N87-11102

NICKEL HYDROGEN LOW EARTH ORBIT LIFE TESTING

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ABSTRACT

A program to demonstrate the long term reliability of NiH_2 cells in low earth orbits (LEO) and support use in mid-altitude orbits (MAO) has been initiated. Both 3.5 and 4.5 inch diameter nickel hydrogen cells are included in the test plan. Cells from all U.S. vendors are to be tested. The tests will be performed at -5 and 10 deg. C at 40% and 60% DOD for LEO orbit and 10 deg. C and 80% DOD for MAO orbit simulations. The goals of the testing are 20,000 cycles at 60% DOD and 30,000 cycles at 40% DOD. Cells are presently undergoing acceptance and characterization testing at NWSC Crane. Funding has been provided by the AFSTC and two AF SPO's to initiate the testing, but additional funding must be acquired to complete the purchase of cells and to assure completion of the testing.

INTRODUCTION

The use of nickel hydrogen (NiH_2) batteries in high orbit applications is well established. Sufficient test data are available to make estimates of the actual reliabilities for both the COMSAT and the Air Force/Hughes designed cells. However, the application of properly designed NiH_2 cells to low earth orbits (LEO) has not been demonstrated. A program has been initiated by the USAF Space Technology Center to develop the necessary data base to support use of NiH_2 batteries in LEO at levels that would offer significant improvements in life and depth of discharge over present state-of-the-art nickel cadmium batteries. The program is to be performed at NWSC Crane using new test control facilities. The plans, requirements and status of the test program are presented.

BACKGROUND

In the Spring of 1984 a survey of life testing status and results for NiH_2 cells was performed (ref. 1). Data were found to either be available or would be available within the next two to three years to demonstrate reliability and confidence in the use of NiH_2 batteries in high orbits requiring up to 3000 cycles at maximum depths of discharge of up to 80%. Calendar life on orbit in excess of ten years was anticipated. It was suggested that optimum performance would be achieved when the temperature of operation was at less than 15 deg. C and the amount of overcharge should be minimized while maintaining an adequate state of charge.

The data available to support use of NiH_2 batteries in low earth orbits are deficient. The extant data base consists of mixtures of technologies and several generations of LEO cell designs. Cells have been tested under extreme conditions with less regard for the limitations of these cells than is normally applied to aerospace secondary cells. By the same token, testing of the most recently built cells under severe conditions (90 min. cycle, 80% DOD, 1.4 C discharge, 0.8 C charge, 105% charge return ratio, 23±4 deg. C) has consistently given 10,000 cycles before failure (due to low voltage) occurred. This suggests that the cells have the capability to surpass the performance of present state-of-the-art NiCd cells in LEO applications. Presently, design variations among NiH_2 cells are beginning to stabilize and future changes are expected to be incremental. Testing to establish reliability and performance appears to be practical at this time.

NiH_2 cells must significantly outperform NiCd cells or they would be disadvantageous to use because of their greater specific volume, present higher unit cost, and the risks inherent in any new design. This increase in performance can be in life and/or usable energy density. Present NiCd batteries used under near-optimum conditions offer 14 - 18,000 cycles at 20 - 25% DOD and 25 - 30,000 cycles at 7 - 14% DOD with high reliability and confidence depending on the specific load profile, power system requirements, and environment. NiH_2 cells must demonstrate significant increases over these levels if they are to be the next generation of LEO batteries. This life test will demonstrate the performance capabilities of state-of- the-art NiH_2 cells in low earth orbit and will provide a database, when combined with other relevant life test data and with program specific testing, that will permit an estimate of reliability at an appropriate confidence level. State-of-the- art, individual pressure vessel-type cells of 3.5 and 4.5 in. diameter are to be tested.

OBJECTIVES

The test will be a predominantly LEO regime (90 min. orbit with 30 min. of eclipse and 60 minutes of sun) with some test packs tested in MAO-to-HEO conditions (400 to 500 cycles per year with a 4 to 12 hour orbit) if funding and schedule permit. The NiH_2 cell life test plan has the following objectives:

1. Demonstrate NiH_2 performance in LEO applications and support use in MAO at levels superior to current NiCd capabilities.
2. Develop a statistically significant NiH_2 battery cell database.
3. Disseminate the test data and results in a timely fashion.
4. Demostrate NiH_2 cell performance in pulse applications.
5. Demonstrate that the Manufacturing Technology Program (MANTECH) cells are capable of performing in high orbit as well as LEO.

STATISTICAL REQUIREMENTS

The statistical requirements for a test must be based on the largest homogeneous unit: single type of cell, same vendor, same test conditions. Analysis after testing has progressed may justify the combination of several of these units to increase the reliability and confidence level for a particular application. Generally tests performed under more severe conditions can support reliability assessments for applications at less severe stress levels.

The two-parameter Weibull function (zero failure rate at the start of the test is assumed) will be used to estimate reliability. The expression for the reliability after integration of the probability density function is,

$$R(t) = \exp[-(t/\mu)\beta] \qquad (1)$$

where β is the shape of the failure distribution parameter, μ is the scale parameter associated with the rate of failure and t is the test time (ref. 2). This is a general function that reduces to an exponential distribution function (β = 1) or closely approximates a normal distribution function (β = 3.313). The use of the function for evaluating NiCd test data has been demonstrated (ref. 3). When no failures occur in a test that has run for time t, the success-run theorem (Bayes' Formula),

$$R = (1 - C)^{1/(n+1)} \qquad (2)$$

can give the relationship between confidence level C, the reliability at that confidence level R, and the sample size n.[2] Table I shows the relationship between sample size, test time, reliability, and confidence level for an assumed normal distribution (β = 3.313). Ten cell packs are chosen as the test unit because of the reliability and confidence levels attainable and because this sample size permits evaluation of the failure distribution function.

REPORTING

Reports will be issued when significant milestones are reached and at regular periods. Each major milestone, e.g. completion of acceptance testing, will result in a brief report. The progress of the test will be reported in an "Annual Report of Cycle Life Testing" and will, in addition, be summarized at least once a year and presented in an appropriate forum. The detailed data will remain available for access by qualified organizations.

COORDINATION WITH OTHER TESTING

In a separate, program-oriented test the Martin-Marietta Aerospace in Denver is performing similar life testing. Their test matrix has been coordinated with this matrix to assure proper distribution and adequate data at the key points; that is, at the center 10 deg. C test area. They are planning to test at 20 deg. C and accounts for that condition missing from this matrix. Any other testing data that becomes available and that is relevant will be incorporated into the growing database.

TEST ARTICLES

It is the intent to test cells from all viable vendors in sufficient numbers to provide a comparison and to establish a statistically significant database with a sufficiently high confidence level. A minimum of 155 3.5 in diameter and 45 4.5 in diameter cells are included in the test plan. Additional cells will be added as the need is demonstrated. Insofar as schedule and funding permits, approximately equal numbers of cells from the four U.S. vendors (GEBBD, Eagle Picher, Yardney, and HAC) are to be tested. The initial test articles will be 3.5 in. diameter cells drawn from purchase orders previously placed with Yardney, Eagle Picher, and GEBBD by AFWAL/POOC and AFWAL/ML. It is hoped that part of the complement of 4.5 in. diameter cells will be drawn from orders already placed (CPV program) by AFWAL/POOC.

In the future cells will be purchased to a "Specification for Nickel Hydrogen Cells" that defines required performance in terms of voltage, capacity, weight, dimensions, and life. Presently used specifications will be covered by this specification because present versions specify additional details that are to be in the MCD or present test requirements are less severe. Each vendor's product will be procured to a designated part number with the details of construction contained in an associated, approved manufacturing control document (MCD). Stability, performance, and conformance to specification will be demonstrated at each vendor's facility. Formal acceptance testing is to be performed at the testing location (Naval Weapons Support Center (NWSC), Crane, IN).

All cells will be in flight configuration (no special test units) and of flight quality. The cells are to be hermetically sealed. Pressure monitoring will be by externally mounted strain gauges only.

TEST OUTLINE

The test consists of acceptance and characterization testing, life testing, and failure and end-of-test analyses.

PRE-LIFE TESTING

Acceptance testing will be conducted at the life test site. Tests include standard capacities at -5, 10, and 20 deg. C using rates appropriate to LEO applications (a rate of C is proposed because this approximates the conditions of the test), overcharge stability and reference capacities, and charged stand loss determinations. The ampere-hour and watt-hour capacities of the cells will be reported to 1.20, 1.15, 1.10, 1.05, 1.00, and 0.5 V. These data will provide reference data for system applications.

A 20% sample of the cells of each type (at least two cells) and from each vendor shall be subject to random vibration testing at levels 6 dB higher than the highest level anticipated in any application. The cells that are vibrated will be distributed throughout the test packs to determine any effects of vibration.

Characterization tests will be performed to determine the required charge characteristics. A group of 5 cells of each type and from each vendor will be tested to determine charge efficiencies at selected rates and temperatures. Watt-hour and ampere-hour efficiencies will be determined at four charge rates, 3 discharge rates, and at 4 temperatures.

The cells are to be assembled into test packs which contain cells from only one vendor. Heat removal is by conduction through flanges attached to the cells onto thermally conductive plates. The flanges will be of a standard type similar to the units used on previous USAF/Hughes-type cells to provide for similar heat removal pathways and rates for all cells. Each pack will have at least one cell with a pressure transducer.

LIFE TESTING

The goals for these tests are to demonstrate at least 30,000 cycles at 40% DOD and at least 20,000 cycles at 60% DOD in LEO and at least 5000 cycles at 80% DOD in MAO or high orbit. The 40% DOD level is greater than present NiCd cells can expect to achieve at three years planned life. A small number of cells (5 from each vendor) will be tested at 25% DOD to provide correlation with present NiCd testing and life databases. Cells could fail to reach a desired goal, e.g. 60% DOD and 5 years, and still perform significantly better than present state-of-the-art NiCd cells.

A second goal is to establish a minimum reliability of 90% with a confidence level of at least 80% at the cycle lives stated above. This goal requires one additional year of testing beyond the life goals stated, but assumes that none of the groups of ten cells can be statistically combined.

The DOD is defined as the percent of the measured capacity to 1.00 V of the lowest capacity cell in the test pack under the most appropriate conditions in acceptance testing. This number may be higher or lower than the rated capacity used during acceptance testing.

Failure is defined as a voltage of less than 0.50 V at the end of the prescribed discharge or a voltage greater than 1.75 V during any portion of the charge. Data for other end-of-useful-life criteria will be available. Upon being declared a failure, the cell will be removed from the test pack and subjected to a repeat of at least part of the acceptance test within 180 days of failure. The cell shall then be dispositioned for failure analysis.

Data (current, voltage, pressure, and temperature) will be recorded for each test pack with sufficient frequency to assure that extrapolation between data points can be performed with adequate accuracy to detect any short term or long term trends. These data will be available for plotting or display and for the computation of watt-hour and ampere-hours input and output as well as charge returns. Periodically, e.g. every 2000 cycles, a complete plot of a charge/discharge cycle will be generated for each cell in test for comparison to detect trends.

The distribution of cells, the DOD's, and the temperatures are shown in Table II for the completely funded test and for the minimum test necessary to meet the primary goals. The LEO test will use 90 min. cycles with 30 min. discharges.

The charge procedure will consist of a high rate charge to return the bulk of the charge removed and a lower rate to complete the charge. This prevents subjecting the cells to high rate overcharge. The planned charge control method is ampere-hour integration (recharge fraction control). This method is flexible and particularly easy to integrate into a digital control system. Control shall be accomplished by changing the charge returned under a fixed depth of discharge until the following parameters are minimized:

1. The decrease in the end of discharge voltage
2. The increase in the end of charge voltage (high rate and trickle)
3. The recharge fraction (both watt-hour and ampere-hour)

These parameters will be adjusted during the test as performance dictates.

Reconditioning will not be performed on the cells in LEO testing. MAO testing may require reconditioning to maintain adequate efficiency. No capacity discharges shall be performed.

The test is scheduled over a seven year period as shown in Figure 1. To maximize the information and provide the best statistics, the test should continue until the majority of the cells in each pack have failed.

SPECIAL TESTING

The general test plan will use continuous constant current discharges. However, the applications requiring pulsed high rate discharge within the envelope of the planned DOD's are sufficiently prevalent to make the correlation of such results with the general life test important. A small group of cells will be placed on life test in a pulsed discharge regime at maximum rates of approximately 5C. The detailed test plan for this portion will conform to the overall test organization, but will be prepared separately. Cells will be acceptance tested at the testing organization and sent to The Aerospace Corporation Battery Evaluation Laboratory for this testing.

STATUS

In the Spring, 1985, two Air Force System Program Offices (SPO), AFWAL AeroPropulsion Laboratory (AFWAL/POOC), and the AF Space Technology Center (STC) completed a transition agreement that seeks to provide data needed to bring NiH_2 battery technology into general use in all intended applications. The two SPO's and the STC committed funds for the initiation of the testing. AFWAL/POOC agreed to provide NiH_2 cells from previous contracts for testing. The AFWAL Materials Laboratory agreed to commit the Manufacturing Technology Program (MANTECH) cells to the life test program. The numbers of 3.5 in. diameter cells committed to the test program and their expected availability dates are listed in table III.

Funding provided was sufficient to purchase test equipment, including a new computer facility for this test at NWSC Crane, and to proceed with the testing of the committed cells. This equipment will also serve as replacements for some of the outdated and less reliable equipment currently in use.

Test documentation including the life test plan, cell specification, and life testing procedure have been prepared and are currently undergoing review. Failure analysis documentation is yet to be prepared.

Cells have been received and are currently undergoing acceptance testing.

Additional funding is sought to complete the purchase of cells for the minimum test matrix shown in Table II and to assure the completion of the program.

SUMMARY

A program to demonstrate the long term reliability of NiH_2 cells in low earth orbits and support use in mid-altitude orbits has been initiated. Both 3.5 and 4.5 inch diameter nickel hydrogen cells are included in the test plan. Cells from all U.S. vendors are to be tested. The tests will be performed at -5 and 10 deg. C at 40% and 60% DOD for LEO orbit and 10 deg. C and 80% DOD for MAO orbit simulations. The goals of the testing are 20,000 cycles at 60% DOD and 30,000 cycles at 40% DOD. Cells are presently undergoing acceptance and characterization testing at NWSC Crane. Funding has been provided by the AFSTC and two AF SPO's to initiate the testing, but additional funding must be acquired to complete the purchase of cells and to assure completion of the testing.

REFERENCES

1. C.C. Badcock and M.J. Milden, "An Industry and Government Survey: Life Testing of Nickel Hydrogen Cells," Proceedings of the 1984 GSFC Battery Workshop, NASA Conf. Pub. 2382, 1985, p. 583.

2. Charles Lipson and Narendo J. Sheth, Statistical Design and Analysis of Engineering Experiments, McGraw-Hill, New York, 1973.

3 J.H. Matsumoto, G. Collins, and W.C. Hwang, "Applicability of Accelerated Test Data," Proceedings of the 19th Intersociety Energy Conversion Engineering Conference, Vol. 1, 303 (1984).

TABLE I. TEST TIME, RELIABILITY, AND CONFIDENCE LEVEL FOR A FIVE YEAR APPLICATION AS A FUNCTION OF THE SAMPLE SIZE

Sample Size Without Failures	Test Time (R=90%, C=69%)	Reliability (C=69%, t=5 yrs)	Confidence Level (R=90%, t=5 yrs)
1	8.36 yrs.	56.0%	19.0%
2	7.40	68.0	27.1
3	6.78	74.9	34.4
5	6.00	82.4	46.9
6	5.73	84.7	52.2
7	5.50	86.5	57.0
8	5.31	87.9	61.3
9	5.15	89.1	65.1
10	5.00	90.0	68.7
15	4.46	93.0	81.5
20	4.12	94.6	89.1

TABLE II. PLANNED NiH_2 LIFE TEST MATRIX

ORBIT	DOD	MFR	3.5" DIA. CELLS[1] TEMPERATURE[2] 10C	3.5" DIA. CELLS[1] TEMPERATURE[2] -5C	4.5" DIA. CELLS[1] TEMPERATURE[2] 10C	TOTAL CELLS 3.5"	TOTAL CELLS 4.5"
LEO	25%	YARD	5			5	
		EP	5			5	
		GEBBD	5			5	
		HAC	5			5	
	40%	YARD	10	10		20	
		EP	10		10	10	10
		GEBBD	10	10		20	
		HAC	10		10	10	10
	60%	YARD	10		10	10	10
		EP	10	10		20	
		GEBBD	10		10	10	10
		HAC	10	10		20	
MAO	80%	YARD	10 (5)		10 (0)	10 (5)	10 (0)
		EP	10 (0)		10 (0)	10 (0)	10 (0)
		GEBBD	10 (0)		10 (0)	10 (0)	10 (0)
		HAC	10 (0)		10 (0)	10 (0)	10 (0)
SPECIAL TESTS:							
	2 or 3 - 3.5 inch cells and 1+ - 4.5 inch cell from each vendor:					10	5
TOTAL CELLS:[3,4]						190 (155)	85 (45)

1. The complete test configuration is shown with the minimum credible test shown in () where the two differ.
2. The temperatures specified are to have tolerances of ±4 deg. C.
3. Strain gauge pressure monitors are required on at least 20% of the cells.
4. An additional set-aside of one each wet and dry cell of each size from each manufacturer is recommended (not in above totals).

Table III. 3.5 Inch Diameter NiH_2 Cells Committed to the Test

SOURCE	APPROXIMATE NUMBER[1]	DATE AVAILABLE
Yardney		
MANTECH	25 (ZA)	Winter 86
AFWAL	5 (ZA)	Winter 86
Eagle Picher		
Adv. Dev. Prog.	24 (A)	Spring 85
AFWAL	15 (Z)	Summer 85
HAC (for AFWAL)	18 (Z)	Spring 85
GE BBD		
AFWAL	15 (Z)	Winter 86

1. The letters indicate the type of separator: (A) asbestos, (Z) Zircar, and (ZA) MANTECH combination.

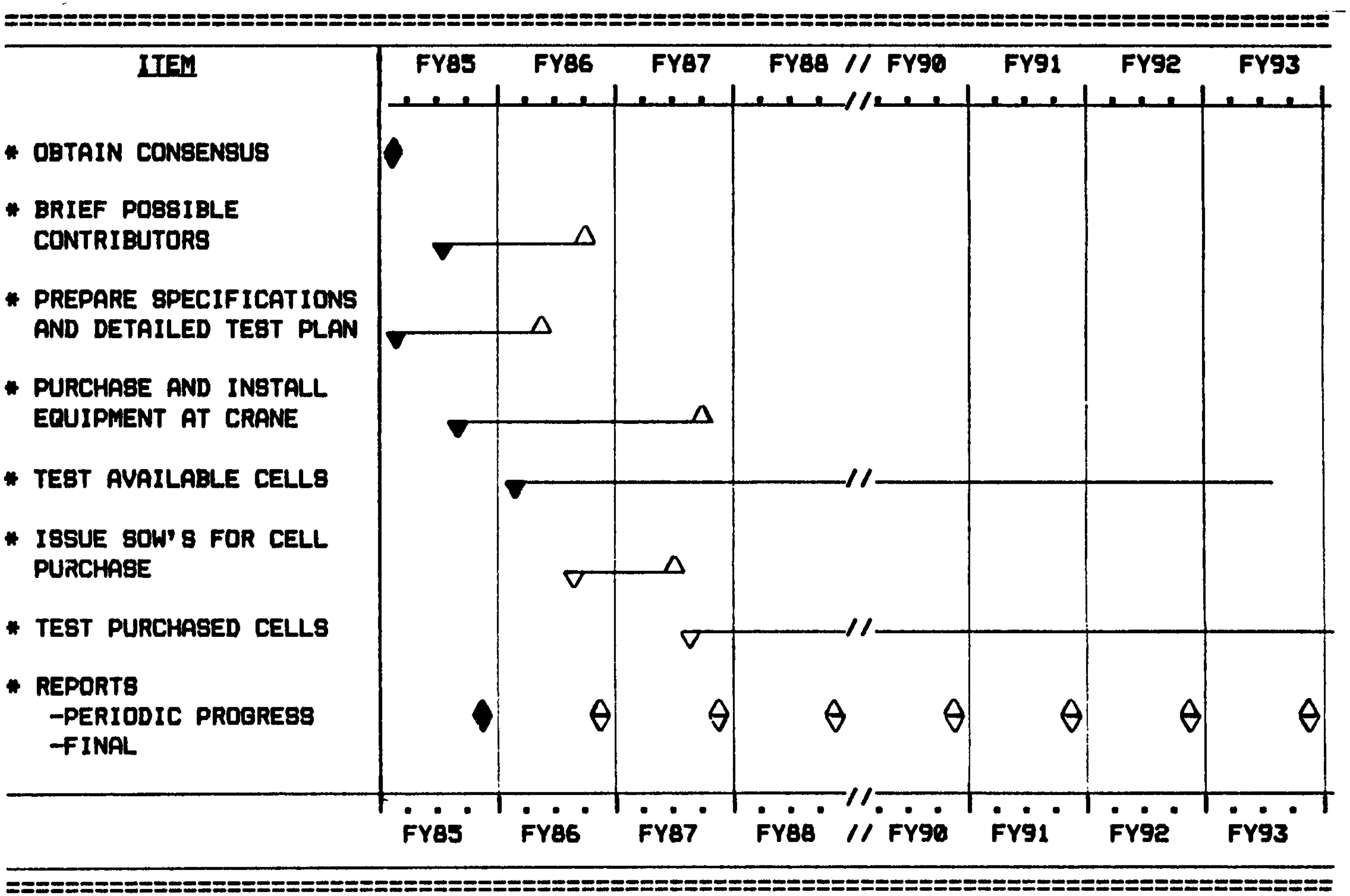

Figure 1. SCHEDULE FOR THE NiH_2 LIFE TEST FOR A MINIMUM OF 7 YEARS. OPEN TRIANGLES INDICATE THAT THE ACTIVITY HAS NOT STARTED OR IS NOT FINISHED. ARROWS INDICATE THE ACTIVITY MAY EXTEND LONGER THAN THE FIGURE SCALE.