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ANALYSIS AND EVALUATION
of
SPACECRAFT BATTERY
LIFE TEST DATA

prepared for
GODDARD SPACE FLIGHT CENTER



QUALITY EVALUATION LABORATORY
NAD CRANE, INDIANA

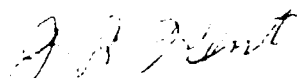
QUALITY EVALUATION LABORATORY
UNITED STATES NAVAL AMMUNITION DEPOT
CRANE, INDIANA

ANALYSIS AND EVALUATION
OF
SPACECRAFT BATTERY
LIFE TEST DATA

QE/C 67-592

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PREPARED UNDER THE DIRECTION OF


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Enclosure (1)

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ABSTRACT

This report presents the findings from the statistical and reliability analysis of large volumes of data on NASA spacecraft batteries. This data was generated from a life cycling test of 660 nickel-cadmium battery cells which was conducted by NAD Crane beginning in December 1963.

A major objective of this work is to develop a life prediction method to reliably estimate the life of any cell after a limited number of test cycles and, hence, allow the screening of inferior battery cells. A promising method is proposed where, after 1000 test cycles, the ultimate cycle lives of cells are predicted and the probability that an inferior cell would be rejected was estimated to be 90.5%. The probability that a good cell would be accepted was estimated to be 84.5%. The test results indicate that the number of test cycles necessary for reliable prediction may be further reduced to a few hundred cycles. No previous method existed to serve this function.

Improved design of future experiments and analysis of existing data not analyzed to date are recommended for future work to establish the minimum number of test cycles required and the extent of applicability of this method to any future spacecraft battery operation. For further refinement of this and similar methods, more frequent cycle monitoring is recommended for future testing.

Additional analysis of failure mode data is needed to correlate failure characteristics with environmental conditions.

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SECTION I
INTRODUCTION

A. GENERAL

This publication is the final report on the analysis of space satellite battery data conducted by the Naval Ammunition Depot, Crane, Indiana, for the National Aeronautics and Space Administration in accordance with NASA Defense Purchase Request No. S-23404-G.

In the past, storage batteries for space and other applications have undergone considerable testing. In retrospect, the past tests and simulation studies have contributed valuable scientific information, but have not clearly indicated the nature and extent of test measurements necessary to determine the ultimate quality and life expectancy of the battery cells. The prime objectives of this investigation were (a) to obtain a more definitive knowledge of the numerous factors which have an effect on the ultimate life of spacecraft batteries, and (b) to develop techniques which will ensure selection of high-quality cells and allow meaningful reliability assessments of spacecraft battery systems.

B. BACKGROUND OF BATTERY DATA ANALYSIS

Over the last three and one-half years, the Quality Evaluation Laboratory at NAD Crane has been engaged in a continuous cycle life testing program for NASA. During this time a massive volume of data was accumulated, but little attention was given to other than cursory examination of the data. Then emphasis was given to the potential of computer analysis of the data from a mathematical and statistical point of view. The analysis and findings presented in this report are a result of this emphasis.

C. TECHNICAL APPROACH

To the extent considered feasible, empirical and theoretical mathematical and statistical techniques have been applied to the accumulated data. Computer programs have been written to facilitate the vast data handling problems. It is appropriate to review the work statement for these tasks as described in the NAD Crane proposal (NAD Crane ltr QEF-EDH:emg 8900-7100 of 13 May 1965 to NASA-GSFC) and the purchase request for these tasks (NASA Defense Purchase Request No. S-23404-G, Amendment No. 14 of 11 Jan 1966 to USNAD Crane, Indiana). These tasks are quoted as follows:

- (1) Determination of cell reliability in terms of the expected number of cycles to failure.
- (2) Determination of factors affecting cell reliability and the depth of such influence.

- (3) The establishment of a system such that conclusions and reliability trends will be updated as testing proceeds.
- (4) The investigation of relationships of variable data as a function of numbers of cycles.
- (5) The development of mathematical models of space batteries."

D. REPORT ORGANIZATION

The following sections of this report give in the order listed: the conclusions which were derived from the data analyses, the recommendations based on conclusions, a description of the data collected, and, finally the data analyses which were directed toward the objectives previously outlined.

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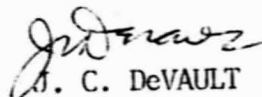
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SECTION II

CONCLUSIONS

Based on the analysis of the test results, the following conclusions are drawn with regard to:

A. ANALYSIS OF BATTERY CELL LIFE TIMES

1. Environmental Factors of the Life Test

No significant difference was found between the 1.5 and 3.0 hour orbits with respect to the mean number of cycles endured by the 10 cell packs. However, large variations in failure times from pack to pack preclude the firm statement that 3 hour orbit cells will always last twice as many hours as 1.5 hour orbit cells for all environments.

The mean lives of the cells of the various manufacturers were found to be significantly different. The battery cells manufactured by General Electric and Sonotone had significantly longer lives than did those manufactured by Gould and Gulton. For example, of the 94 extremely early failures (with failure times less than 2500 cycles), Sonotone 5.0 ampere-hour (A. H.) and General Electric 3.0 A. H. batteries contributed 7 and 12 respectively, while Gould 3.5 A. H. and Gulton 6.0 A. H. had 31 and 44 respectively (120 cells from each manufacturer were used for this comparison).

Although only slight overall significant differences could be detected among the depths of discharge, there was a marked tendency for the higher depths of discharge to cause earlier cell failures at the higher ambient temperatures. This effect is particularly noticeable at 25°C for either the 1.5 or 3.0 hour orbit time, but at 40°C this tendency holds only for the 1.5 hour orbit (see Table 4, page 19 in the Data Analysis Section).

A definite relationship was found to exist between the life of a cell and the ambient temperature. The mean or average time to failure of the cells was found to decrease as the ambient temperatures were increased. Although the ambient temperatures and percent recharges were confounded (i.e., effects of temperature and percent recharge could not be separated), temperature appears to be the important consideration. A statistically designed test, preferably a factorial design, would have allowed the identification and separation of all significant factors and interactions in the experiment.

2. Failure Law Investigation

No single probability distribution consistently described the failure patterns of the various manufacturers and environments. However, certain distributions were used to estimate or assess reliabilities for the different environments across time quite accurately

(historical data was used as a check). This was generally true for the two-parameter Weibull and sometimes true for the lognormal distribution despite inconsistent adherence to these families of curves. The tables on pages 24-27 of the Data Analysis Section give the reliability assessments for the different packs for various times. For instance, the reliability or probability of success for each General Electric 3.0 A. H. cell subjected to an environment similar to that of Pack 63 of General Electric (0°C, 1.5 hr. orbit time, and 15% depth of discharge) for 10,000 cycles is estimated to be .88. The cells of 22 of the 48 packs had such expected reliabilities in excess of .80 for 4,000 cycles, but the number of packs with at least .80 cell reliability dropped to 11 at 10,000 cycles.

The complexities involved in failure analysis of the battery cells have made it difficult or impossible to determine the single failure mode primarily responsible for a failure. Principal among these complexities is that the failure analyst does not usually know what materials and quantities compose the interior of the cell as this information was not available from the manufacturers. This lack of knowledge and standardization is certainly an opponent of accurate failure analysis and hinders the potential of distributional studies of the failure modes and failure mechanisms involved. Nevertheless, it is apparent that too many of the failures are due to the manufacturer's workmanship (design, quality control, etc.). Two hundred and twenty-six of the 480 cells had failed at the time of summarization; of the 226 failures 57.1% failed before completion of 4000 test cycles and 15.5% failed prior to 1000 cycles.

3. Intra-Pack Cell Arrangement

Cell location in the pack arrangement is not indicated to have a significant effect on the life of the cells. However, the fact that the cells of a pack are connected in series does suggest an interrelation between the cells. Due to inherent differences in cells of a similar type it is highly improbable that any two cells will have identical numbers of cycles to failure. But 59 (or 26%) of the 226 cell failures were involved in simultaneous failure. If one would assume that when failures occur and are recorded as simultaneous, one failure caused the others to fail prematurely, then at least 31 failures were premature. For some cells the unusual fluctuation of voltages of non-failing cells, at and directly following the failure times of failing cells, is attributed to the effect discussed above. The mode of cycling the cells could cause some of these simultaneous failures as the pack is turned off for removal of a failed cell. This action may cause the failure mechanism in other weak cells to become more predominant, thereby causing additional failures.

B. APPROACHES TO ANALYSIS OF CELL VOLTAGE DATA

1. Correlation of End of Discharge Voltages and Cell Life Data

Correlation-regression studies associating the number of cycles survived by a cell with the end of discharge voltage (and other voltages of interest) indicated that approximate cell failure order could be determined for cells of some packs. However, due to the inconsistent results obtained across different packs, this method has not contributed sufficiently toward an accurate prediction model.

2. Areas Under Discharge-Charge Curves

The use of the areas under the charge and discharge portions of discharge-charge voltage profile did not reveal a means of detecting early potential failures. It was concluded that the area change with time was too small in comparison with the inherent voltage variation plus the additional variation introduced by approximations necessary due to the infrequent and irregular monitoring points.

3. A Prediction Technique Based on Average Times to Discharge To a Constant Voltage

It was concluded that the time required for a cell voltage to drop from some charged state to some lower specified state gave a more accurate prediction of eventual cell behavior than did other measures investigated. This time, which was approximately determined from available data, was found to decrease as the quality of the cell degraded. When many such times over several test cycles were considered, the early cell failures of a pack could usually be ascertained. This has been done with reasonable success by forming a distribution of the average times to discharge of the cells of a pack after 1,000 test cycles. Then values were mapped from this distribution to another distribution formed from the cell failure times of the same pack to estimate cell failure times (see Data Analysis, pages 28-37).

By arbitrarily considering a good cell as one with a life greater than 10,000 cycles and by using the distributions to make a screening decision on each cell, all cells considered were classified as acceptable or unacceptable. Then by use of the historical or actual test failure times, a check was made on each

decision. It was determined that by employment of this procedure with 1,000 cycles of test data available, the initial failure rate of 74.0% for 10,000 cycles would have been reduced to 24.1% and 67 of the 74 failures in the packs considered would have been properly categorized. Inevitably, some good battery cells (four in this instance) would have been classified incorrectly and could have been used for failure analysis investigations or for some other secondary purpose where the need for high reliability is not so critical. By arbitrarily considering a good cell as one with a life exceeding 5000 cycles, analogous results were obtained (see Tables 13-17, pages 38-42 of Data Analysis Section for results of the prediction system for the different packs examined).

With these predictions considered as a basis for the screening of inferior battery cells, the probability that an inferior cell would be rejected was estimated to be 90.5%. The probability that a good cell would be accepted was estimated to be 84.5%. The test results further indicate (1) that little additional accuracy is gained by testing beyond 1000 cycles and (2) that with improved data and a more refined prediction model, the number of test cycles necessary for reliable prediction may be further reduced to a few hundred cycles. Three hundred cycles of testing, for example, would represent a test time of only 450 hours for an orbit time of 1.5 hours. This would be a trivial portion of the average life of a battery which had been accepted as highly reliable based on the 300 test cycles. By contrast, the present acceptance tests, (the only criterion available to detect inferior cells prior to their spacecraft application) cannot consistently demonstrate that the ultimate cell-life will be beyond even 2000 or 3000 cycles. (This activity is presently conducting a study to correlate battery acceptance results with the life test data and prediction methods of this report to gain additional insight into prediction methods and into the validity and meaning of present acceptance testing.)

Further examination of this prediction procedure has indicated that the shorter orbit time of 1.5 hours yields better prediction possibilities with fewer accumulated test hours than does the orbit time of 3.0 hours. If it should develop that some minimum number of discharge-charge cycles is required, perhaps the charge time or discharge time during each cycle could be reduced to lessen the necessary test time to detect potential failures.

In summary, the employment of this prediction method yields considerable success as to accuracy of prediction. This method has some deficiencies in that too much testing (approximately 1,000 cycles) is required for accuracy and the distributions that have been formed from the historical data are only known to apply for the manufacturers and environments represented by the data. To employ this procedure for other

environments, it would be necessary to either acquire appropriate data and distributions by additional testing or develop relationships which would estimate the parameters representing the desired environments.

The bases for the assumptions and some techniques used in this prediction system can be more critically examined and likely strengthened upon completion of the distribution and prediction studies of all 84 five and ten-cell packs. Time and the voluminous amounts of data to be assimilated have not allowed the examination of all of these packs.

C. VALUE OF OPERATING CELL TEMPERATURE DATA

Although temperature data was not determined to be of significant value in the data analysis, this measurement should not be disregarded in future testing. Instead, an improved method of monitoring temperatures should be sought by NASA since it is considered that the sporadic readings are probably not indicative of the true cell operating temperatures.

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SECTION III
RECOMMENDATIONS

Based on the battery reliability needs for space vehicles and on the data analysis of the cycling test results, the following recommendations are made with regard to:

A. USE OF PREDICTION TECHNIQUE

The failure prediction method (using times to discharge) should be extended to all 84 five and ten-cell nickel-cadmium packs and to at least a portion of the other battery packs tested to date. This extension would permit a more critical review of the parameter estimates of the distributions used and, in general, the prediction process itself.

In future experiments data should be taken more frequently during the cycling and more often and consistently during the discharge-charge cycle. Under the present test scheme, 1,000 cycles of data gives the analyst only 25 or 30 data points (for example, end of discharge voltages) to examine and, for purposes of analysis, most of these must be determined by interpolation or extrapolation. Hence, it is reasonable to expect that test data acquired as follows would be more accurate and would hopefully allow a substantial reduction in the number of cycles of screening required for prediction of cell and pack failures:

- (1) For approximately the first 1,000 cycles, collect data every one or two cycles and after 1,000 cycles collect data less frequently (maybe as infrequently as every 30 cycles).
- (2) For each cycle wherein data is collected, collect every two minutes across cycle discharge and charge. Heretofore, the data was not collected at constant time intervals across each discharge-charge cycle. This factor was a hindrance to analysis especially at the end of charge and at the end of discharge.

Any methods of failure prediction presented in this report which show promise (in particular, the method which uses the times to discharge to some prespecified voltage) should be applied to any additional battery test results obtained with data points collected as recommended above.

B. FAILURE ANALYSIS

Increased emphasis should be placed on techniques of failure analysis, as applied to NASA batteries, to determine more accurately the causes of cell failures. More knowledge of the interior of the battery cells and more standardization of battery

constituents would help the analyst determine how each observed deficiency of a failed unit contributed to the cause and effect relationship. Thus, the following should be accomplished:

- (1) Manufacturers should be required to furnish information at the time of manufacture so the analyst can diagnose battery cell changes experienced during the life test.
- (2) An alternative or supplement to (1) if it develops that adequate information cannot be obtained from the manufacturer would be for NASA to purchase batteries in excess of the required quota from each manufacturer; the excess then could be used to determine the constituents and characteristics of the batteries prior to life test deterioration.
- (3) Major expected failure modes of cells should be ascertained from the combined efforts of battery analysts and computer analysts. Computer failure analysis programs and methods now being developed at NAD Crane and Mauchly Systems will allow correlation studies between existing failure diagnostic results and unique sets of environmental conditions as desired.
- (4) When major expected failure modes are pinpointed, space battery experts should develop means to monitor the characteristics of these modes as the cell degenerates to failures.

C. FUTURE TEST DESIGN

The voltage measurements presently being obtained have shown considerable promise toward the objectives of predicting failure and improving reliability; however this does not preclude the possibility that other test measurements would be even more indicative of ultimate failure or at least supplement information already obtained. NASA battery experts should thoroughly evaluate any potential measurement for possible inclusion in future test plans.

Appropriate factorial or fractional factorial test designs (this modification of a factorial design usually results in a substantial decrease in sample size) should be considered to determine the relative value of any temperatures, discharge depths, orbit times, manufacturers, recharge rates, and other parameters of interest. At this point it would not appear advisable to test only one or two levels of a parameter such as temperature and then estimate or extend results to other levels; to date relationships associating the

different levels of the various parameters are not considered reliable enough to make such estimates. Hence, for each test parameter, the levels of interest should be specified by NASA, preferably at equal intervals (e.g. for temperature; levels of -5°C , 10°C , 25°C , and 40°C would be highly informative possibilities). Results of an adequate test design could be used to model accelerated life tests based on temperature or depth of discharge or some combination of environmental factors.

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SECTION IV
DATA ACQUISITION
AND
MANIPULATION

A. GENERAL DESCRIPTION OF DATA

The original life cycling test program started at NAD Crane in December 1963 included only nickel-cadmium battery cells. There was a total of 84 packs or 660 cells at the inception of the test; these packs were manufactured by General Electric Company, Gould-National Batteries, Inc., Gulton Industries, Inc., and Sonotone Corporation. The number of failures per pack at the time of summarization (1 January 1967) for a particular capacity rating and the environment for each pack is indicated in the table on page 12. All packs are identified by pack numbers in the upper left corner of the table and each initially consisted of either 5 or 10 cells.

The cells were initially subjected to ambient temperatures of 0°C, 25°C, and 50°C, but the 50°C induced six early failures and was considered to be too strenuous. Consequently the 50°C ambient temperature was cut back to 40°C after the first few hundred cycles of testing. A pack was considered to have failed after more than 50% of the included cells had failed (3 for the 5 cell packs and 6 for the 10 cell packs). A cell was considered to have failed when the terminal voltage dropped below 0.5 volt at any time during the discharge-charge cycle. As packs failed they were removed from cycling and subjected to failure analysis. Extensive failure analysis results and other details are made available to NASA in monthly progress reports by Crane battery analysts and cumulative information is summarized annually.

Many additional packs have been added to the life test since its inception. These include other nickel-cadmium types, silver-zinc, silver-cadmium, auxiliary electrode, stabistor, coulometer, Sherley upside-down cycling, and the two-step charge regulator.

Due to the large quantities of data and battery cells involved, the analysis conducted by this facility has been largely confined to the ten-cell nickel-cadmium packs. This allows analysis over more samples for a particular environment or pack. Analysis has indicated that manufacturers have a relatively constant rate of cell failure over the different size packs and over different ampere-ratings. Hence, it is felt that conclusions based on ten-cell nickel-cadmium packs are somewhat typical of those for the five-cell nickel-cadmium packs. Characteristics of other batteries are not necessarily expected to parallel those of the nickel-cadmium, but extensive data analysis on these types is not possible due to the limited amount of data collected for a particular type.

B. DATA HANDLING

All computer analyses for this report were performed on an IBM 1620 or IBM 360 Computer. Any computer programs required and not already available in existing files were developed by NAD Crane personnel.

TABLE 1

Test Environment, Depth and Number of Cell Failures
For Five and Ten Cell Nickel Cadmium Battery Packs

MANUFACTURER AND CAPACITY	ORBIT TIME												TOTAL FAILED CELLS	
	1.5 Hours						3.0 Hours							
	Temperature & Percent Recharge						Temperature & Percent Recharge							
	0°	115°	25°	125°	40°	160°	0°	115°	25°	125°	40°	160°		
	Depth-Discharge 15%	Depth-Discharge 25%	Depth-Discharge 40%	Depth-Discharge 15%	Depth-Discharge 25%	Depth-Discharge 40%	Depth-Discharge 15%	Depth-Discharge 25%	Depth-Discharge 40%	Depth-Discharge 15%	Depth-Discharge 25%	Depth-Discharge 40%	Depth-Discharge 15%	Depth-Discharge 25%
General Electric 3.0 A.H.	63	64	15	16	39	40	67	68	19	20	43	44		
	1/10	0/10	6/10	6/10	6/10	7/10	0/10	1/10	0/10	6/10	6/10	6/10	6/10	45/120
General Electric 12.0 A.H.	110	124	82	96	85	99	111	125	83	97	86	100		
	0/5	2/5	3/5	3/5	3/5	3/5	0/5	0/5	0/5	3/5	0/5	3/5	3/5	20/60
Sonotone 5.0 A.H.	49	50	1	2	25	26	53	54	5	6	29	30		
	2/10	3/10	6/10	6/10	6/10	6/10	0/10	0/10	2/10	6/10	6/10	6/10	6/10	49/120
Gould 3.5 A.H.	51	52	3	4	27	28	55	56	7	8	31	32		
	1/10	6/10	7/10	6/10	6/10	10/10	0/10	0/10	6/10	7/10	7/10	6/10	6/10	62/120
Gould 20 A.H.	84	98	104	118	112	126	30	94	105	119	108	122		
	0/5	3/5	3/5	3/5	3/5	3/5	0/5	0/5	3/5	3/5	3/5	3/5	3/5	27/60
Gulton 6.0 A.H.	61	62	13	14	37	38	65	66	17	18	41	42		
	8/10	5/10	6/10	6/10	6/10	6/10	3/10	6/10	6/10	6/10	6/10	6/10	6/10	70/120
Gulton 20 A.H.	101	115	73	87	76	90	102	116	74	88	77	91		
	3/5	3/5	3/5	5/5	3/5	3/5	1/5	0/5	3/5	4/5	3/5	4/5	4/5	35/60
TOTAL FAILED CELLS	15/55	4/55	22/55	7/55	34/55	20/55	35/55	35/55	33/55	31/55	38/55	34/55		308/660

The data, which is now stored on magnetic tape, consists primarily of cell voltages and corresponding cell operating temperatures for each time examined across the discharge-charge cycle and also a total pack current and pack voltage for time of each cycle. By use of the semi-automatic data collection system, the readings were recorded approximately every 32 cycles. Major obstacles to the data analysis were the lack of more frequent cycling points early in the life of the cell and the lack of more frequent and more uniform readout times during the discharge and charge portions of each cycle. Figure 1 on page 14 which is a section of a computer printout for Cell #1 of Pack #1 illustrates the infrequent and non-uniform time readout points.

Considerable interpolation and extrapolation has been required to obtain time and voltage estimates for computer analyses. A completely automatic data acquisition system would allow considerable latitude in the frequency of readings recorded and would give exact time data as required.

FIGURE 1

COMPUTER PRINTOUT OF CYCLE READOUT TIMES AND VOLTAGESSONOTONE AMP HRS 5.0 ORBIT TIME 1.5 AMB TEMP 25 DISCHARGE 25%PACK 1 CYCLE 1 CELL 1

MISSING VOLTAGE DATA 5 READINGS PRESENT

DISCHARGE
 TIMES 39.80
 VOLTAGES 0.0
 AREA 20.000

CHARGE
 TIMES 49.80 59.80 69.80 79.80
 VOLTAGES 4.00 7.00 11.00 20.00
 AREA 320.000

MINIMUM VOLTAGE 135.

PACK 1 CYCLE 19 CELL 1

MISSING VOLTAGE DATA 12 READINGS PRESENT

DISCHARGE					
TIMES	6.10	9.80	20.10	24.80	29.00
VOLTAGES	8.00	6.00	2.00	1.00	0.0
AREA	76.250				

CHARGE
 TIMES 31.80 39.80 49.80 59.80 69.80 79.80 89.00
 VOLTAGES 7.00 12.00 16.00 19.00 22.00 25.00 28.00
 AREA 1084.600

MINIMUM VOLTAGE 122.

PACK 1 CYCLE 69 CELL 1

MISSING VOLTAGE DATA 13 READINGS PRESENT

DISCHARGE						
TIMES	7.30	11.20	17.50	19.80	24.80	29.30
VOLTAGES	8.00	6.00	4.00	3.00	1.00	0.0
AREA	79.100					

CHARGE
 TIMES 31.70 39.80 49.80 59.80 69.80 79.80 88.80
 VOLTAGES 8.00 12.00 16.00 20.00 23.00 26.00 27.00
 AREA 1109.100

MINIMUM VOLTAGE 121.

PACK 1 CYCLE 111 CELL 1

DISCHARGE
 TIMES 0.10 4.90 9.90 14.90 19.90 24.90 28.90
 VOLTAGES 19.00 10.00 7.00 5.00 3.00 2.00 0.0
 AREA 178.600

NOTE 1:

INFREQUENT CYCLE READOUTS
 EARLY IN LIFE OF CELL;
 CONSECUTIVE READOUT POINTS AT
 CYCLE 1, CYCLE 19, CYCLE 69,
 AND CYCLE 111, ETC. ARE TYPICAL.

NOTE 2:

INFREQUENT READOUT TIMES;
 HERE FIVE TIMES ARE
 DISTRIBUTED OVER 29 MINUTES

NOTE 3:

READOUT TIMES VARY FROM
 CYCLE TO CYCLE AND ARE NOT
 SEPARATED BY A CONSTANT
 TIME INTERVAL.

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SECTION V

DATA ANALYSIS

A. APPROACHES USING FAILURE TIME DATA OF CELLS

1. Environmental Factors

Analysis of variance techniques were applied to the failure data from the 10-cell packs of Gulton, Sonotone, General Electric and Gould. Using the data, various tests of significance were applied to test for differences in manufacturers, temperatures (actually temperature-percent recharge combinations), depth of discharge percents, orbit times and any significant interactions. Two modes of analysis were performed; in one instance an analysis was performed using mean times to failure and then the analysis was performed using non-parametric procedures on the attribute data as a check on conclusions.

A considerable obstacle to these analyses and to other approaches taken was the lack of failure information for cells of a pack that had not yet failed at the time the testing for that pack was truncated. Under the current test plan, test truncation usually occurs at the sixth failure. This obstacle is of particular significance when truncation occurs after a few thousand cycles since little knowledge is gained for the remaining four cells.

Tables 2 and 3 that follow give the number of cell failures for each ten-cell pack and the number of cycles endured at the time of summarization (1 January 1967).

For the analysis of the variable, time to failure, the mean lives were calculated in accordance with the exponential (i.e., constant failure rate) distribution. Earlier investigation of failure distributions indicated that the failure times followed the exponential more consistently than any other single distribution. Mean times to failure (MTTF's) were calculated for each pack as shown by the following formulas; failed cells are not replaced in the pack.

$$MTTF = \frac{\sum_{i=1}^r t_i + (n-r) t_r}{r+1} \quad (\text{for test truncation on time})$$

$$MTTF = \frac{\sum_{i=1}^r t_i + (n-r) t_r}{r} \quad (\text{for test truncation on failures})$$

Where n = the number of samples or cells on test at time zero, equal to ten,

r = the number of failures recorded at the time of test truncation, usually six for the failure truncation case,

t_i = time of the i th cell failure of a pack; here the number of cycles completed is time dependent.

TABLE 2

Table With Number of Cell Failures From Ten-Cell Packs and Number of Test Cycles Completed at Time of Summarization

Temperature (°C)	Depth of Discharge	Orbit Period (Hours)	G. E. 3.0 A. H.	Gould 3.5 A. H.	Gulton 6.0 A. H.	Sonotone 5.0 A. H.	Total Failures
0°	15%	1.5	1 16,230	1 16,503	8 10,146	2 16,725	12
		3.0	0 8,385	0 8,423	3 8,082	0 8,271	3
	25%	1.5	0 17,962	6 13,730	5 16,667	3 16,093	14
		3.0	1 8,568	0 8,403	6 4,414	0 8,052	7
25°	25%	1.5	6 10,382	7 4,751	6 4,021	6 11,745	25
		3.0	0 8,361	6 4,173	6 2,885	2 8,126	14
	40%	1.5	6 5,013	6 3,164	6 2,086	6 6,671	24
		3.0	6 5,410	7 2,494	6 1,550	6 5,211	25
40°	15%	1.5	6 8,109	6 4,485	6 6,064	6 9,328	24
		3.0	6 2,656	7 2,517	6 1,689	6 5,977	25
	25%	1.5	7 2,509	10 1,811	6 1,377	6 3,625	29
		3.0	6 4,487	6 974	6 4,133	6 4,141	24
TOTAL FAILURES			45	62	70	49	226

NOTE: For packs with six or more failures only.

NOTE: For packs with six or more failures, cycling was stopped at the number of cycles indicated; the remaining non-failing cells of these packs were not cycled to failure. The non-failing cells of packs with five or less failures were still cycling at the point indicated.

TABLE 3

Table With Number of Cell Failures From Five-Cell Packs and
Number of Test Cycles Completed at Time of Summarization

Temperature (°C)	Depth of Discharge	Orbit Period (Hours)	G. E. 12. A. H.	Gould 20 A. H.	Gulton 20 A. H.	Total Failures
0°	15%	1.5	0 16,487	0 16,466	3 3,629	3
		3.0	0 8,060	0 8,193	1 8,028	1
	25%	1.5	1 16,114	3 10,641	3 2,291	7
		3.0	0 8,132	0 8,077	0 7,848	0
25°	25%	1.5	3 10,878	3 2,980	3 7,763	9
		3.0	0 8,265	3 5,690	3 1,754	6
	40%	1.5	3 4,020	3 2,937	5 627	11
		3.0	3 5,002	3 1,793	4 358	10
40°	15%	1.5	3 9,710	3 5,213	3 9,348	9
		3.0	0 8,060	2 4,233	3 6,032	5
	25%	1.5	3 4,853	3 1,569	3 4,045	9
		3.0	3 4,424	3 983	4 4,480	10
TOTAL FAILURES			19	26	35	80

NOTE: For packs with three or more failures, cycling was stopped at the number of cycle indicated; the remaining non-failing cells of these packs were not cycled to failure. The non-failing cells of packs with two or less failures were still cycling at the point indicated.

It should be noted that the test has never actually been truncated due to the amount of time elapsed, but rather always because of the number of failures that have occurred. The calculations based on time truncation are made by accumulating total test time to the time of summarization.

Table 4 gives the MTTF of the battery packs for each manufacturer and environment.

These means generally reflect the quality of the various packs. However, in the event none of the pack cells have failed, the exponential mean estimate gives an extremely large estimate since this distribution assumes a constant failure rate with time. To deflate the large variances caused by such means, the natural logarithm of each mean was used in the analysis.

a. Orbit Times

No significant differences were found between the orbit times (1.5 and 3.0 hours) of the ten-cell packs with respect to the number of cycles that a cell would endure. The discharge time of both the 1.5 and 3.0 hour orbit times was 30 minutes.

The total number of successful 1.5 hour test cycles completed by 240 cells with 128 failures was 1,789,705 while the total number of 3.0 hour cycles completed by the other 240 cells with 98 failures was 1,166,835.

b. Manufacturers

Further analysis of the mean lives revealed significant differences among manufacturers. These differences were not surprising since failure analysis had shown that the various manufacturers differed considerably with respect to structure and to failure modes and mechanisms.

Table 5 indicates the relative differences in manufacturers by giving the number of failures to date (in parentheses) and the MTTF's for each temperature environment within manufacturer. Data from the different depths of discharge and different orbit times are combined in this table.

The Gulton 6.0 A. H. batteries had more total failures (70) than did other manufacturers. The main difference here existed at the 0°C environment; 22 (62.9%) of the 35 cells that failed under the 0°C environment were manufactured by Gulton.

A considerable number (94) of the 226 failures occurred as early as 2500 cycles. Of these 44 (46.8%) were Gulton 6.0 A. H., 31 (33.0%) were Gould 3.5 A. H., 12 (12.8%) were General Electric 3.0 A. H., and 7 (7.4%) were Sonotone 5.0 A. H. cells. The different

TABLE 4

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Mean Times to Failure of Batteries
Expressed in Cycles to Failure

Ambient Temperature	Depth of Discharge	Orbit Time (Hours)	G. E. 3.0 A. H.	Gould 3.5 A. H.	Gulton 6.0 A. H.	Sonotone 5.0 A. H.
0°C	15%	1.5	80,720	81,630	6,970	48,630
		3.0	83,850	84,230	18,370	82,710
		1.5	179,620	19,220	24,020	38,380
	25%	3.0	42,080	84,030	4,840	80,520
		1.5	16,240	6,060	5,090	23,660
		3.0	83,610	6,350	3,730	24,680
25°C	40%	1.5	8,020	4,560	2,360	9,240
		3.0	8,340	3,090	1,860	6,310
	15%	1.5	10,210	6,430	7,140	14,350
		3.0	3,780	3,170	2,270	9,690
	25%	1.5	3,410	1,260	1,460	5,470
		3.0	6,690	1,340	4,280	5,920

NOTE: To convert the means given in the table from cycles to hours, multiply the mean number of cycles by the appropriate orbit time.

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TABLE 5

MTTF's For Each Manufacturer-Temperature Combination

Manufacturer	0°C	25°C	40°/50°C	Totals
General Electric 3.0 A.H.	(2) 96,570	(18) 29,050	(25) 7,160	(45) 44,260
Sonotone 5.0 A.H.	(5) 62,560	(20) 15,970	(24) 8,860	(49) 29,130
Gould 3.5 A.H.	(6) 67,390	(26) 5,010	(29) 3,050	(61) 25,150
Gulton 6.0 A.H.	(22) 13,550	(24) 3,260	(24) 3,790	(70) 6,870
TOTALS	(35) 60,020	(88) 13,320	(92) 5,710	(225) 26,350

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capacity ratings of the batteries do not explain the manufacturer differences. When the 5.0 and 6.0 A. H. batteries were combined and compared to the combined data for the 3.0 and 3.5 A. H. batteries, no significant difference was found. This indicates that differences in the manufacturer's product are due to the design and production methods, rather than the ampere-hour rating. It is assumed that the manufacturer's capacity rating is accurate.

c. Depth of Discharge

Only slight overall significant differences were established among the relative depths of discharge, but at the higher ambient temperatures the higher depths of discharge caused a marked decrease in the life of the cell. See Tables 3 and 4 for numerical values illustrating this relation, particularly for the 25°C ambient temperature.

d. Temperature

Highly significant differences were found between the ambient temperature and/or percent recharge (see Table 4). As the ambient temperature and the percent recharge were increased the mean time to failure decreased. Despite the confounding of the recharge rates and the ambient temperatures, temperature appears to be the principal factor since the recharge rates were those recommended for satisfactory battery performance at the different temperatures. Most of the actual percent recharges used were less than those initially recommended. This was due to the cells reaching a predetermined voltage limit before the recommended percent recharge. Values initially recommended were as follows: 115% recharge for 0°C, 125% for 25°C, and 160% for 40°C and 50°C.

Table 5 (page 20) best illustrates the significant differences in the three temperature environments. Caution should be used in attempting comparisons between the 40°C/50°C and either of the other temperatures, 0°C and 25°C. The initial test design included a 50°C environment rather than 40°C but this environment was found too strenuous for satisfactory performance by the batteries and after the first few hundred cycles the temperature was lowered to 40°C. The long-range effect this changed environment had on the cells should be equivalent to a resultant temperature somewhere between 40 and 50°C.

By revising the data in Tables 2 and 3, pages 16 and 17, for a standard number of cycles endured per cell, non-parametric analysis of the attribute data was conducted. Cell failures were assigned a value of one and successful cells a value of zero. After using incomplete data estimation techniques, analysis of variance methods were applied as a check on the conclusions derived from the mean life analysis. It was important that the conclusions agreed, as they did, since the assumptions underlying the analyses were not completely satisfied; the robustness of the analysis of variance depends upon the validity of the assumptions made.

2. Failure Laws

A primary objective of this analysis is to determine if a failure law or pattern can be found to describe the failure behavior of batteries under a particular set of environmental conditions. Ideally, such a relationship could be obtained and would permit accurate predictions of reliability for the various failure modes experienced. Using the number of cycles to failure of each cell, attempts were made to fit various groupings of data (by failure mode, manufacturer, etc.) to the exponential and Weibull distributions.

a. Exponential

Ten-cell packs having four or more failures were subjected to a significance test which would indicate whether the underlying distribution of cell life is exponential or not. This test* is more effective for a moderate to large sample size. Here it is used to determine approximately how often the failure distribution of the packs differs from the exponential.** The test uses the knowledge that in a replacement situation (1) if one observes a Poisson process for a fixed length of time T and if r events occur in time interval $(0, T)$ at times $t_1 \leq t_2 \leq \dots \leq t_r \leq T$, then $\sum_{i=1}^r t_i$ is approximately normally distributed with mean $\frac{rT}{2}$ and variance $\frac{rT^2}{12}$, and (2) if one observes a Poisson process until a preassigned r failures occur and if the failures occur at $t_1 \leq t_2 \leq \dots \leq t_r$, then $\sum_{i=1}^r t_i$ is approximately normally distributed with mean

$$\frac{(r-1)t_r}{2} \text{ and variance } \frac{(r-1)t_r^2}{12}.$$

*Benjamin Epstein, "Statistical Techniques in Life Testing", PB 171580, April 1959, pages 7-9. Distributed by U. S. Department of Commerce, Office of Technical Services, Washington 25, D. C.

**The probability density function of the two parameter exponential distribution is

$$f(t) = \frac{1}{\alpha} e^{-\frac{(t-G)}{\alpha}}, \text{ where } t \geq G, \alpha > 0, \beta > 0$$

$$= 0, \text{ otherwise}$$

and the associated reliability function is

$$R(t) = e^{-\frac{(t-G)}{\alpha}}, \text{ where } t \geq G, \alpha > 0, \beta > 0$$

$$= 0, \text{ otherwise}$$

G = guaranteed lifetime of a unit or units of interest

α = mean life of the unit (also, graphically, the scale parameter)

t = the specified time of interest.

In the case of non-replacement, we can simply substitute the total life of all units tested to the i th failure, $T(t_i)$, for t_i the i th failure.

The tendency for the test results analyzed herein to follow a particular failure pattern seems to depend heavily on the manufacturer and/or the failure mode. For example, all 12 Gulton packs follow the exponential, while only certain packs of other manufacturers conformed to this distribution. Overall, of the 35 ten-cell packs with four or more failures, the exponential assumption was rejected 51% of the time. This was not surprising due to the varying modes of failure. Attempts to combine packs of homogeneous environments and then to classify cell failure modes into the categories of burn-in, useful life and wearout life were not helpful since it was usually impossible to pinpoint the failure mode primarily responsible for the failure. Thus far failure analysis of the cells has resulted in an array of confounded possible failure causes.

b. Weibull

A more general probability distribution often used to explain failure patterns of items is the Weibull. The exponential is actually a special case of the Weibull. Therefore, when the fit to the exponential is poor, improvements in the accuracy of estimation are usually possible by use of the Weibull.*

Plots of cumulative failure percentage versus time were made on Weibull probability paper, yielding estimates of α and β . These estimates were based on failure data which did not separate failure modes or mechanisms according to types; this factor likely accounts in part for the lack of a good linear fit obtained on some plots. Then by assuming that the manufacturer's guarantee time (G) is zero in each instance and by using the plot estimates of α and β , the reliability (R_t) of the cells for each environment of a particular manufacturer was calculated across various times. These reliabilities are presented in Tables 6, 7, 8, and 9 as the best

*The Weibull distribution has a probability density function of

$$f(t) = \frac{\beta}{\alpha} (t - G)^{\beta-1} e^{-\frac{(t-G)^\beta}{\alpha}}, \text{ where } t \geq G, \alpha > 0, \beta > 0$$

$$= 0, \text{ otherwise}$$

and a corresponding reliability function of

$$R(t) = e^{-\frac{(t-G)^\beta}{\alpha}}, \text{ for } t \geq G, \alpha > 0, \beta > 0$$

$$= 0, \text{ otherwise}$$

G = the guaranteed lifetime of a unit or units of interest

α = the scale parameter of the distribution

β = the shape parameter of the distribution

t = the specified time of interest

$R(t)$ = the reliability or probability of survival of the unit(s) for the specified time t .

TABLE 6

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Estimated Reliabilities for Various Test Environments
(Manufacturer - General Electric 3.0 A. H.)

Ambient Temperature	Depth of Discharge	Orbit Time (Hours)	Number of Cycles of Life Required for which Reliabilities are Given							
			1000	2000	3000	4000	6000	8000	10000	12000
0°	15%	1.5	.99	.98	.96	.95	.93	.91	.88	.86
		3.0	.99	.98	.95	.95	.93	.91	.89	.87
	25%	1.5	.99	.99	.98	.98	.97	.96	.95	.94
		3.0	.98	.95	.93	.91	.87	.83	.79	.75
25°	25%	1.5	1.00 ⁻	1.00 ⁻	1.00 ⁻	1.00 ⁻	.99	.86	.36	---
		3.0	.99	.98	.96	.95	.93	.91	.89	.87
	40%	1.5	1.00 ⁻	1.00 ⁻	.99	.86	.01	---	---	---
		3.0	1.00 ⁻	1.00 ⁻	.97	.87	.28	---	---	---
40°	15%	1.5	.86	.79	.73	.67	.59	.53	.47	.43
		3.0	.90	.60	.29	.10	---	---	---	---
	25%	1.5	.99	.86	.13	---	---	---	---	---
		3.0	.96	.87	.72	.55	.26	.09	.03	---

EXAMPLE: For a battery pack with an environment of 1.5 hours orbit time, 0°C, and 15% depth of discharge, the reliability or probability of survival for 3,000 cycles (1.5 hours each) is estimated to be .96.

NOTE: When the reliability is given as 1.00⁻, the reliability was estimated to be between .995 and 1.000.

TABLE 7

Estimated Reliabilities for Various Test Environments
(Manufacturer - Gould 3.5 A. H.)

Ambient Temperature	Depth of Discharge	Orbit Time (Hours)	Number of Cycles of Life Required for which Reliabilities are Given							
			1000	2000	3000	4000	6000	8000	10000	12000
0°	15%	1.5	.99	.98	.96	.95	.93	.91	.88	.86
		3.0	.99	.98	.97	.95	.93	.91	.89	.87
	25%	1.5	1.00-	1.00-	1.00-	.99	.98	.93	.86	.75
		3.0	.99	.98	.96	.95	.93	.91	.89	.87
25°	25%	1.5	1.00-	.98	.91	.74	.20	.01	---	---
		3.0	1.00-	.99	.89	.49	---	---	---	---
	40%	1.5	.98	.80	.44	.12	---	---	---	---
		3.0	.96	.56	.07	---	---	---	---	---
40°	15%	1.5	.97	.87	.71	.53	.21	.06	.01	---
		3.0	.90	.60	.36	.14	.01	---	---	---
	25%	1.5	.47	.07	---	---	---	---	---	---
		3.0	.55	.27	.13	.06	.01	---	---	---

TABLE 8
Estimated Reliabilities for Various Test Environments
(Manufacturer - Gulton 6.0 A. H.)

Ambient Temperature	Depth of Discharge	Orbit Time (Hours)	Number of Cycles of Life Required for which Reliabilities are Given							
			1000	2000	3000	4000	6000	8000	10000	12000
0°	15%	1.5	.97	.93	.87	.81	.70	.58	.48	.38
		3.0	1.00	1.00	.99	.98	.88	.44	.08	---
	25%	1.5	.98	.93	.88	.81	.67	.54	.41	.30
		3.0	.82	.61	.43	.29	.13	.05	.02	.01
25°	25%	1.5	.74	.61	.52	.45	.35	.27	.22	.18
		3.0	.76	.60	.48	.39	.25	.17	.11	.08
	40%	1.5	.61	.45	.34	.27	.18	.12	.08	.06
		3.0	.80	.73	.68	.64	.58	.53	.49	.46
40°	15%	1.5	.80	.68	.58	.51	.39	.31	.24	.20
		3.0	.72	.19	.02	---	---	---	---	---
	25%	1.5	.40	.28	.21	.16	.11	.08	.06	.04
		3.0	.67	.59	.54	.50	.44	.40	.37	.34

TABLE 9
Estimated Reliabilities for Various Test Environments
(Manufacturer - Sonotone 5.0 A. H.)

Ambient Temperature	Depth of Discharge	Orbit Times (Hours)	Number of Cycles of Life Required for which Reliabilities are Given							
			1000	2000	3000	4000	6000	8000	10000	12000
0°	15%	1.5	.98	.96	.94	.92	.88	.85	.81	.78
		3.0	.99	.98	.96	.95	.93	.91	.89	.86
	25%	1.5	.97	.95	.92	.90	.86	.81	.77	.73
		3.0	.99	.98	.96	.95	.93	.91	.88	.86
25°	25%	1.5	.97	.93	.87	.85	.77	.69	.62	.55
		3.0	.96	.92	.89	.85	.78	.72	.67	.62
	40%	1.5	1.00-	.97	.90	.79	.45	.15	.03	---
		3.0	.69	.64	.60	.57	.53	.50	.48	.46
40°	15%	1.5	1.00-	1.00-	1.00-	.99	.95	.83	.63	.37
		3.0	.93	.85	.78	.71	.59	.48	.39	.32
	25%	1.5	1.00-	.96	.65	.11	---	---	---	---
		3.0	.86	.73	.61	.50	.34	.23	.15	.10

assessments available rather than minimum reliabilities quoted with a high degree of confidence and are useful to compare environmental stresses for various lifetimes of interest. Small sample sizes and lack of information about the failure patterns of cells preclude precise reliability statements made with a high degree of confidence. In instances where the number of failures in a pack was insufficient for plotting, the exponential distribution was used to determine the reliabilities.

3. Importance of Cell Location in Pack

It was conjectured that the location of any particular cell in a pack might contribute to the order and time of failure of that cell. That is, adjoining or surrounding cells might furnish additional stress (temperature, electrical, etc.) as the test progresses or as they fail. The cells of packs of the four manufacturers on which our analysis was centered were initially arranged as indicated in Figure 2 on page 29. The failure data was examined to determine if a non-random pattern of failure order existed. The cell failure order results for each manufacturer are given in Table 10 on page 30; the number given in each category is the cell position.

The analysis performed on this data indicated a slight tendency for centrally located cells to fail early. This tendency was considered too small to include in a model for prediction of cell failure,

B. APPROACHES TO ANALYSIS OF CELL VOLTAGE DATA

1. Comparisons Among Average Times to Discharge of Battery Cells

a. Discussion

One may consider the time that a cell voltage requires to drop from a charged state to some lower specified voltage as a measure of capacity. The study and use of this measure, which can be approximately obtained from available data, has yielded the most promising predictive device to date. It was determined that for most potential early cell failures, the discharge times to some specified voltage (for example, 1.25 volts) after some specified number of cycles are shorter than for cells with relatively long life. Restated, the discharge time tends to decrease as the quality of a cell degrades with time. For an illustration of this, see Figure 3, page 31, where the discharge time (to 1.25 volts) is plotted on the vertical axis as t and the number of cycles is plotted on the horizontal.

The use of 1.25 volts for the determination of the time to discharge is not unique and was chosen only because it allowed analysis over a greater number of data points. It is conceivable that the use of other voltage points might yield even better results and this possibility should be examined.

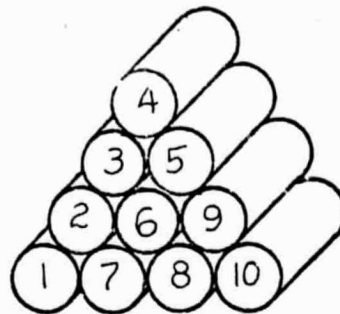
FIGURE 2

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DIAGRAM OF PACK ARRANGEMENTS
(Numbers identify cell position and electrical sequence)



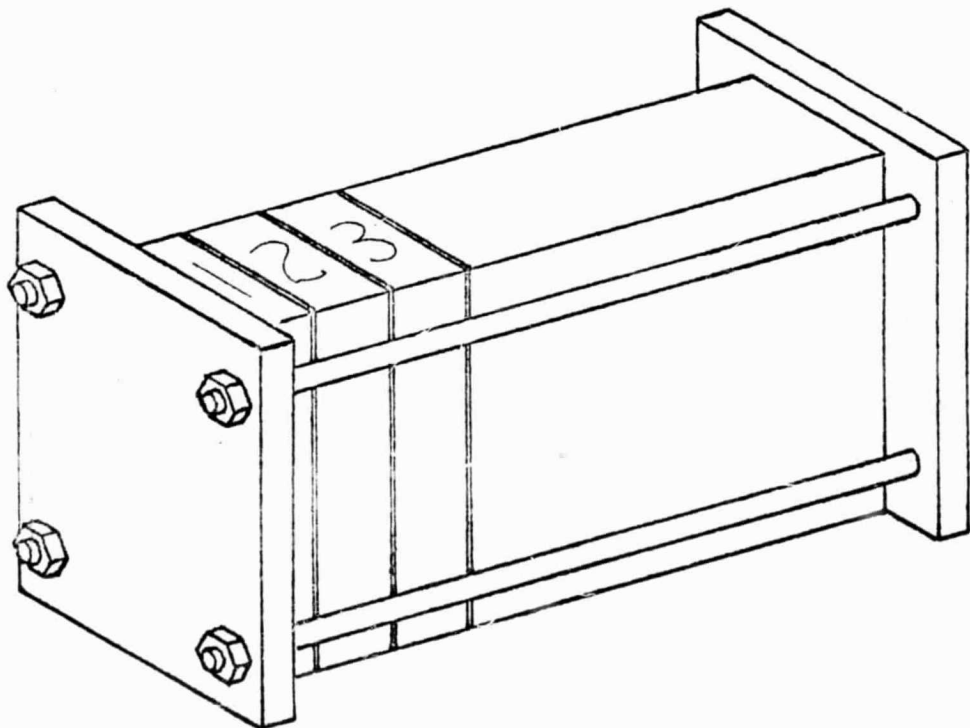
a. G.E. 3.0 ah



b. Gould 3.5 ah



c. Sonotone 5.0 ah



d. Gulton 6.0 ah

TABLE 10

Cell Failure Order

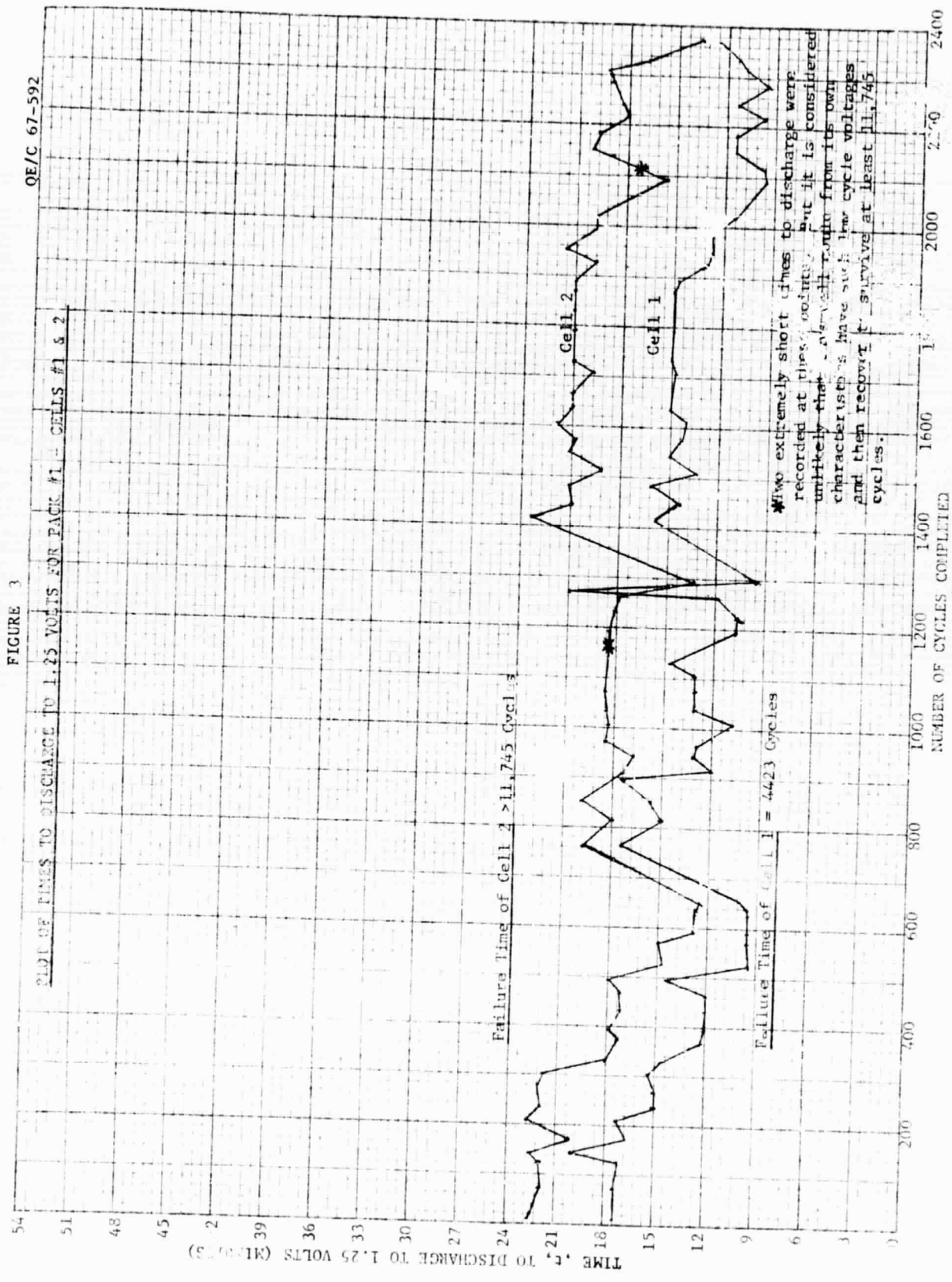
Manufacturer	Pack Number	Ambient Temperature	Failure Order							
			1	2	3	4	5	6	7	8
G. E.	15	25°C	7	8	5	10	4*	9*	--	--
	16	"	7	6	1	5*	10*	4	--	--
	20	"	5	2*	6*	3	4*	9*	--	--
	39	40°C	(2)	6	7	1	5*	8*	--	--
	40	"	3	8*	7*	5	10	2*	6*	--
	43	"	4	3	6	9	7	10	--	--
	44	"	6	8	1*	3*	2*	10*	--	--
	63	0°C	6	--	--	--	--	--	--	--
	"	"	9	--	--	--	--	--	--	--
	68	"	9	--	--	--	--	--	--	--
Sonotone	1	25°C	4	1	6	5	3*	10*	--	--
	2	"	10	5	2	6*	7*	1	--	--
	5	"	2	3	--	--	--	--	--	--
	6	"	8	10	4	9	7	6	--	--
	25	40°C	5	4	1	3	6	2	--	--
	26	"	1	9	6*	7*	3	4	--	--
	29	"	1	7	8	9	5	6	--	--
	30	"	7	4*	9*	8	1*	10*	--	--
	49	0°	9	3	--	--	--	--	--	--
	50	"	5	3	4	--	--	--	--	--
Gould	3	25°C	5	2	9	6	7	4*	10*	--
	4	"	"	8	1	6	3	10	--	--
	7	"	2	1	6	5	7	3	--	--
	8	"	6	8	1*	10*	7	2*	9*	--
	27	40°C	3*	8*	7	10	9	2	--	--
	28	"	(2)	7*	8*	5	10	1*	3*	4*
	31	"	9*	10*	2	3	8	1*	6*	--
	32	"	6	3	1	4*	7*	9	--	--
	51	0°C	10	--	--	--	--	--	--	--
	52	"	8	10	7*	9*	2	--	--	--
Gulton	13	25°C	1	10	5	7	4	2	--	--
	14	"	4*	5*	1	2	3	7	--	--
	17	"	5*	3*	10	1	2	9	--	--
	18	"	6	3	7*	9*	5	1	--	--
	37	40°C	(3)	8	4	10	7	6	--	--
	38	"	(8)	(6)	9	3	5	2	--	--
	41	"	9	6	2	7*	8*	3	--	--
	42	"	(8)	7	9	1	6	4	--	--
	61	0°C	2	8	5	4	10	6	3	1
	62	"	10	4	5	7	--	--	--	--
	65	"	4	6	8	--	--	--	--	--
	66	"	6	8	5	3	7	4	--	--

() These cells failed under the 50° C ambient temperatures prior to the lowering of the temperature to 40° C.

* Indicates simultaneous failures for consecutive cells.

FIGURE 3

PLOT OF PINES TO DISCHARGE TO 1.25 VOLTS FOR PACK #1 - CELLS #1 & 2



In general, cells of the same pack with different failure times will yield curves showing differences in the times to discharge as in Figure 3, page 31. Where the curves deviate from this general pattern it is difficult to explain the behavior of the cells. It is felt that the bulk of the unexpected variation is contributed by the different failure mechanisms operating within a single pack. It is not known how to account for the differences in failure mechanisms since the data limits accurate classification of failure mechanisms and modes. The ability to accurately categorize and describe each failure mechanism and mode would allow considerable improvement in the prediction techniques presented in the following paragraphs.

b. Predicting Order of Failure

The value of t as a predictor is best shown by Pack 1 where, by use of 2,000 cycles of data, the precise order of failure of the six failed cells could have been foreseen. The values of t for each cycling point (the point at which data was recorded) in Pack 1 were determined and the mean ($\bar{t}_i$) was calculated for each cell. Table 11 gives the failure times and the mean $\bar{t}_i$ for each cell.

Data reduction programs were used on IBM 360 computer and similar calculations were made for 16 other packs. The ability to correctly forecast the order or approximate order of pack failures varied from average to excellent for these packs. Obviously, just specifying order of failure is not sufficient since this does not indicate when the cell actually fails. At this juncture, methods were examined to attempt to combine data of the various cells and packs to determine the nature of $\bar{t}_i$ such that the times to failure could be approximated. However, the $\bar{t}_i$ vary considerably from pack to pack since each pack represents a different environment, and attempts to develop factors to normalize the means of all packs have not been successful to date.

Attention was then focused on the development of some predictive technique based solely on the performance of the individual packs.

c. General Procedure for Prediction of Cell Failure Time

The technique chosen was as follows for each pack:

1) The $\bar{t}_i$'s for the ten cells of the pack were assumed to be normally distributed and the mean and variance of the pack were estimated as follows:

$$\hat{\mu}_t = \frac{\sum_{i=1}^n \bar{t}_i}{n}, \quad \hat{\sigma}_t^2 = \frac{\sum_{i=1}^n (\bar{t}_i - \hat{\mu}_t)^2}{n-1}$$

The $\bar{t}_i$'s of a pack for cells with failure times less than 1,000 cycles were not used in these calculations because of their extreme deviations from the pack means. The elimination of these values from the estimates does not

TABLE 11Cell Failure Times and Associated $\bar{t}_1$ for Pack 1

Cell Number (i)	Failure Time (T_1)	$\bar{t}_1$ (minutes)
4	2,995	13.34
1	4,423	13.95
6	7,782	14.78
5	11,361	15.42
10	11,745	16.28
3	11,745	16.33
8	Not Failed	16.42
7	Not Failed	16.71
2	Not Failed	18.08
9	Not Failed	20.36

$\bar{t}_1 = \frac{\sum_{j=1}^m t_{ij}}{m}$, where the t_{ij} are the individual times to discharge to 1.25 volts; m is the number of cycling points where data was available in the interval from 0 to 2000 cycles for the i th cell.

seem to create a problem in prediction since the cells with such low failure times would be detected by a screening process encompassing several hundred cycles.

2) Since the failure times of several of the packs were distributed approximately lognormal (i.e., the logarithms of the failure times tend to give a normal distribution), the logarithms of the actual failure times (T_i 's) were obtained. Where the number of failures were sufficient, a mean ($\hat{\mu}_{F.T.}$) and variance ($\hat{\sigma}_{F.T.}^2$) were estimated from the natural logarithms of the actual failure times.

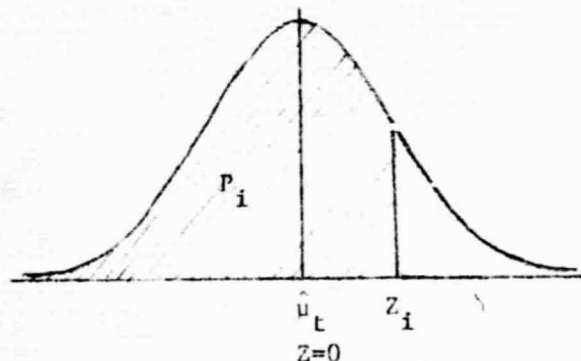
$$\hat{\mu}_{F.T.} = \frac{\sum_{i=1}^n (\ln T_i)}{n}$$

$$\text{and } \hat{\sigma}_{F.T.}^2 = \frac{\sum_{i=1}^n (\ln T_i - \hat{\mu}_{F.T.})^2}{n-1}$$

We now have another approximate normal distribution with mean estimated by $\hat{\mu}_{F.T.}$ and variance estimated by $\hat{\sigma}_{F.T.}^2$. In instances where the failure times are insufficient for estimates of μ and σ , conservative estimates are made.

3) Now for any calculated t_i , the number of standard normal deviates from the mean may be determined from the distribution of discharge times and mapped to the failure time distribution.

FIGURE 4

AREA UNDER THE NORMAL CURVE

The number of standard normal deviates (Z_i) is found by,

$$Z_i = \frac{\bar{t}_i - \hat{\mu}_t}{\hat{\sigma}_t}$$

and the cumulative probability or area, P_i , for the i th battery cell is given by,

$$P_i = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Z_i} e^{-\frac{x^2}{2}} dx$$

4) After determining each of the Z_i , apply these same Z_i to the failure time distributions. From this mapping a predicted failure time may be obtained such that the cumulative probabilities or areas on each distribution are equal.

$$\text{Let } P_i(\bar{t}_i) = P_i(\ln T_i)$$

and

$$Z_i(\bar{t}_i) = Z_i(\ln T_i)$$

Then Z_i may be used to determine a unique $\ln T_i$ for each $\bar{t}_i$ and, hence, a unique T_i , the predicted or estimated failure time for the i th cell having an average time to discharge of $\bar{t}_i$.

$$Z_i = \frac{\text{Est. } \ln T_i - \hat{\mu}_{F.T.}}{\hat{\sigma}_{F.T.}}$$

then $\text{Est. } \ln T_i = Z_i \hat{\sigma}_{F.T.} + \hat{\mu}_{F.T.}$

and $\text{Est. } T_i = \text{antilog}(Z_i \hat{\sigma}_{F.T.} + \hat{\mu}_{F.T.})$

d. Application of Prediction Procedure to a Particular Ni-Cad Battery Pack

As an example of this procedure consider Pack 1 for which the $\bar{t}_i$'s and failure times were given in Table 11. The mean and standard deviation estimates for the distribution of discharge times were calculated to be $\hat{\mu}_t = 16.2$ and $\hat{\sigma}_t = 2.03$ and for the distribution of failure times $\hat{\mu}_{F.T.} = 9.371$ and $\hat{\sigma}_{F.T.} = .814$. The $\bar{t}_i$, the actual failure time, the standard normal deviate, the corresponding estimated $\ln T_i$, and the estimated T_i for each cell are given in Table 12. From Table 12 one can see that the estimates are excellent for most cells with failure times known. The 63,130 cycle life estimate for cell 9 is surely optimistic, but at least does correctly characterize the cell as one with a long life (cells 2, 7, 8, and 9 had not failed at the time the test was stopped).

e. Prediction Summary of All Packs Subjected to this Procedure

A total of 17 packs were processed by this technique. If we assume that a satisfactory cell is one that will last at least 5,000 cycles and anything less constitutes unsatisfactory performance, then we have a basis for judging the value of this procedure for prediction. Of the 51 actual failures (cells with less than 5,000 cycles of life) 39 or 76.5% of these would have been correctly identified as unsatisfactory by use of

TABLE 12
Prediction and Evaluation for Pack #1

Cell # (i)	Actual Failure Time in Cycles for ith Cell (T_i)	Average Time to Discharge ($\bar{t}_i$) to 1.25 Volts for Each Cell	Number of Standard Normal Deviates (Z_i) of $\bar{t}_i$ from the Mean	Estimated $\ln T_i$ Where T_i will be the Estimated Failure Time of the ith Cell	Estimated T_i
4	2,995	13.34	-1.395	8.235	3,700
1	4,423	13.95	-0.891	8.480	4,820
6	7,782	14.78	-0.685	8.813	6,720
5	11,361	15.42	-0.370	9.070	8,690
10	11,745	16.28	0.054	9.415	12,270
3	11,745	16.33	0.079	9.435	12,500
8	>11,745	16.42	0.123	9.471	12,980
7	>11,745	16.71	0.266	9.588	14,590
2	>11,745	18.08	0.942	10.138	25,140
9	>11,745	20.36	2.066	11.053	63,130

The estimated parameters of the two distributions are as follows:

$$\hat{\mu}_t = 16.2, \quad \hat{\sigma}_t = 2.03$$

$$\hat{\mu}_{F.T.} = 9.371, \quad \hat{\sigma}_{F.T.} = .814$$

2,000 cycles of testing. For the 170 cells from the 17 packs, failure times of 16 cells were not known as these cells were not tested to failure. Since the original failure rate for a minimum life of 5,000 cycles is 33.1% (or 51 failures of 154), this prediction or screening procedure could have reduced the failure rate to 11.9% (or 12 failures of 101).

If, instead of 5,000 cycles, we require that a cell defined as good will last at least 10,000 cycles, we can once more evaluate the prediction system. Of the 74 failures, 64 (86.5%) would have been identified. The failure rate of 74.0% could have been reduced to 32.3% by screening out those cells identified as bad by use of the discharge times.

It should be noted that it is not expected, nor should it be, that point estimates of failure times be within a few percent of the actual failure times. This system uses statistical tools to improvise decision-making criteria, but due to deficiencies of the data, no attempts are made here to develop confidence statements on the estimates. Tables 13 and 14 give a detailed breakdown for each of the 17 packs and categorize whether the proper decision would have been made for each cell and indicate how close the estimate would have been for cells defined as good. Table 13 uses 5,000 cycles as the minimum acceptable life and Table 14 uses 10,000 cycles.

Preliminary examination of the data indicated that results with this prediction system would not be good if the number of test cycles used for prediction was less than 2,000 cycles. However, summarization where accumulated test information for 1,000 cycles of testing was used has revealed that faulty cells can be separated from the higher quality cells.

If the life requirement of a good cell is again considered to be at least 5,000 cycles, 37 (72.5%) of the 51 actual failures would have been correctly identified after 1,000 cycles of test. The present failure rate of 33.1% for a minimum life of 5,000 cycles would have been reduced to 14.0% by detecting 72.6% of the inferior units.

If the life requirement is set at 10,000 cycles, 67 (90.5%) of the 74 cells with a life less than 10,000 cells would have been correctly identified. The initial failure rate of 74.0% would have been reduced to 24.1% at the expense of only four good units which would have been inadvertently classified as bad. Tables 15 and 16 give a breakdown of the prediction results for each pack examined. Table 15 assumes 5,000 cycles as the minimum acceptable life and Table 16 assumes 10,000 cycles. Table 17 gives a summary of all the four different situations examined, minimum acceptable lives of 5,000 and 10,000 cycles for each of 1,000 and 2,000 cycles of testing.

2. Correlation of End of Discharge Voltages with Failure Times

Through at least portions of the life of a cell there exists a significant correlation between the number of cycles completed and the end

TABLE 13

Evaluation of Predictions for a Minimum Acceptable Life of 5000 Cycles Based on 2000 Cycles of Voltage Data

Pack No.	Frequency of Wrong Decisions		Frequency of Correct Decisions When			No. of Cells Prediction System Would		Total Cells That Could Be Evaluated
	Retain Bad Cell	Discard Good Cell	Magnitude of Prediction Error is		Discard	Retain		
			≤2000 Cycles	>2000 Cycles				
							No. Known	
1	0	0	5	1	4	2	8	10
2	1	0	5	0	4	2	8	10
4	0	0	6	0	0	6	0	6
5	0	2	2	0	6	3	7	10
13	1	0	4	1	0	5	1	6
19	0	2	0	0	8	2	8	10
25	0	0	5	1	4	0	10	10
29	2	1	2	2	3	3	7	10
37	1	2	4	0	3	6	4	10
39	1	1	3	1	4	3	7	10
42	2	0	4	0	0	4	2	6
51	0	1	0	1	8	1	9	10
61	2	2	5	0	1	6	4	10
62	0	0	3	1	6	3	7	10
65	0	2	1	2	5	2	8	10
66	2	0	2	2	0	4	2	6
68	0	1	0	1	8	1	9	10
TOTAL	12	14	51	19	64	53	101	154

TABLE 14

Evaluation of Predictions for a Minimum Acceptable Life
of 10,000 Cycles Based on 2,000 Cycles of Stage Data

Pack No.	Frequency of Wrong Decisions		Frequency of Correct Decisions When			No. of Cells Prediction System Would		Total Cells That Could Be Evaluated
	Retain Bad Cell	Discard Good Cell	Magnitude of Prediction Error is		Discard	Retain		
			≤2000 Cycles	>2000 Cycles				
							Not Known	
1	0	1	5	0	4	4	6	10
2	0	0	5	1	0	6	0	6
4	0	0	6	0	0	6	0	6
5	0	0	2	0	0	2	0	2
13	0	0	6	0	0	6	0	6
19	0	0	0	0	0	0	0	0
25	2	0	4	0	0	4	2	6
29	0	0	2	4	0	6	0	6
37	0	0	4	2	0	6	0	6
39	2	0	2	2	0	4	2	6
42	0	0	4	2	0	6	0	6
51	0	2	0	0	8	2	8	10
61	2	2	4	1	1	7	3	10
62	1	0	3	0	6	3	7	10
65	2	0	1	0	0	1	2	3
66	0	0	2	4	0	6	0	6
68	1	0	0	0	0	0	1	1
TOTAL	10	5	50	16	19	69	31	100

TABLE 15

Evaluation of Predictions for a Minimum Acceptable Life
of 5000 Cycles Based on 1000 Cycles of Voltage Data

Pack No.	Frequency of Wrong Decisions		Frequency of Correct Decisions When		No. of Cells Prediction System Would		Total Cells That Could Be Evaluated	
	Bad Cell	Good Cell	Magnitude of Prediction Error is	Discard	Retain	Discard		
	Cycles	Cycles	Cycles	Cycles	Cycles	Cycles		
1	0	0	4	2	4	2	8	10
2	2	2	2	2	2	3	7	10
4	0	0	5	1	0	6	0	6
5	0	1	2	0	7	2	8	10
13	1	0	5	0	0	5	1	6
19	0	2	0	0	8	2	8	10
25	0	1	5	1	3	1	9	10
29	3	1	2	1	3	2	8	10
37	1	1	3	1	4	5	5	10
39	1	1	3	1	4	3	7	10
42	0	0	4	0	0	4	2	6
51	0	2	0	0	8	2	8	10
61	2	1	5	0	2	5	5	10
62	1	0	2	1	6	2	8	10
65	0	3	0	2	5	3	7	10
66	1	0	4	1	0	5	1	6
68	0	2	0	1	7	2	8	10
TOTAL	14	17	46	14	63	54	100	154

TABLE 16

Evaluation of Predictions for a Minimum Acceptable Life
of 10,000 Cycles Based on 1,000 Cycles of Voltage Data

Pack No.	Frequency of Wrong Decisions		Frequency of Correct Decisions When Magnitude of Prediction Error is			No. of Cells Prediction System Would		Total Cells That Could Be Evaluated
	Retain Bad Cell	Discard Good Cell	≤2000 Cycles		Not Known	Discard	Retain	
			>2000 Cycles	Cycles				
1	0	1	4	1	4	4	6	10
2	0	0	2	4	4	6	0	6
4	0	0	5	1	0	6	0	6
5	0	0	2	0	0	2	0	2
13	0	0	6	0	0	6	0	6
19	0	0	0	0	0	0	0	0
25	2	0	4	0	0	4	2	6
29	0	0	2	4	0	6	0	6
37	0	0	3	3	0	6	0	6
39	1	0	3	2	0	5	1	6
42	0	0	4	2	0	6	0	6
51	0	2	0	0	8	2	8	10
61	1	1	5	1	2	7	3	10
62	1	0	2	1	6	3	7	10
65	1	0	1	1	0	2	1	3
66	0	0	4	2	0	6	0	6
68	1	0	0	0	0	0	1	1
TOTAL	7	4	47	22	20	71	29	100

TABLE 17

Summary of Prediction and Screening Technique

	Results Using 1000 Cycles of Test Data For A Minimum Acceptable Life of		Results Using 2000 Cycles of Test Data For A Minimum Acceptable Life of	
	5,000 Cycles	10,000 Cycles	5,000 Cycles	10,000 Cycles
Original Failure Rate	$\frac{51}{154}$ (33.1%)	$\frac{74}{100}$ (74.0%)	$\frac{51}{154}$ (33.1%)	$\frac{74}{100}$ (74.0%)
New Failure Rate By Screening Based on Prediction Results	$\frac{14}{154}$ (1/.0%)	$\frac{7}{29}$ (24.1%)	$\frac{12}{101}$ (11.9%)	$\frac{10}{31}$ (32.3%)
Number of Bad Battery Cells Retained	14	7	12	10
Number of Good Battc.y Cells Discarded	17	4	14	5
Percentage of Correct Decisions	$\frac{123}{154}$ (79.9%)	$\frac{89}{100}$ (89.0%)	$\frac{128}{154}$ (83.1%)	$\frac{85}{100}$ (85.0%)

of discharge voltage. The tendency is for the end of discharge voltage to decrease as the life of the cell increases.

Figure 5 (page 44) shows typical discharge-charge voltage curves of cell 5, Pack 2, for cycles 906 and 1623 and, along with Figure 6 (page 45), illustrates the degradation of voltages as the number of cycles increase. Figure 7 (page 46) depicts the gradual decay of the end of discharge voltage for the same cell.

To study the relation between end of discharge voltage and cell life, regression analysis techniques were applied to the end of discharge voltages of each pack cell. It was concluded that the data would fit a straight line more consistently than any non-linear function. The parameters a (y-intercept) and b (slope) from equations of the type $y = a + bx$ were estimated for cells of several packs. Here the dependent variable y is the end of discharge voltage while the independent variable x is the number of cycles from zero to failure. (For example, the equation of the best linear fit from the data plotted on Figure 7, page 46, is given by $y = 1.202 - 0.000039x$). Voltages less than .50 were not included in the least squares fitting of the data to avoid distortion of the line.

By examining the magnitudes of the slopes for various cells, the order of failure of the cells could be predicted with some success. This relation is best shown for Pack 1 by Table 18.

After the failure times of cells 9, 7, 8, and 2 were set at the conservative figure of 11,745 cycles, the correlation was computed to be .97. A perfect correlation or relationship would be indicated by 1.00.

This same procedure of obtaining the slopes and correlating with failure time was utilized on cells of several packs with lower resulting correlation for data 1) from zero cycles to 1,500 cycles, 2) from 600 cycles to 1,500 cycles, and 3) from zero to failure. The computer results for these operations yielded the correlations as given in Table 19 which shows the inconsistency of the end of discharge voltage as an indicator or predictor of cell failure.

For certain of the packs investigated, it is clear that the slopes do indicate a tendency to failure. But the tendency to failure is best indicated by using all the failure data rather than just the first few hundred cycles of data. Hence, the results of this method were not incorporated into a model for prediction. However, if new data with more frequent data points is obtained, further investigation of the slopes is warranted. Certain portions of the end of discharge curve could yet prove to be a valuable indicator of early failure and programs are readily available to make such calculations.

3. Areas Under Discharge-Charge Profile

The voltage degradation and rebuilding of the discharge-charge curve (as shown in Figures 5 and 6, pages 44-45) prompted an investigation

P	total pressure, psia
p	static pressure, psia
Q	mass rate of flow, ft^3/sec
r	radius, ft.
R_c	streamline radius of curvature, ft.
Re	blade chord Reynolds number
s	blade spacing, in. (Fig. 3)
t	blade thickness, in.
u	induced velocity normal to streamline, ft/sec
V	fluid velocity, ft/sec
w	induced velocity in the spanwise direction, ft/sec
x	coordinate direction
z	coordinate direction
α	slope of streamline in meridional plane, $\arctan (V_r/V_z)$, deg.
β	flow angle, angle between flow and axial direction, deg.
Γ	blade circulation (Eq. 6)
γ	blade stagger angle, angle between chord line and axial direction, deg (Fig. 3)
δ	deviation angle, deg. (Fig. 3)
δ_0	reference deviation angle for zero camber, deg.
$(\delta_0)_0$	reference zero camber deviation angle for NASA 65-series blade section with $t_{\max}/c = 0.10$, deg.
δ_1	boundary layer thickness, in.
$\delta_{AVR=1.0}$	deviation angle for plane, two-dimensional cascade flow ($AVR = 1$), deg.
ϵ	flow turning angle $\beta_1' - \beta_2'$, deg.
ζ	flow angle projected onto the stream surface normal to the blade leading edge, deg.
η	angle between the normal to the Bernoulli surface and principal normal to streamline, deg. (Fig. 17)

θ	coordinate in tangential direction
κ	blade angle, angle between tangent to blade mean camber line and axial direction, deg. (Fig. 3)
λ	sweep angle, deg. (Fig. 28)
μ	projection of λ into meridional plane, deg. (Fig. 30)
ν	dihedral angle, deg. (Fig. 28)
ξ	streamwise component of vorticity, sec^{-1}
ξ_1	component of vorticity normal to streamline, sec^{-1}
ρ	fluid density, lb_m/ft^3
τ	angle between blade axis and radial direction projected into $r - \theta$ plane, deg. (Fig. 30)
T	angle of attack
σ	blade solidity, c/s
ϕ	velocity potential
ϕ^0	blade camber angle, $\kappa_1 - \kappa_2$, deg. (Fig. 3)
ψ	stream function
W	axial velocity density ratio
$\bar{w}$	total pressure loss coefficient, $\frac{P_{2,id} - P_2}{P_1 - P_1}$

Subscripts

b	plane b (Fig. 12)
c	leakage secondary flow
cor	corrected
e	blade element
i	induced by secondary flow
id	ideal
j	summation index
m	mean
max	maximum
min	minimum
n	component of secondary flow normal to streamline and tangent to the axisymmetric stream surface, (Fig. 25)

nom	at nominal incidence angle
r	radial direction
ref	reference (Fig. 6)
s	secondary flow
v	primary flow
VA	actual flow
x	x-coordinate direction
y	y-coordinate direction
z	axial direction
θ	tangential direction
1	cascade inlet
2	cascade outlet
2D	two-dimensional
∞	vector mean of inlet and outlet value

Superscripts

'	relative to moving blade
-	circumferential average
$\rightarrow$	vector quantity
A	average over streamtube

APPENDIX - CASCADE CONFIGURATION VARIABLES AND FLOW PARAMETERS

Starred items* in these tables are significant only when cascade flow is not two-dimensional (uniform entrance conditions, exit/entrance density-axial velocity ratio = 1.0).

TABLE 1 - CASCADE CONFIGURATION VARIABLES

BLADE SECTION GEOMETRY

Camber Line Form

Chordwise location of maximum camber
Value of maximum camber (or camber angle)

Basic Profile Form

Chordwise distribution of profile thickness
 $\frac{\text{maximum thickness}}{\text{chord length}}$ ratio value
Leading-edge radius
Trailing-edge radius or thickness

Manufacturing Tolerances

Profile errors
individual coordinate
surface contour waviness
Surface finish

BLADE CHORD ANGLE $\neq$ STAGGER ANGLE

SOLIDITY

MISCELLANEOUS CASCADE GEOMETRY

Blade Leading-Edge Sweep	
Blade Aspect Ratio*	
Spanwise Blade Section Variation*	} Annular cascade
Blade twist*	
Dihedral*	
Tip Clearance	

Row Spacing in Direction Perpendicular to Leading-Edge Plane	} Tandem cascades
Relative Orientation of Rows in Direction Tangential to Leading-Edge Plane	

FLOW CONTROL SYSTEMS

Variable-Geometry Blading

Flaps

Slots

Boundary-Layer Control

Suction

Blowing

TABLE 2 - CASCADE FLOW PARAMETERS - INDEPENDENT VARIABLES

THERMODYNAMIC PROPERTY CHARACTERISTICS OF WORKING FLUID

Entrance Total Pressure and Temperature

Fluid Specific Heat Ratio

ENTRANCE FLOW CHARACTERISTICS

Entrance Mach Number

Cascade Reynolds Number

Spanwise Distribution of Entrance Velocity (Shear Flow)*

Time Variation in Entrance Velocity and Flow Angle

Magnitude of variation

Frequency of variation

Form of variation (time profile)

ENTRANCE TURBULENCE CHARACTERISTICS

Intensity

Scale

Isotropy

INCIDENCE ANGLE

CASCADE DENSITY $\times$ AXIAL VELOCITY RATIO*