

N69-13454
NASA CR-97935

65 pages

STUDY OF SPACE BATTERY ACCELERATED TESTING TECHNIQUES
PHASE I REPORT
SURVEY OF TESTING METHODS APPLICABLE TO SPACE BATTERY EVALUATION

September, 1968

Contract No.: NAS 5-11594

Prepared by

R. E. Thomas, E. W. Brooman, J. Waite, and J. McCallum

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for

Goddard Space Flight Center
Greenbelt, Maryland

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Contract No.: NAS 5-11594

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Contracting Officer: John C. Comstock
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7/6 X 5752

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November 21, 1968

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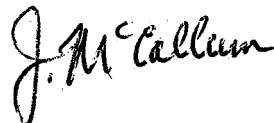
Attention Mr. E. F. Colston (Code 716.2)

Gentlemen:

"Study of Space Battery Accelerated Testing Techniques"
Contract NAS 5-11594

Enclosed is a copy of the Phase I report, "Survey of Testing Methods Applicable to Space Battery Evaluation", prepared under Contract Number NAS 5-11594. As directed in the GSFC Specification S-250-P-1 (January, 1967), one reproducible copy is being forwarded to the Documentation Branch, Code 256. Other copies are being distributed according to the contract requirements.

Yours truly,



John McCallum
Project Manager

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FOREWORD

This report describes work performed at Battelle Memorial Institute, Columbus Laboratories, 505 King Avenue, Columbus, Ohio, 43201, under Contract NAS 5-11594.

The authors wish to thank Mr. E. F. Colston, NASA Goddard Space Flight Center, for his review of this report and Mr. E. A. Roeger, Jr., Battelle, for providing much of the information for the examples given of Operational Life Tests.

The report was submitted by the authors in September, 1968. Publication of this report does not constitute approval of the report's findings or conclusions by the National Aeronautics and Space Administration. It is published only for the exchange and stimulation of ideas.

ABSTRACT

The object of this research program is to develop testing procedures to accelerate the aging of electrochemical cells so that years of data may be acquired in significantly less time to enable a valid prediction of cell life. The program is divided into three phases. The first phase is to conduct a literature survey.

A literature survey of accelerated testing has been made with special reference to spacecraft batteries. Although increased sophistication is shown in measuring equipment and data processing, the survey shows that considerable differences exist among published investigations with respect to basic definitions, terms, and concepts. In particular, the terms "stress", "quality", and "failure" need to be defined in ways that are consistent with laboratory measurement techniques and possible physical mechanisms associated with degradations of quality over time. It is concluded that the greatest single difficulty in accelerated testing consists of obtaining quantitative evidence that the dominant failure mechanisms are not changed by increasing the stress level.

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STUDY OF SPACE BATTERY ACCELERATED TESTING TECHNIQUES

PHASE I REPORT

SURVEY OF TESTING METHODS APPLICABLE TO SPACE BATTERY EVALUATION

by

R. E. Thomas, E. W. Brooman, J. Waite, and J. McCallum

INTRODUCTION

Some space batteries are so reliable that a desired service life of 3 to 5 years may be easily met with high confidence. However, there is increasing demand for lighter, more compact, more powerful batteries on future space missions. Therefore, new battery designs must be quickly evaluated and tested to insure adequate quality to survive the anticipated life of the spacecraft. In some respects, the simplest test would be a test in which a set of batteries is operated under service conditions until failure, in order to obtain an estimate of a minimum or average life. This approach is extremely time-consuming, and also suffers from the fact that the service conditions encountered in space may not be similar to those simulated in the laboratory. Another failing of such a test is that it would generally require 3 or more years to establish that the battery would, in fact, last that long. The economic disadvantages of long-life tests are immediately apparent, but there are also technological disadvantages. First, for an assured 3-year life, the batteries must be available at least 3 years before the mission date, and a sufficient number of the batteries must be available for testing. Second, because of the lengthy testing period and the rapidly advancing technology, a new and improved battery may be available by the time life tests are completed. Thus, obsolescence is also part of the problem.

These comments serve to point out the need for different types of testing, and testing procedures which can predict the useful life of a battery in a comparatively short time period. High confidence is required in such predications because, during certain portions of an orbit, the battery is often the sole source of power for operations and instrumentation needs.

In summary, an acceptable and proven "accelerated life test" is greatly needed to reduce test time. In an accelerated life test, a battery is operated at higher "stress" levels than those associated or anticipated with normal operation. The data taken at the higher stress levels are then analyzed in order to predict how long such a battery would be expected to perform within specified tolerances at normal "stress" levels (service conditions). If the required test time can be reduced to the order of days or months, in contrast to years, then the evaluation of new battery designs may be effectively accomplished before the battery is put into service. Considerable cost reductions may then be made in laboratory test equipment and personnel, and the risk of using improved batteries on critical missions would be substantially reduced.

Because accelerated life tests require less time than simulated life-cycle tests, it may appear that accelerated life tests are easier to run. Certainly the requirement of maintaining a given set of test conditions for a period of 1 month is less stringent

than the same requirement for a period of 1 year. However, the primary difficulties associated with accelerated life testing result from different considerations. In general, such considerations involve the problem of whether operation at higher levels of stress yields failures for different reasons than operation at normal levels of stress. Because of the necessity of extrapolating observed behavior at high stresses to predicted behavior at normal stresses, the data must indicate whether such extrapolations are permissible. This imposes severe requirements on data acquisition, analysis, and interpretation.

The purposes of this report are to survey and to report on existing testing methods that may be applicable to space-battery evaluation, and to indicate, where possible, how such tests might be used in space-battery accelerated testing. To accomplish these objectives, the report has been divided into several sections.

Section 1 consists of a review of the literature related to the general evaluation of spacecraft batteries. Four representative evaluation programs are discussed in some detail, together with brief mention of additional failure analysis procedures and testing methods. In Section 2, attention is focussed on accelerated testing of electrochemical energy conversion devices. Brief reference is also made to the literature on accelerated testing of non-electrochemical devices. General conclusions regarding data acquisition and analysis are also given in this section.

The discussions included in these two sections are supplemented by the bibliography given at the conclusion of the report.

SECTION 1. EXISTING TESTING METHODS APPLICABLE TO SPACE BATTERY EVALUATION

Introduction

Tests currently applied to spacecraft cells and batteries are predominantly oriented towards showing performance capabilities of existing battery designs and evaluating proposed battery designs. Most of these tests are life-cycle tests and the tests are often carried out until failure occurs. A subsequent failure analysis is made to determine why the cells failed. In some instances, this procedure enables corrective measures to be made. Several major manufacturers conduct their own life-cycle tests or contract to have them done by independent laboratories. One such laboratory is the Inland Testing Laboratories of the Cook Electric Company. The Federal Government is also interested in the performance characteristics of spacecraft cells and batteries, and has supported life-cycle testing. These tests are often carried out under simulated orbital conditions at Federal facilities. Such facilities include the Naval Ammunition Depot, Quality Evaluation Laboratory, Crane, Indiana, and the Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio.

Because of the central role of the life-cycle test, the following review focuses attention on the design of these tests, including the measurements taken, the environmental controls, and attempts to modify these tests so that accelerated life tests are obtained. Modifications of life-cycle tests, such as increasing suspected operational stresses, comprise most of the accelerated tests reported on electrochemical devices. Adequate reviews of the principles and philosophies involved in accelerated testing of electrochemical devices have not been found.

Operational Life Tests

Operational life tests are usually classed under terms such as life-cycle tests, cycle-life tests, or cycling tests for secondary batteries. These terms are intended to infer that the batteries are subjected to a specified, repetitive charge-discharge regime. Usually the charge-discharge regimes are arranged to simulate actual operational requirements, so that the results may be applied in practice.

Four programs associated with operational life tests are described to illustrate the nature of the tests and the various degrees of sophistication. The four programs have been operated by the Inland Testing Laboratories, Dayton, Ohio; the Quality Evaluation Laboratory, Crane, Indiana; Battelle's Columbus Laboratories in conjunction with the Air Force; and the Union Carbide Laboratories, Parma, Ohio. Following the four examples, given for the various types of operational life tests and their implementation, is a section which summarizes in tabular form the experimental conditions which have been used for evaluating the life of spacecraft batteries.

Battery Evaluation Programs of
the Inland Testing Laboratories

These programs were operated by the Inland Testing Laboratories of the Cook Electric Company under Government Contracts NAS 5-1048, AF 33(616)-7529, AF 33(657)-8450, and AF 33(615)-1580.

The NASA program consisted of subjecting 100 3.5 amp-hr and 50 6.0 amp-hr nickel-cadmium cells to a series of qualification and/or acceptance tests followed by life tests and subsequent post-test analyses.

The qualification and/or acceptance tests included a visual and mechanical inspection, capacity determinations, electrical leakage checks, overcharge capability, and internal resistance measurement. Also included were electrolyte leakage, vibration, shock, and acceleration (g) tests. However, not all of these tests were applied to all cells.

Having satisfied the necessary preceding requirements, the cells were separated into ten-cell groups and were then subjected to an operational life test having the following characteristics:

Charge time	60 minutes	} One cycle = 100 minutes
Discharge time	40 minutes	
Ambient temperature	-10, 25, and 50 C	
Depth of discharge	10, 25, and 40 percent	

The life-test-cycle regime was operated continuously until one-half of the cells in each ten-cell group displayed terminal voltages below 1.0v during the discharge portion of the cycle. The total number of cycles successfully completed by each cell was recorded.

All cells which failed were subjected to a visual inspection, followed by dimensional measurement checks and capacity and electrical leakage (open-circuit stand) checks. For each cell, the data obtained before and after the test were compared to ascertain the magnitude of any changes. However, no additional tests were performed as a result of the findings.

The Air Force Aero Propulsion Laboratory contracts with Inland Testing Laboratories were concerned with an evaluation of a wider range of secondary cells and batteries. Contract AF 33(616)-7529, for example, involved the evaluation of the operational life of 192 25-amp-hr silver-zinc cells; 192 20-amp-hr silver-cadmium cells; 150 20-amp-hr nickel-cadmium cells; and 240 12-amp-hr nickel-cadmium cells. Most nickel-cadmium cell groups consisted of ten cells, whereas the silver-zinc and silver-cadmium cell groups consisted of eight cells. Typical operational parameters were as follows:

Nickel-cadmium cells:

Charge time	55 minutes	} One cycle = 90 minutes
Discharge time	35 minutes	
Ambient temperature	-10, 5, 25, and 50 C	
Depth of discharge	25, 50, and 75 percent	

Silver-zinc or silver-cadmium cells:

Charge time	85 minutes or 22.8 hours	} One cycle = 120 minutes or 24 hours
Discharge time	35 minutes or 1.2 hours	
Ambient temperature	-10, 5, 25, and 50 C	
Depth of discharge	25, 50, and 75 percent	

All discharges were made at a constant current rate, and all charges were made at a constant current rate to a preset voltage limit, after which the group was charged at constant voltage. The cell groups were cycled continuously (24 hours a day, 7 days a week) and each group was controlled by its own charge-discharge cycling apparatus, except for the cycle timer and counter, which were common for each test regime. The charge/discharge rates were determined using the manufacturer's rated amp-hr capacity. Capacity checks were made on samples of each type of cell to verify these rates.

During the life tests, the cell voltages, group voltages, temperatures, and group currents were monitored. Most of the data for group voltages and currents were obtained on recorder-chart paper and very little information about individual cells was permanently recorded. For this reason, retrospective analysis of the evaluation is difficult in terms of individual cell behavior.

The cell failure criterion under Contract AF 33(616)-7529 was the inability of a cell to deliver the required discharge current for the full time of the discharge period without the voltage falling below a preset limit. This limit was selected according to the cell type and test condition. This was done because of the differences in electrical characteristics of the cells, and the effects of depth of discharge and temperature on those electrical characteristics. If a cell failed or showed some other defect that could lead to damage of other cells, then the cell was removed and the group cycle parameters were reset in order to maintain the original test conditions. Group failure was said to have occurred when one-half or more of the individual cells in each group had failed.

After the operational (cycling) tests were completed, a comprehensive failure analysis of a selected sample of the failed cells was performed by the respective cell manufacturer. The purpose of this analysis was to determine the causes of the failures and to recognize precursors associated with these causes. This procedure was used so that cell-failure mechanisms would be better understood, and the manufacturers could take steps to avoid these failures whenever possible. The failure analysis procedures, and the documentation arising from them under this particular evaluation, represent an improvement over the NASA program previously described. However, the results of this program received limited distribution and appear to have had little impact on other battery users and manufacturers.

The objectives and applications of Contract AF 33(657)-8450 were similar to Contract AF 33(616)-7529 just described. The evaluation program was concerned with the operational life and resulting failure analysis of a large number of cells. These included two types of 25-amp-hr silver-zinc cell; one type each of 15- and 20-amp-hr silver-cadmium cells, and one type of 20-amp-hr nickel-cadmium cell.

The test parameters, test equipment, and data collection procedures for this program were essentially the same as those described in the preceding paragraphs for AF 33(616)-7529. Again, it appears that the dissemination of the results was limited.

Contract AF 33(615)-1580 was terminated before completion of the proposed program. As a result, little useful information was reported under this contract.

None of these battery-evaluation programs were specifically designed to accelerate the aging of cells or groups of cells. Instead, the operational tests were designed to provide a broad base of data related to the operating characteristics of the cells over a range of anticipated uses and environments. In a sense, this was not achieved because the collection of data was often poorly organized, and hindsight shows that, for example, more individual cell data would have been useful.

The fact that the tests were not designed to be accelerated tests does not mean that the selection of the variables did not cause aging to occur more rapidly under certain test conditions. For example, it could be postulated that the tests at 50 C and 75 percent depth of discharge were more stressful than those tests at 5 C and 25 percent depth of discharge. If aging occurred more rapidly under the more stressful conditions, then accelerated test data were obtained. The lack of individual cell data, however, would appear to prevent a re-analysis of the observed results (cycle life) to obtain evidence as to whether the failure mechanisms were the same at the more stressful condition, and if so, to obtain a numerical estimate of the acceleration factor.

Battery Evaluation Programs of the Quality Evaluation Laboratories

Several battery evaluation programs were operated by the Quality Evaluation Laboratory at the Naval Ammunition Depot, Crane, Indiana. Most of this effort is being done under NASA contract number W11, 252B. The program began in 1963 with the objective of gathering specific information concerning the performance characteristics and limitations of secondary cells under various electrical and environmental operational conditions. As a result of the program, it is intended that cell weaknesses, including the causes of failure of present designs, will be identified so that appropriate modifications can be made in future designs. Also, the large volume of data collected is intended to serve as reference material for power-system designers and users.

The original program began with 660 sealed, nickel-cadmium cells from four manufacturers and in seven capacity groups, ranging from 3.0 to 20 amp-hours. The operational parameters were as follows:

Charge time	1, 2-1/2, or 23 hours	} One cycle = 1-1/2, 3, or 24 hours
Discharge time	1/2, 1/2, or 1 hour	
Ambient temperature	0, 25, or 50/40 C	
Depth of discharge	15, 25, and 40 percent	

The cells cycled at 50 C were found to have very short lives. Consequently, in order to obtain a greater volume of data, the temperature was lowered to 40 C for subsequent tests. Not all combinations of the above parameters were used. The following tabulation shows the combinations used with the respective charge voltage limit, and amount of recharge. All the tests were performed in air, and those cell packs which were cycled at 0 C and 50/40 C were in temperature-controlled chambers. The cell packs at 25 C were left standing in an air-conditioned room. The ambient temperature quoted is believed to be accurate to ± 2 C.

	Ambient Temperature, C		
	0	25	50/40
Depth of discharge, percent	{ 15 25	-- 25	15 25
Amount of Recharge, percent	{ -- 115	40 125	-- 160
Charge Voltage Limit, v/cell	1.55	1.49	1.41/1.45

Those cells which passed the acceptance tests were arranged in five and ten cell groups. Each group had its own solid-state current-controlling unit to control the charge rate both in the constant current mode and in the constant voltage mode after the preset voltage limit had been reached. These two charging modes were achieved by regulating the current supplied with a 28 v d-c generator common to all units. Relay switching systems changed the loads in the units to affect discharges. Auxiliary equipment scanned every cell on test once every 2 minutes. When any cell voltage rose above 1.7 v or fell below 0.5 v, the equipment sounded an alarm, and disconnected that cell from the charge/discharge control circuits. If more than half of the cells in a group failed, then the group was said to have failed.

Disconnected cells were subjected to a failure analysis procedure performed at Quality Evaluation Laboratory, Crane. The manufacturers had the option of participating if they wished. This arrangement had the advantage that a common failure analysis procedure was applied to each cell. Consequently, greater uniformity was obtained in evaluation and interpretation. The failure analyses were successful in indicating to several manufacturers where improvements could be made in cell design and materials.

Data for the cells on test were obtained and recorded on punched paper tape approximately every 32 cycles for the 1-1/2-hour orbit, every 16 cycles for the 3-hour orbit, and every 8 cycles for the 25-hour orbit. The parameters measured were group current, voltage, and temperature, together with individual cell voltages. The maximum number of cell groups which could be measured simultaneously was 18. A computer converted the data to obtain amperes, volts, and degrees C. This information was stored on punched cards for evaluation. About every 88 cycles a capacity check was made on each cell, but these data were not integrated with the above measurements.

This NASA program gave more tangible results than the previous program because of the better organization of the tests and subsequent analyses, and the more efficient data collection system. Subsequent analysis of this NASA Crane data, which will be discussed later, has yielded much additional useful information and has led to techniques of predicting cell failures during a test. The disadvantages of the program include the fact that it is costly, and the results may already be out-dated when they become available. However, as noted previously, these disadvantages are characteristic of many operational life tests. The capacity check about every 88 cycles was found to condition the cell, and thus lead to an extended cycle life. No controls were run to determine the effects of the capacity checks. However, it was noticed that after such a check, the cycle behavior took considerable time to settle down to that observed prior to the test. Further details may be found in Reference (1).

The original tests at the Quality Evaluation Laboratory, Crane, have been extended to include a wider range of cells of more recent manufacture. These include silver-cadmium cells, silver-zinc cells, and cells with different types of charge-control devices. Thus, the program is producing information on recently available cells even

though the test procedures have been changed very little from those described above. In order to accommodate the different electrical characteristics of these newer cells, and in order to cover a wide range of anticipated environmental conditions, the temperature range has been extended to -20 C; the depth of discharge range has been extended from 10 to 75 percent in some cases; and an 8-hour orbit period has been introduced (1-hour discharge: 7-hours charge) with a recording frequency of 12 cycles⁽²⁾. At the present time, operational tests are still being performed, and the results are being published annually, as shown in the bibliography at the end of this report.

Battery Evaluation Programs of the Wright-Patterson Air Force Base

The Wright-Patterson Air Force Base battery-evaluation program is currently being operated by the Columbus Laboratories of Battelle Memorial Institute at the Aero-Propulsion Laboratories, Wright-Patterson Air Force Base, Ohio, under Contract AF 33(615)-3701. The object of this program is to investigate the performance characteristics and establish the optimum operational parameters for 3 to 5-year spacecraft battery operation in polar and synchronous simulated orbits.

Because the emphasis in this program is placed on obtaining operational parameters under simulated orbit conditions, care was taken in setting up the acceptance and cell matching tests to use procedures common to those practiced by manufacturers in qualifying their batteries for actual missions. The actual operational cycling tests were also designed to match expected orbital mission requirements.

A detailed description of the test procedures, and the test equipment are given in References (3) and (4). A brief description of this work is given in the following paragraphs.

Preliminary acceptance and matching tests were used to condition the nominal 20-amp-hour sealed, nickel-cadmium cells. This was done in order to verify the performance data given by the manufacturers, and to obtain the information necessary to match the cells closely for the simulated orbital tests. Matching was based upon measured capacity and end-of-charge voltage after the cells had been checked for physical defects and electrical defects, such as internal shorts.

A total of 25 cells from each of four manufacturers was tested in the above manner in order that four groups of ten cells could be placed on the life test proper. Each group of ten cells was chosen from only one of the manufacturers. Two of the four groups were tested under a simulated polar orbit regime of 5.31 hours while the other two groups were tested under a simulated synchronous orbit regime of 24 hours. These two regimes are shown in Figures 1 and 2. Both sets of groups were mounted on a heat sink platform and cycled in an environmental chamber held at a constant 25 C. Some of the cells placed on test had pressure transducers affixed; others had dummy tubes of equal volume.

Thus far, two important differences in this test procedure and those described earlier are apparent. First, the cells are matched as far as possible for electrical performance to minimize the effects that varying operational characteristics might have on cell life. Second, a fixed charge/discharge cycle regime is not used. Instead, the time duration of the charge and discharge periods varies according to the load cycle

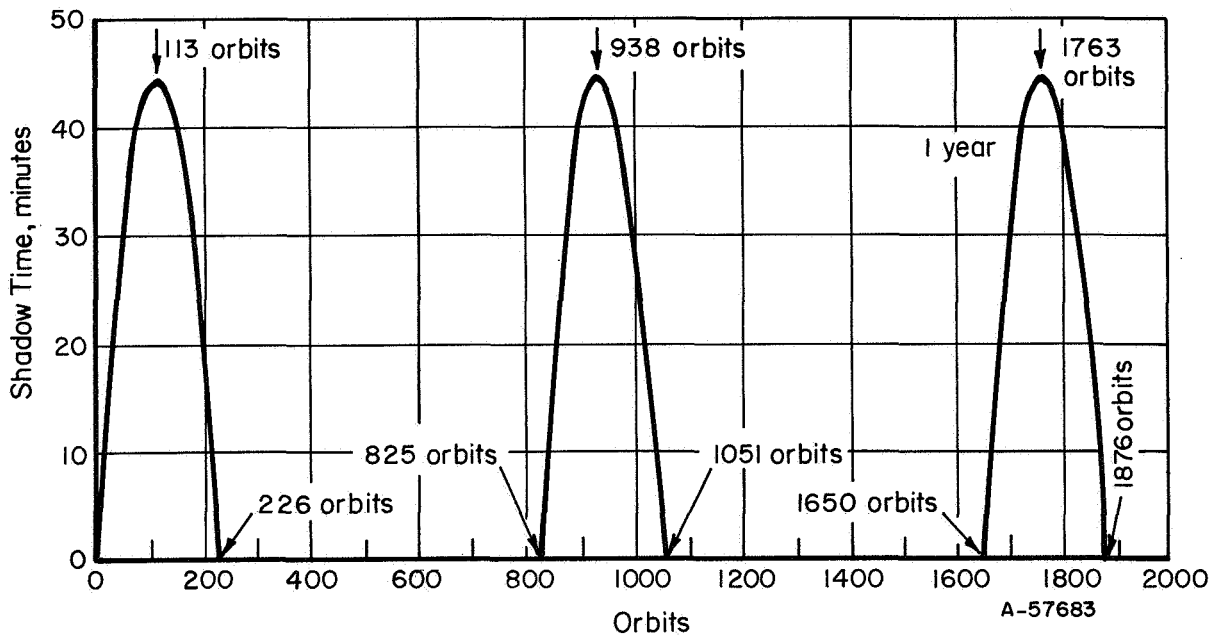


FIGURE 1. SIMULATED 5000-NAUTICAL-MILE CIRCULAR POLAR ORBIT

Each cell group (10 cells/group) evaluated under the polar-orbit-time conditions is alternately charged and discharged for 225 cycles, with the discharge ranging from 0 minutes for the first cycle to a maximum of 45 minutes on the 113th cycle, and back to 0 minutes on the 225th cycle, in such a manner that the discharge time, as a function of cycle number, approximates a sinusoidal function. The total time per cycle is a constant value of 5.31 hours. The remaining time per cycle not accounted for by the above schedule is used for charging. At the completion of the 225 cycles the cells are subjected to a continuous charging for 599 cycles (3180.7 hours). After the completion of 599 cycles, the previously described 225-cycle discharge routine is repeated.

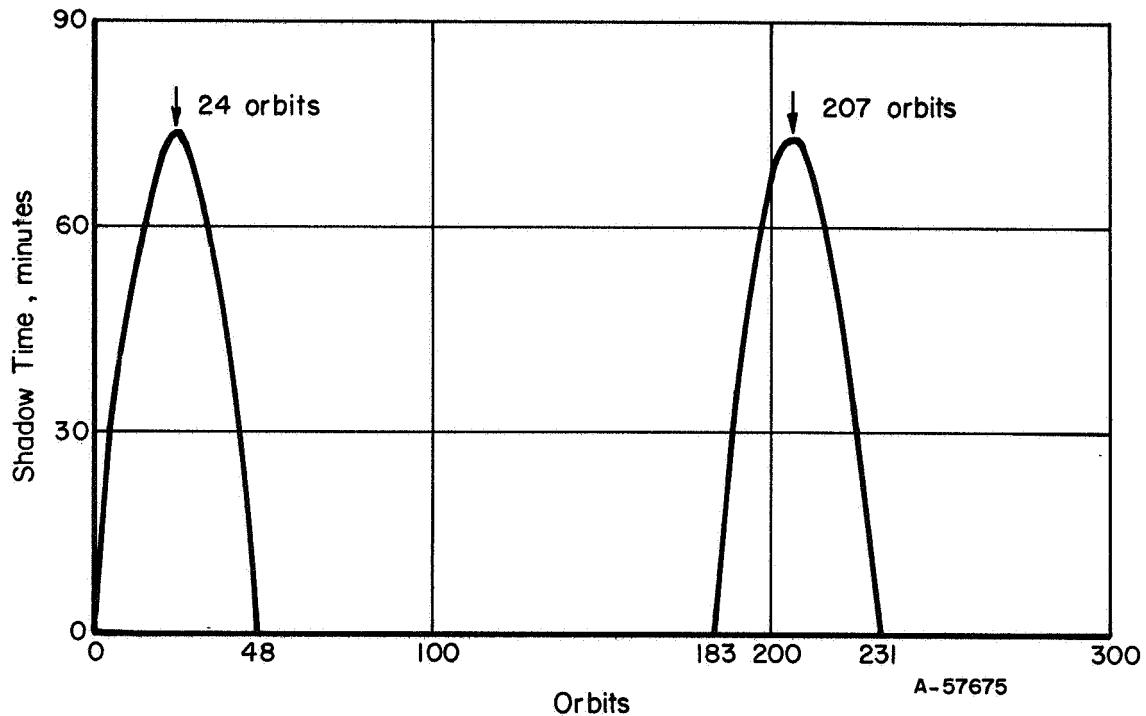


FIGURE 2. SIMULATED SYNCHRONOUS EQUATORIAL ORBIT

Each cell group (10 cells/group) evaluated under the actual equatorial orbit time conditions is cycled in the following manner. Each cycle is 24 hours in length. The cells are alternately charged and discharged for a total of 48 cycles as follows: the discharge period ranges from 0 minutes on the first cycle to a maximum of 74 minutes on the 24th cycle, and returns to 0 minutes on the 48th cycle in such a manner that the discharge time, as a function of cycle number, approximates a sinusoidal variation. Upon completion of these 48 cycles, the cell group is subjected to a continuous charge for 135 cycles. After these 135 cycles, the 48-cycle charge-discharge routine, specified above, is repeated.

of the associated simulated orbit. (See Figures 1 and 2) Moreover, the depth of discharge is controlled to a maximum preset limit of 80 percent.

All charges and discharges are made with constant current. A two-step charge is used with the switch-over from a high rate to a low rate charge when the group voltage reaches 14.5 v (about 1.45 v per cell). There are preset voltage limits outside of which a cell is classed as failed. An automatic warning device indicates when a cell exceeds tolerances, and removes it from the circuitry. The operator then has a choice of placing the cell back into the circuit or removing it and performing a failure analysis.

To date, after more than a year of continuous testing, only one cell has failed. Consequently, specially designed failure analysis procedures have not yet been validated in this program.

Data are recorded every 2 minutes during the discharge portion and the first part of the charge portions of selected cycles in the eclipse season of the test regimes. The cycles are selected to give the maximum amount of useful information with a minimum amount of punched tape from the data console. The data includes individual cell voltages, temperatures, and pressures where applicable; group currents and voltages; and heat sink/base plate temperatures. Thus, this test is primarily orientated to give data for individual cells while only monitoring group properties. The punched tapes are converted into magnetic tape to be compatible with a computer program designed to print out the desired information in tabular form.

Although the orbital tests were not designed to be accelerated tests, it may be possible to analyze the comprehensive data collected in terms of an accelerated test once the appropriate stresses and strains are identified.

Battery Evaluation Programs of the Union Carbide Laboratories

The battery evaluations of the Union Carbide Laboratories, Parma, Ohio, are basically "in-house" research carried out for the evaluation and analysis of their own products.⁽⁵⁾ The cycling facilities consist of equipment capable of programmed charges and discharges of up to 5 amperes for 12-cycle regimes with a maximum of 16 cells in each regime.

The Union Carbide Laboratories use a DSI 1000 computer to control their cycling tests in addition to using it for data collection and analysis. The computer is used to select the charge and discharge times; also it can select any one of four pre-adjusted charge or discharge voltages. The computer scans the measurement points every 36 seconds. A reading is recorded if the difference between the present reading and the last reading is greater than a variable threshold. This variable threshold is determined each time a reading is measured by taking the difference between the last recorded reading and the present reading and dividing this difference by the number of measurement points which can still be recorded out of the original limit of 10.⁽⁵⁾ The idea is to record only those data points which convey the most information. For example in the measuring of a discharge curve, the greatest changes in voltage per unit time base will occur at the beginning, and at the end of the discharge. The computer will recognize this and give a high density of recording points in these areas. On the other hand, during that part of the discharge when the voltage changes very little (the "plateau"), the

computer will record a minimum number of data points. At the end of any charge/discharge cycle there is an option to store the information on magnetic tape, or to erase the memory.

The cycling facility can be programmed to measure for each cell on each cycle the amp-hour capacity, watt-hour capacity, amp-hour efficiency, and various other parameters in addition to the charge and discharge voltages. There is also provision to measure cell temperature and pressure, although this has not yet been implemented. Most tests presently being performed are cycle tests at room temperature, although environmental testing may be performed if desired.

This last example of an operational life test is the most sophisticated of those considered, at least as far as instrumentation application and utilization is concerned. However, because of the 5-ampere limit, there is a limit to the number and type of cells which can be tested, and the rates at which the cells may be cycled.

No accelerated tests were originally planned for the facility. However, as will be discussed later, the rate of change of certain parameters, such as voltage, is being used to predict cell life. A graphic record of the changes of the parameters of interest may be obtained. Thus, if different stress levels are introduced into the cycling regime, then observation of the rate of change of the parameters could form the basis of an accelerated test.

Experimental Conditions Used in Operational Life Testing

Previous paragraphs have described examples of different types of operational life tests and their implementation. In the following tables (Tables 1-3), some of the other experimental conditions used in testing spacecraft cells are listed according to the three cell types: nickel-cadmium, silver-cadmium, and silver-zinc. The information, taken from the tabulated references (Table 4), has been condensed to give the testing facility contract number, orbit or cycle type, temperature, and depth of discharge. Thus, the tables suggest the experimental conditions that have been used.

Although limited, the tables encompass a broad range of the available literature published over the past 7 or 8 years.

Figure 3 shows a plot of the various combinations of temperature and depth of discharge for the references used in Tables 1, 2, and 3. In most instances, the reference associated with a specified point in the plot can be easily identified by referring to the appropriate table for nickel-cadmium, silver-cadmium, or silver-zinc cells.

Failure Analysis Procedures

In the operational life tests described in the preceding paragraphs, analyses of the failed cells are important for identifying the failure determinants, which are defined below. Such studies lead to improvements in cell design and manufacture which result in prolonged life.

TABLE 1. EXPERIMENTAL CONDITIONS USED IN THE LIFE TESTING OF NICKEL-CADMIUM CELLS

Testing Facility	Contract No., Program Duration	Cell Capacity, amp-hr	Testing Variables		References (b)	
			Cycle (a)	Temperature, C		
Battelle-Columbus	AF 33(615)-3701, 1966-1969	20	Simulated synchronous and polar orbits 50/40 min	25	40, 80	1
Eagle-Picher	Air Force SSD, Lockheed Missiles, USAERDL, 1960-63	36		60	25	2
General Electric	--	--	55/35 min; or 1 or 2 discharges per week or 7-3/4 hr charge of total 10-3/4 hr cycle including rest period after discharge	0, 25, 40 0, 25, 40 0, 25, 40	21 10, 25, 50, 75 to 0.9 v	3
Gulton	(1962)	--	65/35 min	9, 25, 49	36 at 9 and 49 C; 36, 58, 70 at 25 C	4
Gulton	(1961)	20	55/35 min	25	70	5
Gulton	1961-1962	--	65/36 min	-15, 9, 32, 43	36	6
Inland Testing Lab, Cook Electric	AF 33(616)-7529, 1960-1964	12	55/35 min	-34, -18, 24, 49	25, 50, 60, 75	7
Inland Testing Lab, Cook Electric	AF 33(616)-7529	12	55/35 min	-34, -18, 24, 49	25, 50, 60, 75	8
Inland Testing Lab, Cook Electric	S/A-1, 1960-1964	20	55/35 min	-10, 5, 25, 35	25, 50, 75	9
Inland Testing Lab, Cook Electric	AF 33(657)-8450 S/A-1	20	55/35 min	-10, 5, 25, 35, 50	25, 50, 75	
Inland Testing Lab, Cook Electric	AF 33(657)-8450 S/A-2					
Inland Testing Lab, Cook Electric Martin Marietta	1962-1964 NAS 5-1048	3.5, 6.0	60/40 min	-10, 25, 50	10, 25, 40	--
QEL, NAD, Crane	NAS 5-3027, 1963-1966	6	Variable	25	25, 50, 100	10
QEL, NAD, Crane	W11, 252B	6	65/35 min	10, 25, 40	50, 100 every fifth cycle	11
QEL, NAD, Crane	W11, 252B	3 to 50	55/35 min	0, 25, 50/40	15, 25	12
QEL, NAD, Crane	W11, 252B, 1963-1965	3 to 20	55/35 min	0, 25, 50/40	15, 25 at 0 and 50/40 C; 25, 40 at 25 C	13
QEL, NAD, Crane	W11, 252B, 1963-1966	3 to 20	55/35 min 150/30 min	-20, 0, 25, 50/40	25, 40 at -20 and 25 C; 15, 25, 40 at 0 C; 15, 25 at 50/40 C	14
QEL, NAD, Crane	W11, 252B, 1963-1967	3 to 20	55/35 min 150/30 min	-20, 0, 25, 50/40	25, 60 at -20 C; 15, 25, 60 at 0 C; 15, 25 at 50/40 C; 25, 40 at 25 C	15
Royal Aircraft Establishment (England)	1965	3	60/30 min	-10, 0, 20, 40, 50	10	16

(a) Charge/discharge time.

(b) Source: Table 4.

TABLE 2. EXPERIMENTAL CONDITIONS USED IN THE LIFE TESTING OF SILVER-CADMIUM CELLS

Testing Facility	Contract No., Program Duration	Cell Capacity, amp-hr	Testing Variables			References (b)
			Cycle (a)	Temperature, C	Depth Discharge, percent	
Boeing	NAS 5-2155	12	Simulated 300-mile orbit 65/35 min	-10, 20, 40 -10, 20, 40	35 25, 35, 50, 65	17
Gulton	1961	3	65/35 min	25	25, 35, 50, 65	5
Gulton	--	6	55/35 min	25	20	18
Inland Testing Lab, Cook Electric	Air Force, 1960	--	55/35 min 85/35 min	-29, 25, 49 25	17, 33 50	7
Inland Testing Lab, Cook Electric	AF 33(616)-7529 AF 33(616)-7529 S/A-1,	15	55/35 min	-10, 5, 25, 35, 50	25, 50, 75	8
Inland-Testing Lab, Cook Electric	1960-1964 AF 33(657)-8450 AF 33(657)-8450 S/A-1, -2, 1962-1964	15, 20	85/35 min 22.8/1.2 hr	5, 25, 35, 50 5, 25, 35, 50	25, 37.5, 50, 75 25, 50, 75	9
QEL, NAD, Crane	W11, 252B	3 to 300	23/1 hr 71/1 hr	25	25, 40	12
QEL, NAD, Crane	W11, 252B, 1963-1965	5, 12	23/1 hr	0, 25, 40	20, 50	13
QEL, NAD, Crane	W11, 252B, 1963-1966	3 to 12	60/30 min 23/1 hr	-20, 0, 25, 40	25, 60 at -20 C; 20, 25, 40, 50, 60 at 0 C; 16.7, 20, 25, 40 at 25 C; 20, 50 at 40 C	14
QEL, NAD, Crane	W11, 252B,	3 to 12	1-1/2, 8, and 24 hr cycles	-20, 0, 25, 40	25 at -20 C; 20, 25, 40, 50 at 0 C; 16.7, 20, 25, 27, 30, 40, at 25 C; 20, 50 at 40 C	15
Various	USAERDL	--	55/35 min 60/40 min 65/35 min 85/35 min 18/2 hr 22.8/1.2 hr	-29, -12, 25, 49 -7, 27 25 5, 25, 35, 50 27 5, 25, 35	17, 33 10 25, 35, 50, 75 25, 50, 75 100 25, 50, 70	19

(a) Charge/discharge time.

(b) Source: Table 4.

TABLE 3. EXPERIMENTAL CONDITIONS USED IN THE LIFE TESTING OF SILVER-ZINC CELLS

Testing Facility	Contract No., Program Duration	Cell Capacity, amp-hr	Testing Variables			References(b)
			Cycle(a)	Temperature, C	Depth of Discharge, percent	
Douglas Aircraft Co.	--	1, 4	30/30 min 60/30 min 60/30 min	25, 100, 125 135, 145 25	15 35	25 20
General Electric	JPL 952121, NAS 7-100 (prime)	7				
General Motors	AF 33(600)-41600	25	85/35 min	-1, 24, 38	21, 30, 40	21
General Motors	AF 33(600)-41600	37	85/35 min	10, 27, 38	25	22
General Motors	JPL 950177	25	85/35 min	125	8, 21	23
General Motors	NASw 6 (prime) AF 33(600)-41600, 1961	13 to 48	85/35 min	-1, 25, 38	21, 29, 40.5	24
Inland Testing Lab, Cook Electric	(Air Force, 1960-)	25	22.8/1.2 hr	5, 25, 35, 50	25, 50, 75	7
Inland Testing Lab, Cook Electric	AF 33(616)-7529 AF 33(616)-7529	25	85/35 min 22.8/1.2 hr	5, 25, 35, 50 5, 25, 35, 50	25, 37.5, 50, 75 25, 50, 75	8
Inland Testing	S/A-1, 1960-64 AF 33(657)-8450 AF 33(657)-8450	25	85/35 min 22.8/1.2 hr	5, 25, 35, 50 5, 25, 35, 50	25, 37.5, 50, 75 25, 50, 75	9
QEL, NAD, Crane	S/A-1, -2, 1962-1964 W11, 252B, 1963-1965	12 to 40	150/30 min 23/1 hr	25 25	40, 42 40, 42	13
QEL, NAD, Crane	W11, 252B, 1963-1964	12 to 40	23/1 hr	25	40, 42	14
QEL, NAD, Crane	W11, 252B, 1963-1967	12 to 40	150/30 min 23/1 hr	25 25	40, 42 40, 42	15

(a) Charge/discharge time.

(b) Source: Table 4.

TABLE 4. LISTING OF REFERENCES USED IN TABLES 1, 2, AND 3

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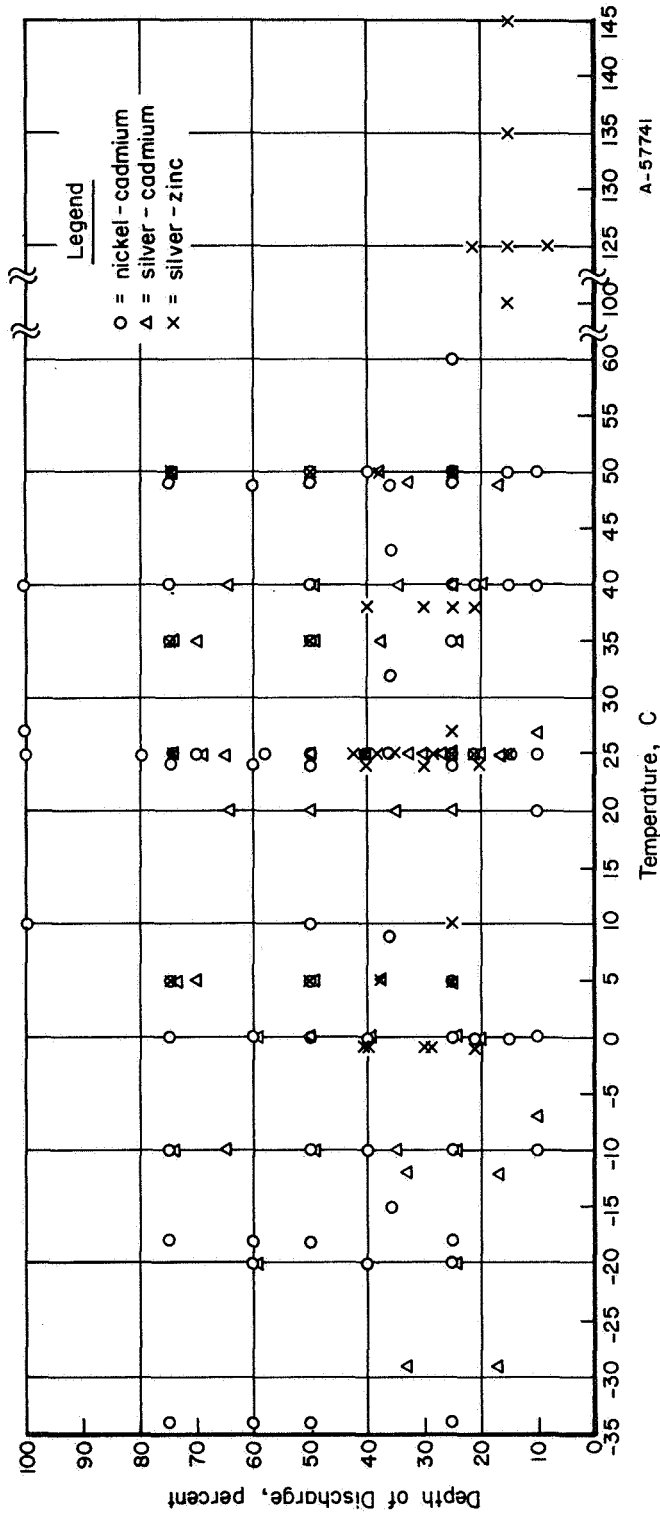


FIGURE 3. VARIOUS COMBINATIONS OF TEMPERATURE AND DEPTH OF DISCHARGE USED IN THE LIFE TESTING OF SPACECRAFT CELLS

Simple failure analysis procedures were used in the Inland Testing Laboratories program, and more sophisticated procedures, with a high degree of standardization were used in some Quality Evaluation Laboratory, Crane(6, 7), and other(8) programs. More recently special procedures for the failure analysis of silver-zinc and nickel-cadmium spacecraft batteries have been devised by Battelle's Columbus Laboratories.(4, 9) The procedures consist of three main parts patterned after medical examinations and autopsies. First, there are instructions to record the previous history and physical condition of the cell. These include visual observations, determination of weight, presence of cracks, electrolyte leakage, and internal short tests. Second, there are instructions to determine the electrical characteristics of the cells. These instructions call for performance tests and capacity determinations, for example. Third, there are instructions for cell disassembly and examination to determine the conditions of the electrodes, separators, and other internal cell components.

The failure mode is known from the failure history of the cell, so the purpose of the failure analysis procedure is to identify the failure determinant. The failure analysis procedure is not designed to identify failure mechanisms, although some of these mechanisms may be inferred from the observations and measurements made.

Several terms are used in the above paragraphs which have been given a precise meaning.(4) These definitions were found necessary because of the vague and ambiguous manner in which these terms are used in the literature. These proposed definitions are listed below because they are believed sufficient to include meanings given to terms such as failure causes, characteristics, modes, mechanisms, analyses, reasons, antecedents, factors, fashions, way, symptoms, and similar phrases.

Failure: The failure of a secondary cell is its inability to deliver on discharge, or to accept on charge, a preselected quantity of electrical energy under a specified set of environmental conditions. Thus, if the user decides that the electrical parameters are outside of desired limits, the cell does not "work", and is said to have failed.

Failure Mode: The failure mode is a particular manifestation of failure such as a lower voltage than desired on discharge. Failure modes have dimensions of the physical quantity, voltage, current, and/or time, that went out of tolerance.

Failure Determinant: The primary cause of the failure mode is defined as failure determinant. Thus, the failure determinant is an immediate cause for the voltage, current, and/or time going out of tolerance. For example, a failure mode of low discharge capacity (current and time out of tolerance) may be the result of loss of active material, the failure determinant. The word "determinant" is chosen because of its preferred dictionary meaning: "A cause that fixes the nature of what results as an outcome".

Failure Mechanism: These are fundamental physical or chemical processes which contribute to producing the failure determinant. A knowledge of the mechanisms is desirable for understanding cell failures, but knowledge of the failure mechanisms is not necessarily essential in a failure analysis procedure, which usually seeks failure determinants.

Failure Analysis Procedure: A failure analysis procedure comprises a collection of physical, visual, electrical, and/or chemical tests arranged in such a manner as to lead to the elucidation of the determinants of a failure mode.

In summary these definitions form a hierarchy in which the failure mechanisms give rise to failure determinants which lead to failure modes and thus describe failure. The definitions describe a direct cause and effect relationship between each level in the hierarchy. This hierarchy should be taken as a structural description of possible failures. The different levels in the structure may be used to interpret failure according to the level of sophistication desired.

In the Crane Reports, a written description is given of the failure analysis procedures applied to failed cells. Waite and Epstein⁽¹⁰⁾, in reducing the operational life data for empirical analysis, included a list of the failure characteristics. This list of 21 characteristics for nickel-cadmium cells is given in Table 5. It should be noticed that this list contains both failure modes and failure determinants, and is thus an example of the ambiguity in reporting which has occurred with failure analysis. Items A and B in Table 5, for example, are failure modes, but most of the other characteristics are difficult to relate directly to electrical parameters and thus do not fit into the hierarchy of causes and effects.

TABLE 5. SUMMARY OF THE FAILURE CHARACTERISTICS FOR NICKEL-CADMIUM CELLS OBSERVED IN THE Q.E.L. CRANE TEST PROGRAM⁽¹⁰⁾

(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, bulge, convex side(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
(S)	Cell blew up
(T)	Circuit: short, open
(U)	High voltage charge

Under Contract AF 33(615)-370, Battelle's Columbus Laboratories reviewed much of the literature on failure analysis tests⁽⁴⁾, and using the background information given above came to the following conclusions. Among nickel-cadmium batteries, or cells tested beyond 4000 charge/discharge cycles, most failures resulted from mismatched voltages, memory effects, or internal shorts. Practically all failed cells showed evidence of high internal pressure, such as bursting, loss of electrolyte through leaks, and bulged cases. Many of the cells which failed because of memory effects could be restored to operational use by deep cycling, such as during the determination of the capacity of the cell, or during a check for internal shorts.

With life tests for silver-zinc cells, excessive pressure and bursting were also evident in reported failures, but the most common failure determinants were internal shorts and loss of negative electrode capacity.

A summary of published failure modes is given in Table 6. The table shows a more definitive set of failure determinants, with less chance of ambiguous interpretation. The newer terminology is suggested as an improvement over the listing and terminology used in Table 5. In Table 6, six of the more important failure determinants are listed, in comparison with the 21 failure characteristics listed in Table 5.

Because of the differing electrical and physical characteristics of the various types of electrochemical energy conversion devices, it would be unwieldy to devise one failure analysis procedure applicable to all types. Different procedures for different cell types are, therefore, desirable. Standardization of each procedure will then have the advantage that results will be comparable among the different manufacturers.

Other Testing Methods

Testing methods applicable to spacecraft battery evaluation also include the so-called acceptance tests and screening tests. It is customary before starting any operational, or accelerated life test to perform certain tests to insure that the batteries are of high initial quality and possess desirable characteristics. It is these tests which are usually referred to as acceptance and/or screening tests. This relationship is graphically shown in Figure 4.

Because these tests are usually tailored to each individual application and to each individual cell, general descriptions of the tests are not easily given. Therefore, only the distinction felt to hold between the tests and the general nature of these tests will be described. The reader is directed to the extensive collection of references in the bibliography for details of individual test procedures which have been used.

Acceptance tests are usually performed in order to insure that the cells satisfy the manufacturer's specifications. Acceptance tests often involve physical examination. Such examinations may include the taking of X-ray photographs and checking the dimensions of the cell. The tests may also involve the disassembly of sample cells to check on the quality of the manufacturing process.

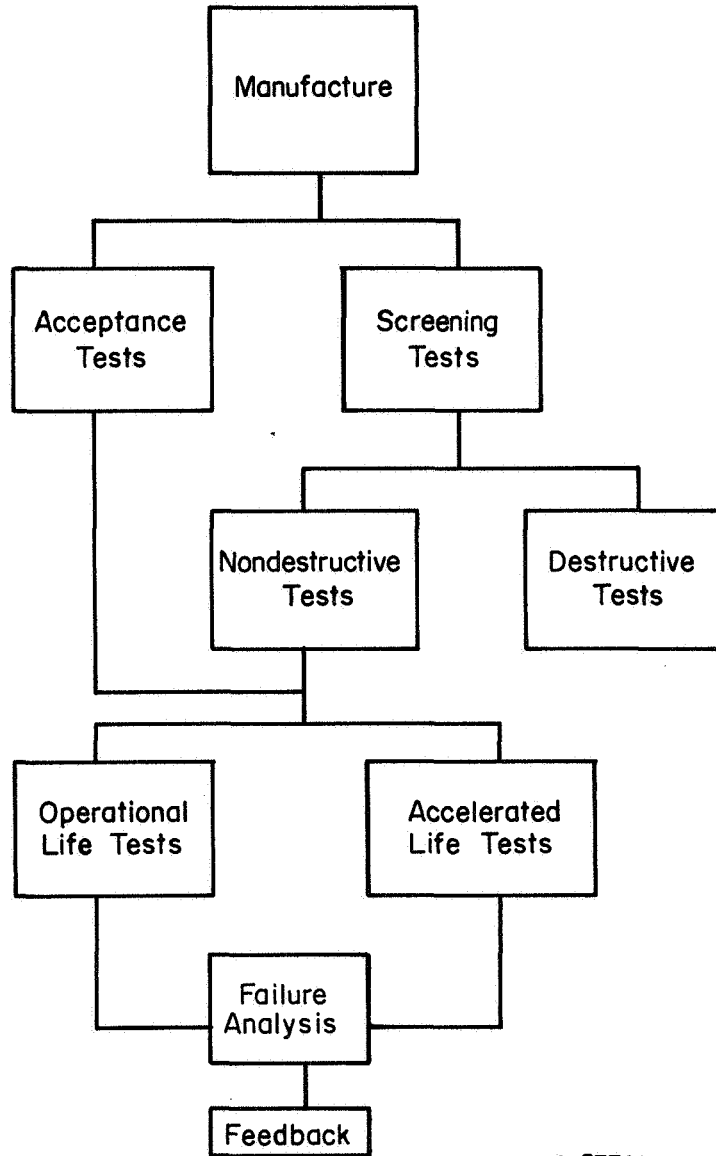
Screening tests are often intermediate between acceptance tests and operational or accelerated life tests. For example, an accelerated life-test procedure may require that all cells, before the test is run, are matched as closely as possible. This entails

TABLE 6. SUMMARY OF AN ANALYSIS OF REPORTED BATTERY FAILURES^(a)

Failure Mode ^(b)			Failure Determinant	Possible Failure Mechanism
Charge	Charge/ Discharge	Discharge		
<u>Nickel-Cadmium</u>				
+V		-V	Memory	Temporary passivation
	$+\left(\frac{V}{I}\right)$		High impedance	Material migration, electrolyte loss
	$-\left(\frac{V}{I}\right)$		Shorts	Separator deterioration, inferior quality control
+V, +I		-V, -t	Leaks, bursting	Overcharging
	$-(I \times t)$		Loss of active material	Permanent passivation
	$-I, \pm t, -V$		Defective structure, impurities	Side reactions, inferior quality control
<u>Silver-Zinc</u>				
	$-(I \times V \times t)$		Loss of active material	Migration, passivation
	$-\left(\frac{V}{I}\right)$		Shorts	Dendrite formation, separator deterioration
+V		-V, -t	Leaks, bursting	Overcharging
-I		-V, -t	Defective structure, impurities	Side reactions, inferior quality control

(a) From Technical Report AFAPL-TR-67-48, Part II, Reference (4).

(b) Failure mode indicates undesired value of current (I), time (t), or voltage (V). Plus sign (+) indicates excessive magnitude; minus sign (-) indicates deficient magnitude.



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FIGURE 4. VARIOUS FORMS OF SPACECRAFT BATTERY TESTING RELATED TO ACCELERATED LIFE TESTS AND FAILURE ANALYSIS PROCEDURES

the performance of acceptance tests on the type of cell selected, then further procedures such as cell conditioning and controlled charge/discharge cycling to enable the electrical characteristics of the cells to be matched as closely as possible. Using this screening test, atypical cells can be screened out and could not adversely affect any subsequent tests. Many references to reliability tests may also be found. In essence, all operational life tests are reliability tests for the chosen set of conditions, because both kinds of tests determine life of the cells.

Various other tests have been devised for more specific purposes and are described in the literature. Some of these, such as the "upside-down" test and tests-to-failure, are briefly described below to further indicate the scope of the methods used in battery testing.

The "upside-down cycle" test for nickel-cadmium cells has been described by Sherfey.⁽¹¹⁾ It is an operational life test based upon a 65/35 minute charge/discharge cycle. The characteristic which sets it apart from operational life tests already described is a "bleed" cycle every fifth cycle. In this bleed cycle a low value resistor is connected across each cell and left there for the next complete cycle so that the cell is almost completely discharged. The main advantage of this technique would seem to be that cell memory effects are avoided by the reconditioning which occurs. Although longer cycle life was shown by comparison with other data, no controls were run to justify this conclusion.

The upside-down cycle tests were performed at 10, 25, and 40 C; shorter cycle lives were obtained at each higher temperature. If the failure mechanisms remain the same with change in temperature, then the basis for a valid accelerated test may exist. However, because the upside-down cycle procedure conditions the cell, a similar set of experiments without the bleed cycle would yield reduced cycle life and would constitute an accelerated test provided the failure mechanisms are the same.

Step-stress tests to failure have been recommended in the past by the U.S. Army.⁽¹²⁾ The advantage of the step-stress test-to-failure concept, as compared with operational life tests, is stated to be the fact that a high reliability can be established with reasonable confidence on the basis of small samples. A step-stress test-to-failure involves submitting a test specimen to a programmed incrementally increased stress until failure occurs. A lower limit of stress below which the probability of failure is sufficiently small can be selected by using appropriate means and standard deviations of the data generated by such tests. These tests, as was described for thermal batteries by Langlie⁽¹²⁾, are thus a form of reliability test. However, because of the time compression obtained through using increasingly severe levels of stress, an accelerated life test framework may also exist.

The disadvantage of the step-stress method (or the corresponding continuously increasing stress method) is that often there is little proof that the same failure mechanisms occur at operational levels as at the higher stress levels. The validity of the threshold value of the chosen stress level is then open to question.

Factorial designs and fractional factorial designs have been introduced into the testing of electrochemical energy conversion devices^(13, 14) for evaluating improvements in design, construction and materials, and in the testing of solar cells for space application⁽¹⁵⁾. Fractional factorial designs may be used to determine the minimum number of tests required when a large number of independent variables is involved and yet obtain

useful data. For example, in the preliminary screening of various sealed, silver-zinc cell components⁽¹⁴⁾ only 200 cells were required to evaluate approximately 25 different separator systems plus several levels of concentration of four negative electrode binders, three surfactants, and three "voltage additives". In addition, the experiments with these cells also enabled the zinc to silver ratio, zinc to zinc oxide ratio, positive electrode density, electrolyte concentration and quantity to be evaluated. The time and cost saved in the above screening experiments can be readily appreciated.

The drawback with fractional factorial designs is that little information is obtained on some of the interaction effects on life. Fractional factorial experimental designs may achieve a reduction in the number of cells required for testing. However, the price for this reduction is an increased risk of failing to get information on important interactions. Further discussion of the advantages and disadvantages is given in the Proceedings of the NASA Battery Workshop.⁽³¹⁾

Various other tests have been applied to spacecraft cells. Some have been designed to measure specific characteristics. For example, double-layer capacities⁽¹⁶⁾ and internal impedances or resistances⁽⁴⁾ have been measured in situ in efforts to characterize electrodes and cells. Changes in surface area and pressure changes, including evolved gas analysis⁽¹⁶⁾, have also been measured to help describe the operating characteristics. Empirical tests, such as applying an a-c pulse to an operating cell⁽¹⁷⁾ to screen good from bad cells, have also been used.

Pulse techniques, or other methods for measuring fast transients, such as those described in the preceding paragraph, appear to be advantageous for an accelerated test procedure for several reasons. First, because of the short time duration of the pulse and its possible intermittent application, the volume of data required for analysis would be relatively small. Second, the time response to the transients might give some convenient measure of the rate of degradation of quality. If a large or small hysteresis occurs in the response to a pulsed stress and is found to be highly correlated with the rate of degradation of quality, then this would appear to be a useful criterion in an accelerated test. Third, a short accelerated test might be obtained at a low average stress level by applying pulsed stresses of relatively more severe nature and analyzing the resulting transients. However, the problem remains of determining whether the failure mechanism is unchanged.

SECTION 2. ACCELERATED LIFE TESTS

Introduction

A review of the literature pertaining to accelerated life testing of secondary spacecraft batteries reveals that little is actually known of the processes which are associated with the rates of degradation, or of the phenomenological laws associated with degradation processes. In the past, an operational life test was sometimes called an accelerated test if the operating conditions gave a shorter cycle life. Having found, by trial and error usually, those operating conditions which increased the rate of degradation, extrapolations were then made to normal conditions under the assumption that the degradation processes did not change. Until quite recently, this approach existed in many laboratories. A re-evaluation of the whole problem of accelerated testing of spacecraft batteries is now in progress. This re-evaluation has resulted from: (1) the need for accelerated tests which could be interpreted phenomenologically and unambiguously; and (2) recent advances in the theory of accelerated testing techniques developed for non-electrochemical energy storage devices.

This section of the report on accelerated testing summarizes previous work in the field of electrochemical energy storage devices. The inadequacies of this work are indicated. This section also includes a review of general theories of accelerated testing of nonelectrochemical devices. A review of the use of data reduction and analysis as a predictive tool in accelerated testing concludes this section.

Several key terms are defined and used in the following paragraphs. The definitions are taken from a report on failure mechanisms and accelerated life testing prepared for the Air Force.⁽¹⁸⁾

A secondary cell is assumed to possess a certain "quality" which is measurable in quantitative terms. It is further assumed that over a sufficiently long time the quality of a cell will degrade. A widely used description of battery quality is the guaranteed life. Thus, a battery with a 3-year guarantee is generally taken to have a higher initial quality than a battery with a 2-year guarantee. Such a general description of quality, however, is not suitable for accelerated life tests. For the description, or definition, to be suitable it must be conceptually possible to measure the quality of a battery at any time, and practically possible to measure the quality at least within the charge or discharge cycles. Such within-cycle measurements can then be used to compare the quality from one cycle to another. The changes of the within-cycle quality over a period of many cycles can then be used to determine the "time rate" or "cycle rate" of "degradation of quality". It has been suggested that at least three different definitions of quality based upon the above considerations may be necessary to describe the characteristics of a secondary cell.⁽¹⁸⁾ These three qualities are voltage quality (Q_v), temperature quality (Q_t), and pressure quality (Q_p). These three qualities were suggested because changes in voltage, temperature, and pressure are observed in each cycle during cell operation.

For the purposes of this report, a high-quality battery is defined as a battery which exhibits small changes in measurable parameters during closed circuit operation within a cycle which begins with the closing of the circuit.

Mathematically, quality may be expressed as

$$Q_{\pi} = \frac{1}{\Delta\pi \times n}$$

where π is the voltage, temperature, or pressure parameter chosen for measurement and n is the hourly rate at which the cell is charged or discharged. By including n in the definition of quality, the rate of charge or discharge is related to battery size.

One consequence of the above definition of quality is that those cells which allow the highest C/n rates of charge or discharge will have the highest quality. Therefore, silver-zinc cells will have a higher initial voltage quality, Q_v , than nickel-cadmium cells. This follows because, for a given change in voltage, ΔV , the silver-zinc cells will discharge at a smaller hourly rate, n . However, the number of cycles required for a given amount of degradation of quality depends also on the cycle-rate of change of quality and not only on the initial quality.

At any given time the operation of a secondary cell is assumed to be associated with a certain "level of stress". A report by McCallum, et al, (18) states that a "stress" for a secondary cell is always expressible as an intensity factor of some form of energy. The report indicates how stresses can be distinguished from strains (expressed as a capacity factor), and concludes that there are four principal stresses associated with the operation of a battery. These four stresses are temperature, voltage, gas pressure (as a mechanical force) and mechanical forces introduced by cell construction, e.g., by the use of retaining plates or electrode structures.

Higher rates of degradation are assumed to occur at higher levels of stress. In an acceptable accelerated life-test procedure, the mechanisms of "aging", associated with the time rate of degradation of quality, must be the same at both the high level of stress and the normal level of stress. Also, failures should occur because of the gradual degradation of quality, and not by some instantaneous (catastrophic) means. In the latter case, interpretation and extrapolation of the test results may be very difficult, if not impossible.

Although various approaches to accelerated life testing are possible, there are several assumptions common to most of these approaches:

- (1) The quality of a component varies over time, and after the elapse of a sufficiently long time the quality degrades
- (2) The time rate of degradation of quality depends on the level of stress experienced by the component during its operating life.
- (3) Higher degradation rates occur at higher levels of stress
- (4) The time rate of degradation of quality will eventually lead to failure by degradation of quality.

Accelerated tests are performed in order to establish "acceleration factors" in a short period of time that permit degradation rates at low levels of stress to be predicted by using degradation rates obtained at higher levels of stress. In simple cases, the "acceleration factor" is equal to the ratio of the rate of degradation at the high stress to

the rate of degradation at normal stress. Accordingly, the larger the acceleration factor the more efficient and desirable the accelerated life test, provided the dominant failure mechanism is the same for both the accelerated and normal operating conditions.

Accelerated Testing of Electrochemical Energy Conversion Devices

The main source of references concerning the accelerated life testing of spacecraft batteries is the Battery Workshop Proceedings.⁽¹⁴⁾ This workshop was sponsored by the National Aeronautics and Space Administration, and more than half of the speakers presented papers dealing with information related to accelerated testing of batteries. Three generalities may be extracted from the papers:

- (1) Any accelerated life test should hasten only normal failure processes; that is, the test should not change the primary causes of failure
- (2) An accelerated life test should be related to service conditions to facilitate interpretation of the results and to facilitate application of the results
- (3) Methods for accelerating operational life tests are uncertain because of a lack of knowledge of the principles involved in testing such complex devices as spacecraft batteries and also because of a lack of knowledge of the aging mechanisms and their physics and chemistry.

In many life tests, several variables are often associated with relatively short cycle life. These variables include increases in temperature, load or current, depth of discharge, and rate of charge or discharge. Higher levels of these variables are usually identified with the higher levels of stress discussed earlier. Because increasingly high levels of these variables appear to shorten cell life with no apparent change in failure determinants, and because some interpolation and extrapolation of the data to other levels of "stress" are possible, the tests are often described as being accelerated life tests. For these reasons, it is convenient to discuss the literature in terms of those variables which are found to affect the cycle life.

Temperature increases sometimes lead to shortened cycle life and constitute the most commonly used stress. Some of the reported tests have been analyzed according to an Arrhenius-type model.⁽¹⁹⁾ This represents a certain degree of sophistication over other methods of analysis.⁽²⁰⁾

In a research project concerned with the development of improved sealed nickel-cadmium batteries⁽²⁰⁾, Gulton Industries has reported on operational life tests performed at elevated temperatures. It is reported that the "accelerated elevated temperature cycling" of three-plate cells, made with candidate separator materials, appears to be a very informative test. Where shorts appear in the elevated temperature test, the nature of the separator defects appears to be the same as those encountered in the failure analysis of cells failing under normal operational conditions. Thus, it may be assumed that separators showing a small probability of failure on the accelerated life test would also show a small probability of failure during continuous charge/discharge cycling.

Willihnganz, in a paper at the Battery Workshop⁽²¹⁾, emphasized some of the generalities given above. Although he describes the accelerated testing of lead-acid automobile and telephone batteries, his remarks apply to any accelerated life test procedure, and are paraphrased as follows: First, in setting up life tests it is desirable to have prior knowledge of why and how the battery will fail. Any accelerated test must then cause similar batteries to fail by the same mechanism. Second, if the service conditions to which the batteries are to be subjected are changed, then the tests must be altered accordingly. Third, the results of accelerated tests must be compared with the results of field tests under normal levels of stress to insure that the failure modes and determinants are the same.

A linear relationship between the logarithm of cycle life and the reciprocal of absolute temperature is qualitatively described by Willihnganz in his paper on the testing of telephone batteries⁽²²⁾; extrapolation to a temperature of 25 C, to predict life, is said to be possible. Because the normal life of telephone batteries is about 20 years, such an extrapolation to normal temperatures is desirable.

Biddick, at the Battery Workshop⁽²³⁾, also reported upon work at the Bell Telephone Laboratories. Studies were made of the growth of the positive plates in lead-acid telephone batteries as a function of increasing ambient temperature. Over a test period of about 20 years⁽²⁴⁾, and in later studies⁽²²⁾, the rate of growth of the positive plate was found to nearly double for each 10 C incremental increase in temperature at a given overpotential of the electrode. At about 82 C, the growth rate is 60 times faster than at room temperature.⁽²¹⁾ Thus, 20-years of growth can be obtained in 120 days. Furthermore, the failure mode and failure determinants appear to be the same for the accelerated test run at an overpotential of 75 mv and the normal operational life test. This seems to be an ideal test for lead-acid, stationary, emergency batteries. An acceleration factor of 60 is very large indeed. It appears that no other sources have reported validated acceleration factors of this magnitude.

Screening tests of prototype silver-cadmium cells at elevated temperature have been described by Scott.⁽²⁵⁾ The results were limited and the author declined to make any extrapolation or interpolations based on only two measurements (room temperature and 60 C). It may be inferred that the 60 C temperature was chosen in order to reduce the test time, although this was not elaborated.

The effects of temperature increases on chosen variables were described semi-quantitatively in a paper by Bowers on the non-destructive testing of silver-zinc cells.⁽²⁶⁾ He stored the charged batteries for 3, 6, and 12 months at ambient temperatures of about 21, 43, 50, and 60 C. The amp-hour capacity was measured and also calculated from the silver and silver oxides content. At 21 C, there was little change in chemical composition or amp-hour capacity over the year. Similar observations were made for the tests at 43 C. At 50 C, chemical changes in the silver electrode were observed because of silver (II) oxide decomposition. Also at 50 C, there was a drop in amp-hour capacity from about 105 to about 95 after 1 month of storage. At 60 C, after 1 month of storage, the loss in measured capacity increased to approximately 30 percent, and after 6 months of storage there was practically no silver (II) oxide left in the silver electrodes.

If the mechanism for silver (II) oxide decomposition and the loss in measured capacity can be shown to be the same over this temperature range, then there exists the possibility of designing an accelerated life test based on these observations. However, at about 50 C or above, Bowers pointed out that physical degradation of the case material also occurred.⁽²⁶⁾ This fact would impose an upper limit on the range of selected temperatures.

Chreitzberg⁽¹⁹⁾ also performed experiments similar to those of Bowers and measured the loss in amp-hour capacity of silver-zinc cells stored at temperatures in the range of approximately 0 through 50 C. Plots of the logarithm of the measured capacity versus storage time at each temperature level were essentially linear, although there was not much separation between the curves for the 0 and 15 C data. For cells stored between about 15 and 50 C the results obeyed an Arrhenius-type relationship. That is, when a straight line plot was obtained the slopes of the linear plots of log capacity versus time were plotted against the reciprocal at absolute temperature. Chreitzberg stated that there was some theoretical justification for the slope of log capacity versus time to be proportional to the rate constant for the reaction associated with the capacity loss. The slopes of the Arrhenius-type plots were found to be in the range 20.5 - 22.5 kcal/mole. From this, Chreitzberg concluded that probably there was only one overall activation energy for the reactions which occurred in silver-zinc cells of differing construction.

Chreitzberg's analysis of his experiments in terms of a physical model using an Arrhenius-type model suggests that a mathematical and phenomenological model for the accelerated life testing of spacecraft batteries may be possible. Chreitzberg concluded that the cycle life of secondary cells could be estimated from such storage tests with acceleration factors that would probably lie in the range of 2 to 3.

In contrast with this optimistic statement, the above discussion of storage temperature as a level of stress should be appended by the following statements by Sulkes⁽¹⁴⁾ related to charge/discharge cycling at elevated temperatures:

"When cycling is done at an elevated temperature in an attempt to speed testing, the resultant cycle life may be increased if poor charge acceptance is the cause of failure, or decreased if the failure mechanism is silver attack on the separator. Increasing the number of cycles per day to speed testing may shift the failure mechanism from shorting, to capacity loss caused by negative shape change. It is clear, therefore, that in most cases the testing of experimental silver-zinc cells cannot be accelerated . . ."

As a reply to this pessimistic view of accelerated testing, it appears that the following argument needs to be considered. Suppose that a battery is operated under a reference (normal) set of conditions. Under these normal conditions, it is further supposed that although several failure mechanisms occur simultaneously, only one of these mechanisms dominates. That is, failure will result from exactly one of these competing underlying failure mechanisms, and the dominant mechanism is completely determined by the operating conditions. Now suppose that the operating conditions are changed to achieve an accelerated test. If the change is sufficiently small, it is asserted that the dominant relation will probably not be changed so that failure will occur for the same reason as that associated with normal operating conditions. If the dominant relation were changed for any, arbitrarily small, change from the normal operating conditions, it would suggest that the two competing failure mechanisms change relative importance exactly at the operating conditions. Because this is unlikely, it follows, in general, that some change can be made to achieve an accelerated test. True, the change may be so small that the reduction in test time may not be impressive. However, the argument is intended to show that some acceleration is obtainable. The real question is how much acceleration is possible without changing the dominant failure mechanism.

The rate of discharge or charge is mentioned several times in the literature as one possible variable for controlling an accelerated life test. Biddick describes tests on

nickel-cadmium cells in which the rate of charge/discharge cycling was varied.⁽²³⁾ He found that changes in the observed amp-hour capacity with cells cycled eight times a day differed little from cells cycled two times a day. Moreover, in both cases there was a gradual loss in capacity of the negative plates. Biddick thus obtained an acceleration factor of four, and concluded that the rate of degradation was a function of the number of cycles, not time, in these experiments. This latter conclusion was also partially confirmed by the work of Scott for nickel-cadmium cells.⁽²⁵⁾ Scott concluded that the rate of degradation is proportional to the number of cycles provided a C rate of charge and discharge is not exceeded.

With silver-cadmium cells, high rate cycling using C/2.5 currents also caused a decrease in the measured capacity.⁽²⁵⁾ However, because of decreasing charging efficiency at this rate of cycling, the voltage-time characteristics also changed because the upper discharge plateau became non-existent. Although physical interpretation of the results was thus impeded, the method of increasing the number of cycles per unit of time was found more satisfactory than increasing the actual C rates of charge and discharge.

Recent work by the General Electric Company on a reduced gravity battery test program for silver-zinc cells has described a preliminary accelerated life test using rapid cycling with selected depths of discharge as the accelerating stress.⁽²⁷⁾ The test includes preliminary conditioning of the cell, followed by five consecutive 60/30 minute charge/discharge cycles to 35 percent depth of discharge. Transient capacity and cell voltage measurements were made during the 90-minute cycles. Polarization measurements and discharge-capacity measurements were made before and after each cycle. However, none of the measurements indicated that a desirable rate of degradation of quality could be obtained when the depth of discharge was limited to 35 percent. It was, therefore, recommended that the depth of discharge be increased for future studies.

Depth of discharge has been mentioned elsewhere⁽¹⁴⁾ as an acceleration stress, but successful accelerated life test has not yet been designed utilizing this parameter. Also Belove has suggested that the amount and rate of overcharge should be considered in an accelerated test because overcharge probably represents the greatest proportion of actual battery conditioning on a spacecraft.⁽²⁸⁾

Increasing the battery load⁽¹⁴⁾, current⁽²³⁾, or physical intervention, such as removing all free electrolyte⁽²⁵⁾, have been investigated as possible stresses for accelerating the rate of degradation of spacecraft batteries. However, actual accelerated tests based on these methods have not been reported.

Accelerated Testing of Non-Electrochemical Devices

A wide variety of life tests have been performed on components other than batteries. The areas of electronic reliability and mechanical fatigue contain many representative examples of serious attempts to obtain valid accelerated life tests. In electronics, accelerated tests have been carried out for certain types of resistors, capacitors, transistors, and integrated circuits. A large amount of the fatigue testing of mechanical components is directed toward the determination of stress levels at which the life of the component can be expected to exceed a specified design life. Section (f) of the bibliography contains references to some of these efforts in electronics and mechanical fatigue.

Although many disciplines are confronted with the problem of predicting life in a short time period, it appears that an accepted general approach to accelerated life testing has not evolved. Most tests are so specialized that little information is directly applicable to other components. Consequently, such references are of uncertain value to investigators in other areas.

Minimal Requirements for Accelerated Tests

Many laboratory tests are not carried out for the purpose of predicting the life of a component. Nevertheless, the data obtained from these tests are often relevant to making such predictions, and when this is the case, the tests may loosely be labeled as accelerated tests. In more strict terms, such tests cannot be called accelerated tests unless the following minimal requirements are fulfilled:

- (1) The test conditions involve several levels of stress that are higher than a normal stress level
- (2) Measurements of quality are taken at successive times at each level of stress
- (3) The resulting measurements are analyzed to determine the time rate of degradation of quality as a function of stress level and these results are extrapolated to obtain an estimate of life at the normal stress level.

It is clear that these minimal requirements cannot be met unless the terms, "stress", "quality", and "failure" are properly defined. Such definitions must relate quantities that are both measurable in the laboratory and meaningful in the context of possible physical mechanisms associated with the operation of the component.

Further requirements on accelerated tests are usually imposed in an attempt to insure that the mechanism of failure has not changed at the higher stress levels. The actual methods of data analysis vary widely depending on whether an empirical, statistical, or physical approach is used. (18)

Common Deficiencies of Accelerated Tests

A survey of the literature shows that several common deficiencies are often found in accelerated tests. First, it appears that too little effort is put into the task of obtaining suitable definitions of "stress", "quality", and "failure". It is often assumed that variables which describe the operation characteristics of the device are the same variables as those needed to describe how long the device will last. It is conceptually possible that those variables which indicate the present "quality" of the device may have nothing to do with the prediction of how long the present quality will be maintained in the future. It appears that much more attention should be given to the basic definitions and their associated laboratory measurements in the design of accelerated tests.

A second common deficiency consists of the failure to measure variables that can yield degradation rates as a function of stress level. High precision is required in the measuring techniques in order to detect and measure small degradation rates.

A third common deficiency in accelerated tests results from the use of only one high level of stress instead of a set of higher stress levels. Even if the relevant variables are measured with sufficient precision to yield the degradation rate at a single high level of stress, there is no suitable method of extrapolating this rate to obtain the predicted degradation rate at the normal stress level. At least two different high levels of stress are required to permit a straight-line extrapolation to a normal stress level. More than two levels are required to obtain evidence regarding possible changes in the failure mechanism.

Mathematical and Statistical Theories Related To Accelerated Testing

A component may be subjected to higher-than-normal stresses in several ways. In the "constant stress" approach, the component is subjected a single level of stress and this level of stress is maintained at the same level for the life of the component. In the "step-stress" approach, the component is subjected to an increasing sequence of constant stress levels. That is, after the initial stress level is maintained constant for a specific time interval, a higher level of stress is then imposed for an additional time interval and the process is repeated until the component fails. In the "continuously-increasing-stress" approach, the initial stress on the component is gradually increased until the component fails.

Special methods of data analysis have been developed for these different methods of applying higher stress levels. Data analysis problems of this type have given rise to some literature. Several of these references are included in Section (g) of the bibliography. Also, it should be noted that nearly all of the statistical literature in the area of reliability is relevant to the analysis of accelerated test data. In general, reliability problems are concerned with the prediction of life; accelerated tests simply augment the reliability problem by requiring that the prediction be valid at a normal stress condition for which no test data were taken.

Data Acquisition and Analysis

A review of the literature indicates that previous battery test programs have used rather rigid test designs. Primarily, the data records have served to monitor the functioning of equipment and to identify battery and cell histories. Computers have served mostly to retrieve specific information and to tabulate results. The data have not served as a feedback to improve the test design.

If the physical mechanisms and their laws were well defined, there would be little need to provide a data feedback to the design. However, in the case of accelerated tests, all available information should be used to shorten the test time. Two basic methods are available to provide a shorter test time. One method is based on increasing the rate of the aging process; another method consists of obtaining more information from the test data so that cell life can be predicted using early life measurements. To accomplish the latter, a more flexible approach to data acquisition and analysis must be taken. The data processing capability of the computer permits the search for patterns to detect important deterministic and probabilistic associations within the data to determine behavior cycles, and to relate key parameters to dependent variables. In general, empirical methods are best suited for initial data processing. Empirical methods – in contrast

to the statistical or physical approaches to accelerated testing – do not assume any prior structure in the data. Instead, the empirical approach searches for objective properties of the data. Once identified, these properties are available for the interpretation and exploitation of the statistical and physical approaches. These objective properties of the data structures and some of the empirical techniques used to identify them are described in the following paragraphs.

Empirical Techniques and Data Structure

The general structure of a set of measurements may possess some or all of the following features:

- (1) A frequency distribution of measured values over time
- (2) An association among measured values
- (3) A repetitive cycle, or period, among measured values
- (4) A functional dependence among measured values.

The presence of these general features can be quickly detected on a modern computer. These features provide information on patterns among the measurements. The computational effort required in these tasks virtually exceeds man's capability. But once detected, the observed patterns, in turn, can be further analyzed for both physical and statistical significance to develop quantitative models capable of predicting life.

The field of cryptanalysis appears to offer an existing discipline with methods and procedures for identifying important features of data structure. This results from the fact that much code-cracking work is not done on languages but on numerical information. The cryptanalytical approach includes computerized tools to detect data structure and to eliminate a prodigious amount of human effort.

There are many methods in cryptanalysis for extracting the structure of data. A review of the field suggests that four of these methods are directly related to the four objective features listed above. These four methods may be described in general terms as follows.

1. Distribution Features. The frequency of occurrence of the voltage measurements for a given point in a cycle may be obtained by classifying the measurements into class intervals. The resulting frequency distribution can be used to regroup adjacent class intervals and thereby determine a more appropriate precision. A similar argument holds for each measured variable. If all data measurements (variables and levels of variables) are coded by letters, and the resulting codes are analyzed by a "poly-gram" frequency distribution program, a distinct pattern would be obtained for the measurements. For a non-aging component in a constant environment, this pattern would be invariant over time. If aging occurs, the patterns will change and one can begin to establish a basis for the extrapolation of changes and possibly predict the life of the component. An examination of the patterns may also indicate whether the measurements should be taken more frequently or less frequently. This poly-gram distribution technique is a conventional technique in cryptanalysis.

2. Association Features. The interdependence of variables upon each other is an important data structure in accelerated testing. Consequently, a method is needed which can determine the frequency of occurrence of those combinations of variables which occur most often under certain environmental conditions. Where the number of possible combinations of measured variables is large, a computer is required to make such analysis. With relatively few variables, the poly-gram technique may suffice. With a large number of variables, a more powerful technique, such as the index of coincidences⁽²⁹⁾, must be used, together with proper information encoding.

3. Periodic Features. As the components age, periodic changes in the patterns can furnish a valuable clue for analysis using a more refined statistical or physical method. The Kasiski method is one technique for determining periodic structure.⁽³⁰⁾ This method essentially counts the interval between the poly-gram repeats. From the frequency tabulation of the number variables, the method determines the period of the phenomena. It would appear that proper interpretation of periodic behavior would permit the development of a predictive process earlier in the life of the component.

4. Functional Dependence. The search for more complex relations among the variables can be pursued using a number of tools. Some of these tools are associated with both statistical methods and cryptanalysis, and include the use of Bayes' theorem and the Automatic Interaction Detection (AID) computer program. Bayes' theorem is based on the use of probabilistic relations. The AID program expresses the data structure in the form of a "tree".

In summary, a review of cryptanalytic methods suggests that methods exist to identify the four types of structure described above. It appears that the use of these methods, concurrently with the generation of data, would permit useful feedback to the experimental design. This procedure would greatly improve the efficiency of data taking. Moreover, early detection of patterns and changes in these patterns would permit the early application of statistical and physical methods to obtain predictions of component life.

For example, cryptanalytical techniques have been used to analyze some of the data generated by the Quality Evaluation Laboratory testing programs.⁽²⁾ Indications were extracted from the data (charge-discharge voltage measurements, primarily) which were applicable to predicting life expectancy of the cells on test after about 1 percent of their useful life had been consumed. The computer programs used generated (1) first difference voltage histograms which established the slopes of the charge-discharge curves between the monitoring points, (2) superimposed charge-discharge curves, and (3) frequency counts over set thresholds.

The first set of data indicated which cells show the greatest voltage changes per time increment chosen. There appears to be good correlation between cells which fail and those which show the greatest voltage changes. The second set of data indicate which cells showed deviations in electrical performance from the average performance exhibited. Once again, there is a good correlation between cell failure and abnormal electrical characteristics. The third set of data give the frequency of the excursions of the cell voltage outside limits chosen from observed normal cell performance characteristics. The greater the frequency of excursions outside the limits the more likely a cell is to fail.

CONCLUSIONS

The following conclusions summarize the preceding survey:

- (1) Although the need exists for generally accepted procedures for accelerated testing, such procedures do not exist at the present time.
- (2) Increased sophistication is developing in the use of automatic measuring equipment and computerized data processing for controlling and monitoring life tests.
- (3) Accelerated testing of electronic components and mechanical fatigue tests have generated some diverse literature that is useful to the methodology of accelerated testing of spacecraft batteries.
- (4) In addition to careful definitions of the terms stress, quality, and failure, the greatest single difficulty in accelerating testing consists of obtaining quantitative evidence that the dominant failure mechanisms have not changed under the accelerated condition.

RECOMMENDATIONS

Phase II of this program involves the development of an idealized accelerated test program for space batteries. From the preceding conclusions it is recommended that the ideal test program be based upon the simultaneous use of the empirical, statistical, and physical approaches to accelerated testing. These approaches would (1) permit the gradual evolution of accepted procedures for accelerated testing; (2) increase the use of sophisticated automatic measuring and data processing systems; and (3) allow additional use to be made of the theories and methods reported in diverse applications of accelerated testing to mechanical, electrical, and electrochemical systems. Such an unrestricted approach also allows the development of idealized specifications for the associated solid-state hardware.

The idealizations developed in the Phase II work will then serve as guides for the practical implementation to be arrived at in Phase III of this program. These implementations will be based on the then existing equipment and knowledge of battery technology.

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Many of the tests, and test methods in the literature are not limited to one aspect of cell or battery evaluation, and as such are difficult to classify without undue duplication. However, an effort has been made to divide the references into major groups as follows:

- (a) Quality, acceptance, and screening tests
- (b) Life (operational) tests, including failure analysis tests
- (c) Life (accelerated) tests
- (d) Test instrumentation and implementation
- (e) Data reduction and analysis.

Usually a reference is only given under the heading in which its main subject matter lies, but when a reference is also believed to contribute useful information to another field it is also listed under that heading.

In addition, the bibliography includes references related to the accelerated testing of components other than batteries. These references are classed as follows:

- (f) Life (accelerated) tests for components other than batteries
- (g) Mathematical and statistical theories related to accelerated testing.

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