COMPUTER METHODS
for the
REDUCTION, CORRELATION AND ANALYSIS
of
SPACE BATTERY TEST DATA

PHASE 2

FINAL REPORT PART 1

November 1, 1967—December 31, 1967

by

J. W. MAUCHLY

J. H. WAITE

S. D. EPSTEIN

Prepared for

GODDARD SPACE FLIGHT CENTER

Greenbelt, Maryland

CONTRACT NAS 5-10203

MAUCHLY SYSTEMS, INC.

MONTGOMERYVILLE INDUSTRIAL CENTER

Montgomeryville, Pa.

FINAL REPORT
PART I

for
NiCd SPACE BATTERY TEST DATA
ANALYSIS PROJECT
PHASE 2
(November 1, 1967 --- December 31, 1967)

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APPROVED: J H Waite

J. H. WAITE
Project Manager

PREPARED BY

MAUCHLY SYSTEMS, INC.
for
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

ATTENTION: Mr. Eugene R. Stroup
Project Engineer

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DISCLAIMER

The material in this report deals with the evaluation of data taken from items manufactured by different companies. This evaluation should not be construed as an endorsment or rejection of any manufactured item or method of manufacture. The thrust of the evaluation is critical for the purpose of suggesting ways to improve the items envolved through research and development, from which all manufacturers can equally profit.

ABSTRACT

Batteries have assumed a new importance for spacecraft since they are often their only source of power, charged perhaps by solar cells. NASA initiated massive battery testing at the NAD Quality Evaluation Laboratory in Crane, Indiana in the 1960s. The voluminous Crane data has helped establish procedures and outline the problem araes for battery R & D. The current effort is devoted to applying sophisticated mathematical statistical analysis and pseudo-cryptanalytic this effort since they are ideally suited to dealing with very large amounts of data. The theroretical investigation led to establishing indicators applicable to charge-discharge measurements by which life expectancy could be predicted. The three main computer methods developed for cell-life prediction are: first-difference voltage histograms that establish the slopes of the charge-discharge curves between individual monitor points on a set of Crane data cycles; superimposed charge-discharge curves; and frequency count/thresholds that establish voltage thresholds and counts the frequency as a given cell passes through it. Combinations of these predictive techniques on a computer with a simple Boolean "and" logic gives the best overall predictive technique. Specific examples are given of each method and various combinations thereof, using 600,000 punched cards of battery testing from the Crane data base. In general, the conclusions of this part of the investigation are that cell-life prediction is feasible with a 1% sample out of 30,000 cycle charge-discharge lifetime history. Recommendations are also made to improve the initial data-gathering techniques to facilitate similar future analyses of large-volume statistical data on cells.

A pseudo-cryptanalytic method of analysis is then performed on the English language post-mortem remarks that describe the reasons for each cell failure. The assumption is that these data contains hidden information secreted within the remarks which cryptanalytic techniques can recover. Analyzing frequencies of occurrence of failure conditions, and also of multi-gram combinations of these failure conditions, as coded from the English language post-mortem remarks, does indeed give much new, otherwise overlooked information about the conditions of cell failure. This information related manufacturers and other operational variables, leading to the establishment of new criteria for cell design.

SECTION I

INTRODUCTION

A. GENERAL BACKGROUND

The first man-made satellite provided dramatic evidence of the critical importance of batteries as a reliable source of power. The entire world heard the faltering signals of this first satellite but did not realize that a multi-million dollar space program hinged on this most taken-for-granted item. Overnight, battery testing and evaluation became the first order of business to try and analyze their performance and to establish criteria for their development. Initially, battery testing was conducted in the traditional way: cells of different types and manufacturer were charged and loaded, and their various changes in characteristics were measured and compared. The main problem was to match the cell characteristics with the spacecraft power requirements--but since spacecraft were in their infancy, their requirements were still vague.

By the early 1960s NASA realized that it was essential to begin a more comprehensive battery testing program with the ultimate goal of developing techniques using the most modern scientific data processing methods available. They initiated a program of battery testing on sealed nickel-cadmium cells under different environmental conditions. The program was conducted by the Secondary Battery Section of the Quality Evaluation Department of the Naval Ammunition Depot in Crane, Indiana (hereafter called the Crane program). This program began to generate and accumulate data and to analyze cells for the purpose of quality control and proposed manufacturing developments leading to better and more reliable batteries.

The function of the Crane program was to provide information about secondary spacecraft cells, including their performance characteristics and limitations. This information was used by spacecraft power-systems planners, designers, researchers and equipment integration teams. In addition weaknesses in cell design, discovered at Crane, were used to guide research and development efforts toward improving the reliability of space batteries. Some of the space programs using batteries which were studied and improved by using the Crane data include the IMP, NIMBUS, OGO and OAO satellites. The Appendix outlines the details of the Crane program, and it evaluates alternative data acquisition methods.

In time, the data flowing from the Crane program became so voluminous that it became obvious that more sophisticated methods would have to be employed for its reduction and analysis. The present approach began with the hopes that the new techniques of mathematical statistics could be put to good use, especially using the computer as an adjunct, a device with the capacity for handling large quantities of information. Some statistical analysis techniques considered initially were the principle of least squares, chi-squared tests, Kolmogorov-Smirnov testing and Wiener's time-series or auto-correlation analysis. *

* Johnson and Leone, Statistics and Experimental Design in Engineering and the Physical Sciences, Two Volumes, New York, John Wiley and Sons, 1949.

B. ESTABLISHING CRITERIA FOR CELL PREDICTION AND ANALYSIS

Two basic approaches emerged for guiding battery research in general: the Probabilistic approach in which some of the batteries out of a group are life tested in order to predict the life of the remainder in that group; and the Deterministic approach in which each cell in a group is tested a little to predict its life expectancy. These approaches both have their obvious drawbacks: it is not easy to determine the most meaningful size of the data sample in the Probabilistic approach; and the Deterministic approach slightly drains each battery, and a small test does not assure the future life expectancy to presist.

Empirically examining the actual data convinced the investigators that the Probabilistic approach on the data accumulated by the Crane program would indeed result in considerable information not previously recognized by conventional data-reduction techniques. It was necessary, however, to establish special new criteria in order to make any meaningful data reduction from this corpus of data. A simple charge-discharge curve did not take into account the effects of temperature which had the action of elevating or depressing the cell voltage curves in the Crane measurements. Data taking variance was reduced by plotting a distribution of the first differences occurring point by point in the voltage change. The distribution curve, however, required a number of cycles of data. Second Differences could also be examined, much as second differentials are examined in calculus, to determine inflections in the data which may be significant.

Statistical indications derivable from the given Crane data were assumed to contain information which could lead to a determination of the mode of failure, in terms of the chemistry and physical construction of the battery. The problem of developing the most meaningful indicators to be applied in a Probabilistic fashion to the Crane data was investigated. Previous work in analyzing the Crane data had arrived at seven statistical indicators of possible future failure in the cells.* Using the following symbols:

f = frequency count

c_f = frequency count for charge portion of cycle

d_f = frequency count for discharge portion of cycle

f_{ij} = frequency for each V against cell number

where

i = cell number

j = measure of difference between two successive voltage readings,

the following expressions describe the indicators:

1. $$c_{f_{i9}} \Big/_{i=1}^{10} = \max.$$

* Schulman, I., Correlation of Data from Tests on Nickel-Cadmium Batteries, Final Report, Nov. 1965, Contract NASW-1001, NASA (RCA), pp. 25-29.

(Read this expression: Look at frequency counts for charge only and for V = 9 only, and select the maximum out of all ten cells.)

2. $$c_{f_{i0}} \Big/ \sum_{i=1}^{10} > K \ ,$$

3. $$\sum_{j=6}^{9} c_{f_{ij}} - \sum_{j=1}^{2} c_{f_{ij}} \Big/ {}_{i\,=\,1}^{10} \geq 0,$$

4. $$\sum_{j=1}^{9} \left(j \times c_{f_{ij}} \right) \Big/ {}_{i=1}^{10} \longrightarrow \text{max.},$$

5. $$d_{f_{k_i}} \Big/ {}^{j=10}_{\substack{j\,=1 \\ j\,=2,\,3}} \longrightarrow \text{max.},$$

6. Several simple inequalities, such as a high occurrence of V = 0.8 as compared to occurrences of V = 0.2, used as indications of failure.

7. $$\sum_{j\,=\,1}^{j\,=\,9} \left(\Delta V_j \times d_{f_j} \right) \longrightarrow \text{min.}$$

It became clear from this previous work that different failure modes affected different indicators, making it desirable to construct a point system and thresholds for the number of occurrences of each indicator in the development of reliable prediction filters.

C. WORK PERFORMED

a. Theoretical Investigations

The theoretical effort at the beginning of the current work was devoted to refining the criteria for arriving at practical schemes by which the empirical data could be made to yield the most information possible. The major problem area was to determine simple and effective ways to handle a very large bulk of data, in particular the 600,000 punched cards produced by the Crane program. It was important to find ways to reduce the volume of this data, without introducing significant distortions or overlooking important data, so that critical scanning of the data would be economically feasible or physically possible within a reasonable length of time. Reduction, of course, simplifies the analysis and helps lead to accurate prediction methods for selecting reliable cells or cells which are apt to fail.

The problem of discovering ways to validate the various statistical methods devised was attacked first, trying to find ways to identify significant changes in the data. These changes, or indicators, resulted when three methods of analysis were applied: the voltage-difference histogram, the superimposed charge-discharge curve comparison method, and the frequency count/threshold analysis method. These indicators supplement the straightforward voltage level criteria usually applied to determine cell life predictability.

Next for evaluation was the possibility of applying cryptanalytic techniques to the English post-mortem information included in the Crane program. These data are formulated after each failing battery is removed from cycling and dissected. This information is a straightforward description of what is visually observed about the failure characteristics. Implicit in this approach are the following five assumptions.

1. That the Crane data does contain information discernible by appropriate analysis methods.

2. That new techniques are needed since the classical statistical methods used in the past have not been very successful or reliable.

3. That defects in cells, and incipient cell failure, are reflected in their operational behavior long before failure.

4. That the optimum information elements which reflect these conditions are unknown.

5. That reliable cell selection and prediction capabilities will result from the identification and correlation of the information elements.

b. Testing Cells to Predict their Life

There are many reasons to test cells in an attempt to predict their life expectancy, and generally to attempt to improve the results of future research and development into batteries. The following reasons clearly define the boundaries of testing secondary spacecraft cells.

1. Cells are evaluated by testing:
   - (A) To compare the performance of cells produced by various manufacturers.

(B) To evaluate "improvements" in cell design and material.
(C) To determine the operational life expectancy of cells, relative to mission requirements and constraints.
(D) To determine the operating characteristics of Space cells.
(E) To establish non-destructive maximum and minimum operational limits.
(F) To establish criteria for reliable cell acceptance and/or selection.

2. Battery packs are evaluated:
   (A) To evaluate the "cell-set" performance.
   (B) To evaluate the stress' and strains resulting from partial pack failure.
   (C) To determine the pack life expectancy.
   (D) To establish accurate cell-matching procedures to improve pack performance and life.

3. Electrical power systems for spacecraft are evaluated:
   (A) To evaluate the performance of control logic.
   (B) To correlate and match power capability with mission requirements and environment.
   (C) To optimize component design.

4. The test systems themselves are tested and evaluated:
   (A) To evolve a more flexible system for testing that is adaptable to new test variables.
   (B) To determine if the inclusion of an electronic computer will generate more and better data at a lower cost per data unit.
   (C) To determine the possibility that the acquisition of critically accurate data will improve the analysis methods and lead to an early predictive capability regarding possible cell failure.

c. Optimum Utilization of Data

The reduction process applied to the 600,000 punched cards from the Crane program was reduced to 20,000--30 to 1. During the reduction process cards were discovered out of order, duplications occurred, missing cards became obvious, and data errors appeared. The computer programs used to accomplish data reduction were designed to check for various types of errors, to take action to eliminate those which were easily corrected, and to produce error messages showing what type of error was encountered. With some error types, for example -- "Cards out of order", an option permitted operator intervention (to re-sort the cards), to correct the error condition.

For reasons determined during the theoretical investigation it was decided that the cell voltage measurement data included the vital information on cell behavior from which predictions could be made. The voltage patterns were therefore indicative of incipient failure in the cells, and the methods for discovering significant variations in the patterns began with the 5-cycle delta-volt histograms. This method took the Crane program data as an input and produced the first difference voltage histograms. These histograms contain all of the voltage difference information for each identified cell for a set of five observed cycles of data. Another computer program for reduction and analysis of the Crane data is the Superimposed Curve-pattern Indicator Program. This program creates overlayed or superimposed sets of charge-discharge cycle curves. These are then analyzed for patterns which are associated with a history of high occurrence in failed cells. Thirdly, the threshold/frequency analysis method that uses distributions of voltage measurements in the Crane data was applied by a computer program. These methods, either singly or in combination with the application of a simple "and" logic on the computer, enabled the selection and prediction of spacecraft cells with a much higher reliability than is available by any current method.

To be useful for these analysis techniques, the test information went through the following processing programs.

1. The test data were utilized to monitor and validate the functions of the test control facilities.
2. The data were sampled and compared, cycle to cycle, for measurable changes in performance.
3. Life distributions were established.
4. The data were used to establish characteristic behavior for voltage and temperature measurements.

This method seemed to lead to the optimum utilization of the given data, and the results of analysis would be more significant if the data itself is improved (see the recommendations for improving this data in Section V and the Appendix.)

This final report has been prepared in two sections: Part 1 and Part 2. This section, Part 1, contains a discussion of the work done under this contract and the conclusions and recommendations based thereon. Part 2 contains tabular listings of the computer programs developed under this contract along with the operating instructions and examples of data and analysis results. Most of the computer programs are written for the IBM 1620; one program, in FORTRAN IV, is for the IBM 7040. Part 2 of this final report is available at a nominal price from the National Aeronautics and Space Administration, Scientific and Technical Information Facility, College Park, Maryland 90740.

SECTION II

THEORETICAL INVESTIGATIONS

A. INTRODUCTION

Reducing a large body of data to significant indicators for prediction purposes is a problem which many disciplines encounter. Noisy data bases occur in almost all phases of modern science, including the social sciences. A scientist can collect all of the observable data in a given subject or field, and create an hypothesis to account for the distributions or accumulations of order that become apparent, but he must be able to make significant predictions from his hypothesis before it can be considered meaningful. Mathematically the problem lies in the middle ground between statistical and combinatorial analysis, especially when the data reaches very large proportions with many variables. When distributional analysis results in low figures there is usually insufficient basis for using standard statistical techniques. And when the number of combinations of the variables becomes inordinately large, standard combinatorial analysis does not suffice to reduce the gaming or probablematic challenge of the data.

Since the Crane data, or any other type of similar data derived from many components with many variables contributing to their functioning or mal-functioning, clearly falls into the category of large combinatorial variables, it was realized that new methods of analysis would have to be discovered for economically feasible data reduction. The original intuition was to use cryptanalytic methods. The data in this case appeared like a vast code holding secrets that would require the best cryptanalyst to decipher.

Two basic types of data were available from the Crane program (see the Appendix): first, numerical data accumulated when banks of cells were cycled through predetermined periods of time (called orbits), during which charge-discharge voltage-level values were recorded, and second, English descriptions of the conditions of failure in each cell that becomes inoperative. The numerical data lends itself to the more conventional mathematical approach used in some deciphering techniques. The English cell-failure post-mortem data, however, would have to be handled in a different way--perhaps in the more traditional cryptanalytic method of deriving the frequencies of occurrence of elements, the monogram frequencies, and further combinations of these elements, the so-called n-gram analysis technique.

B. PREVIOUS ATTEMPTS AT STATISTICAL PREDICTION

The mathematical approach used in the past for predicting trends in statistical data, not employing cryptanalytic methods, was first evaluated. Logical combinations of given conditions with significant distributions for translating and defining logical connectives appears to be a valid way to develop a theory of finite sets. The outcome and conditions of such an analysis and theory can be considered to be a sub-basis of a topology on the sets of the given subjects. With some modification of a standard method for forming a matrix it is possible to begin to develop a complete structure of a topology leading to a working hypothesis.

For example, a screening methodology developed by the scientists at the Battelle Memorial Institute to predict the quality of NPN small-signal transistors, based on measurements of many different parameters, appears to be as good a result as can be expected from straight mathematical combinatorial analysis prediction.* They used a set of 120 NPN small-signal transistors, operated at 100°C, at full power dissipation for approximately 1000 hours, as the data base. Nine different parameters were measured, two of which were found to be good predictors of the future quality of the transistors. Based on measurements available after 100 hours of operation the reliability screening criterion correctly predicted the quality of 109 transistors (91%), at 1000 hours of operation. Only 3 of the 60 failures (5%), at 1000 hours, were not predicted by the screening criterion. The corresponding expected values of these probabilities of correct prediction were calculated and found to be 87% and 13%. This is a partial verification of the screening criterion. Further reductions in the probability of missclassifying a potential failure can be made by adjusting the critical value of the screening criterion. These results suggest that the reliability screening criterion may be a useful technique for improving the reliability of electronic components.

C. STATISTICAL VALIDATION OF HYPOTHESES

As data becomes available for use and bits and pieces of information are extrapolated from the identified differences and patterns, various assumptions must be made regarding operational parameters and conditions. Some statistical tests of the hypotheses are now required in order to evaluate the significance of the assumptions within the structure of the data. Because, by definition, the methods of non-parametric statistics do not require the assumption of normality; and the non-parametric tests are often applicable to crude or dirty data, involving rankings (ordinal scales); these methods were chosen to establish a basis for more refined and sophisticated subsequent analysis techniques.

* Thomas, Dr. R. E., "Component-Part Screening Procedures Based on Multi-Parameter Measurements", IRE Trans. on Component Parts, Vol. CP-6, No. 4, December 1959

The Mann-Whitney U Test is a most powerful non-parametric method that approaches the power-efficiency of the most powerful parametric test, the so-called "Student's T test". The power efficiency of the Mann-Whitney approaches $3/\pi = 95.5\%$ as N approaches 20 and is close to 95% even for moderate (6 to 10) sized samples. It is, therefore, an excellent alternative to the T test and, of course, it does not have the restrictive assumptions and requirements associated with the T test. A numerical example of this test follows:

Table I gives actual Crane-based data for the frequency of low-end-of-discharge-voltage measurements at two different strain levels: (1) those cells (denoted by H) that failed at some period in time and, (2) those cells (denoted by L) that did not fail within the bounds of the data. It is assumed that the cells which failed were under high strain and that cell failure is therefore reflected by the specified voltage measurements.

The value of U is given by

$$U = n_1 \; n_2 + \left[(n_1) \; (n_1 + 1) \; / \; 2 \right] - R_1$$

Where n_1 and n_2 denote the number of cells at the high and low strain levels, and R_1 denotes the sum of ranks associated with the components at the high strain level. In the present example we have

$$U = (13) \; (14) + \left[(13) \; (14) \; / \; 2 \right] - 126.5$$

so that

$$U = 182 + 91 - 126.5 = 146.5$$

Applying the transformation $U = \left(n_1 \; n_2 \right) - U'$

Then $U = 182 - 146.5$

$U = 35.5$

Special tables are available for judging the significance of the computed value of U. For the present example, with n_1 and n_2 equal to 13 and 14 respectively, the critical value of U is 43 at the .01 significance level. Thus, if the calculated U exceeds 43, the assumption is rejected that cell failure is reflected by the frequency of low-end-of-discharge-voltage measurements.

Because the calculated value of U does not exceed 43, it is concluded, with the confidence level of .99, that cell failure is reflected by the frequency of low-end-of-discharge-voltage measurements. In addition to simple voltage-range criteria, voltage measurements for use with this method may be derived from these techniques:

1. Voltage first differences,
2. Superimposed charge-discharge curves,
3. Frequency of counts at voltage-level thresholds.

TABLE I.

CELLS RANKED ACCORDING TO
FREQUENCY OF
LOW-END-OF-DISCHARGE-VOLTAGE MEASUREMENT

Pack and Cell No.	Measure-ment	Strain	Ranking: High Strain	Ranking: Low Strain
112-3	70	L		1
39-4	71	L		2
85-1	80	L		3
39-5	83	H	4	
39-3	88	L		5
85-5	89	L		6
39-10	90	L		7
127-4	92	L		8
85-4	104	H	9	
39-9	106	L		10
85-2	107	H	11	
112-4	110	L		12
127-5	112	L		13.5
39-1	112	H	13.5	
39-8	116	H	15	
127-3	117	L		16
112-2	119	H	17	
85-3	127	H	18	
127-1	130	L		19
112-5	133	H	20	
127-2	146	H	21	
240-2	148	H	22	
240-4	149	H	23	
240-1	160	L		24
240-5	170	H	25	
112-1	171	H	26	
240-3	177	H	27	
$n_1 = 13$; $n_2 = 14$; $R_1 = 126.5$				126.5

It is suggested in earlier work that the Kolmogorov-Smirnov statistic can be utilized to determine the probability with which two samples are derived from the same population.* This non-parametric statistical test was investigated and evaluated in regard to spacecraft battery data, but the Mann-Whitney U test was empirically determined to be the more powerful discriminant of hypotheses.

D. PSEUDO-CRYPTANALYTIC TECHNIQUES

In the strict sense, of course, cryptanalysis involves the reduction of "purposeful" noise, that is noise introduced for the purpose of confusion. In the case of using cryptanalytic tools to attempt to reduce data, the noise in the data is a result of inaccuracies due to many complex factors, both chemical, physical and due to the methods of collecting the data. The cryptanalytic methods are applied in the belief that the methods developed for eliminating "purposeful" noise represent considerable sophistication for reducing and analyzing any type of data, and therefore would be extremely useful in any case.

Cryptanalysis is defined as a system for encoding or decoding secret messages. The word "cryptanalysis" is derived from the Greek words KRYPTO, to hide; the prefix ANA, implying distribution; and LYSIS, a loosing or resolving. Modern cryptanalytic methods make full use of both mathematics and electronics to extrapolate the information content from a secret or enigmatical language or to detect and define the "signal" from a "noisy" or error-filled data-base. These cryptanalytic methods, developed over many centuries, have heretofore been the sole domain of security and intelligence agencies and used both to maintain secrecy in vital government, military and industrial communications and to maintain surveillance on the communications and traffic of other governments or regimes.

Cryptanalytic systems permit the definition of parameters from large samples of operational data. Operational parameters are defined as factors which affect significant distributions of measurements existing within the data. Once the distributions are defined, but not necessarily translated into pertinent meaning or information, the data itself may be used to model a system and provide solutions based on assumption. Traditionally, formal statistical methods have been used to provide these solutions; however, any statistical method requires numerous assumptions based on the parameters, and the validity of these assumptions is unknown, especially with a large, "noisy" data-base. Dependent on the data, the statistical method used, and the skill and cunning of the Statistician, an operational model may be evolved, but due to some degree of invalidity in the pre-requisite assumptions, the acquired solutions may be diametrically opposed to the real problem. It follows then, that a statistical model should not be applied to unknown data because chances are that it will either "blow up" or produce incorrect results. Before applying formal statistics to this problem area, some method is required to define and delineate the information elements and their distributions.

* Schulman, I., op. cit., Appendix

A professional Cryptanalyst regards both cryptanalytic and statistical methods as parts of the same discipline and utilizes both to provide the solutions for his analysis problems. When the Cryptanalyst "cracks" a code, the methods and techniques used are immaterial because the basic emphasis of "Crypt" is pragmatic. On the other hand, the Statistician must solve a problem and then precisely describe and justify his methods. If his methods are not within the realm of formal statistics, his solutions are suspect. The basic difference then, between the Cryptanalyst and the formal Statistician, is one of emphasis. This critical difference has enabled the Cryptanalyst to assemble an entire system of techniques, analogous in part to the techniques used by the chemical analyst.

These techniques provide him with a starting point and, dependent on positive or negative results, provide the direction to be taken in the procedures that follow. These procedures, combining both empiricism and heuristics, can provide the conclusions, assumptions, and hypotheses for the application of a vast array of classical statistical methods.

Mountains of data are being generated by vast numbers of machines in many areas of business, industry and science. This has resulted in many problems relative to the extrapolation of information vital to management and the conversion of such information to real savings or real profits. For this purpose, the classical Statistician is at a disadvantage because the problems have not been sufficiently delineated for the construction of a model. Successful statistical models are dependent on assumptions based on the accurate definition of parameters and information elements within the data.

The Cryptanalyst requires or makes fewer prior assumptions. His basic assumption is that any non-random behavior is significant and that its meaning may be inferred from distributional relationships within the data. Nonrandom behavior is considered to be any non-symmetric distribution of elements. For example, the English Language is composed of non-symmetric distributions of the letters of the alphabet. The Statistician also determines random and non-random characteristics, but his approach is an non-procedural selection of formal methods whereas the cryptanalytic approach provides a step by step development of an information system by combination of separate elements into a whole, the opposite of statistical analysis.

The Cryptanalyst utilizes a variety of specialized sequential techniques to detect patterns which exist in the data and define the distributions and periodicity of such patterns. Association of parameters with patterns and distributions within the data permits identification and validation of the information content. Additional parameters or unsuspected dependencies between parameters will also appear.

A problem encountered in the implementation of this approach is that of handling the large volume of data. Some reduction of this volume must be made in order to critically view a portion of it, and yet this reduction must not distort or eliminate any part of the data. Application of Cryptanalytic techniques to samples of the data indicated a high association of detectable voltage-patterns and pattern distributions to observed cell failure. These voltage-patterns often appeared ten-thousand cycles before actual cell failure. A computer program was created both to extrapolate voltage-patterns from the cell voltage data and to effect a data reduction. The data were reduced by a ratio of 30 to 1. Additional Cryptanalytic procedures were applied to the reduced voltage data resulting in a "good cell or bad cell" predictive capability that was 60% to 100% reliable, based on the data used and the operational parameters involved.

The results of these analysis procedures permitted further insights into the operational mechanics of sealed spacecraft cells, relative to space mission requirements. These analysis results and insights enabled the creation of additional cryptanalytically-oriented computer techniques for the extrapolation of additional scientific and engineering information from the entire data-base. Both the reliability and selectivity of the cell predictive capability were enhanced.

The cell post-mortem autopsy data, mentioned earlier, were also analyzed by unique Cryptanalytic methods. These data were encoded into a structure of twenty-one coded failure characteristics, encompassing the entire descriptive content of the cell autopsy reports. The coded failure characteristic data were treated as a code or cipher containing a hidden "signal" or "message" to be decoded. Systematic Cryptanalytic procedures permitted extrapolation of the significant information content contained in the coded cell post-mortem autopsy reports. This information enabled the definition of cell failure as a function of (1) cell manufacturer; (2) environmental and operational parameters; (3) quality control; and (4) significant combinations of (1), (2), and (3). Information feedback to the cell manufacturer and designer has resulted in the enhancement of both product and product reliability.

SECTION III

CELL LIFE PREDICTION

A. INTRODUCTION

a. Developing a Mathematical Model

In order to make a qualitative prediction of the behavior of a cell, based on the statistical treatment of measurements of selected variables, a good mathematical model must be defined. The variables of any real-world system usually contain random distortions which can only be established after a thorough study of their probability distributions. The model is only an approximation of the real-world in every case, and its usefulness is always open to question, especially when it begins to diverge drastically from the empirical results. Measures must be built into the model for detecting this possibility. The present investigation has established three mathematical models by using the methods of cryptanalysis discussed in the preceeding section. The empirical data were derived from the Crane program data described in the Appendix.

The three models are:

1. First-Difference voltage Histograms which establishes the slope of the charge-discharge curves between individual monitor points on a set of Crane cycles of data;

2. Superimposed Charge-Discharge curve which produces graphic/numeric representations of sets of charge-discharge curves; and

3. Frequency count/threshold analysis which establishes a voltage threshold and counts the frequency as a given cell passes through it.

The stresses and strains in a battery system with their interrelated dependencies are the factors which are going to determine the distributions of measurements which make up the model. The scientific method to develop the model would be to identify each stress independently and to experimentally justify, by repetition, the associated variation of measurements for each stress level. When all the stresses and their effects on measurement have been identified, then combinations of stresses would be studied until one could mathematically define the battery system.

In reality, it is difficult to define all the stresses in a battery system. Furthermore, the variations are linear for only a portion of the stress levels measured. Such things as deterioration of separator material at high temperatures, the appearance of dendrites, blistering on the plates, seal leaks, high pressure distortions and others, all contribute to confusion in the development of a model. By this method, the alternative to the synthesis of a model by the identification of its component parts and their behavior is the reverse process of separating the behavior of the distributions of the whole system into sets of normal and abnormal patterns, and correlating these abnormal patterns to the known incidences of failure. The high correlation of abnormal distribution patterns to cell failure forms the basis for prediction. This model can be extended by the addition of new abnormal patterns derived from new operational restrictions and/or new battery designs, and correlation to new failure observations. It is important to note that in either approach the actual prediction is made with the same kind of statistical validation.

b. Accelerated Testing Feasibility

Accelerated life testing is defined as an evaluation system that permits the ageing of a component to be accelerated so that months or years of operational behavior may be predicted by using data acquired in a few days or weeks. Many problems inherent in accelerated life testing, however, suggest that this type of testing may not be possible. In general, most of the problem area stems from the possibility, if not probability, that several failure mechanisms will evolve simultaneously within the cell and that these failure mechanisms are accelerated at varied rates by increasing the stress or work load applied. To further complicate the situation, the failure mechanisms can be independent of each other or interacting to produce additional stress and strains. This set of circumstances decreases the possibility of valid extrapolation of operational behavior observed at accelerated or higher stress levels to the expected operational behavior at normal stress levels.

The concept of accelerated life testing can be validated only by experiment. The experimental effort, however, must be based on empirical evidence such as the cause and result relationships to cell failure as defined by the analysis of the Crane data. These relationships should be utilized to establish the non-destructive testing limits for accelerated life testing. For example, the maximum stress induced in the cell by various combinations of the several operational/environmental parameters should be extrapolated from the Crane data.

If the approach to accelerated life testing simply involved increasing all stress, thereby increasing the rate of occurrence of catastrophic cell failure, the approach may not be valid. Because of the possibility that several degredation processes occur simultaneously within a cell, accelerated life testing is <u>not</u> simply a matter of increasing the component failure rate; it is a matter of increasing the time rates of the degradation processes while maintaining non-variant relations of dominance among the processes. To determine whether the dominance/degredation relationships are preserved, it will probably be necessary to test at several stress levels to generate data that can be used to assess the validity of the extrapolations to "normal" stress levels. The Crane data can provide insights from which to define "normal" stress levels.

In considering the feasibility of accelerated testing, the contribution of effective predictive models could be enormous if not essential. The approach taken to develop these models determines the procedures, schedules and number of cells required and data equipment for the accelerated test program. The conventional approach is the identification of each stress parameter and their mutual interaction in order to develop the model. This approach requires considerable independent research to derive the functional properties of each stress parameter, after which the system may be tested and modeled. The alternate approach to acceleration testing is the distributional analysis of an operational system for both normal and abnormal patterns of behavior. This approach requires the testing of a multiple system package under various levels of overstress before it is possible to develop a model.

c. Cost and Time Reduction in Evaluation Programs

Cost and time reduction of a battery life test can be approached in two ways: (A) The previously discussed accelerated testing, and (B) by improved cell selection and analysis methods.

(A) Accelerated testing will greatly decrease the time required to life-test space cells. However, neither the systems for accelerated testing nor the methods for extrapolation of accelerated test data relative to real-time have been evolved.

(B) Improved methods of cell selection for life testing are presently available. These methods can result in several significant benefits; for example:

1. Those cells that produce voltage patterns indicative of impending failure can be removed from testing.

2. The data acquired from poor or defective cells has little information content relative to extended cell life and will not enhance the analysis techniques.

3. Based on voltage pattern identification, those cells selected for life testing will have a longer operational life.

4. The selection process will permit the acquisition of "good" data from "good" cells.

5. The gross number of cells required for the test program will be reduced. Better data will be acquired from fewer cells.

6. Due to the lesser number of cells involved and the consequent reduction of data, cost and man-hour economies will result.

7. Test control and acquisition functions can be more critically accurate with a smaller cell population; analysis procedures will be enhanced.

8. Classic statistical tests, as well as cryptanalytic procedures can be applied to accurate data for the definition of basic engineering information.

Acceptance procedures could include sufficient pre-test cycling and data collection so that cell selection methods could be effected before life testing.

Based on the experience gained from analysis of the Crane data, it may be stated that probably 80% of the cells tested could have been eliminated from the life-test program after approximately 2, 000 cycles of testing. By that time the potential cell failures could have been identified by their voltage patterns and removed from cycling. The remaining cells could have been life tested with a resultant higher probability that effective operational life would be extended.

Those cells removed from cycling could have been analyzed and autopsied, "in-vivo", to determine failure predictive abnormal voltage patterns, as a function of quality, design, and manufacturing parameters.

This conclusion could not have been reached, of course, without the magnitude and extent of the Crane Evaluation Program and the data resulting therefrom.

This method can be utilized for operational cell selection. Large numbers of candidate cells can be evaluated, and those cells with a very low failure probability can be selected and matched for space-flight missions. This type of selection should provide much higher power system reliability than the present "State of the Art". Possibly only 10% of the cells evaluated would be selected for operational usage; this method may seem costly and wasteful, but it is economically justified by the cost and importance of the power supply relative to total mission cost.

For example, assume that a given space mission requires a 10 cell power supply and the purchase cost, per cell, is $250.00. One-Hundred cells of the desired type can be acquired for evaluation and selection at the cost price of $25,000.00. The ten best cells from the lot, relative to mission requirements, can be selected by the low-end-of-discharge-voltage-measurement/frequency method and packaged for operational use. The total cost of cell purchase, testing and packaging might be in the range of from $150,000.00 to $300,000.00, perhaps higher; but a multi-million dollar space flight mission would not fail due to a power system of unknown reliability. The 90 remaining cells can be used for other, less critical purposes.

It is desirable that operational selection be made from testing 1% of cell life, on the basis of a 30,000 cycle lifetime. It is believed that such capability can be gained by the application of these methods to accurately generated and acquired cell voltage data.

With the Crane data, approximately 2,000 elapsed cycles are required to differentiate good cells from incipient failed cells. Due to the data recording frequency of the Crane Program, 2,000 elapsed cycles result in approximately 60 recorded cycles for analysis purposes. It is believed that reliable cell selection and life prediction can be accomplished from approximately 300 consecutive, accurately measured and timed cycles.

B. FIRST DIFFERENCE VOLTAGE HISTOGRAM METHOD

a. Description of Method

The first difference voltage histogram method establishes the slope of a set of charge-discharge curves by calculating the voltage-level differences between the individual monitor points of a set of cycles per cell. The charge and discharge portions of the curve sets are treated separately. The first-difference values or voltage-level differences are taken in a 10-class interval, DV = 0.0 to DV = 0.9, where DV stands for Delta Volts. All voltages differences greater than 0.9 are rounded to 0.9. Histograms are constructed to tally the observed frequency for each of the ten DV class intervals, both for charge and discharge and for N number of cycles. The ordinate of the histogram is always frequency, boxed in by the ten DV class intervals along the abscissa.

b. Example of Method

The output of the data reduction from the first-difference voltage histogram program contains sets of five-cycle tallies on a per-cell basis for both charge and discharge. Each output card is identified by the pack number. Each card contains the starting and ending cycle numbers of its cycle group. Each card contains the voltage first difference history, both discharge and charge, of one identified cell for the indicated cycle group.

Table II

5-Cycle Delta Volt Histogram Output

X	062	0001	0125	05	0 512 3 4 0 2 1 0 0	27	2 2 3 6 9 5 3 0 0 0	30	03	-06	1P
X	062	0001	0125	05	1 3 9 6 4 2 2 0 0 0	27	0 0 1 9 7 3 4 3 2 1	30	01	-82	2P
X	062	0001	0125	05	0 410 6 4 1 2 0 0 0	27	1 0 2 9 8 6 0 0 0 4	30	03	-83	3P
X	062	0001	0125	05	0 311 5 3 2 1 2 0 0	27	0 0 1 6 9 1 3 1 1 8	30	26	-60	4P
X	062	0001	0125	05	0 215 2 3 2 1 2 0 0	27	1 0 2 5 6 5 2 0 3 6	30	02	-83	5F
X	062	0001	0125	05	1 3 9 7 2 2 1 1 0 0	26	0 1 112 5 5 2 0 4 0	30	75	-02	6P
X	062	0001	0125	05	0 410 5 4 1 1 1 0 0	26	0 1 2 8 9 4 1 1 4 0	30	04	-42	7P
X	062	0001	0125	05	1 311 5 2 1 1 1 0 1	26	2 2 2 8 7 4 2 2 1 0	30	75	-02	8P
X	062	0001	0125	05	0 511 4 2 1 2 0 0 1	26	0 2 4 7 9 4 4 0 0 0	30	03	-01	9P
X	062	0001	0125	05	0 211 7 4 1 1 0 0 0	26	0 2 2 610 3 4 1 0 2	30	-00	-85	10P
X	062	0158	0286	05	0 314 4 1 5 2 1 0 0	30	0 5 2 8 7 4 3 1 1 0	31	39	-37	1P
X	062	0158	0286	05	0 311 6 2 4 3 1 0 0	30	0 0 1 510 4 1 2 4 4	31	03	-01	2P
X	062	0158	0286	05	0 5 9 7 0 5 3 1 0 0	30	1 0 2 511 7 0 1 1 3	31	04	-03	3P
X	062	0158	0286	05	0 212 5 4 2 2 1 1 1	30	0 0 0 213 4 2 2 2 6	31	04	-11	4P
X	062	0158	0286	05	0 4 8 8 2 3 3 1 1 0	30	0 0 0 4 9 6 2 1 2 7	31	76	00	5P
X	062	0158	0286	05	1 412 5 3 3 4 1 0 0	33	0 0 3 7 6 4 0 4 1 1	26	06	-93	6P
X	062	0158	0286	05	2 312 6 1 5 3 1 0 0	33	0 0 4 6 7 3 2 1 2 1	26	77	02	7P
X	062	0158	0286	05	1 510 6 3 2 4 0 1 1	33	0 1 3 7 5 5 1 3 0 1	26	77	-82	8P
X	062	0158	0286	05	1 610 5 5 3 2 0 1 0	33	0 1 4 6 6 5 1 3 0 0	26	77	-91	9P
X	062	0158	0286	05	6 210 3 4 3 3 1 0 1	33	0 4 2 5 6 4 2 1 0 2	26	04	-86	10P
X	062	0318	0579	05	0 115 5 3 1 4 0 0 0	29	1 2 1 6 9 2 5 2 1 0	29	42	-13	1P
X	062	0318	0579	05	0 210 9 2 2 3 1 0 0	29	0 0 0 6 6 7 0 1 2 7	29	77	-03	2P
X	062	0318	0579	05	0 5 7 8 1 5 0 3 0 0	29	2 1 2 111 6 1 0 0 5	29	58	-20	3P
X	062	0318	0579	05	0 1 911 0 2 3 2 1 0	29	0 0 0 3 9 4 4 0 1 8	29	03	-85	4P
X	062	0318	0579	05	0 01110 2 2 1 3 0 0	29	0 0 0 015 0 5 0 2 7	29	03	-91	5P
X	062	0318	0579	05	0 114 6 2 3 1 2 0 0	29	0 0 2 412 6 0 2 1 2	29	39	-04	6P
X	062	0318	0579	05	0 015 6 2 3 2 1 0 0	29	1 2 1 410 6 0 1 3 1	29	-00	-86	7P
X	062	0318	0579	05	0 115 5 2 2 2 2 0 0	29	1 2 1 7 8 4 1 2 2 1	29	75	-03	8P
X	062	0318	0579	05	0 312 6 3 2 1 2 0 0	29	1 3 0 510 5 2 3 0 0	29	37	-03	9P
X	062	0318	0579	05	0 112 6 3 3 3 1 0 0	29	3 1 0 511 3 3 3 0 0	29	41	-82	10P
X	062	0610	0732	05	0 313 3 3 5 1 0 0 0	28	1 2 5 8 5 8 0 3 1 0	33	58	-03	1P
X	062	0610	0732	05	0 213 4 3 3 2 1 0 0	28	0 3 2 4 9 3 4 1 1 6	33	01	-93	2P
X	062	0610	0732	05	0 312 2 3 6 1 1 0 0	28	1 2 5 210 7 2 0 0 4	33	37	-82	3P
X	062	0610	0732	05	0 1 9 7 2 6 1 2 0 0	28	0 2 2 5 4 8 4 1 0 7	33	42	-02	4P
X	062	0610	0732	05	0 2 6 9 4 4 3 0 0 0	28	0 2 2 110 9 0 1 1 7	33	41	-03	5P
X	062	0610	0732	05	3 311 4 2 5 2 1 0 0	31	2 0 3 310 6 1 2 1 1	29	77	-82	6P
X	062	0610	0732	05	0 511 4 1 7 1 1 0 1	31	0 4 2 4 8 6 2 1 0 2	29	37	-93	7P
X	062	0610	0732	05	0 512 5 2 4 3 0 0 0	31	1 2 3 5 9 5 0 2 1 1	29	01	-86	8P
X	062	0610	0732	05	2 213 4 3 3 3 0 0 1	31	2 2 1 8 4 7 2 2 0 1	29	01	-86	9P
X	062	0610	0732	05	1 2 9 8 3 6 1 0 1 0	31	0 5 4 4 7 7 1 1 0 0	29	77	-86	10P
X	062	0760	0896	05	0 213 6 7 1 1 0 0 0	30	4 3 2 9 6 5 3 1 0 0	33	16	-43	1P
X	062	0760	0896	05	0 4 8 7 6 3 2 0 0 0	30	1 1 210 9 2 1 2 2 3	33	39	-03	2P
X	062	0760	0896	05	0 311 7 3 4 1 1 0 0	30	1 0 3 713 3 0 3 2 1	33	03	-35	3P
X	062	0760	0896	05	0 1 7 9 5 5 2 1 0 0	30	0 1 3 6 8 5 4 3 1 2	33	02	-01	4P

Each card contains the minimum and maximum temperatures recorded, for its identified cell, for the cycle group.

The format of each output card is as follows:

Note: C. C. denotes card column

C. C.	1 -	X - Denoting ten cell pack. V - Denoting five cell pack.
C. C.	3-5:	Pack number
C. C.	7-10:	Group Starting Cycle Number
C. C.	12-15:	Group ending cycle Number
C. C.	17-18:	Number of cycles contained in this cycle group
C. C.	20-39:	Ten, two digit fields starting with voltage difference or delta-volts equal zero to delta-volts equal nine. Each of the two digit fields records the occurrences of delta-volt values for its respective level. For example--the first two digit field records the number of occurrences of the zero delta-volt level; the second two digit field records the number of occurrences of the one delta-volt level. This section is for discharge.
C. C.	41-43:	Records the total number of delta-volt occurrences in the discharge section.
C. C.	44-63:	The same as C. C. 20-39 but for charge.
C. C.	65-67:	The same as C. C. 41-43 but for charge.
C. C.	70-76:	Two, three digit fields recording the maximum and minimum temperatures for the cell for its cycle group.
C. C.	78-79:	Records the individual cell number.
C. C.	80:	The letter "P" denoting that this output was checked and found error free by the error checks within the program.

On TableII several discharge histograms are underlined, cells number 4 and 5, which failed at 4066 and 4441 elapsed cycles respectively. These underscored histograms display a significant increase in the occurrence of high (DV high = 7, 8, 9 volts) voltage differences, and a corresponding decrease in the more normal (DV low = 1, 2, 3) voltage differences. This shift reflects an abnormal change in the slope of the discharge curve and it correlates highly with impending cell failure. The data pattern in this case is detectable approximately 4000 cycles prior to the actual cell failure.

c. First Difference Indicators of Incipient Failure

The above example validates the asumption that the digitalization of the charge-discharge curve can be achieved by noting the initial cell voltage at the beginning of discharge and subsequently listing the change in voltage for each monitor point. The resulting indicators of incipient failure are based on voltage patterns extrapolated from the digitized curves. Digitalization and representation on one punched card is possible with this method since the slopes of the N cycle charge-discharge curves are directly represented by the delta volt indicator.

As indicated above the difference method is related to the differential of calculus, but accurate data are required for the most accurate results because the method is so sensitive to changes. The lack of uniform monitor times in the Crane data created a considerable amount of "noise" in the histograms, and led to errors in pattern recognition and predictive results. The mass of the Crane data, however, caused some of the "noise" to be averaged out and enabled predictive "good or bad cell" methods to show 60% to 100% reliability, based on the data analyzed and the operational parameters involved.

Operational variables, such as ambient temperature and depth of discharge, cause a shift or displacement within the histogram. Higher stress on a cell produces an increase in the frequency of higher voltage difference values and a corresponding decrease in the frequency of lower voltage difference values.

Three subdivisions were made in the nine delta-volt (DV) cell ranges: the summed value of DV 1-2-3; DV 4-5-6; and DV 7-8-9. These were called DV low, DV mid and DV high respectively. A series of values were then established by which cell-life prediction could be accomplished, tallying each of the indicator counts and finding out the cells with the most counts against them. The nine new indicators were:

Indicators in Discharge

- Indicator #1 - If DV high equals 9 - - - count 1 against cell,
- Indicator #2 - If DV high equals >9 - - - count 2 against cell,
- Indicator #3 - If DV high is more than $\frac{1}{4}$ the value of DV low - - - count 1 against cell,
- Indicator #4 - If DV low is $\pm$ 15 from DV mid - - - count 1 against cell,
- Indicator #5 - If DV low and DV mid differ by more than +15 - - - count 2 against cell,
- Indicator #6 - If DV mid is higher in value than DV low - - - count 1 against cell,

Indicators in Charge

- Indicator #7 - If DV low is 4 or more times larger or $\frac{1}{4}$ or less the value of DV mid - - - count 1 against cell,
- Indicator #8 - If DV high is more than $\frac{1}{2}$ the value of DV low - - - count 1 against cell,

Indicator in Charge - Discharge

- Indicator #9 - If DV mid charge is more than twice or less than $\frac{1}{2}$ the value of DV mid (discharge) - - - count 1 against cell.

These counts are then totaled for each cell; cells that have highest count are predicted to fail earliest.

The sub-divisions are compared within various empirical ratios. Nine ratios, or comparisons with threshold indicators, are utilized to score points against an identified cell. The cell or cells that

(1) IF F = 9 — CT. 1

(2) IF F => 9 — CT. 2

(3) IF H:L > 1:4 — CT. 1

(4) IF G ± 15 = H; IF H ± 15 = G — CT. 1

(5) IF G − H => 15; IF H − G => 15 — CT. 2

(6) IF G > H — CT. 1

(7) IF K:L > 4:1 OR IF L:K > 4:1 — CT. 1

(8) IF H:L > 1:2 — CT. 1

(9) IF G:K > 1:2 OR IF K:G > 1:2 — CT. 1

A	B	C	D	E	F	G	H	I	J	K	L	M	N
51	1	132	5	106	9	44	53	95	9	43	43	1	1
51	1	132	5	96	0	47	49	100	9	56	35	0	2
51	1	132	5	98	0	51	47	100	9	54	37	0	3
51	1	132	5	92	0	41	51	87	0	43	44	0	4
51	1	132	5	93	7	45	41	95	16	31	48	0	5
51	1	132	5	94	0	48	46	93	9	41	43	0	6
51	1	132	5	97	7	39	51	96	16	35	45	0	7
51	1	132	5	91	0	44	47	95	0	52	43	0	8
51	1	132	5	90	0	38	52	90	7	35	48	0	9
51	1	132	5	88	0	43	45	90	7	40	43	0	10
51	164	324	5	91	0	35	56	98	16	46	36	1	1
51	164	324	5	93	0	35	58	102	17	58	27	2	2
51	164	324	5	96	0	45	51	108	18	65	25	1	3
51	164	324	5	91	0	34	57	89	9	37	43	1	4
51	164	324	5	92	0	53	39	98	16	48	34	0	5
51	164	324	5	90	0	35	55	90	16	24	50	1	6
51	164	324	5	91	0	34	57	92	17	32	43	1	7
51	164	324	5	94	0	48	46	87	9	44	34	0	8
51	164	324	5	93	0	35	58	94	16	37	41	1	9
51	164	324	5	91	0	44	47	91	16	33	42	0	10
51	356	514	5	90	0	36	54	87	0	38	49	1	1
51	356	514	5	90	7	38	45	96	7	46	43	0	2
51	356	514	5	95	0	45	50	100	21	32	47	0	3
51	356	514	5	87	0	33	54	70	0	4	66	3	4
51	356	514	5	90	0	39	51	76	0	20	56	0	5
51	356	514	5	90	0	39	51	75	0	16	59	0	6
51	356	514	5	92	0	36	56	76	0	20	56	1	7
51	356	514	5	92	0	46	46	74	0	20	54	0	8
51	356	514	5	91	0	29	62	76	0	12	64	2	9
51	356	514	5	90	0	40	50	72	0	28	44	0	10

Table III. Example of Delta-Volt Histogram Method Showing Indicators of Failure achieved the highest score(s) within an N-cycle set are selected to fail before the remaining lower scored cells. These selections evidenced 60% to 100% reliability with data from a specific operational/environmental set.

Because each operational/environmental variable set produces an individual frequency distribution pattern within the first-difference histogram, each set will probably require an indigenous set of indicators to differentiate abnormal voltage patterns from normal. When critically accurate data are available, it will be possible to determine whether the same set of indicators can be applied to every set of variable combinations --- with indicator weights varied in proportion to the stress and strains induced by those variables. Table III shows these indicators for a specific example. The legend for Table III is as follows:

Column Heading	Explanation
A	Pack Number.
B	Starting Cycle Number of Set.
C	Ending Cycle Number of Set.
D	Number of Cycles in Set.
E	Area Under Entire Histogram - Disch.
F	Area Under DV High - Disch.
G	Area Under DV Mid - Disch.
H	Area Under DV Low - Disch.
I	Area Under Entire Histogram - Chg.
J	Area Under DV High - Chg.
K	Area Under DV Mid - Chg.
L	Area Under DV Low - Chg.
M	Accumulated Score Against Cell.
N	Cell Identity Number.

The numbers 1 through 9, enclosed in parentheses, identify each of the indicators of cell failure.

d. Evaluation of Method

The advantages and disadvantages of employing the first voltage difference histogram method to the data are listed below.

ADVANTAGES:

1. The generation of voltage patterns for sets of charge-discharge curves are easily computer generated from initial digital input measurement data, coded, retrieved and associated with failure and non-failure.
2. The technique and programs can be adapted to different types of input systems and data, for instance one in which more points are monitored to give other changes in orbit regime.
3. The patterns so derived can be computer-gamed to determine abnormal behavior.
4. The initial data is reduced by this method by a ratio of 30 to 1.

DISADVANTAGES:

1. The method is very sensitive to careless control in the acquisition of the data measurements, in particular, the imprecise timing intervals at which the voltages are measured, since this results in unevenly distributed difference voltages. It is interesting to note, however, that contrary to the use of first differences in calculus where the intervals of measurement on the curve are uniform, as long as the time intervals, although non-uniform, are consistent from cycle to cycle, the resultant patterns for good and bad cells is sufficient for bad or good cell identification.
2. The method, as programmed, involves the loss of two types of information: Identical charge-discharge curves displaced by initial voltage starting positions have the same identical first-difference histograms; and there is no way to determine what portion of the curves contribute to the specific voltage difference levels listed. These losses can be avoided if there is evidence that the additional information actually is required to improve abnormal pattern recognition or to improve the identification of failure mechanisms from the pattern profiles.

C. SUPERIMPOSED CHARGE-DISCHARGE CURVE METHOD

a. Description of Method

The superimposed charge-discharge curve analysis method uses the original Crane program data to produce graphic/numeric representations of sets of charge-discharge curves. These curve-set representations enabled the extraction of qualitative information regarding cell performance and the empirical definition of data patterns indicative of impending cell failure. Failure predictions, based on portions of the Crane data, have an average lead time of greater than 5, 000 elapsed cycles, where the predictions were made after 1, 000 elapsed cycles of data. *

Analysis of tabular listings of the curve-sets revealed that the charge-discharge curve profile is a function of the environmental/operational parameters. In the Crane data, the entire charge-discharge curve set profile lowers inversely with both higher ambient temperature and higher depth of discharge; the slope of the curve set changes also (see appendix). These phenomena explain the displacement observed in the first difference voltage histograms. Higher ambient temperature also resulted in the dispersion of individual curves within the curve set. In addition to voltage distributions, monitor-time distributions were also calculated and graphically/numerically presented. These time distribution plots display the non-uniformity of data-monitor-times which led to errors in analysis results.

* Mauchly, Dr. J. W. and Waite, J. H., Computer Methods for the Reduction, Correlation and Analysis of Space Battery Test Data, Goddard Space Flight Center, Contract NAS 5-10203, May 1-Dec. 31, 1966, pages 35 and 83 to 92.

EXAMPLE OF DISTRIBUTION OF MONITOR TIME DIFFERENCES

```
DIST.TIME DIFF.  1   2   3   4   5   6   7   8   9  10
   62 3970  93       .                   .     1             .           01 DT
   62 3970     1     210 7193511 8       .                   .           02 DT
   62 3970   3       1 2   2 51744 5   1 1                   .           03 DT
   62 3970   2       . 1 4   71261 3 5 1 1   1               .           04 DT
   62 3970           1   1 2 52457 4 2 1 .       1   1       .           05 DT
   62 3970   2 1     1 2 1 2 12260 3 3   1                   .           06 DT
   62 3970         2 1 21116241440 1 7 2 .       1           .           07 DT
   62 3970   1   110352714 7 1           1                   .           08 DT
   62 3970           .   2     1 2 2 2 7 110361617 2 1       1           09 DT
   62 3970   1     1 1   1   3       1   1 1   4  2857 1 1 2 .           10 DT
   62 3970   2 1 1   .   1   1       1 1 . 1 1 1  1968 3 1   .           11 DT
   62 3970           1 1     2 2         .     1 12065 3   3 1     1     12 DT
   62 3970           .   1   1   1   2   .   3   22063 4     .           13 DT
   62 3970     3     .         1     1   1 522132910 9       .           14 DT
```

Table IV

b. Example of Method

Tables V, VI, and VII are examples of the program printout for the superimposed charge-discharge curve method. The first column is the individual pack identity. The second column specifies the elapsed cycle count. The column of numbers at the extreme right, headed CLN gives the cell identity number. The column headed TP indentifies the 14 monitor interval periods: 01 through 07 identify discharge time; and 08 through 14 identify charge time. These values are the ordinate of the graph. The abscissa of the graph is voltage level, ranging from 1.0 volts to 1.6 volts, represented by the number 100 through 160 along the top row of each graph. The body of the graph consists of numerous two-digit counters which map the distribution of voltage levels within the 14 monitor interval periods for a set of charge-discharge curves. As individual curves pass through the same X, Y coordinates, the appropriate counter is incremented by 1 for each curve. Thus an entire set of voltage curves is reduced to a graphic/numeric representation which is particularly sensitive to cummulative voltage differences and abnormal distributions and ranges of voltage-level values.

c. Monitor Time Differences

Table IV is an example of the program printout for the distribution of monitor time differences, and adjuct to the superimposed charge-discharge curve method. The first column is the pack identity, in this case pack 62. The second column gives the elapsed cycle count, which in this case is 3970 cycles. The column of numbers at the right is coded in the following way: 01 through 14 identifies the 14 monitor interval periods; 01 through 07 identify the discharge; and 08 through 14 the charge. These values are the ordinate of the graph. The abscissa is the observed monitor time, specified in minutes and identified by the numbers 1 through 10 at the head of each class interval. The body of the graph consists of numerous two-digit counters which indicate the distribution of monitor time differences within each of the 14 time periods. For example, the observed frequency at the intersection of time period 3 (row) and the 5 minute class interval (Column) is 44. Approximately 60% of the monitor times are correct for the middle portions of the discharge and charge sections (01 through 07 and 05 minutes; 08 through 14 and 10 minutes respectively). The terminal portions of the curves are not as good. If the mean of both the discharge and charge time distributions were plotted the resultant curves would be horse-shoe shaped. If the monitor times were accurate and uniform, the resultant curves would, of course, be linear.

The charge-discharge curve profile is a function of both ambient temperature and of the depth os discharge. The entire curve structure is lowered when either of these factors are increased. Several examples illustrating this lowering are given in Tables V, VI and VII. In these tables are the graphic/numeric representations of sets of voltage curves for several specified packs of Crane data are cycled within various identified environmental and operational conditions. The position of the curve-set is inversely proportional to the rise of both the ambient temperature

CHARGE-DISCHARGE DATA FOR 40% D.O.D, 25°C AMBIENT TEMPERATURE, AND 1.5 HOUR ORBITS.

```
  VOLTS X 100...   120                      140                     160           TP CLN
096 1006   1        .         21014 1        .                       .            01 01
096 1006            .       914 6            .                       .            02 01
096 1006            . 1 718 1                .                       .            03 01
096 1006            2 817 3                  .                       .            04 01
096 1006            915 3                    .                                    05 01
096 1006        21314 3                      .                  40% D.O.D.        06 01
096 1006   81010 4 2                         .                                    07 01
096 1006            1    617 4 1 1           .                  25° AMB.TEMP.     08 01
096 1006            .          41311 2       .                                    09 01
096 1006            .               51114 .                     1.5 HR.ORB.       10 01
096 1006            .                 2 819                      .                11 01
096 1006   1        .                   21019                    .                12 01
096 1006            .                     1 41214                .                13 01
096 1006   1        .                 1    . 1 11013 1           .                14 01

  VOLTS X 100...   120                      140                     160           TP CLN
014 0968            .            1211 1      .                       .            01 06
014 0968            .        1211            .                       .            02 06
014 0968            .   1 810                .                       .            03 06
014 0968            . 11215 1                .                                    04 06
014 0968            11111 3                  .                  40% D.O.D.        05 06
014 0968        1 11111 1                    .                                    06 06
014 0968   3 5 614 5 2 2                     .                  25° AMB.TEMP.     07 06
014 0968            2   1011 1 1             .                                    08 06
014 0968            .       2 813 5          .                  1.5 HR.ORB.       09 06
014 0968            .           11012 5 .                        .                10 06
014 0968            .               314 8                        .                11 06
014 0968            .                 215 9                      .                12 06
014 0968            .                   11210 3                  .                13 06
014 0968            .                    . 41210                 .                14 06

  VOLTS X 100...   120                      140                     160           TP CLN
002 1004            .          2 9 9 3       .                       .            01 09
002 1004            .      1 810 6           .                       .            02 09
002 1004            .    4 714 2             .                                    03 09
002 1004            . 4 814 1                .                  40% D.O.D.        04 09
002 1004            4 714 3                  .                                    05 09
002 1004   1      410 8 2                    .                  25° AMB.TEMP.     06 09
002 1004   2 2 710 4 2 1                     .                                    07 09
002 1004         1 .   613 4 2 1             .                  1.5 HR.ORB.       08 09
002 1004            .       1 810 5 4        .                       .            09 09
002 1004            .             513 2 9 1                          .            10 09
002 1004            .               113 5 5 3                        .            11 09
002 1004            .                   412 2 7 1                    .            12 09
002 1004            .                    . 4 8 8 5 2                 1            13 09
002 1004            .                    .   7 5 9 4 1 1             .            14 09
```

Table V

CHARGE-DISCHARGE DATA FOR 40% D. O. D., 25°C, 50/40°C, AMBIENT TEMPERATURE, AND 1.5 HOUR ORBITS.

```
  VOLTS X 100...  120                 140                160           TP CLN
003 1028   1       .             110 610 1                 .           01 01
003 1028           .         2 914 1 1 .                   .           02 01
003 1028           .     3 814 2 1     .                   .           03 01
003 1028           .   2 913 1 1       .                   .           04 01
003 1028           . 2 916 2 1         .             25% D.O.D.        05 01
003 1028           5 713 2 1           .                               06 01
003 1028         6 813 1   1           .             25° AMB.TEMP.     07 01
003 1028           . 1     71110       .                               08 01
003 1028           .           31015   .             1.5 HR.ORB.       09 01
003 1028           .               61013                   .           10 01
003 1028           .                 3 815 1               .           11 01
003 1028           .                   11211 2 1           .           12 01
003 1028           .                   . 3 7 710           .           13 01
003 1028           .                   .   7 5 8 3         .           14 01

  VOLTS X 100...  120                 140                160           TP CLN
013 1041   1       .         1 31012 1 .                   .           01 03
013 1041           .       2 719 2     .                   .           02 03
013 1041           .     2 910 1       .                   .           03 03
013 1041           .   1 812 8         .                               04 03
013 1041           1 1 613 7           .             25% D.O.D.        05 03
013 1041           2 814 7             .                               06 03
013 1041         21415 7 1             .             25° AMB.TEMP.     07 03
013 1041           . 1 1 817 3         .                               08 03
013 1041           .       31213 2     .             1.5 HR.ORB.       09 03
013 1041           .           61211   .                   .           10 03
013 1041           .             41111 3                   .           11 03
013 1041           .             1 2 813 6                 .           12 03
013 1041           .             1   5 21110 2             .           13 03
013 1041           .               1 1 1 3 410 5 3         .           14 03

  VOLTS X 100...  120                 140                160           TP CLN
026 0999           .       4 411 9     .                   .           01 08
026 0999           .   4 611 5 2       .                   .           02 08
026 0999           . 4 8 7 4           .                               03 08
026 0999           21213 3             .             25% D.O.D.        04 08
026 0999       1 21213 2               .                               05 08
026 0999   1 3 1 913 2                 .             50/40° AMB.TEMP.  06 08
026 0999  12 9 8 7 3                   .                               07 08
026 0999           1 2 614 4 1         .             1.5 HR.ORB.       08 08
026 0999           .       1   11311 3 .                   .           09 08
026 0999           .               323 5                   .           10 08
026 0999           .                1311 4     1           .           11 08
026 0999           .                 913 6     1           .           12 08
026 0999           .                 913 5     1           .           13 08
026 0999           .               1 912 9                 .           14 08
```

Table VI

CHARGE-DISCHARGE DATA FOR 40% D. O. D. 50/40°C, 0° AMBIENT TEMPERATURE, AND 1. 5HOUR ORBITS.

```
  VOLTS X 100...   120                   140                    160          TP CLN
037 0990   1        .          2 713 2    .                      .           01 05
037 0990            .        811 8 1      .                      .           02 05
037 0990            1    3 5 4 5 1        .                      .           03 05
037 0990          1 . 4 3 512 1           .                      .           04 05
037 0990        1 1 4 5 8 8               .                 15% D.O.D.       05 05
037 0990    1 2 3 3 212 4 1               .                                  06 05
037 0990   18 2 4 9 4 3                   .                 50/40° AMB.TEMP. 07 05
037 0990            . 2 516 4 1           .                                  08 05
037 0990            .          418 6      .                 1.5 HR.ORB.      09 05
037 0990            .            2 719 1 .                                   10 05
037 0990            .              2 618 1                       .           11 05
037 0990            .                416 8                       .           12 05
037 0990            .                21015 1                     .           13 05
037 0990            .                2 416 2                     .           14 05

  VOLTS X 100...   120                   140                    160          TP CLN
085 1134   1        .         1 6 7 9 4   .                      .           01 04
085 1134            .      3 6 415        .                      .           02 04
085 1134            1    4 5 2 8 1        .                      .           03 04
085 1134            1 6 4 5 9 5           .                                  04 04
085 1134   1      1 6 4 710 1             .                 15% D.O.D.       05 04
085 1134        1 6 312 9                 .                                  06 04
085 1134   1 2 2 71610                    .                 50/40° AMB.TEMP. 07 04
085 1134            . 1 4 515 4           .                                  08 04
085 1134            .         3 7 8 9 4   .                 1.5 HR.ORB.      09 04
085 1134            .             5 6 9 9 .                                  10 04
085 1134            .               6 310 9                      .           11 04
085 1134            .               2 5 512 6                    .           12 04
085 1134            .                 6 510 8                    .           13 04
085 1134            .                 4 510 7                    .           14 04

  VOLTS X 100...   120                   140                    160          TP CLN
049 5315            .                410 9    1                  .           01 10
049 5315            .            813 3 1 .                       .           02 10
049 5315            .        519 1 1      .                                  03 10
049 5315            .      914    1       .                 15% D.O.D.       04 10
049 5315            .  1015 1 1           .                                  05 10
049 5315            . 716    1            .                 0° AMB.TEMP.     06 10
049 5315            617 1 1               .                                  07 10
049 5315            .      421 1          .                 1.5 HR.ORB.      08 10
049 5315            .          11014      .                      .           09 10
049 5315            .              1 915 .                       .           10 10
049 5315            .                  1 515 4                   .           11 10
049 5315            .                     .   1 2 1 511 5        .           12 10
049 5315            .                     .         612 7        .           13 10
049 5315   1        .                     .          1013 1 .                14 10
```

Table VII

and/or the depth of discharge (D. O. D. percentages given on the tables.) Comparing these tables it can be seen that higher ambient temperatures produce increasing amounts of "scatter" or dispersion, within a multi-cycle curve-set. The higher temperature gives a rounder or "fatter" resultant curve-set plot, and higher temperature alone causes the curve-set profile to lower. As the D. O. D. is kept constant, the curve profile lowers in an inverse proportion to the increase in the ambient temperature. Both higher D. O. D. and ambient temperature independently lower the curve-set profile.

d. Superimposed Charge-Discharge Curve Indicators of Incipient Failure

Sets of voltage curves, like those shown in Table VII, enable the detection of small cumulative differences which lead to indicators of failure. These small differences are lost when the individual curves are studied, and they form qualitative patterns of cell life. The bounded area labled A in Table VIII, for example, is discontinuous from the remainder of the curve-set profile, and it indicates an incipient cell failure. The bounded areas labeled B and C indicate a high degree of dispersion within the curve-set, and are also indicators of failure. These indicative areas on the table would have been difficult, if not impossible, to detect by the analysis of single voltage curves. This method brings them out quite clearly, however. The information is mainly qualitative, and the inherent difficulties of quantizing this type of data are obvious.

An effort to analyze the superimposed curve data by a computer program, given this numeric/graphic curve-set profile as input, was made. The program calculated the sum of squares of the differences, within each time period, for each identified cell. The output of the program is a tabular listing, for each pack and cell, of the sum-of-squares calculation for each time period. Those time periods that showed a higher dispersion in the curve-set data, produced a relatively higher sum-of-squares value. Curve-set dispersion, however, is only one of several criteria of incipient cell failure empirically established for analysis of superimposed curve sets, and, as such, is insufficient for reliable results. When critically accurate data are available, this method can be modified and extended to encompass several failure criteria for additional reliability in data analysis and pattern detection.

e. Evaluation of Method

The advantages and disadvantages of employing the superimposed charge-discharge curve method to the Crane program data are listed below.

ADVANTAGES:

1. It provides the battery engineer with an immediate display in digital or analog form for any desired time period. It is analogous to the use of an oscilloscope for checking cell behavior. For large test monitoring, it would be ideal where repeated random interrogations on cell behavior are of value.

CHARGE-DISCHARGE DATA USED TO
GENERATE INDICATORS OF INCIPIENT FAILURE.

```
VOLTS X 100...  120                 140                 160            TP CLN
52 4551          .           1 2   2 2 3                 .             01 07   4
52 4551          .       3 1 5 1     .                   .             02 07   3
52 4551          .   2 4 2           .                   .             03 07   8
52 4551          . 1 5 5             .                   .             04 07
52 4551          . 5 4               .                   .             05 07
52 4551          3 5 2               .                   .             06 07
52 4551        3 7 2                 .                   .             07 07
52 4551          .         2 8       .                   .             08 07
52 4551          .               2 7 1                   .             09 07
52 4551          .                   3 3 3 2             .             10 07
                                                               A
52 4551          .                   .     2 2 4 1 1     . 1           11 07
52 4551          .                   .         2 1 2 1 3 .     1       12 07
52 4551          .                   .         1   1   1 . 2 4   1     13 07
52 4551          .                   .             1 1 1 . 1 1 2 2 1   14 07


VOLTS X 100...  120            C    140                 160            TP CLN
52 1402          .         1     3 1 2 9 3 1             .             01 02
52 1402          .       2 3   5 5 3 2                   .             02 02
52 1402          .   3 1 1 4 7 2     .                   .             03 02
52 1402          1 3 1 5 6 4         .                   .             04 02
52 1402        1 3 1 6 9             .                   .             05 02
52 1402    1 1 2 1 7 6 2             .                   .             06 02
52 1402  1   3 2 9 6 1               .                   .             07 02
52 1402                1 1 2 5 4 5 2 .                   .             08 02
52 1402                          4 7 8                   .             09 02
52 1402                            1 8 5 6               .             10 02
52 1402                              . 3 9 6 1           .             11 02
                                                       B
52 1402                              .   2 2 6 7 2 1     .             12 02
52 1402                              .     1 2 2 3 7 5 3 .             13 02
52 1402                              .       1 3 2 2 7 1 2 1           14 02
```

Table VIII

For example, if a temporary power failure or current surge occurred in the test system, cell by cell reaction and effects could be examined at any time thereafter. This could be easily adapted to various kinds of on-line display devises.

2. This technique is invaluable in the case where the test data contain a lot of noise. For example, (a) if the time periods for monitoring cell voltages are not consistant, or (b) if the cycle time for discharge/charge varies, or, (c) if the load is changed; patterns which develop from many cycles of data appear in the build-up of distribution counts at the intersection of the voltage-time plots and provide a solid basis for intuitive selection of model parameters.

3. This technique demonstrates the various types of abnormal voltage behavior for any portion of the charge-discharge curve. The Crane data revealed the following kinds of voltage behavior:
   a. A sporadic but ever-increasing occurrance of low voltage readings (i.e., less than 1.0 volts) at any part of the curve for cells about to fail.
   b. A scattering of high voltage readings at the end of charge in high pressure cells.
   c. A depressed low-voltage flattening out of end-of-discharge readings.

DISADVANTAGES:

1. The technique requires the most computer memory for effective implementation.
2. The patterns which are easy to observe intuitively are difficult to digitalize and model for automatic prediction and validation.
3. Separation of the specific curves contributing to the abnormal distributions is not possible without considerable modification.

D. FREQUENCY COUNT/ THRESHOLD ANALYSIS METHOD

a. Description of Method

The frequency count/threshold analysis method uses a threshhold voltage-level value as a criteria of impending cell failure by counting the number of times a given cell passes that value and establishing an indicator from the data. This threshold voltage-level is empirically assumed in the initial analysis and a computer program examines the Crane program data output in order to corroborate or refute its validity. The frequency of threshold counting made on a per-cell basis was taken in data sets of 1000 elapsed cycles. It was assumed that the cell which exhibited the greatest cumulative voltage excursion or high-low range of voltages, and therefore the highest frequency count in passing the thresholds, would be the first cell to fail.

Rank values were assigned to cells on the basis of high to low frequency counts at various discharge voltage-level thresholds.

Those cells that exceeded -- went below -- the thresholds with the highest frequency were assigned the highest rank. Thus, the assigned ranks are relative to the excess voltage in the end-of-discharge section of a set of charge-discharge curves.

The ranks were averaged and plotted for nine sets of cell-lives. Each set consisted of both cells, which failed at some point in time and cells that did not fail, within the bounds of the data. The abscissa of each graph is time, in cycles; the ordinate is the averaged rank of frequency for low end-of-discharge voltage measurements.

There is a high degree of separation between (1) the curves for the cells which ultimately failed and (2) the curves for the cells which did not fail. A relative probability of cell failure and/or success is associated with end-of-discharge voltage measurements and the curves derived therefrom.

The high degree of curve separation, however, infers that this method may be the basis for application of more sophisticated statistical techniques to more and better data.

This method can be utilized for operational cell selection with higher reliability than qualitative judgments, based largely on subjective experience. For example, present day operational cell selection is done on the basis of cell matching---by ampere-hour capacity. This method would consider cell capacity also, but as a function of voltage-level patterns. Those cells selected for operational space missions would come from the set of cells with the lowest frequency of low end-of-discharge voltage measurements. This set, empirically, has the highest probability of success. Although, lower voltages are a well known characteristic of suspect cells, what appears to have been overlooked in the past is the gradual build-up of these subnormal voltages early in the life of a cell. In order to detect this phenomenon, it is necessary to observe the charge-discharge voltage distributions for a certain number of elapsed cycles.

b. Example of Method

The example* employed seven voltage-level thresholds, three in the charge and four in the discharge cycle, as follows:

Charge:
1. Crane specified cell voltage limit
2. Voltage limit plus 5 centivolts
3. Voltage limit plus 10 centivolts

* This effort was programmed jointly with Dr. George Shrenk, Associate Director of the Computer Center at the University of Pennsylvania, using the IBM 7040 and 3-$\frac{1}{2}$ reels of magnetic tape with Crane data ordered and sorted.

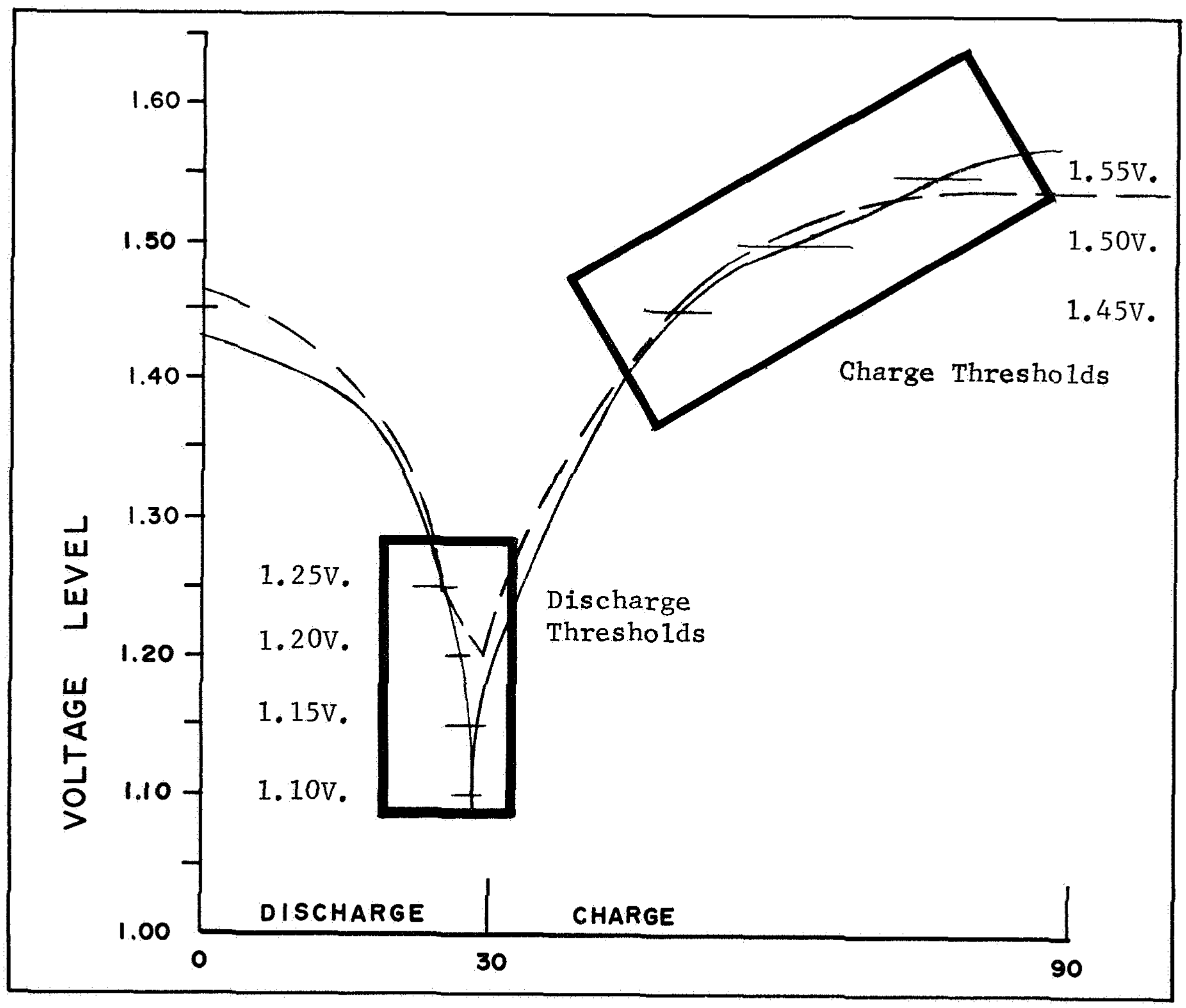
Discharge
1. 1.25 Volts
2. 1.20 Volts
3. 1. 15 Volts
4. 1.10 Volts

Figure 1 shows the location of a set of voltage-level thresholds for this example. Frequency counts are produced at every threshold which is exceeded by each individual charge-discharge curve in a set. Similarly, temperature counts are produced from those temperature measurements which fall in two bands as follows:

High - Nominal Ambient	+ ($\geq$ 5.0	$\leq$ 10.0)
Low - Nominal Ambient	+ ($\geq$-5.0	$\leq$ -10.0)

Temperature measurements that do not fall within these two 5^{o} bands, above and below the nominal ambient, are disregarded.

Figure 1. Discharge-Charge Thresholds



Time averages are calculated for each voltage-level threshold in both discharge and charge. The discharge time-average is the summed time from the start of the discharge to the specific voltage-level threshold for each observed cycle in the set; divided by the number of observed cycles. The charge time-average is the summed time from the attainment of the specific voltage-level to the end of charge (90 minutes from start of discharge) for each observed cycle in the set; divided by the number of observed cycles.

In this particular analysis only 1.5 hour orbit packs were used so that the maximum times for discharge and charge are 30 and 60 minutes respectively. Occasionally, a negative time is indicated for the charge average; referral to the original data indicates a total cycle time of more than 90 minutes.

Effort was made to interpolate the time to several voltage levels in both discharge and charge. Quadratic (Parabolic) interpolation was attempted, but the condition of the data---noise, errors, etc.-precluded this method. The computer would find or seek a number out of range possibly by an order of magnitude, produce nonsense results, and occasionally abort the program. Data smoothing was not attempted in order to prevent the synthesization or further bias of the data.

Linear interpolation was used with some greater success, but, here too, the data condition produced some nonsense results.

The approximately 7,000 punched cards, representing counts and time averages from more than 100,000 Crane data cards, were in ten categories, identified by the numbers 0 through 9 in card column 80. For this analysis, cards 2, 3, 4, 5, 8 and 9 were used. The identification and meaning of each of these cards is as follows:

Card No.

2. -Voltage-Level threshold; charge
3. -Voltage-Level threshold; discharge
4. -Time Averages; charge
5. -Time Averages; discharge
8. -Temperature - above nominal ambient
9. -Temperature - below nominal ambient

The counts and averages were calculated from 1,000 elapsed cycle sets, each set containing approximately 30 observed cycles. The output cards from each set contain pack, cycle, threshold, category identification and the count or average time value for each cell in the pack, cell 1 through cell 10, recorded sequentially.

A computer program accepted these cards as input and produced output cards with the counts or averages sorted numerically, left to right, in descending order. Cell identities were carried with each count and average.

This counting technique permits the examination of selected portions of a set of discharge-charge curves in a manner not dependent on accurately controlled monitor time periods. Examination of the counts indicated that the end-of-discharge portion of the curve seemed most indicative of impending cell failure; in many cases 10, 000 cycles before actual failure.

Twenty-one battery packs, with seventy-five cells that failed within nine cyclic groups, were impartially selected for the construction of curve sets based on high counts in end-of-discharge. The first cyclic group contains cells that failed between 2, 000 and 3, 000 cycles; etc., to the ninth cyclic group which contains cells that failed at some point in time past 10, 000 cycles.

The counts for each cell were produced by summing the count frequencies calculated for each of the four voltage-level thresholds in discharge, 1, 000 cycles at a time, until the cell failed or went beyond 10, 000 cycles. Table IX identifies the packs used in this analysis.

c. Frequency Count/Threshold Indicators of Incipient Failure

On the assumption that the cell which received the highest count would be the first to fail, every cell in each pack was ordered by the algebraic value of its count. Rank values of one to ten were assigned to each cell on the basis of the ordered count. The unfailed cell with the highest count received the rank of ten and the lowest count received the rank of one; the remaining cells received ranks of nine through two, based on their position in the order. As cells failed within a 1, 000 cycle group they were assigned a rank of ten and each of the remaining cells received from nine to whichever sequential rank number applied as the counts descended in order.

The assigned rank values for each set of cells was summed and averaged, per 1, 000 cycles. Each of the nine sets of cells was plotted to show the average occurrence of failure in 1, 000 cycle steps---from cycle 2, 000 to failure, using just one failure criterion: high counts in end-of-discharge. Figure 2 plots the number of times (Ranked) that the end-of-discharge-voltage fell below the threshold (two pages). Rank values assigned to non-failing cells were extracted from the same data which contained the cells that did fail. These ranks were also summed and averaged in 1, 000 cycle sets; they are plotted (lower line, same scale) on the same graphs as the failed cells. The average rank of end-of-discharge measurements for the starting point of the nine sets of unfailed cells is 2. 75; the average of the nine end points is 3. 4 (7 and 8. 6 respectively for cells that did fail.)

The curves shown in Figure 2 for both failed and non-failed cells demonstrate that cells with the highest occurrence of low end-of-discharge voltage-level-values have the highest observed occurrence of failure. Conversely, those cells with the lowest occurrence of low end-of-discharge-voltage-level-values have the lowest occurrence of failure.

Table IX Frequency Count/Threshold PACK IDENTIFICATION

Pack Number	Manufacturer	Capacity A. H.	Temperature C	DOD %
1	SO	5.0	25	25
2	SO	5.0	25	40
15	GE	3.0	25	25
25	SO	5.0	40	15
39	GE	3.0	40	15
49	SO	5.0	0	15
50	SO	5.0	0	25
51	GO	3.5	0	15
52	GO	3.5	0	25
61	GU	6.0	0	15
62	GU	6.0	0	25
82	GE	12.	25	25
85	GE	12.	40	15
98	GO	20.	0	25
112	GO	20.	40	15
127	GU	5.0	40	15
214	GU	4.0	25	40
218	GU	6.0	25	40
240	GU	4.0	40	25
296	GU	12.	25	40
301	GU	12.	0	25

GE=General Electric
SO=Sonotone
GU=Gulton
GO=Gould

NUMBER OF TIMES (RANKED) THAT END-OF-DISCHARGE-

VOLTAGE FELL BELOW THRESHOLDS.

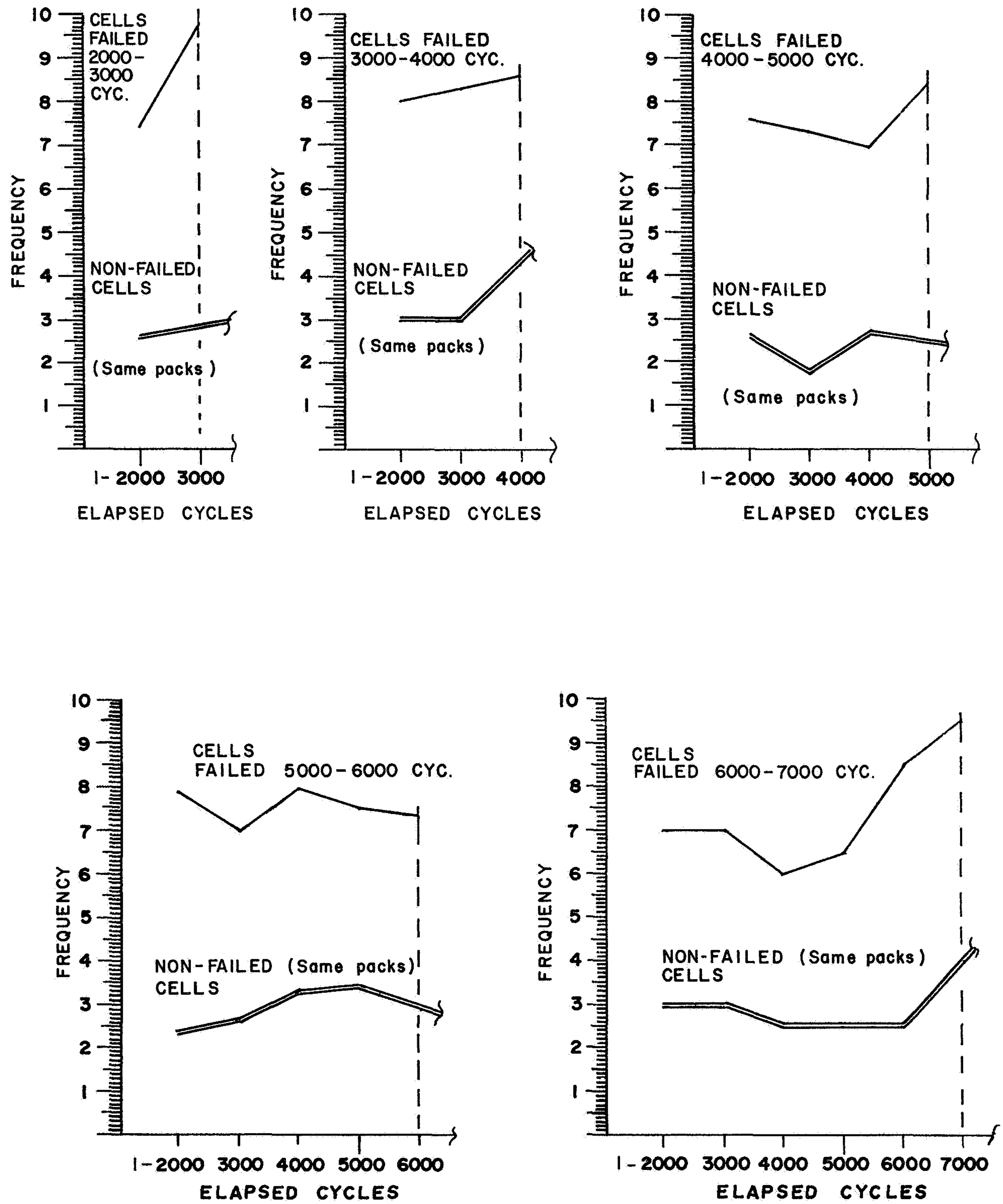


Figure 2. (page one)

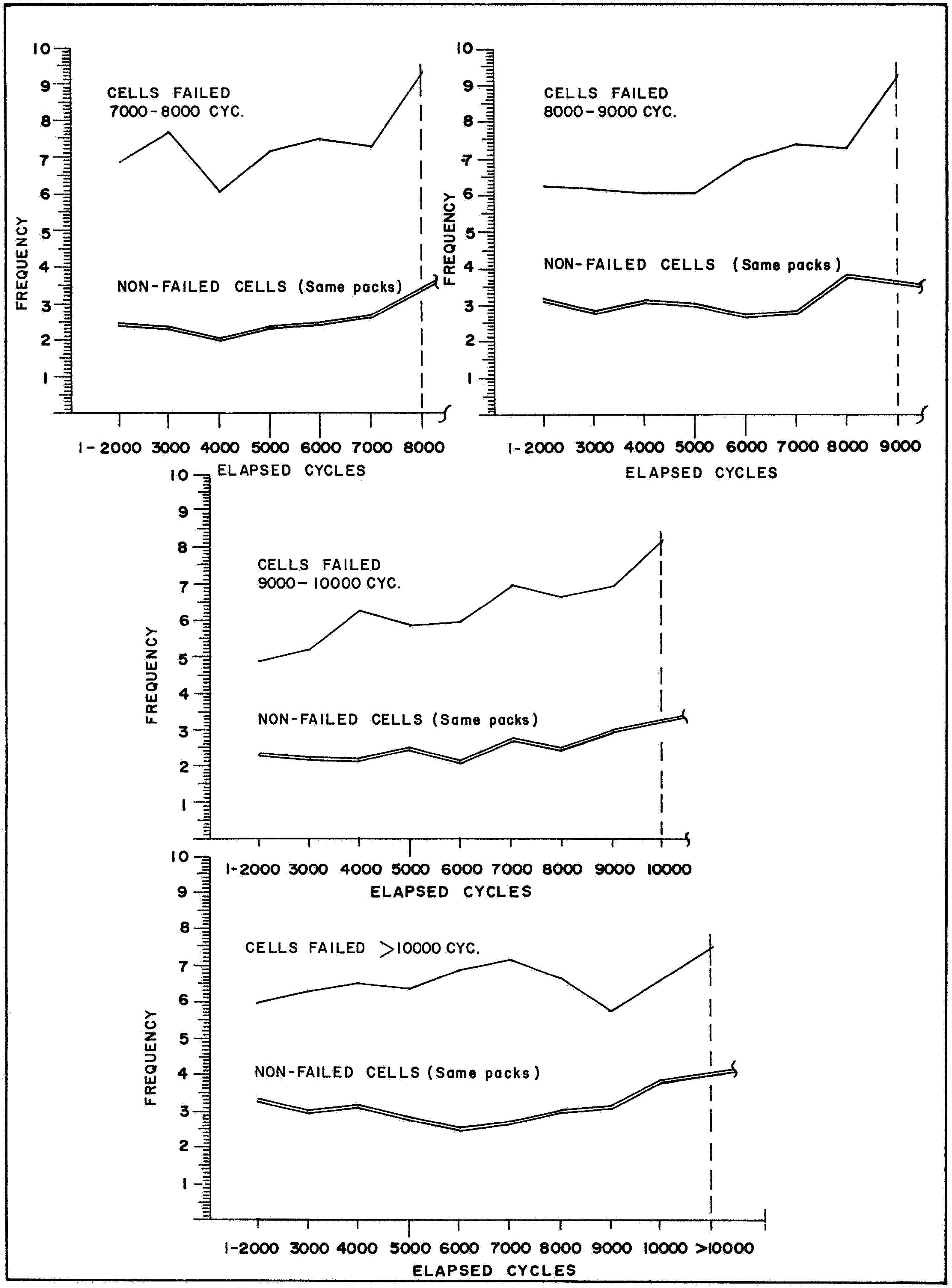


Figure 2. (page two)

This counting technique was applied to 1,000 cycle data sets of individual battery packs. In most cases those cells with the highest count frequency of low end-of-discharge voltage failed in the same sequence as the order of the counts. This process often appeared many thousands of cycles before actual failure.

The significance of the counts derived from the charge portion of the curve sets has a different distribution from the discharge portion which is not as sensitive to overthreshold counts as it is to the dispersion of these counts. It also appears that a cell can recover from a limited amount of high voltage on charge readings.

Because of the difficulty involved in the extrapolation of time to voltage level, the calculated time averages do not seem to contain sufficient information indicative of impending cell failure. There is, however, a trend for those cells which fail to have a higher time-average than those cells that did not fail. This would indicate that the cells which did fail drop to a lower voltage-level faster than the cells which did not fail.

The temperature counts neither predict nor confirm cell failure. These counts do, however, corroborate the fact that temperature control improved as the evaluation program progressed.

d. Evaluation of Method

The advantages and disadvantages of employing the frequency count/threshold analysis method are given below.

ADVANTAGES:

1. It is best suited to on-line digital test data reduction. It requires the least computer memory.
2. It is the closest related to present definitions of battery failure.
3. It is the easiest to model statistically for validation, since the pattern of interest is represented by one measurement, that is the distribution of occurrences of voltage readings below or above specific thresholds.
4. It is relatively immune to carelessly acquired data.

DISADVANTAGES:

1. It eliminates most of the voltage patterns identified by the other methods.
2. It is least likely to show correlations of voltage patterns which indicate a failure mechanism behavior.

E. COMBINING PREDICTION METHODS

The three cell-life predictive techniques can be easily combined in any desired way since they operate independently upon the data. By adding an "and" function to the program it can be combined with any other program desired. Table X summarizes the results of making various combinations of the techniques. Using the data listed in Table XI, the actual breakdown of successful prediction by the various techniques and combinations of the techniques is specified in Table XII. As would be expected the greatest success was obtained by combining all three of the predictive methods. The three together resulted in the detection of twenty-five out of twenty-six cell failures, with an average lead time prediction of 6330 cycles. The average amount of data required to achieve these predictions was 3228 elapsed cycles.

Only one cell failure remained undetected by combining all three techniques--namely cell no. 4 in pack 15 which failed at 10382 cycles. The descriptive data of this cell are:

Manufacturer - Sonotone
Ambient Temperature - 25°C
Depth of Discharge - 25%
Orbit Period - 1.5 hour

The English remarks concerning a post-mortem of the characteristics of failure are:

1. Low-voltage discharge
2. Migration of plate material
3. Separator deterioriation
4. Blistering on positive plates

An effort was made to predict lead time to cell failure but the data did not possess sufficient inherent detail or accuracy to allow this determination. The monitor point times, for example, and the elapsed cycle intervals between the recordings, are not uniform. The rate of change of cell performance could not be related to a well-structured reference system. Extrapolation was therefore impossible. This leads to the conclusion that much more control must be exercised over the mode of collecting data in order to permit more significant information about both cell failure and the ability of any given method to predict cell failure (see appendix).

SUMMARY OF CAPABILITY OF INDIVIDUAL AND COMBINED PREDICTIVE TECHNIQUES

	(A)	(B)	(C)	A&B	B&C	A&C	A&B&C
CELLS IN SET	65	55	40	65	65	65	65
PREDICTED TO FAIL	39	33	19	50	40	45	53
FAILED AS PREDICTED	19	14	15	22	19	23	25
ACTUAL FAILURES	26	20	17	26	26	26	26
SUCCESSFUL PREDICTION	73%	70%	88%	85%	73%	88%	96%

Table X

Table XI. BREAKDOWN OF DATA USED IN PREDICTION

PACK	CELL	CODE	FAILURE CYCLE
15	1	1	
15	2	2	
15	3	3	
15	4	4	10382
15	5	5	8714
15	6	6	
15	7	7	8065
15	8	8	8254
15	9	9	10382
15	10	10	10123
50	1	11	
50	2	12	
50	3	13	13500
50	4	14	
50	5	15	12609
50	6	16	
50	7	17	
50	8	18	
50	9	19	
50	10	20	
51	1	21	
51	2	22	

Table XI. BREAKDOWN OF DATA USED IN PREDICTION (cont.)

PACK	CELL	CODE	FAILURE CYCLE
51	3	23	
51	4	24	17373
51	5	25	
51	6	26	
51	7	27	
51	8	28	
51	9	29	
51	10	30	14737
52	1	31	
52	2	32	
52	3	33	10994
52	4	34	
52	5	35	
52	6	36	
52	7	37	9724
52	8	38	7858
52	9	39	9724
52	10	40	8367
62	1	41	
62	2	42	
62	3	43	
62	4	44	4066

Table XI. BREAKDOWN OF DATA USED IN PREDICTION (cont.)

PACK	CELL	CODE	FAILURE CYCLE
62	5	45	4441
62	6	46	
62	7	47	8590
62	8	48	
62	9	49	
62	10	50	2995
82	1	51	10878
82	2	52	7527
82	3	53	
82	4	54	
82	5	55	10624
98	1	56	8619
98	2	57	
98	3	58	
98	4	59	10641
98	5	60	3556
301	1	61	
301	2	62	
301	3	63	
301	4	64	5586
301	5	65	

Table XI BREAKDOWN OF DATA USED IN PREDICTION (cont.)

Average Amount of Data Required for Prediction -------------	3228 CYC
	HI - 4911
	LO - 2122
Average Lead Time Prediction to Failure ------------------	6330 CYC
	HI - 11910
	LO - 675

BREAKDOWN OF CELL IDENTITIES IN COMBINED PREDICTION EVALUATION

(A) THRESHOLD TECHNIQUE	
FAILED AS PREDICTED	PREDICTED TO FAIL
5, 7, 8, 10, 13, 15, 24, 30, 33, 37, 38, 40, 44, 45, 50, 52, 56, 60, 64	2, 5, 6, 7, 8, 10, 11, 13, 14, 15, 19, 20, 22, 23, 24, 25, 29, 30, 32, 33, 36, 37, 38, 40, 42, 43, 44, 45, 46, 50, 52, 53, 54, 56, 58, 60, 63, 64, 65
TOTAL 19	TOTAL 39

(B) VOLTAGE DIFFERENCE TECHNIQUE	
FAILED AS PREDICTED	PREDICTED TO FAIL
9, 10, 13, 15, 24, 30, 33, 37, 38, 39, 44, 45, 47, 50	1, 2, 6, 9, 10, 11, 13, 14, 15, 16, 18, 20, 23, 24, 25, 26, 28, 30, 32, 33, 34, 36, 37, 38, 39, 43, 44, 45, 46, 47, 48, 50, 62
TOTAL 14	TOTAL 33

(C) SUPERIMPOSED CURVE TECHNIQUE	
FAILED AS PREDICTED	PREDICTED TO FAIL
24, 30, 33, 37, 38, 39, 40, 44, 45, 50, 51, 55, 56, 59, 60	24, 25, 26, 28, 29, 30, 33, 37, 38, 39, 40, 44, 45, 50, 51, 55, 56, 59, 60
TOTAL 15	TOTAL 19

Table XII

Table XII (page two)

A & B 50	
FAILED AS PREDICTED	PREDICTED TO FAIL
5, 7, 8, 9, 10, 13, 15, 24, 30, 33, 37, 38, 39 40,44, 45, 47, 50, 52, 56, 60, 64	1, 2, 5, 6, 7, 8, 9, 10, 11, 13, 14, 15, 16, 18, 19, 20, 22, 23, 24, 25, 26, 28, 29, 30, 32, 33, 34, 36, 37, 38, 39, 40, 42, 43, 44, 45, 46, 47, 48, 50, 52, 53, 54, 56, 58, 60, 62, 63, 64, 65
TOTAL 22	TOTAL 50

B & C 40	
FAILED AS PREDICTED	PREDICTED TO FAIL
9, 10, 13, 15, 24, 30, 37, 38, 39, 40, 44, 45, 47, 50, 51, 55, 56, 59, 60,	1, 2, 6, 9, 10, 11, 13, 14, 15, 16, 18, 20, 23, 24, 25, 26, 28, 29, 30, 32, 33, 34, 36, 37, 38, 39, 40, 43, 44, 45, 46, 47, 48, 50, 51, 55, 56, 59, 60, 62,
TOTAL 19	TOTAL 40

A & C 45	
FAILED AS PREDICTED	PREDICTED TO FAIL
5, 7, 8, 10, 13, 15, 24, 30, 33, 37, 38, 39, 40, 44, 45, 50, 51, 52, 55, 56, 59, 60, 64,	2, 5, 6, 7, 8, 10, 11, 13, 14, 15, 19, 20, 22, 23, 24, 25, 26, 28, 29, 30, 32, 33, 36, 37, 38, 39, 40, 42, 43, 44, 45, 46, 50, 51, 52, 53, 54, 55, 56, 58, 59, 60, 63, 64, 65
TOTAL 23	TOTAL 45

A & B & C 53	
FAILED AS PREDICTED	PREDICTED TO FAIL
5, 7, 8, 9, 10, 13, 15, 24, 30, 33, 37, 38, 39, 40, 44, 45, 47, 50, 51, 52, 55, 56, 59, 60, 61.	1, 2, 5, 6, 7, 8, 9, 10, 11, 13, 14, 15, 16, 18, 19, 20, 22, 23, 24, 25, 26, 28, 29, 30, 32, 33, 34, 36, 37, 38, 39, 40, 42, 43, 44, 45, 46, 47, 48, 50, 51, 52, 53, 54, 55, 56, 58, 59, 60, 62, 63, 64, 65
TOTAL 25	TOTAL 53

SECTION IV

CELL FAILURE ANALYSIS

A. INTRODUCTION

The Crane program included detailed descriptive English information concerning the nature of the various failings in the cells (see Appendix). Close examination of these data suggested that much information was contained in these autopsy reports not obvious by directly reviewing the data itself. It was determined that information on various failure mechanisms within nickel-cadium cells could be gained by assuming that the data were an elaborate cipher system containing hidden secrets. The use of cryptology and cryptanalytic techniques as applied to data reduction and industrial failure mechanisms, especially when the information is contained in written English, is believed to be novel.

Cryptanalytic decipherment of coded English depends upon the fact that about 13 percent of the letters in a normal text will be Es, 9 percent Ts, 8 percent Os, 2 percent Ps, and so on. Even though these frequencies (which are called monograms in cryptanalysis) vary from sample to sample, large bodies of text adhere sufficiently accurately to them so that they form one of the main tools of cryptanalysis. From monogram frequencies for a given encoded text it is possible to calculate the frequencies of occurrence of letter-pairs, called bigrams. The frequency of bigrams obtained from English usage are, of course, much different than random frequencies. Message structure is detected by making an elaborate of as many N-gram combinations as are necessary to recover the original text.

The present approach began by taking the Crane program autopsy data and encoding each item construed to be a significant failure characteristic or a significant failure symptom, trying to be as unambiguous as possible to prevent overlaps. This was found to be impossible, however, and future coding of such information can profit by this example (see Appendix for recommendations for future post-mortem descpiptors of failure). Next, applying the coded technique to all of the data, and allowing up to seven coded letters per cell, a computer was used to construct the frequency of failure of each item alone--the monogram frequencies of cell failure. As is the case with message decoding, it is possible to perform considerable analysis of the monogram frequencies of cell failure. Also a computation of tri-gram frequencies of cell failure proved important. This analysis did in fact retrieve much information from the data which was occulted by both the nature of the data and the way in which they were obtained.

Table XIII.

CODES USED FOR ENCODING DESCRIPTIONS OF FAILURE

A. Low Voltage Charge.

B. Low Voltage Discharge.

C. Separator: Deteriorated, Dissolved, Burned, Pinpoint Penetration, Short.

D. Plate Material Shorted Through Separator.

E. Separator Impregnated with Negative Plate Material.

F. Migration of Positive and/or Negative Plate Material.

G. Extraneous Material Between Plates.

H. Deposit on Positive and/or Negative Terminals.

I. Blistering on Positive Plate(s).

J. Plate(s) Stuck to Case.

K. Excess Scoring of Case.

L. High Pressure, Buldge, Convex Slide(s).

M. Concave Side(s), Short(s) due to Internal Shift.

N. Broken Seal(s): Ceramic, Glass.

O. Ceramic Short.

P. Electrolyte Leak, Weight Loss, Separator Dry, Electrolyte Shorted Out Cell.

Q. Tab(s): Burned, Broken, Welds Weak.

R. Third Electrode Shorted to Plate.

T. Circuit: Short, Open.

U. High Voltage Charge.

Table XIV.

TEMPERATURE SUB-SET WITHIN MONOGRAMS

Set Name	No. of cells in set	Number of cells per coded Failure Characteristic					
		A	B	C	D	I	U
0^{o} AMB.	47	23	38	16	7	22	12
25^{o} "	147	67	127	93	24	40	22
40^{o} "	165	60	112	113	29	29	28
Total "	359	150	277	222	60	91	62

Table XV.

NORMALIZED TEMPERATURE SUB-SET WITHIN MONOGRAMS

Set Name	No. of Cells in set	A	B	C	D	I	U
0^{o} AMB.	47	.49	.81	.34	.15	.47	.26
25^{o} "	147	.46	.86	.63	.16	.27	.15
40^{o} "	165	.36	.68	.69	.18	.18	.17
Total "	359	.42	.78	.62	.17	.25	.17

B. MONOGRAM FREQUENCIES OF FAILURE

The actual coded information from the Crane program uses the letters A through U, indicating the failures listed in Table XIII. Note that several of the coded descriptions are not failure characteristics, but instead they are symptoms. The codes A, B and U, for example, include information necessary to contain all of the post mortem data by this method of analysis. Several of the code legends overlap or seem ambiguous; for example; C, D, E, T. This can be eliminated if the failure characteristic structure is re-defined by a battery-oriented electro-chemist, as recommended in detail in the Appendix.

Even with this seeming imperfection in the failure characteristic structure, many significant and interesting patterns have been identified by constructing monogram frequency tables for each of several test variables and cell manufacturers.

It was discovered that the frequency tables prepared for the monograms of cell failure contained interesting and important subdivisions, called sub-sets. For example, the ambient temperature set listed in Table XIV, whows the number of battery cells that failed within the identified temperature range, and the number of failed cells for each of the coded failure characteristics that occurred. These frequency tables have little meaning in this form, however. To permit correlation within each variable sub-set, each of the failure characteristic totals is normalized, divided by its sub-set total, to determine the average fraction contrubution for each failure characteristic within the identified set. For example, 23 (A, O^o AMB)/47 (O^o AMB total) = .49. Continuing with the rest of the data we arrive at the distribution instead in Table XV, the normalized or average-fraction contribution for the charge in ambient temperature and failure characteristic listed in Table XIV.

Bar charts were then constructed for three test variables and for four manufacturers. These charts are shown in Figures 3 through 10. The three test variables are ambient temperature, depth of discharge (D. O. D.) and orbit period (period of charge-discharge cycle).

C. TRIGRAM FREQUENCIES OF FAILURE

Combining three coded failure characteristics results in the trigram frequencies. There are 1330 alphabetized three-letter combinations possible for the twenty-one code letters used. Trigram frequency tables were constructed by a computer program for each of four manufacturers, individually and for the same four manufacturers in total. A portion of these trigram frequency failure characteristics are given in Tables XVI through XIX for each of the four manufacturers, and Table XX sums them up together.

Tables XXI through XXIV are partial listings by manufacturer of the total and partial trigram frequencies accountable to each identified manufacturer. In these tables the column headed trigram code indicates the specific combination of the coded failure characteristics; the column headed <u>part</u> indicates the named manufacturer's portion of the total frequency that is specified in the column headed <u>total</u>. These tables indicate that individual manufacturer's cells were responsible for the total of many individual trigram failure characteristics or failure mechanisms. It may be seen that manufacturer No. 2, for example, is responsible for all occurrences of BCK:

B = Low Voltage Discharge

C = Separator Deteriorated, Dissolved, Etc.

K = Excess Scoring of Case

Manufacturer No. 2 was responsible for all occurrences of failure characteristic K.

Manufacturer No. 3 was responsible for all occurrences of BIO:

B = Low Voltage Discharge

I = Blistering on Positive Plate (s)

O = Ceramic Short

Manufacturer No. 3 was responsible for all occurrences of failure characteristic O.

Much valuable information converning manufacturer/design effect on failure characteristics and failure mechanisms has been gained by application of these techniques. This information can be used by cell manufacturers to assay the extent of possible defects in their product within all operating conditions and to evaluate the interrelating effects of new components with each other and with standard parts. Specific areas of concern are pinpointed for attention by the cell-design and quality control engineer. For example, manufacturer No. 2, Sonotone, was responsible for all cell failures involving "Excess Scoring of Case", manufacturer No. 3, Gulton, was responsible for all cell failures involving "Ceramic Short", and manufacturer No. 4, Gould, was responsible for all cell failures involving "Extraneous Material Between Plates". This corroborates the ultimate purpose of this work, namely, to provide the engineer with a method to assess the potentialities of space-battery-cells relative to various environmental and functional parameters, permitting correlation and selection within space-mission operational requirements and constraints.

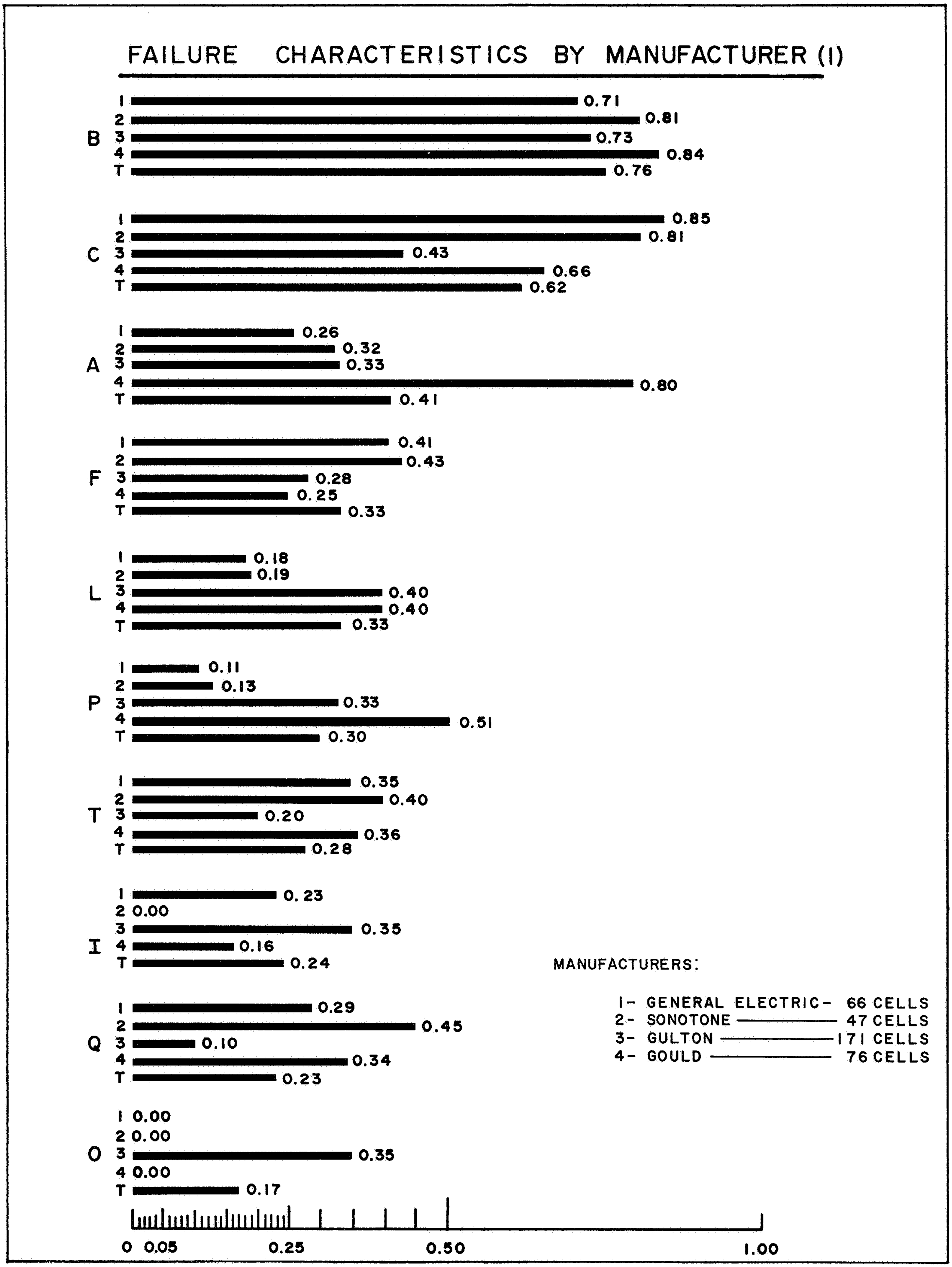

FAILURE CHARACTERISTICS BY MANUFACTURER (1)
B
1 0.71
2 0.81
3 0.73
4 0.84
T 0.76
C
1 0.85
2 0.81
3 0.43
4 0.66
T 0.62
A
1 0.26
2 0.32
3 0.33
4 0.80
T 0.41
F
1 0.41
2 0.43
3 0.28
4 0.25
T 0.33
L
1 0.18
2 0.19
3 0.40
4 0.40
T 0.33
P
1 0.11
2 0.13
3 0.33
4 0.51
T 0.30
T
1 0.35
2 0.40
3 0.20
4 0.36
T 0.28
I
1 0.23
2 0.00
3 0.35
4 0.16
T 0.24
Q
1 0.29
2 0.45
3 0.10
4 0.34
T 0.23
O
1 0.00
2 0.00
3 0.35
4 0.00
T 0.17
0 0.05 0.25 0.50 1.00
MANUFACTURERS:
1- GENERAL ELECTRIC- 66 CELLS
2- SONOTONE 47 CELLS
3- GULTON 171 CELLS
4- GOULD 76 CELLS

Figure 3. (1)

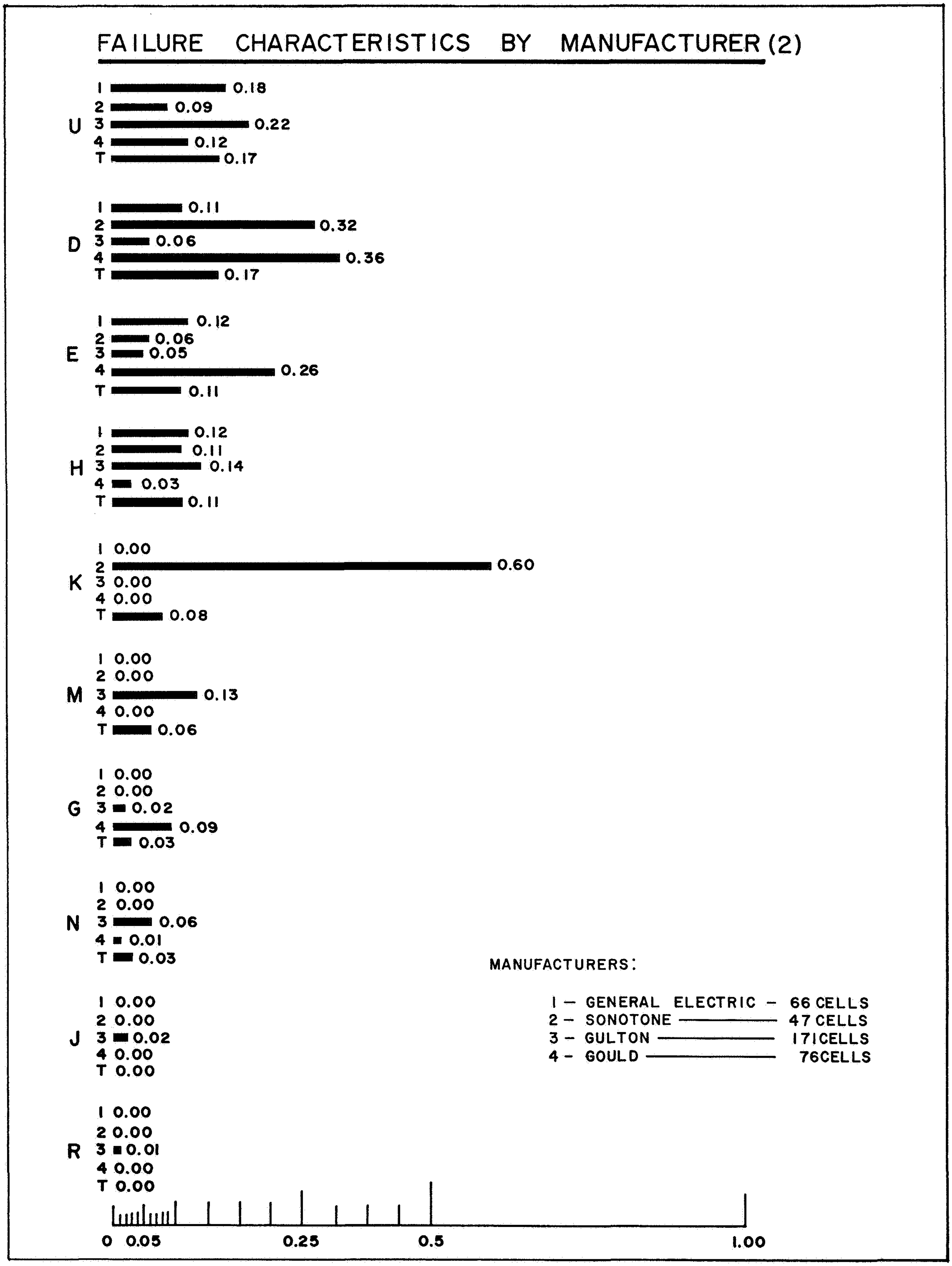

FAILURE CHARACTERISTICS BY MANUFACTURER (2)
U
1 0.18
2 0.09
3 0.22
4 0.12
T 0.17
D
1 0.11
2 0.32
3 0.06
4 0.36
T 0.17
E
1 0.12
2 0.06
3 0.05
4 0.26
T 0.11
H
1 0.12
2 0.11
3 0.14
4 0.03
T 0.11
K
1 0.00
2 0.60
3 0.00
4 0.00
T 0.08
M
1 0.00
2 0.00
3 0.13
4 0.00
T 0.06
G
1 0.00
2 0.00
3 0.02
4 0.09
T 0.03
N
1 0.00
2 0.00
3 0.06
4 0.01
T 0.03
J
1 0.00
2 0.00
3 0.02
4 0.00
T 0.00
R
1 0.00
2 0.00
3 0.01
4 0.00
T 0.00
0 0.05 0.25 0.5 1.00
MANUFACTURERS:
1 — GENERAL ELECTRIC — 66 CELLS
2 — SONOTONE — 47 CELLS
3 — GULTON — 171 CELLS
4 — GOULD — 76 CELLS

Figure 4

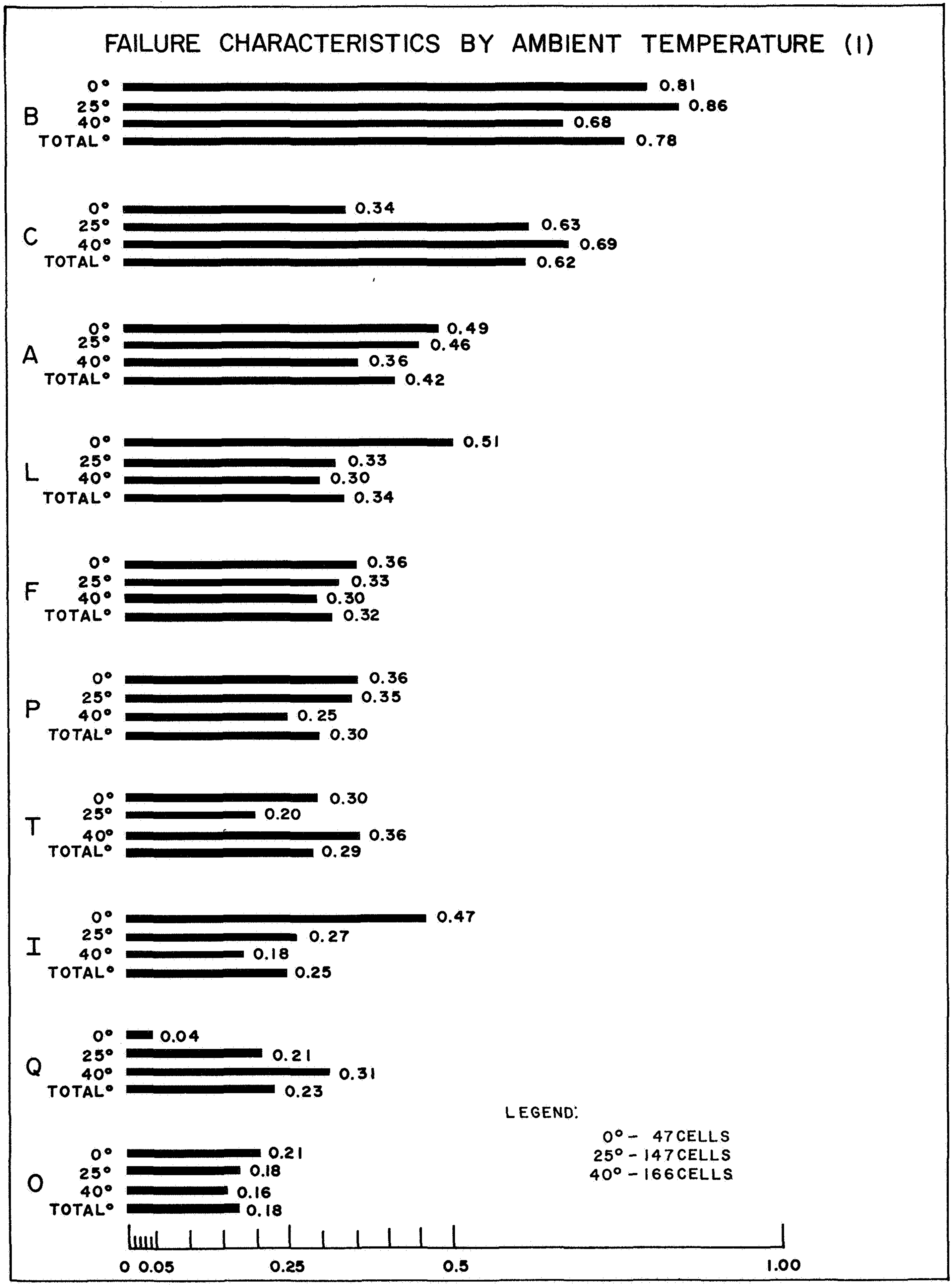

FAILURE CHARACTERISTICS BY AMBIENT TEMPERATURE (1)
B
0° 0.81
25° 0.86
40° 0.68
TOTAL° 0.78
C
0° 0.34
25° 0.63
40° 0.69
TOTAL° 0.62
A
0° 0.49
25° 0.46
40° 0.36
TOTAL° 0.42
L
0° 0.51
25° 0.33
40° 0.30
TOTAL° 0.34
F
0° 0.36
25° 0.33
40° 0.30
TOTAL° 0.32
P
0° 0.36
25° 0.35
40° 0.25
TOTAL° 0.30
T
0° 0.30
25° 0.20
40° 0.36
TOTAL° 0.29
I
0° 0.47
25° 0.27
40° 0.18
TOTAL° 0.25
Q
0° 0.04
25° 0.21
40° 0.31
TOTAL° 0.23
O
0° 0.21
25° 0.18
40° 0.16
TOTAL° 0.18
LEGEND:
0° - 47 CELLS
25° - 147 CELLS
40° - 166 CELLS
0 0.05
0.25
0.5
1.00

Figure 5

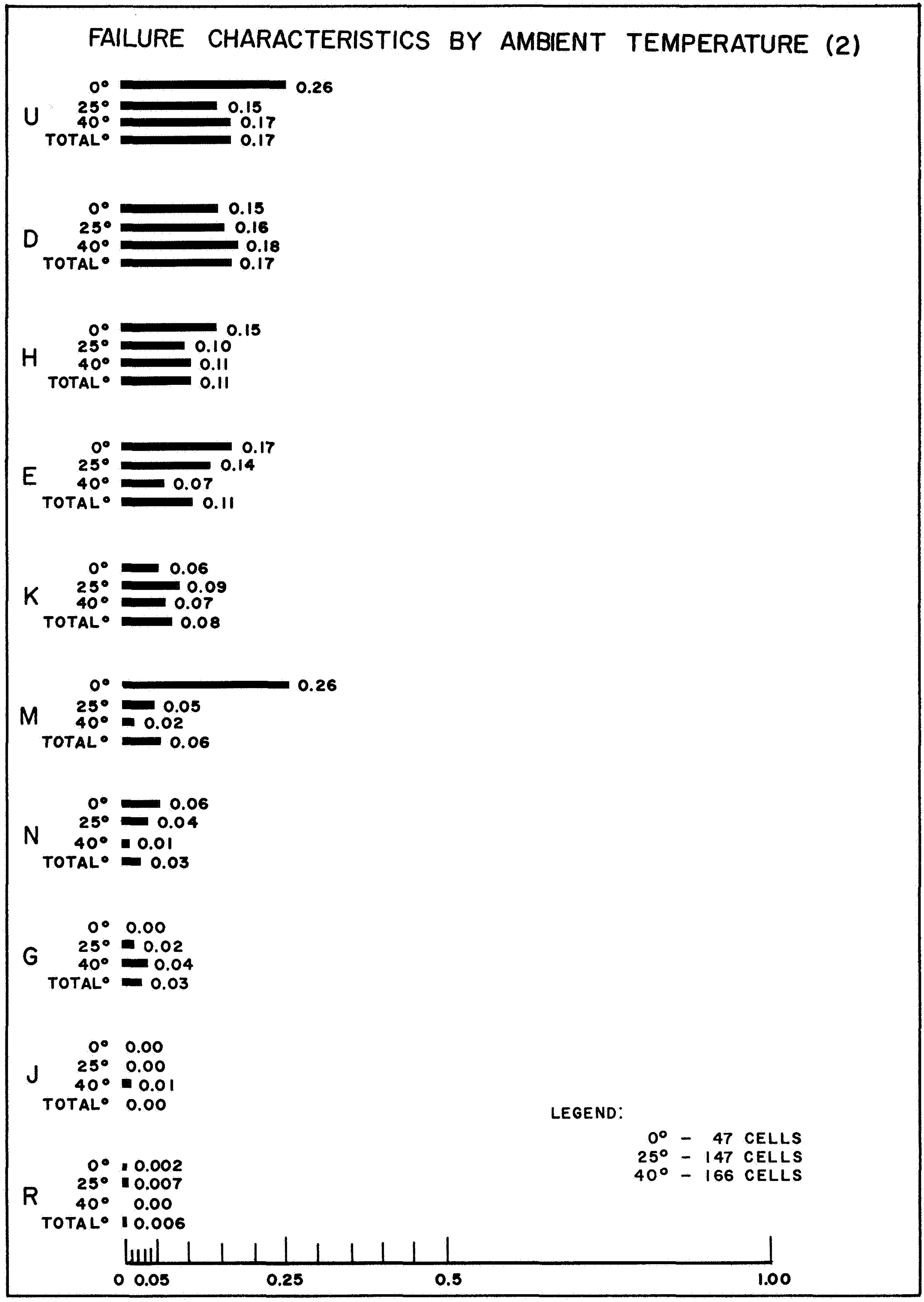

FAILURE CHARACTERISTICS BY AMBIENT TEMPERATURE (2)
U
0° 0.26
25° 0.15
40° 0.17
TOTAL° 0.17
D
0° 0.15
25° 0.16
40° 0.18
TOTAL° 0.17
H
0° 0.15
25° 0.10
40° 0.11
TOTAL° 0.11
E
0° 0.17
25° 0.14
40° 0.07
TOTAL° 0.11
K
0° 0.06
25° 0.09
40° 0.07
TOTAL° 0.08
M
0° 0.26
25° 0.05
40° 0.02
TOTAL° 0.06
N
0° 0.06
25° 0.04
40° 0.01
TOTAL° 0.03
G
0° 0.00
25° 0.02
40° 0.04
TOTAL° 0.03
J
0° 0.00
25° 0.00
40° 0.01
TOTAL° 0.00
R
0° 0.002
25° 0.007
40° 0.00
TOTAL° 0.006
LEGEND:
0° - 47 CELLS
25° - 147 CELLS
40° - 166 CELLS
0 0.05 0.25 0.5 1.00

Figure 6

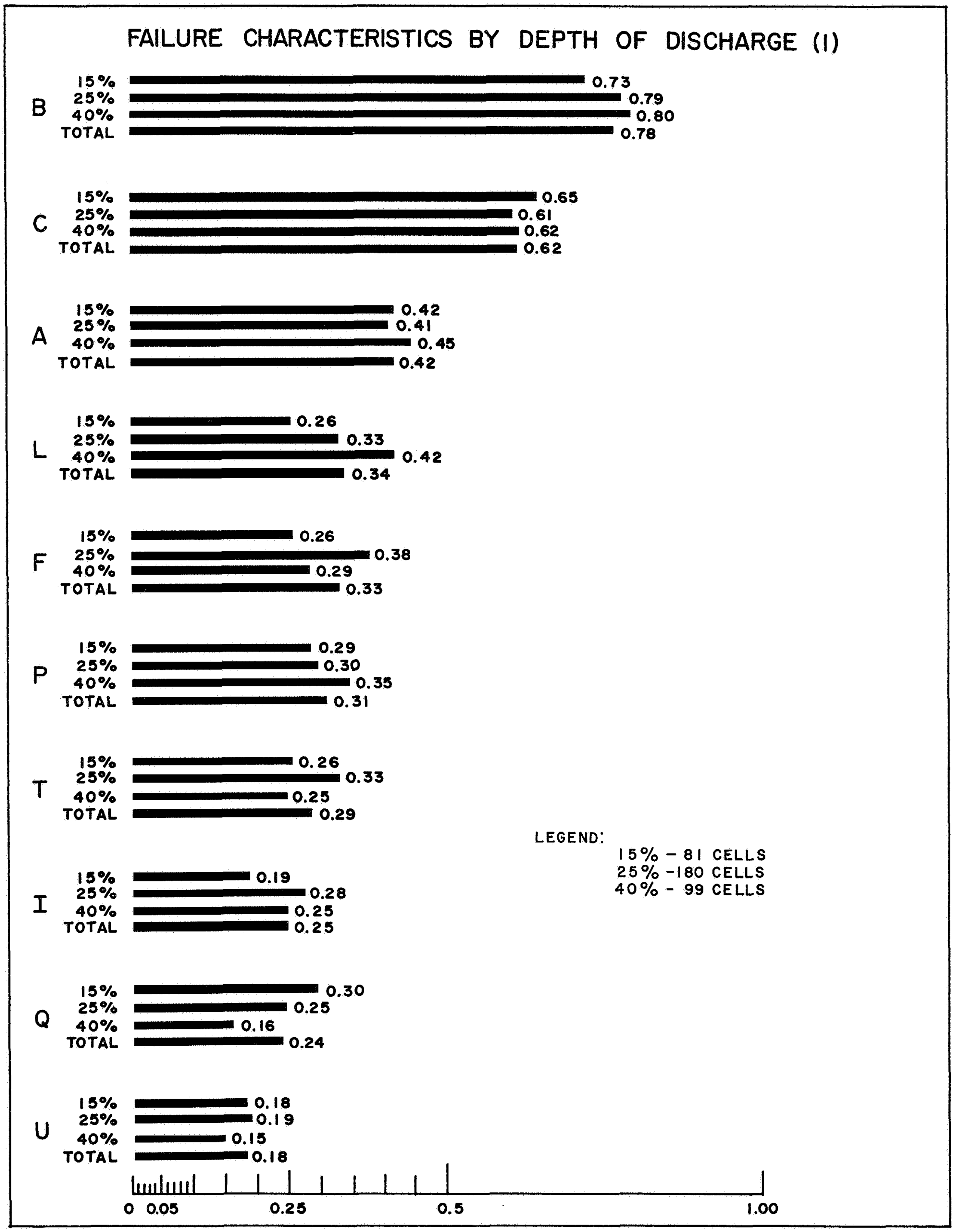

FAILURE CHARACTERISTICS BY DEPTH OF DISCHARGE (I)
B
15% 0.73
25% 0.79
40% 0.80
TOTAL 0.78
C
15% 0.65
25% 0.61
40% 0.62
TOTAL 0.62
A
15% 0.42
25% 0.41
40% 0.45
TOTAL 0.42
L
15% 0.26
25% 0.33
40% 0.42
TOTAL 0.34
F
15% 0.26
25% 0.38
40% 0.29
TOTAL 0.33
P
15% 0.29
25% 0.30
40% 0.35
TOTAL 0.31
T
15% 0.26
25% 0.33
40% 0.25
TOTAL 0.29
LEGEND:
15% - 81 CELLS
25% -180 CELLS
40% - 99 CELLS
I
15% 0.19
25% 0.28
40% 0.25
TOTAL 0.25
Q
15% 0.30
25% 0.25
40% 0.16
TOTAL 0.24
U
15% 0.18
25% 0.19
40% 0.15
TOTAL 0.18
0 0.05 0.25 0.5 1.00

Figure 7

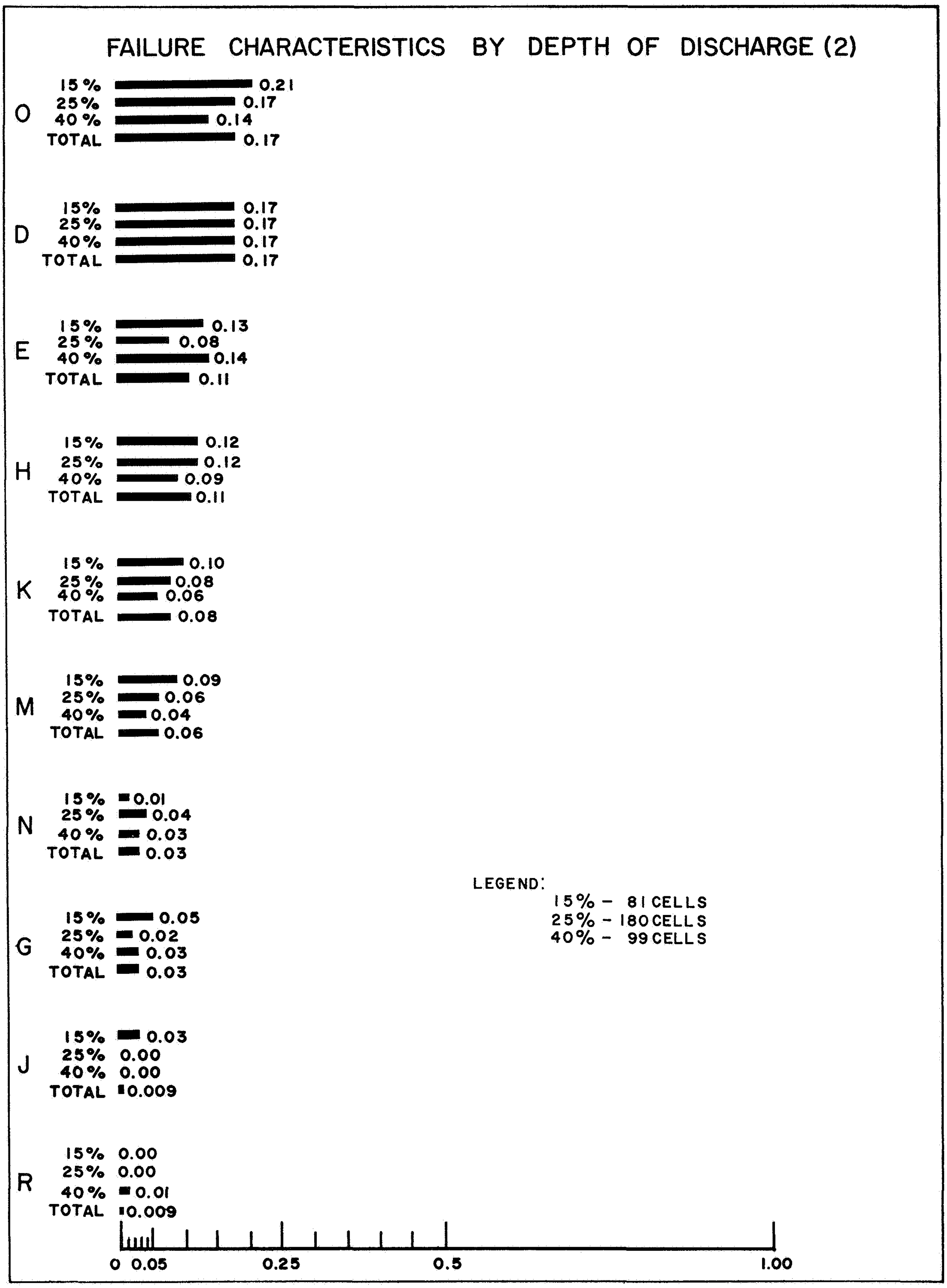

FAILURE CHARACTERISTICS BY DEPTH OF DISCHARGE (2)
O
15% 0.21
25% 0.17
40% 0.14
TOTAL 0.17
D
15% 0.17
25% 0.17
40% 0.17
TOTAL 0.17
E
15% 0.13
25% 0.08
40% 0.14
TOTAL 0.11
H
15% 0.12
25% 0.12
40% 0.09
TOTAL 0.11
K
15% 0.10
25% 0.08
40% 0.06
TOTAL 0.08
M
15% 0.09
25% 0.06
40% 0.04
TOTAL 0.06
N
15% 0.01
25% 0.04
40% 0.03
TOTAL 0.03
G
15% 0.05
25% 0.02
40% 0.03
TOTAL 0.03
J
15% 0.03
25% 0.00
40% 0.00
TOTAL 0.009
R
15% 0.00
25% 0.00
40% 0.01
TOTAL 0.009
0 0.05 0.25 0.5 1.00
LEGEND:
15% - 81 CELLS
25% - 180 CELLS
40% - 99 CELLS

Figure 8

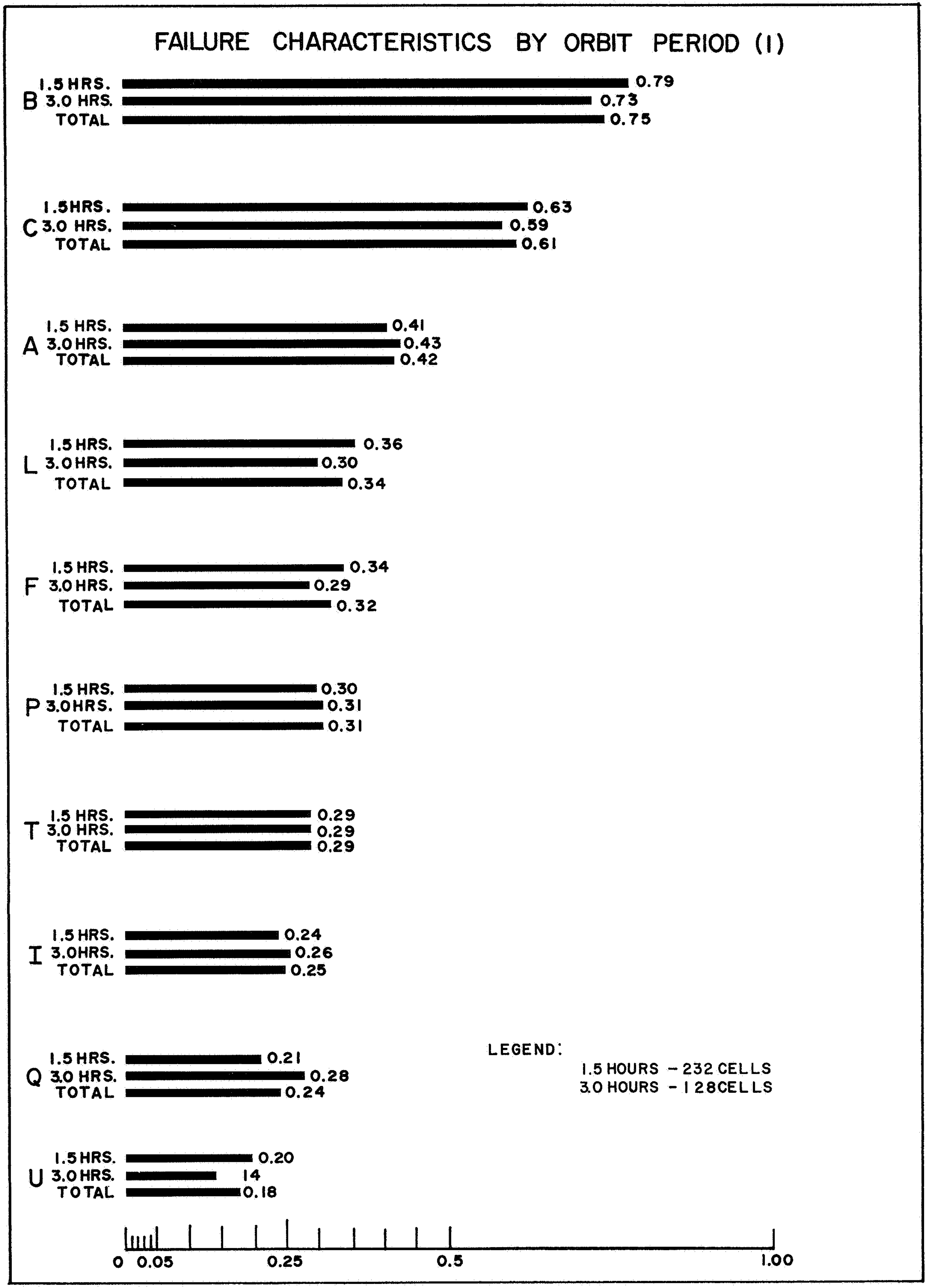

FAILURE CHARACTERISTICS BY ORBIT PERIOD (I)
B
1.5 HRS. 0.79
3.0 HRS. 0.73
TOTAL 0.75
C
1.5HRS. 0.63
3.0 HRS. 0.59
TOTAL 0.61
A
1.5 HRS. 0.41
3.0 HRS. 0.43
TOTAL 0.42
L
1.5 HRS. 0.36
3.0 HRS. 0.30
TOTAL 0.34
F
1.5 HRS. 0.34
3.0 HRS. 0.29
TOTAL 0.32
P
1.5 HRS. 0.30
3.0 HRS. 0.31
TOTAL 0.31
T
1.5 HRS. 0.29
3.0 HRS. 0.29
TOTAL 0.29
I
1.5 HRS. 0.24
3.0 HRS. 0.26
TOTAL 0.25
Q
1.5 HRS. 0.21
3.0 HRS. 0.28
TOTAL 0.24
U
1.5 HRS. 0.20
3.0 HRS. 14
TOTAL 0.18
LEGEND:
1.5 HOURS - 232 CELLS
3.0 HOURS - 128 CELLS
0 0.05 0.25 0.5 1.00

Figure 9

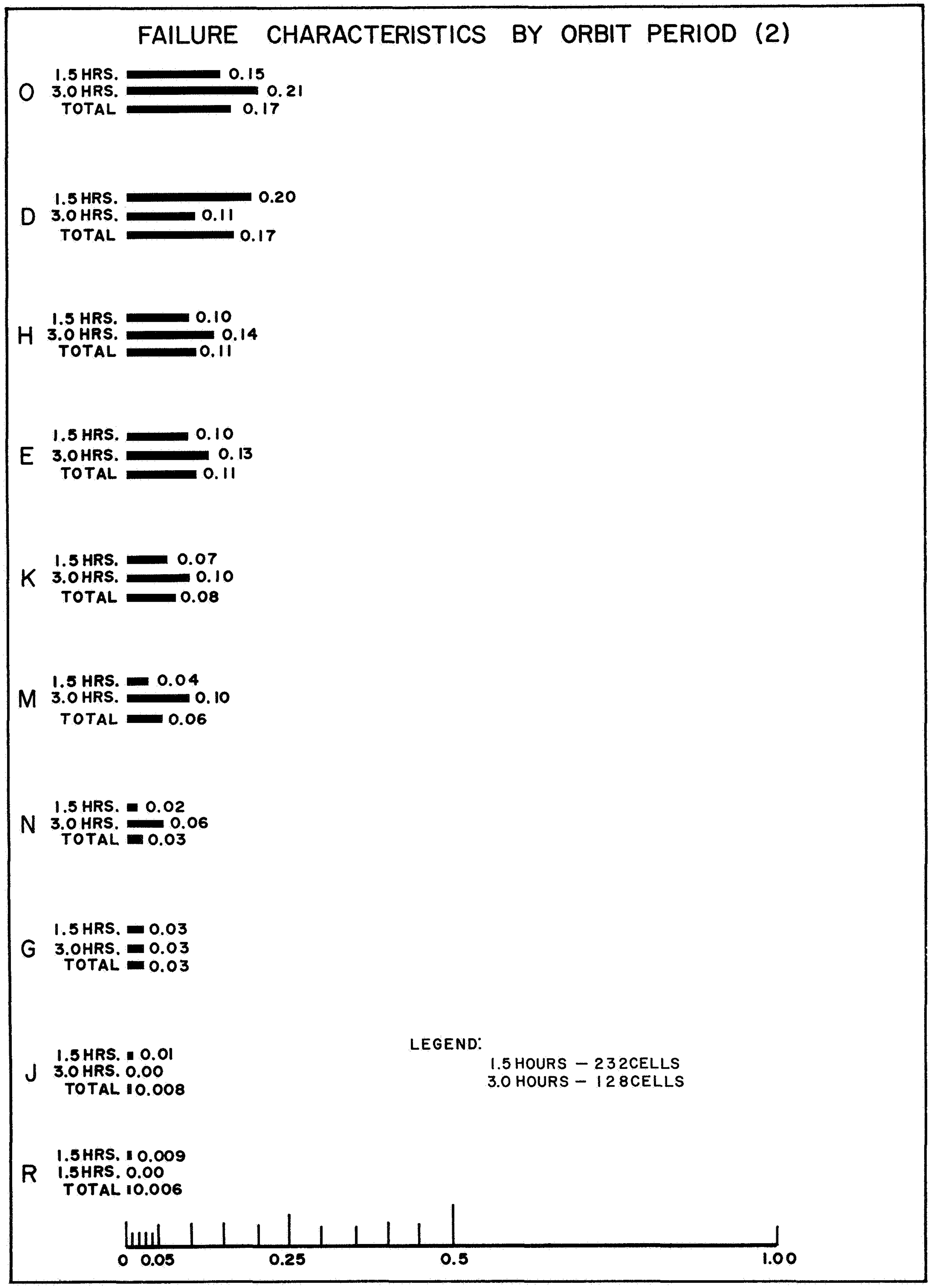

FAILURE CHARACTERISTICS BY ORBIT PERIOD (2)
O
1.5 HRS. 0.15
3.0 HRS. 0.21
TOTAL 0.17
D
1.5 HRS. 0.20
3.0 HRS. 0.11
TOTAL 0.17
H
1.5 HRS. 0.10
3.0 HRS. 0.14
TOTAL 0.11
E
1.5 HRS. 0.10
3.0 HRS. 0.13
TOTAL 0.11
K
1.5 HRS. 0.07
3.0 HRS. 0.10
TOTAL 0.08
M
1.5 HRS. 0.04
3.0 HRS. 0.10
TOTAL 0.06
N
1.5 HRS. 0.02
3.0 HRS. 0.06
TOTAL 0.03
G
1.5 HRS. 0.03
3.0 HRS. 0.03
TOTAL 0.03
J
1.5 HRS. 0.01
3.0 HRS. 0.00
TOTAL 0.008
R
1.5 HRS. 0.009
1.5 HRS. 0.00
TOTAL 0.006
LEGEND:
1.5 HOURS — 232 CELLS
3.0 HOURS — 128 CELLS
0
0.05
0.25
0.5
1.00

Figure 10

MANUFACTURER NO. 1 15 PACKS 66 CELLS

AB	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	1
	17	03	04	08	00	02	06	00	00	02	00	00	00	00	02	00	00	01	00	1
AC	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U		2
	03	04	08	00	02	06	00	00	02	00	00	00	00	02	00	00	01	00		2
AD	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U			3
	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00			3
AE	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U				4
	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00				4
AF	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U					5
	00	01	06	00	00	02	00	00	00	00	01	00	00	00	00					5
AG	H	I	J	K	L	M	N	O	P	Q	R	S	T	U						6
	00	00	00	00	00	00	00	00	00	00	00	00	00	00						6
AH	I	J	K	L	M	N	O	P	Q	R	S	T	U							7
	01	00	00	00	00	00	00	00	00	00	00	00	00							7
AI	J	K	L	M	N	O	P	Q	R	S	T	U								8
	00	00	00	00	00	00	00	01	00	00	00	00								8
AJ	K	L	M	N	O	P	Q	R	S	T	U									9
	00	00	00	00	00	00	00	00	00	00	00									9
AK	L	M	N	O	P	Q	R	S	T	U										10
	00	00	00	00	00	00	00	00	00	00										10
AL	M	N	O	P	Q	R	S	T	U											11
	00	00	00	00	00	00	00	00	00											11
AM	N	O	P	Q	R	S	T	U												12
	00	00	00	00	00	00	00	00												12
AN	O	P	Q	R	S	T	U													13
	00	00	00	00	00	00	00													13
AO	P	Q	R	S	T	U														14
	00	00	00	00	00	00														14
AP	Q	R	S	T	U															15
	00	00	00	00	00															15
AQ	R	S	T	U																16
	00	00	01	00																16
AR	S	T	U																	17
	00	00	00																	17
AS	T	U																		18
	00	00																		18
AT	U																			19
	00																			19

First page of a "Tri-Gram" table. This page features every three letter combination that contains the letter A for the indicated manufacturer.

Table XVI

MANUFACTURER NO. 2 11 PACKS 47 CELLS

AB	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	1
	11	05	01	05	00	01	00	00	08	00	00	00	00	01	06	00	00	02	00	1
AC	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U		2
	04	01	03	00	00	00	00	06	00	00	00	00	01	06	00	00	01	00		2
AD	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U			3
	01	01	00	00	00	00	03	00	00	00	00	00	02	00	00	00	00			3
AE	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U				4
	00	00	00	00	00	01	00	00	00	00	00	01	00	00	00	00				4
AF	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U					5
	00	01	00	00	04	00	00	00	00	01	01	00	00	02	00					5
AG	H	I	J	K	L	M	N	O	P	Q	R	S	T	U						6
	00	00	00	00	00	00	00	00	00	00	00	00	00	00						6
AH	I	J	K	L	M	N	O	P	Q	R	S	T	U							7
	00	00	01	00	00	00	00	00	00	00	00	01	00							7
AI	J	K	L	M	N	O	P	Q	R	S	T	U								8
	00	00	00	00	00	00	00	00	00	00	00	00								8
AJ	K	L	M	N	O	P	Q	R	S	T	U									9
	00	00	00	00	00	00	00	00	00	00	00									9
AK	L	M	N	O	P	Q	R	S	T	U										10
	00	00	00	00	01	04	00	00	02	00										10
AL	M	N	O	P	Q	R	S	T	U											11
	00	00	00	00	00	00	00	00	00											11
AM	N	O	P	Q	R	S	T	U												12
	00	00	00	00	00	00	00	00												12
AN	O	P	Q	R	S	T	U													13
	00	00	00	00	00	00	00													13
AO	P	Q	R	S	T	U														14
	00	00	00	00	00	00														14
AP	Q	R	S	T	U															15
	00	00	00	01	00															15
AQ	R	S	T	U																16
	00	00	00	00																16
AR	S	T	U																	17
	00	00	00																	17
AS	T	U																		18
	00	00																		18
AT	U																			19
	00																			19

Table XVII

MANUFACTURER NO. 3 49 PACKS 172 CELLS

AB	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	1
	26	05	05	13	00	06	29	00	00	24	08	00	34	14	04	00	00	04	00	1
AC	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U		2
	04	01	12	00	03	15	00	00	13	03	00	09	06	04	00	00	04	00		2
AD	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U			3
	00	01	00	01	03	00	00	02	01	00	01	01	00	00	00	01	00			3
AE	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U				4
	00	00	00	05	00	00	04	01	00	04	01	00	00	00	00	00				4
AF	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U					5
	00	04	05	00	00	06	02	00	03	05	04	00	00	01	00					5
AG	H	I	J	K	L	M	N	O	P	Q	R	S	T	U						6
	00	00	00	00	00	00	00	00	00	00	00	00	00	00						6
AH	I	J	K	L	M	N	O	P	Q	R	S	T	U							7
	01	00	00	02	03	00	02	01	00	00	00	01	00							7
AI	J	K	L	M	N	O	P	Q	R	S	T	U								8
	00	00	15	04	00	18	05	02	00	00	02	00								8
AJ	K	L	M	N	O	P	Q	R	S	T	U									9
	00	00	00	00	00	00	00	00	00	00	00									9
AK	L	M	N	O	P	Q	R	S	T	U										10
	00	00	00	00	00	00	00	00	00	00										10
AL	M	N	O	P	Q	R	S	T	U											11
	02	00	13	05	02	00	00	02	00											11
AM	N	O	P	Q	R	S	T	U												12
	00	02	02	00	00	00	02	00												12
AN	O	P	Q	R	S	T	U													13
	00	00	00	00	00	00	00													13
AO	P	Q	R	S	T	U														14
	07	01	00	00	00	00														14
AP	Q	R	S	T	U															15
	01	00	00	00	00															15
AQ	R	S	T	U																16
	00	00	00	00																16
AR	S	T	U																	17
	00	00	00																	17
AS	T	U																		18
	00	00																		18
AT	U																			19
	00																			19

Table XVIII

MANUFACTURER NO. 4 17 PACKS 76 CELLS

AB	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	1
	27	16	11	11	03	01	07	00	00	21	00	00	00	15	12	00	00	18	00	1
AC	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U		2
	07	11	15	02	01	05	00	00	12	00	01	00	17	14	00	00	08	00		2
AD	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U			3
	02	02	02	00	02	00	00	10	00	00	00	04	07	00	00	09	00			3
AE	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U				4
	04	01	00	01	00	00	01	00	00	00	08	06	00	00	01	00				4
AF	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U					5
	00	01	02	00	00	07	00	01	00	07	03	00	00	03	00					5
AG	H	I	J	K	L	M	N	O	P	Q	R	S	T	U						6
	00	00	00	00	01	00	00	00	01	02	00	00	01	00						6
AH	I	J	K	L	M	N	O	P	Q	R	S	T	U							7
	00	00	00	01	00	00	00	00	00	00	00	01	00							7
AI	J	K	L	M	N	O	P	Q	R	S	T	U								8
	00	00	05	00	00	00	00	00	00	00	03	00								8
AJ	K	L	M	N	O	P	Q	R	S	T	U									9
	00	00	00	00	00	00	00	00	00	00	00									9
AK	L	M	N	O	P	Q	R	S	T	U										10
	00	00	00	00	00	00	00	00	00	00										10
AL	M	N	O	P	Q	R	S	T	U											11
	00	00	00	03	01	00	00	13	00											11
AM	N	O	P	Q	R	S	T	U												12
	00	00	00	00	00	00	00	00												12
AN	O	P	Q	R	S	T	U													13
	00	01	01	00	00	00	00													13
AO	P	Q	R	S	T	U														14
	00	00	00	00	00	00														14
AP	Q	R	S	T	U															15
	14	00	00	01	00															15
AQ	R	S	T	U																16
	00	00	00	00																16
AR	S	T	U																	17
	00	00	00																	17
AS	T	U																		18
	00	00																		18
AT	U																			19
	00																			19

Table XIX

MANUFACTURERS NO. 1.2.3.4 92 PACKS 361 CELLS

AB	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	1
	81	29	21	37	03	10	42	00	08	47	08	00	34	30	24	00	00	25	00	1
AC	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U		2
	18	17	38	02	06	26	00	06	27	03	01	09	24	26	00	00	14	00		2
AD	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U			3
	03	04	02	01	05	00	03	12	01	00	01	05	09	00	00	10	00			3
AE	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U				4
	04	01	00	06	00	01	05	01	00	04	09	07	00	00	01	00				4
AF	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U					5
	00	07	13	00	04	15	02	01	03	13	09	00	00	06	00					5
AG	H	I	J	K	L	M	N	O	P	Q	R	S	T	U						6
	00	00	00	00	01	00	00	00	01	02	00	00	01	00						6
AH	I	J	K	L	M	N	O	P	Q	R	S	T	U							7
	02	00	01	03	03	00	02	01	00	00	00	03	00							7
AI	J	K	L	M	N	O	P	Q	R	S	T	U								8
	00	00	20	04	00	18	05	03	00	00	05	00								8
AJ	K	L	M	N	O	P	Q	R	S	T	U									9
	00	00	00	00	00	00	00	00	00	00	00									9
AK	L	M	N	O	P	Q	R	S	T	U										10
	00	00	00	00	01	04	00	00	02	00										10
AL	M	N	O	P	Q	R	S	T	U											11
	02	00	13	08	03	00	00	15	00											11
AM	N	O	P	Q	R	S	T	U												12
	00	02	02	00	00	00	02	00												12
AN	O	P	Q	R	S	T	U													13
	00	01	01	00	00	00	00													13
AO	P	Q	R	S	T	U														14
	07	01	00	00	00	00														14
AP	Q	R	S	T	U															15
	15	00	00	02	00															15
AQ	R	S	T	U																16
	00	00	01	00																16
AR	S	T	U																	17
	00	00	00																	17
AS	T	U																		18
	00	00																		18
AT	U																			19
	00																			19

Every entry on this page is the sum of the corresponding entries on Tables XVI through XIX.

Table XX

MANUFACTURER NO. 1

15 PACKS

66 CELLS

TRI-GRAM CODE	PART	TOTAL
BQT	8	13
BTU	8	12
CQU	6	11
CTU	6	8
PQT	4	7
PQU	4	8
PTU	4	4
QTU	7	8

TABLE XXI

MANUFACTURER NO. 2

11 PACKS
47 CELLS

TRI-GRAM CODE	PART	TOTAL
ABK	8	8
AKQ	4	4
BCK	22	22
BDK	4	4
BFK	15	15
BFT	7	13
BKL	5	5
BKQ	13	13
CKQ	12	12
DFK	2	2
DQT	4	4
KQT	5	5
KTU	3	3
LQT	2	4

TABLE XXII

MANUFACTURER NO. 3

49 PACKS
172 CELLS

TRI-GRAM CODE	PART	TOTAL
ABH	6	10
ABI	29	42
ABO	34	34
ACI	15	26
AIL	15	20
AIO	18	18
BCI	28	47
BFH	11	22
BIL	23	31
BIO	26	26
BIP	16	16
BLP	21	24
CHT	10	14
EIO	5	5
FIL	7	10
ILO	11	11
LPU	14	14
LQT	2	4
MPU	3	3
NPU	4	4

TABLE XXIII

MANUFACTURER NO. 4

17 PACKS

76 CELLS

TRI-GRAM CODE	PART	TOTAL
ABD	16	29
ABP	15	30
ABQ	12	24
ACP	17	24
BDL	11	16
BEP	10	11
BLT	13	18
CEP	9	9
CPQ	14	24
DLT	8	11
EPQ	7	7
GIL	2	2
GLT	3	3

TABLE XXIV

SECTION V
CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

a. General

Mathematical, pseudo-cryptanalytic methods of data reduction, applied to information accumulated by the Crane program and implemented on computers, allows the extraction of much previously hidden information pertinent to predicting cell failure and discovering the reasons for these failures. These techniques have allowed the identification of patterns in the charge-discharge voltage characteristics which are indicative of incipient cell failure. In many instances these predictions begin to appear in the data several thousand elapsed cycles of charge-discharge before the actual failure occurrs.

Three methods of analysis were formulated to take the same body of data and view it in a different light, assuming that hidden information might appear as a result of a different technique of data reduction. A predictive capability of at least 60% and in some instances of 100% resulted, based on the choice of the data and upon the parameters used to view the data. This high degree of success infers that an early prediction capability is feasible so that reliable cells can be anticipated from a small empirical sampling -- the Probabilistic sampling approach outlined in Section I. Any inprovement in the sampling technique or in the methods for obtaining the original data would be reflected in an improvement in the prediction capabilities of the present technique. (See the Appendix for an evaluation of the Crane program, and recommendations for new parameters to be taken that are more pertinent to prediction and analysis by these techniques.) The virtue of this approach, borne out by the results, is that pertinent information is available from the data, even if data collection is poorly controlled. This is true especially if the original corpus of data is very large. The noise and randomness introduced by uncontrollable factors is overcome when a very large sampling of data is subjected to the present pseudo-cryptanalytic techniques.

The analysis of the English post-mortem remarks about the cell failures also proved invaluable in obtaining lost information. This technique for essentially reading between the lines of English sentences to discover unforseen but implicit information is considered novel. It will be useful in many other areas of data reduction.

b. Predicting Cell Failure

The Crane program for accumulating data on spacecraft cells has provided the opportunity for creating new and novel computer techniques for extrapolating much hidden information. An analysis of this data by these computer programs shows that cell failure is associated with the voltage measurement patterns. The frequency of low end-of-discharge voltage measurements, which exceed certain voltage-level thresholds, is relative to both cell failure and success. These patterns appear quite early in the cycle life (1000 to 2000 elapsed cycles), and they remain constant to the point of the cell failure. This technique is not dependent on critically accurate monitor times. Looking at the nine curves of Figure 2 in Section III, it should be noted that the separation is remarkably constant from the 1000-2000 cycle period to the point of actual cell-set failure. From this it can be seen that highly reliable information can probably be obtained quite early in the cycle life. Observed cell failure or success is clearly associated with high and low frequency count distributions of the low-end-of-discharge-voltage-level measurements. A relatively clear indication is present that those cells which attain higher measurements will fail earlier than those cells which do not.

The curves plotted for those cells that fail after 4000 to 6000 elapsed cycles of testing exhibit an increase in measurement frequency to the point of actual cell-set failure in eight out of nine graphs. The curves plotted for the non-failed cells (non-failed within the bounds of the data) start and remain consistently low throughout battery pack life; they rise gradually, as a function of time, and exhibit a remarkably constant degree of separation from the failed cell curves. At no time do the curves approximate or intersect each other.

As previously indicated, the voltage counts/measurements used in this technique are acquired from the discharge portion of a set of charge-discharge curves. This portion, historically, seems most indicative of incipient cell failure. The voltage counts/measurements derived from the charge portion of the curve sets have a different distribution than the discharge portion and are not as sensitive to overthreshold counts as they are to the dispersion of those counts. It also appears that a cell can "recover" from a limited amount of high voltage excursion on charge.

This analysis method, when applied to highly accurate, continuous, and voluminous data, will probably enable reliable cell selection and prediction capabilities to function with very early data; hopefully, this capability can be achieved with 1% of cell life data, based on a 30,000 cycle lifetime. The high curve separation at the 1000-2000 elapsed cycle point in the Crane data based graphs infers that pertinent information is available from very early test data and that a 1% prediction/selection capability is entirely possible, dependent on data conditions.

The first-difference histogram method of data reduction, depending as it does upon slight differences in the voltage, measurements are more apt to respond to innacurate input data. Nevertheless, despite the error conditions inherent in the Crane program (non-uniformity of collection, especially with respect to time and temperature), the large corpus enabled relatively high success in the predictive capability since

Table XXV. Failure Criteria for Superimposed Charge-Discharge Curve Technique

1. End of charge must be greater than the start of discharge.
2. End of charge must be greater than 1.40 volts.
3. End of charge must be below 1.60 volts.
4. Dispersion during charge must be less than 0.12 volts.
5. There must be no zeros in the charge.
6. The charge-limiter should not cut-in below 1.45 volts.
7. The end-of-charge voltage should not drop more than 0.06 volts after charge-limiter cut-in.
8. The superimposed curve-set should not have 'side shoots', or unusual translations, in the profile
9. The start of discharge must be greater than 1.30 volts.
10. The end-of-discharge should not be lower than 1.15 volts.
11. Dispersion during discharge should not be greater than 0.08 volts.
12. There must be no zeros in the discharge.
13. The last measurement in charge should be greater than the next to last measurement.

much error is ironed out. The superimposed-charge-discharge curve technique, however, gives an extremely accurate means of analyzing the patterns of both normal and adnormal cell voltages. The criteria listed in Table XXV were established on the basis of the curve-set data plotted empirically from battery pack lifetime histories. Error conditions are also present here, due to inherent data defects, that make prediction less accurate.

This method is particularly effective for the detection of abnormal voltage distribution patterns in the end-of-charge portion of a curve-set. The voltage-level range achieved by a curve-set and the dispersion of voltage-level measurements within individual time periods both produce indentifiable data patterns which are indicative of the potential lifetime of the cell. By combining sets of charge-discharge curves, this technique permits the evaluation of cumulative differences that are lost by the analysis of individual curves. These differences tend to form significant data-patterns also.

Table XXVI is a summary of the first 5000 elapsed cycles for approximately 20 battery packs, impartially selected from the Crane data, and the average observed cell lifetimes -- relative to class interval ranks in the 0 to 1000 cycle group. All battery packs contained in this sample are in a 1.5 hour orbit period, but differing depth of discharge and ambient temperature combinations.

Table XXVI

Summary of Failures in 20 Packs

Frequency of Low-End-of-Discharge Voltage-Level Measurements (Ranked)	PERCENT OF CELLS FAILING (Catastrophic Failures Included)					Catastrophic Early Failures (< 3000 cyc.)	Average Observed Cell Life For the Failed Cells (Based on Rank at 0-1000 Elapsed Cycles)
	ELAPSED CYCLES 0-1000	1-2000	2-3000	3-4000	4-5000		Elapsed Cycles
1.0	72.7	80.9	86.3	78.3	90.0	5	6516
0.9	57.1	41.7	66.6	76.9	85.7	2	6700
0.8	71.4	65.0	65.0	57.9	60.0	0	7250
0.7	75.0	80.0	72.7	45.5	63.6	1	7651
0.6	42.8	66.6	53.0	43.6	42.8	1	7354
0.5	30.0	50.0	50.0	46.1	35.7	0	8731
0.4	40.0	26.3	40.0	38.8	42.8	0	7919
0.3	42.7	25.0	09.0	14.3	11.7	2	7909
0.2	35.3	26.3	27.7	33.3	26.6	0	9205
0.1	11.4	22.1	33.3	20.0	10.0	0	8714

On a per-cell basis and at 1000 elapsed cycle intervals, a computer program calculated the occurrence frequency of low-end-of discharge-voltage measurements below specific voltage-level thresholds. At 1000 cycle intervals, the frequency distribution calculations, per pack were ordered by algebraic value and ranked, (0.1 to 1.0) relative to their low to high position in that order. Each class interval indicates the per-cent of cells that ultimately failed, having achieved the specified rank value within the specified cyclic group. In the first class interval, namely, the 0-1000 cycle group, 71.4% of the cells in the 0.8 rank class interval failed at some point in time; in the second, the 4-5000 cycle group, 90% of the cells in the 1.0 rank class interval failed at some point in time; and in the third, the 0-1000 cycle group, only 11.4% of the cells in the 0.1 rank class interval exhibited failure.

The average cell lifetime was calculated for each rank class interval in the 0-1000 cycle group. The observed average cell life varies in inverse proportion to the rank magnitude. For example, those cells in the 1.0 rank class interval exhibited an average lifetime of 6516 cycles while the cells in the 0.2 rank class interval exhibited an average lifetime of 9205 cycles.

The regression curve of these cell failure percentages is virtually linear for all cycle groups as is a curve plotted for the observed average cell lifetimes, (see Table XXVI). Such linearity is remarkable in view of the fact that the table represents measurements from combined environmental and operational variables. It has been shown that each variable effects a characteristic charge-discharge curve profile and results in varied distributions of voltage-level measurements which probably confound the table. The linearity observed in Table XXVI implies that cell selection methods can be improved. Cells may be selected for operational and evaluation programs with increased reliability, based on observation. The relative uniformity of class interval values between consecutive cycle intervals, in Table XXVI implies that pertinent information is available in less than 1000 cycles. Such early information is, however, dependent on high accuracy and quality in the data to be analyzed.

The average cell lifetime is relative to its frequency of low-end-of-discharge-voltage-level-measurements. This factor results in several significant benefits to the cell use, namely;

1. The identification and removal of early catastrophic failures;

2. An increased operational life for the remaining cells;

3. The ability to select cells, relative to mission lifetime requirements; for example, a limited operational mission can be supplied with cells that have a reliable operational lifetime expectancy longer than the planned mission lifetime; and the extended, or long operational life space flight mission can use those proportionally longer-lived cells selected relative to mission requirements and constraints;

4. Cells to provide power for extended satellite missions and particularly extended manned space-flight demanding power sources of the highest reliability are clearly feasible. This method should enable the proper selection of long-life cells for these objectives; and,

5. An improvement in cost and time economies for cell evaluation which results due to early screening and removal of incipient failures, allowing both cell population and the extent of the evaluation facility to be reduced.

c. Predicting cell failure from 1% of the test Data

From the results of this program for data reduction it can be said with some degree of certainty that prediction is feasible after less than 1% of the test data has been gathered. Cells which fail have a much higher frequency of low-end-of-discharge-voltage measurements than those which do not or which have not failed within the bounds of the given data. This higher frequency of failure is evident very early in the cycle life in most cases. The lower frequency achieved by the non-failed cells is also evident within the same cycle period.

The degree of curve separation seen in the nine graphs of Figure 2 is remarkably constant. They do not intersect from the 1000-2000 cycle period to the point of actual cell failure. The curve sets for the longer life cells appear to converge toward zero cycles, and probably they do intersect at some point after the start of cycling (see Figure 2). However, the high separation seen at the 1000-2000 cycle point implies that valuable information can be obtained quite early in the cycle life from these curves.

The ultimate goal is a cell prediction system with the capability for reliable operational cell selection, based on the first 300 cycles of cell life. Such a capability may be possible if test data are generated for this purpose. Such data must be generated, acquired, and recorded with the highest accuracy and all test variables, operational and environmental, must be tightly controlled. In past experience, good failure predictions were made from 1000 to 3000 elapsed cycle data-sets with approximately 30 observations per 1000 elapsed cycles. This success, based on fewer than 100 observations of loosely controlled data, implies that greater success and reliability are possible with 300 continuous observations of highly accurate, tightly controlled data.

It has been stated that nickel-cadmium cells require approximately 600 charge--discharge cycles to more or less "burn in" and settle in a cycling regime. It has also been stated that the voltage patterns during this settling period are "scattered". This effect should be investigated. If it is found to be present, the effect on one-percent testing should be determined. Perhaps a pre-test cell exercise regime would eliminate this possible factor from consideration.

Observation of the Crane data reveals that a large majority of those cells that fail are detectable from their data patterns within the first 10% of life. It is entirely possible that early exercise of cells will accentuate the early detection of those incipient failures and also enable those potentially successful cells to settle into a cycling regime.

d. Failure Characteristic Analysis

Using the English autopsy reports it is possible to observe the relationships between cell failure and certain manufacturing and environmental parameters. The cryptanalytic analysis of this data indicated, for example, that cells produced by individual vendors are responsible for the disproportionate occurrence, in some cases 100%, of certain failure characteristics. Gulton cells were responsible for all or most occurrences of characteristics O, ceramic short and characteristic I, blistering on positive plate. Sonotone cells were responsible for all or most occurrences of characteristics K, excess scoring of case and Q, tab(s) burned, broken, etc. Sonotone cells did not contribute to characteristic I, blistering on positive plate.

	CODED FAILURE CHARACTERISTICS (Table XIII)																			
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	T	U
0° AMBIENT TEMPERATURE	X				X	X		X	X			X	X	X	X	X				X
25° AMBIENT TEMPERATURE		X									X							X		
40° AMBIENT TEMPERATURE			X	X			X			X							X		X	
15% DEPTH OF DISCHARGE			X	O			X	O		X	X		X		X		X			
25% DEPTH OF DISCHARGE				O		X		O	X					X					X	X
40% DEPTH OF DISCHARGE	X	X		O	X							X				X		X		
1.5 HR. ORBIT		X	X	X		X	O			X		X						X	O	X
3.0 HR. ORBIT	X				X		O	X	X		X		X	X	X	X	X		O	
GENERAL ELECTRIC			X																	
SONOTONE						X					X						X		X	
GULTON								X	X	X		O	X	X	X			X		X
GOULD	X	X		X	X		X					O				X				

LEGEND:

X = HIGHEST OBSERVATION
O = TIE OBSERVATION.

Table XXVII

Operational/Environmental variables are similarly accountable. For example, (1) the occurrence of characteristic C, separator failures, varies somewhat proportionally with the increase in ambient temperature and (2) characteristic I, blisetering on positive plate, varies inversely with temperature.

This information is derived from the bar charts of figures 3 through 10 in Section III. Table XXVII summarizes this data, indicating the major contributions of each factor considered as a function of the failure characteristics (encoded in Table XIII in Section III.)

The data indicates cause and/or result associations between manufacturer and cell failure that seem indicative of design problems, inherent material defects, and deficiencies in quality control. Table XXVII permits the correllation of manufacturer/variable relationships to the observed characteristics of failure. Table XXVII shows the highest percent of failure observed for each of three operational/environmental variables and each of four manufactureres. Every column of coded failure characteristics has four entries, signified by X's, to present the highest variable/vendor failure occurrence. In five cases, equal occurrences are signified by the letter O. From Table XXVII, it can be seen that the major contributors to failure characteristic L, high pressure, were (1) 0° ambient temperature, (2) 40% depth of discharge, (3) 1.5 hour orbit period, and (4) Gulton and Gould cells.

This method presents the basis for a study, in depth, of the cause and result factors of cell failure as a function of manufacturer and/or environment. Determination of these factors is of paramount importance for both the attainment of extended operational life and for the fixing of limits and constraints relative to accelerated testing.

B. RECOMMENDATIONS

a. General

It is clear from the foregoing that there is an important body of information, not obvious through normal data-reduction techniques, which pseudo-cryptanalytic procedures can recover. This applies both to numerical data taken from voltage measurements of spacecraft cells and to English descriptions of failure characteristics. It is therefore generally recommended that continued effort be devoted to further work into new ways to apply cryptanalytic reduction to massive data, especially using the computer, a device ideally suited to the handling of very bulky data.

These techniques have defined the major hidden informational elements reducable from the Crane program data, and they have suggested many lines of attack to retrieve this data.

The voltage histograms taken from the data generates information for the entire charge and discharge portions of the cell orbit respectively. It may be that more critical data is concentrated at the ends of discharge and charge instead. In this case many more points would be required during these critical periods, and if they were available, it is possible that very striking results could be obtained from these analysis techniques. By updating the Crane data-acquisition techniques, in one of the ways suggested specifically in the Appendix following, it is conceivable that error free prediction could be made with less than 1% of the Life data. This would mean that those batteries which are good would not have to suffer much pre-flight use by testing to make this determination. This method of employing empirical data from each cell to predict its future life expectancy was defined previously as the Deterministic approach.

b. Recommendations for Future Analytic Work

The following specific recommendations suggest future research possibilities from the standpoint of improving the pseudo-cryptanalytic attack on the problem of prediction analysis, and the reduction and analysis of failure information.

1. The present techniques should be applied to another massive body of data resulting from more tightly controlled data-acquisition techniques.

2. A renewed look should be taken at the data from the Crane program in hopes of discovering even more significant indicators of failure than those outlined here, especially in the light of the techniques which have resulted to date.

3. Other pseudo-cryptanalytic techniques should be investigated to see if they will yield significant information from massive cell-testing data.

4. Other sophisticated methods of mathematical reduction should be investigated, as for instance the use of Latin or Orthogonal Squares, Galois Fields, and so on, for the design of new test experiments.*

5. Using the prediction methods of linear programming, it would be useful to determine if other gaming schemes can be developed, perhaps by gaming the multi-level thresholds to determine which are most informative.

6. A voltage-difference accumulation should be carried along with the present techniques in order to find techniques that will alert the battery engineer to abnormal voltage behavior, a fact not identified by the threshold technique.

* Mann, H.G., Analysis and Design of Experiments, New York, Dover, 1949

7. By developing a gaming program for the first difference histograms that assigned various combinations of weights to voltage difference levels, it is probable that more strict monitoring of cell characteristics would be obtained.

8. The voltage histogram should be considered as a basic data element, and measurements of the rate of data change between different elements should be made on a time-series basis to determine its value for prediction.

c. Recommendations for Improving the Numeric Data Base

Alternate schemes for gaining more accurate and more carefully controlled data on the activities of the secondary spacecraft cells are presented in the Appendix. The methods of analysis advanced in this report would have an even greater reliability and prediction capability if the original data reflected certain information which the Crane program overlooked, in general with respect to a stricter control over the testing, timing, and cell temperatures. As recommended here, a computer could best serve the purpose of keeping a very accurate accounting and control over the Generation and Acquisition of data. The present cell acceptance tests screen out only those cells with gross defects. This is evidenced by the very high failure rate during the first few thousand cycles. The acceptance test regime should be improved and/or extended so that those more subtle cell defects are identified. Greater economy would result if only better cells were cycled. The advantages of cell matching by voltage pattern should be considered and analyzed. Vendor design and quality control factors are of major importance in both acceptance testing and operational use. The vendor should inform the user regarding any material or design changes within a cell, proprietary and otherwise since such changes may produce unexpected functional characteristics and confuse the analysis and selection methods.

The following specific recommendations are made to improve the numeric data base obtainable from the testing procedures.

1. More monitor points per charge-discharge curve, at least 45 points per 90-minute curve.

2. Accurate accounting must be taken of the monitor time intervals.

3. A continuous data base must be obtained with no cycle gaps.

4. Accurate cell and ambient temperature measurements must be obtained.

5. Internal cell pressure and cell impedance studies should be conducted.

6. Separation of the environmental and operational variables should be attempted, perhaps under special battery test setups which provide an accurate control over individual factors.

7. Analysis should proceed on the data obtained by means of telemetry from the many spacecraft operating under actual space conditions. The present methods of analysis could be applied, and the fact that the parameters are limited to actual operating conditions would clearly make the conclusions extremely concise and useful.

d. Recommendations for Improving the Failed-Cell Autopsy Reports

Based on a careful analysis of the results of the pseudo-cryptanalytic investigation into the causes of battery failure, the following recommendations are made to include both quantitative and new qualitative information in the failed cell autopsy reports. This effort was conducted in conjunction with Dr. A. Fleischer of Orange, New Jersey. The cause and effect relationship of cell failure versus the environmental/operational/vendor variables could be established and related to specific physical-chemical conditions within the cell if the following information were obtained.

1. Carbonate Content of the Electrolyte.
2. Spectrophotometer Analysis .
3. Quantified Separator Deterioration.
4. Quantified Blisters on Plate(s).
5. Quantified Migration of Active Material.
6. Quantified Extraneous Material.
7. Quantified Separator Impregnation.
8. Weight Loss or Gain of Positive and Negative Plates.
   (vs. control cells)
9. Dendrite Formation

APPENDIX. EVALUATION OF CYCLE LIFE TESTING OF SECONDARY SPACECRAFT CELLS

A. CRANE PROGRAM

a. Numerical Data

The program of cycle life testing of secondary spacecraft conducted for NASA by the Quality Evaluation Laboratory of the Naval Ammunition Depot of Crane, Indiana, began with 660 sealed, nickel-cadmium cells from four manufacturers. They contained seven sample classifications ranging from 3 to 20 ampere-hour capacity. Several types of cells were added to the original test program including nickel-cadmium cells ranging in capacity from 5.0 to 50.0 ampere-hours; silver-cadmium cells ranging in capacity from 5.0 to 12.0 ampere-hours; and silver-zinc cells ranging in capacity from 16.0 to 40.0 ampere-hours. One purpose of the life-test program was to determine the cycle performance capabilities of packs of cells (5 to 10 cell packs) under different load, charge control and temperature conditions. The load conditions included cycle length (defined as orbit period) of 1.5, 3.0, 8.0 and 24 hours. The depth of discharge (D. O. D.) ranged from 10 to 75 percent. The charge control methods used were voltage limit, auxiliary electrode, coulometer, stabistor and a two-step regulator. Environmental conditions included ambient temperatures of -20°C, 0°C, 25°C, 40°C, 50°C within a period of 24 hours.*

For the purpose of the present analysis it is important to note the following facts. The orbit periods and their individual charge-discharge time periods are listed in Table XXVIII.

Table XXVIII. Orbit Period (Charge-Discharge) Times

Orbit Period In Hours	Recording Frequency In Cycles	Discharge Period In Hours	Charge Period In Hours
1.5	32	0.5	1.0
3.0	16	0.5	2.5
8.0	12	1.0	7.0
24.0	8	1.0	23.0

*Bruess, E. C., Evaluation Program for Secondary Spacecraft-Cells, Fourth Annual Report, Goddard Space Flight Center, Contract WII, 252B, 14 May, 1968, Ind.

Every orbit period is not recorded, and the cycles recorded are determined by the following test design. The cells are connected in series to form packs of five or ten cells each. The packs are cycled in the ambient temperature and D. O. D. combinations listed in Table XXIX.

Table XXIX. Combinations of Conditions Used

	TEMPERATURE -- DEGREES CENT.			*	
		-20	0	25	50/40
Depth	15%	X	X		X
of	25%	X	X	X	X
Discharge	40%		X	X	

* 25° ambient was not as well regulated since the cells were simply sitting in an air conditioned room.

The packs being cycled are monitored. Individual cell voltage, cell temperature, pack current, pack voltage, monitoring time after the beginning of the cycle, and pack identification are recorded. A maximum of eighteen battery packs may be monitored simultaneously.

Recordings are taken at monitor points during the orbit period. An example of monitor points in a ninety minute orbit period is shown in Figure 11.

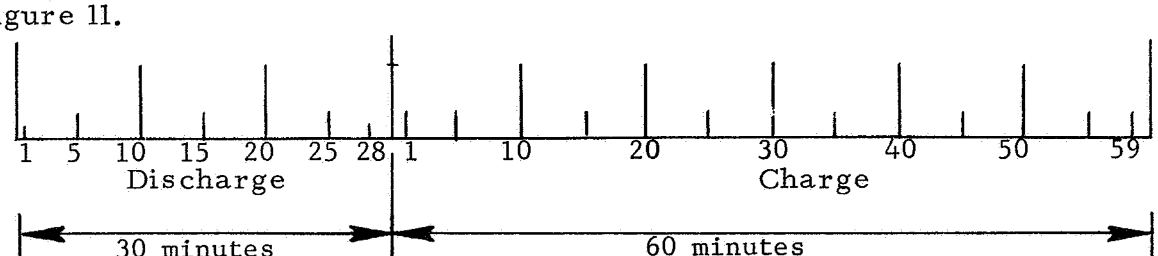


Figure 11. Example of Monitor Points

b. English Remarks on Failures

When a cell failed during cycling it was removed from the pack, opened, and a post-mortem examination was performed by the Crane program. The examination results were then reported in descriptive English, such as the following report for Pack 5, Cell 3: "Low voltage discharge, normal voltage charge, still under pressure when opened, weak tab to plate welds, short caused by excess scoring, migration of negative plate material, separator completely deteriorated." Since this information was included to preserve as much information about the failure as possible it was natural that it was established on a free basis with no attempt at codification. In retrospect, however, it is easy to discover certain recurring classifications of failure, and to suggest a very strict means of encoding the information. Such an encoding was listed in Table XIII in Section IV, derived from the Crane program data in English. Refinements in this listing can and should be improved, and recommendations for such an improvement, based on the knowledge which a battery specialist can bring to bear, as given in the previous Section V.

B. MINIMUM DATA REQUIREMENTS FOR THE PRESENT STUDY

The Crane program generated a very large volume of data, but not all of it is significant for the present study. Some battery packs were cycled for about four years, putting them through approximately 20,000 cycles. Most of the original battery packs, however, had a much shorter lifetime. In general it can be remarked that the data from the Crane program was acquired for the historical recording of a life test, not primarily for analysis. The data reached about a million IBM punched cards, but it represents less than 10% of the actual data generated since the test acquisition system, designed primarily for record keeping, became saturated at the set recording level, resulting in a loss of the remaining 90% of the data. For instance, the present Crane Evaluation Program does not record every elapsed cycle for each of the battery packs in the program. This is due to the physical limitations of the manual plug-board (to electrically connect battery packs to the data acquisition system) and the data acquisition system itself; the scanner device has only thirty data-points.

Data from battery packs that are cycled within a ninety-minute orbit reqime (30 min. charge, 60 min. discharge) are recorded approximately every thirty-second elapsed cycle or one recording every two days. This limited recording capability disregards over ninety per-cent of the data being generated. Other orbit regimes, sililarly, do not record every cycle of data. Recording frequencies for various orbit periods are as follows:

1. 1.5 Hr. Orbit --- Recorded approximately every 32rd cycle.

2. 3.0 Hr. Orbit --- Recorded approximately every 16th cycle.

3. 8.0 Hr. Orbit --- Recorded approximately every 12th cycle.

4. 24.0 Hr. Orbit --- Recorded approximately every 8th cycle.

The information "gaps" produced by this limited recording capability causes total lack of continuity in the acquired data leading to many difficulties in analysis techniques. Recorded temperatures lose all meaning when sampled every two days.

The present recording frequencies are inexact due to the necessity to give individual attention (data-taking out of recording sequence) to a battery pack when certain operational anomalies, such as high or low voltage, are detected. This produces recorded cycles from variable numbers of elapsed cycles (recordings every tenth to fiftieth elapsed cycle) and creates sheer havoc with statistical sampling techniques. This problem is basically an effect of the limited capability of the present data acquisition system.

On the basis of recordings, approximately every thirty-two cycles, computer programs were created to detect certain patterns, early in the life of a NiCd cell, (after approximately two-thousand elapsed cycles), that are indicators of incipient failure of that cell. A time factor, pattern detection to actual failure, could not be created by the analysis methods due partly to the lack of continuous data. The present analysis of the Crane data permitted the definition of the following basic minimum data requirements for both reliable cell prediction/selection and the acquisition of basic engineering data, pertinent to sealed Nickel-Cadmium.

1. Monitor Points. The present Crane program monitors approximately 14 points per 90-minute charge-discharge curve. It is believed that this should be increased three-fold, to approximately 45 monitor points, at 2-minute intervals, per 90-minute curve. At present, it is unknown if the curve is smooth or rippled, or has momentary changes in magnitude (spikes). If these characteristics are present in the Crane data, they would appear as "noise" when they occur at a monitor point. More monitor points per curve would eliminate this "noise" factor and permit the accurate definition of both normal and adnormal curve profiles. The degenerative changes within a cell are probably reflected by subtle changes in both cell voltage patterns. Monitor points at 2-minute intervals should enhance the analysis and result in more and better information. A small sample of data was acquired from pack 64 after more than 15,000 cycles had elapsed. This sample consisted of 20 consecutive cycles monitored at 2-minute intervals. Analyzing this data showed that voltage information was present at that time interval. Table XXX is a computer printout of the test data from pack 64, acquired at 2-minute intervals. The topmost row contains data on cells 1 through 5, recorded at 0.0 time or at the start of discharge. The data from cell 5 is underlined on Table XXX for clarity. It is apparent that much voltage-change information is present within the 2-minute data-taking interval. The voltage change is, of course, pronounced at the start of both the discharge and the charge.

2. Data Continuity. The data recording frequency in the present Crane program is determined by test design and orbit period. The analysis used data from the 1.5 hour orbit regime almost exclusively. The data, taken every thirty-second cycle, or once every two days, totally lack continuity of measurement. For example, obviously the levels of the first measurements at the start of discharge are dependent on the levels at the end of charge. This discontinuity in the data precludes the analysis of the cycle relationships involved and injects "noise" into analysis methods. With the present data recording frequency, approximately 3000 elapsed cycles (more than 6 months) are required to obtain 100 cycles of data for analysis. Continuous, accurate data should both enhance the analysis methods and reduce the time necessary to generate sufficient data for predictive techniques. All of the data generated need not be recorded. For example, perhaps the first 100 consecutive cycles would be recorded to provide continuous data. After that is done, the recording frequency could be changed to take perhaps one "ten cycle data set" per 100 elapsed cycles. The analysis would determine the recording frequency, and data continuity would be enhanced.

Table XXX (page one)

.0	15876.	64	15.37	1.42	150	152	160	164	151	4.1	2.8	1.2	2.8	.8	2.61
.0	15876.	64	15.37	1.42	156	153	151	155	150	2.4	2.8	1.8	2.7	3.0	2.62
2.0	15876.	64	13.49	1.50	134	135	137	138	135	2.4	.6	1.0	2.0	.8	1.21
2.0	15876.	64	13.49	1.50	137	137	133	135	132	1.6	1.3	.4	1.8	.9	1.22
4.0	15876.	64	13.25	1.51	133	133	134	135	133	2.4	2.4	2.8	2.0	8.8	.41
4.0	15876.	64	13.25	1.51	134	134	131	133	131	2.6	2.0	-.6	.5	-.1	.42
6.0	15876.	64	13.07	1.51	131	132	132	132	132	1.4	.6	1.6	.8	-.9	-.31
6.0	15876.	64	13.07	1.51	131	132	130	132	129	.8	1.6	.8	.8	.6	-.32
8.0	15876.	64	12.94	1.51	130	131	130	131	131	2.8	.8	4.6	3.2	1.4	.01
8.0	15876.	64	12.94	1.51	130	130	129	131	128	3.3	1.5	-.3	.8	.4	.02
10.0	15876.	64	12.83	1.51	129	130	129	129	130	3.0	2.2	2.3	2.0	1.6	.81
10.0	15876.	64	12.83	1.51	129	129	128	130	127	2.8	2.4	1.2	2.8	.8	.82
12.0	15876.	64	12.75	1.51	128	129	128	128	129	4.4	1.0	4.4	1.8	.8	.81
12.0	15876.	64	12.75	1.51	128	128	127	129	126	4.4	2.4	1.8	4.4	1.5	.82
14.0	15876.	64	12.67	1.51	128	128	127	128	129	3.4	1.4	2.8	2.0	.8	.91
14.0	15876.	64	12.67	1.51	127	128	127	128	126	1.8	1.0	.5	1.8	1.4	.92
16.0	15876.	64	12.59	1.51	127	127	126	127	128	4.0	3.7	4.1	2.8	1.0	1.31
16.0	15876.	64	12.59	1.51	126	127	126	128	125	2.2	3.4	1.8	3.0	1.8	1.32
18.0	15876.	64	12.51	1.51	126	127	125	126	127	3.6	2.0	2.8	2.4	3.2	1.71
18.0	15876.	64	12.51	1.51	125	126	125	127	124	3.2	3.2	2.4	3.6	2.1	1.72
20.0	15876.	64	12.43	1.51	125	126	125	125	126	4.1	2.8	2.8	4.4	1.4	2.41
20.0	15876.	64	12.43	1.51	124	125	124	126	123	2.8	2.1	1.5	1.6	1.2	2.42
22.0	15876.	64	12.35	1.51	125	125	124	124	125	4.8	2.8	4.4	3.7	2.6	2.11
22.0	15876.	64	12.35	1.51	123	124	123	125	122	3.5	3.3	2.8	2.4	1.2	2.12
24.0	15876.	64	12.25	1.51	123	124	123	123	124	4.3	3.4	4.4	4.3	1.2	1.81
24.0	15876.	64	12.25	1.51	123	123	122	124	121	-39.1	3.4	2.2	2.4	1.0	1.82
26.0	15876.	64	12.16	1.51	123	123	122	123	123	3.2	1.6	3.0	2.6	.8	.41
26.0	15876.	64	12.16	1.51	122	122	121	124	120	.5	2.0	.4	3.2	1.6	.42
28.0	15876.	64	12.07	1.51	121	122	121	122	122	4.6	2.8	2.2	2.3	2.8	-.91
28.0	15876.	64	12.07	1.51	121	122	120	123	119	1.3	.8	1.5	2.4	1.1	-.92
30.0	15876.	64	12.24	.89	123	124	123	123	123	4.0	2.8	4.4	3.4	-2.3	.81
30.0	15876.	64	12.24	.89	122	123	122	124	121	.8	.8	.8	2.0	1.4	.82
32.0	15876.	64	12.85	.87	129	129	129	130	130	3.4	2.0	3.2	2.2	20.4	.81
32.0	15876.	64	12.85	.87	129	129	128	130	127	.8	3.2	2.2	1.9	1.6	.82
34.0	15876.	64	13.01	.87	130	131	130	131	131	7.4	3.0	3.6	2.3	-.7	.41
34.0	15876.	64	13.01	.87	131	131	130	132	129	3.3	2.8	2.6	2.1	-.5	.42
38.0	15876.	64	13.24	.87	132	133	133	133	134	.8	.3	.7	5.8	2.8	5.81
38.0	15876.	64	13.24	.87	133	133	132	134	132	10.6	6.1	5.7	.3	-1.0	5.82

Tabulation Of Test Data From Pack 64.

Table XXX (page two)

40.0	15876.	64	13.34	.87	133	134	134	134	134	.8	.1	5.8	9.8	-.4	-.41
40.0	15876.	64	13.34	.87	134	134	133	135	132	6.2	.8	.8	6.1	.7	-.42
42.0	15876.	64	13.43	.87	134	135	135	135	135	-.4	9.0	5.8	9.8	6.1	5.31
42.0	15876.	64	13.43	.87	135	135	134	135	133	.7	10.6	5.7	-.4	-3.8	5.32
44.0	15876.	64	13.51	.87	135	136	135	136	136	7.3	9.8	.8	1.6	35.8	8.81
44.0	15876.	64	13.51	.87	136	136	134	136	134	10.6	9.8	9.0	.7	.7	8.82
46.0	15876.	64	13.59	.87	136	137	136	137	137	.8	6.1	20.4	2.4	8.8	.71
46.0	15876.	64	13.59	.87	137	137	135	137	135	35.8	20.0	-.4	6.1	-3.1	.72
48.0	15876.	64	13.66	.87	136	137	137	138	138	-3.1	-3.1	-3.1	-7.1	16.2	.11
48.0	15876.	64	13.66	.87	138	137	136	138	136	35.8	.8	-11.1	6.8	.8	.12
50.0	15876.	64	13.73	.87	137	138	138	138	138	-9.1	-3.1	16.2	-7.0	28.1	-1.51
50.0	15876.	64	13.73	.87	138	138	137	138	136	.8	.8	.8	-3.5	-10.3	-1.52
52.0	15876.	64	13.80	.87	138	139	138	139	139	-3.1	.8	-7.1	16.2	4.8	.41
52.0	15876.	64	13.80	.87	139	139	137	139	137	-3.1	-3.1	16.2	.8	.8	.42
54.0	15876.	64	13.86	.87	138	139	139	140	139	-11.1	16.6	8.6	.6	8.8	.61
54.0	15876.	64	13.86	.87	140	139	138	140	138	4.8	14.3	-7.1	-3.1	.8	.62
56.0	15876.	64	13.92	.87	139	140	140	140	140	12.7	.2	-3.1	6.2	-13.1	.81
56.0	15876.	64	13.92	.87	141	140	138	140	138	-11.1	20.4	-7.1	.8	.8	.82
58.0	15876.	64	13.99	.87	140	140	140	141	141	-3.1	-5.1	.8	18.5	.8	8.81
58.0	15876.	64	13.99	.87	141	141	139	141	139	16.2	20.4	-3.5	20.4	-3.5	8.82
60.0	15876.	64	14.05	.87	140	141	141	142	141	12.5	8.4	.8	.4	-3.1	.81
60.0	15876.	64	14.05	.87	142	141	139	141	139	7.6	-7.1	4.4	.8	-11.1	.82
62.0	15876.	64	14.11	.87	141	141	142	143	142	-11.1	.8	.8	16.6	.8	.81
62.0	15876.	64	14.11	.87	143	142	140	142	140	20.4	-11.1	20.0	.8	.8	.82
64.0	15876.	64	14.18	.87	141	142	143	143	142	.8	.8	-3.1	5.8	-3.1	3.81
64.0	15876.	64	14.18	.87	144	143	140	142	140	5.8	6.8	-11.1	.8	-3.1	3.82
66.0	15876.	64	14.26	.87	142	142	143	144	142	8.8	-3.1	5.8	4.0	6.8	.41
66.0	15876.	64	14.26	.87	102	144	141	143	141	5.6	7.6	-15.1	5.8	.8	.42
68.0	15876.	64	14.35	.87	143	143	144	146	143	10.0	5.9	-11.1	-11.1	-3.2	3.21
68.0	15876.	64	14.35	.87	147	145	142	144	142	20.0	5.7	.8	-3.1	8.4	3.22
70.0	15876.	64	14.45	.87	144	144	145	147	144	-3.1	1.2	-3.1	16.6	2.4	.71
70.0	15876.	64	14.45	.87	149	146	142	145	142	3.6	6.4	.8	-.3	-7.1	.72
72.0	15876.	64	14.60	.87	146	145	148	149	145	20.4	2.9	4.4	-1.1	20.8	4.01
72.0	15876.	64	14.60	.87	151	148	143	147	143	-1.3	6.2	-2.3	4.8	4.6	4.02
74.0	15876.	64	14.85	.87	149	147	150	153	147	-1.5	21.2	22.0	-1.7	-1.0	-1.31
74.0	15876.	64	14.85	.87	155	150	145	149	145	21.6	-1.7	2.2	21.2	5.2	-1.32
76.0	15876.	64	15.31	.82	156	150	154	161	151	8.6	2.6	22.0	8.6	19.2	.81
76.0	15876.	64	15.31	.82	159	152	149	156	148	-2.3	-19.1	8.5	21.6	-1.7	.82
78.0	15876.	64	15.45	.64	154	153	157	164	154	-1.3	-20.3	39.6	22.1	7.0	1.71
78.0	15876.	64	15.45	.64	157	151	152	157	151	-1.7	22.0	4.6	7.0	22.0	1.72
80.0	15876.	64	15.53	.54	152	156	159	163	155	4.6	-1.6	22.1	22.0	22.0	-5.31
80.0	15876.	64	15.53	.54	156	152	154	156	154	39.8	-1.6	-1.8	7.0	-19.5	-5.32
82.0	15876.	64	15.59	.49	152	157	160	164	156	-19.5	-20.3	-1.4	-1.3	-19.1	-.51
82.0	15876.	64	15.59	.49	156	152	155	156	155	7.2	-20.3	21.9	-7.1	-1.6	-.52

3. Precision. The present Crane test system possesses sufficient accuracy to fulfill its intended purpose, namely data for record keeping. The data, however, lack the critical accuracy required by classical statistical tests and necessary for high reliability in analysis results. Critical accuracy is required in the following areas, for exampls:

a. Monitor Time. Monitor times or data taking points should be accurate and uniform. The delta's of time, from point to point, should be equal for the entire cycle or for the charge and discharge portions individually.

b. Cycle Sequence. The sequence of cycle recording should be accurate and uniform. This will provide the standardized, uniform sample spaces required by statistical methods.

c. Analog/Digital Conversion. In the present Crane test, voltage information is acquired in millivolts but rounded down to centivolts. A small degree of inaccuracy (+ 25 MV) is admittedly present in the voltage readings. Present day technology enables the acquisition and conversion of analog voltages with high accuracy (+ 1%). Such capability is required for the timely detection of subtle voltage changes.

The temperature measurement system must be established so as to overcome the difficulties encountered early in the Crane test. (Thermocouples, with insufficient resistance to isolate cell voltage, connected to the cell terminal, etc.). This resulted in some virtually impossible temperature readings; for example, indicated temperature changes of approximately 200^{o} in 20 minutes. This effect was most evident in the end-of-change portion of a cycle, when the charge-limiter "cut-in." Temperature control improved as the Crane program evolved.

Accurate cell temperature measurements can be effected by an intra-cell temperature sensing device; however, the cost of such cells and possible problem areas created by the additional seals preclude their extensive use. External transducers can also monitor cell temperatures, however, the hardware costs to effect accurate measurement rise in proportion to the acuracy desired.

d. Test Control Functions. In the present Crane test program, all test control functions are manually instituted, and are, therefore, for the greatest part, fixed, repetitive, inflexible, and error prone. An electronic computer in the test system could institute all control functions, such as (1) Data Generator, (2) Data Acquisition, (3) Analog/Digital Conversion, (4) Monitor Point and Cycle Time Control, (5) On-Line Calculations, etc. The computer generated test functions would be automatic -- under program control, flexible, accurate, and economical. An evaluation of alternate test set-ups is given in the next major paragraph.

4. Test Variables.

a. Cell Voltage. This variable is the basis of the analysis techniques. Cell voltage measurements have high information content and possess identifiable voltage patterns, both normal and abnormal, early, in cycle life that indicae incipient cell failure several thousand cycles before actual failure.

It appears that accurate cell voltage data will be sufficient to enable reliable cell selection and prediction. This is meant in no way to negate the importance of other test variables; when accurately acquired and correlated, they will probably enhance and validate the voltage-derived information.

b. Cell Temperature. Because of the condition of the temperature data, "noise" errors, etc., very little information could be gained. Most of the data available were generated early in the test program, before temperature control and acquisition methods were improved.

A small sample of data was acquired from NAD Crane; 20 consecutive cycles from pack 64, after more than 15,000 elapsed cycles. Analysis of these data, including cell and ambient temperature graphs, indicated that the temperature readings were within reasonable bounds, i.e., cell temperatures were clustered around the ambient; 0^{o} C. Cell temperature graphs indicated that the cells cooled during charge and warmed during discharge, as normally expected.

This sample of data, however, was too small to reach any conclusions regarding the existence and definition of relationships between cell failure and cell temperature.

For purposes of additional economy in cell testing, it may be desirable to eliminate the large scale acquisition of cell temperature data. These data could be acquired from a small sub-set of the evaluation program, then analyzed and correlated to cell failure. If the information content of this data is considered valuable, temperature data could be acquired from additional cells and packs. Conversely, if the information content of the data is low, cell temperature acquisition could be entirely eliminated from the test program.

Ambient temperature has been shown to produce characteristic effects on the charge-discharge curve profile and should be monitored and recorded with the voltage data.

c. Depth of Discharge. In the present Crane program, this variable is fixed and repetitive. To more closely simulate operational space-flight power requirements, for example, the variable power demands encountered in a synchronous orbit, the depth of discharge should be varied for both time and power requirements. Such variability can be accomplished by a computer in the test system.

Two sub-variables of depth of discharge should be considered; time to certain voltage levels both in charge and discharge. Such time measurements will reflect cell efficiency and probably provide additional data-patterns for correlation with cell history.

d. Cell Pressure.

1. This variable could be evaluated, on-line, within small sub-sets of the test program. It could be extended to additional cells or eliminated from consideration, based on the information content.

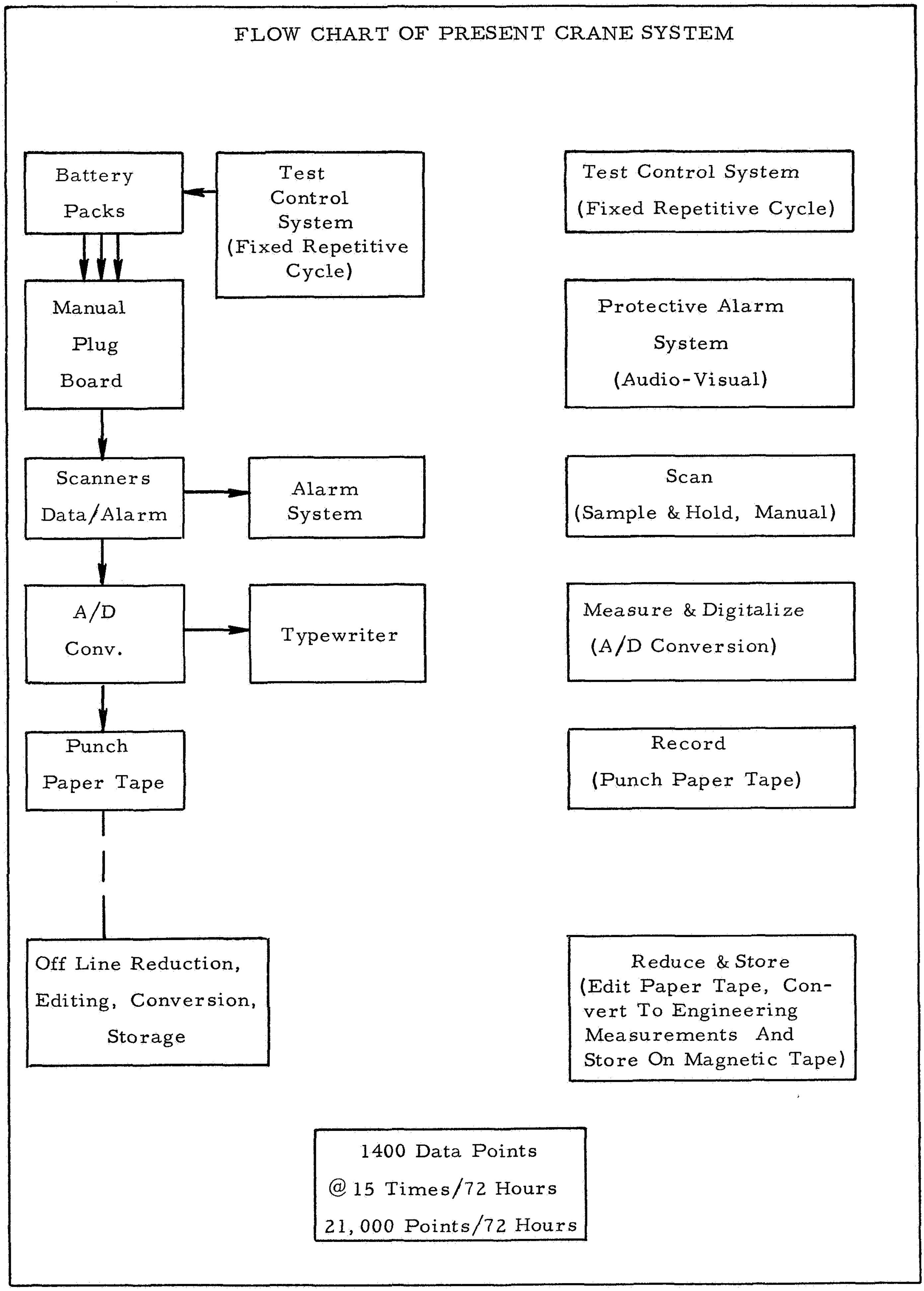

FLOW CHART OF PRESENT CRANE SYSTEM
Battery Packs
Test Control System (Fixed Repetitive Cycle)
Test Control System (Fixed Repetitive Cycle)
Manual Plug Board
Protective Alarm System (Audio-Visual)
Scanners Data/Alarm
Alarm System
Scan (Sample & Hold, Manual)
A/D Conv.
Typewriter
Measure & Digitalize (A/D Conversion)
Punch Paper Tape
Record (Punch Paper Tape)
Off Line Reduction, Editing, Conversion, Storage
Reduce & Store (Edit Paper Tape, Convert To Engineering Measurements And Store On Magnetic Tape)
1400 Data Points @ 15 Times/72 Hours 21,000 Points/72 Hours

Figure 12

FLOW CHART OF THE UPDATED CRANE SYSTEM

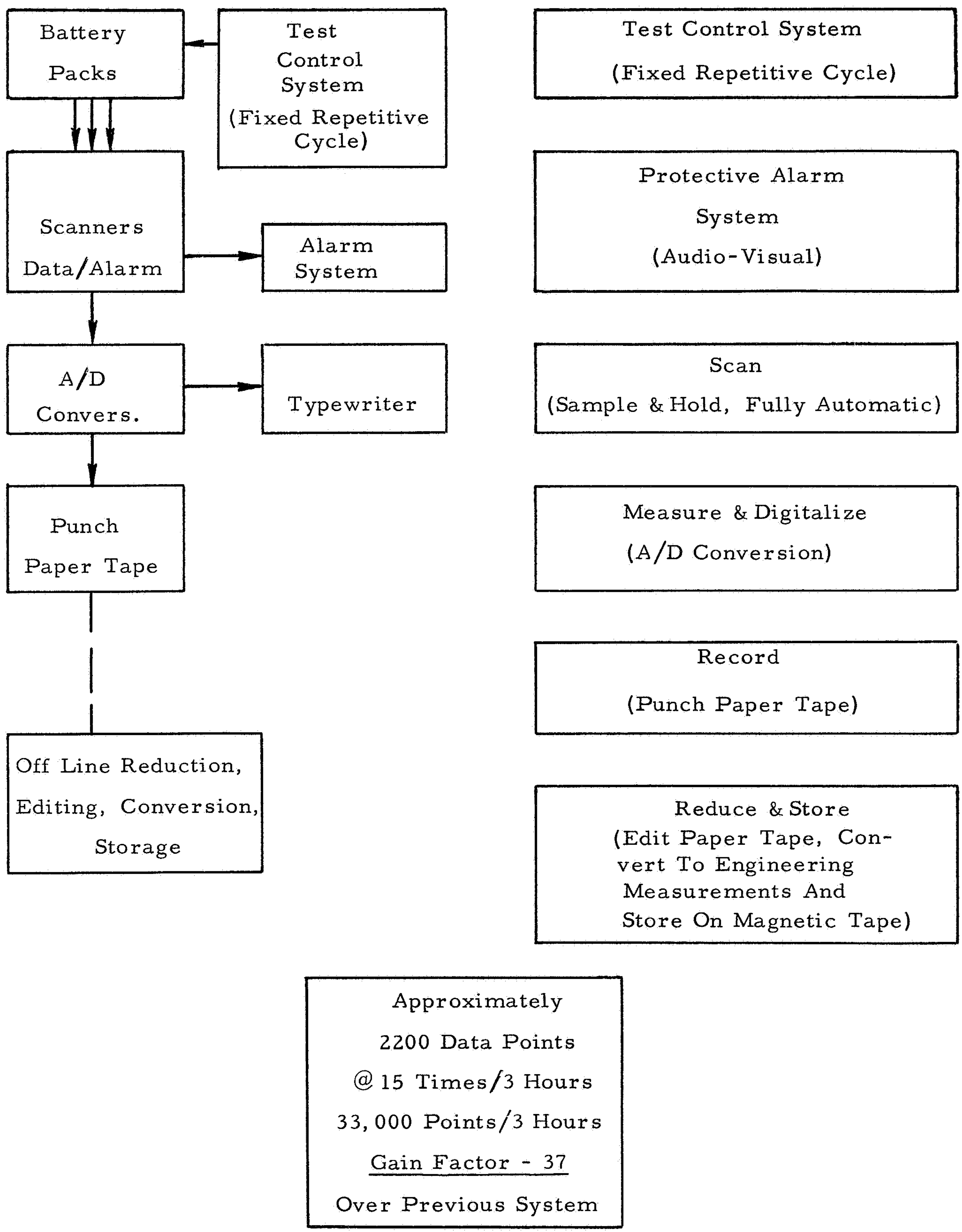


Figure 13

Internal pressure measurements are now being made on a small scale. The cost of the transducers needed for a large scale evaluation is prohibitive.

e. Cell Impedance. Present "state-of-the-art" instrumentation permits on-line cell impedance measurements. Such measurements might provide additional information regarding changes within the cell and produce data-patterns that would correlate with voltage information.

If impedance measurements are to be made, the AC waveform (s) to be utilized must be determined by analysis. A computer in the test system could institute control functions for these measurements.

C. DISCUSSION OF UP-DATING THE TEST SYSTEM

a. Introduction. In the present Crane System, the test control functions are manual. The test output data are acquired on punched paper tape which must be converted, off-line, to engineering units, edited, and stored on magnetic tape. The data conversion costs are not charged to the battery project. It is estimated that these costs would be $30,000.00 per year on the open market. The system possesses two scanners; one for a protective alarm system and one for data acquisition. The latter scanner has the capacity of thirty data points and is electrically connected to the battery packs being scanned through a manual plug-board. A maximum of eighteen battery packs may be sequentially scanned and recorded at one time. The test control functions are manually instituted and the cycling regimes are fixed and repetitive. The maximum capability of the present Crane system is 1400 data points, measured 15 times each, every 72 hours. Figure 12 shows a flow chart of the present Crane System.

b. Up-Dated Crane System. The present Crane System can be updated by elimination of the manual plug-board and the installation of a fully-automatic scanner and additional A/D converters. An increase in the data base is desirable, so the updated system will have the capacity to measure 2200 data points, 15 times each, every 3 hours. The estimated cost of the fully-automatic scanner is $150,000. The data acquired would represent a gain factor of over the previous system and a yearly data conversion cost of approximately $400,000.00 to $700,000.00. All other capabilities of the present system, including manual test control functions are fixed, repetitive cycles would remain the same. Figure 13 shows a flow chart of this up-dated system.

c. Minimal Computer System. The addition of an on-line electronic computer to the battery test system will permit on-line data conversion, editing, and magnetic tape output. Due to the economy introduced by on-line data conversion, etc., the data base can be further broadened. The 2200 data points will be measured 60 times each, every three hours. This represents a data gain factor of four over the previous system. The estimated cost of the computer is $50,000.00. The computer would initiate the same scanner as the updated Crane System. Manual test control functions will remain as will the fixed, repetitive cycle regime.

FLOW CHART OF THE MINIMAL COMPUTER SYSTEM

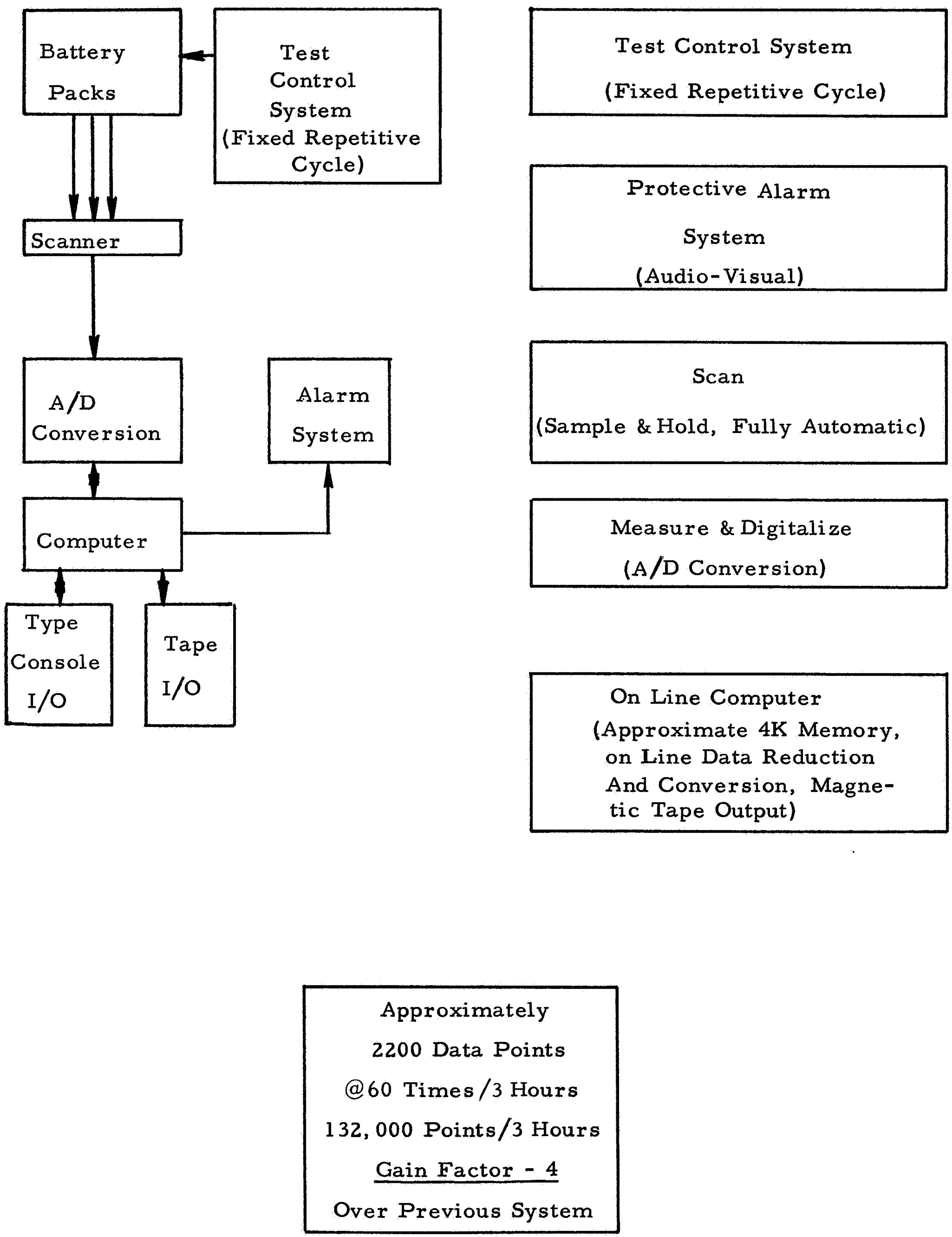
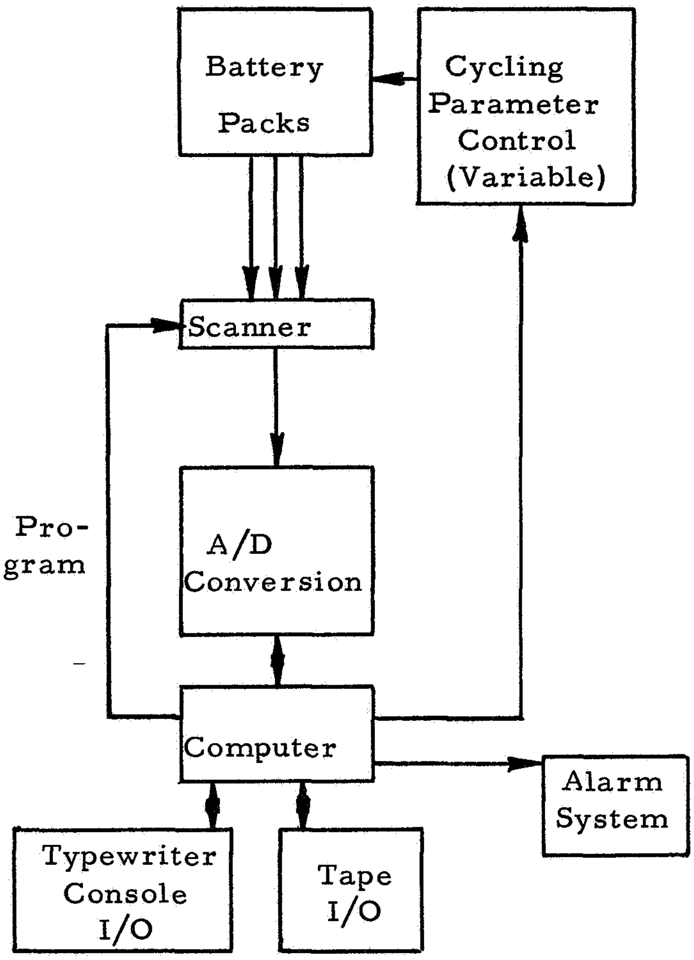


Figure 14

FLOW CHART OF THE COMPLETELY AUTOMATED COMPUTER SYSTEM



Test Control System
(Variable Cycle And Operational Parameters)

Protective Alarm System
(On Line Control Of All Data Points)

Scan

(Sample & Hold, Fully Automatic)

Measure & Digitalize

(A/D Conversion)

On Line Computer

(Additional 16-32K Memory To Control Entire System)

Approximately

5000 Data Points

@ 75 Times/1.5 Hours

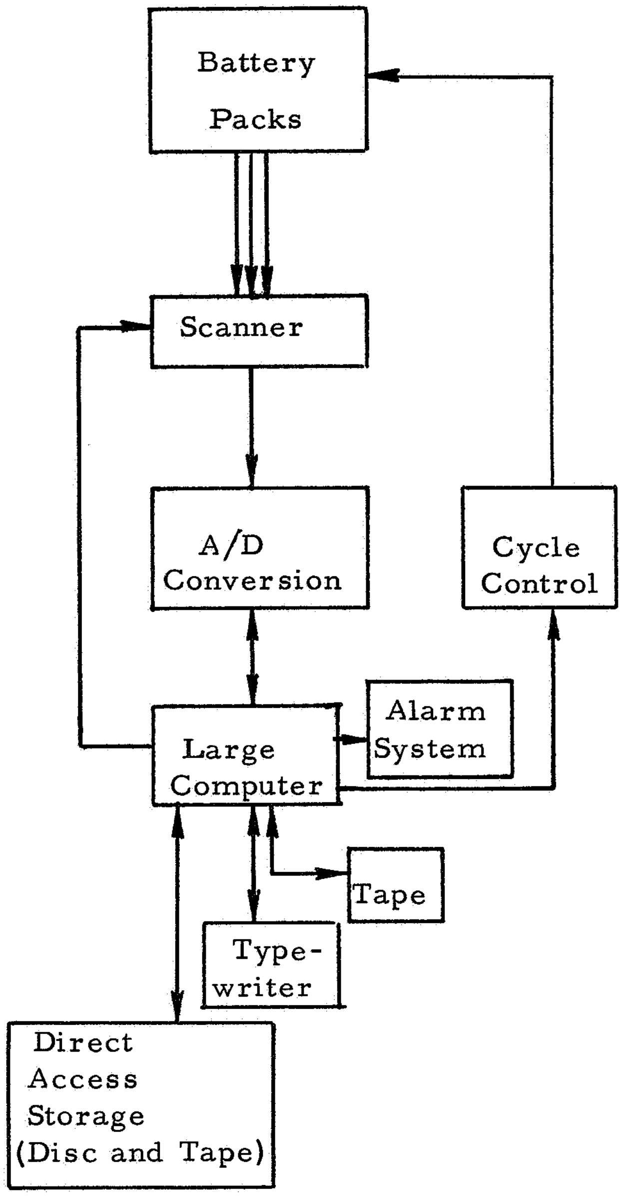
375,000 Points/1.5 Hours

Gain Factor - 9

Over Previous System

Figure 15

FLOW CHART OF THE MAXIMUM COMPUTER SYSTEM



Test Control System (Variable Cycle And Operational Parameters)

Protective Alarm System (On Line Control Of All Data Points)

Scan (Sample & Hold, Fully Automatic)

Measure & Digitalize (A/D Conversion)

On-Line Data Analysis Capability

On-Line Large Computer To Control Entire System. Direct Access Storage To Enable On-Line Analysis

Figure 16

A flow chart of the minimal computer system is shown in Figure 14.

d. Completely Automated Test System. The automated test system features computer generated test control and data acquisition functions, completely integrated. Computer generation of these functions effect many significant advantages. For example:

1. Elimination of the human error-factor in test control.
2. Data generated in accurate time intervals.
3. Capability to acquire more data at a much lower cost per data-unit.
4. Capability to compare every data-point with individual, variable, pre-set thresholds.
5. Complete flexibility of all test variables.
6. Capability to produce on-line calculations from data as it is acquired.
7. Permits system flexibility so that additional papameters can be measured.
8. High-speed generation and acquisition capability.
9. Orbit periods can be varied by program control.
10. Protective alarm system will check every data-point.
11. The computer will perform systems safety checks to validate the function of all components.

These highly desirable test capabilitits can be achieved by the addition, to the previous system, of 16 to 28 K of computer memory and the design and implementation of software to generate the control and acquisition functions. The additional memory and software to effect these functions will cost approximately $85, 000. 00. In this automated system, the computer, under programmed internal clock control, generated the test control functions, initiates the sequencing and control of the data acquisition scanner, issue "encode" commands to the digital voltmeters or A/D converters, converts the analog data into engineering units, performs efficiency calculation, edits the data and produces output on magnetic tape, all functions integrated.

This system will have the capability to scan and measure 5000 data-points, every 1. 5 minutes. This represents a data gain factor of 9 over the previous system. A flow chart of the completely automated test system is shown in Fugure 15.

e. Maximum Computer System. The maximum computer system is functionally similar to the completely automated test system, but it possesses a large on-line computer and direct access disc packs and read/write magnetic tape drives to enable large scales on-line data analysis. It is estimated that an additional cost of $300, 000 would be required for these devices. Figure 16 shows the maximum computer system flow chart.

f. Hewlett-Packard Computer System. A systems design for a battery data-acquisition system has been engineered by the Hewlett-Packard Company, Dymec Division, Palo Alto, California.. This system has the capability of measuring 5200 data points, both high and low level, utilizing a HP 2116A computer; also 26 crossbar scanners (200 three wire points each), four channel selectors, four crossbar selectors, four integrating

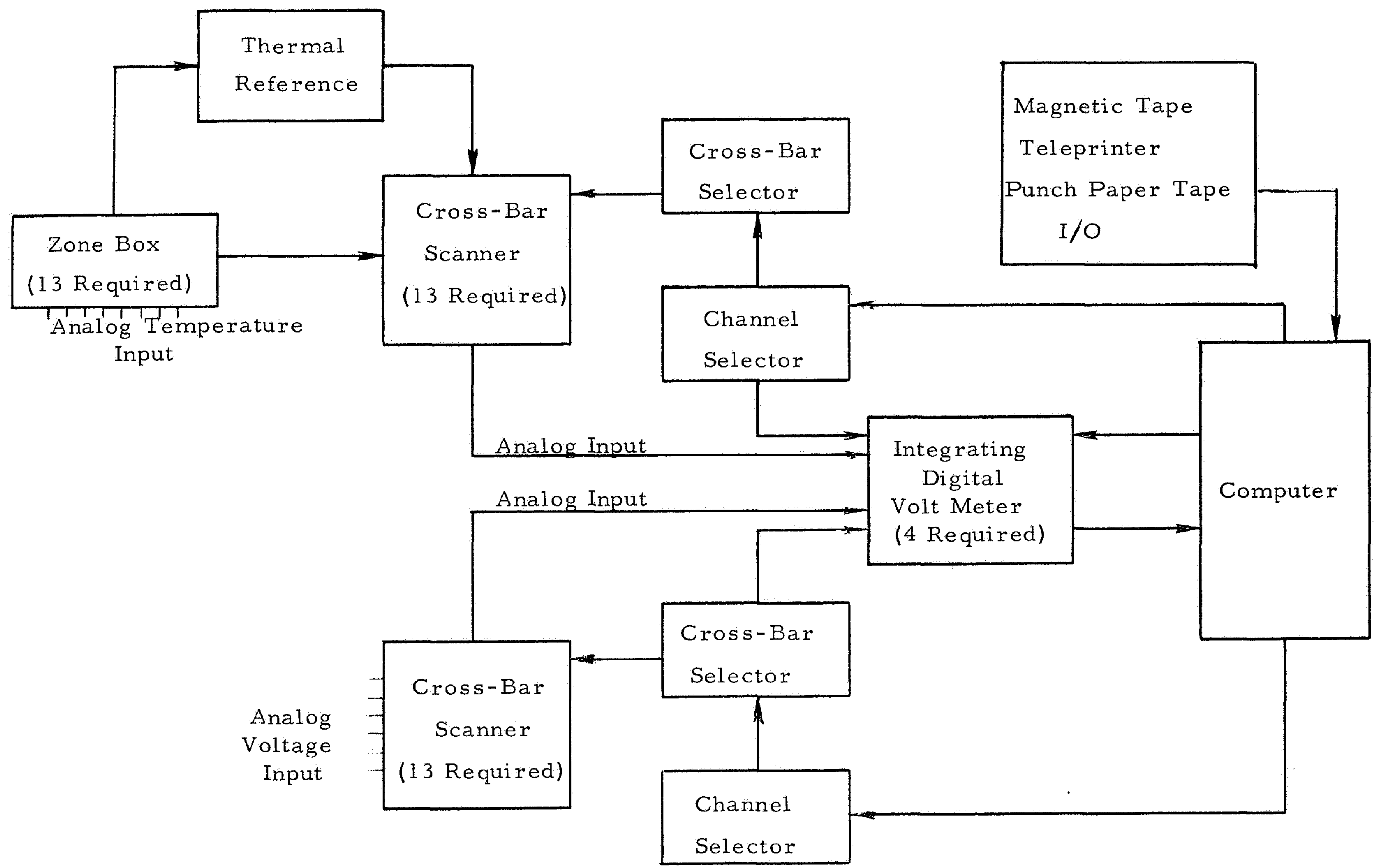


Figure 17

Flow Chart of the Hewlett-Packard Computer Oriented Data Acquisition System.

digital voltmeters, power supply, magnetic tape, teleprinter, and punched paper tape I/O, additional core memory, all cabinets and cabling and temperature zone and reference boxes. Turnaround time, for measuring all 5200 Data points, will be within two minutes. The estimated price of the system is $295,000.00.

This system is primarily data-acquistion oriented. The computer is used as a data-comparator, to convert analog measurements to engineering units, to output edited magnetic tape, and to institute control functions for the scanners and A/D converters in the acquistion system. No options are provided for the generation of test control functions with this system; these functions would remain manual, as they are at present. The Hewlett-Packard design utilizes standard, off the shelf, hardware components whose reliability and serviceability are assured by the manufacturer. Hewlett-Packard claims vast experience and great success in instrumentation design and implementation. The Hewlett-Packard cross-bar scanner switch is the Cunningham type with all signals guarded. The contacts are solid gold which achieves low signal path resistance and low thermo-electropotential and permits accurate transference of low-level signals. This type of switch is of higher reliability and longer operational life than the reed-relay type switch.

This system has 26 individual crossbar switches, cabled together. The switching logic and function is provided by crossbar-select and channel select devices on program command from the computer. The four digital voltmeters will perform A/D conversion on the scanner acquired data and forward it, the data, to the computer on programmed command. The system will have 2600 data points for differential cell-voltage measurement; low-level thermocouple outputs. The temperature measurements will be made through 200-channel zone boxes in conjunction with temperature reference junctions. The HP 2116A computer, unlike most others available, is specifically designed for scientific and industrial measurement applications. It is easily interfaced with both test instrumentation and peripheral I/O devices and is supported with an extensive software library. This computer, with additional memory and extended software, can regulate both data-acquisition and test control functions to eliminate the human-error factor from the test system.

A flow chart of this system is shown in figure 17.

g. Hewlett-Packard System Without Computer. Working in conjunction with the engineers at Hewlett-Packard, the following 5,000 point data acquisition system was designed that did not require a computer.

This system features the same number of scanners, scanner control and logic devices, digital voltmeters, and temperature zone and reference boxes as their previously described computer oriented system. Elimination of the computer creates several significant, unacceptable, differences. The scan and record functions would be accomplished by several non-standard specially built instruments -- namely a crossbar scanner, integrating digital voltmeter, comparator, digital clock, tape reader, tape programmer, and magnetic tape coupler. An incremental magnetic tape unit (write only) and an on-line printer are the only standard hardware items included. The

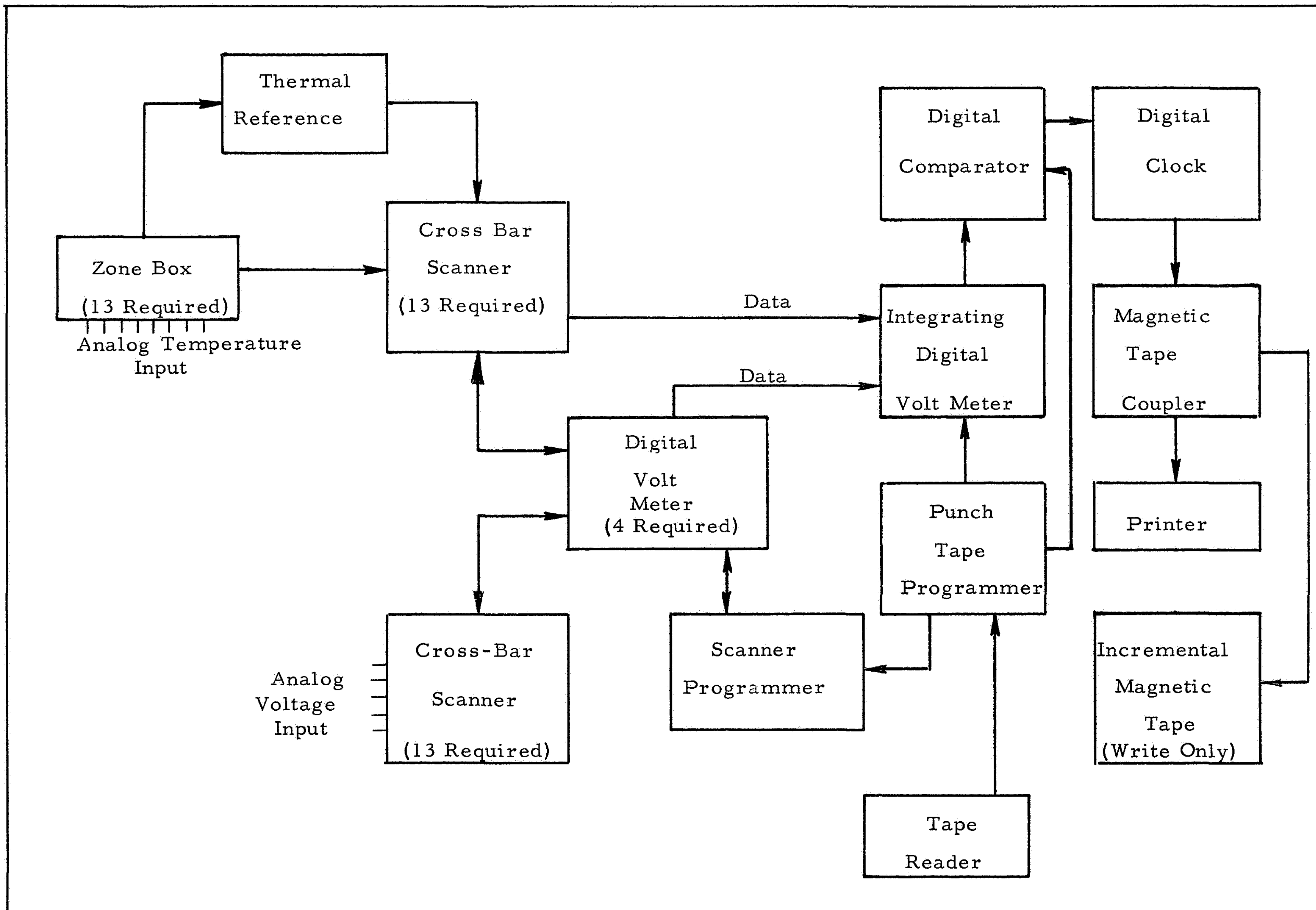


Figure 18

Flow Chart of the Hewlett-Packard
Data Acquisition System Without Computer.

Comparator will compare data acquired from each of the 5000 points with pre-set high/low thresholds input to it from the tape reader and tape programmer. The high/low thresholds will be contained in a 120 foot long punched plastic tape, one threshold set for each of the 5000 data points. The alarm function, instituted by the Comparator, will be incapable of corrective action on the cells that exceed their thresholds and will not "flag" the data from these cells on the output magnetic tape. The on-line printer will write a warning message to the operator who must then manually seek and correct the cause.

This system would require 13 minutes for one scan of the 5000 data points. This very slow scan rate could be approximately halved by adding three additional sets of the above named devices. The faster scan rate achieved, 5 to 7 minutes per 5000 point scan, would still be too low.

An incremental magnetic tape writer will record only one measurement per tape-space, not the densely packed recordings of the usual read/write magnetic tape units. This will cause the output tape to be filled in less than one-half hour, at the higher scan rate, and necessitate frequent tape changes and a large inventory of extra tapes. The approxmate price of this system, with one set of scan and record devices, is $195, 000. 00. With four sets of scan and record devices, to achieve a higher scan rate, the price rises to an estimated $295, 000. 00. The hardware cost factors for the computer oriented and non-computer systems are comparable. The Computerized Data Acquisition System will produce much more data, at a much lower cost per data unit, than the computerless system.

The equipment manufacturer strongly opposes the non-computer approach because of the unknown reliability and service factors involved for the special purpose instrumentation. A flow chart of this system is shown on Figure 18.

h. Summary of Evaluation of Test Systems. Table XXXI lists the various attributes of these test systems for comparision purposes. The following remarks summarize the pro's and con's regarding their usefulness:

A. PRESENT CRANE SYSTEM

The present Crane Battery Evaluation has proved to be a great value. The data from this program has been used to:

1. Define data elements
2. Isolate and identify data patterns that are indicative of incipient cell failure.
3. Give insight to the functional characteristics of space battery cells.
4. Identify failure characteristics generally and also those failure characteristics accuntable to a specific cell manufacturer.
5. Create and demonstrate new techniques for data analysis

The present Crane program has achieved a significant "first step" toward the better understanding and utilization of space-battery cells.

Legend: * = Estimated		Present Crane System	Updated Crane System	Minimal Computer System	Automated Computer System	Maximum Computer System	Hewlett-Packard System Computer Oriented	Hewlett-Packard System No Computer
Orbit Periods:	Fixed, Repetitive	X	X	X			X	X
	Variable				X	X		
Test Parameters DOD, Temp, Etc.:	Fixed, Repetitive	X	X	X			X	X
	Variable				X	X		
Test Control:	Manual	X	X	X			X	X
	Automated				X	X		
Protective Alarm System:	Separate	X	X					X
	Integrated			X	X	X	X	
On Line Control Of All Data Points:	Yes				X	X	X	X
	No	X	X	X				
Data Conversion:	On-Line			X	X	X	X	X
	Off-Line	X	X					
On-Line Calculations:	Yes				X	X	X	X
	No	X	X	X				
On-Line Data Analysis:	Yes					X		
	No	X	X	X	X		X	X
Scanner:	Solid-State		Either	Either	X	X		
	Electro-Mechanical	X	"	"			X	X
Computer Integrated Control And Acquisition Functions:	Yes				X	X		
	No	X	X	X			X	X
System Applicable To Other Areas:	Yes				X	X		
	No	X	X	X			X	X
Data Conversion* Cost -- Yearly:		$30,000.00	$ 400,000.00 To $ 700,000.00	NONE	NONE	NONE	NONE	NONE
Price-Computer: *		NONE	NONE	$ 50,000.00	$ 50,000.00	$ 100,000.00	$ 295,000.00	NONE
Price-Scanner: *			$ 150,000.00	$ 150,000.00	$ 150,000.00	$ 150,000.00	INCLUDED	INCLUDED
Price-Additional * Core And Software:				Software $ 35,000.00	$ 85,000.00	$ 200,000.00	Software $ 30,000.00	NONE
Price-Peripheral * Equipment:			$ 50,000.00	$ 50,000.00	$ 50,000.00	$ 200,000.00	INCLUDED	INCLUDED
Total Price: *			$ 200,000.00	$ 285,000.00	$ 335,000.00	$ 650,000.00	$ 325,000.00	$ 195,000.00 To $ 295,000.00

Table XXXI Comparison of Data Acquisition Systems

This test system, however, effective it has been in past years, has reached the maximum limits of its capability. The desirability and necessity for mass battery evaluation within parameters that simulate space-mission operational requirements can not be practically achieved with the present system. For example; a synchronous orbit with its varying charge-discharge periods may be simulated within the present test system only by the full-time participation of a technician to institute the control functions. Because of the complexity of the control functions for this type orbit, one technician could control only one or two battery packs; so the generation of a sufficiently broad data-base would require the participation of several expensive technicians on an around-the-clock basis.

The fixed, repetitive cycle regime within the present test structure cannot be easily or economically varied, as stated above. However, the data from the present program indicates the need for the capability to vary the orbit regimes as necessary for analysis methods.

As with the orbit variable, all other test variables, now fixed and repetitive, should be flexible.

Test control functions are completely manual and, therefore, quite error prone. Data acquisition functions are manually instituted and, along with the very limited 30 point scanner, produce irregular monitor times, irregular recording intervals, and effect the disregard of 90% of the data generated. The data produced under these conditions lacks both adequacy and accuracy for ultimate utilization of analysis and prediction techniques.

The present system requires off-line conversion, editing and storage of the acquired data, at the estimated cost of $30, 000. 00 yearly. This off-line data conversion can produce error conditions due to the lack of continuity inherent in the process.

Several options are presented, either to update the present Crane system or to establish an original functional approach for a new battery evaluation program.

B. UPDATED CRANE SYSTEM

Addition of a new, large scanner and additional A/D converters to the present Crane system will achieve a desirable expansion of the data base; however, the off-line data conversion cost will rise to $400, 000. 00 - $700, 000. 00 per year. The test control functions will remain manually generated and the cycling regimes will remain fixed and repetitive. To. update the present Crane system with a new scanner will be neither practical nor economical for these reasons.

C. MINIMAL COMPUTER SYSTEM

This option would add a small electronic computer to the Updated Crane System for the purpose of direct-on-line date conversion, editing, and magnetic tape output. While this method would effect a large cost reduction for data conversion, the test control functions would remain manual and all test variables would remain fixed and repetitive.

D. AUTOMATED COMPUTER SYSTEM

This option will enable the complete integration, by Computer, of both test control and data acquisition functions, permit simplified, economical variability of all test parameters, and permit total system flexibility. This system will utilize the high rate of a solid-state scanner to scan each of the 5000 data points every 10 to 30 seconds. The computer has the capability to control and compare each data point as it is scanned and permit recording either as a scheduled function or as a function of the data condition. For example, assume the data recording function is scheduled, by program control, to record at 2 minute intervals; the scan and compare function is effected every 20 seconds; the data that exceeds comparision thresholds during the 20 second scan intervals can be individually recorded out of sequence to permit a closer look at the "out-of bounds" measurements. Data that does not exceed these thresholds can be recorded or ignored, as desired. This feature will greatly enhance the analysis techniques. There is an immediate need for this high speed feature to accurately "picture" charge-discharge curve profiles.

The Automated Computer System will produce accurate data in sufficient volume so that pertinent engineering data, now difficult or impossible to obtain, may be defined and utilized.

The addition of extended "memory" to the computer and the development of specialized software will enable total automation of the system and eliminate the human error factor from control functions.

The automated system has application in areas other than battery evaluation. For example; transistors, integrated circuits, and other electronic components may be automatically evaluated with the system by changing the computer software. Also, operational battery data, telemetered from space, could be evaluated with the system.

E. MAXIMUM COMPUTER SYSTEM

Functionally similar to the Automated Computer System but will permit on-line data analysis at high additional costs. This feature may be desirable but cannot, at present, be justified.

F. HEWLETT-PACKARD SYSTEM --- COMPUTER ORIENTED

This system is data-acquisition oriented and does not enable computer generation of test control functions or permit flexibility of test variables.

The computer controls the following functions:

1. Scanner Sequence.
2. A/D Conversion.
3. Comparision of Every Data Point
4. Protective Alarm System.
5. On-Line Data Conversion, Editing, and Storage

G. HEWLETT-PACKARD SYSTEM WITHOUT COMPUTER

This system is unacceptable for the following reasons:

1. Very low scan and acquisition rate.
2. It contains much specially built hardware.
3. No price differential compared to the computer oriented system.
4. Much higher cost per data unit.
5. Test control functions remain manual.
6. The manufacturer is in opposition to it.

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Department of the Army

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8900 De Sota Avenue
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Bell Laboratories
Attn: U. B. Thomas
D. O. Feder
Murray Hill, New Jersey 07974

Dr. Carl Berger
13401 Kootenay Dr.
Santa Ana, Calif. 92705

Burgess Battery Company
Attn: Dr. Howard J. Strauss
Foot of Exchange Street
Freeport, Illinois 61032

C & D Batteries
Attn: Dr. Eugene Willihnganz
Division of Electic Autolite Co.
Conshohocken, Pennsylvania 19428

Calvin College, Science Bldg.
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Hughes Aircraft Corporation
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IIT Research Institute
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Institute for Defense Analyses
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