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NICKEL HYDROGEN BATTERY CELL TESTING DATA BASE: AN
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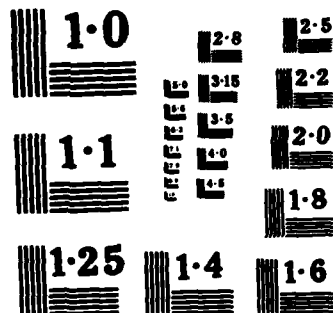
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**Nickel Hydrogen Battery Cell
Testing Data Base:
An Industry and Government Survey**

**C. C. BADCOCK and M. J. MILDEN
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Laboratory Operations
The Aerospace Corporation
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31 December 1985

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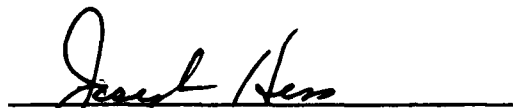
Lt Christine Bonniksen, SD/YASB, was the Air Force Project Officer.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.



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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Both government and industry were surveyed to determine the level of testing of nickel hydrogen (NiH ₂) battery cells and to evaluate the demonstrable capabilities of the couple. Only flight-type cells undergoing ground test were incorporated in the data base; no boilerplate cells or flight batteries were included. Both USAF-design and COMSAT-design cells, as well as a few cells produced by SAFT, were listed. The USAF design is in test in both		

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high and low-earth-orbit simulations, whereas the COMSAT design, intended specifically for high-orbit applications, is being tested predominantly in high orbits. The data from over 400 cells show that the reliability and capability of both designs for high-orbit applications are reasonably established out to ten years in geosynchronous orbit, and to approximately 3000 cycles in other high-orbit applications. However, the data base is weak and incomplete for applications of the USAF cell in low earth orbit. This results from the harsh testing environment to which these cells have been subjected, as well as from various minor design questions that were not resolved when these cells began testing. It must also be pointed out that most of the testing data base is constructed from cells that were developmental in design or manufacture (all cells purchased for a test are used, even if their performance is questionable), as contrasted to a flight program where it can be assumed that many of the failures listed would have been rejected prior either to life test or their use in a flight battery.

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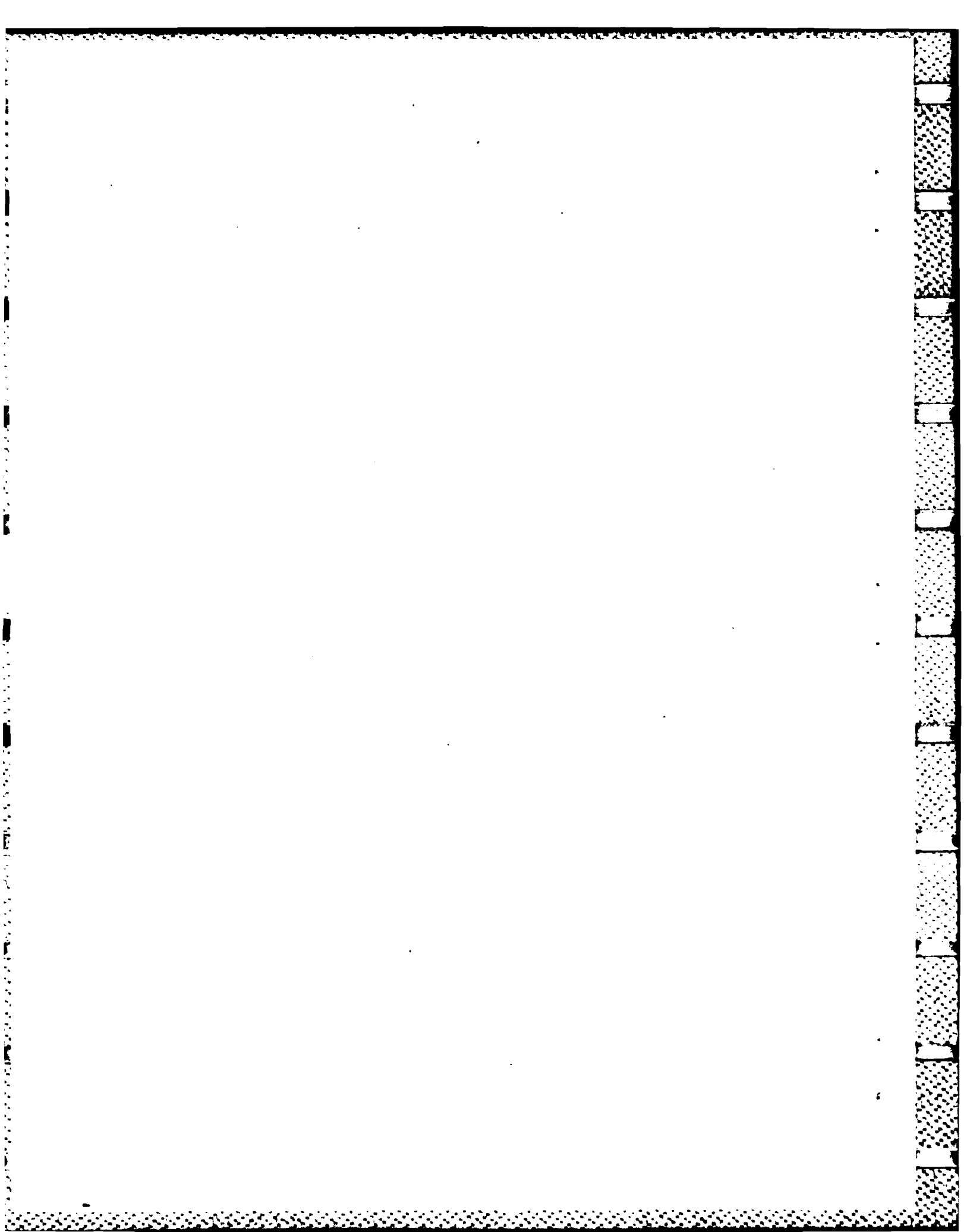


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I. INTRODUCTION

A survey of the testing data base for nickel hydrogen (NiH_2) battery cells has been performed. The objective of this survey was to evaluate the status of cell testing in general and of the Air Force-design nickel hydrogen cell in particular. Sufficient detail was sought so that a critical evaluation of the test results and cell performance could be made. As subtle differences in test conditions can result in large differences in cell performance, an effort was made to define the actual test environment as closely as possible. These data, obtained between February and May of 1984, reflect the status of tests at that time. Periodic updates of the information are planned.



II. THE DATA BASE

Potential sources of test data in the United States and Canada were asked to provide results of testing of any and all NiH_2 cells. These sources were provided with a questionnaire that was either completed by the respondent or by the interviewer from data received by telephone. These inputs were supplemented by reviewing IR&D reports and reports in Proceedings of the IECEC and the GSFC Battery Workshop. COMSAT Laboratories testing is not included in this report; this omission results in the loss of a significant portion of the COMSAT-design NiH_2 cell data base.

In this survey the term "USAF design" applies to cells with annular electrodes, leads placed on the inner perimeter of the electrodes, and, generally, a recirculating stack. The electrolyte has a net flow within the recirculating stack, wherein the negative and positive plates alternate in the plate pack so that the gas screen separates the rear of the positive and negative plates. The front faces of the plates are separated by asbestos or zirconia fabric (Zircar) separators. The gas screen provides for delivery of hydrogen gas and for transport of oxygen gas during overcharge, directly across the screen from the adjoining positive to the catalytic negative.

The COMSAT design indicates cells with circular electrodes with chords removed for leads on the outer perimeter and a back-to-back plate pack design. In this design two positives are placed back to back, separated by asbestos from negatives that are also back to back with a gas screen separating them; during overcharge, oxygen escapes from the positives along the plate pack edge to the backs and sides of the negative. This design does not produce a net electrolyte flow. The COMSAT cell was designed for high-orbit use and is not a high-rate, high-cycle-frequency cell. The USAF cell was originally designed for high-rate, high-cycle-frequency, low-earth-orbit (LEO) use; however, it can be used in any less stressful orbit.

The data obtained relate to some 412 cells from several generations of both COMSAT and USAF designs. Thus, some of the longest tests and most impressive data are from cells of earlier designs. Differences in designs

are, for the most part, evolutionary in nature: changes in seals, improvements in positive electrodes, and minor changes in construction are typical. From a performance standpoint the most significant change in cell design in this data base is the introduction of the wall wick for electrolyte management in the USAF design. The earliest test data are for cells without this feature. All cells manufactured in the U.S. included in this survey use electrochemically impregnated positive plates. Ten SAFT cells manufactured in France and included in the COMSAT grouping may use chemically impregnated positives, as well as a separator system different from the asbestos used universally in the COMSAT design or the asbestos or Zircar used in the USAF design.

The distribution, according to their design type, of cells in test shows that at least 192 cells of the COMSAT design are either being tested, are in preparation for testing, or have been tested. All but four of these have been tested in some type of high-orbit simulation. Of the 271 USAF cells already tested, being tested, or in preparation for testing, well over half have been subjected to, or are planned to be tested in, simulated low-earth-orbit regimes. No "boiler plate" test data were included in the data base because of the questionable relevance of such data to flight-type cell performance. Generally "boiler plate" data are applicable, but instances of rework during test and variation in electrolyte quantity, pressure, and plate-to-volume ratios compared to flight-type cells are sufficiently common that these data cannot readily be evaluated.

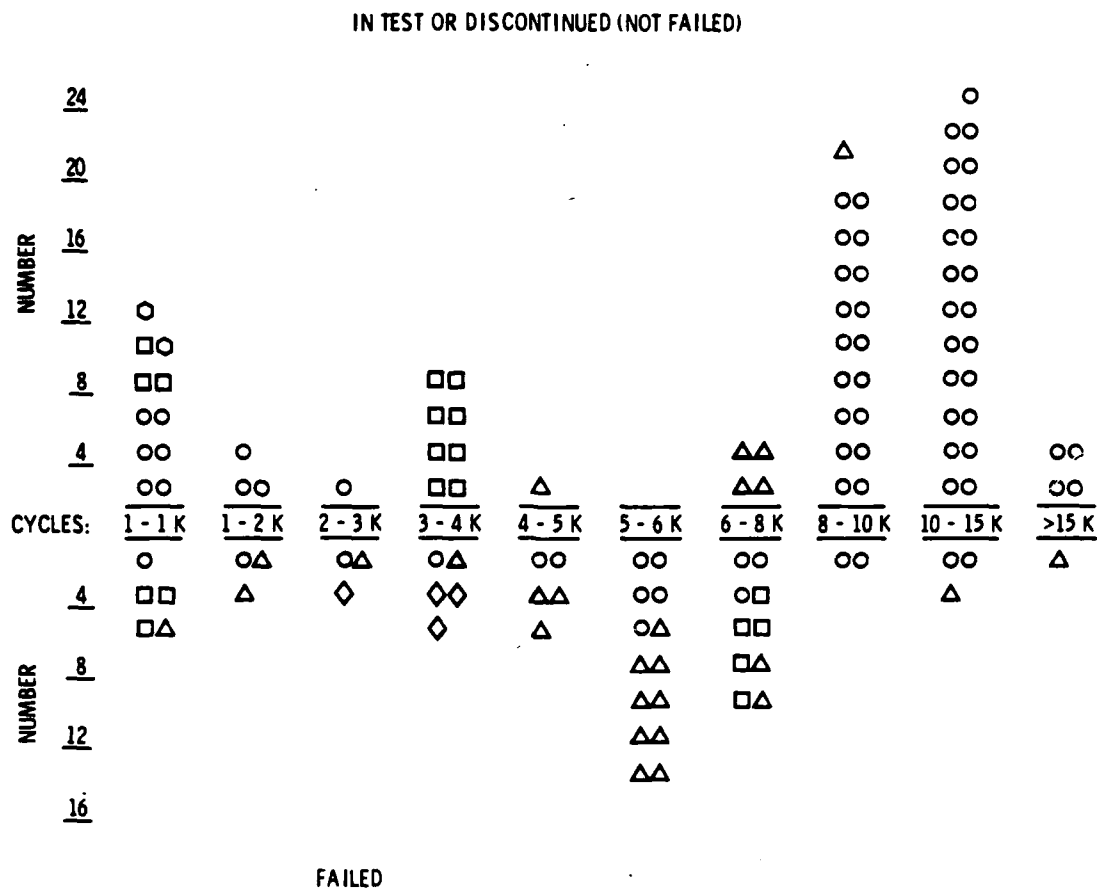
III. DISTRIBUTION OF TESTING AND FAILURES

Figures 1 through 4 summarize in bar graph form the data on the distribution of test durations and failures. The definition of failure is taken from the data reviewed. Most failures are defined as the inability of the cell to maintain a minimum of 1.0 V during discharge. Fewer than one-half of the failed cells shorted. The rest were low-voltage failures without confirmed shorts. No cells were reported to have failed open-circuit testing. If a test was terminated without cell failure, it is reported as a discontinued test.

Figure 1 summarizes all LEO test experience for the USAF-design cell. These data are skewed somewhat by the 20 of 21 cells that have experienced over 8000 cycles and the 20 of 21 cells that exceeded 10,000 cycles from the two ground-test batteries of the Air Force Flight Experiment. These cells are of an older design (ca. 1975) and do not represent the current state of the art; they used back-to-back electrodes and had no wall wick. Only one cell in each group of 21 failed early. The remaining 20 cells are either continuing in test or were discontinued without additional failures.

Removal of these Flight Experiment test batteries from the distribution results in the distribution shown in Fig. 2. The data for the USAF design in low earth orbit suggest that a significant difference in performance exists between cells tested predominantly at 80% depth of discharge (DOD) and those tested at less than that depth. There are insufficient data to make a finer distinction. The triangles indicate cells tested at 80% DOD in Figs. 1 and 2.

Figure 3 summarizes the experience for both USAF cell designs in high-orbit simulations. Figure 4 shows similar data for the COMSAT cell design, except that all the testing is for simulated geostationary orbit conditions. Both accelerated and real-time testing are combined in both of these figures. There is no apparent difference between DODs of 80% and lower in the performance under these conditions. Most failures, ten for the COMSAT design and one for the USAF design, can probably be attributed to workmanship or design defects that have since been corrected or would not have been included in a flight cell selection process.

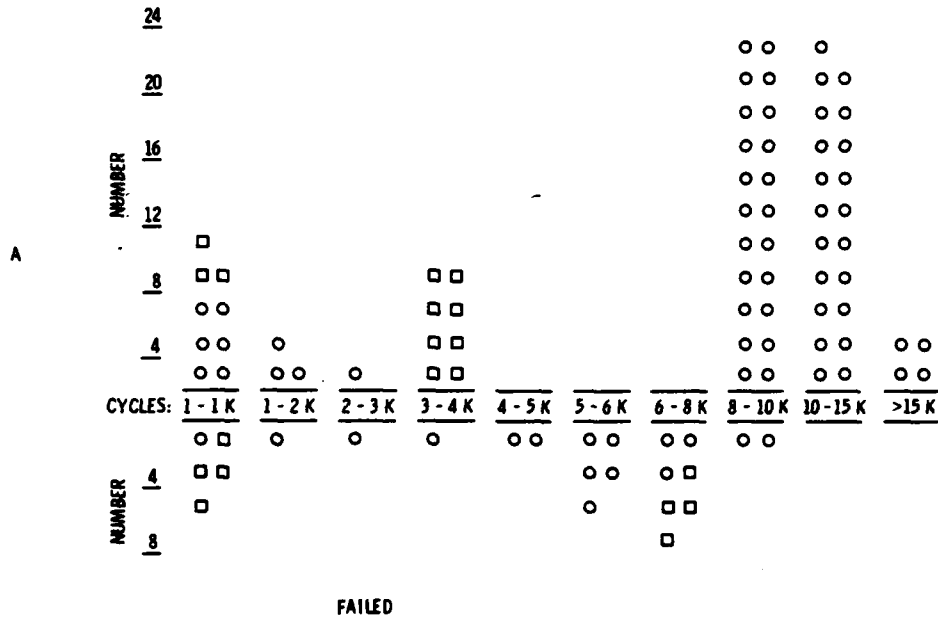


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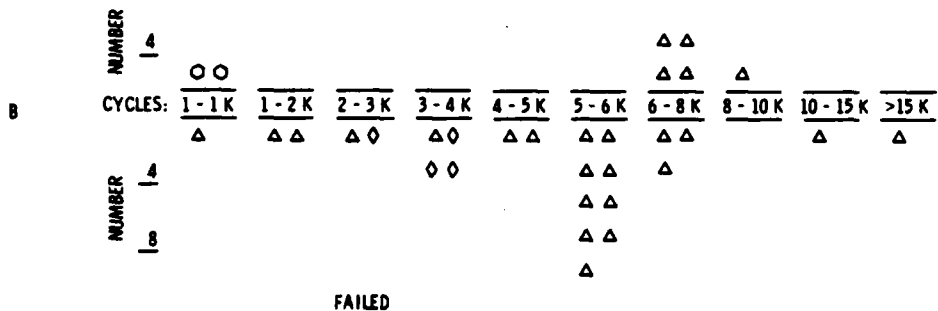
- non ADP II (Advanced Development Program) cells at less than 80% DOD;
- ADP II cells at less than 80% DOD; △ non ADP II cells at 80% DOD;
- ◇ ADP II cells at 80% DOD; ○ MANTECH cells. Each symbol represents one cell.

Fig. 1. Distribution of Testing and Failures for All USAF-Design Cells (128 Cells) in Low-Earth-Orbit (LEO) Simulations. Triangles indicate numbers of cells tested at 80% depth of discharge. Circles indicate the major contribution from cells in the two USAF Flight Experiment batteries.

a. USAF-DESIGN CELLS TESTED: LEO AT LESS THAN 80% DOD
IN TEST OR DISCONTINUED (NOT FAILED)



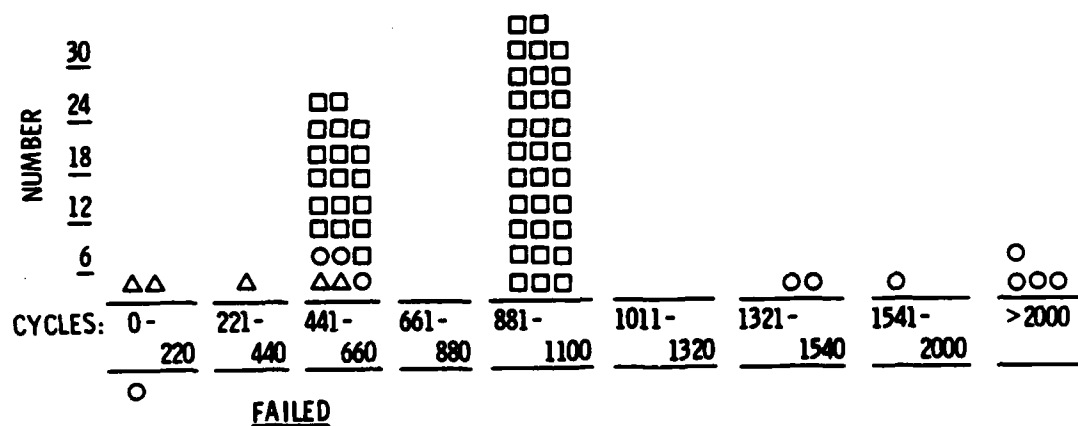
b. USAF-DESIGN CELLS TESTED: LEO AT 80% DOD
IN TEST OR DISCONTINUED (NOT FAILED)



Legend: ○ non ADP II (Advanced Development Program) cells at less than 80% DOD;
□ ADP II cells at less than 80% DOD; △ non ADP II cells at 80% DOD; ◇ ADP II
cells at 80% DOD; ○ MANTECH cells. Each symbol represents one cell.

Fig. 2. Distribution of Testing and Failures for USAF-Design Cells in LEO Simulations, Excluding Those 42 Cells in the Two USAF Flight Experiment Test Batteries. Triangles indicate numbers of cells tested at 80% depth of discharge.

IN TEST OR DISCONTINUED (NOT FAILED)



10

COMSAT-DESIGN CELLS: HIGH ORBIT

IN TEST OR DISCONTINUED (NOT FAILED)

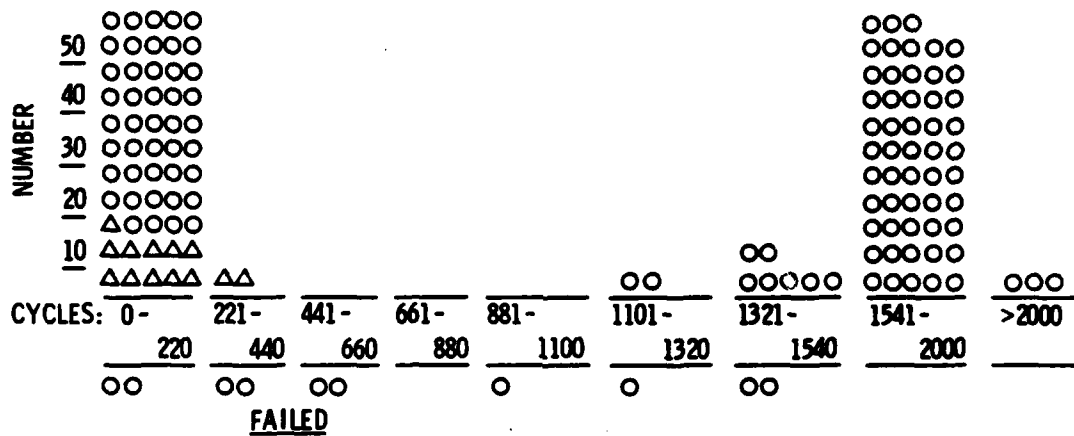


Fig. 4. Distribution of Testing and Failures for COMSAT-Design Cells in Geostationary-Orbit Simulation for 132 Cells.

IV. DISCUSSION

The data available at this time suggest that both the USAF and the COMSAT-design cells can be used in high orbit with high reliability. This assumes that the observed failures were for the most part manufacturing defects and activation problems that have been solved or would be screened out in a flight program. Certainly the number of cells that have survived at least 1000 cycles (equivalent to a ten-year geostationary orbit) at up to 80% DOD is impressive at so early a point in the technology development cycle. Taking total numbers and including both high- and low-orbit testing for the USAF design, some 148 cells have been tested to 1000 or more cycles at DODs greater than 50%; there have been seven failures prior to reaching 1000 cycles. A similar comparison for the COMSAT design shows that at least 65 cells have provided 1000 cycles or more, with seven failures. The failures that have occurred must be considered to be from development lots of cells; the failures would be reduced or eliminated in an actual flight program. (It must be pointed out that these data do not support use at 80% DOD, because no contingency for acceptable degradation or system failures has been included. The ultimate capability of the cells from which power system designs can be derived is, however, demonstrated.)

Low-earth-orbit testing has not demonstrated the long life at the great depths of discharge that the USAF-design cell promises. Examining the data and coupling it with other information suggest that several elements may well serve to cause premature failure of cells. The stresses in low earth orbit can be much greater, particularly at greater depths of discharge. First, recognizing that the nickel electrode is inherently the weakest component of the cell, steps must be taken to minimize the possible stresses. Second, designs and procedures that might prove satisfactory for high-orbit use, but that may not permit cell performance to be maintained over the more than 25,000 cycles required for LEO, must be scrutinized. Finally, the charge procedures (the discharge is largely dictated by mission considerations) and thermal environment must be adjusted to ensure that these do not limit cell

life. It is important to note that the capability of NiCd batteries to perform for more than three years at 20 to 25% DOD has been developed over the years by a better understanding of how the cells work; by improvements in cell components; and by fine tuning of cell manufacturing procedures, battery handling practices, and power subsystem and thermal designs. Similar attention to NiH₂ batteries could result in very significant improvements.

The positive electrode is subject to stresses due to charge-discharge cycling, and especially to overcharge. These are caused by molecular volume changes between the various phases of charged and discharged material, by relaxation of these phases, by oxygen gas evolution, and by a host of design variables involved in the plate manufacturing process. Research and development can certainly lead to more stress-resistant and efficient nickel electrodes. Similarly the stresses can be mitigated by minimizing overcharge, by limiting charging and discharging that cause high strain, and by keeping temperatures low so that electrode efficiency is maximized.

The design and production of NiH₂ cells is still evolving. Improvements in design such as those shown by MANTECH will continue to make the cells that are under test less than the state of the art. Recent problems with asbestos separators in both cell designs and the historic problems with pinholing of the negative electrode in Zircar-separated cells suggest that a better separator material is needed. The test data show that neither separator is superior in terms of life or performance. However, it may be that both separators are satisfactory and that activation or other handling procedures are deficient. The performance of some recently manufactured cells may be related to testing or specific manufacturing problems, because other cells produced near the same time with similar materials have not shown similar anomalies. Careful review of past procedures and of any proposed changes must be made, and acceptability must be demonstrated by test.

The electrical environment must also be adjusted to minimize stress. Overcharge, particularly at high rates, must be avoided. Constant voltage charging does not appear to be an acceptable charge-control procedure because the slope of the voltage vs. the capacity-returned curve is shallow in NiH₂

cells, and because the abrupt voltage rise near the end-of-charge characteristic of NiCd cells may not be reliable in NiH_2 cells. Tests using constant voltage charge have given good results; however, the variations in the charge-return ratios indicate that better control of overcharge may be useful. The easiest way to minimize the quantity of overcharge required is to maintain the cells in a cool environment. By minimizing the thermal gradients in the cell and keeping the temperature low, the charge efficiency is maximized and the necessity for large charge-return ratios is eliminated. Although it is enticing to treat NiH_2 batteries as "super" NiCd batteries, the cell is a different couple with unique charge-control and environmental requirements.

V. CONCLUSIONS

The testing data collected from most North American sources indicate that the basis for using NiH_2 cells in high orbits is firm. Results from over 227 cells have produced only 14 failures up to 1000 cycles. The failures are of the type that have either been corrected or would be screened out in a flight program. Recent flight experience appears to support this position.

The data base is very weak for low-orbit applications. Few cells have more than 8000 cycles (equivalent to 1.4 years in low orbit) before failure or test discontinuance. However, tests have generally been run under unrealistically harsh conditions of high depth of discharge, large charge-return ratios, and temperatures near ambient. A particular problem is that the charge-return ratios that have been used appear small until it is realized that even a 105% charge-return ratio results in a large quantity of extra charge at high DODs. In comparison, a typical NiCd cell run with a 107% charge-return ratio at shallow DOD receives a much smaller quantity of extra charge. It is such problems as these, coupled with minor design and procedural changes that may not have been beneficial, which lead to the lack of sufficient, demonstrable capability for NiH_2 cells in low earth orbit. A carefully controlled LEO test using reasonable conditions with properly specified and quality-controlled cells would appear to be mandatory in order to demonstrate life.

LABORATORY OPERATIONS

The Laboratory Operations of The Aerospace Corporation is conducting experimental and theoretical investigations necessary for the evaluation and application of scientific advances to new military space systems. Versatility and flexibility have been developed to a high degree by the laboratory personnel in dealing with the many problems encountered in the nation's rapidly developing space systems. Expertise in the latest scientific developments is vital to the accomplishment of tasks related to these problems. The laboratories that contribute to this research are:

Aerophysics Laboratory: Launch vehicle and reentry fluid mechanics, heat transfer and flight dynamics; chemical and electric propulsion, propellant chemistry, chemical dynamics, environmental chemistry, trace detection; spacecraft structural mechanics, contamination, thermal and structural control; high temperature thermomechanics, gas kinetics and radiation; cw and pulsed chemical and excimer laser development including chemical kinetics, spectroscopy, optical resonators, beam control, atmospheric propagation, laser effects and countermeasures.

Chemistry and Physics Laboratory: Atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiative signatures of missile plumes, sensor out-of-field-of-view rejection, applied laser spectroscopy, laser chemistry, laser optoelectronics, solar cell physics, battery electrochemistry, space vacuum and radiation effects on materials, lubrication and surface phenomena, thermionic emission, photo-sensitive materials and infrared detectors, atomic frequency standards, and environmental chemistry.

Computer Science Laboratory: Program verification, program translation, performance-sensitive system design, distributed architectures for spaceborne computers, fault-tolerant computer systems, artificial intelligence, microelectronics applications, communication protocols, and computer security.

Electronics Research Laboratory: Microelectronics, solid-state device physics, compound semiconductors, radiation hardening; electro-optics, quantum electronics, solid-state lasers, optical propagation and communications; microwave semiconductor devices, microwave/millimeter wave measurements, diagnostics and radiometry, microwave/millimeter wave thermionic devices; atomic time and frequency standards; antennas, RF systems, electromagnetic propagation phenomena, space communication systems.

Materials Sciences Laboratory: Development of new materials: metals, alloys, ceramics, polymers and their composites, and new forms of carbon; non-destructive evaluation, component failure analysis and reliability; fracture mechanics and stress corrosion; analysis and evaluation of materials at cryogenic and elevated temperatures as well as in space and enemy-induced environments.

Space Sciences Laboratory: Magnetospheric, auroral and cosmic ray physics, wave-particle interactions, magnetospheric plasma waves; atmospheric and ionospheric physics, density and composition of the upper atmosphere, remote sensing using atmospheric radiation; solar physics, infrared astronomy, infrared signature analysis; effects of solar activity, magnetic storms and nuclear explosions on the earth's atmosphere, ionosphere and magnetosphere; effects of electromagnetic and particulate radiations on space systems; space instrumentation.

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