X-761-73-183
PREPRINT

NASA TM X- 70524

ACCELERATED TEST PLAN FOR NICKEL CADMIUM SPACECRAFT BATTERIES

OCTOBER 1973

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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FOREWORD

This report is an accumulation of several inputs that outline the Accelerated Test Program that is being initiated by NASA/Goddard Space Flight Center at the Naval Ammunition Depot, Crane, Indiana with support by the U.S. Air Force, Wright Patterson Air Force Base. Contributers to the various inputs are identified below. Primary funding support for the program is provided by NASA Headquarters, Office of Aeronautics and Space Technology (OAST) on Work Unit 502-25-58. The interest and guidance of Mr. William H. Woodward and Mr. Ernst M. Cohn of OAST have been instrumental in making the program possible. In addition to the inputs from the contributers listed below, several other organizations have provided assistance, namely, Cryptanalytic Computer Sciences, Inc., Battelle Memorial Institute and the General Electric Company.

Input	Contributing Agency
1. Introduction	NASA/GSFC
2. Cell Design	NASA/GSFC
3. Manufacturer's Acceptance Test	NASA/GSFC
4. Baseline Tests and Post Cycling Tests	NASA/GSFC NAD/Crane
5. Accelerated Test Program	
A. Test Facilities	NAD/Crane
B. Summary of Accelerated Test Design	NAD/Crane
C. Air Force Removal Schedule for Unfailed Cells	USAF/WPAFB
6. Chemical and Physical Analyses	NASA/GSFC
7. Data Analyses	
A. Analysis of Manufacturer's Data	NASA/GSFC
B. Analysis of Base Line and Post Cycling Tests	NASA/GSFC NAD/Crane
C. Outline of Accelerated Test Data Analysis	NAD/Crane
D. Air Force Data Analysis	USAF/WPAFB

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ACCELERATED TEST PLAN FOR NICKEL CADMIUM SPACECRAFT BATTERIES

ABSTRACT

This report outlines an accelerated test matrix, the acceptance, baseline and post-cycling tests, the chemical and physical analyses and the data analysis procedures to be used in determining the feasibility of an accelerated test for sealed, nickel cadmium cells.

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SECTION 1

INTRODUCTION

The purpose of the Accelerated Program is to develop (1) a tool for spacecraft projects and other battery users to determine the life capability of sealed, nickel cadmium cells, (2) a method of evaluating the effect of design and component changes in cells and (3) a means of reducing the time and cost of cell testing. At the present time, it is the practice to life test a sample lot of cells, from a prototype or production lot, to determine the life cycle capability of cells for the flight mission. This procedure usually is not practical for long term missions of several years since it is not possible to procure cells for a long term mission, e.g., five years, to complete the five year test program prior to launch. Also, if major problems occur in a lot, the time required to procure an additional lot and initiate a new test program can result in a substantial decrease of life test data. A similar situation exists in the testing of design changes or the evaluation of new components, i.e., a long term test is required to evaluate if the change or new component is comparable to or better than the initial design with regards to life cycling and performance. Experience has shown, in this latter case, the information gained from the prolonged test program tends to become obsolete. Also, variables inherent in manufacturing, such as process changes or installation of new equipment, can result in testing of cell designs that are no longer available.

An accelerated test program would be instrumental in reducing the cost of cell testing. The most time consuming and costly phase associated with programs using high reliability batteries is the testing of the cells and batteries. The cost of testing can vary between several thousands to several hundreds of thousands of dollars and is dependent on the size of the power supply, unmanned or manned missions, size of the spacecraft, production problems, etc. However, an example of a routine test cost is $10,000 per year, at the Naval Ammunition Depot/Crane, to test a few five cell batteries on continuous cycle with some data and chemical analyses included. This cost is based on major facilities and experienced personnel being available. For a five year program, this cost would be approximately $50,000. It is expected that an accelerated test would be less than 10% of this cost. The cost reduction is enhanced as a result of data and information being available within a few months rather than after several years of testing.

One may question the capability of an accelerated test as primarily being useful for determining that a production lot of cells is good or bad with respect to life cycling. In other words, an accelerated test would be destructive, sampling of a production lot would be required, and marginal or defective cells in the non-tested group would not be detected. However, since past experience has shown that perfectly bad lots, with respect to continuous cycling, are capable of passing conventional acceptance tests, it can be argued that a valid accelerated test could be of value in this case alone. The avoidance of the marginal or defective cell can be controlled by the use of process and material control specifications of which Reference (b) is an example. However, the avoidance of these type of cells, even using this approach, cannot be eliminated since perfection in production can be achieved but cannot be maintained indefinitely. It would be most rewarding if an indicator of cycle life to failure was found, early in an accelerated test, that would predict life but the test would not be detrimental to the useful life of the cell.

During 1965, a program was initiated by NASA to investigate the possibility of predicting the cycle life to failure of nickel cadmium batteries that were being tested at the Naval Ammunition Depot, Crane, Indiana. The work was performed by Mauchley Associates, the NAD/Crane Statistical Branch and Battelle Memorial Institute. Statistical and cryptanalytical techniques were used to predict life. The task was most difficult since the data available had resulted from sealed, nickel cadmium cells from different suppliers, under various test conditions and of several ampere hour capacities. The data had accumulated during the first five years of the test program where, especially in the first two years, numerous failures could be attributed to design problems associated with the developmental cells. For instance, defective seals resulting in leaking cells were a major problem. However, even with these obstacles, the use of statistical and/or cryptanalytic techniques appeared to be a useful tool to predict life. The results and recommendations of these past programs are reported in Reference (a).

The U.S. Air Force (WPAFB) has supported several programs, both in-house and at the Battelle Memorial Institute, to determine the feasibility of predicting the life of sealed, nickel cadmium cells in simulated synchronous orbits. Although the tests have not been designed to be accelerated, data analysis has shown that some trends exist that may predict cycle life in this mode of operation. The overall results of these programs are reported in Reference (a) with additional references listing the Battelle Memorial Institute reports.

The test unit to be used in the program is a 6 AH, sealed nickel cadmium cell that is typical of cells used in spacecraft batteries. The cells will be subjected to a manufacturer's test, a base line test, the accelerated test, a post cycling test and chemical and physical analyses. All the electrical tests are similar to conventional acceptance tests except the accelerated test which is based on a test matrix designed by the NAD/Crane Statistical Branch and Dr. Virgil L. Anderson, of Purdue University.

The accelerated test plan is entitled the Fractional Composite Design. At the time of this writing, some changes are required in the numerical values of the design, especially with respect to the percent of overcharge. All data, including production data, will be in a form that can be readily used in computer analysis. Working computer programs are available at GSFC, NAD/Crane and the U.S. Air Force to perform data analysis. The equipment has been procured and is operative at NAD/Crane to perform the test program. The program requires approximately 600 cells. Obviously, a useable accelerated test will depend on one additional factor, i.e., a smaller and simpler test program will evolve that will require significantly fewer cells.

All electrochemical cells have, to a greater or lesser degree, a self degrading mechanism that affects their useful life. Also, the life and performance of electrochemical cells is dependent on their past history, whether active or passive. One of the most difficult tasks in planning an accelerated test is to determine if the test will accelerate the degradation mechanisms that occur in normal storage or use and to assure that the conditions that accelerate wear out or failure are related to normal useage. The program includes a chemical and physical analyses plan on cells removed before failure, on a schedule estimated by U.S. Air Force personnel, and on cells that are considered failed.

SECTION 2

CELL DESIGN

The cells used as the test samples in the Accelerated Test Program are sealed 6 AH cells, manufactured by the General Electric Company per GSFC Specification S-716-P-6 (Ref. b) and General Electric Manufacturing Document 232A2222AA-36 (Ref. c). The catalogue number assigned to the cell is 42B006AB62. Design information, from the plate level to the finished cell, is contained in the Manufacturing Document. General information on the various cell components is as follows:

a. Cell Case. The cell case is drawn from 304 stainless steel with a wall thickness of 0.016 in. (0.040 cm) to 0.022 in. (0.056 cm). The wall thickness at the bend radii is 0.011 in. (0.028 cm) minimum.

b. Cell Header. The cell cover is fabricated from 304 stainless steel and contains two alumina ceramic seals with nickel iron (alloy 42) stress relief collars and nickel terminal posts. The braze used in the ceramic to metal seals is a nickel titanium alloy whereas the braze used to join the collar to the cover is a silver palladium alloy. Each terminal is tinned with solder. The header assembly has a 0.187 in. (0.475 cm) O.D. stainless steel fill tube welded to the cover.

c. Positive Plates. Each cell contains ten sintered positive plates. The nominal dimensions of the plate, not including the tab, are 2.170 in. (5.51 cm) high, 1.968 in. (5.02 cm) wide and 0.027 in. (0.66 cm) thick. All edges of the positive plates are coined 0.08 in. (0.20 cm). The tab is an integral part of the nickel plated steel grid. The nominal flooded capacity, at the two hour discharge rate, is 0.75 ampere hours per plate.

d. Negative Plate. Each cell contains eleven sintered negative plates. The nominal dimensions, of the plate, excluding the tab, are 2.170 in. (5.51 cm) high, 1.968 in. (5.02 cm) wide and 0.0315 in. (0.80 cm) thick. All edges of the negative are coined 0.08 in (0.20 cm). The tab is an integral part of the nickel plated steel grid. The nominal flooded capacity, at the two hour rate, is 1.3 ampere hours per plate.

e. Separator. The separator used in the cells is a PELLON, Nylon 6, nonwoven material, style number 2505. Each positive plate has a separate, single thickness bag which is heat sealed on two edges with the fold along the height of the positive plate. The as received material

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is double water washed by the material manufacturer. No surfactants are added to the material.

f. Insulation Wrapper. The electrode/separator assembly is insulated from the case walls by a film of polypropylene of 0.0050 in. (0.012 cm) nominal thickness.

g. Cell Variables. In order to determine the effects of cell physical variables on the accelerated testing, three cell design parameters were varied, namely, concentration of electrolyte, volume of electrolyte and amount of negative precharge obtained by oxygen venting. These variables are shown in the following matrix.

	Physical Design Parameters				
Concentration of KOH electrolyte Percent by weight	22.0	26.0	30.0	34.0	38.0
Volume of electrolyte, cc.	17.5	18.5	19.5	20.5	21.5
Negative precharge, AH	2.20	2.50	2.80	3.00	3.30

No additives are added to the electrolyte. The 6 AH cell normally supplied by General Electric would have a 34% concentration of electrolyte, an 18.5 cc volume of electrolyte and a 2.50 ampere hour negative precharge.

The incorporation of these variables in the Accelerated Test Program Matrix is described later in the report.

h. Negative to Positive Ratio. The ratio of the full negative to the full positive is 1.7. The value is based on a measurement, per GSFC Specification S-716-P-6, (Ref. b) made on five production cells of the standard design, i.e., 34% concentration of electrolyte, 18.5 cc of electrolyte and 2.50 ampere hours of negative precharge.

i. Pressure Transducers. Approximately one-third of the cells are equipped with 5000 ohm potentiometric pressure transducers with a range of 0 to 300 PSIA. These transducers, Model 2-400, are manufactured by the Edcliff Instrument Company. They are attached to the cell fill tube by means of a Swagelok fitting. All other cells are capped off with a Swagelok fitting. The transducers and fitting are made from

304 or 316 stainless steel. All fitting assemblies are Helium leak checked before installation on the cells and a final leak check is performed after assembly on the cells. Maximum leak rates are 10^{-7} Std. cc/sec.

A photograph of cells with and without a transducer is shown in Figure 1.

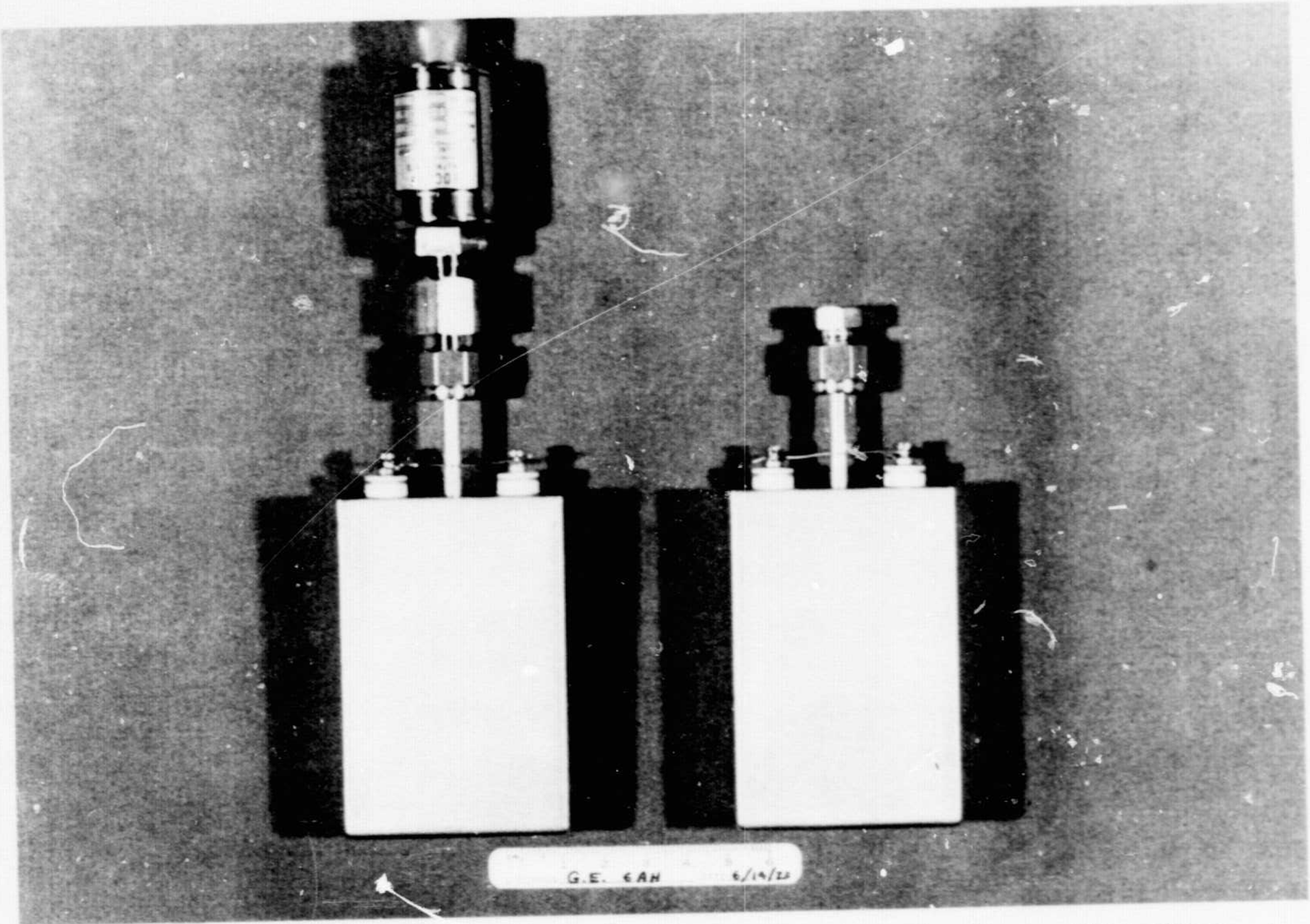

Figure 1. General Electric 6 AH Nickel Cadmium Cells with and without Pressure Transducer

SECTION 3

MANUFACTURER'S ACCEPTANCE TEST
(General Electric)

3.1 SCOPE

The tests listed below are the acceptance tests used by the General Electric Company on the 6 AH sealed nickel cadmium cells for the Accelerated Test Program. All tests are performed with pressure gages attached to the cells. These tests are based on G.E. Specification P24A-PB-150 included in (Ref. c).

3.2 ACCEPTANCE TESTS

3.2.1 CAPACITY TEST AT 24°C

a. Charge at 600 ma. for 16 hours. Record cell voltage, pressure and ambient temperature at start of charge and every four hours.

b. Discharge at 3.0 amperes to 1.0 volt. Record voltage at 120 minutes and time to 1.0 volt.

Short cells with one ohm resistor for four hours minimum.

3.2.2 CAPACITY TEST AT 38°C

a. Condition cells at 38°C for four hours.

b. Charge at 600 ma. for 16 hours. Record cell voltage, pressure and ambient temperature at start of charge and every four hours.

c. Discharge at 3.0 amperes to 1.0 volts. Record time to 1.0 volt.

d. Short cells with one ohm resistor for four hours minimum.

3.2.3 CAPACITY AND OVERCHARGE AT 0°C

a. Condition cells at 0°C for four hours.

b. Charge cells at 300 ma. for 72 hours. Record voltage and pressure at start of charge and every eight hours.

c. Discharge at 3.0 amperes to 1.0 volt. Record time to 1.0 volt.

3.2.4 CHARGE RETENTION 24°C

a. Short cells with one ohm resistor for 16^{+8}_{-0} hours followed by a dead short for 1^{+1}_{-0} hours.

b. Charge cells at 600 ma. for five minutes.

c. Measure and record voltage at end of charge and after twenty four hours of open circuit stand.

3.2.5 INTERNAL RESISTANCE 24°C

The internal resistance of each cell shall be measured as follows:

a. Charge cells at 3.0 amperes for 2.0 hours.

b. Discharge at 3.0 amperes for one hour and record end voltage at the one hour point. Discharge at 20 amperes for ten seconds and record voltage at the end of the ten second pulse. Minimum voltage shall be 1.10 volts.

c. Short cells on one ohm resistor for eight hours minimum.

3.2.6 LEAK TEST

a. Leak test cells with Helium Leak Detector.

b. Phenolphthalein leak check cells and weld closures.

The manufacturer's tests are also shown on Flow Diagram 1, Figure 2. All data is recorded on 80-column forms and punched on IBM cards for computer analysis.

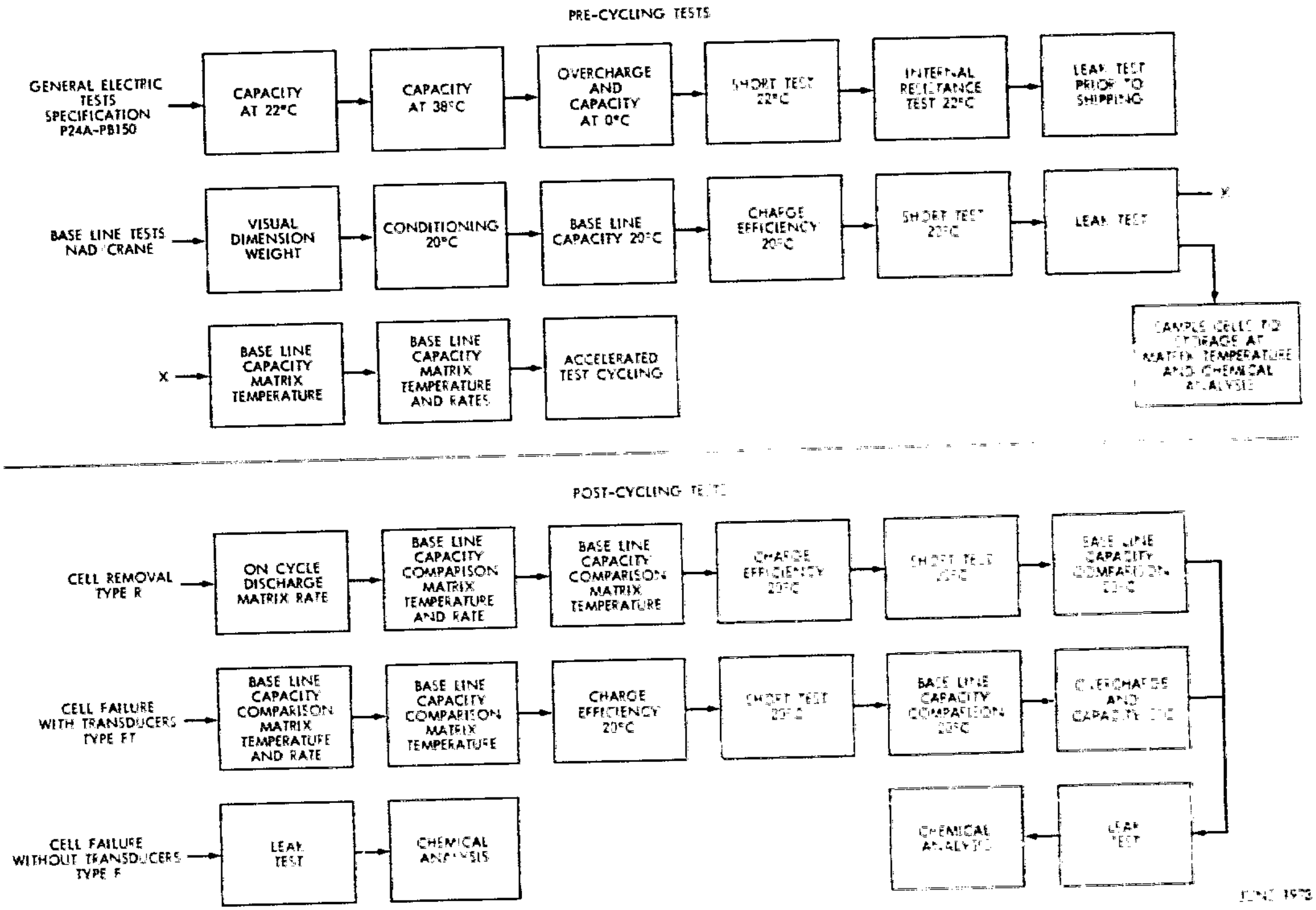

Figure 2. Flow Diagram 1

SECTION 4

BASELINE TESTS AND POST-CYCLING TESTS

4.1 SCOPE

The purpose of this test plan is to define the Base Line Tests and Post-Cycling Tests oi the Accelerated Test Program at NAD/Crane. The tests apply to the General Electric 6 AH sealed, nickel cadmium cells purchased on NASA/GSFC Contracts NAS5-17865 and NAS5-19024. The cells were fabricated per NASA/GSFC Specification S-761-P-6 (Ref. b) and General Electric Document 232A2222AA-36 (Ref. c). All tests are shown in Flow Diagram 1, Figure 2.

4.2 GENERAL REQUIREMENTS AND INSTRUCTIONS

4.2.1 TRANSDUCERS

When handling cells with transducers, care must be taken to support the transducer during handling so that the fill tube/cell header joint is not stressed.

When removing pressure transducers from a cell, apply open end wrenches to Swagelok fittings only. DO NOT USE A WRENCH ON THE TRANSDUCER HEXNUT.

Immediately after removing the pressure transducer from a cell, store in a sealed polyethylene bag.

In the calibration of pressure transducers, only use water pumped nitrogen.

4.2.2 TEMPERATURE CHAMBER BREAKDOWN

When temperature chamber breakdown occurs, the following procedures will apply:

a. Continue packs to end of discharge at the cycle rate.

b. Put packs on open circuit and monitor once every hour.

c. Following chamber repair, bring chamber up to test temperature and condition packs for eight hours. Monitor thermocouples on packs to assure pack temperatures are constant (±2°C) for one hour.

d. Resume cycling on cyclic charge.

e. Maintain log book on each chamber to record temperature chamber anomalies and breakdowns and procedure used to return packs to cycling.

4.2.3 REMOVAL OF SHORTS AT END OF DISCHARGE

When it is required to dead short cells in a pack at the end of discharge, the shorts should be removed from all cells in the pack immediately after the last cell in the pack reaches the required discharge cutoff voltage.

4.3 <u>BASELINE TESTS OF 6 AH NICKEL CADMIUM CELLS FOR ACCELERATED TEST PROGRAM</u>

4.3.1 MEASUREMENTS

a. Height

b. Length

c. Width

d. Weight

All measurements to be made using procedures and instrumentation in Reference (d).

4.3.2 CAPACITY TESTS 20 ±2°C

a. Charge at 300 ma. for 40 hours at 1.60 voltage per cell limit. Set pressure cutoff at 100 psia.

b. Open circuit stand for one hour.

c. Discharge at 3.0 amperes to $0.75^{+0.00}_{-0.20}$ volts, each cell. Open circuit voltage (OCV) each cell at the cutoff voltage.

d. Open circuit stand one hour after last cell discharges.

e. Charge at 600 ma. for 16 hours at 1.60 volt per cell limit. Set pressure cutoff at 100 psia. Measure internal impedance (HP) within 5 minutes after end of charge.

f. Open circuit stand one hour.

g. Discharge at 3.0 amperes to $0.75 \begin{smallmatrix} +0.00 \\ -0.20 \end{smallmatrix}$ volts, each cell. OCV each cell at the cutoff voltage.

During discharge:

(1) Measure internal impedance with HP Ohmmeter during the first five minutes and within five minutes after last cell discharges.

(2) Record pressure decay during discharge at 15 minute intervals.

h. Short with a 0.5-ohm resistor for 16 hours. During this period, record pressure decay, every two hours, if end of discharge pressure is greater than 15psia.

4.3.3 CHARGE EFFICIENCY TEST 20 ±2°C

a. Remove resistors and charge at 150 ma. for 20 hours.

b. Open circuit stand for one hour.

c. Discharge at 3.0 amperes to $0.75 \begin{smallmatrix} +0.00 \\ -0.20 \end{smallmatrix}$ volts, each cell. OCV each cell at cutoff voltage.

4.3.4 INTERNAL SHORT TEST 20 ±2°C

a. When the last cell reaches the cutoff voltage and the pack is removed from discharge, discharge each with a 0.5 ±3% resistor across each cell for 16 hours. Measure the decay voltage of each cell every hour during the 16-hour period.

b. Remove resistor and measure recovery voltage of the pack every 30 minutes until the average pack voltage is equal to or greater than 1.15 volts per cell. If after three hours, the pack voltage has not met this requirement, measure each cell until it reaches 1.15 volts. Total time to be 24 hours.

4.3.5 LEAK TEST

Measurement to be made using procedures and instrumentation in Reference (d).

4.3.6 SHORT CELLS ON 0.5 OHM UNTIL INITIATION OF ACCELERATION TEST

No voltage reading required. Time limit in storage to be three days.

4.3.7 TEMPERATURE CONDITIONING, MATRIX TEMPERATURE

Condition cells at the matrix temperature for a minimum of 8 hours.

4.3.8 CAPACITY TEST, MATRIX TEMPERATURE

a. Remove resistors and charge cells at matrix temperature at 600 ma. for 16 hours at 1.60 volt per cell limit. Measure internal impedance (HP) within 5 minutes after end of charge.

b. Open circuit stand for one hour.

c. Discharge at 3.0 amperes to $0.75^{+0.00}_{-0.20}$ volts, each cell. OCV each cell at the cutoff voltage. Measure internal impedance within 5 minutes after last cell discharges.

d. Short with a 0.5-ohm resistor for 16 hours. During this period, record pressure decay every two hours, if end of discharge pressure is greater than 15 psia.

4.3.9 CAPACITY TEST, MATRIX TEMPERATURE, MATRIX RATE

a. Remove resistor and charge cells at matrix temperature and matrix rate to matrix overcharge. Measure internal impedance within 5 minutes after charge.

b. Open circuit stand for 10 minutes.

c. Discharge at matrix discharge rate to $0.50^{+0.00}_{-0.20}$ volts, each cell. OCV each cell at cutoff voltage. Measure internal impedance within 5 minutes after last cell discharges.

d. Short with 0.5-ohm resistor for 16 hours. During this period, record pressure decay, every two hours, if end of discharge pressure is greater than 15 psia.

4.3.10 INITIATE ACCELERATED TEST

a. Remove resistor and charge cells at matrix temperature, rate and overcharge.

b. Discharge cells at matrix depth of discharge and matrix rate. This cycle is to be designated cycle six (6) of the Accelerated Test for the pack.

4.4 ACCELERATED TEST CELL POST-CYCLING TESTS

Three types of cell will require post-cycling tests:

a. Type R - Cell removed before failure per Air Force Removal Schedule.

b. Type FT - Cell removed after failure, with transducers.

c. Type F - Cells removed after failure, without transducers.

Cells removed before failure (Type R). These packs will have eight cells. Cells are to be removed from test per Air Force Removal Schedule.

4.4.1 CELL REMOVED BEFORE FAILURE (TYPE R)

a. On cycle that cell is to be removed, disconnect cell from pack at end of charge. Immediately discharge at matrix rate and matrix temperature to $0.50 \begin{smallmatrix} +0.00 \\ -0.05 \end{smallmatrix}$ volts.

b. Short with 0.5-ohm resistor at matrix temperature for 16 hours.

c. Remove short and charge cell at matrix temperature, rate and overcharge. Measure internal impedance within 5 minutes after charge.

d. OCV for 10 minutes.

e. Discharge at matrix rate to $0.50 \begin{smallmatrix} +0.00 \\ -0.05 \end{smallmatrix}$ volts. Measure internal impedance within 5 minutes after the end of discharge.

f. Short cell with a 0.5-ohm resistor for 16 hours.

g. Remove resistor and charge at 600 ma. for 16 hours at matrix temperature at 1.60 volt limit. Measure internal impedance within 5 minutes after charge.

h. Open circuit stand for 1 hour.

i. Discharge at 3.0 amperes to $0.75\,^{+0.00}_{-0.20}$ volts. Measure internal impedance within 5 minutes after end of discharge.

j. Short cell with a 0.5-ohm resistor.

k. Within 16 hours condition cell for 8 to 72 hours at 20 ±2°C.

4.4.2 CHARGE EFFICIENCY 20 ±2°C

a. Remove resistor and charge at 150 ma. for 20 hours.

b. Open circuit stand for 1 hour.

c. Discharge cell at 3.0 amperes to $0.75\,^{+0.00}_{-0.20}$ volts. OCV at cutoff voltage.

4.4.3 INTERNAL SHORT TEST

a. Discharge the cell with a 0.5 ±3% resistor for 16 hours. Measure the decay voltage every hour during the 16 hour period.

b. Remove resistor and measure recovery voltage every 30 minutes until cell voltage is equal to or greater than 1.15 volts. Then read once every hour for the remaining time. Total time of test to be 24 hours.

4.4.4 CAPACITY TEST 20 ±2°C

a. Charge at 600 ma. for 16 hours at 1.60 volts limit. Measure internal impedance within 5 minutes after end of charge.

b. Open circuit stand for 1 hour.

c. Discharge at 3.0 amperes to 0.75 $^{+0.00}_{-0.20}$ volts.

During discharge:

(1) Measure internal impedance (HP) during the first five minutes and within five minutes after end of discharge.

d. Short cell with 0.5-ohm resistor for 16 hours.

e. Remove resistor and solder short across cell. Store at 20 ±2°C.

4.4.5 PERFORM CHEMICAL ANALYSIS

4.5 <u>CELL REMOVAL AFTER FAILURE, WITH TRANSDUCERS (TYPE FT)</u>

4.5.1 CONDITION FOR FAILURE

- Cell voltages between 0.05 and 0.00 volts, set warning at 0.5 volts.
- Pressure greater than 250 psia, set warning pressure at 200 psia.
- Do not remove cells at high voltage.

a. <u>If high pressure failure</u>, discharge at matrix rate to 0.50 $^{+0.00}_{-0.05}$ volts.

b. Remove cell from pack.

c. Short cell with a 0.5-ohm resistor at matrix temperature for 16 hours. Record pressure decay if greater than 15 psia.

d. Remove resistor and charge cell at matrix temperature and matrix rate to matrix overcharge. Measure internal impedance within 5 minutes after end of charge.

e. Open circuit stand for 10 minutes.

f. Discharge at matrix rate to 0.50 $^{+0.00}_{-0.05}$ volts.

g. Short cell with a 0.5-ohm resistor for 16 hours.

h. Remove resistor and charge cell at matrix temperature at 600 ma. for 16 hours at 1.60 volts limit. Measure internal impedance within 5 minutes after end of charge.

i. Open circuit stand for 1 hour.

j. Discharge at 3.0 amperes to 0.75 $^{+0.00}_{-0.20}$ volts. OCV cell at the cutoff voltage. Measure internal impedance within 5 minutes after end of discharge.

k. Short cells with a 0.5-ohm resistor.

l. Within 16 hours condition cell for 8 to 72 hours at 20 ±2°C.

4.5.2 CHARGE EFFICIENCY 20 ±2°C

a. Remove resistor and charge at 150 ma. for 20 hours.

b. Open circuit stand for one hour.

c. Discharge cell at 3.0 amperes to 0.75 $^{+0.00}_{-0.20}$ volts. OCV at cutoff voltage.

4.5.3 INTERNAL SHORT TEST

a. Discharge the cell with a 0.5 ±3% resistor for 16 hours. Measure the decay voltage every hour during the 16 hour period.

b. Remove resistor and measure recovery voltage every 30 minutes until the cell voltage is equal to or greater than 1.15 volts. Then read once every hour for the remaining time. Total time of test to be 24 hours.

4.5.4 CAPACITY TEST 20 ±2°C

a. Charge at 600 ma. for 16 hours at 1.60 volts. Set pressure cutoff at 100 psia. Measure internal impedance within 5 minutes after end of charge.

b. Open circuit stand for one hour. Record pressure decay during the open circuit stand.

c. Discharge at 3.0 amperes to 0.75 $^{+0.00}_{-0.20}$ volts.

During discharge:

(1) Measure internal impedance (IIP) during the first five minutes and within 5 minutes after the end of discharge.

(2) Record pressure decay during discharge at 15 minute intervals.

d. Short cell with a 0.5-ohm resistor for 16 hours. During this period, record pressure decay every hour if end of discharge pressure is greater than 15 psia.

e. Condition cells at 0 ±2° C for 16 hours.

f. Remove resistor and charge cells at 300 ma. for 72 hours at 0 ±2°C. Record voltages and pressures at one hour intervals and at end of charge. Set pressure cutoff at 100 psia.

g. Discharge cells at 3.0 amperes to $0.75\,^{+0.00}_{-0.20}$ volts.

h. Short cell with 0.5-ohm resistor for 16 hours.

i. Remove resistor and solder short across cell. Store at 20 ±2°C.

4.5.5 PERFORM FAILURE ANALYSIS

4.5.6 CALIBRATE TRANSDUCER

See "General Requirements and Instructions" for removal of transducer from cell.

4.6 CELL REMOVAL AFTER FAILURE, WITHOUT TRANSDUCERS (TYPE F)

4.6.1 CONDITIONS FOR FAILURE

- Cell voltages between 0.05 and 0.00 volts.
- Do not remove cells at high voltage.

a. Remove cell from pack and place 0.5-ohm resistor across cell for 16 hours.

b. Remove resistor and solder short across cell. Store at 20 ±2°C.

4.6.2 PERFORM CHEMICAL ANALYSIS

SECTION 5

ACCELERATED TEST PROGRAM

5.1 TEST FACILITIES

The ambient test temperatures of 0°C, +20°C, +30°C, +40°C, +50°C, and +60°C, are maintained by environmental chambers with temperature controls accurate to within ±1.5°C, whereas test items cycling at +25°C are located in an air conditioned room with other temperature critical equipment and the temperature is maintained at 25°C ±2°C. Several chambers, with a temperature range of -75°C to +175°C, are available for additional tests which require special temperatures.

5.1.1 AUTOMATIC DATA ACQUISITION AND CONTROL SYSTEM (ADACS)

5.1.1.1 Brief Summary

a. The system is capable of testing 200 battery packs with 3000 channels available for data input from these packs.

   (1) Each battery pack has its own power supply and system interface, remotely programmed by the system, to provide its test requirements. During test, the system routinely scans each pack's data every 2.4 minutes and compares each data point, whether voltage, temperature, or pressure, with programmed limits to insure that the test items meet their test specifications. If a parameter is out of limits the system will initiate an alarm and also type out a message identifying which pack's parameter was out of limits.

   (2) As data is being scanned, it is recorded on magnetic tape and also on a teletype, in report form, if requested.

   (3) The system was designed to provide an accuracy of 1.0 millivolt on directly read data such as auxiliary electrode and cell voltages. The accuracy of temperature (thermistor) and pressure (transducer) measurements are 0.05°C and 0.05psia respectively.

b. The system is organized in three functional hardware groupings as follows:

   (1) Computer and computer peripherals:

      (a) Honeywell 316 computer and options

(b) Two ASR35 heavy duty teletypes

(c) Honeywell 316-50 high speed paper tape recorder and spooler

(d) Datum, Inc., Model 5091-H316 magnetic tape I/O system with two tape transports

(e) Datum, Inc., Model 6078-H316 mass memory system with 131,000 word drum memory

(2) Auxiliary digital functions include:

(a) The real time clock, the system shut-down timer and alarm circuits, and medium speed analog input sub-system.

(b) Two John Fluke, Model 8300-A digitizers

(c) 3000-Channel reed relay scanner

(d) Computer interface

(3) Control subsystem

(a) 200 Control channels providing the digital resistance conversion and control-relay outputs to the interface between the system and the test items.

5.1.1.2 Measurements

a. Cell and auxiliary electrode voltages are presented directly to the system. Throughput measurement is 1.0 millivolt maximum.

b. Currents are measured by means of sampling the voltage drop across a low-resistance shunt of 100 MV full current value. Throughput measurement error of the shunt voltage is 1 millivolt maximum.

c. Temperatures; cell and ambient, are measured by means of sampling the output of a thermistor bridge which is driven by an excitation voltage. The temperature range is -30°C to +70°C and is resolved in increments of 0.1°C, with an error of less than 0.05°C resulting from linearity.

d. Cell pressures are measured by means of sampling the output of a pressure transducer which is driven by an excitation voltage. The pressure range is 0 to 300 psia, and is resolved in increments of 0.1 psia with an error of less than 0.05 psia resulting from linearity.

e. Battery pack voltages, which exceed 10 volts, are attenuated by resistors to the extent that the scanner and system measures a maximum of 10 volts.

5.1.1.3 Expandability

a. The system is expandable on a modular plug-in cabled-together basis up to a maximum of 5000 analog input channels, and 256 control output channels.

b. The computer memory may be expanded to 32,000 words and an additional drum mass memory system may be added.

5.1.1.4 Calibration

a. The system was designed for a maximum throughput measurement error of 1.0 millivolt.

b. The digitizers are routinely calibrated off-line, and when on-line, measures the temperature and pressure bridge excitation voltages along with a secondary standard reference voltage each scan (2.4 minutes) to insure maximum system accuracy.

5.2 SUMMARY OF ACCELERATED TEST DESIGN

5.2.1 OBJECTIVE OF ACCELERATED TEST PROGRAM

The main objective of the accelerated test program is to produce battery failures under stressful conditions and relate these failures to failures under normal space flight conditions. This test design is set up such that the statistical evaluation of these acceleration factors is possible. Once these acceleration factors are determined, they will be used in predicting battery life with a minimum of cycling time.

5.2.2 ACCELERATED TEST DESIGN

The accelerated test design to be utilized is a fractional composite design. This type of test design and the general approach discussed herein were arrived at following consultation with Dr. Virgil L. Anderson of Purdue University. The final form for this design is dependent upon the number of factors involved, the type of factor involved (either qualitative or quantitative), and the number of levels of each factor. A qualitative factor is one in which the different levels cannot be arranged in order of magnitude; manufacturer or separator type represent qualitative factors because there are no a priori reasons for arranging them in any particular order. A quantitative factor is one whose values can be arranged in order of magnitude. Such values can usually be associated with points on a numerical scale, e.g., temperature, depth of discharge, or amount of electrolyte. The addition of qualitative factors to the design greatly increases the number of packs required for the test. The addition of a quantitative factor will cause an increase in the number of packs required for the test, but the increase will not be as great as with the qualitative factor. This point will become more clear as the fractional composite design is discussed.

The fractional composite design is used to keep the number of packs required for the test at a minimum while obtaining information on a maximum number of factors and levels of those factors. This requirement becomes more important with increased number of factors in the entire test design. The design has three parts consisting of: (a) a factorial part, (b) "star" points, and (c) "center" points.

The factorial part is analyzed separately to determine which main effects and/or interactions have a significant effect on battery life. A 2^n factorial is used for this factorial part, using two levels of the n quantitative factors. As the number of quantitative factors increase, the need for a fractional replication of the full factorial increases.

The fractional replication minimizes the number of packs needed for analysis, but still permits the analysis of the main effects and two factor interaction. Table 1 shows the increase in the number of packs required for the fractional factorial part of the design as the number of quantitative factors increases. This part of the design is independent of the number of levels of a quantitative factor because it uses a high and a low level of each factor. For example, if there are three levels of the factor, the first and third levels are used in the factorial. If there are five levels, the second and fourth levels are used.

Since qualitative factors have no continuous relationship between levels, they present a different problem to the design. For each level of each qualitative factor used in the test, the factorial part (whether full or fractional) must be multiplied by the number of factors and the number of levels of each qualitative factor. For example, a 1/2 replication of a 2^5 requires 16 packs for the five quantitative factors. If one qualitative factor were added with three levels, 48 packs are required. If another qualitative factor were added with two levels, 80 packs are required.

The "star" points of the composite design take each extreme level of each quantitative factor in combination with the center level of every quantitative factor. This part of the composite design gives a method of evaluating the non-linear

Table 1

Packs Required for Factorial Part of the Composite Design

Fractional Replication*	Number of Quantitative Factors	Number of Packs Required
1/2	5	16
1/2	6	32
1/2	7	64
1/4	8	64
1/4	9	128
1/8	10	128
1/16	11	128
1/16	12	256
1/32	13	256
1/64	14	256

*This fraction is minimum to estimate main effects and two-factor interactions.

effect of the factors without a sizeable increase in the number of packs required. The star points require two times the number of quantitative factors times each level of each qualitative factor. For example, for five quantitative factors there would be ten star points. For two additional qualitative factors each with three levels, there would be 60 star points.

The "center" points of the design take the center point of each quantitative factor with each level of each qualitative factor. Repeats of these center points are made for estimation of error which is used in the statistical analysis.

"Star" and "center" points of a composite design permit approaching the investigation as a response surface experiment but with less experimental units. Thus the efficiency of this test design is considerably greater than that of the conventional response surface design.

The flexibility of this design varies as the number of quantitative factors increase. (Qualitative factor increases require multiplication of the entire design.) As can be seen in Table 1, when the number of factors increase from five to six, 16 additional packs are required for the evaluation of main effects and all two factor interactions. In other words, all of the 16 packs used in the $1/2 \times 2^5$ are used in the $1/2 \times 2^6$.

The same holds true for an increase from six to seven. The 32 packs used in the $1/2 \times 2^6$ are used as part of the 64 cells used in the $1/2 \times 2^7$. A problem arises when an increase from seven to eight quantitative factors occurs. Table 1 shows that a $1/4 \times 2^8$ design will allow the evaluation of main effects and all two factor interactions. This design requires 64 cells, the same number as in the $1/2 \times 2^7$ design. However, none of the 64 packs used in the $1/2 \times 2^7$ are included in the $1/4 \times 2^8$. This means that 64 additional packs would be required for the one additional quantative factor. If the test is started with eight quantitative factors, 64 packs are required. If the test is started with seven or less quantitative factors and increases to eight, 128 packs are required for the factorial part of the composite design. Additional quantitative factors in the star points and center points present no problem because all previous star points and center points are useable. From the above discussion it can be concluded that a decision as to how many factors are to be added to the design should be made before the test is started.

5.2.3 NUMBER OF CELLS IN A PACK

In previous analysis it was concluded that there was no significant difference in the reliability of prediction of ten cell packs and five cell packs. Since the number of cells in a pack does not influence the composite design, the five cell pack is used for the accelerated test. A fewer number could have an adverse effect on the reliability of predictions, since the standard deviation of cells in a pack is used in the NAD Crane Prediction Technique.

5.2.4 ANALYSIS OF THE COMPOSITE DESIGN

The analysis of the composite design is geared toward the evaluation of acceleration factors. The factorial part of the design will be analyzed in an analysis of variance which will examine main effects and two factor interactions. The significant effects will then be used with the star points and the center point in the regression analysis to evaluate the effect of acceleration.

A split-plot analysis will be used in the factorial part of the composite design because of the restrictions on randomization which is caused by the physical factors on the environmental factors. The physical factors make up the whole plot while the environmental factors make up the split plot. The error term used to test the environmental factors can be estimated by replication of the center point. This is the reason for the repeat observations of the center points in all the designs.

5.2.5 PREDICTION TECHNIQUES AND THE ACCELERATED TEST

Once the acceleration factors have been determined in the form of a non-linear regression equation, Crane's prediction technique will then be applied to the accelerated data. Times to failures will be used as the response element in the equation. Cells will be put on test under accelerated conditions, cycled until failure, then the failure times will be put into the regression equation to get non-accelerated failure times. Similar cells will then be put on a normal test, cycled a "few" cycles, and then predictions made on the cells using the previously acquired failure times in the prediction equation.

Another use of the accelerated test will be the monitoring of time to discharge to 1.25 volts (t_i) and use this as the response element. These readings from the accelerated test will be put into the regression equation and obtain non-accelerated t_i's for use in the prediction equation.

Another use of the accelerated test will be the use of the cryptanalytic technique of prediction. Measurements of voltage changes (Δ volts) over a fixed time interval will be taken and formed into histograms of Δ volts. The associated failure times with the Δ volt histograms will be put into the regression equation to obtain actual failure times. The Δ volt histograms will be matched with these failure times. When new cells are put on test, the Δ volt histogram will be plotted and matched with a histogram whose failure time is known and prediction can be made.

5.2.6 FINAL COMPOSITE DESIGN INCLUDING SUPPLEMENTARY REQUIREMENTS

The final composite design is a $1/4 \times 2^8$ design that consists of one qualitative factor at one level and eight quantitative factors at five levels. Table 2 lists the quantitative factors and levels. The composite design is summarized in Table 3 and includes four additional packs required at "normal" conditions. Normal conditions for temperature (0°C) and percent recharge (105) are not included in the levels listed in Table 2. Therefore, to tie these conditions into the design, a 2^2 factorial using two levels of temperature (0°C and 20°C) and one level of percent recharge (105) is utilized.

Supplementary requirements are additional tests and analyses that correlate with the basic composite design and benefits the overall program. These requirements consist of an analysis of uncycled cells, scheduled removal of unfailed cycled cells, and a conditional storage. Table 4 summarizes the supplementary requirements.

Table 2

Factors and Levels

	1*	2**	3***	4**	5*
A. Temperature °C (T)	20	30	40	50	60
B. Depth of Discharge (DOD)	20	40	60	80	100
C. Charge Rate (CR)	C/4	C/2	C	2C	4C
D. Discharge Rate (DR)	C/2	C	2C	4C	8C
E. Percent Charged (%C)	110	140	170(1)	200	230(1)
F. Concentration of KOH (% KOH)	22	26	30	34	38
G. Amount of KOH (cc)	17.5	18.5	19.5	20.5	21.5
H. Precharge (AH)	2.20	2.50	2.80	3.00	3.30

*Star Point Levels
**Factorial Levels
***Center Point Levels

(1) Preliminary tests have shown that the values of 170 and 230 should be reduced to 140 and 200, respectively.

Table 3

Composite Design

A. Factorial Part - $1/4 \times 2^8$	64 packs - 320 cells
B. Star Points - 2 x 8	16 packs - 80 cells
C. Center Point - 1 + 5 cells repeated for error	2 packs - 10 cells
D. Normal Conditions	4 packs - 20 cells
E. Total Required	86 packs - 430 cells

Table 4

Supplementary Requirements

A. Analysis of Uncycled cells - 2 x 15 conditions	30 cells
B. Unfailed Removal - 3 x 21 conditions/points	63 cells
C. Conditioned Storage - 3 x 8 conditions	24 cells
D. Total Required	117 cells

Table 5 is a complete matrix listing of all factor combinations of the composite design with time values for charge and discharge and number of cells per pack. Also listed are the storage conditions for the associated cells. The packs that show a requirement for eight cells include three cells designated for early/ unfailed removal and analysis.

5.3 AIR FORCE REMOVAL SCHEDULE FOR UNFAILED CELLS

During the test program, three cells will be removed from cycling before failure to determine the mode and rate of degradation affected by the test conditions. At the same time of removal, a cell with the same physical variables will be removed from storage, the storage temperature being the same as the test temperature. Both cells will be subjected to chemical and physical analyses for comparison of the cycling effects with storage effects. The removal of the cells before failure will be from the star, center and normal points with eight cells in a pack.

An estimate for the cycle at which to remove the cells has been made by Dr. John Lander, Reference (g). Primarily, the estimates are based on temperature and depth of discharge cycle data resulting from test programs performed by the U.S. Air Force, NAD/Crane and the Royal Aircraft Establishment. The removal schedule is shown on Table 6. The cells will be removed from the Accelerated Test at the end of discharge.

Table 5

Matrix of Factor Combinations

A. Fractional Factorial

Pack No.	Temp (°C)	DOD (%)	Disch Rate	Disch (Hrs)	Charge (Hrs)	Chg Rate	Rechg (%)	KOH (%)	KOH (cc)	Prechg (AH)	No. Cells
1 N	30	40	C	0.4	1.12	C/2	140	26	18.5	2.50	5
2 N	50	80	C	0.8	0.56	2 C	140	34	20.5	3.00	5
3 N	30	80	4 C	0.2	0.80	2 C	200	26	18.5	3.00	5
4 N	50	40	4 C	0.1	1.60	C/2	200	34	20.5	2.50	5
5 N	30	40	C	0.4	1.60	C/2	200	34	20.5	3.00	5
6 N	50	80	C	0.8	0.80	2 C	200	26	18.5	2.50	5
7 N	30	80	4 C	0.2	0.56	2 C	140	34	20.5	2.50	5
8 N	50	40	4 C	0.1	1.12	C/2	140	26	18.5	3.00	5
9 N	30	40	4 C	0.1	0.28	2 C	140	26	20.5	3.00	5
10 N	50	80	4 C	0.2	2.24	C/2	140	34	18.5	2.50	5
11 N	30	80	C	0.8	3.20	C/2	200	26	20.5	2.50	5
12 N	50	40	C	0.4	0.40	2 C	200	34	18.5	3.00	5
13 N	30	40	4 C	0.1	0.40	2 C	200	34	18.5	2.50	5
14 N	50	80	4 C	0.2	3.20	C/2	200	26	20.5	3.00	5
15 N	30	80	C	0.8	2.24	C/2	140	34	18.5	3.00	5
16 N	50	40	C	0.4	0.28	2 C	140	26	20.5	2.50	5
17 N	50	80	C	0.8	0.56	2 C	140	26	18.5	3.00	5
18 N	30	40	C	0.4	1.12	C/2	140	34	20.5	2.50	5
19 N	50	40	4 C	0.1	1.60	C/2	200	26	18.5	2.50	5
20 N	30	80	4 C	0.2	0.80	2 C	200	34	20.5	3.00	5
21 N	50	80	C	0.8	0.80	2 C	200	34	20.5	2.50	5
22 N	30	40	C	0.4	1.60	C/2	200	26	18.5	3.00	5

Table 5 (continued)

A. Fractional Factorial (Cont'd)											
Pack No.	Temp (°C)	DOD (%)	Disch Rate	Disch (Hrs)	Charge (Hrs)	Chg Rate	Rechg (%)	KOH (%)	KOH (cc)	Prechg (AH)	No. Cells
23 N	50	40	4 C	0.1	1.12	C/2	140	34	20.5	3.00	5
24 N	30	80	4 C	0.2	0.56	2 C	140	26	18.5	2.50	5
25 N	50	80	4 C	0.2	2.24	C/2	140	26	20.5	2.50	5
26 N	30	40	4 C	0.1	2.28	2 C	140	34	18.5	3.00	5
27 N	50	40	C	0.4	0.40	2 C	200	26	20.5	3.00	5
28 N	30	80	C	0.8	3.20	C/2	200	34	18.5	2.50	5
29 N	50	80	4 C	0.2	3.20	C/2	200	34	18.5	3.00	5
30 N	30	40	4 C	0.1	0.40	2 C	200	26	20.5	2.50	5
31 N	50	40	C	0.4	0.28	2 C	140	34	18.5	2.50	5
32 N	30	80	C	0.8	2.24	C/2	140	26	20.5	3.00	5
33 N	30	80	4 C	0.2	3.20	C/2	200	34	20.5	2.50	5
34 N	50	40	4 C	0.1	0.40	2 C	200	26	18.5	3.00	5
35 N	30	40	C	0.4	0.28	2 C	140	34	20.5	3.00	5
36 N	50	80	C	0.8	2.24	C/2	140	26	18.5	2.50	5
37 N	30	80	4 C	0.2	2.24	C/2	140	26	18.5	3.00	5
38 N	50	40	4 C	0.1	0.28	2 C	140	34	20.5	2.50	5
39 N	30	40	C	0.4	0.40	2 C	200	26	18.5	2.50	5
40 N	50	80	C	0.8	3.20	C/2	200	34	20.5	3.00	5
41 N	30	80	C	0.8	0.80	2 C	200	34	18.5	3.00	5
42 N	50	40	C	0.4	1.60	C/2	200	26	20.5	2.50	5
43 N	30	40	4 C	0.1	1.12	C/2	140	34	18.5	2.50	5
44 N	50	80	4 C	0.2	0.56	2 C	140	26	20.5	3.00	5

Table 5 (continued)

A. Fractional Factorial (Cont'd)											
Pack No.	Temp (°C)	DOD (%)	Disch Rate	Disch (Hrs)	Charge (Hrs)	Chg Rate	Rechg (%)	KOH (%)	KOH (cc)	Prechg (AH)	No. Cells
45 N	30	80	C	0.8	0.56	2 C	140	26	20.5	2.50	5
46 N	50	40	C	0.4	1.12	C/2	140	34	18.5	3.00	5
47 N	30	40	4 C	0.1	1.60	C/2	200	26	20.5	3.00	5
48 N	50	80	4 C	0.2	0.80	2 C	200	34	18.5	2.50	5
49 N	50	40	4 C	0.1	0.40	2 C	200	34	20.5	3.00	5
50 N	30	80	4 C	0.2	3.20	C/2	200	26	18.5	2.50	5
51 N	50	80	C	0.8	2.24	C/2	140	34	20.5	2.50	5
52 N	30	40	C	0.4	0.28	2 C	140	26	18.5	3.00	5
53 N	50	40	4 C	0.1	0.28	2 C	140	26	18.5	2.50	5
54 N	30	80	4 C	0.2	2.24	C/2	140	34	20.5	3.00	5
55 N	50	80	C	0.8	3.20	C/2	200	26	18.5	3.00	5
56 N	30	40	C	0.4	0.40	2 C	200	34	20.5	2.50	5
57 N	50	40	C	0.4	1.60	C/2	200	34	18.5	2.50	5
58 N	30	80	C	0.8	0.80	2 C	200	26	20.5	3.00	5
59 N	50	80	4 C	0.2	0.56	2 C	140	34	18.5	3.00	5
60 N	30	40	4 C	0.1	1.12	C/2	140	26	20.5	2.50	5
61 N	50	40	C	0.4	1.12	C/2	140	26	20.5	3.00	5
62 N	30	80	C	0.8	0.56	2 C	140	34	18.5	2.50	5
63 N	50	80	4 C	0.2	0.80	2 C	200	26	20.5	2.50	5
64 N	30	40	4 C	0.1	1.60	C/2	200	34	18.5	3.00	5
B. Star Points											
65 N	20	60	2 C	0.3	1.02	C	170	30	19.5	2.80	8
66 N	60	60	2 C	0.3	1.02	C	170	30	19.5	2.80	8

Table 5 (continued)

Pack No.	Temp (°C)	DOD (%)	Disch Rate	Disch (Hrs)	Charge (Hrs)	Chg Rate	Rechg (%)	KOH (%)	KOH (cc)	Prechg (AH)	No. Cells
B. Star Points (Cont'd)											
67 N	40	20	2 C	0.1	0.34	C	170	30	19.5	2.80	8
68 N	40	100	2 C	0.5	1.70	C	170	30	19.5	2.80	8
69 N	40	60	2 C	0.3	4.08	C/4	170	30	19.5	2.80	8
70 N	40	60	2 C	0.3	0.255	4 C	170	30	19.5	2.80	8
71 N	40	60	C/2	1.2	1.02	C	170	30	19.5	2.80	8
72 N	40	60	8 C	0.075	1.02	C	170	30	19.5	2.80	8
73 N	40	60	2 C	0.3	0.660	C	110	30	19.5	2.80	8
74 N	40	60	2 C	0.3	1.38	C	230	30	19.5	2.80	8
75 N	40	60	2 C	0.3	1.02	C	170	22	19.5	2.80	8
76 N	40	60	2 C	0.3	1.02	C	170	38	19.5	2.80	8
77 N	40	60	2 C	0.3	1.02	C	170	30	19.5	2.20	8
78 N	40	60	2 C	0.3	1.02	C	170	30	19.5	3.30	8
79 N	40	60	2 C	0.3	1.02	C	170	30	17.5	2.80	8
80 N	40	60	2 C	0.3	1.02	C	170	30	21.5	2.80	8
C. Center Points											
81 N	40	60	2 C	0.3	1.02	C	170	30	19.5	2.80	8
82 N	40	60	2 C	0.3	1.02	C	170	30	19.5	2.80	5
D. Normal Conditions*											
83 N	0	40	C/1.20	5.0a	2.52a	C/4.76	105	34	18.5	2.50	8
84 N	20	20	C/2.40	2.5a	1.26a	C/2.38	105	34	18.5	2.50	8
85 N	0	20	C/2.40	2.5a	1.26a	C/2.38	105	34	18.5	2.50	8
86 N	0	40	C/1.20	5.0a	2.52a	C/4.76	105	34	18.5	2.50	8

*Discharge time is 0.48 hour and charge time is 1.0 hour; therefore, the value in column DISCH (Hrs) is discharge current (in amperes) and CHG (Hrs) is charge current (in amperes).

Table 5 (continued)

E. Storage											
Pack No.	Temp (°C)	DOD (%)	Disch Rate	Disch (Hrs)	Charge (Hrs)	Chg Rate	Rechg (%)	KOH (%)	KOH (cc)	Prechg (AH)	No. Cells
87 N	20							30	19.5	2.80	3
88 N	60							30	19.5	2.80	3
89 N	40							22	19.5	2.80	3
90 N	40							38	19.5	2.80	3
91 N	40							30	19.5	3.30	3
92 N	40							30	21.5	2.80	3
93 N	0							34	18.5	2.50	3
94 N	20							34	18.5	2.50	3

Table 6

Cell Removal from Eight Cell Packs

Star Points				
Pack No.	Estimated Cycles to Failure	Estimated Cycles to Cell Removal Before Failure		
		First Cell	Second Cell	Third Cell
65 N	3000	750	1500	2250
66 N	900	225	450	675
67 N	9000	2250	4500	6750
68 N	400	100	200	300
69 N	2000	500	1000	1500
70 N	1600	400	800	1200
71 N	2800	700	1400	2100

Table 6 (continued)

Star Points (continued)				
Pack No.	Estimated Cycles to Failure	Estimated Cycles to Cell Removal Before Failure		
		First Cell	Second Cell	Third Cell
72 N	200	50	100	150
73 N	1000	250	500	750
74 N	500	125	250	375
75 N	3000	750	1500	2250
76 N	1000	250	500	750
77 N	2000	500	1000	1500
78 N	1000	250	500	750
79 N	1800	450	900	1350
80 N	1800	450	900	1350
Center Point				
81 N	2000	500	1000	1500
Normal Points				
83 N	17000	4250	8500	12750
84 N	27000	6750	13500	20250
85 N	48000	12000	24000	36000
86 N	13000	3250	6500	9750

SECTION 6

CHEMICAL AND PHYSICAL ANALYSES

Chemical and physical analyses will be performed on cells from various phases of the test program. These analyses will be performed as follows:

a. Two uncycled cells of each physical variable group, i.e., concentration of electrolyte, volume of electrolyte and amount of negative precharge.

b. Three cells from each star point of accelerated cycling removed before failure.

c. Three cells from a center point of accelerated cycling removed before failure.

d. Three cells from each normal test removed before failure.

e. Three cells from each matrix temperature storage condition for comparison with above.

f. Each cell that fails or cannot cycle under test conditions.

A flow diagram of the failure analyses plan is shown in Flow Diagram 2, Figure 3. After opening, the cells will be subjected to a separator analysis. During this operation, part of the separator is removed for analysis and the remaining core is Soxhlet extracted. The remaining separator and plates will be sealed in polyethylene bags for analysis at a later date. The complete procedure for the chemical and physical analyses of all cell component parts is in the final stages of report preparation, Reference (e).

NASA/GSFC, NAD/Crane and USAF/WPAFB have facilities to perform special analysis if required.

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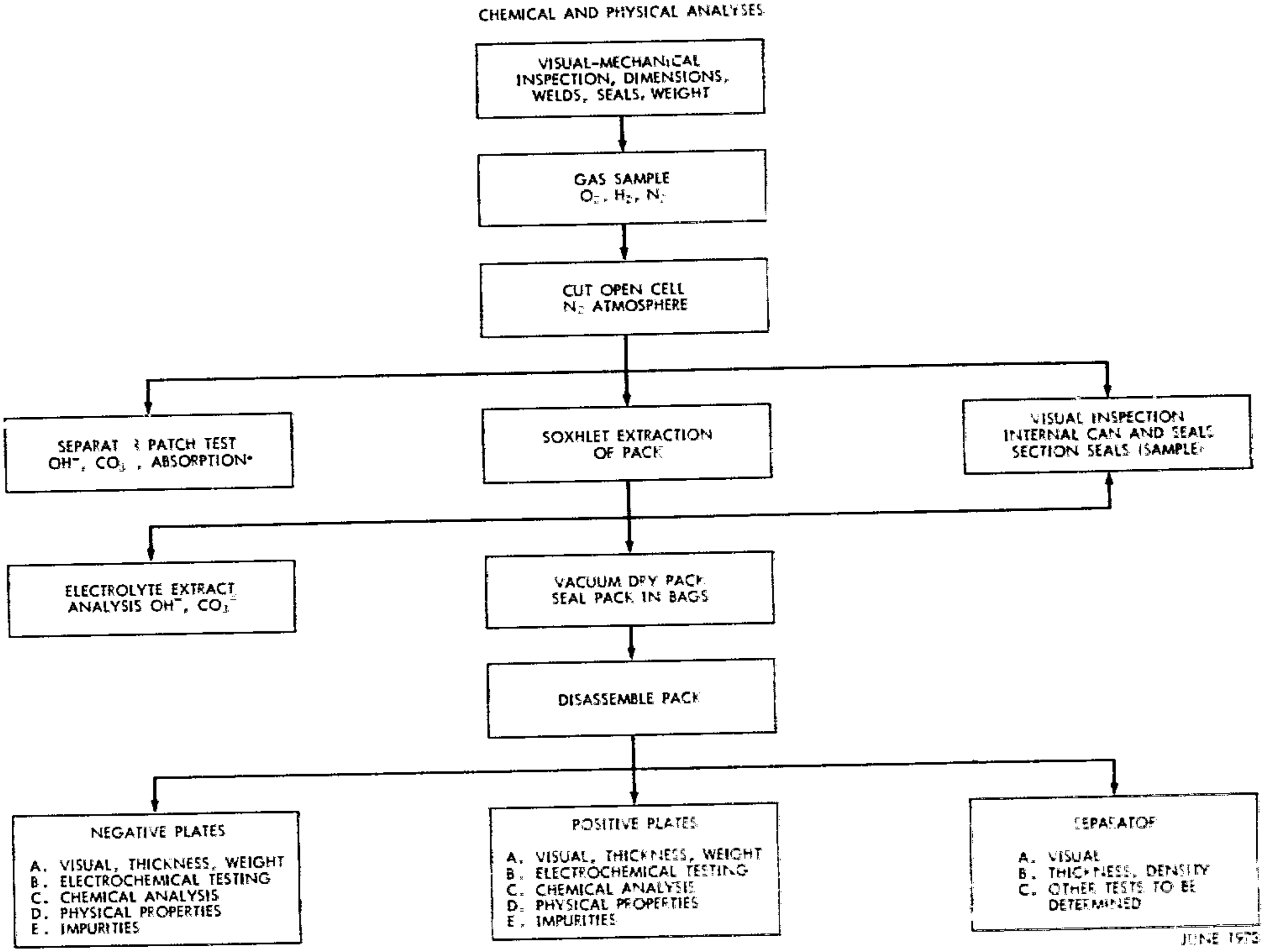

Figure 3. Flow Diagram 2

SECTION 7

DATA ANALYSES

7.1 ANALYSES OF MANUFACTURER'S DATA

a. Regression analysis to determine relationships between physical design parameters and the manufacturer's electrical tests.

b. Histograms of data.

7.2 ANALYSES OF BASE LINE AND POST-CYCLING TESTS

a. Compare, where applicable, with 7 A-(a) and 7 A-(b) above.

b. Compare Base Line Tests with Post-Cycling Tests.

7.3 OUTLINE OF ACCELERATED TEST DATA ANALYSES

(See Flow Diagram 3, Figure 4.)

7.3.1 INITIAL DATA GENERATED - STAR AND CENTER POINTS

a. Predictions made using $\bar{t}_i$ method with t = time to discharge to 1.25 volts and failure times extrapolated from post data. Reference (g).

b. Investigate other times to discharge and various times to charge in $\bar{t}_i$ model.

7.3.2 SECOND SET OF DATA GENERATED - FACTORIAL POINTS

a. Predictions made in similar manner as 7.3.1a.

b. Continue investigation in 7.3.1b with factorial data.

c. Analyze data using analysis of variance (ANOVA) techniques and various response elements - can be utilized in conjunction with output of cryptanalytic procedures, if any promising response elements have been found.

d. Find all main effects (e.g., Temp., DOD, CR, etc.) and two-way interactions (e.g., TxDOD, DODxCR, etc.) that show a statistical difference.

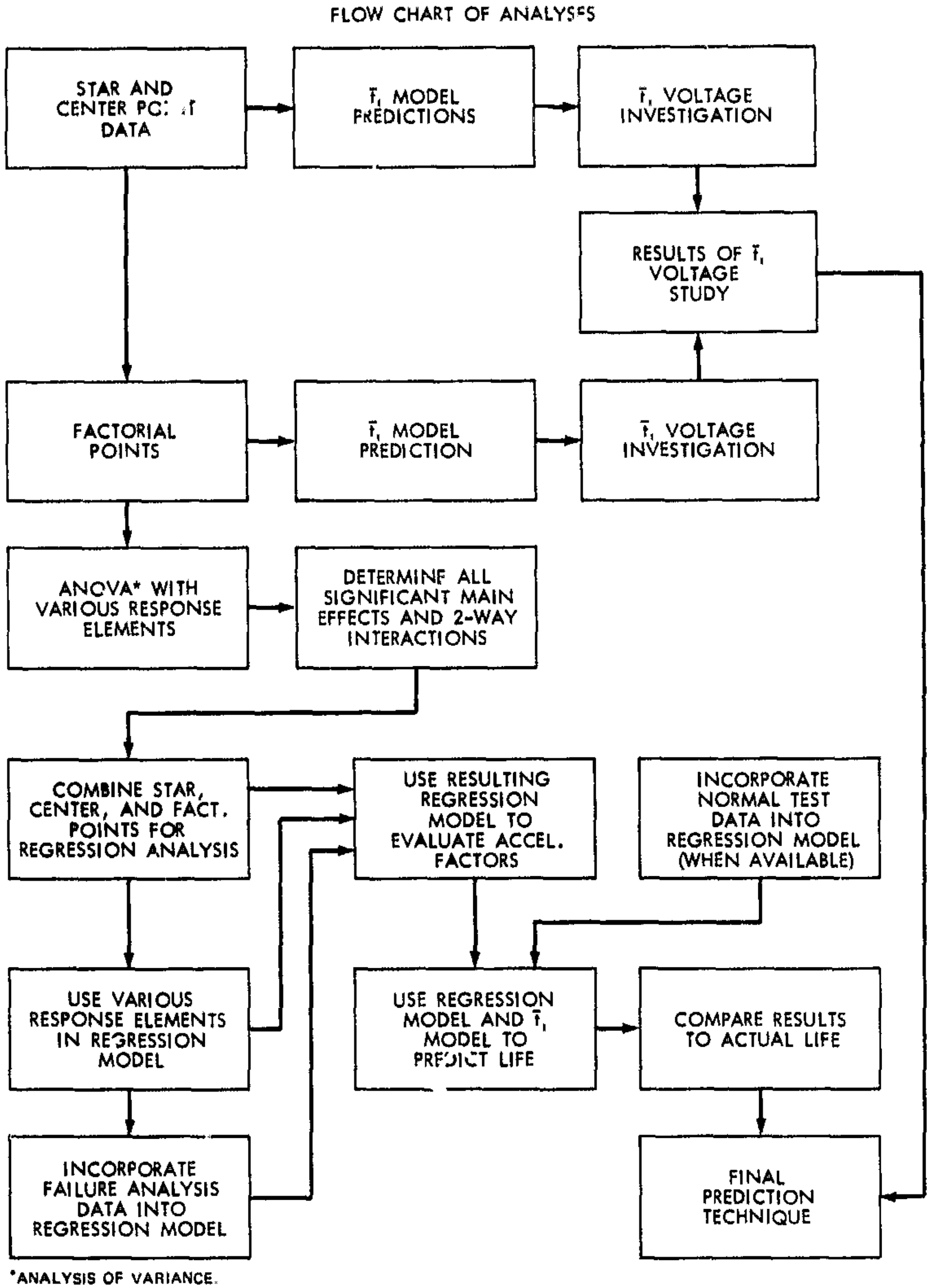

Figure 4. Flow Diagram 3

7.3.3 COMBINATION OF STAR, CENTER, AND FACTORIAL POINTS

a. Combine star and center points with all significant factors of the factorial points in multiple regression models.

b. With failure time as the dependent variable in the resulting regression model, use the model to relate accelerated failures back to normal failures.

c. Use various response elements in analysis of variance and regression model to find their accelerated relationship to normal life.

d. Incorporate failure analysis data into regression model using Battelle (Dr. Thomas) technique.

7.3.4 PREDICTION OF BATTERY LIFE

a. Use regression model estimates of failure times in $\bar{t}_i$ model with best indicator of life ($\bar{t}_i$ = x volts) from results of voltage study in 7.3.1b and 7.3.2b.

b. Compare and/or combine results with other life prediction methods (namely, cryptanalytic).

7.4 AIR FORCE DATA ANALYSIS

a. Determine correlation between prediction model (Ref. f) and accelerated test data.

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