The 1991 NASA Aerospace Battery Workshop

Proceedings of a workshop held at the
U.S. Space and Rocket Center
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The 1991 NASA Aerospace Battery Workshop

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Proceedings of a workshop sponsored by the NASA Aerospace Flight Battery Systems Program, hosted by the George C. Marshall Space Flight Center, and held at the U.S. Space and Rocket Center, Huntsville, Alabama, October 29–31, 1991
Preface

This document contains the proceedings of the 22nd annual NASA Aerospace Battery Workshop, hosted by the Marshall Space Flight Center on October 29-31, 1991. The workshop was attended by scientists and engineers from various agencies of the U.S. Government, aerospace contractors, and battery manufacturers, as well as international participation in like kind from a number of countries around the world.

The subjects covered included nickel-cadmium, nickel-hydrogen, silver zinc, and lithium based technologies, as well as advanced technologies including nickel-metal hydride and sodium-sulfur.
Introduction

The NASA Aerospace Battery Workshop is an annual event hosted by the Marshall Space Flight Center. The workshop is sponsored by the NASA Aerospace Flight Battery Systems Program which is managed out of NASA Lewis Research Center and receives support in the form of overall objectives, guidelines, and funding from Code Q, NASA Headquarters.

The 1991 Workshop consisted of three full days divided into five sessions. The first day consisted of a General Topic Session and a Primary Technologies Session. The second day began with the Nickel-Cadmium Technologies Session, a part of which was the Cadmium Issues Panel Discussion, and concluded with the Advanced Technologies Session. The third and final day was devoted to the Nickel-Hydrogen Technologies Session. Another panel discussion entitled Current Nickel-Hydrogen Cell Designs was a part of that session.

On a personal note, I would like to take this opportunity to thank all of the many people that contributed to the organization and production of this workshop:

The NASA Aerospace Flight Battery Systems Steering Committee, for their financial support as well as their input during the initial planning stages of the workshop.

Shahid Habib, NASA Headquarters; Bob Bragg, NASA Johnson Space Center; Frank Deligiannis, Jet Propulsion Laboratory; Dean Maurer, AT&T; Larry Thaller, The Aerospace Corporation; Sal Di Stefano, Jet Propulsion Laboratory; Ed Buzzelli, Westinghouse Science & Technology Center; Joe Stockel, Office of Research & Development; and Michelle Manzo, NASA Lewis Research Center, for serving as Session Organizers, which involved soliciting presentations, organizing the session agenda, and orchestrating the session during the workshop;

George Rodney, NASA Headquarters, for taking time out of his busy schedule to deliver the keynote address for the workshop during the opening session;

Dr. Constance Dees, Alabama A&M University, for her contributions in managing the contract with the U.S. Space and Rocket Center to conduct the workshop;

U.S. Space and Rocket Center, for doing an outstanding job in providing an ideal setting for this workshop and for the hospitality that was shown to all who attended;

Marshall Space Flight Center employees, for their help in stuffing envelopes, registering attendees, and handling the microphones during the discussion periods.

Finally, I want to thank all of you that attended and/or prepared and delivered presentations for this workshop. You were the key to the success of this workshop.

Jeff Brewer
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Good morning and welcome to the annual NASA Battery Workshop.

In the nearly 20 years that NASA has been conducting these workshops, they have proven to be highly effective forums on aerospace battery technology. These industry gatherings have greatly benefitted the NASA Aerospace Flight Battery Systems Program. Over the years, sharing ideas with experts from industry and other government agencies has helped us to determine the direction of our Battery Program, identify potential problems, and seek solutions for technology issues.

Clearly, the foremost technology issue this year is the pending OSHA ruling on cadmium use. At this point, we can only speculate about the impact of the ruling on; for example, how it will affect: 1) cost, 2) the availability of cadmium, or 3) the number of suppliers.

With NASA's heavy dependence on cadmium for flight programs, the ruling represents a critical concern for our Battery Program. If at some point domestic batteries were no longer available, we would have to identify other means of acquisition, which could mean using foreign sources or adapting our programs to accommodate replacement technologies.

With the final limits unknown, however, NASA still has options. The Lewis Research Center in Cleveland, Ohio; the Goddard Space Flight Center in Greenbelt, Maryland; the Jet Propulsion Laboratory (JPL) in Pasadena, California; and other NASA facilities are researching both system improvements and replacement technologies. These technologies include alternatives such as nickel hydrogen and metal hydrides. Metal hydrides would provide a volume advantage over nickel hydrogen and a weight advantage over Nickel-Cadmium (Ni-Cd). However, this technology is developmental and is a long way from being flight-ready.

These efforts are aided by the NASA Battery Steering Committee, an advisory group chaired by the NASA Headquarters Office of Safety and Mission Quality. Committee members represent each NASA Center, JPL, and Headquarters. In addition, there are representatives from the Department of Defense (DoD) and other government agencies.

The NASA Battery Program has several initiatives underway to ensure that battery issues and concerns are addressed and resolved effectively, and in a timely manner. A cross-section of the projects being worked for the major tasks of the Battery Program include the following:
A NASA-wide Data Base is being developed for the Battery Systems Technology task by the Lewis Research Center, to centralize battery-related information and alerts.

A major project for the Goddard Space Flight Center in support of the Secondary Battery Technology task, is the resolution of nickel-cadmium cell quality and reliability problems. A short-term goal is to resolve problems with the current NASA standard Ni-Cd Cell. The long-term goal is to develop a standard advanced Ni-Cd cell.

An electrochemical model of the Ni-Cd system is being created by JPL for use in developing an accelerated test to determine the quality and reliability of flight lot cells. The model also would be used to predict battery performance based on operating conditions.

A system of independent checks and balances is being developed that will include, for example:

1) test facility upgrades at Goddard and JPL,
2) an independent Destructive Physical Analysis facility to conduct diagnostic component testing, and
3) Nondestructive Evaluation (NDE) testing for nickel-hydrogen cell cases.

The Johnson Space Center is seeking to improve the safety and reliability of primary battery systems by reducing the number of cell chemistries used to qualify high performance of NASA standard primary cells.

This is a brief look at some of the initiatives underway to ensure that NASA programs will have the batteries needed for primary technologies, secondary batteries, and systems technologies for integrating the batteries.

Whatever direction that NASA takes based on the final OSHA ruling, there will be continued emphasis on providing safe, reliable, and high quality batteries. Safety, reliability, and quality assurance considerations for the NASA Battery Program include a range of activities for battery systems and technologies. For example, engineers within the Office of Safety and Mission Quality establish safety plans and procedures, advocate and monitor testing to ensure reliability, and implement quality assurance procedures. The aim is to keep new battery technologies moving forward, anticipate future NASA battery requirements, and bridge the gap between technology development and flight applications.

I have mentioned some of the future scenarios and options being considered at NASA as well as some of the initiatives underway to foster continuous improvement of our battery systems.
The NASA Battery Program has done an excellent job overall in focusing the Agency's attention on the pending OSHA decision, apprising management on the status of the options and increasing the level of communication throughout NASA on battery issues in general. We recognize that the success and effectiveness of our Battery Program is due in large part to the strong contributions of our industry partners and other government agencies.

As always, we look forward to learning of your plans and concepts for battery systems and replacement technologies.

Thank you.
General Topic Session

Organizer: Shahid Habib
NASA Headquarters
The major objective of the NASA Aerospace Flight Battery Systems Program is to provide NASA with the policy and posture to increase and ensure the safety, performance and reliability of batteries for space power systems. The program was initiated in 1985 to address battery problems experienced by NASA and other space battery users over the previous ten years. The original program plan was approved in May of 1986 and modified in 1990 to reflect changes in the agency's approach to battery related problems that are affecting flight programs. The NASA Battery Workshop is supported by the NASA Aerospace Flight Battery Systems Program. The main objective of the discussions at this workshop is to aid in defining the direction which the agency should head with respect to aerospace battery issues.

Presently, primary attention in the Battery Program is being devoted to issues revolving around the future availability of nickel-cadmium batteries as a result of the proposed OSHA standards with respect to allowable cadmium levels in the workplace. The decision of whether or not to pursue the development of an advanced nickel-cadmium cell design and the qualification of vendors to produce cells for flight programs hinges on the impact of the OSHA ruling. As part of a unified Battery Program, the evaluation of a nickel-hydrogen cell design options and primary cell issues are also being pursued to provide high performance NASA Standards and space qualified state-of-the-art primary cells. The resolution of issues is being addressed with the full participation of the aerospace battery community.

INTRODUCTION

The NASA Aerospace Flight Battery Systems Program represents a unified NASA wide effort with the objective of providing NASA with the policy and posture which will increase the safety, performance, and reliability of space power systems. The program consists of three major technical tasks designed to accomplish this objective. These are: Battery Systems Technology, Secondary Battery Technology, and Primary Battery Technology. The approach to achieving the program objectives involves 1) increasing the fundamental understanding of primary and secondary cells; 2) providing for improved cell/battery manufacturing process control, specifically in the nickel-cadmium area; 3) addressing and investigating the establishment of a NASA standard nickel-hydrogen cell design; 4) establishing specifications, design and
operational guidelines for both primary and secondary cells and batteries; 5) providing training relating to the above areas; and 6) opening and maintaining communication lines within NASA and the aerospace community.

The NASA Lewis Research Center (LeRC) has the overall responsibility for management of the program. Dr. Patricia O'Donnell of the Lewis Research Center is the program manager. The majority of the NASA centers are involved in the execution of specific tasks within the program. The overall objectives, guidelines and funding are provided by NASA Headquarters through Code Q, the Office of Safety and Mission Quality. In July of this year Mr. Shahid Habib was named as the Headquarters, Code Q program manager, replacing Mr. Frank Manning. The original organization of the tasks in the program plan, the initiation of the plan and annual status updates have been previously reported in references 1 through 5.

The major issue facing the agency today revolves around the future of Ni-Cd technology and the potential impact of the proposed OSHA standards on future Ni-Cd cell production, both in terms of cost and the willingness and ability of the manufacturers to meet the new standards. The goals and objectives of the NASA Aerospace Flight Battery Systems Program are reevaluated periodically to address such concerns in a timely manner. The overall plan, the specific modifications, and the status of the tasks will be addressed in this paper.

PROGRAM PLAN OVERVIEW - TASK STATUS

This program is designed to enhance the safety, reliability, and performance of NASA's aerospace primary and secondary batteries as well as battery power systems. The NASA Aerospace Flight Battery Systems Program is organized under four major tasks: Program Management, Battery Systems Technology, Secondary Battery Technology, and Primary Battery Technology.

Program Management

The NASA Lewis Research Center is responsible for the management of this program. The NASA Lewis Research Center Program Manager provides continuing coordination with all the NASA centers, Jet Propulsion Laboratory (JPL), NASA Headquarters and the NASA Aerospace Flight Battery Systems Steering Committee. The NASA Aerospace Flight Battery Systems Steering Committee provides advice on battery issues. The Committee is chaired by the Office of Safety and Mission Quality, membership is comprised of one representative from each of the NASA centers and one representative from Aerospace Corporation, representing the Air Force. The Lewis Research Center Program Manager has full responsibility for technical management, cost and scheduling of the program.

Battery Systems Technology

The Battery Systems Technology Task addresses the overall systems aspects associated with the
integration of cells into batteries and batteries into power systems. The objective is to improve the reliability of energy storage, space power system design, integration, and checkout.


As a part of the Handbook Development Task of the Battery Program, GSFC is also preparing a Handbook for the Handling and Storage of Aerospace Nickel-Cadmium Batteries. This handbook is not intended to duplicate the information covered in NASA reference Publication 1052, Sealed-Cell Nickel-Cadmium Battery Applications Manual. The purpose of this handbook is to update the handling procedures and practices for working with nickel-cadmium batteries. The Handbook covers changes in guidelines resulting from improvements in design, manufacturing, and testing of nickel-cadmium cells and batteries. The heritage of many GSFC flight Ni-Cd battery developments over the past three decades is covered in the handbook. This handbook specifically covers the following 1) Background, 2) Nickel-Cadmium Cell Primer, 3) The Environment and Nickel-Cadmium Batteries, 4) Battery Handling and Storage Guidelines and 5) Nickel-Cadmium Cell Design and Evolution (from 1960-1989).

The handbooks are intended to serve as the basis for a training plan, at the engineer and technician levels, that will ensure that personnel involved with the test and operations of batteries and their related power systems are fully qualified to implement safe and proper operational procedures including storage practices. The Kennedy Space Center (KSC) has responsibility for this task. A subcommittee consisting of engineers who have direct flight battery expertise has been formed at KSC. The subcommittee is in the process of assessing battery training requirements first at KSC then within the agency. Safety and handling procedures used by individual projects are being assembled. Presently, safety and handling procedures have been mission specific. This task will attempt to develop an integrated plan to be used agency wide.

The Battery Data Base subtask addresses a NASA Battery System Data Base Environment to serve the NASA battery community for the dissemination of technical notes, policy documentation and test data. Efforts are underway to develop a battery specific data base that would provide access to operational cycle test data in addition to a problem reporting system. The battery data base will serve as an integrated repository of knowledge gained from manufacturing, ground testing, and flight experience. The goal is to permit all NASA centers to input and retrieve pertinent information, and to facilitate the issuance of rapid alerts when potential problems and/or trends have been identified. Data base capabilities in the following areas will be established: bulletin boards, a documentation library, test data archives, and battery models. In the past few months, responsibility for the implementation of this subtask has been transferred from Ames-Dryden Flight Research Facility to the Lewis Research Center.
The majority of the NASA cell test data base resides at the Naval Weapons Support Center, Crane, IN. Efforts are underway to organize and structure the Crane test data so that it will be easily accessible within the data base. As part of this subtask, Crane has updated NASA pack history files dating back to 1975, provided pack record structure information, and converted data tapes to a useable format for all NASA tests dating back to 1981. This initial data is presently accessible through direct interactions with Crane. A plan to establish on-line capabilities for data access through Crane is being pursued.

The NASA Battery Workshop comes under the sponsorship of the NASA Aerospace Battery Systems Program. The Marshall Space Flight Center hosted the Workshop in December 1990 and is the sponsor of this year's workshop as well. NASA Conference Publication 3119, *The 1990 NASA Aerospace Battery Workshop*, (ref. 6) summarizes the proceedings of last year’s workshop. The workshop serves as a forum for open communication of battery related activities between industry and government. The panel discussion sessions covering the Cadmium Issue and Current Nickel-Hydrogen Cell Designs should provide valuable input into NASA programs.

The future requirements and applications for both primary and secondary battery systems are continuously monitored as part of Battery Systems Task. The Lewis Research Center has responsibility for this subtask. The potential loss of nickel-cadmium cell suppliers and the development of nickel-metal hydride technology as a potential replacement technology are of prime importance in addressing NASA's future secondary battery requirements.

**Secondary Battery Technology**

The Secondary Battery Technology Task was established to improve the performance, quality, safety, and reliability of secondary battery systems. This task presently focuses on the nickel-cadmium and nickel-hydrogen systems which encompass the majority of NASA's present and planned secondary battery applications. Again, the issues being raised with respect to the proposed OSHA cadmium ruling and its potential impact will have an effect on the direction of the Battery Program with respect to secondary technologies.

Nickel-cadmium batteries provide the storage capability for the majority of NASA's missions. As a result, the future of nickel-cadmium manufacturing and the availability of nickel-cadmium cells are of major concern to the agency. NASA is in the process of evaluating the impact of the cadmium ruling and the direction required to ensure that future missions will have the needed storage systems. This involves decisions with respect to nickel-cadmium and nickel-metal-hydride technologies. NASA had developed a recovery plan to address the nickel-cadmium cell quality and reliability problems that surfaced in the late 1980's. Near-term and far-term options for the resolution of the life and reliability problems with the current design nickel-cadmium cells were formulated and are being implemented. The near-term approach is aimed at the re-establishment of a qualified NASA Standard Nickel-Cadmium Cell. The far-term solution involves the establishment of an Advanced Nickel-Cadmium NASA Standard Cell design which would incorporate electrochemically impregnated plates and non-nylon separators. The procurement to implement the far-term solution has not been initiated, pending a determination of the future of nickel-cadmium batteries. The need for a program addressing nickel-metal-
hydride development is also being evaluated.

In order to support flight programs and address NASA's future needs with respect to nickel-cadmium cells, GSFC is responsible for a subtask that involves the evaluation of SAFT cells and Hughes "advanced" Ni-Cd. A number of cells has been provided by SAFT for evaluation by NASA. 20 and 24 AH cells are currently on test. Tests have been in progress for greater than two years. Testing is being conducted at 40% DOD and 0 and 20°C. The data accumulated to date shows performance of the SAFT cells to be comparable to that of the NASA Standard cells used for LANDSAT. Sixty advanced design Ni-Cd cells have been purchased from Hughes. Six, five to eight cell test packs of advanced design cells and an additional eight cell pack of 'super' Ni-Cd cells are currently undergoing stress testing at 20 or 30°C and 40% DOD at Crane. An additional pack of advanced Ni-Cd cells with Z/PS or Z/PBI separators is being evaluated under a GEO regime. The advanced design cells do not contain the electrolyte additive used in the 'super' Ni-Cd cells. To date, the cells have accumulated >8000-10000 cycles. A summary of the status of these tests appears in reference 6.

Modifications to the present Gates cells are also being investigated as a part of the near-term solution. An interactive contract with Gates, under the management of the Lewis Research Center, has been initiated that would allow variations in the porosity, nickel attack level, and the loading level of the positive electrodes as well as the incorporation of alternate separators, and varied electrolyte levels. Modified cells will be constructed and tested to evaluate the effectiveness of the component changes. The composite Task Force Group on Near Term Nickel-Cadmium Cell Design has made recommendations regarding the selected parameters and levels to be evaluated. Plans are to initially evaluate the effects of nickel attack level, positive plate loading and negative plate loading in a statistically designed experiment. The first cell order has been placed, plaque production is scheduled to begin in mid November.

NASA, through the Goddard Space Flight Center, is also in the process of revising the NASA Specification for Manufacturing and Performance Requirements of NASA Standard Aerospace Nickel-Cadmium Cells, NHB 8073.1. The NHB was originally written to update the existing specification to correlate with the current NASA Standard Nickel-Cadmium Cell Manufacturing Control Documents at Gates Aerospace Batteries. The NHB is presently being revised to do the following: 1) strengthen the technical contents and requirements of the document; 2) incorporate performance assurance requirements and thereby improve the quality of the cells produced; and 3) incorporate comments received from Gates Aerospace Batteries on the present version of NHB 8073.1.

The approach for the long-term resolution of the nickel-cadmium problems involves the definition and development of a NASA standard advanced nickel-cadmium cell for NASA Secondary battery applications. It is to be accomplished by developing detailed, rigid specifications and sponsoring the development of manufacturing, testing and inspection processes by both government and contractor agencies. The present approach is to procure cells, from any qualified bidders, built to the rigid specifications required to ensure the quality and reliability of the cells. The cells will be tested and vendors qualified. The advanced design requires electrochemically impregnated plates and a separator capable of sustained operation at 30°C. Goddard Space Flight Center has responsibility for the management of this subtask. As
mentioned previously, the initiation of the procurement has not been implemented pending a decision with respect to the future manufacture of nickel-cadmium cells.

The Jet Propulsion Laboratory is responsible for the Applied Nickel-Cadmium Technology subtask. This subtask involves the development of an electrochemical model of the nickel-cadmium system that involves physical, chemical, and electrochemical studies at the component and cell levels. The model will be used to develop an accelerated test which can be used to determine the quality and reliability of flight lot cells without extensive life testing and to predict the performance of a battery from a set of spacecraft operating conditions. Phase I of the model, which involves using a table lookup approach for determining cell performance, has been implemented and is available for distribution through COSMIC. Phase II of the model involves the replacement of the table lookup approach used in Phase I with a one dimensional electrochemical model being developed under a contract with Texas A&M. The model, simulating the charge and discharge has been developed. The Phase II model is presently undergoing verification. The model predictions match actual test data through much of the cycle life. The Phase II model is presently undergoing modifications to incorporate proton diffusion and a more rigorous treatment of the active material conductivity as improvements to modelling the response at the positive electrode that were identified during work on a Ni-H₂ electrochemical model at Texas A&M. The third and final phase of the model involves the expansion to a two dimensional model and the incorporation of factors to predict performance degradation. The Phase III model is scheduled to be complete in 1992. Additional information on the status of this effort is available in references 7-15.

The major goal of the Nickel-Hydrogen Technology subtask is to evaluate design features for incorporation into nickel-hydrogen cells for NASA missions. Steps are underway to evaluate the critical aspects of nickel-hydrogen technology in order to prevent a situation similar to that presently being experienced with nickel-cadmium cells and to ensure the consistent production of quality cells. The Lewis Research Center has responsibility for the Nickel-Hydrogen Technology subtask. It involves coordination of Code R, Office of Aeronautics and Space Technology, technology development efforts and Code Q support for the verification and qualification of technology advances identified through the Code R program. Currently, the effects of the NASA advanced design features and the effects of 26% vs 31% KOH are being evaluated in flight cells being tested at Crane. Preliminary results of the testing of cells with varied KOH concentration support the accelerated boiler plate tests run previously. The three cells containing 31% KOH failed at cycles 3729, 4165, and 11,355. One of the cells with 26% KOH failed at cycle 15,314, the remaining cells have accumulated >17,000, 80% DOD LEO cycles at 10°C, and continue on test. DPA's have been performed on the failed cells. The testing of the advanced design specifically involves evaluating the effect of the catalyzed-wall wick on cell life and performance. These cells are being cycled at 60% DOD and 10°C in a LEO regime. The cells with the catalyzed wall wick have accumulated >14,000 LEO cycles with no cell failures. One of the cells without the catalyst on the wall failed at cycle 9,588, the two remaining cells continue to cycle and have accumulated >14,000 cycles. Details on the status of these evaluations can be found in references 16 and 17. Flight cells evaluating potential replacements for the asbestos separators presently used in nickel-hydrogen cells have been delivered and are scheduled to begin characterization testing in November of this year. Battery program funds support cycle testing of the above groups of cells and the performance of
destructive physical analyses as the cells fail. Cells have also been ordered to evaluate the effects of impregnation method and cell design on performance and cycle life. This subtask involves close coordination with Hubble Space Telescope and Space Station Freedom, missions which are using or will use nickel-hydrogen batteries for energy storage.

A subtask which involves the implementation of a program of independent checks and balances was added to the Secondary Battery Technology Task in response to the current nickel-cadmium situation. The increased checks and balances are aimed at identifying potential problem areas in a timely manner so that appropriate actions can be taken to correct the problems with minimal impact. The independent checks and balances include the following: 1) test facility upgrades; 2) support of task force activities to investigate specific problem areas; 3) the establishment of an independent DPA facility to perform routine diagnostic component testing; 4) the investigation of impedance as a diagnostic tool for predicting cell performance, life and quality; and 5) the development of advanced NDE methods for nickel-hydrogen cell cases.

The expansion and upgrading of test facilities at JPL and the GSFC, planned as part of the independent checks and balances sub task, will provide increased capability within NASA for the testing and mission simulation testing of cells and batteries for future NASA missions. JPL has built ten test stands capable of performing parametric characterization and mission simulation type testing. Upgrades to GSFC test facilities have been supported as well. Goddard is designing stands capable of testing nickel-cadmium and nickel-hydrogen cells. These test racks will have the added advantage of being transportable to the launch site for on-site, pre-launch testing or conditioning.

Several of the task force activities initiated at the Nickel-Cadmium Mini-Workshop held at the NASA Marshall Space Flight Center (MSFC) in June of 1988 are continuing as a part of the increased checks and balances sub task. These include the Crane Data Evaluation Task Force, the effort for the Establishment of Standard DPA Procedures, and the Separator Test Procedures Task.

The Crane Data Evaluation Task Force group determined that the present data base of Crane data is not useful for the determination of product consistency or statistical relationships. The task force role was expanded to include the identification of a meaningful test matrix for the testing and evaluation of cells for LEO and GEO applications. JPL contracted with MRJ to perform this work. Reports by MRJ and JPL, discussing the evaluation of the procedures used in testing nickel-cadmium cells have been issued (ref 19, 20). The recommendations will be evaluated and new test procedures established.

The Marshall Space Flight Center has the responsibility for developing and establishing NASA standards for the performance of destructive physical analyses. Current DPA procedures used in the industry are being evaluated in an effort to identify a standard procedure for the agency. Plans are to implement an approved procedure at the independent DPA facility that is being established as part of this subtask. Here the objective is to establish an independent facility for the performance of DPA’s and routine diagnostic tests for secondary cells. The Marshall Space Flight Center is organizing efforts relating to the establishment of the independent DPA facility.
A task force group was formed to evaluate the present separator test procedures used to screen and evaluate separator uniformity and quality for use in nickel-cadmium cells. The Lewis Research Center is involved in defining improved tests that will more closely evaluate separator characteristics as related to the actual cell environment. A support service contractor has been hired to perform this subtask. Procedures will be made available as they are developed.

As part of an effort to understand and define the component properties that lead to reliable, high performance cells JPL performed a task comparing properties of plates produced in the 1970's when cells were relatively problem free to those of plates made more recently. Preliminary evaluation of materials made in 1978 and 1985 showed no major differences in physical characteristics. This sub task provided valuable input for the modelling effort. References 21 and 22 summarize the work performed to date under this subtask.

The use of impedance spectroscopy as an interpretive tool for predicting cell performance, life, and quality is being investigated. The Lewis Research Center is responsible for this effort. To date Ni-Cd, Ni-H, and Li-SO cells have been evaluated. Cells of the same chemistry exhibit characteristic impedance spectra that relate to manufacturer. It remains to be seen if these characteristics correlate with life and performance. The status of the efforts in this area has been reported in references 23-29.

The mechanical aspects of nickel-hydrogen case integrity and non-destructive evaluation of the cell closure welds are of particular concern for determining flight worthiness of nickel-hydrogen cells. As a part of this program, the Langley Research Center is responsible for investigating advanced NDE techniques for flaw definition and flaw growth in nickel-hydrogen cell cases. X-Ray residual stress characterization, Bragg diffraction, Shearography and Thermoelectricity are being investigated. This subtask involves close coordination with related activities being conducted by the Space Station Freedom Program Office.

**Primary Battery Technology**

The objective of the Primary Battery Technology Task is to improve the performance, reliability and safety of primary battery systems. The major thrust of this effort is to reduce the number of different cell chemistries now used by identifying and qualifying high performance NASA Standard Primary Cells. The Johnson Space Center has primary responsibility for work performed in the primary battery area.

A Primary Battery Design and Safety Handbook has been prepared and is expected to be published in the near future. It is intended that the handbook provide National Space Transportation System users with the necessary guidelines, standard testing procedures and requirements to ensure mission success.

An excess of a dozen different cell chemistries are presently used by NASA to provide the power requirements for primary battery applications. Many of the cells and batteries used are commercially available off-the-shelf items. As a result, NASA has no control over the manufacturing processes used to produce these cells. Therefore, NASA, through JSC, is in the
process of setting up a logistics source of primary cells that will have been previously screened and qualified. This will help to ensure the cell/battery quality and result in greater system reliability.

Studies have been conducted in order to minimize the number of cell chemistries which would represent an overall optimum for all NASA missions. Lithium D-Cell, and Zn-O₂ cell development are part of the primary battery efforts. Subtasks are underway which are designed to optimize these systems and make them safer for use.

JSC contracted with Yardney Technical Products to investigate the development of internal/external short circuit protection for lithium cells. The objective of this subtask was to develop a positive control for both internal and external short circuits in lithium cells. The control is activated by temperature, shutting the cells down from the heat generated by shorts. The protective coating developed under this contract was so thick (~25 mils) that the capacity was reduced by 50% and the rate capability was also substantially reduced. Yardney Technical Products is pursuing additional development of the film as part of an internal IR&D effort.

Lithium D-Cell development encompasses the development of an optimized lithium D-cell, or a family of D-cells, that can serve as a building block for the for the varied applications now flying and those to be flown in the near future. The goal is to develop cells capable of meeting relatively high rate requirements while being as tolerant as possible to electrical and thermal abuse. The candidates for evaluation and selection are the JSC Li-BCX, the JPL high rate LiSOCl₂, and the Wilson Greatbatch, Ltd. Li-CSC.

The NASA Aerospace Flight Battery Systems Program also supports the development of a pair of Zn-O₂ cells: a high capacity cell of 150-200 AH at rates of 25-100 hours and smaller capacity 9-12 AH cell to be operated at higher rates of 3-12 hours.

CONCLUDING REMARKS

The NASA Aerospace Flight Battery Systems Program provides for a balanced cell, battery and systems program which includes primary and secondary battery activities in support of NASA’s flight programs. It has provided for increased communication within the agency and with the battery industry as well. The program addresses flight battery and related flight power system activities which are essential for ensuring safe and reliable performance. The future of the secondary nickel-cadmium cells is presently the top priority of the program. In addition, continuing efforts in the nickel-hydrogen and primary battery areas are aimed at preventing the problems in these areas.
REFERENCES


CONCEPTUAL DOCUMENTATION

ANALYSIS

By: Carolyn Ausborn

INNOVATIVE KNOWLEDGE ENGINEERING

AUSBORN & BREWER, INC.
CONCEPTUAL DOCUMENTATION ANALYSIS: INTRODUCTION

- Knowledge Management
- Preserve Corporate Asset -> Knowledge
- Spur Technology Forward
CONCEPTUAL DOCUMENTATION ANALYSIS

- Importance of "GOOD" Documentation

- WORDMAP: Documentation Analysis Tool

- Battery Technology Example
IMPORTANCE OF "GOOD" DOCUMENTATION

- Customer Correspondence
- Customer Relations
- Contracts Renewed / Won
- Departmental Records
- Knowledge Representation
WORDMAP: Document Analysis Tool

- Natural Language Processing Technology
- Only Limitation: Spelling
  Minimum of Two Words
- No Syntax / Grammar Parsing
- Produces List of Concepts Represented
Battery Technology Example

ABSTRACT RELATIONS

QUANTITY

ORDER

COMPARATIVE QUANTITY

COLLECTIVE ORDER

INCREASE

ASSEMBLAGE

DIMENSIONS

EXTERNAL & INTERNAL

INTERIORITY

LOCATION

SPACE

SPACE IN GENERAL

RELATIVE SPACE

PHYSICS

ELECTRICITY & ELECTRONICS

ELECTRICITY

PHYSICS

WAYS & MEANS

ELECTRONICS

MEANS

VOLITION

VOLITION IN GENERAL

USE

INNOVATIVE KNOWLEDGE ENGINEERING
PROFILE OF A CELL TEST DATABASE AND
A CORRESPONDING RELIABILITY DATABASE

George R. Brearley
Glenn C. Klein

Gates Energy Products
Gates Aerospace Batteries
Abstract

The development of computerized control, and data retrieval for aerospace cell testing affords an excellent opportunity to incorporate three specific concepts to both manage the test area and to track product performance on a real-time basis: [1.] DoD 5000.51-G: The adoption and incorporation of precepts fostered by this TQM initiative are critical to us for retaining control of our business while substantially reducing the separate QC inspection activity; [2.] CLASSIFICATION OF TEST DISCREPANCIES: Test Discrepancies are all "equally bad" in cell Acceptance Testing because, for example, we presently do not discriminate between 1mV or 25mV for an overvoltage condition. We must take leadership in classifying such discrepancies in order to expedite their clearance and redirect our resources for prevention activities.[3.] ENGINEERING ALERTS: The development and use of engineering alerts [or guardbanding] which more closely match our product capabilities and are tolerated tighter than the required Customer Specification are paramount to managing the Test Unit in order to remain both quality and cost effective.

Introduction to the current GAB Test Unit:

The GAB Test Unit is a 3,750 square foot facility located on the first floor of the GAB Aerospace complex. It is equipped with 550 ambient temperature test stations for NiCd Pre-Acceptance Testing and 330 environmentally controlled test stations for NiCd Acceptance Testing. There are an additional 192 test stations dedicated to NiH2 Cell Activation and Acceptance Testing; these stations are 100% computer controlled including active temperature control and pressure monitoring via strain gages. There are additional test positions utilized for electrode stress testing and for flooded electrode capacity testing. This Test Unit operates 24 hours a day, 7 days a week and is staffed by a crew of fifteen operators over three shifts. Each shift includes three Test Operators, one Lead Technician, and one Quality Inspector. The Test Unit is supported one a full time basis by an Electronic Technician, a Refrigeration Specialist, and an Equipment Development Engineer. Test capability spans a range of designs from 0.25 amp-hour to 150 amp-hour capacity over a temperature regime of -10 to +35 C. Test capability also covers 40 different NiCd and NiH2 programs for commercial and military programs. The Test Unit is a dynamic, state-of-the-art facility which performs its own maintenance (tracked on a computerized database), develops its own test equipment, and is increasing their capability on a daily basis for computerized data retrieval, information handling, and test control.

Total Quality Management Guide DoD 5000.51-G

This TQM philosophy fosters continuous improvement by the real-time recognition of improvement opportunities through the use of data collection, various statistical or mathematical tools for the identification and analysis of variation, and thereafter providing guidance for reduction and elimination of this variance depending upon the nature of the common cause or special cause. Specific improvement opportunities addressed within the Test Unit include: a] reduction in test discrepancies; b] reduction in performance variation within a lot; and, c] reduction in lot-to-lot performance variation.

Reduction in Test Discrepancies

Over the past three years, the Test Unit has significantly reduced the number of test anomalies through the elimination and reduction of Special Causes. Chart No. 1 graphically displays how personnel in the Test Unit lowered the number of discrepancies by the applied analyses of Man, Method, Machine, Materials, and Environment in order to understand the role of each, and their associated interactions:

MAN: The Test Unit now employs skilled, trained and competent technicians. On each of the three shifts, there is a Lead Technician, three Test Technicians, and one dedicated QC Inspector. In addition, there is a full time maintenance technician and refrigeration specialist.

MACHINE: Numerous equipment additions include 1] Failsafe Devices for preventing cell reversal, for ensuring proper transitions of test procedure, audible warning devices; and, usage of data loggers; 2] charge/discharge status indicators; 3] refurbishment of existing equipment and adoption of customized en-
METHOD: We are constantly improving our method of operations by reviewing our training and by the validation of functional procedures, adoption of trend analyses, standardization of temperature control, and standardization of test instructions. One specific example is the Extended Pre-ATP wherein 32F and 86F performance tests are used to emulate the forthcoming acceptance test.

MATERIAL: Product as well as the accompanying data package undergoes a substantial review prior to transfer from the fabrication shop into the Test Unit.

Reduction in Performance Variation

Further reduction of variation within the Test Unit is hampered somewhat by the currently imposed contractual obligations and restrictions. Whether we consider performance variation within a lot or consider lot-to-lot performance variation, two additional steps must be taken. These steps include the adoption of a classification scheme for test discrepancies, and the incorporation of internal performance guidelines. The present Failure Reporting and Corrective Action System (FRACAS) is both labor and time intensive. Presently our FRACAS is a conglomeration of inputs from MIL-STD-1520C (Corrective Action and Disposition System for Nonconforming Material) and 40 plus Program Offices. The MIL-STD states in part that a Minor Nonconformance does not adversely affect any of the following: [a] health or safety, [b] performance, [c] interchangeability, reliability, or maintainability, [d] effective use or operation, [e] weight or appearance. Most of the customer contracts parrot some or all of this specification; but, no where are definitive examples provided to guide the shop, test, or inspection personnel. To compound this issue, one customer specification spends 20 plus pages defining failures, power-on failures, discrepancies, nonconformances (Type 1 & 2), deviations (functional and performance), anomalies, and out-of-family conditions while still not providing for quantitative descriptions to be used at the shop level. By default, all Test Discrepancies in cell Acceptance Testing become Major Nonconformances and are "equally bad." For example, we presently do not discriminate between 1 mV or 25 mV for an overvoltage condition, nor do we discriminate between 1 amp-minute or 10 amp-hour for low capacity.

Classification of Test Discrepancies

The standardized definition, and classification of discrepancies occurring in cell Acceptance Testing is necessary for us to manage the Test Unit and to avoid the untimely delay of customer level material review for insignificant issues. As regards our example of low capacities of 1 amp-minute versus 1 amp-hour, both conditions are subject to a Gates Anomaly Report, an internal Material Review meeting, customer contact and approval to continue, and Customer Material Review. Table Nos. 1 & 2 contain standardized definitions which should be applied to discrepancies which occur within acceptance testing, and are endemic to starved NiCd cells and NiH2 cells. Thereafter, discrepancies are classified as to whether they are Critical, Major or Minor; and, then to whether the discrepancy is a Cell Response Discrepancy [such as pressure or capacity], or a Test Control Discrepancy [such as time or temperature]. By this classification scheme then, our example for discrimination of overvoltages shows 1mV to be a Minor Discrepancy versus the 25mV as a Critical Discrepancy. The use of this classification scheme must respect the Customer Specification, and the use of potential Engineering Alerts. There is provision for an automatic retest when any of the defined Minor Discrepancies occurs. Obviously these definitions and the retest provisions require customer approval; however, the presentation of these definitions at the NASA Battery Workshop is expected to expedite their acceptance. The adoption of these or similar standardized definitions will significantly improve the resolution of discrepancies when they do occur.
TEST FAILURES BY CATEGORY (1991)

(Atp + Pre-Atp Failures)

NOTE: INFORMATION TAKEN FROM GAR DATABASE
Created by: Richard Calloway
**TABLE 1**  
Acceptance Testing: NiCd Discrepancy Definitions

<table>
<thead>
<tr>
<th>CELL RESPONSE DISCREPANCIES</th>
<th>TEST CONTROL DISCREPANCIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Overvoltages &gt; 25mV</td>
<td>1. Cell Case Temperature excursion ≥ 10° C</td>
</tr>
<tr>
<td>2. Pressures ≥ 80 PSIG</td>
<td>[and never above 30° C]</td>
</tr>
<tr>
<td><strong>CRITICAL</strong></td>
<td>2. Cell reversal (&lt; 0.000 volts]</td>
</tr>
<tr>
<td>1. Overvoltages &gt; 10mV but ≤ 25mV</td>
<td>3. Cell charged in reverse</td>
</tr>
<tr>
<td>2. Overpressures &gt; 5 PSIA</td>
<td>4. Cells overcharged at &gt; C/5 rate</td>
</tr>
<tr>
<td>3. Capacities ≥ 2.0% below specification</td>
<td>5. Any hard or direct short</td>
</tr>
<tr>
<td>4. Cell Impedance over specification</td>
<td></td>
</tr>
<tr>
<td>5. Pulse Disc: minimum voltage not met</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MAJOR</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Overvoltages ≤ 10mV</td>
<td>1. Cell Case Temp. excursion &gt; 5° C but &lt; 10° C</td>
</tr>
<tr>
<td>2. Overpressures ≤ 5 PSIA</td>
<td>2. Resistor on cell during charge</td>
</tr>
<tr>
<td>3. Capacities &lt; 2.0% below specification</td>
<td>3. Charge rate &gt; 10% above specification</td>
</tr>
<tr>
<td>4. Capacity over &quot;Max. Allowable&quot; spec.</td>
<td>4. Discharge rate &gt; 20% above specification</td>
</tr>
<tr>
<td>6. EOCV Dispersion out-of-specification</td>
<td></td>
</tr>
<tr>
<td>7. Failure to meet 24 Hr minimum OCV</td>
<td></td>
</tr>
<tr>
<td>8. Excess residual pressure on Internal Self-Discharge</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MINOR</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Overvoltages ≤ 10mV</td>
<td>1. Cell Case Temperature excursion ≤ 5° C</td>
</tr>
<tr>
<td>2. Overpressures ≤ 5 PSIA</td>
<td>2. Charge rate ≤ 10% above specification</td>
</tr>
<tr>
<td>3. Capacities &lt; 2.0% below specification</td>
<td>3. Discharge rate ≤ 20% above specification</td>
</tr>
<tr>
<td>4. Capacity over &quot;Max. Allowable&quot; spec.</td>
<td>4. Insufficient shutdown voltage (EOSV)</td>
</tr>
<tr>
<td>5. Capacity dispersion out-of-specification</td>
<td>5. Interrupted Burn-in cycle &gt; 30 minutes</td>
</tr>
<tr>
<td>6. EOCV Dispersion out-of-specification</td>
<td>6. Interrupted test sequence:</td>
</tr>
<tr>
<td>7. Failure to meet 24 Hr minimum OCV</td>
<td></td>
</tr>
<tr>
<td>8. Excess residual pressure on Internal Self-Discharge</td>
<td></td>
</tr>
<tr>
<td>9. Excess residual pressure on Internal Self-Discharge</td>
<td></td>
</tr>
</tbody>
</table>

**NOTE:**  
[1] Any Minor Discrepancy is subject to an automatic retest after customer notification; Minor Discrepancies are automatically advanced to a Major Discrepancy following a second failure to perform.  
[2] All Major Discrepancies, whether a first time occurrence or whether an upgraded occurrence from a Minor Discrepancy, will be subject to immediate Customer notification as described within relevant Contract documentation.  
### Table 2

**Acceptance Testing: NiH$_2$ Discrepancy Definitions**

<table>
<thead>
<tr>
<th>CELL RESPONSE DISCREPANCIES</th>
<th>TEST CONTROL DISCREPANCIES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CRITICAL</strong></td>
<td></td>
</tr>
<tr>
<td>1. Overvoltages $&gt;$ 25mV</td>
<td>1. Cell Case Temperature excursion $\geq 10^\circ$ C [and never above $40^\circ$ C]</td>
</tr>
<tr>
<td>2. Pressures $\geq$ 20% above MOP</td>
<td>2. Cell reversal ($&lt; 0.000$ volts)</td>
</tr>
<tr>
<td>3. Hydrogen leakage</td>
<td>3. Cell charged in reverse</td>
</tr>
<tr>
<td><strong>MAJOR</strong></td>
<td></td>
</tr>
<tr>
<td>1. Overvoltages $&gt;$ 10mV $\leq$ 25mV</td>
<td>1. Cell Case Temp. excursion $&gt; 5^\circ$ C but $&lt; 10^\circ$ C</td>
</tr>
<tr>
<td>2. Overpressures $&gt;$ 50 PSIA</td>
<td>2. Resistor on cell during charge</td>
</tr>
<tr>
<td>3. Capacities $&gt; 2.0%$ below specification</td>
<td>3. Charge rate $&gt; 10%$ above specification</td>
</tr>
<tr>
<td>5. Max. Allowable Strain Gage voltage is violated</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MINOR</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Overvoltages $\leq$ 10mV</td>
<td>1. Cell Case Temp. excursion $\leq 5^\circ$ C</td>
</tr>
<tr>
<td>2. Overpressures $\leq$ 50 PSIA</td>
<td>2. Charge rate $\leq 10%$ above specification</td>
</tr>
<tr>
<td>3. Capacities $&lt; 2.0%$ below specification</td>
<td>3. Discharge rate $\leq 20%$ above specification</td>
</tr>
<tr>
<td>4. Capacity over &quot;Max Allowable&quot; spec.</td>
<td>4. Insufficient shutdown voltage (EOSV)</td>
</tr>
<tr>
<td>5. Average Capacity out-of-specification</td>
<td>5. Improper Open-Circuit time</td>
</tr>
<tr>
<td>6. Capacity Range out-of-specification</td>
<td>6. Interrupted test sequence:</td>
</tr>
<tr>
<td>7. EOCV Range out-of-specification</td>
<td>[ \leq 30 \text{ minutes on charge cycle,} \leq 10 \text{ minutes on discharge cycle} ]</td>
</tr>
<tr>
<td>8. Improper Open-Circuit time</td>
<td>7. Improper Open-Circuit time</td>
</tr>
<tr>
<td>9. Incomplete/truncated test paragraph</td>
<td>8. Incomplete/truncated test paragraph</td>
</tr>
</tbody>
</table>

**NOTE:**

1. Any Minor Discrepancy is subject to an automatic retest after customer notification; Minor Discrepancies are automatically advanced to a Major Discrepancy following a second failure to perform.
2. All Major Discrepancies, whether a first time occurrence or whether an upgraded occurrence from a Minor Discrepancy, will be subject to immediate Customer notification as described within relevant contract documentation.
3. All Critical Discrepancies are subject to emergency Material Review Board.
### TABLE 3

<table>
<thead>
<tr>
<th>TEST</th>
<th>DATA REQ'D.</th>
<th>PERFORMANCE STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set Neg. Pre-Chg.</td>
<td>time to <em>first</em> vent</td>
<td>normality of times &amp; review of lot-to-lot data</td>
</tr>
<tr>
<td></td>
<td>time to <em>last</em> vent</td>
<td>normality of times &amp; review of lot-to-lot data</td>
</tr>
<tr>
<td></td>
<td><em>O₂</em> weight loss</td>
<td>± 0.5 amp-hour (<em>O₂</em> equivalent) from lot average</td>
</tr>
<tr>
<td>Room Temp. O/C [after KOH adj.]</td>
<td>EOCP</td>
<td>range of 20 to 45 PSIG &amp; delta <em>P</em> ≤ +3 PSI in last 8 hours</td>
</tr>
<tr>
<td>72° F Capacity</td>
<td>EOCP</td>
<td>range of 20 to 45 PSIG</td>
</tr>
<tr>
<td></td>
<td>EOCV</td>
<td>± 12 mV from lot average</td>
</tr>
<tr>
<td></td>
<td>Capacity</td>
<td>± 3.0% from lot average</td>
</tr>
<tr>
<td>32° F Test</td>
<td>EOCP</td>
<td>range of 10 to 35 PSIG</td>
</tr>
<tr>
<td></td>
<td>EOCV</td>
<td>± 12 mV from lot average</td>
</tr>
<tr>
<td></td>
<td>Capacity</td>
<td>± 3.0% from lot average</td>
</tr>
</tbody>
</table>
### TABLE 4

NiCd ATP Test Performance: Engineering Alerts (non-normalized)

<table>
<thead>
<tr>
<th>TEST</th>
<th>DATA REQ'D.</th>
<th>PERFORMANCE STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Each capacity test</td>
<td>EOCV dispersion</td>
<td>±12mV from lot average</td>
</tr>
<tr>
<td></td>
<td>EOCP ranges</td>
<td>20-45 PSIG @ 75°F; 10-35 PSIG @ 32°F</td>
</tr>
<tr>
<td></td>
<td>Capacity dispersion</td>
<td>±3.0% from lot average</td>
</tr>
<tr>
<td>Each overcharge test</td>
<td>EOCV dispersion</td>
<td>±12mV from lot average</td>
</tr>
<tr>
<td></td>
<td>EOCP ranges</td>
<td>20-45 PSIG @ 75°F; 10-35 PSIG @ 32°F</td>
</tr>
<tr>
<td></td>
<td>EOCP</td>
<td>delta P ≤ 3 PSI in last 8 hours</td>
</tr>
<tr>
<td></td>
<td>Capacity dispersion</td>
<td>±3.0% from lot average</td>
</tr>
</tbody>
</table>
More importantly, we will benefit by applying our resources to the prevention of Major and Critical discrepancies.

**Engineering Alerts**

This rededication or redirection of the Technical Staff to resolving and preventing Major and Critical Discrepancies allows the development and internal implementation of Engineering Alerts. Much like Upper and Lower Control Limits in classical Shewhart Analysis, the Engineering Alert [previously called Tollgates or Guardbanding] provides performance limits which more closely match our product capabilities and are tolerated tighter than the Customer Specification. This is the first step in identifying and reducing Common Causes and the accompanying variation, or performance dispersion. Tables 3 & 4 contain the Engineering Alerts to be applied to NiCd Pre-ATP and to NiCd ATP performance testing. These are non-normalized limitations for several reasons: [1] this removes one more crutch or excuse for non-performance; and, [2] software sub-routines for real time normalization of multiple data points appears counterproductive and very demanding of computer memory. Similar Engineering Alerts for NiH2 performance testings are being developed and will be implemented following successful implementation of those for the NiCd cell product line. Necessarily, the entire program is dependent upon the continued implementation of computerized control and data loggers.

**Reduction of Lot-to-Lot Performance Variation**

The full implementation of computerized control and data retrieval allows the development of databases that allow us to track and reduce performance variation in long term multi-year programs. By definition, this database becomes the baseline or embryo for the Reliability Database. Further development of this Reliability Database is dependent upon development of indexing schemes by cell configuration or by plate type since there exists little parity between plate design and cell design.

**Conclusions and Recommendations**

1. We have introduced you to the current Test Unit and shared the plans for improvement; we have discussed the Improvement Opportunities available through reduction of Test Discrepancies, and through the reduction of variation within a lot and variation from lot-to-lot.

2. Standardized definitions of test discrepancies for both product lines in Acceptance Testing have been proposed; implementation will begin on an individual program basis via customer approved Engineering Change Notices.

3. Engineering Alerts are proposed for internal usage and are already being implemented on the NiCd product line.
A Computerized Aircraft Battery Servicing Facility

Richard D. Glover
NASA Dryden Flight Research Facility
Edwards, California

The 1991 NASA Aerospace Battery Workshop

Marshall Space Flight Center
Huntsville, Alabama
October 29-31, 1991
Battery Assignments by Aircraft

The NASA Dryden Flight Research Facility at Edwards, California, operates a fleet of research aircraft which use a variety of nickel-cadmium storage batteries. These batteries range in capacity from 3 to 40 Ah with numbers of cells ranging from 10 to 22. All employ flooded cells with pressure relief vent caps and are manufactured by the Marathon Battery Co. of Waco, Texas.

To meet the stringent safety requirements of research flight operations, batteries are serviced every 30 to 60 days. To handle the volume of servicing with limited manpower, Dryden developed the computerized Battery Servicing Laboratory in the 1970s. This presentation describes the latest upgrade to this facility which has been renamed the Aerospace Energy Systems Laboratory (AESL).

Battery Assignments by Aircraft

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Model number</th>
<th>Part number</th>
<th>Amp-hr rating</th>
<th>Batteries/project</th>
<th># ship sets</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-747</td>
<td>CA-54-1</td>
<td>28002-001</td>
<td>5</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>C-140</td>
<td>CA-5H-20</td>
<td>24535-19</td>
<td>30</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>F-16</td>
<td>DA-81755</td>
<td>30192-03C</td>
<td>10</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>F-18</td>
<td>ARC-14M220-19</td>
<td>31310-001</td>
<td>10</td>
<td>14</td>
<td>7</td>
</tr>
<tr>
<td>F-18</td>
<td>ARC-40SP100-19</td>
<td>F18-C-113</td>
<td>40</td>
<td>16</td>
<td>2</td>
</tr>
<tr>
<td>F-104</td>
<td>MA-300H</td>
<td>18241-001</td>
<td>3</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>F-111</td>
<td>MA-7</td>
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<tr>
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<td>10H120-21</td>
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<tr>
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<tr>
<td>T-38</td>
<td>MA-500H</td>
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<tr>
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<td>30134-001</td>
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<td>31463-001</td>
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</table>
AESL Overview

The AESL is a distributed digital system consisting of a central system and battery servicing stations connected by a high-speed serial data bus. The entire system is located in two adjoining rooms; the bus length is approximately 100 ft.

Each battery station contains a digital processor, data acquisition, floppy diskette data storage, and operator interfaces. The operator initiates a servicing task; thereafter the battery station monitors the progress of the task and terminates it at the appropriate time.

The central system provides data archives, manages the data bus, and provides a timeshare interface for multiple users. The system also hosts software production tools for the battery stations and the central system.
The battery station benches are 34-in. wide modular wooden structures which can be moved through a standard doorway with a pallet mover. The following components are mounted to the bench:

- **Charger – analyzer**
- **Status and control panel**
- **Primary power panel**
- **Barcode reader gun**
- **Temperature probes**
- **Left Connector panel**
  - Terminal connector
  - Printer connector
  - Load bank control connector
- **Right connector panel**
  - Battery cable connector
  - Monitor plate connector
- **Controller assembly**
  - Cardcage
  - Floppy diskette drive
  - Current leakage box
  - Accessory power box

  - Placed on top of the bench
  - Mounted beneath top of bench
  - Mounted behind bench (near top)
  - Holster at right side of work surface
  - Connected at rear of work surface
  - Mounted under left side of work surface
  - Mounted under right side of work surface
  - Mounted on lower shelf
Monitor Plate Attached to CA-9-20

This photo shows the monitor plate design used with the CA-9-20 battery. This is a 20-cell, 24-Ah battery used on the X-29A forward-swept wing aircraft to supply power to onboard instrumentation. The plate is made of Lucite with spring loaded plunger pins to provide contacts to all the busbars. The connector is standard for all monitor plates so that only a single interconnect cable is required at each battery bench.

Electrical connections are provided for up to 30 cell voltages, total battery volts, and the battery case leakage test circuit. While not electrically part of the monitor plate, the hot vapor sensor is installed in a hole drilled in the center of the monitor plate.
AESL Functional Overview

The operator initiates a servicing task by positioning the case temperature probes, attaching the monitor plate and power cable, installing the hot vapor sensor, selecting the task, and reading the barcode tag on the side of the battery. The database files necessary to support the servicing of this battery are automatically transferred from the central system and an open circuit data file is created. The operator then configures the charger – analyzer and initiates the run phase of the task; a start of run file is created.

While the task is running, numerous parameters are analyzed automatically, and data files are created at timed intervals during the run. If desired, the task may be monitored at the battery station using the status and control panel, or may be monitored by the central system multiuser interface using real-time status transferred on the data bus.

When programmed conditions are met, an end of run data file is created, the charger – analyzer is shut off, and the operator is notified by the audible alarm on the battery station. All data files are stored locally on floppy diskettes and are also sent to the central system archives as servicing records.
Analog Subsystem Channels

Each battery station has an intelligent A/D subsystem consisting of a Datel ST701-A2 microcomputer board and a companion ST742 expander board. This provides a total of 48 channels using a multiplexer feeding a single ±10 V, 12 bit, 20 μs converter. A programmable-gain amplifier at the input to the converter provides gains up to 128X.

Dryden developed software for the Z80 processor on the ST701 board provides several input algorithms. For the reflex charger pulse waveform, the channels are scanned rapidly in succession and 32 past values for each channel are saved in a 32-frame buffer. These equally spaced samples permit pulse shape analysis, plateau averaging, and pulse period computation. For the constant current mode (typically full wave rectified 60 Hz), each channel in turn is allocated a window 1/60-sec. wide. During the window, as many samples as possible are taken in a burst which is then averaged. Ampere-hour integration is also performed by the ST701 using a 64-bit integral and a 64-bit counter tallying the number of iterations.

Analog Subsystem Channels

- 30 cell voltages
- 1 battery monitor plate voltage
- 1 battery cable voltage
- 1 charger–analyzer current
- 5 temperature probes
- 1 case leakage current
- 1 programmable load bank voltage
- 1 programmable load bank current
- 1 programmable load bank temperature probe
Temperature Probes

Each battery bench has five temperature probes to monitor the battery being serviced. Four are mounted on stainless-steel shoes which slide beneath the bottom of the battery case. Installed in a Lucite holder, the fifth probe slips into a hole in the monitor plate to detect hot vapors.

The sensors used are miniature 50-ohm nickel foil elements biased with 2.4 mA. The calibration curve is embodied in a second-order polynomial which gives good accuracy over the 70-170 °F range.
Battery servicing in the Dryden AESL consists of the following:

1. Incoming inspection
2. Return capacity test
3. Cell equalization (zero volts per cell)
4. Cleaning (teardown if required)
5. Charge No. 1 (main and top)
6. Capacity test
7. Charge No. 2 (main and top)
8. Electrolyte level check
9. Load test
10. Charge No. 3 (main and top)
11. Check busbars torqued per spec
12. Quality assurance inspection

Case leakage is monitored continuously during servicing.
Pushbuttons Panel

The pushbuttons matrix on the Status and Control Panel provides the operator with means to set up, control, and monitor the battery servicing task in progress. The top row of pushbuttons allows the operator to select the task to be performed: open circuit, return capacity, charge 1 main, charge 1 top, capacity test, charge 2 main, charge 2 top, 2 minute load, 3 minute load, variable load, charge 3 main, and charge 3 top.

The second row of pushbuttons allows the operator to control the progress of the task. The equipment power button turns on the 220 v AC power to the charger – analyzer. The run mode button signals the software that the charger – analyzer setup is complete and shutdown tests can be run. The hold mode button signals the software to suspend shutdown tests temporarily. The stop mode button removes power from the charger – analyzer. The write file button allows the operator to create additional data files. The read file button is an indicator only.

The bottom row of pushbuttons is used to control the display unit.
Shutdown Criteria

The battery station controller software monitors the progress of each servicing task and terminates the task when the appropriate conditions are sensed. There are three abnormal conditions which always cause immediate shutdown: hot vapor sensed at the top of the battery, high case temperature sensed at the bottom of the battery, or excessive case leakage current.

During reflex charge, normal shutdown occurs when the pulse rate slows to one per second or when the desired amp-hrs is reached. During constant current charge, normal shutdown occurs when the desired amp-hrs is reached or when the maximum battery voltage is reached. Abnormal shutdown conditions include rapid cell voltage drop indicating thermal runaway, or excessively high cell voltage.

During capacity tests, normal shutdown occurs when the lowest cell voltage drops below 1.00 V.

During load tests, the normal shutdown is based on elapsed time. An abnormal shutdown would occur if a lower limit were reached for either a low cell voltage or a low total battery volts.

```
<table>
<thead>
<tr>
<th>Shutdown Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General</strong></td>
</tr>
<tr>
<td>- Hot vapor sensor (top of battery)</td>
</tr>
<tr>
<td>- High case temperature</td>
</tr>
<tr>
<td>- Excessive case leakage current</td>
</tr>
</tbody>
</table>

**Charging tasks**

| - Minimum pulse rate (reflex charger) |
| - Cell voltage drop (thermal runaway) |
| - Maximum ampere-hours |
| - Maximum cell voltage (typ. 1.80 V) |

**Capacity tests**

| - Minimum cell voltage (typ. 1.00 V) |

**Load tests**

| - Elapsed time |
| - Minimum cell/battery voltage |
```
Central System Console

The AESL central system consists of an Intel System 310 CPU, an auxiliary chassis containing hard disk drives, a Wyse Model 60 terminal, and a Dataproducts M200 printer.

The CPU chassis contains a 80286/80287 processor board, 5 Megabytes of RAM, two communications boards providing 12 RS-232 ports, and piggyback modules for the BITBUS interface and the clock – calendar. Also installed in this chassis are a 5.25-in. floppy diskette drive, and a 0.25-in. streaming tape drive.

The auxiliary chassis contains two large hard disk drives plus power supplies. One of the drives contains the data archives and can store 65,500 data files (several years worth). The other is the system drive containing all the software production tools.

The Wyse terminal is used for software production and for the maintenance of the specification files controlling battery servicing operations. The printer is used to dump the nightly log of the automatic archives maintenance operations.
Central System Features

The AESL central system provides data archives, several resident software jobs which provide automatic operations, and a variety of utility programs.

The data archives contain specification files regulating battery servicing operations, data files created during battery servicing, technician's logs for each battery, indexes providing rapid access to data records, and cross-indexes relating battery types, cell types, and applications.

Resident jobs running within the central system provide bus polling, download of specification files, upload of data files, purging the floppy diskettes at the battery stations, and maintaining indexes within the archives. In addition, if the operator inserts a tape cartridge, the archives are backed up to the tape automatically.

Utility programs are provided to review data files, update logs, assess operations schedule, and print the inspector's summary report.

Central System Features

- **On-line records storage**
  - Large archives for battery servicing data files
  - Battery servicing operations logs
  - Cross indexes for battery types, cell types, and applications

- **Automatic operations**
  - Data bus polling
  - Specification files download to stations
  - Data files upload to central
  - Purging temporary storage media at battery stations
  - Updating indexes of data files when required
  - Tape backup of archives when requested by operator

- **User utilities**
  - Servicing data files access
  - Operations logs access–update
  - Operations scheduling
  - Inspector's summary printout
Battery Simulator

NASA Dryden has developed a NiCd battery simulator which has proven useful in checking out battery station hardware and software. It generates 30 individual cell voltages, total battery voltage, and the discrete logic specifying number of cells. In addition, it simulates the signal from the shunt which monitors charger - analyzer current.

The 30 cell switches on the left side of the panel have three positions: center is normal (1.40 V), up is high (1.90 V), and down is low (0.90 V). The knob at lower center of the panel allows total battery voltage to be set, while the five switches above it determine the number of cells.

The controls for the current shunt simulation are on the right side of the panel. It can simulate the pulsed waveform of the reflex charger or the steady-state signal of constant current charging. In addition, it can simulate discharge currents for capacity tests and load tests.
The history of the Dryden AESL project covers several years because only limited manpower was allocated for the effort. Fewer than ten people have been involved on a part-time basis and the priority of the effort has always been low.

The first three milestones in the timeline coincide with the publication of NASA technical memorandums describing progress to date. Design of the production battery stations was a lengthy process because of the complete redesign of the bench structure. Integrated testing of the first three production stations proved that the data bus hardware and software protocols were robust and heavy traffic could be accommodated.

The facility renovation has delayed moving in the new equipment and beginning shakedown testing with contractor operations personnel. It is anticipated that the AESL will be certified by the end of 1991 and that a full complement of 10 stations will be in service by September 1992.

A final report coauthored by Richard Glover and William Kelly will be published in early 1992. Additional information on the AESL can be obtained from William Kelly at (805) 258-3365.

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Project Timeline

May 1988 – Requirements and design approach finalized

July 1989 – Prototype system operational (single station)

Nov 1989 – Data bus protocols finalized

June 1990 – Production station design complete

Mar 1991 – Integrated testing using three production stations

Sept 1991 – Facility renovation complete

Oct 1991 – Begin shakedown production testing with four stations

Dec 1991 – Certify facility for production battery servicing

Sept 1992 – Complete phasing in remaining six production stations
PL BATTERY PROGRAM:
OVERVIEW

- NICKEL HYDROGEN
  LEO TESTING
  EMBRITTLEMENT TESTING

- SODIUM SULFUR
  FLIGHT EXPERIMENT
  HOT LAUNCH EVALUATION

- SOLID STATE POLYMERS
  GEO BATTERY DEVELOPMENT
  PULSE POWER BATTERY SBIR
  IN-HOUSE EVALUATION
Battery development and testing efforts at Phillips Laboratory fall into three main categories: nickel hydrogen, sodium sulfur, and solid state batteries. Nickel hydrogen work is broken down into a LEO Life Test Program, a LEO Pulse Test Program, and a Hydrogen Embrittlement Investigation. Sodium sulfur work is broken down into a GEO Battery Flight Test and a Hot Launch Evaluation. Solid state polymer battery work consists of a GEO Battery Development Program, a Pulse Power Battery SBIR, and an In-House Evaluation of current generation laboratory cells.
PL BATTERY PROGRAM:

- NICKEL HYDROGEN LEO TESTING EMBRITTLEMENT TESTING
The Phillips Laboratory Nickel Hydrogen testing effort consists of a LEO Life Test Program, a Pulse Test Program, and a Hydrogen Embrittlement Investigation.
NIH2 TEST PROGRAM: OBJECTIVES

- Demonstrate NIH2 Performance in LEO
- Develop a statistically significant battery cell database
- Demonstrate that data base for 3.5 in cells can be applied to 4.5 in cells
- Demonstrate NIH2 cell performance in pulse applications
The objectives of the LEO Life Test Program are to: demonstrate NiH2 performance in low earth orbit, develop a statistically significant battery cell database, and demonstrate that the database for 3.5 inch cells can be applied to 4.5 inch cells. The NiH2 Pulse Test, which is a subset of the larger LEO Life Test Program, has the objective of demonstrating NiH2 cell performance in pulse applications.
NIH2 TEST PROGRAM:
GOALS

- DEMONSTRATION OF CYCLE LIFE

30,000 CYCLES AT 40% DOD
20,000 CYCLES AT 60% DOD

- ESTABLISH MINIMUM RELIABILITY OF 90%
WITH CONFIDENCE LEVEL OF 80%
Goals of the NiH2 LEO Life Test Program are to demonstrate 20,000 cycles at 60% DOD and 30,000 at 40% DOD. An additional goal will be to establish a minimum reliability of 90% with a confidence level of 80%.
NIH2 TEST PROGRAM:
OVERVIEW

- ACCEPTANCE TEST
  ALL CELLS

- CHARACTERIZATION TEST
  5 CELLS PER DESIGN PER MANUFACTURER

- RANDOM VIBRATION TEST
  20% OF CELLS PER DESIGN PER MANUFACTURER

- LIFE TESTS
  LEO - 25%, 10C
  40%, 10C & -5C
  60%,10C
  PULSE TEST
  STORAGE TEST
  CHARGE CONTROL TEST
The NiH2 LEO Life Test Program consists of four main parts: acceptance testing, characterization testing, vibration testing, and life testing. The acceptance test consists of a visual inspection and leak test, a conditioning and stability check, standard capacity measurements, impedance measurements, overcharge test, and a charge stand loss measurement. The purpose of the acceptance test is to ensure that cells meet the requirements stated in our specification document.

The purpose of the characterization test is to determine cell charge characteristics and efficiencies. Twenty percent of the cells in each lot are subjected to random vibration testing. The life test program consists of DOD's of 25%, 40%, & 60% at temperatures of -5C and 10C. In addition, ten cells are undergoing storage testing, while a charge control test is scheduled to begin in early FY93.
## NIH2 TEST PROGRAM: TEST MATRIX

<table>
<thead>
<tr>
<th>TEST</th>
<th>MFR</th>
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<th>4.5 IN DIAM</th>
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<tr>
<td></td>
<td></td>
<td>10C</td>
<td>-5C</td>
</tr>
<tr>
<td>LEO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25%</td>
<td>(EPI-CS/GEP)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>YARD</td>
<td>5</td>
<td></td>
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<tr>
<td>40%</td>
<td>HUGHES</td>
<td>10</td>
<td>10</td>
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<tr>
<td></td>
<td>YARD</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>EPI-J</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>GATES</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>60%</td>
<td>HUGHES</td>
<td></td>
<td>10</td>
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<tr>
<td>PULSE</td>
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<td></td>
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</tr>
<tr>
<td>40%</td>
<td>EPI-J</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>STORAGE</td>
<td>(EPI-CS/GEP)</td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| TOTAL CELLS | 92 - 3.5 INCH | 41 - 4.5 INCH |
The LEO Life Test Program test matrix consists of 123 cells from four manufacturers: Eagle Picher, Hughes, Yardney, and Gates. Cells are of either the 3.5 inch diameter type or 4.5 inch diameter type. Once again, temperatures involved are -5C and 10C with DOD's of 25%, 40%, and 60%. The 25% DOD cells will be used in a comparison with nickel cadmium performance. Ten cells are undergoing storage testing.
## NIH2 TEST PROGRAM: RESULTS

(AS OF 1 JUN 91)

<table>
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<th>MFR</th>
<th>ID#</th>
<th># CELLS</th>
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<th>DOD</th>
<th>TEMP</th>
<th>CYCLES</th>
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<td>10C</td>
<td>DIS 5,369</td>
</tr>
<tr>
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<td>5001G</td>
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<td>10C</td>
<td>DIS 5,206</td>
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<tr>
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<tr>
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<td>5003Y</td>
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<td>EPI-CS LT</td>
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<td>4.5</td>
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<td>10C</td>
<td>6,464</td>
</tr>
<tr>
<td>EPI-J</td>
<td>5002E</td>
<td>7</td>
<td>3.5</td>
<td>40%</td>
<td>10C</td>
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<tr>
<td>EPI-J</td>
<td>BEL-PUL</td>
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<td>3.5</td>
<td>40%</td>
<td>10C</td>
<td>4,300</td>
</tr>
</tbody>
</table>
As of 1 June 1991, Phillips Lab's LEO Life Test Program has 123 cells undergoing cycling with 10 cells on storage test. Cycles range from a low of 2,937 to 23,877.
HYDROGEN EMBRITTLEMENT TEST:
OBJECTIVES

PHASE I:

- TEST THE EMBRITTLEMENT SUSCEPTIBILITY OF NICKEL HYDROGEN BATTERY VESSEL MATERIAL IN 1,000 psig HYDROGEN ENVIRONMENT UNDER A SUSTAINED LOAD

PHASE II:

- INVESTIGATE FATIGUE CRACK PROPAGATION
The Hydrogen Embrittlement Test consists of a two phase program. Phase I was just completed and was designed as a quick-look experiment to investigate the embrittlement susceptibility of NiH2 vessel material in 1000 psi hydrogen environment under a sustained load. Phase II is still underway and will investigate fatigue crack propagation in Inconel 718.
HYDROGEN EMBRITTLEMENT TEST:
APPROACH

PHASE I: EMBRITTLEMENT INVESTIGATION

- SAMPLES CUT FROM 3 SPENT CELLS FROM LEO LIFE TEST (EP-13,000 CYCLES, YARD-3,770 CYCLES, GATES-4,300 CYCLES). ALL 60% DOD. INCONEL 718 CASES.

- TENSILE SPECIMENS CUT PARALLEL TO LONG AXIS OF YARDNEY CELL

- 13 STRIPS CUT FROM OTHER TWO CELLS IN A CIRCUMFERENTIAL DIRECTION. WERE THEN BENT INTO U SHAPES AND PLACED IN A 1000 psig HYDROGEN ENVIRONMENT FOR 200 HOURS. 8 SAMPLES (6 OF WHICH WERE SCRIBED AT THE OUTER SURFACE OF THE U-BEND TO A DEPTH OF 0.0002-0.0005 IN) WERE THEN EXPOSED FOR AN ADDITIONAL 200-400 HOURS
In Phase I, samples were cut from three spent cells that had undergone LEO cycling (varying from 3,770-13,000 cycles) at 60% DOD. All cases were Inconel 718. Several specimens were cut parallel to the long axis of one of the cells and subjected to tensile testing. Thirteen strips were cut from the other two cells in a circumferential direction, bent into U shapes and placed in 1000 psig hydrogen for 200 hours. Eight samples were then exposed for an additional 200-400 hours.
HYDROGEN EMBRITTLEMENT TEST: RESULTS

PHASE I:

- TENSILE DUCTILITY OF INCONEL 718 DECREASED AFTER LONG EXPOSURE TO NIH2 CELL ENVIRONMENT. FRACTURE MODE REMAINED DUCTILE.

- ONE FAILURE OBSERVED IN U-BEND SPECIMENS AFTER 200 HOURS. DETERMINED TO BE CAUSED BY APPLIED BENDING STRESS, HYDROGEN ENVIRONMENT, AND SURFACE DEFECT CAUSED BY IMPROPER MACHINING.

- INCONEL 718 THAT HAS BEEN EXPOSED TO THE NIH2 CELL ENVIRONMENT APPEARS TO BE MORE SUSCEPTIBLE TO HYDROGEN EMBRITTLEMENT THAN VIRGIN INCONEL 718. THRESHOLD INTENSITY FACTOR COULD BE DECREASED FROM 22 ksi for VIRGIN INCONEL TO BELOW 17 ksi for MATERIAL EXPOSED TO HYDROGEN FOR LONG TIMEFRAMES.
Initial results indicate that the tensile ductility of Inconel 718 decreased after long exposure to the NiH2 cell environment. However, the fracture mode remained ductile. One failure was observed in the group of u-bend specimens after 200 hours exposure. However, the failure was determined to have been caused by a combination of the applied bending stress, the hydrogen environment, and a surface defect that was introduced as a result of improper machining during the process of cutting the sample from the cell. Inconel 718 that has been exposed to the NiH2 battery environment appears to be more susceptible to hydrogen embrittlement than virgin material.
PHASE I:

- MAXIMUM APPLIED STRESS INTENSITY FACTOR FOR CELL SHELL IS APPROX 15 ksi/\text{in}, WHICH MAY BE VERY CLOSE TO THRESHOLD STRESS INTENSITY FACTOR OF THE INCONEL EXPOSED TO HYDROGEN OVER LONG PERIODS. ADDITIONAL TESTS NEEDED TO DETERMINE THRESHOLD STRESS INTENSITY FACTOR VALUE OF SHELL MATERIAL FOR SAFE OPERATION OF CELLS.
The maximum applied stress intensity factor for the cell shell has been calculated at approximately 15 ksi in, which may be very close to the threshold stress intensity factor of the Inconel material exposed to hydrogen over long periods of time. Therefore, it is recommended that additional tests be conducted to determine the threshold stress intensity factor value of shell material to warrant safe operation of the cells.
HYDROGEN EMBRITTLEMENT TEST: 
APPROACH

PHASE II: CRACK PROPOGATION RATES

- SAMPLES CUT FROM SPENT CELLS FROM LEO LIFE TEST. ALL INCONEL 718 CASES

- U-BEND SPECIMENS WITH PRECRACKS EMPLOYED TO ESTIMATE THE CRACK PROPOGATION RATE OF INCONEL 718 IN 1000 psig HYDROGEN. KOH ALSO PRESENT IN TEST ENVIRONMENT

- SOLENOID USED TO PLACE EACH SAMPLE UNDER A CYCLIC LOAD PROFILE

NOTE: PHASE II IS STILL IN PROGRESS
In Phase II, samples will be cut from spent cells from Phillips Lab's LEO Life Test (as in phase I). Specimens will be bent into U shapes and precracks will be employed. A solenoid will be used to place each sample under a cyclic load profile, roughly simulating the loading that cells would encounter under cycling. The test environment will consist of 1000 psig hydrogen as well as KOH solution.
PL BATTERY PROGRAM:

• SODIUM SULFUR FLIGHT EXPERIMENT
• HOT LAUNCH EVALUATION
The Phillips Laboratory Sodium Sulfur development and testing effort consists of a flight test of a 16 cell GEO NaS battery and an evaluation of the hot launch capabilities of NaS cells.
NaS FLIGHT EXPERIMENT:
OBJECTIVES

- VERIFY NaS TECHNOLOGY IN ZERO-G
- VERIFY NaS CELL DESIGN FOR GEO APPLICATIONS
- MONITOR THERMAL CONTROL PROCESSES
- ENABLE TRANSITION OF NaS TECHNOLOGY
The primary objective of the NaS Flight Experiment is to verify that the GEO cell design functions properly in zero-g. The end goal of the program is the transition of NaS technology to the user.
**Why NaS Batteries?**

- **ENABLING TECHNOLOGY FOR HIGH POWER SATELLITE MISSIONS**
- **ENHANCING TECHNOLOGY FOR MANY SATELLITE MISSIONS**
- **BENEFITS OF 100WHR/KG NaS BATTERY VS SOTA NiH2 BATTERY**
  - 60% REDUCTION IN BATTERY MASS
  - 15% REDUCTION IN POWER SYSTEM MASS
  - 60% REDUCTION IN BATTERY VOLUME
  - 40% REDUCTION IN BATTERY COST
Sodium sulfur batteries should provide a variety of advantages over SOTA batteries. NaS is expected to be an enabling technology for high power satellite missions and an enhancing technology for many other satellite missions. Benefits of NaS batteries over NiH2 batteries include: 60% reduction in battery mass, 15% reduction in power system mass, 60% reduction in battery volume, and a 40% reduction in battery cost.
SCHEDULED TO FLY ABOARD P91-1 IN 1995

FTU (FLIGHT TEST UNIT) WILL CONSIST OF:
- 16 CELL, 28 VOLT, 40 AMPERE-HOUR HEDRB MODULE (GFE)
- EXPERIMENT SCIENCE PACKAGE

GTU (GROUND TEST UNIT) WILL DUPLICATE THE FLIGHT EXPERIMENT
The flight experiment will utilize a 16 cell, 28 volt, 40 amp-hr GEO battery under development at Wright Patterson AFB. This battery will be delivered GFE to Phillips Lab for integration onto the Air Forces's P91-1 satellite which will fly in 1995. A separate ground test unit will duplicate the experiment concurrently on the ground.
Nas Hot Launch Evaluation

Objectives

- Evaluate cell performance under hot launch conditions. Hot launch is a launch in which the cells are at operating temperature.

- To evaluate structural integrity of cells under hot launch conditions.
The purpose of the Sodium Sulfur Hot Launch Evaluation is to investigate cell performance under hot launch conditions. For our purposes, a hot launch is defined as a launch in which the cells are at operating temperature.
NaS HOT LAUNCH EVALUATION:
TEST PLAN

- TWO APPROACHES
  2 CELLS MOUNTED ORTHOGONALLY
  EACH CELL TESTED INDEPENDENTLY IN TWO AXES

- CELL PREPARATION
  PHYSICAL EXAMINATION
  COLD OPEN CIRCUIT VOLTAGE
  MOUNTING AND PROBE CONNECTION
  CELL THAW
    AMBIENT TO 90 C AT 25 C PER HOUR MAX
    90 C TO 140 C AT 10 C PER HOUR MAX
    140 C TO 350 C AT 25 C PER HOUR MAX
  FUNCTIONAL TESTING
Two cells will be mounted orthogonally to each other and subjected to vibration testing designed to simulate the worst launch environment that the cells are likely to see. Preparation for the test consists of a physical examination, cold open circuit voltage measurement, the mounting and connection of instrumentation, a controlled thaw procedure, and functional testing to determine initial state-of-health of the cells.
NaS HOT LAUNCH EVALUATION:
VIBRATION ENVIRONMENT

POWER SPECTRAL DENSITY (g²/Hz)

FREQUENCY (Hz)
The cells will be subjected to the vibration environment shown. This environment corresponds to the worst environment that an operational NaS battery is likely to see on launch.
BENEFITS DERIVED FROM LAUNCHING HOT

- Able to have satellite on-line immediately upon reaching orbit
- Eliminate the need for an alternate power source for cell thaw once on orbit
There are several reasons for wishing to launch a sodium sulfur battery in a hot condition as opposed to launching in the frozen state. For one thing, launching hot would allow the satellite to be on-line immediately upon reaching orbit. If launched in a frozen state, the battery would require approximately eighteen hours to complete its thaw cycle. A second advantage is gained due to the fact that the need for an alternate power source is eliminated. This alternate power source (such as a backup battery) would usually be needed to provide power to the satellite during the thaw period of the NaS battery and would also be used to provide power to the heaters used to thaw the NaS battery.
PL BATTERY PROGRAM:

- SOLID STATE POLYMERS
- GEO BATTERY DEVELOPMENT
- PULSE POWER BATTERY SBIR
- IN-HOUSE EVALUATION
The Phillips Laboratory Solid State Polymer Battery development and testing effort consists of a GEO Battery Development Program, a Pulse Power Battery SBIR, and an in-house evaluation of current-design laboratory polymer battery cells.
GOALS:

- DEVELOPMENT OF HIGH ENERGY DENSITY POLYMER BATTERIES FOR GEO SATELLITE SYSTEMS
  - >200 WHR/KG
  - 10 YR LIFE, 1000 CYCLES, 80% DOD
  - CELL SIZE - 50 AH

APPROACH:

- DESIGN AND FABRICATION
- SCALABILITY AND PRODUCIBILITY ANALYSIS
- CELL PERFORMANCE TESTING AND ANALYSIS

STATUS:

- FY92 NEW START
- 2 YR BAA EFFORT FOLLOWED BY EXPANDED PROGRAM
An FY92 new start program will begin the process of developing a solid state battery for use in GEO orbits. Goals of the program will be the development of cells with energy densities of greater than 200 WHR/KG having at least a ten year life, with the capability of at least 1000 cycles at 80% DOD. Cell capacities will be on the order of 40-50 amp-hr. As stated previously, the program will start in early FY92 with several concepts being funded during the first two years under a BAA contract. In the third year, one concept will be chosen for an expanded program.
SOLID STATE BATTERIES:
PULSE POWER BATTERY DEVEL

GOAL:

DEVELOPMENT OF SOLID-STATE, PULSE POWER BIPOLAR BATTERY
WITH MAX SPECIFIC POWER OF 50 kW/kg AND MAX SPECIFIC ENERGY
OF >50 Wh/kg

APPROACH:

- POLYACRYLONITRILE (PAN) POLYMER ELECTROLYTE (2x10^-3 OHM CM AT 25°C)
- LINIO2 HIGH VOLTAGE (3.5 V) INTERCALATION CATHODE
- CARBON INTERCALATION ANODE

STATUS:

- PHASE I SBIR NEARING COMPLETION
Phillips Lab is currently managing a phase I SBIR for SDIO with the goal of developing a pulse power battery with a specific power of approximately 50 kW/kg and an energy density of greater than 50 Wh/kg. The battery will utilize a polyacrylonitrile electrolyte, a high voltage cathode, and a carbon-based anode. Phase I is currently nearing completion.
GOALS:
- Assess capabilities of current-generation solid state cells
- Gain insights into areas requiring future development efforts

APPROACH:
- Procure sample cells from several manufacturers
- Cycle until failure
- Perform analysis to determine failure modes/mechanisms

STATUS:
- Procuring equipment and cells
- Testing should begin in early January
An in-house program at Phillips Lab will also assess the capabilities and limitations of current solid state cells, thus providing valuable information for use on our GEO battery development program. The approach will be to procure cells from several manufacturers, cycle them until failure, and perform a series of tests to determine the failure modes/mechanisms.
BATTERY and CELL TESTING
at
Marshall Space Flight Center

Marshall Space Flight Center
Huntsville, Alabama
35812

Tom Whitt and Lorna Jackson

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ON-GOING BATTERY/CELL TESTING AT MSFC

Hubble Space Telescope Applications:

- Ni-Cd 6, 4-Cell Packs, RSN-55-15
- Ni-H2 14-Cell Pack, RNH-30-1
- Ni-H2 12-Cell Pack, RNH-35-3
- Ni-H2 3, 4-Cell Packs, RNH-90-3
- Ni-H2 Six Battery Test, RNH-90-3
- Ni-H2 "Flight Spare" Battery, RNH-90-3

Other Applications:

- CRRES Ni-Cd Testing
- Ag-Zn 4, 6-Cell Packs, LR 350 DC-1
- Ni-H2 6, 4-Cell Packs, RNH-90-3
- Ni-H2 2, 2-Cell Packs, RNH-90-3

This presentation is an overview covering the ten cell/battery tests ongoing at Marshall Space Flight Center. The presentation is not intended to give specific results on any test. This presentation acknowledges the purpose and related program that applies to each test.

Except for the Combined Release and Radiation Effects Satellite (CRRES), all are energy-stored and retrieval devices at low earth orbit (LEO) cycles.
HST NiCd Six, 4-Cell Packs

- 55 ampere-hour cells developed by Eagle-Picher Inc.
  RSN-55-15, Type 44 Cells

- These were the baseline cells for HST before their replacement by Ni-H2 batteries.

- Characterize cell behavior and demonstrate life capability of the originally designed HST batteries.

- Completed over 27,000 LEO cycles

- The cells met the 3 year HST capacity requirement even after 59 months of cycling.

HST Ni-Cd Six, 4-Cell Packs - The 24 Ni-Cd cells are Eagle-Picher, Type 44, RSN-55-15, matched to the six Type 44 flight batteries for the Hubble Space Telescope (HST). These cells were received from Lockheed Missiles and Space Company (LMSC) after 4 years of LMSC cycling. They represent the baseline cells for HST before their replacement by Ni-H2 batteries. The packs are configured into six packs of four cells each. The system was designed for the cells to operate at a depth of discharge equivalent to 16 percent of nameplate capacity of 55 ampere-hours during normal cycling. On line since 1990, this test will be used to characterize cell behavior and demonstrate life capability of the originally designed HST batteries.

A modified Battery Protection and Reconditioning Circuit (BPRC) is used to prevent cell reversal during failure and/or reconditioning. This BPRC is one of the six MSFC designed and qualified for flight taken from the Ni-Cd 6-Battery Mission Simulation Test.
HST Ni-H2 14 Cell Pack

- 30 ampere-hour cells developed by Eagle Picher Inc. RNH-30-1 (COMSAT design)

- On test since 1986, to build data base for Ni-H2 LEO operation at shallow DODs

- Completed over 26,000 LEO cycles at 13% DOD.

- Capacity after 4.5 years of cycling was 22 Ah.

EB12/MSFC
Ni-H2 12 Cell Pack

- 33 ampere-hour (Ah) cells developed by Eagle Picher Inc. RNH-35-3 (Air Force design)


- Completed over 26,000 HST LEO Cycles at 13% DOD with a step-to-trickle charge scheme.
  - Cycling capacity of approx. 27 Ah

- Presently cycling at 22% DOD, with a step-taper charge scheme.

1991 NASA Aerospace Battery Workshop -109- General Topic Session
CRRES Ni-Cd Testing

- 18 ampere-hour cells developed by Gates for Ford Aerospace

- Simulating the highly elliptical orbit of the CRRES spacecraft (588 minute orbit)

- Determining the optimum charge levels to maximize battery life and effectiveness

- Completed over 488 orbital cycles ranging from 0 to 50% DOD

CRRES Ni-Cd Testing - At MSFC testing is being performed on Ni-Cd cells used for the Combined Release and Radiation Effects Satellite (CRRES) program. These Ni-Cd cells were manufactured by Gates for Ford Aerospace and have a nameplate capacity of 18 ampere-hours.

The two MSFC applications which apply to the CRRES program are the Two-Cell Test and CRRES Flight Spare Battery Test (an actual 21 cell battery). They simulate the highly elliptical orbit seen by the CRRES spacecraft. This elliptical orbit has a period of 588 minutes with varying eclipse times. Both tests will undergo an over-temperature, over-charge event experienced on the actual spacecraft. The main objective of these tests is to determine the most efficient charge levels for the actual spacecraft battery to maximize battery life and effectiveness.
Silver-Zinc Pack Testing
Four, 6-Cell Packs

- 350 ampere-hour (Ah) cells developed by Yardney.
- Originally tested for OMV; now applicable to CTV
- Determine operational life of similar cells subjected to periodic deep discharges.
- Test profile consist of the following:
  - Shallow DOD LEO cycles (1.2 Ah)
  - Deep DOD "Mission Discharges" (295 Ah)
- 19 Deep Discharges and over 8200 LEO cycles
- Total capacity after 18 months of cycling was 295 Ah.

EB12/MSFC
HST Ni-H2 4-Cell Packs

- 88 ampere-hour cells developed by Eagle Picher Inc. for the HST project. RNH-90-3
- One 4-cell pack of TM1 cells, One 4-cell pack of TM2 cells, and One 4-cell pack of FSM cells
- Packs used for parametric testing. First of the HST cells to arrive at MSFC for testing.
- Testing parallels HST system test with ability to investigate proposed changes or duplicate recent occurrences without affecting integrity of system test.

- Months on test  TM1- 34  TM2- 32  FSM- 30

HST Ni-H2 Three, 4-Cell Packs - Three four cell packs of Eagle-Picher RNH-90-3 cells from different lots (4 Flight Spare Module (FSM) Lot Cells, 4 Test Module 1 (TM1) Lot Cells and 4 Test Module 2 (TM2) Lot Cells) following an Hubble Space Telescope (HST) low earth orbit (LEO) (6/35) cyclic profile at 7% - 9% DOD. The FSM cells were placed in the test bed in March 1989 and are into their 30th month of cycling. The TM1 cells began cycling during November of 1988 and are into their 34th month of cycling while the TM2 cells began cycling in February of 1989 and presently are into their 32nd month of cycling.

The packs provided early data on the operation of HST Ni-H2 cells cycled according to a Voltage versus Temperature (VT) curve already in place for use on the HST with Ni-Cd batteries. The test bed uses programmable power supplies and load banks with digital system control and data collection while solar array decay, seasonal sun intensity, off nominal roll and other parameters are variable. These cells were used for parametric testing on Ni-H2 cells of HST design. This test will continue HST LEO cycling when not performing system evaluation tests.
HST Ni-H$_2$ Three, 4-Cell Packs
Testing of RNH-90-3 Cells

- HST Ni-H2 Three, 4-Cell Packs
- HST Ni-H2 Six Battery Test
- HST "Flight Spare" Battery Test
- Ni-H2 Two, 2-Cell Packs
- Ni-H2 Six, 4-Cell Packs at 22 & 33% DOD
HST Ni-H2 Six Battery Test

- 88 ampere-hour cells developed by Eagle Picher Inc. for the HST project. RNH-90-3
- 22 cells/battery, 6 batteries in parallel (3 batteries from the TM1 lot and 3 batteries from the TM2 lot)
- DODs range from 6 to 9% of the battery nameplate capacity.
- Battery cycling capacities vary from 75 to 80 Ah.
- 13,200 cycles (29 months) as of 10/21/91
- 11 month lead time on the HST mission

EB12/MSFC

HST Ni-H2 Six Battery System Simulation - A full scale Hubble Space Telescope (HST) Ni-H2 six battery electrical power system simulation began in May of 1989. This test utilized Test Module 1 (TM1) and Test Module 2 (TM2) cells (six 23 cell batteries) in a flight configuration with full instrumentation. Solar panel assemblies (SPAs) were simulated by power supplies, the electrical load by programmable load banks and the actual DF-224 by a system control computer. The test system has safety and protection measures built in to prevent catastrophic failure (fuses, overtemperature shutdowns, power timeout circuits, uninterruptible power supply and auto dialer). This test provides life cycle data on the HST Ni-H2 modules in a low earth orbit (LEO) power system; these modules are operating at the current HST Charge Current Control (CCC) levels in a 0°C environment.

To date, over 13,200 cycles have been completed on the system with nominal performance noted. Optimum operating parameters previously indicated were confirmed by the system simulation. The simulation will continue to operate for an undetermined period of time in support of the HST.
HST Ni-H2 "Flight Spare" Battery

- 88 ampere-hour cells developed by Eagle Picher Inc. for the HST project. RNH-90-3
- 22 cells from the Flight Spare Lot of cells
- DOD ranges from 6 to 9% of the battery nameplate capacity.
- Battery cycling capacities vary from 70 to 78 Ah.
- 12,800 cycles (28 months) as of 10/21/91
- 10 month lead time on the HST mission

EB12/MSFC
HST Ni-H₂ "Flight Spare" Battery
Ni-H2 Two, 2 Cell Packs

- 88 ampere-hour cells developed by Eagle Picher Inc. for the HST project. RNH-90-3

- Previously used in the HST 4 Cell Pack Testing.

- 1 pack with 26% KOH / 1 pack at 31% KOH

- Compare performance of the KOH concentrations at high DODs (20-50%) in a LEO cycling profile

- 24 months of testing at the higher DODs

EB12/MSFC

Ni-H2 Two, 2-Cell Packs - Four test cells from the Hubble Space Telescope (HST) engineering lot of cells (Eagle-Picher RNH-90-3) are divided into two packs of two cells dependent upon their electrolyte concentration (2 cells with 26% KOH, Pack #1; and 2 cells with 31% KOH, Pack #2). On line since 1988, this test was set up to research the behavior of Ni-H2 cells of HST design, having differing electrolyte concentrations, when operated at high depths of discharge (20% - 50%) in a low earth orbit cycling program. This test utilizes cells which were previously used in the HST three, 4-cell pack testing program. These cells are currently cycling according to a parametric test matrix which will be completed in 1992.
EAGLE PICHER RNH-90-3 CELLS CYCLING AT 22% & 33% DODs

• 88 ampere-hour cells developed by Eagle Picher Inc. for the HST project.

• Four 4-cell packs cycling at 22% DOD
  Two 4-cell packs cycling at 33% DOD

• Gather data to determine best charge control method to use for Ni-H2 cells at moderate DODs.

• Study the effect of reconditioning on Ni-H2 cells.

• Demonstrate the ability of the HST design to provide extended life cycle at DODs required by AXAF, Space Station, etc.

Six Ni-H2 4-Cell Packs - This test utilizes 24 Eagle-Picher RNH-90-3 Ni-H2 cells from the Hubble Space Telescope (HST) program. The cells are low earth orbit (LEO) cycling on a 61/35 orbit. On line since May of 1991, the purpose of this test is to evaluate the performance and operating characteristics of the HST cell at moderate depths of discharge (DOD's) and investigate the long term effects of periodic reconditioning.

The cells are divided into six packs of four cells each based on their manufacturing lot. Two of the packs are cycling at 22% DOD and will be used to study the effects of reconditioning. These two packs charge until a set recharge ratio (RR) is achieved then, step to a trickle charge level. One of these packs will be reconditioned periodically while the other is not. The electrical performance of the two packs as well as the electrochemical effects of the reconditioning through destructive physical analysis (DPA) will be monitored.

Four packs are dedicated to studying the performance of the cells at moderate DOD's. Two of the packs are LEO cycling at 22% DOD while the other two are cycling at 33% DOD. One pack at 22% and one pack at 33% are charging to a recharge ratio with a voltage versus temperature (VT) curve to limit overvoltage on the cell. The packs step to trickle after achieving the RR. The remaining packs (1 at 22% and 1 at 33%) are also charging to a RR; but, the charge cutback to half the original charge current is controlled by sensing the beginning of overcharge. The current then steps to a trickle level after reaching the RR.
Six, Ni-H$_2$ 4-Cell Packs
Testing of Eagle Picher RNH-90-3

at MSFC:

Summary

<table>
<thead>
<tr>
<th>TEST</th>
<th># of Cells</th>
<th>Cycling DOD</th>
<th>Project(s)</th>
<th>Months of testing</th>
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<td>HST NI-H2 4-Cell Packs</td>
<td>12</td>
<td>6 - 9%</td>
<td>HST</td>
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<td>24</td>
<td>22 &amp; 33%</td>
<td>AXAF</td>
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</tr>
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</table>

SS Freedom
Summary of LDEF Battery Analyses

Presented at
1991 NASA Aerospace Battery Workshop

by
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SUMMARY OF LDEF BATTERY ANALYSES

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ABSTRACT

Tests and analyses of NiCd, LiSO2 and LiCF batteries flown on the Long Duration Experiment Flight (LDEF) includes results from NASA, Aerospace and commercial labs. The LiSO2 cells illustrate six-year degradation of internal components acceptable for space applications, with up to 85% battery capacity remaining on discharge of some returned cells. LiCF batteries completed their missions, but lost any remaining capacity due to internal degradation. Returned NiCd batteries tested at NASA-Goddard, showed slight case distortion due to pressure build up, but were functioning as designed.

INTRODUCTION AND BACKGROUND

Boeing in conjunction with LDEF Systems SIG has assisted in organizing the LDEF battery investigations on lithium sulfur dioxide (Li/SO2), lithium carbon monofluoride (Li/CF) and nickel cadmium (NiCd) batteries. A summary of the batteries used on specific LDEF experiments are listed in Table 1. The quantity, type of battery and state of charge remaining for each experiment are tabulated to indicate the range of battery status upon return of LDEF. Sections following describe tests and analyses being performed on each battery type, thus the division of sections by type of battery.

ANALYSES ON LITHIUM SULFUR DIOXIDE BATTERIES

Four organizations are involved in studying the lithium sulfur dioxide batteries used on the majority of LDEF experiments: Aerospace Corporation, Jet Propulsion Laboratory, Naval Test Laboratories, and SAFT America (Manufacturer of the batteries). The primary objective of the study is to identify degradation modes of the batteries, and to provide information useful to future missions. This study is still underway, with only preliminary results thus far reported. All LDEF lithium sulfur dioxide batteries performed satisfactorily for the experiments they were designed. Interest in the ability of these batteries to maintain charge retention has prompted testing to understand the benefits and limitations of maintaining charge in lithium sulfur dioxide batteries for space applications.

1991 NASA Aerospace Battery Workshop -126- General Topic Session
Table 1. Summary of Battery Type, Quantity and State of Charge.

<table>
<thead>
<tr>
<th>Exp #</th>
<th>Experiment Name</th>
<th>Battery Type</th>
<th>Voltage</th>
<th># of Batteries</th>
<th>SOC</th>
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<tr>
<td>A 0038</td>
<td>Pyro Cable Cutter</td>
<td>LiSO2</td>
<td>12</td>
<td>7</td>
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<td>A 0054</td>
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<td>1</td>
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<td>49%</td>
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<td>Recorders to Space Exposure</td>
<td>LiSO2</td>
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<td>2</td>
<td>76%</td>
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<td>2</td>
<td>0%</td>
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<tr>
<td>S 0069</td>
<td>Carousel, Opt system</td>
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<tr>
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<tr>
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<td>12</td>
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<td>28</td>
<td>6</td>
<td>0%</td>
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<tr>
<td>S 1001</td>
<td>Low Temperature Heat Pipes</td>
<td>NiCd</td>
<td>10</td>
<td>1</td>
<td>Recharge</td>
</tr>
</tbody>
</table>
Discharge data of selected experiment batteries was performed by L. Thaller of The Aerospace Corporation (3). The discharges were performed by placing resistive loads across the cells and monitoring the voltage to determine capacity remaining. Data from these experiments are included in Table 1, which summarizes the state of charge remaining in the lithium sulfur dioxide batteries for specific experiments.

Lithium sulfur dioxide batteries generally exhibit good charge retention, with loss in capacity of less than 3-5 percent per year. LDEF lithium sulfur dioxide batteries showed charge retention properties commensurate with that expected based on the temperature profile experienced by these batteries. The state of charge remaining versus the quantity of batteries is shown in Figure 1. Some batteries retained greater than 80 percent of their original capacity. Ground stored batteries retained charge better than the flight batteries, which saw minimal use. This is an expected result, since the average storage temperature of the ground batteries was lower than that of the flight batteries. Ground stored batteries remained in refrigeration at NASA Langley with an average temperature of 0 \(^\pm\) 5 °C.

The average temperature of LDEF flight batteries was 15 \(^\pm\) 10 °C, which would produce a greater degradation of the lithium electrode. Ground stored batteries experienced an average capacity loss of 11 percent over the 6-year LDEF flight time, while some flight batteries on LDEF showed up to 30 percent capacity loss (2). The favorable performance of LDEF lithium sulfur dioxide batteries adds credence to the selection of lithium sulfur dioxide batteries of similar design for the Galileo mission.

ANALYSES ON LITHIUM CARBON MONOFLUORIDE BATTERIES

Investigation of lithium carbon monofluoride batteries was accomplished with a subcontract from The Boeing Company to AZ Technology. Ten Li/CF batteries were flown on LDEF as listed on Table 1. The batteries were depleted on return of LDEF. Figure 2 shows the gradual degradation of battery voltage with time for the battery used on the Thermal Control Surfaces Experiment (4). The required experiment life was twelve months, with an expected life of 18 months, which the batteries exceeded.

The LiCF batteries experienced slight leakage of one cell in one of the LDEF batteries. An "Odor" was detected in the battery case of experiment S0069, upon opening. H. L Lewis and V. L. Hammersley at the Naval Weapons Center, Crane, Indiana, are investigating the phenomena and will be presenting their findings in January 1992 (5). The electrolyte used in the Eagle-Picher Industries LiCF batteries is dimethyl sulfide, which contains small amounts of other sulfur compounds that can be quite odorous. AZ Technology investigated the effect of the leaked electrolyte vapors on the O-ring seal of the battery containment case (6). The seal experienced a softening and deformation due to the attack, however indications are that any leakage was contained in the case and created no performance problem for the battery or associated experiment.
Figure 1. State of Charge Remaining in Li/\text{SO}_2\text{O}_2 Batteries Returned from LDEF Flight.

Figure 2. Gradual Degradation of Voltage with Flight Duration for Li/CF Batteries
TESTS AND ANALYSES ON THE NICKEL CADMIUM BATTERY

One nickel cadmium battery was flown on the Low Temperature Heat Pipe Experiment Package (Experiment #S1001). Analysis and test of the battery has been conducted by S. Tiller and D. Sullivan of NASA Goddard Space Flight Center (7). The battery consisted of two 9-cell packs, which were mounted onto a 0.75 inch thick aluminum baseplate. Prior to flight, power analysis for the 12-Ah NiCd battery indicated a need for 2 to 3 ampere discharge; however, reduction in the experiment during flight resulted in a much lower power demand. The resulting over charge of the battery became a duration test for the NiCd battery. These batteries are not known for their ability to withstand excessive overcharging for long times. The battery survived the entire 6-year usage and was still functioning upon retrieval. The overcharge was reported to have developed internal pressure, resulting in bulging of the cell cases, especially those cells on the end of the cell pack.

The loss of overcharge protection is obvious from the difference in voltage performance shown for pre-flight and post-flight cells on constant charge, see Figure 3. Preflight charge profile showed all cells were matched and reached full state of charge in 18 hours, while maintaining voltage below 1.46V. Post-flight data experienced considerable differences between cells with cell # 10 reaching a high voltage of 1.52 volts, which tripped the charge for the battery off at 14 hours of charge. Discharge performance produced similar results with pre-flight reaching 6.4 hours discharge at a C/4.8 rate, while post-flight cells attained only 6 hours for the same conditions, see Figure 4.

CONCLUSIONS

LDEF batteries experienced mild temperature extremes during flight providing a favorable environment for life considerations. All batteries performed to expectations meeting and exceeding original design requirements. Minor leakage was experienced on one cell of a LiCF battery, which resulted in minor attack of the o-ring on the battery case, with no damage to experiment hardware. The NiCd battery endured considerable over charge and returned with case bulging, but still functioned with decreased capacity capability.
**Figure 3.** Constant Current Charge Indicates Loss of Overcharge Protection

**Figure 4.** Constant Current Discharge Produces Low Capacity, Post Flight
REFERENCES

1. Raman, "Experimentation and Destructive Physical Analysis for the Space-Exposed Lithium-Sulfur Dioxide (Li/SO2) Batteries From the Long Duration Exposure Facility (LDEF)", SAFT America Inc., Attachment 1, 1991, pp. (1)-1,2.


5. H. L Lewis and V. L. Hammersley, "Long Duration Exposure Facility (LDEF) Lithium Carbon Monofluoride (LiCF) Cells -- Analytical Comparison To Earth Based Cells", To Be Presented at The Seventh Annual Battery Conference, California State University, Long Beach, CA. January 21-23, 1992


Primary Technologies Session

Organizers: Bob Bragg
NASA Johnson Space Center

Frank Deligiannis
Jet Propulsion Laboratory
THE SWELLING MECHANISM OF CATHODES

IN Li/(CFx)n CELLS

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PRESENTED AT THE
NASA AEROSPACE BATTERY WORKSHOP
OCTOBER 29-31, 1991
MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, AL
ABSTRACT

Active material particles spatial arrangement in combination with the nature of the electrochemical reduction mechanism were found to be the major cause of excessive swelling in cathodes in Li/(CFx)n cells. A better understanding of the chemical reaction mechanism, a possible new role for the carbon and a model for cathode growth are discussed.
INTRODUCTION

Early developers of lithium-organic electrolyte cells were attracted to (CF_x)_n as a potential cathode material. This attraction was based on calculated theoretical energy values of which the most outstanding was a theoretical specific energy approaching 2000 wh/kg*. Calculations of solid volume changes in the Li/(CF_x)_n cells, based on "crystallographic" densities, indicated a volume reduction caused by active materials transforming into products of about 35%. However, in practice, loading of active materials was limited by an unexplained severe cathode swelling which resulted in cell choking and/or bulging of flat cell walls.

This investigation was aimed at trying to understand the cathode swelling phenomenon and, if possible, find a way to increase the active material loading in Li/(CF_x)_n cells.

The results of the first part of this project were reported in the 1990 NASA Aerospace Battery Workshop. This presentation covers a review of the early results, new insight into the role of carbon in the cathode reaction mechanism, a swelling model based on microscopic observation and cells swelling behavior and conclusion.

* This number is based on the assumption that the EMF of the electrochemical reaction is between 2.8 and 2.9 volts. See - J. P. Gabano, "An Overview" in "Lithium Batteries" (J. P. Gabano ed) P. 2, Academic Press, New York, NY, 1983.
VOLUME CHANGES OF CATHODES IN BR-2325 CELLS DUE TO DISCHARGE

WET CATHODES VOLUME BEFORE DISCHARGE

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>PC/DME</td>
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</tr>
<tr>
<td>GBL</td>
<td>0.251</td>
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CATHODES FROM DISCHARGED CELLS

32°F and 120°F Discharge Across a 37,500 ohm Load

<table>
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<th>ΔVolume* (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>32°F</td>
</tr>
<tr>
<td>PC/DME</td>
<td>36</td>
</tr>
<tr>
<td>GBL</td>
<td>36</td>
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75°F Discharge Across a 15,000 ohm Load

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</thead>
<tbody>
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<td>PC/DME</td>
<td>27</td>
</tr>
<tr>
<td>GBL</td>
<td>28</td>
</tr>
</tbody>
</table>

* ± 1%
APPORACH

The problem is illustrated by the data obtained from measurements performed on cathodes from fresh and discharged BR-2325 cells.

Approximately doubling of electrodes volume was reported for experiments conducted with essentially free "standing" electrodes.* That report indicated that no temperature effect was observed with the highly porous "free standing" electrodes.

Initially, the source of the problem was thought to be related to the reaction mechanism, hence the prevailing mechanism for the electrode reduction required a careful review.

As no mechanistic answer on the atomic level could explain the observed magnitude of electrode swelling, microscopic observations of active cathode material particles behavior during discharge were investigated in search for an explanation for the excessive growth.

Finally, an atomic-microscopic model was evolved which can explain the observed swelling phenomenon.

ELECTROCHEMICAL REDUCTION OF PTFE AND (CF<sub>x</sub>)<sub>n</sub> BY LITHIUM

PROPOSED MECHANISMS

\[
(CF_x)_n
\]

\[
\begin{align*}
\text{n Li + (CF)}_n & \rightarrow \text{[CFLi]}_n^* \rightarrow \text{nLiF + nC} \\
\end{align*}
\]

\* Prevailing literature intermediate [CF\cdot Li(S)<sub>n</sub>]

PTFE (Dousek et al)

\[
\begin{align*}
\text{Li} + \text{PTFE} & \stackrel{\text{Fast}}{\rightarrow} \text{LiF-C-C-C-} \stackrel{\text{Slow}}{\rightarrow} \text{LiF + \(-C=C-\)}_n \\
\end{align*}
\]

\([-C=C-]_n \rightarrow \text{to more ordered form}

\text{LiF} \rightarrow \text{to larger crystals}

PROBLEM:

In both cases x-ray diffraction patterns do not show intermediate; hence

HOW DOES THE LITHIUM REACH REACTION SITES?
ROLE OF CARBON
(Reaction Mechanism)

Reaction mechanisms proposed, in the literature, for the \((CFx)_n\) electrode reduction by lithium assume lithium ion penetration to reaction sites between layers of active material via an intermediate. A similar mechanism is proposed for the reduction of PTFE by lithium metal.

X-ray diffraction patterns show only the presence of LiF on both reduction products and disordered carbon on the surface of discharged \((CFx)_n\) particles. Hence, lithium has to penetrate the discharging active material particles in both cases through the discharge products as complete disintegration of particles down to the "molecular" level was not observed.

Based on carbon intercalation chemistry literature, which is abundant, and the expected slow lithium ion diffusion through LiF crystals, we proposed last year that lithium could be first "intercalated" into the discharged carbon and then proceed to \((CFx)_n\) sites. Experiments designed to verify the proposed lithium migration path gave interesting results.
"Lithium passage through carbon" cell.

Schematic Drawing of the "lithium passage through carbon" experimental setup.

- A1 - Resistor used to measure total current flow.
- A2 - Resistor used to measure current flow to (CFx)N.
- A3 - Resistor used to measure current flow to carbon.
- L - Resistive load controlling current flow.
ROLE OF CARBON
(Experimental)

The experimental setup designed to understand the role of carbon in
the cathode reaction consisted of a Li/Li salt in an organic
solvent/(CF$_x$)$_n$ cell separated into two compartments by a piece of
Pyrolytic Graphite - Coated Graphite (Pyrotech, PT101).

This cell was discharged through a large resistance, L and the
currents flowing from the lithium, to the carbon and to the (CF$_x$)$_n$
electrodes were measured through smaller calibrated resistors A1, A3 and
A2, respectively, using DVMs. The voltage between the two electrodes, Li
and (CF$_x$)$_n$ was also monitored during the experiments.

Initial results with a 1MLiAsF$_6$ in DMSI solution indicated no
current flow through A2 unless the carbon was loaded with some lithium.
Loading the carbon, by disconnecting A2, and unloading the carbon, by
disconnecting A1, resulted in increasing and decreasing the ability of
the cell to deliver current at several predesigned discharge voltages
indicating limits on cell performance dependent on lithium presence in
the carbon.

However, gas formation was detected in the positive electrode
compartment as the experimental work progressed. Consequently, the
experiments were repeated with a 1MLiAsF$_6$ in PC.
Current distribution for cell B at the start of loading. (Load @ 102K ohm)

Cell A - Total cell voltage, vs. time, for beginning of loading (first run load @ 200K).
ROLE OF CARBON
(Results)

Results obtained with the PC solution varied some with the piece of carbon used. In the case of one cell similar results to those obtained with DMSI were obtained.

However, more interesting were results which were obtained with, what could be assumed to be, not completely sealed surfaces of the carbon. With such slightly open faced pieces current started flowing to both the carbon and the (CF\textsubscript{x})\textsubscript{n} with the sum of the currents equal, within the measuring accuracy (two significant figures), to that flowing from the lithium electrode. Furthermore, current was flowing to the carbon even as the cell voltage was significantly above 2 volts.

Such behavior indicates carbon loading with lithium while the cell is discharging. Hence, if one assumes that (CF\textsubscript{x})\textsubscript{n} is fully covered with discharge product, even if slightly cracked, then the observed discharge voltages could be attributed to mixed potentials involving lithium loading on carbon and its ultimate reaction with the positive active material.

Attributing an ionic current conducting role to carbon in the cathode reaction could account for some positive electrode swelling due to lithium presence in carbons in the (CF\textsubscript{x})\textsubscript{n} electrode, \textit{i.e.}, both the discharge product and the conductive additive.

Still the observed magnitude of swelling cannot be explained in terms of the carbon-lithium reaction above.
a. Cathode pellet after some scraping of adherent materials.

b. Cathode pellet after intensive scraping.

Current collecting surfaces of pellets from PC test tube cells after discharge.
MICROSCOPIC OBSERVATION

Visual and microscopic examination of specially made "electrodes" gave better insight into the swelling mechanism.

These electrodes consisted of a pellet made from shiny high purity graphite powder on which gray (CFx)\_n powder was sprinkled and allowed to discharge slowly vs lithium (CCV 1.8 volts) under flooded condition in a 1mLiAsF\_6 in PC solution.

Surprisingly, partially discharged material on the surface of these electrodes hardened into a porous matrix and had to be scraped for further observation. Scraping of such partially discharged electrodes revealed a gray upper layer of partially discharged material on the top of the electrode and a dull black layer on top of the shiny graphite surface of the pellet.

Further examination of the layers revealed that even the partially discharged particles were fused together allowing for sizable pores between particles. Some shrinkage of particles, but not the disappearing of cavities, was observed with the dark material.

Furthermore, in all cases the fused active material particles were fused also to the graphite.
a. Gray surface.

b. Black surface.

SEM micrographs of the gray and black surfaces on a scraped current collecting surface of the graphite pellet from cell LT 2.
SWELLING MODEL

Based on the above, a reasonable model for \((\text{CF}_x)_n\) cathode swelling will consist of the following steps:

1. Electrons reach \((\text{CF}_x)_n\) particles' surfaces through the conductive additive - carbon, and lithium ions reach reaction sites via solution.

2. Reaction taking place at sites of least resistance, e.g., the conductive carbon surface, resulting in fusion of discharging particles to the carbon.

3. The reaction proceeds by advancing through partially discharged particles to undischarged particles which touch them resulting in particles fusion at touching surfaces before full reduction of the fused particles.

4. Any further reduction of the fused particles matrix which results in particle swelling, i.e., incorporation of lithium in carbon, LiF crystal formation and further layer separation will result in amplified three dimensional swelling around the fused matrix cavities.

5. Such swelling will continue unimpeded in free standing electrodes but will be limited if the electrode is swelling against a solid metal wall. In the latter case the wall pressure could result in particle matrix breakage and densification resulting in less bulging and cell choking.

One could also expect the matrix-wall interaction to be more sensitive to temperature than the swelling of a free standing electrode.
CONCLUSIONS

The major contributor to cathode swelling in Li/(CFx)\textsubscript{n} cells is the formation and three dimensional expansion of the fused particulate matrix.

Lithium reaction with carbon in the (CFx)\textsubscript{n} electrode provides for an acceptable explanation for lithium ion migration during discharge and might explain observed voltages during discharge.

ACKNOWLEDGEMENT

We would like to thank Ms. L. M. King, from our laboratory, for her assistance in carrying out the experimental work.
INTRODUCTION

Zinc-air batteries are an excellent power source for aerospace use because they have the highest specific energy of all primary batteries (Table 1) and they are inherently safe.

<table>
<thead>
<tr>
<th>System</th>
<th>Specific Energy (Wh/lb)</th>
</tr>
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<tbody>
<tr>
<td>Alkaline-Manganese</td>
<td>60</td>
</tr>
<tr>
<td>Alkaline-Mercuric Oxide</td>
<td>55</td>
</tr>
<tr>
<td>Lithium-Sulfur Dioxide</td>
<td>125</td>
</tr>
<tr>
<td>Lithium-Manganese Dioxide</td>
<td>135</td>
</tr>
<tr>
<td>Zinc-Air</td>
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Despite decades of development there are currently only two types of zinc-air batteries on the market, button cells and low rate industrial batteries. Zinc-air button cells (Figure 1), used almost exclusively in hearing aids, are similar in design to zinc-mercuric oxide button cells, which they have displaced because of a twofold capacity advantage. The button cell configuration is an excellent means of packaging the zinc-air cell in small sizes (1 Ah or less), but scaleup to larger capacities has proven difficult because of performance and leakage problems.

Industrial zinc-air batteries are of a prismatic configuration which employ flat plate electrodes and a molded plastic case (Figure 2). Employed in low voltage railroad track signal circuits and in lighted aids to navigation, where a service life of 2-3 years is required, their maximum continuous drain rate is 1 A or less. Their full capacity is delivered only at drain rates below C/1200.
NASA-JSC has contracted with MATSI to expand zinc-air technology to two cell designs with high capacity and high rate capability, at specific energies which can only be met safely with zinc-air (Table 2).

<table>
<thead>
<tr>
<th>Cell</th>
<th>Drain Rate</th>
<th>Capacity</th>
<th>Specific Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR</td>
<td>1 A</td>
<td>12 Ah</td>
<td>160 Wh/lb</td>
</tr>
<tr>
<td>HR</td>
<td>3 A</td>
<td>9 Ah</td>
<td>-</td>
</tr>
<tr>
<td>LC</td>
<td>2 A</td>
<td>200 Ah</td>
<td>200 Wh/lb</td>
</tr>
<tr>
<td>LC</td>
<td>6 A</td>
<td>150 Ah</td>
<td>-</td>
</tr>
</tbody>
</table>

This has produced a novel prismatic design (Figure 3) which achieves the rate and specific energy targets and allows for stacking in multicell batteries. The thickness of the anode determines the capacity of the cell, and the area determines the maximum rate capability. An anode thickness of 0.5 cm, for example, produces an achievable specific capacity of 750 mAh/cm², while the maximum continuous current density is 50 mA/cm².

The next section discusses the a priori basis for our cell designs. This is followed by results of preliminary experimental work. Finally, we present data from parametric testing of HR and LC batteries.

**DESIGN BASIS**

The cell design (Figure 3) employs an anode paste of amalgamated zinc powder in a gelled potassium hydroxide electrolyte, a microporous polymeric separator, a porous, PTFE-bonded carbon oxygen electrode, and a plastic cell tray. Selection of anode thickness is dependent upon the specific capacity (mAh/cm²) to be delivered and the utilization (%) achieved at a given current density. Figure 4 shows typical anode utilization data for a zinc-air button cell and for three sizes of alkaline cylindrical cells, all of which use similar anodes. The tailoff in the zinc-air cell curve is the result of air access restrictions to the cathode. The much lower utilizations for the alkaline cells are the result of the cylindrical geometry and the moisture uptake of the manganese dioxide cathode. We assumed AA utilizations for the initial designs, to be conservative, but those achieved in practice were more in agreement with the zinc-air curve, as extrapolated linearly.

The oxygen cathode is a high performance gas-diffusion electrode comprising two layers. The active layer on the electrolyte side employs high surface area carbon for the oxygen reduction reaction, and a metal oxide catalyst for peroxide decomposition. The barrier layer on the air side, having a higher PTFE content, prevents
electrolyte weepage. A microporous polymeric separator placed against the cathode surface prevents internal shorting.

Stacking cells in a battery requires that provision be made for air access to the cathodes. This is achieved by placing a porous spacer between cells. The thickness of this spacer is dependent on the lateral dimensions of the cell and the operating current density. If the spacer is too thin, interior portions of the cathode will become oxygen-starved, while too thick a spacer increases battery weight and volume unnecessarily.

An oxygen transport model was developed to assist in design of the intercell spacer. The model assumes only diffusion of oxygen through a stagnant nitrogen layer, since in space there is no natural convection, and forced convection of air to the cells is not assured. The model (Figure 5) assumes oxygen access from two sides only, and that the current distribution is uniform. It then calculates the spacer thickness (s) required for a given cell height (2L) and current density (I). Solution of the diffusion equation for this geometry yields the following relationship:

\[ s = I \cdot L^2 / 1100. \]

That is, the minimum gap is proportional to the current density and the square of the path length for diffusion. Figures 6 and 7 show this relationship as applied to the LC and HR cells for three aspect ratios. Clearly, a low aspect ratio (height:width) is desirable for minimizing spacer thickness. Our design has therefore fixed on an aspect ratio of 1/2 for both cell designs.

Based on the above, the design points shown in Table 3 were set for the LC and HR cells.

<table>
<thead>
<tr>
<th>Variable</th>
<th>HR Cell</th>
<th>LC Cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facial Dimensions</td>
<td>6 cm x 12 cm</td>
<td>13 cm x 25 cm</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.7 cm</td>
<td>0.8 cm</td>
</tr>
<tr>
<td>Weight</td>
<td>93 g</td>
<td>540 g</td>
</tr>
<tr>
<td>Spacer Thickness</td>
<td>0.6 cm</td>
<td>0.8 cm</td>
</tr>
<tr>
<td>Capacity</td>
<td>30 Ah @ 1 A</td>
<td>204 Ah @ 2 A</td>
</tr>
<tr>
<td>Specific Energy</td>
<td>170 Wh/lb @ 1 A</td>
<td>210 Wh/lb @ 2 A</td>
</tr>
</tbody>
</table>

PRELIMINARY DEVELOPMENT

A series of experiments was conducted on subscale prototype cells to test the elements of the design basis and to optimize electrode.
formulations. The first set focussed on anode optimization. Test cells were discharged at four different zinc contents (weight percentages), and their specific capacities were calculated. The data in Figure 8 indicate that, while there are no substantial differences statistically, a zinc content of 70% consistently performed well, and so it became the standard.

Another set of experiments elucidated the sensitivity of anode utilization to KOH concentration. Two concentrations, 30% and 35%, were tested at two ambient relative humidities, 35% and those in equilibrium with the two electrolyte concentrations (58% RH and 47% RH, respectively). The data shown in Figure 9 show that utilization is consistently higher for the 35% KOH concentration, and for that concentration the utilization is less sensitive to low ambient relative humidity. The 35% concentration therefore became the standard.

The cathode optimization studies showed the need for a peroxide decomposition catalyst, not only for improved cell voltage, but also for improved anode utilization. Figure 10 shows that anode utilization is substantially higher when the catalyst is used. The weight gain data, expressed as the quotient of cell weight after and before discharge (over and above the weight gain calculated for oxygen uptake based on delivered capacity, i.e. 0.3 g/Ah), indicate that the no-catalyst cell anodes were non-faradaically converted to oxide because of peroxide migration and reaction there. In other words, the peroxide acts as a soluble form of oxygen which, if not decomposed in the pores of the cathode, acts to corrode the zinc in a direct chemical reaction.

Finally, the discharge data for more than 40 cells were employed to create an empirical model of cell performance. Figure 11 shows the derived relationship between utilization and current density, and Figure 12 relates average cell voltage to current density. These are expressed mathematically as follows:

\[ U (%) = 97 + 32 \ln(1 - \frac{i}{70}) \]

\[ V_{av} (V) = 1.29 - 0.0058i. \]

Based upon this model, the sensitivity of specific energy to anode thickness for the HR cell was calculated (Figure 13), which showed the need for a 0.4 cm thick anode to meet the 160 Wh/kg requirement at a 1 A drain rate.

BATTERY TESTING

The HR and LC cell designs were finalized based on the preliminary experimental work, and cells were built and tested both as individual cells and as five cell batteries. Figure 14 shows the individual HR and LC cells, and Figure 15 shows a five cell LC battery. A typical load curve at 100% state-of-charge for an HR cell (LC is similar) is shown in Figure 16. The trace curves
upward toward an open circuit voltage of 1.4 V below 5 mA/cm², but is essentially linear at higher current densities.

Typical cell discharge curves at 25°C are shown in Figures 17 and 18 for the three currents tested. Cell voltages are relatively flat throughout most of the discharge, their negative slope and curvature proportional to the drain rate. The voltage knee is fairly sharp, with little capacity beyond the 0.9 V cutoff value. Capacity dependence on current is shown in Figures 19 and 20.

Individual cell data points for each of the three drain rates and temperatures tested are shown in Figures 21 and 22 (HR), and Figures 23 and 24 (LC), along with the empirical model data for 25°C. The HR data show good performance relative to the model predictions under all conditions except the 2 and 3 A runs at 50°C. For these runs forced air circulation was required in the test oven to ensure adequate oxygen supply to the batteries, and this accelerated dryout of the cells, which lowered utilization.

LC battery utilizations were consistently below model predictions at all temperatures tested because of dryout, in what we term a chimney effect. The cells ran at least 20°C warmer than ambient, and this, in combination with oxygen depletion, produced an updraft of air in the intercell spacers which enhanced dryout. The most dramatic evidence of this is shown in Figures 25 and 26. Figure 25 shows utilization by cell for the 6 A, 25°C run. Utilization is at a minimum for Cell 3, the center cell, and is at a maximum for cells 1 and 5, the end cells. Figure 26 shows the water loss data for this test, cell by cell, with a maximum in the center and lower values at the ends. While there is not a reproducibly uniform dependence of utilization on water loss (accelerated localized dryout can be as much a detriment as uniform dryout), the generally high electrolyte weight (moisture) losses observed (as high as 43%) account for the suppressed utilizations. Water loss data are compared in terms of flux (g/h/cm²) versus current density in figure 27 for HR and LC cells. Water flux for the LC batteries is approximately a factor of ten higher than that for the HR batteries when compared at equivalent current densities.

The chimney effect can be mitigated, for testing at 1 G, by reducing air access to and thickness of the intercell spacers. In space, at 0 G, there would be no chimney effect, and utilizations would likely be much higher. Furthermore, if the batteries were fed pure oxygen at a stoichiometric rate, dryout could be reduced to near zero, as could the spacer thickness.

Water loss data are compared in terms of flux (g/h/cm²) versus current density in Figure 27 for HR and LC batteries. Water flux for the LC batteries is about a factor of 10 higher than that for HR batteries, when compared at equivalent current densities. This is probably the result of cell size and intercell spacer thickness differences between the two designs.
CONCLUSION

The prismatic HR and LC cells and batteries built and tested performed well with respect to the program goals (Table 4).

<table>
<thead>
<tr>
<th>Cell Type</th>
<th>Drain Rate</th>
<th>Capacity</th>
<th>Specific Energy (Wh/lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Goal</td>
<td>Achieved</td>
</tr>
<tr>
<td>HR</td>
<td>1 A</td>
<td>12 Ah</td>
<td>29 Ah</td>
</tr>
<tr>
<td>HR</td>
<td>3 A</td>
<td>9 Ah</td>
<td>24 Ah</td>
</tr>
<tr>
<td>LC</td>
<td>2 A</td>
<td>200 Ah</td>
<td>203 Ah</td>
</tr>
<tr>
<td>LC</td>
<td>6 A</td>
<td>150 Ah</td>
<td>188 Ah</td>
</tr>
</tbody>
</table>

The HR batteries suffered reduced utilizations owing to dryout at the 2 and 3 A rates for the 50°C tests owing to the requirement for forced convection. The LC batteries suffered reduced utilizations under all conditions owing to the chimney effect at 1 G, although this effect would not occur at 0 G. An empirical model was developed which accurately predicted utilizations and average voltages for single cells, although thermal effects encountered during battery testing caused significant deviations, both positive and negative, from the model. Based on the encouraging results of the test program, we believe that the zinc-air primary battery of a flat, stackable configuration can serve as a high performance and safe power source for a range of space applications.
Figure 1: Button Cell Design

- Void Volume
- Anode
- Anode Can
- Insulator
- Cathode Disc
- Cathode Can
Figure 2: Industrial Zinc-Air Battery
Figure 3: Cell Design Concept
Figure 4: Anode Utilization of Zinc-Air versus Alkaline Cells
Figure 5: Oxygen Transport Model Geometry
Figure 6: LC Electrode Dimensions at Various Gap Widths
Figure 7: HR Electrode Dimensions at Various Gap Widths
Figure 8: Dependence of Anode Specific Capacity on Zinc Content
Figure 9: Effect of KOH Concentration and Relative Humidity on Anode Utilization
Figure 10: Effect of Peroxide Catalyst in Cathode on Anode Utilization

<table>
<thead>
<tr>
<th>PEROXIDE CATALYST</th>
<th>WEIGHT GAIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO</td>
<td>45%</td>
</tr>
<tr>
<td></td>
<td>37%</td>
</tr>
<tr>
<td>YES</td>
<td>8%</td>
</tr>
<tr>
<td></td>
<td>16%</td>
</tr>
</tbody>
</table>
Figure 11: Empirical Model of Anode Utilization
Figure 12: Empirical Model of Average Voltage
Figure 13: Calculated Dependence of HR Cell Specific Energy on Anode Thickness
Figure 14: HR and LC Cells
Figure 15: LC Cell Battery Stack
Figure 16: HR Cell Load Curve (100% SOC)
Figure 17: HR Cell Discharge Curves at 25°C
Figure 18: LC Cell Discharge Curves at 25° C
Figure 19: HR Cell Capacity at 25° C
Figure 20: LC Cell Capacity at 25° C
Figure 20: LC Cell Capacity at 25°C
Figure 21: HR Battery Anode Utilization
Figure 22: HR Battery Average Voltage
Figure 23: LC Battery Anode Utilization
Figure 24: LC Battery Average Voltage

1991 NASA Aerospace Battery Workshop -181- Primary Technologies Session
Figure 25: LC Battery Anode Utilization @ 6 A and 25°C
Figure 26: LC Battery Water Loss @ 6 A and 25° C
Figure 27: Dependence of Water Flux on Current Density
RISE TIME AND RESPONSE MEASUREMENTS ON A LiSOCl₂ CELL

[C. BASTIEN (SAFT) - E. LECOMTE (ETCA)]

ABSTRACT

Dynamic impedance tests have been performed on a 180Ah LiSOCl₂ cell in the frame of a short term work contract awarded by Aerospatiale as part of the Hermes space plane development work. These tests consisted of Rise Time and Response Measurements.

The Rise Time Test was performed to show the ability to deliver 4KW, in the nominal voltage range (75 - 115V), within less than 100 microseconds, and after a period at rest of 13 days.

The Response Measurements Test consisted of Step Response and Frequency Response tests.

The Frequency Response test allowed to determine the "small signal" impedance of the LiSOCl₂ cell. The cell impedance was measured for various frequencies, temperatures, intensities and depths of discharge.

The Step Response test was performed to characterize the response of the LiSOCl₂ cell to a positive or negative load step of 10A starting from various currents. The test was performed for various depths of discharge and various temperatures.

The test results were used to build a mathematical, electrical model of the LiSOCl₂ cell which are also presented.

Slides 5 to 17 give the test description and test results. Slides 18 to 25 give the electrical modelization description (for which additional comments are given hereafter). Slide 26 gives the conclusions of the presentation.
MATHEMATICAL MODEL OF THE LiSOCl₂ CELL (Slides 18 to 25)

Three models of increasing complexity are presented. Their validity is limited to the conditions of the tests presented:

- Frequency: 5 to 100,000 Hz
- Temperature: 10 to 70°C (50 to 160°F)
- Depth of Discharge: 25 to 75%
- Bias Currents: 0 to 80 A

The Frequency Response Tests directly give the impedance versus the frequency. The model is built on the basis of the Frequency Tests and validated and refined to match the measured Step Response.

The first model accounts for the Frequency Response when the temperature is greater or equal to 40°C (104°F) while the second one is a refinement valid also for low temperatures. Model 2 was validated by simulating its response to the Step Response Test and by comparing it to the experimental response. The validity proved to be good except for low DC currents.

MODEL 1 (Slides 18 to 19)

At temperatures greater than 40°C (104°F), all frequency responses are similar: a plateau at low frequencies and a resonance at 76 KHz.

The plateau is modelized by a Series Resistance (6 mΩ) and the resonance by an R-L-C parallel cell.

R₂ of the R-L-C cell is given by the impedance at the resonance frequency:

\[ R₂ = 41 - 6 = 35 \text{ mΩ} \]

The resonance frequency \( F₀ \) is equal to \( 1/2π\sqrt{LC} \) and the ratio \( ΔF/F₀ \) is equal to \( R/\sqrt{C/L} \). This allows to determine \( L \) and \( C \) where \( L = 32 \text{nH} \) and \( C = 137 \text{μF} \).

R₁ varies slightly with \( T^* \) and \( I_{DC} \), so as \( I \) or \( T^* \) increase, \( R₁ \) decreases.
**MODEL 2 (Slides 20 to 22)**

At low temperatures (10°C, 50°F), the impedance is higher for the low frequencies (below 2KHz), while the response is identical above 2KHz. This phenomenon is modelized by an RC parallel cell, added to Model 1.

R₃ is given by the value of the plateau: 
\[ R₃ = 30 - 6 = 24 \text{mΩ} \]

C₂ is given by the value of the impedance at \( F = 2 \text{KHz} \).

Model 2 also applies at high temperatures, with \( R₃ = 0 \text{mΩ} \) (Model 1).

Model 2 is validated by comparing the experimental results of the Step Response Test to the simulated results. Slide N° 22 shows a good matching when the initial DC current is greater or equal to 10A for positive or negative steps.

**MODEL 3 (Slides 23 to 24)**

Slide N° 23 shows that for a DC current smaller than 10A, positive and negative responses are not symmetrical.

Model 3 is similar to Model 2 (RC cell, series resistance and R-L-C cell) except that the resistance of the R-L-C cell is increased when the current measured before the application of the current step is smaller than 10A. The simulated Step Response is similar to the experimental Step Response, as shown in slide N° 24, which validates Model 3.

**BATTERY MODEL (Slide 24)**

The equivalent electrical model of 28 cells in a series is the electrical model of a cell with resistors and inductor values multiplied by 28 and capacitor values divided by 28.

An additional series resistance (R₄) and inductance (L₂) must be added in order to take into account the influence of the cabling between cells.

R₄ = 4.3mΩ 
L₂ = 1.2μH 
As R₄ << R₁, R₄ can be neglected
RISE TIME AND RESPONSE MEASUREMENTS
ON A LiSOCl₂ CELL

BY

C. BASTIEN  
SAFT (FRANCE)

E. LECOMTE  
ETCA (BELGIUM)
* THE ELECTRICAL POWER GENERATION OF THE HERMES SPACE PLANE COMPRISSES:

- THE MAIN ELECTRICAL POWER GENERATION:

  2 FUEL CELL POWER PLANTS TO PROVIDE ELECTRICAL ENERGY FOR THE COMPLETE MISSION

- THE SECONDARY ELECTRICAL POWER GENERATION:

  2 LITHIUM BATTERIES TO PROVIDE ELECTRICAL ENERGY AS AUXILIARY SOURCES IN NOMINAL MODES AND BACK-UP SOURCES FOR EMERGENCY RE-ENTRY
* A SHORT TERM WORK CONTRACT WAS AWARDED BY AEROSPATIALE TO SAFT TO DEMONSTRATE THE FEASIBILITY OF A LiSOCl₂ BATTERY DESIGN, AS PART OF THE HERMES SPACE PLANE PRELIMINARY DEVELOPMENT WORK.

* THE PROPOSED LiSOCl₂ BATTERY CONSISTS OF 28 CELLS OF 180 Ah CONNECTED IN SERIES

  TOTAL ENERGY = 16.6 kWh

  TOTAL MASS = 60 KG (132 LB)

  TOTAL VOLUME : 54 L
INTRODUCTION

* SUMMARY OF THE ELECTRICAL CHARACTERISTICS OF EACH BATTERY

- OUTPUT POWER : 0 TO 6 KW
- OUTPUT VOLTAGE : 75 V < u < 115 V
- REQUIRED ENERGY : 16 KWh
- RISE TIME : EACH BATTERY SHALL BE ABLE TO START DELIVERING 4 KW WITHIN LESS THAN 100 MICROSECONDS AND WITH U IN THE SPECIFIED RANGE, AFTER A PERIOD AT REST OF 13 DAYS, AT T BETWEEN 15 AND 40°C (59 AND 104°F).
INTRODUCTION

* DYNAMIC IMPEDANCE TESTS HAVE BEEN PERFORMED ON A 180 AH LiSOCl₂ CELL:
  - A RISE TIME TEST WAS PERFORMED TO SHOW THE ABILITY OF THE CELL TO MEET THE RISE TIME REQUIREMENT
  - RESPONSE TESTS WERE PERFORMED IN ORDER TO BUILD A MATHEMATICAL ELECTRICAL MODEL OF THE LiSOCl₂ BATTERY

THE TESTS HAVE BEEN PERFORMED AT SAFT BY ETCA (BELGIUM) WHO ALSO PROPOSED THE MATHEMATICAL MODEL.

ETCA IS INVOLVED IN THE HERMES PROGRAM AS THE POWER SYSTEM CONTRACTOR.
* RISE TIME TEST:

- DISCHARGE AT 40A, VOLTAGE MEASUREMENT DURING THE FIRST 200 μS OF THE DISCHARGE.

- 13 DAYS REST PERIOD, DURING WHICH A 50mA DISCHARGE CURRENT IS IMPOSED IN ORDER TO AVOID THE PASSIVATION EFFECT.

- DISCHARGE AT 40A, VOLTAGE MEASUREMENT DURING THE FIRST 200 μS OF THE DISCHARGE.
**RESPONSE TESTS**

They consisted of step response and frequency response tests.

- Step response test: The cell voltage to a negative and positive 10A step was measured starting from various currents, at various DOD's and cell temperatures.

<table>
<thead>
<tr>
<th></th>
<th>25% DOD</th>
<th>75% DOD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T = 43°C</td>
<td>T = 11°C</td>
</tr>
<tr>
<td></td>
<td>I = 0, 1, 2, 5, 10, 20, 40, 70 A.</td>
<td>I = 0, 10, 40, 70 A.</td>
</tr>
<tr>
<td></td>
<td>T = 11°C</td>
<td>T = 11°C</td>
</tr>
<tr>
<td></td>
<td>I = 0, 10, 40, 70 A.</td>
<td>I = 0, 10, 40, 70 A.</td>
</tr>
<tr>
<td></td>
<td>T = 72°C</td>
<td></td>
</tr>
</tbody>
</table>
* RESPONSE TESTS

- FREQUENCY RESPONSE TEST: A SMALL SINUSOIDAL CURRENT WAS SUPERIMPOSED ON A GIVEN CURRENT AND THE VOLTAGE RESPONSE WAS MEASURED FOR VARIOUS FREQUENCIES, TEMPERATURES, INITIAL CURRENTS AND DOD'S. THIS TEST ALLOWED TO DETERMINE THE "SMALL SIGNAL" IMPEDANCE OF THE LiSOCL₂ CELL.

<table>
<thead>
<tr>
<th>25% DOD</th>
<th>75% DOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>T = 43°C</td>
<td>T = 11°C</td>
</tr>
<tr>
<td>0, 1, 2, 5, 10, 20</td>
<td>1, 2, 5, 10, 20</td>
</tr>
<tr>
<td>30, 40, 60, 78 A.</td>
<td>40, 78 A.</td>
</tr>
</tbody>
</table>

FOR EACH CASE, THE FREQUENCY VARIED BETWEEN 5 Hz and 100 kHz
The cell was discharged under the following profile (T = 40°C):

- **13 days rest period**
- 50 mA discharge current

**Test Sequence**

**Rise time measurements**

**Response measurements**
RESPONSE TESTS SEQUENCE

- FRT: Frequency response test
- SRT: Step response test

Discharge at I = 40A

T(°C)

25%  75%  DOD
RISE TIME TEST

RISE TIME MEASUREMENT AT T = 40 °C, DOD ~ 20%. AFTER 13 DAYS WITH A 50mA DISCHARGE CURRENT (LOAD VARIATION 40A).

* RISE TIME MEASUREMENTS ARE THE SAME BEFORE AND AFTER THE 13 DAY REST PERIOD

* THE VOLTAGE RESPONSE STABILIZED AFTER 60µS AND ALWAYS STAYED SUPERIOR TO 3V (U BATTERY ≥ 84V)

* NO DELAY EFFECT
STEP RESPONSE TEST

AT T = 43°C, DOD = 25%, I = 20A
STEP RESPONSE TEST

AT T = 43°C, DOD = 25%, I = 0A

RISE TIME AND RESPONSE MEASUREMENTS ON A LISOCO-2 CELL

TEST RESULTS
STEP RESPONSE TESTS

- DYNAMIC RESPONSE (0 TO 70 μS):
  * WHEN 40 < T < 70°C, NEGATIVE STEP RESPONSE IS IDENTICAL FOR ALL CURRENT AND DOD.
  * WHEN T < 40°C, THE VOLTAGE VARIATION DUE TO THE 10 A STEP INCREASES AND VARIES WITH THE DOD.
  * THE POSITIVE STEP RESPONSE IS THE OPPOSITE OF THE NEGATIVE STEP RESPONSE FOR I > 10 A.
  * FOR I ≤ 10 A, THE VOLTAGE VARIATION DUE TO THE POSITIVE 10 A LOAD STEP, IS HIGHER
  * THE VOLTAGE ALWAYS STABILIZED WITHIN 70 μS WITH ΔV ALWAYS INFERIOR TO 0.13V.

- STATIC RESPONSE :
  * AFTER T = 70μS, THE VOLTAGE SLOWLY VARIES WITH TIME BEFORE REACHING ITS NOMINAL VALUE
### RISE TIME AND RESPONSE

**MEASUREMENTS ON A LiSOCl₂ CELL**

### TEST RESULTS

**GENERAL OBSERVATIONS ON DYNAMIC RESPONSES OF LiSOCl₂ CELLS:**

- The higher the starting current, the lower the voltage variation due to the 10A step.
- The higher the temperature, the lower the voltage variation due to the 10A step.
- The lower the depth of discharge, the lower the voltage variation due to the 10A step.
STATIC RESPONSES OF LiSOCl₂ CELLS

VLS 250 AM AVERAGE VOLTAGE Vs CURRENT FOR VARIOUS TEMPERATURES

-10 TO +20°C
-40 TO +45°C

CURRENT (AMPS)
TEST RESULTS

FREQUENCY RESPONSE TEST

AT T = 43°C, DOD = 25%, I = 40, 60, 78 A

* THE MAXIMUM CELL IMPEDANCE IS 41 mΩ
  ALWAYS MEASURED AT 76000 Hz INDEPENDENTLY OF T°, DOD, I.

* OVER 50 KHz, THE FREQUENCY RESPONSE CURVES ARE IDENTICAL FOR ALL T°, DOD, I.

* BELOW 50 KHz, AND WHEN T < 40°C, TEMPERATURE IMPACT IS NOTICEABLE: WHEN T DECREASES,
  IMPEDANCE INCREASES
TEST RESULTS

CELL DISCHARGE

DELIVERED ENERGY : 612.1 WH (400 WH/KG)
DELIVERED CAPACITY : 204.8 AH
CELL ELECTRICAL MODELIZATION BASED ON FREQUENCY RESPONSE TEST

MODEL 1: $T \geq 40^\circ C$

![Graph showing electrical modelization](image)

- **Plateau at** $6 \text{ m}\Omega$

  $\rightarrow$ SERIES RESISTANCE: $R_1$

- **Resonance at** 76 KHz, $41 \text{ m}\Omega$

  $\rightarrow$ RLC PARALLEL CIRCUIT: $R_2 = 35 \text{ m}\Omega$

  \[ \frac{1}{2\pi f_0\sqrt{LC}} = 76 \text{ KHz} \]
MODEL 1: \( T \geq 40^\circ C \)

\[ R_1 = 6 \text{ m}\Omega \text{ TO } 10 \text{ m}\Omega \]
(R\(_1\) INCREASES AS \( T^* \) AND/OR DC CURRENT DECREASES)

\[ R_2 = 35 \text{ m}\Omega \]

\[ L = 32 \ \mu \text{H} \]

\[ C = 137 \ \mu \text{F} \]
CELL ELECTRICAL MODELIZATION BASED ON FREQUENCY RESPONSE TEST

MODEL 2: T < 40°C

- Higher impedance at low frequencies
- Same as Model 1 above 2kHz

→ Add a RC parallel circuit to Model 1
SAFT

DIVISION ESPACE
SPACE DEPARTMENT

ETCA

RISE TIME AND RESPONSE
MEASUREMENTS ON A LiSOCl2 CELL

ELECTRICAL MODELIZATION

MODEL 2: T < 40°C

R3 = 0.01 Ω TO 24 mΩ
(R3 INCREASES AS T- AND/OR DC CURRENT DECREASES)

C2 = 35.4 mF
MODEL VALIDATION WITH STEP RESPONSE RESULTS (I_{DC} \geq 10A)
MODEL VALIDATION WITH STEP RESPONSE RESULTS (I_{DC} < 10A)

FOR I < 10A, THE POSITIVE AND NEGATIVE STEP RESPONSES ARE NOT SYMMETRICAL. THE CELL VOLTAGE VARIATION DUE TO THE POSITIVE STEP IS HIGHER.

THE MODEL MUST INCLUDE A VARIABLE RESISTOR (R) WHICH WILL BE A FUNCTION OF THE CURRENT DELIVERED BY THE CELL.
MODEL 3: MODEL2 + RESISTOR (R)

Simulation Result

- 1991 NASA Aerospace Battery Workshop
- 1991 NASA Aerospace Battery Workshop
- Primary Technologies Session
IEEE Aerospace Battery Workshop

SAFT DIVISION SPACE DEPARTMENT

RISE TIME AND RESPONSE MEASUREMENTS ON A LiSOCL_2 CELL

ELECTRICAL MODELIZATION

BATTERY ELECTRICAL MODELIZATION

$T > 40^\circ$C

WORST CASE
(LOW CURRENT, LOW TEMPERATURE, HIGH DOD)

Diagram of battery electrical modelization.
**CONCLUSION**

* The 180 Ah LiSOCl₂ cell has shown the ability to deliver 40 A within less than 60 μs in the specified voltage range (> 3 volts).

* No delay effect was noticed after 13 days during which a 50 mA permanent current was discharged.

* Several electrical models have been presented which simulate the dynamic behaviour of the cell for different conditions of temperature, current and DOD.

* Two models of the 28 LiSOCl₂ cell battery are proposed to be used for the mathematical analysis of the HERMES power system and for an electrical simulator specification.
DEVELOPMENT OF INTERNAL/EXTERNAL SHORT CIRCUIT PROTECTION FOR LITHIUM D CELLS

NAS 9-18279

DR. ROBERT C. MCDONALD
YARDNEY TECHNICAL PRODUCTS, INC.
AND
BOBBY J. BRAGG
NASA JOHNSON SPACE CENTER
AGENDA

- HISTORICAL NEED
- PROGRAM OBJECTIVES
- COMPOSITE THERMAL SWITCH (CTS) DEVELOPMENT
- LABORATORY CELLS WITH CTS
- INCORPORATION INTO LITHIUM D CELLS
- RESULTS/CONCLUSIONS
HISTORICAL NEED

- AN "INTERNAL CELL SHORT" IS CONSIDERED A CRIT 1/1 FOR SHUTTLE ORBITER LITHIUM C, D, & DD CELL APPLICATIONS
  - CRIT 1/1 IS LOSS OF VEHICLE/CREW
  - INDICATES NO "POSITIVE CONTROL" AVAILABLE

- LITHIUM CELLS OF C, D, DD SIZES REQUIRE A "WAIVER" TO FLY
  - WAIVER APPROVAL JUSTIFIED BY "ACCEPTABLE RISK"
  - SUPPORT FOR WAIVER APPROVAL
    - HISTORICAL DATA BASE WITH NO SUCH FAILURES
    - EXTENSIVE MFG PROCESS CONTROL PROVISIONS
    - EXTENSIVE QUALITY CONTROL PROVISIONS
    - EXTENSIVE CELL/BATT ACCEPTANCE/LOT CERT TESTING

- APPLICATIONS WITH APPROVED WAIVERS
  - Li-BCX C CELLS: BATTERIES OF 2 & 3 CELLS EACH
  - Li-BCX D CELLS: BATTERIES OF 1, 2, 4, 8, & 16 CELLS EACH
  - Li-CF "DD" CELLS: BATTERY OF 12 CELLS
PROGRAM OBJECTIVES

- DEVELOP POSITIVE CONTROL ACTIVATED BY TEMPERATURE
  - POSITIVE CONTROL LIKE A FUSE OR THERMOSTAT
  - MFG PROCESSES, QC, ATP, LCT ARE ALL INDIRECT CONTROLS
  - ACTIVATION TEMPERATURE OF 75 ºC < T < 150 ºC

- DEMONSTRATE CONTROL CONCEPT IN LITHIUM D CELLS
  - MUST BE COMPATIBLE WITH LI-BCX & LI-SOCL2
  - COVER PERFORMANCE UP TO 10 MA/CM2
  - IMPACT VOLTAGE < 5%
  - IMPACT CAPACITY/STORAGE LIFE < 10%

- DEMONSTRATE ABUSE TOLERANCE
  - INTERNAL/EXTERNAL SHORT CIRCUIT
  - CHARGING, OVERDISCHARGING, OVERTEMPERATURE
  - SHOCK & VIBRATION
INTERNAL/EXTERNAL SHORT CIRCUIT PROTECTION FOR LI D CELLS

CTS DEVELOPMENT

- CONTROL CONCEPT IS PTC-TYPE CTS FILM
  - PTC (POSITIVE TEMPERATURE COEFFICIENT)
    - ELECTRICALLY CONDUCTIVE AT -40 'C TO +70 'C
    - STEP INCREASE TO INSULATOR AT 75 'C < T < 150 'C
  - CTS FILM TO REPLACE OR COAT CATHODE CURRENT COLLECTOR
  - CTS FILM IS SINTERED MIXTURE OF METAL & FLUOROCARBON PARTICLES
    - DIFFERENT THERMAL EXPANSION COEFFICIENTS (3-30X) PROVIDE SWITCHING

- CTS IS YTP PATENT NO. 4,603,165 (1986)
  - VARIETY OF METAL PARTICLE SIZES AND PERCENTAGES
    - CONSIDER NI, MO, W OF 3-20 MICRONS
  - VARIETY OF FLUOROCARBON PARTICLE SIZES AND PERCENTAGES
    - TEFLONS (PFTE, FEP, PFA) OF 3-20 MICRONS
    - HALAR ECTFE
    - TEFZEL ETFE
  - USE COMBINATIONS IN VARIOUS FILM THICKNESSES
### FABRICATION OF FILM

- **MATERIALS EVALUATED AS COUPONS (1 " DIA X 0.05" THK)**
  - USED NICKEL POWDERS (INCO)
    - NI HDNP, 4SP, 123, 128 OF 3-20 MICRONS
  - USED FLUOROCARBON POWDERS (DUPONT)
    - TEFLONS MP1000-MP1500, TE3607, AND TEFZEL HT2020
    - PARTICLE SIZES OF 3-60 MICRONS

- **TECHNIQUES EVALUATED FOR COUPONS**
  - COLD PRESSING (3600-5000 LBS F) WITH SINTERING @ 260-413 'C
  - SLURRIES OF WATER, POLYMER SUSPENSIONS, & ORGANIC SOLVENTS WITH SUBSEQUENT SINTERING
  - DOCTOR BLADING & SINTERING UNDER PRESSURE
LABORATORY CELLS WITH CTS

- 15 CELLS BUILT

- CATHODE FABRICATION
  - NICKEL EXMET SUBSTRATE
  - 0.020" CTS FILM
  - CARBON THERMALLY BONDED OR PRESSURE BONDED

- CELL OF 0.22 AH AND 26 CM2
  - DISCHARGED AT 2 MA/CM2 AT VARIOUS TEMPS FOR CAPACITY AND POLARIZATION

- CELLS HEATED FOR SWITCHING DEMONSTRATION
  - SOME DEMONSTRATED SWITCHING BETWEEN 136 °C AND 141 °C
  - SOME DID NOT SWITCH UP THRU 170 °C, AND INDICATED INCOMPLETE COVERAGE OF SUBSTRATE
INTERNAL/EXTERNAL SHORT CIRCUIT PROTECTION FOR LI D CELLS

INCORPORATION INTO LITHIUM D CELLS

USED YTP BA6590 MODEL: SUB D CELL
- 10 AH CELL @ 2 AMPS
- CATHODE PLATE AREA OF ~ 535 CM²
- CATHODE THICKNESS OF 0.005"

CTS CELLS WITH 0.025" CATHODE THICKNESS MINIMUM
- MAXIMUM PLATE AREA OF 268 CM² IN ABOVE CELL CASE
- 70 % CAPACITY DECREASE COMPARED TO BA6590
- CTS CATHODE HAS TWICE THE INTERNAL RESISTANCE

CONTROL CELLS: USED BA6590 CELL CASE WITH CTS ELECTRODE AREAS
- APPROACH CHOSEN FOR SHORT CIRCUIT TEST COMPARISON
- NOT POSSIBLE TO DIRECTLY COMPARE PERFORMANCE
- NEEDED LARGER MANDREL OR BETTER CARBON/EXMET CONTACT
RESULTS/CONCLUSIONS

- QUALITATIVELY DEMONSTRATED PROTECTION
  - CTS & CONTROL CELLS INSULATED & SHORTED (20-40 M-OHMS)
  - CTS CELL WITH 10 % NICKEL SHUT DOWN ON SHORT CIRCUIT
    - 2.9 AMPS MAX CURRENT AT 0.05 VOLTS
    - REACHED THERMAL EQUILIBRIUM (41 'C) AFTER 5 MINUTES
    - BOTH CURRENT & VOLTAGE REDUCED AT 7 MINUTES
  - CONTROL CELL VENTED WITH LOUD REPORT & BURNED
    - 5 AMPS AT 0.5 VOLTS
    - REACHED 160 'C AT 11.5 MINUTES - VENTED
    - TOP AND BOTTOM BLOWN OFF
    - ELECTRODE MATERIAL EJECTED & BURNED

- PERFORMANCE OBJECTIVES NOT ACHIEVED

- OTHER ABUSE CHARACTERISTICS NOT ADDRESSED

- POTENTIAL FOR FUTURE WORK UNDER CONSIDERATION
Figure 5: Comparison of Wound Cell Polarization

- Cell # 25 - Control
- Cell # 21 - 10% CTS
- Cell # 3 - 8.75% CTS
Li/BCX (Thionyl Chloride) Battery for the NASA AN/PRC-112 Survival Radio

S.J. Ebel, W.D.K. Clark, D.P. Eberhard
Electrochem Industries
Division of Wilson Greatbatch Ltd.
Clarence, New York 14031

AND

E.C. Darcy
National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas 77058

ABSTRACT

As part of the NASA contingency planning related to aborting a launch after liftoff, an emergency radio is required for use by the crew when they return to Earth at some unplanned location. The power source for the radio must be able to satisfy the performance requirements for the radio's mission as well as be compatible with in-cabin storage in the space shuttle. The radio needs a base load power of about 1W with capability to handle power spikes greater than 6.5W. A slightly enlarged battery pack using the Li/BCX chemistry in C-size cells has been developed that meets these power levels and extends the operational life of the radio by over a factor of four compared to its operation using a Li/SO₂ cell battery pack. In addition, the cells meet the requirements for the Li/BCX cells used for extra-vehicular activities by the crew of the shuttle. One of the major qualifying tests is the ability of the cells to withstand exposure to high temperature (149°C) without leaking. Electrical performance and thermal abuse test data will be presented for the cells.
Li/BCX Battery for the NASA AN/PRC-112 Survival Radio

S. J. Ebel, W. D. K. Clark, D. P. Eberhard
Wilson Greatbatch Ltd.

and

E. C. Darcy
National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Objectives

Overall Objective
Develop a battery to power a survival radio to be used by space shuttle crew in case of an emergency termination of a launch after liftoff or inability to land.

Requirements
- compatible with space shuttle requirements for extra-vehicular activities and in-cabin storage

- base load electrical power output of 1W, power spikes to 6.5W

- extend operational life by a factor of four compared to operation using a Li/SO₂ battery
Background

- The AN/PRC-112 is an army radio which was designed with a Li/\text{SO}_2\text{ battery consisting of four }\frac{1}{2}\text{ C cells (vent design) in series. This type of battery was deemed unacceptable for use on the space shuttle.}

- Li/BCX cells as produced by Wilson Greatbatch Ltd. have a history of successful deployment for space shuttle applications.

- The previously NASA qualified Li/BCX C cell had insufficient power capability to meet the survival radio electrical requirements. A higher power version was needed.

- A battery consisting of three "universal" Li/BCX C-size cells was proposed.
C-Cell Technical Requirements

- Cell designed to accommodate thermal excursions to 149°C without leaking both prior to use and after discharge.

- Cell must be capable of operating for 43 hours (5.8 Ah) to a 2.7 V cutoff under the radio pulse regimen shown below.
**Universal BCX 149 C-Cell Design and Technical Data**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>outside diameter</td>
<td>1.009 in.</td>
</tr>
<tr>
<td>overall length</td>
<td>1.899 in.</td>
</tr>
<tr>
<td>nominal weight</td>
<td>58 g</td>
</tr>
<tr>
<td>nominal volume</td>
<td>24.9 cm³</td>
</tr>
<tr>
<td>working electrode surface area</td>
<td>110 cm²</td>
</tr>
<tr>
<td>chemistry</td>
<td>Li/BrCl + SOCl₂</td>
</tr>
<tr>
<td>polarity</td>
<td>case negative</td>
</tr>
<tr>
<td>nominal capacity rating</td>
<td>7 Ah</td>
</tr>
<tr>
<td>nominal discharge rate</td>
<td>75 mA</td>
</tr>
<tr>
<td>maximum continuous rate</td>
<td>1000 mA</td>
</tr>
<tr>
<td>nominal specific energy</td>
<td>432 Wh/kg</td>
</tr>
<tr>
<td>nominal energy density</td>
<td>0.95 Wh/cc</td>
</tr>
<tr>
<td>safety fuse rating</td>
<td>4 A</td>
</tr>
</tbody>
</table>
CELL TESTING

**Thermal Abuse Testing**
- cells were tested at both 0% DOD and 100% DOD
- cells were heated at a max. rate of 5°F/min. to each of the following temperatures: 200, 225, 250, 275, and 300°F
- each temperature was maintained for at least 15 min.
- after each temperature excursion the cells were cooled to room temp., cell heights were measured, cells were checked for electrolyte leakage.

**Electrical Abuse Testing**
- **short-circuit testing** through a finite external circuit resistance of 0.5Ω.
- **force overdischarge** (FOD) testing on discharged cells after 2 weeks end-of-life storage.
  - 3 rates employed: 0.125 A, 0.5 A, and 1 A
  - 2 test temperatures: 21°C and 71°C
  - test duration: 7 hours
  - power source voltage: 38 V

**Electrical Discharge Testing**
- Testing under constant R loads of 6Ω, 9Ω, 30Ω, and 60Ω conducted at temperatures of -29, 0, 21, 55, and 71°C.
- radio pulse regimen testing at room temp.
Li/BCX (149) C-CELL SWELLING AS A RESULT OF THERMAL CYCLE

---

**Graph:**
- **Legend:**
  - Undischarged cells (N = 25)
  - Discharged cells (N = 20)

**Axes:**
- **Y-axis:** Length (in.)
  - 1.80
  - 1.85
  - 1.90
  - 1.95
  - 2.00
- **X-axis:** Temperature (°C)
  - 0
  - 25
  - 50
  - 75
  - 100
  - 125
  - 150
  - 175
  - 200

**Note:**
- Cells did not leak or vent as a result of this test.
Electrical Abuse Testing Results

Short Circuit Testing
- 52 cells tested
- average initial current: 5.8 A
- average peak temperature: 87°C
- average time to peak temperature: 30 minutes
- no vents, leaks, or ruptures

Force Overdischarge Testing
In general...
- current could not be maintained
- cells swelled
- 2 cells mildly vented through glass seal area
- peak temperature exceeded 200°C in some cases
- to-date, 54 cells have been force overdischarge tested
Li/BCX (149) C-CELL DISCHARGE RESULTS UNDER 6Ω LOADS AT VARIOUS TEMPERATURES
BCX 149 C-Cell discharge capacity as a function of load and temperature.
Li/BCX (149) C-CELLS: TYPICAL PERFORMANCE UNDER SURVIVAL RADIO PULSE REGIMEN AT ROOM TEMP.

[Graph showing cell voltage (V) vs. capacity (Ah) with markers for background and minimum pulse voltage.]
Battery Technical Requirements

- Designed to accommodate three "universal" Li/BCX C cells in series.

- Safety features to include a 4A fast-blow fuse built into each cell, two shunt diodes in parallel with each cell, two thermal fuses rated at 72°C in the battery, and one 1.5A fast-blow fuse in the negative leg of the battery.

- Battery weight to be 280 g max.

- under 0.5A load at room temperature and higher the battery must attain an 8V minimum operating voltage within 5 sec.

- Capacity rated at 5.0 Ah under a 0.5A load to an 8V cutoff.
NOTES:

⚠️ USE 3T632 TO ASSEMBLE THIS MODULE.

ELECTRICAL SCHEMATIC

1. 1.5A
2. BLACK
3. RED
4. 72° T/C
5. 72° T/C

ITEM NO. DESCRIPTION
10 1 ASSEMBLY-T/C 3B2697
9 1 0.05 x 0.125 x 0.125 NRIBBON 90090-6
8 1 0.187 DIA. x 0.375 SHRINK TUBE 90104-2
7 1 24 AWG WIRE X 6.00 RED 90187-3-3
6 1 SPLICE 50017-17
5 1 0.05 x 0.125 x 0.125 NRIBBON 90090-6
4 1 HOT MELT ADHESIVE 90101-2
3 1 ASSEMBLY-T/C & FUSE 3B2696
2 1 PERMABOND 105 800020
1 1 ASSEMBLY-BATTERY w/Shunt Diodes 3B2692-XA

PROPRIETARY INFORMATION CONFIDENTIAL TO HEWLETT-PACKARD
DO NOT COPY REPRODUCE OR DISCLOSE TO OTHERS WITHOUT PRIOR WRITTEN CONSENT
NASA AN/PRC-112 Battery
L and I test: 0.5A discharge

25°C (I)
-29°C (L)

hours on test

voltage
NASA AN/PRC-112 Battery
HR test: 1.5 A discharge at room temp.

activated 72°C thermal fuse
Battery Environmental Testing

**Shock Testing**
- sawtooth pulse of $20 \pm 0.5$ g peak for an 11 msec rise and 1 msec decay in both directions of 3 perpendicular axes
  - batteries passed (no leak, vent, or rupture)

**Vibration Testing**
- $12.1 \pm 0.1$ min. in each of three mutually perpendicular axes according to the following spectrum:
  - $20 - 150$ Hz $+ 6$ dB/octave
  - $150 - 1000$ Hz $0.03$ g²/Hz
  - $1000 - 2000$ Hz $- 6$ dB/octave
  - batteries passed (no leak, vent, or rupture)

**Altitude**
- rapid decompression to 100,000 ft within 3 sec.
  - batteries passed

**Leakage**
- helium leak rate less than $1.4 \times 10^{-5}$ cc/sec
  - batteries passed, average leak rate was $5.8 \times 10^{-7}$ cc/sec
SUMMARY

• An updated BCX 149 C-cell/battery has been designed for the AN/PRC-112 survival radio battery and is nearing qualification for extra-vehicular activities and in-cabin shuttle deployment.

• The battery has demonstrated power outputs of 1 W with power spikes to 6.5 W.

• The BCX battery will extend the operating life by a factor of four compared to operation using a Li/SO₂ battery.

• Qualification testing will be complete during the second half of Nov91.
EMU AG-ZN BATTERY WET-LIFE EXTENSION TEST

<table>
<thead>
<tr>
<th>EMU AG-ZN BATTERY WET-LIFE EXTENSION TEST</th>
<th>Propulsion and Power Division</th>
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<tr>
<td>B.J. Bragg</td>
<td>10/29/91</td>
</tr>
</tbody>
</table>

EMU AG-ZN BATTERY
WET-LIFE EXTENSION TEST

BY
CLAUDE M. WOOTEN / EP6
AND
BOBBY J. BRAGG / EP5

NASA JOHNSON SPACE CENTER
EMU AG-ZN BATTERY WET-LIFE EXTENSION TEST

AGENDA

• EMU BATTERY DESCRIPTION
• BACKGROUND - REASON FOR TEST
• TEST OBJECTIVES
• TEST DESCRIPTION
• RESULTS/CONCLUSIONS
EMU AG-ZN BATTERY DESCRIPTION

- 11 CELL BATTERY OF ~ 30 AH, WEIGHING 10 LBS
- TWO 4-CELL MONOBLOCKS, ONE 3-CELL MONOBLOCK
- DIMENSIONS: 10.5" LONG X 4.89" HIGH X 2.87" DEEP
- RATED FOR 8, 26.6 AH CYCLES WITHIN 135 DAYS WET-LIFE
- POWERS SPACE SUIT BACKPACK AT 3.8 AMPS FOR 7 HOURS TO 16.0 END V
- BATTERY COST IS ~ $26K
- PRIMARY SEPARATOR IS 4 TURNS OF C-19
- CELL MONOBLOCKS ARE MANUFACTURED BY YTP
- BATTERY IS ASSEMBLED BY HAMILTON STANDARD (EMU VENDOR)
- BATTERY IS DELIVERED DRY WITH ACTIVATION KITS TO JSC
BACKGROUND - REASON FOR TEST

- FEW PLANNED EVA'S IN CURRENT SHUTTLE FLIGHT SCHEDULE
- CONTINGENCY EVA REQUIREMENT
  - POTENTIALLY 3 EVA'S REQUIRED PER MISSION
  - 7 HOURS/MISSION @ 3.8 AMPS (26.6 AH/EVA)
- CURRENT WET-LIFE OF 135 DAYS SUPPORTS 2 VEHICLES; EVERY OTHER FLT
  - ASSUME SHUTTLE FLIGHT SCHEDULE OF 12 FLIGHTS/YEAR
  - DELTA 20 DAYS ACTIVATION/FORMATION CYCLING PERIOD
  - DELTA 10 DAY SHIPPING/INSTALLATION LEAD TIME
  - ASSUME NO USE ON FIRST VEHICLE SUPPORT
  - DELTA 60 DAYS TO SUPPORT 2ND VEHICLE; CUMULATIVE 90 DAYS
  - THUS; 135 DAY WET-LIFE DOES NOT SUPPORT A 3RD VEHICLE IN 60 DAYS
- TO SUPPORT 3RD VEHICLE; DELTA 60 DAYS FROM 2ND WITH 16 DAY MISSION
  - CUMULATIVE 150 DAYS PLUS 16 DAYS Requires 166 DAYS WET-LIFE
- TO SUPPORT 4 VEHICLES; ANOTHER DELTA 60 DAYS REQUIRES 226 DAYS
TEST OBJECTIVES

- PRIMARY TEST OBJECTIVE
  - INCREASE VEHICLE SUPPORT FROM 2 TO 3
  - DEMONSTRATE CAPABILITY OF THREE 26.6 AH CYCLES
  - DESIGN TEST FOR CUMULATIVE WET-LIFE OF 166 DAYS

- SECONDARY TEST OBJECTIVE
  - POTENTIALLY INCREASE VEHICLE SUPPORT TO 4 VEHICLES
  - PERFORM ADDITIONAL 3 CYCLES AT 226 DAYS
  - THIS OBJECTIVE PERTURBED BY 3 PREVIOUS CYCLES AT 166 DAYS
TEST DESCRIPTION

- TEST ARTICLES ARE FLIGHT BATTERIES WITH >135 DAYS WET-LIFE

- BATTERY SPEC REQUIRES CONDITIONING CYCLE(S) FOR CHARGED STAND OF > 85 DAYS
  - EACH MISSION NORMALLY REQUIRES CONDITIONING CYCLE(S)
  - EIGHT CYCLE SPEC MUST COUNT CONDITIONING CYCLES

- TOP CHARGE AT 1.55 AMPS FOR 10 MINUTES (OR TO 21.8 V) BEFORE DISCHARGE

- DISCHARGE AT CONSTANT CURRENT OF 3.8 AMPS TO AN END VOLTAGE OF 16.0 V (MUST BE >/= 7 HOURS; >/=26.6 AH)
EMU AG-ZN BATTERY WET-LIFE EXTENSION TEST

TEST RESULTS/CONCLUSIONS

- NINE BATTERIES HAVE BEEN TESTED FROM FOUR FLIGHT SHIPSETS FROM JAN '89 TO THE PRESENT

- ALL NINE HAVE SUCCESSFULLY PASSED THE 3-CYCLE REQUIREMENT AT 166 DAYS WET-LIFE

- THREE HAVE FAILED THE 3-CYCLE REQUIREMENT OF 226 DAYS

- FOUR HAVE PASSED THE 3-CYCLE REQUIREMENT OF 226 DAYS

- TWO ARE PROJECTED TO PERFORM THE 226-DAY 3-CYCLE REQUIREMENT STARTING NOV 11, 1991

- TWO MORE BATTERIES ARE SCHEDULED FOR TESTING FROM A FUTURE FLIGHT

- IT IS EXPECTED THAT THE WET-LIFE SPEC CAN BE INCREASED FROM 135 DAYS TO 166 DAYS ON THE BASIS OF THESE TEST RESULTS
TEST 2P323, EMU SILVER-ALKALINE SECONDARY BATTERY EVALUATION

BATTERY SERIAL NO.: 1143
DEPTH OF DISCHARGE: 100%
DISCHARGE CURRENT: 3.6 amps

BATTERY MFG.: Yardney
TEST MSR.: C. M. Wooten
BATTERY TYPE: EMU
CHARGE CURRENT: 1.55 amps

Cycle # | Type Test
--- | ---
1 | Conditioning Topping Charge
2 | Conditioning Cycle
3 | Topping Charge

(176 Day Wet-Life)

1991 NASA Aerospace Battery Workshop -256- Primary Technologies Session
TEST 3F323, BAU SILVER-ALKALINE SECONDARY BATTERY EVALUATION

BATTERY SERIAL NO.: 1143
DEPTH OF DISCHARGE: 100%
DISCHARGE CURRENT: 3.8 amps

BATTERY MFG.: Yardney
TEST MGR.: C. M. Wooten
BATTERY TYPE: BAU
CHARGE CURRENT: 1.55 amps

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Type Test</th>
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<tr>
<td>4</td>
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<td>5</td>
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(176 Day Wet-Life)

1991 NASA Aerospace Battery Workshop

Primary Technologies Session
TEST 2P323, BAU SILVER-ALKALINE SECONDARY BATTERY EVALUATION

BATTERY SERIAL NO.: 1143
DEPTH OF DISCHARGE: 100%
DISCHARGE CURRENT: 3.8 amps

BATTERY MFG.: Yordney
TEST MGR.: C. W. Wooten
BATTERY TYPE: BAU
CHARGE CURRENT: 1.55 amps

AMP HOURS

Cycle #     Type Test

7         Topping Charge
8         Test Cycle
9         Test Cycle

(226 Day Wet-Life)

1991 NASA Aerospace Battery Workshop -258- Primary Technologies Session
TEST 2P323, B&J SILVER-ALKALINE SECONDARY BATTERY EVALUATION

BATTERY SERIAL NO.: 1143
BATTERY MFG.: Yardney
DEPTH OF DISCHARGE: 100%
TEST MGR.: C. M. MOOTEN
DISCHARGE CURRENT: 3.8 amps
CHARGE CURRENT: 1.55 amps

Charge 21-Mar-91
Discharge 26-Mar-91

Cycle #   Type Test
10        Test Cycle

(226 Day Wet-Life)

1991 NASA Aerospace Battery Workshop

Primary Technologies Session
Test 2F323, BAU Silver-Alkaline Secondary Battery Evaluation

Battery Serial No.: 1143
Battery Mfg.: Yardney
Battery Type: BAU

Depth of Discharge: 100%
Test Mgr.: C. M. Wooten

Discharge Current: 3.8 amps
Charge Current: 1.55 amps
Test End Date: 21-Mar-91

AMP-HRS CHARGE

AMP-HRS DISCHARGE

CYCLE NUMBER
High-Rate Li-MnO₂ Cells for Aerospace Use

R. Becker-Kaiser, J. Ruch, H.-J. Harms
P. Schmöde, J. R. Welsh,
M.-J. Vollmers, H. Pack

HOPPECKE Batteries
P. O. Box 1140
D-5790 Brilon 2
Germany
1. Introduction

HOPPECKE Li history in the search for a safe, high-rate Li technology

HOPPECKE is a company primarily concerned with the production of lead-acid and nickel-cadmium batteries which has also diversified into the field of alternative battery systems. In 1978, the R&D Department at HOPPECKE started to evaluate the advantages and disadvantages of the most common lithium systems at that time in both liquid and solid cathode technologies such as:

\[
\begin{align*}
\text{SO}_2\text{Cl}_2 \\
\text{SOCl}_2 \\
\text{SO}_2 \\
\text{Li}-(\text{CF}_x)_n \\
\text{CuO} \\
\text{MnO}_2
\end{align*}
\]

A series of comparative studies were undertaken on representative cells as objectively as possible in order to appreciate the respective advantages of the different systems. After reviewing the first test results our attention was soon focussed on the following four lithium systems:

\[
\begin{align*}
\text{SOCl}_2 \\
\text{SO}_2 \\
\text{Li}-(\text{CF}_x)_n \\
\text{MnO}_2
\end{align*}
\]

This resulted in the decision in 1982 to adopt the Li-MnO\textsubscript{2} system for high-rate applications.
The reason for this was that it appeared the most promising system in its overall characteristics. With the main goal to achieve the good properties of the couple Li-MnO₂ such as high energy density, long shelf life, insignificant voltage delay and environmental safety, HOPPECKE succeeded in the development of high-rate Li-MnO₂ cells.

The development was guided by military requirements with respect to performance and by the highest safety requirements that could be achieved. The first German Military Approvals were obtained for C and D cells and several batteries in 1987/88. Further approvals were obtained in the course of time, followed by first approvals for some space applications.

Based on the considerable experience in this technology HOPPECKE was awarded a Development Contract by ESA to produce a 200 Ah high-rate cell. The cell is intended to be used in a 16 kWh battery which forms part of the electrical power system of the HERMES spaceglider.

The present paper describes the design properties and performance characteristics as well as safety aspects of our high-rate Li-MnO₂ cells which have been used for many years in several industrial and military applications. The use in some space applications is also described. As a conclusion, a brief report of the development status of our HERMES cell is given. The results, although preliminary, are very promising.
2. Design description

How did HOPPECKE LSC cells meet the high performance and safety requirements?

Fig. 1 shows a sectional drawing of HOPPECKE LSC cells in coil type construction.

Fig. 1

- Cell case and cover:

The cell case is a deep drawn cylindrical can of stainless steel. The cell cover contains the positive terminal feed-through insulated by a glass-to-metal seal. Both parts, cell case and cover, are hermetically sealed by plasma-arc-welding.

The cell cover is designed as a pressure release vent which operates with very tight venting tolerances. Although the cell is not pressurized at room temperature, the internal cell pressure increases with rising temperature. At about 110°C, the vent opens and releases those components of the electrolyte with the lowest boiling point.

- Electrodes:

The electrodes are spirally wound, and high-rate capability is achieved by the large surface area. The rigid design of the jelly roll assures that the cell resists even severe vibration and shock conditions. All connections between the cell case, terminals, tabs and current collectors are welded or riveted. No connection can be broken by chemical or mechanical degradation as the cell ages.

- Cathode:

A mixture of MnO₂ (CMD), carbon and binder is pressed onto a metal grid. Very good electrochemical efficiencies of MnO₂ are achieved by this technique. The metal grid consists of stripes with selvaged edge on each side, hence sharp points or projections cannot occur while assembling the cathodes or even if the cell case is deformed. In particular, serious shorts by separator puncture are highly unlikely. The cathode is connected to the glass-to-metal feed-through in the cell cover.
- Anode:

The anode consists of lithium foil rolled onto a current collector foil. The large area of the current collector makes sure that the lithium will be completely consumed at the end of discharge. The anode is connected to the cell case.

- Separator:

Presently a double-layer separator system is used. The anode is completely enveloped by a Celgard wrap. This microporous separator is supported by a glass mat to increase the distance between anode and cathode.

- Electrolyte:

The electrolyte consists of a mixture of different organic solvents and a lithium salt. The electrolyte is not toxic, corrosive or aggressive. The lithium salt is lithium perchlorate (LiClO₄). Other alternatives were not considered because of environmental objections caused by fluorine or arsenic components. The main goal during the development phase has been to avoid environmentally doubtful liquids with halogen, nitrogen or sulfur chemistry.

Only components consisting of carbon hydrogen and oxygen were used because environmental problems are known to be minimum.
3. Performance description

What are the performance advantages of HOPPECKE LSC cells?

Fig. 2 shows the observed discharge potentials versus the capacity of D-sized HOPPECKE LSC cells. The discharges were performed over a wide temperature range on cells stored for two years with an overall constant discharge current of 2 A.

Fig. 2

Note the consistency: The capacity down to 0 V is almost the same for all discharge temperatures. The reasons for this are the precision of the limited lithium design and the ability of the anode current collector to discharge the lithium completely. Even after two years storage at ambient conditions, neither capacity losses nor serious passivation effects occur, as is shown in Fig. 3.

Fig. 3

Fig. 4 shows the capacity advantage of HOPPECKE Li-MnO₂ cells compared to standard SO₂ D cells for the temperature range of -20°C to 55°C, and with a constant discharge current of 2 A. The comparison demonstrates the excellent performance of the MnO₂ technology for high-rate applications over a wide temperature range.

Fig. 4
4. Safety aspects

What happens to LSC cells in case of abuse?

- Overdischarge (pole reversal):

Fig. 5 shows the behaviour of a D-sized LSC cell in the event of overdischarge.

Fig. 5

An aged cell (storage conditions 28 days at 72°C and 6 months at ambient conditions) was discharged at -30°C with a current of 5 A. The following results were obtained when a load of 200% of the nominal capacity was passed through the cell at 5 A.

- Under the severe charge and storage conditions a voltage delay is observed, but the cell soon recovers and full capacity is available at a positive voltage.

- The temperature rises to critical values just below the venting temperature due to the increase of internal resistance at the final stage of discharge, but the separator system is not damaged.

- During the pole reversal phase no significant voltage drops or voltage instability are observed. No significant heating occurs. Hence, parallel diodes are not required, the cell is inherently safe.

These results are due to the fact that no adverse changes occur to the electrolyte, that at the end of discharge no active lithium is left on the anodes, and that the reversal current is distributed over a large electrode surface area.

Charging:

Protective diodes are recommended if inadvertent charging could occur.

Squeezing:

The safety vent opens, but no serious shorts are observed. Thus, the vented cell does not heat up. This is a result of the special grid design and the separator system.
Overheating:

Overheating could happen for a variety of different reasons. In all cases the safety vent will release pressure at a temperature well below the point at which the separator system would fail.

Perhaps the simulation of an internal short by nail penetration is the most impressive example for the high safety standard of our LSC cells. The vent opens after 30 - 60 seconds due to overheating. The power of the cell is reduced because the electrolyte is ejected and further heat generation is prevented. The ejected electrolyte is not corrosive and nontoxic.

It is most important that our cells react predictably, and that the electrochemistry is safe and well controlled, so no sudden exothermic reactions or violent explosions occur.

5. Space applications

HOPPECKE high-rate Li-MnO₂ cells for aerospace use

The high performance results and the safe electrochemical behaviour of the Li-MnO₂ couple makes this technology suitable for space applications.

Fig. 6 gives a brief overview of some applications in space missions where HOPPECKE LSC cells have been used.

As a further extension of this technology, HOPPECKE is currently developing a 200 Ah high-rate Li-MnO₂ cell. This cell is a candidate to form the basis of a 16 kWh battery for a possible use in the HERMES spaceglider.

The development work was awarded by ESA to the team Telefunken System Technik (TST) / HOPPECKE in September, 1990. Within the team TST is responsible for the battery design whereas HOPPECKE is responsible for the cell design.

A brief design and performance description, and the present status of this development is given below.
5.1 Design description (HERMES cell)

- Cell case:

The cell case is prismatically shaped and made of stainless steel. At present, a folded cell design is used and all seams are welded by laser.

Fig. 7 shows the complete cell.

- Cell cover:

The cell cover contains the pole terminals, the vent and the filling tube. The terminal feed-throughs are insulated by ceramic seals. These ceramic seals have already been approved for space application.

Fig. 8 shows the complete cell cover.

- Vent:

The vent is a domed membrane which - in case of overpressure - is forced backwards and punctured by a star-shaped knife.

- Electrodes:

The design of the anode and cathode is very similar to our spirally wound cells, except that they are flat. The high-rate electrical performances are achieved by the large surface area of the electrodes.

- Separator:

The separator consists of non-woven sheets of microglassfiber with excellent mechanical properties achieved by a special binder which guarantees a maximum of safety against mechanical stress and abusive conditions.

- Cathode frames:

The cathodes are placed in plastic frames and the whole electrode stack is mounted into the cell case. Thus, the plastic frames together with the properties of the separator gave the necessary mechanical stability so that the mechanical test requirements were fulfilled without any failures or malfunctions.
Electrolyte:
The electrolyte is the same mixture of organic solvents used for our commercial cell, except for a higher Li salt concentration.

5.2 Performance description (HERMES cell)

Discharge performance:
Fig. 9 shows the discharge performance at ambient temperature and at a constant discharge current of 40 A. The cell did not heat up significantly because the heat could be easily dissipated to the surroundings. A capacity of 208 Ah was measured to a COV of 2 V and the calculated energy density was 260 Wh/kg.

Fig. 9 describes the discharge performance at nearly adiabatical test conditions (the so-called "thermal worst case" discharge mode). The test conditions simulate the situation where a very small heat transfer to the surroundings can take place. The cell was discharged with a pulsed current corresponding to a specified mission load profile for the whole battery.

Fig. 10

Due to the higher temperatures during discharge the electrochemical efficiency of the cell was somewhat increased. The capacity measured to a COV of 2.2 V was 213 Ah, and the calculated energy density was 280 Wh/kg.
- Overdischarge (pole reversal):

Fig. 11 shows the behavior of a cell in the overdischarged mode. Note: No significant voltage instability and heat generation were observed. We see this aspect as one of the most important safety features. This was achieved by the safe electrochemistry and the safe design of the cell. Parallel diodes were not required.

Fig. 11

- Miscellaneous tests:

Further tests have been performed on cells to investigate the cell behavior in terms of low and high charging currents, rise time and response time, heat treatment and mechanical stress. The results can be summarized as follows: No hazardous or inexplainable behavior of the cells was observed. This supports our view that Li-MnO₂ technology gives one of the safest lithium systems currently available.

6. Conclusion

- The electrochemical couple Li-MnO₂ is suitable for high rate applications

- HOPPECKE Li-MnO₂ cells have been carefully designed and developed to ensure good quality and high safety

- The combination of solid cathode electrochemistry and sealed, but safe cell design sets new standards in terms of both high performance and environmental safety

- HOPPECKE Li-MnO₂ cells and batteries meet and often considerably exceed most military requirements

- First applications of HOPPECKE Li-MnO₂ technology in space missions already have been succesful and the Li-MnO₂ system is a promising candidate for future space applications
Structure of a HOPPECKE LSC cell in coil type construction
Schematic illustration

Fig. 1

Fig. 2

LSC 3460 M
Performance after 2 years storage at ambient conditions, discharge current 2A

Voltage (V)

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Capacity (Ah)</th>
</tr>
</thead>
<tbody>
<tr>
<td>55</td>
<td>COV</td>
</tr>
<tr>
<td>24</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>-15</td>
<td></td>
</tr>
<tr>
<td>-20</td>
<td></td>
</tr>
<tr>
<td>-25</td>
<td></td>
</tr>
<tr>
<td>-30</td>
<td></td>
</tr>
</tbody>
</table>

1991 NASA Aerospace Battery Workshop -272- Primary Technologies Session
LSC 3460 M: Performance and pulse response after 2 years storage at ambient conditions, discharge current 2A at -30 °C.

**Fig. 3**

Comparison of Li-MnO$_2$-D-cells and Li-SO$_2$-D-cells.

**Fig. 4**

Comparison of Li-MnO$_2$-D-cells and Li-SO$_2$-D-cells.

Capacity (Ah) 2A discharge current 2V COV (measured May 1990)

- LSC 3460 M production lot May 1988
- Li-SO$_2$ purchased Oct. 1989

NASA Aerospace Battery Workshop 1991 Primary Technologies Session -273-
Fig. 5

LSC 3460 M
Discharge and reverse discharge

![Graph showing voltage (V) and temperature (°C) over time (h).]

- Storage 28 days 72 °C
- +6 months ambient conditions
- Discharge current 5A at -30 °C

Fig. 6  HOPPECKE LSC cells in space applications

<table>
<thead>
<tr>
<th>Mission</th>
<th>Application</th>
<th>Battery Systems</th>
<th>Approval status of Batteries</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIR 91</td>
<td>goggles experiment</td>
<td>14 V, 10 Ah and 5.6 V, 10 Ah</td>
<td>approved by ESA passed all mechanical tests</td>
</tr>
<tr>
<td>MIR 92</td>
<td>portable calculator</td>
<td>14 V, 4.5 Ah</td>
<td>concept approved by ESA delivered for mechanical testing</td>
</tr>
<tr>
<td>Cosmos 10</td>
<td>project biobox</td>
<td>28 V, 80 Ah</td>
<td>approval in process at ESA</td>
</tr>
<tr>
<td>Texas 23</td>
<td>microgravity experiment</td>
<td>30.8 V, 10 Ah</td>
<td>successful flight in Nov. 1989</td>
</tr>
<tr>
<td>MIR 92</td>
<td>video recorder supply</td>
<td>14 V, 20 Ah</td>
<td>delivered for prototype experiments in Feb. 1991</td>
</tr>
<tr>
<td>Cosmos 10</td>
<td>microgravity experiment</td>
<td>22.4 V, 4.5 Ah and 11.2 V, 10 Ah</td>
<td>will be delivered for prototype experiments in Nov. 1991</td>
</tr>
</tbody>
</table>
Fig. 9

200 Ah Li-MnO₂-cell
Discharge 40 A at room temperature

Fig. 10

200 Ah Li-MnO₂-cell
Discharge test under thermal worst case conditions
Fig. 11

200 Ah Li-MnO₂-cell
Overdischarge test at 40 °C
I=20 A

[Graph showing voltage (U) and temperature (T) over time (t)]
CALORIMETRIC EVALUATION OF 250 AHR Li/SOC12 CELLS

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NASA JOHNSON SPACE CENTER

1991 NASA AEROSPACE BATTERY WORKSHOP
U.S. SPACE AND ROCKET CENTER
29-31 OCTOBER 1991, HUNTSVILLE, ALABAMA

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1991 NASA Aerospace Battery Workshop -279- Primary Technologies Session
OVERVIEW

CENTAUR 250 AHR Li/SOCl₂ BATTERIES ARE CURRENTLY BEING DEVELOPED

DESIGN EFFORTS

PERFORMANCE
  VOLTAGE AND CAPACITY, LAUNCH SHELF LIFE WITH NEGLIGIBLE VOLTAGE DELAY

STRUCTURAL
  ENVIRONMENTAL DYNAMICS, WEIGHT

THERMAL
  WIDE OPERATION RANGE AND SAFETY

ONE FRENCH AND TWO AMERICAN CONTRACTORS
  SAFT FRANCE
  ALLIANT TECHNICAL SYSTEMS
  YARDNEY TECHNICAL PRODUCTS
OBJECTIVE

SURVEY CELL DESIGN OPTIONS FOR EFFECTS ON HEAT GENERATION, AND DETERMINE CELL HEAT CAPACITY.

EXPERIMENTAL DESCRIPTION

HEAT GENERATION RATES FOR FULL SIZE 250 AHr CENTAUR CELLS WERE MEASURED IN A HART CONDUCTION CALORIMETER. HEAT CAPACITY MEASUREMENTS WERE CONDUCTED ON FRESH AND DISCHARGED CELLS.

HEAT CONDUCTION CALORIMETRY
42 AMP CONSTANT CURRENT DISCHARGES AT 40 C.

HEAT CAPACITY
DROP CALORIMETRY, 15 C DELTA, 25 C

DESIGN OPTIONS
CARBON: SAB AND HIGH SURFACE AREA CARBONS
SALT CONCENTRATION: 1.0 TO 1.8 M LiAlCl4/SOCl2
BINDER: BINDER PERCENTAGE (3.5 TO 6.5 %)
ELECTROLYTE ADDITIVE: PVC
Fig. 1. Schematic of the cell in an aluminum cell holder in the calorimeter.

1991 NASA Aerospace Battery Workshop

Primary Technologies Session
A battery calorimeter from Hart Scientific, Inc., was used. The heart of the system is the combination of water and air baths to provide heat conduction calorimetry in a temperature controlled range of 0 to 100 °C with heat sources up to 200 W. The battery chamber of the calorimeter (Fig. 1) is 5.5 inches in diameter and 11.5 inches tall. The system relies on the Seebeck or thermocouple effect in which a voltage is produced proportional to the temperature difference across a semiconductor thermoelectric sensor located in the heat flow between the battery and the water bath. Since the sensors have a stable thermal conductivity and are placed so as to be in the major heat flow path, the temperature difference, and hence, the voltage generated across the sensors is directly proportional to the heat flow from the calorimeter chamber to the temperature stabilized water bath heat sink. The system maintains the water bath stabilized to within ± 0.005 °C.
VOLTAGE PERFORMANCE
SAB vs BLEND 250 AHrs 40 C

TIME (Hrs)

1 BLEND
2 SAB
DISCHARGE PERFORMANCE OF STANDARD CARBON AND BLENDED CARBON ELECTRODES AT 40 C AND 42 AMP CONSTANT CURRENT TO 250 AHRS IS GIVEN. THE BLENDED CARBON ELECTRODE CELL SHOWS HIGHER VOLTAGE PERFORMANCE THROUGHOUT THE DISCHARGE.
HEAT GENERATION RATES ARE DISPLAYED FOR STANDARD AND BLENDED CARBON ELECTRODE CELLS. HIGHER HEAT GENERATION IS OBSERVED FOR THE STANDARD SAB CELLS.
VOLTAGE PERFORMANCE THROUGH 250 AHRS FOR CELLS WITH ELECTROLYTE SALT CONCENTRATION FROM 1.0 TO 1.8 M LiAlCl4/SOCl2 SHOW INCREASING VOLTAGE PERFORMANCE WITH INCREASING SALT CONCENTRATION.
HEAT GENERATION
1.0–1.8M LiAlCl4/SoCl2 250 AHrs 40 C

Graph showing heat generation over time with different labels for 1.8M, 1.5M, 1.2M, and 1.0M.
HEAT GENERATION RATES INCREASE WITH HIGHER SALT CONCENTRATION.
EFFECTIVE THERMAL POTENTIAL
1.0-1.8 MOLAR LIAICl4/SOCI2 40 C

SALT CONCENTRATION (LIAICl4 M)

EEL (eV)

-0.1

Primary Technologies Session

1991 NASA Battery Workshop
Effective thermal potentials (ETP) are shown as a function of cell salt concentration. ETP values are generated from instantaneous heats, load current, and load voltage by the following equation:

$$ETP = q/I + V_l$$

Where:
- $q =$ heat generation (watts)
- $I =$ discharge current
- $V_l =$ load voltage

ETP is a relative measure of the heat generation of the cell and may be used for engineering comparison.
HEAT GENERATION
SAB CATHODES 3.5-6.5% 250 AHrs 40 C

WATTS

TIME(Hrs)

1  3.5%  2  6.5%
THE EFFECT OF BINDER PERCENTAGE ON CELL HEAT GENERATION IS GIVEN. CELL HEAT GENERATION IS OBSERVED TO INCREASE WITH INCREASING BINDER CONTENT OVER THE RANGE TESTED.
INCREASED HEAT GENERATION IS OBSERVED FOR CELL CONTAINING 0.3 g/l PVC OVER CELL WITHOUT PVC WHEN DISCHARGED WITH LITTLE OR NO STORAGE.
HEAT CAPACITY FOR FRESH AND COMPLETELY DISCHARGED CELLS (315+ AHR) SHOW A 10% DROP IN THE Cp OF THE DISCHARGE CELL.
CONCLUSION

BLENDED CARBON CELLS SHOW INCREASED DISCHARGE VOLTAGE AND DECREASED HEAT EVOLUTION OVER CELLS WITH STANDARD SAB ELECTRODES.

DECREASING LiAlCl₄ IN SOCl₂ ELECTROLYTES SHOW DECREASING CELL LOAD VOLTAGES AND LOWER HEAT EVOLUTION.

INCREASED PTFE BINDER CONTENT SHOWS INCREASED HEAT GENERATION OVER THE RANGE TESTED (3.5-6.5%).

ADDITION OF PVC TO THE CELL ELECTROLYTE PRODUCES HIGHER HEAT OUTPUTS IN FRESH CELLS.

CELL HEAT CAPACITY DECREASES WITH CELL DISCHARGE ON THE ORDER OF 10% AT FULL DISCHARGE.
Preliminary Test Results for Li-SOCl₂ High-Rate "D" Cells

by B.J. Bragg and Paul Johnson

NASA Johnson Space Center

10/29/91
AGENDA

- Background
- Test Results
  - Weight, OCV, and Load Check
  - Shock Test
  - Vibration Test
  - Capacity Performance
  - Uninsulated Short Circuit
  - High Temperature Exposure
  - Overdischarge
- Conclusions
PRELIMINARY TEST RESULTS FOR LI-SOCl2 HIGH-RATE "D" CELLS

BACKGROUND

- Objective - Evaluate the performance and abuse characteristics of 55 D-Size lithium-thionyl chloride (Li-SOCl2) cells at relatively high rates.

- Cells developed by Electrochem Industries, Inc. under contract to the Jet Propulsion Laboratory.

- Cells manufactured in October 1989.
  - Li wt, - 3.44 g
  - Li anode area - 530 sq. cm
  - 1 anode tab - 0.25" w X 0.005" thk.
  - Cathode (carbon) wt. - 5.2 g
  - Cathode thk. - 0.025"
  - 2 cathode tabs - 0.125" w X 0.005" thk.
  - Electrolyte - 1.8M LiAlCl4 in SOCl2 - 44-45 g


- 55 cells delivered to JSC
  - 39 used in this test program
  - 14 cells discharged in calorimetry testing
  - 2 held as spares
TEST RESULTS

• Weight Check: 121.31 - 122.79 grams

• Open Circuit Voltage: 3.658 - 3.662 VDC

• Load Check Voltage (5 ohm load for 90 sec.): 3.045 - 3.176 VDC
  • None of the cells met 3.50 VDC minimum.
  • Cells were almost two years old.

• Shock Test (2 Cells)
  • Sawtooth shock pulse, 20 g peak with a $11 \pm 1$ millisecond rise and a $1 \pm 1$ millisecond decay.
  • Results: No change in OCV
- Vibration Test (3 Cells)
  - Random vibration for 15 minutes in each of 3 mutually perpendicular axes according to the following spectrum:

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 to 80</td>
<td>+3 dB/octave</td>
</tr>
<tr>
<td>80 to 350</td>
<td>0.1 g²/Hz</td>
</tr>
<tr>
<td>350 to 2000</td>
<td>-3 dB/octave</td>
</tr>
</tbody>
</table>

- Results: No change in OCV.
### Capacity Performance (32 Cells)

- **Ah to 1.5 VDC**
  - **-40°F, 2 ohm load**
    - 5 Cells
    - 4.10 - 4.98 Ah
    - Avg. 4.52 Ah
  
  **Room Temperature, 1 ohm load**
  - 7 Cells
  - 10.38 - 10.75 Ah
  - Avg. 10.57 Ah

  **160°F, 1 ohm load**
  - 5 Cells
  - 9.48 - 9.61 Ah
  - Avg. 9.55 Ah

  **Room Temperature, 2 ohm load**
  - 11 Cells
  - 10.42 - 11.11 Ah
  - Avg. 10.7 Ah

  **160°F, 2 ohm load**
  - 4 Cells
  - 9.45 - 9.75 Ah
  - Avg. 9.61 Ah
Li-SOCl₂ High Rate "D" Cell

One ohm discharge at room temperature to 1.5 volt
Li-SOCl₂ High Rate "D" Cell
Two ohm discharge at room temperature to 1.5 volt
Li-SCl₂, High Rate "D" Cell

Two ohm discharge at room temperature to 1.5 volt
Li-SOCl₂ High Rate "D" Cell

One ohm discharge at 160°F to 1.5 volt
Li-SOCl₂ High Rate "D" Cell

Two ohm discharge at 160°F to 1.5 volt
Preliminary Test Results for Li-SOCl2 High-Rate "D" Cells

1. Uninsulated Short Circuit (3 Cells)

   - Cell S/N 048396
     - Load: 0.075 ohm
     - Maximums: 0.27 VDC, 30 Amp, 118°F
     - Duration: 11 seconds until internal lead fused.
     - Post-test: 0.396V on 100 ohm load

   - Cell S/N 048422
     - Load: 0.120 ohm
     - Maximums: 1.21 VDC, 25.2 Amp, 198°F
     - Duration: 4 min 42 sec until internal lead fused.
     - Post-test: 0.18 V on 20 ohm load
Li-SOCL₂ High Rate "D" Cell
Uninsulated short circuit test
Cell S/N 048422 on 0.12 ohm load

Time (sec)

Current (Amp)

Voltage (V)
Li-SOCl$_2$ High Rate "D" Cell
Uninsulated short circuit test
Cell S/N 048422 on 0.12 ohm load
Preliminary Test Results for Li-SOCl2 High-Rate "D" Cells

- Cell S/N 048439
  - Load: .120 ohm
  - Maximums: 1.21 VDC, 25 Amp, 130°F
  - Duration: 1 min 43 sec until internal lead fused.
  - Post-test: No OCV

- High Temperature Exposure
  - Cells tested for one hour at 225, 250, 275, and 300°F.
  - No leakage was found on any of the cells one week after high temperature exposure.
Preliminary Test Results for Li-SOCl2 High-Rate "D" Cells

- Overdischarge; 2 Weeks Post-Discharge (6 Cells)
  - With Shunt Diodes
    - 1.5 A at 160°F
    - No cells vented, max temperature 209.4°F
  - Without Shunt Diodes
    - 1.5 A at 160°F to 245°F: Chamber temp. control drifted during test.
    - One cell vented at 19 hours and 3 cells at 19.25 hours, max temperature 348.7°F

- Overdischarge; 4 Weeks Post-Discharge (6 Cells)
  - With Shunt Diodes
    - 1.5 A at 160°F
    - No cells vented, max temperature 226.4°F
  - Without Shunt Diodes
    - 1.5 A at 160°F
    - One cell vented at 1.6 hours, max temperature 328.8°F
Li-SOCl₂ High Rate "D" Cell

Two week post-discharge overdischarge without shunt diodes

1.5 A at 160°F (°F)

Current (Amp)

Time (Hours)

Voltage

(°F)
Li-SOCl$_2$ High Rate "D" Cell
Two week post-discharge overdischarge without shunt diodes
1.5 A at 160$^\circ$F

Chamber temperature controller drifted from 160 to 250$^\circ$F during testing
Li-SOCl$_2$ High Rate "D" Cell

Four week post-discharge overdischarge without shunt diodes

1.5 A at 160°F
CONCLUSIONS

- Take note of presented capacity to 1.5 volt end voltage.
- RT data, in particular, shows gradual decline from 3 v to 1.5 v.
- Final report will compare fresh capacities at higher end voltages.
- Overdischarge Tolerance
  - Data taken after a 2-week interval of OCV was very tolerant.
  - Data taken after a 4-week interval vented very quickly.
  - Susceptibility to venting on overdischarge increases with length of OCV interval after discharge.
  - By-pass diodes protect the cell from this effect.
Nickel-Cadmium Technologies Session

Organizers:  Dean Maurer
AT&T

Larry Thaller
The Aerospace Corporation
RESULTS OF DEEP DOD LIFE CYCLE TESTS AT HIGH RATES ON 12Ah NiCd CELLS

Paul E. Panneton and John R. Meyer

The Johns Hopkins University
Applied Physics Laboratory
Laurel, MD 20723
RESULTS OF DEEP DOD LIFE CYCLE TESTS
AT HIGH RATES ON 12Ah NiCd CELLS

This presentation reviews a 12Ah NiCd LEO lifecycle test that induced 47% more deep DOD cycles by mixing them with shallow DOD cycles. This test also showed how aggressive recharging to a C/D ratio of 1.15 nearly doubled performance over cycling below a C/D of 1.11.
RESULTS OF DEEP DOD LIFE CYCLE TESTS AT HIGH RATES ON 12Ah NiCd CELLS

JHU/APL spacecraft program - JANUS MISSION II
- 2 year Low Earth Orbit (LEO) mission
- Size and weight critical

Electrical Power System (EPS)
- Solar array
- Nickel cadmium (NiCd) battery
- Battery charge regulator
  - Voltage-temperature (V-T) limiting
  - Shunt excess array current

NiCd Battery
- High discharge rates (1.8C)
- Deep Depth-of-discharge (DOD)
  - 1500 cycles @ 70% DOD
  - 10000 cycles @ 20% DOD
* Little applicable performance data

⇒ Lifecycle test
RESULTS OF DEEP DOD LIFE CYCLE TESTS
AT HIGH RATES ON 12Ah NiCd CELLS

Gates Aerospace Batteries
- 12 Ampere-hour (Hr) nameplate capacity
- Pellon #2536 nylon separator

- Hermetically sealed
- Standard space qualified design
- Negative plates not teflonated
- Positive plates not passivated
- Negative terminal attached to the case

- All cells were from the same lot
- Filled in April 1988
- Short circuited
- Put in sealed plastic bags
- Refrigerated at 5° Centigrade
RESULTS OF DEEP DOD LIFE CYCLE TESTS AT HIGH RATES ON 12Ah NiCd CELLS

The test parameters were chosen to produce the:
- Worst case eclipse, and
- Lowest battery cell voltages

95 minute cycles at ambient temperature (20° to 30° C.)
- Discharge to 70% DOD (35 minutes - actual 69.44%)
  -- C/3 rate for 15 minutes (unswitched loads)
  -- 1.8C rate for 20 minutes (switched loads)
- Charge for 60 minutes
  -- 1C rate until reach V-T limit
  -- V-T controlled taper

Relatively high end-of-charge (EOC) rates were required to fully recharge the battery in the short amount of time allowed.
RESULTS OF DEEP DOD LIFE CYCLE TESTS AT HIGH RATES ON 12Ah NiCd CELLS

<table>
<thead>
<tr>
<th>METHOD</th>
<th>REMARKS</th>
<th># OF CYCLES</th>
<th>TOTAL 70% DOD</th>
<th>TOTAL 20% DOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contiguous 70% DOD Cycles. Raise VT Limit to Control C/D Ratio. 1V Cutoff.</td>
<td>C/D=1.036</td>
<td>913</td>
<td>913</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C/D=1.069</td>
<td>219</td>
<td>1132</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C/D=1.107</td>
<td>122</td>
<td>1254</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C/D=1.146</td>
<td>1021</td>
<td>2275</td>
<td></td>
</tr>
<tr>
<td>70% DOD Cycles Interspersed with 20% DOD Cycles. 1V Cutoff.</td>
<td>Above Cutoff</td>
<td>1072</td>
<td>3347</td>
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<tr>
<td></td>
<td>Below Cutoff</td>
<td>583</td>
<td>3930</td>
<td></td>
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<tr>
<td></td>
<td>20% DOD Cycles</td>
<td>695</td>
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<td>695</td>
</tr>
<tr>
<td>20% DOD Cycles</td>
<td>C/D=1.178</td>
<td>6104</td>
<td></td>
<td>6799</td>
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<tr>
<td>70% DOD Cycles</td>
<td>.95V Cutoff</td>
<td>100++</td>
<td></td>
<td>4030++</td>
</tr>
</tbody>
</table>
JANUS LIFE TEST - FLIGHT2

End of Discharge Voltages - After Recovery (6/15)

End of Discharge Voltages - Successful (10/72)

End of Discharge Voltages - Failures (5/83)

CELL VOLTAGE or RATIO

Power In/Out

C/D Ratio

JANUS LIFE TEST - FLIGHT2

Recovery

After Recovery

Rest of the Time

BATTERY END OF CHARGE CURRENT IN AMPS

CYCLE #

1991 NASA Aerospace Battery Workshop

-335- Nickel-Cadmium Technologies Session
VOLTAGE-TEMPERATURE LIMITS for DEEP DOD LEO TEST

- First Limit (cycles 1-929)
- Second Limit (cycles 930-1152)
- Third Limit (cycles 1153-1289)
- Fourth Limit (cycles 1290-..)
- 15 Min. Limit
- Cutoff Limit

CELL VOLTAGE (Volts)

TEMPERATURE (Degrees C)
T: 0 = 22.8, 1 = 27.2  V: 0 = 0.96, 1 = 1.49  I: 0 = -22.0, 1 = 12.0
Deep DOD LEO missions don’t usually require contiguous deep cycling, so batteries can perform better than what most life cycle tests indicate. Significantly more deep DOD cycles are obtainable if the thermal design can dissipate the heat generated by an aging NiCd overcharged to high voltages to obtain a C/D of 1.15.

This test is continuing in order to determine how many more cycles can be achieved as a function of lowering the criteria for end-of-discharge voltage. It will also investigate how high the V-T limit can be pushed before the benefit of higher EOD voltages is negated by the shortened lifetime.
NASA STANDARD 50 A.H. NICKEL CADMIUM BATTERY CELL

CELL-LEVEL PERFORMANCE HISTORY

PRESENTED: 1991 NASA AEROSPACE BATTERY WORKSHOP
OCTOBER 29 - 31, 1991

PREPARED BY: MARK R. TOFT
BATTERY ENGINEER
SPACECRAFT ELECTRICAL POWER SUBSYSTEMS
(314)-233-8649

McDonnell Douglas Electronic Systems Company - Laser & Electronic Systems Division
NASA STANDARD 50 A.H. NICD CELL HISTORY

SYNOPSIS:
- CONCEPT, DESIGN & COMMITMENT FOR A NASA STANDARD NICKEL CADMIUM BATTERY CELL COALESCED 1975 - 1977
- SINCE THAT COMMITMENT:
  28 PLATE LOTS HAVE BEEN MANUFACTURED
  24 CELL LOTS HAVE BEEN BUILT, 23 OF WHICH WERE DELIVERED TO BUILD:
  23 FLIGHT BATTERIES AND 20 TEST/SPARE BATTERIES

7 MISSIONS SUPPORTED:
- LANDSAT 4
- LANDSAT 5
- EARTH RADIATION BUDGET SATELLITE (ERBS)
- GAMMA RAY OBSERVATORY (GRO)
- UPPER ATMOSPHERE RESEARCH SATELLITE (UARS)
- EXPLORER PLATFORM (EP)
- OCEAN TOPOGRAPHY EXPERIMENT / POSEIDON (TOPEX)

LAUNCH:
7/82
3/84
10/84
3/91
9/91
(1/92)
(5/92)

- SOLE SUPPLIER: GENERAL ELECTRIC BBD / GATES AEROSPACE BATTERIES

McDonnell Douglas Electronic Systems Company - Laser & Electronic Systems Division
NASA STANDARD NICKEL CADMIUM BATTERY CELL:

DEFINING DOCUMENTS: (NASA)

GSFC 74 - 15000 SPECIFICATION FOR THE MANUFACTURING OF AERO-SPACE NICKEL-CADMIUM STORAGECELLS

NHB 8073.1 NASA SPECIFICATION FOR MANUFACTURING AND PERFORMANCE REQUIREMENTS OF NASA STANDARD AEROSPACE NICKEL-CADMIUM CELLS

EXECUTIVE DOCUMENTS: (GE/GAB)

232A2222AA-84 APPLICABLE QUALITY PLAN FOR NASA STANDARD NiCd CELLS (MASTER MCD)

232A2222AA-87 APPLICABLE QUALITY PLAN FOR NASA STANDARD NiCd CELLS (MASTER MCD)

232A2222AA-88 TEMPLATE FOR JOB-SPECIFIC MCD's

McDonnell Douglas Electronic Systems Company - Laser & Electronic Systems Division
NASA STANDARD 50 A.H. BATTERY CELL

CELL VENDOR DESIGNATIONS:

50AB20
ORIGINAL NASA STANDARD 50 A.H. CELL WITH 2505 SEPARATOR

50AB21
ORIGINAL NASA STANDARD 50 A.H. CELL - SIGNAL ELECTRODE

50AB25
NASA STANDARD 50 A.H. CELL DESIGN WITH 2536 SEPARATOR

50AB34
"ADOPTED" NASA STANDARD; ORIGINALLY 50AB29 (LOCKHEED HST CELLS):
- PASSIVATED, NON-CADMIUM TREATED POSITIVE PLATE
- G.F.E. 2505 SEPARATOR (EAGLE PICHER STOCKPILE)

50AB35
NASA STANDARD 50 A.H. CELL DESIGN WITH G.F.E. 2505 SEPARATOR

50AB39
NASA STANDARD 50 A.H. CELL DESIGN WITH FREUDENBERG 2538 SEPARATOR

McDonnell Douglas Electronic Systems Company - Laser & Electronic Systems Division
NASA STANDARD 50 A.H. BATTERY CELL

CURRENT DESIGN ELEMENTS:

- UNPASSIVATED POSITIVE PLATE (*)
- CADMIUM-TREATED POSITIVE PLATE (*)
- POSITIVE LOADING: 11.90 - 13.10 grams/dm²
- 16 POSITIVE PLATES PER CELL
- POSITIVE PLATE SURFACE AREA = 22.75 dm²

- TEFLONATED NEGATIVE PLATES
- NEGATIVE PLATE LOADING: 15.10 - 16.30 grams/dm² (**)
- 17 NEGATIVE PLATES PER CELL

(*) - EXCEPT FOR 50AB34, AS NOTED BEFORE (FD05)
(**) - EXCEPT FOR 50AB34, WHICH IS LOADED 14.85 - 16.15 grams/dm² (FD06)

- CELL HEIGHT = 6.447 " MAX (CELL BASE TO TOP OF CELL TERMINALS)
- CELL WIDTH = 4.956 " MAX
- CELL THICKNESS = 1.343 " MAX
- CELL WEIGHT = 2081 GRAMS MAX

- 31% POTASSIUM HYDROXIDE (KOH) AS ELECTROLYTE
- NYLON SEPARATOR (2505, 2536, 2538)
## NASA STANDARD 50 A.H. BATTERY CELL

### ACCEPTANCE TEST PROCEDURE

<table>
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<tr>
<th>PARA. NO.</th>
<th>TITLE</th>
<th>REGIME</th>
<th>REQUIREMENT</th>
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<tr>
<td>3.0</td>
<td>SHORT</td>
<td>SHORT WITH 0.2 OHM RESISTORS</td>
<td>EOSV = 0.010V MAX</td>
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<tr>
<td>4.0, 8.0</td>
<td>74°F CAPACITY</td>
<td>CHARGE 24H @ 5 AMPS</td>
<td>V &lt; 1.48V; P &lt; 65 PSIG</td>
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<td>DISCHARGE @ 25 AMPS TO 1.00V</td>
<td>3000 &lt; CAP &gt; 3900 A-M</td>
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<td>RESISTIVE SHORT</td>
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<td>RESISTIVE SHORT</td>
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<td>6.0</td>
<td>32°F OVRCHG</td>
<td>CHARGE 72H @ 2.5 AMPS</td>
<td>V &lt; 1.53V; P &lt; 75 PSIG</td>
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<td>RESISTIVE SHORT</td>
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<td>7.0</td>
<td>LOW RATE EFFICIENCY</td>
<td>CHARGE 20H @ 1.25 AMPS</td>
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<td>RESISTIVE SHORT</td>
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<td>9.0</td>
<td>HIGH - RATE DISCHARGE</td>
<td>CHARGE 16H @ 5 AMPS</td>
<td>EODV &gt; 1.00V AFTER 30 SECONDS @ 150 AMPS</td>
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<td></td>
<td></td>
<td>DISCHARGE @ 150 AMPS FOR 30 SECONDS, THEN @ 25 AMPS TO 1.00V:</td>
<td>24 HOUR MAX SHORT</td>
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<td></td>
<td>RESISTIVE SHORT</td>
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<tr>
<td>10.0</td>
<td>CHARGE RETENTION &amp; IMPEDANCE</td>
<td>OPEN CIRCUIT FOR 24 HOURS</td>
<td>V &gt; 1.17V AFTER 24 HOUR OPEN CIRCUIT</td>
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<td></td>
<td></td>
<td>MEASURE IMPEDANCE (HP 4328)</td>
<td>3 MILLIOHMS MAX</td>
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* McDonnell Douglas Electronic Systems Company - Laser & Electronic Systems Division*
## NASA STANDARD 50 A.H. BATTERY CELL: PLATE / CELL LOTS

<table>
<thead>
<tr>
<th>PLATE LOT</th>
<th>NOTES</th>
<th>CELL LOT / DISPOSITION</th>
<th>LOT SIZE</th>
<th>MISSION USE</th>
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<tbody>
<tr>
<td>50AB20/21 LOT 1</td>
<td>-</td>
<td>50AB20/21 LOT 1</td>
<td>44 CELLS</td>
<td>50 A.H. QUAL BATTERY</td>
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<td>50AB20/21 LOT 2</td>
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<td>50AB20/21 LOT 2</td>
<td>101 CELLS</td>
<td>4 TEST BATTERIES</td>
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<td>50AB20/21 LOT 3</td>
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<td>50AB20/21 LOT 3</td>
<td>78 CELLS</td>
<td>2 TEST BATTERIES; 1 LANDSAT 4 FLIGHT BATTERY</td>
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<td>50AB20/21 LOT 4</td>
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<td>50AB20/21 LOT 4</td>
<td>52 CELLS</td>
<td>2 LANDSAT 4 FLIGHT BATTERIES</td>
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<td>50AB20/21 LOT 5</td>
<td>-</td>
<td>50AB20/21 LOT 5</td>
<td>55 CELLS</td>
<td>2 LANDSAT 5 FLIGHT BATTERIES</td>
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<tr>
<td>50AB20/21 LOT 6</td>
<td>OVERLOADED</td>
<td>SCRAPPED</td>
<td>-</td>
<td>-</td>
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<tr>
<td>50AB20/21 LOT 7</td>
<td>-</td>
<td>50AB20/21 LOT 7</td>
<td>54 CELLS</td>
<td>1 LANDSAT 5 FLIGHT BATTERY; 1 LANDSAT SPARE BATTERY</td>
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<td>50AB20/21 LOT 8A/8B</td>
<td>POSITIVE REJECTED, (PASSIVATED); 8B NEGATIVE USED FOR 50AB25 LOT 1 &amp; 50AB20 LOT 13</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>50AB20/21 LOT 9</td>
<td>-</td>
<td>50AB20/21 LOT 9</td>
<td>92 CELLS</td>
<td>SCRAPPED, ERRATIC &amp; HIGH VOLTAGE. CONTAMINATION?</td>
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McDonnell Douglas Electronic Systems Company - Laser & Electronic Systems Division
## NASA STANDARD 50 A.H. BATTERY CELL: PLATE / CELL LOTS

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<tr>
<th>PLATE LOT</th>
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<td>50AB20/21 LOT 10</td>
<td>INSUFFICIENT MAT'L</td>
<td>-</td>
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<td>-</td>
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<td>50AB20/21 LOT 11</td>
<td>INSUFFICIENT MAT'L</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>50AB20/21 LOT 12</td>
<td>LOT 10 + LOT 11</td>
<td>50AB20/21 LOT 12</td>
<td>91 CELLS</td>
<td>2 ERBS FLIGHT BATTERIES; 1 ERBS CHARACTERIZATION BATTERY</td>
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<td>LOT 11 POSITIVE</td>
<td>50AB20 LOT 13</td>
<td>21 CELLS</td>
<td>GSFC PRECHARGE EXPERIMENT</td>
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<td>LOT 8 NEGATIVE</td>
<td>50AB25 LOT 1</td>
<td>12 CELLS</td>
<td>2536 SEPARATOR QUAL TEST CELLS</td>
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<td>50AB20 LOT 14</td>
<td>POSITIVE NOT CADMIUM TREATED</td>
<td>50AB20 LOT 14</td>
<td>78 CELLS</td>
<td>3 GRO TEST BATTERIES</td>
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<td>50AB20 LOT 15A/15B</td>
<td>BAD 2505 SEPARATOR</td>
<td>50AB20 LOT 15</td>
<td>7 CELLS</td>
<td>PRE-ACCEPT CELLS</td>
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<td>CHANGED TO 2536 SEPARATOR IN FLIGHT CELLS</td>
<td>50AB20 LOT 16</td>
<td>7 CELLS</td>
<td>3 GRO FLIGHT SPARE BATTERIES</td>
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<td>50AB20 LOT 16</td>
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<td>50AB20 LOT 16</td>
<td>81 CELLS</td>
<td>PRE-ACCEPT CELLS</td>
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<td>50AB20 LOT 17A/17B</td>
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<td>50AB20 LOT 17</td>
<td>6 CELLS</td>
<td>PRE-ACCEPT CELLS</td>
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<td>50AB20 LOT 18A/18B/18C</td>
<td>OVERLOADED</td>
<td>SCRAPPED</td>
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## NASA STANDARD 50 A.H. BATTERY CELL: PLATE / CELL LOTS

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<thead>
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<th>PLATE LOT</th>
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<th>MISSION USE</th>
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<tr>
<td>50AB29 LOT 5</td>
<td>FROM 2536 TO G.F.E.</td>
<td>50AB34 LOT 1</td>
<td>73 CELLS</td>
<td>3 GRO SPARE / TEST BATTERIES</td>
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<td>50AB20 LOT 19A/B</td>
<td>POS. SCRAPPED</td>
<td>50AB35 LOT 1</td>
<td>81 CELLS</td>
<td>3 GRO FLIGHT BATTERIES</td>
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<tr>
<td>50AB20 LOT 20</td>
<td>NEG. SCRAPPED</td>
<td>50AB35 LOT 2</td>
<td>83 CELLS</td>
<td>3 UARS FLIGHT BATTERIES</td>
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<td>50AB35 LOT 2A/2B</td>
<td>REBUILT USING 2536</td>
<td>50AB25 LOT 2</td>
<td>77 CELLS</td>
<td>COMPLETED CELL ATP, DELIVERED TO GSFC COLD STORAGE</td>
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<td>50AB35 LOT 3</td>
<td>JPL TEST CELLS</td>
<td>STOP WORK ORDER</td>
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<td>50AB29 LOT 4</td>
<td>FROM 2536 TO G.F.E.</td>
<td>50AB34 LOT 2</td>
<td>4 CELLS</td>
<td>GSFC KOH FILL AMOUNT EXPERIMENT</td>
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<td>50AB29 LOT 6</td>
<td>FROM 2536 TO G.F.E.</td>
<td>50AB34 LOT 3</td>
<td>13 CELLS</td>
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<td>50AB35 LOT 4A/4B</td>
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<td>50AB35 LOT 4</td>
<td>107 CELLS</td>
<td>3 EP FLIGHT BATTERIES; 1 EP SPARE BATTERY</td>
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<td>50AB35 LOT 2A/2B</td>
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<td>50AB35 LOT '2A'</td>
<td>7 CELLS</td>
<td>GAB 2538 SEPARATOR LIFE TEST CELLS PLUS CONTROL CELLS</td>
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<td>50AB35 LOT 5A/5B</td>
<td>INSUFFICIENT MATERIAL</td>
<td>50AB25 LOT '3'</td>
<td>7 CELLS</td>
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<td>50AB35 LOT 6A/6B/6C</td>
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<td>50AB39 LOT '1'</td>
<td>7 CELLS</td>
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<td>50AB35 LOT 6</td>
<td>112 CELLS</td>
<td>3 TOPEX FLIGHT BATTERIES 1 TOPEX SPARE BATTERY</td>
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McDonnell Douglas Electronic Systems Company - Laser & Electronic Systems Division
NASA STANDARD 50 A.H. BATTERY CELL: SIGNIFICANT ANOMALIES

50AB20 LOT 9
- WENT THROUGH ATP 3 TIMES BEFORE FINAL REJECTION
- CELLS EXHIBITING ERRATIC AND HIGH VOLTAGES AT ROOM TEMPERATURE
- MULTIPLE KOH ADJUSTMENTS FOR HIGH PRESSURE
- REPEATED, EXCESSIVE SHORTDOWNS
- DESTRUCT CELLS SHOW LOSS OF OVERCHARGE PROTECTION
- CONTAMINATION?

50AB20 LOT 13 / 50AB25 LOT 1
- SEVERAL PERIODS OF EXCESSIVE SHORTDOWNS
- LOT 13 CELLS BUILT WITH 2505 LOT 30158, PIECE LR037 (GIDEP ALERT)
- CELLS WITH BOTH TYPES OF SEPARATOR WERE RETURNED FROM NWSC
  WITH OVERCHARGE PROTECTION VIRTUALLY GONE

50AB20 LOT 14
- NO CADMIUM TREATMENT OF POSITIVE PLATE
- SHARPLY REDUCED CAPACITY AT 95°F
- EOCV AT ROOM TEMPERATURE ~30mV LOWER THAN NORMAL

50AB20 LOT 17
- 17 FULLY-CHARGED CELLS WERE FURTHER CHARGED @ 25 AMPS FOR 42
  MINUTES BEFORE BEING DISCOVERED (SHOULD HAVE BEEN DISCHARGING)
- EXTENSIVE INVESTIGATION CLEARED CELLS FOR FLIGHT USE

50AB34 LOT 1 / 50AB35 LOT 1
- BOTH LOTS REQUIRED ADDITIONAL PRECHARGING
### NASA STANDARD 50 A.H. BATTERY CELL: TYPICAL PLATE SUMMARY

#### 50AB35 LOT 6 (TOPEX)

<table>
<thead>
<tr>
<th>DATA</th>
<th>POSITIVE</th>
<th>NEGATIVE</th>
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<tbody>
<tr>
<td>PLATE LOT</td>
<td>6A</td>
<td>6B</td>
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<tr>
<td>POST #</td>
<td>05103</td>
<td>05104</td>
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<td>SPIRALS</td>
<td>1 - 7</td>
<td>1 - 7</td>
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</table>

#### AVERAGE LOADING (gm/dm2)
- Positive: 12.58, 12.64, 15.68, 15.60, 15.44
- Negative: 27.56, 27.60, 32.17, 31.80, 31.93

#### AVERAGE PLATE THICKNESS (mills)
- Positive: 38.48, 38.31, 45.04, 44.98, 44.90
- Negative: 38.55, 38.34, 45.22, 45.08, 45.01

#### SAMPLE PLATE WEIGHT (grams)
- Positive: 100%
- Negative: 100%

#### 100% PLATE WEIGHT (grams)
- Positive: 3902, 4052, 7278, 7403, 7469
- Negative: 3946, 4024, 7343, 7417, 7486

#### ANTI-POLAR MASS (gm/dm2)
- Positive: 0.65, 0.63, NA, NA, NA
- Negative: 1.19, 1.17, - , - , -

#### STRESS GROWTH (mills)
- Positive: - , - , 3.35, 2.83, 3.08
- Negative: - , - , NA, NA, NA

#### STRESS RATING
- Positive: - 
- Negative: -

#### NICKEL ATTACK (%)
- Positive: 28.27, 29.73, NA, NA, NA
- Negative: 31.93, 32.47, 33.41, 32.73, 33.32

#### PLATE POROSITY (%)
- Positive: 3902, 4052, 7278, 7403, 7469
- Negative: 3946, 4024, 7343, 7417, 7486

#### N/P RATIO
- Positive: - , - , 1.860, 1.851, 1.851
- Negative: - , - , 1.860, 1.851, 1.851

#### SAMPLE ECT (A-M)
- Positive: 100.75, 100.70, 85.13, 80.2, 79.2

#### CAPACITY STABILITY PERCENT
- Positive: 100.75, 100.70, 85.13, 80.2, 79.2

#### ALSO: DATES OF PROCESSING, THEORETICAL CAPACITY FROM HYDRATE LOADING, PERCENT OF THEORETICAL FROM 100% ECT (UTILIZATION), % COBALT.
NASA STANDARD 50 A.H. BATTERY CELL: TYPICAL TEST DATA

50AB35 LOT 4 (EXPLORER PLATFORM) PRE-ATP:

R: = RANGE; X: = AVERAGE; EOCV = END-OF-CHARGE VOLTAGE; EOCP = END-OF-CHARGE PRESSURE (PSIG); CAP = CAPACITY IN AMP MINUTES; 16HRV, 20HRV, 32HRV = VOLTAGE AT 16, 20, 32 HOURS INTO CHARGE

3.0 FORMATION CYCLES - EOCV

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<th>CYCLE</th>
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<th>GR4</th>
<th>GR5</th>
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<tr>
<td>1 R:</td>
<td>1.438 - 1.443</td>
<td>1.435 - 1.440</td>
<td>1.437 - 1.443</td>
<td>1.431 - 1.435</td>
<td>1.433 - 1.439</td>
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<td></td>
<td>1.44057</td>
<td>1.43729</td>
<td>1.44024</td>
<td>1.43281</td>
<td>1.43630</td>
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<td>2 R:</td>
<td>1.442 - 1.449</td>
<td>1.435 - 1.443</td>
<td>1.437 - 1.443</td>
<td>1.441 - 1.446</td>
<td>1.433 - 1.442</td>
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<td>1.44590</td>
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<td>3 R:</td>
<td>1.436 - 1.451</td>
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<td>1.431 - 1.442</td>
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<td>4 R:</td>
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4.0 NEGATIVE PRECHARGE - 30 VENTS + 13 PSI [MINUTES TO VENT]

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<th>TOTAL VENT TIME</th>
<th>R: 2933 - 4687</th>
<th>3506 - 5279</th>
<th>3502 - 5014</th>
<th>3397 - 5621</th>
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<td>4117</td>
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<td>AVG VENT TIME:</td>
<td>124.1</td>
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6.0 PRESSURE STABILIZATION

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<th>EOCV</th>
<th>1.451 - 1.457</th>
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<td>1.44390</td>
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ALL CELLS ADJUSTED TO 160 mL

McDonnell Douglas Electronic Systems Company - Laser & Electronic Systems Division
7.0 ROOM TEMPERATURE OVERCHARGE

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# NASA STANDARD 50 A.H. BATTERY CELL: TYPICAL TEST DATA

## 50AB35 LOT 4 PRE-ATP (cont.)

### 10.0 ROOM TEMPERATURE OVERCHARGE

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NASA STANDARD 50 A.H. BATTERY CELL: TYPICAL TEST DATA

50AB35 LOT 4 ATP:

4.0 1st 74°F CAPACITY TEST

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## NASA STANDARD 50 A.H. BATTERY CELL: TYPICAL TEST DATA

### 50AB35 LOT 4 ATP (cont.)

#### 7.0 LOW RATE EFFICIENCY

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#### 8.0 2nd 74°F CAPACITY TEST

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McDonnell Douglas Electronic Systems Company - Laser & Electronic Systems Division
NASA STANDARD 50 A.H. BATTERY CELL: TYPICAL DPA RESULTS

DESTRUCT CELL CHEMICAL ANALYSIS RESULTS (ALL VALUES IN AMP-HOURS)

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FINAL FILL AMT (cc's) | 160 | 160 | 161.8 | 158 - 161 | 163 | 162 | 160 | 165 | 165 | 170 |

McDonnell Douglas Electronic Systems Company - Laser & Electronic Systems Division
TIPS ON INTERPRETING THE DATA

32HRV - VOLTAGE 32 HOURS INTO CHARGE
EOCV - END OF CHARGE VOLTAGE
EOCP - END OF CHARGE PRESSURE
CAP - CAPACITY TO 1.0 VOLT IN AMP-MINUTES (A-M)
PCG - PRECHARGE
ATP - ACCEPTANCE TEST PROCEDURE
DPA - DESTRUCT PHYSICAL ANALYSIS
AVN - OVERCHARGE PROTECTION
P/A - PRE-ACCEPT CELL
R/A - CELL RETURNED TO VENDOR FOR ANALYSIS
F/A - FAILURE ANALYSIS

FOR:

50AB20 LOT 16 AND LOT 17
1.509 / 1.507
PRE-ACCEPT DATA / FLIGHT CELL DATA

50AB20 LOT 13 (NASA PRECHARGE EXPERIMENT)
15.6 / 13.1 / 7.4
NORMAL PCG / 50% OVERPCG / 50% UNDER PCG

50AB34 LOT 3 (NASA KOH FILL EXPERIMENT)
3511 / 3602 / 3571
NORMAL KOH FILL / KOH UNDER-FILL / KOH OVER-FILL (161.5 / 148 / 174.5 cc's)
(0.85 / 0.77 / 0.93 fill index)
## NASA STANDARD 50 A.H. BATTERY CELL: PLATE PACK DATA

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<th>PACK WEIGHT (grams)</th>
<th>TEFLONATION (gm/dm²)</th>
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*McDonnell Douglas Electronic Systems Company - Laser & Electronic Systems Division*
### NASA STANDARD 50 A.H. BATTERY CELL: 95°F/86°F CAPACITY

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McDonnell Douglas Electronic Systems Company - Laser & Electronic Systems Division
NASA STANDARD 50 A.H. BATTERY CELL: 32°F CAPACITY

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NASA STANDARD 50 A.H. BATTERY CELL

32°F VOLTAGE TREND - 32HRV AND EOCV VS CELL LOT

CELL VOLTAGE

CELL GROUP

McDonnell Douglas Electronic Systems Company - Laser & Electronic Systems Division

1991 NASA Aerospace Battery Workshop -365- Nickel-Cadmium Technologies Session
NASA STANDARD 50 A.H.
BATTERY CELL

32°F VOLTAGE TREND -
32HRV AND EOCV VS
CELL LOT

McDonnell Douglas Electronic Systems Company - Laser & Electronic Systems Division

1991 NASA Aerospace Battery Workshop - Nickel-Cadmium Technologies Session
NASA STANDARD 50 A.H. BATTERY CELL

32°F VOLTAGE TREND - 32HRV AND EOCV VS CELL LOT

CELL VOLTAGE

CELL GROUP

McDonnell Douglas Electronic Systems Company - Laser & Electronic Systems Division

1991 NASA Aerospace Battery Workshop -368- Nickel-Cadmium Technologies Session
## NASA STANDARD 50 A.H. BATTERY CELL: 2nd 74°F CAPACITY

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NASA STANDARD 50 A.H.
BATTERY CELL

74°F VOLTAGE TREND -
EOCV VS CELL LOT

CELL VOLTAGE

CELL GROUP

McDonnell Douglas Electronic Systems Company - Laser & Electronic Systems Division

1991 NASA Aerospace Battery Workshop Nickel-Cadmium Technologies Session
### NASA STANDARD 50 A.H. BATTERY CELL: DPA CELL DATA

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McDonnell Douglas Electronic Systems Company - Laser & Electronic Systems Division
### NASA STANDARD 50 A.H. BATTERY CELL: DPA CELL DATA

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<td>L1-32</td>
<td>140.28</td>
<td>25.56</td>
<td>29.17</td>
<td>X</td>
</tr>
<tr>
<td>LOT 2-36</td>
<td>133.91</td>
<td>34.16</td>
<td>23.39</td>
<td>X</td>
</tr>
<tr>
<td>L2-63</td>
<td>135.80</td>
<td>27.84</td>
<td>28.41</td>
<td>X</td>
</tr>
<tr>
<td>50AB25 LOT 2-37</td>
<td>138.01</td>
<td>30.85</td>
<td>24.72</td>
<td>X</td>
</tr>
<tr>
<td>50AB34 LOT 3-20</td>
<td>139.26</td>
<td>31.64</td>
<td>24.65</td>
<td>X</td>
</tr>
<tr>
<td>50AB35 LOT 4-39</td>
<td>137.97</td>
<td>30.90</td>
<td>26.32</td>
<td>X</td>
</tr>
<tr>
<td>L4-108</td>
<td>138.27</td>
<td>28.39</td>
<td>27.37</td>
<td>X</td>
</tr>
<tr>
<td>LOT 6-27</td>
<td>134.64</td>
<td>31.18</td>
<td>25.59</td>
<td>X</td>
</tr>
<tr>
<td>L6-103</td>
<td>136.82</td>
<td>24.35</td>
<td>26.00</td>
<td>X</td>
</tr>
</tbody>
</table>
NASA STANDARD 50 A.H. NICKEL CADMIUM BATTERY CELL

SUMMARY OF PERFORMANCE STUDY:

1. THE NASA STANDARD 50 A.H. CELL IS AN EXCELLENT DESIGN WHEN THE CELL PRODUCTION PROCESS IS PROPERLY MANAGED BY BOTH SUPPLIER AND CONTRACTOR
   - EVIDENCED BY CONSISTENT CELL TEST RESULTS OBTAINED
   - EVIDENCED BY IN-FLIGHT PERFORMANCE

2. FINAL KOH AMOUNT MUST BE INTELLIGENTLY BALANCED AGAINST CELL VENDOR PRESSURE LIMITS

3. MELANGING OF TWO OR MORE POSTS IS A PROVEN TECHNIQUE

4. ADDITIONAL PRECHARGING IS A PROVEN TECHNIQUE

5. PRE-ACCEPT CELLS SEEM TO BE AN EXCELLENT PRECURSOR TO FLIGHT LOT PERFORMANCE

McDonnell Douglas Electronic Systems Company - Laser & Electronic Systems Division
NASA STANDARD 50 A.H. NICKEL CADMIUM BATTERY CELL

SUMMARY OF PERFORMANCE STUDY:

6. HIGHLY LOADED POSITIVE PLATE SHOULD BE AVOIDED

7. POSSIBLE CELL PROBLEMS CAN BE DETECTED EARLY IN PRE-ATP

8. LONG AND REPEATED SHORTDOWNS SHOULD BE AVOIDED

9. EOCV HAS INCREASED AT BOTH 32°F AND 74°F
NASA STANDARD 50 A.H. NICKEL CADMIUM BATTERY CELL

CELL-LEVEL PERFORMANCE HISTORY

THIS RESEARCH WAS MADE POSSIBLE THROUGH THE HELPFULNESS, COOPERATION, AND EXTREME PATIENCE OF THE FOLLOWING INDIVIDUALS AND THEIR ORGANIZATIONS:

DAN DELL
GLEN KLEIN
GUY RAMPEL
TRISH BROWN
DR. GERRY HALPERT
THOMAS YI
KEN SCHWER
DON WEBB

GATES AEROSPACE BATTERIES
GATES AEROSPACE BATTERIES
GATES AEROSPACE BATTERIES
GATES AEROSPACE BATTERIES
JET PROPULSION LABORATORY
NASA - GODDARD SPACE FLIGHT CENTER
NASA - GODDARD SPACE FLIGHT CENTER
McDONNELL DOUGLAS (Retired)
LIFE EVALUATION of 35AH Ni-Cd CELL in JAPAN

1991 NASA AEROSPACE BATTERY WORKSHOP

October 29-31, 1991

S. KUWAJIMA, N. KAMIMORI & K. NAKATANI *
National Space Development Agency of Japan
* SANYO Electric Co., Ltd.
The National Space Development Agency of Japan (NASDA) has been developing Ni-Cd cells for space use from 1985. Sanyo Electric Co., Ltd (Sanyo) have been responsible for the cell design, manufacturing, and initial tests, etc.

The life of cells have been evaluated by NASDA in the Tsukuba Space Center (TKSC).

The development is presently in the Qualification Test (QT) phase.

The Flight Model (FM) cells for Engineering Test Satellite-6 (ETS-VI) is in the process of manufacturing.

The design of the FM cells is same as QT cells.

We present recent life-cycle data of 35AH Ni-Cd cells.
CONTENTS

INTRODUCTION

CELL DESIGN

INITIAL DATA

BATTERY TEST FACILITY IN TSUKUBA SPACE CENTER

EVALUATION OF CELL PARAMETERS
  • SEPARATOR  • ELECTROLYTE  • PRECHARGE

TYPICAL LIFE DATA
  • GEO TEST  • LEO TEST  • BATTERY ASSY LEO TEST
  • ACCELERATED TEST

ADVANCED CELL DESIGN

CONCLUSION
ETS-VI Ni-Cd BATTERY

*Engineering Model*
### CELL MAJOR SPECIFICATIONS

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rated Capacity</strong></td>
<td>35 AH</td>
</tr>
<tr>
<td><strong>Mission</strong></td>
<td>GEO</td>
</tr>
<tr>
<td></td>
<td>10 Years, 1,000 cycles</td>
</tr>
<tr>
<td></td>
<td>LEO</td>
</tr>
<tr>
<td></td>
<td>3 Years, 20,000 cycles</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>max. 1050g</td>
</tr>
<tr>
<td><strong>Energy Density</strong></td>
<td>40 WH/kg</td>
</tr>
<tr>
<td><strong>Mechanical Strength</strong></td>
<td>Burst Pressure 3.5 kgf/cm²</td>
</tr>
<tr>
<td></td>
<td>Pressure Cycling 50,000 cycles (0~3.5 kgf/cm²G)</td>
</tr>
</tbody>
</table>

**EXTERNAL VIEW OF Ni-Cd CELL**
In order to satisfy the satellite demands for high power, light weight, and long mission, electrodes with high sinter plate porosity, and high active material loading level (positive plate: 2.4 g/cc-void, and negative plate: 3.0 g/cc-void) were required.

Nylon is used as separator according to the result of evaluation tests for separators.

Precharge capacity of 12AH, and electrolyte weight of 98g have been chosen, according to the results of evaluation tests for precharge and electrolyte.
### CELL DESIGN

<table>
<thead>
<tr>
<th></th>
<th>(+)</th>
<th>(-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrode Dimension</td>
<td>$104.4 \times 100 \times 0.63\text{mm}$</td>
<td>$104.4 \times 100 \times 0.80\text{mm}$</td>
</tr>
<tr>
<td>Sinter Plate Porosity</td>
<td>85 %</td>
<td>86 %</td>
</tr>
<tr>
<td>Loading Level</td>
<td>2.4 g/cc-void</td>
<td>3.0 g/cc-void</td>
</tr>
<tr>
<td>Number of Plate</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>Electrode Capacity</td>
<td>42.0 AH</td>
<td>72.8 AH</td>
</tr>
<tr>
<td>Capacity Ratio</td>
<td>1.73</td>
<td></td>
</tr>
<tr>
<td>Separator</td>
<td>Nylon</td>
<td></td>
</tr>
<tr>
<td>Precharge Capacity</td>
<td>12 AH</td>
<td></td>
</tr>
<tr>
<td>Electrolyte</td>
<td>31%KOH 98g</td>
<td></td>
</tr>
<tr>
<td>Cell Dimension</td>
<td>$115.2H \times 106.9W \times 25.2T\text{mm}$ (max.127Hmm)</td>
<td></td>
</tr>
<tr>
<td>Cell Weight</td>
<td>max.1050g</td>
<td></td>
</tr>
<tr>
<td>Cell Capacity</td>
<td>38.6AH</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Theoretical</td>
<td>Electrochemical</td>
</tr>
<tr>
<td>----------------</td>
<td>-------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Precharge</td>
<td>12 AH</td>
<td></td>
</tr>
<tr>
<td>Overcharge</td>
<td>22.2 AH</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Theoretical</td>
<td>46.2 AH</td>
</tr>
<tr>
<td></td>
<td>Electrochemical</td>
<td>42.0 AH</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electrochemical</td>
<td>72.8 AH</td>
</tr>
<tr>
<td></td>
<td>Theoretical</td>
<td>101.1 AH</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The main initial tests of QT phase are as follows:
- overcharge capacity test (-5°C, 20°C, 35°C)
- high rate discharge test
- internal impedance
- alkaline leakage
- open circuit voltage recovery
- weight & dimensions check
- some mechanical strength tests

94 sample cells have been used for these tests.

Cell capacity, end of charge voltage, and weight data were distributed within narrow range.
94 sample cells have been used for initial tests of QT-phase. Capacity, EOCV, & Weight data are within narrow range.

**Test Condition**
- **Charge**: 0.1 C for 24 Hours (in -5°C, 0.05 C for 48 Hours)
- **Discharge**: 0.5 C to 1 V
NASDA has a battery test facility in TKSC, which consists of 4 equipment for Ni-Cd batteries, and 1 equipment for Ni-H2 batteries and for electrodes respectively.

Each test equipment is independently controlled by each computer, and finally collected on the hard-disc automatically.

Test data and plotter are available for NASDA engineers and technicians by using any 4 data-terminals.

A total of 24 independent tests on Ni-Cd batteries can be performed by the 4 equipment.

For temp control, temp-controlled chambers can control cell temperature within a ±2°C range of the expected temp.

Also cooling plates are available especially for battery assembly tests.
BATTERY TEST SYSTEM IN TSUKUBA SPACE CENTER

<DATA PROCESSING SYSTEM> -<DATA-LINK>-<GP-IB LINE>

SERVER  HP50960A
HARD DISC1  HARD DISC2
HP7963B (600MB)  HP7958A (130MB)
MAG. TAPE  HP9144A
PLOTTER  HP7550A

<Ni-Cd BATTERY EQUIPMENT No. 1>
CONTROL COMPUTER  HP310
POWER SUPPLY 1  CHAMBER

<Ni-Cd BATTERY EQUIPMENT No. 2>
CONTROL COMPUTER  HP310

<Ni-Cd BATTERY EQUIPMENT No. 3>
CONTROL COMPUTER  HP310

<Ni-Cd BATTERY EQUIPMENT No. 4>
CONTROL COMPUTER  HP330

<Ni-H2 BATTERY EQUIPMENT>
CONTROL COMPUTER  HP310
POWER SUPPLY 1  CHAMBER

<ELECTRODES TEST EQUIPMENT>
CONTROL COMPUTER  HP216
POWER SUPPLY 1  DRAFT CHAMBER

Total 24 independent tests for Ni-Cd batteries

3 independent tests for Ni-H2 batteries

4 independent tests for electrodes
BATTERY TEST at NASDA TKSC
LIFE TEST DATA

- BBM phase cells were our first trial to make high capacity cells, so most of samples failed.
- With the exception of the BBM cells, most of the sample cells with normal design have shown good performance, especially the EM1 cells are the best ones.
- EM2 phase cells have been used for evaluation of precharge, electrolyte, and separator washing method.
- PM1 phase cells have been evaluated for accelerated cycling.
- PM2 phase cells have been evaluated for 4 types of tests which were GEO test, LEO test, trickle charge test, battery assembly GEO test.
**LIFE TESTS OF 35AH Ni-Cd CELL**

<table>
<thead>
<tr>
<th>No.</th>
<th>SAMPLE</th>
<th>TEST TYPE</th>
<th>DOD</th>
<th>TEMP</th>
<th>NUMBER of CYCLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BBM (*1)</td>
<td>GEO</td>
<td>60%</td>
<td>20°C</td>
<td>1186 (Finished)</td>
</tr>
<tr>
<td>2</td>
<td>BBM</td>
<td>LEO</td>
<td>25%</td>
<td>20°C</td>
<td>17334</td>
</tr>
<tr>
<td>3</td>
<td>BBM (*2)</td>
<td>ACCELERATED</td>
<td>60%</td>
<td>30°C</td>
<td>1429 (Finished)</td>
</tr>
<tr>
<td>4</td>
<td>EM1</td>
<td>GEO</td>
<td>60%</td>
<td>20°C</td>
<td>1530</td>
</tr>
<tr>
<td>5</td>
<td>EM1</td>
<td>LEO</td>
<td>25%</td>
<td>20°C</td>
<td>15235</td>
</tr>
<tr>
<td>6</td>
<td>EM2</td>
<td>GEO</td>
<td>60%</td>
<td>20°C</td>
<td>1350</td>
</tr>
<tr>
<td>7</td>
<td>EM2</td>
<td>LEO</td>
<td>25%</td>
<td>20°C</td>
<td>12517</td>
</tr>
<tr>
<td>8</td>
<td>EM2</td>
<td>TRICKLE CHG</td>
<td>----</td>
<td>20°C</td>
<td>677 day</td>
</tr>
<tr>
<td>9</td>
<td>EM2 ASSY</td>
<td>LEO</td>
<td>20%</td>
<td>5°C</td>
<td>7560</td>
</tr>
<tr>
<td>10</td>
<td>PM1</td>
<td>ACCELERATED</td>
<td>80%</td>
<td>20°C</td>
<td>1968</td>
</tr>
<tr>
<td>11</td>
<td>PM2</td>
<td>GEO</td>
<td>60%</td>
<td>20°C</td>
<td>370</td>
</tr>
<tr>
<td>12</td>
<td>PM2</td>
<td>LEO</td>
<td>25%</td>
<td>20°C</td>
<td>2795</td>
</tr>
<tr>
<td>13</td>
<td>PM2</td>
<td>TRICKLE CHG</td>
<td>----</td>
<td>20°C</td>
<td>175 day</td>
</tr>
<tr>
<td>14</td>
<td>PM2 ASSY</td>
<td>GEO</td>
<td>50%</td>
<td>20°C</td>
<td>210</td>
</tr>
</tbody>
</table>

*1: It was finished because EOCV reached 1.6V  
*2: It was finished because EODV dropped to 1V
**TEST CONDITION**

The typical test conditions are as follows:

<table>
<thead>
<tr>
<th>Condition</th>
<th>GEO</th>
<th>LEO</th>
<th>Accelerated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge</td>
<td>0.1C, 9 Hours</td>
<td>0.3C, 52.5 min</td>
<td>0.3C, 220min</td>
</tr>
<tr>
<td>Discharge</td>
<td>0.5C, 1.2 Hours</td>
<td>0.5C, 30min</td>
<td>0.5C, 96min</td>
</tr>
<tr>
<td>DOD</td>
<td>60%</td>
<td>25%</td>
<td>80%</td>
</tr>
<tr>
<td>Charge return</td>
<td>150%</td>
<td>105%</td>
<td>138%</td>
</tr>
<tr>
<td>Reconditioning</td>
<td>every 4.5 cycles</td>
<td>DO NOT</td>
<td>DO NOT</td>
</tr>
<tr>
<td>Capacity test</td>
<td>every 4.5 cycles</td>
<td>about every 5000 cycles</td>
<td>about every 1000 cycles</td>
</tr>
</tbody>
</table>

*1 : Reconditioning is $1/80C$ discharge to 1 Volt, and then charge return is $0.1C$ for 16 Hours.

*2 : Capacity test is $0.5C$ discharge to 1 Volt, and then charge return is $0.1C$ for 16 Hours.
BBM cells have been used for this test.

Candidates for the separator material were nylon, poly-propylene (PP), and poly-phenylene sulfide (PPS).

The test condition was accelerated cycling with higher temperature than for the other tests.

As the result of this test, EODV of PP & PPS cells dropped to 1V before 1,000 cycles, but EODV of the nylon cell was stable.

On the other hand, EOCV of PP & PPS cells were stable, but the EOCV of the nylon cell was rising a little.
The current cells are using a nylon separator, since PP & PPS separator cells could not keep normal EODV.

### SEPARATOR CANDIDATES

<table>
<thead>
<tr>
<th></th>
<th>Nylon</th>
<th>PP</th>
<th>PPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>0.21 mm</td>
<td>0.21 mm</td>
<td>0.22 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>87 g/m²</td>
<td>79 g/m²</td>
<td>84 g/m²</td>
</tr>
<tr>
<td>Retention</td>
<td>326%</td>
<td>282%</td>
<td>320%</td>
</tr>
</tbody>
</table>

### TEST CONDITION

- **Charge**: 0.3C, 144 min
- **Discharge**: 0.5C, 72 min
- **DOD**: 60%
- **Temp**: 30°C

### CYCLE TREND OF CELL VOLTAGE

- **End of Charge Voltage**
- **End of Discharge Voltage**
- **Nylon**
- **PP**
- **PPS**
The range of electrolyte weight in this test was 98–119g, and the range of precharge was 7–22AH.

Electrolyte evaluation

- When comparing the electrolyte under constant precharge at 12AH, excess of electrolyte caused more stable capacity, but caused higher pressure,
- We selected a 98g electrolyte, because the cell of even 98g electrolyte cells have enough stability of capacity, and it was the lowest pressure.

Precharge evaluation

- When comparing the precharge under constant electrolyte at 106g, higher precharge caused the rising of EOCV and EOCP.
- We selected a 12AH precharge, because the 12AH-precharge cell has a lower EOCP, and is more stable in capacity than the 7AH-precharge cell.
EVALUATION OF ELECTROLYTE

An over 98g electrolyte is necessary for stability of capacity, but excess of electrolyte causes higher internal pressure.

Cycle Trend of Voltage & Pressure

Cycle Trend of Capacity

Test Condition: Same as Geo Test
Higher precharge causes the rise of EOCV,
The current design cell has 12AH precharge.

**CYCLE TREND OF VOLTAGE & PRESSURE**

**CYCLE TREND OF CAPACITY**

**TEST CONDITION**: SAME AS GEO TEST
TYPICAL LIFE DATA

GEO test
- EM1 cells data is presented as typical GEO life data.
- Voltage & pressure data were stable, but the capacity degradation was observed after about 1,000 cycles.
- It satisfied mission-required cycles, and presently cycling is still continuing.

LEO test
- Also in LEO test, EM1 cells data is typical LEO data.
- The present cycle number is about 15,000 cycles.
- It shows little rising of EOCV & pressure, and little degradation of EODV & capacity.
- Mission requirements for LEO cycling are over 20AH of capacity, and over 1.05V of EODV after 20,000 cycles.
Battery assembly LEO test

- The sample battery is built from 16 cells of the EM2 phase.
- Charging method is changed to taper charge from constant current charging when battery (of 16 cells) voltage reaches to 23.82V, and total charging time is 60 minutes.
- Each cell voltage shows uniformity under taper charging, during these 7,500 cycles.

Accelerated test

- PM1 cell have been used for this test.
- At 225 cycles, it was changed from GEO test of DOD60% to Accelerated test of DOD80% because we wanted to know the effects of some treatments earlier.
- As the result, the cycle life of current design cell was about 1,400 cycles, and we knew some treatment effects.
Cell voltage, pressure, and capacity is stable during the mission-required cycles.

**CYCLE TREND OF VOLTAGE & PRESSURE**

- End of Charge Voltage
- End of Discharge Voltage
- End of Charge Pressure
- End of Discharge Pressure

**CYCLE TREND OF CAPACITY**

- Reconditioning Capacity
- Capacity test

Mission Requirement
The expected result is over 20AH of capacity, and over 1.05V of EODV after 20,000 cycles.
The uniformity of EOCV & EODV of each cell was observed under constant voltage charging with battery assy.

**CYCLE TREND OF CELL VOLTAGE**

![Graph showing cycle trend of cell voltage with end of charge voltage, end of discharge voltage, capacity test, and cycle count.]

**TEST CONDITION**

- **Charge (taper charge)**
  - constant rate: 0.3C
  - limit voltage: 23.82V/16 cells
  - charge time: 60min

- **Discharge**: 0.33C, 36min
- **DOD**: 20%
- **Temp**: 5°C
The life of over 1,000 cycles was obtained in the case of DOD 80% cycling.

**CYCLE TREND OF VOLTAGE & PRESSURE**

- **End of Charge Voltage**
- **End of Discharge Voltage**
- **End of Charge Pressure**
- **End of Discharge Pressure**
We have tried some treatments, and two methods of these treatments were good & effective for cell performance.

Alkaline washing for separator
- Current design cells showed degradation of capacity after 1,000 cycles in GEO cycling, but the cells using the washed separator showed stability in capacity.
- Both cells have no difference in charge and discharge voltage presently.

This washing method is simply to wash the separators in an alkaline solution and next reduce it by water, and dry it.

Organic compound treatment for negative plates.
- In the accelerated cycling, the cycle life of current design cells was about 1,400 cycles, but the cells treated with organic compound on the negative plates have an over 2,000 cycles life, and this cycling is still continuing.
ALKALINE WASHING FOR SEPARATOR IS EFFECTIVE FOR STABILITY OF CAPACITY.

CURRENT DESIGN CELL  ALKALINE WASHING FOR SEPARATOR

Reconditioning Capacity

Capacity test

TEST CONDITION: SAME AS GEO SIMULATION
ORGANIC COMPOUND TREATMENT FOR NEGATIVE ELECTRODE IS EFFECTIVE FOR LIFE OF CELL

CURRENT DESIGN CELL

ADVANCED NEGATIVE ELECTRODE TREATMENT

TEST CONDITION: SAME AS ACCELERATED CYCLING
CONCLUSION

- We think this development of 35AH Ni-Cd cell for space use will be completed successfully.
- We think the fruits of this development are high energy density, long life, and verifying of some effective treatments.
- Energy density of 40WH/kg is higher than conventional Ni-Cd cells.
- The GEO cycle life of 1,000 cycles that is one of mission requirements was verified, so we will use these cells in ETS-6 confidently.
- Presently the LEO test is at about 15,000 cycles, of course, we expect to achieve the 20,000 cycles successfully, since we want to use these cells for the LEO mission of ADEOS which is our test satellite launched in 1995.
CONCLUSION (cont.)

- It was verified that two treatments were effective for the cell performance.
- But these methods were not adopted for flight cell design of ETS-6, since there is not enough data in the time when the flight cell design might be decided.
- We will adopt it for future cell design.

Our future program on Ni-Cd cells is as follows:
1. Improvement of 35AH cells (and use in ADEOS)
2. Development of 25AH cells based on 35AH cells
3. Development of 50AH cells with another design.
SUMMARY

1. High energy density of 40WH/kg with current design was developed.

2. The life of current design cell is as follows:
   - GEO Test (DOD 60%) --- over 1,400 cycles
   - LEO Test (DOD 25%) --- over 15,000 cycles
   - Accelerated Test (DOD 80%) --- 1,400 cycles

3. The following methods are effective for increasing the cycle life in the advanced cell design:
   - Alkaline washing for separator
   - Organic compound treatment for negative electrode
1. Improvement of 35AH cells (and use in ADEOS)
2. Development of 25AH cells based on 35AH cells
3. Development of 50AH cells with another design
ANALYSIS OF NICKEL-CADMIUM BATTERY RELIABILITY DATA CONTAINING ZERO FAILURES

William K. Denson
Reliability Analysis Center
IIT Research Institute

Glenn C. Klein
Gates Aerospace Batteries
Analysis of Nickel-Cadmium Battery Reliability Data
Containing Zero Failures

William K. Denson
Reliability Analysis Center
Glen C. Klein
Gates Aerospace Batteries

INTRODUCTION

This paper summarizes an effort by Gates Aerospace and the Reliability Analysis Center (RAC) to analyze reliability data on NiCd batteries used on various spacecraft. This data has been collected by Gates and represents a substantial reliability database from which 183 satellites have been in operation from between 1.1 and 22 years each, for a total of 278 million cell-hours of operation, with no failures to date. The survival time data for each satellite, which has been extracted from Ref. 3, is included in Table 1.

There are two primary concerns when addressing the reliability of parts or systems; 1) the reliability during the useful life and 2) the lifetime. It is possible with the data collected thus far to draw limited conclusions regarding both of these concerns. However, since the data contains no failures, the quantification of accurate failure rates or lifetimes cannot be made. The appropriate analysis methodology to use under these conditions is the use of confidence limits. By the use of this methodology, an upper bound (or worst case value) on failure rate and a lower bound on lifetime can be made.

To accomplish this, the methodology proposed by Nelson (Ref. 2) to attach confidence limits to the Weibull distribution has been used. Advantages of the Weibull distribution are that it has a sound theoretical basis in reliability theory, it is flexible in that it can approximate many distribution shapes, and solutions from it can be obtained in closed form without the calculation of integrals necessary for the normal and lognormal distributions.
### TABLE 1: NiCd SURVIVAL TIMES (IN YEARS)

<table>
<thead>
<tr>
<th>NiCd</th>
<th>Survival Time</th>
<th>NiCd</th>
<th>Survival Time</th>
<th>NiCd</th>
<th>Survival Time</th>
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<td>2.2</td>
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<td>2.8</td>
<td>1.8</td>
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</table>
The analysis being accomplished in the report is based on the entire battery and not individual cells. The reason for this is that the data was collected at the battery level and not the cell level. It is conceivable that individual cells could have failed and not been observed at the system level (Ref. 1). In this manner, for the purposes of this analysis, cell redundancy can be disregarded since the data is at the next higher level of assembly.

**BACKGROUND**

The probability density function $f(t)$ of the Weibull time to failure distribution is:

$$f(t) = \frac{\beta}{\alpha} \left(\frac{t}{\alpha}\right)^{\beta-1} e^{\left(\frac{t}{\alpha}\right)^\beta}$$

where

- $\alpha =$ characteristic life, time to 63% population failure
- $\beta =$ Weibull shape parameter
- $t =$ time

The reliability (probability of survival to a time $t$) is:

$$R(t) = e^{\left(\frac{t}{\alpha}\right)^\beta}$$

And the hazard rate $h(t)$ (or instantaneous failure rate), given the part has survived until time $t$ is:

$$h(t) = \left(\frac{1}{\alpha}\right) \left(\frac{t}{\alpha}\right)^{\beta-1}$$
To estimate the value of the characteristic life in the Weibull distribution, the following maximum likelihood estimator is typically used:

\[
\alpha = \left[ \sum_{i=1}^{n} \frac{T_i^\beta}{r} \right]^{\frac{1}{\beta}}
\]

where

- \(T_i\) = Time to fail of the \(i^{th}\) part or survival time of the \(i^{th}\) part if it has not failed
- \(r\) = Number of failures
- \(n\) = Total population of parts

Since the data collected and presented in Table 1 indicates \(r=0\), a characteristic life of infinity implied by this estimate is clearly erroneous. The fact that no failures have been observed indicates only that enough time has not elapsed to experience failures. As stated previously, the appropriate analysis methodology to use under these conditions is to apply confidence limits to derive worst case reliability values. From this, lower bound estimates of lifetimes can be made within a given confidence level. To accomplish this, the Chi-square distribution can be utilized. The lower confidence limit for the Weibull distribution in the case where no failures have occurred is:

\[
\alpha = \left[ 2 \sum_{i=1}^{n} \frac{T_i^\beta}{\chi^2(C; 2r+2)} \right]^{\frac{1}{\beta}}
\]

where

\(\chi^2 = \) the chi-square percentile at \(C\%\) confidence and \(r\) failures

**DATA ANALYSIS**

This value of characteristic life was then calculated from the data for various values of beta and various confidence levels. Various beta values were used in this
calculation to allow interpretation of this data in the event that a specific beta value is determined in the future. Since time-to-failure data is not available, empirical betas cannot be determined. Typical beta values have been derived from Weibull analysis from similar NiCd cells and will be presented later in this paper.

The sum of the individual survival times raised to the power beta, as a function of beta, are as follows;

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>$\sum_{i=1}^{n} T_i^\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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</tr>
<tr>
<td>2</td>
<td>6360.9</td>
</tr>
<tr>
<td>3</td>
<td>69923.6</td>
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<td>4</td>
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<td>15012172</td>
</tr>
<tr>
<td>6</td>
<td>$2.64 \times 10^8$</td>
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</tbody>
</table>

The values of the Chi-square percentiles, taken from Chi-square tables are;

<table>
<thead>
<tr>
<th>C (Confidence Level)</th>
<th>Chi-Square Percentile</th>
</tr>
</thead>
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<tr>
<td>.75</td>
<td>2.773</td>
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<tr>
<td>.90</td>
<td>4.605</td>
</tr>
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<td>.95</td>
<td>5.991</td>
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<tr>
<td>.975</td>
<td>7.378</td>
</tr>
<tr>
<td>.990</td>
<td>9.210</td>
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<td>.995</td>
<td>10.60</td>
</tr>
<tr>
<td>.999</td>
<td>13.82</td>
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</tbody>
</table>

The resulting characteristic life estimates, as a function of beta and confidence level are given in Table 2. It is important to note here that the values in this table have been derived by assuming that the population of batteries from which the survival data was taken could exhibit the $\beta$ values listed. For example, the $\alpha$ lower
limit of 52 at 90% confidence is only valid if a $\beta$ of 2 represented the original population.

TABLE 2: LOWER LIMIT OF $\alpha$ (YEARS)

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>.25</th>
<th>.50</th>
<th>.75</th>
<th>.90</th>
<th>.95</th>
<th>.975</th>
<th>.990</th>
<th>.995</th>
<th>.999</th>
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<td>572</td>
<td>344</td>
<td>265</td>
<td>215</td>
<td>172</td>
<td>150</td>
<td>115</td>
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<td>148</td>
<td>96</td>
<td>67</td>
<td>52</td>
<td>46</td>
<td>42</td>
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</table>

While the values of $\alpha$ in Table 2 may appear to be unrealistically high for low confidence levels and low $\beta$ values, they are included to illustrate the dependency of characteristic life to these values.

The characteristic lifes listed in Table 2 are therefore the lower confidence limit of the actual failure distribution. For example, assuming a beta of 4, one can be 90% certain that the characteristic life is greater than 25 years, or 99.9% certain it is greater than 19 years.

To estimate typical $\beta$ values for NiCd batteries that can be used as estimates for this analysis, time to failure information contained in reference 1 was analyzed for cells made by four different manufacturers. Table 3 contains the results of Weibull plots from which the $\alpha$ and $\beta$ values were derived. From this data, the range of $\beta$ values were observed to be between 1 and 4. Although the characteristic life $\alpha$ from this data is a function of cycles, its absolute value is not important for the purposes of this analysis since extraction of typical $\beta$ values was the primary concern. Based on this information, a conservative $\beta$ value of 4 can be used in lieu of empirical $\beta$'s for Gates NiCd cells. If time-to-failure data becomes available, the chosen value of $\beta$ can be modified.
TABLE 3: WEIBULL ANALYSIS RESULTS

<table>
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<th>Manufacturer</th>
<th>$\alpha$</th>
<th>$\beta$</th>
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<td>4</td>
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<tr>
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<td>4</td>
</tr>
<tr>
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<tr>
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While the characteristic life may be very high, of more interest may be the time to 0.1% or 1% cumulative failure, which will be much less than $\alpha$. If it is desired to calculate the time ($t$) to the $P$ percentile failure of the population, the following can be used:

$$t = \alpha \left[ -\ln \left(1 - \frac{P}{100}\right) \right]^{\frac{1}{\beta}}$$

If the characteristic life is the lower confidence limit as tabulated previously, the time to $P$ percent failure will also be the lower confidence limit. Tables 4 and 5 present the lower limit of time to 1% and 0.1% cumulative population failure, respectively.

TABLE 4: LOWER LIMIT OF TIME TO 1% FAILURE

<table>
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<th>.90</th>
<th>.95</th>
<th>.975</th>
<th>.990</th>
<th>.995</th>
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TABLE 5: LOWER LIMIT OF TIME TO .1% FAILURE

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<th>.995</th>
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</tbody>
</table>

For example, using the characteristic life of 25 years for beta = 4 and 90% confidence, the worst case time (at 90% confidence) to reach 1% failure is:

\[ t = 25 \left[ -\ln \left( 1 - \frac{1}{100} \right) \right]^{\frac{1}{4}} = 7.92 \text{ years} \]

In this example, there is 90% confidence that the time to 1% failure will be greater than 7.92 years.

CONCLUSIONS

Survival data of NiCd batteries was analyzed to determine what, if any, conclusions could be drawn regarding the NiCd battery reliability or lifetime. Conventional techniques of using an exponential (constant failure rate) distribution with the Chi-square distribution to obtain confidence intervals of failure rate are of limited value since it addresses only the failure rate in the products useful life and does not address the product lifetime. Additionally, it is of limited value since it assumes a constant failure rate which is an erroneous assumption for NiCd cells.

In the case where survival data only is available (no observed failures) and where failure mechanisms are known to be wearout related, the use of the Weibull time to failure distribution can be used in conjunction with the Chi-square distribution (Ref. 2) to yield a lower limit of characteristic life (or time to a given percent failure). This estimate of the lower limit is a function of the confidence level of the characteristic life estimate and of the Weibull shape parameter, β. The
shape parameter $\beta$ is a critical factor in lower bound life estimations and since the data used in this methodology is survival data only, the $\beta$ cannot derived from empirical data. Therefore to adequately use the analysis methodology outlined in this paper, a $\beta$ value must either be known or derived from alternative means, such as life testing.

REFERENCES


REPORT OF INVESTIGATIONS
INTO CHARGE CADMIUM
REACTIVITY: NICKEL-CADMIUM CELL
ESD 91-86
19 SEP 1991

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REPORT OF INVESTIGATIONS INTO
CHARGED CADMIUM REACTIVITY:
NICKEL-CADMIUM CELLS

Ref: (a) Comparison of Physical and Chemical States of Two
Separator Type Ni-Cd Cells From a Satellite Simulation
Program, Presentation at 25th Annual IECEC Meeting

1. Introduction.
   a. In August 1990, a presentation was given, reference (a),
at the 25th Annual IECEC meeting in Reno, Nevada on the results
of Destructive Physical Analysis (DPA) on two successive sets of
Ni-Cd cells. The cells were of two different separator types,
Pellon 2505 and 2536. One cell of each separator type was
analyzed on two occasions; the first pair were analyzed
October-November 1988 to establish baseline data on essentially
new cells; the second pair were analyzed in January-February 1990
after the cells had been on charge-discharge cycling for a year
in connection with a satellite simulation study at Naval Weapons
Support Center Crane (NWSCC).

   b. During the report presentation, several questions arose
concerning the gas composition found in the cells, the absence of
charged cadmium in the analytical data presented, and the
appearance of dried-out portions on the Cd plates in the one-year
cell S/N 7 which utilized Pellon 2505 as its separator material.
It is the intention of this report to respond to the stated
concerns and to clarify the observational results.

2. Procedures.
   a. Gas Compositions. The data presented in reference (a)
for gas compositions in the cell head spaces were given as
percent of total, and it was stated that the actual cell
pressures were much less than one atmosphere. In the Results
section following, the original data are converted to mole
quantities for clarification.

   b. Cadmium Analysis. The absence of residual quantities of
cadmium metal in the analytical data from the anode analysis
utilizing the 1980 Revision A NASA Goddard\Procedure for DPA has
been studied through several experiments. First, attempts have
been made to cause reaction between Cd metal in potassium
hydroxide (KOH) solution and ambient air. Second, the
possibility that Cd metal may have dissolved during the first
stage of the analysis scheme was investigated by subjecting Cd
metal to the reagent conditions used to separate discharged from
charged Cd in the DPA procedure. Third, a set of nine 1/2 AA Ni-cd cells was divided into three sets of three each and analyzed as follows:

(1) Three cells were opened in an inert atmosphere chamber under argon (Ar) containing < 0.2ppm oxygen. The negative plates were immersed in water which had been previously sparged with Ar and frozen before transfer into the chamber. The resealed container was removed from the chamber and the negative plates were immediately transferred to an Ar purged soxhlet extractor where they were extracted by Ar sparged water until the extractate tested neutral. The plates were then transferred immediately to an Ar-purged vacuum drying oven and dried at reduced pressure under an Ar leak at ambient temperature. Subsequently, the analysis for charged and discharged Cd was performed.

(2) Three more cells were opened, this time in the glove box, in a manner which would allow the greatest likelihood for reaction of charged Cd with air. The glove box was first purged with an N₂ flow for 30 minutes. The cells were opened and the negative plates placed in 400ml of de-ionized (DI) water which had not been previously sparged, then rinsed and placed in a second 400ml of DI water. These plates in water were then brought out of the glove box and allowed to stand in ambient air for >48 hours. Next, they were placed in an N₂ purged soxhlet extractor in ordinary DI water and extracted until the extractate tested neutral. These plates were then dried in an unpurged vacuum oven at reduced pressure under an Ar leak at ambient temperature and subsequently analyzed for charged and discharged Cd.

(3) The last three cells were treated as in paragraph (1) through the drying stage. At that point, the negative plates were cut in half and one-half of each plate was immersed in 31 percent KOH and heated at 70 to 75°C for 20 hours with pure O₂ bubbling through the solution. The intent was to provide insofar as possible a ready environment for alkaline solution oxidation of residual Cd in the plates. After this treatment, the plates were extracted and dried as before, and analyzed along with the control half-plates for charged and discharged cadmium. The nickel plates from the cells utilized in this paragraph were treated exactly the same to determine whether the nickel in the Ni(OH)_2 state could be reoxidized to NiOOH or NiO. These plates were then analyzed for charged and discharged nickel material, using the unreacted half-plates as controls.

c. Separator Characterization. To determine whether the cells S/N 7 and 9 were interchanged during teardown so that the dried-out Cd plates were identified with incorrect separator material, an infrared analysis of the separators was performed for materials from the four cells analyzed thus far.
3. Results and Discussion.

a. Gas Composition. With respect to the gas analyses, the following data were presented in the original paper:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell History</td>
<td>Baseline</td>
<td>One Year</td>
<td>Baseline</td>
<td>One Year</td>
</tr>
<tr>
<td>% H₂</td>
<td>53.64</td>
<td>18.44</td>
<td>17.84</td>
<td>17.34</td>
</tr>
<tr>
<td>% He</td>
<td>14.48</td>
<td>6.97</td>
<td>33.08</td>
<td>24.81</td>
</tr>
<tr>
<td>% N₂</td>
<td>30.45</td>
<td>62.95</td>
<td>48.44</td>
<td>55.74</td>
</tr>
<tr>
<td>% O₂</td>
<td>1.43</td>
<td>11.64</td>
<td>0.64</td>
<td>2.11</td>
</tr>
</tbody>
</table>

These were the gas chromatographic compositional analyses in percent of the gases present in the cell head space. The gas chromatographic technique uses a thermal detector response. Argon is used as the carrier gas to allow a clean measure of the four components. We take one example of composition, and convert it to an approximate amount of gas present using rather generous estimates in order to develop maximum gas quantity calculations:

In S/N 28, the recorded pressure was 150.4 torr. The gas expands into an evacuated fixture of approximate volume 2-3cc. The free volume in the cell can is about 5-8cc. The increase in available volume is thus about 33 percent for a maximum total volume of about 10cc. Then an estimate of the original pressure in the can would be 150torr x 4/3 = 220torr. Next, using \( n = \frac{PV}{RT} \) to calculate a mole quantity gives:

\[
n(H_2) = \frac{(2\times10^2\text{torr} \times 0.5364) \times 10\text{cc}}{6.24\times10^6\text{cc torr K}^{-1}\text{mol}^{-1} \times 3\times10^9\text{K}} = 5.7\times10^{-5}\text{mol}
\]

for hydrogen gas. Similar calculations for all components yields the following:

<table>
<thead>
<tr>
<th>Gas Sample</th>
<th>S/N 28</th>
<th>S/N 9</th>
<th>S/N 95</th>
<th>S/N 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured P</td>
<td>150 torr</td>
<td>280 torr</td>
<td>380 torr</td>
<td>530 torr</td>
</tr>
<tr>
<td>Moles H₂</td>
<td>5.7x10⁻⁵</td>
<td>3.7x10⁻⁵</td>
<td>4.8x10⁻⁵</td>
<td>6.6x10⁻⁵</td>
</tr>
<tr>
<td>Moles He</td>
<td>1.5 x10⁻⁵</td>
<td>1.4x10⁻⁵</td>
<td>8.9x10⁻⁵</td>
<td>9.4x10⁻⁵</td>
</tr>
<tr>
<td>Moles N₂</td>
<td>3.2x10⁻⁵</td>
<td>1.3x10⁻⁵</td>
<td>1.3x10⁻⁴</td>
<td>2.1x10⁻⁴</td>
</tr>
<tr>
<td>Moles O₂</td>
<td>1.5x10⁻⁶</td>
<td>2.3x10⁻⁵</td>
<td>1.7x10⁻⁶</td>
<td>8.0x10⁻⁵</td>
</tr>
</tbody>
</table>
From these data the following observations may be inferred:

(1) The actual quantities of gases present in the cell are very small.

(2) The amount of hydrogen observed is about constant.

(3) The helium is probably present because it was inserted for leak detection.

(4) If no purging or back flushing is performed, then the nitrogen present is residual from the air evacuation and the amounts are not unusual.

(5) The amount of oxygen observed has increased with cycling. In fact, if the \( \text{N}_2 \) present is residual from the evacuation of air, then the \( \text{O}_2 \) content should be about 20 percent of \( \text{N}_2 \). For \( S/N \) 28 and 95, \( \text{O}_2 \) is much less than 20 percent of \( \text{N}_2 \), while in \( S/N \) 7 it is about 2X and in \( S/N \) 9 very much larger than the natural \( \text{O}_2/\text{N}_2 \) ratio, indicating an initial (baseline) \( \text{O}_2 \) depletion and then accumulation during cycling.

b. Limiting Electrode. A statement in reference (a) that the cells were negative plate limited was a cursory observation based on the analytical evidence that the discharged cells still contained NiOOH but no residual Cd. This was a too casual conclusion. In fact, the cells are manufactured to have an excess of Cd (positive limited). A more thorough review of the analytical data gives the following results:

Each cell contained 11 positive and 12 negative plates. The analytical weights of \( \text{Cd(OH)}_2 \), from three plates in \( S/N \) 28 for example were 7.84g, 8.40g, and 8.49g, giving an average of 8.24g \( \text{Cd(OH)}_2 \) per plate. For 12 plates this is about 100g \( \text{Cd(OH)}_2 \). The cell reaction on discharge is

\[
\text{Cd} \rightarrow \text{Cd}^{2+} + 2e^- \quad (\text{Cd}^{2+} \text{ as } \text{Cd(OH)}_2)
\]

so the recovered cadmium hydroxide converts as

\[
100\text{g } \text{Cd(OH)}_2 \times \frac{1\text{mol} \text{Cd(OH)}_2}{146.4\text{g} \text{Cd(OH)}_2} \times \frac{1\text{mol} \text{Cd}}{1\text{mol} \text{Cd(OH)}_2} \times \frac{2\text{mol} e^-}{1\text{mol} \text{Cd}} = 1.37\text{mol} e^- 
\]

For nickel, three plates analyzed of the eleven present gave an average of 5.38g \( \text{Ni(OH)}_2 \) and 0.662g NiOOH. For eleven plates in the cell there were 59.2g \( \text{Ni(OH)}_2 \) and 7.28g NiOOH total. The reaction is

\[
\text{NiOOH} + \text{H}_2\text{O} + e^- \rightarrow \text{Ni}^{2+} + 3\text{OH}^-
\]

and so the reduced \( \text{Ni(OH)}_2 \) has consumed
59.2g Ni(OH)$_2$ x \( \frac{1\text{mol Ni(OH)}_2}{92.7\text{g Ni(OH)}_2} \times \frac{1\text{mol NiOOH}}{1\text{mol NiOOH}} \times \frac{1\text{mol e}^-}{1\text{mol e}^-} = 0.639\text{mol e}^- \)

while the remaining NiOOH would consume

7.28g NiOOH x \( \frac{1\text{mol NiOOH}}{91.7\text{g NiOOH}} \times \frac{1\text{mol e}^-}{1\text{mol NiOOH}} = 0.0729\text{mol e}^- \)

for a total of 0.718mol e\-. The ratio of Cd to NiOOH is almost 2:1 in terms of electron exchange, so the positive electrode (Ni) should be the limiting electrode. However, if upon complete discharge of a cell no Cd is found during DPA, but NiOOH is observed, then it is probable that the cell would have behaved as though it was negative plate limited if driven to reversal.

c. Cadmium Reactivity. The previous calculations raise an immediate question as to why no cadmium metal was found in the analysis. There are several possible explanations:

(1) Cd metal could dissolve in the electrolyte once air is admitted to the cell. It has been observed in these labs that the Cd plates from AA-size cells become warm to the touch during cell disassembly in ambient air and it is known that Zn plates from Ag/Zn batteries will ignite in air if saturated with KOH. The Ni and Cd plates within the cell are exposed to an air atmosphere once the cell has been tapped for gas analysis, and transfer to a nitrogen-purged glove box occurred immediately after gas sampling. Cotton and Wilkinson\(^2\) state that Cd does not react directly with alkaline solutions because Cd is not amphoteric like Zn; Cd cannot form the cadmiate analog to the zincate ion (ZnO$_2^{2-}$). However, Cd(OH)$_2$ apparently does dissolve in concentrated alkali as a [Cd(OH)$_4$]$^{2-}$ ion. Mellor\(^7\) reports that Cd forms Cd(OH)$_2$ in moist air. The conversion Cd$\rightarrow$CdO$\rightarrow$Cd(OH)$_2$ $\rightarrow$ [Cd(OH)$_4$]$^{2-}$ is thus possible. However, when tests were performed in this lab where mossy Cd was immersed in 36 percent KOH and allowed to stand in contact with ambient air for two hours, the samples showed no significant weight loss for Cd. Nevertheless, the observation that plates coated with concentrated KOH and exposed to ambient air become warm indicates that a chemical reaction does occur, and electrochemically prepared Cd may be reactivity different from the chemically prepared Cd which was used in these tests.

(2) Cd metal may be attacked by the solution of ammonium acetate in ammonium hydroxide designed to separate Cd(OH)$_2$ (discharged material) from Cd metal (charged material) in the negative plate. Again, it is known that Zn plates from silver-zinc batteries suffer the problem of solution of Zn in ammonium acetate-ammonium hydroxide solution. However, when mossy Cd metal was stirred with heating for 2 hours at 80\(^\circ\)C in the solution designed for the separation procedure, no weight reduction was observed for Cd metal. Consequently, it does not
appear that this explanation will account for the absence of charged Cd either.

(3) In the GSFC-DPA procedures' no reagent blank is specified in the Cd metal titration. It has been found that a reagent error amounting to 60 to 70 percent of the total titer for Cd metal must be accounted in this analysis. This would explain why some analysts might report Cd presence from this procedure if it is determined in an analysis where reagent blank corrections are not utilized.

(4) The total Cd analysis performed for the four cells analyzed thus far has accounted for 97 to 99 percent of the weight recorded for the whole plate, for a total of 12 plates analyzed. If a significant analytical error were occurring where Cd metal was being accidently analyzed as Cd(OH)$_2$, then the total analytical weight would be greater than the actual plate weight by 10 to 15 percent at least, since two hydroxy groups are 30 percent of the weight of cadmium. But in fact, in all the cells analyzed, the accumulated weight did not vary from the actual weight by more than +3 percent and in some cases the variation was negative.

d. Cadmium Analysis. The next step was to determine whether charged Cd could be found if Cd plates from another cell type which were known to contain excess charged Cd were dissected and great care were taken to exclude air during cell dissection and plate handling up through the soxhlet extraction of KOH. The procedure is described in Section 2b(1). The analytical results, following that procedure, are as follows:

<table>
<thead>
<tr>
<th>Cell' Number</th>
<th>Discharged Cd (g)</th>
<th>Charged Cd (g)</th>
<th>Total Cd (g)</th>
<th>Charged Cd (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>2.4960</td>
<td>0.1009</td>
<td>2.5969</td>
<td>3.88</td>
</tr>
<tr>
<td>15</td>
<td>2.3521</td>
<td>0.0934</td>
<td>2.4455</td>
<td>3.82</td>
</tr>
<tr>
<td>17</td>
<td>2.5026</td>
<td>0.1262</td>
<td>2.6288</td>
<td>4.80</td>
</tr>
</tbody>
</table>

* 1/2 AA-Size

Next, the experiment was repeated using the procedure in 2b(2). In this case, the data obtained are:

<table>
<thead>
<tr>
<th>Cell' Number</th>
<th>Discharged Cd (g)</th>
<th>Charged Cd (g)</th>
<th>Total Cd (g)</th>
<th>Charged Cd (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>2.4788</td>
<td>0.1209</td>
<td>2.5997</td>
<td>4.65</td>
</tr>
<tr>
<td>23</td>
<td>2.5518</td>
<td>0.1199</td>
<td>2.6717</td>
<td>4.49</td>
</tr>
<tr>
<td>24</td>
<td>2.6090</td>
<td>0.1083</td>
<td>2.7173</td>
<td>3.99</td>
</tr>
</tbody>
</table>

* 1/2 AA-Size
From these data, it appears that the consequences of somewhat less than scrupulously oxygen-free handling prior to the soxhlet extraction has negligible effects upon the presence of charged Cd.

(1) Then the obvious question which follows is whether a reaction of charged Cd in the plate with oxygen can be forced to occur at an appreciable rate. To test this, the procedure in 2b(3) was utilized. The results of the analysis on the respective samples are:

<table>
<thead>
<tr>
<th>Cell Number</th>
<th>Discharged Cd (g)</th>
<th>Charged Cd (g)</th>
<th>Total Cd (g)</th>
<th>Charged Cd (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>2.5434</td>
<td>0.0589</td>
<td>2.6023</td>
<td>2.26</td>
</tr>
<tr>
<td>27 w O₂</td>
<td>2.4202</td>
<td>0.0382</td>
<td>2.4584</td>
<td>1.55</td>
</tr>
<tr>
<td>28</td>
<td>2.5416</td>
<td>0.0760</td>
<td>2.6176</td>
<td>2.90</td>
</tr>
<tr>
<td>28 w O₂</td>
<td>2.4497</td>
<td>0.0169</td>
<td>2.4666</td>
<td>0.69</td>
</tr>
<tr>
<td>30</td>
<td>2.5707</td>
<td>0.0602</td>
<td>2.6309</td>
<td>2.29</td>
</tr>
<tr>
<td>30 w O₂</td>
<td>2.4613</td>
<td>0.0518</td>
<td>2.5131</td>
<td>2.06</td>
</tr>
</tbody>
</table>

* 1/2 AA-Size

It appears from these data that although there is a decrease in the Cd content upon reaction of the plate with O₂ in alkaline solution, the reaction is not rapid. Therefore, on the time scale associated with cell teardown and removal of plates to soxhlet extractors, casual exposure to ambient air would not cause total depletion of charged Cd present in the plates. Further, from the variation in Cd composition over the nine 1/2 AA cells analyzed, it seems evident that the formation of charged Cd during plate preparation and cell assembly and conditioning is inexact and non-reproducible.

(2) During the previous studies, two approaches were taken to the removal of negative plate material from the grids. In one set of samples, the entire sample, grid included was dissolved in nitric acid. Then both samples were treated according to standard methods for DPA¹. The following table presents the analytical results:
As can be seen, those samples where the grid was dissolved with the charged Cd exhibited significantly lower Cd content than those where the charged Cd was removed from the grid prior to solution and analysis. The grid material is nickel plated iron wire and in the analytical scheme the acid solutions are adjusted to pH 10 prior to determination of Cd content. At that pH, iron forms a very gelatinous precipitate which occludes the Cd$^{2+}$ ions, even after repeated washings to a filtrate volume of 500ml. Thus an analytical procedure which requires solution of grid substrate containing iron will inherently lower the amount of charged Cd found during analysis.

e. Nickel Reoxidation. A final question which arose during the attempted oxidation of Cd with $O_2$ was whether Ni(OH)$_2$ could be reoxidized to NiOOH or NiO, in alkaline solution. A procedure similar to that for Cd was used for the positive plates of two cells to investigate this possibility, and the data are reported in the following table:

<table>
<thead>
<tr>
<th>Cell Number</th>
<th>Sample w Grid Charged Cd (%)</th>
<th>Sample wo Grid Charged Cd (%)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>2.28</td>
<td>3.82</td>
<td>40.3</td>
</tr>
<tr>
<td>17</td>
<td>3.18</td>
<td>4.80</td>
<td>33.8</td>
</tr>
<tr>
<td>22</td>
<td>2.37</td>
<td>4.65</td>
<td>49.0</td>
</tr>
<tr>
<td>23</td>
<td>1.95</td>
<td>4.49</td>
<td>56.6</td>
</tr>
<tr>
<td>24</td>
<td>1.69</td>
<td>3.99</td>
<td>57.6</td>
</tr>
<tr>
<td>27</td>
<td>0.55</td>
<td>2.26</td>
<td>75.7</td>
</tr>
</tbody>
</table>

As can be seen, those samples where the grid was dissolved with the charged Cd exhibited significantly lower Cd content than those where the charged Cd was removed from the grid prior to solution and analysis. The grid material is nickel plated iron wire and in the analytical scheme the acid solutions are adjusted to pH 10 prior to determination of Cd content. At that pH, iron forms a very gelatinous precipitate which occludes the Cd$^{2+}$ ions, even after repeated washings to a filtrate volume of 500ml. Thus an analytical procedure which requires solution of grid substrate containing iron will inherently lower the amount of charged Cd found during analysis.

e. Nickel Reoxidation. A final question which arose during the attempted oxidation of Cd with $O_2$ was whether Ni(OH)$_2$ could be reoxidized to NiOOH or NiO, in alkaline solution. A procedure similar to that for Cd was used for the positive plates of two cells to investigate this possibility, and the data are reported in the following table:

<table>
<thead>
<tr>
<th>Cell Number</th>
<th>NiO$_2$(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>0.09</td>
</tr>
<tr>
<td>28 w $O_2$</td>
<td>7.02</td>
</tr>
<tr>
<td>30</td>
<td>0.09</td>
</tr>
<tr>
<td>30 w $O_2$</td>
<td>7.51</td>
</tr>
</tbody>
</table>

It appears that oxidation of Ni(OH)$_2$ is not only possible, but relatively easy. Consequently, any weight gain observed for a whole cell if $O_2$ is deliberately used to estimate residual Cd in that cell before DPA may just as well be due to nickel re-oxidation. And in fact, the possibility that iron in the grids can be converted to Fe$_2$O$_3$ must also be considered, and we have obtained some evidence which suggests that occurs as well.
f. Analysis Summary. In summary, the following statements may be made:

1) If there is residual charged Cd in a cell, it does not react so easily with ambient air under alkaline conditions that analysis should give zero Cd. In the original analysis of cells with S/N's 28, 95, 7, and 9, the individual cell results were:

<table>
<thead>
<tr>
<th>Cell Number</th>
<th>Plate Number</th>
<th>Charged Cd (g)</th>
<th>Charged Cd (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 (2536)</td>
<td>3</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td>95 (2505)</td>
<td>3</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td>9 (2536)</td>
<td>3</td>
<td>0.026</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.093</td>
<td>1.27</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>0.298</td>
<td>3.77</td>
</tr>
<tr>
<td>7 (2505)</td>
<td>3</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>0.011</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Only in cell S/N 9 were significant quantities of Cd metal found. It is concluded that the other three cells did in fact have no significant residual Cd. It is important to state that all four cells were handled in identical manner during DPA procedures prior to the soxhlet extraction of KOH from the alkaline-soaked plates.

2) Suggestions have been made that residual Cd could be estimated from cell weight gain as a consequence of deliberate oxidation of the negative plates while still in the cell. There appears to be good evidence that such weight gains may just as well be attributed to reoxidation of discharged Ni materials, and perhaps also of Fe in the grids.

3) Care must be taken with regard to Cd$^{2+}$ occlusion in gelatinous Fe$_2$O$_3$ • xH$_2$O formed when the entire negative grid and plate material are dissolved in nitric acid in the charged Cd analysis procedures.

G. Infrared Characterization of Separators. The infrared scans of the two separator materials, Pellon 2505 and 2536, are very similar, as expected. However there is a prominent peak at 934cm$^{-1}$ in the 2536 spectrum which is absent from the 2505 spectrum. The spectra of S/N's 28 and 9 both exhibit this peak,
and have been identified throughout the analyses as Pellon 2536, while spectra of S/N's 95 and 7, which have been identified with Pellon 2505, are missing this peak. There are, in addition, position shifts in peaks in the 2505 material at 1263, 1170, and 1122 cm\(^{-1}\), to 1274, 1180, and 1146 cm\(^{-1}\) respectively for 2536 which are consistent in both separator sets identified by S/N's 2505 and 2536. Thus, that separator material identified with S/N 7 in which the Cd plates had appeared dried out and discolored is unambiguously Pellon 2505.

Conclusions.

a. As a consequence of the presentation discussed in the introduction to this report, four areas of concern arose in the Ni-Cd community with regard to the reported DPA results on the first four nickel-cadmium cells from a satellite simulation study analyzed at NWSCC in 1988-1989 and 1989-1990. An investigation of the procedures and results which were the basis of those concerns has been completed and the results have been detailed in the preceding sections. The analytical problems and their resolution were developed as follows:

(1) The analysis data of head space gases for the four cells have been converted to mole quantities, using estimations of the head space and sampling device volumes. These are within ten percent of actual volumes but are deliberately estimated large. From the data it can be concluded that the analytical values were consistent with expectations based on the cell preparation procedures and subsequent cycling history.

(2) Calculations based on the analytical values of cadmium and nickel contents of one of the four cells have shown that the mole ratio of cadmium to nickel, in terms of electron exchange, is about 2:1. Therefore, the cells were constructed to be nickel (positive electrode) limiting. But in fact in three of the four cells no residual (charged) cadmium metal was found after complete discharge, while residual NiOOH was found in significant quantities. Indeed, even in the single cell where residual Cd was found, the ratio of residual NiOOH to Cd was 4:1 based on moles of electrons. Consequently, even if the cells were manufactured to be cadmium-rich, if driven to reversal, they would operate as if they were negative-limited.

(3) Several of the steps in the DPA procedure were examined to determine whether Cd metal could be converted to Cd(OH)\(_2\) or CdO\(_2\) prior to the analytical processes for its determination. The results were negative in the sense that the actual procedural steps did not appear to be at fault.

(4) Next, several Ni-Cd cells of another size which were known to contain residual Cd at full discharge were analyzed after being subjected to conditions where it was possible for Cd
to be oxidized to Cd$^{2+}$ prior to the chemical characterization. Only in circumstances where the negative plates were deliberately oxidized for 24 hours in alkaline solution at elevated temperature was a decrease in the Cd content observed in comparison electrode strips. Even then, residual analyzable Cd was still present in significant quantities.

(5) During these last studies, it was found that the DPA procedure incorporated an inherent loss of analyzable Cd if grids with significant iron content were dissolved in acid during the analysis. In that event, gelatinous Fe$_2$O$_3$ $x$H$_2$O occluded 25-50% of the Cd$^{2+}$, preventing its determination. Also, it was found that deliberate attempts to oxidize Cd to Cd$^{2+}$ while the plates were still in the cell may result in reoxidation of Ni(OH)$_2$ to NiOOH, and of iron to Fe$_2$O$_3$.

(6) Therefore, if NiCd cells contain residual Cd at complete discharge, the DPA procedure should detect it. Moreover, exposure of the alkaline cell pack to ambient air for periods up to 24 hours should not reduce the Cd content to zero.

(7) With respect to the stated observation that cell pack S/N 7 with Pellon 2505 separator exhibited drying of some plates and consequent darkening of the negative plates, it has been confirmed that this observation was correctly attributed. The separator materials, 2505 and 2536, have sufficiently different IR spectra to allow unambiguous identification. The plates and separators were placed in similarly marked zip-lock bags during the dissection, extracted to remove KOH simultaneously, and then placed in fresh, similarly marked zip-lock bags and stored over desiccant until analyzed. Since each cell was dissected and packaged separately, the separator materials serve as a positive identifier of the cell of origination. Infrared reanalysis has confirmed that S/N 7 did indeed contain the 2505 separators.

b. In summary, the data and discussions submitted to the Reno, Nevada IECED Meeting (1990) by NWSCC were representative of the DPA procedures utilized, and were correct with respect to analytical results. If misunderstandings arose as a consequence of the manner in which the data were presented, they should be ascribed to the fact that these space satellite cells were the first complete DPA analyses performed by the Material Sciences Lab personnel on the nickel cadmium chemistry.

5. Recommendations. In order that the previous results may be unambiguously tied to the Navy Navigational Satellite cells, two tasks should be undertaken:

a. A third set of cells from the NWSCC simulation study, one of each separator type, should be subjected to DPA procedures.
utilizing the tightest possible control over the cell tear-down, including gas sampling, by conducting the operations in an argon atmosphere dry-box. Such a procedure would also lay to rest any doubts regarding the gas sampling procedure because if the fixture leaks during sampling, argon would become a major constituent of the gas analysis. The gas analysis procedures will be modified to detect Ar contamination.

b. Two fresh cells of either separator type with "excess" charge should be made available by the manufacturer of the original cells for DPA. These would be conditioned by several charge/discharge cycles, then discharged for DPA. One would be subjected to rigorously secure DPA, the other opened in ambient air, allowed to stand open to air for 24 hours, then disassembled under inert atmosphere conditions. One-half the cadmium plates from each cell would be subjected to immediate analysis while the other half would be allowed to stand wet with KOH in ambient air for another 24 hours prior to analysis. The objective would be to determine whether significant analytical cadmium content changes could be found in these plates as a consequence of ambient air handling. These recommended tests should finally establish the veracity of the DPA procedures performed and the results reported by the Material Sciences Laboratory in Code 305 at NWSCC.


Cadmium Issue Panel Discussion

The following section contains input from the various participants in the panel discussion. Some of the materials submitted are the actual charts or speech that was used during the discussion; other materials are copies/summaries of related letters submitted by the individuals that summarize their points made during the discussion.
The following is a brief summary of NASA's position with respect to the cadmium issue.

The proposed regulation by the Occupational Safety and Health Administration (OSHA) on the permissible exposure level (PEL) to cadmium has the potential to adversely affect NASA flight programs. This is due to the high dependance on cadmium for flight batteries in many NASA programs. For the past 25 years, nickel-cadmium (Ni-Cd) batteries have been the energy source for a vast majority of NASA missions. Ni-Cd technology also is currently planned for use on many future missions.

The only qualified supplier for NASA Standard Ni-Cd batteries has just recently announced it will cease production of these cells in the United States if the PEL is enacted as proposed. If this takes place, there will be no alternative but to consider other less-desirable options. One option is to develop new technologies such as nickel-metal hydrde as a Ni-Cd replacement. This has risks similar to those of any development program: spacecraft redesign may be required, schedule delays may occur, development costs may be unexpectedly high, and successfully qualifying the technology is anything but assured. Another option would be for NASA to procure Ni-Cd batteries from foreign suppliers. Due to going to a new supplier, this option would have similar schedule, development cost, and success risks as if developing a new technology.

Also, the proposed PEL would hamper NASA's ability to internally analyze problems that may result from manufacturing errors or test failures. Because the analysis process, in part, requires the cutting and slicing of the cadmium plates, a PEL enacted at the proposed level would severely complicate the procedure. This type of analysis is critical to understanding problem causes and formulating potential resolutions.

NASA is also concerned that proposed PEL values would make it difficult to obtain qualified cadmium plated fasteners and seals that are presently designed into launch vehicle and spacecraft systems. In the past, counterfeit fasteners have been difficult to detect. Forcing NASA to look at foreign suppliers for this type of fastener will only increase the difficulty in controlling the use of counterfeit fasteners.

In conclusion, the proposed PEL of 1 μg/m³ or 5 μg/m³ would significantly impact NASA battery systems. Our ongoing Aerospace Battery Program addresses alternate secondary power sources to replace Ni-Cd; however, new space-qualified power sources will not be available until the late 1990's. Whatever direction NASA takes based on the OSHA ruling, there will be continued emphasis on providing safe, reliable, and high quality batteries.
June 24, 1991

The Honorable J. Danforth Quayle
Vice President of the United States
Old Executive Office Building
17th Street and Pennsylvania Avenue, NW
Washington, DC 20501

Dear Mr. Vice President:

I am writing to ask that you consider utilizing the President’s Council on Competitiveness and the National Space Council to review a proposed regulation from the Occupational Safety and Health Administration (OSHA) concerning cadmium, a metal considered vital by NASA, the White House Office of Science and Technology Policy and several other agencies of the Executive Branch.

I, along with representatives from my client, The Cadmium Council, have previously met with Mr. David McIntosh and Ms. Nancy Mitchell of your office concerning this matter.

Cadmium is an inevitable co-product of zinc production and is used in nickel-cadmium batteries, as a pigment or as a heat and weathering stabilizer in engineering plastics, and as a corrosion-resistant coating in aerospace, electronic and industrial applications. Cadmium compounds also play important roles in advanced detector systems, imaging sensors and photovoltaic energy devices.

The Cadmium Council, which represents the North American cadmium industry, is deeply concerned with OSHA’s proposed rule for occupational exposure to cadmium, which was published in the February 6, 1990 Federal Register. If implemented, the proposed rule will most likely result in the demise of the domestic cadmium industry and will have serious economic consequences for many other major industries.

Public comments filed by the Office of Management and Budget, the Department of Commerce, the Department of Interior, the Bureau of Mines, the Small Business Administration and NASA all indicate severe consequences if OSHA is successful with its proposed regulation. Cadmium is also mentioned eight times in the report recently filed by the National Critical Technologies Panel, a study which identifies important technologies and materials which are crucial to their development.

The heart of our concern with OSHA’s proposal is that it violates the Occupational Safety and Health Act, which states that OSHA may adopt a standard only if it is technologically and economically feasible for affected industries to meet the standard.
The Honorable J. Danforth Quayle, Page Two.

All of the federal bodies mentioned above believe OSHA has failed that crucial test. After several meetings with OSHA, it appears that OSHA itself agrees that the industries cannot meet the levels put forth in their proposal through engineering controls and work practices. However, OSHA has proposed standards of either 1 or 5 micrograms of cadmium per cubic meter of air, well below the level of 50 micrograms per cubic meter currently considered generally feasible in the industry.

OSHA’s approach will create international competitiveness inequities and is contrary to current case law. The Cadmium Council believes that the effects upon employment and the balance of trade deficit will be substantial if OSHA is successful in implementing this new regulation.

Independent studies predict that imposition of the new OSHA standards would result in the closure of three U.S. nickel-cadmium battery manufacturing facilities comprising 55% of U.S. sales and 99% of U.S.-owned facilities, with the loss of more than 2300 jobs in the United States.

In addition, because the U.S. firm which manufactures over 90% of all nickel-cadmium battery cells for space vehicles and satellites would be among those closed, power supplies for the U.S. civilian and military space effort would have to be obtained, if possible, from foreign suppliers, further contributing to employment and trade losses.

The cost impact of the proposed rule would result in almost all U.S. nickel-cadmium batteries being manufactured off-shore, following the example of VCR’s and other small electronic products.

As for the health risk argument, OSHA has developed risk assessments for cancer and renal dysfunction which the Office of Management and Budget has criticized as unreasonable.

Finally, OSHA has ignored the fact that most other industrialized nations have cadmium health standards in the range from 20 to 50 micrograms per cubic meter and that with those standards in place, no major health problems have been observed.

Toward that end, members of The Cadmium Council and other major trade associations would appreciate any action you, the Presidents’ Council on Competitiveness or the National Space Council might take to urge OSHA to follow its legal guidelines.

Respectfully Submitted,

ROBERT DALE WILSON
Attorney At Law

CC: Mr. John Sununu
    Mr. Alan Hubbard
GATES ENERGY PRODUCTS
BACKGROUND

- CURRENT OSHA EXPOSURE LIMIT IS 200 ug/m³ -- ESTABLISHED IN 1972

- GEP -- AND OTHER NiCd BATTERY MAKERS WORLD-WIDE -- ARE GENERALLY ENGINEERED TO 50 ug/m³

- OSHA'S PROPOSED RULE-MAKING WOULD IMPOSE A MAXIMUM EXPOSURE OF EITHER 1 OR 5 ug/m³

- OSHA'S RULE-MAKING IS EXPECTED TO BE PROMULGATED IN Q1 OR Q2 OF 1992

MRH1
GATES ENERGY PRODUCTS

POSITION

- GEP HAS TAKEN LEADERSHIP ROLE IN SEEKING A REASONABLE SOLUTION
- COST TO ENGINEER PLANT TO 25 ug/m³ IS ESTIMATED TO BE AN ADDITIONAL: $20 MILLION CAPITAL
  $4 MILLION/YEAR OPERATING COST
- MARGINS ARE UNDER SEVERE PRESSURE FROM FOREIGN COMPETITION; THESE COSTS WOULD MAKE US LESS COMPETITIVE
- GEP IS NOT ABLE -- OR WILLING -- TO PAY THE ADDITIONAL COSTS TO MEET THE PROPOSED RULE, BASED ON SOUND BUSINESS PRACTICE
- BOB SHILEY -- GEP PRESIDENT:
  "IF THE REGULATION IS ESTABLISHED AT EITHER OF THOSE LEVELS (i.e., 1 OR 5 ug/m³, GATES WILL CEASE PRODUCTION OF NICKEL CADMIUM BATTERIES IN THE UNITED STATES"
- GEP REQUIRES A NUMERICAL WORKPLACE STANDARD TO ALLOW US TO CONTINUE IN BUSINESS, OR SUFFICIENT TIME FROM OSHA TO PHASE OUT OF THE MANUFACTURE OF NiCd BATTERIES
- GEP IS DEVELOPING STATE-OF-THE-ART NiMH CELLS, AND CONVERTING FROM NiCd TO NiMH
GATES AEROSPACE BATTERIES

(IF RULE IS ESTABLISHED AT LESS THAN 50 ug/m3)

- GAB IS SUBJECT TO SAME CONSIDERATIONS AS GEP -- ADDED COSTS WILL MAKE US UNCOMPETITIVE

- GAB WILL NOT MANUFACTURE NiCd CELLS AFTER GEP HAS PHASED OUT OF NiCd

- ACTIVATION (FROM DRY STORAGE) OF WELDED CELLS DOES NOT PRESENT A CADMIUM HAZARD -- DRY STORAGE COULD PROVIDE A SCHEDULE BUFFER

- OSHA RULE-MAKING THREATENS GAB'S ABILITY TO PROVIDE CONTINUING SUPPLY OF NiCd CELLS

- CUSTOMERS ARE ADVISED TO WATCH THE RULE-MAKING CLOSELY TO ENSURE THAT THEIR PROGRAM NEEDS ARE COVERED:
  -- ACCELERATE PRODUCTION AND DRY STORE (IF OSHA ALLOWS TIME)
  -- OTHER SOURCES (FOREIGN)
  -- OTHER COUPLES - NiH2
      - NiMH

- GATES AEROSPACE BATTERIES IS DEVELOPING NiMH CELLS TO REPLACE NiCd AEROSPACE CELLS -- RESULTS ARE VERY ENCOURAGING -- PAPER LATER TODAY
1991 NASA AEROSPACE
BATTERY WORKSHOP

ROLAN C. FARMER, OPERATIONS MGR.
EAGLE-PICHER INDUSTRIES, INC.
COLORADO SPRINGS, CO

CADMIUM ISSUE & NICKEL-CADMIUM
BATTERIES

• BACKGROUND:
  1. All EPI Ni-Cd Battery Business consolidated at Colorado Springs.
  2. EPI builds 3 types of Ni-Cd's
     a. Vented Ni-Cd
     b. Sealed Maintenance-Free Ni-Cd's
     c. Sealed Aerospace Ni-Cd's

• ENVIRONMENTAL REGULATIONS:
  1. Clean Water Act - EPI has reduced process water discharge 90%. Current discharge is non-detectable in Cadmium.
  2. R.C.R.A. disposal of spent batteries
     a. EPI recycles all Cd material, therefore does not generate hazardous waste.
     b. INMETCO currently accepts spent batteries as hazardous waste.
  3. OSHA Workplace Standards
     a. Due to be issued in early '92.
     b. OSHA has reopened the rule making record.
     c. May be two tier P.E.L. or possible exemption for plate making and assembly.
EPI NICKEL-CADMIUM PLANS

EPI's current plans are to continue in the Nickel-Cadmium business.

1. Standard issued in 82 will likely be phased in over 2-5 years.
2. Negative plate making and assembly might be exempt or the higher two tier approach accepted.
3. EPI will be able to meet a reasonable level for smaller markets such as Aerospace.

ADVICE "DON'T PANIC" - CD IS NOT THE ONLY ISSUE

1. Lead levels are also proposed to be lowered.
2. Nickel has been listed as priority material by "Industrial Hygienists"
3. Most battery materials will eventually receive the same attention as Cadmium.
I am David F. Pickett, Manager of the Energy Storage Product Line at Hughes Aircraft Company. We are a product line in the Electron Dynamics Division which is in the Industrial Electronics Group. Our mission is to supply high technology batteries and other energy storage devices and technology to other divisions and groups within Hughes Aircraft as well as General Motors, the U.S. Government and the aerospace industry. Our main customer is the Space & Communications Group (S&CG) at Hughes. Prior to January 1990 most of our organization was in S&CG. About two-thirds of our sales volume is directly related to Space hardware and about 20 to 30 percent of this volume is sales of nickel-cadmium batteries to either S&CG, Government agencies or other aerospace companies. It was our plan in moving from S&CG to acquire a source of nickel-cadmium, nickel-hydrogen and sodium sulfur cells either through business arrangements with other suppliers or to build the facility ourselves. In the past we fabricated our own nickel-hydrogen cells in-house, buying some piece parts such as nickel electrodes from other suppliers. We currently are building sodium sulfur cells. In the case of the nickel-cadmium technology, we still depend on outside sources to furnish us cells. Thus our business would be significantly affected should all nickel-cadmium suppliers go out of business because of the new OSHA 5 microgram per cubic meter of airborne cadmium standards.

Our position on nickel cadmium cell technology is quite unique compared to the rest of the industry. We have our own technology which we have developed with our IR&D funding. We call it Super NiCd technology. We have agreements in place with Eagle Picher and Gates, who make cells for us using this technology. We also have an agreement with Eagle Picher whereby they build cells for us for sale to other aerospace contractors. We have not issued a license to anyone to manufacture or sell this technology without our involvement.

I personally have examined the testimony and exhibits listed in OSHA Docket H-057A and the reports generated by Pace Incorporated for the Cadmium Council and appreciate the conclusion that implementing the proposed new requirements of 5 micrograms of cadmium per cubic meter (5 ug/m³) would be expensive; however, detailed studies were not performed for a totally enclosed, low volume, aerospace flat plate nickel cadmium cell operation. The studies address mainly wound cell plant operations of a high volume level. Before we could come to any cost figures on a totally enclosed aerospace line, we would need to look at this very closely. We have performed no
detail studies as yet. We have been hopeful that our sources of nickel cadmium cells will stay in business. If they don’t then we will have to reconsider our position.

Should we make a decision to go into limited production of nickel cadmium cells for space applications, we have a number of strong points which could be of consideration. Our facility in Torrance, California has been manufacturing traveling wave tubes for satellites and military applications for well in excess of 25 years, and cryogenic coolers and aerospace quality heat pipes for about 10 years. We not only have to adhere to very strict aerospace standards and particle controls for these products but have to comply with environmental regulations in the Southern California area such as those imposed by the Air Quality Management District (AQMD), Proposition 65 and the like. We think we could probably make nickel cadmium cells and satisfy the newly proposed OSHA air borne cadmium requirements. We have not concentrated our efforts into designing a nickel cadmium facility, as yet, in Torrance but very likely may do so if our sources threaten to disappear.

Starting any off shore operations with a facility which exceeds the new OSHA air borne cadmium requirement is simply out of the question for us for numerous reasons. First of all we could not, in good conscience, let any subcontractor employees work under standards inferior to those imposed by Hughes in the U.S. In offshore operations which we currently maintain, Hughes and OSHA type standards are still the enforced rule. Going around the regulation also implies that we do not agree with the health risks and are imposing our own standards. We are not qualified to do this.
Advanced Technologies Session

Organizers: Sal Di Stefano
Jet Propulsion Laboratory

Ed Buzzelli
Westinghouse Science & Technology Center
A New Composite Electrode Architecture
For Energy Storage Devices

R.E. Ferro, G.M. Swain and B.J. Tatarchuk
Department of Chemical Engineering and
the Space Power Institute
Auburn University, AL 36849

Acknowledgements

NASA-LeRC Electrochemical Technology Branch
Contract # NAG3-1154

Doris Britton
Patricia O'Donnell
Peggy Reid
T.S. Lee
EVOLUTION OF ELECTRODE ARCHITECTURES

Nickel Hydroxide Half-Cell Reaction Studies

POWDER-BASED PLAQUES

FIBREX MESH

COMPOSITE ELECTRODE STRUCTURES

Tatarchuk and co-workers:
Research Objective

How does the electrode architecture (microstructure) affect the performance of the nickel hydroxide electrochemical system?

A. Determine if the properties of the FIBREX mesh can be improved by sinter bonding small diameter metal fibers into the electrode architecture.

* provide an increase in the surface area available for deposition without significantly reducing the void volume thereby reducing the thickness of the active material.
* provide an interior network of conducting pathways to reduce the ohmic resistance within the active material.
* create an interior void/microstructure which influences crystallite size and defect density in the deposited layer.

B. Compare the performance of several composite electrode architectures with that of FIBREX mesh and electrodes prepared by Eagle-Picher in short term life-cycle tests.

C. Determine if there is a synergism between the impregnation method and the electrode architecture (microstructure)

D. Determine if the composite electrode architectures influence the conditioning time required for full utilization of the active material.
1. Nickel FIBREX mesh (28 um dia.)

2. Nickel FIBREX mesh/ stainless steel fibers (2 um dia.)

3. Stainless steel fibers

4. Nickel FIBREX mesh/nickel fibers (2 um dia.)

5. Nickel fibers

**Electrode Preparation**

![Diagram showing electrode preparation]

**Sintering Conditions**
Cell Design For Electrode Cycle Tests

Computerized software developed and tested in our laboratory which provides computer control of the potentiostat/galvanostat and data acquisition during the cycle tests.
Results and Discussion

I. Unique attributes and properties of the composite electrode architectures.

II. Discussion of the important variables involved in the electrochemical impregnation of nickel hydroxide and for a given electrode architecture do the characteristics of the impregnation method influence the performance of the electrochemical system.

III. Evaluation of the performance (% utilization) of the electrochemical system using Eagle-Picher, FIBREX mesh and a variety of composite electrode architectures in short term life-cycle tests.

* effect of electrode architecture on performance.
* effect of discharge rate on performance.
* comparison of times required to reach full utilization.

IV. Electrode Reaction Kinetics - determine the ohmic, polarization and mass transport resistances as a function of loading (thickness) and state of charge using linear sweep and cyclic voltammetry, current-time transients and AC impedance analysis.
I. Unique attributes and properties of the composite electrode architectures

1. High specific surface area (>100 fold increase in \( \text{m}^2/\text{g} \) over FIBREX).

2. Low ohmic resistance within the architecture due to the sinter bonded fibers.

3. Low mass transport resistance within the architecture voids resulting in easy accessibility of electrolytes.

4. Adjustable void volume and surface area over several orders of magnitude.

5. Electronic properties are not dependent on mechanical pressing.

**PHYSICAL PROPERTIES OF ELECTRODES**

<table>
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<tr>
<th></th>
<th>FIBREX</th>
<th>FIBREX+SS</th>
<th>FIBREX+N</th>
<th>SS</th>
<th>Ni</th>
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<tbody>
<tr>
<td><strong>BEFORE IMPREGNATION</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>35</td>
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<tr>
<td><strong>AFTER IMPREGNATION</strong></td>
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<td>Wt. of Ni(OH)₂/ cm³ of Void</td>
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<td>7.53</td>
<td>21.0</td>
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<td>20.5</td>
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</table>
Figure 1. Electron micrograph of a FIBREX/nickel fiber composite electrode prior to impregnation.

Figure 2. Electron micrograph showing the sinter bonded small diameter nickel fibers to the FIBREX mesh.
Figure 3. Electron micrograph of a FIBREX/nickel fiber composite electrode after aqueous impregnation galvanostatically at 10 mA/cm² for 3 hours.

Figure 4. Electron micrograph of the same electrode as above but at higher magnification.
Potential vs. Time Curve for a Nickel Fiber Composite Electrode During Charge and Discharge.

Solution = 26 wt% KOH
Active Material Weight = 44 mg
Electrode Weight = 31 mg
Geometric Area = 2.8 cm²
Charge Rate = C/2
Discharge Rate = 3C/2

Plot of % Utilization vs. Discharge Rate for Different Composite Electrode Architecture

Solution = 26 wt% KOH
Active Material Weight = 53 mg (FIBREX/SS)/64 mg (SS)/85 mg (SS)
Electrode Weight = 27 mg (FIBREX/SS)/29 mg (SS)/125 mg (SS)
Geometric Area = 2.8 cm²
Charge Rate = C/2
Plot of % Utilization vs. Discharge Rate for a Nickel Fiber and a FIBREX/Nickel Fiber Composite Electrode.

Solution = 26 wt% KOM
Active Material Weight = 31 mg (Ni) / 105 mg (FIBREX/Ni)
Electrode Weight = 31 mg (Ni) / 185 mg (FIBREX/Ni)
Geometric Area = 2.8 cm²
Charge Rate = C/2

Plot of % Utilization vs. Discharge Rate for FIBREX/Stainless Steel Composite Electrode at Different Charge Rates.

Solution = 26 wt% KOM
Active Material Weight = 53 mg (C/2) / 70 mg (1C) / 52 mg (3C/2)
Electrode Weight = 268 mg (C/2) / 249 mg (1C) / 326 mg (3C/2)
Geometric Area = 2.8 cm²
Summary

1. Microstructure and additional surface area make a difference! Best architectures are the FIBREX/nickel and nickel fiber composite electrodes.

2. Conditioning time for full utilization greatly reduced.
   < 5 cycles vs. 200 or more

3. Accelerated increase in capacity vs. cycling appears to be a good indicator of the condition of the electrode/active material microstructure and morphology. Conformal deposition of the active material may be indicated and important.

4. Higher utilizations obtained.
   > 80% after less than 5 cycles
   > 300%* after more than 5 cycles using nickel fiber composite electrode assuming a 1 electron transfer per equivalent.
Current and Future Research Efforts

1. Broaden fundamental understanding of microstructural influence on utilization, efficiency, charge and discharge rates, proton diffusion rates, deposition synergy, etc.

2. Determine influences and physical mechanisms for limiting electrode kinetic processes.

3. Optimize electrode microstructure with respect to the above noted constraints, limits and rates for a desired application.

4. Examine selected candidate composite electrode structures during long term cycle-tests (>200).

5. Evaluate promising candidates in full-cell Ni-H₂ batteries.
Composite Overwrapped Nickel-Hydrogen Pressure Vessels

John Reagan, NASA Lewis Research Center
Joe Lewis, TRW
COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

- The purpose of this paper is to stimulate interest in composite overwrapped nickel-hydrogen pressure vessels.

- Composite overwrapped pressure vessels should:
  - Be more economical to produce
  - Require less schedule time to produce
  - Be more reliable
  - Be inherently more resistant to fatigue damage
  - Potentially improve heat transfer characteristics
  - Reduce membrane stress
  - Allow a potentially wide range of liner materials

States purpose of paper - stimulate interest in Composite Overwrapped pressure vessel technology as applied to Nickel-Hydrogen Battery pressure vessels. Includes technical and economic forces that could be utilized in such a design.
COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

- HISTORY OF NICKEL-HYDROGEN PRESSURE VESSELS
  - TECHNOLOGY IS FIFTEEN YEARS OLD
  - EXCEPT FOR THE LAST TWO YEARS ALL KNOWN APPLICATIONS HAVE BEEN IN GEO ORBIT AT 800 PSI
  - OVER THE LAST THREE YEARS APPLICATIONS HAVE MOVED TO LEO ORBITS WITH PRESSURE INCREASED TO EXCESS OF 1000 PSI
    - DEPTH OF DISCHARGE HAS ALSO BEEN INCREASED FROM 10% TO PRESENT REQUESTS THAT ARE NOW APPROACHING 40%
    - WEIGHT HAS BEEN REDUCED AT THE EXPENSE OF PRESSURE VESSEL WALL THICKNESS
  - BOTH EUROPE AND JAPAN ARE PLANNING NICKEL-HYDROGEN BATTERIES FOR SPACE APPLICATIONS

- HISTORY (cont)
  - INCONEL 718 HAS BEEN THE MATERIAL OF CHOICE SINCE EARLY DESIGNS
    - ALL PRESENT DESIGNS KNOWN TO THE AUTHORS PRESENTLY USE OR ANTICIPATE THE USE OF INCONEL 718
    - INCONEL 718 HAS PROVED TO BE VERY RELIABLE
    - THE ADVANTAGES OF COMPOSITE OVERWRAPPED MATERIAL HAVE BEEN SUGGESTED SEVERAL TIMES BUT THE TECHNOLOGY HAS ALWAYS BEEN ELIMINATED EARLY ON DUE TO:
      - FEAR OF ADVERSE THERMAL REACTIONS' EFFECTS
      - UNKNOWNS OF DESIGN
      - LACK OF COMPOSITE OVERWRAPPED EXPERTS IN THE DESIGN PROCESS
    - DESIGNERS HAVE ACKNOWLEDGED THE ABILITY OF COMPOSITE OVERWRAPPED TECHNOLOGY TO REDUCE THE OVERALL STRESS IN THE CRITICAL GIRTH WELD(S) AREA

---

Presents the history of Nickel Hydrogen Pressure Vessels over the last 15 years including materials, operating conditions, and market expansion to internationals.

Discusses minor interest in Composite Overwrap technology as applied to Nickel-Hydrogen Batteries to date.
COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

- MATERIAL PROPERTIES DESIRED FOR PRESSURE VESSEL
  - COMPATIBILITY WITH KOH
    - GENERAL CORROSION
    - FRACTURE CONTROL
  - GOOD THERMAL CONDUCTIVITY
  - HIGH STRENGTH-TO-WEIGHT RATIO
  - HIGH CYCLE LIFE
    - APPROXIMATELY 41,000 ACTUAL CYCLES FOR 15 YEAR SERVICE LIFE
    - 164,000 ANALYTICAL CYCLES

Itemizes basic materials properties: thermal, corrosion, strength.
COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

APPROACHES TO ACHIEVING DESIRE PROPERTIES

MONOLITHIC METAL CONSTRUCTION

DIFFICULT TO OPTIMIZE PROPERTIES IN ONE ALLOY

COMPROMISE OF SOME PROPERTY USUALLY REQUIRED

COMPOSITE OVERWRAPPED CONSTRUCTION

EACH DESIRED PROPERTY CAN BE OPTIMIZED IN DIFFERENT COMPONENTS OF COMPOSITE VESSEL

COMPATIBILITY IN INNER LINER

THERMAL CONDUCTIVITY IN OUTER LINER

STRENGTH-TO-WEIGHT RATIO IN COMPOSITE OVERWRAP

CYCLE LIFE IN INNER LINER

Monolithic and Composite Overwrapped construction approach compared.
COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

- POTENTIAL ADVANTAGES OF COMPOSITE PRESSURE VESSEL
  - OPTIMIZED PROPERTIES
  - POTENTIALLY LOWER COST
    - COMPOSITE HIGH-PRESSURE GAS STORAGE VESSELS COST APPROXIMATELY 20% OF EQUIVALENT TITANIUM VESSEL
    - POTENTIAL FOR ELIMINATION OF WELDS
  - POTENTIALLY SHORTER MANUFACTURING SCHEDULE
    - COMPOSITE VESSELS ARE BEING PRODUCED IN APPROXIMATELY ONE-THIRD "TIME FOR EQUIVALENT TITANIUM VESSELS"
  - IMPROVED FRACTURE CONTROL CAPABILITY
    - COMPOSITE VESSELS SHOW POTENTIAL FOR MILLIONS OF CYCLES BEFORE LEAKAGE
  - POTENTIALLY LOWER WEIGHT
    - COMPOSITE HIGH-PRESSURE GAS STORAGE VESSELS WEIGH APPROXIMATELY 20% OF WEIGHT OF EQUIVALENT TITANIUM VESSEL
  - PRECISE CONTROL OF VESSEL WALL GROWTH DUE TO PRESSURE WITH MINIMAL EFFECT ON WEIGHT

Detailed description of the advantages of Composite Overwrapped Pressure vessels showing weight savings, manufacturing schedule reductions, and improved fatigue life.
COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

- Graphite/Epoxy overwrapped pressure vessel with Inconel X-750 liner is currently flying on B-1 bomber.
- No known reason why Inconel 718 liners or liners of any ductile nickel alloy could not be overwrapped with graphite/epoxy.

COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

Optimized Properties

Schematic section of vessel wall.

Discussion of B-1 application, wide range of usable materials, and a sketch of a possible optimized design.
COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

THERMAL CONDUCTIVITY OF SOME CANDIDATE MATERIALS

- **COPPER:** 226 BTU FT/HR FT²
- **NICKEL:** 90 BTU FT/HR FT²
- **GRAPHITE:** 46 BTU FT/HR FT² (PARALLEL TO FIBER)
- **INCONEL 718:** 6.5 BTU FT/HR FT²
- **GRAPHITE/EPOXY:** 0.1 BTU FT/HR FT² (TRANSVERSE TO FIBER)

Table showing recent successes using Graphite/Epoxy Composite Overwrapped technology in actual flight systems.
Discussion of joining technology and the opportunity to: reduce risk in manufacturing, increase production, and improve reliability by adopting Composite Overwrapped technology.
Fracture Control problems in present designs are addressed and possible solutions proposed. Emphasis is on the improvement possibilities with Composite Overwrapped technology in the area of a large analytical increase in total pressure vessel life.
COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

- **NDI METHODOLOGY FOR WROUGHT METAL LINER**
  - WROUGHT METAL IS CONVENTIONALLY MACHINED TO A THICKNESS OF 0.030-0.040 INCH PER SURFACE GREATER THAN FINAL DESIRED THICKNESS
  - BOTH SURFACES OF WROUGHT METAL ARE INSPECTED USING NTS'S "SPECIAL" PENETRANT INSPECTION
  - EXTRA 0.030-0.040 INCH THICKNESS IS CHEMICALLY MILLED FROM EACH SURFACE
  - REMAINING MATERIAL IS "CRACK-FREE"
  - CHEM-MILLING SOLUTIONS DO NOT GENERATE CRACKS.
    - NASA AND DoD SPECIFICATIONS REQUIRE "ETCHING" BEFORE PENETRANT INSPECTION
    - ANY SURFACE CRACK IN ORIGINAL 0.030-0.040 INCH THICKNESS RESULT IN HOLES THROUGH FINAL THICKNESS

COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

- **NDI METHODOLOGY**

![Diagram](image)

RESULT IF NO CRACK EXISTS  RESULT IF CRACK EXISTS

Non-destructive testing is described for monolithic designs and for the proposed Composite Overwrapped technology. The elimination of virtually any flaw by using Chem-milling to reduce the overall membrane thickness is detailed. Adopting this technology proves the extended analytical life predicted above.

1991 NASA Aerospace Battery Workshop Advanced Technologies Session
COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

FLIGHT HISTORY OF GRAPHITE-OVERWRAPPED PRESSURE VESSELS WITH THIN METALLIC LINERS

<table>
<thead>
<tr>
<th>PROGRAM</th>
<th>TYPE OF TANK</th>
<th>DATE FLOWER</th>
<th>FLUID</th>
<th>FIBER</th>
<th>OPERATING PRESSURE (PSIA)</th>
<th>BURST PRESSURE (PSIA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEDI</td>
<td>PRESSURANT</td>
<td>JAN. 1990</td>
<td>NH$_3$</td>
<td>T-40</td>
<td>7,000</td>
<td>14,000</td>
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<tr>
<td>PEBASUS</td>
<td>PRESSURANT</td>
<td>APR. 1990</td>
<td>NH$_3$</td>
<td>HT 46-9</td>
<td>2,500</td>
<td>5,000</td>
</tr>
<tr>
<td>EROS</td>
<td>PRESSURANT</td>
<td>JAN. 1991</td>
<td>NH$_3$</td>
<td>T-1000</td>
<td>9,000</td>
<td>18,000</td>
</tr>
<tr>
<td>EROS</td>
<td>PROPELLANT</td>
<td>JAN. 1991</td>
<td>HTO/99%</td>
<td>HT 46-9</td>
<td>2,500</td>
<td>5,000</td>
</tr>
<tr>
<td>DEEPLIGHT</td>
<td>PRESSURANT</td>
<td>MAR. 1991</td>
<td>NH$_3$</td>
<td>T-1000</td>
<td>9,000</td>
<td>18,000</td>
</tr>
<tr>
<td>PEBASUS</td>
<td>PROPELLANT</td>
<td>JULY 1991</td>
<td>HYDRAZINE</td>
<td>T-1000</td>
<td>666</td>
<td>1,000</td>
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<tr>
<td>PEBASUS</td>
<td>PRESSURANT</td>
<td>JULY 1991</td>
<td>NH$_3$</td>
<td>T-1000</td>
<td>6,000</td>
<td>12,000</td>
</tr>
<tr>
<td>MICROBAT</td>
<td>PRESSURANT</td>
<td>JULY 1991</td>
<td>NH$_3$</td>
<td>T-1000</td>
<td>6,000</td>
<td>12,000</td>
</tr>
</tbody>
</table>

Pictorial of how NDI combined with chem-milling assure total freedom from flaws.
COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

- NOW IS THE RIGHT TIME TO STUDY THIS ALTERNATIVE
- THE COMPOSITE OVERWRAP TECHNOLOGY HAS TOTALLY SUPPLANTED CONVENTIONAL MONOLITHIC METAL TECHNOLOGY IN MANY SPACE FLIGHT APPLICATIONS IN THE LAST FIVE YEARS
- IT IS INHERENTLY SAFER
- USED EXTENSIVELY WITH MONOPROPELLANT SYSTEMS AS WELL AS OTHER HIGH PRESSURE APPLICATIONS
- LOW-PRESSURE BIPROPELLANT VESSELS CURRENTLY BEING DEVELOPED
- THE USA SHOULD STRIVE TO MAINTAIN ITS TECHNOLOGICAL SUPERIORITY IN THIS TECHNOLOGY BY EXPLORING ALL FACETS AND APPLICATIONS (BOTH NICKEL-HYDROGEN AND COMPOSITE OVERWRAPPED TECHNOLOGIES)

Suggests that now is the correct time for the USA to thoroughly investigate composite overwrapped technology. This activity will protect our market share while promoting greater knowledge of Nickel-Hydrogen Batteries.
COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

- A PRELIMINARY INVESTMENT OF $300k$ WOULD BE ADEQUATE TO DEVELOP THE BASIC FEASIBILITY OF PRODUCING SUCH A DESIGN.
- THIS INVESTMENT WOULD PRODUCE A PROTOTYPE PRESSURE VESSEL ALONG WITH ALL PRELIMINARY DATA REGARDING THERMAL PROPERTIES, MANUFACTURING METHODS AND FRACTURE CONTROL.
- A MANUFACTURING PLAN WOULD ALSO BE ESTABLISHED WITH COST PER UNIT ESTIMATED FOR PRODUCTION.
- WORK COULD BEGIN IN 3 - 6 MONTHS.
- COMPLETION WOULD BE EXPECTED IN 16 - 20 MONTHS.

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Presents cost and schedule information.
THE LiAl/FeS₂ BATTERY
POWER SOURCE FOR THE FUTURE


NASA AEROSPACE BATTERY WORKSHOP
October 29 - 31, 1991
MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

SAFT AMERICA INC
RESEARCH AND DEVELOPMENT CENTER
109 BEAVER COURT
COCKEYSVILLE, MD 21030
The LiAl/FeS$_2$ Battery

Power Source for the Future

J.D. Briscoe, J. Embrey, S. Oweis, K. Press

SAFT R&D Center
Cockeysville, MD 21030

Abstract:

Advanced high power density rechargeable batteries are currently under development at SAFT. These batteries have the potential of greatly increasing the power and energy densities available for space applications. Depending on whether the system is optimized for high power or high energy, values up to 150 Wh/kg and 2,100 W/kg (including hardware) are projected. This is due to the fact that the system employs a high conductivity molten salt electrolyte. The electrolyte also serves as a separator layer with unlimited freeze thaw capabilities. Life of 1,000 cycles and ten calendar years is projected. The electrochemistry consists of a lithium aluminum alloy negative electrode, iron disulfide positive electrode, and magnesium oxide powder immobilized molten salt electrolyte. Processed powders are cold compacted into circular discs which are assembled into bipolar cell hardware with peripheral ceramic seals. The culmination of SAFT's development work will be a high energy battery of 40 kWh and a high power battery of 28 kWh.

Introduction:

Advanced rechargeable high energy batteries are desirable for a number of applications where the performance of present day lead acid batteries is
inadequate. Such applications as electric vehicle propulsion, utility load leveling, military and space demand high power and energy from reliable power sources. Rechargeable high temperature electrochemistries employing molten salt electrolytes and high energy electrodes offer promise for fulfilling present and future requirements in lower weight and volume packages.

Today, SAFT is developing LiAl/FeS$_2$ batteries in sealed bipolar configuration having superior energy and power densities. Such batteries promise to give improved performance with lower weight for future space applications.

**Space Power Systems:**

At the 1989 IECEC conference, a paper was presented entitled: "Advanced Electrochemical Concepts for NASA Applications"\(^{(1)}\). Presented in that paper were the results of a Jet Propulsion Laboratory survey of 23 electrochemical systems for space applications. The highest ranked advanced systems for operation in planetary inner-orbit spacecraft included Na/beta' alumina/z (where z = S, FeCl$_2$, or NiCl$_2$), upper plateau (U.P.) Li(Al)/FeS$_2$ and H$_2$O$_2$ alkaline regenerative fuel cell (RFC). The achievable specific energy for these as operational batteries was estimated to be 130, 180, and 100 Wh/kg respectively. Energy storage requirements of six anticipated space missions are tabulated as shown in Figure 1. GEO, planetary rover, and lunar based applications were designated as shown to be good candidates for LiAl/FeS$_2$ primarily because of moderate cycles and large energy requirements.

As compared to present state-of-the-art nickel/cadmium and nickel/hydrogen batteries, the projected specific energy (Wh/kg) for bipolar constructed lithium
aluminum/iron disulfide batteries is three times that of nickel hydrogen with five times improvement in energy density (Wh/l) as shown in Figure 2.

**Lithium/Metal Sulfide System Description:**

During the 1970s, work was performed at Argonne National Laboratory (ANL) to develop batteries for electric vehicle propulsion and utility load leveling\(^2\). Both lithium aluminum/iron disulfide and iron sulfide couples were investigated. The complete discharge (two plateaus) of lithium aluminum/iron disulfide can be written as

\[
4\text{LiAl} + \text{FeS}_2 \rightarrow 2\text{Li}_2\text{S} + \text{Fe} + 4\text{Al}
\]

Failure to achieve good cycle life with this couple caused development emphasis to shift heavily in favor of the lower energy and less corrosive lithium aluminum/iron sulfide system. The discharge has a theoretical specific energy of 460 Wh/kg and can be written as

\[
2\text{LiAl} + \text{FeS} \rightarrow \text{Li}_2\text{S} + \text{Fe} + 2\text{Al} (1.34\text{V})
\]

Full scale prismatic multiplate cells and small batteries were built at Eagle Pitcher, Gould, and ANL.

In the 1980s, some work was continued at ANL on LiAl/FeS\(_2\) by Kaun and others. Success was achieved in 1986 by cycling only the upper plateau

\[
2\text{LiAl} + \text{FeS}_2 \rightarrow \text{Li}_2\text{S} + \text{FeS} + 2\text{Al} (1.66\text{V})
\]

with a theoretical specific energy of 490 Wh/kg. Over 1,000 cycles was demonstrated in LiAl/FeS\(_2\) prismatic bicell configuration\(^3\). Further developments in 1988 of an electrochemical overcharge tolerance\(^4\) and in 1990 of a peripheral seal material\(^5\) make bipolar stack construction both workable and practical.
At SAFT, primary reserve thermal batteries containing bipolar LiAl/FeS₂ have been manufactured since 1978, and research and development on rechargeable prismatic LiAl/FeS and bipolar LiAl/FeS₂ has been conducted since 1990.

The LiAl/FeS₂ electrochemistry consists of components fabricated from cold uniaxial pressed dry mixed powders. Three cell components are the negative electrode, electrolyte/separator, and positive electrode, all containing molten salt electrolyte. The negative electrode contains LiAl alloy and the positive electrode FeS₂. The electrolyte/separator consists of molten salt immobilized by MgO ceramic powder which acts as a binder-separator at operating temperature.

Cell components are fabricated in prismatic or disc geometries for either prismatic multiplate cells (Figure 3) or cylindrical bipolar configurations (Figure 4). The bipolar battery is a triple seal construction. First, all cells are individually sealed around the periphery as shown in Figure 4. Second, arrays of series cells are sealed inside a steel case to form a module. And finally, the modules are contained inside a sealed thermally insulated enclosure (Figure 5). Integral cooling and heating systems maintain the modules at a constant temperature. The thermal enclosure is double walled construction with vacuum and multifoil insulation. Heaters are powered by the charging source during charge and the battery during discharge. Heat loss is limited to approximately 16% of battery capacity per day.

**System Advantages:**

As compared to other advanced battery chemistries, the LiAl/FeS₂ system offers some distinct advantages. In addition to high volumetric power and energy
densities, the system offers high reliability with intrinsic safety. Cells have performed for over 1,000 cycles with negligible performance degradation.

Single cell and battery tests have demonstrated that cells always fail short circuit. Configured as series arrays of bipolar cells, remaining series cells will continue to operate normally even with shorted cells included in the string. This is in contrast to the sodium/sulfur system where cells fail open circuit and the remaining series cells are inoperable.

The battery is intrinsically safe because it contains no liquids or gases. Unlike most lithium batteries, the negative electrode is not pure lithium but an alloy containing approximately 20 weight percent lithium which is less reactive and solid at the battery operating temperature. During operation the salt is molten in the electrodes and "wets" the active particles. If the container is punctured exposing the chemistry to the atmosphere, the salt freezes forming a protective coating over the lithium aluminum particles.

The electrochemistry in bipolar configuration is tolerant to dynamic environments as has been demonstrated for over 14 years in thermal batteries. These are primary reserve LiAl/FeS2 batteries designed for military application. Installed in missiles, guided bombs, and projectiles, these batteries withstand severe environments of shock, vibration, and acceleration in both non-operating and operating conditions. The dense paste-like electrolyte/separator is not subject to cracking typical of solid ceramic separators. For secondary applications, this separator property provides unlimited freeze thaw capability.
An advantage over ambient temperature batteries is that the electrochemistry is always operating at optimum temperature independent of environmental changes.

**Development Goals:**

Currently, SAFT is working on development of two batteries utilizing LiAl/FeS$_2$ electrochemistry in bipolar construction. One battery will be optimized for high energy utilizing thick electrodes at moderate current densities to achieve 150 Wh/kg with power of 340 W/kg. This battery is being developed for electric vehicle propulsion. The second battery will be optimized for high power utilizing thin electrodes at high current densities up to 5.0 amperes/cm$^2$ to achieve extremely high specific power of 2.9 kW/kg at a relatively low specific energy of 39 Wh/kg. This battery will provide high power for an electric weapon application. A comparison of development goals for these batteries is shown in Figure 6.

**Development Status:**

At SAFT, bipolar primary thermal batteries have been made since the 1950s. In 1978, SAFT introduced the LiAl/FeS$_2$ technology developed by ANL into thermal batteries. Since 1990, work on rechargeable lithium metal sulfide technology has been conducted at SAFT’s Baltimore facility. This work included LiAl/FeS prismatic multiplate cells (200 Ah), LiAl/FeS$_2$ prismatic bicells (40 Ah), and LiAl/FeS$_2$ bipolar cells (0.3 to 3.2 Ah).

A number of recent accomplishments are noteworthy. Specific energy of 89 Wh/kg was achieved for LiAl/FeS prismatic multiplate cells tested at the C/3 rate.
Battery hardware was developed to accommodate 27 multiplate cells. Bipolar LiAl/FeS$_2$ cells and batteries have achieved 2,100 W/kg, and 6,700 W/l, at very high rates of charge (3C) and discharge (75C).

**Development Issues:**

A target of 1993 has been set to develop a 7 kW high power bipolar LiAl/FeS$_2$ scaleable module for test. A 5 kWh high energy module is targeted for development by 1994.

In order to achieve these development goals, work must progress towards improvement and scale up of peripheral seals, chemical equalization, and corrosion resistant materials at the cell and cell stack level. Engineering of stack pressure/restraint and current collection systems and methods for electrical isolation need development.

At the battery level, development of an optimized thermal management system that is reliable and producible at minimum cost is essential. The high battery volumes required for electric vehicles require development of a recycling program.
References:


## ENERGY STORAGE REQUIREMENTS OF SIX ANTICIPATED SPACE MISSIONS

<table>
<thead>
<tr>
<th>Priority/Applications</th>
<th>Charge/Discharge Durations</th>
<th>Typical Operational Cycles Required</th>
<th>Typical Peak Power and Energy Storage Required</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GEO</strong></td>
<td></td>
<td>Actual: 500 *Qual: 1000 Desired: 2000</td>
<td>0.50 C (1 kWh)</td>
</tr>
<tr>
<td><strong>LUNAR</strong></td>
<td></td>
<td>Actual: 3000 *Qual: 6000 Desired: 10000</td>
<td>1.50 C (2 kWh)</td>
</tr>
<tr>
<td><strong>LEO</strong></td>
<td></td>
<td>Actual: 1500 *Qual: 2000 Desired: 4000</td>
<td>1.50 C (5 kWh)</td>
</tr>
<tr>
<td><strong>ROVER</strong></td>
<td></td>
<td>Actual: 300 *Qual: 600 Desired: 800</td>
<td>1.30 C (3 kWh)</td>
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<tr>
<td><strong>LUNAR BASED</strong></td>
<td></td>
<td>Actual: 80 *Qual: 160 Desired: 350</td>
<td>0.02 C (5 MWh)</td>
</tr>
<tr>
<td><strong>LEO</strong></td>
<td></td>
<td>Actual: 30000 *Qual: 35000 Desired: 50000</td>
<td>1.10 C (25 kWh)</td>
</tr>
</tbody>
</table>

**GEO:** Geosynchronous Orbit  
**LEO:** Low Earth Orbit  
**CANDIDATES FOR LiAl/FeS$_2$**  
*QUAL: Minimum number of cycles needed to qualify for application.  
**SOURCE: G. Halpert and A. Attia, JPL**

**Figure 1**
### Technology Performance Comparison

**Geosynchronous Orbit**

<table>
<thead>
<tr>
<th></th>
<th>Ni-Cd</th>
<th>Ni-H₂</th>
<th>Projected Bipolar LIAL/Fe₅S₉</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Specific Energy, Wh/kg</strong></td>
<td>25 -30</td>
<td>45 - 50</td>
<td>150</td>
</tr>
<tr>
<td><strong>Energy Density, Wh/L</strong></td>
<td>45</td>
<td>55</td>
<td>270</td>
</tr>
<tr>
<td><strong>Cycle Life</strong></td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>- DOD (%)</td>
<td>70</td>
<td>70 - 80</td>
<td>80 - 100</td>
</tr>
<tr>
<td><strong>Calendar Life, YR</strong></td>
<td>15</td>
<td>15</td>
<td>10</td>
</tr>
</tbody>
</table>

*Figure 2*
Bipolar LiAl/FeS2 Battery Concept Design

1 of 10 Cell Modules

(-) NEG

(+) POS

Thermocouples

Heating

(+) POS

Cooling

Research & Development Center

Figure 5
### SAFT LiAl/FeS₂ Bipolar Battery

#### Development Goals

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Optimized for High Energy</th>
<th>Optimized for High Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy, kWh</td>
<td>40</td>
<td>28</td>
</tr>
<tr>
<td>Voltage, Volts</td>
<td>210 - 350</td>
<td>450 - 550</td>
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<tr>
<td>Specific Energy, Wh/kg</td>
<td>150 (C/3)</td>
<td>39 (75C)</td>
</tr>
<tr>
<td>Energy Density Wh/L</td>
<td>270 (C/3)</td>
<td>56 (75C)</td>
</tr>
<tr>
<td>Peak, Specific Power, W/kg</td>
<td>340</td>
<td>2900</td>
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<tr>
<td>Peak, Power Density, W/L</td>
<td>610</td>
<td>4164</td>
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<tr>
<td>Cycle Life</td>
<td>1000</td>
<td>1000</td>
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<tr>
<td>DOD (%)</td>
<td>80</td>
<td>40</td>
</tr>
<tr>
<td>Calendar Life, Yr</td>
<td>10</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 6
SECONDARY LITHIUM CELLS FOR SPACE APPLICATIONS

JPL

S. SURAMPUDI, D. H. SHEN, C.-K. HUANG,
S. R. NARAYANAN, A. ATTIA, G. HALPERT

1991 NASA Aerospace Battery Workshop
U. S. Space and Rocket Center
Huntville, AL
October 29-31, 1991
SECONDARY LITHIUM CELLS/BATTERIES
OUTLINE

(1) JPL PROGRAM GOAL

(2) SPACE APPLICATIONS

(3) JPL PROGRESS

(4) SUMMARY

(5) ACKNOWLEDGEMENTS
SECONDARY LITHIUM CELLS/BATTERIES PROGRAM GOAL

- DEMONSTRATE THE FEASIBILITY OF AMBIENT TEMPERATURE SECONDARY LITHIUM CELL TECHNOLOGY BY 1994

- TARGETS
  - 100 Wh/kg
  - 1000 CYCLES (50% DOD)
  - 5 YEAR ACTIVE STORAGE LIFE
  - SAFE
SECONDARY LITHIUM CELLS/BATTERIES

ADVANTAGES

- 3-4 FOLD INCREASE IN SPECIFIC ENERGY AND ENERGY DENSITY OVER Ni-Cd
- LOW SELF DISCHARGE
- LONG ACTIVE SHELF LIFE
RECHARGEABLE LITHIUM CELL PROGRAM
PROJECTED APPLICATIONS

PLANETARY ORBITERS
(MERCURY ORBITER)

MISSIONS TO COMETS (COMET NUCLEUS
SAMPLE RETURN TAIL PROBE)

MARS ROVER

PENETRATORS
(GLOBAL NETWORK MISSION)
CLASSIFICATION OF SECONDARY LITHIUM CELLS

RECHARGEABLE LITHIUM BATTERY SYSTEMS

ORGANIC ELECTROLYTE SYSTEMS
- Li-TiS
- Li-MoS
- Li-NbSe
- Li-MnO
- Li-CoO
- Li-V O

POLYMERIC ELECTROLYTE SYSTEMS
- Li-TiS
- Li-V O
- Li-CoO

INORGANIC ELECTROLYTE SYSTEMS
- Li-SO-C
- Li-CuCl

MOLTEN SALT SYSTEMS
- U.P. Li(Al)-FeS
- Li(Al)-FeS

INORGANIC ELECTROLYTE SYSTEMS

POLYMERIC ELECTROLYTE SYSTEMS

ORGANIC ELECTROLYTE SYSTEMS
### Secondary Lithium Cells/Batteries

**Specific Energy of Selected Cathode Materials**

<table>
<thead>
<tr>
<th>Material</th>
<th>Ave. V (Volt)</th>
<th>Li Eq.* per mole</th>
<th>Specific Energy (Wh/kg)</th>
<th>Cycle Life</th>
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<tr>
<td>JPL Studies (Experimental Cells)</td>
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<tr>
<td>Li-TiS₂</td>
<td>2.1</td>
<td>0.9</td>
<td>473</td>
<td>300+</td>
</tr>
<tr>
<td>MoS₂</td>
<td>1.9</td>
<td>2.0</td>
<td>717</td>
<td>50+</td>
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<tr>
<td>NbSe₃</td>
<td>1.8</td>
<td>2.8</td>
<td>412</td>
<td>150+</td>
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<tr>
<td>V₆O₁₃</td>
<td>2.2</td>
<td>4.0</td>
<td>636</td>
<td>50+</td>
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<td>From Literature (Prototype Cells)</td>
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<tr>
<td>Li-TiS₂</td>
<td>2.1</td>
<td>0.8</td>
<td>473</td>
<td>200+</td>
</tr>
<tr>
<td>NbSe₃</td>
<td>1.8</td>
<td>2.5</td>
<td>412</td>
<td>200+</td>
</tr>
<tr>
<td>MoS₂</td>
<td>1.7</td>
<td>0.8</td>
<td>272</td>
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<tr>
<td>MnO₂</td>
<td>3.0</td>
<td>0.5</td>
<td>855</td>
<td>200+</td>
</tr>
<tr>
<td>CoO₂</td>
<td>4.0</td>
<td>0.5</td>
<td>1094</td>
<td>50+</td>
</tr>
<tr>
<td>CuCl₂</td>
<td>3.2</td>
<td>2.0</td>
<td>1125</td>
<td>140+</td>
</tr>
<tr>
<td>SO₂</td>
<td>3.1</td>
<td>1.0</td>
<td>524</td>
<td>30+</td>
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</table>

* Experimentally reversible
** Experimentally reversible lithium eq./mole, binder and conducting diluents were taken into consideration.
RECHARGEABLE AMBIENT-TEMPERATURE LITHIUM BATTERIES

SCHEMATIC DIAGRAM OF A Li-TiS2 CELL

**CELL REACTIONS**

**DISCHARGE** .. LI INTERCALATION (INSERTION)

**CHARGE** .. LI DE-INTERCALATION (REMOVAL)

\[
\text{Li} + \text{TiS}_2 \xrightarrow{D/C} \text{Li-TiS}_2
\]

**ELECTROLYTE**

LITHIUM ARSENIC HEXAFLUORIDE (LiAsF6) - SALT
2-METHYL TETRA HYDROFURAN (2-MeTHF) WITH ETHYLENE CARBONATE (EC) - MIXED SOLVENT
TYPICAL CHARGE/DISCHARGE CURVE FOR 1 Ah Li-TiS$_2$ CELL

![Graph showing charge/discharge curve for a 1 Ah Li-TiS$_2$ cell. The curve shows voltage (V) on the y-axis and elapsed minutes on the x-axis. The graph includes data points for 176 mA discharge and 88 mA charge.](image-url)
CYCLE LIFE PERFORMANCE OF 1 AHR LITHIUM–TITANIUM DISULFIDE CELLS WITH VARIOUS ELECTROLYTES

END OF DISCHARGE VOLS

50% DOD CYCLES (C/5 DISCHARGE AND C/10 CHARGE TO 2.6 VOLTS)
C/5 PERFORMANCE (200MA) OF
AA 1 AMPERE-HOUR LITHIUM
TITANIUM DISULFIDE CELL

\( \Delta \) CYCLE 1 PERFORMANCE \( \Diamond \) AFTER 503 50% DOD CYCLES

WATT HOURS PER KILOGRAM

0 20 40 60 80 100 120 140
TYPICAL PERFORMANCE OF MANUFACTURED AA 1 AMPERE-HOUR LITHIUM TITANIUM DISULFIDE CELL

■ CYCLE 2 AT 200MA □ CYCLE 3 AT 300MA ◆ CYCLE 4 AT 400MA ◆ CYCLE 5 AT 500MA
PERFORMANCE OF A TYPICAL MANUFACTURED AA 1 AMPERE-HOUR LITHIUM TITANIUM DISULFIDE CELL

WATTS PER KILOGRAM

WATTS PER KG

5 HR TO 1.7 VOLTS

4 HR

3 HR

2.5 HR

2 HR
CYCLE LIFE CHARACTERISTICS OF JPL 1 Ah Li-TiS\textsubscript{2} CELL AT 100\% DOD
# Required Technology Improvements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Present Status</th>
<th>NASA Requirement</th>
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<tr>
<td>Cycle Life</td>
<td>335+ (100% DOD)</td>
<td>500 (100% DOD)</td>
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<tr>
<td></td>
<td>650+ (50% DOD)</td>
<td>1000 (50% DOD)</td>
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<tr>
<td>Rate Capability</td>
<td>C/5</td>
<td>C/2</td>
</tr>
<tr>
<td>Cell Size</td>
<td>1 Ah</td>
<td>30 Ah</td>
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<tr>
<td>Overcharge/Overdischarge</td>
<td>Sensitive</td>
<td>Tolerant</td>
</tr>
<tr>
<td>Active Storage</td>
<td>1 Year</td>
<td>5 Years</td>
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</table>
RECHARGEABLE LITHIUM CELL PROGRAM

JPL ADVANCES IN Li-TiS\textsubscript{2} CELL TECHNOLOGY

FIGURE OF MERIT (FOM) – Li CYCLING EFFICIENCY

ASSUMPTIONS
ELECTRODE CAPACITY RATIO = 6
100% DOD

CATHODE PERFORMANCE IMPROVEMENT

THF

2-MeTHF

R&D STRATEGIES

(1) LOW TEMP
(2) DESIGN
(3) OPERATION LIMITS
(4) ELECTROLYTE

ANODE PERFORMANCE IMPROVEMENT

THF + 2-MeTHF + Z
EC + 2-MeTHF

FY89 FOM

FY90 GOAL

FY95 GOAL

1980
1985
1989
1990
1995

100% DOD

0 50 100 150 200 250 300 350 400 450 500

CYCLE LIFE
### ALTERNATE Li ANODE MATERIAL STUDIES

#### EXPERIMENTAL EVALUATION OF SELECTED Li ALLOYS

<table>
<thead>
<tr>
<th>Material</th>
<th>Stability</th>
<th>Ave. E vs. Li (mV)</th>
<th>Reversibility **</th>
<th>Specific Energy *** (wh/Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li&lt;sub&gt;1.2&lt;/sub&gt;Al</td>
<td>good</td>
<td>380</td>
<td>1.0</td>
<td>&lt; 0.8</td>
</tr>
<tr>
<td>Li&lt;sub&gt;2.85&lt;/sub&gt;Cd</td>
<td>poor</td>
<td>0</td>
<td>2.6</td>
<td>--</td>
</tr>
<tr>
<td>Li&lt;sub&gt;4.5&lt;/sub&gt;Pb</td>
<td>good</td>
<td>388</td>
<td>3.5</td>
<td>&lt; 1.5</td>
</tr>
<tr>
<td>Li&lt;sub&gt;0.15&lt;/sub&gt;C</td>
<td>good</td>
<td>200</td>
<td>0.15</td>
<td>&lt; 0.08</td>
</tr>
<tr>
<td>Li&lt;sub&gt;4.4&lt;/sub&gt;Si</td>
<td>poor</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Li&lt;sub&gt;4.3&lt;/sub&gt;Sn</td>
<td>good</td>
<td>411</td>
<td>2.0</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td>Li&lt;sub&gt;1.1&lt;/sub&gt;Zn</td>
<td>good</td>
<td>191</td>
<td>0.6</td>
<td>&lt; 0.12</td>
</tr>
</tbody>
</table>

* Microcalorimetric and OCV measurements.

** Galvanostatic cycling studies.

*** Calculated based on TiS2 cathode.

### SUMMARY OF FINDINGS:

- Li-Si & Li-Cd ALLOYS WERE FOUND TO BE UNSTABLE.
- SELECTED Li-Al and Li-C ALLOY SYSTEMS FOR DETAILED ASSESSMENT.
ELECTROCHEMICAL INTERCALATION & DE-INTERCALATION OF Li IN Li_xC

Li in at I = 0.28 mA/cm²
Li out at I = 0.84 mA/cm²
COMPARISON OF CHARGE & DISCHARGE CHARACTERISTICS OF 1 Ah & 32 mAh CELLS

1 Ah CELL

32 mAh CELL

Li out at \( I = 0.158 \text{ mA/cm}^2 \)

Li out at \( I = 0.0389 \text{ mA/cm}^2 \)

Li out
\( I = 0.84 \text{ mA/cm}^2 \)

Li out
\( I = 0.28 \text{ mA/cm}^2 \)
REDOX SHUTTLE APPROACH TO OVERCHARGE PROTECTION
JPL RECHARGEABLE LITHIUM CELL PROGRAM
STUDIES ON OVERCHARGE PROTECTION

CHEMICAL ENERGY CONVERSION (BATTERY) TECHNOLOGY

I- CHEMICAL ENERGY CONVERSION (BATTERY) TECHNOLOGY

JPL RECHARGEABLE LITHIUM CELL PROGRAM
STUDIES ON OVERCHARGE PROTECTION

TYPICAL CHARGE CHARACTERISTICS OF Li-TiS2 CELL
TMPD = TETRAMETHYL PHENYLENE DIAMINE

AFTER 25 CYCLES,
CHARGE RATE = C/20

WITH TMPD

WITHOUT TMPD

Capacity (mAh)

3800 3300 2800 2300 1800

Cell Voltage (mV)

ANNUAL RTOP REVIEW

1991 NASA Aerospace Battery Workshop -523- Advanced Technologies Session
SECONDARY LITHIUM CELLS/BATTERIES

CONCLUSIONS

• SECONDARY LITHIUM BATTERIES ARE SUITABLE FOR PLANETARY MISSIONS REQUIRING
  • HIGH SPECIFIC ENERGY
  • LONG ACTIVE SHELF LIFE
  • LIMITED CYCLE LIFE

• TiS$_2$ CATHODE MATERIAL MEETS ALL REQUIREMENTS FOR RECHARGEABLE Li CELL
  • HIGH INTRINSIC REVERSIBILITY
  • REALIZABLE SPECIFIC ENERGY

• SECONDARY LITHIUM TECHNOLOGY IS STILL EVOLVING
  • LOW CAPACITY CELLS (~1 Ah) DEMONSTRATED
  • > 700 CYCLES (@ 50% DOD) ACHIEVED

• WORK IS IN PROGRESS TO IMPROVE CYCLE LIFE AND SAFETY
  • ELECTROLYTES
  • ALTERNATE Li ANODE
  • SEPARATORS
SECONDARY LITHIUM CELLS/BATTERIES

ACKNOWLEDGEMENTS

This work described here was carried out at the Jet Propulsion Laboratory, California Institute of Technology, through an agreement with the National Aeronautics and Space Administration. (Code RP)
THE DEVELOPMENT OF
NICKEL-METAL HYDRIDE TECHNOLOGY
FOR USE IN AEROSPACE APPLICATIONS

Guy Rampel, Herschel Johnson

Dan Dell, Tony Wu, and Vince Puglisi

GATES ENERGY PRODUCTS, INC.
GATES AEROSPACE BATTERIES

October 30, 1991
BACKGROUND

The nickel metal hydride technology for battery application is relatively immature even though this technology was made widely known by Philips' Scientists as long ago as 1970. In particular Willem's 1984 dissertation in the Philips Journal of Research, Volume 39 Supplement No. 1, summarized for the reader the implications of metal hydrides for battery applications. However, recently, because of the international environmental regulatory pressures being placed on cadmium in the workplace and in disposal practices, battery companies worldwide have initiated extensive development programs to make this technology a viable commercial option. These hydrides do not pose a toxicological threat as does cadmium. In addition, they provide higher energy density and specific energy when compared to the other nickel based battery technologies as will be shown. For these reasons, the nickel metal hydride electrochemistry is being evaluated as the next power source for varied applications such as laptop computers, cellular telephones, electric vehicles and satellites.

The NIMH system uses a positive electrode that is similar to both NiCd and NiH2 systems. The negative electrode is a metal alloy that absorbs hydrogen generated on charge and desorbs hydrogen during discharge. This leads to a cell that operates at a much lower pressure than a NiH2 cell, 50 psig versus 950 psig. The technology would be a direct replacement for NiCd technology in most applications, along with a significant improvement in both specific energy and energy density. Since the technology is low pressure and has similar electrical performance to a NiCd cell, it can be used in prismatic designs that are similar to current aerospace NiCd cell designs. In addition, since the cells would be prismatic in design, the battery design would be very similar to current NiCd battery designs.

GAB's parent company, Gates Energy Products (GEP), has a substantial ongoing effort to develop commercial NiMH wound cell technology. GEP's investigations and development started in mid 1987 in search of the best technology. A license agreement, established with Ovonic Battery Company in October 1990, initiated an intense product development.

GAB has a parallel development effort with GEP to look at aerospace applications for NIMH cells. This effort is focused on life testing of small wound cells of the commercial type to validate design options and development of prismatic design cells for aerospace applications. The manufacturing techniques for NiMH cells will be similar to current NiCd manufacturing techniques; however, some development of technology for flat plate metal hydride electrodes is required.

Although the promise is beckoning, one cannot lose sight of the shortfalls. These must be identified, studied, overcome or circumvented. The list includes end-of-life failure mechanisms; identification of optimum charge rates and charge termination methods; and stability of end-of-charge pressure. This will require intensive dedicated effort in the years ahead.

DESCRIPTION OF TABLES AND FIGURES


The data tabulated compares two current well-established Aerospace NiCd & NiH2 product designs with the prototype 22AH NIMH cells assembled with flight qualified hardware. As can be seen, the specific energy and energy density of the NiMH cell are significantly better than that of the NiCd and NiH2 cells. The advantage which the NiMH cell exhibits relative to the NiCd cell is derived from the higher energy density of the metal hydride electrode, expressed as AH/in³, versus the sintered cadmium electrode. On the other hand, the disadvantage the NiH2 exhibits relative to the NiMH cell stems primarily from the pressure vessel weight and volume, which is a particularly large percentage of the total cell weight and volume for capacities less than about 30AH.

TABLE II: A comparison of nickel metal hydride, nickel cadmium and nickel hydrogen 22AH cell dimensions.

TABLE III: A comparison of 6 and 22AH nickel metal hydride cell designs.

It should be noted that for the 6AH cell design nylon separator is employed as the baseline and is therefore listed. However, some of these cells have been assembled with polypropylene separator which is di-
mensionally a direct substitute for the nylon. The significance for examining polypropylene is its stability in the alkaline environment of the cell. This is to be contrasted to the slow degradation experienced by nylon, even though nylon is the primary separator utilized in most qualified Aerospace nickel cadmium cell applications.

FIGURE 1: Prototype Aerospace Prismatic 6AH cells on cycle life test.

FIGURE 2: Prototype Aerospace Prismatic 6AH cell discharge rate capability.

To examine the dependence of capacity as a function of discharge rate, cells were discharged at either the C/2, C or 3C rate following a C/10 charge. These tests were conducted at room temperature. As can be seen, the dependence on discharge rate over the range tested is minimal.

FIGURE 3: Cylindrical cell capacity vs temperature @ C rate.

FIGURE 4: Prototype Aerospace Prismatic 6AH cell EOCV and EODV trends as a function of number of 50% DOD LEO cycles.

The data shown illustrates the end-of-charge voltage (EOCV) and end-of-discharge voltage (EODV) trend over the cycle life accumulated to date. The discharge/charge regime is currently set at 11.0AH and 11.6AH, respectively. This equates to a 1.05 recharge ratio. Seventeen cycles are accumulated in a 24 hour period which totals to over 6000 cycles per year. Thusfar, the performance has been stable and appears promising.

FIGURE 5: Prototype Aerospace Prismatic 6AH cell charge voltage curve while undergoing 50% DOD LEO cycle: Recharge ratio = 1.05, cycle 1010.

FIGURE 6: Prototype Aerospace Prismatic 6AH cell discharge voltage curve while undergoing 50% DOD LEO cycle: Recharge ratio = 1.05, cycle 1010.

FIGURE 7: Prototype Aerospace Prismatic 6AH cell pressure curve while undergoing 50% DOD LEO cycle: Recharge ratio = 1.05, cycle 788.

The pressure fluctuates during the course of a given cycle. Hydrogen builds up somewhat and is present during the entire regime. Towards the conclusion of charge, the nickel electrode begins to evolve oxygen resulting in a pressure spike. The oxygen is simultaneously being consumed at the metal hydride electrode where it reacts with hydrogen to form water.

At the conclusion of the charge sequence, the oxygen evolution from the nickel electrode ceases and the oxygen in the gas space is removed by its continued reaction at the metal hydride electrode.

FIGURE 8: Prototype Aerospace Prismatic 22AH cell EOCV and EODV trends as a function of number of 50% DOD LEO cycles.

The data shown illustrates the end-of-charge voltage (EOCV) and end-of-discharge voltage (EODV) trend over the cycle life accumulated to date. The discharge/charge regime is currently set at 11.0AH and 11.6AH, respectively. This equates to a 1.05 recharge ratio. Seventeen cycles are accumulated in a 24 hour period which totals to over 6000 cycles per year. Thusfar, the performance has been stable and appears promising.

FIGURE 9: Prototype Aerospace Prismatic 22AH cell charge voltage curve while undergoing 50% DOD LEO cycle: Recharge ratio = 1.05, cycle 512.

FIGURE 10: Prototype Aerospace Prismatic 22AH cell discharge voltage curve while undergoing 50% DOD LEO cycle: Recharge ratio = 1.05, cycle 512.

FIGURE 11: Prototype Aerospace Prismatic 22AH cell pressure curve while undergoing 50% DOD LEO cycle: Recharge ratio = 1.05, cycle 401.

FIGURE 12: Program conclusions to date.
### Table I

**Comparison of Nickel Battery Cell Performance in 22AH Geometries**

<table>
<thead>
<tr>
<th>Performance Attribute</th>
<th>NiCd (Note 1)</th>
<th>NiH₂ (Note 1)</th>
<th>NiMH (Note 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Midpoint Discharge Voltage (v)</td>
<td>1.20</td>
<td>1.24</td>
<td>1.24</td>
</tr>
<tr>
<td>Typical Capacity @ C/2 (AH)</td>
<td>22</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Charge Retention (%)</td>
<td>92</td>
<td>82</td>
<td>90</td>
</tr>
<tr>
<td>Cell Weight (Kg)</td>
<td>0.80</td>
<td>0.79</td>
<td>0.57</td>
</tr>
<tr>
<td>Specific Energy (WH/Kg)</td>
<td>33.0</td>
<td>34.5</td>
<td>47.9</td>
</tr>
<tr>
<td>Energy Density (WH/in³)</td>
<td>1.67</td>
<td>0.62</td>
<td>2.56</td>
</tr>
</tbody>
</table>

**Note 1:** Gates Aerospace Batteries Product  
**Note 2:** Actual Prototype Cell Data  
**Note 3:** Room Temperature 72 Hour Retention

### Table II

**Comparison of Nickel Cell Dimensions in 22AH Geometries**

<table>
<thead>
<tr>
<th>Cell Dimensions (Inches)</th>
<th>NiCd (Note 1)</th>
<th>NiH₂ (Note 1)</th>
<th>NiMH (Note 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Height</td>
<td>4.97</td>
<td>8.25</td>
<td>4.43</td>
</tr>
<tr>
<td>Case Height</td>
<td>4.55</td>
<td>5.94</td>
<td>4.01</td>
</tr>
<tr>
<td>Width</td>
<td>3.66</td>
<td>3.44(Dia)</td>
<td>2.98</td>
</tr>
<tr>
<td>Depth</td>
<td>0.95</td>
<td>N/A</td>
<td>0.89</td>
</tr>
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</table>

**Note 1:** Gates Aerospace Batteries Product  
**Note 2:** Actual Prototype Cell Data
Table III

NiMH Prismatic Cell Design Summary

**Prismatic Cell Design (Note 1)**

<table>
<thead>
<tr>
<th>Item</th>
<th>6AH</th>
<th>22AH</th>
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</thead>
<tbody>
<tr>
<td><strong>Positive Electrodes</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td>Thickness (in)</td>
<td>0.028</td>
<td>0.028</td>
</tr>
<tr>
<td>Capacity (AH) theoretical</td>
<td>7.5</td>
<td>27.6</td>
</tr>
<tr>
<td><strong>Negative Electrodes</strong></td>
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<td></td>
</tr>
<tr>
<td>Number</td>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td>Thickness (in)</td>
<td>0.0125</td>
<td>0.0125</td>
</tr>
<tr>
<td>Capacity (AH)</td>
<td>11.5</td>
<td>42.2</td>
</tr>
<tr>
<td><strong>Separator</strong></td>
<td>Nylon-2538</td>
<td>Nylon-2538</td>
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<tr>
<td><strong>Negative to Positive Capacity Ratio</strong></td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>Electrolyte</strong></td>
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<tr>
<td>Type</td>
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<td>KOH</td>
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<tr>
<td>Concentration (%)</td>
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<td>31</td>
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<td><strong>Cell Dimensions (in)</strong></td>
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<td>Overall Height</td>
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<td>Case Height</td>
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<td>Width</td>
<td>2.12</td>
<td>2.98</td>
</tr>
<tr>
<td>Depth</td>
<td>0.82</td>
<td>0.89</td>
</tr>
</tbody>
</table>

*Note 1: Capacities are C/2 typicals at room temperature for prototype cells*
Figure 1  Prototype Aerospace Prismatic 6AH cells on cycle life test

Figure 2  Prototype Aerospace Prismatic 6AH Cell Discharge Rate Capability
Figure 3  Cylindrical Cell Capacity vs. Temperature @ C Rate

Figure 4  Prototype Aerospace Prismatic 6AH Cell EOCV and EODV Trends as a Function of Number of 50% DoD LEO Cycles
Figure 5  Prototype Aerospace Prismatic 6AH Cell Charge Voltage Curve While undergoing 50% DoD LEO Cycle: Recharge Ratio = 1.05, Cycle 1010

Figure 6  Prototype Aerospace Prismatic 6AH Cell Charge Voltage Curve While undergoing 50% DoD LEO Cycle: Recharge Ratio = 1.05, Cycle 1010
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Figure 10  Prototype Aerospace Prismatic 22AH Cell Discharge Voltage Curve While Undergoing 50% DoD LEO Cycle: charge Ratio = 1.05, Cycle 512
Figure 11  Prototype Aerospace Prismatic 22AH Cell Pressure Curve While Undergoing 50% DoD LEO Cycle: Recharge Ratio = 1.05, Cycle 401
Conclusions

Acceptable Pressures < 50 PSIG

Wide Operating Temperature Range, -10 to + 40 C

Insensitive to High Rate Regime - 3C

Promising Cycle Life - 1000 LEO cycles and counting

Energy Density > NiH₂ and NiCd

Specific Energy > NiCd and NiH₂
Sealed Aerospace Metal-Hydride Batteries

Dwaine Coates, Eagle Picher Industries
1991 NASA AEROSPACE BATTERY WORKSHOP

SEALED AEROSPACE METAL-HYDRIDE BATTERIES

DWAIN COATES
ADVANCED SYSTEMS OPERATION
Eagle-Picher Industries, Inc.
Joplin, Missouri
Nickel-metal hydride and silver-metal hydride batteries are being developed for aerospace applications by Eagle-Picher. There is a growing market for smaller, lower cost satellites which require higher energy density power sources than aerospace nickel-cadmium at a lower cost than space nickel-hydrogen. These include small LEO satellites, tactical military satellites and satellite constellation programs such as Iridium and Brilliant Pebbles. Small satellites typically do not have the spacecraft volume or the budget required for nickel-hydrogen batteries. NiCd's do not have adequate energy density as well as other problems such as overcharge capability and memory effect. Metal hydride batteries provide the ideal solution for these applications. Metal hydride batteries offer a number of advantages over other aerospace battery systems.
SEALED METAL-HYDRIDE BATTERIES FOR AEROSPACE APPLICATIONS

NICKEL-METAL HYDRIDE

TWICE GRAVIMETRIC ENERGY DENSITY OF AEROSPACE NICKEL-CADMIUM

TWICE VOLUMETRIC ENERGY DENSITY OF SPACE NICKEL-HYDROGEN

SILVER-METAL HYDRIDE

THREE TIMES ENERGY DENSITY OF NICKEL-METAL HYDRIDE
Nickel-metal hydride batteries offer twice the gravimetric and volumetric energy density of aerospace nickel-cadmium. They also achieve twice the volumetric energy density of space nickel-hydrogen. Silver-metal hydride batteries have the potential of three times the energy density of nickel-metal hydride.
SEALED METAL-HYDRIDE BATTERIES FOR AEROSPACE APPLICATIONS

HERMERICALLY SEALED
OPERATE AT LOW PRESSURE
PRISOMATIC GEOMETRY
EXCELLENT OVERCHARGE
EXCELLENT OVERDISCHARGE
EXCELLENT THERMAL
LOW COST
Metal hydride batteries are hermetically sealed, operate at low pressure and are prismatic in geometry. They exhibit excellent overcharge and overdischarge characteristics. Preliminary calorimetry testing indicates that the batteries have superior thermal performance as compared to nickel-cadmium and nickel-hydrogen. The cells are lower in cost than aerospace nickel-cadmium and much lower in cost than space nickel-hydrogen.
SOURCES OF HYDRIDE MATERIALS AND ALLOYS

Morton International
Treibacher-Austria
Rhone-Poulenc
Nissho-Iwai America
Sumitomo
Ergenics
HCl-Denver
Aesar/Johnson Matthey
Baotou Research

Tricoastal Lanthanides
Crucible
Goldschmidt AG
Indian Rare Earths
Molycorp/Unocal
REMACOR
Santoku Metal
Chori-Osaka
Japan Metals
There are currently a large number of companies interested in the metal hydride battery business. Nearly all of the commercial battery companies have either announced products or are in the development stage of a product. There are a lot of potential sources for hydride electrode materials. This table shows only the sources that I am aware of and is not necessarily complete. Materials from several of these sources are currently on test and other materials are either in-house or in-transit. A comprehensive development effort is currently underway at Eagle-Picher to evaluate as many prospective materials as possible.
METAL-HYDRIDE ENERGY DENSITY

RATE: 50 mA
TEMP: 23 DEG.C

- TREIBACHER
- OVONICS
- RHONE-POULENC

CAPACITY (mAh/g)

DISCHARGE VOL.

DISCHARGE TIME
Eagle-Picher has evaluated materials from several of the sources previously listed. The chart shows comparative data for Ovonics material, Treibacher material and material from Rhone-Poulenc. The materials are in various stages of testing. Other materials are in-house but have not been evaluated yet. Materials have not yet been obtained from some of the sources. It would not be appropriate at this stage to start making claims about whose material is better than whom's. However, it seems conclusive that there are several materials on the market which will provide adequate function in an electrochemical cell. The markets for the metal hydride system are varied and extensive enough that most likely a single material would not be able to satisfy all of the applications. It is important that parallel development work of metal hydride materials be continued.
Sealed Metal-Hydride Batteries for Aerospace Applications

Figure 2
Prismatic Aerospace Nickel-Metal Hydride Cell

NYLON SEAL
TERMINAL BOSS
ELECTRODE STACK
FILL TUBE
CELL TERMINAL
CELL CASE
The advantage of the metal hydride cell over nickel-hydrogen is that the hydrogen is stored as a solid metallic hydride rather than as a gas. Therefore the cell operates at low pressure and a rectangular geometry can be used for the cell container. The volumetric energy density of the cell is much higher because no free volume is required in the cell to contain hydrogen gas. The cell is much simpler and cheaper to build than nickel-hydrogen because there are no complex internal components. Standard aerospace or commercial nickel-cadmium battery separators can be used. W.R. Grace is currently developing separator materials specifically for the nickel-metal hydride system. The cell design is essentially an aerospace nickel-cadmium design in which the cadmium electrodes have been replaced by hydride electrodes. Because the hydride electrode has a much higher energy density than the cadmium electrode the energy density of the cell is correspondingly higher. The cell design is such that the aerospace heritage of the parent NiCd system is retained. Current aerospace designs yield about 50 watt-hours per kilogram and 200 watt-hours per liter.
Sealed Metal-Hydride Batteries for Aerospace Applications

Figure 3
Prototype Nickel-Metal Hydride Aerospace Battery Design
Prismatic cells are much easier and more volume efficient to package into a battery than cylindrical cells. The cells are sandwiched between two lightweight endplates and held together by stainless steel connecting rods. The endplates are machined from aluminum and are painted with Chemglaze paint. The cells are insulated from each other and from the endplates with Kapton and Mylar. Nickel or silver foil is used as the intercell connectors. Connectors and on-board electronics can be integrated into the design as required by the application.
Sealed Metal-Hydride Batteries for Aerospace Applications

Figure 4
Nickel-Metal Hydride Alternative Battery Design
Another concept for an aerospace battery is to package commercial cylindrical cells into an aerospace battery pack. Some small satellite designers use this method rather than using aerospace cells. The Defense Advanced Research Projects Agency (DARPA) published a study which concluded that there was virtually no benefit in flying commercial cells rather than aerospace cells because of the extensive testing and cell matching required by the commercial cells. They also concluded that a redundant set of batteries had to be flown in order to achieve any level of reliability. This greatly reduces the effective energy density of the system and increases the cost.
Sealed Metal-Hydride Batteries for Aerospace Applications

Figure 7
Nickel-Metal Hydride Aerospace Cells

RMH-10
Temperature: 22°C

Voltage

Capacity (Ampere-Hours)

1.0 AMP
2.0 AMP
5.0 AMP
10 AMP
15 AMP
20 AMP
30 AMP
This is a set of discharge curves for a 10 amp-hour aerospace nickel-metal hydride cell. The cell was discharged at a variety of rates ranging from 1 amp to 30 amps. The data shows excellent rate capability for the aerospace nickel-metal hydride system. The cell delivered 11.5 amp-hours at the low rates and even at the 30 amp rate still did better than nameplate capacity. There is some discharge plateau voltage depression at the higher rates. However, all discharges were at room temperature with no active cooling so the effect is probably compounded by the larger amount of heat being generated at the higher rates.
NiMH LEO SIMULATION

CHG: 55MIN@ 1.65+-.05A
DIS: 35MIN@ 2.55+-.05A

37% DOD

CELL VOLTAGE

TIME (MINUTES)

-558-

Advanced Technologies Session

1991 NASA Aerospace Battery Workshop
Several metal hydride cells are currently on cycle life test. The cells are operating under a low-earth-orbit regime at 37 per cent depth-of-discharge. The cells are on charge for 55 minutes and then discharge 35 minutes. The charge return ratio is about 1.02. The cells are being cycled at room temperature with no active thermal control. There is significant end-of-discharge voltage depression at cycle number 4268 as compared to an earlier cycle, number 89. The cell was reconditioned in a manner similar to aerospace NiCd's and the EOD voltage immediately recovered to its original value. The trend of increased charge voltage is continuing with cycling. The charge-to-discharge return factor is being increased slightly to offset the EOD voltage degradation being observed.
Sealed Metal-Hydride Batteries for Aerospace Applications

Figure 9
Silver vs Nickel Hydride

Both cells discharged at C/4 Rate: 22°C
This graph directly compares the nickel-metal hydride system with the silver-metal hydride system. The silver electrode has a much higher energy density than the nickel electrode. The silver-metal hydride system delivers about three times the electrical capacity of the nickel-metal hydride system, although at a slightly lower voltage. The silver-metal hydride system has a number of applications where the higher energy density available offsets the lower cycle life. This could include laptop computers and cellular telephones where increased run time is a valuable premium to the user. Military and aerospace applications include portable battlefield computers, portable communications equipment, lightweight weapons systems and tactical satellites.
This graph shows the temperature dependence of the nickel-metal hydride system. Two discharges were done at the same rate, one at 10 degrees C and the other at 30 degrees C. The cell yields the same capacity at either temperature, however, there is a depression of the discharge plateau voltage at the colder temperature. Warm temperature performance is slightly better than NiCd and much better than NiH2.
This data was included to illustrate the design versatility of the metal hydride system. Cells can be constructed in virtually any size or shape. This is a small diameter nickel-metal hydride button cell design. The cell is assembled and die-crimped such that it is a sealed cell. About 40 of these cells have been assembled. The cell was discharged at four different rates and yields around 200 milliamp-hours. The depression in the discharge voltage occurs because this is a low rate cell design such as that used in a wristwatch.
Some preliminary calorimetry testing is being done with aerospace nickel-metal hydride cells in conjunction with Chris Johnson at Boeing. Initial data shows that nickel-metal hydride should be thermally superior to both nickel-cadmium and nickel-hydrogen. The chart shows that heat flow is negative on charge until 100% state-of-charge is reached. As more and more oxygen is being generated on the nickel electrodes the heat output of the cell gradually increases. The heat output increases more rapidly going into discharge with a plateau that corresponds to the discharge voltage plateau. As the cell state-of-charge decreases towards reversal the heat output again increases.
AC Impedance Data Acquisition System
Eagle-Picher is currently collaborating with TRI-Austin under a contract with the U.S. Air Force, Phillips Laboratory, Edwards Air Force Base, for impedance spectroscopy analysis of nickel-hydrogen and nickel-metal hydride batteries. The purpose of the study is evaluate indicators of cell and battery aging and performance which are more readily determined and appear earlier than the traditional voltage and capacity degradation which occurs on long term cycling. Preliminary impedance spectral data ranging from 3 milliHertz to 30 kiloHertz has been acquired on approximately 100 cells. Data interpretation and a mathematical battery modeling effort is currently underway. The measurement test set-up includes a Schlumberger 1260 Impedance Analyzer interfaced with a PC. An extensive software package was developed by TRI for data acquisition and management.
## Summary of the Significant Groups of Cells for which AC Impedance Data Were Collected

<table>
<thead>
<tr>
<th>Cell Type</th>
<th>Capacity (Amp-Hrs)</th>
<th>No. of Cells Measured</th>
<th>Storage Time (Years)</th>
<th>No. of Aging Cycles</th>
<th>Type of Life Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiH₂</td>
<td>30</td>
<td>1</td>
<td>7</td>
<td>10,800</td>
<td>Real-Time LEO</td>
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<tr>
<td></td>
<td>30</td>
<td>1</td>
<td>0</td>
<td>10,800</td>
<td></td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td>30</td>
<td>9</td>
<td>7</td>
<td>38,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>9*</td>
<td>5-6</td>
<td>1,500</td>
<td>Real-Time LEO</td>
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<tr>
<td></td>
<td>50</td>
<td>1</td>
<td>5</td>
<td>0</td>
<td>None</td>
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<tr>
<td></td>
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<td>50</td>
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<td>62,000</td>
<td>Accel. LEO</td>
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<tr>
<td></td>
<td>65</td>
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<td>0</td>
<td>Real-Time GEO</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>4</td>
<td>?</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td></td>
<td>76</td>
<td>4</td>
<td>?</td>
<td>0</td>
<td>Proprietary</td>
</tr>
<tr>
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<td>76</td>
<td>2</td>
<td>?</td>
<td>3,057</td>
<td></td>
</tr>
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<td>76</td>
<td>2</td>
<td>?</td>
<td>23,309</td>
<td>Proprietary</td>
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<td></td>
<td>76</td>
<td>4</td>
<td>?</td>
<td>43,000</td>
<td>Accel. LEO</td>
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<tr>
<td>NiMH</td>
<td>4</td>
<td>8</td>
<td>0.33</td>
<td>3,801</td>
<td>Real-Time LEO</td>
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<td></td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>3,801</td>
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<tr>
<td></td>
<td>C-cell</td>
<td>3</td>
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<td>2,001</td>
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<tr>
<td></td>
<td>C-cell</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

* A number of fabrication variations

[Best Aging Comparisons]
Data was acquired on a large number of life test cells including aerospace nickel-metal hydride cells, commercial nickel-metal hydride cells and space nickel-hydrogen cells. The cells are being tested under several regimes including a real-time low-earth-orbit (LEO) regime, an accelerated LEO regime and a real-time geostationary-earth-orbit (GEO) regime. A number of cell designs are represented in size ranging from 3.5 amp-hours to 76 amp-hours.
5 REPEATED MEASUREMENTS OF A 50 AMP-HR NICKEL HYDROGEN CELL (62,000 CYCLES)
A typical scan ranges from 3 milliHertz to 30 kiloHertz. Multiple runs were frequently made on the same cell at random intervals to evaluate the reproducibility of the method. This data represents five runs on the same cell made at various times during a two week period. The data shows excellent reproducibility.
RAW IMPEDANCE DATA FOR 76 AMP-HR NICKEL HYDROGEN CELLS

3057 Cycles (2-Cell Average)

43,000 Cycles (3-Cell Average)

Failed Cell (2-Cell Average)
A plot of impedance versus the base ten log of frequency shows some interesting characteristics in the low frequency region below 1 Hertz. This is the Warburg region where the availability of charge carriers is diffusion controlled. The AC impedance in this frequency range decreases with the age of the cell. The graph shows spectral data for cells of identical design with 3000 cycles, 43,000 cycles and a cell which had been cycled to failure. The trend in the data is decreased impedance with age.
ARGAND DIAGRAM FROM 3 mHz TO 10 Hz FOR TWO 30 AMP-HR NICKEL HYDROGEN CELLS

REACTANCE (OHMS)

0.2

0.4

0.6

0.8

1

1.2

38,000 Charge/Discharge Cycles

38,000 Charge/Discharge Cycles
The Argand diagram for two 30 amp-hour Intelsat V type cells also shows a definite trend. Two cells are compared, one with 3800 cycles and the other with 38,000 cycles. The capacitive to Warburg transition is significantly frequency shifted for the aged cell.
COMPARISON OF RESISTANCE AND REACTANCE
OF TWO NICKEL METAL HYDRIDE CELLS

One Year Storage, Zero Aging Cycles

200 Cycles

(RESISTANCE (OHMS)

LOG(10) FREQUENCY

-3 -2 -1 -0.5 0 0.5 1 1.5

8 6 4 2 0 0.2 0.4 0.6

1991 NASA Aerospace Battery Workshop -578- Advanced Technologies Session
Comparisons of resistance and reactance also show some trends with cell aging. The gap between the two decreases as the cell is cycled. The uncycled cell shows a much larger delta between resistance and reactance than the cell with 2001 cycles. This relationship also hold true for nickel-hydrogen cells.
THE FUTURE

BASIC ELECTRODE MATERIALS

FABRICATION TECHNIQUES

CYCLE LIFE TESTING

IMPROVEMENTS:

ENERGY DENSITY

PERFORMANCE

CYCLE LIFE
The idea for a metal hydride battery has been around for a long time. However, practical batteries have only come about recently. So recently that they are still not generally available. The development of the metal hydride chemistry is still in the early stages particularly for aerospace applications. Future efforts will be aimed at the further refinement of the nickel and silver metal hydride battery chemistry. Work is being continued on developing and improving hydride electrode materials and fabrication techniques. Life cycle testing will be continued. The system will be optimized to yield improved energy density, improved performance and longer cycle life.
SODIUM SULFUR BATTERIES
FOR
SPACE APPLICATIONS

James A. DeGruson

Eagle-Picher Industries, Inc.
C&Porter Streets
Joplin, MO

30 October 1991

1991 NASA AEROSPACE
BATTERY WORKSHOP
PRESENTATION ABSTRACT

Name        James A. DeGruson
Company     Eagle-Picher Industries, Inc.
Address     P.O. Box 47, Joplin, MO 64802

Telephone   417-623-8000, ex. 491

Preliminary Title Sodium Sulfur Batteries for Space Applications

Brief Abstract In 1986, Eagle-Picher Industries was selected by the Air Force to develop sodium sulfur cells for satellite applications. Specifically, the development program was geared toward low Earth orbit goals requiring high charge/discharge rates. A number of improvements have been made on the cell level and a transition to a complete space battery has been initiated at Eagle Picher.

The results of six months of testing a 250 watt-hour sodium sulfur space battery look very promising. With over 1,000 LEO cycles conducted on this first battery, the next generation battery is being designed. This next design will focus on achieving greater energy densities associated with the sodium sulfur chemistry.
EAGLE PICHÉR

ELECTRONICS DIVISION
JOPLIN, MO

THERMAL-ORDNANCE OPERATION

Na-S BATTERIES

SODIUM SULFUR 40AH CELL

SAFETY TUBE
SODIUM WICKS

COMPRESSION RINGS
<table>
<thead>
<tr>
<th>CELL DESIGN</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
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<tbody>
<tr>
<td>DISCHARGE RATE</td>
<td>75 AMPS</td>
<td>75 AMPS</td>
<td>75 AMPS</td>
<td>75 AMPS</td>
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<tr>
<td>DISCHARGE TIME</td>
<td>33 MIN</td>
<td>32 MIN</td>
<td>35 MIN</td>
<td>35 MIN</td>
</tr>
<tr>
<td>AVE. VOLTS (DIS)</td>
<td>1.20 VOLTS</td>
<td>1.24 VOLTS</td>
<td>1.39 VOLTS</td>
<td>1.56 VOLTS</td>
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<tr>
<td>Whrs DISCHARGE</td>
<td>49.5 Whrs</td>
<td>49.9 Whrs</td>
<td>61.1 Whrs</td>
<td>67.7 Whrs</td>
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<tr>
<td>AVE. CHARGE RATE</td>
<td>33.5 AMPS</td>
<td>33.2 AMPS</td>
<td>34.81 AMPS</td>
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<tr>
<td>CHARGE TIME</td>
<td>73 MIN</td>
<td>73 MIN</td>
<td>73.9 MIN</td>
<td>65.2 MIN</td>
</tr>
<tr>
<td>AVE. VOLTS (CHG)</td>
<td>2.44 VOLTS</td>
<td>2.43 VOLTS</td>
<td>2.44 VOLTS</td>
<td>2.39 VOLTS</td>
</tr>
<tr>
<td>Whrs CHARGE</td>
<td>98.6 Whrs</td>
<td>98.3 Whrs</td>
<td>104.6 Whrs</td>
<td>104.6 Whrs</td>
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<tr>
<td>EFFICIENCY (Whrs DIS/Whrs CHG)</td>
<td>50.20%</td>
<td>50.70%</td>
<td>58.40%</td>
<td>64.70%</td>
</tr>
<tr>
<td>SPECIFIC ENERGY</td>
<td>72.6 Whrs/Kg</td>
<td>73.1 Whrs/Kg</td>
<td>87.4 Whrs/Kg</td>
<td>98.6 Whrs/Kg</td>
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<tr>
<td>ENERGY DENSITY</td>
<td>159.2 Whrs/l</td>
<td>160.5 Whrs/l</td>
<td>196.0 Whrs/l</td>
<td>217.4 Whrs/l</td>
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<tr>
<td>END OF DISCHARGE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RESISTANCE (mOhms)</td>
<td>8.8 mOhms</td>
<td>8.8 mOhms</td>
<td>6.4 mOhms</td>
<td>6.1 mOhms</td>
</tr>
<tr>
<td>F1 (%)</td>
<td>30.00</td>
<td>31.42</td>
<td>21.61</td>
<td>14.08</td>
</tr>
</tbody>
</table>

Note: F1 is a measure of the percent nonavailable theoretical cell capacity.
Na-S BATTERIES

TD-75 CYCLE 1828 (LEO 60% DOD)

SPLIT CHARGE RATE
50/40/30/25/20/15/10/8
F1 = 19.30
7.90 mOhms

DISCHARGE RATE
54 AMPS

DISCHARGE CAPACITY
TD-75 CYCLE 5008 (LEO 60% DOD)

SPLIT CHARGE RATE
45/35/30/25/20/18/15/13.5
FL = 43.83
7.44 mOhms

DISCHARGE RATE
54 AMPS

DISCHARGE CAPACITY
TD-75 (LEO 60% DOD)

- Split Charge
- Cycle 1828
- Discharge
- Cycle 5008

Discharge Capacity

Volts

0 1 2 3

0 5 10 15 20 25 30 35 40 45 50 55 60 65 70
CAPACITY VS. CYCLE LIFE

- TD-75
- TD-87
- TD-89
RESISTANCE (EOD) VS. CYCLE LIFE

Thermal-Ordnance Operation

Na-S Batteries
LIFE CYCLE TESTS

55AH CELLS DISCHARGED TO 60% DOD AT "C" RATE

CYCLES ACCOMPLISHED TO DATE: 7,200

AVERAGE VOLTS WHILE DISCHARGING: 1.50

AVERAGE VOLTS DURING CHARGE: 2.40

SPECIFIC ENERGY: 63.3 WH/KG

ENERGY DENSITY: 145 WH/L

E.O.D. RESISTANCE: .0088 ohms
LATEST CELL DESIGN

55Ah cells discharged to 60% DOD at "C" rate

Cycles accomplished to date: 5,000

Average volts while discharging: 1.63

Average volts during charge: 2.40

Specific energy: 73 Wh/kg

Energy density: 165 Wh/l

E.O.D. resistance: 0.075 ohms

SPECIFICATIONS

ENERGY DENSITY: 165 Wh/l

SPECIFIC ENERGY: 73 Wh/kg

AVERAGE VOLTS DURING CHARGE: 2.40

AVERAGE VOLTS WHILE DISCHARGING: 1.63

CYCLES ACCOMPLISHED TO DATE: 5,000

55Ah CELLS DISCHARGED TO 60% DOD AT "C" RATE
IMPROVED CELL TECHNOLOGY AVAILABLE NOW

55AH CELLS DISCHARGED TO 60% DOD AT "C" RATE

AVERAGE VOLTS WHILE DISCHARGING: 1.75

SPECIFIC ENERGY: 100 WH/KG

ENERGY DENSITY: 225 WH/L

E.O.D. RESISTANCE: .005 ohms
1. CELL OPTIMIZATION AND DEVELOPMENT

A. IMPROVED LOW-RESISTANCE CATHODE
B. POROUS ANODE STRUCTURE
   LIGHT WEIGHT
   REGULATES / LIMITS AVAILABLE SODIUM FOR SAFETY
C. FABRICATION OF LIGHT-WEIGHT MOLYBDENUM COMPONENTS
D. DEFINE OPTIMUM ELECTROLYTE PARAMETERS
   BALANCE OF PHYSICAL / ELECTRICAL PROPERTIES
   TAILOR TO CELL REQUIREMENTS AND GEOMETRY
   PROCESS DEFINITION / FORMULATION
   INSPECTION CRITERIA
2. CELL TESTING - BUILD STATISTICAL BODY OF DATA
   A. MONITOR TEMPERATURE AND ELECTRICAL DATA
   B. VARYING LENGTHS OF ORBITS
   C. OPTIMUM RECHARGE PARAMETERS VS. DOD
   D. ESTABLISH PERFORMANCE TRENDS DURING LIFE CYCLE
   E. DETERMINE VARIABILITY / CONSISTENCY WITHIN CELL POPULATION

3. INCORPORATION INTO BATTERY CONFIGURATION
   A. AIDED BY HISTORY OF NUMEROUS SECONDARY BATTERY CHEMISTRIES
   B. USE CELL-LEVEL RESULTS TO ACHIEVE BATTERY REQUIREMENTS
   C. FIX MEANS OF MONITORING AND ELECTRICAL CONTROLS
   D. PACKAGE FOR EFFICIENCY, RUGGEDNESS, AND SAFETY
EAGLE PICHÉ ELECTRONICS DIVISION JOPLIN, MO

THERMAL-ORDNANCE OPERATION

Na-S BATTERIES

CELL TEST LABORATORY
EAGLE-PICHER INVOLVEMENT IN SODIUM SULFUR SPACE BATTERIES BEGAN IN 1986.

U.S. AIR FORCE SELECTED EAGLE-PICHER AS THE SOLE DEVELOPER FOR SODIUM SULFUR LEO CELLS.

EAGLE-PICHER'S EXPERIENCE IN NICKEL HYDROGEN SPACE BATTERIES PROVIDES A VALUABLE BASE FOR TRANSITIONING TO SODIUM SULFUR SPACE BATTERIES.
ENTRY LEVEL BATTERY EFFORTS FUNDED INTERNALLY

UNIT APPROACHING 1000 CYCLES
CONSTANT CURRENT CHARGE / DISCHARGE
NOMINAL 60% DOD (= 30 A.H.)

CYCLE CONTROLLED BY FIRST CELL TO ACHIEVE PRE-SET VALUES
(OTHERWISE BY CYCLE DEFINITION ONLY)

CALENDAR LIFE NOW FIVE MONTHS
IRD BATTERY (CYCLE 32)

SPLIT CHARGE RATE

\[ F(IRD \ 7) = 15.48 \]
\[ F(IRD \ 8) = 16.05 \]
\[ F(IRD \ 9) = 15.39 \]

DISCHARGE RATE

\[ 31.5 \ AMPS \]

VOLTS

DISCHARGE CAPACITY
IRD BATTERY (CYCLE 918)

SPLIT CHARGE RATE
35/25/20/15/10/8 AMPS

DISCHARGE RATE
37.5 AMPS

F1(IRD 7) = 24.59
F1(IRD 8) = 26.39
F1(IRD 9) = 26.46
1. NUMBER OF CELLS DEPENDENT UPON USER SPECIFICATION
   (ENERGY, POWER, CAPACITY, VOLUME CONSTRAINT, CYCLE LIFE)

2. CELLS ORIENTED VERTICALLY
   INTERCONNECTS DEPEND UPON REQUIREMENT

3. EFFICIENT THERMAL ENCLOSURE TAILORED TO APPLICATION
   "MONOLITHIC WALL"
   MULTILAYER - EVACUATED WALL
   PROVISIONS FOR ELECTRICAL HEATING
   ACTIVE OR PASSIVE COOLING

4. MONITOR / CONTROLS
   CELL / BATTERY VOLTAGE
   TEMPERATURE (SAMPLED OR INDIVIDUAL)
   ASSURANCE AGAINST EXCESSIVE CHARGE / DISCHARGE
   PROTECTS MAY BE ELECTRICAL (SWITCHING)
   OR PHYSICAL (FUSIBLE)
SODIUM - METAL CHLORIDE BATTERIES

B. V. RATNAKUMAR, A. I. ATTIA, G. HALPERT

OCTOBER 30, 1991
THE 1991 NASA AEROSPACE BATTERY WORKSHOP

BATTERY SYSTEMS GROUP
CONFIGURATION AND ADVANTAGES

CAPABILITIES OF THE SYSTEMS

STUDIES AT JPL

AREAS OF FURTHER STUDY
SODIUM - METAL CHLORIDE BATTERIES

• CONFIGURATION

Na (m) // Beta" ALUMINA // NaAlCl₄ (m) // MCl₂ (s)
Anode Solid Electrolyte Separator Basic or Neutral Transition Metal Chloride

• CELL REACTION

\[ \text{disch} \]
\[ 2 \text{Na} + \text{MCl}_2 \rightleftharpoons \text{M} + 2 \text{NaCl} \]
\[ \text{ch} \]

• METAL CHLORIDES

FERROUS CHLORIDE
NICKEL CHLORIDE

• OPERATING TEMPERATURES : \( \geq 250^\circ\text{C} \)
<table>
<thead>
<tr>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOWER OPERATING TEMPERATURES (≥ 250°C)</td>
<td>MORPHOLOGICAL CHANGES AT THE CATHODE</td>
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<tr>
<td>WIDER RANGE OF OPERATING TEMPERATURES (180 - 425°C)</td>
<td>LOWER POWER DENSITIES</td>
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<td>SAFETY IN THE EVENT OF INTERNAL SHORT AND TEMPERATURE EXCURSIONS</td>
<td>FAILS SHORT CIRCUIT (NO NEED FOR BYPASS)</td>
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<td>BUILT-IN OVERCHARGE MECHANISM</td>
<td>TOLERANCE TO OVERDISCHARGE</td>
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<tr>
<td>ASSEMBLY IN THE DISCHARGED STATE WITH LITTLE OR NO SOOT</td>
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**Comparison with Na-S**
CAPABILITIES OF THE SYSTEMS

SUMMARY OF DEVELOPMENT IN THE U.K. / SOUTH AFRICA

- **FERROUS CHLORIDE**
  
  ENERGY DENSITIES OF 150 - 170 Wh/kg AT 2 - 4 h RATES WITH ELECTRODE POROSITIES ABOVE 80 % AND CONVERSION PERCENTAGES OF 30 - 40 %

  1000 CYCLES AND ONE YEAR OF OPERATION IN A 5 Ah CELL

  HIGH RATE DISCHARGE CAPABILITY IN AN 8 Ah CELL

  FLAT DISCHARGE CURVES (1.8 V) AT THE 1 h RATE (180 mA/cm²)

- **NICKEL CHLORIDE**

  2047 CYCLES IN A 7.5 Ah CELL WITH SULFUR ADDITIVE

  75 % OF THE ORIGINAL CAPACITY RETAINED AT THE 1 h RATE

  NO DEGRADATION OF BETA ALUMINA

  NO LOSS IN THE SINTERED STRUCTURE OF THE ELECTRODE

BATTERY SYSTEMS GROUP
## PERFORMANCE OF MCl₂ CELLS AND BATTERIES

<table>
<thead>
<tr>
<th>TYPE</th>
<th>CAPACITY</th>
<th>PRACTICAL ENERGY DENSITY @ 5 hr RATE</th>
<th>SPECIFIC POWER @2/3 OCV AND 70%DOD</th>
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<tr>
<td></td>
<td>Amp. Hr</td>
<td>Wh / Kg</td>
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<tr>
<td><strong>BETA 33 CELL</strong></td>
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<tr>
<td>FeCl₂</td>
<td>42</td>
<td>142</td>
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<td>NCl₂</td>
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<td>310</td>
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<td>33 mm dia and</td>
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<td>160-200 mm long</td>
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<tr>
<td><strong>BETA 55 CELL</strong></td>
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<tr>
<td>FeCl₂</td>
<td>140</td>
<td>110</td>
<td>172</td>
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<td>NCl₂</td>
<td>100</td>
<td>109</td>
<td>155</td>
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<td>55 dia and</td>
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<tr>
<td>230-300 mm long</td>
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<tr>
<td><strong>BETA 55 BATTERY</strong></td>
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<tr>
<td>FeCl₂</td>
<td>15 KWh</td>
<td>88</td>
<td>103</td>
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<tr>
<td>NCl₂</td>
<td>30 KWh</td>
<td>88</td>
<td>95</td>
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</tbody>
</table>

A. R. Tilley and R. N. Bull, 22<sup>nd</sup> IECEC; 1078 (1987)
ENVIRONMENTAL TESTS ON Na/MCl₂ CELLS

- CRUSHING: NO CELL BREACHING; TEMP. RISE OF 75°C
- SHORT CIRCUIT:
  - INTERNAL: TEMPERATURE RISE TO 500°C
  - EXTERNAL: NO EFFECT
- OVERHEATING TO 750°C: NO CELL BREACHING; SLIGHT LEAKAGE
- FREEZE-THAW CYCLING: NO FAILURE AFTER 50 CYCLES
- OVERCHARGE: NO EFFECT (SLIGHT LEAKAGE ABOVE > 100%)
- OVERDISCHARGE: NO EFFECT
- SHOCK AND VIBRATION: NO FAILURE IN BOTH FIXED AMPLITUDE AND VEHICLE SIMULATION TESTS

Na/NiCl₂ CELLS FOR SPACE APPLICATIONS AT ESTEC

- FEASIBILITY STUDIES: 100 - 120 Wh/Kg
  PROTOTYPE CELLS: 59 - 70 Wh/Kg

- AFTER 2810 GEO AND LEO CYCLES
  - NO DEGRADATION FOR BETA ALUMINA
  - RECHARGE RATIO ~ UNITY
  - ROUND TRIP ENERGY EFFICIENCY HIGH
  - CAPACITY DECLINED BY 40%.

- NEED FOR CELL OPTIMIZATION
  - ELECTRODE THICKNESS
  - ALTERNATE ELECTROLYTE GEOMETRIES

![Cell Capacity at 1 A Rate Before & After 2810 Cycles](image)

B. Hendel and G. DUDLEY, NASA Workshop, December 1990
JPL EFFORT

OBJECTIVE

• TO DEVELOP A HIGH SPECIFIC ENERGY BATTERY FOR FUTURE NASA MISSIONS

APPROACH

• TO IDENTIFY, EVALUATE AND DEVELOP ALTERNATE CATHODE MATERIALS TO SULFUR FOR RECHARGEABLE SODIUM BATTERIES

INITIAL STUDIES

• ORGANIC CATHODE MATERIALS
  EVALUATED TCNE AND TCNQ AS POSSIBLE ALTERNATIVES
  PROBLEMS OF THERMAL INSTABILITY, POLYMERIZATION LIKELY

• INORGANIC CATHODE MATERIALS
  TRANSITION METAL CHLORIDES IN CHLOROALUMINATE MELTS
JPL EFFORT - PRESENT APPROACH

METAL CHLORIDE CATHODES

- FUNDAMENTAL STUDIES IN SINGLE ELECTRODE CONFIGURATION TO
  ESTABLISH THE MECHANISMS FOR THE REDUCTION OF FeCl₂ AND NiCl₂

PREDICT THE FEASIBILITY OF USING OTHER TRANSITION METAL CHLORIDES

IDENTIFY RATE-LIMITING PROCESSES

DETERMINE THE ELECTRODE KINETICS

STUDY THE EFFECTS OF ADDITIVES

- PERFORMANCE EVALUATION IN LABORATORY TEST CELLS

- IDENTIFY THE FAILURE MODES
MECHANISM OF FeCl₂ REDUCTION

- EVIDENCE FOR TWO-STEP REACTION MECHANISM FROM CYCLIC VOLTAMMETRY
  Na₆FeCl₈ INTERMEDIATE

Fig. 3. Cyclic voltammograms of Fe electrode (area: 0.05 cm²) in NaAlCl₄ at 220°C at scan rates of 1.) 20, 2.) 10, 3.) 5, 4.) 2, and 5.) 1 mV/s. Scale on the y axis is 1 mA/cm (reduced to half) for curves 4 and 5.

- Ni ADDITIONS FOR OVERCHARGE PROTECTION OF FeCl₂

BATTERY SYSTEMS GROUP
MECHANISM OF NiCl₂ REDUCTION

- SINGLE-STEP REACTION SCHEME CONFIRMED BY CYCLIC VOLTAMMETRY

Cyclic voltammetric curves of Ni electrode in NaAlCl₄ at 220°C at different scan rates of 1) 50, 2) 20, 3) 10, 4) 5, 5) 2 and 6) 1 mV/s.

- GOOD REVERSIBILITY
OTHER METAL CHLORIDES

- REQUIRED CRITERIA FROM CYCLIC VOLTAMMETRY
  - Low oxidation currents subsequent to peak indicate low solubility for the chloride
  - Reversible peaks and single step
- Ti, V, Mn, Cr, Au and Ag UNLIKELY.
  - High oxidation currents.
- COPPER EXHIBITS TWO-STEP OXIDATION (SECOND STEP FORMS SOLUBLE CHLORIDE)
  - Unlikely.
- COBALT AND MOLYBDENUM ARE LIKELY CATHODE MATERIALS
  - Low oxidation currents.
- MOLYBDENUM IS A STABLE CURRENT COLLECTOR FOR NiCl₂.

Voltammograms of Co (E₀: 870 mV) at 1) 50, 2) 20, 3) 10, 4) 5, 5) 2 and 6) 1 mV/s.

Voltammograms of Mo (E₀: 997 mV) at 1) 50, 2) 20, 3) 10 and 4) 5 mV/s (Scale on Y-axis doubled for curve 4).
PASSIVATION OF NiCl₂

- PASSIVATION DURING REDUCTION BY NaCl PRECIPITATION
- PASSIVATION ARE PROMINENT THAN IN FeCl₂
PASSIVATION OF NiCl$_2$

- PASSIVATION INCREASES AT LOWER STATES OF CHARGE AND LOWER ELECTRODE POTENTIALS.

- PASSIVATION IS ALLEVIATED BY INCREASING THE PORE SIZE OF THE ELECTRODE

- PASSIVATION CAN BE REDUCED BY OPERATING AT HIGHER TEMPERATURES

CURRENT-POTENTIAL CURVES OF NI WIRE AT 1) 210 2) 270C 3) 300C AND 4) 330C

SCANNED FROM HIGH OXIDATION POTENTIAL THRO' OCV TO HIGH NEGATIVE POTENTIAL

BATTERY SYSTEMS GROUP
KINETICS OF MCi₂ REDUCTION

- HIGH EXCHANGE CURRENT DENSITIES (1 mA/cm²) FOR BOTH FeCl₂ AND NiCl₂.

- 10 % INCREASE IN THE EXCHANGE CURRENT DENSITY OF NiCl₂ FOR EACH 10°C RISE IN THE OPERATING TEMPERATURE.

- OPTIMUM TEMPERATURE FOR NiCl₂ ≥ 250°C.
ADDITIVE REQUIRED FOR NiCl₂

- DECLINE IN CAPACITY PREMATURELY
  EFFECT MORE PROMINENT AT HIGHER POROSITIES
- LOSS OF SINTERED STRUCTURE DUE TO AN AGGLOMERATION OF Ni PARTICLES

R. J. Bones, D. A. Teagle, S. D. Brooker and F. L. Cullen

**Fig. 9.** Effect on cell capacity retention of sulfur and PbCl₂ dopants in the NaAICl₄.
EFFECT OF SULFUR ON NiCl₂ KINETICS

- HIGHER PEAK CURRENTS IN CYCLIC VOLTAMMETRIC CURVES
- IMPROVEMENT IN RECHARGEABILITY
- ENHANCED KINETICS OF NiCl₂ REDUCTION
- REDUCED PASSIVATION
- MAXIMUM SULFUR CONTENT ~0.2 w% IN THE ELECTROLYTE
PRELIMINARY PERFORMANCE DATA OF 1 Ah CELL

- HIGH ROUND TRIP EFFICIENCY (~95%)
- 50% CONVERSION OF NaCl
- HIGH DISCHARGE YIELDS OF ABOVE 80% AT THE 4 - 5 h RATES
- FORMATION APPEARS TO BE INCOMPLETE AND REQUIRES OPTIMIZATION

DISCHARGE CURVES OF 1 Ah Na\textsubscript{1-x}Ni\textsubscript{x}Cl<sub>2</sub> CELL AT 75 mA (7.5 mA/cm\textsuperscript{2}) AND AT 250°C

1) FIFTH CHARGE AT 75 mA
2) FIFTH DISCHARGE
3) SIXTH DISCH. AFTER CHARGE AT 30 mA
4) SEVENTH DISCH. AFTER CHARGE AT 20 mA

BATTERY SYSTEMS GROUP
FABRICATION PARAMETERS VS. ENERGY DENSITY

- OPTIMIZE CONVERSION EFFICIENCY (RATIO OF NaCl : M) AND ELECTRODE POROSITY

![Graph showing energy density vs. discharge rate for central cathode cell.](image)

- STATE OF THE ART ELECTRODES:

  33% CONVERSION AND 90% POROSITY

---

5 Ah CELL AS TEST VEHICLE

- CYLINDRICAL CENTRAL CATHODE,;
  CATHODE - LIMITED DESIGN
  (Na : ~ 200 - 300%)

- BETA ALUMINA TUBES WITH ALPHA
  ALUMINA HEADER

- MECHANICAL COMPRESSION SEAL

- KOVAR TO GLASS SEAL FOR
  CATHODE

BATTERY SYSTEMS GROUP
AREAS OF STUDY

- IMPROVEMENT IN POWER DENSITIES
  - ALTERNATE ELECTRODE DESIGNS
    - OTHER METHODS OF ELECTRODE FABRICATION
  - ALTERNATE ELECTROLYTE GEOMETRIES
    - FLAT PLATE BETA WITH POSSIBLY Na ALLOYS
- IMPROVEMENT IN CYCLE LIFE
  - NON-SULFUR ADDITIVES FOR MORPHOLOGICAL BENEFITS
    - ELECTRODE FABRICATION
    - CELL DESIGN FOR SCREENING OF ADDITIVES
- DESIGN OPTIMIZATION FOR HIGH SPECIFIC ENERGIES
  - CELL / BATTERY DESIGN
    - SEALING METHODS
    - COMPONENTS RATIO
    - CELL CONFIGURATION
- RELIABILITY
  - FAILURE ANALYSIS
## Sodium-Metal Halide Cell Program

<table>
<thead>
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<th>Activity</th>
<th>88</th>
<th>89</th>
<th>90</th>
<th>91</th>
<th>92</th>
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<td>IDENTIFY SYSTEM CAPABLE OF PROVIDING &gt; 1000 CYCLES AND 150 Wh/Kg</td>
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<td>Evaluate organic and inorganic cathodes</td>
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<td>Down select to Na/MCl2</td>
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<td>DEFINE DESIGN REQUIREMENTS FOR 20-25 Ah CELLS</td>
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<td>Short term studies performance and reversibility</td>
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<td>Identify and overcome rate limiting processes</td>
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<td>DEMONSTRATE CYCLE LIFE AND PERFORMANCE IN OPTIMIZED 20-25 Ah CELL</td>
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<td>Develop 5 Ah TEST CELL</td>
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<td>Identify cell failure mechanism</td>
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<td>Develop performance database</td>
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<td>FINAL DEMONSTRATION</td>
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<td>Demo 1000 cycles and 150 Wh/Kg</td>
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PUBLICATIONS FROM JPL ACTIVITIES

1. "AEROSPACE APPLICATIONS OF SODIUM BATTERIES USING NOVEL CATHODE MATERIALS",

2. "ORGANIC CATHODE MATERIALS IN SODIUM BATTERIES"

3. "ADVANCED RECHARGEABLE SODIUM BATTERIES WITH NOVEL CATHODES"

4. "ELECTROCHEMISTRY OF METAL CHLORIDES IN SODIUM BATTERIES"

5. "ALTERNATE CATHODES FOR SODIUM - METAL CHLORIDE BATTERIES"

6. "SODIUM - METAL CHLORIDE BATTERY RESEARCH AT JPL"

7. "PROGRESS AND RECENT DEVELOPMENTS IN SODIUM - METAL CHLORIDE BATTERIES"

BATTERY SYSTEMS GROUP
CONCLUSIONS

- Rapid development in the technology of Na/MCl₂ batteries has been achieved in the last decade mainly due to the:
  - expertise available with Na/S system
  - safety and
  - flexibility in design and fabrication

- Long cycle lives of over 1000 and high energy densities of ~ 100 Wh/kg have been demonstrated in both Na/FeCl₂ and Na/NiCl₂ cells.

- Optimization of porous cathode and solid electrolyte geometries are essential for further enhancing the performance.

- Fundamental studies confirm the capabilities of these systems. NiCl₂ emerges as the candidate cathode material for high power density applications such as electric vehicle and space.
PRESENTATION TO
1991 NASA AEROSPACE BATTERY WORKSHOP
OCTOBER 29-31, 1991
U.S. SPACE & ROCKET CENTER
HUNTSVILLE, AL

PULSED POWER MOLTEN SALT BATTERY

CONTRACT NO. F33615-88-C-2911

AERO PROPULSION LABORATORY
WRIGHT LABORATORY, WL/POOS-2
WRIGHT PATTERSON AIR FORCE BASE, OH 45433

S.D. ARGADE

TECHNOCHEM COMPANY
203-A CREEK RIDGE RD.
GREENSBORO, NC 27406
INTRODUCTION

CHLORINE CATHODES

UNIT CELL DEVELOPMENT

CELL STACK DEVELOPMENT

SUMMARY
INTRODUCTION

CHLORINE CATHODES

UNIT CELL DEVELOPMENT

CELL STACK DEVELOPMENT

SUMMARY
INTRODUCTION

PHASE II PROGRAM GOALS

- Develop and demonstrate a Li/Al/chlorine molten salt battery design
- Develop improved chlorine cathodes
- Develop unit cell design
- Demonstrate a stack/battery design
INTRODUCTION

CHLORINE CATHODES

UNIT CELL DEVELOPMENT

CELL STACK DEVELOPMENT

SUMMARY
CHLORINE CATHODES

- Uniform Pore Size Distribution
- Good Permeability to Chlorine
- Activated Surface
- Electrochemical Activation
Fig. 5  Discharge characteristics for a Li-Al/carbon 8-9-2 absorbed chlorine cell under test cycle 1 regime, 250 mA for 200 sec followed by 1 A
Li-Al/Chlorine Cell, 450°C

- 3.5 A total current 400 10 ms pulses
- 3.5 A total current 200 100 ms pulses

**Maximum voltage during test run**

**Minimum voltage during test run**

Time (sec)
Cathode Performance Summary

- Single Pulsing
- Repetitive Pulsing
- Steady State Discharge
- 200 sec Steady State Load + 5 sec Pulse
- Steady State Load + 100, 10 ms pulses
INTRODUCTION

CHLORINE CATHODES

UNIT CELL DEVELOPMENT

CELL STACK DEVELOPMENT

SUMMARY
Cell Development

- Test Hardware
  - Glass Enclosure Cell
  - Anode Wafer in Stainless Steel or Ni Cup, Nickel leads
  - Cathode rests on EB salt wafer backed by graphite current collector
  - Chlorine fed to the wafer-ambient pressure

- Test Regime
  - Steady discharge load + 400 10 ms pulses + 200 100 ms pulses
1.5V

ΔV2 = 0.56V

20A 10ms Pulse on top of 4A steady

1V

PEAKDET 2ms

Δt = 0.10ms

SAVE

TEKTRONIX 2221

Advanced Technologies Session

-649-

1991 NASA Aerospace Battery Workshop

Cell #12-92

Oct 19/90
INTRODUCTION

CHLORINE CATHODES

UNIT CELL DEVELOPMENT

CELL STACK DEVELOPMENT

SUMMARY
1. Anode Current Collector
2. Li-Al Anode
3. Salt Wafer
4. Carbon Cathode
5. Grafoil
6. Nickel Cup
7. Cathode Current Collector with Chlorine Feed Tube
<table>
<thead>
<tr>
<th>Delivered Energy</th>
<th>Output Voltage</th>
<th>No. of Cells</th>
<th>Open Circuit Voltage</th>
<th>Capacity</th>
<th>Weight</th>
<th>Volume</th>
<th>Current Density</th>
<th>Pulsing</th>
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<tr>
<td>56 Wh</td>
<td>96 V</td>
<td>40</td>
<td>134 V</td>
<td>0.56 Ah</td>
<td>1.34 kg</td>
<td>1.32 L</td>
<td>0.25 A/sq. cm</td>
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<td>10 ms</td>
<td>4.3</td>
<td>4.3</td>
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<td>10 ms</td>
<td>3.9</td>
<td>3.9</td>
<td>1.7</td>
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**POWER DENSITY**

4A DC, 24A PULSE REGIME
## ENERGY DENSITY

**4A DC, 24 A PULSE REGIME**

<table>
<thead>
<tr>
<th></th>
<th>Wh/kg</th>
<th>Wh/L</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CELL</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 cycle</td>
<td>102</td>
<td>112</td>
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<tr>
<td>2 cycle</td>
<td>183</td>
<td>201</td>
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<tr>
<td><strong>STACK</strong></td>
<td>95</td>
<td>104</td>
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<tr>
<td><strong>BATTERY</strong></td>
<td>42</td>
<td>43</td>
</tr>
</tbody>
</table>
INTRODUCTION

CHLORINE CATHODES

UNIT CELL DEVELOPMENT

CELL STACK DEVELOPMENT

SUMMARY
SUMMARY

- Carbon Cathodes with chlorine work well
- Li-Alloy/chlorine at 450 deg. C, 1 atm
  - High Power capability
  - High energy density
- DC + pulsing - 600 pulses
- No initial peak
- Can go to red heat without burn-up
SUMMARY

- Electrochemical performance at the cell and cell stack level under demanding test regime

- Engineering and full prototype development for advancing this technology is warranted
Nickel-Hydrogen Technologies Session

Organizers: Joe Stockel
Office of Research & Development

Michelle Manzo
NASA Lewis Research Center
The nickel hydrogen battery has become the battery of choice for satellite power systems. Because of its superior energy density and long cycle life, it is replacing nickel cadmium systems in space applications. In general, nickel hydrogen chemistry has shown a greater tolerance for depth of discharge with a lower effect on cycle life than nickel cadmium [1].

To date all nickel hydrogen batteries that have flown in space have been of the individual pressure vessel (IPV) form. The fully integrated IPV cell system in a battery assembly reduces the specific energy density from 55 Wh/kg at the cell level to 34 Wh/kg at the battery level [2] (Figure 1). The next natural step in the maturing development of nickel hydrogen battery systems is to combine all of the cells into a common pressure vessel (CPV). In 1984, Johnson Controls and COMSAT Laboratories started on the development of the CPV nickel hydrogen battery. This work has evolved into a range of products to serve both the terrestrial and extra-terrestrial markets. Today Johnson Controls is producing multicell CPV nickel hydrogen batteries from 7 Ah to 190 Ah and voltages in excess of 50 all in one vessel. This approach to putting all the cells in one vessel reduces the volume and weight over a more typical IPV installation. The actual differences vary with the power requirements and installation space available. A comparable nickel hydrogen battery installation for an Intelsat I-7A satellite can save as much as 36 kg when using a CPV instead of an IPV.

There are three different diameter batteries being produced today in the CPV design by Johnson Controls, 5", 10" and 12" (Figure 2). Designs for a 2.5" and 7.5" diameter have been established. As the system voltage requirements change, it is a simple process of adding another cell stack to the CPV design which will add to its total length only. Cell shapes are offered in several different shapes from full circles (disc shape) (Figure 3) and half circles (Figure 4) to rectangular (Figure 5). Each application dictates what cell shape should be used. In the case of our 190 Ah stationary battery, weight and size were of no importance since the batteries are intended to be buried in the ground for good thermal stability, low cost was the main driver in this application. In keeping with that objective, we used a thin wall stainless steel hydrogen barrier liner and end domes that are epoxy bonded on and the entire vessel is over-wrapped with the lower cost filament "E" glass. This gave us a vessel with a 5:1 safety factor and a very desirable failure mode on over pressure. The cells have 90 mil thick positives, are rectangular in shape and they fit into a standard automotive container made of polypropylene.

For the aircraft starting battery the requirement was to weigh less than the nickel cadmium battery presently used and provide improved reliability. The weight savings was only 3 kg but the cycle life reliability has gone up more than 10 times. This battery used a 10" diameter and the half circle cell design to provide the shortest discharge path for the cell connections. We provide
in excess of 1000 A for 90 seconds because of the short intercell connection which have an internal resistance of less than 1.35 millivolts per cell.

Our 5" diameter battery is generally offered in full circle cell form. We have made batteries from 12 volts to 28 volts (10 to 22 cells) and can go higher if needed.

The CPV battery can be provided with specific energy densities of 55 wh/kg or more if needed.

In all the designs we use a heat fin which is generally aluminum or copper. This fin picks up the heat from the broad surface of the cell and conducts it to the wall of the vessel. This patented feature is one of the key design factors that permits the CPV battery to meet all operating thermal demands. Temperature differentials are kept to less than 10°C between any extreme point in the assembly and it can be altered by simply changing the thickness of the fin.

Each cell is enclosed in a double layer, three part plastic enclosure which has two gas vent ports to hold the moisture and KOH in and allow the hydrogen gas to pass through.

The typical air force back-to-back cell configuration is used (Figure 6). Our minimum cell arrangement is two positive and two negative catalyst plates which we call a module. If more ampouths are required, more modules will be connected in parallel as required.

We generally use a negative precharge but can provide a positive precharge to prevent damage from 100% depth of discharge.

Our first CPV battery design for space application in concert with Comsat Laboratories was a 10" diameter, half circle cell 24 A, 32 volt (26 cell) design. It lasted 18 months and performed 7,000 cycles at 44% depth of discharge in a LEO cycle of 16 cycles per day at 10°C ambient. This battery experienced a premature failure because of an assembly error. Two of the plastic (single layer at this time) cell enclosures had been cut open during cell insertion in a heat transfer assembly we no longer use. It was felt by all involved in the program that if a plastic enclosure ever leaked, the KOH would bridge the cells and the battery would fall in a very short time. Surprisingly there was no recognized evidence of this assembly defect for over a year and a half of cycling and it wasn't until the DPA at Comsat, after 7,000 cycles, that the truth was known. This heat transfer housing design is no longer used and the new design has eliminated the threat of this type of error completely. Only the first prototype battery used the difficult to assemble design.

Our present design uses an open disk which allows the cell to be set into a shallow cavity and subsequent cells are stacked on each other with the total number based on the battery voltage required (Figure 7). This approach not only eliminates the assembly error threat but also more readily assures equal contact pressure to the heat fin between each cell which further assures balanced heat transfer. These heat fin dishes with their appropriate cell stacks are held together with tie bars which in turn are connected to the vessel weld rings at each end of the tube.
All batteries can be activated with the KOH and placed in a boiler plate vessel for check out prior to final welding into the Inconel 718 vessel. A CO₂ laser weld is used to seal the dome and tube assembly to the weld ring.

We have passed the 2 minute - 3 axis - 19.5 g random vibration test and thermal vacuum.

All of the design features are intended to provide ease of assembly which enhances reliability and lower cost. Johnson Controls continues to develop the CPV technology for all its markets and their mutual benefit.

References:


FIGURE 1: 26-CELL CPV BATTERY AND IPV EQUIVALENT

FIGURE 2: VARIETY OF CPV BATTERIES CURRENTLY IN PRODUCTION

ORIGINAL PAGE IS OF POOR QUALITY
FIGURE 5: RECTANGULAR CPV CELL MODULE AND COMPONENTS

FIGURE 6: Schematic of a CPV Nickel-Hydrogen Cell
2 Module Cell, Back-to-Back Configuration
E = 1.318 V
FIGURE 7: 22 CELL CPV LEO BATTERY STACK
A NICKEL-HYDROGEN COMMON PRESSURE VESSEL SPACEFLIGHT EXPERIMENT

J.GARNER
NAVAL RESEARCH LABORATORY
SPACE SYSTEMS DEVELOPMENT DEPARTMENT
4555 OVERLOOK AVENUE
S.W. WASHINGTON D.C. 20375
INTRODUCTION

DATA FROM NRL’S 1977 NTS-2 NiH2 BATTERY ENABLED RISK FREE INTRODUCTION TO COMMERCIAL AND DOD GEO MISSIONS

GOOD WORKING RELATIONSHIP BETWEEN NRL AND COMSAT

OCTOBER 1988 COMSAT/JOHNSON CONTROLS APPROACH NRL WITH COMMON PRESSURE VESSEL (CPV) BATTERY DESIGN

JOHNSON CONTROLS (JCI) AND NRL AGREE TO A SPACEFLIGHT EXPERIMENT OF A JCI NiH2 CPV BATTERY
COOPERATIVE RESEARCH AND DEVELOPMENT AGREEMENT

- COOPERATIVE RESEARCH AND DEVELOPMENT AGREEMENT (CRDA) SIGNED BY NRL AND JCI

- NO FUNDS EXCHANGED BETWEEN PARTIES

- JCI TO PROVIDE TWO NiH2 CPV BATTERIES, ONE FOR QUALIFICATION TEST, ONE FOR FLIGHT

- NRL TO PROVIDE QUALIFICATION/ACCEPTANCE TESTS, SPACECRAFT INTEGRATION, AND FLIGHT DATA
A NIH2 CPV BATTERY SPACEFLIGHT EXPERIMENT

SCHEDULE

NRL/JC1 NIH2 CPV BATTERY EXPERIMENT

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<td>Deliver For SC Integration</td>
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</table>
EXPERIMENT DETAILS

- **LAUNCH CY 92**

- **240 MINUTE ORBIT**

- **MAXIMUM ECLIPSE PERIOD 45 MINUTES**

- **BATTERY SIZED TO SUPPORT A 50% DEPTH OF DISCHARGE**

- **EXPERIMENT DURATION 3+ YEARS**

- **DATA WILL INCLUDE:**
  - BATTERY VOLTAGE
  - CHARGE/DISCHARGE CURRENT
  - BATTERY TEMPERATURE
  - PRESSURE BY TWO METHODS
    (PRESSURE TRANSDUCER & STRAIN GAUGES)
**JOHNSON CONTROLS INC 5" DIA NiH2 CPV BATTERY FEATURES**

- **NOMINAL CAPACITY:** 10.7 Ah
- **THEORETICAL CAPACITY:** 13.4 Ah
- **NUMBER OF CELLS:** 22
- **WEIGHT:** 6.80 kg (15.0 lbs)
- **NO. MODULES/CELL**
  - 3
- **PRESSURE VESSEL**
  - INCONEL 718
  - LENGTH - 20.7"
  - DIAMETER - 5.0"
NiH2 CPV BATTERY WITH S/C ELECTRICAL POWER SUBSYSTEM

- NiH2 CPV BATTERY ON-LINE BATTERY
- NiCd BATTERY BACK-UP
- NiH2 CPV BATTERY USES EITHER A-H INTEGRATION OR CONSTANT CURRENT CHARGING
- CBE ELECTRONICS PROVIDES AUTOMATIC SWITTOVER TO NiCd
Technology Update

Nickel-Hydrogen Common Pressure Vessel (CPV) 2.5V Twin Stack Cell Designs

Tim Harvey and Lee Miller
EAGLE-PICHÉR INDUSTRIES, INC.
Joplin, Missouri
Common Pressure Vessel (CPV) 2.5 Volt (2 Stack) Technology

** Dual cell CPV batteries represent a 30% reduction in volume, approximately a 7% reduction in mass, and approximately a 50% reduction in mounting footprint when compared with an equivalent battery of IPV cells of like capacity (higher gravimetric and volumetric energy density results).

** Reduced conductor "IR" loss due to shorter internal series connections than if cells were IPV with external connections (at battery level only half the number of intercell connections required).

** Low voltages associated with two (2) electrode stack design (2.5 volts) minimizes potential for electrolyte "bridging" or communication.
Common Pressure Vessel (CPV) 2.5 Volt (2 Stack) Technology (cont.)

** Very low risk approach to CPV technology, components are flight tested through the IPV heritage.

** Improvements suggested for IPV designs, such as reduced platinum catalyst electrodes and alternative separators can be equally applied to CPV cells.

** The factor of possible cost savings represented by the CPV design in conjunction with Eagle-Picher’s range of lower cost 5-20 A-hr. cells makes this design particularly attractive for ‘‘small-sat’’ and commercial applications.
CPV (2.5 V) vs. IPV: "Same Energy" Analysis (Cell Level)

1. Example: 80 Ah (IPV) vs. 40 Ah (CPV)

2. Discharge:

<table>
<thead>
<tr>
<th>Rate C/2</th>
<th>Ah</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPV</td>
<td>40 A</td>
<td>80.0 Ah</td>
</tr>
<tr>
<td>CPV</td>
<td>0 A</td>
<td>40.0 Ah</td>
</tr>
</tbody>
</table>

3. Reduced rate results in reduction in current conductor mass required.

4. Cell Mass Comparison:
   80 Ah (IPV) = 1960 grams
   40 Ah (CPV) = 1840 grams

   **Difference due to reduction in current conductor mass.

5. Energy Density (gravimetric) Comparison:
   80 Ah (IPV) = 52.2 Wh/kg
   40 Ah (CPV) = 55.6 Wh/kg
CPV (2.5 V) vs. IPV: “Same Energy” Analysis
(Battery Level)

1. Example: 28 cell/80 Ah (IPV) vs. 28 cell/40 Ah (CPV)

2. Wiring Configuration:
   IPV = One 28 cell series string = 80 Ah and 2.9 kWh
   CPV = Two 14 cell series strings connected in parallel = 80 Ah and 2.9 kWh

3. Assume a two (2) battery spacecraft in which an open string failure occurs:
   IPV = 50% Capacity Loss
   CPV = 25% Capacity Loss
CPV (2.5 V) vs. IPV: “Same Energy” Analysis (Battery Level) (cont.)

4. Given this difference in reliability equip the IPV battery with diodes:

<table>
<thead>
<tr>
<th>Battery</th>
<th>Mass</th>
<th>Energy Density (gravimetric)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPV</td>
<td>66.3 kg (w/diodes) per batt.</td>
<td>43.7 Wh/kg</td>
</tr>
<tr>
<td>CPV</td>
<td>60.6 kg (no diodes) per batt.</td>
<td>47.8 Wh/kg</td>
</tr>
</tbody>
</table>

5.7 kg difference of which 1.68 kg is due to diodes.
The remaining wt. savings is due to conductor mass reduction.

6. The mass savings achieved per two (2) battery spacecraft without significant mechanical design or cost impact:
11.4 kg
## CPV Design Comparison

<table>
<thead>
<tr>
<th>Design</th>
<th>RNHC-6-1</th>
<th>RNHC-12-1</th>
<th>RNHC-35-9</th>
<th>RNHC-40-3 (Proto.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design:</td>
<td>Two 6 Ahr Stacks In Series</td>
<td>Two 12 Ahr Stacks In Series</td>
<td>Two 35 Ahr Stacks In Series</td>
<td>Two 40 Ahr Stacks In Series</td>
</tr>
<tr>
<td>Rated Cap. (C):</td>
<td>6 Ah</td>
<td>12 Ah</td>
<td>35 Ah</td>
<td>40 Ah</td>
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<tr>
<td>Positive Electrodes:</td>
<td>Same Standard Technology</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td># of Pos. Elect. Per Stack:</td>
<td>10 (7.4&quot; dia.)</td>
<td>10 (3.4&quot; dia.)</td>
<td>26 (3.4&quot; dia.)</td>
<td>32 (3.4&quot; dia.)</td>
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<tr>
<td>Plate Config.:</td>
<td>Mantech</td>
<td>Intelsat</td>
<td>Mantech</td>
<td>Intelsat</td>
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<td></td>
<td>RNHC-6-1</td>
<td>RNHC-12-1</td>
<td>RNHC-35-9</td>
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<tr>
<td>Separator:</td>
<td>Zircar</td>
<td>Asbestos</td>
<td>Zircar</td>
<td>Asbestos</td>
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<tr>
<td>Negative Elect.:</td>
<td>--------Platinum/Teflon Catalyst Over Patented Nickel Grid --------w/Reduced Pt</td>
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<tr>
<td>No Weld Ring</td>
<td></td>
<td></td>
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<td>Open Spoke Weld Ring</td>
</tr>
<tr>
<td>Design MEOP:</td>
<td>500 psig</td>
<td>480 psig</td>
<td>950 psig</td>
<td>950 psig</td>
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</table>
### CPV Design Comparison (cont.)

<table>
<thead>
<tr>
<th></th>
<th>RNHC-6-1</th>
<th>RNHC-12-1</th>
<th>RNHC-35-9</th>
<th>RNHC-40-3 (Proto.)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capacity (C/2 Discharge to 2.0 volts, 10 deg. C):</strong></td>
<td>7.6 Ah</td>
<td>15.0 Ah</td>
<td>38.9 Ah</td>
<td>45.4 Ah</td>
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<tr>
<td><strong>Max. Length:</strong></td>
<td>6.75&quot;</td>
<td>9.0&quot;</td>
<td>11.6&quot;</td>
<td>10.0&quot;</td>
</tr>
<tr>
<td><strong>Max. Diameter:</strong></td>
<td>2.55&quot;</td>
<td>3.51&quot;</td>
<td>3.51&quot;</td>
<td>3.51&quot;</td>
</tr>
<tr>
<td><strong>Cell Mass:</strong></td>
<td>663 g</td>
<td>1022 g w/S.G.</td>
<td>2000 g w/S.G.</td>
<td>1850 g w/S.G.</td>
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<tr>
<td>(S.G. = Strain Gage)</td>
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<tr>
<td><strong>Energy Density:</strong></td>
<td>28.7 Wh/kg</td>
<td>36.7 Wh/kg</td>
<td>48.6 Wh/kg</td>
<td>61.4 Wh/kg</td>
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<tr>
<td>(Gravimetric)</td>
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</tbody>
</table>
CPV Designs Developed and Tested

RNHC-6-1
&
RNHC-10-1
CPV Designs Developed and Tested

RNHC-12-1
*RNHC-35-9
&
*RNHC-40-3

*See Design Details
RNHC-6-1 (CPV): Characterization Testing: Performance Summary

1. -10°C Std. Cap. Test
   Charge 0.6 Amps for 16 hrs.
   Discharge 3.0 Amps to 2.0 V: ............ 7.79 Ah

2. 10°C Std. Cap. Test
   Charge 0.6 Amps for 16 hrs.
   Discharge 3.0 Amps to 2.0 V: ............ 7.64 Ah

3. 10°C Charge Retention Test
   Charge 0.6 Amps for 16 hrs.
   72 hr. OCV
   Discharge 3.0 Amps to 2.0 V: ............ 6.60 Ah
   % Retention Compared to #2: ............ 86.4%

4. Life Test: RNHC-10-1: ................. 3300 40% DOD
   Cycles As of 11-1-91

See plots to follow
RNHC-6-1 (CPV) Characterization Tests: Comparison of Charge Voltage: -10°, 10° & 30°C: Charge 0.6 Amps for 16 Hours

- Voltage: 2.4 to 3.2 Volts
- Hours: 0 to 16

- SN 1 -10
- SN 1 10 C
- SN 1 30 C
RNHC-6-1 (CPV) Characterization Tests: Comparison of Discharge Voltage: -10°, 10° & 30°C: Discharge 3.0 Amps to 2.0 Volts
RNHC-10-1 (CPV) Life Test: 10°C: 40% DOD: 3300 Cycles As of 11-1-91
RNHC-12-1 (CPV) Characterization Testing:

Performance Summary

1. Test Sequence “A”: 5% DOD Cycles
   - 10°C Charge at 1.2 Amps for 16 hrs.
   - 6 minute Discharge at 6.0 Amps
   - 10 minute Charge at 3.8 Amps
   - Repeat Charge/Discharge above for 15 cycles
   - Final Discharge at 6.0 Amps to 2.2 V: ............. 12.00 Ah

2. Test Sequence “B”: 80% DOD Cycles
   - 10°C Charge at 1.2 Amps for 16 hrs.
   - 1.6 hr. Discharge at 6.0 Amps
   - Repeat Charge/Discharge above for 15 cycles
   - Final Discharge at 6.0 Amps to 2.2 V: ............. 12.75 Ah

   See following plots

3. Current Disposition: Delivered for flight program.
RNH-12-1 (CPV) Characterization Tests: Test Sequence "B":
10°C Charge: 1.2 Amps for 16 Hrs.
RNH-12-1 (CPV) Characterization Tests: Test Sequence "B":
10°C Discharge: 6.0 Amps to 2.0 Volts

![Graph showing voltage over time for CPV discharge test.](image-url)

1. **10°C Std. Cap. Test**
   Charge 3.5 Amps for 16 hrs.
   Discharge 17.5 Amps to 2.0 V
   Cap. to 2.2 V: ........................................... 38.80 Ah
   Cap. to 2.0 V: ........................................... 38.88 Ah

2. **Current Disposition:**
   Under test at Martin Marietta
RNHC-35-9 (CPV) Characterization Test:
10°C Charge: 3.5 Amps for 16 Hours
RNHC-35-9 (CPV) Characterization Test:
10°C Discharge: 17.5 Amps to 1.8 Volts

EAGLE ELECTRONICS DIVISION
Joplin, MO

RNHC-40-3 (Prototype) (CPV): Characterization Testing/Life Test: Performance Summary

1. 0°C Std. Cap. Test
   Charge 4.0 Amps for 16 hrs.
   Discharge 20.0 Amps to 2.0 V: ............... 47.2 Ah

2. 10°C Std. Cap. Test
   Charge 4.0 Amps for 16 hrs.
   Discharge 20.0 Amps to 2.0 V: ............... 45.4 Ah

3. 10°C Charge Retention Test
   Charge 4.0 Amps for 16 hrs.
   72 hr. OCV
   Discharge 20.0 Amps to 2.0 V: ............... 36.6 Ah
   % capacity retained vs. #2 above: ............... 80.6%
4. 20°C Std. Cap. Test
   Charge 4.0 Amps for 16 hrs.
   Discharge 20.0 Amps to 2.0 V: .................. 41.7 Ah

5. 10°C Overcharge Test
   Charge 2.0 Amps for 72 hrs.
   Discharge 20.0 Amps to 2.0 V: .................. 53.8 Ah
RNHC-40-3 (Prototype) (CPV): Life Test

Cycles: Charge 1.5 hrs. at C/3
Discharge 55 minutes at C/2
46% DOD

As of 6-91: 15,266 Cycles Completed (Rockwell)
RNHC-40-3 (Prototype) (CPV): Characterization Testing/Life Test:
Performance Summary
(Cont.)

Capacity Retention Results: Life Test

<table>
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</thead>
<tbody>
<tr>
<td>(M/YY)</td>
<td>Number</td>
<td>Ah</td>
<td>72 hr. (Ah)</td>
<td>Ret. %</td>
<td>ºC</td>
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<tr>
<td>6-84</td>
<td>Accept. Test</td>
<td>45.4</td>
<td>36.6</td>
<td>80.6</td>
<td>10.0</td>
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<tr>
<td>8-87</td>
<td>8,201</td>
<td>54.7</td>
<td>46.3</td>
<td>84.6</td>
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<tr>
<td>10-87</td>
<td>8,303</td>
<td>54.5</td>
<td>48.2</td>
<td>88.4</td>
<td>5.0</td>
</tr>
<tr>
<td>4-89</td>
<td>9,592</td>
<td>46.1</td>
<td>39.7</td>
<td>86.1</td>
<td>12.5</td>
</tr>
<tr>
<td>6-89</td>
<td>10,003</td>
<td>47.3</td>
<td>40.4</td>
<td>85.4</td>
<td>10.0</td>
</tr>
<tr>
<td>12-89</td>
<td>11,546</td>
<td>45.6</td>
<td>39.2</td>
<td>86.0</td>
<td>8.6</td>
</tr>
<tr>
<td>7-91</td>
<td>13,425</td>
<td>41.7</td>
<td>35.5</td>
<td>85.1</td>
<td>9.7</td>
</tr>
</tbody>
</table>
RNHC-40-3 (Proto.) (CPV) Life Test Data:
Approx. 10°C Charge 4.0 Amps for 16 Hours:
Discharge 20.0 Amps to 2.0 Volts
RNHC-40-3 (Proto.) (CPV) Life Test: Approximately 10°C:

Cycle # 15,266: Charge 4.0 Amps for 16 Hours

Voltage
Pressure

Hours

3.2 3.1 3 2.9 2.8 2.7 2.6 2.5 2.4 2.3 2.2
3.2 3.1 3 2.9 2.8 2.7 2.6 2.5 2.4 2.3 2.2

1100 1000 900 800 700 600 500 400 300 200 100

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
RNHC-40-3 (Proto.) (CPV) Life Test: Approximately 10°C:
Cycle # 15,266: Discharge 20.0 Amps to 2.0 V
HEAT GENERATION DURING OVERCHARGE OF NI/H$_2$ CELLS

H. VAIDYANATHAN, W. H. KELLY, AND M. W. EARL
COMSAT LABORATORIES
CLARKSBURG, MD. 20871-9475
Abstract

Heat Generation During Overcharge of Ni/H₂ Cells

H. Vaidyanathan, W. H. Kelly, and M. W. Earl
COMSAT Laboratories
Clarksburg, MD 20871-9475

The heat dissipated during various rates of charge and overcharge of a Ni/H₂ cell was measured using a radiative-type calorimeter. A flight configuration-type Ni/H₂ cell was prepared for this study by wrapping it with heater tape (4 in. wide) and instrumenting it with 10 thermocouples. The cell was then insulated with 10 layers of aluminized Mylar. The calorimeter consisted of a liquid-nitrogen-cooled copper chamber arranged inside a vacuum jar. The following heat balance equation was used to calculate the heat dissipated:

\[ mC_p \frac{dT}{dt} = Q_{\text{diss}} + Q_{\text{in}} - Q_{\text{out}} \]

where
- \( m \) = mass of the cell
- \( C_p \) = thermal capacity of the cell
- \( Q_{\text{out}} \) = measured heat using the calibration curve for the calorimeter and cell temperature
- \( Q_{\text{in}} \) = heat input to the cell via the heater tape
- \( Q_{\text{diss}} \) = heat dissipation
- \( T \) = temperature of the cell
- \( t \) = time
Measurements made during charging of the cell to the same state of charge (as indicated by pressure) showed that the total heat evolved was greatest for C/10 charge, compared with C/2 or C/4. The endothermic-to-exothermic transition occurred at 1.43 V for C/10 charge, and increased to 1.467 V at C/2 charge. The magnitude of the endothermic heat was only 3.7 percent of the total heat generated during charging.

Experimentally measured heat values were compared against those calculated using a thermoneutral potential of 1.51 V. Although there was general agreement between the calculated and measured values, a significant difference existed in the instantaneous heat values for the initial stages of cell discharge. Heat dissipated during self-discharge appears to depend on the charge rate preceding open-circuit stand.
EXPERIMENTS USING FLIGHT MODEL NI/H₂ CELL

DETERMINATION OF INSTANTANEOUS HEAT DISSIPATION USING A RADIATIVE TYPE CALORIMETER

ENDOTHERMIC TO EXOTHERMIC TRANSITION DURING CHARGE

HEAT DISSIPATION DURING OVERCHARGE AND DISCHARGE
# LITERATURE DATA

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Cell Type</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>C. J. Johnson</td>
<td>Ni/H₂ cell</td>
<td>Conduction type, Silicon oil bath, Isothermal conditions</td>
</tr>
<tr>
<td>H. Kawamoto and et al.</td>
<td>Na/S cell</td>
<td>Furnace, Heat transfer by convection and radiation</td>
</tr>
<tr>
<td>R. Cohen and et al.</td>
<td>Ca/So Cl₂ cell</td>
<td>Conduction type, Water bath, Carbon cloth as conductor, Heat factor = 1 W/°C</td>
</tr>
<tr>
<td>Eric Darcy</td>
<td>Li/BCX and Li/So Cl₂</td>
<td>Conduction type, Drop calorimetry, Water bath, AI as conductor</td>
</tr>
</tbody>
</table>

*1990 NASA Battery Workshop*
HEAT TRANSFER BY RADIATION

LIQUID N₂ COOLED CHAMBER OF 0.5 M³ (TEMP = -184°C)

CHAMBER ENCLOSED IN A VACUUM JAR (10⁻⁶ MM OF HG)

CELL HEATED BY HEATER TAPE

6 THERMOCOUPLES TO MEASURE THE TEMPERATURE OF THE CHAMBER

2 THERMOCOUPLES TO MEASURE TEMPERATURE OF CELL LEADS

8 THERMOCOUPLES TO MEASURE CELL TEMPERATURE
CALIBRATION AND MEASUREMENT

- SPECIFIC HEAT DETERMINATION OF AL CYLINDER 958 J/KG°C
- HEAT OF FUSION OF WATER, 75.6 CAL/GM
- CELL INSTALLED IN THE DISCHARGED STATE
- 7W OF HEATER POWER TO MAINTAIN CELL AT 0°C
- CELL TEMPERATURE MONITORED CONTINUOUSLY
- CELL THERMAL CAPACITY DETERMINATION, 1631 J/°C
CELL CALIBRATION
ALUMINUM CYLINDER - 100 GRAMS H₂O

10.018 WATTS HEATER

TEMPERATURE - °C

TIME - HOURS
BATTERY CELL CALIBRATION - (1-6 CELL)
NO CHARGE - HEATER POWER ONLY

\[ Q = 7.337 + 0.10421T + 0.00037162T^2 \]

HEATER POWER - WATTS

TEMPERATURE - C
THERMAL ANALYSIS

- HEAT DISSIPATION CALCULATED USING ENTHALPY VOLTAGE

\[ Q_{\text{discharge}} = -I (E_H - E_L) \]

\[ Q_{\text{charge}} = -I (\eta E_H - E_L) \]

- FACTOR ANALYSIS TECHNIQUE (STATISTICAL APPROACH)

\[ Q = C_1 + C_2 Y_1 + C_3 Y_1^2 \ldots \ C_n Y_1^{5m} \]

\[ Y_n = \text{independent variable, } C_n = \text{dimensional constant} \]
GOVERNING EQUATIONS

\[ m \, cp \, \frac{dT}{dt} = Q_{\text{diss}} + Q_{\text{in}} - Q_{\text{out}} \]

- \( cp \) = thermal capacity of the cell
- \( m \) = mass of the cell
- \( Q_{\text{in}} \) = cell heater power = current \( \times \) voltage
- \( Q_{\text{out}} \) = calculated using the equation formulated from experimental values of cell temperature
  \[ = 7.337 + 1.0421T + 0.00037162 \, T^2 \]
- \( Q_{\text{diss}} \) = heat dissipation
# CALCULATION OF THERMAL CAPACITY

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>SPECIFIC HEAT ( \text{J/gM} , ^\circ C )</th>
<th>( M \times Cp ) ( \text{JOULE/}^\circ C )</th>
</tr>
</thead>
<tbody>
<tr>
<td>POLYPROPYLENE SCREEN</td>
<td>1.88</td>
<td>66.928</td>
</tr>
<tr>
<td>POSITIVE</td>
<td>0.7</td>
<td>353.92</td>
</tr>
<tr>
<td>NEGATIVE</td>
<td>0.6</td>
<td>42.24</td>
</tr>
<tr>
<td>ZIRCAR</td>
<td>0.67</td>
<td>59.496</td>
</tr>
<tr>
<td>KOH-31%</td>
<td>3.24</td>
<td>845.64</td>
</tr>
<tr>
<td>INCONEL</td>
<td>0.44</td>
<td>120.428</td>
</tr>
<tr>
<td>NICKEL</td>
<td>0.46</td>
<td>87.63</td>
</tr>
<tr>
<td>ALUMINUM</td>
<td>0.96</td>
<td>80.352</td>
</tr>
<tr>
<td>POLYSULFONE</td>
<td>1.004</td>
<td>30.8228</td>
</tr>
<tr>
<td>POLYPROPYLENE</td>
<td>1.88</td>
<td>39.856</td>
</tr>
<tr>
<td>MISCELL.</td>
<td>1</td>
<td>5.3</td>
</tr>
</tbody>
</table>

**TOTAL**               |                                             | 1732.6128                                     |
VOLTAGE PROFILE OF I-VI S/N 12-1304 DURING C/2 DISCHARGE
<table>
<thead>
<tr>
<th>STATE OF CHARGE</th>
<th>4.8A Charge</th>
<th>12A Charge</th>
<th>24A Charge</th>
<th>24A Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>EOC</td>
<td>-3.75 °C</td>
<td>-5.47 °C</td>
<td>-3.02 °C</td>
<td>-8.98 °C</td>
</tr>
<tr>
<td>Mid-Charge</td>
<td>-15.5 °C</td>
<td>-4.69 °C</td>
<td>-10.66 °C</td>
<td>-6.7 °C</td>
</tr>
<tr>
<td>EOD</td>
<td>-2.89 °C</td>
<td>3.41 °C</td>
<td>6.66 °C</td>
<td>3.61 °C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TEMPERATURE DISTRIBUTION</th>
<th>AT DOME TO STACK</th>
</tr>
</thead>
<tbody>
<tr>
<td>CELL DOMES 1/2 °C</td>
<td></td>
</tr>
<tr>
<td>STACK AVERAGE OF 4 °C</td>
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</tr>
<tr>
<td></td>
<td>1.165</td>
</tr>
<tr>
<td></td>
<td>1.74</td>
</tr>
<tr>
<td></td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>1.48</td>
</tr>
<tr>
<td></td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>3.62</td>
</tr>
<tr>
<td></td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td>2.39</td>
</tr>
</tbody>
</table>
HEAT DISSIPATION AT VARIOUS RATES OF CHARGE

STATE OF CHARGE (Hh)
HEAT DISSIPATION DURING DISCHARGE AT C/2
VARIATION OF HEAT DISSIPATION AT 50% CHARGED STATE

CHARGE RATE (AMPERES)

HEAT DISSIPATION (WATTS)
<table>
<thead>
<tr>
<th>CHARGE INPUT AH</th>
<th>CALCULATED HEAT WATTS</th>
<th>EXPERIMENTAL HEAT WATTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4</td>
<td>-0.575</td>
<td>-0.222</td>
</tr>
<tr>
<td>9.6</td>
<td>-0.32</td>
<td>-0.145</td>
</tr>
<tr>
<td>14.4</td>
<td>-0.219</td>
<td>+0.005</td>
</tr>
<tr>
<td>19.2</td>
<td>-0.143</td>
<td>+0.04</td>
</tr>
<tr>
<td>24.0</td>
<td>-0.095</td>
<td>+0.06</td>
</tr>
<tr>
<td>28.8</td>
<td>+0.39</td>
<td>+0.124</td>
</tr>
<tr>
<td>38.4</td>
<td>+0.47</td>
<td>+0.238</td>
</tr>
</tbody>
</table>
ENDOTHERMIC HEAT

- HEAT DISSIPATION OF 0.453 WATTS IS REQUIRED TO DECREASE THE CELL TEMPERATURE BY 1°C

- BOTH EXPERIMENTAL AND THEORETICAL DATA INDICATE THAT COOLING BY ENDOTHERMIC EFFECT IS NOT VERY SIGNIFICANT (LESS THAN 1.25°C)

- ENDOTHERMIC TO EXOTHERMIC TRANSITION OCCURS AT 1.43V AT C/10 WHICH INCREASES TO 1.467V AT C/2 CHARGE
EXPLANATION FOR INCONSISTENCY

- AMBIGUITIES IN $E_H$, THE ENTHALPY VOLTAGE

1) $\Delta H$ of -69.6 K Cal DERIVED FROM Ni/CD REACTIONS

2) SINCE $\Delta H = \Delta E + P\Delta V$, $E_H$ IS A FUNCTION OF PRESSURE

3) $\Delta H$ FOR CHARGED AND DISCHARGED FORMS OF Ni(OH)$_2$ NOT CONSIDERED

- INACCURATE VALUE FOR CHARGE EFFICIENCY
<table>
<thead>
<tr>
<th>TEMPERATURE (°C)</th>
<th>MEASURED HEAT WATTS</th>
<th>CALCULATED HEAT WATTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.8</td>
<td>1.08</td>
<td>0.9021</td>
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<tr>
<td>4.8</td>
<td>1.017</td>
<td>0.9039</td>
</tr>
<tr>
<td>1.37</td>
<td>0.7552</td>
<td>0.910</td>
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<tr>
<td>-1.07</td>
<td>0.748</td>
<td>0.9176</td>
</tr>
<tr>
<td>-22.6</td>
<td>0.766</td>
<td>0.9746</td>
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RELATIONSHIP BETWEEN HEAT GENERATION AND PRESSURE INCREASE DURING C/10 OVERCHARGE AT -3 +/- 30°C
HEAT DISSIPATION DURING OPEN CIRCUIT STAND

<table>
<thead>
<tr>
<th>CHARGE RATE PROCEEDING THE OPEN CIRCUIT STAND</th>
<th>TEMPERATURE (°C)</th>
<th>CELL PRESSURE (PSI)</th>
<th>HEAT DISSIPATED (WATTs)</th>
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</thead>
<tbody>
<tr>
<td>C/10</td>
<td>1.7</td>
<td>826</td>
<td>0.85</td>
</tr>
<tr>
<td>C/20</td>
<td>6.0</td>
<td>830</td>
<td>1.11</td>
</tr>
<tr>
<td>C/4</td>
<td>6.3</td>
<td>839</td>
<td>1.68</td>
</tr>
<tr>
<td>C/2</td>
<td>13.7</td>
<td>854</td>
<td>1.91</td>
</tr>
</tbody>
</table>
CONCLUSIONS

- Endothermic heat is a very small part of the total heat dissipated during charge.

- Heat dissipation in the first one hour of self-discharge appears to depend on the charge rate prior to open-circuit stand.

- There is a divergence between the calculated and experimental heat dissipation which could be largely due to inaccurate values for $E_H$ and charge efficiency.
NICKEL-HYDROGEN BATTERY DESIGN
FOR THE
TRANSPORTER ENERGY STORAGE SUBSYSTEM (TESS)

BY

JOHN R. LAPINSKI
MDESC-L&ES

DEBORAH S. BOURLAND
NASA-JSC
TESS PROVIDES 120 VOLT POWER DURING TRANSLATION OF MOBILE SERVICING CENTER.

TESS IS RECHARGED USING SPACE STATION 120 VOLT POWER AT BOTH WORK SITES AND HOME BASE.
TESS IN LAUNCH CONFIGURATION

- TESS BATTERY LAUNCHED DISCHARGED AND OPEN CIRCUIT

- TESS REMAINS ON M1 SEGMENT FOR ABOUT 9 MONTHS

LAUNCH MB-4
SEGMENT M1

Space Station Freedom
• TESS INSTALLED ON MOBILE TRANSPORTER DURING MB-7 EVA OPERATIONS.

• TESS PROVIDES ABOUT 3.3 HOURS OF MSC TRANSLATION

• TESS PROVIDES REGULATED 120 VOLTS:
  - 10 KW-HR OF ENERGY
  - 3000 WATTS AVERAGE POWER
  - 6000 WATTS PEAK POWER
BATTERY DESIGN REQUIREMENTS

- SUPPORT TESS/MT INTERFACE POWER & ENERGY REQUIREMENTS
  - 3000 WATTS OF AVERAGE OUTPUT POWER AT 120 VOLTS
  - 6000 WATTS OF PEAK OUTPUT POWER AT 120 VOLTS
  - 12,000 WATTS OF FAULT CLEARING POWER
  - 10 KILOWATT-HOURS OF MAXIMUM OUTPUT ENERGY AT 120 VOLTS
  - 7 KILOWATT-HOURS OF NOMINAL OUTPUT ENERGY AT 120 VOLTS

- OPERATIONAL LIFE OF 10 YEARS, THUS 2 REPLACEMENTS OVER SPACE STATION MISSION LIFE OF 30 YEARS.
  - 150 MOBILE SERVICING CENTER MISSIONS PER YEAR
  - 65% AT NOMINAL ENERGY LEVEL (7 KW-HR), 35% AT MAXIMUM

- SYSTEM RECOVERY, FAIL DEGRADE, FAIL SAFE
BATTERY DESIGN REQUIREMENTS
(CONTINUED)

- STRUCTURAL, CELL PRESSURE VESSEL
  - PROOF PRESSURE: 1.5 x MAXIMUM OPERATING PRESSURE
  - ULTIMATE PRESSURE: 3 x MAXIMUM OPERATING PRESSURE

- THERMAL, PASSIVELY COOLED
  - OPERATING: 0 °C TO +25 °C
  - NON-OPERATING: -10 °C TO +35 °C
TESS BATTERY DESIGN

- TWO 63-CELL NICKEL HYDROGEN BATTERIES
  - THREE 21-CELL SUBASSEMBLIES, CONNECTED IN SERIES
  - 90 AMP-HR HUBBLE SPACE TELESCOPE (HST) CELLS, MODIFIED

- 21-CELL SUBASSEMBLY
  - WEIGHT: 149 LBS INCLUDING MM/OD COVERS
  - SIZE: 14.9 W x 23.7 L x 13.0 H (INCHES)
  - 3 ELECTRICAL CONNECTORS: POWER, INSTRUMENTATION, AND TEST MONITOR
  - CELL ISOLATION: FIBERGLASS WRAP POTTED BETWEEN CELL AND COLLAR
  - BATTERY HOUSING, CELL COLLARS, AND BATTERY COVERS MADE OF ALUMINUM
TESS NICKEL-HYDROGEN BATTERY SUBASSEMBLY DESIGN

TRANSPORTER ENERGY STORAGE SUBSYSTEM

Cell Supplier = TBD
Fiberglass Wrap

+ CV-2942 RTV +

Cell Collars

Battery Housing

+ Wire =

X 21 + CV-2942 RTV +

Space Station Freedom

McDonnell Douglas • GE • Honeywell • IBM • Lockheed
PROOF-OF-PRINCIPLE TESTING OF 6-CELL BATTERY

- CELLS ARE USAF/HUGHES 50 AMP-HR DESIGN OF 1985 VINTAGE (40 AMP-HR.)

- ELECTRICAL CHARACTERISTIC TEST WILL NOT PROVIDE DATA RELATIVE TO TESS CELL/BATTERY.

- DISCHARGE EFFICIENCY TESTS WILL VERIFY THERMAL ANALYSIS AND PERFORMANCE OF BATTERY DESIGN AT 10 °C & 20 °C.
  - 1.9 °C GRADIENT ACROSS BATTERY CELL.
  - 1.7 °C GRADIENT FROM CELL TO CELL WITHIN BATTERY.
  - 9.7 °C GRADIENT FROM MIDDLE-OF-CELL (MOC) TO RADIATOR SURFACE (COLDPLATE)
  - TESS BATTERY WILL HAVE A LOWER BATTERY MOC TO RADIATOR GRADIENT DUE TO THE REDUCED HEIGHT (AXIAL/FILL TUBE)

- RANDOM VIBRATION TEST WILL VERIFY STRUCTURAL ANALYSIS AND INTEGRITY OF THIS BATTERY DESIGN.
  - TEST WILL BE CONDUCTED WEEK OF 4 NOVEMBER.
POSSIBLE DOWNSIZING OF TESS TO SUPPORT MOBILE REMOTE SERVICER BASE SYSTEM (MBS) REDESIGN

Space Station Freedom

1991 NASA Aerospace Battery Workshop - 754 - Nickel-Hydrogen Technologies Session
GROUNDRULES FOR DOWNSIZING TESS

- DESIRED RESULT IS LOWER WEIGHT AND VOLUME OF TESS.
  - SINGLE ORU IS A DESIGN GOAL.

- OPERATIONAL SCENARIOS STILL UNDEFINED.
  - REDUCE OPERATIONAL CONSTRAINTS DURING EVA/EVR MISSIONS

- REDUCTION OF TESS POWER AND ENERGY IS REASONABLE.

<table>
<thead>
<tr>
<th>WAS</th>
<th>NOW</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENERGY LEVEL</td>
<td>10 KWHR</td>
</tr>
<tr>
<td>NOMINAL POWER</td>
<td>3000 W</td>
</tr>
<tr>
<td>PEAK POWER</td>
<td>6000 W</td>
</tr>
<tr>
<td>TRANSLATION TIME</td>
<td>3.33 HRS</td>
</tr>
<tr>
<td>NUMBER OF MISSIONS</td>
<td>150</td>
</tr>
</tbody>
</table>

- MAINTAIN CURRENT LEVEL OF TESS RELIABILITY.
  - FAIL DEGRADE, FAIL SAFE
TRAVEL DISTANCE FOR MT BASED ON TESS SIZE

BASED ON FAILED BATTERY CONDITION FOR AVERAGE & PEAK LOADS

MT TRAVEL DISTANCE (FEET)

- Space Station Freedom

1991 NASA Aeronautics Workshop

McDonnell Douglas • GE • Honeywell • IBM • Lockheed
## TESS TRANSLATION OUTPUT CAPABILITY

**ASSUMING ONE EVA/EVR MISSION PER DAY.**

### TIMELINE - HOURS

<table>
<thead>
<tr>
<th></th>
<th>6, 8, OR 12</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>EVA/EVR MISSION</th>
<th>COOLDOWN/RECHARGE/ PREP FOR NEXT EVA/EVR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TESS</strong></td>
<td></td>
</tr>
<tr>
<td>• SUPPLIES 1.5 HRS OF MT TRANSLATION.</td>
<td></td>
</tr>
<tr>
<td>• SMALL AMOUNT OF COOLDOWN OR CHARGING DURING MBS OPERATIONS.</td>
<td></td>
</tr>
<tr>
<td>• POSSIBLE INCREASE OF MT TRANSLATION TIME TO 2 HRS.</td>
<td></td>
</tr>
<tr>
<td><strong>TESS</strong></td>
<td></td>
</tr>
<tr>
<td>• COOLS AND RECHARGES AS NECESSARY TO BE AVAILABLE FOR NEXT DAY'S ACTIVITIES.</td>
<td></td>
</tr>
</tbody>
</table>

**NOTE: TRANSLATION TIMES WILL BE CUT IN HALF FOR FAILED BATTERY CONDITION**
BATTERY SIZING BASED ON MAXIMUM DOD

NUMBER OF NIH2 CELLS

TOTAL BATTERY WEIGHT (LBS)

RECOMMENDED BATTERY SIZES

- 85 % DOD
- 80 % DOD
- 75 % DOD

MDES · L&ES

Space Station Freedom

McDonnell Douglas · GE · Honeywell · IBM · Lockheed
TESS BATTERY WILL BE DISCHARGE RATE LIMITED

AVERAGE POWER 2300 W
PEAK POWER 3500 W
33 NiH2 CELL BATTERY

REQUIRED BATTERY CAPACITY (AMPHRS)

TESS BATTERY ENERGY (KW-HRS)

MAXIMUM DOD 75%
MAXIMUM DISCHARGE RATE 1.2 C

Space Station Freedom

McDonnell Douglas • GE • Honeywell • IBM • Lockheed
- REMOVE ONE TESS ORU

- REMOVE 63-CELL, 90 AMP-HR NIMH2 BATTERY

- ADD TWO 33-CELL, 90 AMP-HR NIMH2 BATTERIES

- CONNECT BATTERIES IN PARALLEL TO OBTAIN REDUNDANCY
RELATED NIH2 BATTERY CELL TESTING AT NASA-JSC

- OBTAINED 8 HUBBLE SPACE TELESCOPE CELLS FROM NASA-MARSHALL SPACE FLIGHT CENTER

- PAIR CELL'S INTO FOUR, 2-CELL TEST PACKS
  - TWO PACKS FOR SSF ELECTRICAL POWER SYSTEM SCENARIOS
  - TWO PACKS FOR TESS SCENARIOS

- ESTABLISH TESS OPERATING SCENARIOS
  - DISCHARGE RATES AND DURATIONS
  - CHARGE RATES AND DURATIONS
  - STANDBY PERIODS OF CONSTANT TRICKLE CHARGE

- TEST PREPARATION IN PROGRESS
NICKEL HYDROGEN CELL DESIGN
A DESIGNER'S ASPECT

Raymond Rehm

Nickel Hydrogen Battery Cells

October 30, 1991

Gates Energy Products
Gates Aerospace Batteries
1. Scope

The following paper is designed to give added insight into the methodology of Nickel Hydrogen cell design and aid in deciphering the battery cell reference guide which has been distributed to many of GAB's current and potential customers. Due to certain information's proprietary nature, and sensitivity to international restrictions this paper is intentionally vague in some areas.

2. Cell Design

In many aspects the cell design for Gates' nickel hydrogen has been established and is not readily changeable. These areas include stack compression and support, cell seal, closure weld method and materials used for components. Gates has been granted patents for the ceramic seal design (patent number 4,904,551 issued 2/27/90) and two for the support design (patent numbers 4,950,564 issued 8/21/90 and 5,002,842 issued 3/26/91).

Gates currently utilizes the weld rings to act as the compression medium within the cell. The cell stack is compressed via a welding fixture while the cell is undergoing the final closure weld. This method of compression deloads the core and compresses the stack between the two weld rings in contact with the exterior endplates. At this point the core is used solely to electrically separate the positive and negative lead bundles.

Two domes are welded to a central cylinder which is manufactured in lengths up to ten feet. The cylinder is subsequently cut to the length required to accommodate the electrode stack and maintain compression in the welded condition. This method of compression alleviates concerns of deep drawing Nickel Alloy 718 to meet the lengths required by long electrode stacks for higher capacity cells.

The cell sealing method is performed via the GAB patented ceramic seal. This seal has demonstrated 164,000 hydraulic pressure cycles, from 0 to 1000 PSIG, without affecting the cells' hermeticity requirements.

Gates currently utilizes TIG welding for cell closure. This method has been proven reliable to the same cycling regime listed for the ceramic seal.

The component materials utilized in the manufacture of the nickel hydrogen cells have been chosen based on their individual capabilities to withstand the caustic environment of the cell for a design life in excess of 15 years without degradation. The components have also demonstrated capabilities to cycle beyond 10,000, 70 % DoD and 27,000 40 % DoD charge/discharge cycles in low earth orbit regimes at pressures up to 1000 psig of hydrogen.

![Figure 1: Specific Energy for Gates 3.5" Cells](image-url)
3. Cell Stacking Design

Each satellite operates differently in accordance with the operations which must be maintained during the charge/discharge cycle. Low Earth Orbit (LEO) and Geosynchronous Orbit (GEO) have differing cycle life and cycle requirements.

In a typical Geosynchronous orbit a cell will perform approximately 90 cycles in a year and generally less than 1500 cycles in the satellites' operational life. In a typical Low Earth Orbit, a cell will go through a charge/discharge cycle every ninety minutes. This relates to approximately 5850 cycles per year. A typical LEO satellite operational life is in excess of 5 years. For the reason, the LEO regime is considered the more stringent of the two.

A cell which can meet the rigid requirements of the LEO is more than adequate to meet the GEO satellite regime. The benefit of using a GEO satellite cell design is that the design can save enough weight to amount to pounds at the battery level. Conversely, the GEO cell design will not necessarily meet the requirements of a LEO satellite. The difference between the two, as it pertains to the cell design, is the rapidity and rate of charge/discharge and the amount of oxygen generated as a result of the stack design at the higher recharge rate required by the LEO regime. Oxygen generation and recombination is not problematic for a GEO regime from the aspect of lower recharge rates and the number of cycles required for design life.

For the reasons outlined above a stack design which is sufficient for one orbit would not necessarily be recommended for the other. Gates currently employs two designs which can be broken down to a LEO (recirculating) and a GEO (back-to-back) cell stack design. The GEO cell design also incorporates a positive electrode which is nominally thicker than the LEO cell electrode design. This makes it possible to reduce the number of electrode pairs needed to meet the capacity required for the application. The difference in the Volumetric and Mass Energies between the two cell configurations can be seen in Figures I through IV.
4. Capacity

Another major point of confusion is the question of cell capacity. There are as many ways of determining "Nameplate" as there are customers who buy NiH₂ battery cells. For this reason Gates has incorporated a singular method of determining the nameplate which is listed as the cells' cataloged nameplate. The cell nameplate is closely aligned to the nominal cell capacity output at a C/2 discharge to 1.0 volt at 10⁵°C after a C/10 charge for 16 hours. The cell characteristics change as a function of temperature, charge, and discharge rates. The requirements of nominal capacity, minimum average cell capacity, and minimum cell capacity are also concerns which must be resolved prior to signing up to any particular design.

When a customer asks for cell with a "nameplate" capacity of 63 Ah, immediate attention must be focused on the conditions under which the 63 Ah must be provided. The Gates nameplate for the cell mentioned may be anywhere from 55 to 80 Ah, but we are committed to delivering the lightest cell that will meet the requirements of your application for the life of the satellite. A sample of cell capacity design analysis will be demonstrated in the presentation.

Gates utilizes the experience gained in over 25 years of development and manufacture of Nickel Cadmium and Nickel Hydrogen as well as testing and in-flight use to calculate the beginning-of-life capacity required to assure adequate end-of-life capacity for the application. This information (over 1,000,000 cell cycles includes capacity based on cell temperature, discharge rate, charge/discharge regime, previous usage, and point-in-life. The information that has been accumulated coupled with the data management systems available in today's computer systems, allows Gates to project cell responses to various normal and abnormal cell uses.

Figure 3. Energy Density of Gates 3.5" Cells
5. Dynamic Response

The cells’ response to the dynamic environments of launch are a major concern to the satellite industry. The satellite will be subjected to extreme vibration and acceleration, and potentially to dynamic shock. In qualification for flight use, the customer frequently requires that a test for response to these phenomena be performed. The ability of the cell to perform in these dynamic environments is based on the cells’ relative rigidity. The internal components are being tested to assure that they are not being detrimentally compressed and released. This is a test to prove that the compression method used for the cell maintains the stack in compression for the environment that the cell will see during launch. A wide fluctuation in voltage caused by vibration would indicate that the electrode stack is inadequately constrained within the cell. By using the endplates on either end of the cell stack in compressive contact with the weld rings, Gates is confident of the cells’ ability to meet the dynamic requirements of launch and in fact has met the qualification requirements for flight on expendable vehicles.

6. Conclusions

In making a cell reference guide available to the general customer pool, the supplier takes on many risks, including the chance that the guide will be used as a rigid document by which to plan the end item weight of the battery component of the satellite. This can be performed if the guide is used as it is intended but there is more to be considered than the “nameplate” and the weight. Use the guide to assess the approximate requirements for the application and decide if there is adequate margin for weight. If you have any questions on how the guide is intended to be used, contact the cell supplier for further information.
GE Astro Space

THE EARTH OBSERVING SYSTEM (EOS)
NICKEL-HYDROGEN BATTERY

PRESENTED BY
CHARLES W. BENNETT
GENERAL ELECTRIC COMPANY

FOR PRESENTATION AT
THE NASA AEROSPACE BATTERY WORKSHOP
HUNTSVILLE, ALABAMA
OCTOBER 29-31, 1991

PRECEDED PAGE BLANK NOT FILMED

1991 NASA Aerospace Battery Workshop -769- Nickel-Hydrogen Technologies Session
LIFE EVALUATION TEST PHASE

HARDWARE FROM TWO VENDORS
12 CELLS FROM EACH
STRAIN GAGES ON ALL 12 CELLS
PRESSURE TRANSDUCERS ON 4 CELLS

ACCEPTANCE TESTS
PERFORMED AT VENDOR ON ALL CELLS

CHARACTERIZATION TESTS
NINE CELLS
3 CELLS WITH PRESSURE TRANSDUCERS
TESTED AT GE ASD

LIFE TEST
SEVEN CELLS
3 CELLS WITH PRESSURE TRANSDUCERS
TESTED AT GE ASD

ADDITIONAL TESTS
THREE CELLS
1 WITH PRESSURE TRANSDUCER
TESTED AT NASA GSFC
CELL DESCRIPTION

GENERAL

50 AMPERE HOUR NAMEPLATE

3.523 INCHES MAXIMUM OD

RABBIT EAR TERMINAL CONFIGURATION

DOUBLE LAYER ZIRCAR SEPARATOR

BURST FACTOR 3.0 MINIMUM
<table>
<thead>
<tr>
<th>VENDOR COMPARISON</th>
<th>VENDOR A</th>
<th>VENDOR B</th>
</tr>
</thead>
<tbody>
<tr>
<td>CELL WEIGHT (LOT AVE.) GRAMS</td>
<td>1476</td>
<td>1515</td>
</tr>
<tr>
<td>CELL LENGTH (DOME TO DOME)</td>
<td>7.820</td>
<td>6.991</td>
</tr>
<tr>
<td>TERMINAL SEAL</td>
<td>ZIEGLER</td>
<td>CERAMIC</td>
</tr>
<tr>
<td>ELECTRODE CONFIGURATION</td>
<td>BACK-BACK</td>
<td>RECIRCULAT.</td>
</tr>
<tr>
<td>PLAQUE</td>
<td>SLURRY</td>
<td>SINTER</td>
</tr>
<tr>
<td>ELECTROLYTE - % KOH</td>
<td>31.0</td>
<td>31.0</td>
</tr>
<tr>
<td>PRECHARGE</td>
<td>NICKEL</td>
<td>HYDROGEN</td>
</tr>
<tr>
<td>WALL WICK</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>CATALYZED</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>PRESSURE VESSEL THICKNESS (INCHES)</td>
<td>0.023</td>
<td>0.024</td>
</tr>
<tr>
<td>BURST PRESSURE (PSIG)</td>
<td>2900</td>
<td>2700</td>
</tr>
<tr>
<td>PREDICTED MEOP (PSIG)</td>
<td>705</td>
<td>800</td>
</tr>
<tr>
<td>BURST FACTOR</td>
<td>4.1</td>
<td>3.38</td>
</tr>
</tbody>
</table>
THREE OVERCHARGE TESTS (-5C, 10C, 25C)
CHARGE @ C/20 FOR 48 HOURS
DISCHARGE @ C/2

THREE (MINIMUM) BURN IN CYCLES, C/2 @ 10C

SEVEN CAPACITY CHARGE/DISCHARGE CYCLES (WITH LETDOWN)

<table>
<thead>
<tr>
<th>DISCHARGE RATE</th>
<th>TEMPERATURE (DEG C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-5</td>
</tr>
<tr>
<td>C/2</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

ONE PULSE DISCHARGE TEST (10C)
2C FOR 20 SECONDS
DISCHARGE @ C/2

ONE CHARGE RETENTION TEST (10C)
72 HOUR 0C STAND
DISCHARGE @ C/2
# Characterization Tests

**Two (Minimum) Conditioning Cycles, C/2 @ 10°C**

**Eleven Capacity Charge/Discharge Cycles**

<table>
<thead>
<tr>
<th>Discharge Rate</th>
<th>Temperature (Deg C)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-10</td>
<td>-5</td>
<td>0</td>
<td>5</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>C/2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

**One Overcharge Tests (-10°C)**

- Charge @ C/20 for 48 hours
- Discharge @ C/2

**Two Charge Retention Tests (10°C)**

- 72 Hour DC Stand
- Discharge @ C/2

**Twelve Voltage/Temperature Characterization Tests**

- Three Separate V/T Levels
- Four Test Temperatures (-10°C, 0°C, 10°C, 20°C)
LIFE TEST

TESTED AS SEVEN CELL BATTERY PACKS
ONE PACK PER VENDOR
MOUNTING TO SIMULATE ACTUAL BATTERY ASSEMBLY
    VERTICAL MOUNT
    CONDUCTIVE THERMAL SLEEVES
    COLD PLATE
    THERMAL BLANKET

TEST TEMPERATURE: 5C +/- 2C

TEST DURATION: 5 YEARS (26,500 CYCLES)

CHARGE PARAMETERS
    64 MINUTES
    COMPOSITE REGIME (TBD AMPS TO V/T, CLAMP AT V TO TBD C/D,
    TRICKLE TO END OF CHARGE)

DISCHARGE PARAMETERS
    34.9 MINUTES
    DISCHARGE AT C/2 (25 AMPS)
    14.8 AMPERE HOURS (29.6% DOD, BASED ON NAMEPLATE)
BATTERY SYSTEM DESCRIPTION

GENERAL
FOUR BATTERIES PER SATELLITE
TWO BATTERY PACK ASSEMBLIES PER BATTERY
27 CELLS PER BATTERY PACK ASSEMBLY
216 CELLS TOTAL

BATTERY PACK ASSEMBLY
27 CELLS
TOTAL WEIGHT: 118 POUNDS MAXIMUM
ENVELOPE: 24" LONG X 20" WIDE X 9.25" HIGH
CELLS ARE VERTICAL MOUNTED
CONDUCTIVE THERMAL SLEEVES
LETDOWN/RECONDITIONING CIRCUITRY
REDUNDANT HEATERS ON EACH CELL
BYPASS DIODES
INDIVIDUAL CELL VOLTAGE MONITORING
PRESSURE MONITORING (2 CELLS)
FAULT TREE ANALYSIS

NiH₂ AEROSPACE CELLS

FOR LEO MISSION

Glenn C. Klein
Gates Aerospace Batteries

Donald E. Rash, Jr.
Reliability Analysis Center
FAULT TREE ANALYSIS, NiH₂ AEROSPACE CELLS FOR LEO

Glenn C. Klein
Gates Aerospace Batteries

Donald E. Rash Jr.
Reliability Analysis Center

Abstract
The Fault Tree Analysis (FTA) is one of several reliability analyses or assessments applied to battery cells to be utilized in typical Electrical Power Subsystems for spacecraft in LEO missions. FTA is generally the process of reviewing and analytically examining a system or equipment in such a way to emphasize the lower-level fault occurrences which directly or indirectly contribute to the major fault or top-level event. This Qualitative FTA addresses the potential of occurrence for five specific top-level events: HYDROGEN LEAKAGE through either discrete leakage paths or through pressure vessel rupture; and, four distinct modes of performance degradation - HIGH CHARGE VOLTAGE, SUPPRESSED DISCHARGE VOLTAGE, LOSS OF CAPACITY, and HIGH PRESSURE.

Relationship Between Reality, System Model, and Decision Process
Figure 1 schematically depicts one decision making process wherein we may explore the relationship between reality, some model of our system, and the decision process. REALITY is defined by a system of internal and external boundaries. OUR PERCEPTION OF REALITY is defined by the Fault Tree. BASIS FOR DECISION, in this case some measured acceptance of risk, is justified by the degree to which redesign, qualification tests on parts and materials and discrete inspection or test points were utilized. Figure 2 illustrates a generic system to be analyzed with external and internal boundaries. Hence, ITEM E is the Power Sub-System and ITEM F is the Battery Assembly wherein items a-to-r would be individual cells.
FIGURE 1: RELATIONSHIP BETWEEN REALITY, SYSTEM MODEL, AND DECISION PROCESS

FIGURE 2: SYSTEM DEFINITION: EXTERNAL AND INTERNAL BOUNDARIES
The external boundaries describe the interface which the battery assembly, and ultimately the individual cells, experiences in the LEO mission profile. A typical profile requires continuous duty in combination with a solar array to store energy for use during peak power demands and eclipse periods, and may include:

a) 35% Depth of Discharge within 35 to 40 minutes followed by a C/1.67 rate recharge in 50 to 60 minutes
b) nominal temperature range of 0 to 30°C
c) a dynamic mechanical environment during the launch phase including a wide, but well defined spectrum, of random vibration; typical sustained acceleration of 20 g; and broad range of shock spectra
d) life and reliability requirements including on station calendar life of 5.5 years MTBF and a design cycle life of 41,000 cycles

The internal boundaries are described by the cell design and include the rudimentary details such as pressure vessel material composition and thickness, and the electrochemical characteristics of the nickel-hydrogen couple as well as the decision to use a recirculating stack design.

The degree to which a fault described in the Fault Tree may result in battery failure or performance degradation is masked somewhat by the availability of in-flight data; this could be equated to the Limit of Resolution in our generic system of Figure 2. The degree to which the actual mission profile conforms to the intended profile combined with the ability of the NiH₂ cell to perform its intended function, irregardless of the nonconformance, is a measure of "robustness of design."

Basics of Fault Tree Analysis (FTA)
Figure 3 illustrates symbols typical of those used in our NiH₂ FTA; numerous others are available see Reference 2. The rectangle contains a brief description of the top-level event and appears at top of the tree. The rectangle is also used in this tree to signify a lower-level event and contains a brief description; these lower-level events occur throughout the tree and have both their input and output from a logic gate. The circle represents a basic or the lowest-level event which may cause a fault to occur and is used as an input to a logic gate. The diamond is a transfer
FIGURE 3: FAULT TREE SYMBOLOGY
function and is used to signify a connection between two or more sections of the fault tree. Logic Gates include the OR Gate for which output occurs when one or more of the input events occur; whereas, the AND Gate only occurs if all the inputs exist simultaneously.

**Failure Effects, Failure Mode, and Failure Mechanism**

Understanding and defining how a specific failure mechanism produces a discrete failure mode which may effect system operation is important for determining the proper inter-relationships among the events. In addition, the orientation of the analysis, that is whether to concentrate on system response symptoms or specific signatures generated by active components, determines both the success of the analysis and the effectiveness of resulting remedial actions. Failure Effects: what are the effects of the failure, if any, on the system. Failure Mode: what aspect, condition, or position is of concern. Failure Mechanism: what particular mechanism or vehicle prompts the failure mode to occur and what likelihood of occurrence exists. Thereafter, failures may be classified as to component, environmental, human, or software. Component failures occur at the lowest level of examination and may in fact be discrete parts or materials. Environmental failures occur when the system is placed in an environment which the system was not designed to operate in and where overstress has now occurred. Human failures occur due to operator error and are most difficult to quantify given the unpredictably of humans in the elevated stress levels typically accompanying sophisticated, high reliability systems. Software failures are simply errors in the controlling software, but may be considered a sub-set of human failures or component failures. Notwithstanding these failure definitions, their existence simply becomes the further definition of internal and external boundaries of the system under analysis.

**Top-Down Approach of the Fault Tree versus Bottoms-Up Approach of the FMECA**

The top-down approach of the FTA presupposes sufficient examination of the system to enumerate the top-level events or major system performance failures. Thus, the examination and resulting analyses are limited to events which cause the top event to occur. This deductive approach postulates the opportunity for top level failure thereafter reconstructing events or behavior at the lower levels which contribute to this failure. The bottoms-up approach of the FMECA is inductive in
nature. This approach postulates numerous faults or initiating conditions and then attempts to determine the effect of that fault or condition on system operation and integrity. Generally, the FMECA tends to be initially more descriptive as a risk analysis and risk reduction tool because their format typically includes existing/projected compensation or control measures.

Qualitative Fault Tree for NiH₂ LEO

The discussion of faults versus failures necessarily assumes that the fault condition is of sufficient significance and magnitude to cause upper level failure events. Therefore, the role of various contaminants is not an idle reference in the fault tree of Figures 4 thru 22. There is no further assumption nor is there an attempt to yet quantify the level of contamination since some contaminants in small ppm may cause significant events which may lead to failure. No further assumption as regards passive versus active components and their significance is made either. When we analyze the pressure vessel for catastrophic burst and find the present design to leak before burst, there can not be an accompanying assumption which relegates this vessel to a passive component. The fault tree clearly shows a leaking pressure vessel to be an active contributor to upsetting the electrochemistry of the nickel-hydrogen couple which may eventually lead to either outright failure or performance degradation.

Five specific primary faults or top-level events addressed in the fault trees of Figure 4 are: HYDROGEN LEAKAGE through either discrete leakage paths or through pressure vessel rupture (discounted as a potential failure through both this analysis and the Fracture Control Plan); and four distinct modes of performance degradation (1) HIGH CHARGE VOLTAGE, (2) SUPPRESSED DISCHARGE VOLTAGE, (3) LOSS OF CAPACITY, and (4) HIGH PRESSURE.

Hydrogen Leakage

The critical fault, hydrogen leakage, was created in the classical fault tree analysis. By assuming the worst case scenario it was determined that the hydrogen leakage was and is the worst possible fault. All construction techniques were assessed from the top down to determine the different paths the leakage might occur. This event is typical of most NiH₂ pressure vessels and presents a generic path of construction criticality. By placing probabilities in each of the
lower fault events a manufacturer will be able to construct a detailed quantitative fault tree.

**High Charge Voltage**
This fault is divided into three generic failure modes of which two are identical to Loss of Capacity. These generic failure modes are further divided into specific failure modes which can be identified or traced back to respective FMEA failure modes. Some of these failure modes have been traced to their failure causes. These expanded fault trees may have no failure modes associated with them because either they are failure causes or are under review for inclusion into the growing Operational FMEA database.

**High Pressure**
Only two generic failure modes cause high pressure and one is unique to this fault. The flooding of the negative membrane is an operational fault that is a result of various contamination failures. We do not have FMEA worksheets filled out for contamination as it usually is identified in various FMEA worksheets as a failure cause.

**Loss of Capacity**
This fault tree is the least extensive of the operational critical faults. This is because it is associated with wearout mechanisms of the NiH$_2$ battery cell that are not modeled and has duplicity in other failure modes. The purpose of this fault tree is to show unique failure mechanisms associated with just Loss of Capacity. The loss of capacity has been divided into two larger groups of generic failure modes. These in turn have been broken down into other root causes and easily identifiable failure modes.

**Suppressed Discharge Voltage**
This fault tree is broken down into three specific failure modes identified by the operational FMEA worksheet numbers and one failure mode associated with NiH$_2$ wearout. A particularly interesting feature of this fault tree is that both hard and soft shorts can be caused by conductive particles. The conductive particle fault tree shows how these particles can be inherent to a fault process or introduced as foreign particles from material handling.
FIGURE 4
FIGURE 5
FIGURE 6
FIGURE 7
Contamination

Contamination of Positive Plate

Contamination of Platinum Material

Contamination of Plate Grid or Sinter

Contamination of Polysulphone Piece Parts

Contamination of Substrate

Contamination of Electrolyte

Contamination of Foam

Contamination of Ceramic Insulators

FIGURE 8
FIGURE 9
FIGURE 12
FIGURE 14
FIGURE 16
FIGURE 17

Loss of Capacity

Activity Loss

Open

3

4
FIGURE 18
FIGURE 19

1991 NASA Aerospace Battery Workshop
Nickel-Hydrogen Technologies Session
Contamination

- Contamination of Positive Plate
- Contamination of Polysulphone Piece Parts
- Contamination of Negative Plate
- Contamination of Electrolyte
- Contamination of Ceramic Insulators
- Contamination of Plate Grid of Sinter
- Contamination of Platinum Material
- Contamination of Substrate
- Contamination of Zorlex

FIGURE 21
Failure Modes and Effects Analysis on Gates NiH$_2$ Battery for LEO Mission

**FMEA NO.: CA-4B**
- **Critical Item (Yes/No): Yes**
- **Item Name:** Girth weld
- **Part Number:** 149C130A11
- **Quantity:** 1
- **Hardware Location:** (Internal)
- **System:** NiH$_2$ Battery
- **Subsystem:** Cell assembly
- **Reference Designator:**
- **Operating Verification:**
  - (A) **Checkout**
    - (1) Prelaunch **PASS**
    - (2) On Orbit **FAIL**
  - (B) **Detectability** PASS
  - (Appropriate Mission Phases)

**Reliability Analysis Center**
- **Prepared By:** D. Rash
- **Approved By:** G. Ebil

**Gates Battery**
- **Prepared By:**
- **Approved By:**

**Document Number:** RAC NiH$_2$ Battery FMEA
**Document/Revision Date:** 14 June 1991
**Critical Category:** 1
**Failure Effect Phase:**
- X (A) Prelaunch
- X (B) Transportation
- X (C) Assembly
- X (D) Permanently Manned Capability (PMC)
**Is Function Restorable on Orbit? Battery Cell Only**
**ORU Level:** TBD
**Part Name:**
**Part Number:**
**ORU Failure Detectability:** Yes TBD

**EVA Required (Yes/No):** TBD

**Function:** Girth weld
**Failure Mode:** Poor weld quality (cracks, inclusions, low strength, porous)

**Failure Cause(s):** Improper material choices, improper weld techniques; irregularities in weld surfaces; weld surfaces contaminated; weld gas contaminated; inadequate purge gas flow

**Failure Detection/Verification:** Physical, visual, pressure and leakage tests
**Correction Action:**
  - (A) Short Term: Article inspection
  - (B) Long Term: Control welding process

**Time to Effect:** Days
**Failure Effect On:**
  - (A) Crew/TBD
  - (B) Mission Support
  - (C) System Loss of capacity
  - (D) Interfaces

**Rational for Acceptability:**
- (A) Design Safety factor of 3 for burst/operating pressure & safety factor of 4 for burst/operating cycles
- (B) Test Hydrogen leak, chemical leak, cycle, burst and proof tests
- (C) Inspection First article and first piece
- (D) Failure History
- (E) Operations
- (F) Maintainability NA

**Remarks/Hazards:** HAZARD POTENTIAL - Leakage of Hydrogen

FIGURE 23
Establishing Parity with the FMECA

An example of a completed failure mode effects analysis worksheet (Figure 23) is provided to demonstrate how the failure causes are attributed to fault events, in this case Girth Weld Breakdown. The numbering system has been assigned to manufacturing flow steps and the example is FMEA number CA-4B. The failure mode corresponds directly to an event that has three distinct events associated to the upper level event.

Conclusion

The decision process for either qualitative or quantitative analyses is tempered by our view of reality and some model of our system under anlaysis; and, further constrained by our expectations of the external boundaries and robustness of the design. The Fault Tree Analysis is not a stand alone technique due to the top down approach which presupposes the determination of all Top-level or Major fault events; however, the Fault Tree when in a graphic, visual format is an excellent tool for technical reviews. Fault Tree Analyses can be quantified in areas such as System Assessment, Confidence Analysis, and Sensitivity Analysis. The Qualitative Fault Tree Analysis for NiH$_2$ cells in LEO Mission identifies and analyzes five specific Top-Level failure events; quantification of this Fault Tree has already begun.

References


50 Ah Ni H2 CELL LIFE TEST RESULTS

by

Thierry JAMIN
CNES - Toulouse Space Center, France

and

Olivier PUIG
SAFT Aerospace department
HISTORIC

DEVELOPMENT OF A MEDIUM CAPACITY RANGE (30 - 50 Ah) IPV SAFT Ni H2 CELL (1985 - 1988)

SHORT TERM QUALIFICATION TESTING REALISED BY MID 1988

Table 1: Qualification Test Programm

- 22 cells
- 6 vessels with sleeves
- burst tests
- fatigue tests
- safety tests
- thermal tests
- vibration tests
- life tests

1991 NASA Aerospace Battery Workshop -810- Nickel-Hydrogen Technologies Session
SAFT 50 Ah CELL DESIGN (VHS BL SERIE)

MECHANICAL/VESSLE DESIGN

- PRESSURE VESSEL MADE OF HEAT TREATED INCONEL 718 PARTS.
- VESSEL DIAMETER IS 3.2 INCHES AND OVERALL LENGTH IS 8 INCHES.
- WALL THICKNESS IS 0.024 INCHES.
- TERMINALS: BRAZED CERAMIC FEED THROUGH. "RABBIT EAR POSITION"
- FILLING TUBE: HARDENED INCONEL (T TERMINALS PLAN)
- TIG WELDING TECHNIQUE FOR ALL JONCTIONS.
- MOP: 1070 PSI/SAFETY FACTOR: 2.5.
**SAFT 50 Ah CELL DESIGN**

*(VHS BL SERIE)*

- **FILLING TUBE**
- **TERMINALS**
- **PRESSURE VESSEL** *(INCONEL 718)*
- **UPPER END PLATE**
- **ELECTRODE STACK**
- **CENTRAL TIE ROD**
- **LOWER END PLATE**
- **BELLEVILLE WASHERS**
- **SLEEVE (AL ALLOY)**

SAFT 50 Ah CELL DESIGN (VHS BL SERIE)

ELECTROCHEMICAL/STACK DESIGN

GENERAL
- BACK TO BACK CONFIGURATION/MONO STACK.
- CENTRAL TIE ROD/EXTERNAL CONT. LEAD ASSEMBLY
- RIGID END PLATES/EXPANSION SYSTEM
- REDUCED STACK/WALL GAP.

POSITIVE ELECTRODE
- POROUS *NICKEL SINTER (OPTIMIZED POROSITY).
- IEC ACTIVE MATERIAL (APPROPRIATE LOADING).

NEGATIVE ELECTRODE
- CURRENT COLLECTOR: EXPANDED NICKEL GRID.
- CATALYST: PT CHARCOAL + TEFLOMISED BINDER.
- HYDROPHOBIC BACK LAYER: MICROPOROUS PTFE.
SAFT 50 Ah CELL DESIGN (VHS BL SERIE)

- MULTILAYERED NON WOVEN POLYAMID FELT.
- WOVEN NYLON MATERIAL.
- 31 % w KOH (BEFORE ACTIVATION)

ELECTROCHEMICAL/STACK DESIGN (suite)

SEPARATOR
GAS - SCREEN
ELECTROLYTE

THERMAL DESIGN
SINGLE PIECE SLEEVE TO BASEPLATE
LIGHT - ALLOY
GAP INTERFILLER
POLYMERIC RESIN
**SAFT 50 Ah CELL DESIGN (VHS BL SERIE)**

**ELECTRICAL CHARACTERISTICS**

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPACITY</td>
<td>51.5 Ah</td>
</tr>
<tr>
<td>ENERGY DENSITY</td>
<td>48 Wh/Kg</td>
</tr>
<tr>
<td>VOLUMIC ENERGY</td>
<td>70 Wh/L</td>
</tr>
<tr>
<td>INTERNAL RESISTANCE</td>
<td>&lt; 3 mΩ</td>
</tr>
</tbody>
</table>

**MEAN VALUES ON THE QUALIFICATION LOT.**

![Graph showing available capacity vs. temperature for C/5, C/2, and C/1 rates.](attachment:graph.png)
SAFT 50 Ah CELL LIFE TEST

PURPOSE

- TO PERFORM AN ACCELERATED GEO LIFE TEST.
- TO STUDY SENSITIVITY TO MANAGEMENT PARAMETERS.
- TO ASSESS THE EFFECT OF RECONDITIONNING.

OBJECTIVE

- TO EVALUATE LONG TERM ABILITY OF THE DESIGN.
- TO DEMONSTRATE AT LEAST 10 YEARS OF OPERATION.

SCHEDULE

- START UP JULY 1988
- END SEPTEMBER 1991
SAFT 50 AH CELL LIFE TEST

TEST CELLS AND APPARATUS

- NINE CELLS TAKEN FROM THE QUALIFICATION BATCH (1/3 VIBRATED).
- COMPACT INDIVIDUAL SLEEVE MOUNTING ON A COLD PLATE (VERTICAL).
- THERMAL BLANKET TO LIMIT CONVECTION EXCHANGE.
- SAFETY DEVICES (TEMPERATURE CONTROLLER, HYDROGEN DETECTOR, ETC...).
- ANTI DEFLEGRATING CHAMBER.
SAFT 50 Ah CELL LIFE TEST

GEO CYCLING CONDITIONS-GENERAL

- 45 CYCLES ECLIPSE SEASON.
- REAL TIME ECLIPSE PROFILE WITH 72 MINUTES MAXIMUM DISCHARGE TIME.
- 12 HOURS SIMULATED ECLIPSE PERIOD
- REDUCED SOLSTICE SIMULATION.
- RECONDITIONNING + STANDARD CAPACITY MEASUREMENT.

LIFE TEST PARAMETERS

- DISCHARGE REGIM C/1.7
- DOD 70 %
- CHARGE REGIM C/14
- RETURN FACTOR 1.15 - 1.17
- REGIM C/200 - C/100
- REFERENCE TEMPERATURE 10°C
SAFT 50 Ah CELL LIFE TEST

RESULTS

DISCHARGE VOLTAGE EVOLUTION

- STABILITY FOR MEAN DISCHARGE VOLTAGE (1.28 V).
- SLIGHT DECREASE FOR EOD VOLTAGE: 1.16 V/EOL.

![Graph showing discharge voltage evolution](image-url)
SAFT 50 Ah CELL LIFE TEST RESULTS

END OF CHARGE PRESSURE EVOLUTION REFERENCE CYCLE

- NO PRESSURE STABILITY ALONG THE WHOLE TEST.
- AT MAXIMUM CYCLING PRESSURE $\Delta P$ IS 4 BARS.
SAFT 50 Ah CELL LIFE TEST RESULTS

STANDARD CAPACITY MEASUREMENT

- AFTER: CC ON A RESISTANCE (16 H).
- CHARGE AT C/5 WITH A CHARGE RATIO OF 1.54.
- OPEN CIRCUIT DURING 1 HOUR.
- DISCHARGE WITH TWO STEPS: C/2 TO 1 V, C/5 TO 0.5 V
- ALL OPERATIONS AT 10°C.
SAFT 50 Ah CELL LIFE TEST RESULTS

STANDARD CAPACITY MEASUREMENT

- OVERALL CAPACITY REMAINS VERY STABLE.
- SLIGHT STANDARD CAPACITY FADING (54 - 49 Ah)

WITH CORRESPONDING RESIDUAL INCREASE.
SAFT 50 Ah CELL LIFE TEST RESULTS

COMPARISON BETWEEN ON CYCLE AVAILABLE CAPACITY AND STANDARD CAPACITY

- CAPACITY AT 1 V UNDER CYCLING DISCHARGE REGIM REPRESENTS 80 TO 95 % (WRT STANDARD CAPACITY).
- DEPENDS ON STATE OF CHARGE (AND K VALUE, FLOATING REGIM, TEMPERATURE).

1991 NASA Aerospace Battery Workshop - Nickel-Hydrogen Technologies Session
SAFT 50 Ah CELL LIFE TEST RESULTS

COULOMBIC EFFICIENCY EVOLUTION FOR REFERENCE CYCLE

- SMALL DISCHARGE EFFICIENCY DIMINUTION/TO COUPLE WITH MAX PRESSURE EVOLUTION.

![Graph of SAFT 50 Ah Cell Life Test Results]
SAFT 50 Ah CELL LIFE TEST RESULTS

CONSTANT POWER DISCHARGE EFFECT AND TRICKLE CHARGE EFFECT

- ON SEASONS 29 TO 31 CELLS WERE SPLITTED ON 3 GROUPS.
  . STD CYCLING (FOLLOW ON) 3 CELLS.
  . CONSTANT POWER DISCHARGE 3 CELLS
  . TRICKLE CHARGE : CONTINUOUS C/90 FOR TWO MONTHS 2 CELLS

- ONE CELL OUT OF SERVICE (SHORT CIRCUIT) DUE TO TEST ERROR AND INSULATION FAILURE.
COMPARISON BETWEEN CONSTANT CURRENT AND CONSTANT POWER DISCHARGE

SEASON 31, CYCLE 23.

- DISCHARGE VOLTAGE AT P ct IS HIGHER THAN AT I ct.
- EOD VOLTAGES ARE IDENTICAL.
- CURRENT IS 10 % HIGHER (WRT I CT) AT END OF DISCHARGE.
SAFT 50 Ah CELL LIFE TEST RESULTS

RECONDITIONNING EFFECT

- CELL 9 WASN'T RECONDITIONNE AFTER SEASON 26.
- DIRECT EFFECT IS OBSERVED ON SEASON 27.

END OF DISCHARGE VOLTAGE EVOLUTION
SAFT 50 Ah CELL LIFE TEST RESULTS

TEMPERATURE EVOLUTION

- CONDUCTION GRADIENT BETWEEN CELL/SLEEVE WALL AND BASEPLATE ARE SLIGHTLY RISING AS AN AGEING EFFECT WITH CYCLES.
SAFT 50 Ah CELL LIFE TEST RESULTS

EOD CURRENT PROFILE (POWER ct) SEASON 29

ASYMMETRIC CURVE WITH MAXIMUM AT CYCLE 30.
SAFT 50 Ah CELL LIFE TEST RESULTS

TRICKLE CHARGE EFFECT

- CONTINUOUS CHARGE AT C/90 ENHANCE STATE OF CHARGE.
- AS DIRECT RESULT ON CYCLE DISCHARGE CAPACITY IS IMPROVED (50 Ah VERSUS 47 Ah) BUT STD CAPACITY ISN'T AFFECTED.
- DISCHARGE VOLTAGES ON SEASON 31 (AFTER TWO MONTHS OF TRICKLE) ARE 10 mV HIGHER/CELLS WITHOUT TRICKLE.
SAFT 50 Ah CELL TEST RESULTS

SUMMARY

- 33 ECLIPSE SEASONS COMPLETED AND MORE THAN 3 YEARS OF CYCLING REALISED.
- RECONDITIONNING IS MANDATORY TO INSURE SATISFACTORY EOD VOLTAGES.
- AVERAGE EOD VOLTAGES NEVER SLOW DOWN 1.16 V/CELL.
- REAL DOD NEVER EXCEED 73% / CAPACITY FADING ENCOUNTERED.
- NO ELECTRICAL LIMITATIONS WITH CONSTANT POWER DISCHARGE.

ADDITIVES

- DPA RUN ON FAILED CELL.
- EXTENSIVE CHARACTERIZATION PROGRAMM IS SET UP AND WILL BE RUN SOON.

IMPLEMENTED DATA

- ANOTHER LIFE TEST HELD AT AEROSPATIALE (20 SEASONS PLANNED).
  nine 50 Ah SAFT CELLS.
  70% DoD; 10°C; REAL TIME ECLIPSE; K = 1.12;
  AFTER 9 SEASONS RESULTS ARE VERY SIMILAR.
SAFT 50 Ah CELL LIFE TEST

CONCLUSIONS

EXPECTED GOAL (10 YEARS) LARGELY COMPLETED IN EXCESS.

- VHS BL SERIE EXHIBIT A GOOD BEHAVIOUR.
- THIS TECHNOLOGY AUTHORIZED MORE THAN 15 YEARS AT 70 % DoD AND 10°C ON ACCELERATED TESTING.

NEXT STEP WILL CONSIST ON A LIFE TEST TO PERFORM ON 20 VHS 90 CM SAFT CELLS.

- LIFE TEST AT BTC/ESA/ESTEC.
- FIVE YEARS LIFE TEST.
Use of Semi-Automated Test Systems for Nickel-Hydrogen Cells and Batteries

Steve Girard
Eagle-Picher Industries, Inc.
Joplin, Missouri
NICKEL-HYDROGEN TESTING AT EPI

* TEN CELL TEST SYSTEMS -- 1000 CELLS

* FOUR BATTERY TEST SYSTEMS -- 15 BATTERIES

* AN ADDITIONAL TWO-BATTERY SYSTEM IS BEING BUILT

* MULTIPLF. LIFE TESTS AND SPECIAL TEST EQUIPMENT

* LONGEST LIFE TEST IS NOW OVER SIX YEARS

* ALL SYSTEM HARDWARE AND SOFTWARE ARE DESIGNED, BUILT, MAINTAINED BY IN-HOUSE PERSONNEL

* ALL TEMPERATURE CONTROL SYSTEMS FOR PRODUCTION TESTING ARE BUILT IN-HOUSE
TEST DATA

* REAL TIME GRAPHICS
* THIRTY MINUTE HISTORICAL PLOTS DURING TEST
* DATA OUTPUT ON DISK AND PAPER
* EVENT SUMMARY
  * AMPHOURS
  * WATTHOURS
* MAX/MIN VOLTAGE VS. TIME
* VOLTAGE AND TEMPERATURE VS. TIME PLOTS
* LIST OF EXCEPTIONS
**Output Time:** 10:23:51  10 Oct 1991

**EVENT 7**  Charge at 9.3 Amps for 12 Hours

**Élapsed Time:** 02:01:20

### Left Cart
- **Volts:** 1.48, 1.45, 1.50
- **Watts:** 20.80, 21.00
- **Temp:** 19.94

### Right Cart
- **Volts:** 1.48, 1.45, 1.50
- **Watts:** 20.80, 21.00
- **Temp:** 19.94

---

**Sample Real Time Graphics**

---

**Sample Historical Plot**
### Sample Summary Sheets

#### Activation and Conditioning / Cell Selection

**Cell: RH-MXX-X**  
Lot No. 14  
Paragraph 5.2.2

**TEST EVENT 52**  
Cell Matching Discharge

**Time to bypass at 1.000 volt**

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<th>AH</th>
<th>Cell PMSS</th>
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</table>

#### SNAPSHOTS

- **Event start:** 04:22:51 20 Sep 1991  
- **Event stop:** 12:02:56 20 Sep 1991  
- **Event duration:** 04:22:04  
- **Lead duration:** 04:22:00  
- **Difference:** 00:00:44  

**No:**  
**Elapsed Description**  
1 00:25:10 abort due to BYPASS FAILURE, Open circuit for 00:04:40  
2 00:54:10 Test restart at 20 Sep 1991 07:50:09, System down for 00:00:18  
3 01:59:10 Operator pause, Open circuit for 00:00:49  
4 01:59:10 Interruption for TC BYPASS, Open circuit for 00:00:49  

**Event start:** 04:22:51 20 Sep 1991  
**Event stop:** 12:02:56 20 Sep 1991  
**Event duration:** 04:22:04  
**Lead duration:** 04:22:00  
**Difference:** 00:00:44
STANDARD CELL LEVEL TESTING

- MONITORING CAPABILITY - 120 CELL VOLTAGES
- 20 THERMOCOUPLES
- CHARGE CAPABILITY - 0 TO 125 AMPS
- DISCHARGE CAPABILITY - 15 TO 125 AMPS CONTINUOUS
- 125 TO 180 AMP PULSES (10 SECONDS TO 5 MINUTES)
- BYPASS CAPABILITY - INDIVIDUAL CELLS

TEST SYSTEM CONFIGURATION:

- HEWLETT PACKARD 310 COMPUTER
- HEWLETT PACKARD 9153C 10Mb HARD DISK W/3.5" FLOPPY
- HEWLETT PACKARD 2934A PRINTER W/ INTELLIGENT INTERFACES BUFFER
- HEWLETT PACKARD 3852A DATA ACQUISITION AND CONTROL UNIT
- HEWLETT PACKARD 3853A DACU EXTENDER
- ELECTRONIC MEASUREMENT INCORPORATED EMHP-150-200 POWER SUPPLY
STANDARD CELL LEVEL TEST SYSTEM
STANDARD BATTERY LEVEL TESTING

- Monitoring capability - 31 cell voltages per battery
- 10 thermocouples per battery
- 12 additional voltage channels per battery
- Charge capability - 0 to 125 amps
- Discharge capability - 5 to 125 amps continuous
- 125 to 180 amp pulses (10 seconds to 5 minutes)

TEST SYSTEM CONFIGURATION:
- Hewlett Packard 300 Series Computer
- Hewlett Packard 9153C 10Mb Hard Disk W/3.5" Floppy
- Hewlett Packard 2934A Printer W/Intelligent Interface Buffer
- Hewlett Packard 3852A DACU Extender
- Hewlett Packard EHP-80-250 Power Supply

Additional Voltage Channels per Battery:
- 12 additional voltage channels per battery

Charge Capability:
- 0 to 125 amps
- 125 to 180 amp pulses (10 seconds to 5 minutes)

Discharge Capability:
- 0 to 125 amps
- 125 to 180 amp pulses (10 seconds to 5 minutes)
FEATURES

* DESIGNED WITH OPERATOR INTERACTION FOR SAFETY
* TEST DEFINITION SHEETS
* AUTOMATIC CURRENT AND TEMPERATURE CONTROL
* AC AND DC POWER CIRCUIT BREAKERS
* DC VOLTAGE AND CURRENT LIMITS
* CHARGE/DISCHARGE CIRCUIT DIODE PROTECTION
* COMPUTER GUARD
* DATA DISKS IN DIFFERENT FORMATS
**Sample Procedure File**

**Program: ATPXXX**

**Document: ATP-XXX Rev X**

**Paragraph: 14.2.2**

<table>
<thead>
<tr>
<th>Record</th>
<th>Event</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Stabilization at 10C</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Start of Cycle (from 1 to max. of 20)</td>
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<tr>
<td>3</td>
<td>3</td>
<td>Charge at 9.3 Amps for 12 Hours</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>Discharge at 36 Amps (W/Pulse) to 0.5 Volts</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>Drain Cells to 0.1 V/Cell</td>
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<td>6</td>
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<td>Open Circuit for Decision to Continue Cycles</td>
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<td>End of Cycle</td>
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<td>Charge at 9.3 Amps for 12 Hours</td>
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<td>Discharge at 36 Amps (W/Pulse) to 0.5 Volts</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>Drain Cells to 0.1 V/Cell</td>
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<tr>
<td>11</td>
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<td>Open Circuit for Test Verification</td>
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</tbody>
</table>

**Temperature: 10.0 ±10.0 ± 1.0 ± 3.0 (Degrees C)**

**Nominal: 43.0 ± 0.45 ± 0.0° C**

**Warning: Voltage = 1.200**

**Current = 9.30 ± 0.45 ± 0.0° C**

**Print-outs: 5 Minute mark**

**Operator command**

**Maximum voltage and time of same**

---

**Sample Procedure File**

**Program: ATPXXX**

**Document: ATP-XXX Rev X**

**Paragraph: 14.2.3**

<table>
<thead>
<tr>
<th>Event</th>
<th>3 (Discharge)</th>
<th>Discharge at 36 Amps (W/Pulse) to 0.5 Volts</th>
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<td>1</td>
<td>10.0 ±10.0 ± 1.0 ± 3.0 (Degrees C)</td>
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<tr>
<td>2</td>
<td>2</td>
<td>Time ± Volts</td>
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<tr>
<td>3</td>
<td>3</td>
<td>Termination: ±/a</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>Current = 9.30 ± 0.45 ± 0.0° C</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>Nominal: 9.30 ± 0.45 ± 0.0° C</td>
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<tr>
<td>6</td>
<td>6</td>
<td>Warning = Voltage = 1.200</td>
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<tr>
<td>7</td>
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<td>Time ± Volts</td>
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<td>Warning = Voltage ±/a</td>
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<tr>
<td>10</td>
<td>10</td>
<td>Nominal: Current ±/a</td>
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<tr>
<td>12</td>
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<td>Nominal: Time ±/a</td>
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</table>

**Print-outs: 5 Minute mark**

**Operator command**

**Maximum voltage and time of same**

---

**Sample Test Definition Sheets**

**FILE: SG102281.PM4, Page: 12**
SPECIAL TESTING

* HIGHER OR LOWER CURRENT RATES
* CONSTANT VOLTAGE CHARGES
* CONSTANT POWER DISCHARGES
* TEMPERATURE RAMPS
* HIGH SPEED PULSES AND DATA ACQUISITION
* DISCHARGE PULSES DURING CHARGES AND/OR DISCHARGES
* TERMINATION AT DESIGNATED AMPHOURS OR PRESSURE
* RECHARGE TO A PRESELECTED CHARGE/DISCHARGE RATIO
Capacity Loss on Storage and Possible
Capacity Recovery for HST Nickel-Hydrogen Cells

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Nickel-Hydrogen Capacity Loss During Storage

- Observed in cells with Negative (Hydrogen) Precharge.
- Capacity Loss measured in cells stored for one month.
- Amount of recoverable capacity decreases with an increase in length of storage period.
- Plausible explanation is migration of Cobalt in Nickel Plate under Hydrogen pressure.
- At low potentials CoHO2 is formed from Nickel active material.
- CoHO2 will redistribute upon cycling as differences in electrode potentials are increased and held.
- Original lattice structure of active material is altered and cannot be regained.
Nickel-Hydrogen Capacity Loss During Storage

Negatively (Hydrogen) precharged Nickel-Hydrogen battery cells exhibit a capacity loss/fade during storage. Cells from all vendors are prone to this phenomenon. The loss of usable capacity has been observed in cells stored for short periods of time. One month of storage has caused some cells to exhibit a capacity loss. The amount of capacity lost or shifted and the ability to recover this capacity is a function of the length of storage time. The generally accepted mechanism of capacity loss is a migration of Cobalt away from the substrate in the Nickel plate; higher electrolyte concentrations seem to aid this movement. At electrode potentials less than .5 Volts, under Hydrogen pressure, CoHO₂ is formed from the active Nickel material. Destructive Physical Analysis of other battery cells using Nickel couples (Ni-Cd), stored with a Hydrogen pressure, have shown a migration of the Cobalt and the formation of undesirable Cobalt Hydroxides. This migration can lead to the formation of a new voltage plateau below 1.0 Volt. In most cases the lower voltage is not usable and is equivalent to a loss in capacity. Some of the lost capacity can be recovered. The generally accepted method for recovery is to cycle the cell; capacity can be regained more quickly if the difference in electrode potential is raised above 1.2 Volts and the cell is allowed to sit open circuit at 20 to 30 degrees C for several days. Cobalt will redistribute itself in the cell more rapidly by following the latter procedure. The original capacity of the cell cannot be regained after a period of storage in which the capacity fades. The lattice structure of the active material is altered and the Cobalt cannot return to its original form.
Cells

- 24 Cells left from HST Program, TM and FM Lot Cells.

- Stored approximately two years, open circuit at 30 - 40 degrees F.

- Open circuit voltage < .4 Volts.

- Cell Design:
  
  Air Force Design.
  Dry Sintered Nickel Electrodes, "back to back".
  Zircar Separators with wall wicking.
  Rabbit Eared, Pineapple Slice.
  Stacked on Polysulfone Core with Belleville Washer.
  27% KOH.
  Hydrogen Precharged.
A capacity fade on storage has been observed in the negatively precharged Nickel-Hydrogen cells built during the Hubble Space Telescope program. This capacity fade was noted when residual HST cells were brought out of storage for use in other Nickel-Hydrogen test activities. Twenty four cells were removed from storage and placed in mounting sleeves in preparation for LEO cycling at moderate depths of discharge. These cells had been stored for approximately two years, open circuit in a refrigerator at 0 to 5 degrees C. The open circuit voltage of the cells was less than .4 Volts with an average of .2 Volts.

Subject test cells utilized in this test bed are Eagle-Picher RNH 90-3 cells remaining after completion of the Hubble Space Telescope (HST) program. There are 24 cells from three different cell builds (TM-1, FSM and FM-1) divided into six groups of four cells. Each cell has a cylindrical individual pressure vessel of 718 Inconel formed in two halves 40 mils thick providing a safety factor of four when a 1200 psi operating pressure is assumed. Cell walls are coated with zirconium oxide which in combination with zirconium oxide impregnated cloth separators provides improved electrolyte management, wall wicking and better gas flow path establishment. The cell is stacked using the "pineapple slice" system with back to back nickel oxide positive plates to reduce the number of gas diffusion screens required. The stack is built according to the following pattern on a polysulfone core attached to the weld ring: gas diffusion screen, platinum catalyst negative plate, zirconium oxide cloth separator (2 layers), two nickel oxide positive plates, zirconium oxide cloth separator (2 layers), negative platinum catalyst plate followed by a gas diffusion screen. The stack is held on the core by a Belleville washer and nut at the proper compression. The electrode tabs run down the center of the stack and exit the pressure vessel at the same end at a 45 degree angle to the centerline of the cell (rabbit ear design). The cell halves are attached to the center weld ring and the plate tabs attached to the terminal posts by electron beam welding. The cell is sealed with a formed nylon compression washer (Zytel) which acts as an insulator (terminal from case) as well as a seal. The flight cell is activated with 27% potassium hydroxide, charged in a vented condition and the fill tube pinched off and welded closed.
Useable Capacity Fading
EPI RNH 90-3
Negatively Precharged

Acceptance Test Capacity, June 1989 – 1.2 Volts.
First Capacity Test, June 1991 – 1.0 Volts.
After installation in the test bed a baseline charge and capacity test was run on the packs to measure the amount of capacity that had been lost during storage. A baseline charge consists of a 160% charge based on the nameplate capacity rating. This charge is accomplished in a 24 hour period at 9.3 amperes for 10 hours and 4 amperes for 14 hours. An hour is allowed for gas recombination and thermal stabilization and a discharge at C/6 (15 amperes) is run to an average cell voltage of 1.0 volt. The ambient temperature was fixed at a constant 0 degrees C during this time. The measured capacity could then be compared to the capacity measured during acceptance testing of the cells. The acceptance test capacity was measured to 1.2 volts while the later tests measure capacity to 1.0 volt. The amount of capacity between 1.2 and 1.0 volts is very small.

It is interesting to note the differences in the amounts of capacity lost. Pack #3 and pack #5 are both composed of flight spare module cells; pack #5 with the highest initial capacity, showed the largest loss while pack #3 with near the lowest capacity retained the most capacity after storage. Pack #5 cells were activated with 31% KOH while pack #3 had three cells activated with 27% KOH and one cell activated with 31% KOH. Packs #4 and #6 contain flight module 1 cells activated with 27% KOH. These two packs show good matching and provide independent data points.
Capacity Loss After Storage
EPI RNH 90-3

Capacity (Ampere Hours)

Cell #

#420-FM2
#450-FM2
#80-FM1
#83-FM1
#48-FM2
#459-FM2
#193-FSM
#197-FSM
#201-FSM
#336-FM1
#379-FM1
#196-FM1
#227-FSM
#252-FSM
#387-FM1
#388-FM1
#389-FM1
#391-FM1
Looking at the cells on an individual basis, it is easy to pick the five cells activated with 31% KOH, they show the highest capacity loss during storage. The other three cells in this test from the same manufacturing build lot were activated with 26% KOH and show the least capacity loss during storage. This data indicates that higher electrolyte concentrations during storage greatly increase the undesirable reactions leading to capacity fading. Packs #4 and #6 show the same range of loss.

One cell in the group did not show a capacity loss; it delivered the same capacity as measured before storage. This cell belonged to the test module lot of cells and probably had a neutral or positive precharge.
## CAPACITY SUMMARY EPI RNH 90–3 (HST CELL)

Capacity Test #1, June 12, 1991, After baseline charge.

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During activation an attempt was made to achieve a neutral or slightly negative precharge. The activation procedure and the variance allowed on the test module cells could have produced a cell with positive precharge. End of discharge pressures for test module 1 cells indicate that this may have happened. Strain gauges were added to these cells after they were sealed and they subsequently were not able to be individually calibrated. Absolute pressure cannot be discerned; although, these pressures should not be greatly misleading, pressure deltas are correct. The performance of the cell with apparent positive precharge indicates that positively precharged cells are better able tolerate storage periods without degraded performance.
This graph is an attempt to ascertain a shift in capacity to a lower voltage plateau. The graph shows the average cell voltage at the end of the first capacity test as the pack entered reconditioning. The C/6 load was maintained as long as possible until all cells were below 1.0 volts before reconditioning. Packs #4 and #5 and possibly #1 exhibit a shifted (lower) voltage plateau; this plateau does not extend to the original capacity. Pack #6 should have behaved as #4. With the other packs we cannot tell if a shift in capacity has occurred.
Attempts to Recover Capacity
EPI RNH 90-3

1. After 24 Hour Baseline Charge.

2. After 24 Hour Baseline Charge, Temp = 0 Deg C.

3. After 24 Hour Baseline Charge, Temp = 0 Deg C, then
   121 Ampere hours trickle charge (2.5 A) @ T = 15 Deg C.

4. After 292 LEO Orbits @ 10% DOD, Temp = 0 Deg C.

5. After 24 Hour Baseline Charge, Temp = 0 Deg C.

Acceptance Test Capacity, June 1989 - 1.2 Volts.
Other Capacity Tests, - 1.0 Volts.
After the first capacity test a second baseline charge and capacity test were performed to check the validity of the first test. The results of the second test verified the first test. At this point, it was recognized that the HST spare battery module (FM1), stored similarly, probably had the same kind of loss in useable capacity. Several procedures followed in an effort to demonstrate the ability of the cells to recover enough capacity to meet the requirements of the HST specification.

The third capacity test occurred after a baseline charge and extensive overcharge. At 0°C the cells received a 24 hour baseline charge and 121 ampere hours trickle charge at 2.5 amperes rate; the temperature was raised to 15°C during the period of trickle charge. It was hoped that by increasing the electrode potential difference to more than 1.2 volts and maintaining the difference at an elevated temperature, the Cobalt would redistribute. The results were not encouraging. It seems that the gas recombination during overcharge precluded the movement.

LEO cycling is thought by many people to be an effective way of recovering faded capacity; subsequently, 292 LEO orbits at 10% DOD were run. The forth capacity test was ran after the LEO cycles and the fifth test after a baseline charge. Capacity recovered was still not at an acceptable level. The beneficial effects of LEO cycling are magnified as the DOD increases; the 292 orbits at 10% DOD had no appreciable effect. Cycling at a deeper DOD was not immediately attempted. A relatively quick method for regaining lost capacity was desired.
EPI
Capacity Recovery Procedure

Cool Cells to 0 Deg C.

Perform Baseline Charge:
160% Overcharge in a 24 hour Period.
Charge 10 Hours at 9.3 Amperes.
Charge 14 Hours at 4 Amperes.

Raise Temp to 25 Deg C.

Allow Cells to stand open circuit for 10 - 14 days.

Lower Cell Temp to Deg C.

Discharge cell at C/6 to 1.0 V/Cell.
Discharge at 15 Amperes.

Recondition Cell to > .1 V with resistor.

Perform Baseline Charge.

Allow Cells to Stand Open Circuit for 1 Hour.

Discharge cell at C/6 to 1.0 V/Cell.
The cell manufacturer recommended a capacity recovery procedure that elevated the electrode difference of the cell to a high level and allowed the cell to self discharge at room temperature for 10 to 14 days. The manufacturer's suggested procedure was then employed. A capacity test and reconditioning were run after the period of self discharge. A baseline charge and capacity test were then run to measure the effectiveness of the capacity recovery technique.
Attempts to Recover Capacity
EPI RNH 90-3

Acceptance Test Capacity, June 1989 - 1.2 Volts.
Other Capacity Tests, - 1.0 Volts.
Capacity test #6 was after the 239 hour open circuit stand. Capacity test #7 measured the capacity gain related to the charged open circuit stand at room temperature. The measured capacities showed a definite improvement when compared to capacity test #5. After capacity test #7 the packs were LEO cycled at moderate DOD’s for two hundred orbits. Packs #1, #2, #3 and #4 cycled at 22% DOD while packs #5 and #6 cycled at 33% DOD. Capacity test #8 was interrupted by a power outage and data was lost. Capacity test #9 measured the effect of the LEO orbits; the LEO orbits did not significantly increase the measured capacity. The manufacturer’s recovery procedure was run again with the open circuit stand time increased to 384 hours. Capacity test #11 showed the most dramatic increase in recovered capacity. Sufficient capacity had been regained to meet the requirements of the HST specification.
Useable Capacity Fading
EPI RNH 90-3
Negatively Precharged

Acceptance Test Capacity, June 1989 - 1.2 Volts.
Eleventh Capacity Test, Sept 1991 - 1.0 Volts.
After the 11th capacity test, the cells were still 8 to 10 percent degraded in capacity. The capacity will continue to increase slightly with LEO cycling at the moderate DOD's. The effect of the higher concentration of electrolyte (pack #5, 31%) after storage is negligible; the pack with 27% KOH lost much less capacity during storage and showed only slightly less capacity than the pack with 31% KOH. Pack #4 and #6, from the same lot of cells showed capacity recoveries of 10.5 and 10 ampere hours respectively.
Summary

Capacity Fading Of Negatively Precharged Nickel-Hydrogen Cells can be reversed.

Capacity can be recovered through cycling.
Recovery can be accelerated by elevating temp and keeping electrode potential difference high.

Original capacity is lost; the lattice structure of the plate is altered.

If possible, Use Positively Precharged Cells.
In summary, negatively precharged Nickel-Hydrogen cells will experience a useable capacity loss during extended open circuit storage periods. Some of the lost capacity can be recovered through cycling. Capacity recovery through cycling can be enhanced by cycling at high DOD's. The most timely procedure for recovering the faded capacity is to charge the cell fully and allow the cell to sit open circuit at room temperature. This procedure seems to be effective in part because of the enlarged structure of the active material. The compounds that formed during storage at the low electrode potentials can more easily dissolve and redistribute. All of the original capacity cannot be recovered because the lattice structure of the active material is irreversibly altered during storage. The recommendation is to use positively precharged cells activated with 26% KOH if possible. In aerospace applications the benefits of negative precharge are offset by the possibility of delays and storage periods.
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