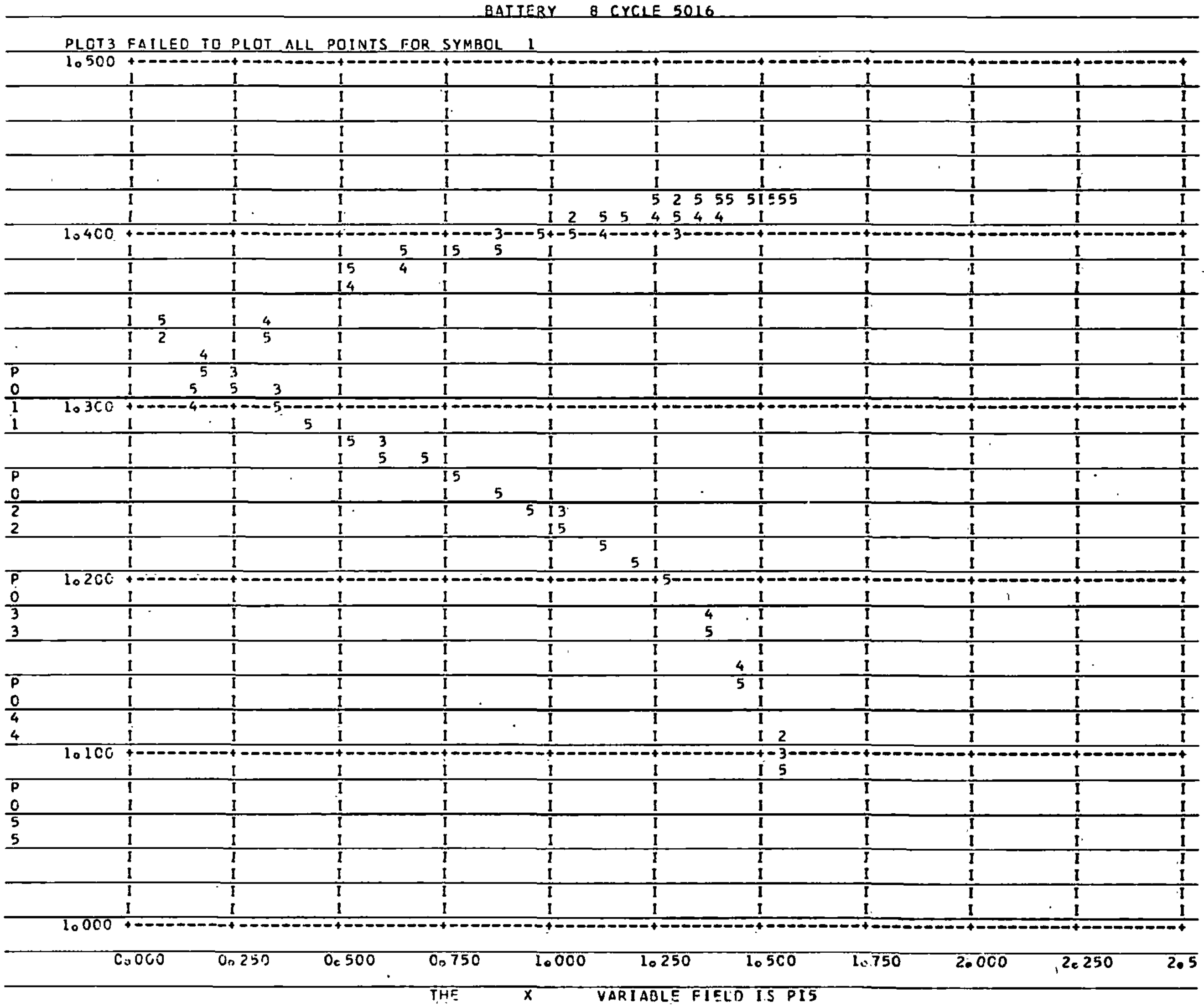

BATTERY 8 CYCLE 5016
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 1
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS PIS

Figure 5ik

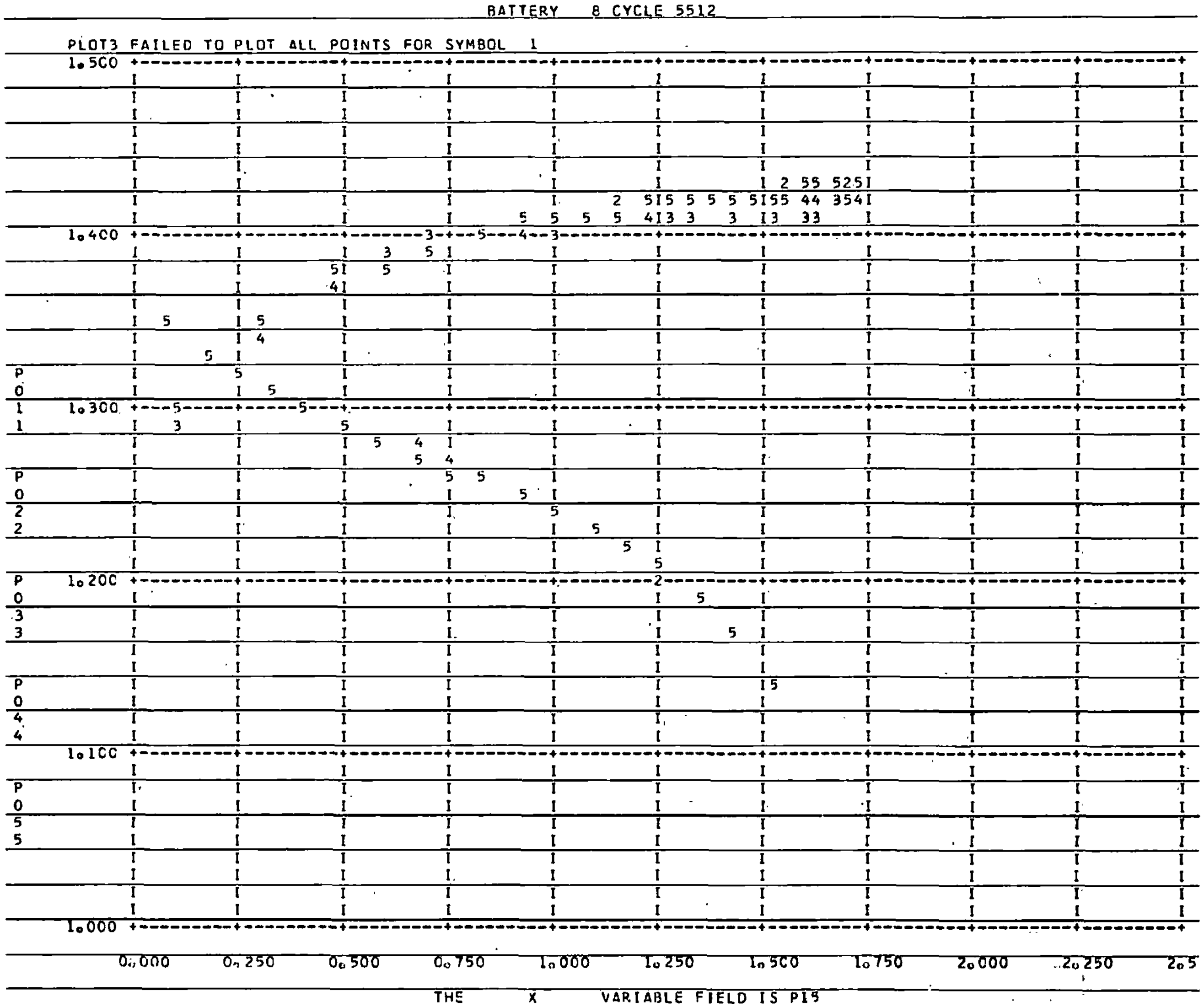

BATTERY 8 CYCLE 5512
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 1
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS PI5

Figure 512

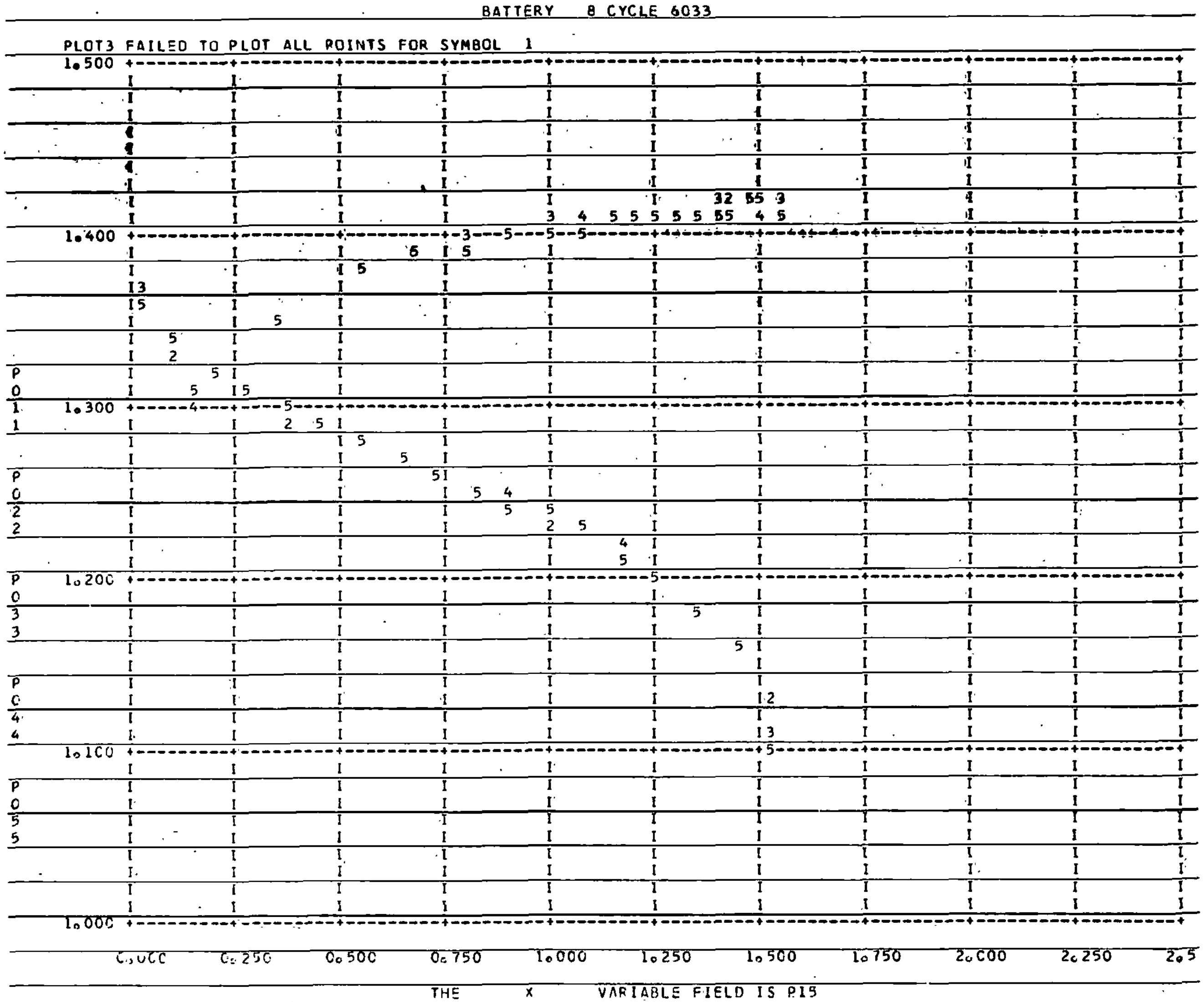
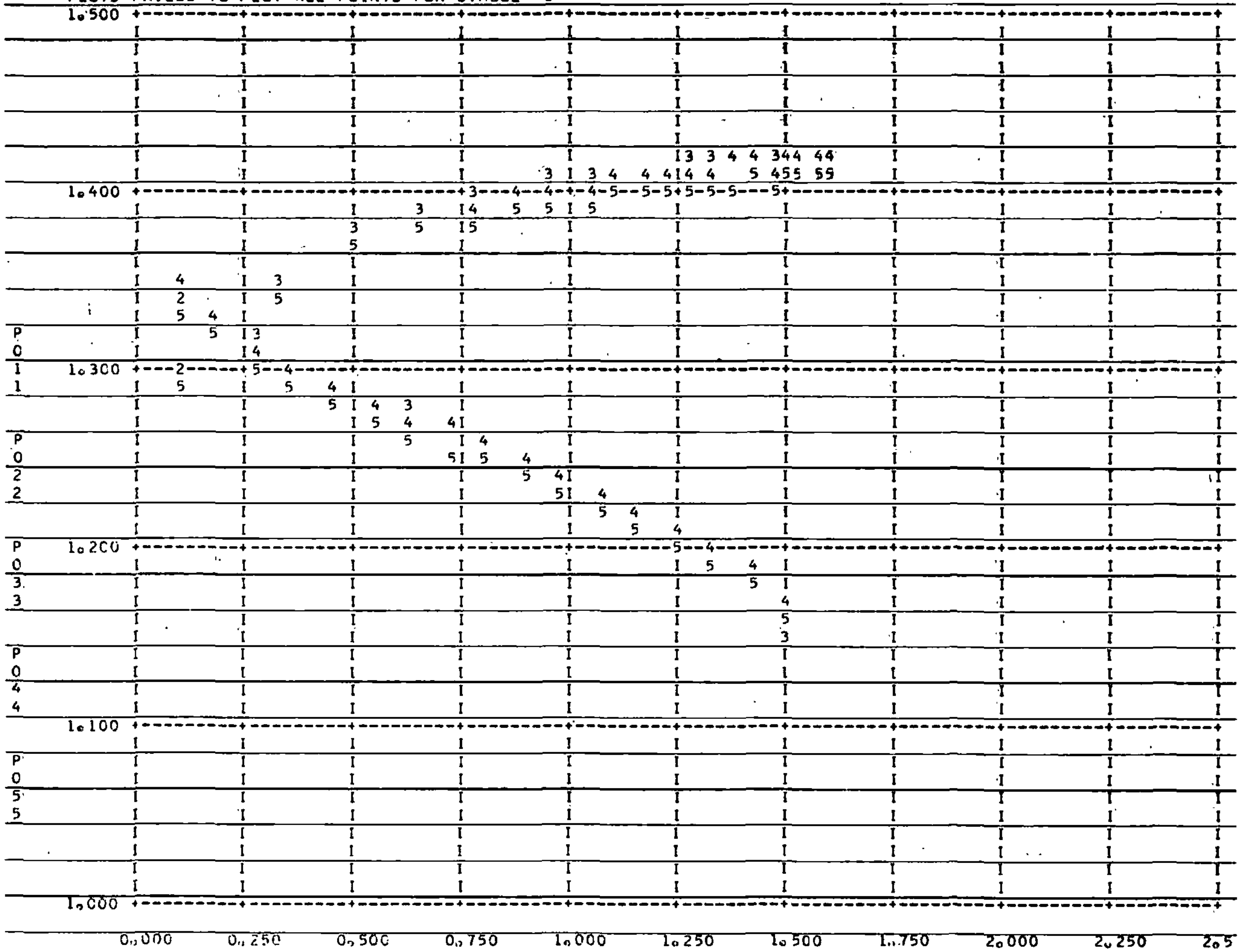

BATTERY 8 CYCLE 6033
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 1
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS P15

Figure 5im

BATTERY 8 CYCLE 6601

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 1

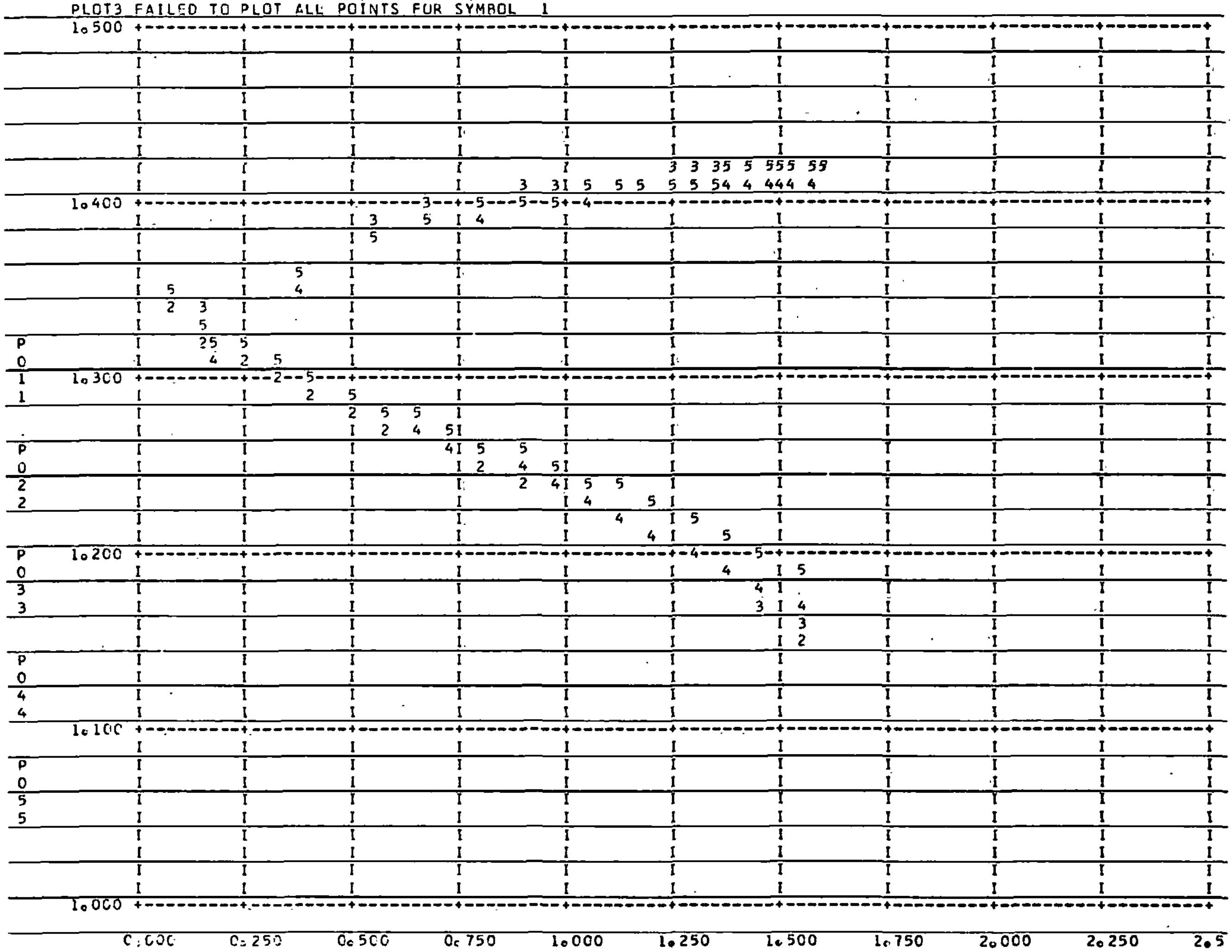


THE X VARIABLE FIELD IS P15

Figure 5in

BATTERY 8 CYCLE 7010

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 1



THE X VARIABLE FIELD IS PI5

Figure 5io

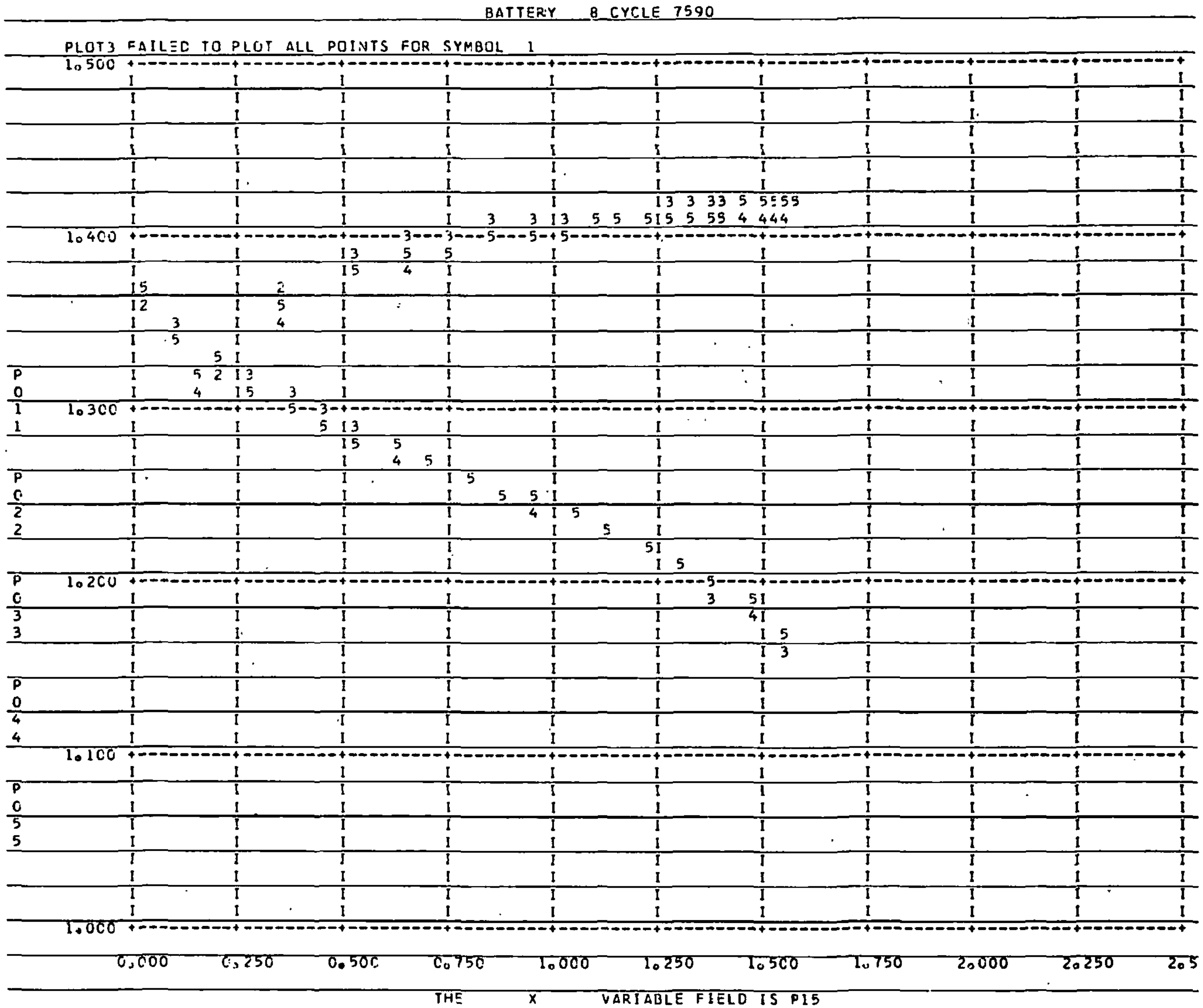

BATTERY 8 CYCLE 7590
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 1
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS P15

Figure 5ip

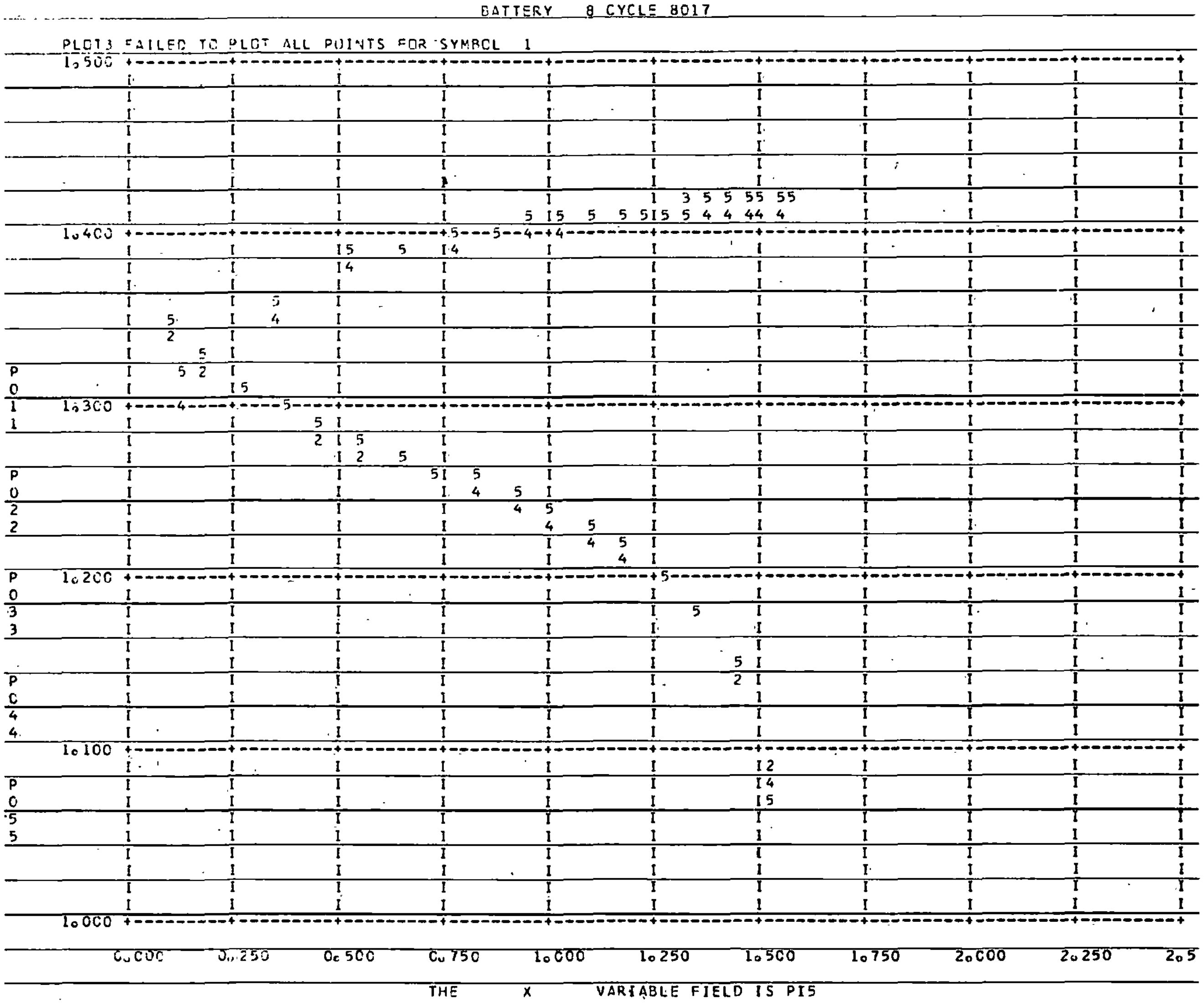
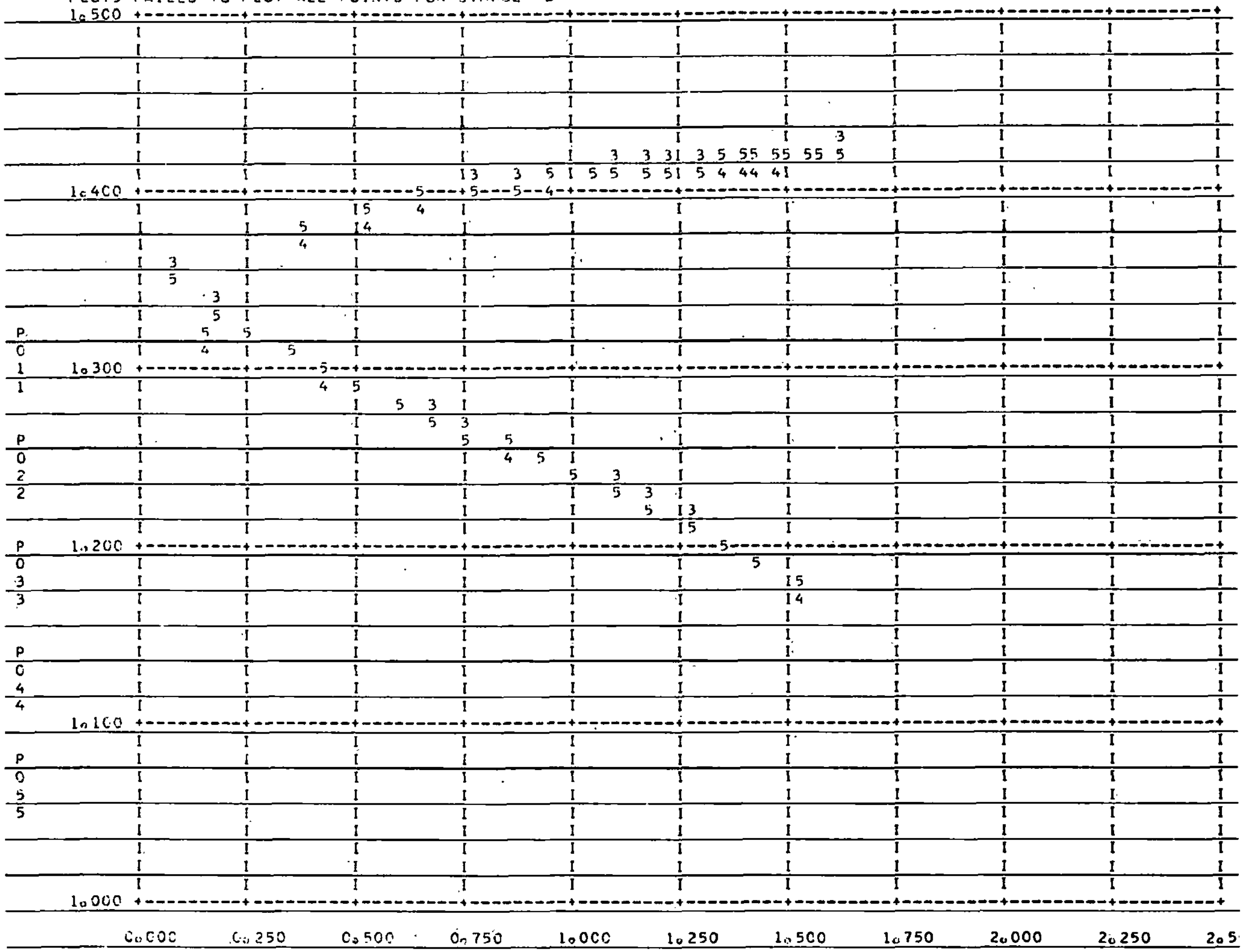

BATTERY 8 CYCLE 8017
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 1
1.500
1.400
1.300
1.200
1.100
1.000
P 0 1 1
P 0 2 2
P 0 3 3
P 0 4 4
P 0 5 5
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS PI5

Figure 5iq

BATTERY 8 CYCLE 8352

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 1
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 2



THE X VARIABLE FIELD IS P15

Figure 5ir

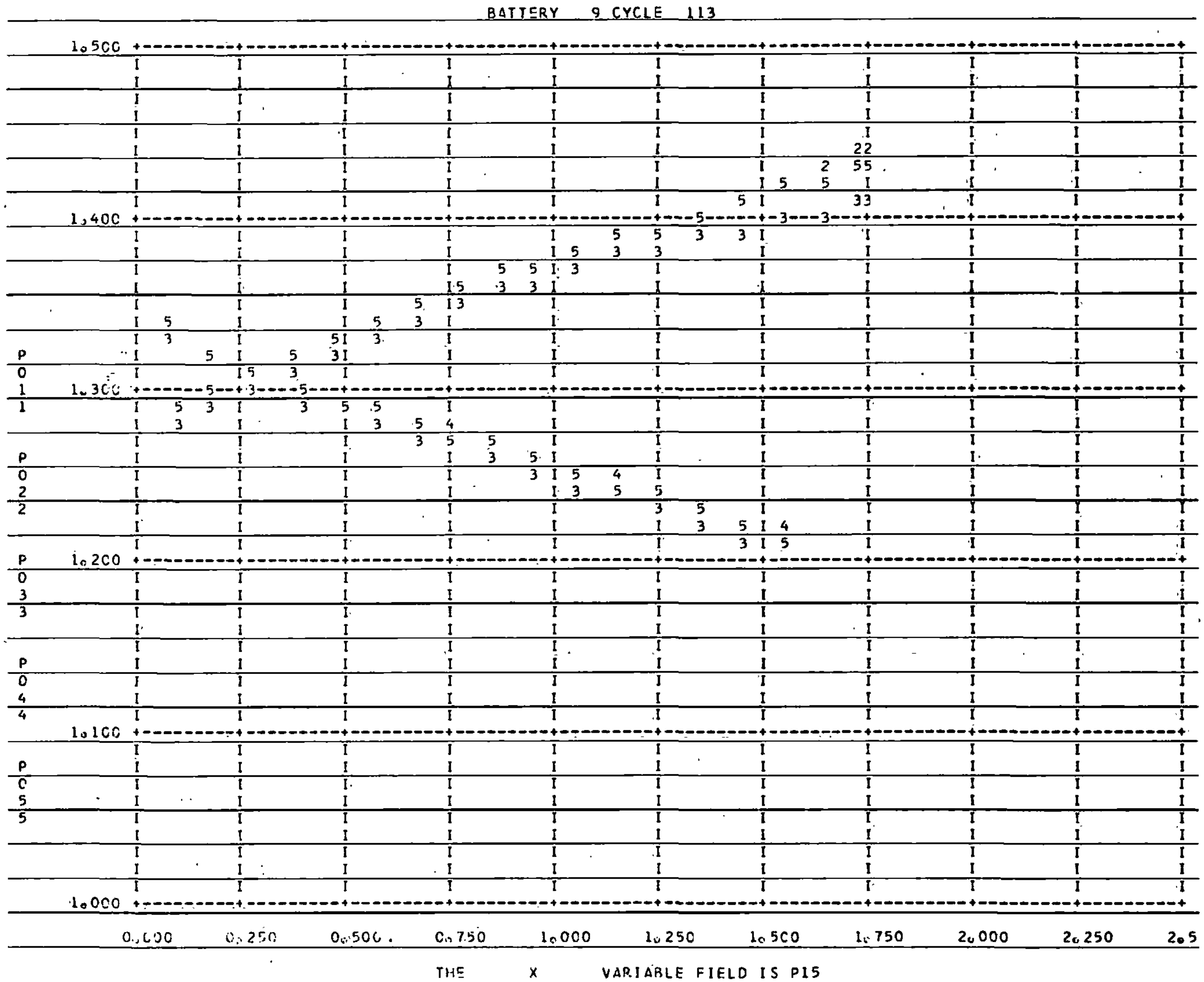

BATTERY 9 CYCLE 113
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS P15

Figure 5ia

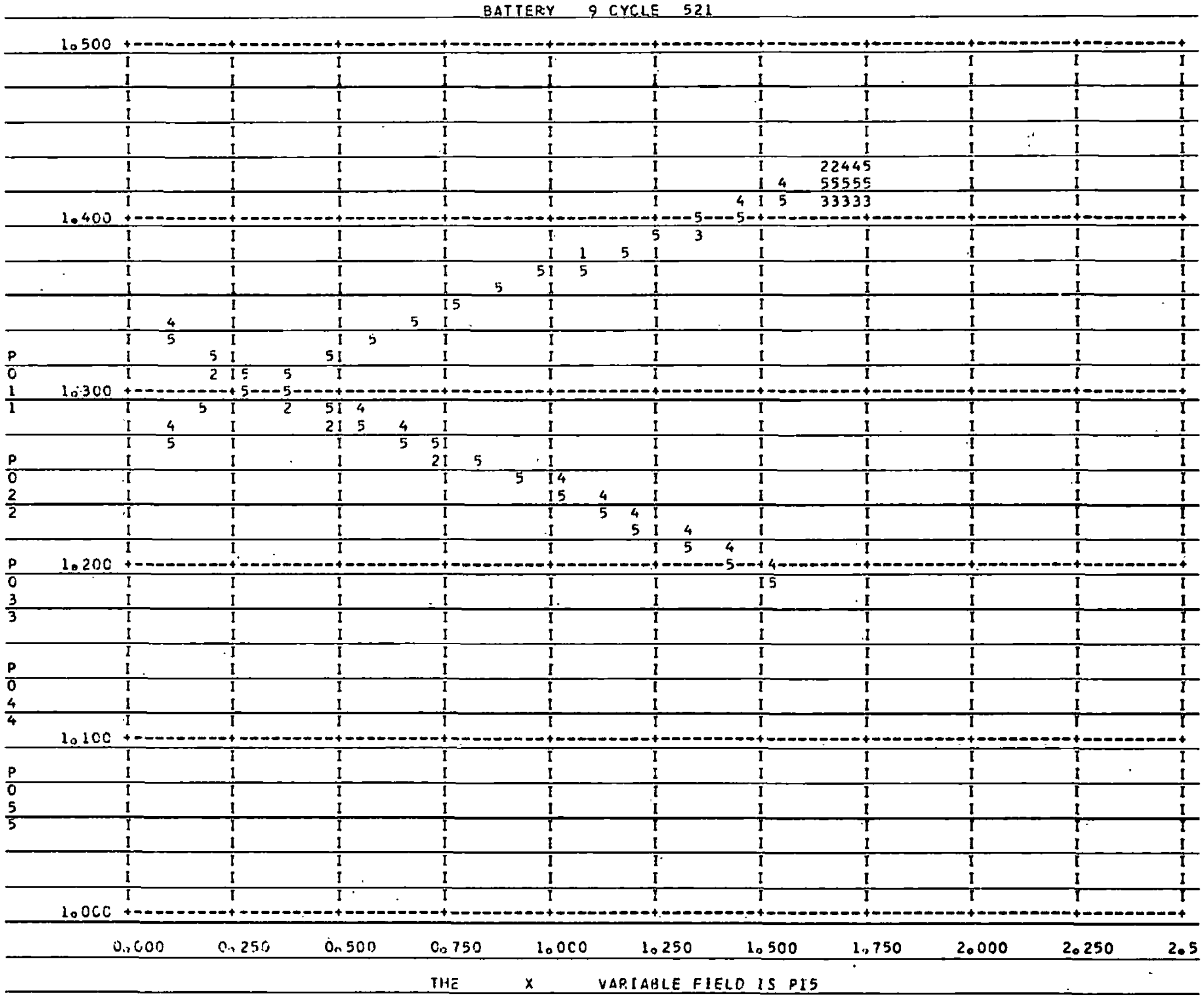

BATTERY 9 CYCLE 521
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS PI5

Figure 51b

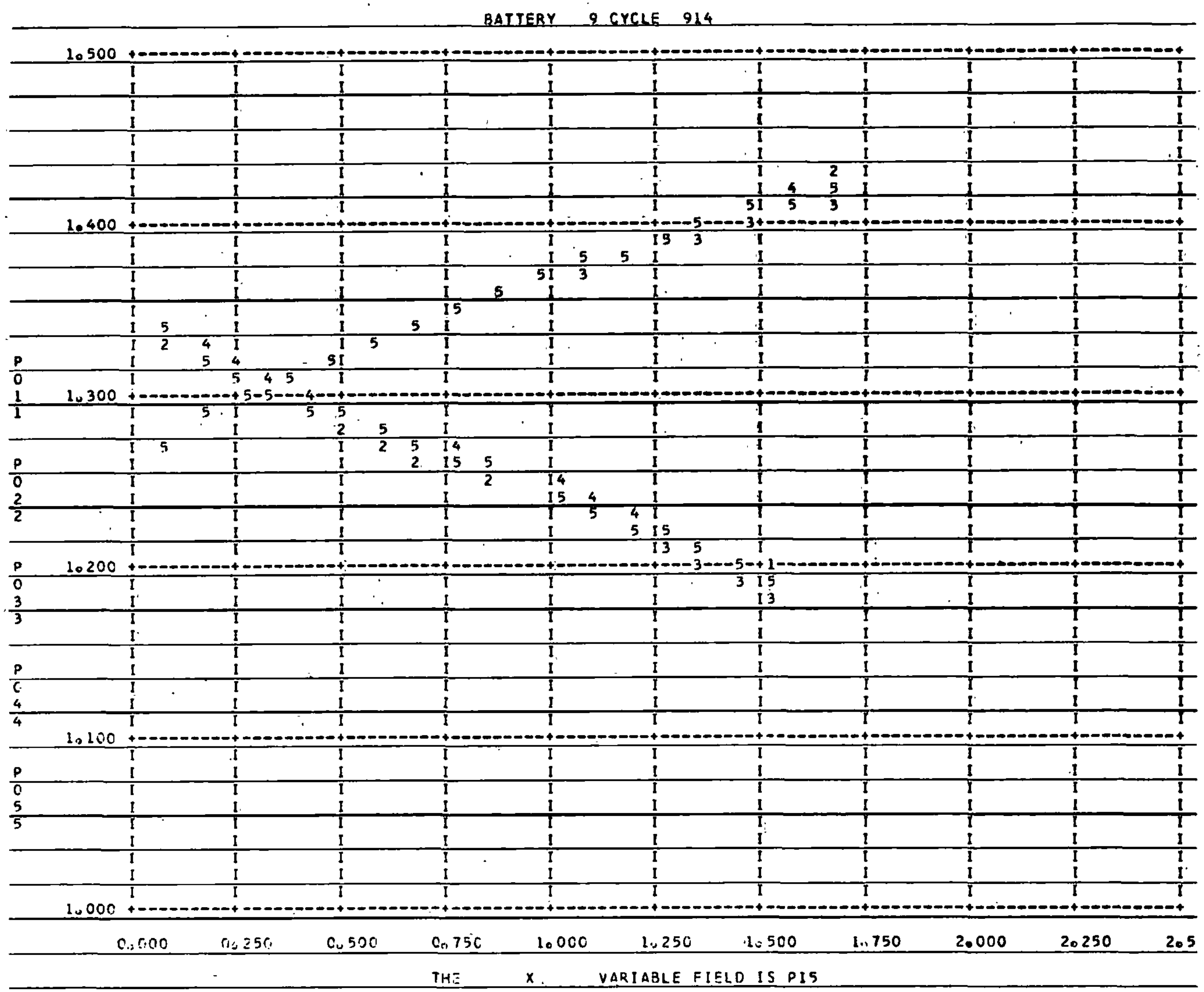
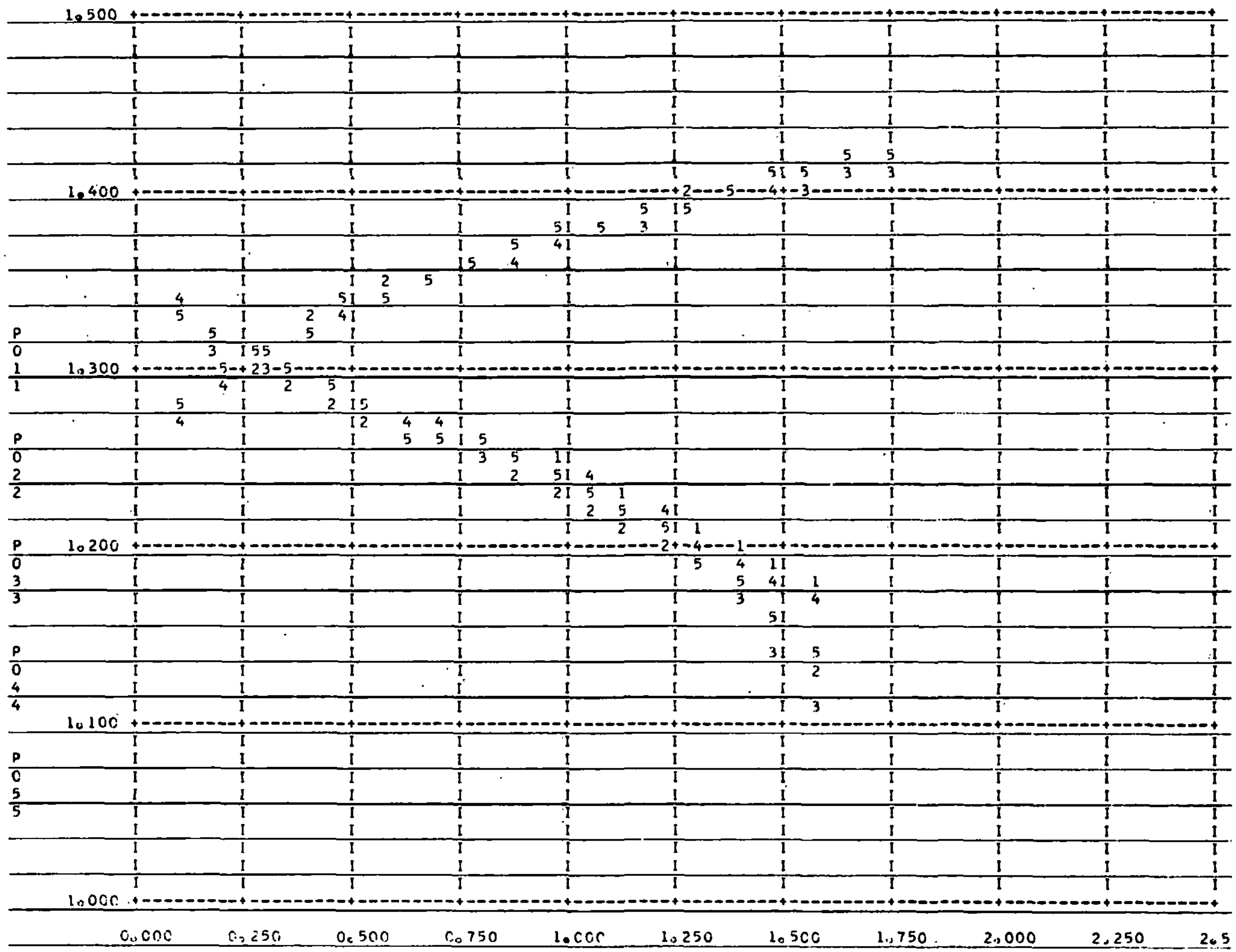

BATTERY 9 CYCLE 914
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS PIS

Figure 5jc

BATTERY 9 CYCLE 1513



THE X VARIABLE FIELD IS P15

Figure 5jd

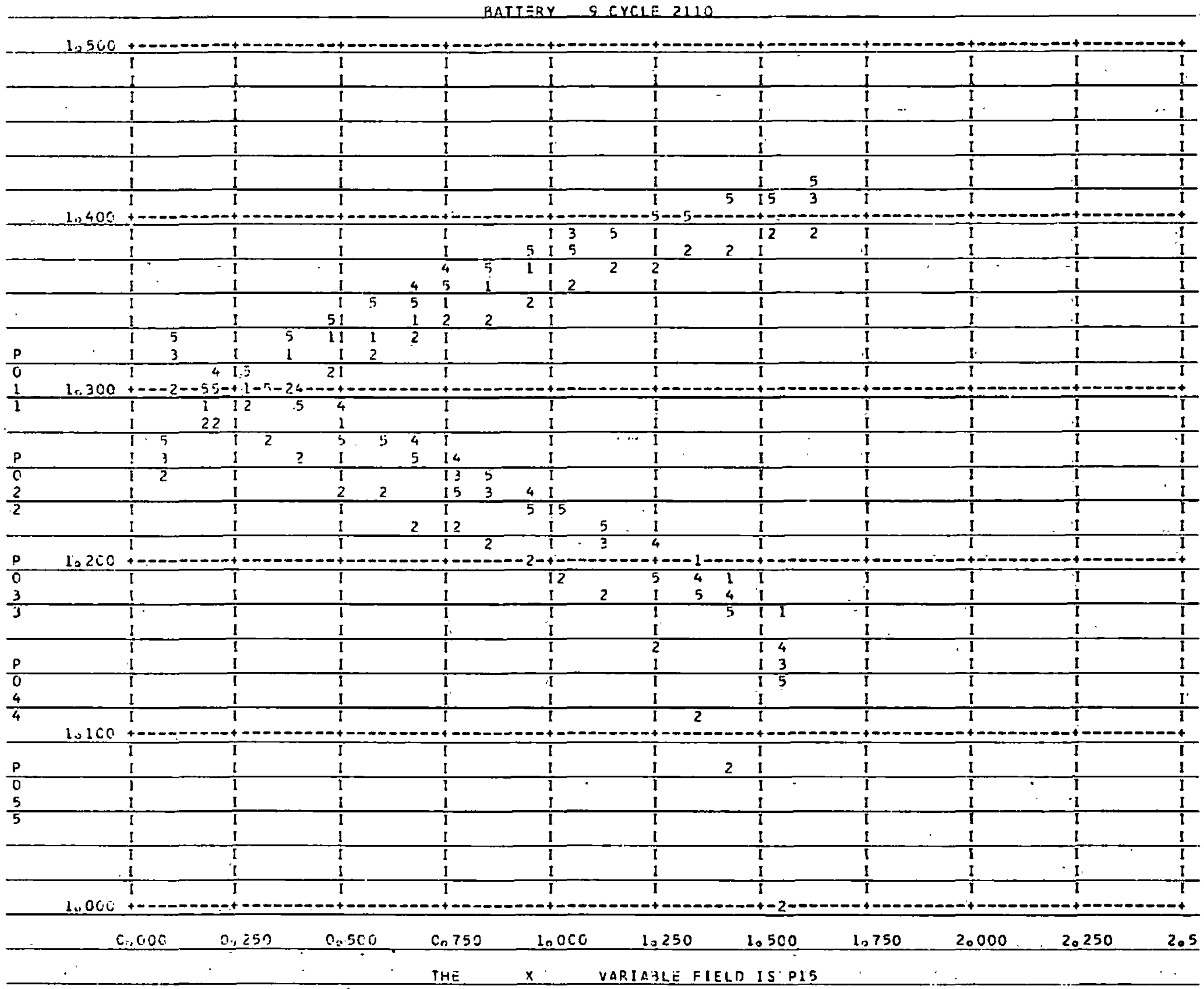
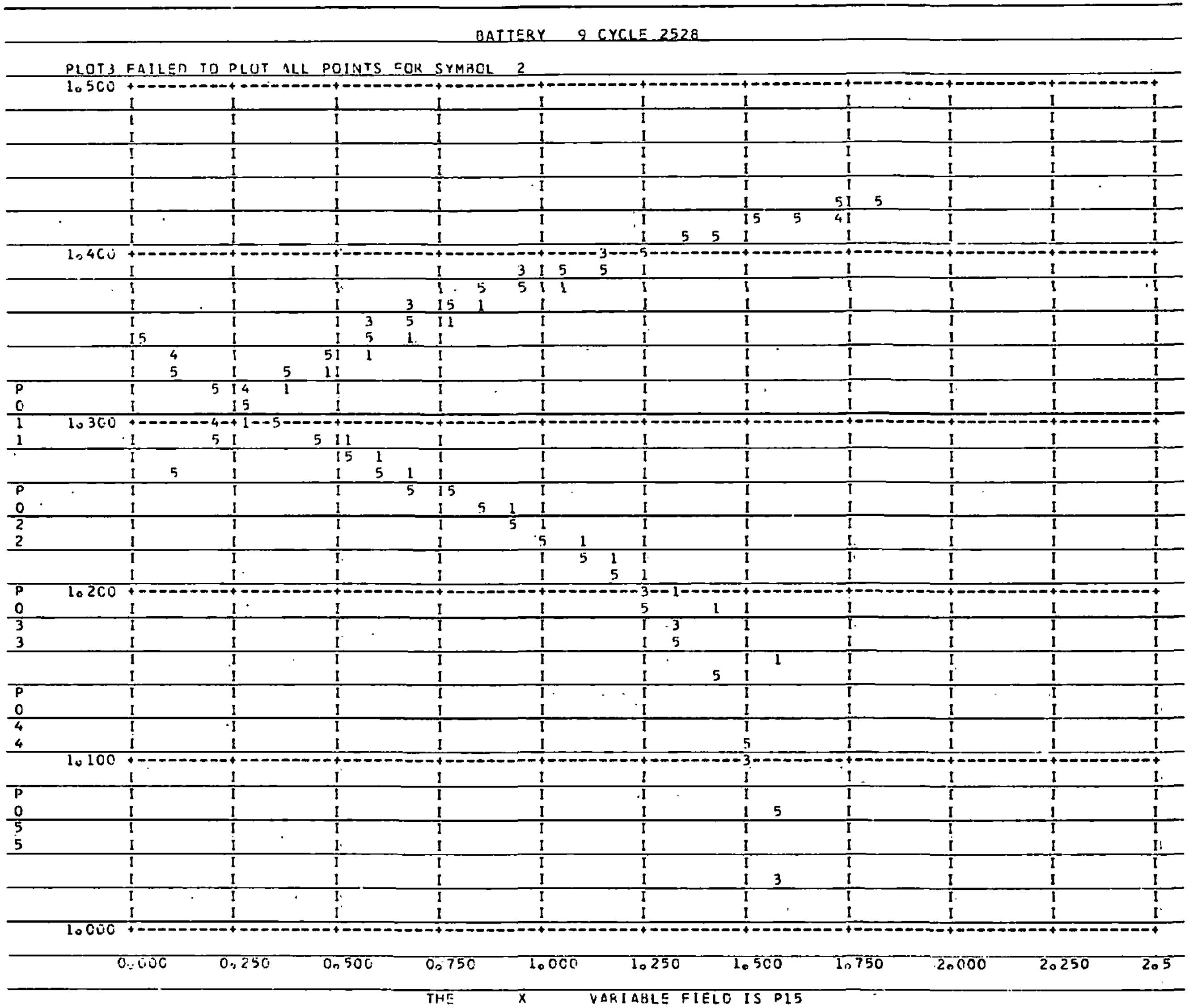

BATTERY 9 CYCLE 2110
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000 0.250 0.500 0.750 1.000 1.250 1.500 1.750 2.000 2.250 2.5
THE X VARIABLE FIELD IS P15

Figure 5je



BATTERY 9 CYCLE 2528
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 2
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS P15

Figure 5jf

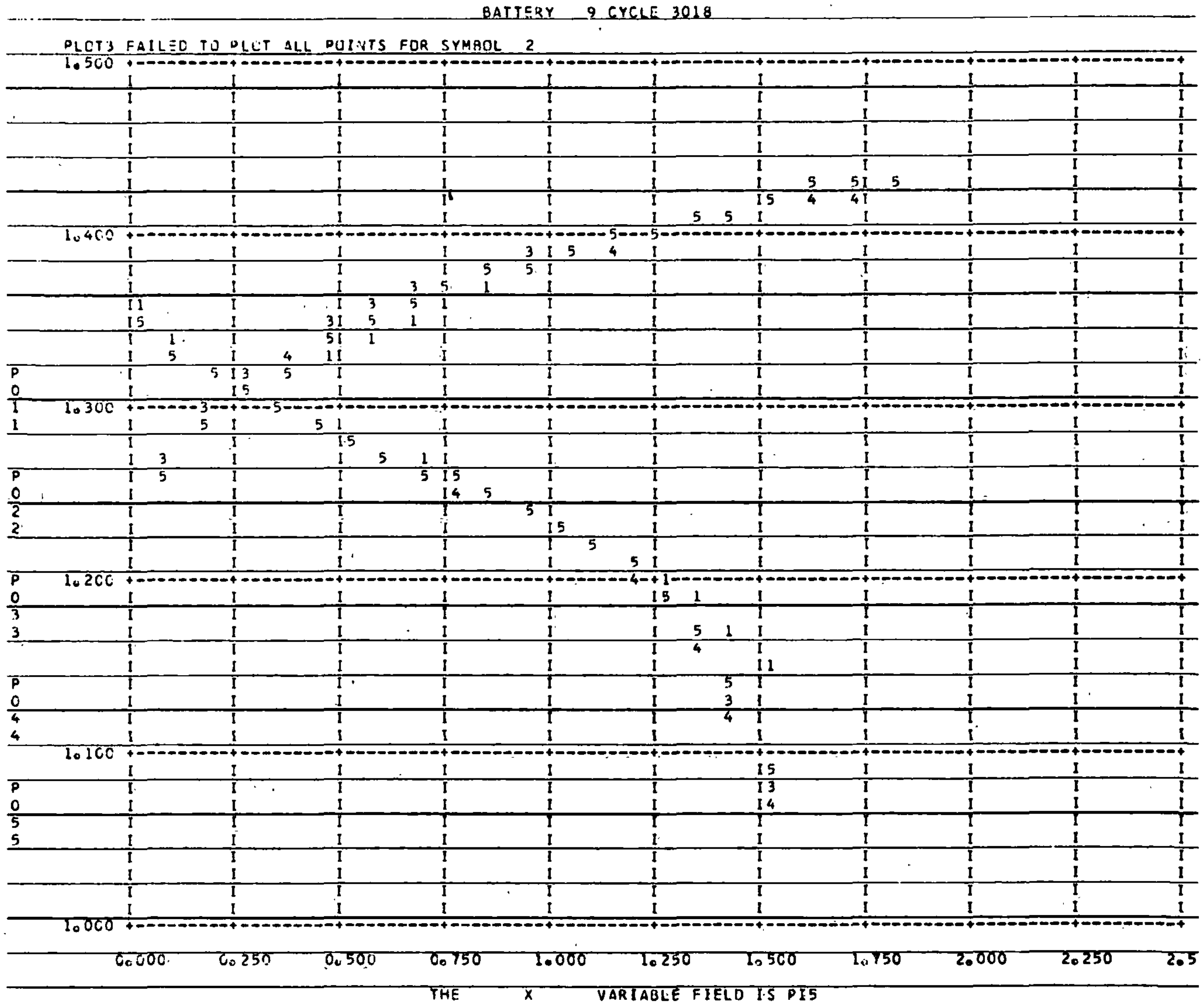

BATTERY 9 CYCLE 3018
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 2
1.500
1.400
1.300
1.200
1.100
1.000
P0 11
P0 22
P0 33
P0 44
P0 55
0.000
0.250
0.500
0.750
1.000
1.250
1.500
1.750
2.000
2.250
2.5
THE X VARIABLE FIELD IS PI5

Figure 5jg

BATTERY 9 CYCLE 3311

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 2

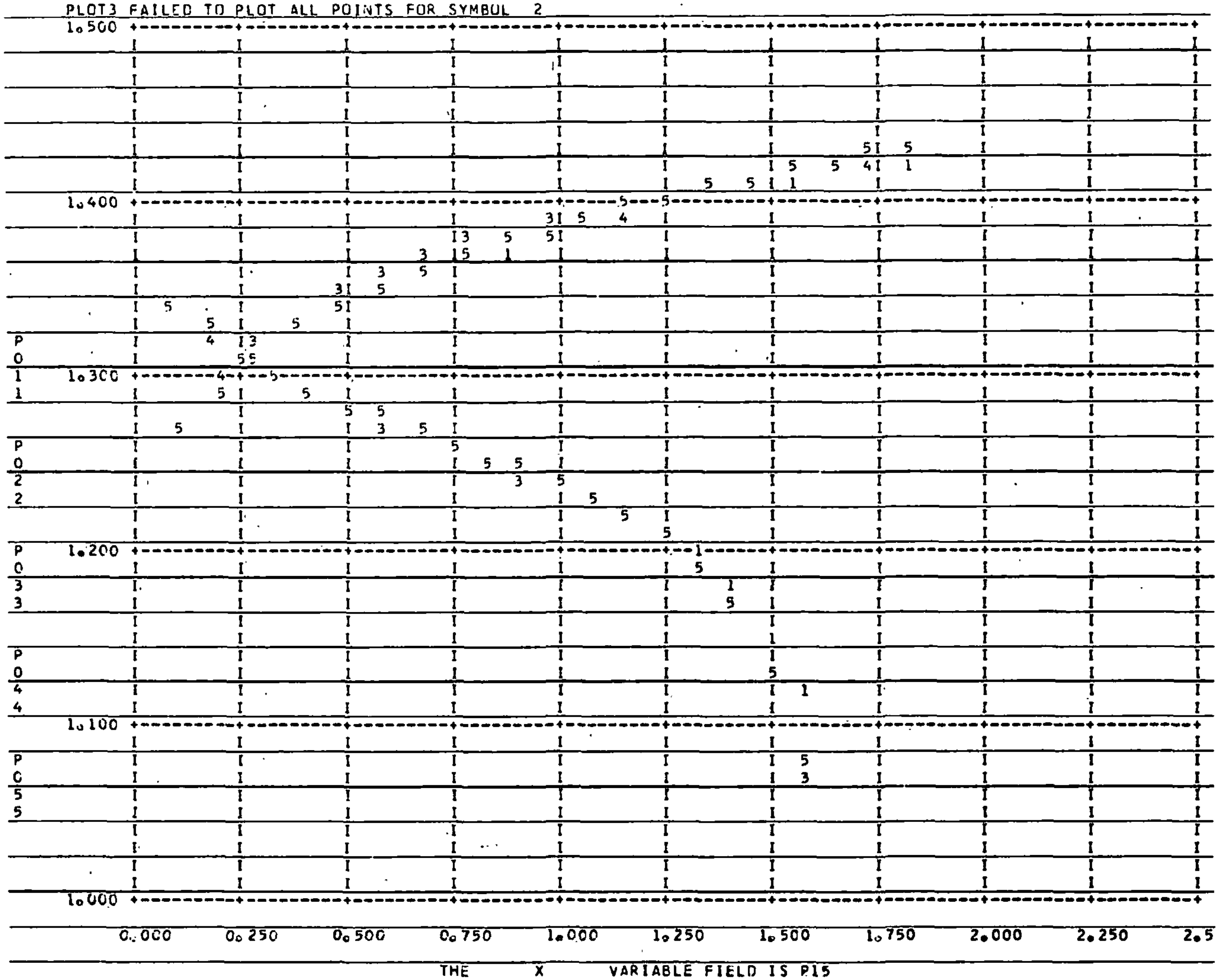
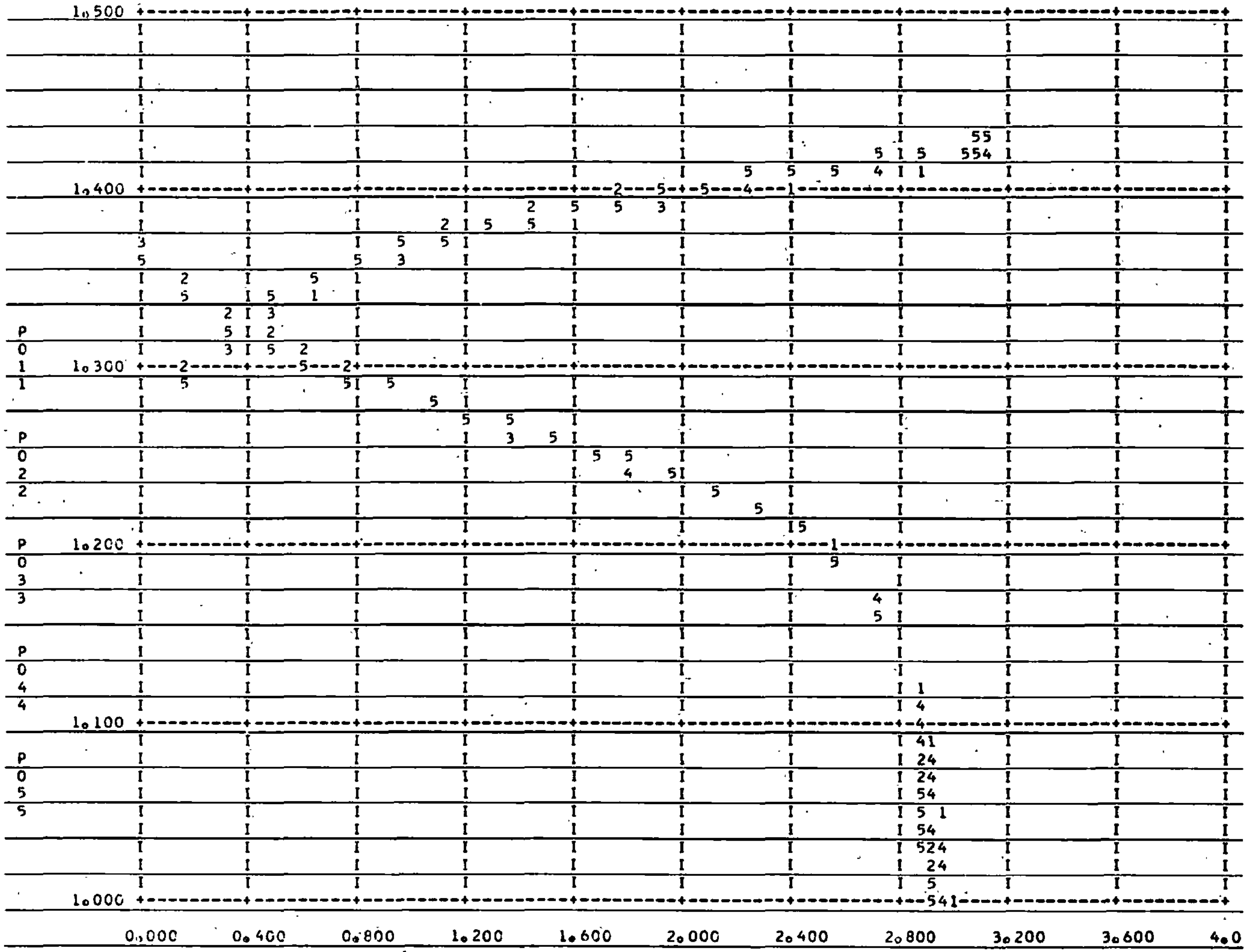


Figure 5jh

BATTERY 10 CYCLE 112

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 2
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 3
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 4
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 5



THE X VARIABLE FIELD IS PIS

Figure 5ka

BATTERY 10 CYCLE 517

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 1
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 2
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 3
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 4
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 5

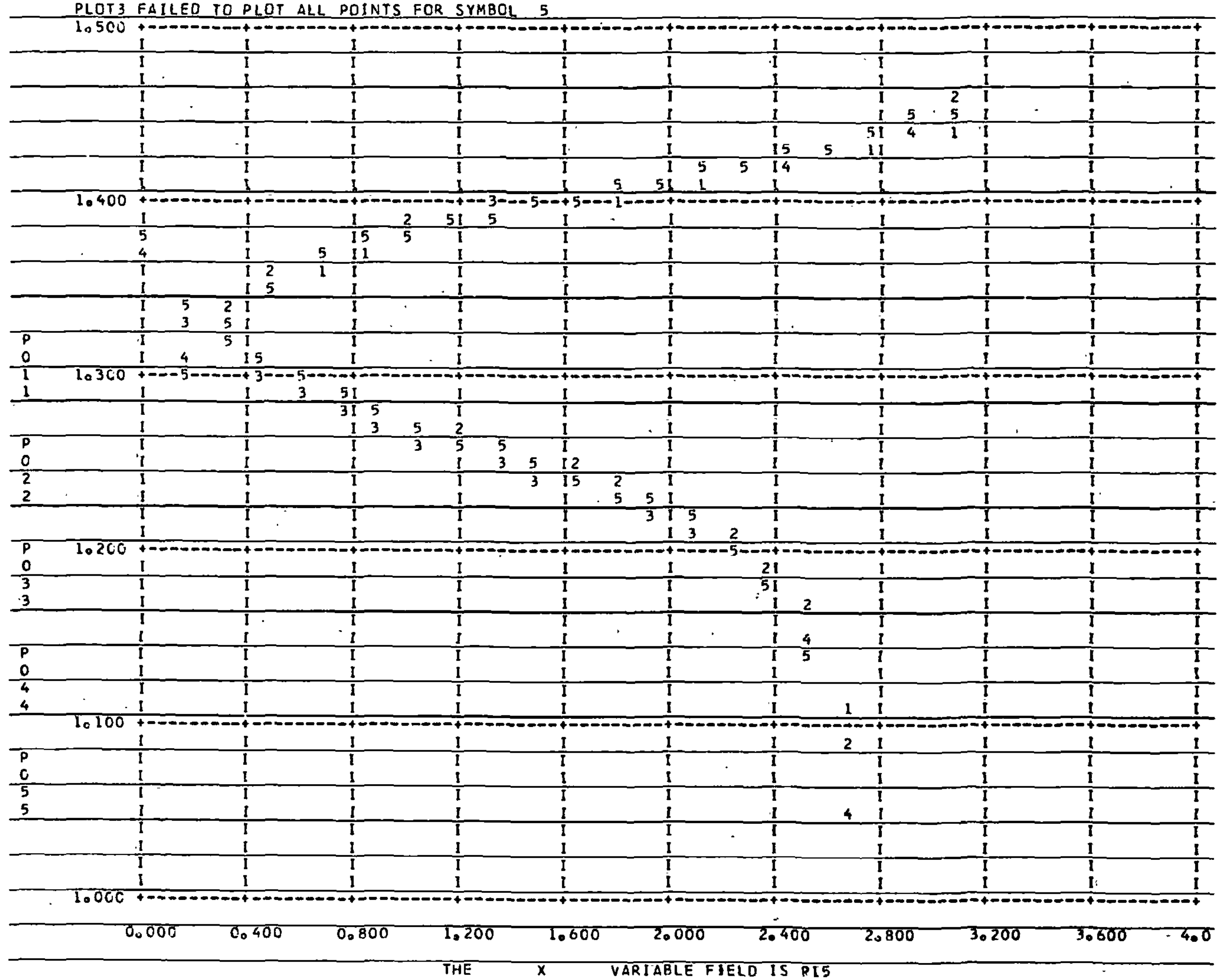
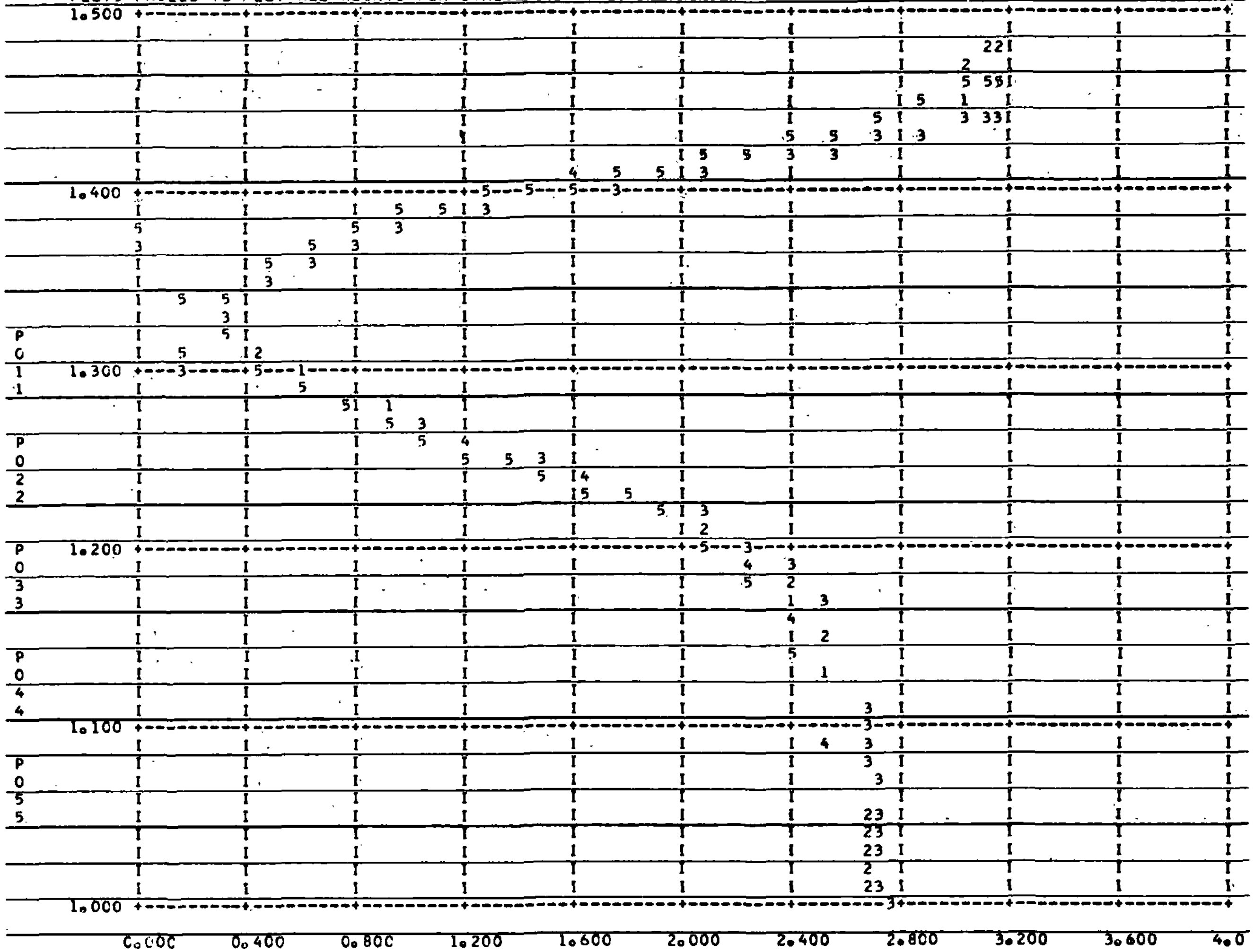


Figure 5kb

BATTERY 10 CYCLE 1035

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 1
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 2
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 3
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 4
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 5

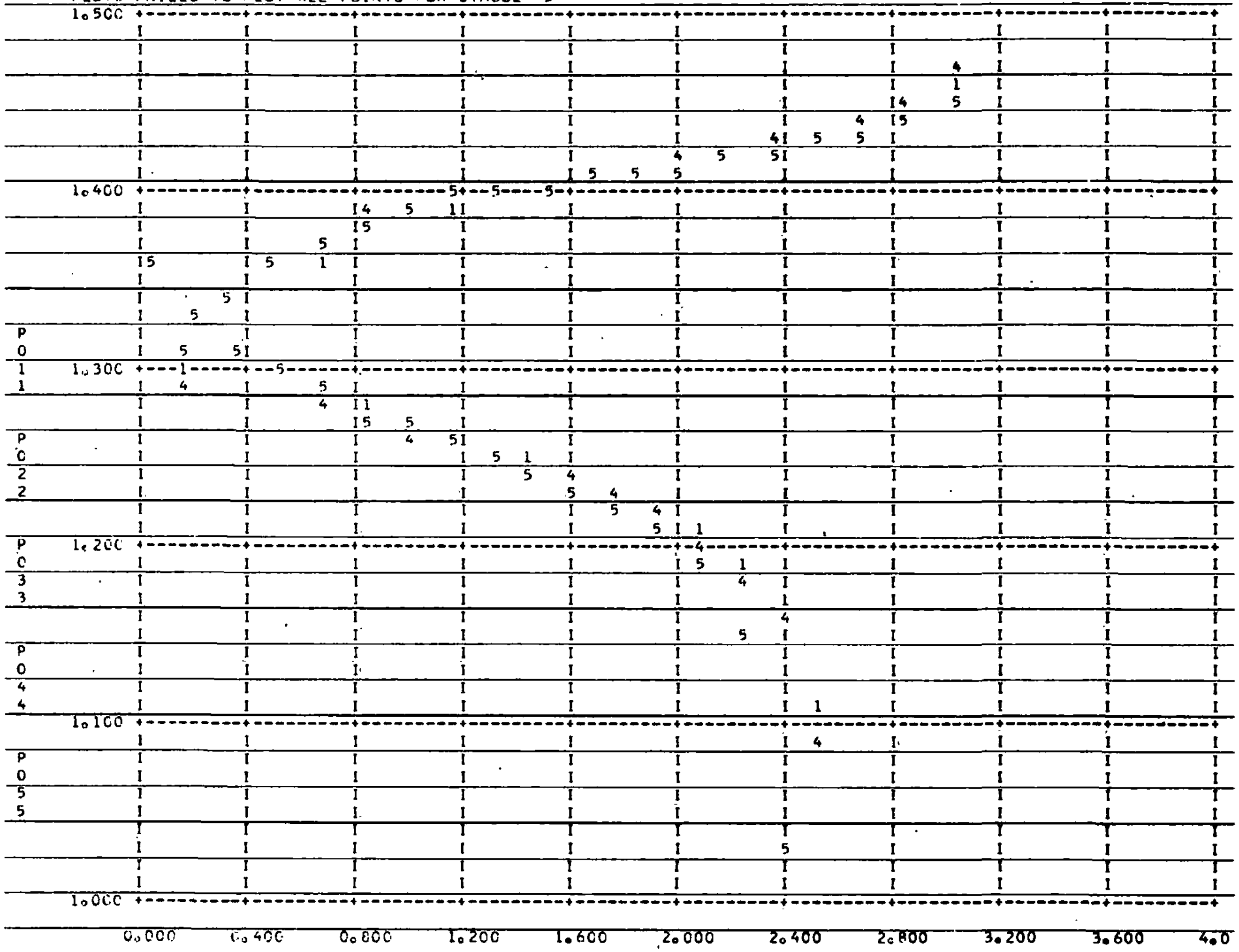


THE X VARIABLE FIELD IS P15

Figure 5kc

BATTERY 10 CYCLE 1523

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 1
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 2
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 3
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 4
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 5

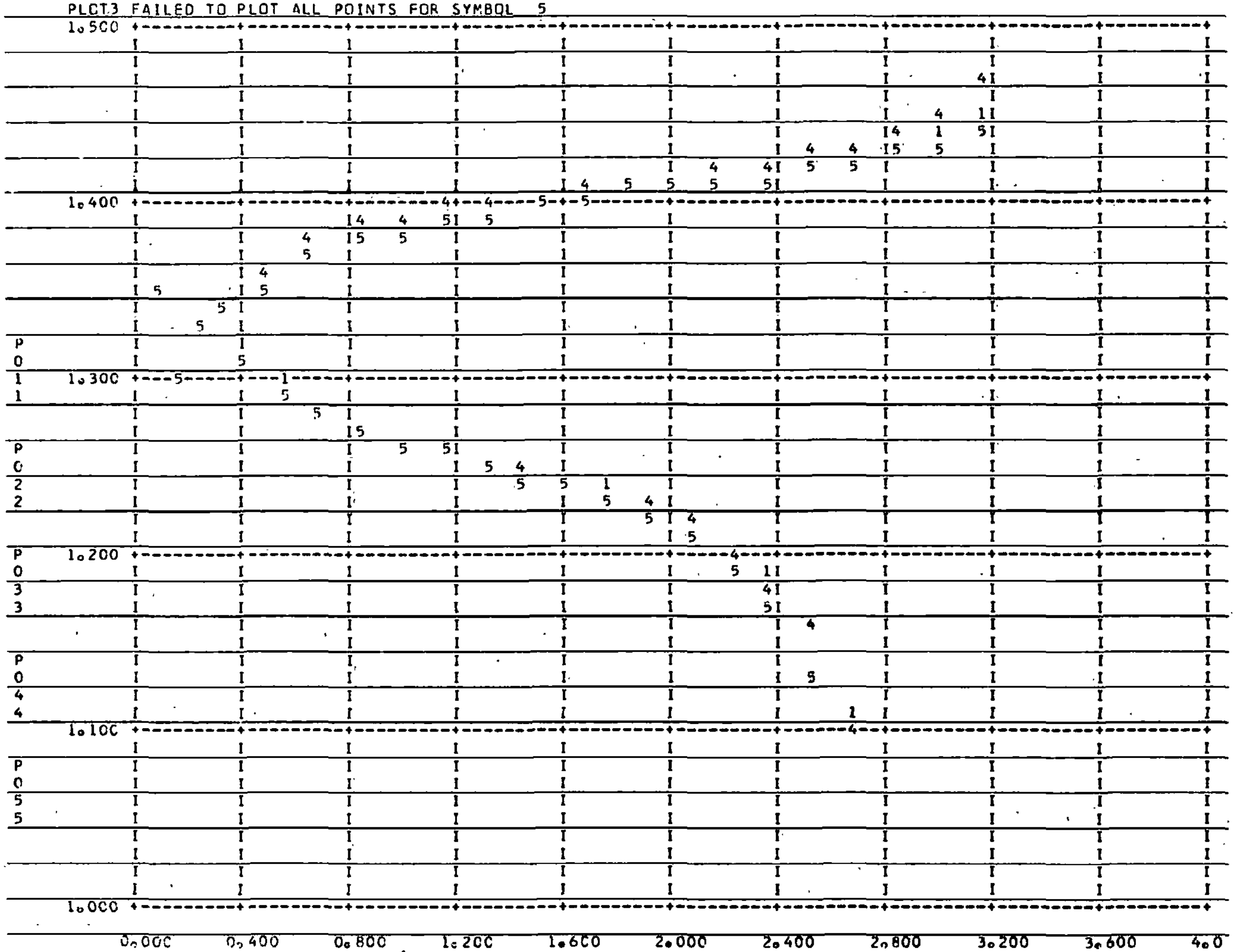


THE X VARIABLE FIELD IS P15

Figure 5kd

BATTERY 10 CYCLE 2037

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 1
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 2
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 3
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 4
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 5



THE X VARIABLE FIELD IS P15

Figure 5ke

BATTERY 10 CYCLE 2557

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 1
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 2
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 3
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 4
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 5

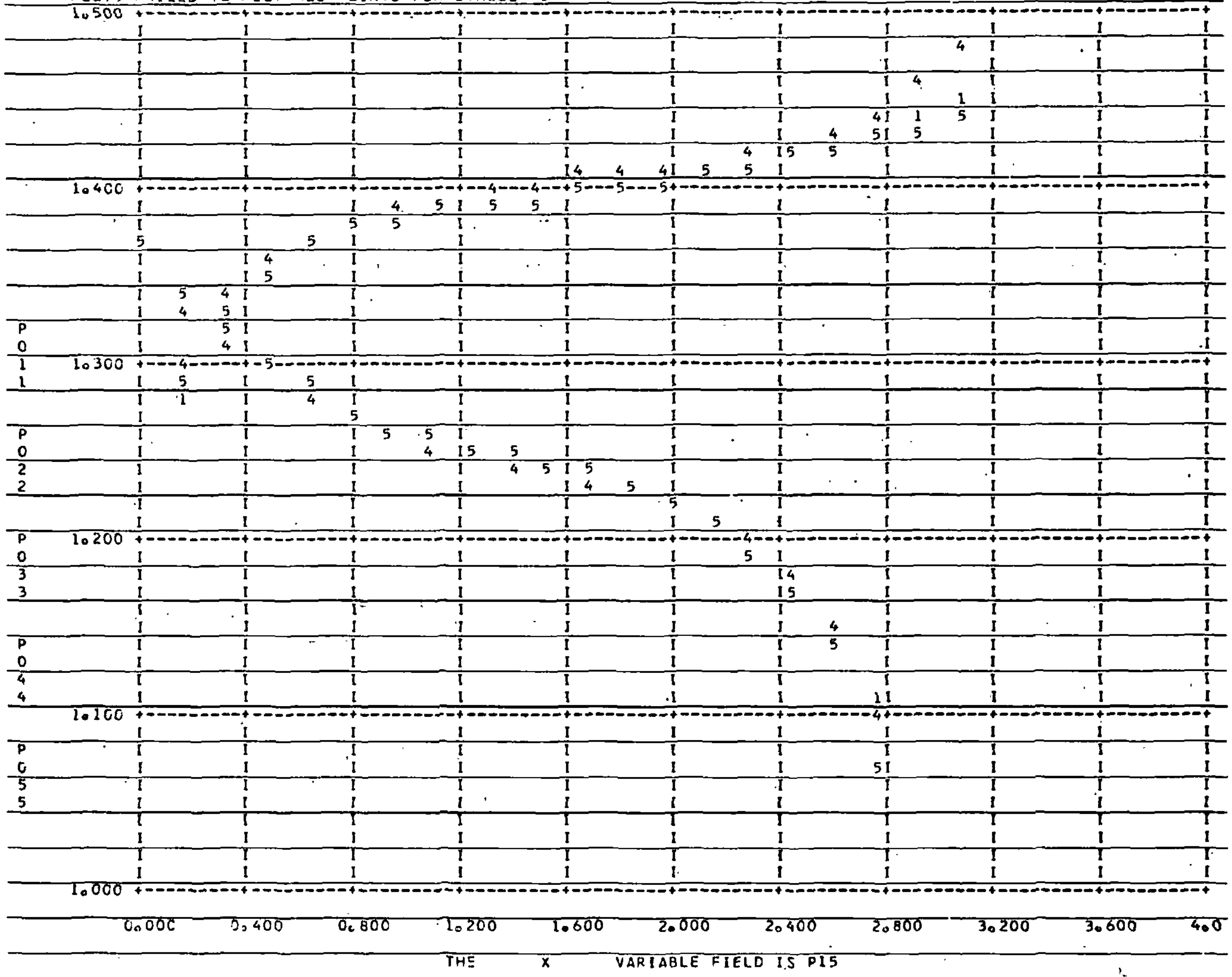
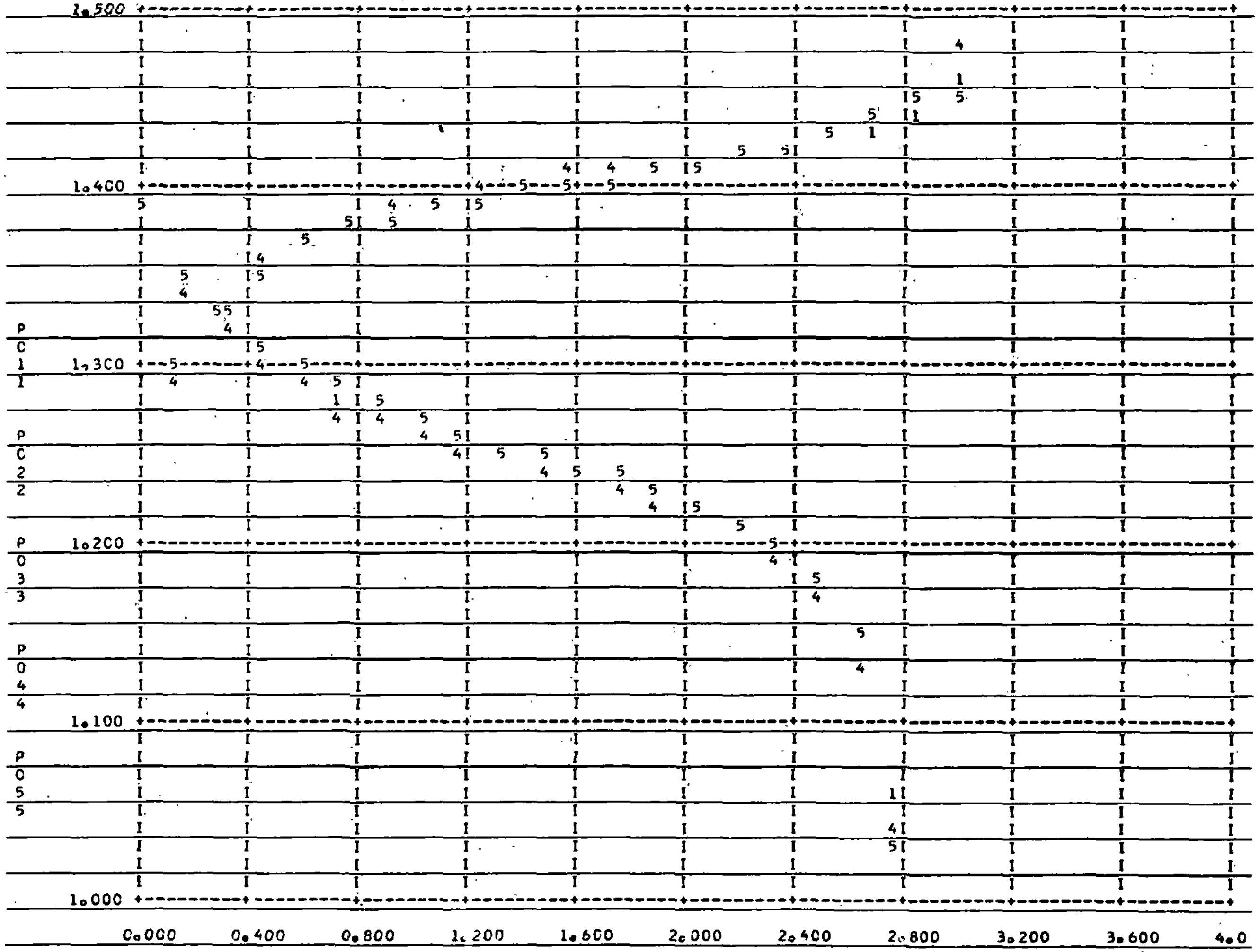


Figure 5kf

BATTERY 10 CYCLE 3010

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 2
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 3

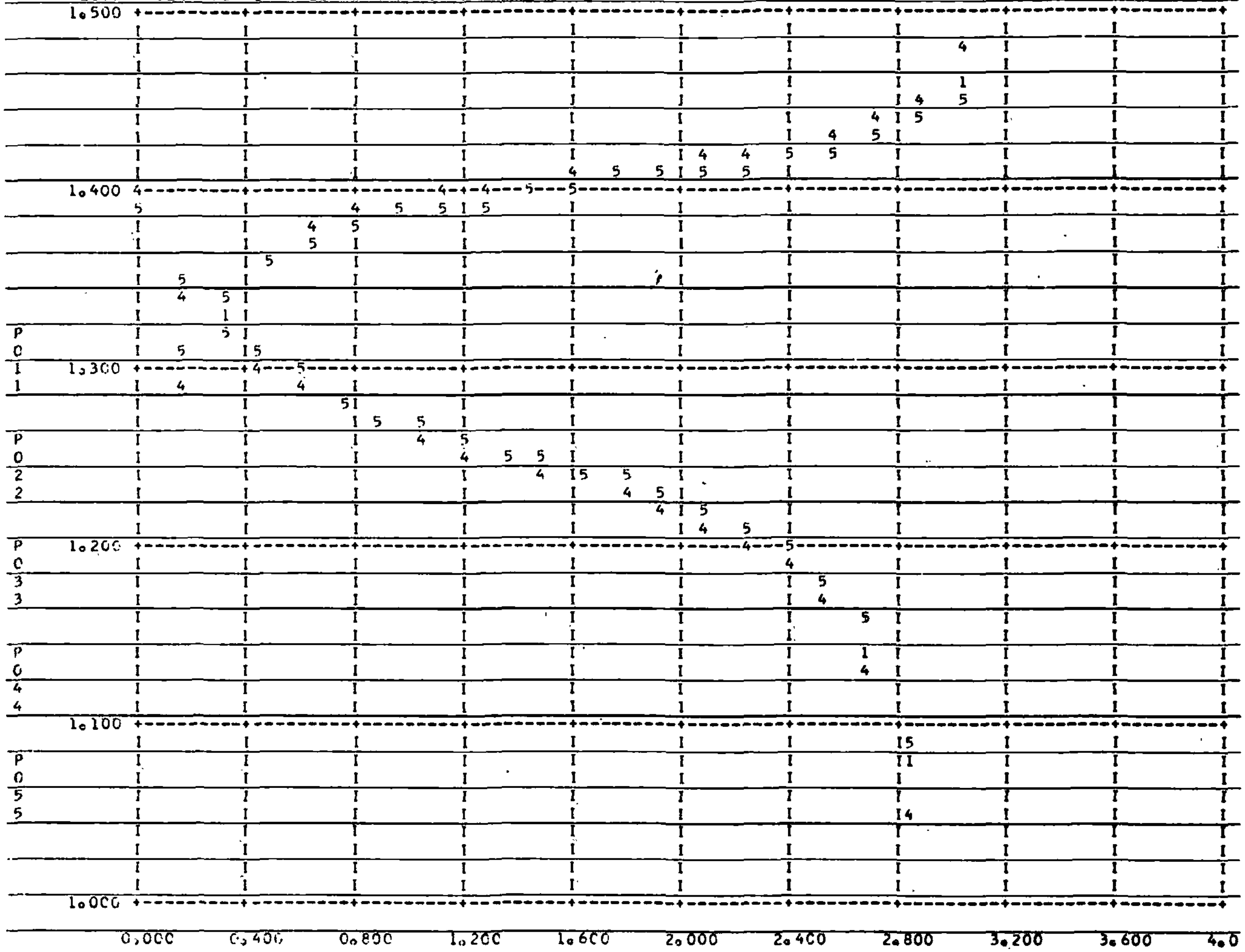


THE X VARIABLE FIELD IS P15

Figure 5kg

BATTERY 10 CYCLE 3444

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 1
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 2
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 3
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 4
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 5

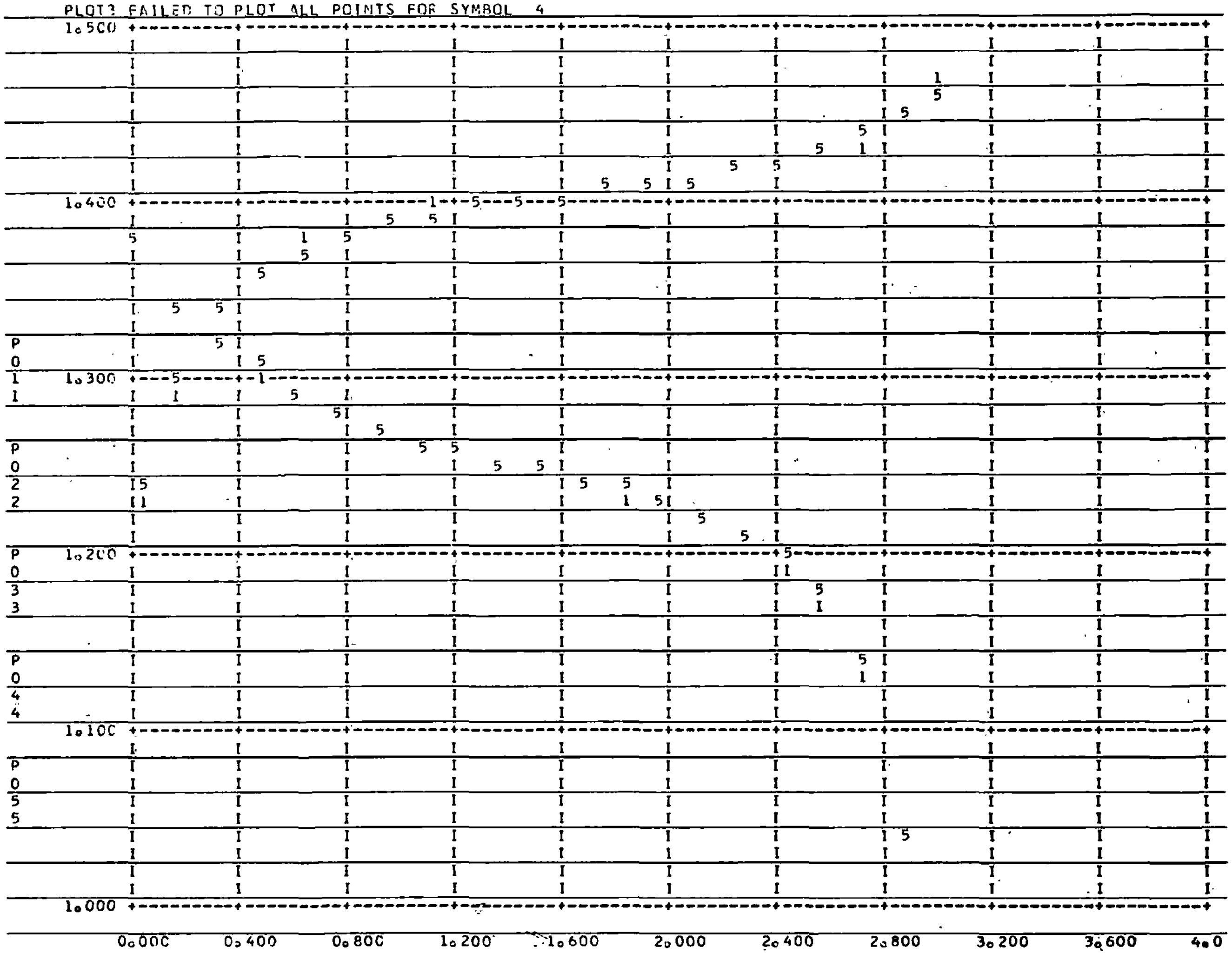


THE X VARIABLE FIELD IS P15

Figure 5kh

BATTERY 10 CYCLE 3830

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 2
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 3
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 4



THE X VARIABLE FIELD IS PI5

Figure 5ki

BATTERY 11 CYCLE 325

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 1
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 2
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 3

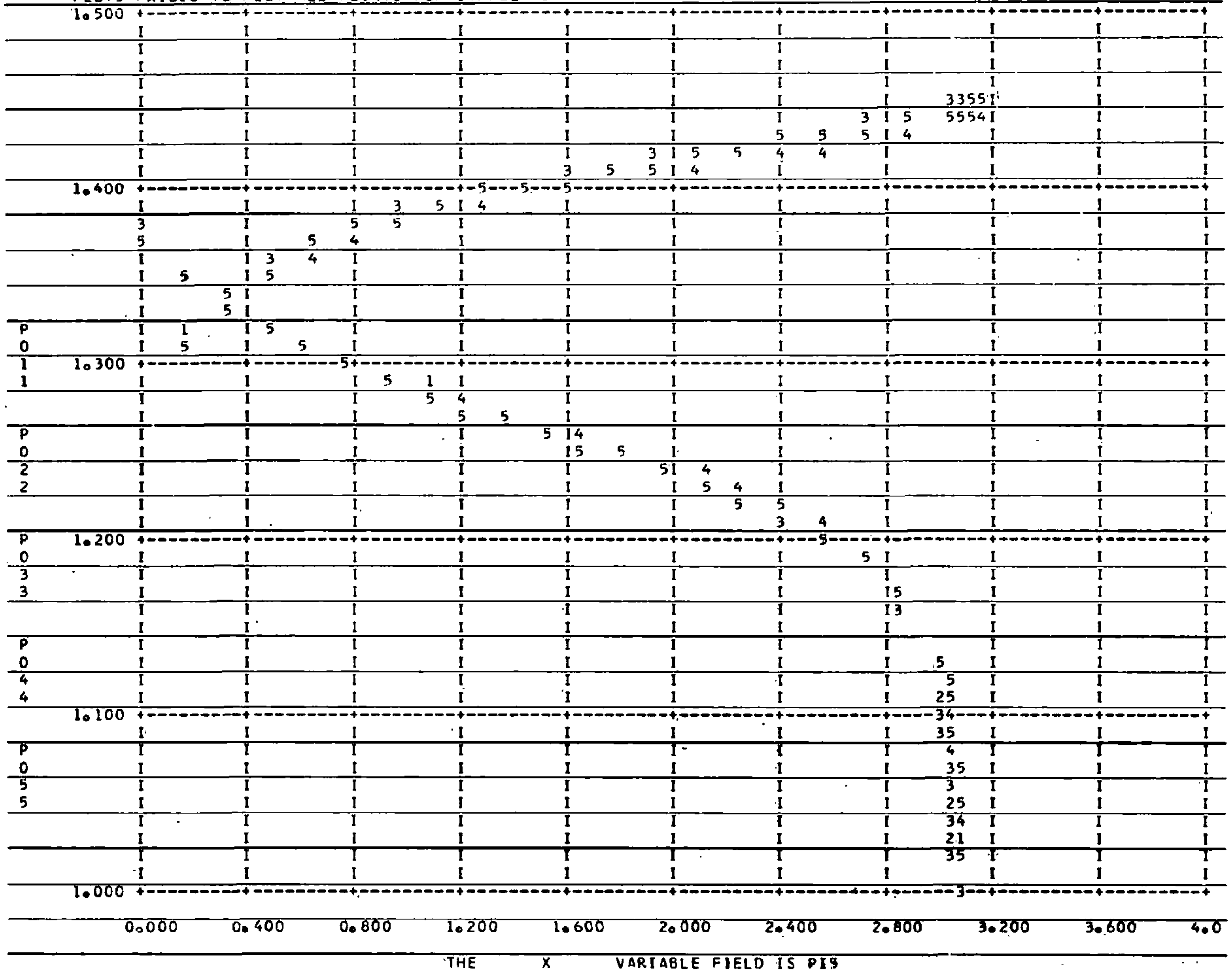


Figure 5ℓa

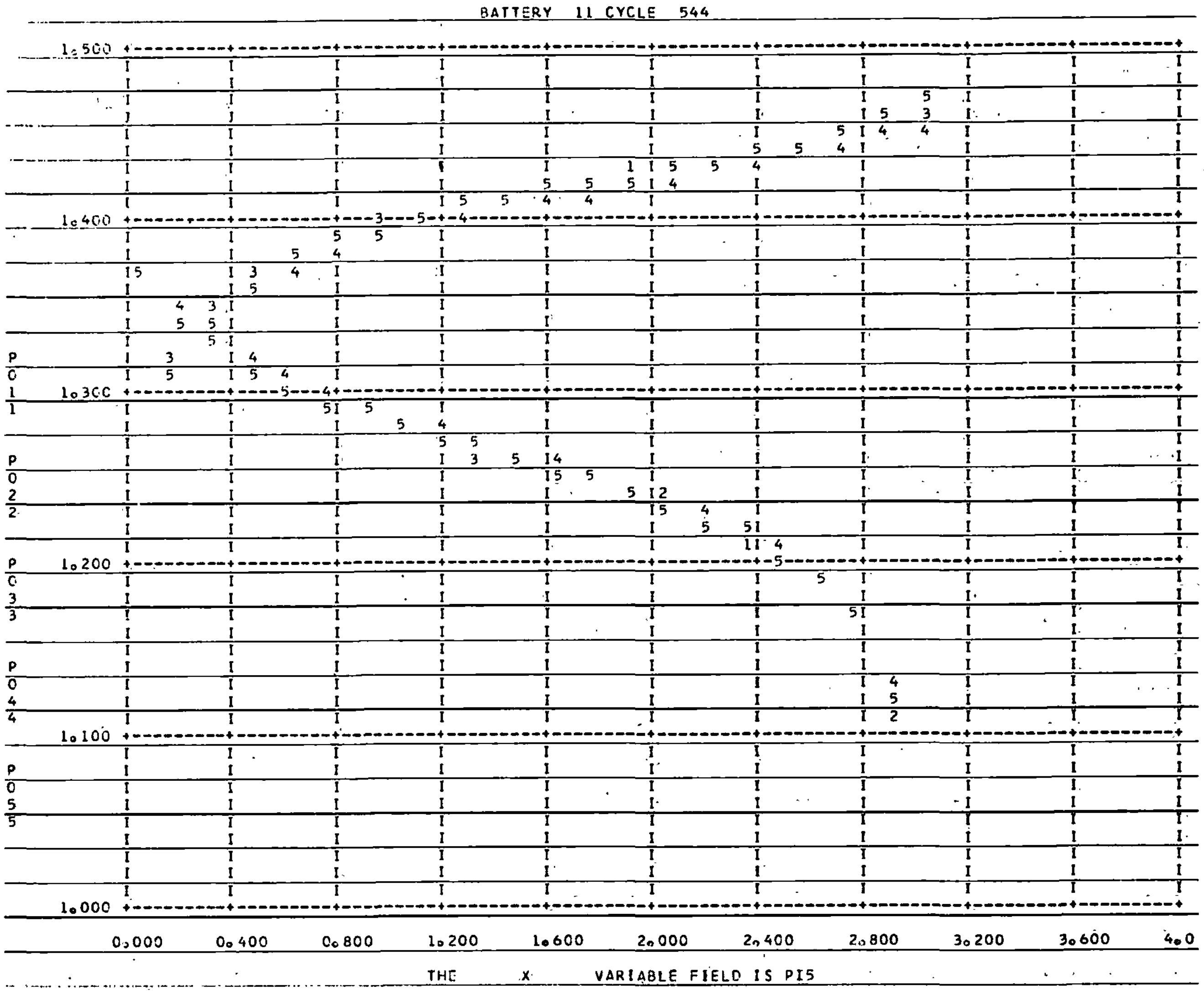
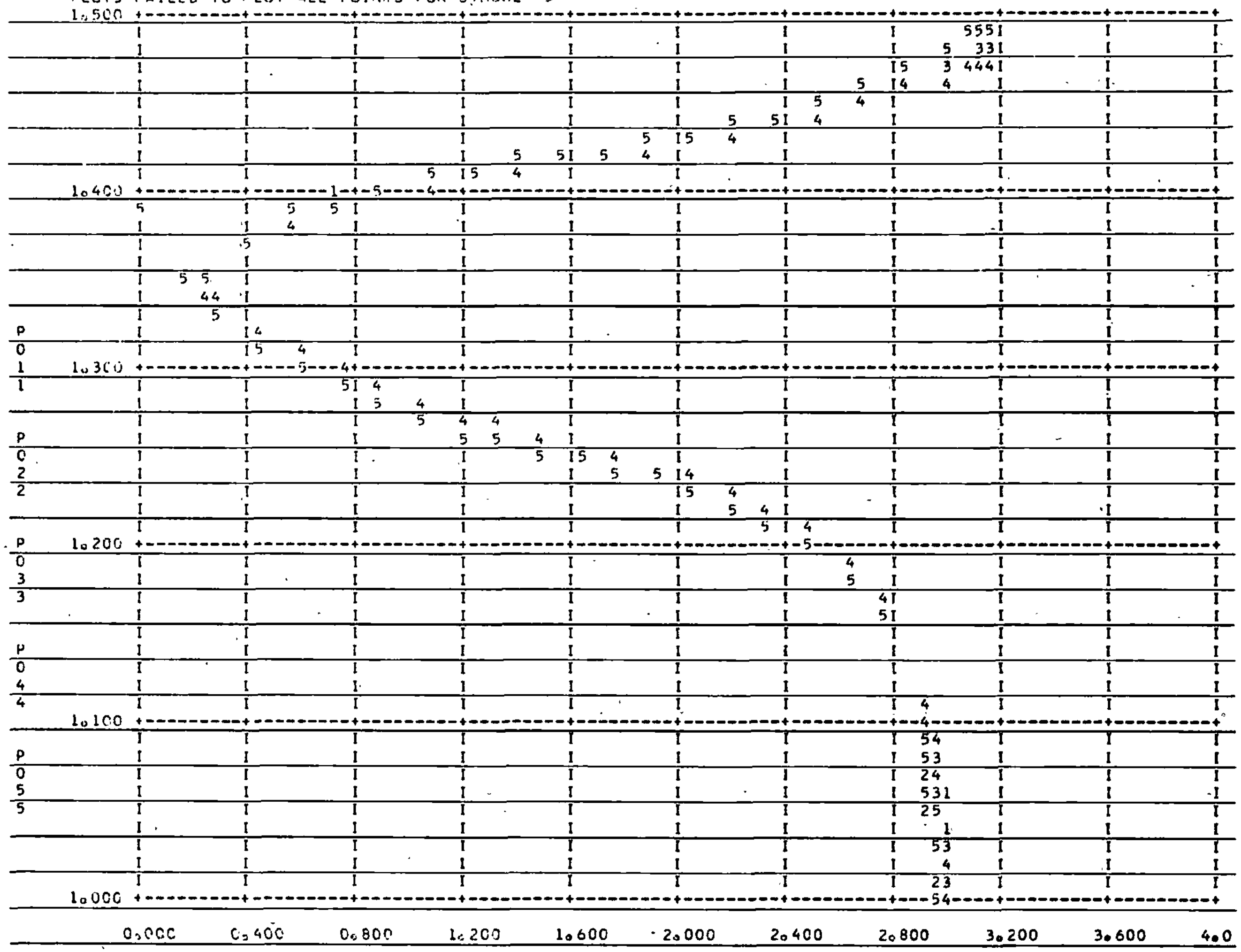

BATTERY 11 CYCLE 544
1.500
1.400
1.300
1.200
1.100
1.000
P011
P022
P033
P044
P055
0.000
0.400
0.800
1.200
1.600
2.000
2.400
2.800
3.200
3.600
4.0
THE X VARIABLE FIELD IS PI5

Figure 5.b

BATTERY 11 CYCLE 1062

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 2
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 3
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 4
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 5

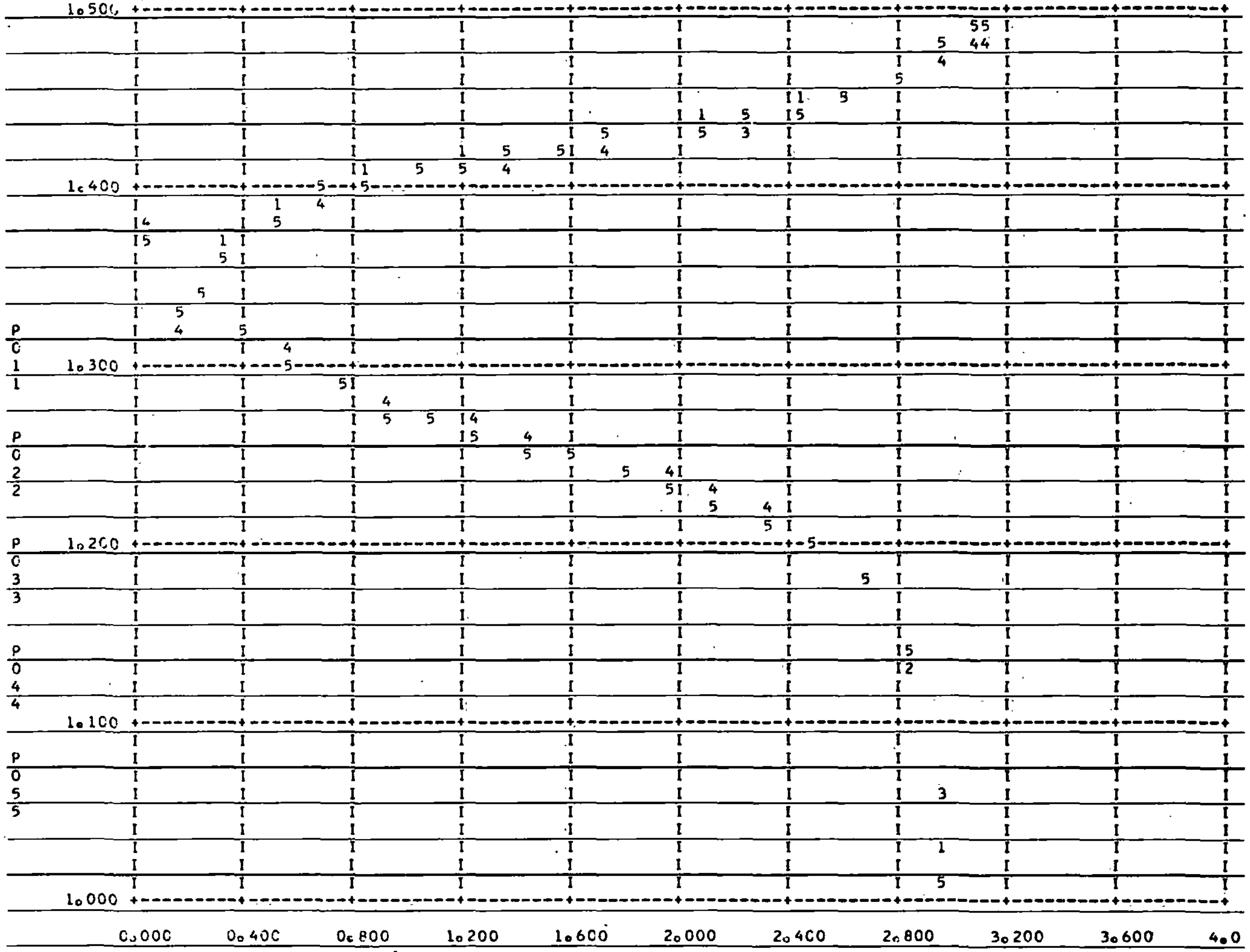


THE X VARIABLE FIELD IS PI5

Figure 5 ℓ c

BATTERY 11 CYCLE 1576

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 2
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 4



THE X VARIABLE FIELD IS P15

Figure 5.2d

BATTERY 11 CYCLE 2025

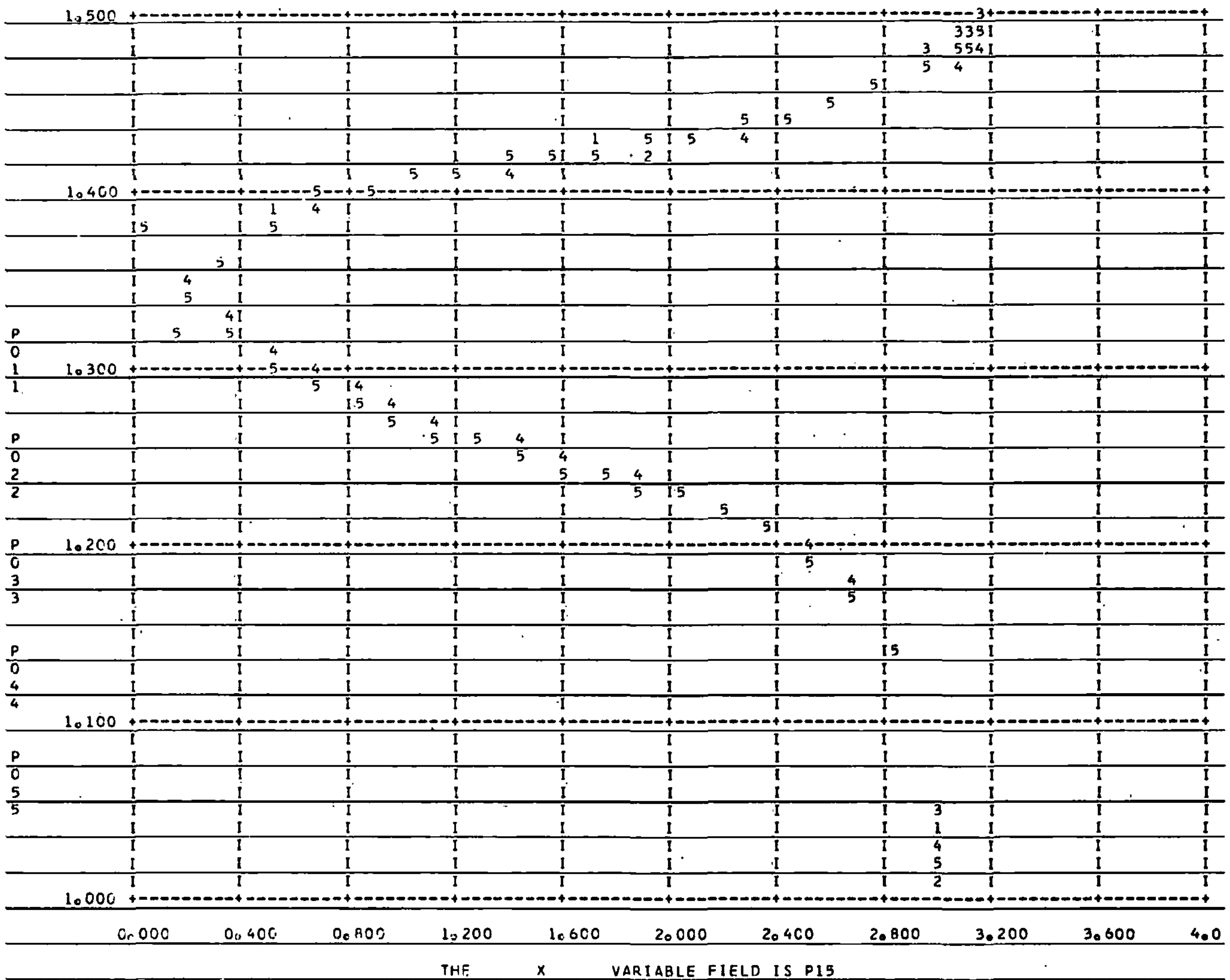


Figure 5.e

BATTERY 11 CYCLE 2626

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 2
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 3
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 4
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 5

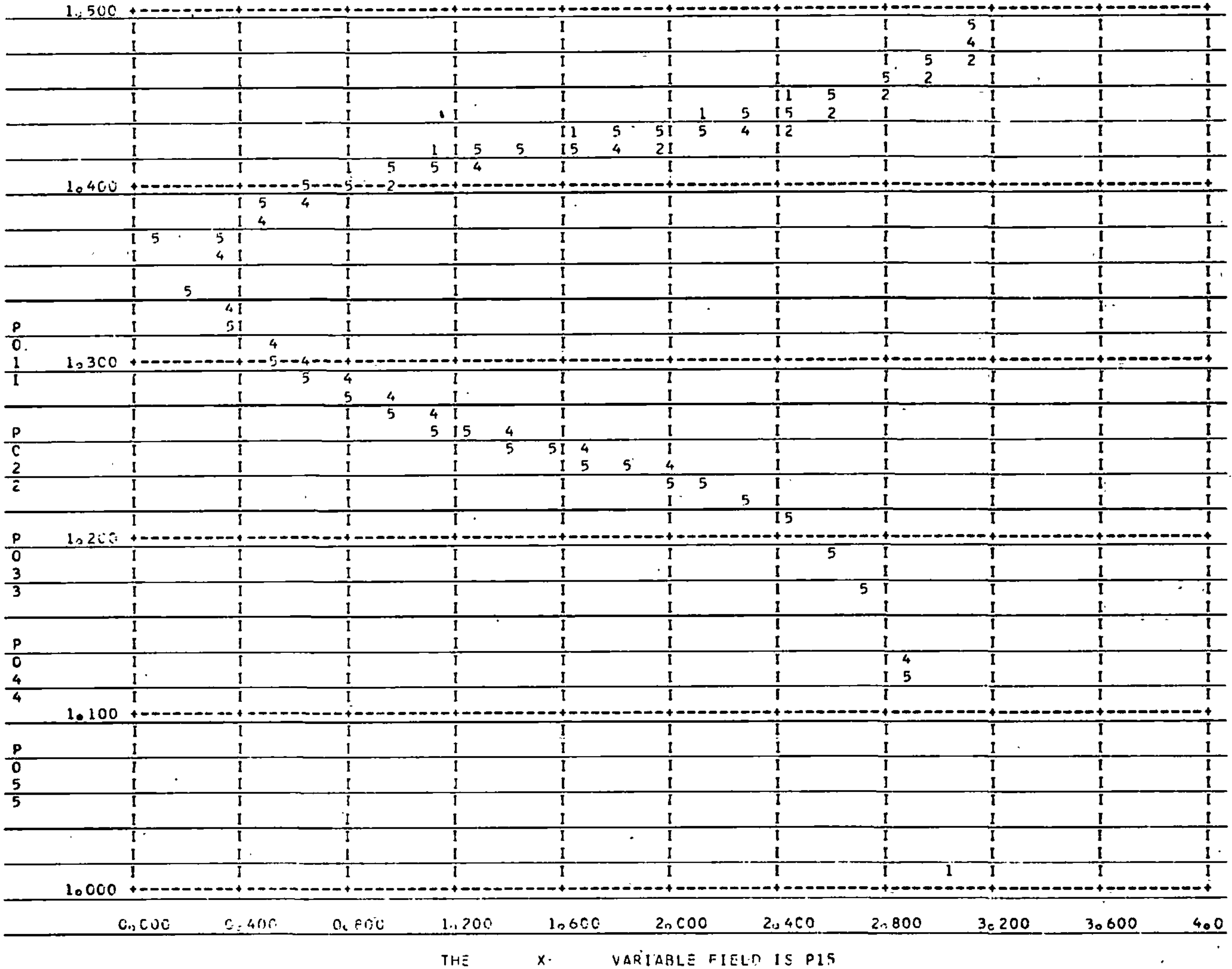


Figure 5 ℓf

BATTERY 11 CYCLE 3041

PLOT2 FAILED TO PLOT ALL POINTS FOR SYMBOL 3

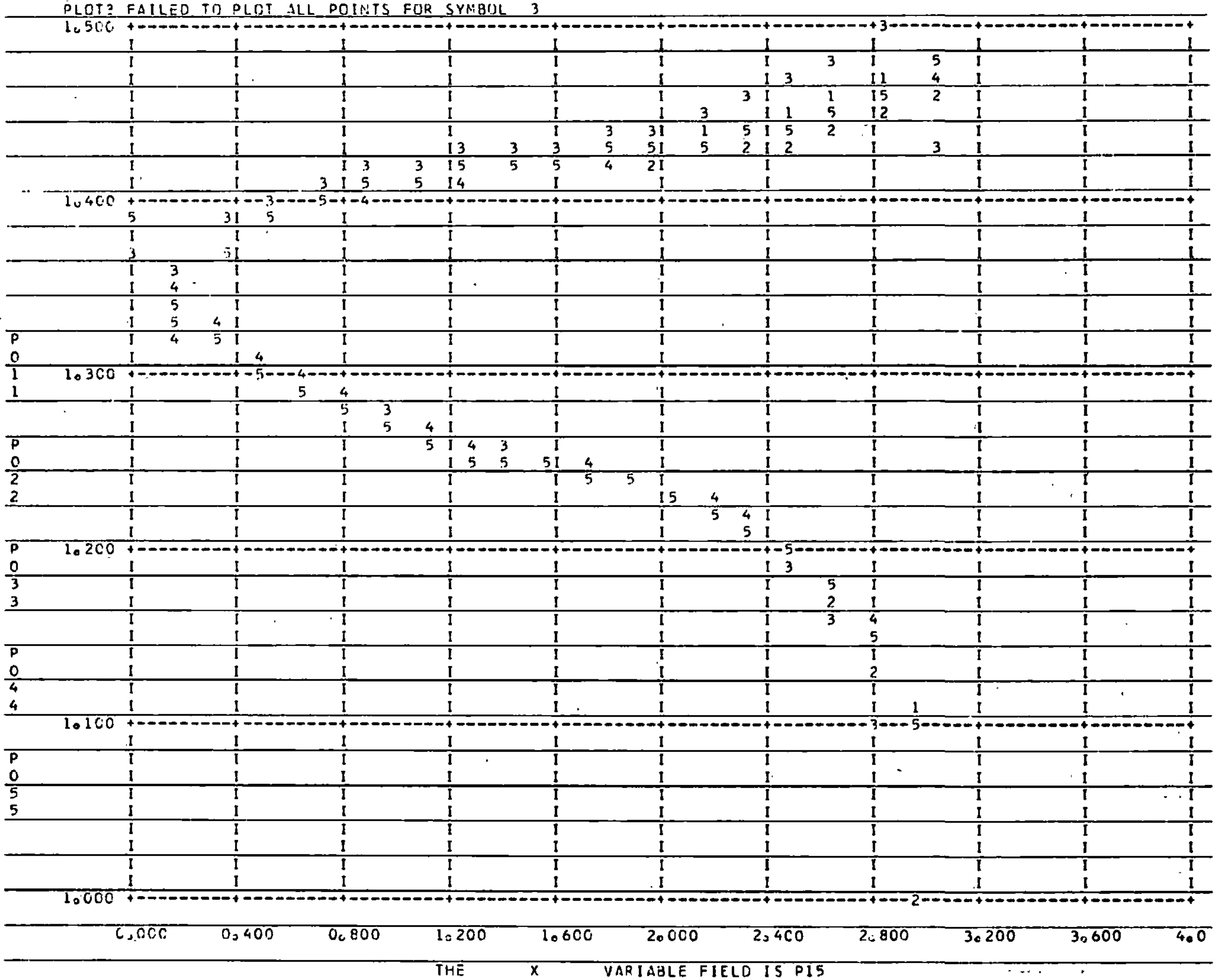


Figure 5 ℓg

BATTERY 11 CYCLE 3512

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 5

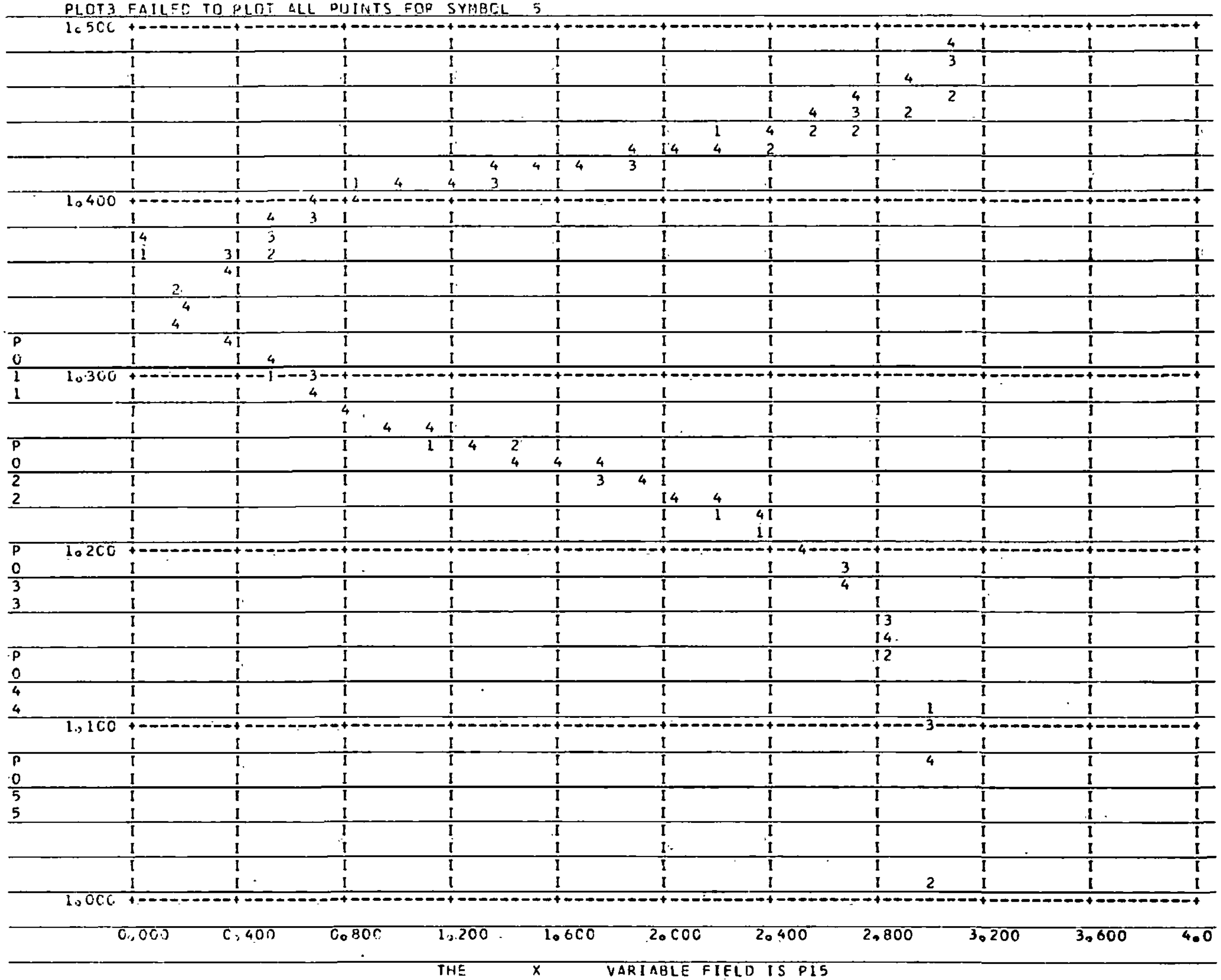
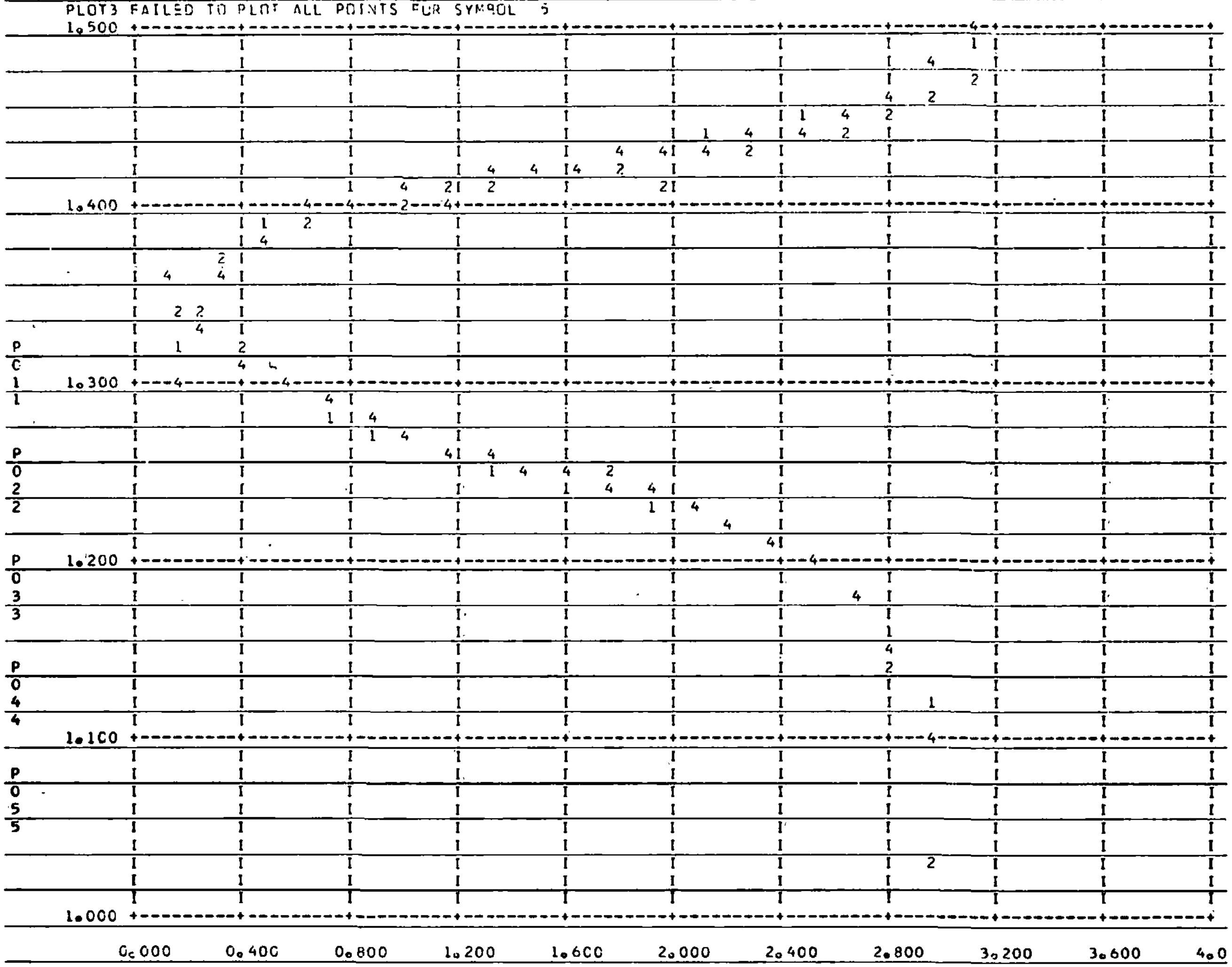


Figure 5 ℓh

BATTERY 11 CYCLE 4037

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 3
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 5



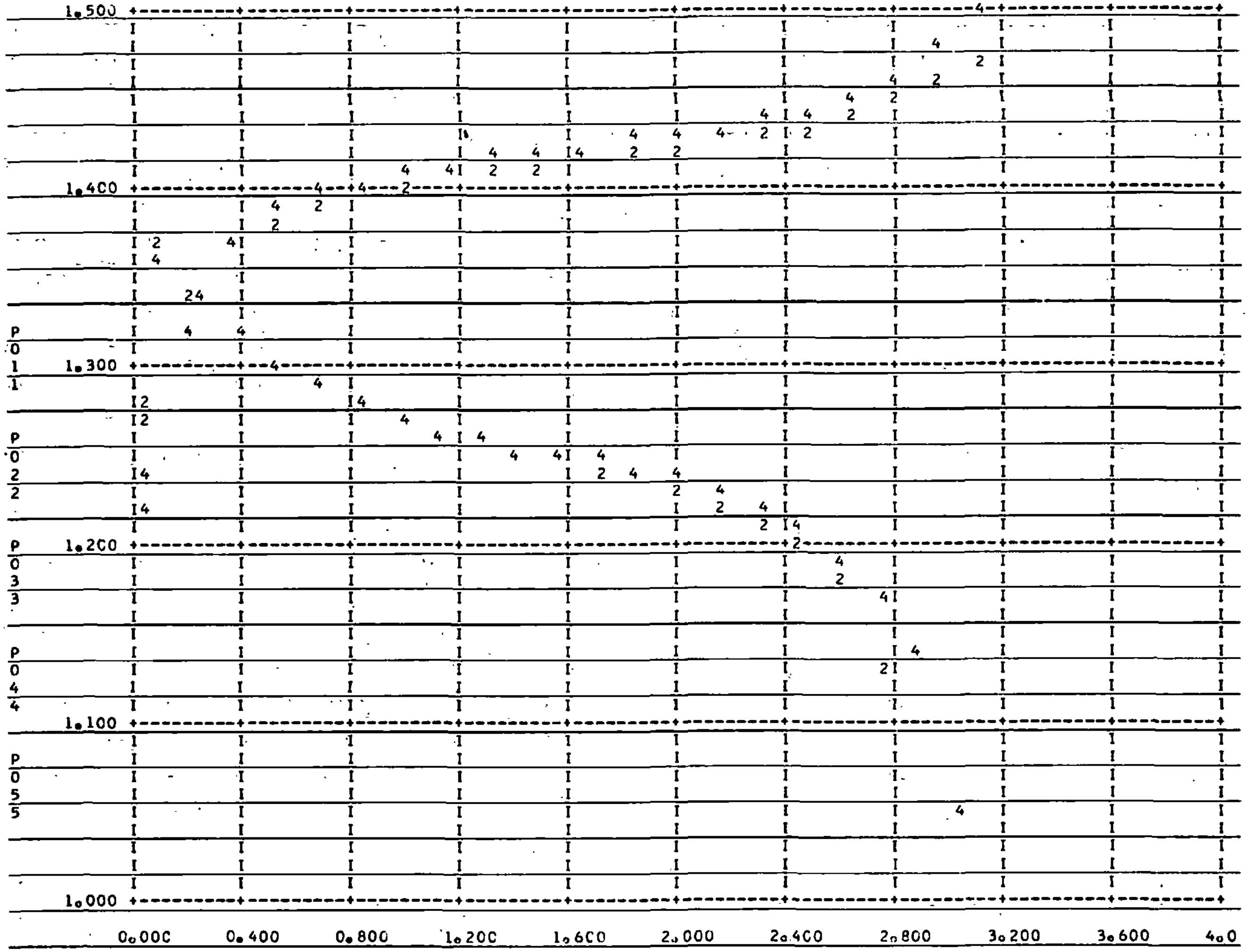
THE X VARIABLE FIELD IS PI5

Figure 5 ℓi

E-101

BATTERY 11 CYCLE 4514

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 1
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 2
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 3
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 5



THE X VARIABLE FIELD IS PI5

Figure 5.1j

BATTERY 11 CYCLE 5001

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 1
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 2
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 3

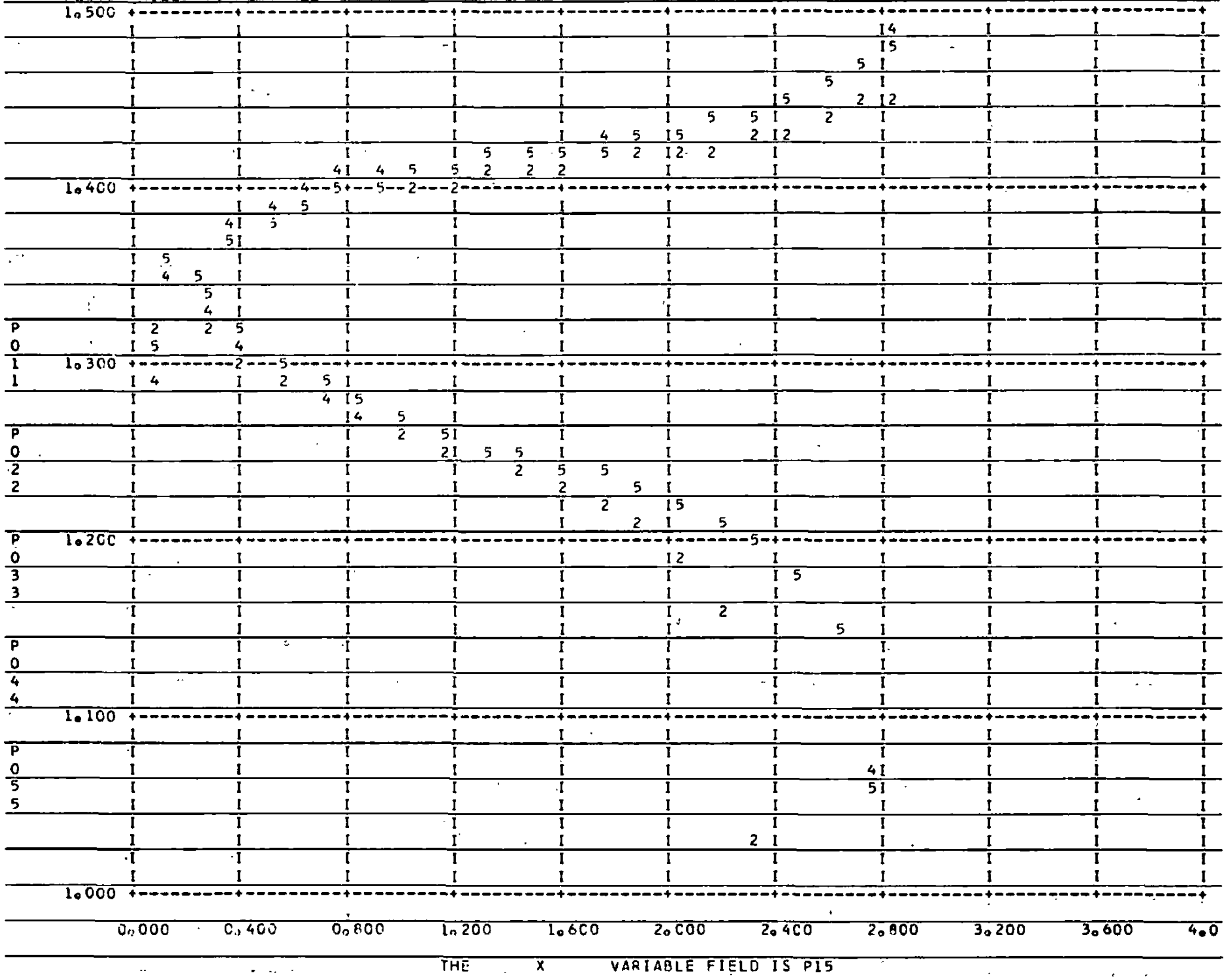
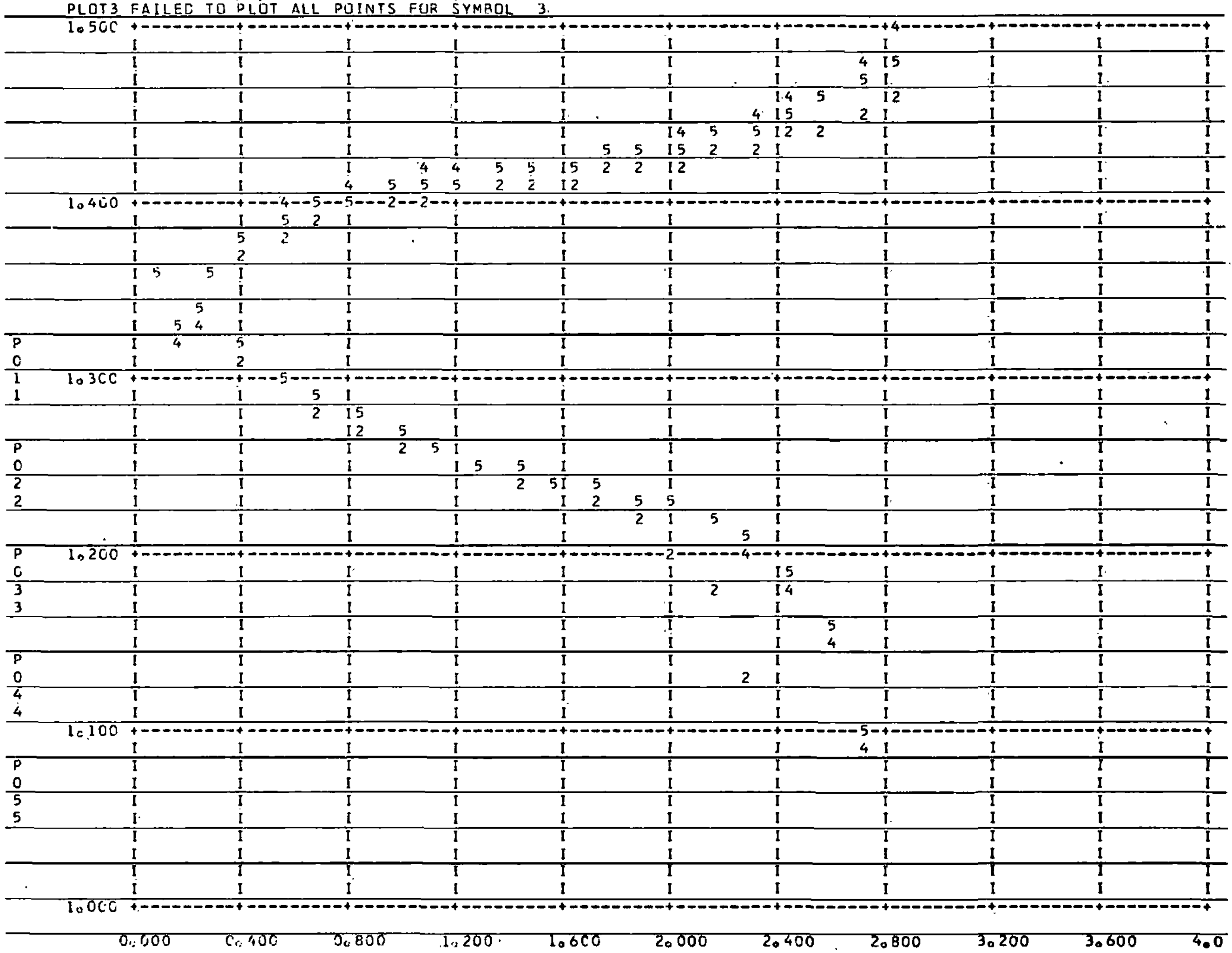


Figure 5 &k

BATTERY 11 CYCLE 5519

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 1
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 2
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 3



THE X VARIABLE FIELD IS P15

Figure 5ℓℓ

BATTERY 11 CYCLE 6038

PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 1
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 2
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 3
PLOT3 FAILED TO PLOT ALL POINTS FOR SYMBOL 4

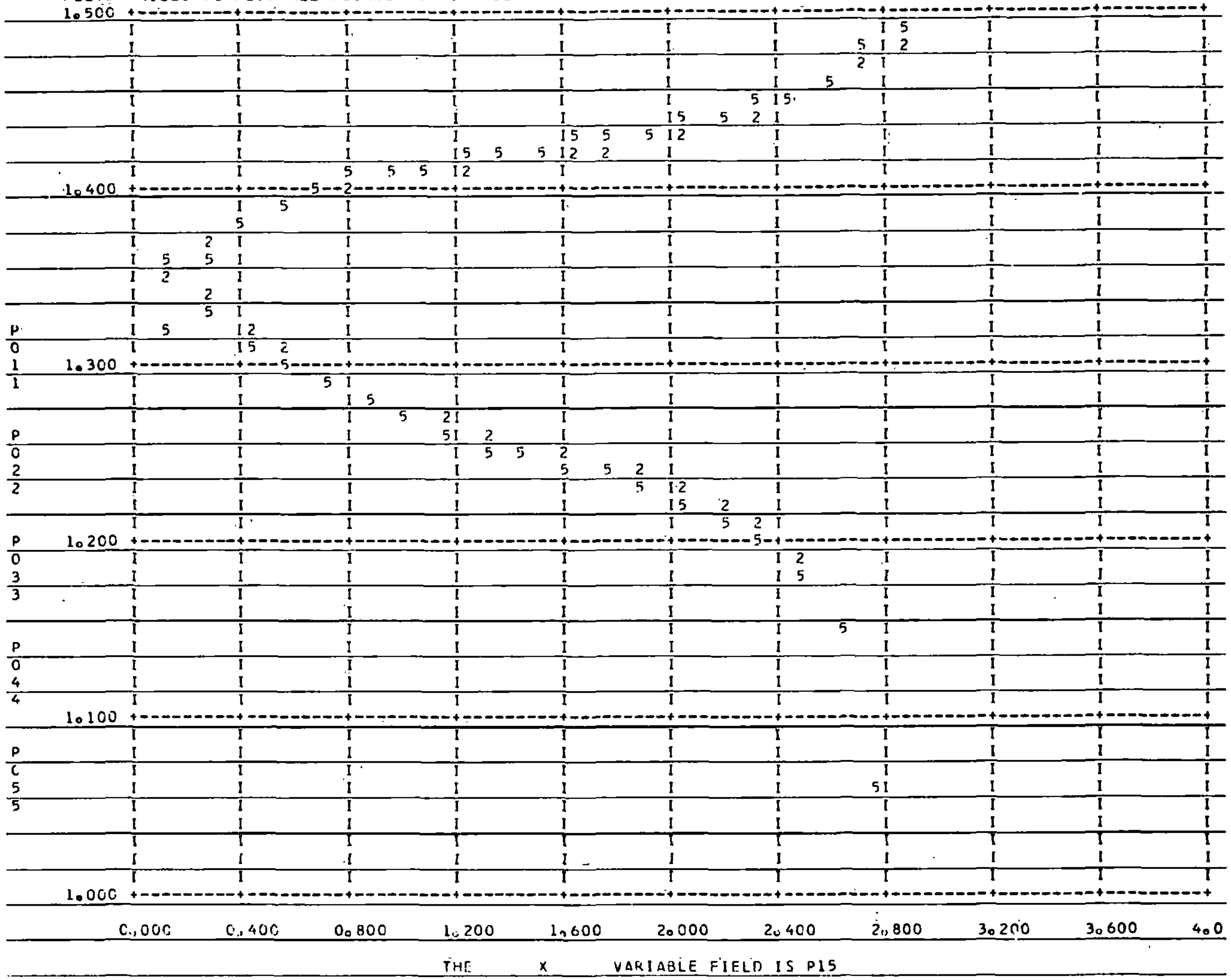


Figure 5 ℓm

APPENDIX F

MINIMUM AND MAXIMUM PRESSURE GAUGE READINGS FOR 250-CYCLE INCREMENTS

Tables F-1 through F-12 list battery pressure ranges in psi for batteries 0, 1, 2, 4, and 7 through 14. The tables give minimum, maximum, and average values by cell.

Table F-1
Battery 0, Pressure Ranges (psi)

Cycle	Cell 0			Cell 1			Cell 2			Cell 3			Cell 4			Cell 5			No. of Cells	Avg ΔP	
	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP			
9	-5	3	8	-8	-2	6	-6 1/2	4	10 1/2	-8	-1 1/2	6 1/2	-8	2	10	-7	1	8	6	8.2	
91	-3 1/2	5	8 1/2	-6 1/2	0	6 1/2	-7	5	12	-7 1/2	0	7 1/2	-7 1/2	3	10 1/2	-6	3	9	6	9.0	
262	-5	3	8	-6	0	6	-7 1/2	5	12 1/2	-7 1/2	0	7 1/2	-7 1/2	3	10 1/2	-7 1/2	1	8 1/2	6	8.8	
495	-5	2	7	-6 1/2	0	6 1/2	-7 1/2	5	12 1/2	-7 1/2	0	7 1/2	-7 1/2	2	9 1/2	-7 1/2	2 1/2	10	6	8.8	
824	-4	3	7	-5 1/2	2	7 1/2	-7 1/2	0	7 1/2	-6	4	10	-8	1	9	2	10	8	6	8.2	
1060	-5	-1 1/2	3 1/2	-7 1/2	-4 1/2	3	-8	0	8	-9	3	12	-10	0	10				5	7.9	
1216	-4	3	7	-7	-3 1/2	3 1/2	-7 1/2	0	7 1/2	-5	5	10	-8 1/2	-1/2	8	3	10	7	6	7.2	
1515	-4	2	6	-7	-3	4	-8 1/2	-2	6 1/2	-5	4	9	-8	0	8				5	6.7	
1769	0	7	7	-6	-3 1/2	2 1/2	-7 1/2	-1	6 1/2	-2 1/2	7	9 1/2	-5	2	7				5	6.5	
1974	-1 1/2	6	7 1/2	-6	-2 1/2	3 1/2	-7 1/2	-1 1/2	6	-2	12	14	-7 1/2	3	10 1/2				5	8.3	
2278				-4 1/2	1	5 1/2	-7 1/2	0	7 1/2	0	12	12	-7	6	13				4	9.5	
2540							-7 1/2	0	7 1/2	1	13	12	-7	6	13				3	10.8	
2749							-6	0	6	-2	7	9	-6	5	11				3	8.7	
3036							-5	2	7	0	10	10	-6	6	12				3	9.7	
Avg ΔP			7.3			5.0			8.4			9.8			10.1			8.3			8.2
																				8.4	

Table F-2
Battery 1, Pressure Ranges (psi)

Cycle	Cell 0			Cell 1			Cell 2			Cell 3			Cell 4			Cell 5			Cell 6			No. of cells	Avg ΔP
	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP		
24	-9	-1/2	8 1/2	-8 1/2	5	13 1/2	-9	1	10	-10	-2	8	-5	4	9	-11 1/2	-2 1/2	9	-9	-1 1/2	7 1/2	7	9.4
117	-8	-1/2	7 1/2	-7	4	11	-9	0	9	-10	-1 1/2	8 1/2	-4 1/2	5	9 1/2	-10	-1	9	-6	0	6	7	8.6
222	-9	0	9	-8 1/2	5	13 1/2	-10	0	10	-10	0	10	-5	5	10	-10	0	10	-7	-1/2	6 1/2	7	9.9
528	-8 1/2	2	10 1/2	-9 1/2	6	15 1/2	-11 1/2	0	11 1/2	-10	2	12	-6	4	10	-11	-1	10	-9	-1 1/2	7 1/2	7	11.0
741	-7 1/2	4	11 1/2	-9	4	13	-10	3	13	-9	2	11	-6	6	12	-10	0	10	-9	0	9	7	11.4
1027	-8	3	11	-1/2	6	6 1/2	-10 1/2	2	12 1/2	-10	0	10	-7	2	9	-11 1/2	-2	9 1/2	-11	-4	7	7	9.4
1237	-7 1/2	6	13 1/2	0	12	12	-9 1/2	4	13 1/2	-7 1/2	2	9 1/2	-5	4	9	-9 1/2	0	9 1/2	-9	-1	8	7	10.7
1522	-7 1/2	7	14 1/2	0	14	14	-9	6	15	-8	3	11	-5	6	11				-9 1/2	-2 1/2	7	6	12.1
1756	-7 1/2	5	12 1/2	0	10	10	-8	6	14	-7 1/2	3	10 1/2	-5	6	11				-10	-3 1/2	6 1/2	6	10.8
2075	-7 1/2	6	13 1/2	-2 1/2	10	12 1/2	-8 1/2	6	14 1/2	-7 1/2	3	10 1/2	-2 1/2	6	8 1/2				-10	-2 1/2	7 1/2	6	11.2
2277	-7	6	13	-5	2	7	-8 1/2	5	13 1/2	-7 1/2	2	9 1/2	-4	6	10				-8 1/2	-1 1/2	7	6	10.0
Avg ΔP			11.4			11.7			12.4			10.0			9.9			9.6			8.0		10.4

Table F-3
Battery 2, Pressure Ranges (psi)

Cycle	Cell 0			Cell 1			Cell 2			Cell 3			Cell 4			Cell 5			No. of Cells	Avg ΔP
	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP		
48	-3	8	11	-1	10	11	-1 1/2	9	10 1/2	-5 1/2	2	7 1/2	-4	4	8	-5	5	10	6	9.7
197	-8	4	12	-5	7	12	-5	5	10	-9	-2	7	-6 1/2	1	7 1/2	-8 1/2	1	9 1/2	6	9.7
331	-8	1	9	-6 1/2	2	8 1/2	-6 1/2	1	7 1/2	-10	-5	5	-7 1/2	-2 1/2	5	-9	-3 1/2	5 1/2	6	6.8
519	-8 1/2	2	10 1/2	-7 1/2	4	11 1/2	-7	3	10	-10	-1 1/2	8 1/2	-7 1/2	2	9 1/2	-10	0	10	6	10.0
738	-6 1/2	1	7 1/2	-3 1/2	7	10 1/2	0	8	8	-8	-1	7	-6	3	9	-7	0	7	6	8.2
1009	-5 1/2	-1/2	5	-2	2	4				-4 1/2	2	6 1/2	-1 1/2	1	2 1/2	-3	1	4	5	4.4
1261	-7 1/2	1	8 1/2	-5	4	9	15	22	7	-8 1/2	-1	7 1/2	-7 1/2	3	10 1/2	-6 1/2	2	8 1/2	6	8.5
1469	-7	-1	6	-4 1/2	2	6 1/2	9	15	6				-7	0	7	-6 1/2	0	6 1/2	5	6.4
1760				-4	8	12	8	18	10	-7 1/2	0	7 1/2	-7 1/2	3	10 1/2	-5	5	10	5	10.0
2016				-2 1/2	9	11 1/2	8	18	10	-7 1/2	0	7 1/2	-7	4	11	-3 1/2	6	9 1/2	5	9.9
2358										-7 1/2	2	9 1/2	-5 1/2	4	9 1/2	-4 1/2	7	11 1/2	3	10.2
Avg ΔP			8.7			9.7			8.8			7.3			8.2			8.4		8.5

Table F-4
Battery 4, Pressure Ranges (psi)

Cycle	Cell 0			Cell 1			Cell 2			Cell 3			Cell 4			Cell 5			Cell 6			Cell 7			No. of Cells	Avg ΔP	
	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP			
260	-7 1/2	-4 1/2	3	-9	-7 1/2	1 1/2	-10	-8	2	-5	-2 1/2	2 1/2	-7 1/2	-5 1/2	2	-7 1/2	-4	3 1/2	0	3	3	-9	-6	3	8	2.6	
582	-9	-5	4	-10	-7 1/2	2 1/2	-11	-8 1/2	2 1/2	-6 1/2	-3 1/2	3	-9	-6	3	-9	-5	4	-1 1/2	2	3 1/2	-10 1/2	-7 1/2	3	8	3.2	
779	-10	-5	5	-10	-7 1/2	2 1/2	-11 1/2	-8	3 1/2	-7	-4	3	-9	-6 1/2	2 1/2	-10	-6	4	-2 1/2	2	4 1/2	-11 1/2	-7 1/2	4	8	3.6	
1049	-7 1/2	-2 1/2	5	-8 1/2	-4	4 1/2	-9 1/2	-5	4 1/2	-5	-2 1/2	2 1/2	-8	-4 1/2	3 1/2	-8	-4	4	2	6	4	-10	-6 1/2	3 1/2	8	3.9	
1237	-7	-3	4	-7 1/2	-4 1/2	3	-9	-6	3	-7 1/2	-3 1/2	4	-7 1/2	-5	2 1/2	-8	-4	4	3	5	2	-10	-7	3	8	3.2	
1493	-7 1/2	-1	6 1/2	-8	-3 1/2	4 1/2	-9 1/2	-4	5 1/2	-6	-2 1/2	3 1/2	-8	-3	5	-8 1/2	-2 1/2	6	3	7	4	-10	-6	4	8	4.9	
1773	-9	-5 1/2	3 1/2	-8	-3	5	-8	-5	3	-5 1/2	-2 1/2	3	-8	-4	4	-8	-4	4	2	5	3	-9 1/2	-7	2 1/2	8	3.5	
2029	-9	-7 1/2	1 1/2	-7	-2 1/2	5	-7 1/2	-2 1/2	5	-5	0	5	-7 1/2	-2 1/2	5	-6	-1 1/2	4 1/2	4	5	1	-8 1/2	-5	3 1/2	8	3.8	
2251				-7 1/2	-2	5 1/2	-7 1/2	-2 1/2	5	-5	0	5	-7 1/2	-2	5 1/2	-5	0	5	3	5	2	-7 1/2	-4	3 1/2	7	4.5	
2599				-8 1/2	-6 1/2	2	-9	-7 1/2	1 1/2	-6	-4 1/2	1 1/2	-8 1/2	-6 1/2	2	-7 1/2	-5	2 1/2				-10	-8 1/2	1 1/2	6	1.8	
2733				-7 1/2	-6 1/2	1	-7 1/2	-5 1/2	2	-5 1/2	-4 1/2	1	-7 1/2	-5	2 1/2	-7	-3 1/2	3 1/2				-10	-7 1/2	2 1/2	6	2.1	
3023				-7 1/2	-5	2 1/2	-7 1/2	-5	2 1/2	-5	-3 1/2	1 1/2	-7 1/2	-5	2 1/2	-7 1/2	-3	4 1/2				-10	-7 1/2	2 1/2	6	2.7	
3288				-6 1/2	-4	2 1/2	-6	-2 1/2	3 1/2	-4	-2	2	-7	-4	3							-9	-6	3	5	2.8	
3499				-6 1/2	-4	2 1/2	-7	-4	3	-4 1/2	-2 1/2	2	-7 1/2	-4	3 1/2							-9	-7	2	5	2.6	
3711				-7 1/2	-4 1/2	3	-7 1/2	-4 1/2	3	-5	-3 1/2	1 1/2	-7	-3 1/2	3 1/2										4	2.8	
3998				-5	1	6	-4	2	6	-1 1/2	2	3 1/2	-5 1/2	1	6 1/2										4	5.5	
4278				-5	-1	4	-4	2	6	-1 1/2	3	4 1/2	-5	1	6										4	5.1	
Avg ΔP			4.1			3.4			3.6			2.9			3.7			4.1			3.0			2.9			3.5
																										3.4	

Table F-5
Battery 7, Pressure Ranges (psi)

Cycle	Cell 0			Cell 1			Cell 2			Cell 3			Cell 4			Cell 5			Cell 6			No. of Cells	Avg ΔP	
	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP			
1	-5 1/2	19	24 1/2	-7 1/2	10	17 1/2	-5 1/2	21	26 1/2	-15	12	27	2	24	22	-11	9	20	-8	13	21	7	22.6	
94	-5	16	21	-5 1/2	7	12 1/2	-7	13	20	-4	9	13	4	16	12	-10	6	16	-7 1/2	9	16 1/2	7	15.9	
401	-8	9	17	-6 1/2	5	11 1/2	-10	6	16	-5	3	8	2	9	7	-13	-1 1/2	11 1/2	-10	4	14	7	12.1	
755	-9	-5	4	-1 1/2	22	23 1/2	-6	18	24	-5	12	17	5	20	15	-10	15	25	-8 1/2	15	23 1/2	7	18.9	
1020	-10	-3 1/2	6 1/2	5	24	19	-5	16	21	-1 1/2	7	8 1/2	7	22	15	-7	11	18	-4	16	20	7	15.4	
1253				0	21	21	-7 1/2	15	22 1/2	-2 1/2	8	10 1/2	6	21	15	-10	8	18	-7 1/2	16	23 1/2	6	18.4	
1465				-2	19	21	-7 1/2	18	25 1/2	-8	6	14	8	31	23	-11	10	21	-8	17	25	6	21.6	
1671				-3 1/2	16	19 1/2	-7 1/2	15	22 1/2	-4	5	9	5	22	17	-9 1/2	9	18 1/2	-7 1/2	17	24 1/2	6	18.5	
Avg ΔP			14.6			18.2			22.3			13.4			15.8			18.5			21.0			17.7
																							17.9	

Table F-6
Battery 8, Pressure Ranges (psi)

Cycle	Cell 0			Cell 1			Cell 2			Cell 3			Cell 4			Cell 5			Cell 9			No. of Cells	Avg ΔP	
	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP			
342	0	4	4	-1	3	4	-5 1/2	-1 1/2	4	-2 1/2	3	5 1/2	-5	1	6	-5 1/2	0	5 1/2	-5 1/2	-1 1/2	4	7	4.7	
1021	0	1	1	1	3	2	0	1	1	0	1	1	-3 1/2	0	3 1/2	-3 1/2	1	4 1/2	-5	-4	1	7	2.0	
1540	-2	1	3	1	4	3	0	2	2	-1/2	2	2 1/2	-2 1/2	0	2 1/2	-2 1/2	1	3 1/2	1	1	0	7	2.4	
2075	-3	-1	2	-1 1/2	0	1 1/2	-7 1/2	-5 1/2	2	-2	0	2	-3 1/2	-1	2 1/2	-5	-2 1/2	2 1/2	-5 1/2	-4	1 1/2	7	2.0	
2509	-2 1/2	-1	1 1/2	-1	0	1	-6 1/2	-5	1 1/2	0	1	1	-2 1/2	0	2 1/2	-6	-4	2	-4	-2 1/2	1 1/2	7	1.6	
3084	0	1	1	-1	-1	0	-6 1/2	-5	1 1/2	1	2	1	1	3	2	-5	-2 1/2	2 1/2	-4	-2 1/2	1 1/2	7	1.4	
3625	2	2	0				-5	-5	0	2	2	0	2	2	0	-3 1/2	-2 1/2	1	-4	-2 1/2	1 1/2	6	0.4	
4097	-1/2	3	3 1/2				-5	-4	1	1	3	2	2	6	4	-3	0	3	-1 1/2	3	4 1/2	6	3.0	
4512	4	6	2				-4 1/2	-2 1/2	2	3	6	3	6	9	3	0	3	3	2	5	3	6	2.7	
5080	4	8	4				-1/2	2	2 1/2	4	8	4	7	10	3	3	9	6	6	10	4	6	3.9	
5562	3	7	4				-2	1	3	5	8	3	7	12	5	4	10	6	7	11	4	6	4.2	
5918	-1/2	1	1 1/2				-5	-2 1/2	2 1/2	1	3	2	1	5	4	-5	-1 1/2	3 1/2	2	5	3	6	2.8	
Avg ΔP			2.3			1.9			1.9			2.3			3.2			3.6			2.1			2.5
																							2.6	

Table F-7
Battery 9, Pressure Ranges (psi)

Cycle	Cell 0			Cell 1			Cell 2			Cell 3			Cell 4			Cell 5			Cell 6			Cell 7			Cell 9			No. of cells	Avg ΔP
	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP		
7	-4	-2 1/2	1 1/2	-9	-7 1/2	1 1/2	-7 1/2	-2 1/2	5	-7 1/2	-5	2 1/2	-7 1/2	-5	2 1/2	-10	-6	4	0	4	4	-10	-7 1/2	2 1/2	-1	1	2	9	2.6
101	-2 1/2	-2	1/2	-7 1/2	-7 1/2	0	-5	-5	0	-5	-5	0	-6 1/2	-6 1/2	0	-7 1/2	-7 1/2	0	-5	-5	0	-10	-8 1/2	1 1/2	3	3	0	9	3.2
262	-2 1/2	0	2 1/2	-8 1/2	-6 1/2	2	-4 1/2	-2 1/2	2	-5	-4	1	-5	-4	1	-8 1/2	-6	2 1/2	-3	0	3	-10	-7 1/2	2 1/2	2	3	1	9	1.9
538	-5	-1 1/2	3 1/2	-9 1/2	-7	2 1/2	-7	-2 1/2	4 1/2	-7	-4 1/2	2 1/2	-5 1/2	-4	1 1/2	-10	-5	5	-3 1/2	0	3 1/2	-11	-7	4	4	4	0	9	3.0
755	-3 1/2	0	3 1/2	-8	-6	2	-5	-2 1/2	2 1/2	-5 1/2	-4 1/2	1	-5 1/2	-4 1/2	1	-9	-5 1/2	3 1/2	-3	-1	2	-10	-6	4	3	4	1	9	2.3
1024	-5	-2 1/2	2 1/2	-8 1/2	-7	1 1/2	-7 1/2	-5	2 1/2	-6	-5 1/2	1/2	-6	-5 1/2	1/2	-10	-8 1/2	1 1/2	-5	-4	1	-10	-8 1/2	1 1/2	2	3	1	9	1.4
1232	-5	-3 1/2	1 1/2	-9 1/2	-8	1 1/2	-8	-7 1/2	1/2	-7 1/2	-6 1/2	1	-7 1/2	-7 1/2	0	-10	-9	1	-7	-5 1/2	1 1/2	-12	-10	2	4	4	0	9	1.0
1563	-5	-2 1/2	2 1/2	-9 1/2	-7 1/2	2	-7 1/2	-6	1 1/2	-5	-5	0	-7 1/2	-7 1/2	0	-10	-7 1/2	2 1/2	-5	-3	2	-10	-7 1/2	2 1/2	5	6	1	9	1.6
1777	-3 1/2	4	7 1/2	-8	-1 1/2	6 1/2	-5	-2	3	-4 1/2	0	4 1/2	-6 1/2	-2 1/2	4	-6 1/2	1	7 1/2	-1/2	7	7 1/2	-8	0	8	8	15	7	9	6.2
2000	-3	3	6	-8 1/2	-3	5 1/2	-7 1/2	-4 1/2	3	-5	-1	4	-7 1/2	-3	4 1/2	-7 1/2	-1 1/2	6	-1 1/2	5	6 1/2	-10	-3	7				8	5.3
2259	-2	4	6	-7 1/2	-3	4 1/2	-6	-2	4	-5	-1 1/2	3 1/2	-7 1/2	-2 1/2	5	-7 1/2	-1	6 1/2	-1 1/2	5	6 1/2	-8 1/2	-2	6 1/2				8	5.3
2437	-2	5	7	-7	-2 1/2	4 1/2	-10	-10	0	-4 1/2	-1	3 1/2	-6	-2 1/2	3 1/2	-6 1/2	0	6 1/2	-1 1/2	6	7 1/2	-9 1/2	-1 1/2	8				8	5.0
Avg ΔP			3.7			2.8			2.4			2.0			2.0			3.9			3.8			4.2			1.4		

3.9

3.0

Table F-8
Battery 10, Pressure Ranges (psi)

Cycles	Cell 0			Cell 1			Cell 2			Cell 3			Cell 4			No. of Cells	Avg ΔP	
	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP			
10	-11	-11	0	-10 1/2	-10 1/2	0	-11 1/2	-11 1/2	0	-10 1/2	-10 1/2	0	-1	-1	0	5	0	
101	-12	-9 1/2	2 1/2	-10	-7 1/2	2 1/2	-11 1/2	-8 1/2	3	-10	-8 1/2	1 1/2	-1	0	1	5	2.1	
215	-11 1/2	-9	2 1/2	-9	-6 1/2	2 1/2	-11 1/2	-9	2 1/2	-9 1/2	-6 1/2	3	-1	0	1	5	2.3	
569	-10	-5	5	-5	7	12	-7 1/2	6	13 1/2	-7	7	14	0	5	5	5	9.9	
752	-5	4	9	1	10	9	4	14	10	10	22	12	3	10	7	5	9.4	
1001	-2 1/2	3	5 1/2	5	10	5	7	15	8	4	9	5	4	9	5	5	5.7	
1223	-1	10	11	6	20	14	1	17	16	25	38	13	5	16	11	5	13.0	
1514	-2	10	12	6	16	10							6	13	7	3	9.7	
1728	0	8	8	6	12	6							7	12	5	3	6.3	
2069	-2 1/2	6	8 1/2	-2	13	15							8	16	8	3	10.5	
2256	1	12	11	5	18	13							8	18	10	3	11.3	
2520	1	9	8	3	12	9							7	15	8	3	8.3	
3019	-2 1/2	4	6 1/2	2	12	10							7	17	10	3	8.8	
Avg ΔP			6.9			8.3			7.6			6.9			6.0			7.1
																	7.4	

Table F-9
Battery 11, Pressure Ranges (psi)

Cycle	Cell 0			Cell 1			Cell 2			Cell 3			Cell 4			Cell 5			Cell 6			Cell 7			No. of Cells	Avg ΔP	
	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP			
6	-12 1/2	-12 1/2	0	-10	-10	0	-12 1/2	-12 1/2	0	0	0	0	-6	-6	0.	-12 1/2	-12 1/2	0	-12 1/2	-12 1/2	0	-5	-5	0	8	0	
158	-10	-10	0	-8	-8	0	-9	-9	0	-5 1/2	1	6 1/2	-12 1/2	-12 1/2	0	-9 1/2	-9 1/2	0	-12 1/2	-12 1/2	0	-12 1/2	-12 1/2	0	8	0.8	
358	-10	-10	0	-9	-9	0	-10	-10	0	0	0	0	-11 1/2	-11 1/2	0	-10	-10	0	-10	-10	0	-12 1/2	-12 1/2	0	8	0	
957	-11	-7 1/2	3 1/2	-7 1/2	-5	2 1/2	-7 1/2	-3 1/2	4	0	3	3	-8	-5	3	-8	0	8	-6	-2	4	-8	-3	5	8	4.1	
1270	-11 1/2	-2 1/2	9	-8	0	8	-9	3	12	0	6	6	-7 1/2	1	8 1/2	-9	3	12	-9	6	15	-11 1/2	6	17 1/2	8	11.0	
1533	-8 1/2	-3	5 1/2	-2 1/2	-1/2	2	-1/2	-1/2	0	0	3	3	4	5	1	2	7	5	4	9	5	1	3	2	8	2.9	
1731	-7 1/2	-4	3 1/2	-2 1/2	1	1 1/2	0	6	6	0	3	3	5	10	5	0	6	6	3	7	4	-2 1/2	3	5 1/2	8	4.3	
2032	-12 1/2	-9 1/2	3	-9	-6	3	-10	-4 1/2	5 1/2	-2	0	2	-7 1/2	-3 1/2	4	-7 1/2	-2 1/2	5	-8	-5	3	-11	-6 1/2	4 1/2	8	3.8	
2577	-7 1/2	-5	2 1/2	0	3	3	0	3	3	-	-	-	12	15	3	3	8	5	8	12	4	2	8	6	7	3.8	
3178	-8 1/2	-7 1/2	1	-1	0	1	-1 1/2	0	1 1/2	0	4	4	3	3	0	3	8	5	5	9	4	-1/2	3	3 1/2	8	2.5	
3999	-8 1/2	-5	3 1/2	-3 1/2	0	3 1/2	-6 1/2	-3	3 1/2				4	8	4				2	6	4				5	3.7	
4573	-9	-7	2				-7 1/2	-5	2 1/2				-1/2	2	2 1/2				12	13	1				4	2.0	
5092	-10	-8 1/2	1 1/2				-10	-9 1/2	1/2				-5	-2 1/2	2 1/2				-5	-1 1/2	3 1/2				4	2.0	
Avg ΔP			2.7			2.2			3.0			2.8			2.6			4.6			3.6			4.4			3.2
																										3.1	

Table F-10
Battery 12, Pressure Ranges (psi)

Cycle	Cell 0			Cell 1			Cell 2			Cell 3			Cell 4		
	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP
162	-9 1/2	-8 1/2	1	-5 1/2	-5	1/2	-8 1/2	-7 1/2	1	-5 1/2	-5 1/2	0	-8 1/2	-7	1 1/2
301	-11	-11	0	-8	-7 1/2	1/2	-10	-8	2	-7 1/2	-7	1/2	-9 1/2	-8	1 1/2
611	-11 1/2	-10	1 1/2	-10	-8 1/2	1 1/2	-10	-8	2	-7 1/2	-7	1/2	-10	-9	1
894	-11	-9 1/2	1 1/2	-9 1/2	-8 1/2	1	-8	-7 1/2	1/2	-6 1/2	-6	1/2	-9	-8 1/2	1/2
Avg ΔP			1.0			0.9			1.4			0.4			1.1

Cycle	Cell 5			Cell 6			Cell 7			Cell 9			No. of Cells	Avg ΔP
	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP		
162	-4 1/2	-3 1/2	1	-7 1/2	-7	1/2	-10	-9	1	5	5	0	9	0.7
301	-7 1/2	-7 1/2	0	-7 1/2	-7 1/2	0	-10	-10	0	4	5	1	9	0.6
611	-8 1/2	-7 1/2	1	-7 1/2	-7	1/2	-10	-9 1/2	1/2	4	5	1	9	1.0
894	-8 1/2	-8	1/2	-7 1/2	-6 1/2	1	-10	-9	1	4	4	0	9	0.7
Avg ΔP			0.6			0.5			0.6			0.5		0.8

Table F-11
Battery 13, Pressure Ranges (psi)

Cycle	Cell 0			Cell 1			Cell 2			Cell 3			Cell 4			No. of Cells	Avg ΔP
	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP		
166	-10	-8	2	-5	-4 1/2	1/2	-7 1/2	-7 1/2	0	-7	-7	0	-7 1/2	-7 1/2	0	5	0.5
289	-10	-9 1/2	1/2	-8	-6	2	-9	-8	1	-7 1/2	-7	1/2	-8 1/2	-8 1/2	0	5	0.8
580	-10	-9	1	-7	-6 1/2	1/2	-9	-8 1/2	1/2	-7 1/2	-7	1/2	-9	-9	0	5	0.5
750	-10	-9 1/2	1/2	-7 1/2	-7 1/2	0	-9	-9	0	-7 1/2	-7 1/2	0	-8 1/2	-8 1/2	0	5	0.1
915	-9 1/2	-9	1/2	-7	-6 1/2	1/2	-8 1/2	-8 1/2	0	-7 1/2	-7	1/2	-8 1/2	-8 1/2	0	5	0.3
Avg ΔP			0.9			0.7			0.3			0.3			0.0		0.4

Table F-12
Battery 14, Pressure Ranges (psi)

Cycle	Cell 0			Cell 1			Cell 9			No. of Cells	Avg ΔP
	Min	Max	ΔP	Min	Max	ΔP	Min	Max	ΔP		
66	-11	-10	1	-2	0	2	-10	-8 1/2	1 1/2	3	1.5
140	-10	-9	1	-1 1/2	-1	1/2	-10	-9	1	3	0.8
Avg ΔP			1.0			1.3			1.3		1.2