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**U.S. DEPARTMENT OF ENERGY
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ABSTRACT

A group of 108 state-of-the-art nominally 6 volt lead-acid batteries were tested in a program of one charge/discharge cycle per day for over two years or to ultimate battery failure. The primary objective of this program was to determine battery cycle life as a function of depth-of-discharge (25 to 75 percent), chopper frequency (100 to 1000 Hz), duty cycle (25 to 87.5 percent), and average discharge current (20 to 260 A). The secondary objective of this test program was to determine the types of battery failure modes, if any, were due to the above parameters. The four parameters above were incorporated in a statistically designed test program which is a variation of a central composite factorial design experiment.

INTRODUCTION

One widely used technique for motor speed control in electric vehicles is the chopper (pulsed) control. Electric vehicle designers have comparatively little data available on battery response to chopper controlled discharge. Also, the question arises as to what effects on battery cycle life could be attributed to chopper control. Some preliminary studies were done at NASA Lewis Research Center using a state-of-the-art lead-acid battery (ref. 1) to determine if there were any effects of pulse discharging on battery response. As a result of this study and under the sponsorship of the DOE Electric and Hybrid Vehicle Program a contract was awarded to TRW, Redondo Beach, California to expand and verify the NASA Lewis findings. TRW was to determine the influence of chopped discharging upon the cycle life of a typical lead-acid traction battery. Parameters to be investigated were: depth-of-discharge, chopper frequency, duty cycle (ratio of on-to-off times), and average discharge current. The tests were statistically designed to maximize the information obtained.

The test design used was a variation of a central composite factorial design involving 36 different test conditions with three batteries in series for each condition, for a total of 108 batteries.

TEST FACILITY

Figure 1 shows two identical independent systems at TRW consisting of 18 test stations each for a total of 36 test stations. The lead-acid batteries were installed on four wooden tables open to the room environment. Discharge load banks, bus bars, and system cabling were contained on the tables. Protective Plexiglass shields encompassed the tables for personnel safety and convenience. System charging power supplies and computer control equipment were positioned separately at either end of the tables. The operation of the 36 test stations, monitoring, and data acquisition were completely automatic and controlled by a microcomputer system. The only manual operation for this program was checking the specific gravities of all 108 batteries. The room temperature and relative humidity conditions were monitored and maintained at $22 \pm 2°$ C and 70 percent RH throughout the test program.

LIFE CYCLING DISCHARGF TESTS

One hundred and twenty 6 volt lead-acid batteries were purchased from ESB (Exide) which were from the same production run and numbered from 1 to 120. The test program required 108 lead-acid batteries. An additional eight spare batteries were procured for contingency purposes. The individual batteries were weighed, electrolyte levels checked, and initial specific gravity measurements recorded for each battery. The batteries were then discharged several times according to the manufacturer's specifications for actual output capacities. According to the test plan (Table I) each of the selected numbered batteries were placed into its designated test station. A test station consisted of three batteries connected in series. Each test station was then discharged to the criteria fixed in the test plan for that station. A discharge cycle was terminated when the required depth-of-discharge was achieved or when the voltage of a battery in a series string reached 3.9 volts. Within the constraints of the test plan it was possible to have one charge/discharge cycle per day for each test station. Discharging was done during the day for purposes of monitoring. Recharging the batteries was done during the evening due to the long recharge times required, usually 8 to 12 hours. Further, a charge or discharge half cycle could not be started until the battery electrolyte temperature was within $\pm 5°$ C of the room ambient temperature.

Equalizing charges were usually done every other week and depended upon the batteries specific gravities (below 1.240) at the end of a normal recharge. If an equalizing charge was required all the batteries were equalized at the same time.

EXPERIMENTAL DESIGN

The four controllable parameters selected (DOD, average current, frequency and duty cycle) were set up in a test matrix so that most of the conditions that could affect battery performance could be isolated, studied and quantified. Other investigators found that depth-of-discharge had an effect on battery cycle life (ref. 2). It is also thought that high average discharge currents may adversely affect battery cycle life. It was not known whether duty cycle and chopper frequency adversely affected battery life or perhaps enhanced the cycle life. Table I, using the conditions mentioned above, shows the experimental conditions selected for this program, which comprise a variation of a central composite factorial design.

The directly controllable variables of this experiment are designated as:

A = average current

C = duty cycle

F = chopper frequency

D = nominal depth of discharge

Figure 2 graphically indicates the points at which tests were performed. Axes A and C represent the average current and duty cycle respectively. The points run were for DOD's = 25, 50, and 75 percent and are shown in Figures 2(a) to (c), respectively. Note that the A and C combinations form a "box" for DOD = 25 and 75 percent and a "star" for DOD = 50 percent. The box and star are tilted with respect to the A and C axes. To achieve the usual scaling of variables in a two-level factorial experiment (i.e., low level is denoted by -1 and high level is denoted by +1)(ref. 5). New (scaled) variables are introduced as:

$$X = \frac{A - 140}{120} + \frac{C - 55}{30} \tag{1}$$

$$X_2 = \frac{A - 140}{-40} + \frac{C - 55}{10} \tag{2}$$

$$X_3 = \frac{F}{500} - 1 \tag{3}$$

$$X_4 = \frac{(D - 50)}{25} \tag{4}$$

Note that the X_1, and X_2 axes are now centered at the middle of the box and star, also X_1 and X_2 range from -1 to +1 from one edge of the box to another. The scaling of frequency defined by X_3 ranges from -0.8 to +1, while the scaling of DOD ranges from -1 to +1 as desired. The experimental design is a full 2^4 factorial on X_1, X_2, X_3, X_4 with replicated center point; star points for X_1 and X_2; and fill-in conditions to investigate the regime near continuous discharge.

DATA ANALYSIS

The resulting cycle lives for each test condition are presented in Table I. Column 1 presents the article number which is comprised of three batteries connected in series. Column 2 indicates whether the test was continuous or chopped. Columns 3, 4, 5, and 6 indicate the average current, duty cycle, frequency, and depth-of-discharge (DOD) for the test conditions. Columns 7, 8 and 9 indicate the last cycle observed for each of the three batteries. Some of the batteries were not tested to ultimate failure and these censored observations are indicated by "(0)" in columns 7, 8, and 9. Column 10 is the predicted mean cycle lives of the batteries. A few other batteries either were taken off test early due to extraneous causes or failed at such early cycle life that they were not considered representative. These are identified by appropriate notes in Table I. Because the data has been censored in some instances, it is not appropriate to fit equations using a simple least squares type of analysis. The model selected is that for any specified values of $X = (X_1,X_2,X_3,X_4)$ the probability of a battery failing before or up to the y^{th} cycle is given by

$$F(y) = 1 - \exp\left\{-\exp\left[(y - \mu)/\sigma\right]\right\} \qquad (5)$$

where $\mu = \mu\ (X_1, \ldots, X_4)$ is a function of the controllable variables. This equation describes what is known as a smallest extreme-value distribution which occurs commonly in reliability and failure analyses (ref. 3). The parameter μ is close to the mean failure time while σ is close to the standard deviation of the distribution of failure times.

As an initial postulate for the functional form of $\mu(X_1,\ldots,X_4)$, a second order polynominal is used,

$$\mu(X_1,\ldots, X_4) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_1^2 + \beta_6 X_1 X_2 + \beta_7 X_2^2 + \beta_8 X_1 X_3 +$$
$$+ \beta_9 X_1 X_4 + \beta_{10} X_2 X_3 + \beta_{11} X_2 X_4 + \beta_{12} X_3 X_4 + \beta_{13} X_4^2 + \beta_{14} X_3^2 \qquad (6)$$

where the $X_1,X_2,\ldots,$ are the scaled variables defined in equations (1) to (4) previously.

RESULTS

It was determined that when only significant terms of equation (6) (approximating polynomial) are retained, the function:

$$\mu(X_1,\ldots, X_4) = 542.98 - 38.57\ X_1 \qquad (7)$$
$$+ 13.79\ X_2 - 97.83\ X_4 - 0.25\ X_2^2$$

was obtained.

The major points obtained from this experiment are: First, frequency has no effect on cycle life because all the terms involving variable X_3 (the scaled frequency variable) were judged to be insignificant. Second, increasing DOD leads to a decreasing cycle life because the coefficient of X_4 (the scaled DOD variable) is -97.83. Thus, for example, the difference in mean cycle life between 25 percent and 75 percent nominal DOD is given by twice the slope of equation (7), i.e., 2(97.83) = 195.6 cycles (because X_4, the scaled DOD variable, changes from $X_4 = -1$ to $X_4 = +1$ as DOD changes from 25 percent to 75 percent). Third, increasing average current and duty cycle simultaneously (as measured by increasing the X_1 variable) leads to decreasing cycle life because the coefficient of X_1 is -38.57. Thus, for example, the fitted equation indicates a decrease in mean cycle life of 2 x (38.57) = 77.2 cycles as X_1 varies from $X_1 = -1$ (i.e., average amps = 100 and duty cycle = 35 percent) to $X_1 = +1$ (i.e., average amps = 220 and duty cycle = 65 percent).

And fourth, the charge in mean cycle life for deviations along X_2 (scaled average current and duty cycle) changes in a nonlinear fashion because the coefficient of X_2^2 is nonzero. The fact that this coefficient is negative implies a maximum exists.

Fifth, all the battery failure modes were characterized by a single failure mode; this is a gradual decrease in output capacity to half-capacity, the ultimate failure. This usually occured after several hundred cycles and is characteristic of electrode aging and/or end of useful battery life. Post-test analysis of 23 of the failed batteries supported the existence of a strong wearout factor which is typical of end of battery life. Also evident from the post-test analysis were positive plate shedding, grid oxidation and loss of active material.

CONCLUSIONS

At this point, the most important conclusions that may be drawn are: (1) there appears to be no significant effect upon cycle life if batteries are discharged in the pulsed mode; (2) the chopped frequency of discharge has no significant effect; (3) the variable with the greatest effect on cycle life remains that of DOD, and (4) increasing both duty cycle and average current have an effect on cycle life, but not as pronounced as DOD. The effect of the controllable variables upon the total energy and/or power delivered by these batteries still remain to be evaluated. Eventual cost/benefit analysis may depend more upon other considerations than cycle life. The final judgment remains to be made.

APPENDIX

We assume the cycle life of a battery is an observation from a smallest extreme-value distribution (ref. 3, Mann, Schafer, Singpurwalla) with parameters μ and σ. That is the probability a battery failing before cycle number y is:

$$F(y) = 1 - \exp\left(-\exp \frac{y-\mu}{\sigma}\right)$$

We also assume that the location parameter μ is a function of the test controllable variable as:

$$\mu(x_1,\ldots,x_4) = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_4 + \beta_5X_1^2 + \beta_6X_1X_2 + \beta_7X_2^2$$

$$+ \beta_8X_1X_3 + \beta_9X_1X_4 + \beta_{10}X_2X_3 + \beta_{11}X_2X_4 + \beta_{12}X_3X_4 + \beta_{13}X_4^2$$

where X_1, X_2, X_3, and X_4 are defined in equations (1) to (4).

We also assume that σ is independent of the test conditions. The β's and σ are estimated by maximum likelihood as in reference 4. Then, as is done in linear regression methods for uncensored data using the normal distribution, variance inflation factors are calculated as the diagonal elements of $(X'X)^{-1}$. These are normalized so the largest is unity and the β's are then divided by the corresponding normalized variance inflation factors to obtain an analog of the t-statistic in ordinary linear regression. The relative significance of such statistics may be judged by producing a dot plot of these statistics and claiming those that deviate markedly from zero are probably significant (ref. 5, Box, Hunter and Hunter).

The results of the first iteration of this procedure are presented in Table II and figure 3. From the dot plot, it seems that the X_1, X_2, X_2^2, X_1X_2 and X_4 terms are the ones of possible major significance. It is clear that X_3 (frequency) has no significant effect. At this point we dropped all terms involving X_3 and re-fit the model. The results are given in Table III, and the dot plot of the coefficients divided by the variance inflation factor in figure 4. Recognizing that the choice of significance is subjective, we decide that the dot plot in figure 4 indicates the only significant effects to X_1,X_2, X_2^2, and X_4. The estimated β's and σ for this model are given in Table IV. In summary, we have,

$$\mu(X_1, X_2, X_3, X_4) = 542.98 - 38.57\,X_1 + 13.79\,X_2 - 97.83\,X4 - 0.25\,X_2^2$$

and $\sigma = 53.67$

For the smallest extreme value distribution the mean life is $E(y) = \mu - \gamma\sigma$ where $\gamma = 0.57722$ is Eulers constant and $V(y) = 1.64493\,\sigma^2$.

One of the purposes of this experiment was to determine if chopped frequency discharges had an effect on cycle life. To this end we used the continuous discharges and fill-in tests to look at those possible effects.

Figures 5(a) to (c) plot the cycle lives observed as a function of duty cycle (where 100 percent duty cycle represents continuous discharge), at the 50 percent nominal DOD level. It seems rather clear that duty cycle exerts no significant effect upon cycle life.

As a comparison to previous experiments, one may also plot life vs. discharge amps for continuous discharge. This is done in figure 6 and we see a dramatic decrease in life as average amps is increased. This is in accord with the results of reference 4.

REFERENCES

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TABLE I

Article Number	Test Mode	Average Current (Amperes)	Duty Cycle (%)	Frequency (Hz)	Nominal DOD (%)	Failure #1 (cycles)	Failure #2 (cycles)	Failure #3 (cycles)	Predicted Life (cycles)
1	CHOPPED	100	75	500	50	(1)408 a	(1)420	(1)468	538.
2	CHOPPED	60	45	100	75	(1)237	(1)382	(0)586	466.
3	CONTINUOUS	180	0	0	50	(1)371	(1)375	(1)407	469.
4	CHOPPED	180	45	500	50	(1)370	(1)414	(1)455	483.
5	CONTINUOUS	100	0	0	75	(1)336	(1)456	(1)466	430.
6	CHOPPED	60	45	1000	25	(0)590	(0)590	(0)590	661.
7	CONTINUOUS	100	0	0	50	(1)472	(1)502	(0)585	528.
8	CHOPPED	180	75	1000	75	(1)345	(1)382	(1)472	389.
9	CHOPPED	220	65	1000	25	(1)484	(1)554	(0)589	557.
10	CHOPPED	260	85	500	50	(0)172 b	(1)433	(1)488	434.
11	CONTINUOUS	20	0	0	50	(0)589	(0)589	(0)589	585.
12	CONTINUOUS	180	0	0	75	(1)359	(1)382	(1)453	371.
13	CONTINUOUS	100	0	0	25	(1)577	(0)587	(0)587	626.
14	CHOPPED	140	55	500	50	(1)487	(1)509	(1)550	512.
15	CHOPPED	180	75	1000	25	(1)589	(0)589	(0)589	584.
16	CHOPPED	220	65	1000	75	(1)366	(1)375	(1)452	361.
17	CHOPPED	100	35	1000	25	(0)589	(0)589	(0)589	634.
18	CHOPPED	100	35	100	75	(1)340	(1)382	(1)507	438.
19	CONTINUOUS	260	0	0	50	(1)408	(1)415	(1)502	408.
20	CHOPPED	20	25	500	50	(1)438	(0)573	(0)573	589.
21	CHOPPED	140	55	500	50	(1)468	(1)508	(1)544	512.
22	CHOPPED	60	45	1000	75	(1)407	(1)446	(1)499	466.
23	CHOPPED	180	75	100	75	(1)363	(1)449	(1)479	389.
24	CHOPPED	100	87.5	500	50	(1)410	(1)468	(0)575	537.
25	CHOPPED	100	35	100	25	(0)576	(0)576	(0)576	634.
26	CHOPPED	220	65	100	25	(1)543	(1)557	(0)574	557.
27	CHOPPED	180	75	100	25	(1)557	(0)574	(0)574	584.
28	CHOPPED	180	87.5	500	50	(0) 85 c	(1)467	(1)510	487.
29	CONTINUOUS	100	0	0	50	(1)509	(1)513	(1)566	528.
30	CHOPPED	100	65	500	50	(1)565	(0)573	(0)573	538.
31	CONTINUOUS	180	0	0	50	(1)417	(1)495	(1)513	469.
32	CHOPPED	220	65	100	75	(0)273	(1)402	(1)404	361.
33	CHOPPED	100	35	1000	75	(1)371	(1)408	(1)487	438.
34	CHOPPED	60	45	100	25	(0)572	(0)572	(0)572	661.
35	CONTINUOUS	180	0	0	25	(0)572	(0)572	(0)572	567.
36	CHOPPED	140	55	500	50	(0)110 d	(1)492	(1)549	512.

a. (1) indicates item tested to failure.
   (0) indicates testing terminated prior to failure.
b. Terminal destroyed due to connector problem. Battery removed from test.
c. Battery suffered a cracked separator.
d. Positive terminal suffered lead run-down.

TABLE II

Coefficient and term		Estimate	"t" - statistic
β_0		509.43	
β_1	X_1	-51.90	-198
β_2	X_2	20.39	170
β_3	X_3	-10.52	-19
β_4	X_4	-115.04	-257
β_5	X_{12}	12.53	63
β_6	X_1X_2	-10.52	-103
β_7	X_2^2	1.96	262
β_8	X_1X_3	9.36	19
β_9	X_1X_4	24.97	64
β_{10}	X_2X_3	-2.37	-6
β_{11}	X_2X_4	-4.67	-46
β_{12}	X_3X_4	-6.65	-12
β_{13}	X_4^2	46.77	47
	σ	50.92	

The coefficients, estimates of coefficients and their "t"-statistics for model 1.

TABLE III

Coefficient	and term	Estimate	"t" - statistic
β_0		507.54	
β_1	X_1	-54.85	-209
β_2	X_2	21.08	212
β_4	X_4	-117.24	-261
β_5	X_1^2	15.04	81
β_6	X_1X_2	-9.74	-119
β_7	X_2^2	1.90	428
β_9	X_1X_4	25.49	65
β_{11}	X_2X_4	-5.66	-62
β_{13}	X_4^2	48.38	48
	σ	52.59	

The coefficients, estimates of these coefficients and their "t" - statistics for model 2.

TABLE IV

Coefficient and term		Estimate
β_0		542.98
β_1	X_1	-38.57
β_2	X_2	13.79
β_4	X_4	-97.83
β_7	X_2^2	-.25
	σ	53.67

The coefficients and their estimates for model 3.

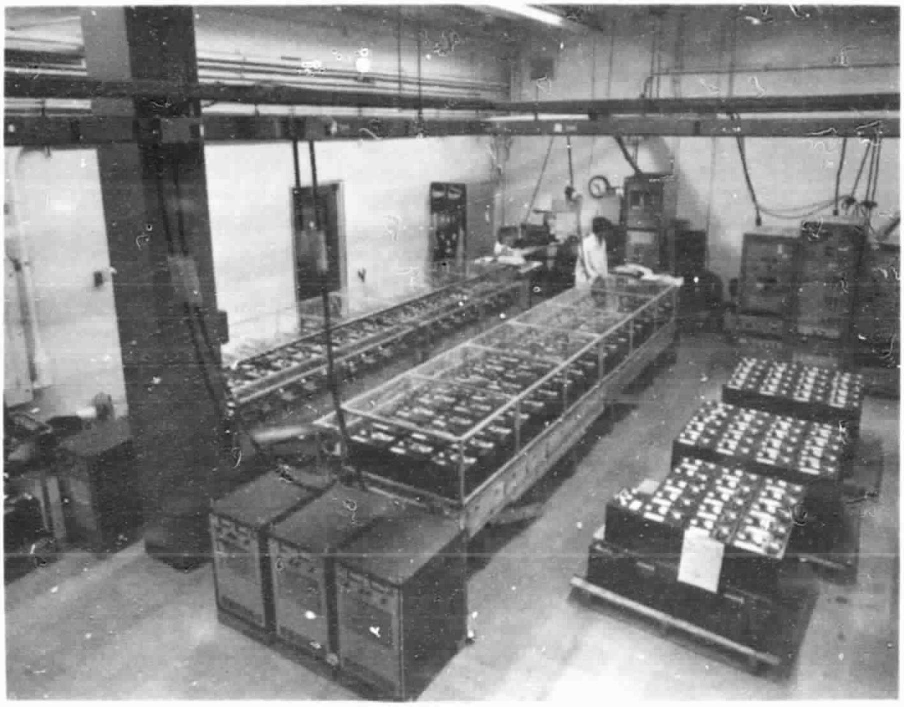
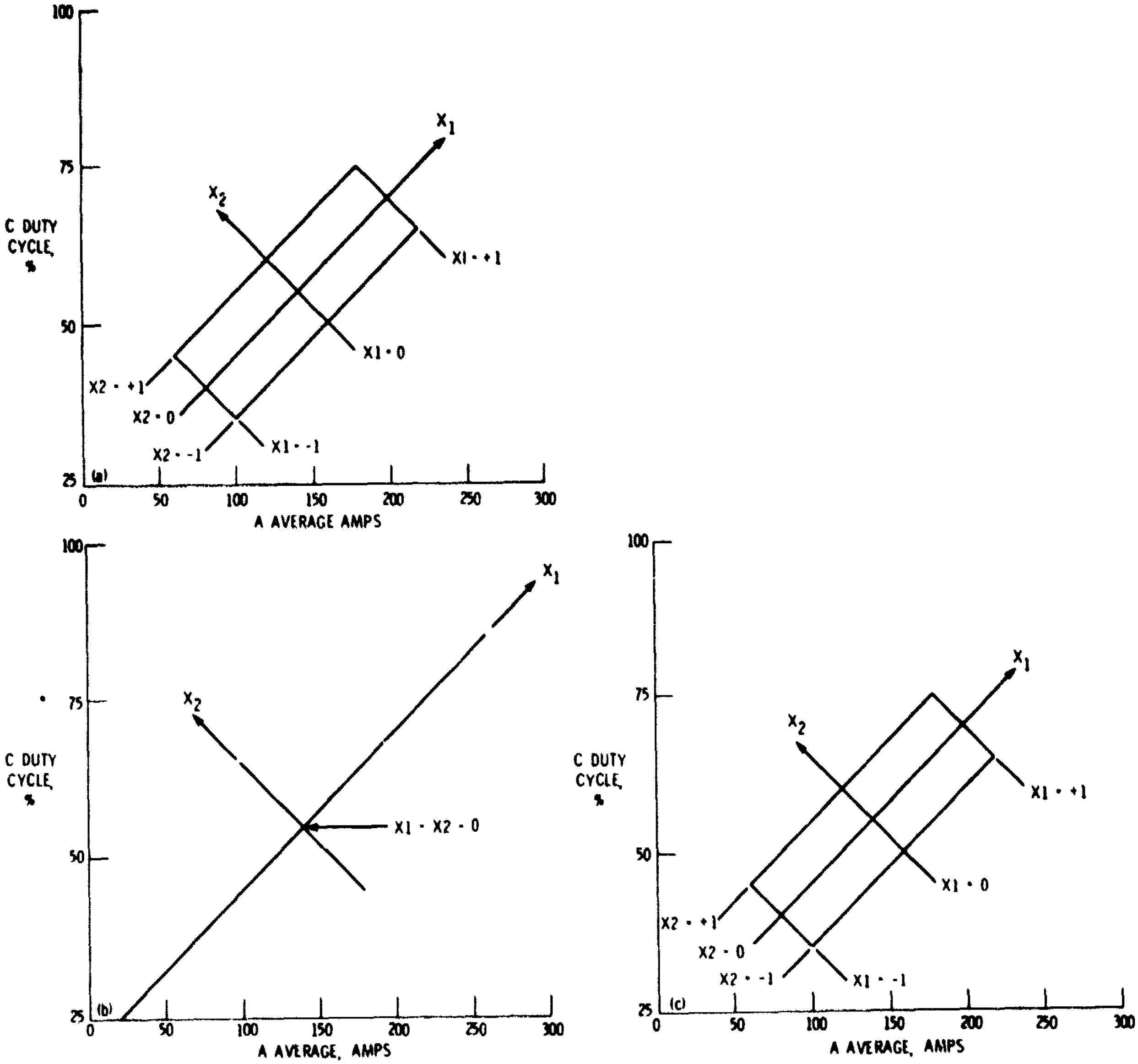


Figure 1. - Test facility.



(a) Depth of discharge, 75%.
(b) Depth of discharge, 50%.
(c) Depth of discharge, 25%.

Figure 2. - Variation of scaled frequency variable X_3.

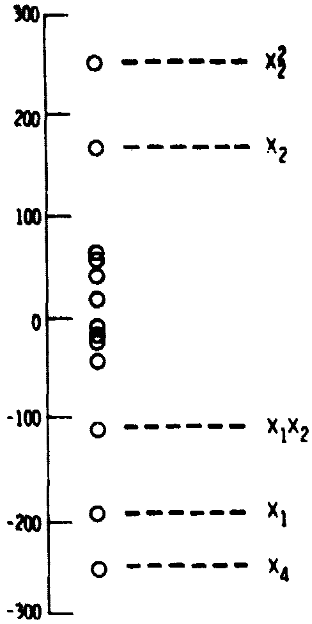


Figure 3. - Dot plot of "t"-statistics corresponding to estimated coefficients in model 1 (from table II).

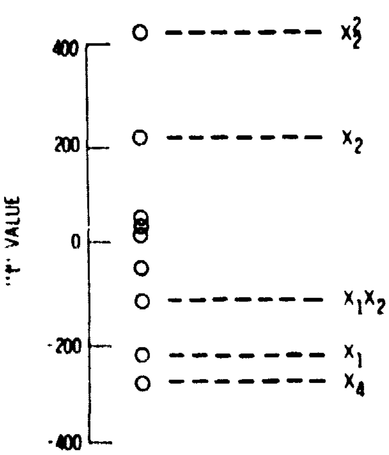
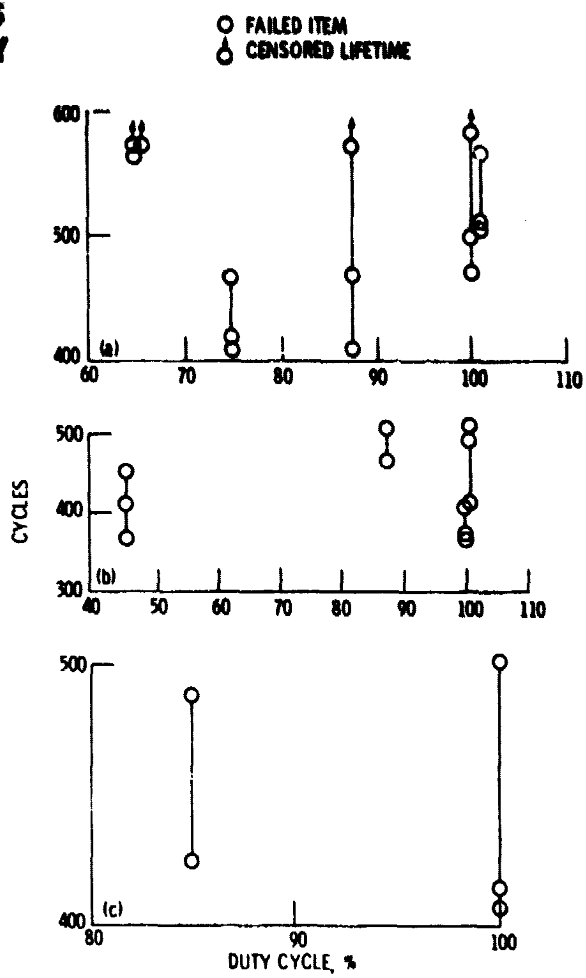


Figure 4. - Dot plot of "t"-statistics corresponding to estimated coefficients in model 2 (from table III).



(a) Average ampere discharge equal to 100.

(b) Average ampere discharge equal to 180.

(c) Average ampere discharge equal to 260.

Figure 5. - Number of cycles observed as a function of duty cycle with depth of discharge equal to 50%.

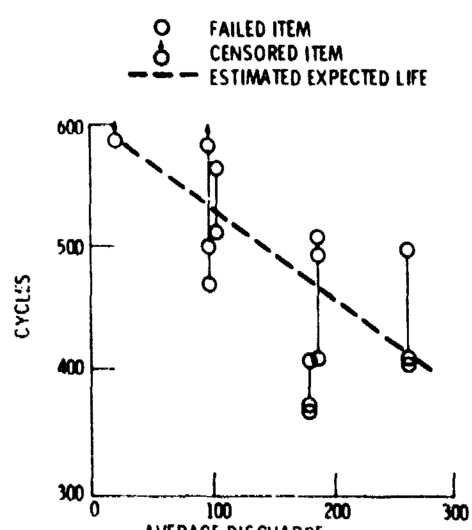


Figure 6. - Number of cycles observed as a function of discharge average ampere for continuous discharge and depth of discharge equal to 50%.