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# The 1991 NASA Aerospace Battery Workshop

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*Proceedings of a workshop held at the  
U.S. Space and Rocket Center  
Huntsville, Alabama  
October 29-31, 1991*

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**NASA**

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*NASA Conference Publication 3140*

# The 1991 NASA Aerospace Battery Workshop

Jeffrey C. Brewer, *Compiler*  
*NASA George C. Marshall Space Flight Center*  
*Marshall Space Flight Center, Alabama*

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

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## 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.

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## 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  
NASA Marshall Space Flight Center



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**ANNUAL NASA AEROSPACE BATTERY WORKSHOP**  
**Marshall Space Flight Center**  
**October 29-31, 1991**

**George A. Rodney**  
**Associate Administrator**  
**NASA Office of Safety and Mission Quality**

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*





## NASA AEROSPACE FLIGHT BATTERY SYSTEMS PROGRAM, AN UPDATE

Michelle A. Manzo  
Patricia M. O'Donnell  
NASA Lewis Research Center  
Cleveland, Ohio 44135

### ABSTRACT

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

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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.

The Goddard Space Flight Center (GSFC) is in the process of developing a NASA Handbook for Nickel-Hydrogen Batteries. Mr. Jim Dunlop has been hired as a consultant to aid in the development of the Ni-H<sub>2</sub> handbook. The handbook is in the final phases of the review process. The NASA Handbook for Nickel-Hydrogen Batteries will address the following subjects: 1) Nickel-Hydrogen Cell Design, 2) Aerospace Applications of Nickel-Hydrogen Batteries, 3) Nickel-Hydrogen Battery Design, 4) Advanced Battery Design Concepts, 5) Performance of Nickel-Hydrogen Batteries 6) Battery Procurement, 7) Standard Test Procedures for NASA, 8) Storage and Handling, and 9) Safety.

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-H<sub>2</sub> 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<sub>2</sub>, and Li-SO<sub>2</sub> 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-O<sub>2</sub> 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 LiSOCl<sub>2</sub>, and the Wilson Greatbatch, Ltd. Li-CSC.

The NASA Aerospace Flight Battery Systems Program also supports the development of a pair of Zn-O<sub>2</sub> 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.

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# **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

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## CONCEPTUAL DOCUMENTATION ANALYSIS

- Importance of "GOOD" Documentation
- WORDMAP: Documentation Analysis Tool
- Battery Technology Example

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**IMPORTANCE OF "GOOD"**  
**DOCUMENTATION**

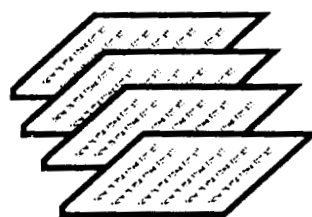
- **Customer Correspondence**
- **Customer Relations**
- **Contracts Renewed / Won**
- **Departmental Records**
- **Knowledge Representation**

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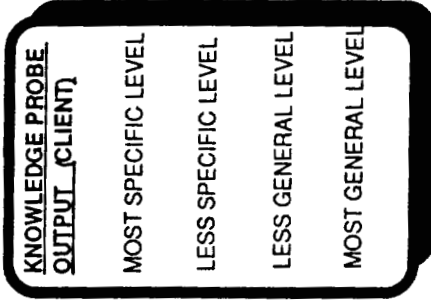
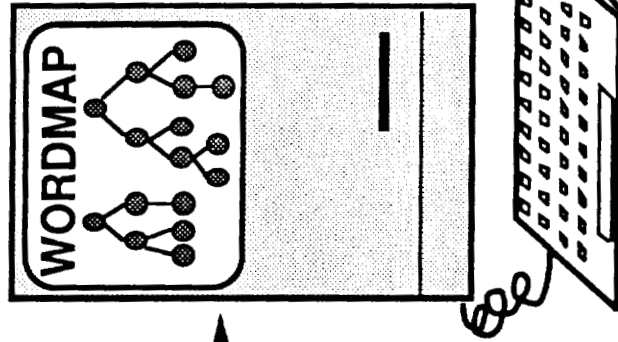
# WORDMAP: Document Analysis Tool



Documentation



(ANY TEXT FILE)



INNOVATIVE KNOWLEDGE ENGINEERING



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## **WORDMAP: Document Analysis Tool**

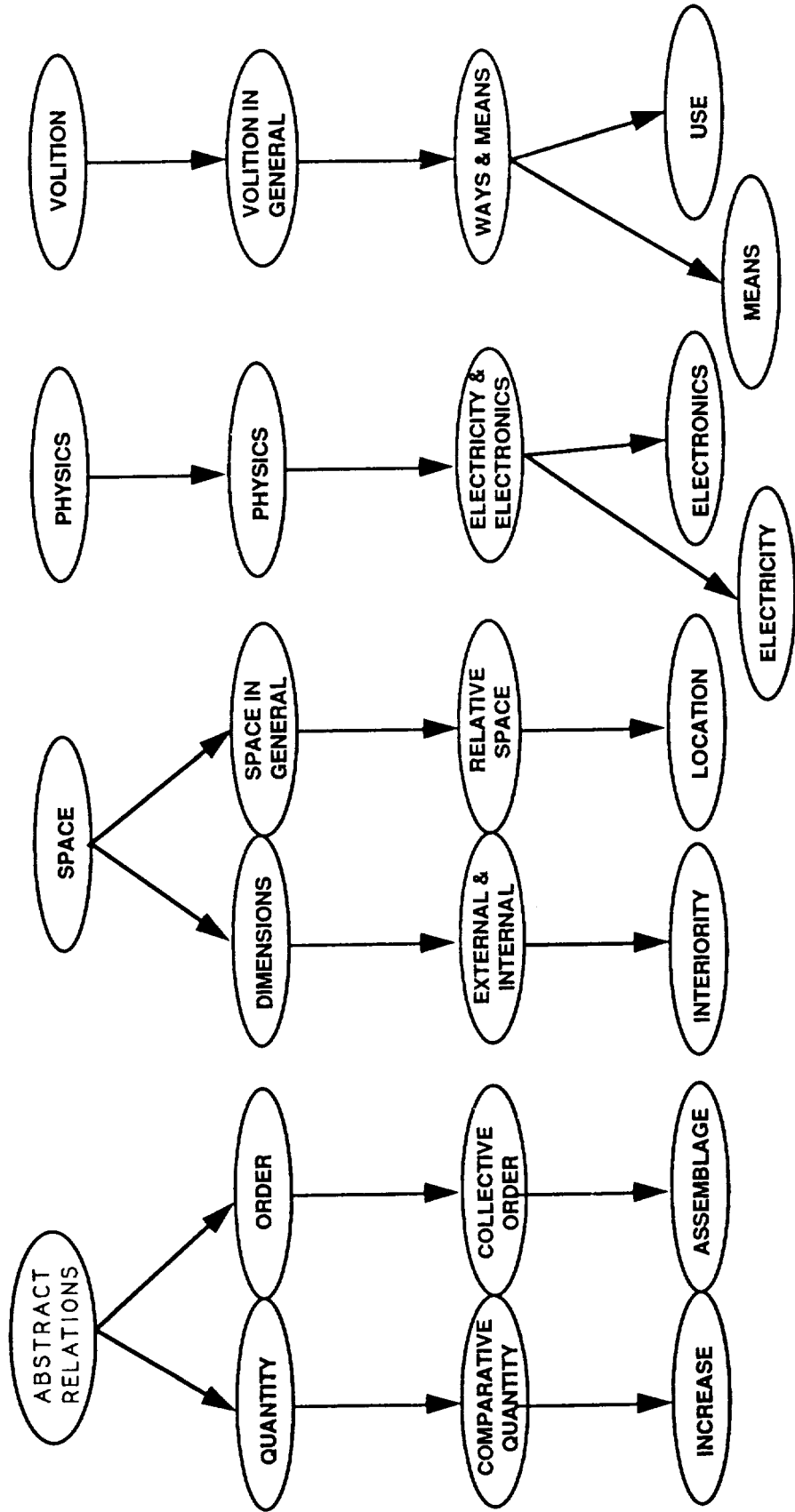
- **Natural Language Processing Technology**
- **Only Limitation : Spelling  
Minimum of Two Words**
- **No Syntax / Grammar Parsing**
- **Produces List of Concepts Represented**

**INNOVATIVE KNOWLEDGE ENGINEERING**



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## Battery Technology Example



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**N 9 2 - 2 2 7 4 2**

**PROFILE OF A CELL TEST DATABASE AND  
A CORRESPONDING RELIABILITY DATABASE**

George R. Brearley

Glenn C. Klein

**Gates Energy Products  
Gates Aerospace Batteries**

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## **Abstract**

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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 toleranced 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 their 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**

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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 vari-

ance 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**

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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-

vironmental chambers; and, incorporation of computer control on 40% of the environmental chambers.

**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**

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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] interchange-

## **Classification of Test Discrepancies**

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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 Dis-

The concept of internal customers within Gates disallows the unilateral transfer of material internally and this concept will be formalized into a series of Delivery Review Boards throughout the entire fabrication and test process.

**ENVIRONMENT:** The physical environment in the Test Unit has expanded and substantially improved to maintain more stable temperature and humidity. This was accomplished by improvement and dedication of the air conditioning units, usage of more humidity monitoring devices, and a restructuring of the coolant control systems for the environmental chambers.

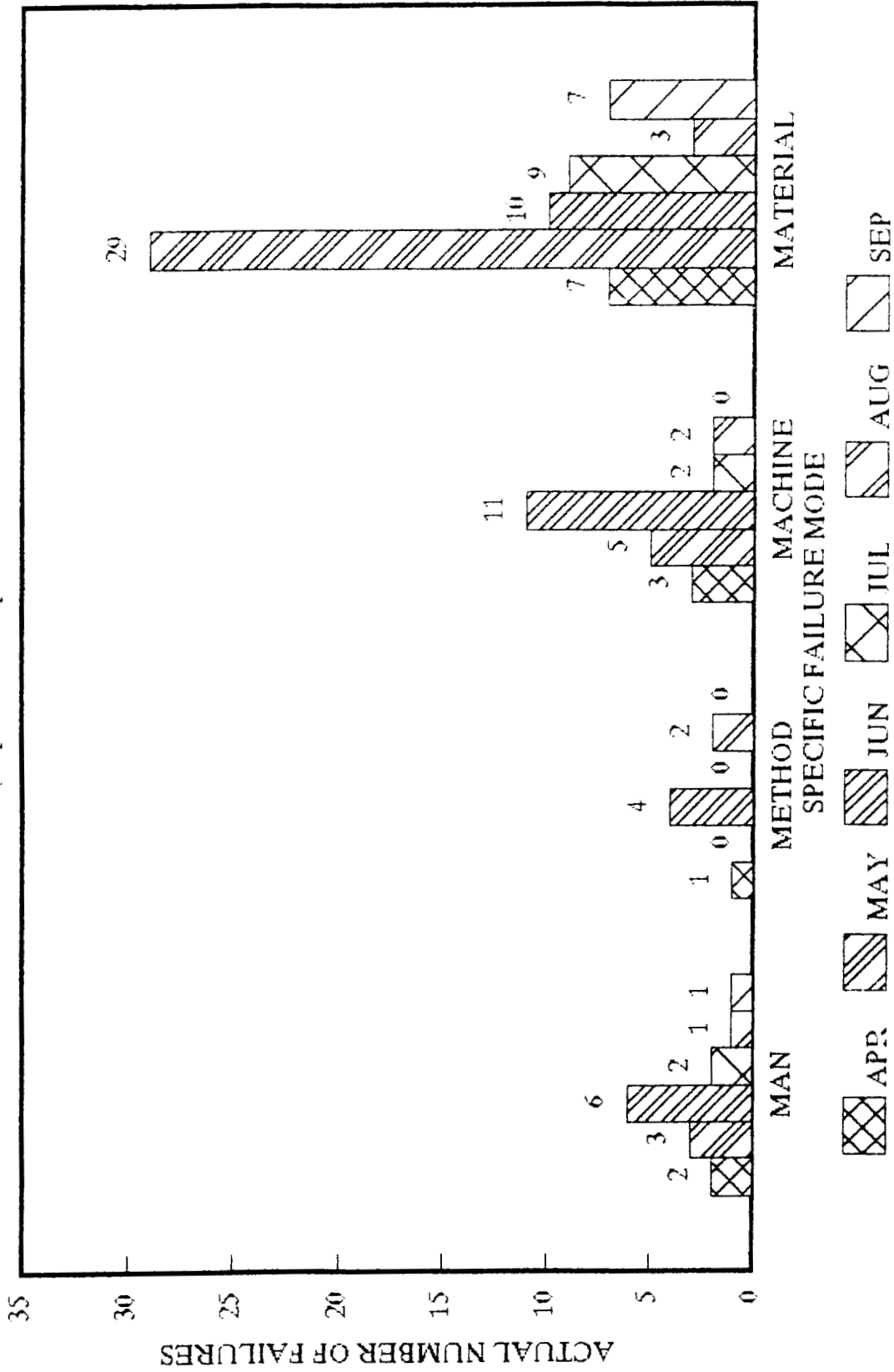
ability, reliability, or maintainability, [d] effective use or operation, [e] weight or appearance. Most of the customer contracts parrot some or all of this specification; but, no where are definitive examples provided to guide the shop, test, or inspection personnel. To compound this issue, one customer 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 1mV or 25mV for an overvoltage condition, nor do we discriminate between 1 amp-minute or 10 amp-hour for low capacity.

crepancy [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

#### CELL RESPONSE DISCREPANCIES

1. Overvoltages > 25mV
2. Pressures  $\geq$  80 PSIG

#### CRITICAL

1. Cell Case Temperature excursion  $\geq 10^{\circ}$  C  
[and never above  $30^{\circ}$  C]
2. Cell reversal [ < 0.000 volts]
3. Cell charged in reverse
4. Cells overcharged at > C/5 rate
5. Any hard or direct short

#### TEST CONTROL DISCREPANCIES

1. Overvoltages > 10mV but  $\leq$  25mV
2. Overpressures > 5 PSIA
3. Capacities  $\geq$  2.0% below specification
4. Cell Impedance over specification
5. Pulse Disc : minimum voltage not met

#### MAJOR

1. Cell Case Temp. excursion >  $5^{\circ}$  C but <  $10^{\circ}$  C
2. Resistor on cell during charge
3. Charge rate > 10% above specification
4. Discharge rate > 20% above specification
5. Delta pressures > 3 PSIG

1. Overvoltages  $\leq$  10mV
2. Overpressures  $\leq$  5 PSIA
3. Capacities < 2.0% below specification
4. Capacity over "Max. Allowable" spec.
5. Capacity dispersion out-of-specification
6. EOCV Dispersion out-of-specification
7. Failure to meet 24 Hr minimum OCV
8. Excess residual pressure on Internal Self-Discharge

#### MINOR

1. Cell Case Temperature excursion  $\leq 5^{\circ}$  C
2. Charge rate  $\leq$  10% above specification
3. Discharge rate  $\leq$  20% above specification
4. Insufficient shutdown voltage (EOSV)
5. Interrupted Burn-in cycle  $\geq$  30 minutes
6. Interrupted test sequence:
  - < 30 minutes on charge cycle,
  - < 10 minutes on discharge cycle
7. Improper Open-Circuit time
8. Incompleted/truncated test paragraph

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 2**  
**Acceptance Testing: NiH<sub>2</sub> Discrepancy Definitions**

<u>CELL RESPONSE DISCREPANCIES</u>	<u>TEST CONTROL DISCREPANCIES</u>
<p><u>CRITICAL</u></p> <ol style="list-style-type: none"> <li>1. Overvoltages &gt; 25mV</li> <li>2. Pressures <math>\geq</math> 20% above MOP</li> <li>3. Hydrogen leakage</li> </ol>	<ol style="list-style-type: none"> <li>1. Cell Case Temperature excursion <math>\geq</math> 10° C [and never above 40° C]</li> <li>2. Cell reversal [ &lt; 0.000 volts]</li> <li>3. Cell charged in reverse</li> <li>4. Cells overcharged at &gt; C/5 rate</li> <li>5. Any hard or direct short</li> </ol>
<p><u>MAJOR</u></p> <ol style="list-style-type: none"> <li>1. Overvoltages &gt; 10mV <math>\leq</math> 25mV</li> <li>2. Overpressures &gt; 50 PSIA</li> <li>3. Capacities <math>\geq</math> 2.0% below specification</li> <li>4. Cell Impedance over specification</li> <li>5. Max. Allowable Strain Gage voltage is violated</li> </ol>	<ol style="list-style-type: none"> <li>1. Cell Case Temp. excursion &gt; 5° C but &lt; 10° C</li> <li>2. Resistor on cell during charge</li> <li>3. Charge rate &gt; 10% above specification</li> <li>4. Discharge rate &gt; 20% above specification</li> </ol>
<p><u>MINOR</u></p> <ol style="list-style-type: none"> <li>1. Overvoltages <math>\leq</math> 10mV</li> <li>2. Overpressures <math>\leq</math> 50 PSIA</li> <li>3. Capacities &lt; 2.0% below specification</li> <li>4. Capacity over "Max Allowable" spec.</li> <li>5. Average Capacity out-of-specification</li> <li>6. Capacity Range out-of-specification</li> <li>7. EOCV Range out-of-specification</li> </ol>	<ol style="list-style-type: none"> <li>1. Cell Case Temperature excursion <math>\leq</math> 5° C</li> <li>2. Charge rate <math>\leq</math> 10% above specification</li> <li>3. Discharge rate <math>\leq</math> 20% above specification</li> <li>4. Insufficient shutdown voltage (EOSV)</li> <li>5. Improper Open-Circuit time</li> <li>6. Interrupted test sequence:               <ul style="list-style-type: none"> <li>&lt; 30 minutes on charge cycle,</li> <li>&lt; 10 minutes on discharge cycle</li> </ul> </li> <li>7. Improper Open-Circuit time</li> <li>8. Incomplete/truncated test paragraph</li> </ol>

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

<u>TEST</u>	<u>DATA REQ'D.</u>	<u>PERFORMANCE STD</u>
<b>Set Neg. Pre-Chg.</b>	time to <u>first</u> vent	normality of times & review of lot-to-lot data
	time to <u>last</u> vent	normality of times & review of lot-to-lot data
	O <sub>2</sub> weight loss	±0.5 amp-hour (O <sub>2</sub> equivalent) from lot average
<b>Room Temp. O/C</b> [ after KOH adj.]	EOCP	range of 20 to 45 PSIG & delta P ≤ + 3 PSI in last 8 hours
<b>72° F Capacity</b>	EOCP	range of 20 to 45 PSIG
	EOCV	± 12mV from lot average
	Capacity	± 3.0% from lot average
<b>32° F Test</b>	EOCP	range of 10 to 35 PSIG
	EOCV	± 12 mV from lot average
	Capacity	± 3.0% from lot average

**TABLE 4**  
**NiCd ATP Test Performance: Engineering Alerts ( non-normalized )**

<u>TEST</u>	<u>DATA REQ'D.</u>	<u>PERFORMANCE STD</u>
<u>Each capacity test</u>	EOCV dispersion	± 12mV from lot average
	EOCP ranges	20-45 PSIG @ 75° F; 10-35 PSIG @ 32° F
	Capacity dispersion	± 3.0% from lot average
<u>Each overcharge test</u>	EOCV dispersion	± 12mV from lot average
	EOCP ranges	20-45 PSIG @ 75° F; 10-35 PSIG @ 32° F
	EOCP	delta P ≤ +3 PSI in last 8 hours
	Capacity dispersion	± 3.0% from lot average

More importantly, we will benefit by applying our resources to the prevention of Major and Critical discrepancies.

## **Engineering Alerts**

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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**

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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**

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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.



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# **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**

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## 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

NASA  
AD89-300

Aircraft	Model number	Part number	Amp-hr rating	Batteries/project	# ship sets
B-747	CA-54-1	28002-001	5	4	2
C-140	CA-5H-20	24535-19	30	4	2
F-16	DA-81755	30192-03C	10	6	3
F-18	ARC-14M220-19	31310-001	10	14	7
F-18	ARC-40SP100-19	F18-C-113	40	16	2
F-104	MA-300H	18241-001	3	12	6
F-111	MA-7	24540-007	10	2	2
	MA-8	27797-001	24	3	3
PA-30	ARC-10H120-21	10H120-21	10	2	2
	CA-24A	27312-001	24	2	2
T-38	MA-500H	23729-01	5	4	4
X-Wing	SP-176	30134-001	17	8	4
X-29	ARC-3H120-21	31463-001	3	9	3
	CA-9-20	28974-01C	24	5	5
	CA-121	19150-01C	12	6	6

## AESL Overview

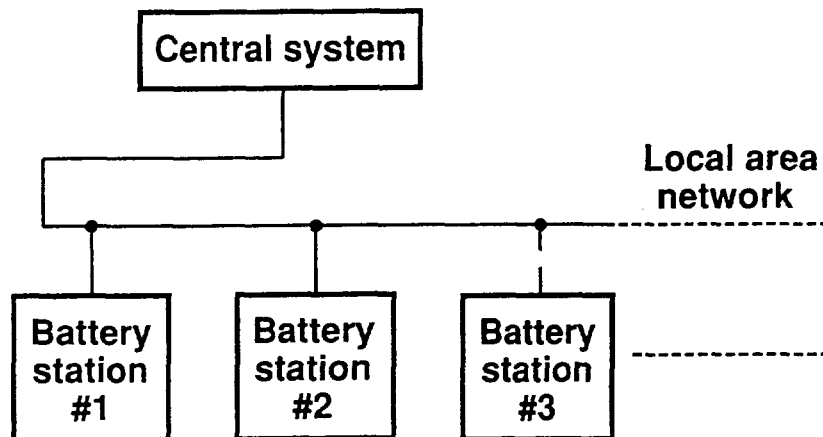
The AESL is a distributed digital system consisting of a central system and battery servicing stations connected by a high-speed serial data bus. The entire system is located in two adjoining rooms; the bus length is approximately 100 ft.

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.

## AESL Overview

NASA  
AD89-503



### Station 3 (Front View)

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	Placed on top of the bench
Status and control panel	Mounted beneath top of bench
Primary power panel	Mounted behind bench (near top)
Barcode reader gun	Holster at right side of work surface
Temperature probes	Connected at rear of work surface
Left Connector panel	Mounted under left side of work surface
Terminal connector	
Printer connector	
Load bank control connector	
Right connector panel	Mounted under right side of work surface
Battery cable connector	
Monitor plate connector	
Controller assembly	Mounted on lower shelf
Cardcage	
Floppy diskette drive	
Current leakage box	
Accessory power box	

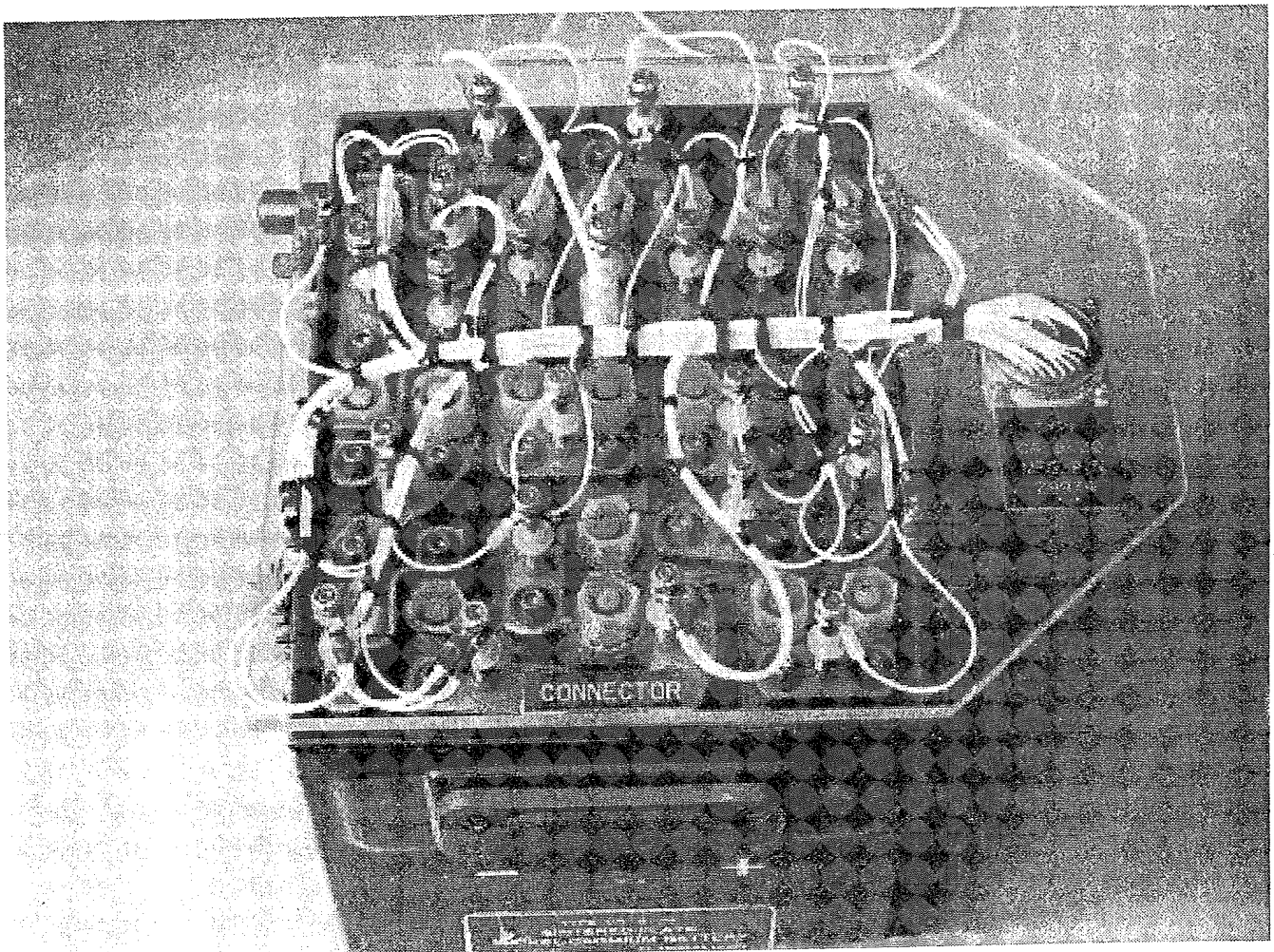
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## Monitor Plate Attached to CA-9-20

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.



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## AESL Functional Overview

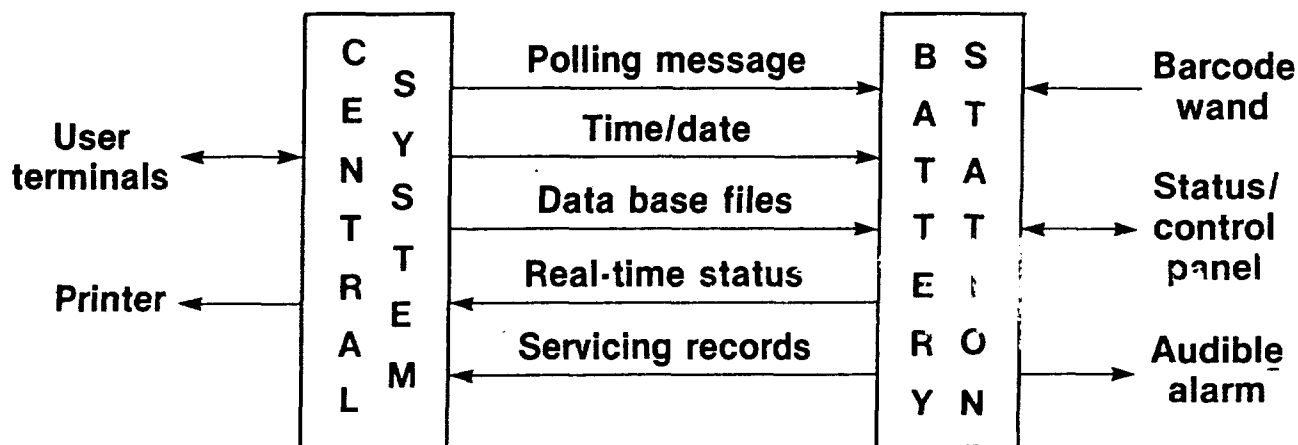
The operator initiates a servicing task by positioning the case temperature probes, attaching the monitor plate and power cable, installing the hot vapor sensor, selecting the task, and reading the barcode tag on the side of the battery. The database files necessary to support the servicing of this battery 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 diskette and are also sent to the central system archives as servicing records.

## AESL Functional Overview

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## 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  $\pm 10$  V, 12 bit, 20  $\mu$ s 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

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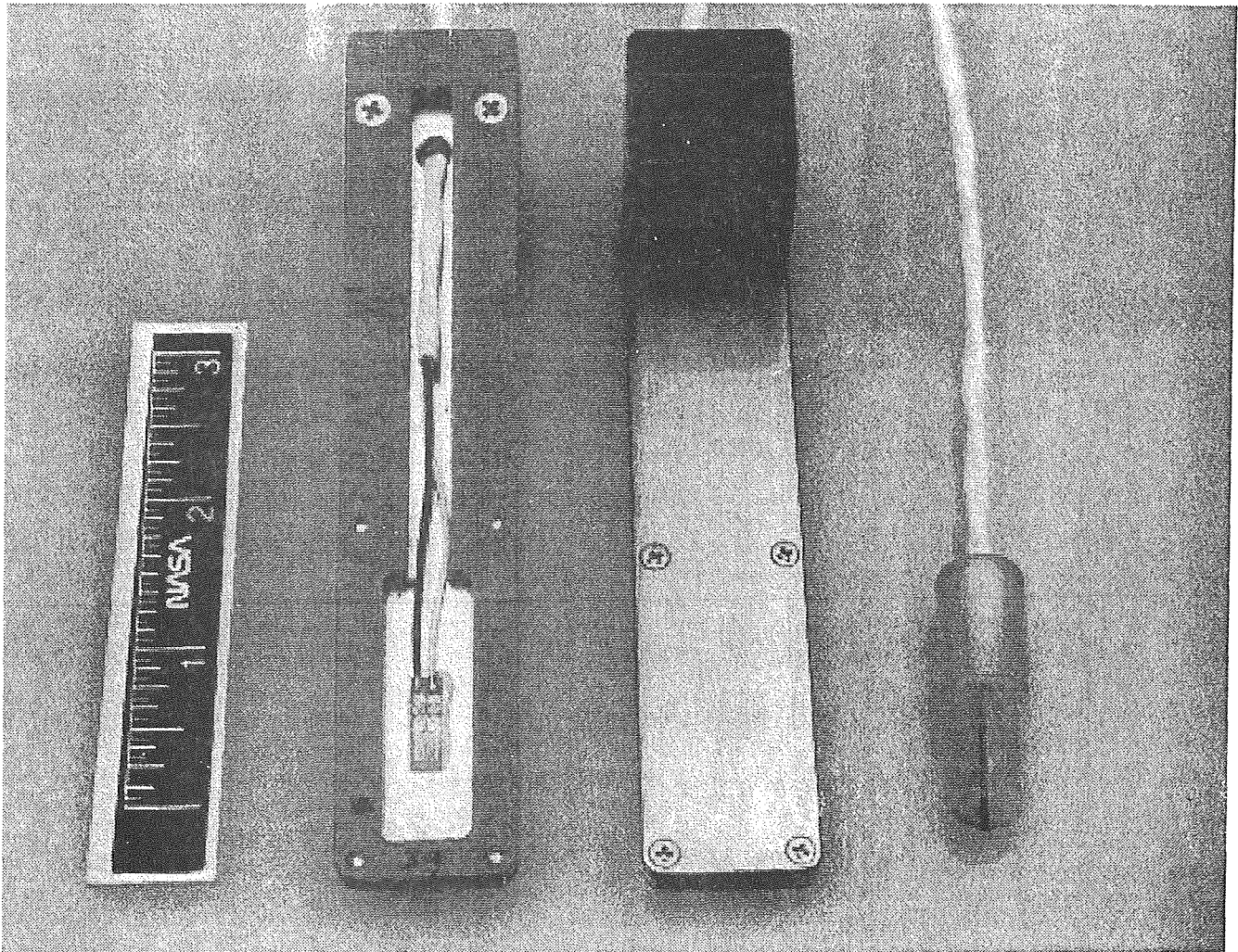
- **30 cell voltages**
- **1 battery monitor plate voltage**
- **1 battery cable voltage**
- **1 charger-analyzer current**
- **5 temperature probes**
- **1 case leakage current**
- **1 programmable load bank voltage**
- **1 programmable load bank current**
- **1 programmable load bank temperature probe**

## 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.

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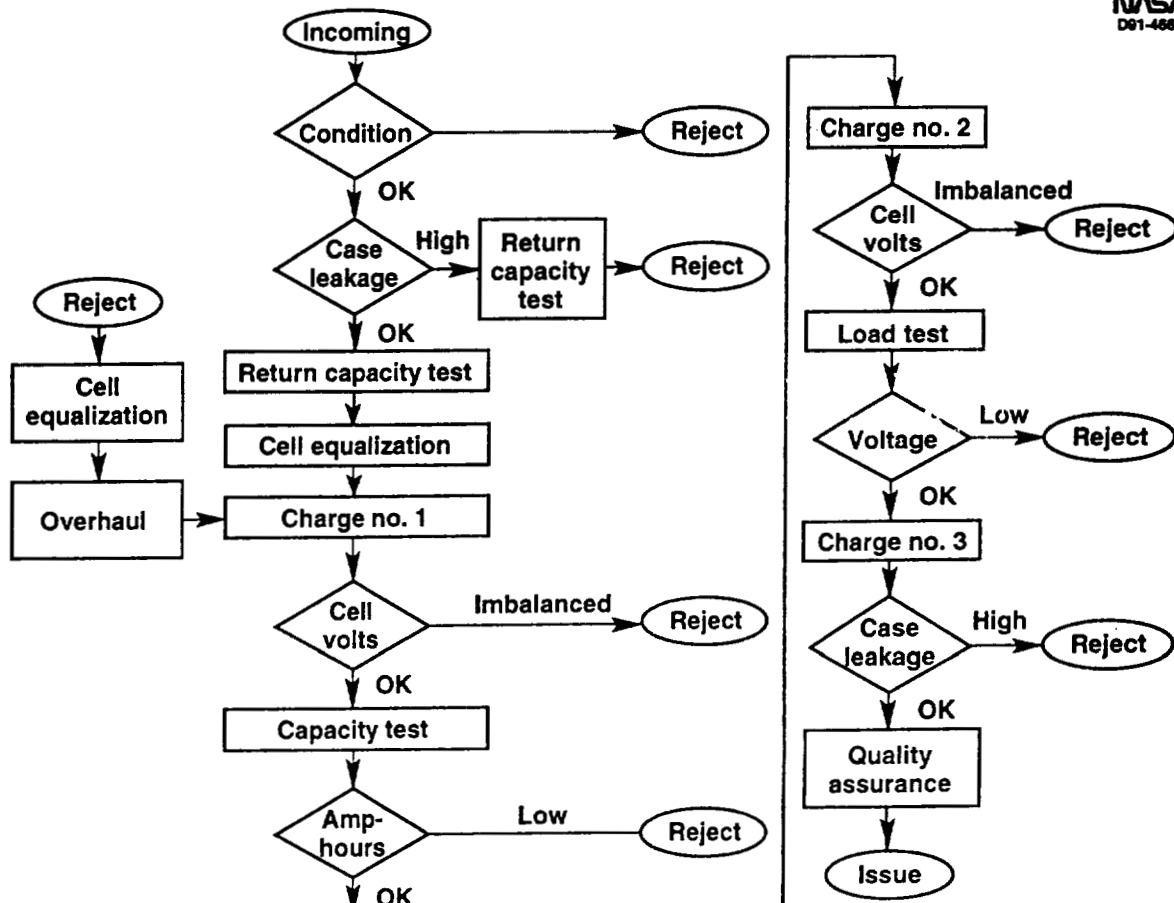


## Servicing Procedure

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.





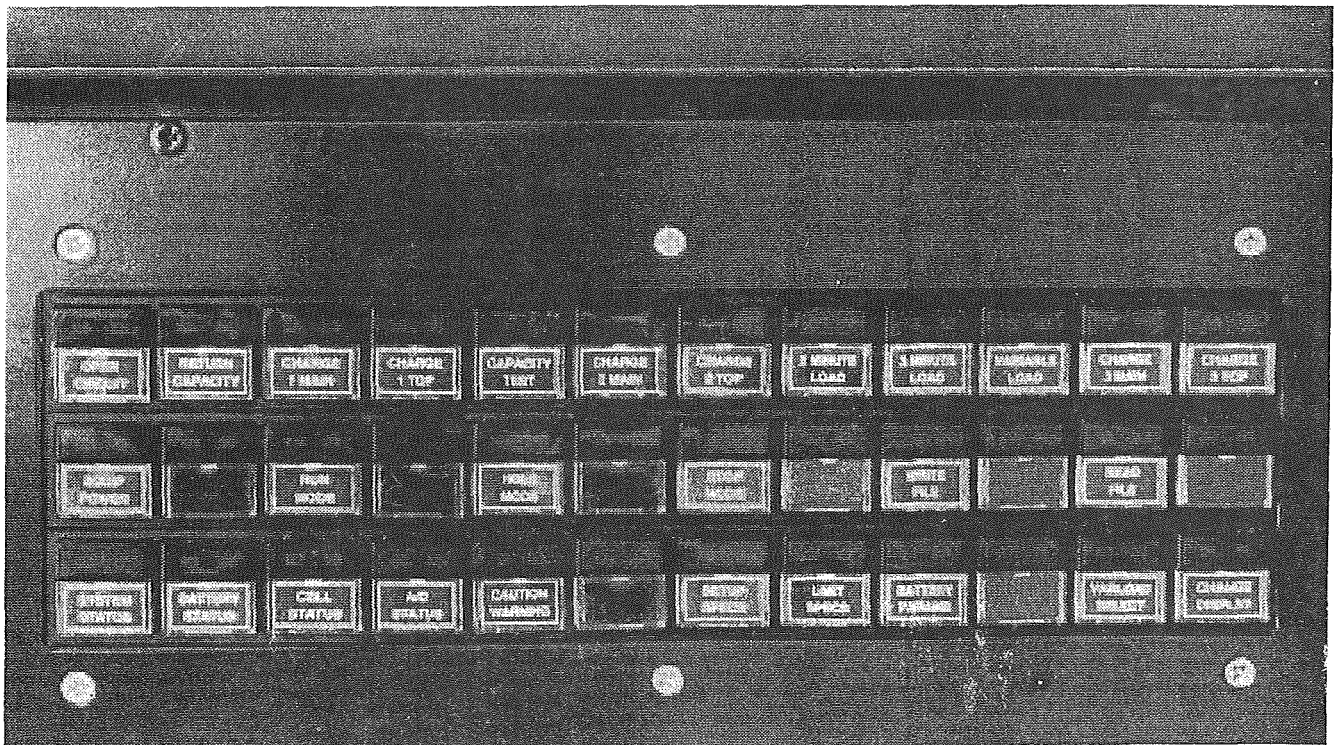
## Pushbuttons Panel

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.

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## 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.

## Shutdown Criteria



### • General

- Hot vapor sensor (top of battery)
- High case temperature
- Excessive case leakage current

### • 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.

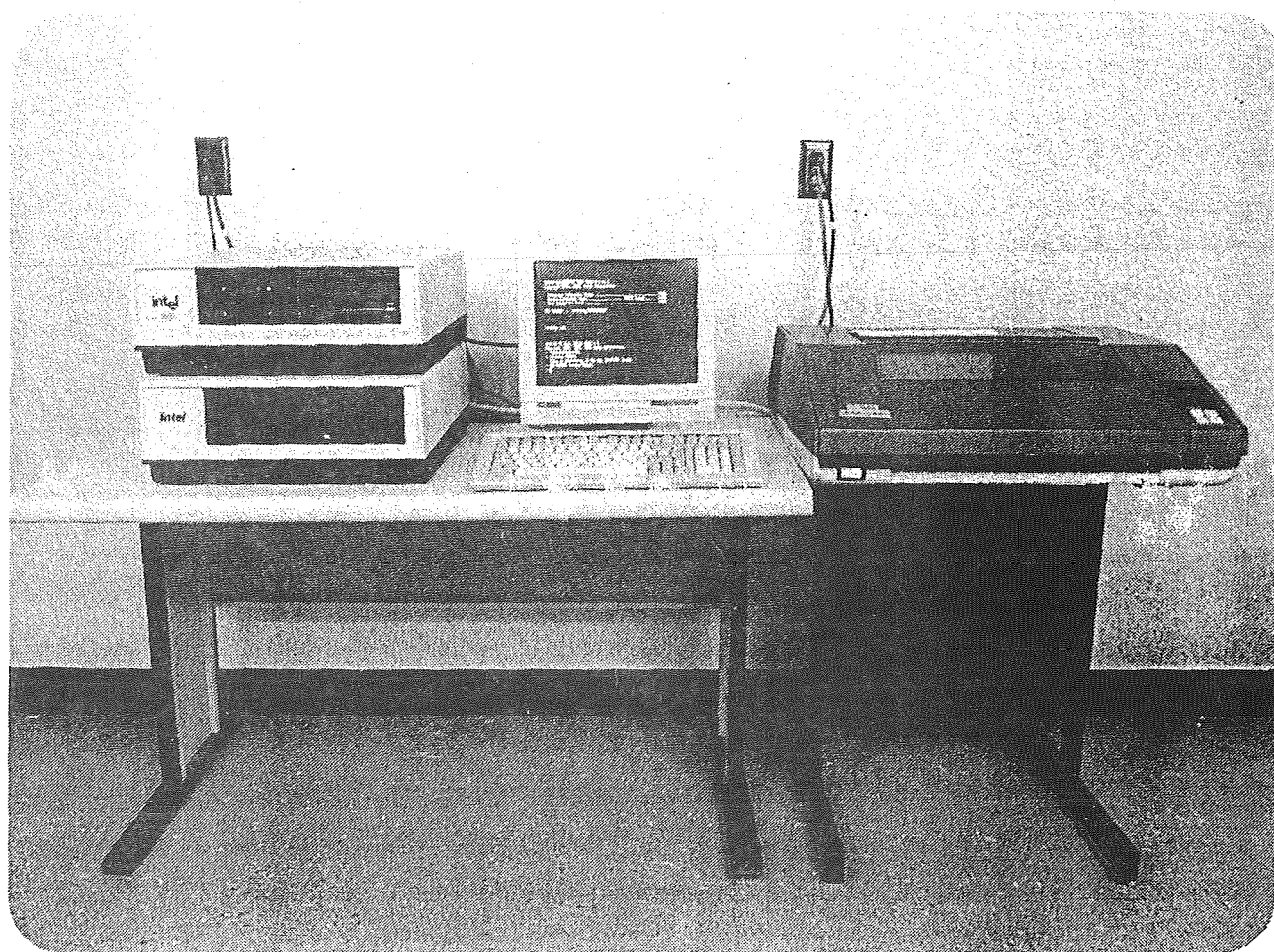
The auxiliary chassis contains two large hard disk drives plus power supplies. One of the drives contains the data archives and can store 65,500 data files (several years worth). The other is the system drive containing all the software production tools.

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 Console

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## 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

**NASA**  
D91-464

### • 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

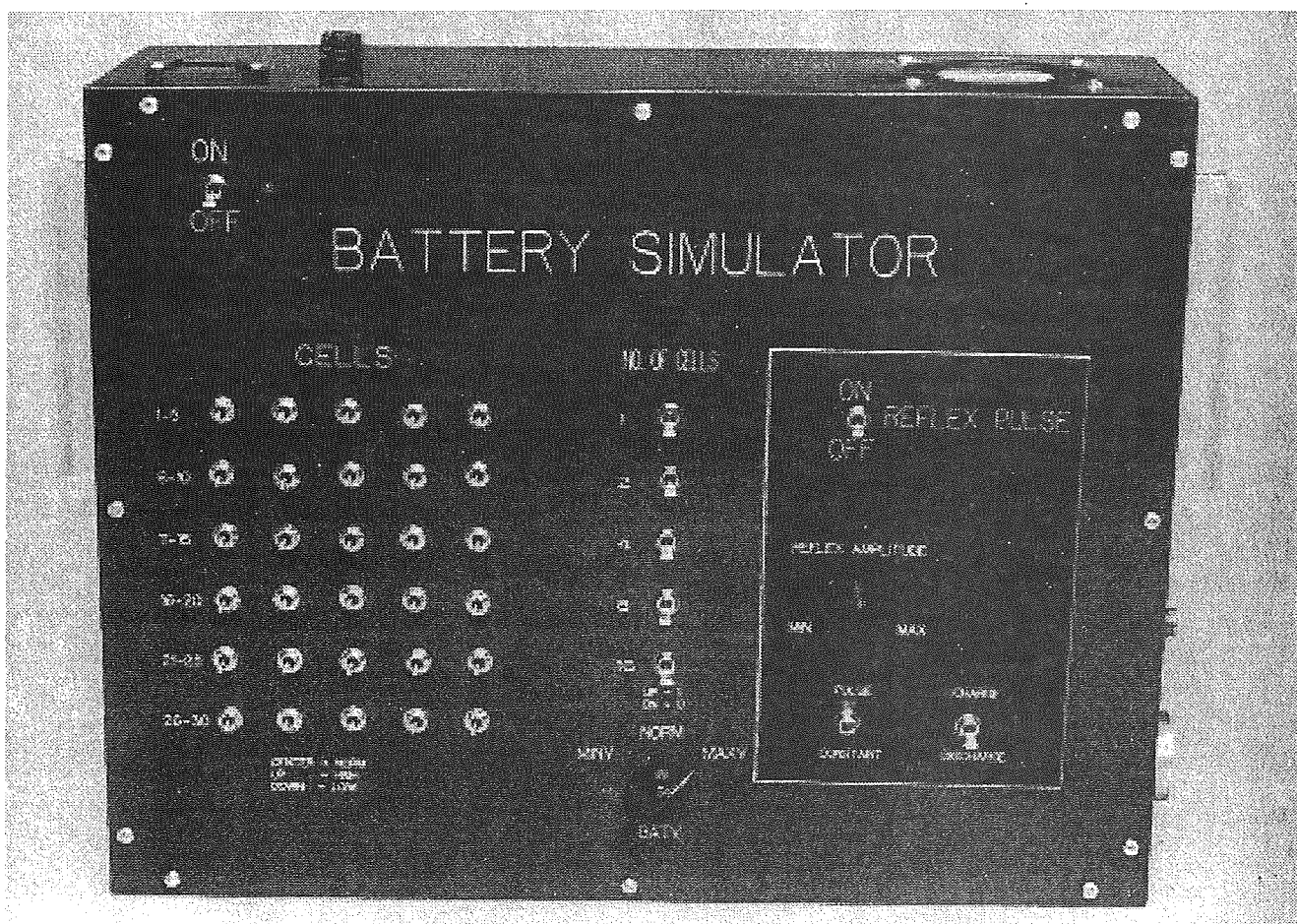
## Battery Simulator

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.

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## Project Timeline

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.

## 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**



AIR FORCE  
PHILLIPS LABORATORY  
BATTERY PROGRAM  
OVERVIEW



LT SHAUN HOUSE  
PL/STPP  
(505)846-1700

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## PL BATTERY PROGRAM: OVERVIEW

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- 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:

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- NICKEL HYDROGEN  
LEO TESTING  
EMBRITTLLEMENT 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 data-base, and demonstrate that the data base 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

TEST	MFR	3.5 IN DIAM		4.5 IN DIAM	
		10C	-5C	10C	10C
LEO	25% (EPI-CS/GEP) YARD		5		10*
	40% HUGHES YARD	10	10	5	
	EPI-J GATES	7	10	8	8
60% HUGHES	10				
PULSE					
40% EPI-J	10				
STORAGE (EPI-CS/GEP)					10*
<b>TOTAL CELLS</b>		92 - 3.5 INCH		41 - 4.5 INCH	

NIH2-1A

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)

MFR	ID#	# CELLS	DIAM	DOD	TEMP	CYCLES
YARDNEY*	5995A	10	3.5	40%	10C	23,877
YARDNEY*	5000Y	10	3.5	40%	-5C	21,401
YARDNEY*	5001Y	10	3.5	60%	10C	DIS 5,369
GEP*	5001G	10	3.5	60%	10C	DIS 5,206
HUGHES*	5002H	10	3.5	40%	10C	16,227
HUGHES*	5000H	10	3.5	40%	-5C	15,910
HUGHES*	5001H	10	3.5	60%	10C	16,043
GEP*	5002G	10	3.5	40%	10C	14,763
GEP*	5000G	10	3.5	40%	-5C	14,438
HUGHES	5402H	5	4.5	40%	10C	13,864
GEP	5402G	8	4.5	40%	10C	13,904
EP-CS	5402E	8	4.5	40%	10C	13,984
YARDNEY	5011Y	10	3.5	60%	10C	DIS 8,979
YARDNEY	5003Y	5	3.5	25%	10C	9,504
EPI-CS LT	5000C	5	4.5	25%	10C	6,464
GEP LT	5000A	5	4.5	25%	10C	6,464
EPI-J	5002E	7	3.5	40%	10C	2,937
EPI-J	BEL-PUL	10	3.5	40%	10C	4,300

NIH2-1

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  $\text{ksi}\sqrt{\text{in}}$  FOR VIRGIN INCONEL TO BELOW 17  $\text{ksi}\sqrt{\text{in}}$  FOR MATERIAL EXPOSED TO HYDROGEN FOR LONG TIMEFRAMES

Initial results indicate that the tensile ductility of Inconel 718 decreased after long exposure to the N<sub>2</sub>H<sub>2</sub> 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 N112 battery environment appears to be more susceptible to hydrogen embrittlement than virgin material.



## HYDROGEN EMBRITTLEMENT TEST: RESULTS (CONT)

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### PHASE I:

- MAXIMUM APPLIED STRESS INTENSITY FACTOR FOR CELL SHELL IS APPROX 15 ksi/√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 EMBRITTLLEMENT TEST: APPROACH

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### 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**

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- **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.



**NaS FLIGHT EXPERIMENT:  
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.



**NaS FLIGHT EXPERIMENT:  
DESCRIPTION**

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- 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

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- 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.



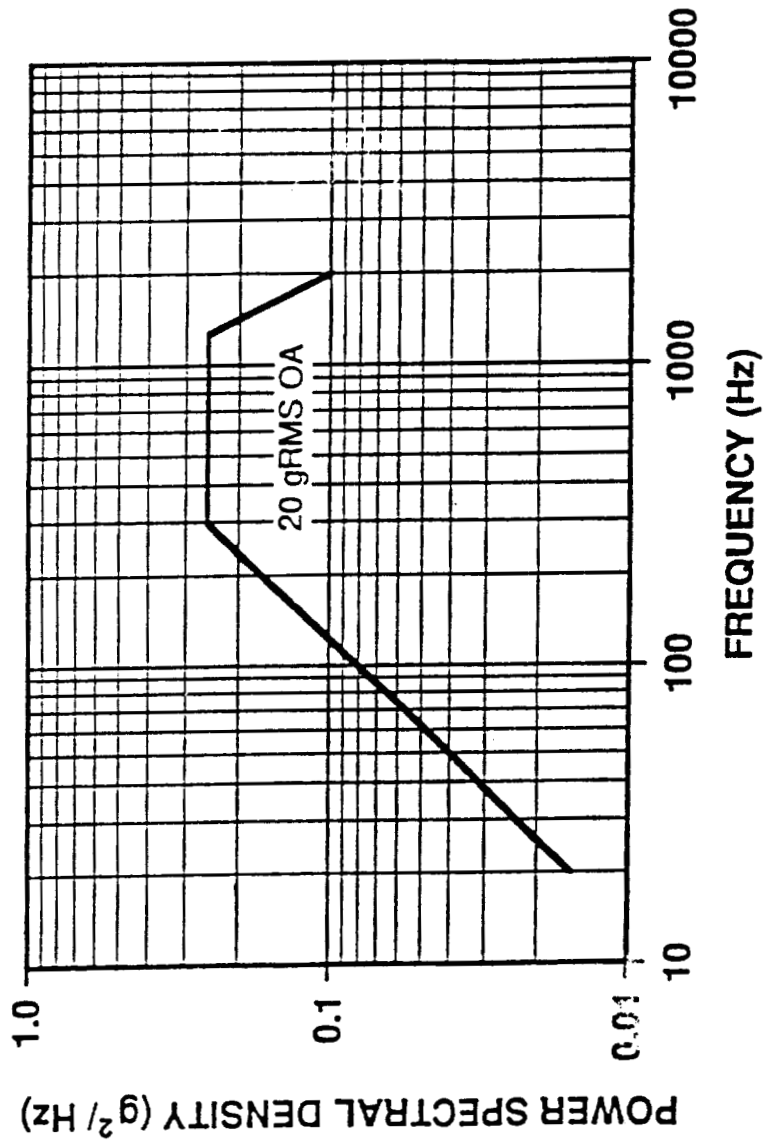
## **NaS HOT LAUNCH EVALUATION: TEST PLAN**

- **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



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.



**NaS HOT LAUNCH EVALUATION:  
PAYOFF**

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**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:**

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- **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.



## SOLID STATE BATTERIES: GEO BATTERY DEVELOPMENT

### 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<sup>-3</sup> OHM CM AT 25C)
- LINO<sub>2</sub> 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 50kW/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.



## SOLID STATE BATTERIES: IN-HOUSE EVALUATION

### 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.





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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

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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.

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# 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-H<sub>2</sub> 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.

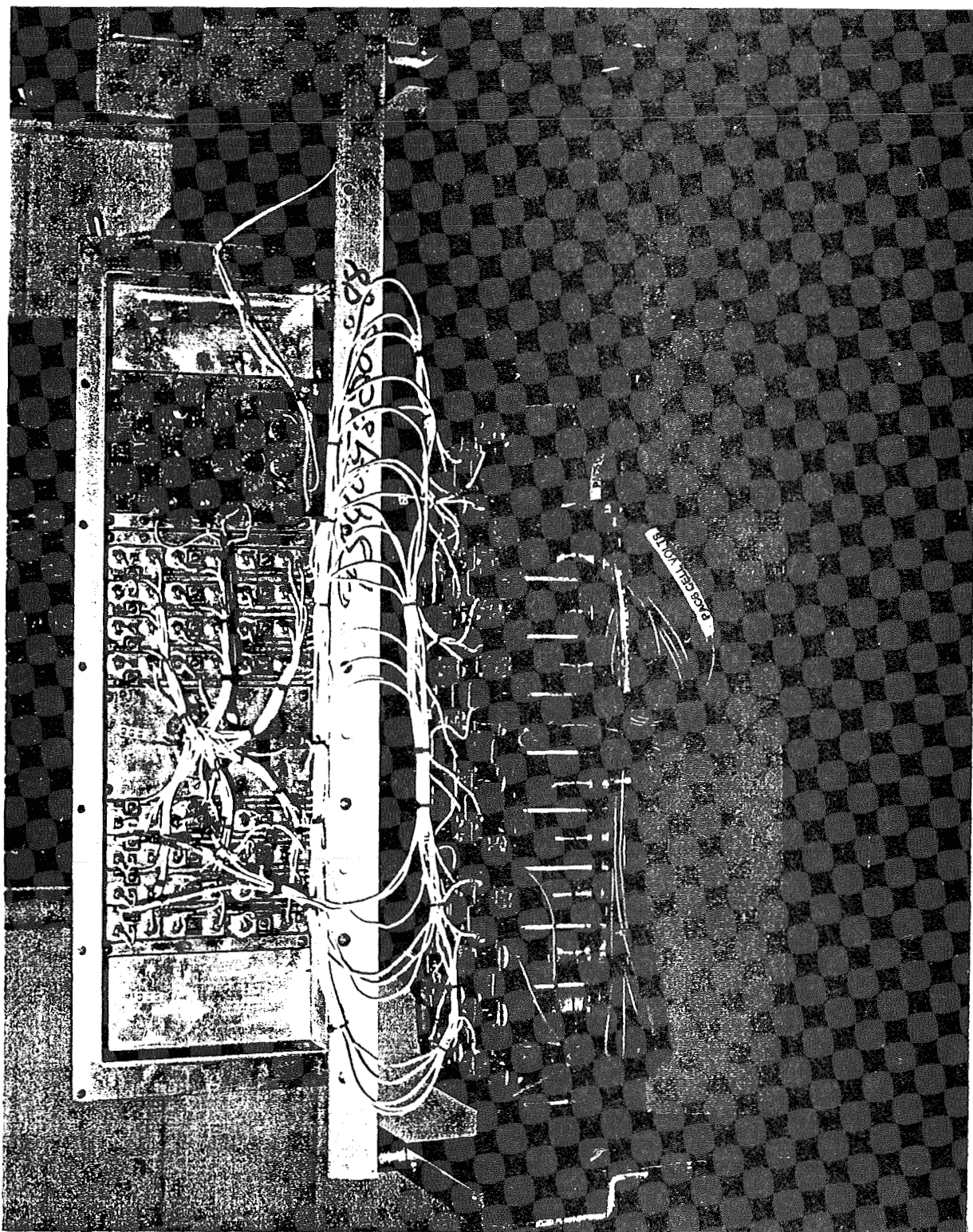
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**HST Ni-Cd Six, 4-Cell Packs** - The 24 Ni-Cd cells are Eagle-Picher, Type 44, RSN-55-15, matched to the six Type 44 flight batteries for the Hubble Space Telescope (HST). These cells were received from Lockheed Missiles and Space Company (LMSC) after ~4 years of LMSC cycling. They represent the baseline cells for HST before their replacement by Ni-H<sub>2</sub> 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.

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HST Ni-Cd Six, 4-Cell Packs

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# HST Ni-H<sub>2</sub> 14 Cell Pack

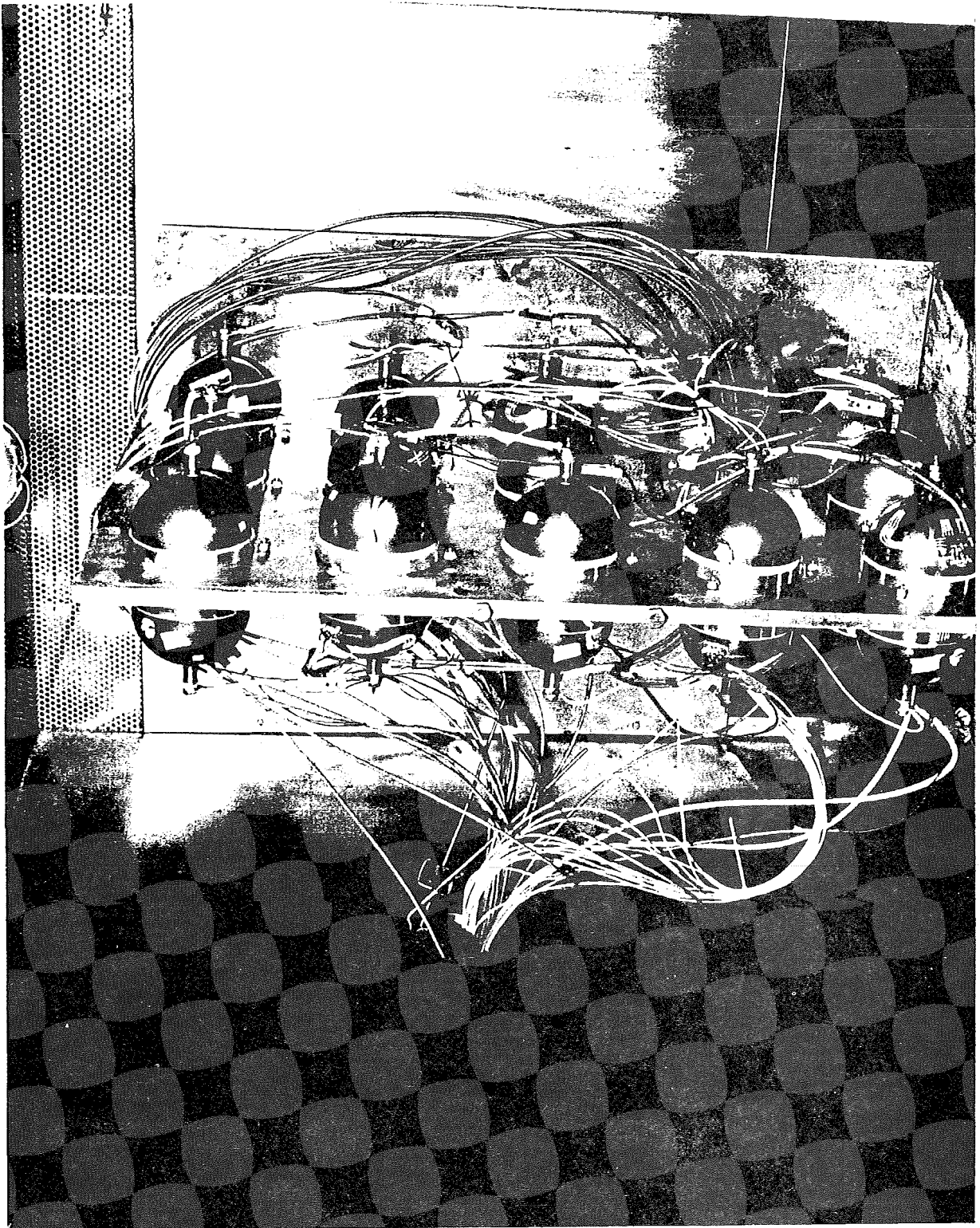
- 30 ampere-hour cells developed by Eagle Picher Inc. RNH-30-1 (COMSAT design)
- On test since 1986, to build data base for Ni-H<sub>2</sub> LEO operation at shallow DODs
- Completed over 26,000 LEO cycles at 13% DOD.
- Capacity after 4.5 years of cycling was 22 Ah.

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**HST Ni-H<sub>2</sub> Fourteen Cell Pack** - Fourteen Eagle-Picher RNH-30-1 (30 ampere-hour capacity) cells of COMSAT design on test since 1986 (First Ni-H<sub>2</sub> cells to be placed in a low earth orbit (LEO) test at MSFC). These cells were used to gather early data on the LEO operation of Ni-H<sub>2</sub> cells in anticipation of a decision to fly Ni-H<sub>2</sub> cells on the Hubble Space Telescope (HST). The cells have undergone over 26,000 LEO cycles at 13% DOD. The test setup of these cells provides for autonomous operation and parameter management through the use of digital data acquisition and system control, power supply simulation of solar array output with relays to allow reduction of current to trickle charge levels and programmable load banks to simulate varying vehicle load. Cells will continue to cycle in the present setup according to current test parameters to build data base for Ni-H<sub>2</sub> LEO operation at shallow depths of discharge.

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HST Ni-H<sub>2</sub> Fourteen Cell Pack

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# Ni-H<sub>2</sub> 12 Cell Pack

- 33 ampere-hour (Ah) cells developed by Eagle Picher Inc. RHN-35-3 (Air Force design)
- Activated in 1976, stored, began testing in 1988.
- 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.

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**Ni-H<sub>2</sub> Twelve Cell Pack** - Twelve Eagle-Picher RHN-35-3 cells (33 ampere-hour capacity) of Air Force design following a low earth orbit (LEO) (61/35) profile. These cells were activated in 1976 and then placed in storage. MSFC began testing these cells in 1987. These cells are cycling to a depth of discharge (DOD) of 22% based on their 33 ampere-hour nameplate capacity and charging with a taper charge. The test bed for these cells is automated; but very limited due to the age of the components, lack of digital data acquisition, lack of equipment interface ability, etc. Previously these cells were cycling according to an Hubble Space Telescope LEO profile and had accumulated 12,600 cycles at this level. Presently this test has completed over 3,800 cycles with the step taper charge scheme.

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# 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

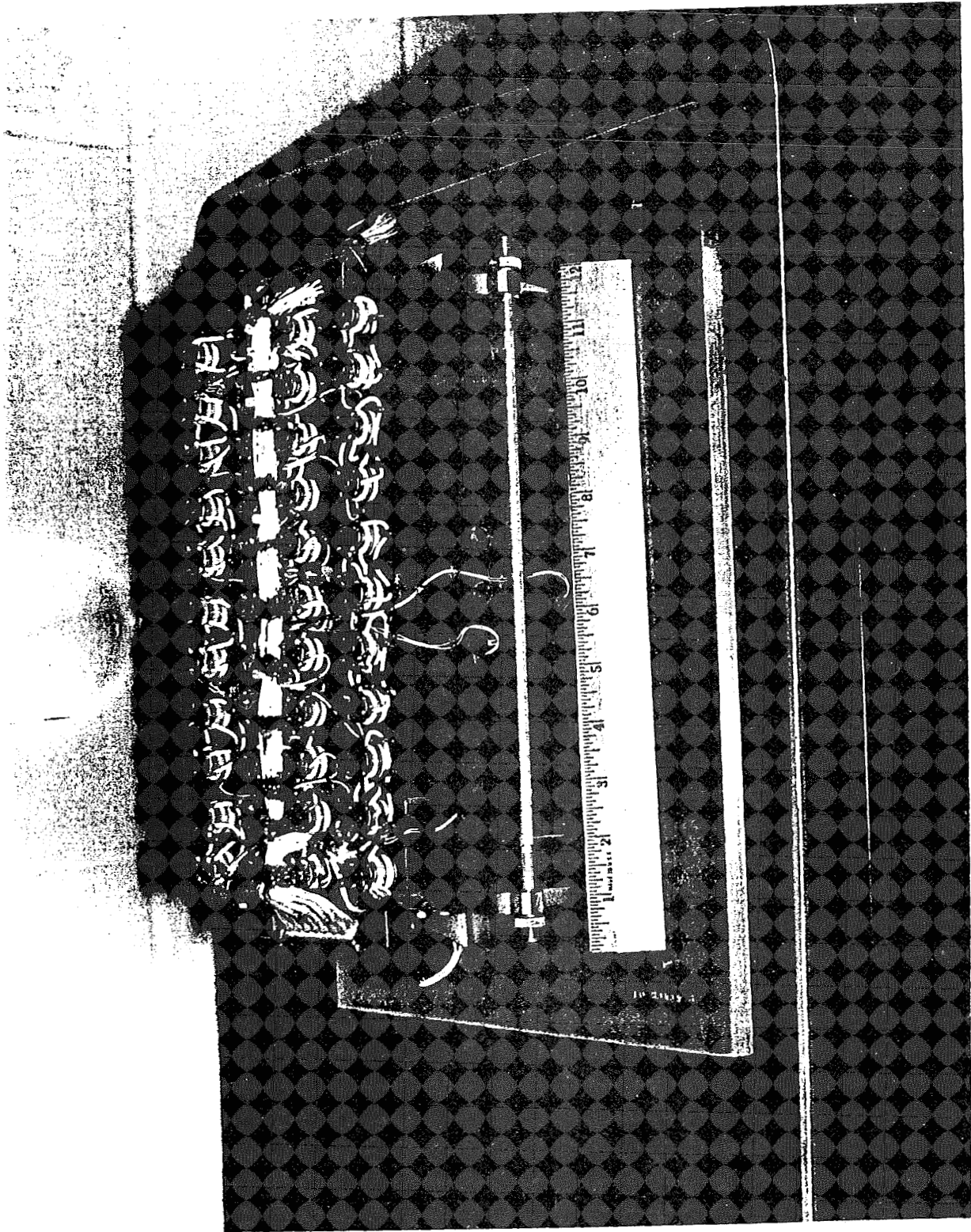
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**CRRES Ni-Cd Testing** - At MSFC testing is being performed on Ni-Cd cells used for the Combined Release and Radiation Effects Satellite (CRRES) program. These Ni-Cd cells were manufactured by Gates for Ford Aerospace and have a nameplate capacity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

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CRRES Flight Spare Battery

# 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.

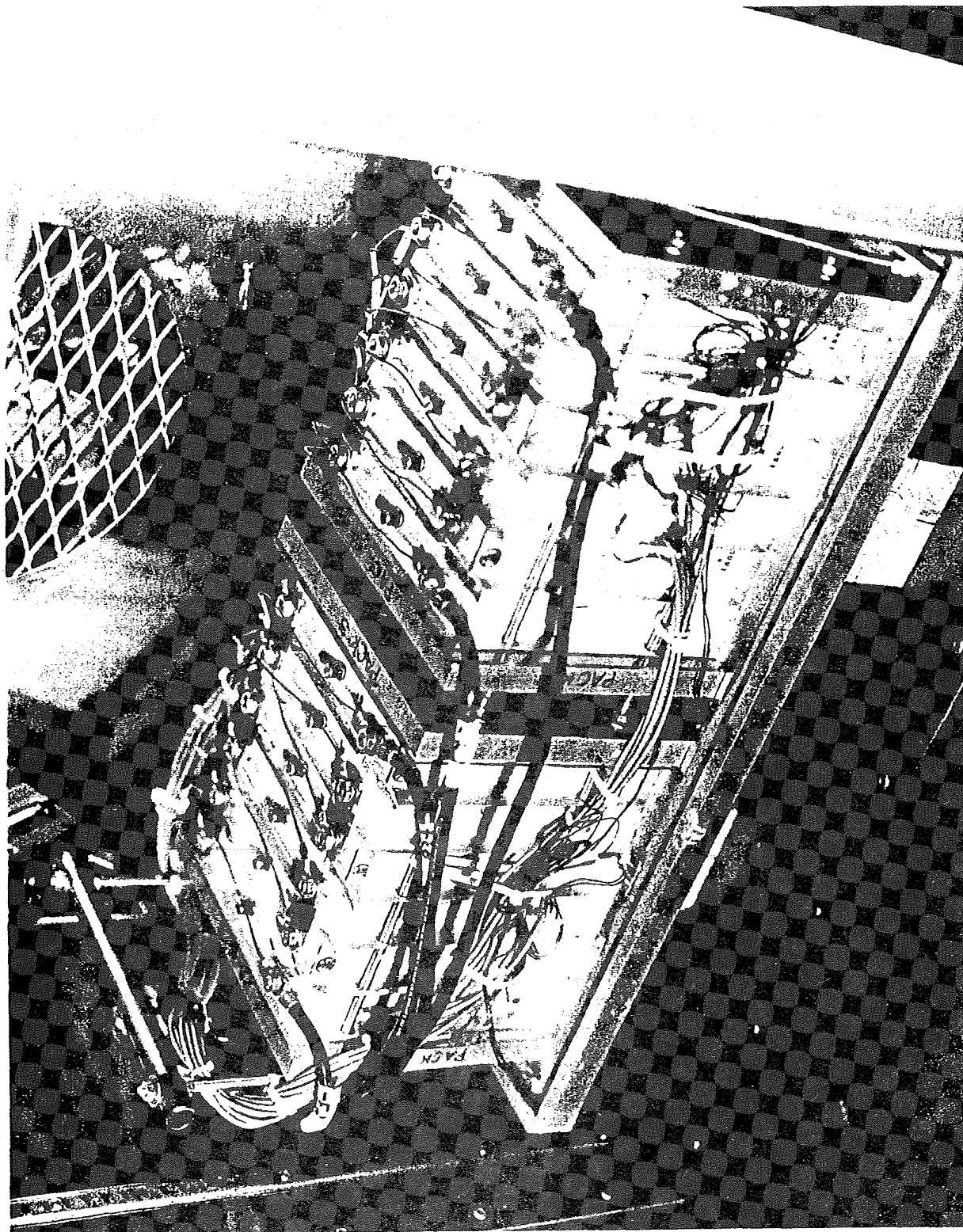
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**Ag-Zn Four, 6-Cell Packs** - Testing has been performed on secondary (rechargeable) Ag-Zn cells at MSFC for over 5 years. The latest test involves a Yardney 350 ampere-hour cell design which has cycled over 18 months and has achieved over 8200 low earth orbit (LEO) cycles as well as 19 deep discharges. The four, 6-cell packs (on line since November of 1989) are cycling to determine operational life of similar cells subjected to periodic, deep discharges. In addition, this test addresses different storage methods for these cells between deep discharges. Impedance measurements were made on one of the packs during periodic deep discharges.

This test was originally designed to determine the feasibility of using such a cell in a long-life (18 months) LEO application, which applied to the Orbiting Maneuvering Vehicle (OMV). Results from this test make it a candidate for other programs such as the Cargo Transfer Vehicle (CTV), and the Aeroassist Flight Experiment (AFE).

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Two of the Four  
Ag-Zn, 6-Cell Packs

# HST Ni-H<sub>2</sub> 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

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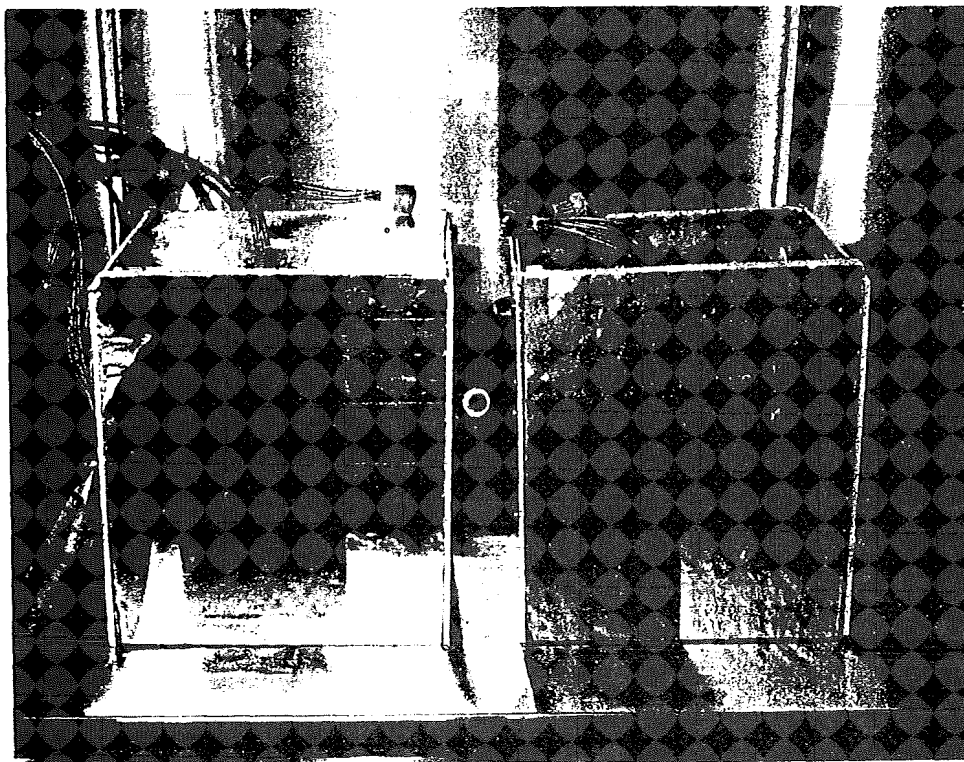
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**HST Ni-H<sub>2</sub> Three, 4-Cell Packs** - Three four cell packs of Eagle-Picher RNH-90-3 cells from different lots (4 Flight Spare Module (FSM) Lot Cells, 4 Test Module 1 (TM1) Lot Cells and 4 Test Module 2 (TM2) Lot Cells) following an Hubble Space Telescope (HST) low earth orbit (LEO) (61/35) cyclic profile at 7% - 9% DOD. The 4 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-H<sub>2</sub> 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-H<sub>2</sub> cells of HST design. This test will continue HST LEO cycling when not performing system evaluation tests.

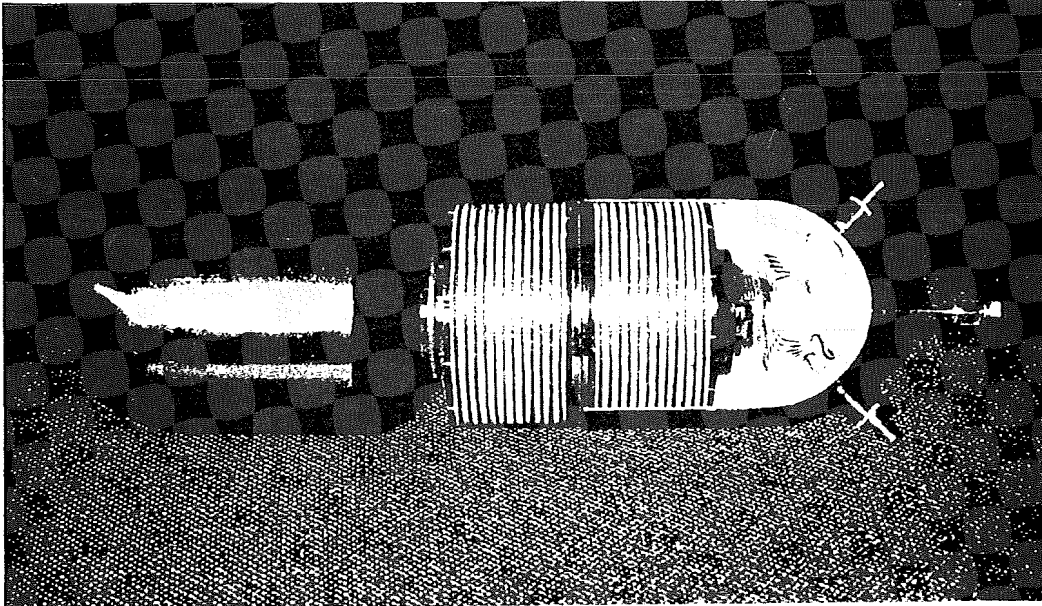
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HST Ni-H<sub>2</sub> Three, 4-Cell Packs



# Eagle Picher RNH-90-3

Developed for the Hubble Space Telescope



## Testing of RNH-90-3 Cells

- HST Ni-H<sub>2</sub> Three, 4-Cell Packs
- HST Ni-H<sub>2</sub> Six Battery Test
- HST "Flight Spare" Battery Test
- Ni-H<sub>2</sub> Two, 2-Cell Packs
- Ni-H<sub>2</sub> Six, 4-Cell Packs at 22 & 33% DOD

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# HST Ni-H<sub>2</sub> 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

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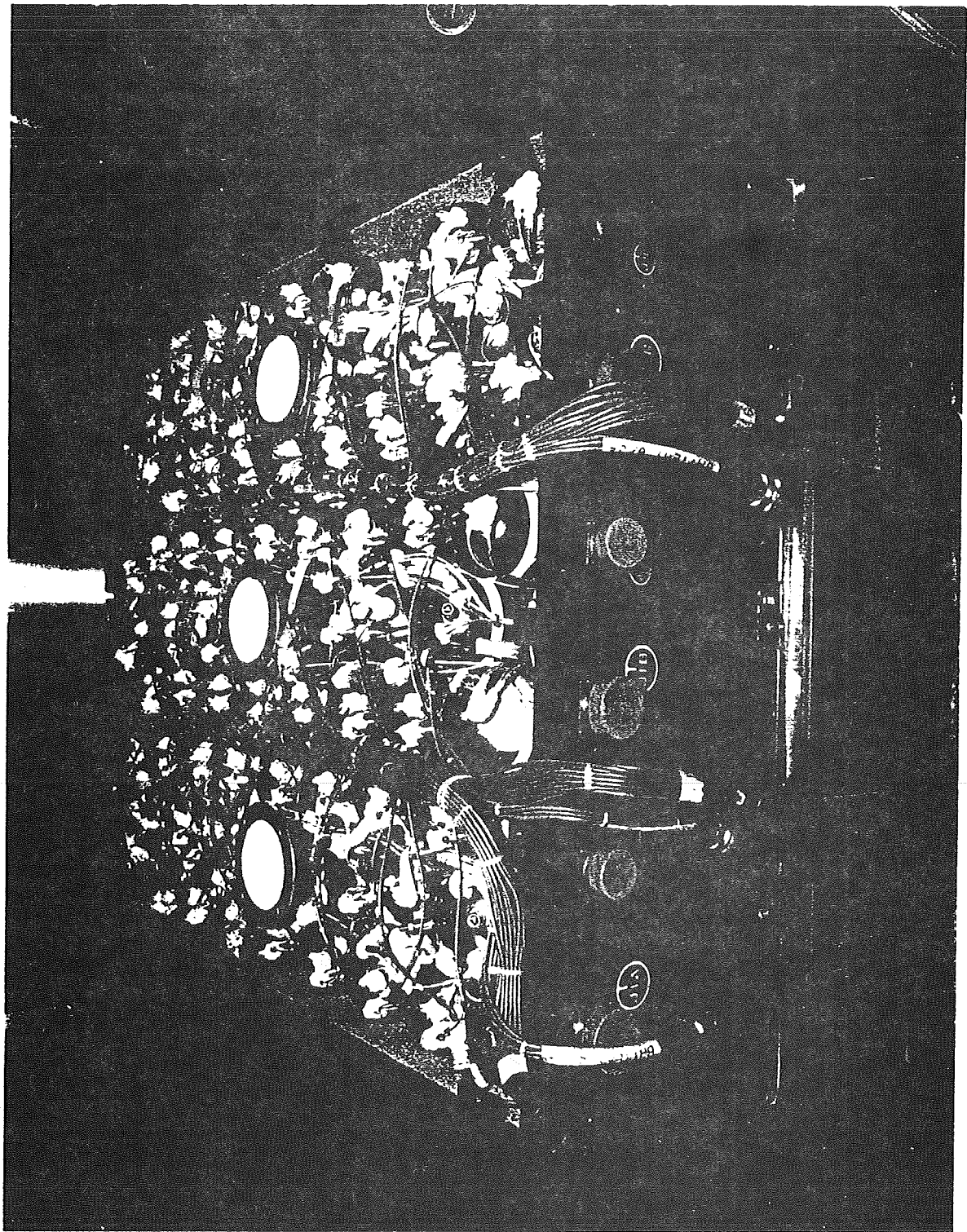
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**HST Ni-H<sub>2</sub> Six Battery System Simulation** - A full scale Hubble Space Telescope (HST) Ni-H<sub>2</sub> six battery electrical power system simulation began in May of 1989. This test utilized Test Module 1 (TM1) and Test Module 2 (TM2) 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-H<sub>2</sub> 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.

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HST Ni-H<sub>2</sub> Three Battery Module

# HST Ni-H2 "Flight Spare" Battery

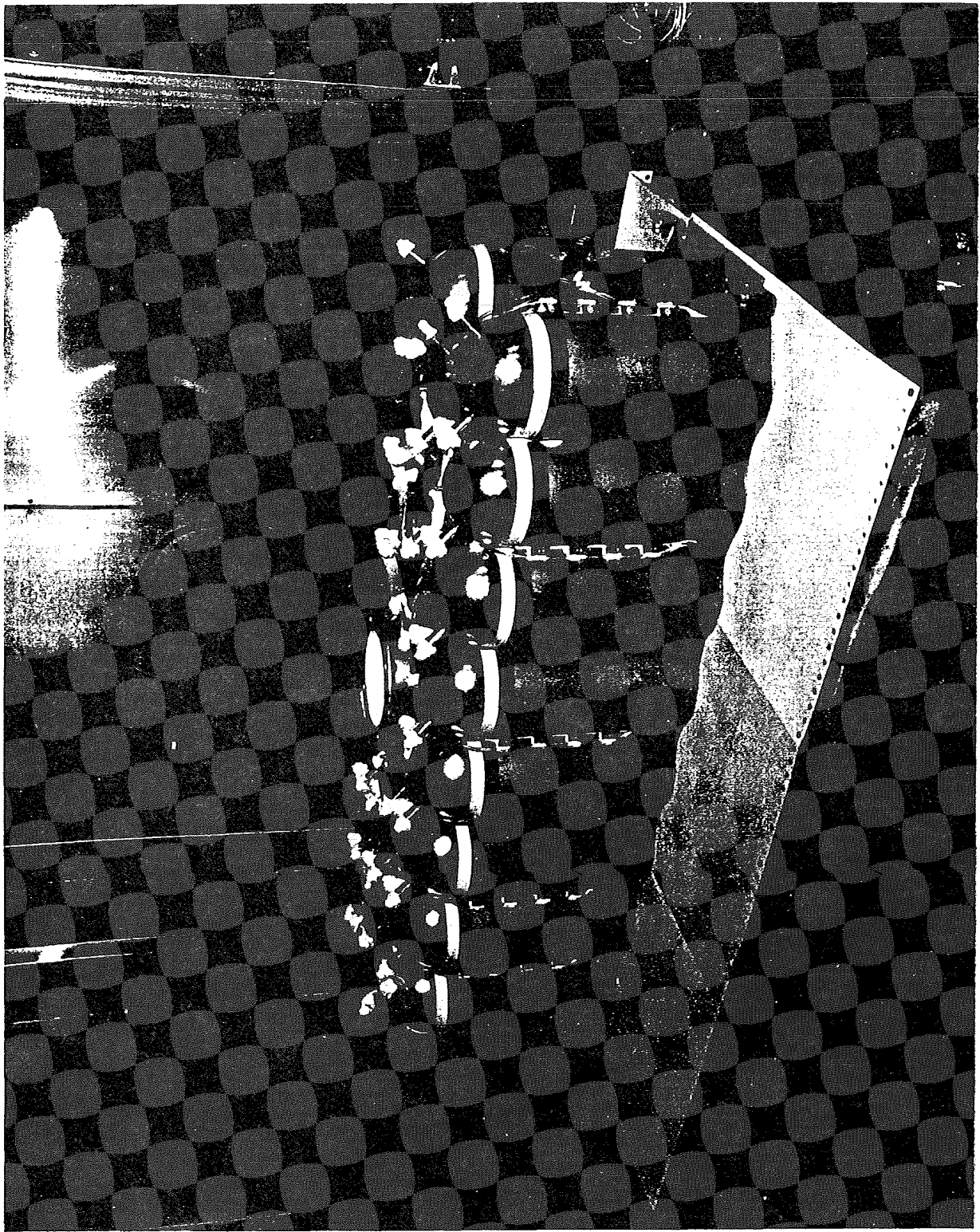
- 88 ampere-hour cells developed by Eagle Picher Inc. for the HST project. RNH-90-3
- 22 cells from the Flight Spare Lot of cells
- DOD ranges from 6 to 9% of the battery nameplate capacity.
- Battery cycling capacities vary from 70 to 78 Ah.
- 12,800 cycles (28 months) as of 10/21/91
- 10 month lead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

EB12/MSFC

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**HST Ni-H2 "Flight Spare" Battery** - One twenty two cell battery made up of Hubble Space Telescope (HST) cells (Eagle-Picher RNH-90-3) left over from the Flight Spare Module (FSM) lot (with full instrumentation, in flight configuration) was delivered to MSFC in June 1989 and entered a test program similar to the six battery system simulation. The test bed is automated with digital data acquisition, programmable loads and programmable power supplies and has safety features equivalent to the 6 Battery System Simulation. This is a battery life test simulating actual HST operation. The test has completed over 12,800 life cycles and will continue to support the HST and add to the low earth orbit (LEO) database.

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HST Ni-H<sub>2</sub> "Flight Spare" Battery

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# Ni-H<sub>2</sub> 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

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**Ni-H<sub>2</sub> 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-H<sub>2</sub> 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.

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# 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-H<sub>2</sub> cells at moderate DODs.
- Study the effect of reconditioning on Ni-H<sub>2</sub> cells.
- Demonstrate the ability of the HST design to provide extended life cycle at DODs required by AXAF, Space Station, etc.

EB12/MSFC

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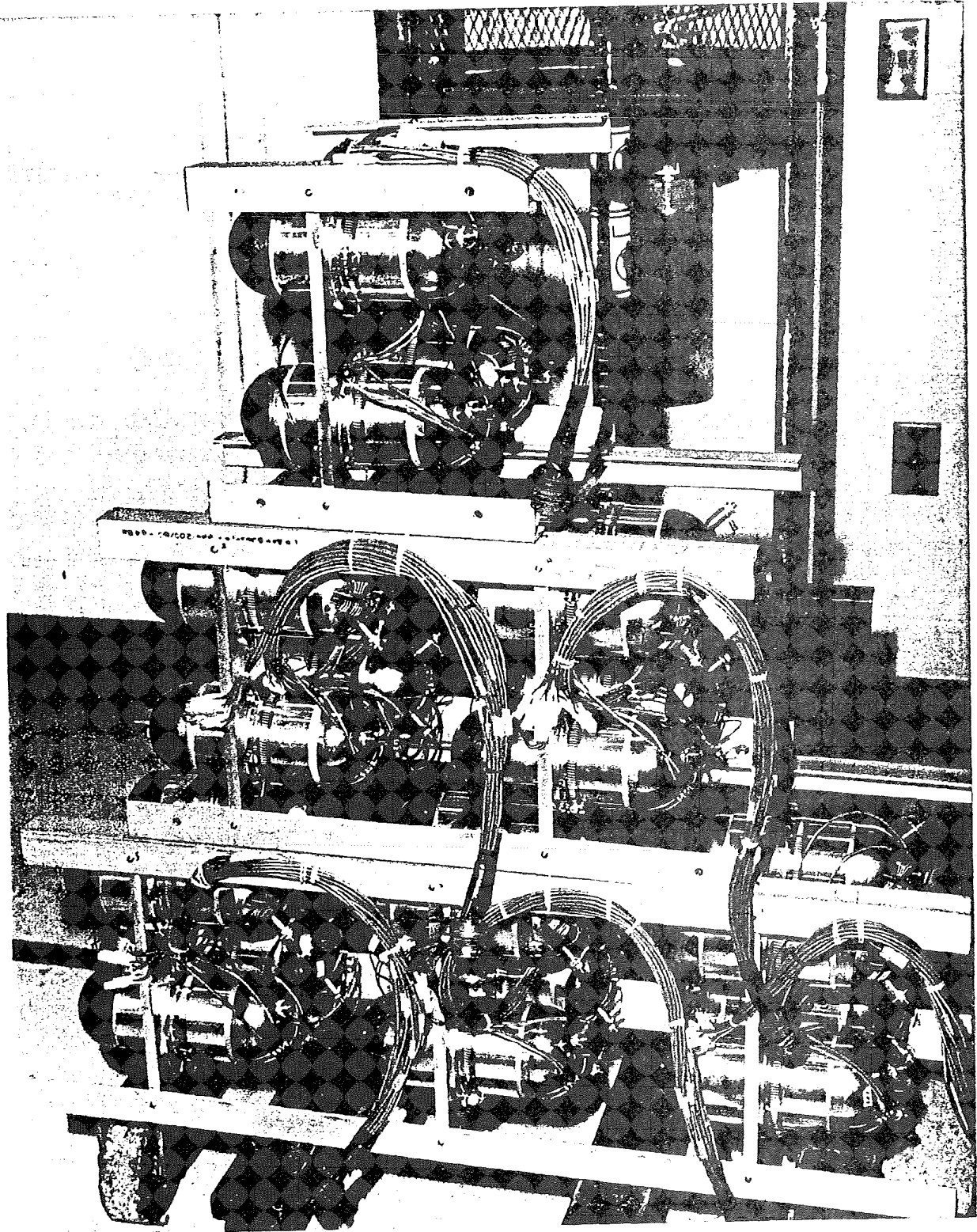
**Six, Ni-H<sub>2</sub> 4-Cell Packs** - This test utilizes 24 Eagle-Picher RNH-90-3 Ni-H<sub>2</sub> cells from the Hubble Space Telescope (HST) program. The cells are low earth orbit (LEO) cycling on a 61/35 orbit. On line since May of 1991, the purpose of this test is to evaluate the performance and 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.

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Six, Ni-H<sub>2</sub> 4-Cell Packs



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## Testing of Eagle Picher RNH-90-3 at MSFC Summary

<u>TEST</u>	<u># of Cells</u>	<u>Cycling DOD</u>	<u>Project(s)</u>	<u>Months of testing</u>
HST NI-H2 4-Cell Packs	12	6 - 9%	HST	34, 32, 30
HST NI-H2 Six Battery Test	132	6 - 9%	HST	29
HST "Flight Spare" Battery Test	22	6 - 9%	HST	28
NI-H2 2-Cell Packs	4	20 - 50%	—————	24
NI-H2 4-Cell Packs at 22 & 33% DOD	24	22 & 33%	AXAF SS Freedom	4

## Summary of LDEF Battery Analyses

Presented at  
1991 NASA Aerospace Battery Workshop

by  
Dr. Chris Johnson

Boeing Defense & Space Group  
P. O. Box 3999; M/S 8C-61  
Seattle, WA 98124

(206) 773-5058

### Contributing Agencies and Laboratories

**Aerospace Corporation**  
Larry Thaller & Harlin Bittner

**Jet Propulsion Laboratories**  
Frank Deligiannis

**NASA Goddard Space Flight Center**  
Smith Tiller & David Sullivan

**NASA-Marshall Space Flight Center**  
Subcontract - AZ Technology

**SAFT America Inc.**  
James Bene  
Boeing Subcontract



# SUMMARY OF LDEF BATTERY ANALYSES

Dr. Chris Johnson

Boeing Defense & Space Group  
P. O. Box 3999; M/S 8C-61  
Seattle, WA 98124

## ABSTRACT

Tests and analyses of NiCd, LiSO<sub>2</sub> and LiCF batteries flown on the Long Duration Experiment Flight (LDEF) includes results from NASA, Aerospace and commercial labs. The LiSO<sub>2</sub> 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/SO<sub>2</sub>), 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.

**Table 1. Summary of Battery Type, Quantity and State of Charge.**

Exp #	Experiment Name	Battery	Voltage	# of Batteries	SOC
A 0038	Pyro Cable Cutter	Li/SO2	12	7	0%
A 0054	Space Plasma - High Voltage	Li/SO2	28	4	39%
A 0076	Variable Conduction Heat Pipes	Li/SO2	7.5	1	0%
A 0076	Variable Conduction Heat Pipes	Li/SO2	28	1	84%
A 0133	Space Based Radar	Li/SO2	7.5	3	25%
A 0133	Phased Array Antenna	Li/SO2	12	2	60%
A 0138-8	Epoxy Composite Materials	Li/SO2	7.5	3	75%
A 0138-8	Frecopa	Li/SO2	28	3	74%
A 0139-A	Crystal Growth Dewers	Li/SO2	7.5	13	49%
A 0180	Recorders for Space Exposure	Li/SO2	12	2	64%
A 0187-1	Clam Shell Elect-Micrometeorites	Li/SO2	7.5	1	59%
A 0187-1	Clam Shell Elect-Micrometeorites	Li/SO2	12	2	73%
A 0201	Sun Sensor-Dust Experiment	Li/SO2	7.5	2	20%
A 0201	Sun Sensor-Dust Experiment	Li/SO2	12	2	85%
A 0201	Sun Sensor-Dust Experiment	Li/SO2	28	6	88%
M 0003	Space Env. Effects on S/C Mater.	Li/SO2	7.5	2	0%
M 0003	Space Env. Effects on S/C Mater.	Li/SO2	7.5	2	76%
M 0003	Space Env. Effects on S/C Mater.	Li/SO2	12	2	0%
M 0003	Space Env. Effects on S/C Mater.	Li/SO2	12	1	46%
M 0003	Space Env. Effects on S/C Mater.	Li/SO2	12	2	76%
M 0003	Space Env. Effects on S/C Mater.	Li/SO2	12	1	88%
M 0004	Space Effects on Fiber Optics	Li/SO2	7.5	1	0%
M 0004	Space Effects on Fiber Optics	Li/SO2	12	1	71%
M 0004	Space Effects on Fiber Optics	Li/SO2	12	2	85%
M 0004	Space Effects on Fiber Optics	Li/SO2	28	6	85%
M 0006	Space Effects - Optical Surfaces	Li/SO2	7.5	1	76%
M 0006	Space Effects - Optical Surfaces	Li/SO2	28	1	77%
P 0003	LDEF Thermal Measurements	Li/SO2	7.5	1	73%
S 0010	Exposure of S/C Coatings	Li/SO2	7.5	1	76%
S 0010	Exposure of S/C Coatings	Li/SO2	28	1	77%
S 0014	Photovoltaic Cells - Sun Sensor	Li/SO2	7.5	1	0%
S 0014	Photovoltaic Cells - Sun Sensor	Li/SO2	12	1	85%
S 0014	Photovoltaic Cells - Sun Sensor	Li/SO2	28	2	0%
S 0069	Carousel, Opt system	Li/SO2	7.5	1	0%
S 1001	Low Temperature Heat Pipes	Li/SO2	7.5	1	0%
S 1001	Low Temperature Heat Pipes	Li/SO2	12	1	85%
S 1002	Solar cells, QCM	Li/SO2	7.5	1	0%
S 1002	Solar cells, QCM	Li/SO2	28	2	80%
S 1005	Flat Plate Heat Pipe Experiment	Li/SO2	7.5	1	0%
S 1005	Flat Plate Heat Pipe Experiment	Li/SO2	12	1	85%
INIT	LDEF Initiation System	Li/SO2	28	2	89%
S 0069	Carousel-Thermal Conductive Surfaces	Li/CF	28	4	0%
S 1005	Flat Plate Heat Pipe Experiment	Li/CF	28	6	0%
S 1001	Low Temperature Heat Pipes	NiCd	18	1	Recharge

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.

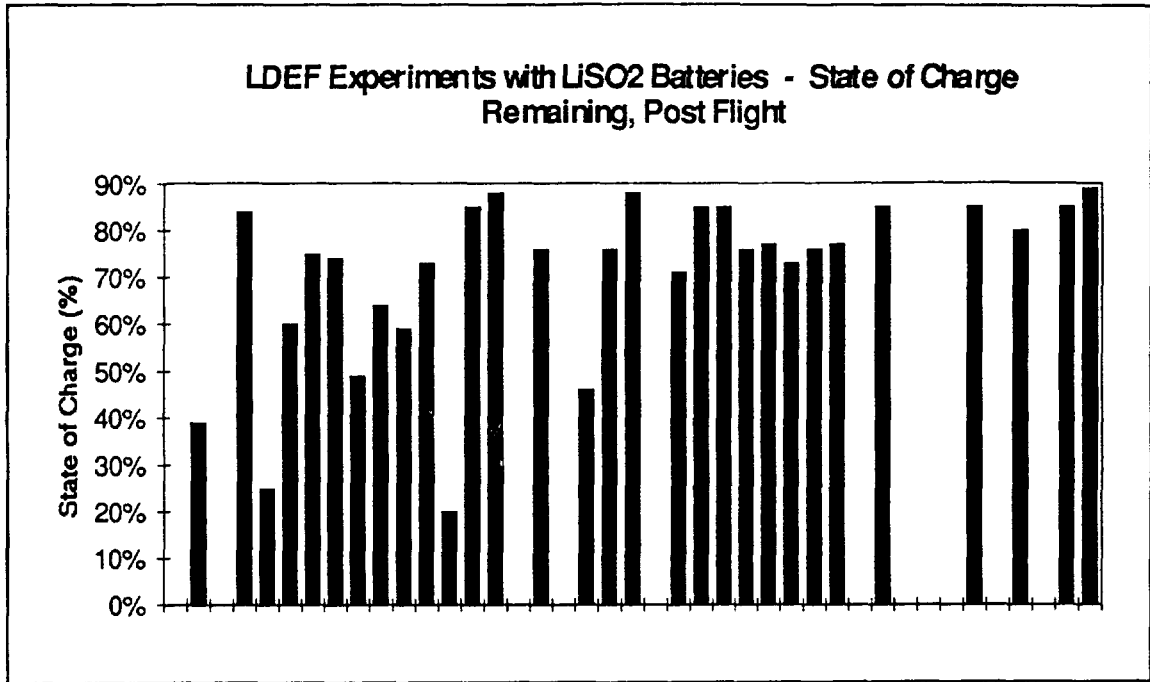


Figure 1. State of Charge Remaining in Li/SO<sub>2</sub> Batteries Returned from LDEF Flight.

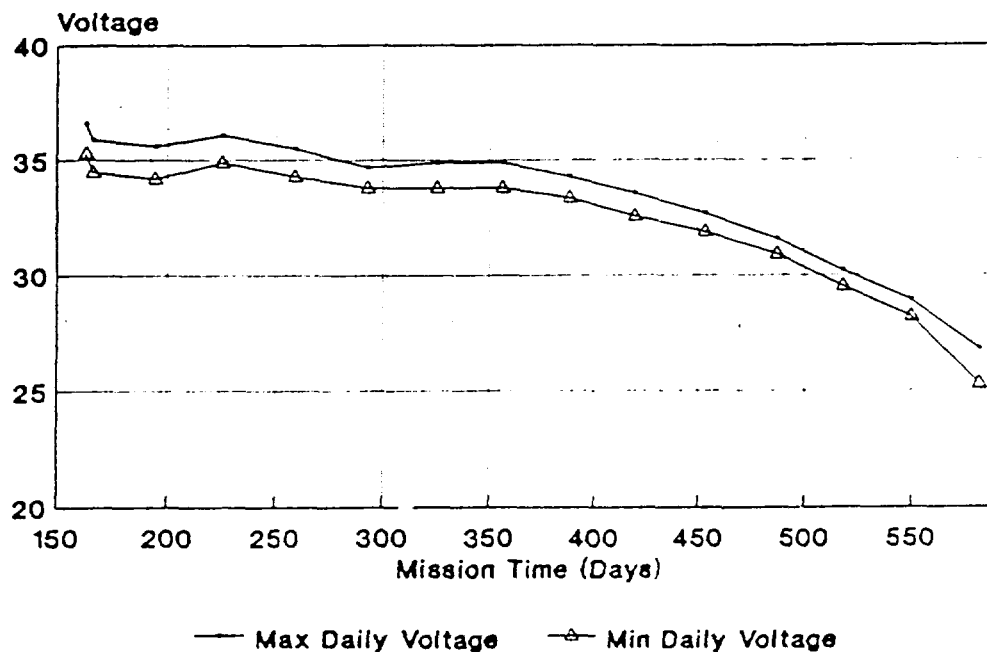


Figure 2. Gradual Degradation of Voltage with Flight Duration for Li/CF Batteries

## 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.

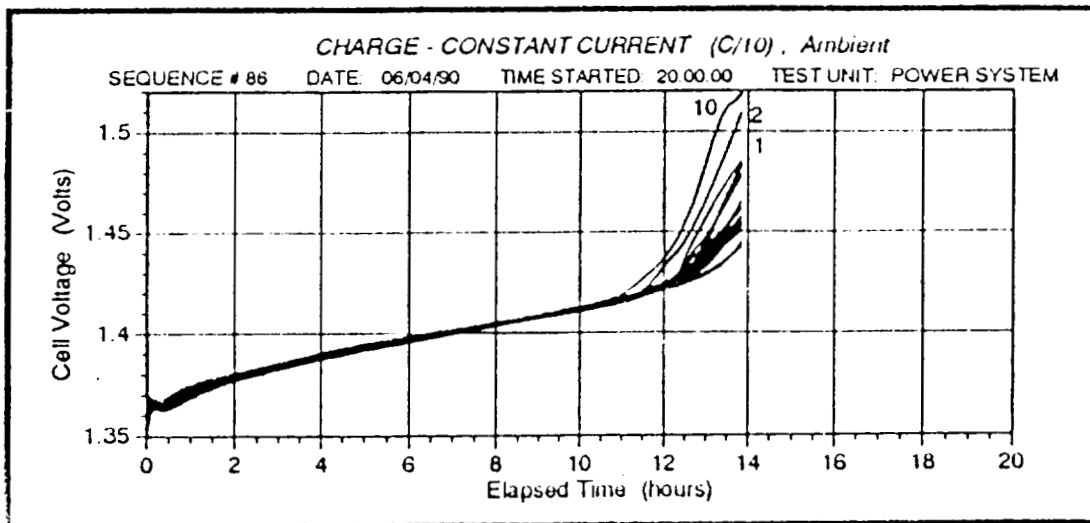


Figure 3. Constant Current Charge Indicates Loss of Overcharge Protection

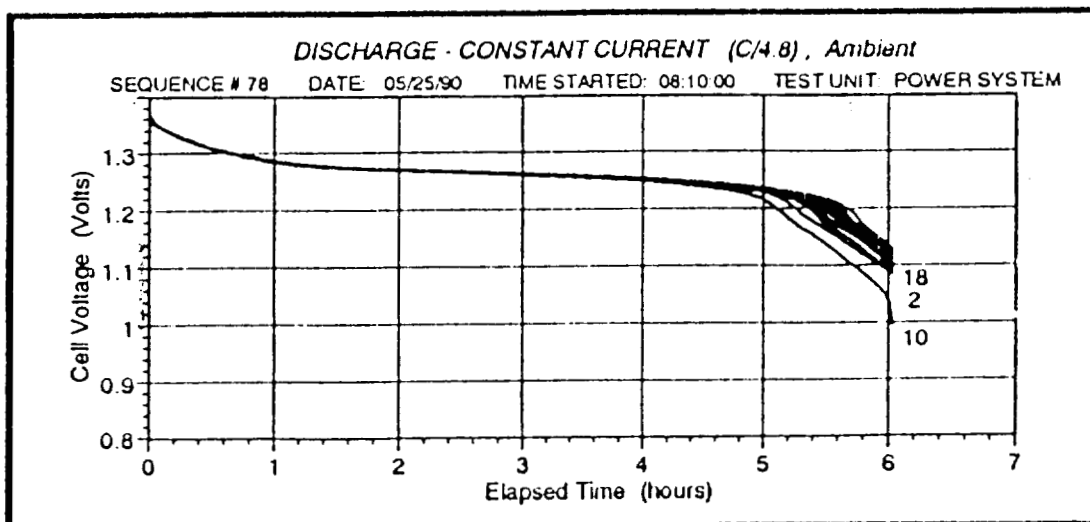


Figure 4. Constant Current Discharge Produces Low Capacity, Post Flight

## REFERENCES

1. Raman, "Experimentation and Destructive Physical Analysis for the Space-Exposed Lithium-Sulfur Dioxide (Li/SO<sub>2</sub>) Batteries From the Long Duration Exposure Facility (LDEF)", SAFT America Inc., Attachment 1, 1991, pp. (1)-1,2.
2. Raman, "Experimentation and Destructive Physical Analysis for the Space-Exposed Lithium-Sulfur Dioxide (Li/SO<sub>2</sub>) Batteries From the Long Duration Exposure Facility (LDEF)", SAFT America Inc., 1991, Attachment 1, p. 39.
3. L. Thaller, Memo Report on Discharge of LDEF LI/SO<sub>2</sub> Cells, Aerospace Corporation, January 1991.
4. F. Deligiannis, Presentation to Lithium Battery Safety Committee, Jet Propulsion Laboratory, July 1991.
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
6. AZ Technology Report No. 90-1-100-2, "Thermal Control Surfaces Experiment Initial Flight Data Analysis Final Report", June 1991, pp. 49-52.
7. S. E. Tiller and D. Sullivan, "Long Duration Exposure Facility Low-Temperature Heat Pipe Experiment Package Power System Results", 1991.

## **Primary Technologies Session**

*Organizers: Bob Bragg  
NASA Johnson Space Center*

*Frank Deligiannis  
Jet Propulsion Laboratory*





THE SWELLING MECHANISM OF CATHODES

IN  $\text{Li}/(\text{CFx})_n$  CELLS

N. MARGALIT AND C.C. BAXAM  
BATTERY TECHNOLOGY CENTER  
TRACOR TECHNOLOGY RESOURCES  
ROCKVILLE, MD 20850

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

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## 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  $\text{Li}/(\text{CFx})_n$  cells. A better understanding of the chemical reaction mechanism, a possible new role for the carbon and a model for cathode growth are discussed.

# Tracor Technology Resources

## INTRODUCTION

Early developers of lithium-organic electrolyte cells were attracted to  $(\text{CFx})_n$  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  $\text{Li}/(\text{CFx})_n$  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  $\text{Li}/(\text{CFx})_n$  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.

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\* 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.

# Tracor Technology Resources

## VOLUME CHANGES OF CATHODES IN BR-2325 CELLS DUE TO DISCHARGE

### WET CATHODES VOLUME BEFORE DISCHARGE

	Volume *(Cm <sup>3</sup> )
PC/DME	0.261
GBL	0.251

### CATHODES FROM DISCHARGED CELLS

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

$\Delta$ Volume\* (%)

	<u>32°F</u>	<u>120°F</u>
PC/DME	36	1
GBL	36	2

75°F Discharge Across a 15,000 ohm Load

$\Delta$ Volume\* (%)

PC/DME	27
GBL	28

\*  $\pm$  1%

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## APPROACH

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.

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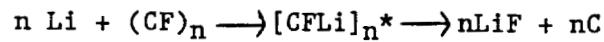
\* D.M Pasquariello, E.B. Willstaedt and K.M. Abraham, The Electrochemical Society, Fall Meeting, Paper No. 17, Seattle, Washington, October 1990.

# Tracor Technology Resources

## ELECTROCHEMICAL REDUCTION OF PTFE AND $(CF_x)_n$ BY LITHIUM

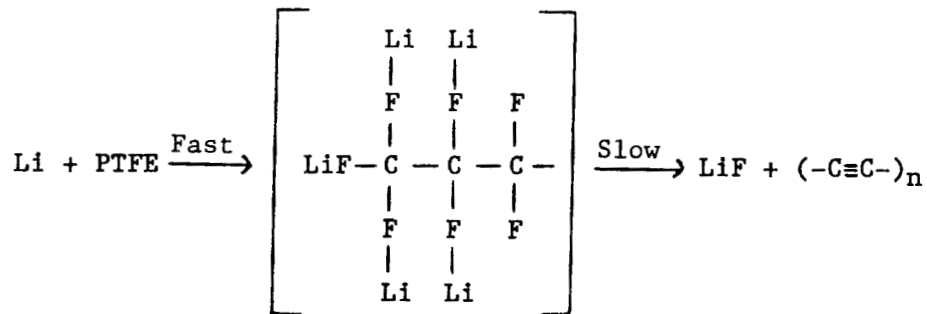
### PROPOSED MECHANISMS

$(CF_x)_n$



\* Prevailing literature intermediate  $[CF \cdot Li(S)_n]$

PTFE (Dousek et al)



$[-C \equiv C-]_n \longrightarrow$  to more ordered form

$LiF \longrightarrow$  to larger crystals

PROBLEM:

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

HOW DOES THE LITHIUM REACH REACTION SITES?

# Tracor Technology Resources

## ROLE OF CARBON

### (Reaction Mechanism)

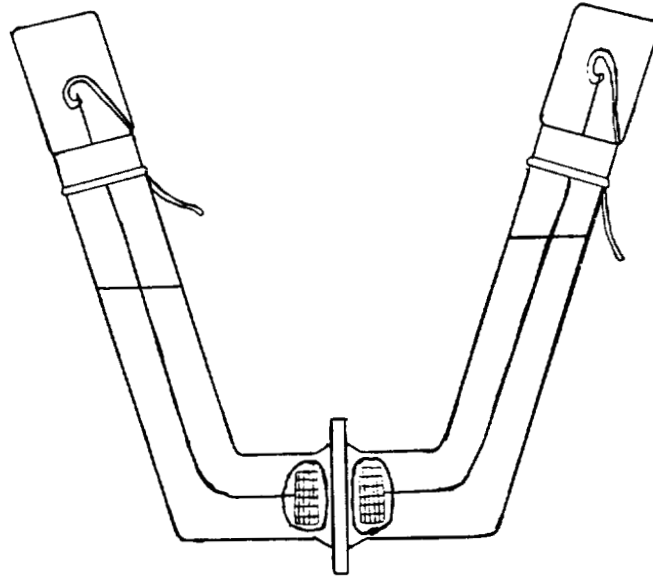
Reaction mechanisms proposed, in the literature, for the  $(CF_x)_n$  electrode reduction by lithium assume lithium ion penetration to reaction sites between layers of active material via an intermediate. A similar mechanism is proposed for the reduction of PTFE by lithium metal.

X-ray diffraction patterns show only the presence of LiF on both reduction products and disordered carbon on the surface of discharged  $(CF_x)_n$  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.

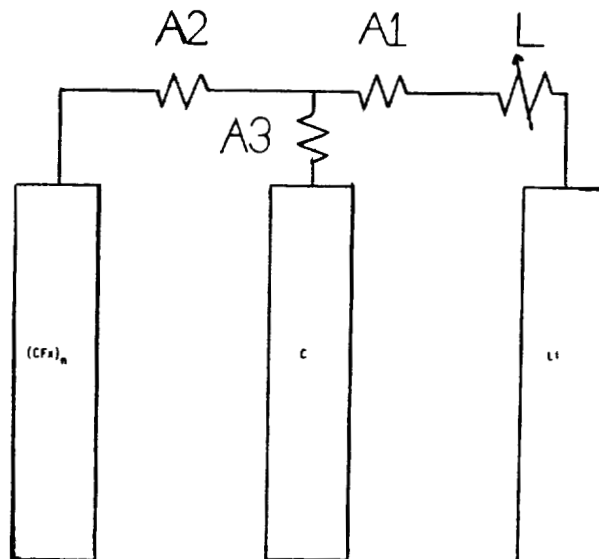
Based on carbon intercalation chemistry literature, which is abundant, and the expected slow lithium ion diffusion through LiF crystals, we proposed last year that lithium could be first "intercalated" into the discharged carbon and then proceed to  $(CF_x)_n$  sites. Experiments designed to verify the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



## Tracor Technology Resources



"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)

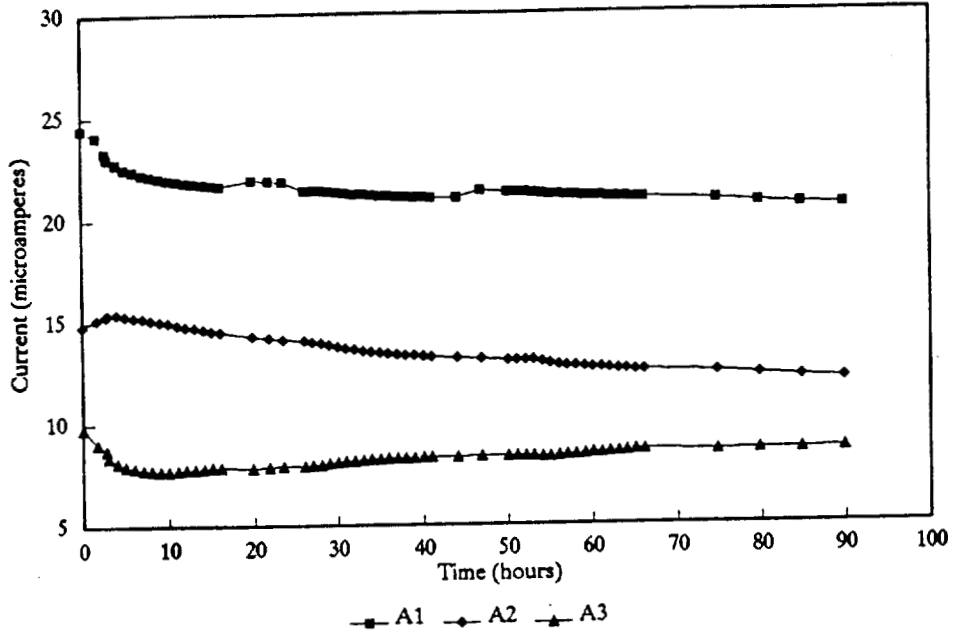
The experimental setup designed to understand the role of carbon in the cathode reaction consisted of a Li/Li salt in an organic solvent/ $(CF_x)_n$  cell separated into two compartments by a piece of Pyrolytic Graphite - Coated Graphite (Pyrotech, PT101).

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.

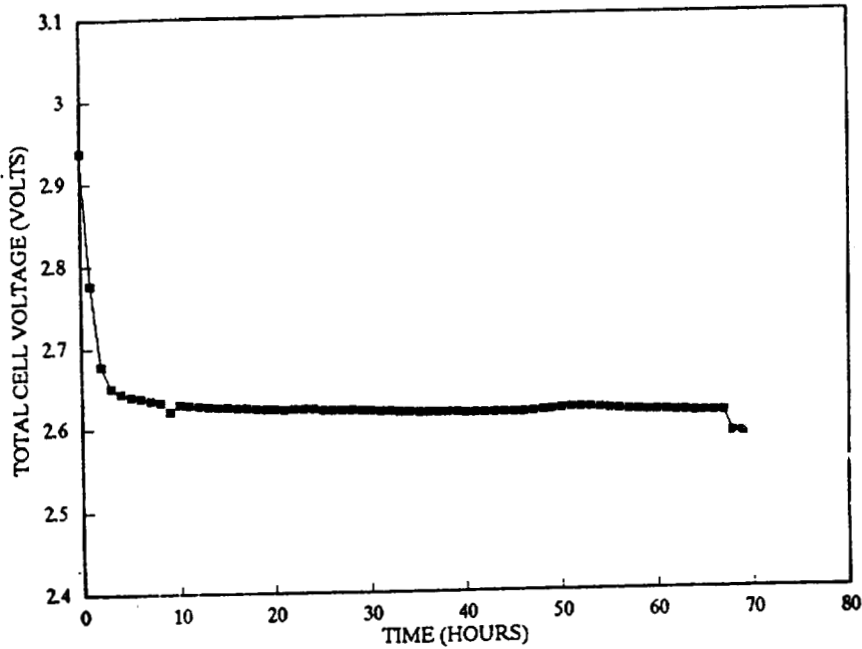
Initial results with a  $1M LiAsF_6$  in DMSI solution indicated no current flow through A2 unless the carbon was loaded with some lithium. Loading the carbon, by disconnecting A2, and unloading the carbon, by disconnecting A1, resulted in increasing and decreasing the ability of the cell to deliver 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  $1M LiAsF_6$  in PC.

# Tracor Technology Resources



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)

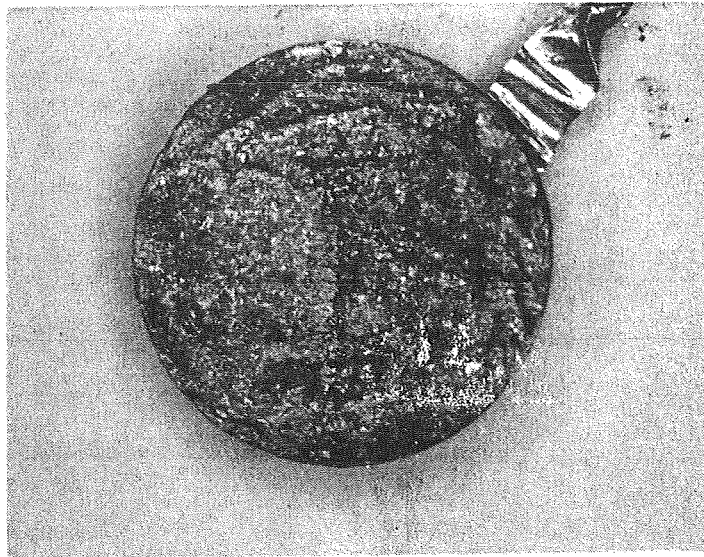
Results obtained with the PC solution varied some with the piece of carbon used. In the case of one cell similar results to those obtained with DMSI were obtained.

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 equally to both the carbon and the  $(CFx)_n$  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.

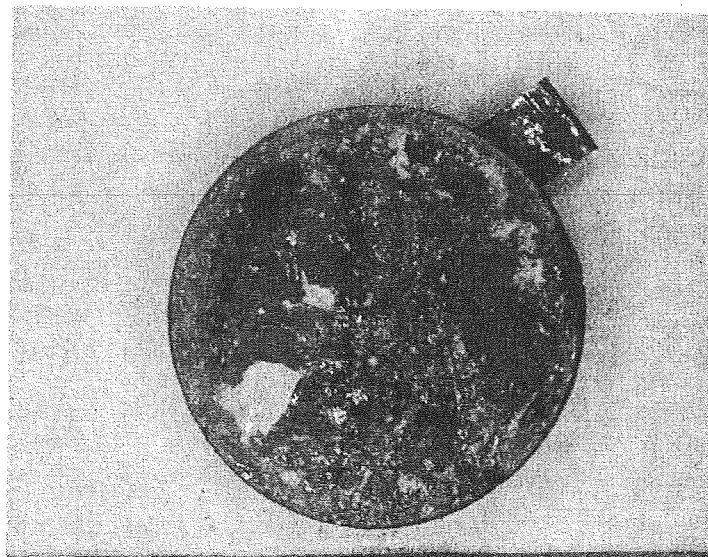
Such behavior indicates carbon loading with lithium while the cell is discharging. Hence, if one assumes that  $(CFx)_n$  is fully covered with discharge product, even if slightly cracked, then the observed discharge voltages could be attributed to mixed potentials involving lithium loading on carbon 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  $(CFx)_n$  electrode, 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

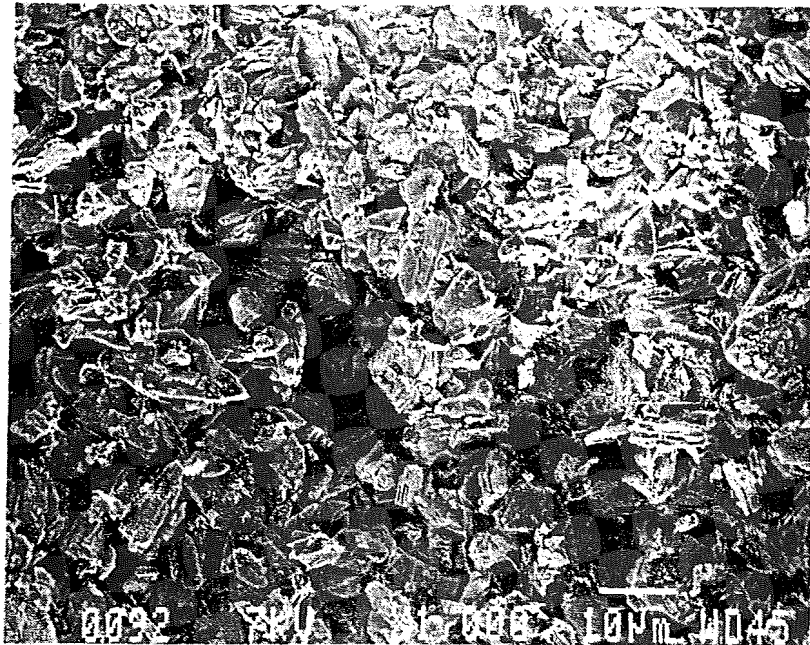
Visual and microscopic examination of specially made "electrodes" gave better insight into the swelling mechanism.

These electrodes consisted of a pellet made from shiny high purity graphite powder on which gray  $(CF_x)_n$  powder was sprinkled and allowed to discharge slowly vs lithium (CCV 1.8 volts) under flooded conditions in a  $1M LiAsF_6$  in PC solution.

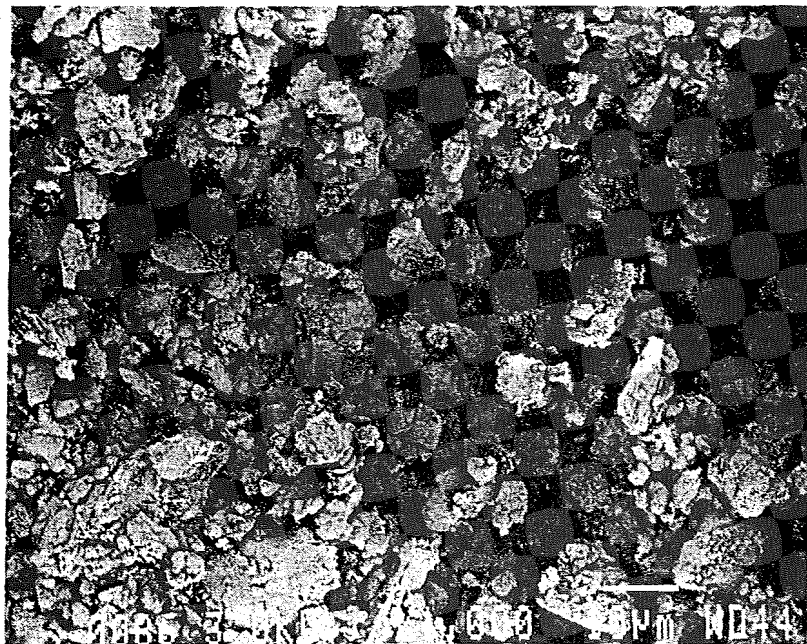
Surprisingly, partially discharged material on the surface of these electrodes hardened into a porous matrix and had to be scraped for further observation. Scraping of such partially discharged electrodes revealed a gray upper layer of partially discharged material on the top of the electrode and a dull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

# Tracor Technology Resources

## SWELLING MODEL

Based on the above, a reasonable model for  $(CFx)_n$  cathode swelling will consist of the following steps:

1. Electrons reach  $(CFx)_n$  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 chocking.

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  $\text{Li}/(\text{CFx})_n$  cells is the formation and three dimensional expansion of the fused particle matrix.

Lithium reaction with carbon in the  $(\text{CFx})_n$  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.

## PRIMARY ZINC-AIR BATTERIES FOR SPACE POWER

by

Bob Bragg and Debbie Bourland  
 NASA Lyndon B. Johnson Space Center  
 Houston, TX 77058

and

Glenn Merry and Ron Putt  
 MATSI, INC.  
 430 10TH ST NW STE S-007, Atlanta, GA 30318

### 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 1: Primary Battery Specific Energies

System	Specific Energy (Wh/lb)
Alkaline-Manganese	60
Alkaline-Mercuric Oxide	55
Lithium-Sulfur Dioxide	125
Lithium-Manganese Dioxide	135
Zinc-Air	200

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 2: HR and LC Cell Specifications

Cell	Drain Rate	Capacity	Specific Energy
HR	1 A	12 Ah	160 Wh/lb
HR	3 A	9 Ah	-
LC	2 A	200 Ah	200 Wh/lb
LC	6 A	150 Ah	-

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/cm<sup>2</sup>, while the maximum continuous current density is 50 mA/cm<sup>2</sup>.

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/cm<sup>2</sup>) 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) assumed 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 3: HR and LC Cell Design Specifications

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

#### 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:

$$U (\%) = 97 + 32 \ln(1 - i/70), \text{ and}$$

$$V_{av} (V) = 1.29 - 0.0058i.$$

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/cm<sup>2</sup>, 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/cm<sup>2</sup>) 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/cm<sup>2</sup>) 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 4: HR and LC Cell Performance (@ 25° C)

Cell Type	Drain Rate	Capacity		Specific Energy (Wh/lb)	
		Goal	Achieved	Goal	Achieved
HR	1 A	12 Ah	29 Ah	160	165
HR	3 A	9 Ah	24 Ah	-	131
LC	2 A	200 Ah	203 Ah	200	211
LC	6 A	150 Ah	188 Ah	-	182

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.

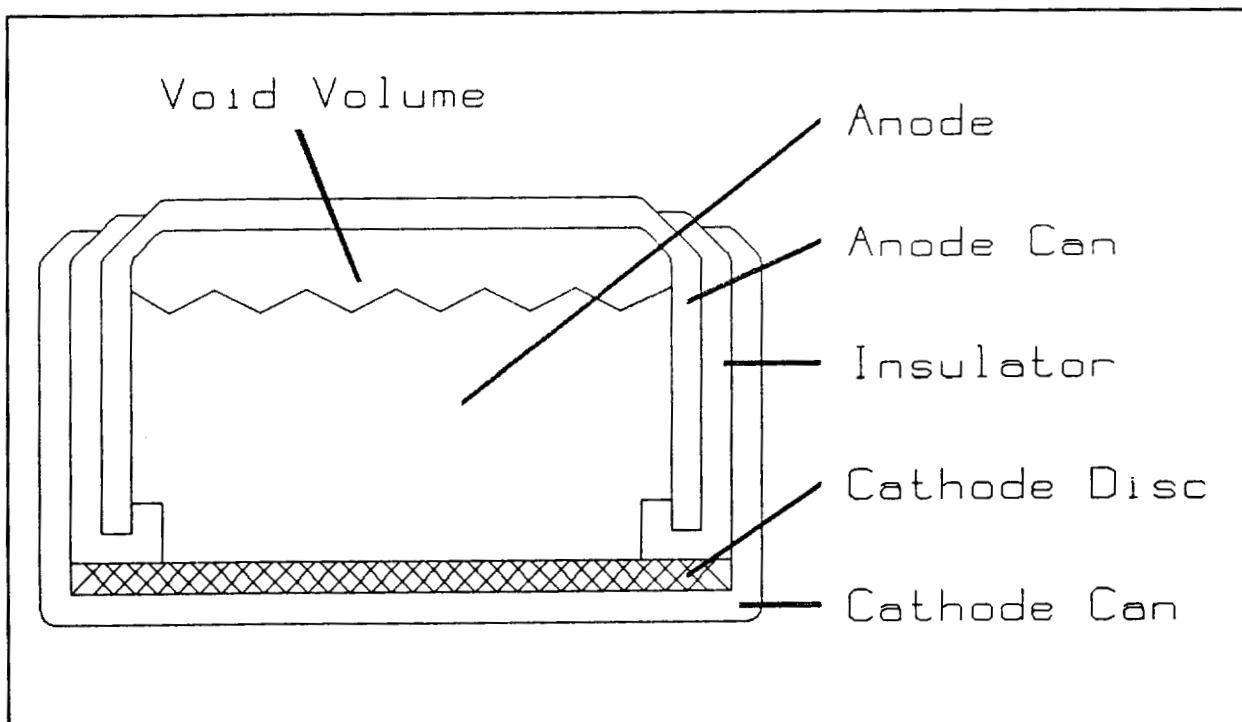


Figure 1: Button Cell Design



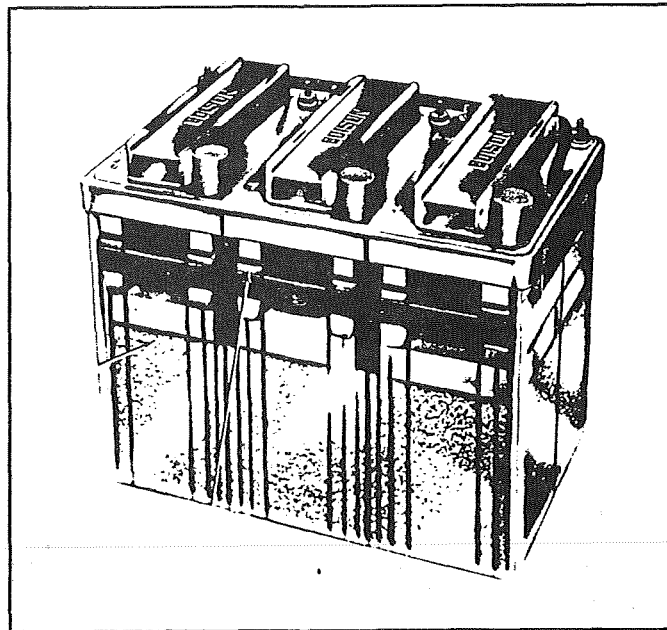


Figure 2: Industrial Zinc-Air Battery

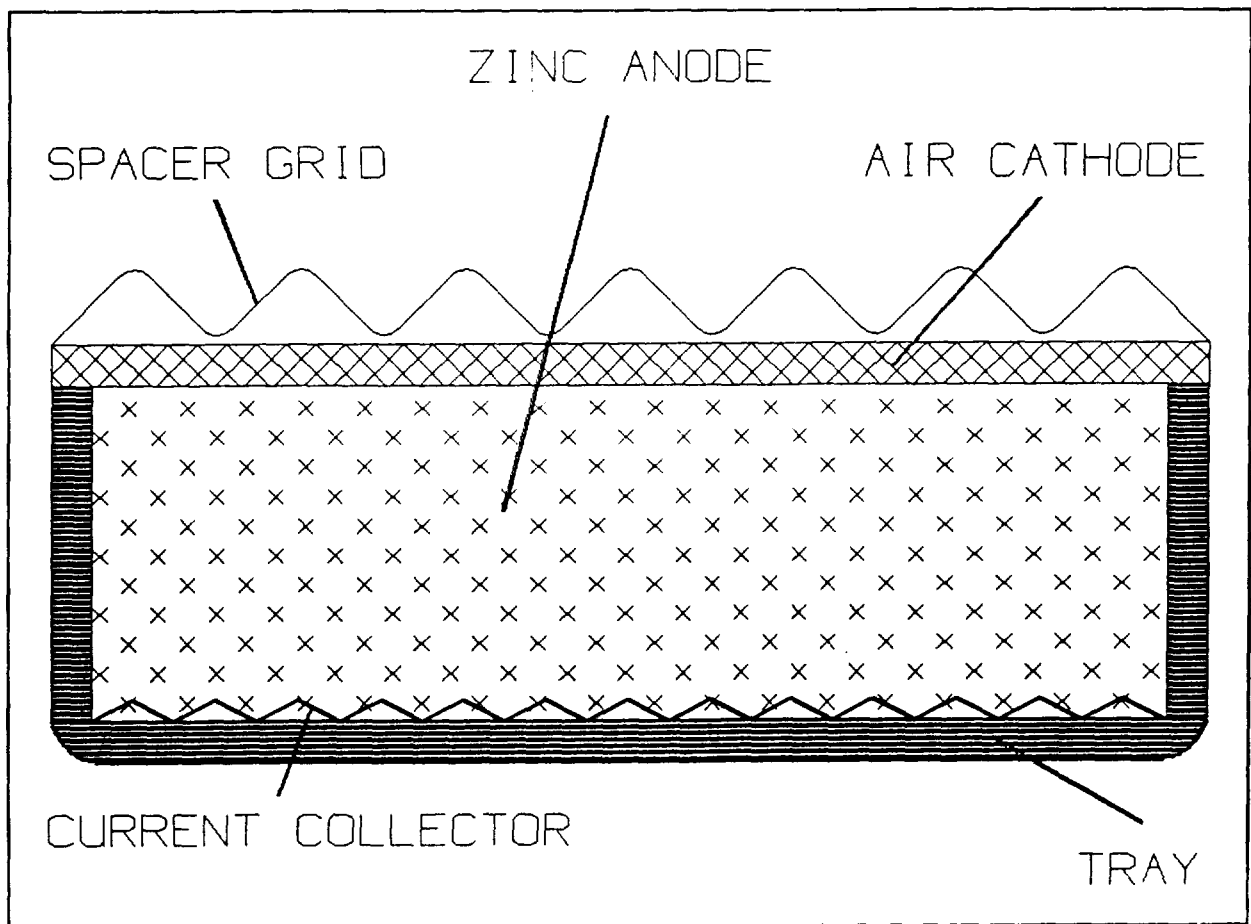


Figure 3: Cell Design Concept

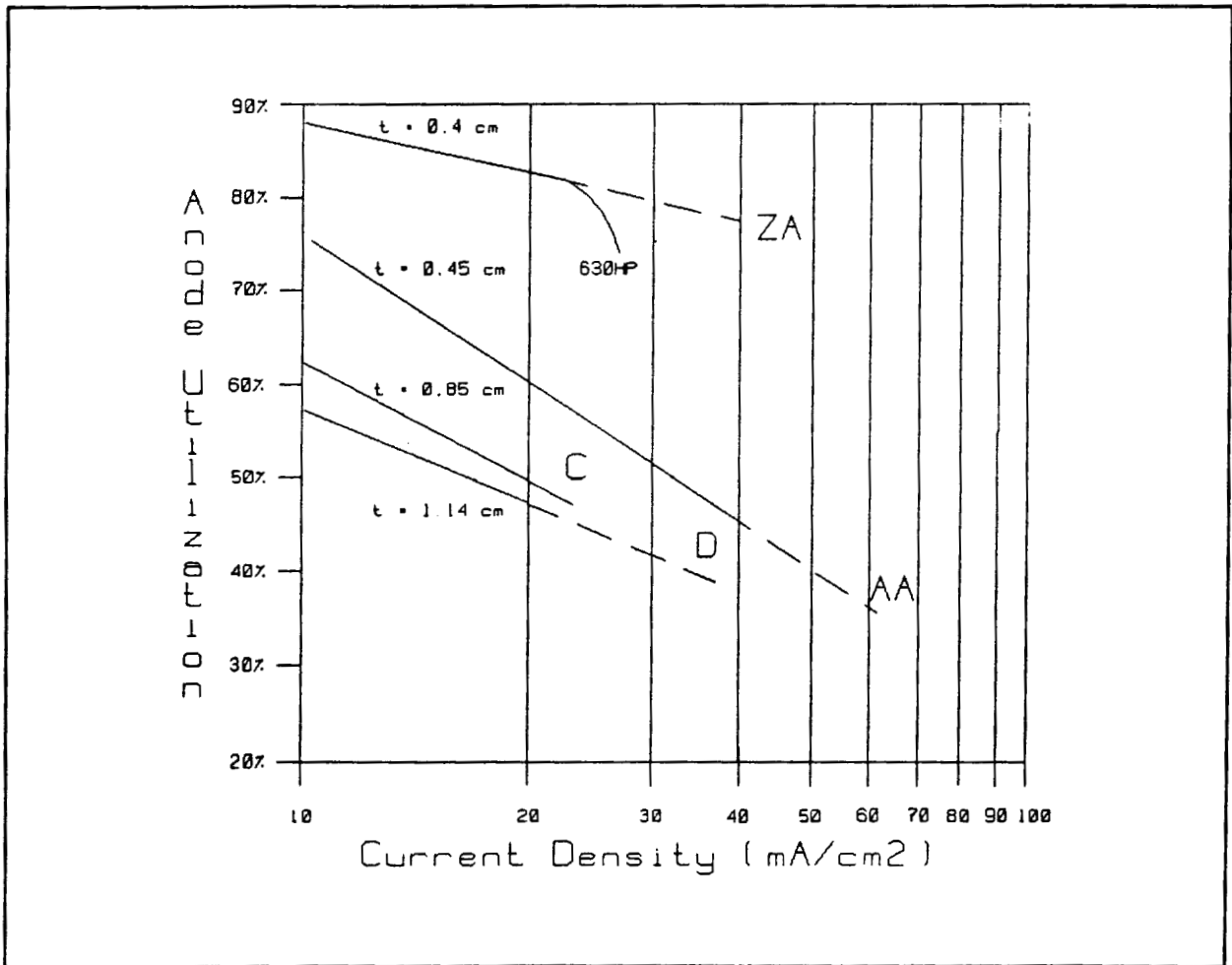
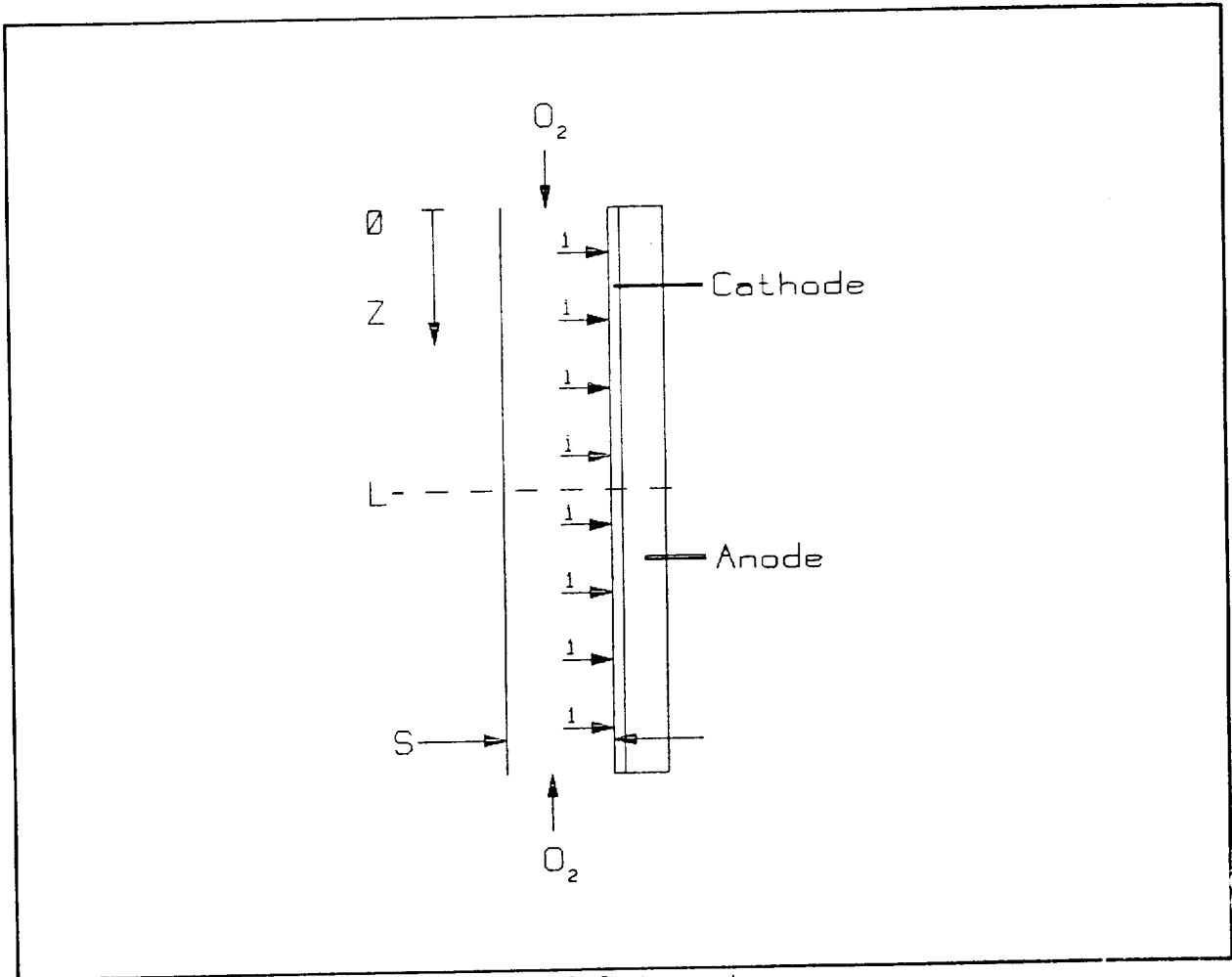
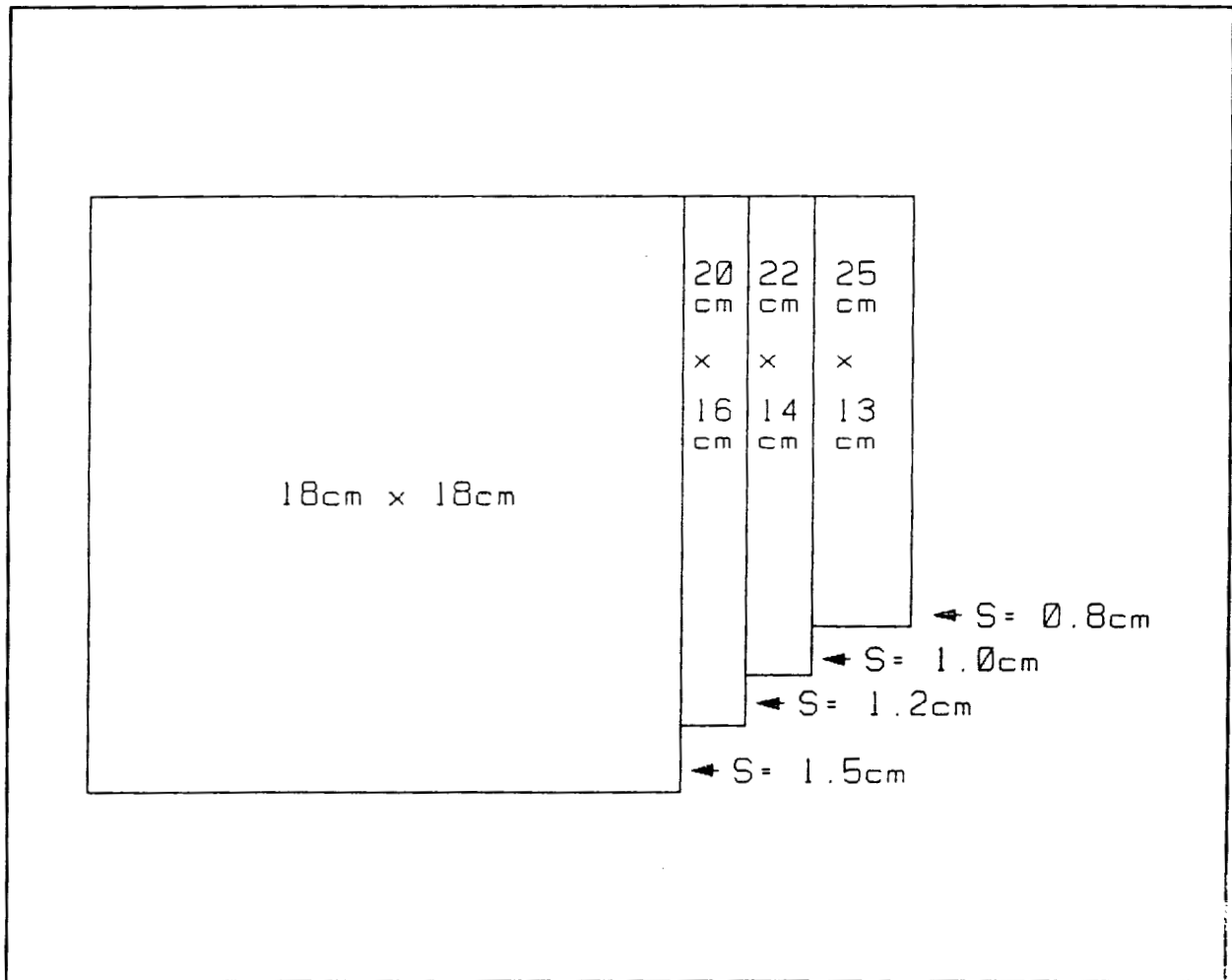


Figure 4: Anode Utilization of Zinc-Air versus Alkaline Cells



**Figure 5: Oxygen Transport Model Geometry**



**Figure 6:** LC Electrode Dimensions at Various Gap Widths

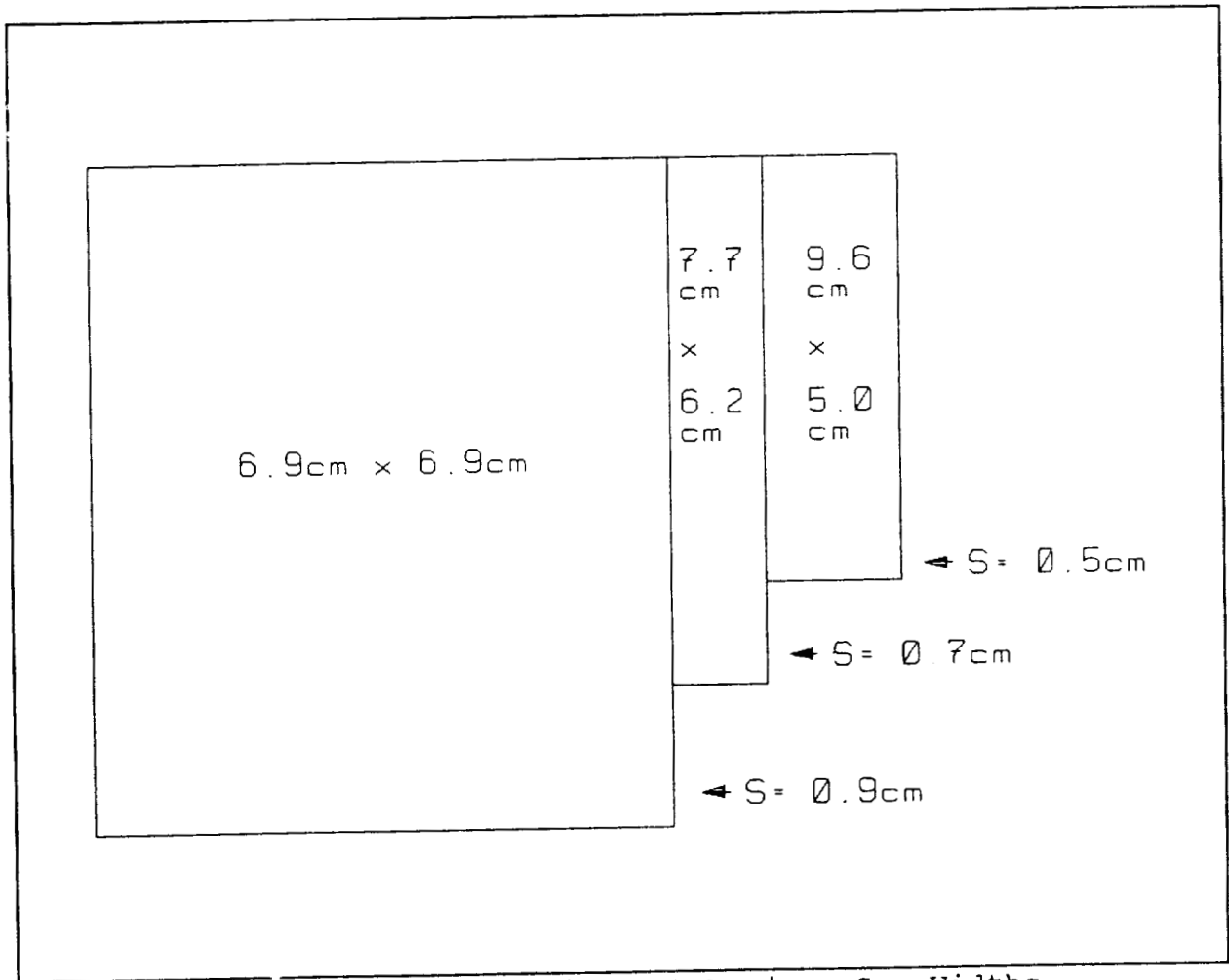


Figure 7: HR Electrode Dimensions at Various Gap Widths

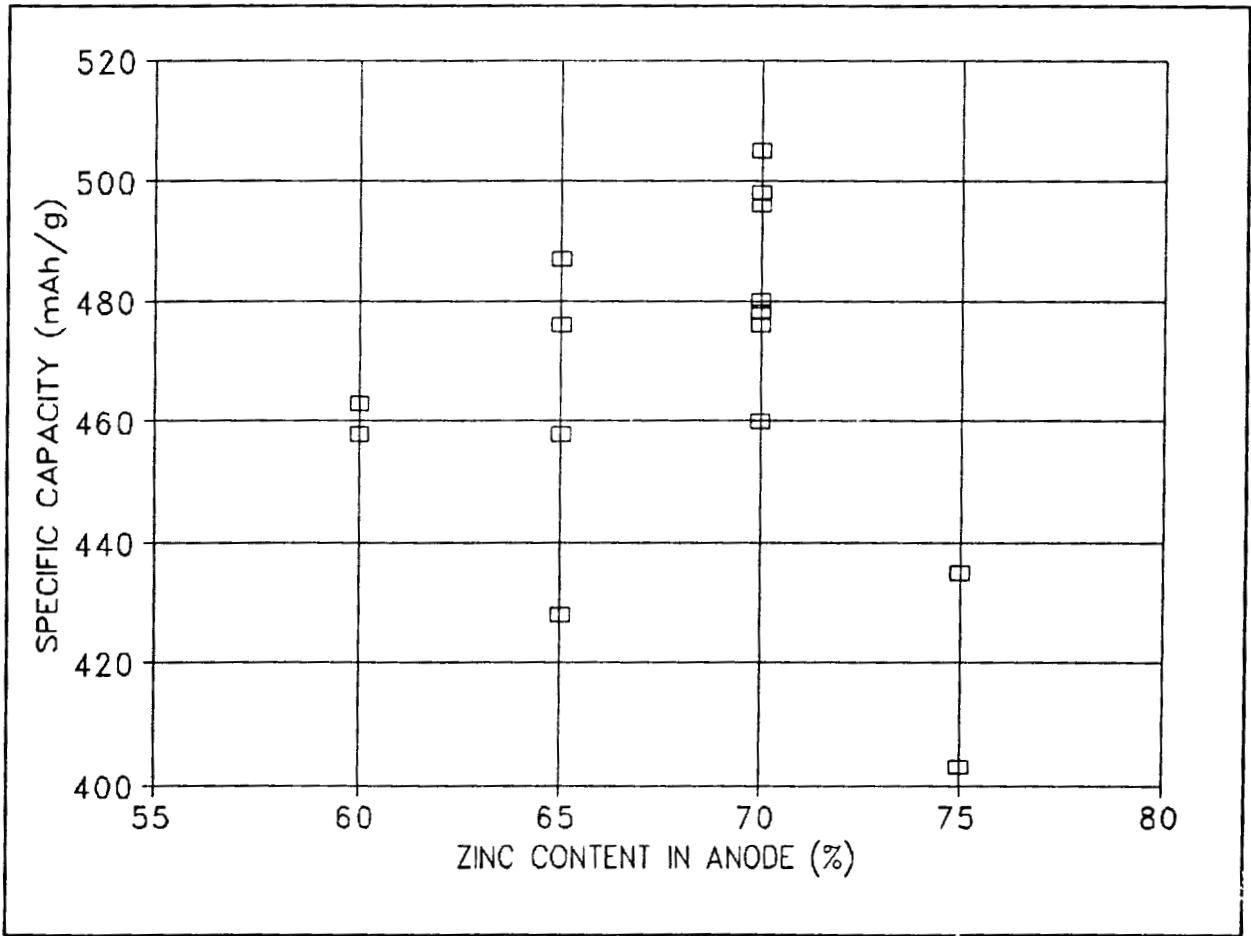


Figure 8: Dependence of Anode Specific Capacity on Zinc Content

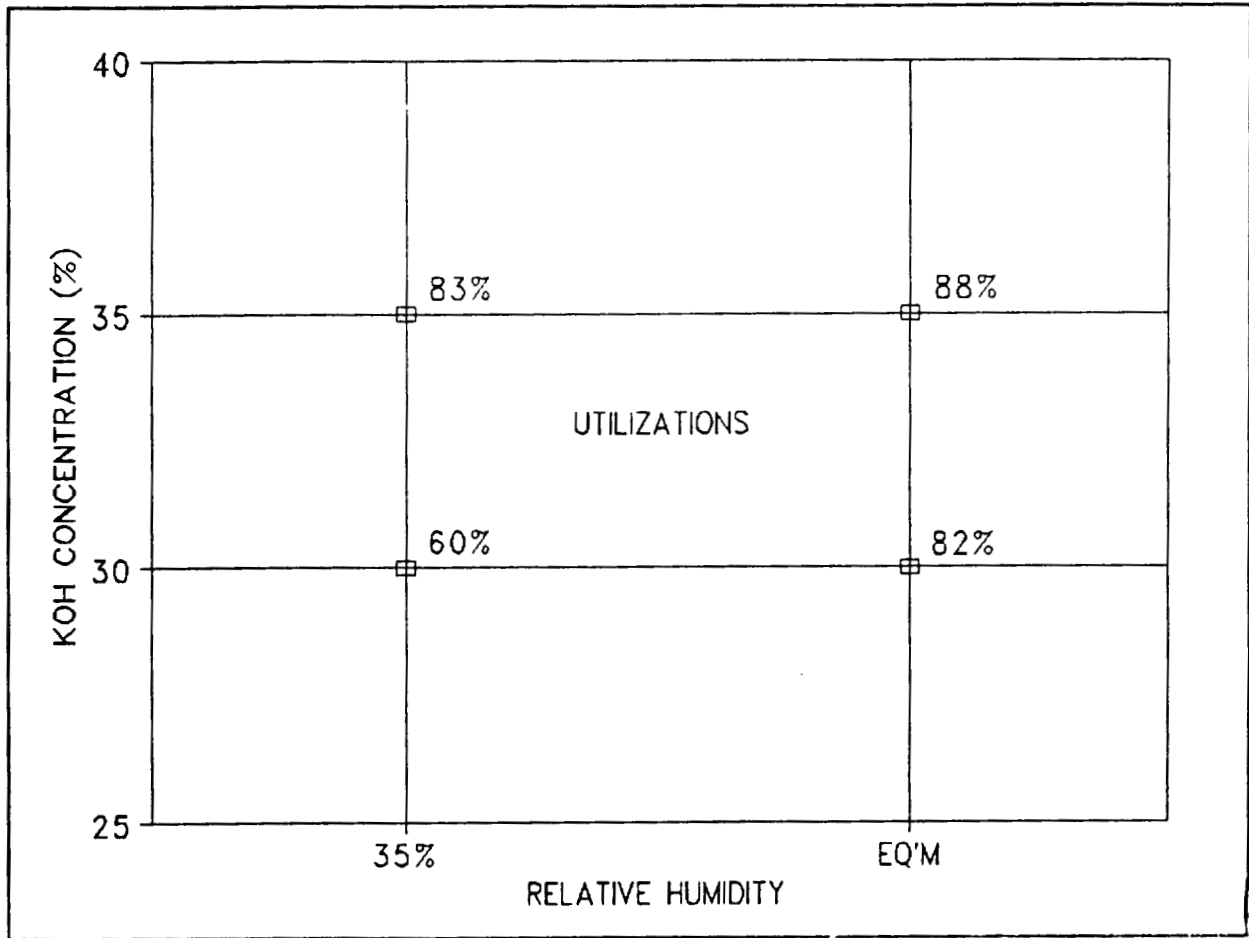


Figure 9: Effect of KOH Concentration and Relative Humidity on Anode Utilization



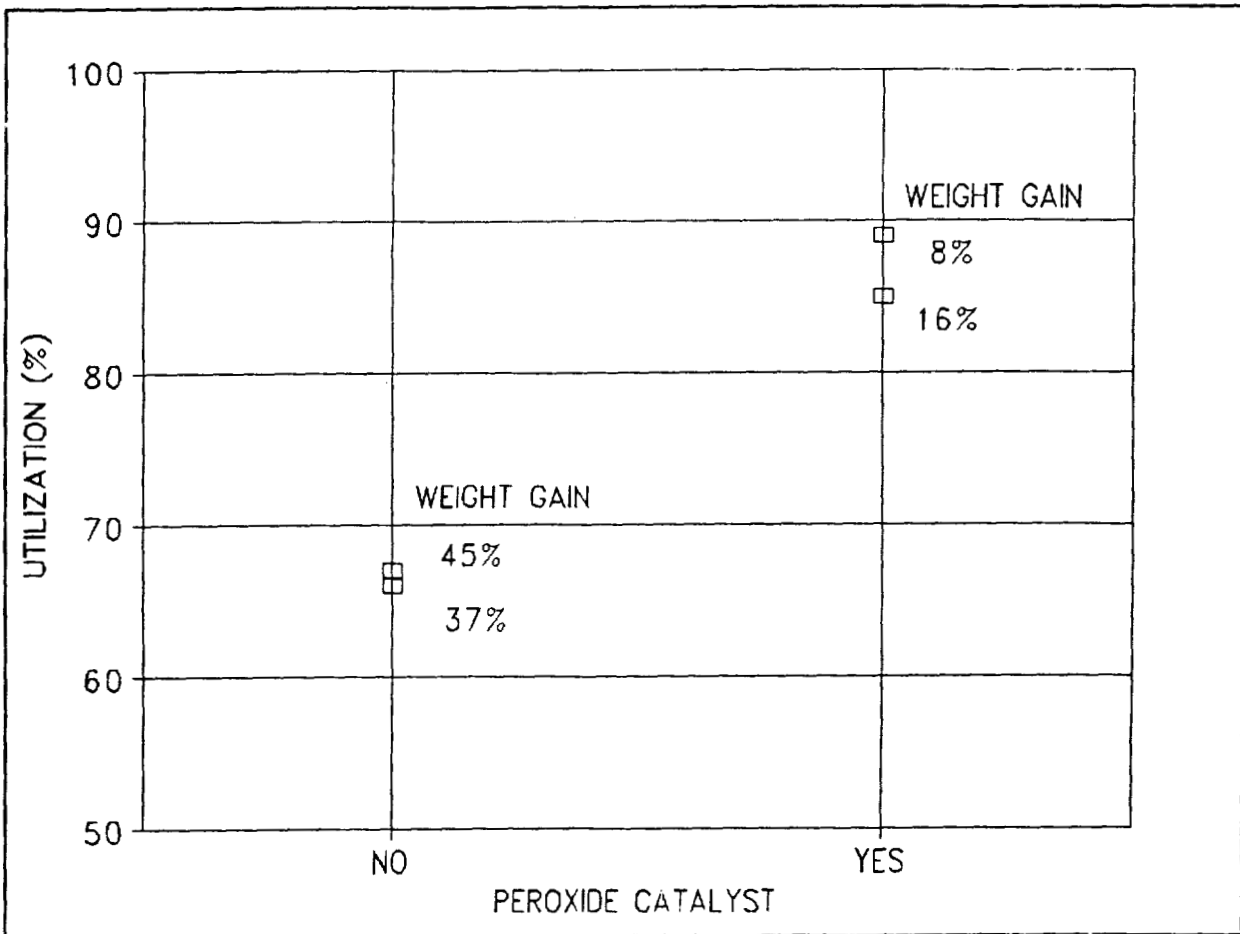


Figure 10: Effect of Peroxide Catalyst in Cathode on Anode Utilization

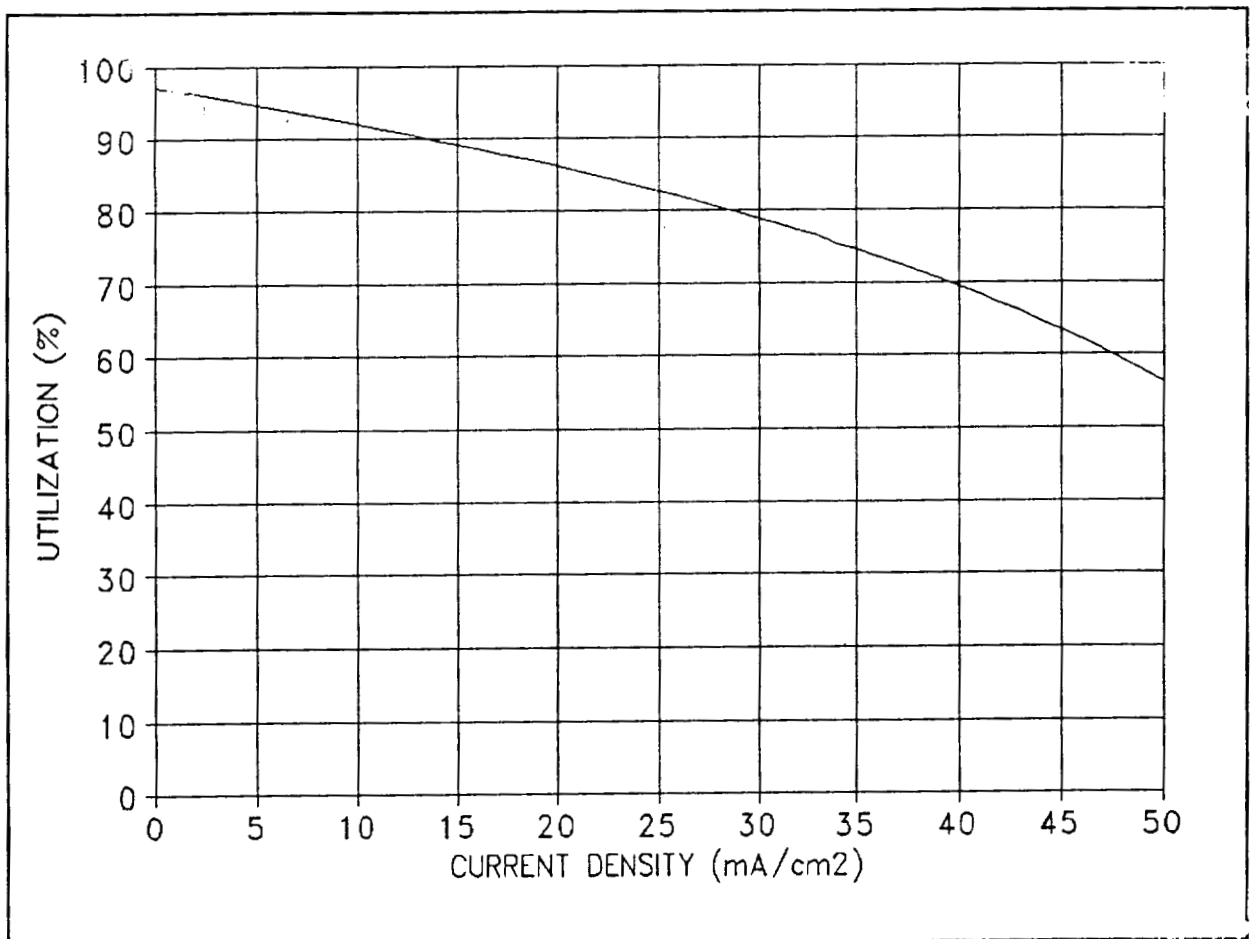


Figure 11: Empirical Model of Anode Utilization

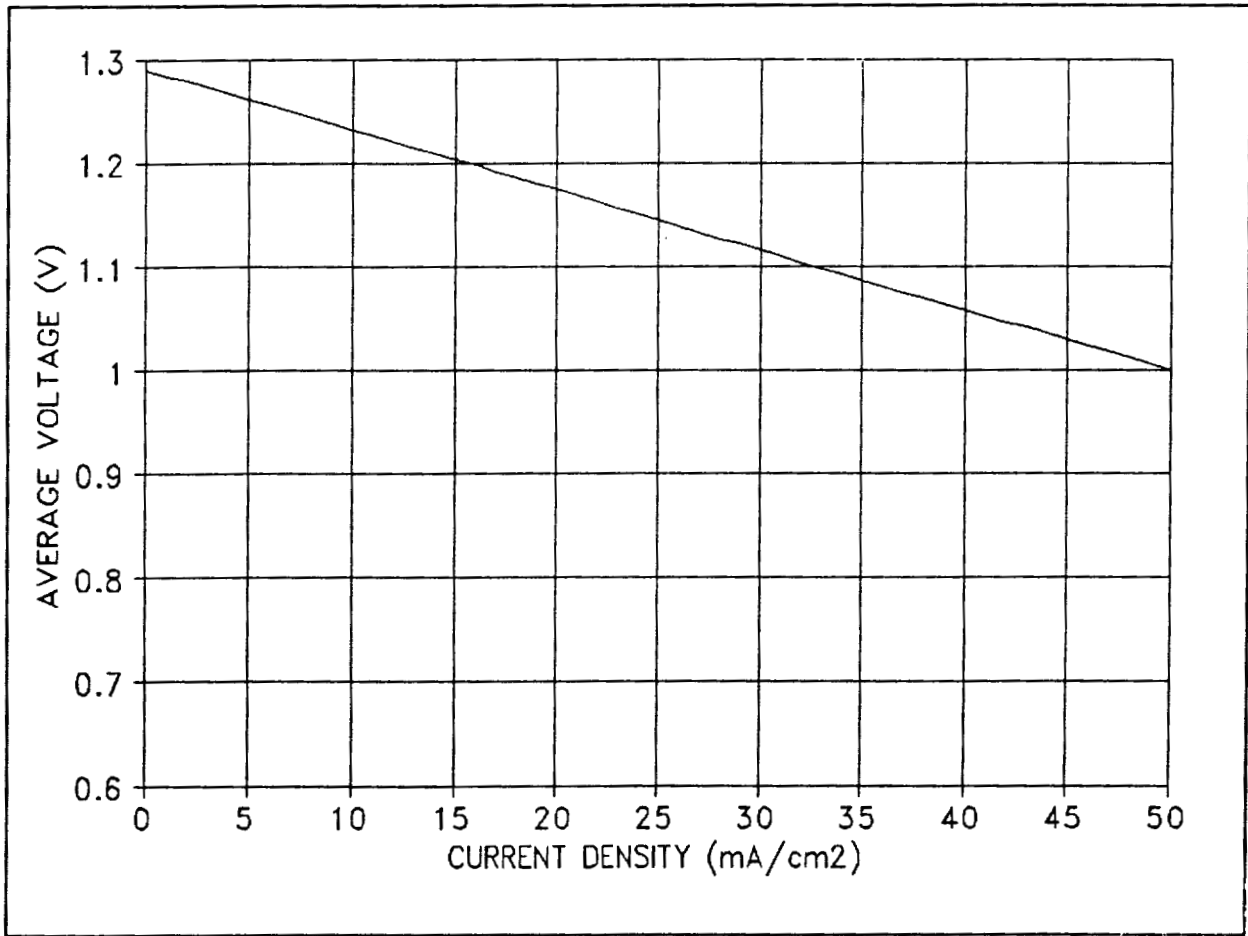


Figure 12: Empirical Model of Average Voltage

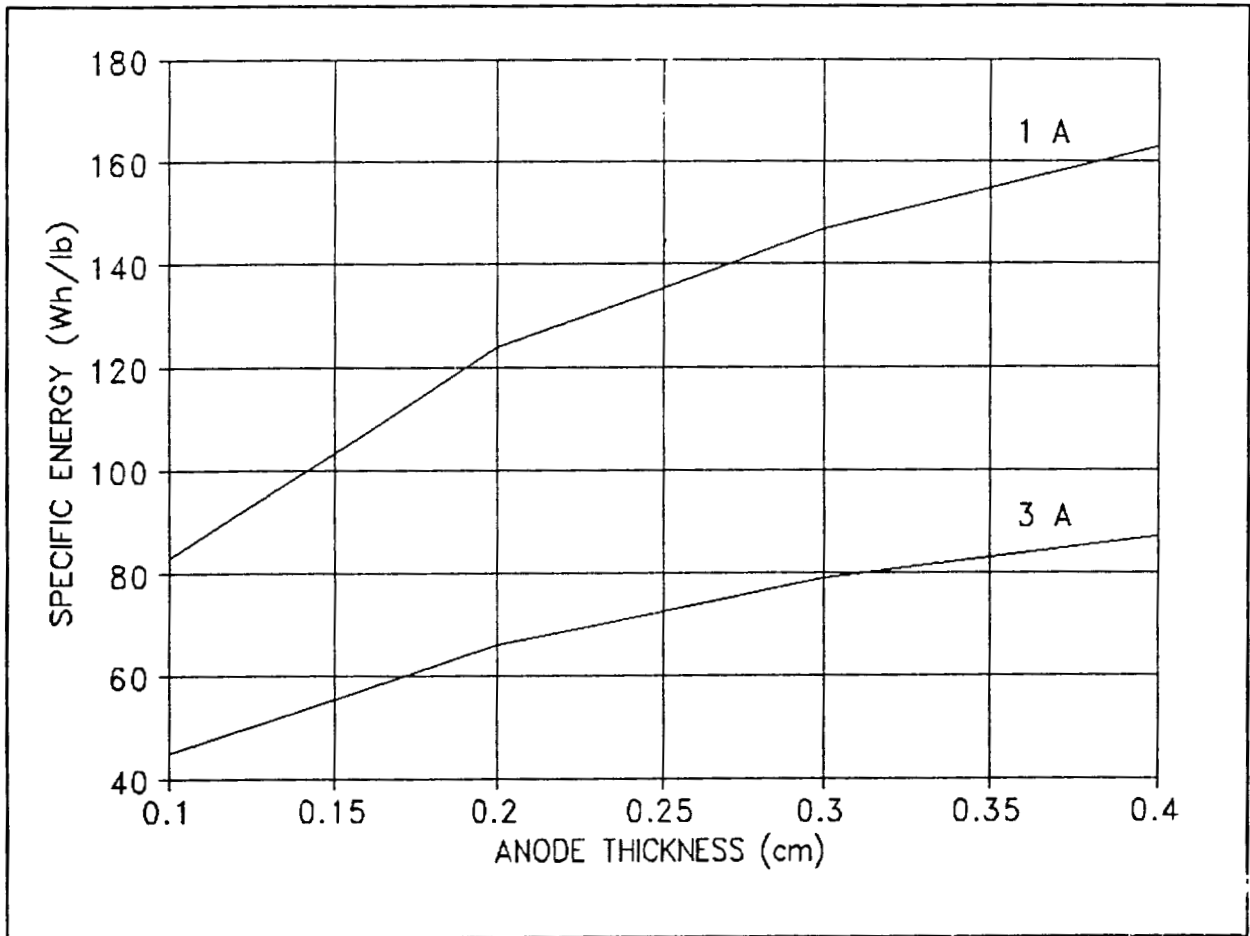


Figure 13: Calculated Dependence of HR Cell Specific Energy on Anode Thickness

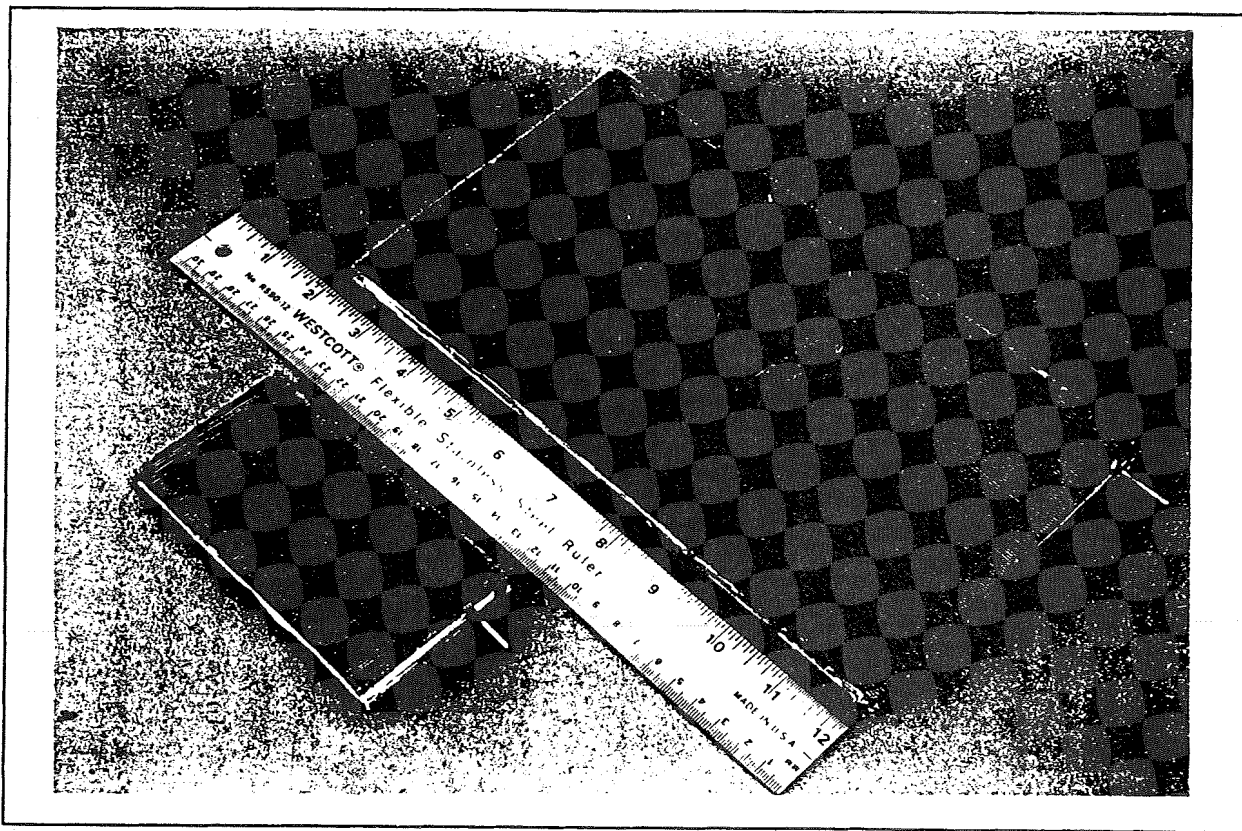


Figure 14: HR and LC Cells

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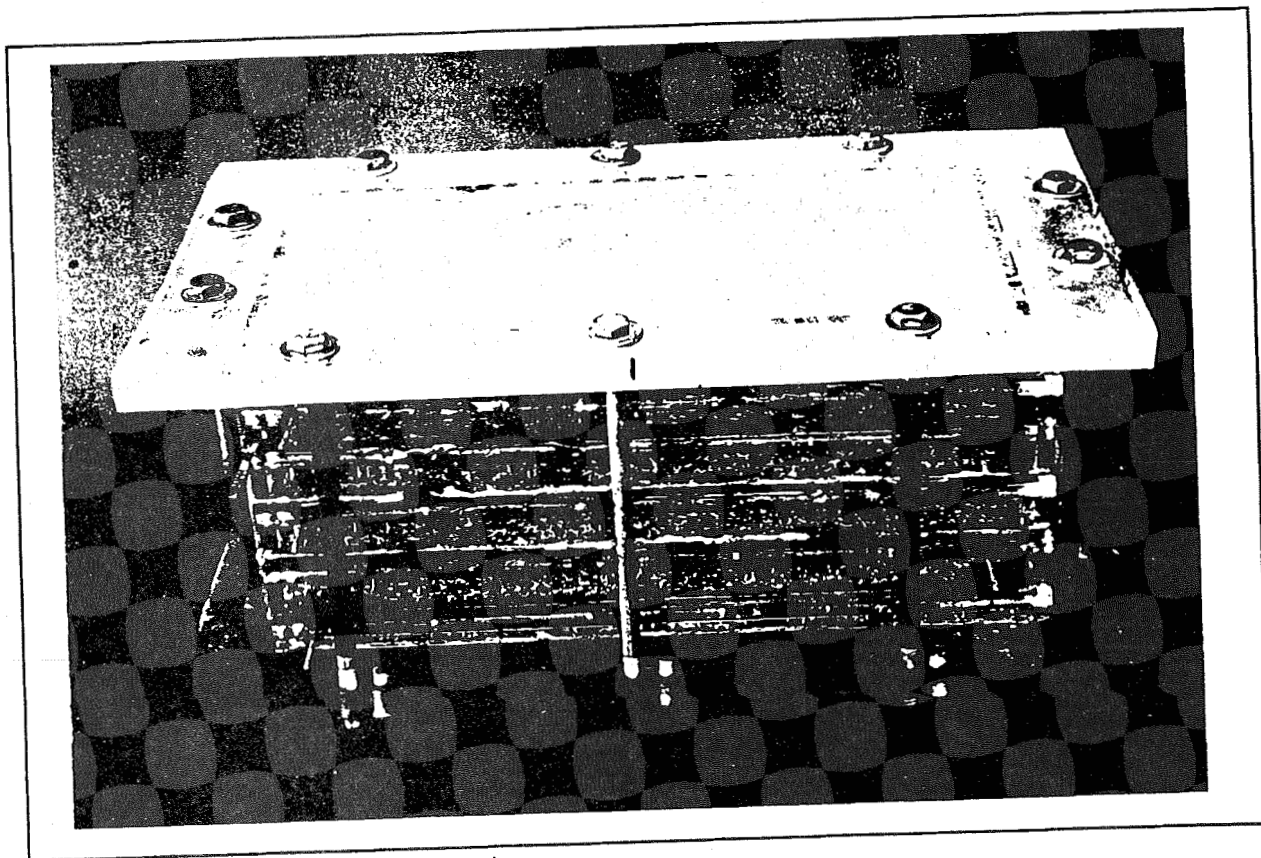


Figure 15: LC Cell Battery Stack

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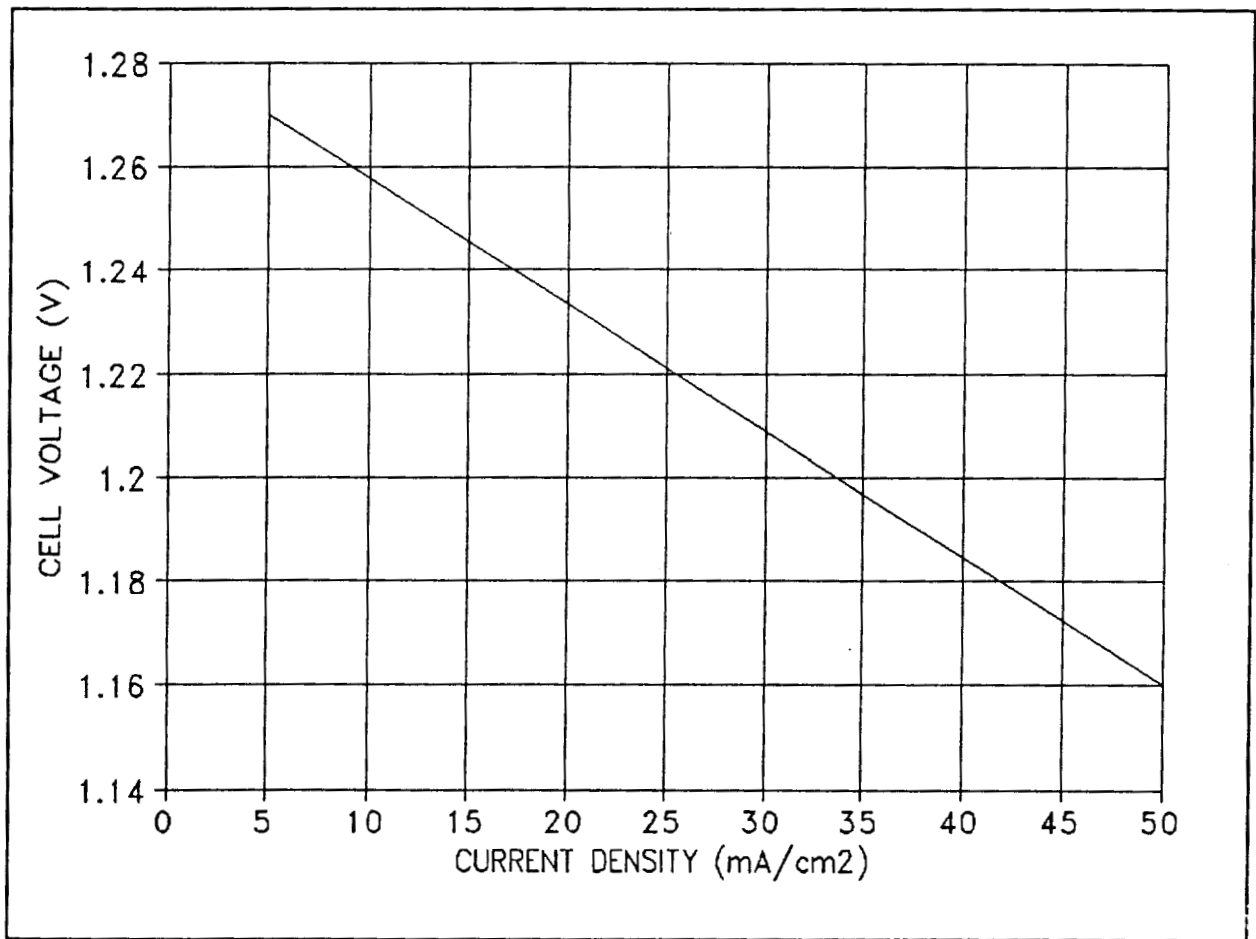


Figure 16: HR Cell Load Curve (100% SOC)

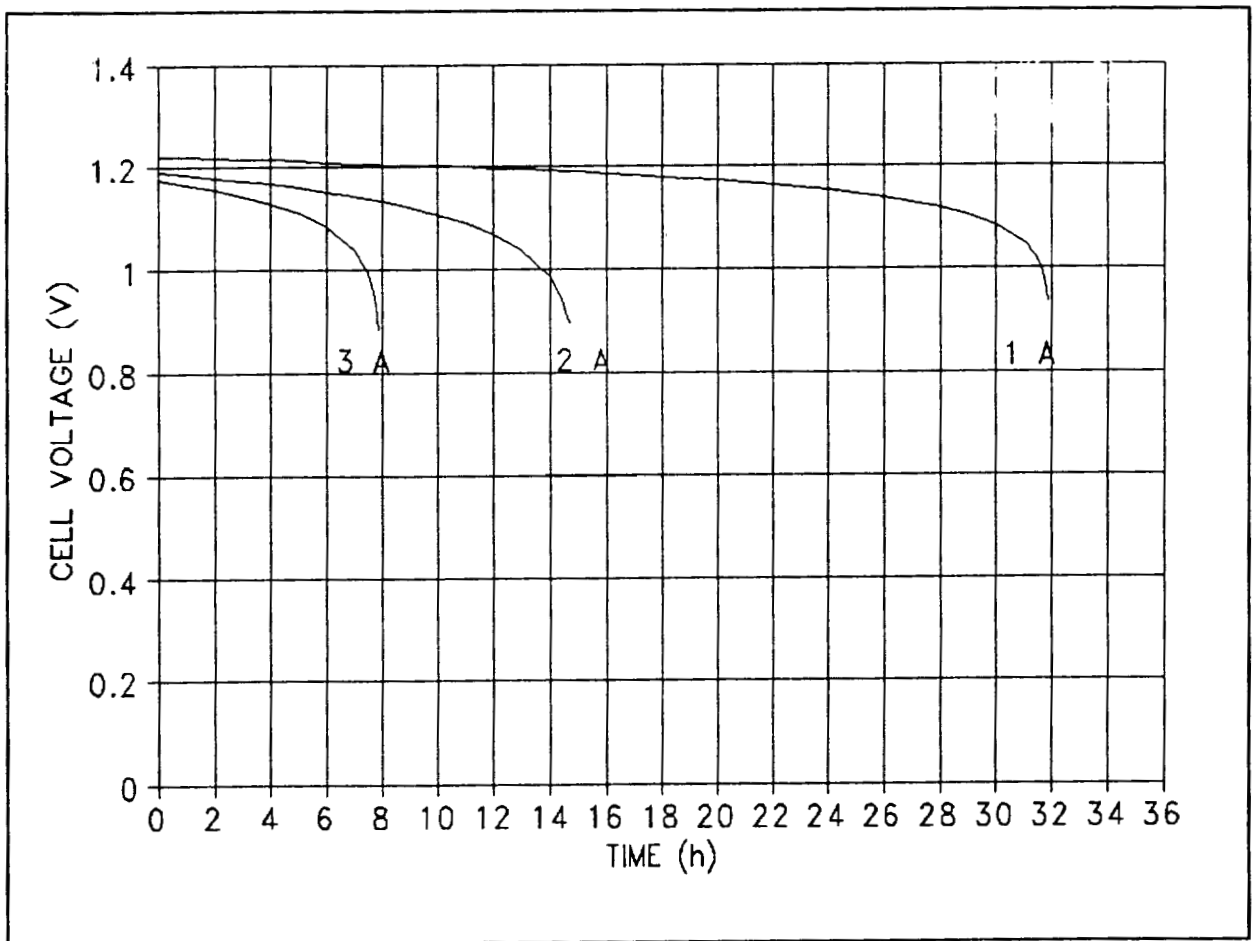


Figure 17: HR Cell Discharge Curves at 25° C



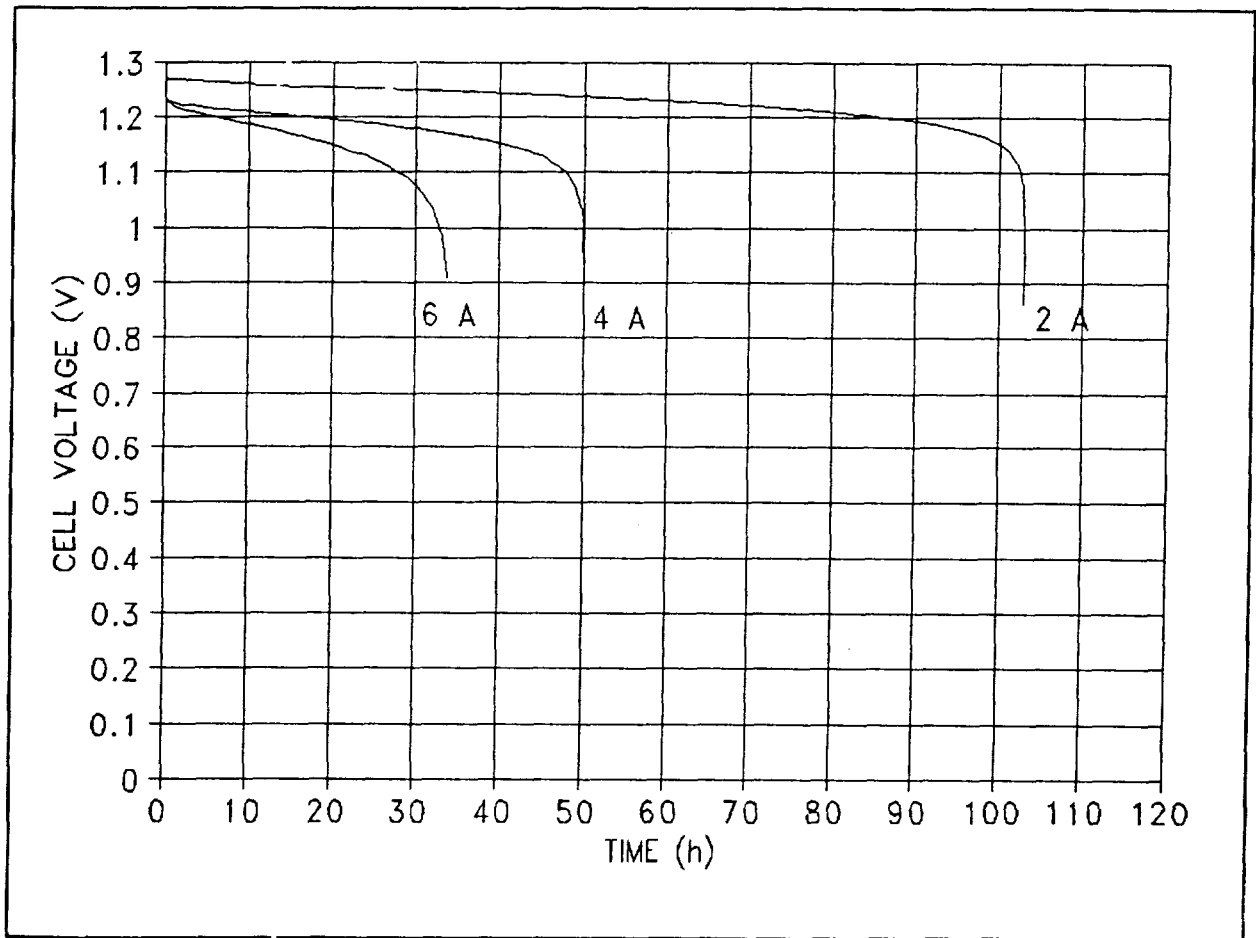


Figure 18: LC Cell Discharge Curves at 25° C

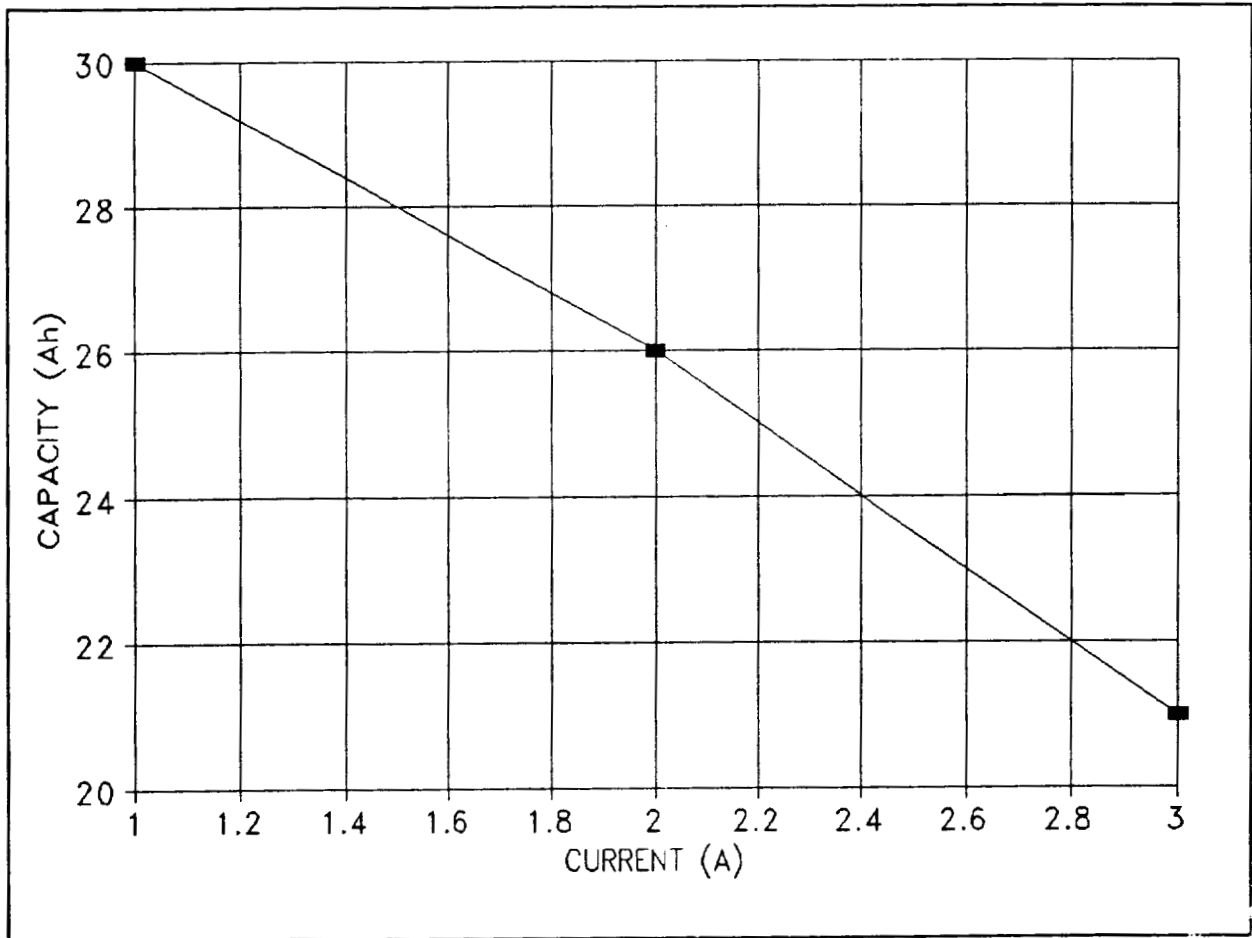


Figure 19: HR Cell Capacity at 25° C

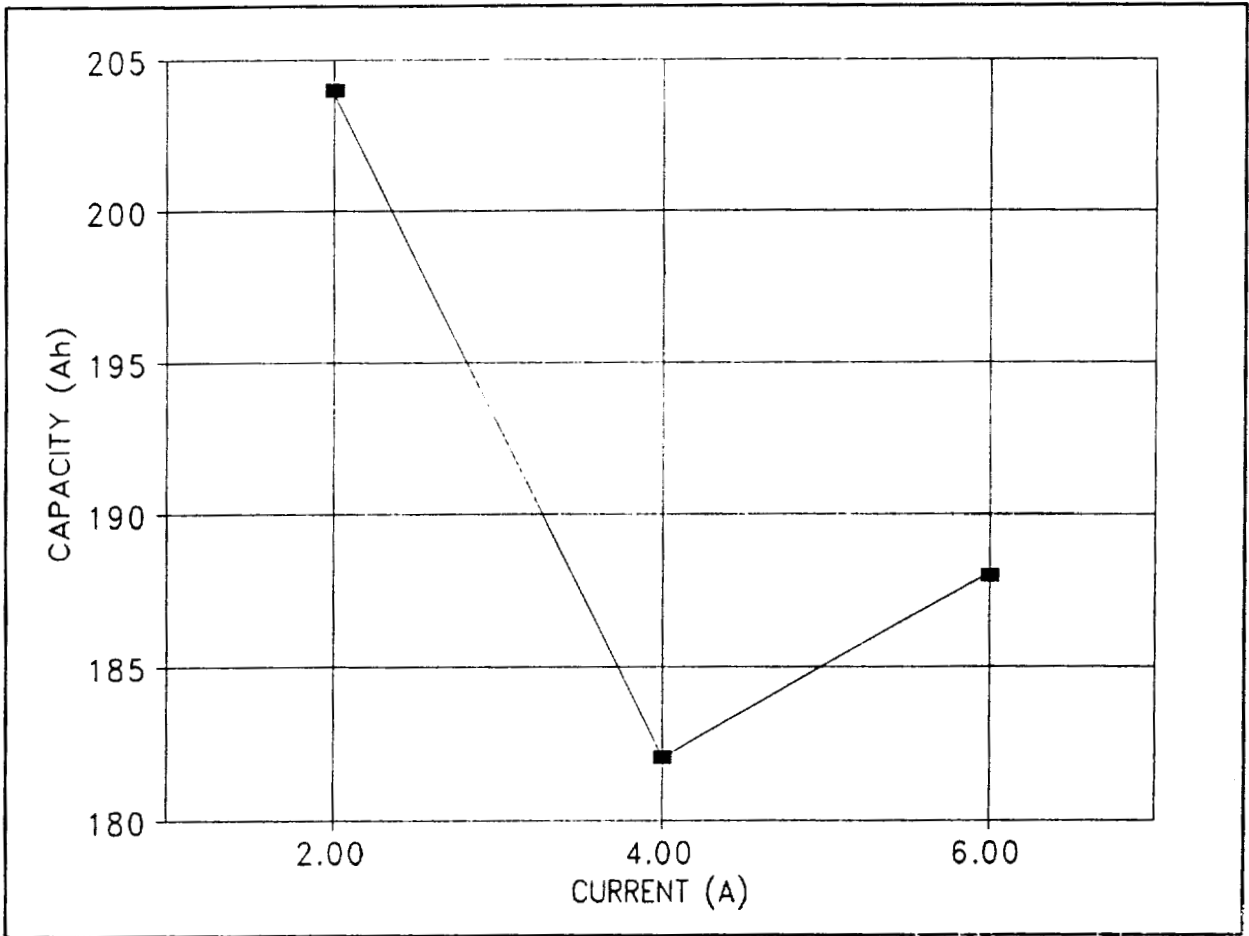


Figure 20: LC Cell Capacity at 25° c

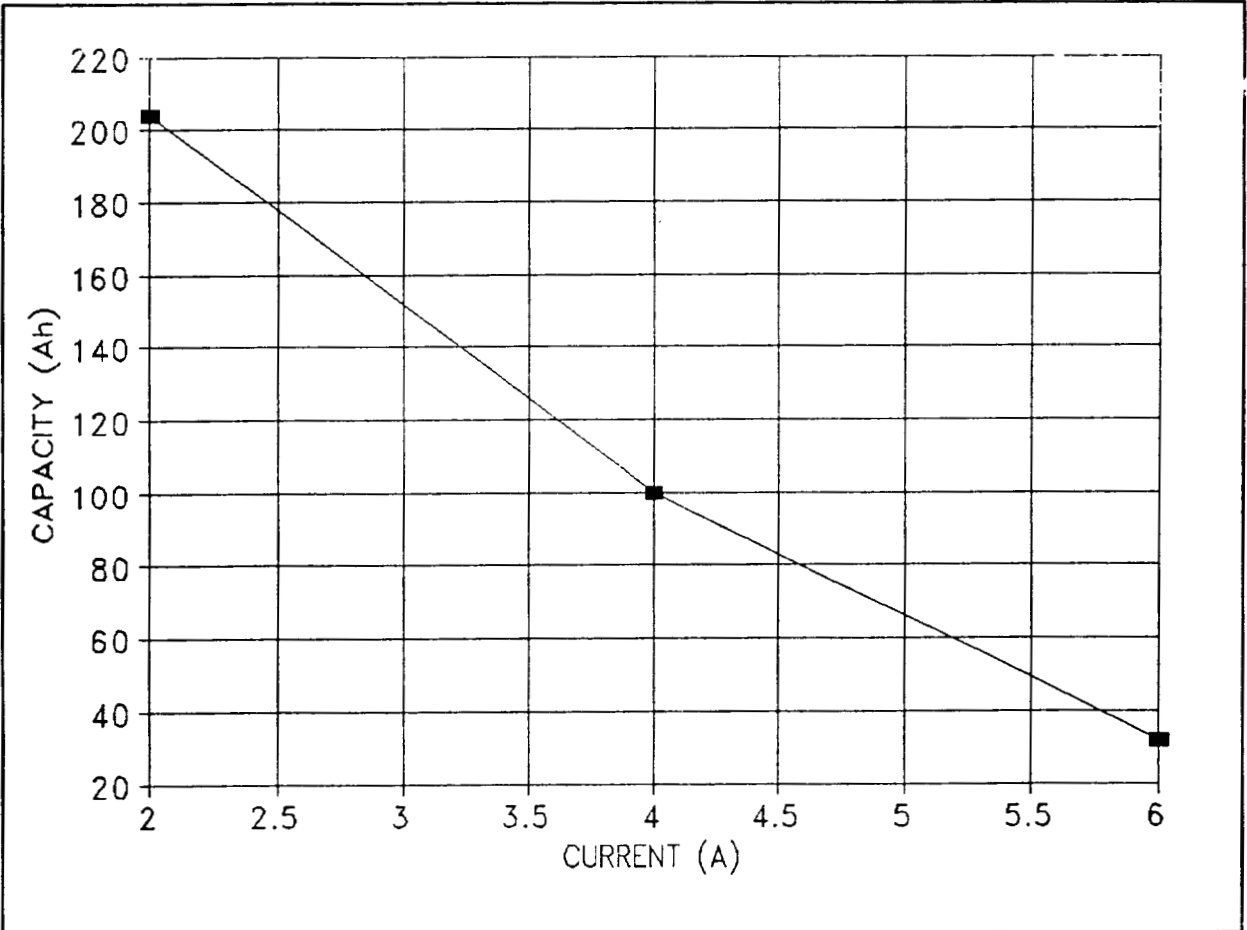


Figure 20: LC Cell Capacity at 25° C

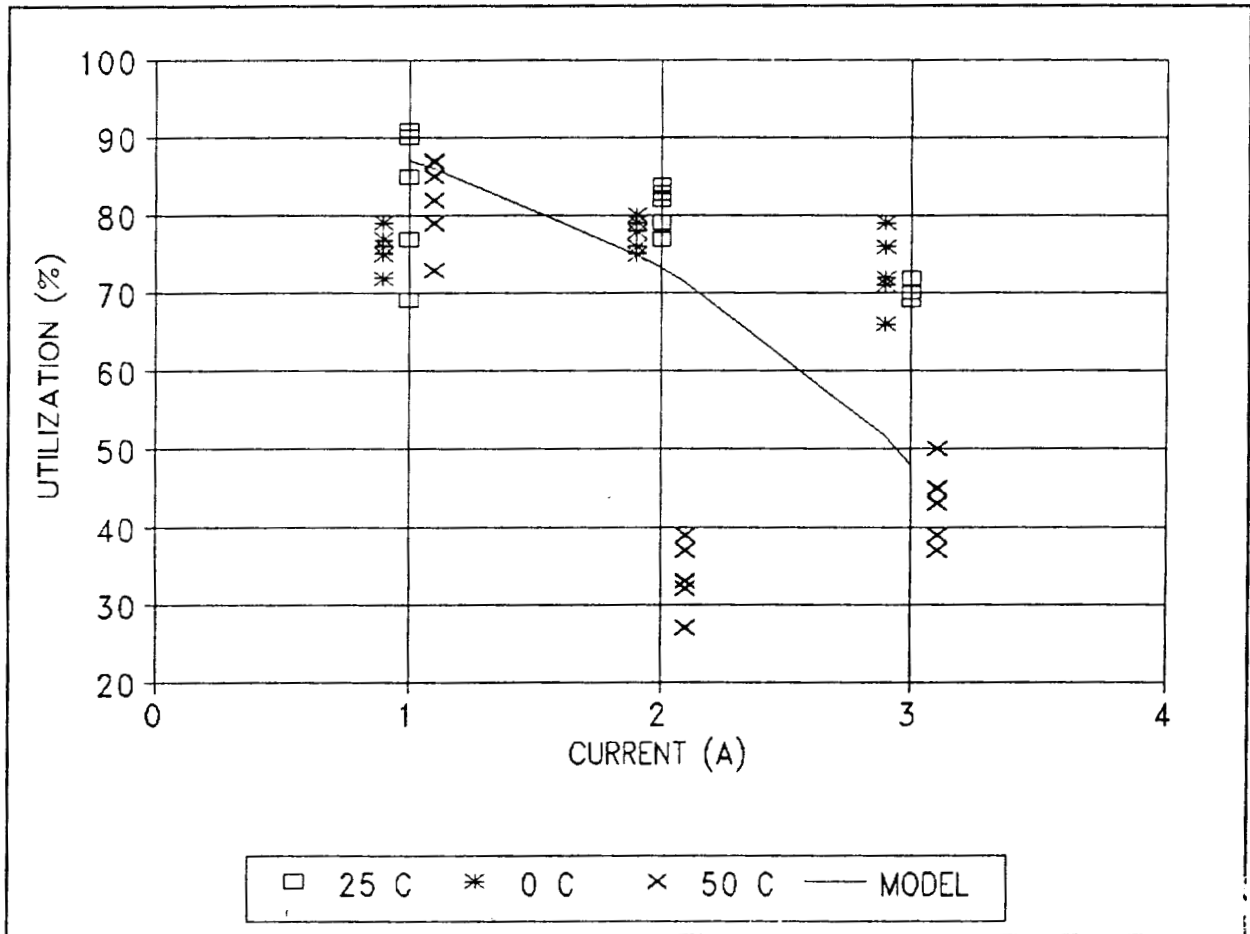


Figure 21: HR Battery Anode Utilization

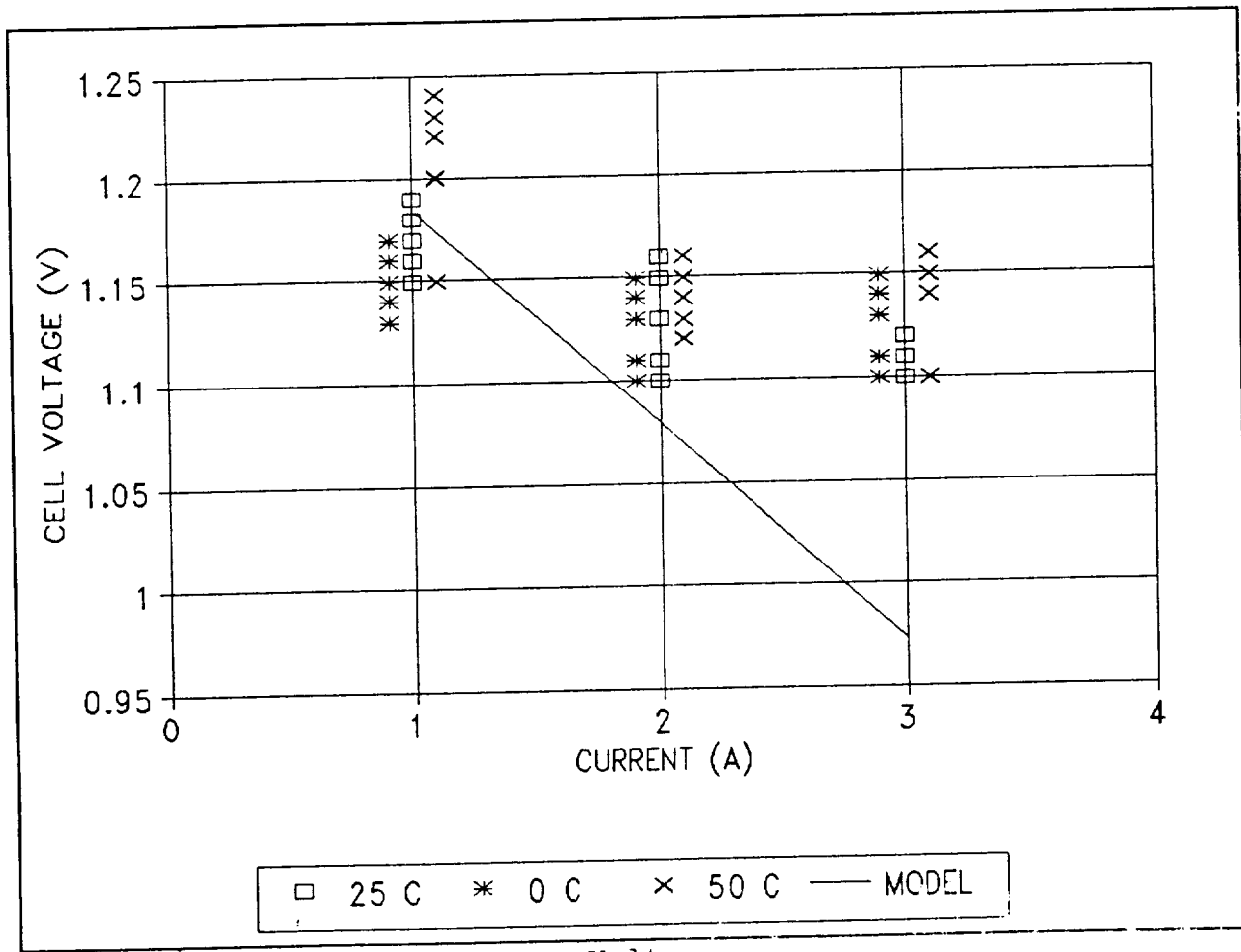


Figure 22: HR Battery Average Voltage

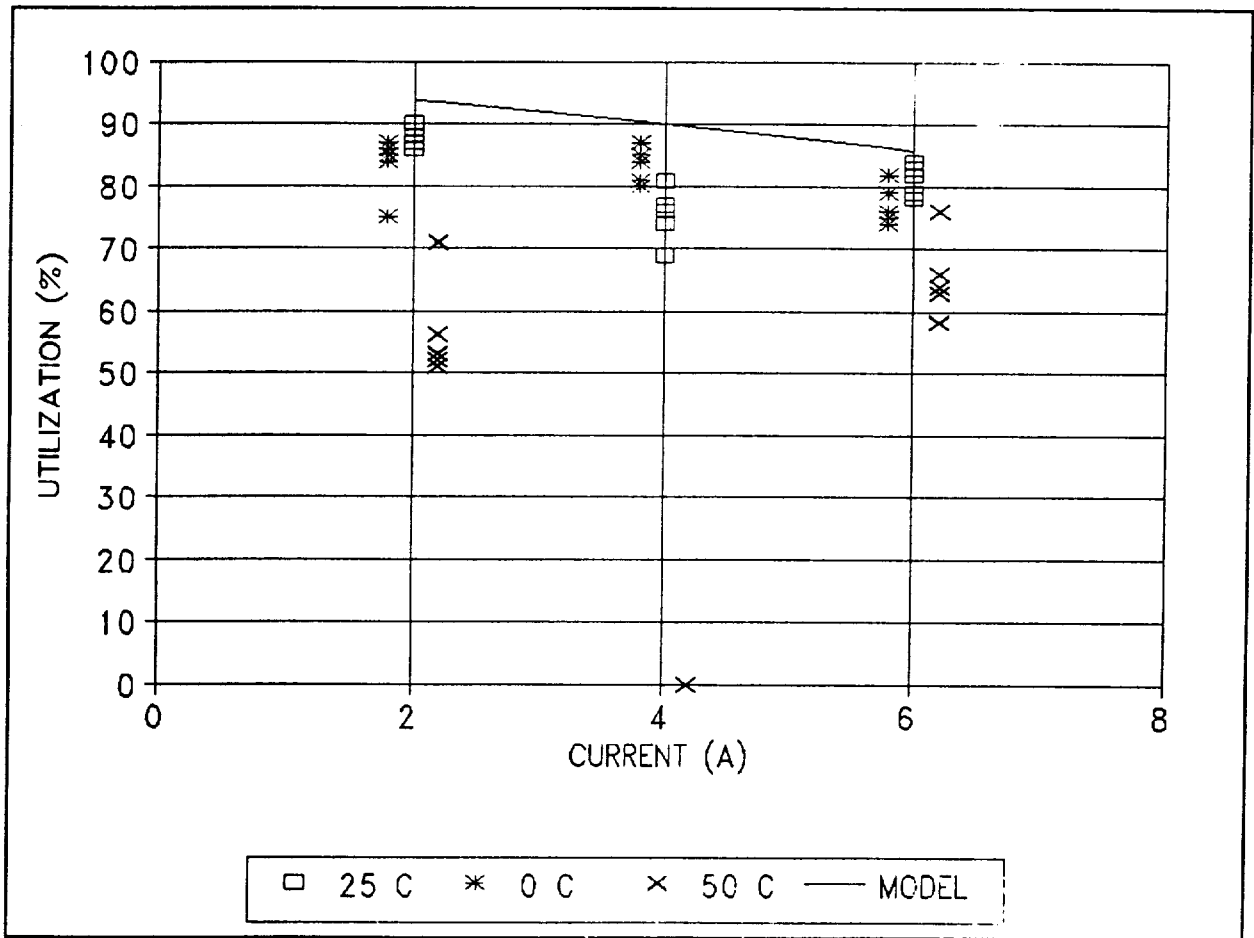


Figure 23: LC Battery Anode Utilization

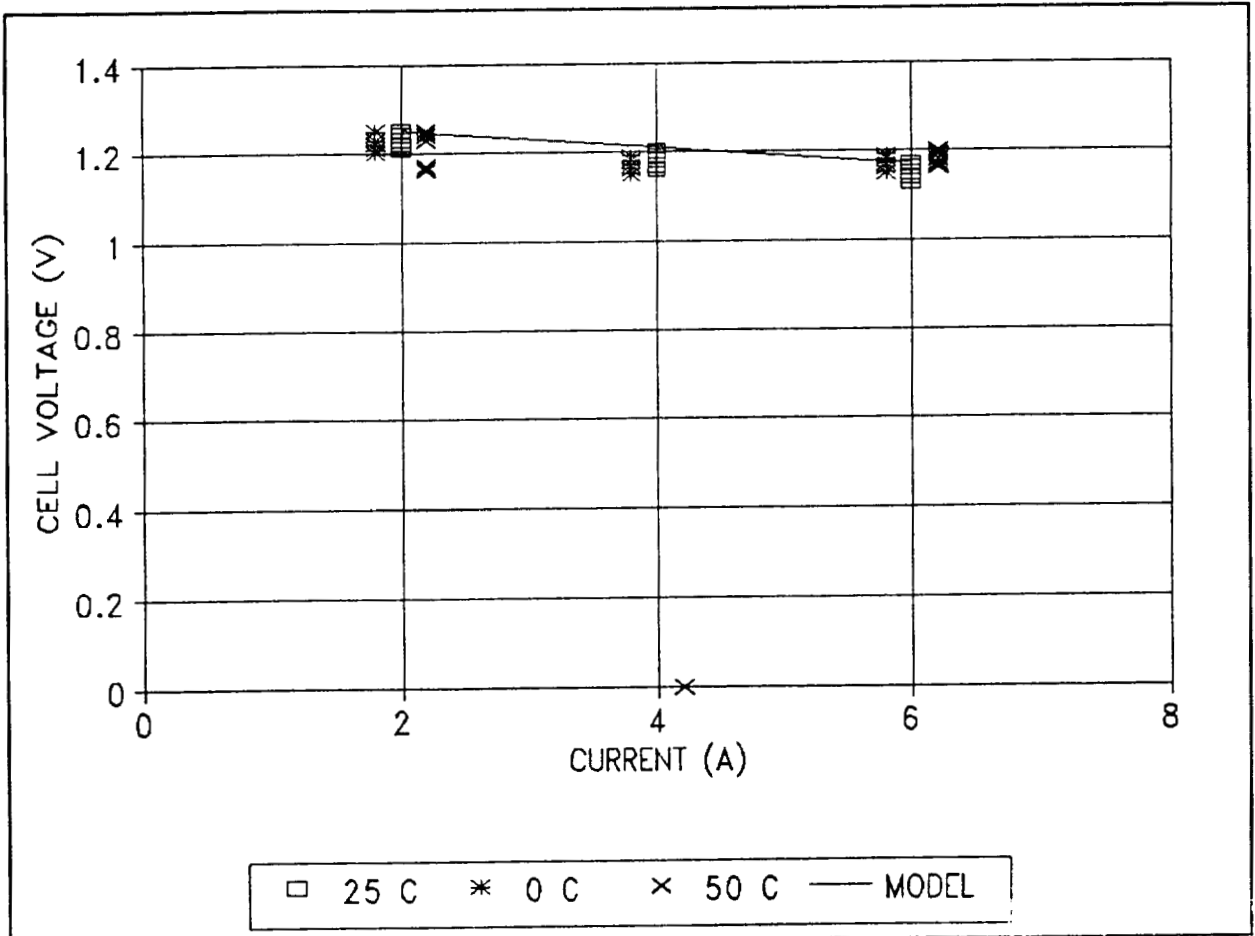


Figure 24: LC Battery Average Voltage



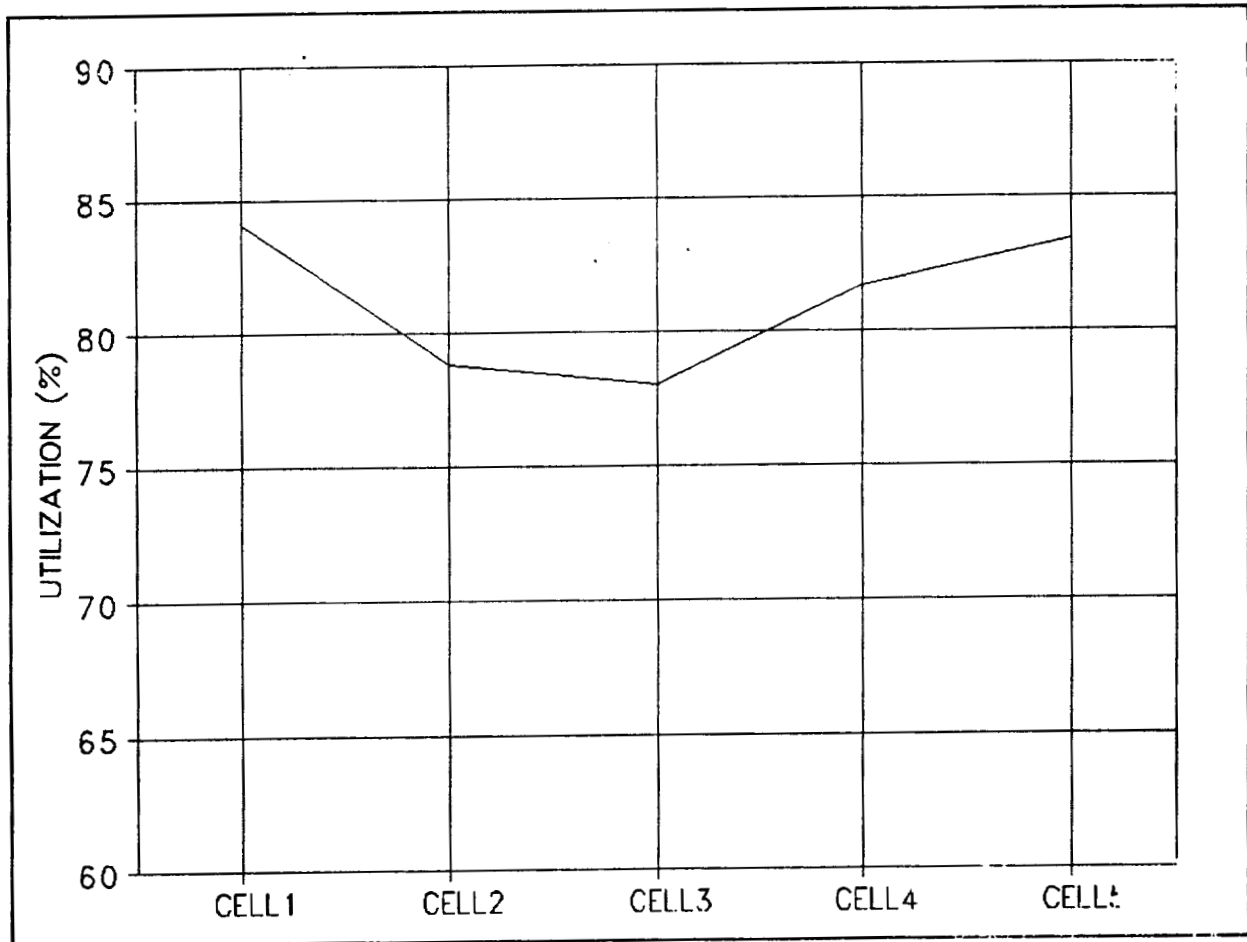


Figure 25: LC Battery Anode Utilization @ 6 A and 25° C

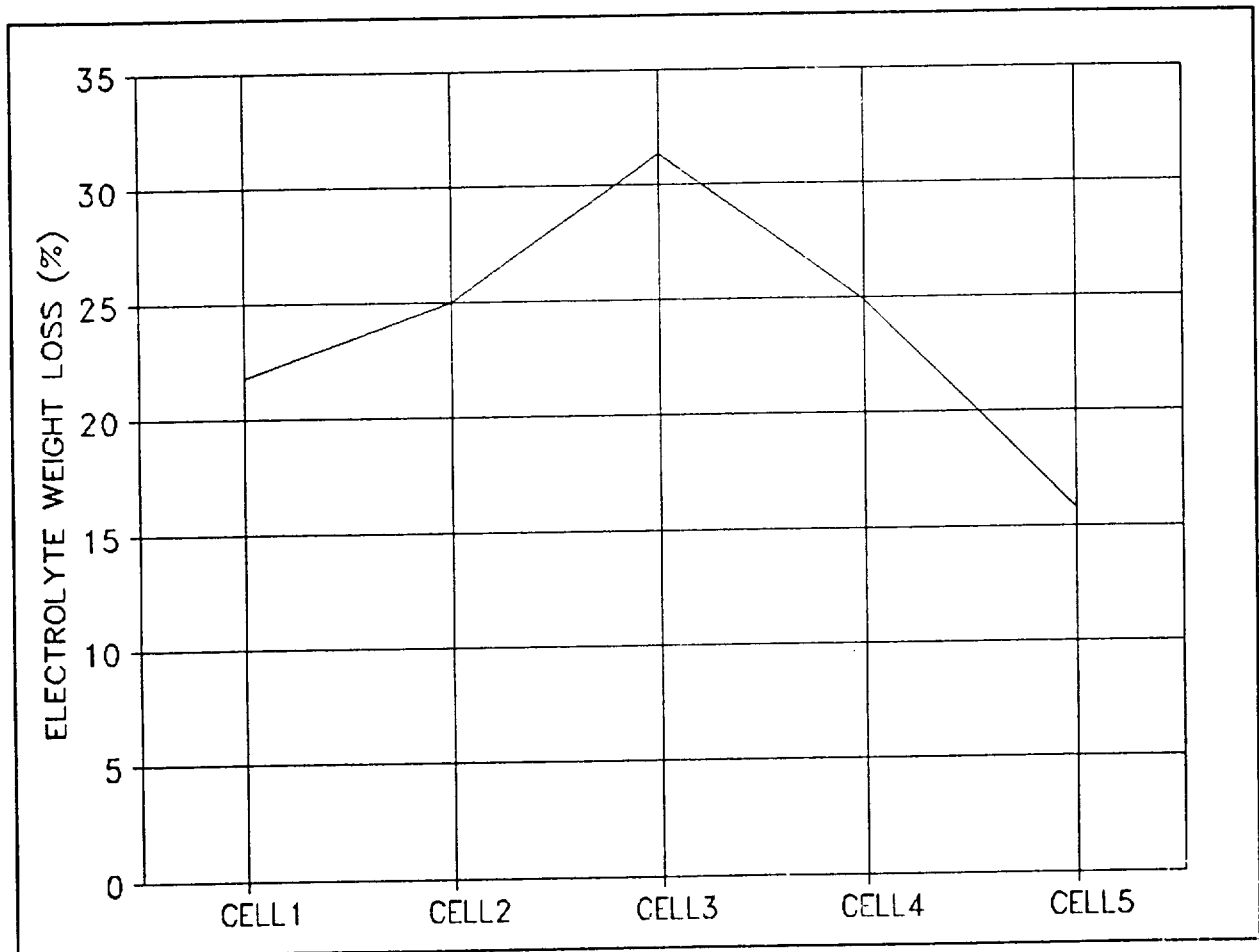


Figure 26: LC Battery Water Loss @ 6 A and 25° C

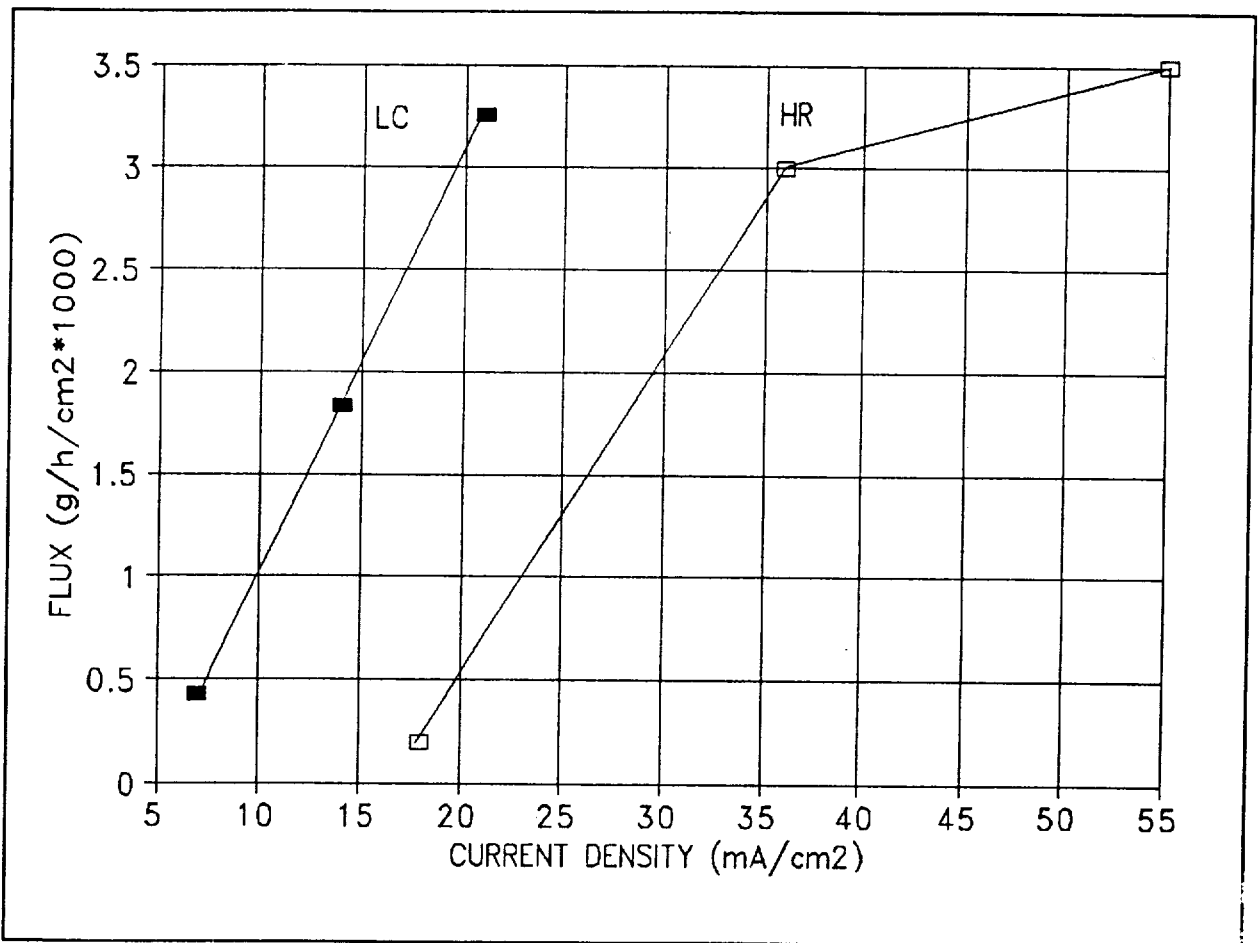


Figure 27: Dependence of Water Flux on Current Density

RISE TIME AND RESPONSE MEASUREMENTS ON A LiSOCl<sub>2</sub> CELL

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

ABSTRACT

Dynamic impedance tests have been performed on a 180Ah LiSOCl<sub>2</sub> 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 LiSOCl<sub>2</sub> 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 LiSOCl<sub>2</sub> 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 LiSOCl<sub>2</sub> 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 LiSOCl<sub>2</sub> 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 000Hz
- Temperature : 10 to 70°C (50 to 160°F)
- Depth of Discharge : 25 to 75%
- Bias Currents : 0 to 80A

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 modeled by a Series Resistance (6mΩ) and the resonance by an R-L-C parallel cell.

$R_2$  of the R-L-C cell is given by the impedance at the resonance frequency :  
 $R_2 = 41 - 6 = 35\text{m}\Omega$ . The resonance frequency  $F_0$  is equal to  $1/2\pi\sqrt{LC}$   
and the ratio  $\Delta F/F_0$  is equal to  $R\sqrt{C/L}$ . This allows to determine L and C  
where  $L = 32\text{nH}$  and  $C = 137\mu\text{F}$ .

$R_1$  varies slightly with  $T^\circ$  and  $I_{DC}$  = as  $I$  or  $T^\circ$  increase,  $R_1$  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 modeled by an RC parallel cell, added to Model 1.

$R_3$  is given by the value of the plateau :  $R_3 = 30 - 6 = 24\text{m}\Omega$ .

$C_2$  is given by the value of the impedance at  $F = 2\text{KHz}$ .

Model 2 also applies at high temperatures, with  $R_3 = 0\text{m}\Omega$  (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 ( $R_4$ ) and inductance ( $L_2$ ) must be added in order to take into account the influence of the cabling between cells.

$$R_4 = 4.3\text{m}\Omega$$

$$L_2 = 1.2\mu\text{H}$$

As  $R_4 \ll R_1$ ,  $R_4$  can be neglected



DIVISION SPACE  
ESPACE DEPARTMENT

1991 NASA BATTERY WORKSHOP

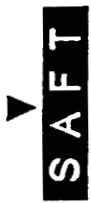



RISE TIME AND RESPONSE MEASUREMENTS  
ON A  $\text{LiSOCl}_2$  CELL



BY



C. BASTIEN  
SAFT (FRANCE)



E. LECOMTE  
ETCA (BELGIUM)


	DIVISION SPACE DEPARTMENT ESPACE	RISE TIME AND RESPONSE MEASUREMENTS ON A LiSOCL <sub>2</sub> CELL	
INTRODUCTION			
<p style="text-align: center;">           * THE ELECTRICAL POWER GENERATION OF THE HERMES SPACE PLANE COMPRISES :         </p> <ul style="list-style-type: none"> <li>- THE MAIN ELECTRICAL POWER GENERATION :             <ul style="list-style-type: none"> <li>2 FUEL CELL POWER PLANTS TO PROVIDE ELECTRICAL ENERGY FOR THE COMPLETE MISSION</li> </ul> </li> <li>- THE SECONDARY ELECTRICAL POWER GENERATION :             <ul style="list-style-type: none"> <li>2 LITHIUM BATTERIES TO PROVIDE ELECTRICAL ENERGY AS AUXILIARY SOURCES IN NOMINAL MODES AND BACK-UP SOURCES FOR EMERGENCY RE-ENTRY</li> </ul> </li> </ul>			

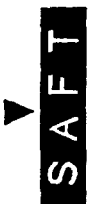



	DIVISION SPACE ESPACE DEPARTMENT	RISE TIME AND RESPONSE MEASUREMENTS ON A $\text{LiSOCl}_2$ CELL	
INTRODUCTION			
<p>* A SHORT TERM WORK CONTRACT WAS AWARDED BY AEROSPATIALE TO SAFT TO DEMONSTRATE THE FEASIBILITY OF A <math>\text{LiSOCl}_2</math> BATTERY DESIGN, AS PART OF THE HERMES SPACE PLANE PRELIMINARY DEVELOPMENT WORK.</p> <p>* THE PROPOSED <math>\text{LiSOCl}_2</math> BATTERY CONSISTS OF 28 CELLS OF 180 AH CONNECTED IN SERIES</p> <p>TOTAL ENERGY = 16.6 KWH          TOTAL MASS = 60 KG (132 LB)          TOTAL VOLUME : 54 L</p>			

	DIVISION SPACE ESPACE DEPARTMENT	RISE TIME AND RESPONSE MEASUREMENTS ON A LISOCL <sub>2</sub> CELL	
INTRODUCTION  * SUMMARY OF THE ELECTRICAL CHARACTERISTICS OF EACH BATTERY <ul style="list-style-type: none"> <li>- OUTPUT POWER : 0 TO 6 KW</li> <li>- OUTPUT VOLTAGE : 75 V &lt; u &lt; 115 V</li> <li>- REQUIRED ENERGY : 16 KWH</li> <li>- 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).</li> </ul>			

	DIVISION SPACE ESPACE DEPARTMENT	RISE TIME AND RESPONSE MEASUREMENTS ON A LISOCL <sub>2</sub> CELL	
INTRODUCTION			
<p>* DYNAMIC IMPEDANCE TESTS HAVE BEEN PERFORMED ON A 180 AH LISOCL<sub>2</sub> CELL :</p> <ul style="list-style-type: none"> <li>- A RISE TIME TEST WAS PERFORMED TO SHOW THE ABILITY OF THE CELL TO MEET THE RISE TIME REQUIREMENT</li> <li>- RESPONSE TESTS WERE PERFORMED IN ORDER TO BUILD A MATHEMATICAL ELECTRICAL MODEL OF THE LISOCL<sub>2</sub> BATTERY</li> </ul> <p>THE TESTS HAVE BEEN PERFORMED AT SAFT BY ETCA (BELGIUM) WHO ALSO PROPOSED THE MATHEMATICAL MODEL.</p> <p>ETCA IS INVOLVED IN THE HERMES PROGRAM AS THE POWER SYSTEM CONTRACTOR.</p>			

<p><b>SAFT</b></p> <p>DIVISION SPACE ESPACE DEPARTMENT</p>	<p>RISE TIME AND RESPONSE MEASUREMENTS ON A LISOC<sub>L2</sub> CELL</p>	
<p>TEST DESCRIPTIONS</p>		
<p>* <u>RISE TIME TEST</u> :</p> <ul style="list-style-type: none"> <li>- DISCHARGE AT 40A, VOLTAGE MEASUREMENT DURING THE FIRST 200 μs OF THE DISCHARGE.</li> <li>- 13 DAYS REST PERIOD, DURING WHICH A 50mA DISCHARGE CURRENT IS IMPOSED IN ORDER TO AVOID THE PASSIVATION EFFECT.</li> <li>- DISCHARGE AT 40A, VOLTAGE MEASUREMENT DURING THE FIRST 200 μs OF THE DISCHARGE.</li> </ul>		

	DIVISION SPACE ESPACE DEPARTMENT	RISE TIME AND RESPONSE MEASUREMENTS ON A LISOC <sub>12</sub> CELL													
TEST DESCRIPTIONS															
<p>* <u>RESPONSE TESTS</u></p> <p>THEY CONSISTED OF STEP RESPONSE AND FREQUENCY RESPONSE TESTS</p> <p>- 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.</p> <table border="1" style="margin-left: auto; margin-right: auto;"> <tr> <td colspan="2">25% DOD</td> <td colspan="2">75% DOD</td> </tr> <tr> <td>T = 43°C</td> <td>T = 11°C</td> <td>T = 11°C</td> <td>T = 72°C</td> </tr> <tr> <td>I = 0, 1, 2, 5, 10, 20, 40, 70 A.</td> <td>I = 0, 10, 40, 70 A.</td> <td>I = 0, 10, 40, 70 A.</td> <td>I = 0, 10, 40, 70 A.</td> </tr> </table>				25% DOD		75% DOD		T = 43°C	T = 11°C	T = 11°C	T = 72°C	I = 0, 1, 2, 5, 10, 20, 40, 70 A.	I = 0, 10, 40, 70 A.	I = 0, 10, 40, 70 A.	I = 0, 10, 40, 70 A.
25% DOD		75% DOD													
T = 43°C	T = 11°C	T = 11°C	T = 72°C												
I = 0, 1, 2, 5, 10, 20, 40, 70 A.	I = 0, 10, 40, 70 A.	I = 0, 10, 40, 70 A.	I = 0, 10, 40, 70 A.												

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DIVISION SPACE  
ESPACE DEPARTMENT

RISE TIME AND RESPONSE  
MEASUREMENTS ON A LISOC<sub>12</sub> CELL



TEST DESCRIPTIONS

\* 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 LISOC<sub>12</sub> CELL.

25% DOD		75% DOD	
T = 43°C	T = 11°C	T = 11°C	T = 72°C
I = 0, 1, 2, 5, 10, 20, 30, 40, 60, 78 A.	I = 1, 2, 5, 10, 20, 40, 78 A.	I = 1, 2, 78, 5, 40, 10, 20 A.	I = 1, 2, 78, 5, 40, 10, 20 A.

FOR EACH CASE, THE FREQUENCY VARIED BETWEEN 5 Hz and 100 kHz

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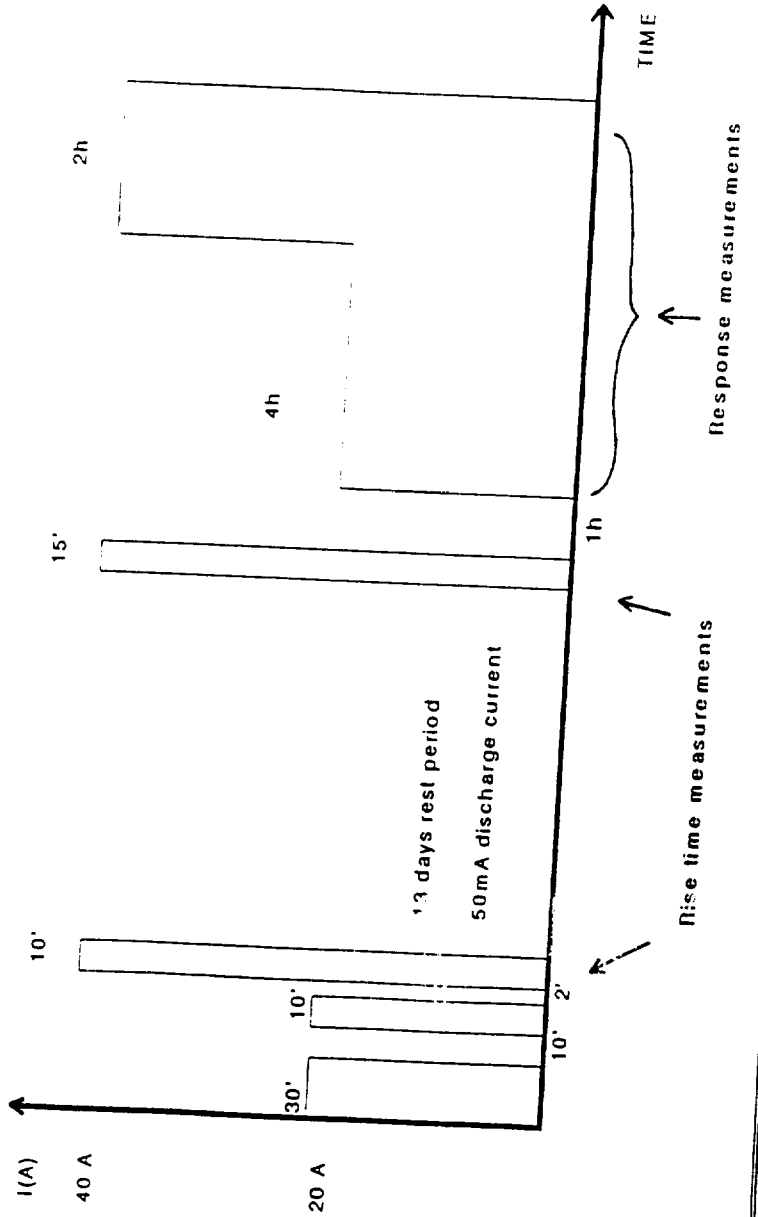
DIVISION SPACE  
ESPACE DEPARTMENT

RISE TIME AND RESPONSE  
MEASUREMENTS ON A LiSOCL2 CELL



TEST SEQUENCE

THE CELL WAS DISCHARGED UNDER THE FOLLOWING PROFILE ( $T = 40^{\circ}\text{C}$ )





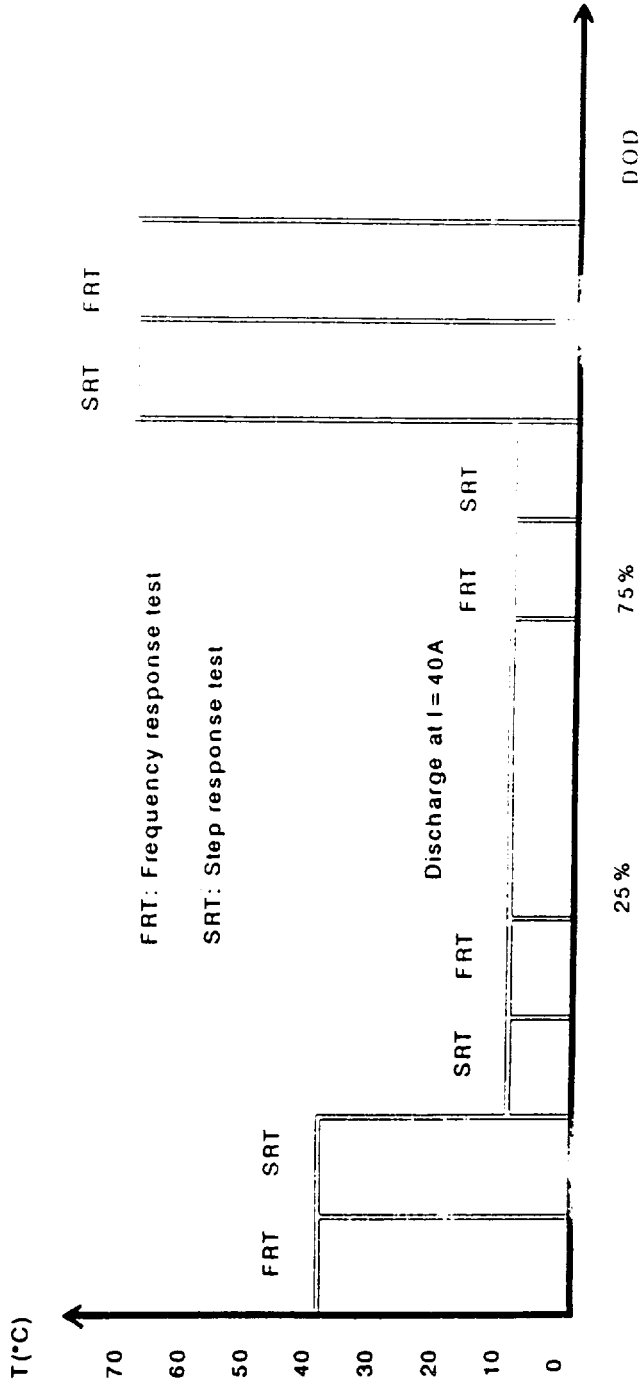
DIVISION SPACE  
SPACE DEPARTMENT

RISE TIME AND RESPONSE  
MEASUREMENTS ON A LISOCL<sub>2</sub> CELL



TEST SEQUENCE

RESPONSE TESTS SEQUENCE





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DIVISION SPACE  
SPACE DEPARTMENT

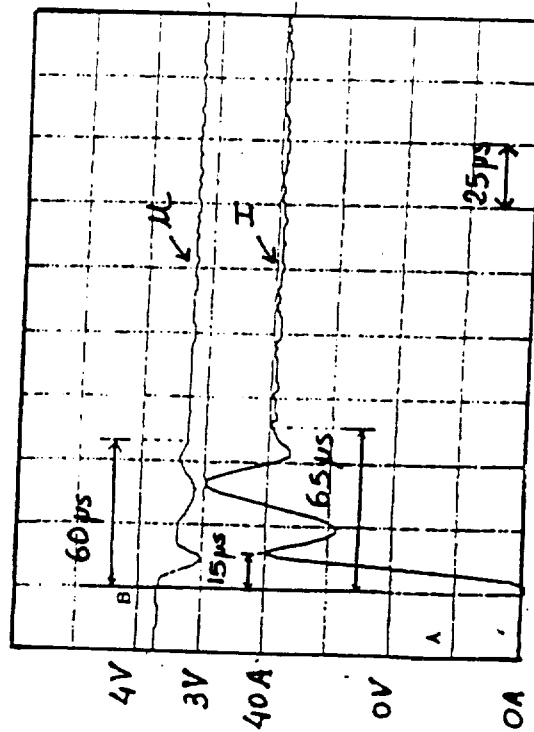
RISE TIME AND RESPONSE  
MEASUREMENTS ON A LISOC<sub>1</sub>-2 CELL



TEST RESULTS

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 60 $\mu$ S AND ALWAYS STAYED SUPERIOR TO 3V (U BATTERY  $\geq$  84V)
- \* NO DELAY EFFECT



DIVISION SPACE DEPARTMENT

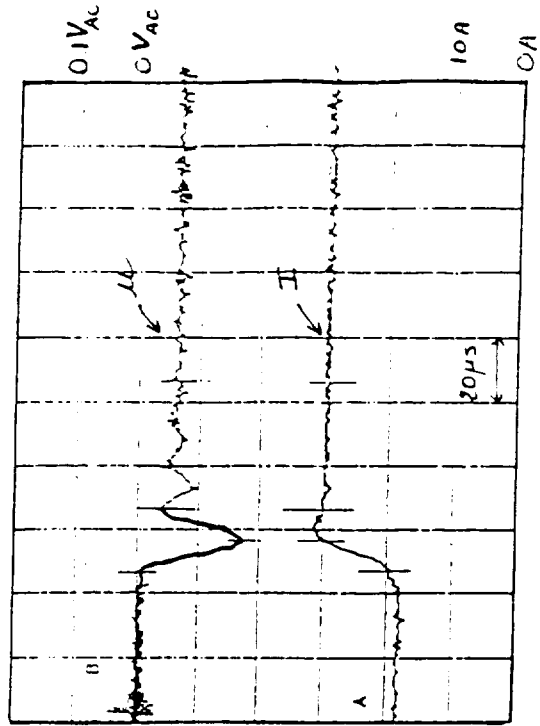
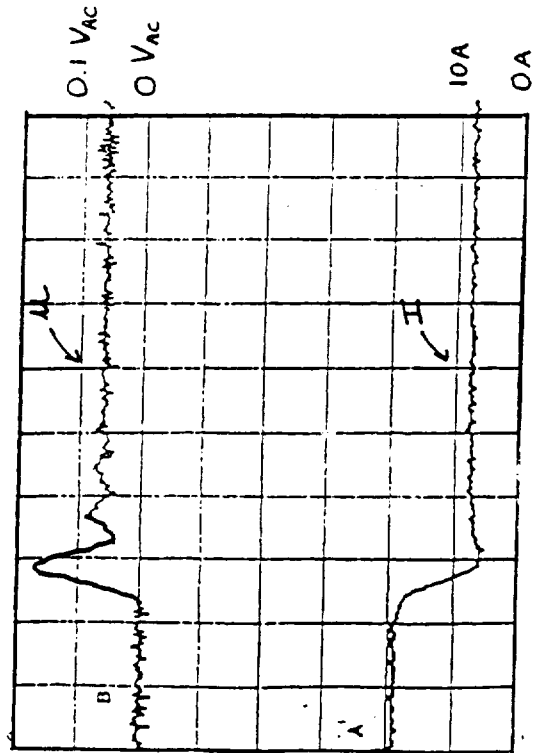
RISE TIME AND RESPONSE MEASUREMENTS ON A LiSOCL<sub>2</sub> CELL



TEST RESULTS

STEP RESPONSE TEST

AT T = 43°C, DOD = 25%, I = 20A





DIVISION SPACE  
ESPACE DEPARTMENT

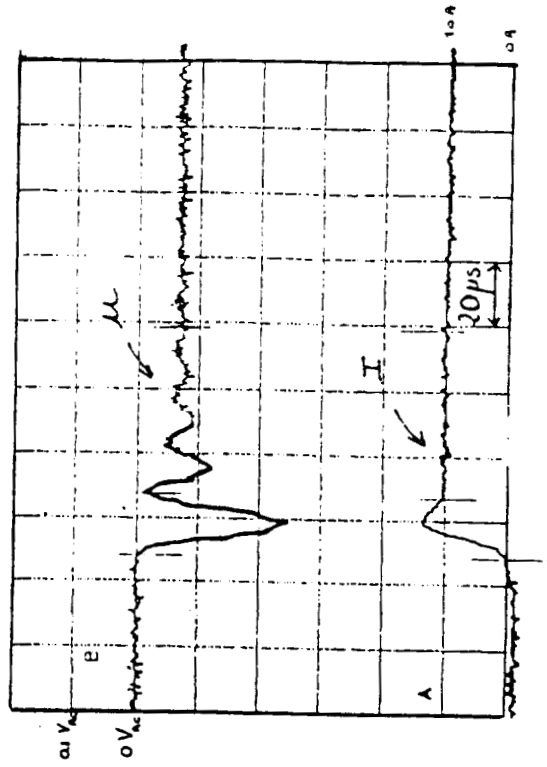
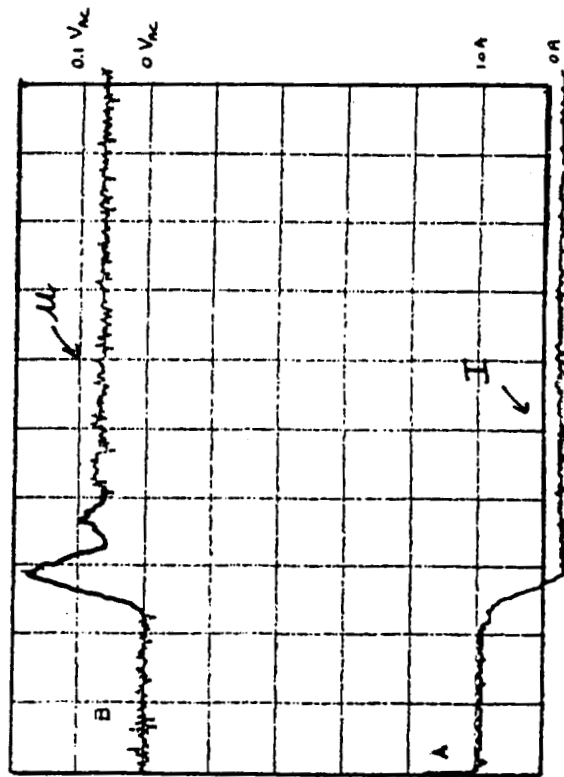
RISE TIME AND RESPONSE  
MEASUREMENTS ON A LISOC<sub>L2</sub> CELL



TEST RESULTS

STEP RESPONSE TEST

AT T = 43°C, DOD = 25%, I = 0A



**SAFT**

DIVISION SPACE  
ESPACE DEPARTMENT

RISE TIME AND RESPONSE  
MEASUREMENTS ON A LiSOCL<sub>2</sub> CELL



TEST RESULTS

STEP RESPONSE TESTS

- DYNAMIC RESPONSE (0 TO 70  $\mu$ S) :
  - \* WHEN  $40 < T < 70^{\circ}\text{C}$ , NEGATIVE STEP RESPONSE IS IDENTICAL FOR ALL CURRENT AND DOD.
  - \* WHEN  $T < 40^{\circ}\text{C}$ , THE VOLTAGE VARIATION DUE TO THE 10A STEP INCREASES AND VARIES WITH THE DOD.
  - \* THE POSITIVE STEP RESPONSE IS THE OPPOSITE OF THE NEGATIVE STEP RESPONSE FOR  $I > 10 \text{ A}$ .
  - \* FOR  $I \leq 10 \text{ A}$ , THE VOLTAGE VARIATION DUE TO THE POSITIVE 10 A LOAD STEP, IS HIGHER
  - \* THE VOLTAGE ALWAYS STABILIZED WITHIN 70  $\mu$ S WITH  $\Delta V$  ALWAYS INFERIOR TO 0.13V.
- STATIC RESPONSE :
  - \* AFTER  $t = 70\mu\text{s}$ , THE VOLTAGE SLOWLY VARIES WITH TIME BEFORE REACHING ITS NOMINAL VALUE

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DIVISION SPACE  
ESPACE DEPARTMENT

RISE TIME AND RESPONSE  
MEASUREMENTS ON A LISOCL<sub>2</sub> CELL



TEST RESULTS

GENERAL OBSERVATIONS ON DYNAMIC RESPONSES OF LISOCL<sub>2</sub> 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

**S A F T**

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ESPACE DEPARTMENT

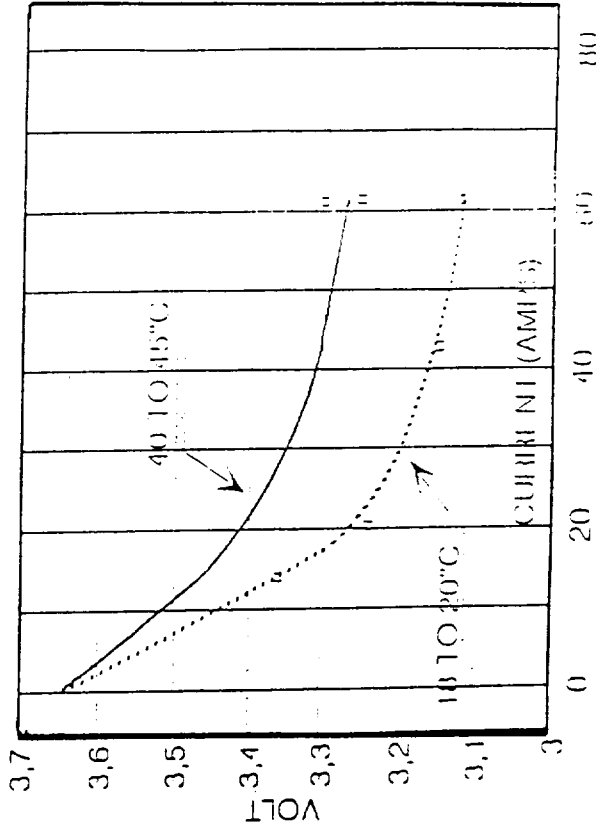
RISE TIME AND RESPONSE  
MEASUREMENTS ON A LiSOCL<sub>2</sub> CELL



TEST RESULTS

STATIC RESPONSES OF LiSOCL<sub>2</sub> CELLS

VLS 250 AM AVERAGE VOLTAGE VS CURRENT FOR VARIOUS TEMPERATURES

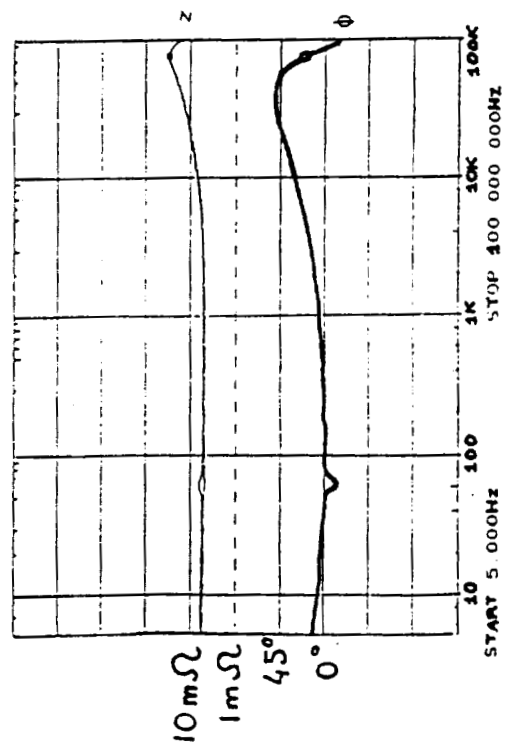




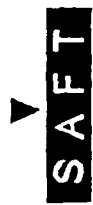

TEST RESULTS

FREQUENCY RESPONSE TEST

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



- \* THE MAXIMUM CELL IMPEDANCE IS 41 m Ω 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

 <p>DIVISION SPACE ESPACE DEPARTMENT</p>	<p>RISE TIME AND RESPONSE MEASUREMENTS ON A LISOCL<sub>2</sub> CELL</p>	
<p>TEST RESULTS</p>		
<p><u>CELL DISCHARGE</u>  DELIVERED ENERGY : 612.1 WH (400 WH/KG)  DELIVERED CAPACITY : 204.8 AH</p>		



**S A F T**

DIVISION SPACE  
ESPACE DEPARTMENT

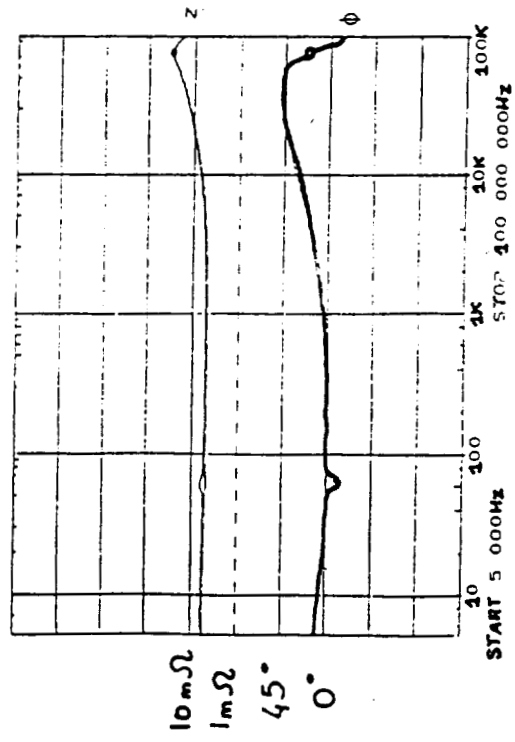


RISE TIME AND RESPONSE  
MEASUREMENTS ON A LI<sub>2</sub>SO<sub>4</sub> CELL

ELECTRICAL MODELIZATION

CELL ELECTRICAL MODELIZATION BASED ON FREQUENCY RESPONSE TEST

MODEL 1 : T ≥ 40°C



- \* PLATEAU AT 6 mΩ  
→ SERIES RESISTANCE : R<sub>1</sub>
- \* RESONANCE AT 76 KHz, 41 mΩ  
→ RLC PARALLEL CIRCUIT : R<sub>2</sub> = 35 mΩ  
 $1/2 \pi \sqrt{LC} = 76 \text{ KHz}$

**S A F T**

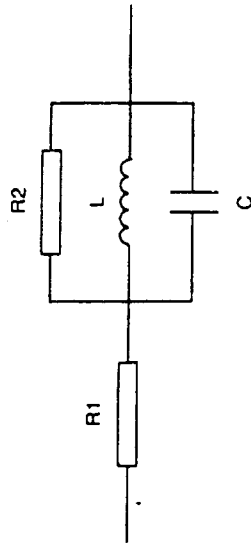
DIVISION SPACE DEPARTMENT  
SPACE DEPARTMENT

RISE TIME AND RESPONSE MEASUREMENTS ON A LiSOCl2 CELL



ELECTRICAL MODELIZATION

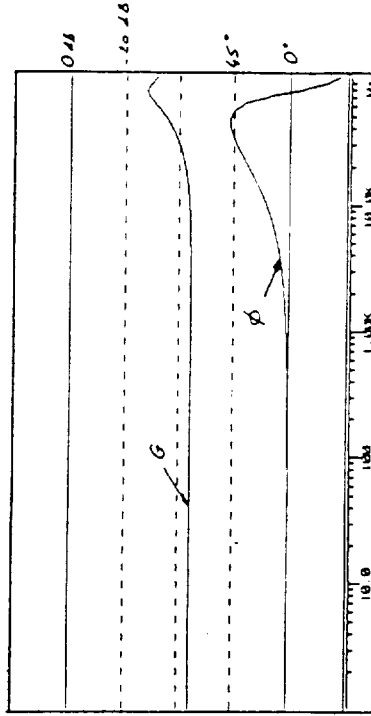
MODEL 1 :  $T \geq 40^{\circ}\text{C}$



$R_1 = 6 \text{ m}\Omega$  TO  $10 \text{ m}\Omega$   
( $R_1$  INCREASES AS  $T^{\circ}$  AND/OR DC CURRENT DECREASES)

$R_2 = 35 \text{ m}\Omega$   
 $L = 32 \text{ nH}$   
 $C = 137 \text{ }\mu\text{F}$

SIMULATION RESULT



**SAFT**

DIVISION SPACE  
ESPACE DEPARTMENT

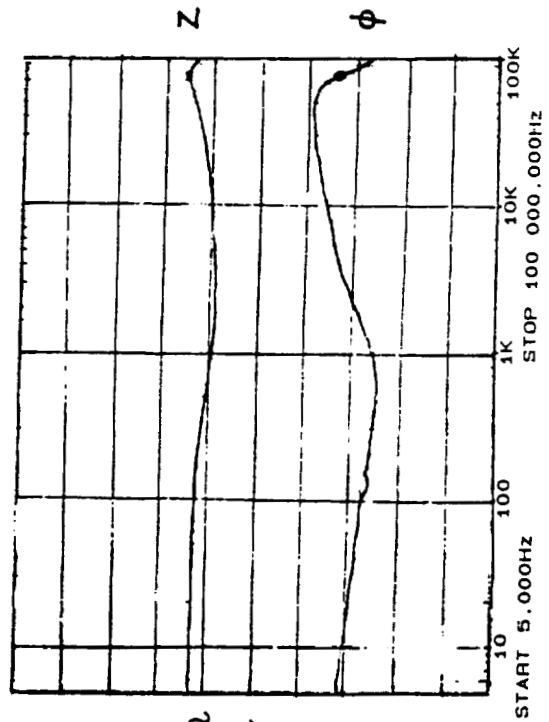
RISE TIME AND RESPONSE  
MEASUREMENTS ON A LISOC<sub>L2</sub> CELL



ELECTRICAL MODELIZATION

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**

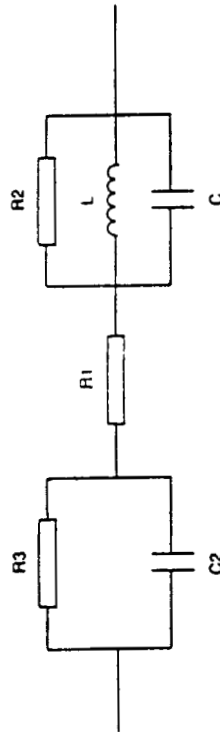
DIVISION SPACE  
ESPACE DEPARTMENT

RISE TIME AND RESPONSE  
MEASUREMENTS ON A  $\text{LiSOCl}_2$  CELL



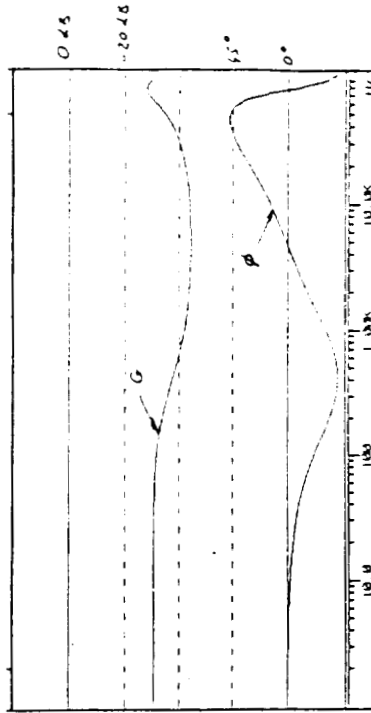
ELECTRICAL MODELIZATION

MODEL 2 :  $T < 40^\circ\text{C}$



$R_3 = 0\text{ m}\Omega$  TO  $24\text{ m}\Omega$   
( $R_3$  INCREASES AS  $T^\circ$  AND/OR DC CURRENT DECREASES)  
 $C_2 = 35.4\text{ mF}$

SIMULATION RESULT



**SAFT**

DIVISION  
SPACE

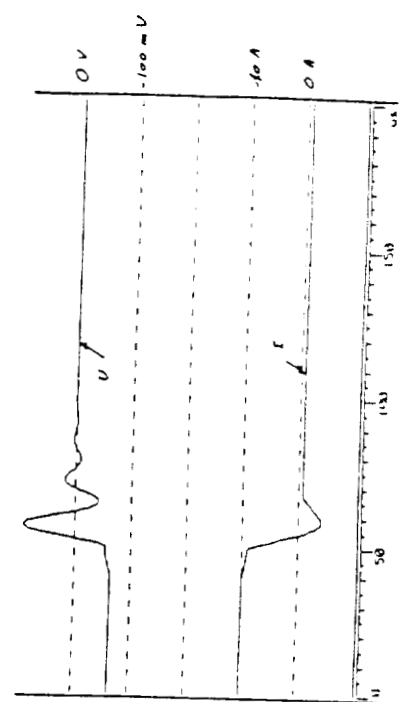
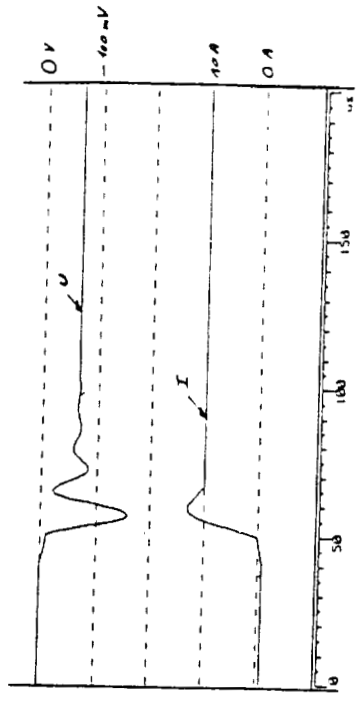
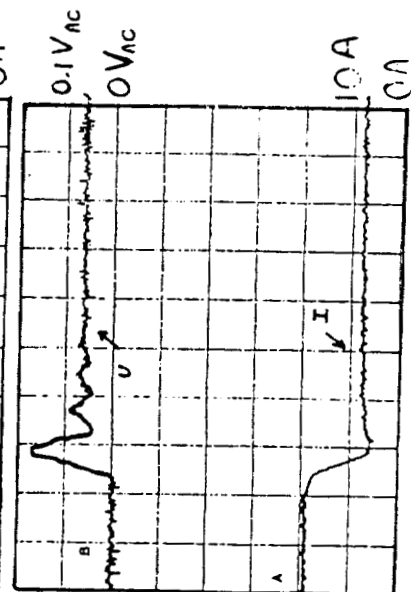
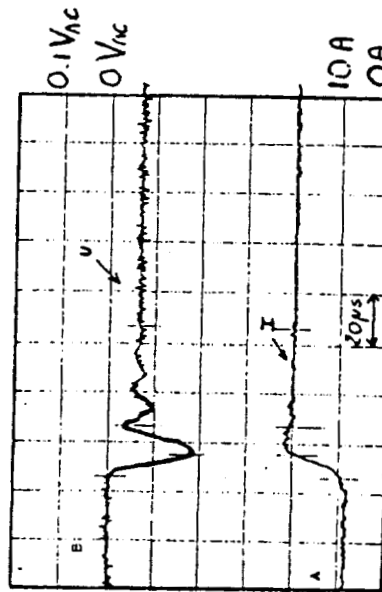
DEPARTMENT

RISE TIME AND RESPONSE  
MEASUREMENTS ON A LiSOCl2 CELL



ELECTRICAL MODELIZATION

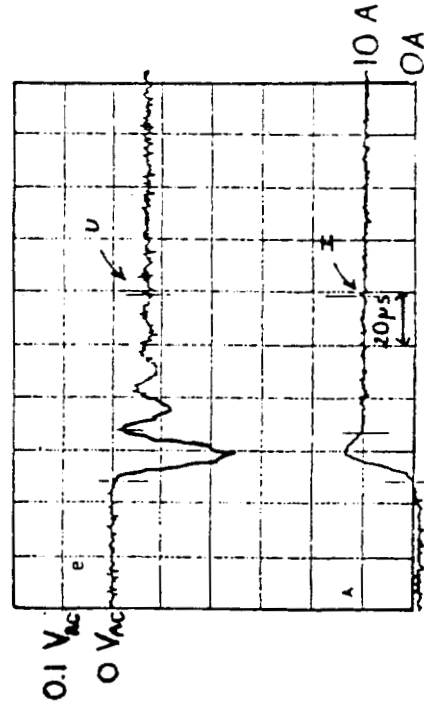
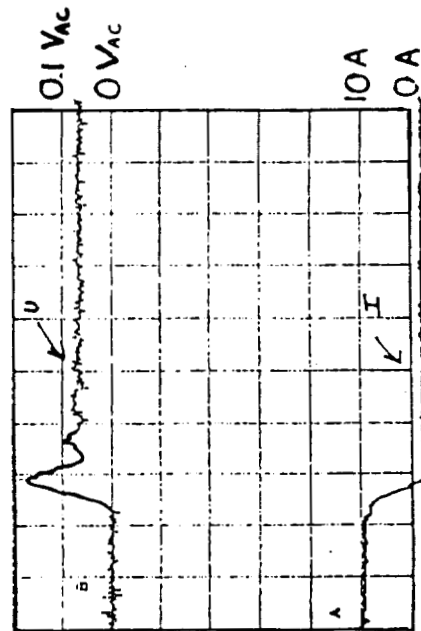
MODEL VALIDATION WITH STEP RESPONSE RESULTS ( $I_{DC} \geq 10A$ )



ELECTRICAL MODELIZATION

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.

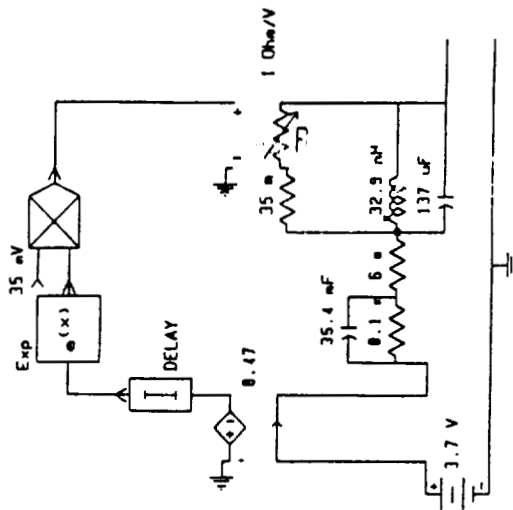


THE MODEL MUST INCLUDE A VARIABLE RESISTOR (R) WHICH WILL BE A FUNCTION OF THE CURRENT DELIVERED BY THE CELL.

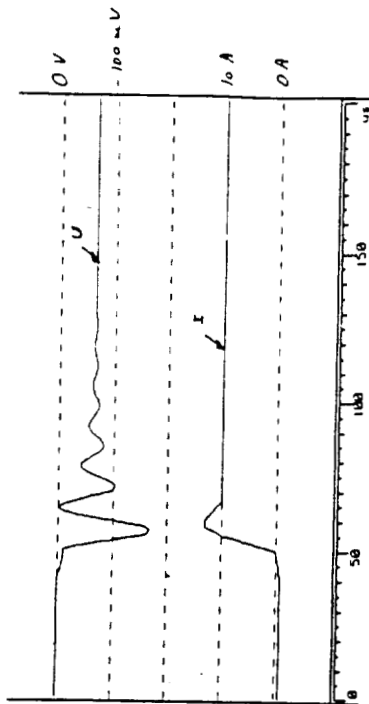


ELECTRICAL MODELIZATION

MODEL 3 : MODEL2 + RESISTOR (R)



SIMULATION RESULT



**SAFT**

DIVISION SPACE  
ESPACE DEPARTMENT

RISE TIME AND RESPONSE  
MEASUREMENTS ON A LISOCL<sub>2</sub> CELL

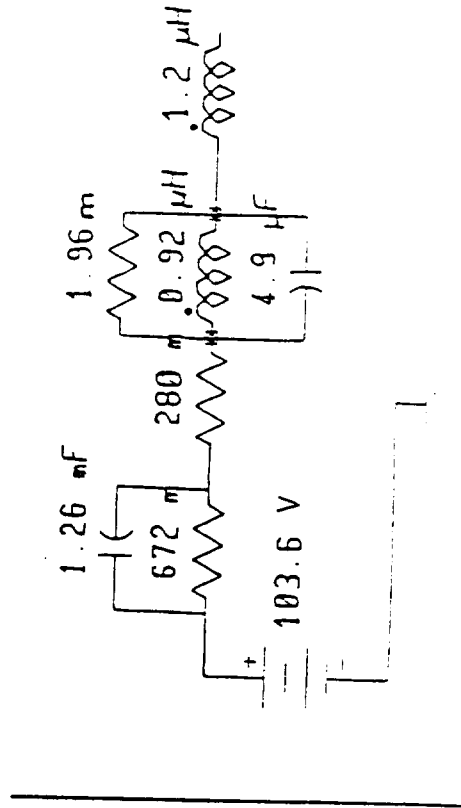
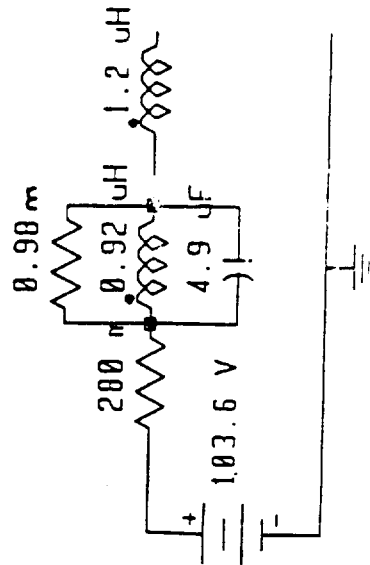


ELECTRICAL MODELIZATION



BATTERY ELECTRICAL MODELIZATION

I > 40°C

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





 <p>DIVISION SPACE ESPACE DEPARTMENT</p>	<p>RISE TIME AND RESPONSE MEASUREMENTS ON A LiSOCl<sub>2</sub> CELL</p>	
<p>CONCLUSION</p>		
<ul style="list-style-type: none"> <li>* THE 180 AH LiSOCl<sub>2</sub> CELL HAS SHOWN THE ABILITY TO DELIVER 40A WITHIN LESS THAN 60 μs IN THE SPECIFIED VOLTAGE RANGE (&gt; 3 VOLTS).</li> <li>* NO DELAY EFFECT WAS NOTICED AFTER 13 DAYS DURING WHICH A 50mA PERMANENT CURRENT WAS DISCHARGED.</li> <li>* SEVERAL ELECTRICAL MODELS HAVE BEEN PRESENTED WHICH SIMULATE THE DYNAMIC BEHAVIOUR OF THE CELL FOR DIFFERENT CONDITIONS OF TEMPERATURE, CURRENT AND DOD.</li> <li>* TWO MODELS OF THE 28 LiSOCl<sub>2</sub> CELL BATTERY ARE PROPOSED TO BE USED FOR THE MATHEMATICAL ANALYSIS OF THE HERMES POWER SYSTEM AND FOR AN ELECTRICAL SIMULATOR SPECIFICATION.</li> </ul>		



Johnson Space Center

Engineering Directorate

**INTERNAL/EXTERNAL SHORT CIRCUIT  
PROTECTION FOR LI D CELLS**

**Propulsion and Power Division**

**B.J. Bragg      10/29/91**

**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**

**N 9 2 - 2 2 7 5 0**



<b>INTERNAL/EXTERNAL SHORT CIRCUIT PROTECTION FOR LI D CELLS</b>	<b>Propulsion and Power Division</b>	
	<b>B.J. Bragg</b>	<b>10/29/91</b>

**AGENDA**

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



<b>INTERNAL/EXTERNAL SHORT CIRCUIT PROTECTION FOR LI D CELLS</b>	<b>Propulsion and Power Division</b>
	<b>B.J. Bragg</b>
	<b>10/29/91</b>

**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

**INTERNAL/EXTERNAL SHORT CIRCUIT  
PROTECTION FOR LI D CELLS****Propulsion and Power Division****B.J. Bragg      10/29/91****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 'C < T < 150 'C**
  
- **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

Propulsion and Power Division

B.J. Bragg 10/29/91

### 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 & FLUOCARBON 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



**INTERNAL/EXTERNAL SHORT CIRCUIT PROTECTION FOR LI D CELLS**

**Propulsion and Power Division**

**B.J. Bragg      10/29/91**

- **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**



**INTERNAL/EXTERNAL SHORT CIRCUIT PROTECTION FOR LI D CELLS**

**Propulsion and Power Division**

**B.J. Bragg 10/29/91**

**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**
**Propulsion and Power Division**

B.J. Bragg      10/29/91

**INCORPORATION INTO LITHIUM D CELLS**
**USED YTP BA6590 MODEL: SUB D CELL**

- 10 AH CELL @ 2 AMPS
- CATHODE PLATE AREA OF ~ 535 CM<sup>2</sup>
- CATHODE THICKNESS OF 0.005"

**CTS CELLS WITH 0.025" CATHODE THICKNESS MINIMUM**

- MAXIMUM PLATE AREA OF 268 CM<sup>2</sup> 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



**INTERNAL/EXTERNAL SHORT CIRCUIT PROTECTION FOR LI D CELLS**

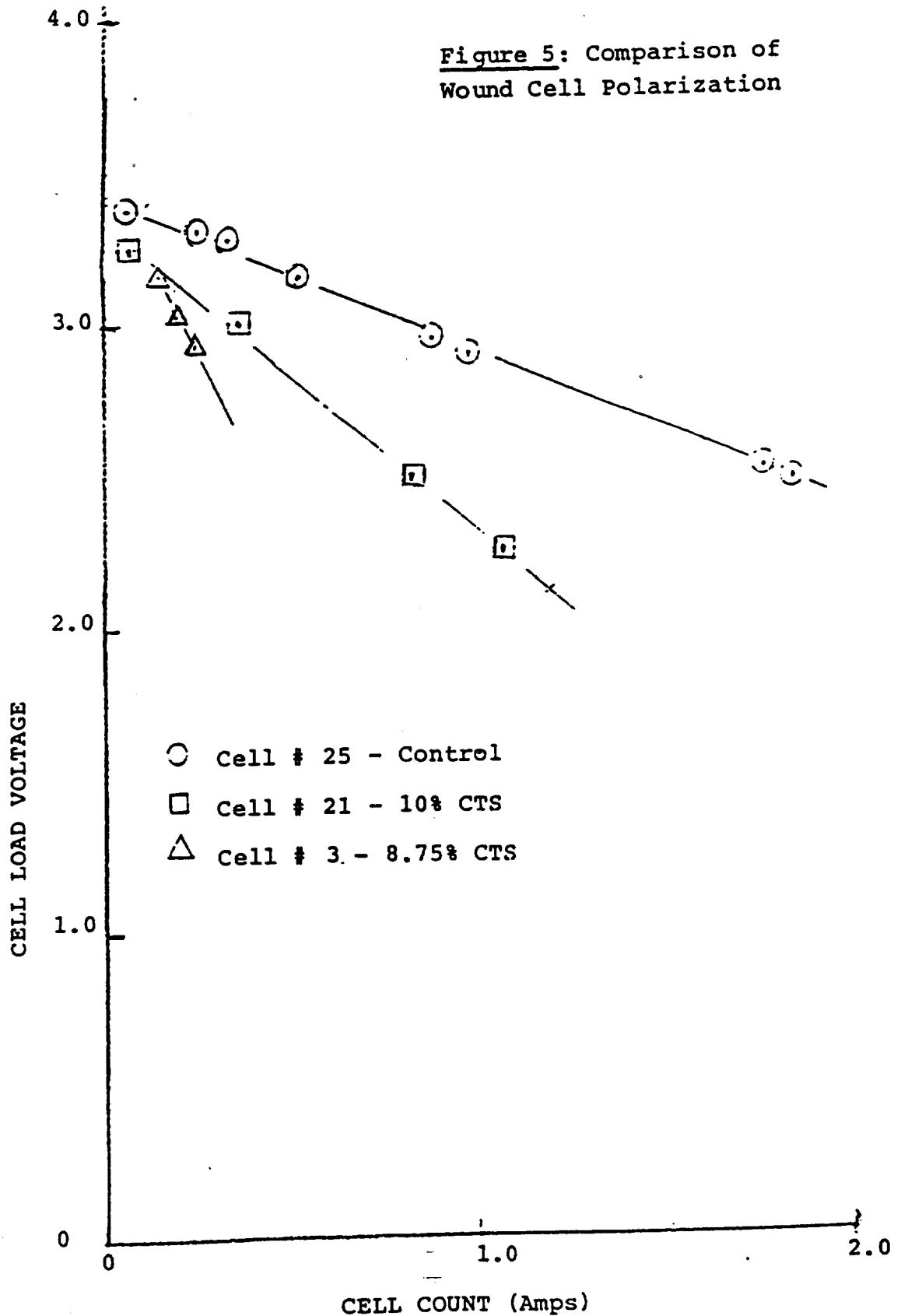
**Propulsion and Power Division**

**B.J. Bragg      10/29/91**

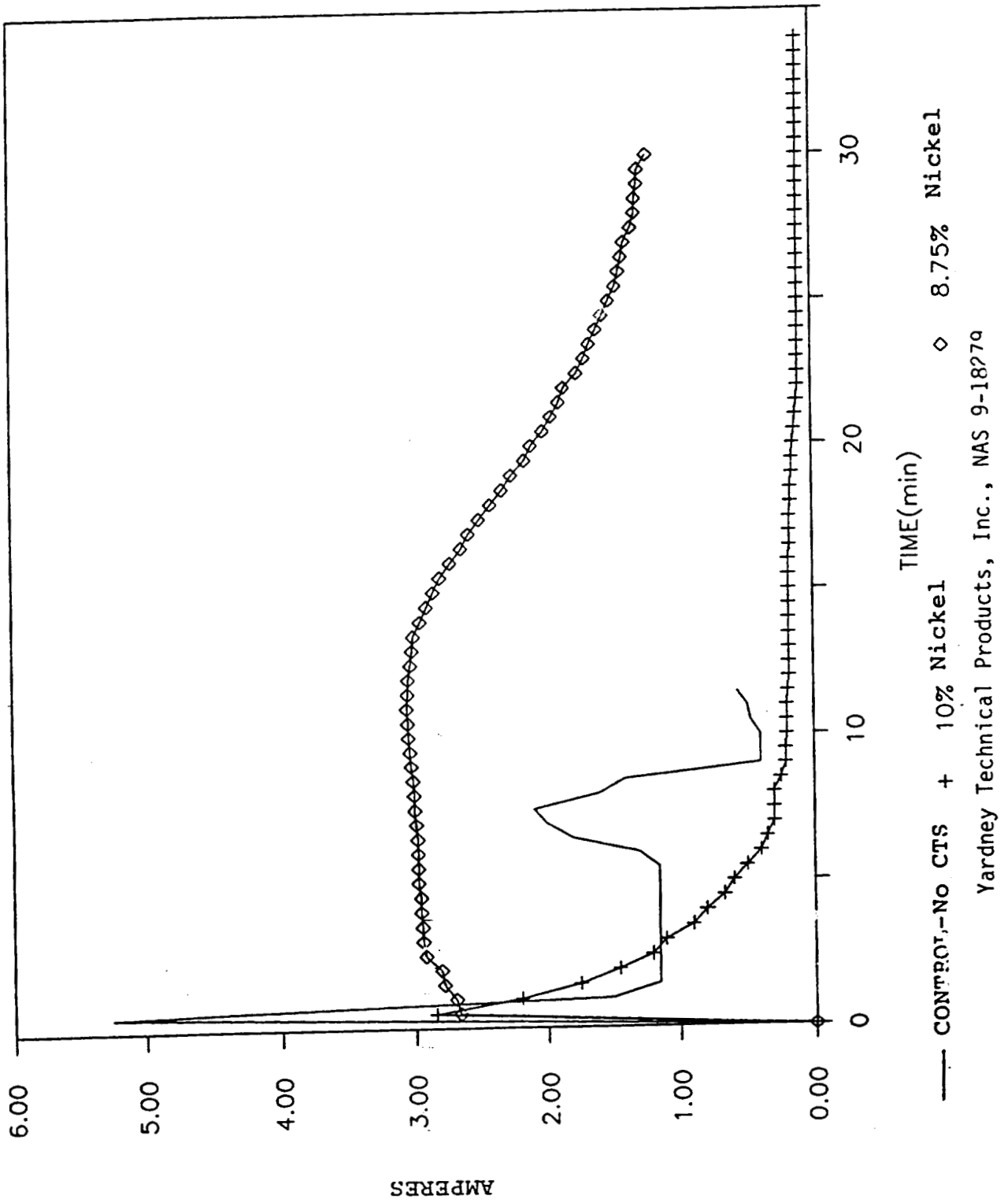
**RESULTS/CONCLUSIONS**

- 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

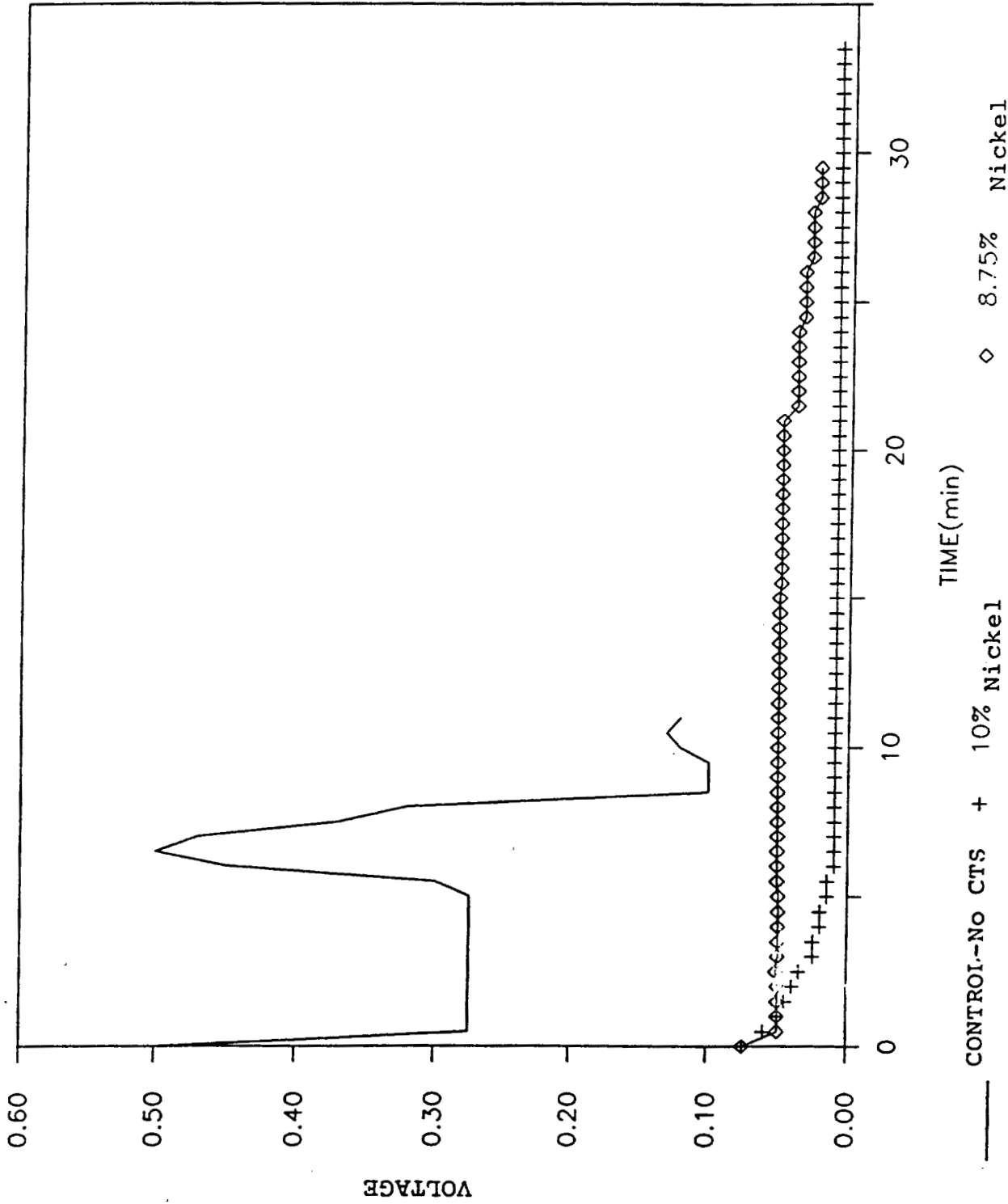
Figure 5: Comparison of Wound Cell Polarization



# CTS SHORT TEST

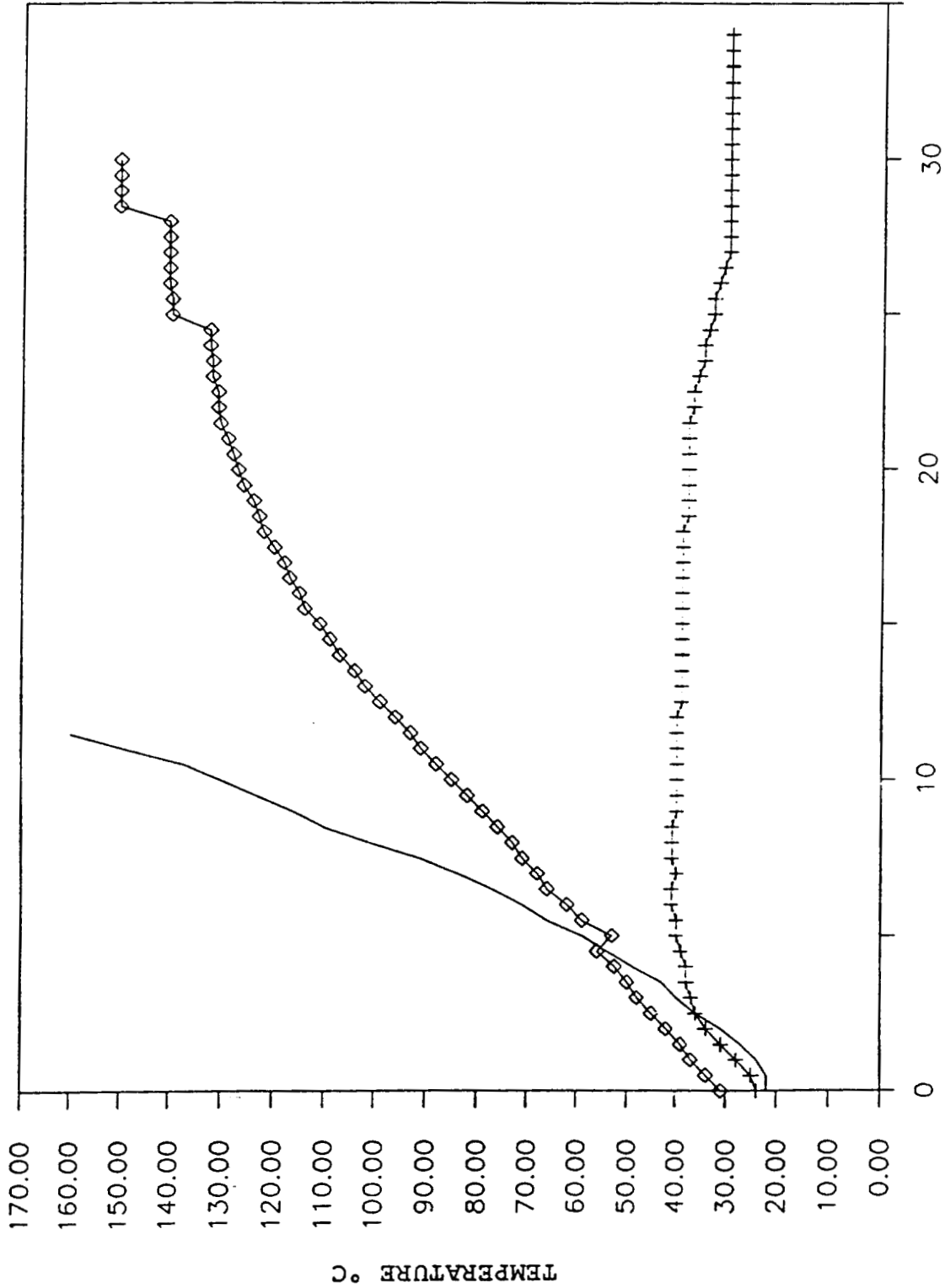


# CTS SHORT TEST



Yardney Technical Products, Inc., NAS 9-18279

# CTS SHORT TEST



— CONTROL No CTS    + 10% Nickel    ◊ 8.75% Nickel  
 Yardney Technical Products, Inc., NAS 9-18279



**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/SO<sub>2</sub> 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.

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# **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

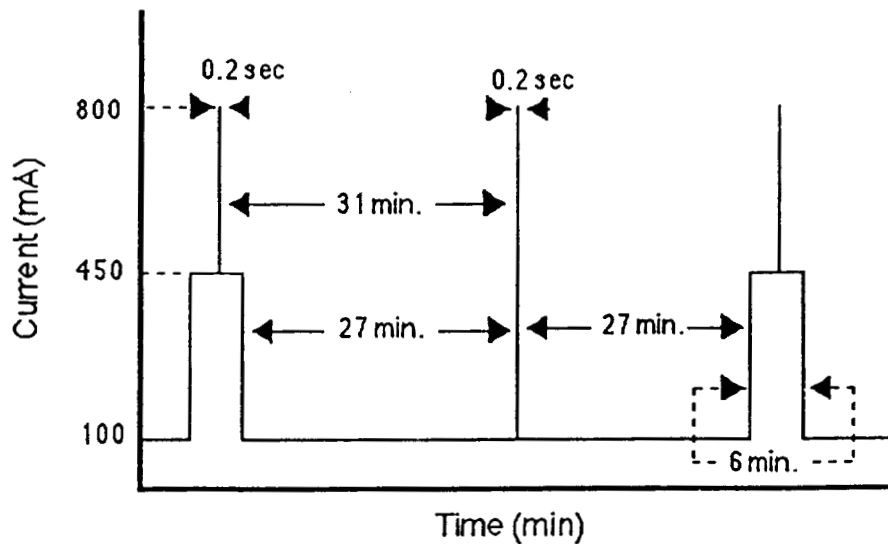
- compatible with space shuttle requirements for extra-vehicular activities and in-cabin storage
- base load electrical power output of 1W, power spikes to 6.5W
- extend operational life by a factor of four compared to operation using a Li/SO<sub>2</sub> battery

## Background

- The AN/PRC-112 is an army radio which was designed with a Li/SO<sub>2</sub> battery consisting of four 1/2 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

outside diameter	1.009 in.
overall length	1.899 in.
nominal weight	58 g
nominal volume	24.9 cm <sup>3</sup>
working electrode surface area	110 cm <sup>2</sup>
chemistry	Li/BrCl + SOCl <sub>2</sub>
polarity	case negative
nominal capacity rating	7 Ah
nominal discharge rate	75 mA
maximum continuous rate	1000 mA
nominal specific energy	432 Wh/kg
nominal energy density	0.95 Wh/cc
safety fuse rating	4 A

# 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.

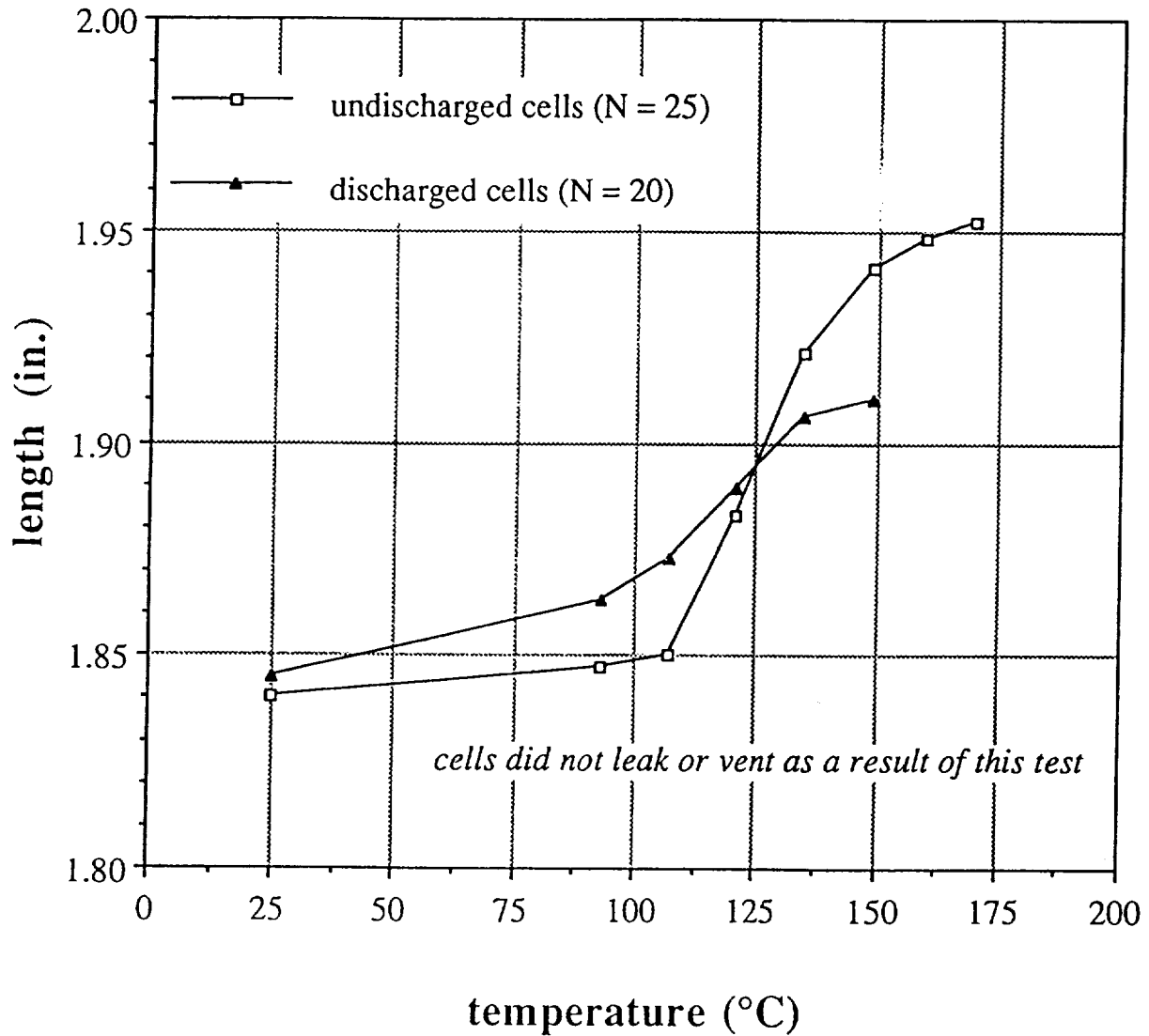
## Electrical Abuse Testing

- 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



# 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

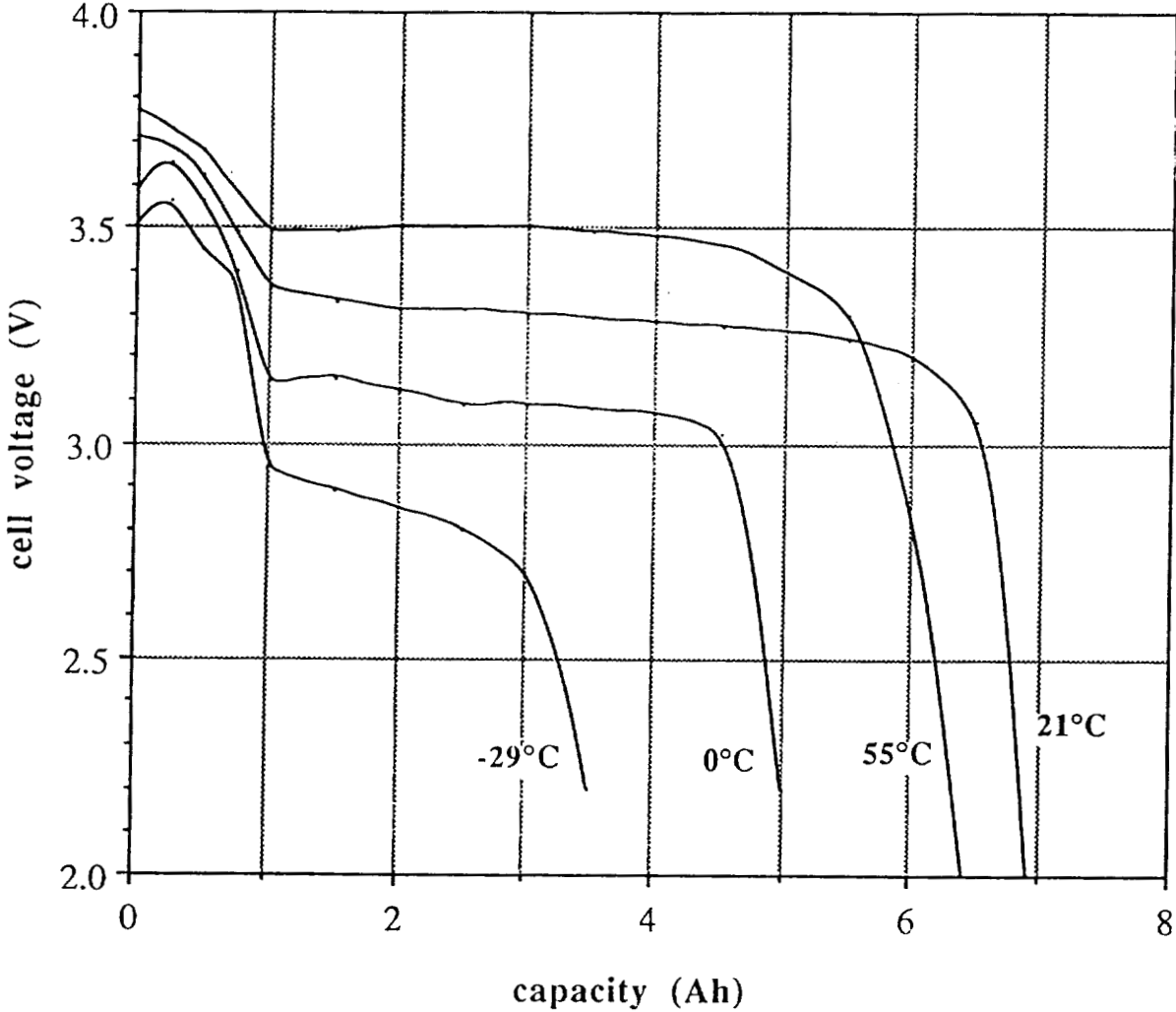
## Force Overdischarge Testing

In general...

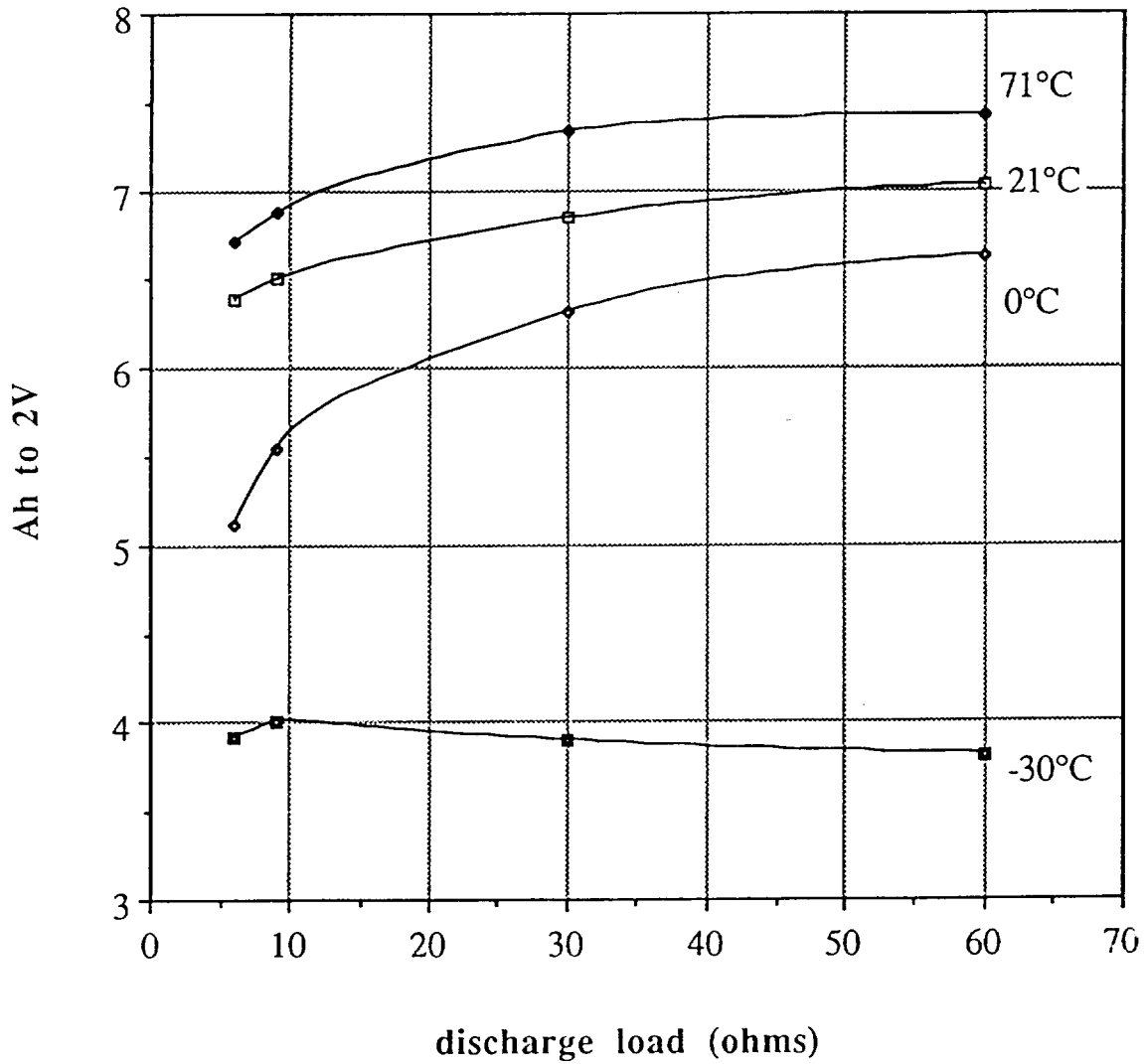
- current could not be maintained
- cells swelled
- 2 cells mildly vented through glass seal area
- peak temperature exceeded 200°C in some cases
- to-date, 54 cells have been force overdischarge tested



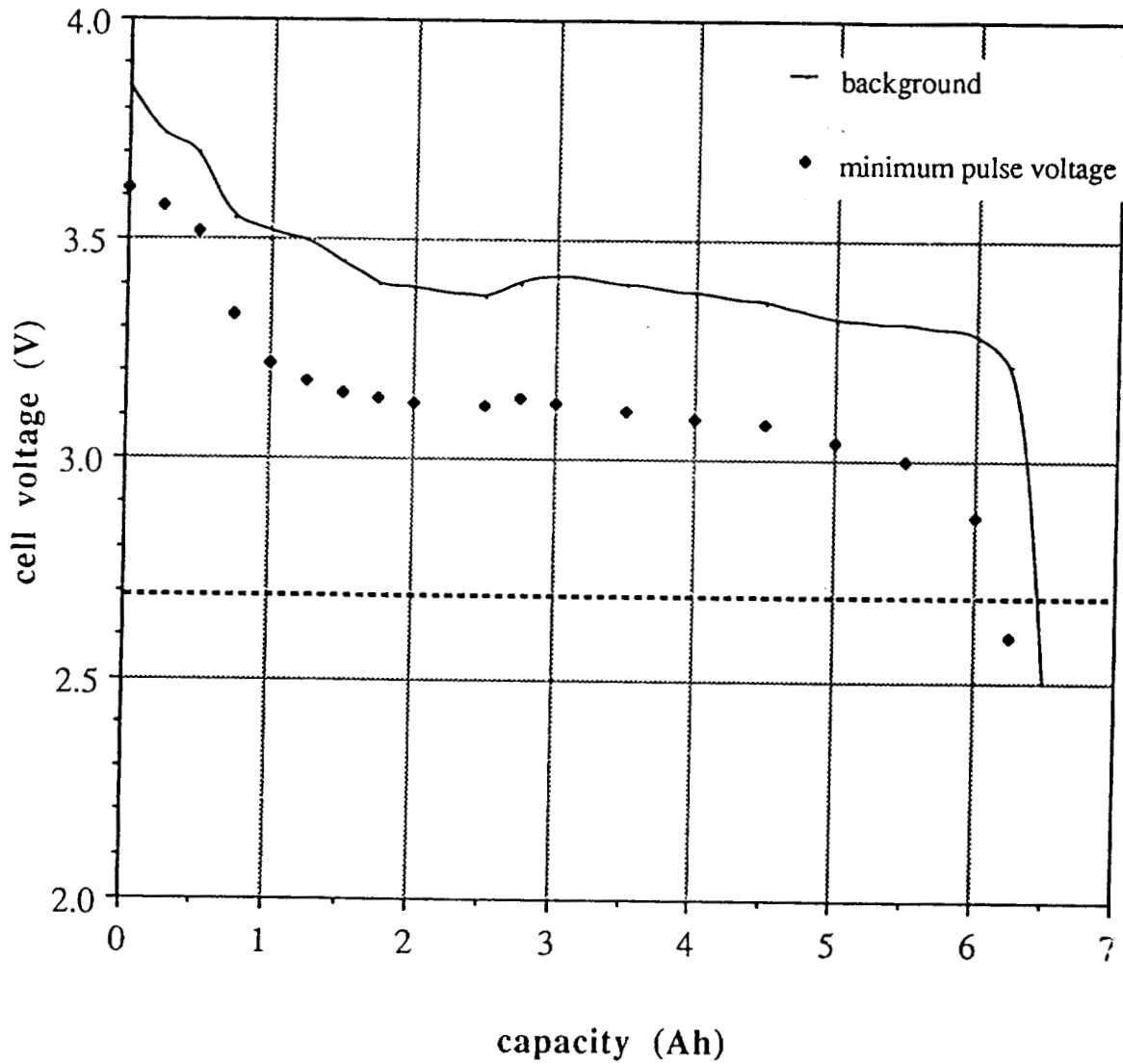
**Li/BCX (149) C-CELL DISCHARGE RESULTS UNDER  
6Ω LOADS AT VARIOUS TEMPERATURES**



### BCX 149 C-Cell discharge capacity as a function of load and temperature.

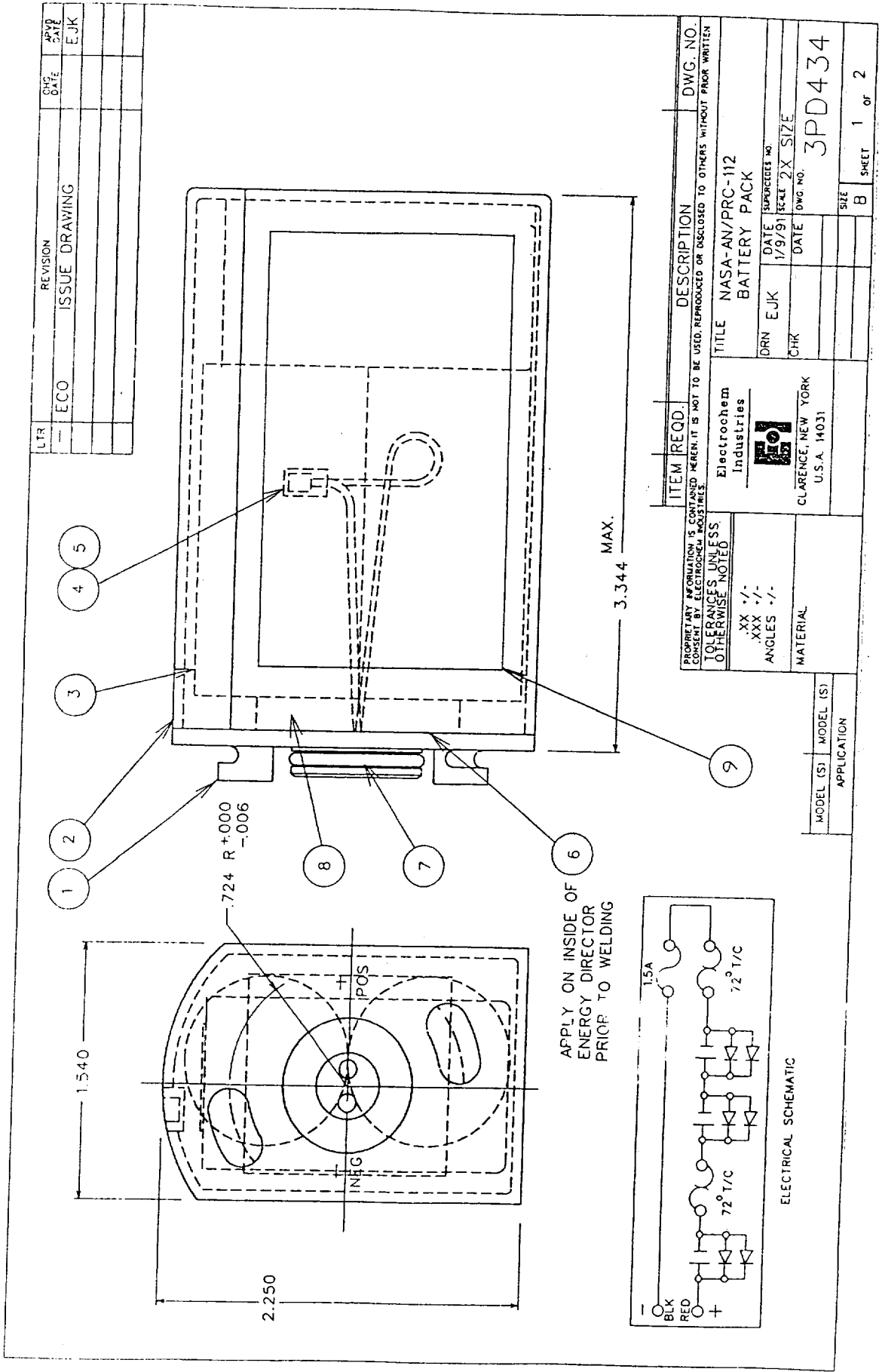


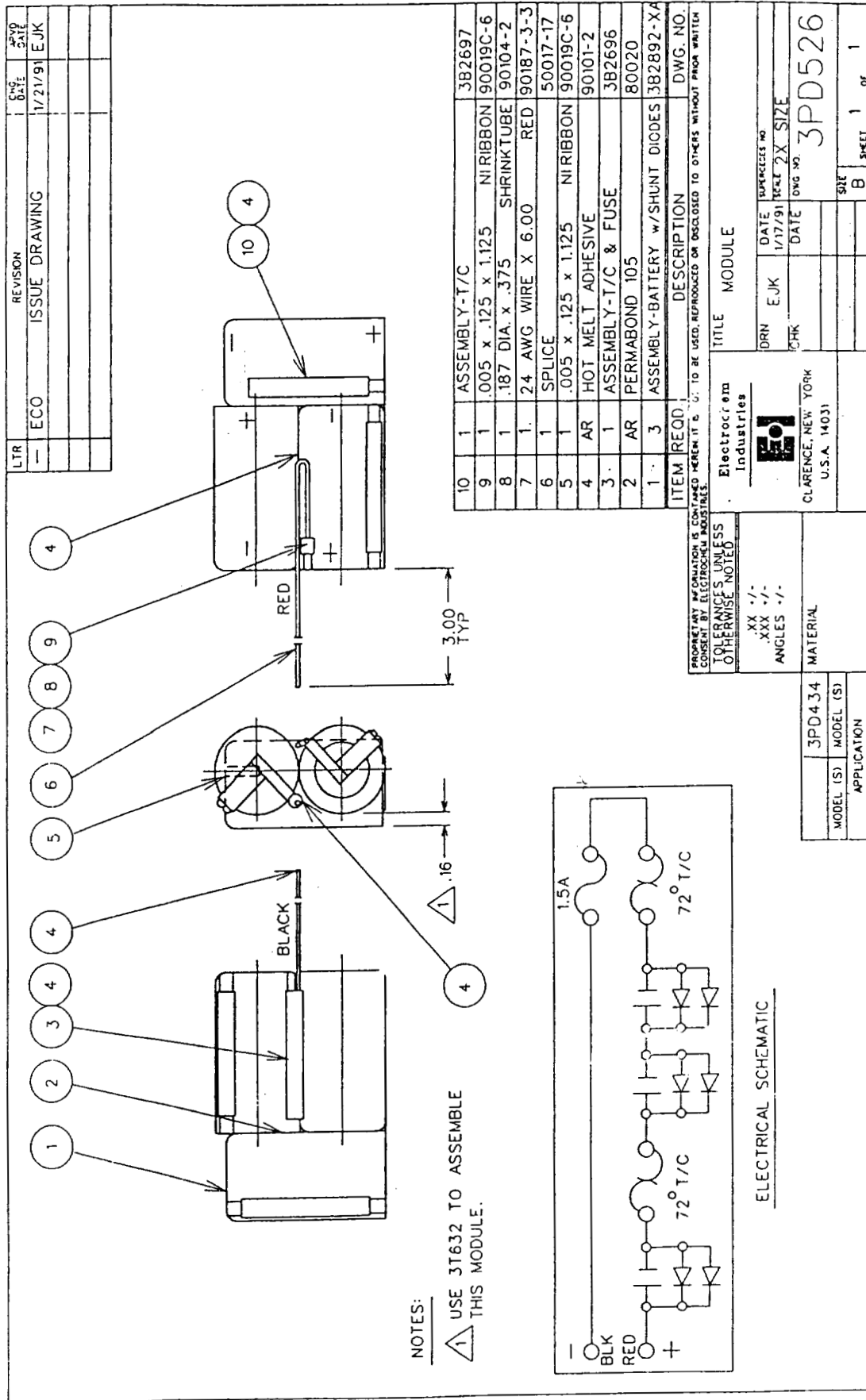
**Li/BCX (149) C-CELLS: TYPICAL PERFORMANCE UNDER SURVIVAL RADIO PULSE REGIMEN AT ROOM TEMP.**



## 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.



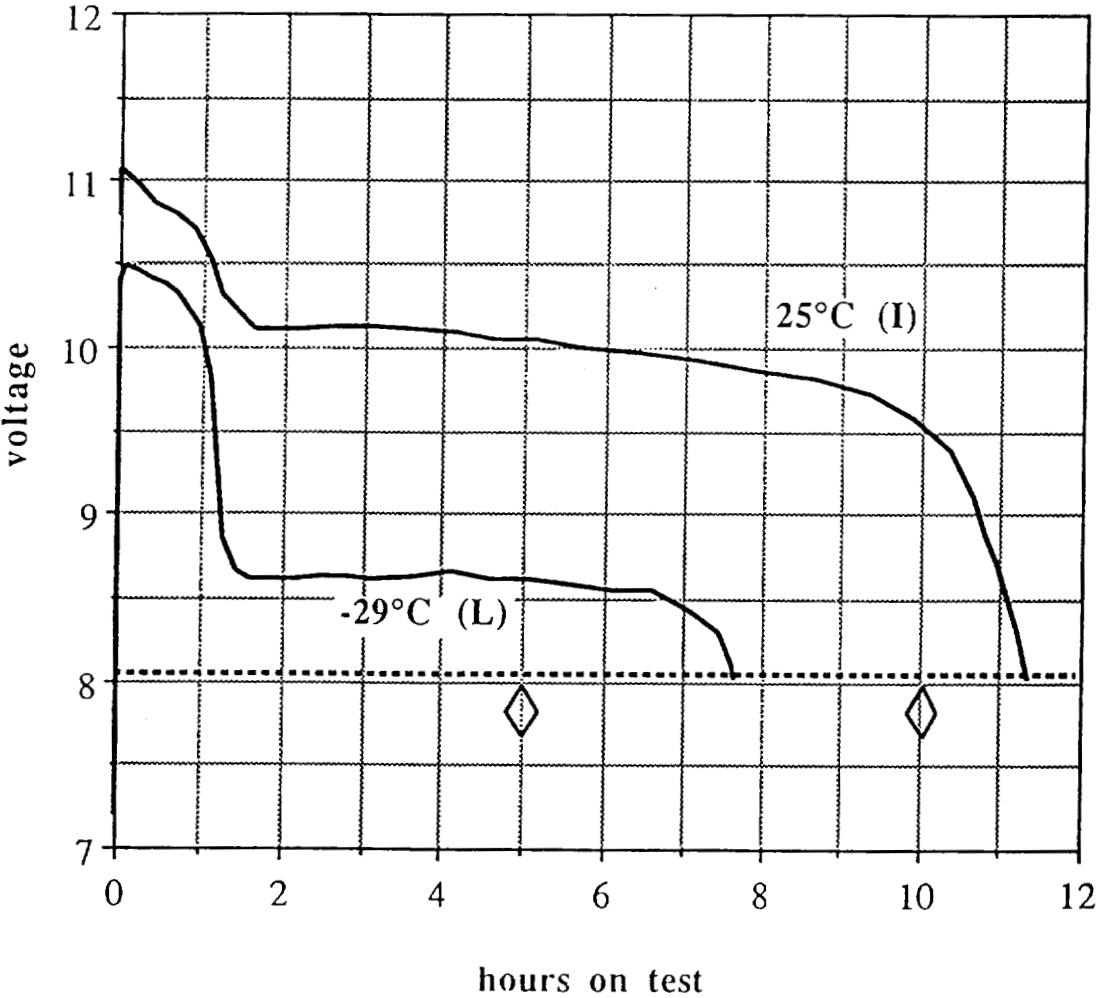


NOTES:

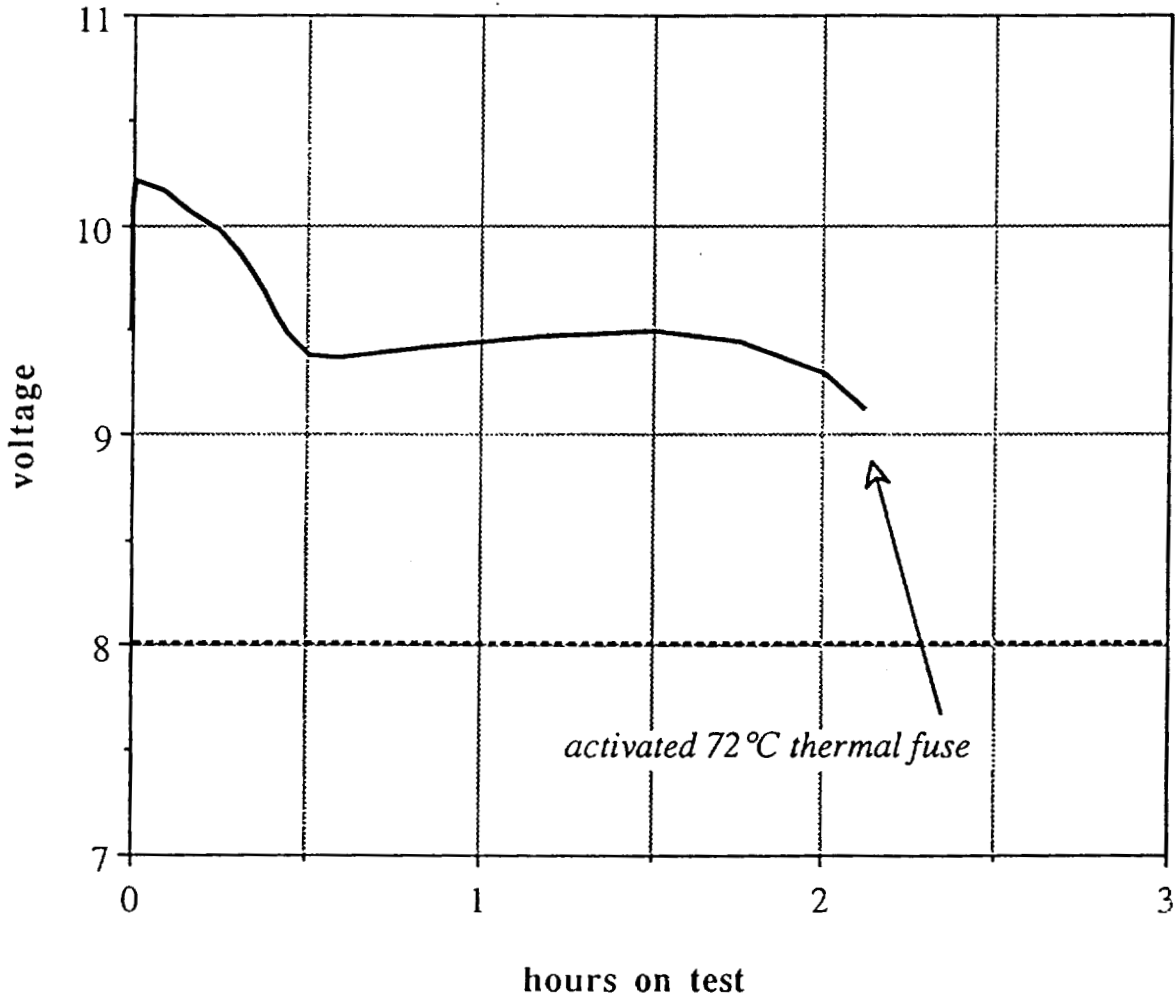
1 USE 3T632 TO ASSEMBLE THIS MODULE.

ELECTRICAL SCHEMATIC

NASA AN/PRC-112 Battery  
L and I test: 0.5A discharge



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





# 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	$0.03 \text{ g}^2/\text{Hz}$
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/SO<sub>2</sub> battery.
- Qualification testing will be complete during the second half of Nov91.





Johnson Space Center

Engineering Directorate

**EMU AG-ZN BATTERY WET-LIFE  
EXTENSION TEST**

**Propulsion and Power Division**

**B.J. Bragg      10/29/91**

**EMU AG-ZN BATTERY  
WET-LIFE EXTENSION TEST**

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

**NASA JOHNSON SPACE CENTER**

**N92-22752**

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**EMU AG-ZN BATTERY WET-LIFE  
EXTENSION TEST**

**Propulsion and Power Division**

**B.J. Bragg      10/29/91**

**AGENDA**

- **EMU BATTERY DESCRIPTION**
- **BACKGROUND - REASON FOR TEST**
- **TEST OBJECTIVES**
- **TEST DESCRIPTION**
- **RESULTS/CONCLUSIONS**



**EMU AG-ZN BATTERY WET-LIFE  
EXTENSION TEST**

**Propulsion and Power Division**

**B.J. Bragg      10/29/91**

**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 STANDAR (EMU VENDOR)
- BATTERY IS DELIVERED DRY WITH ACTIVATION KITS TO JSC



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**EMU AG-ZN BATTERY WET-LIFE  
EXTENSION TEST**

**Propulsion and Power Division**

**B.J. Bragg      10/29/91**

**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



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**EMU AG-ZN BATTERY WET-LIFE  
EXTENSION TEST**

**Propulsion and Power Division**

**B.J. Bragg**      **10/29/91**

**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**





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**EMU AG-ZN BATTERY WET-LIFE  
EXTENSION TEST**

**Propulsion and Power Division**

**B.J. Bragg      10/29/91**

**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  $\geq$  7 HOURS;  $\geq$  26.6 AH)**



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**EMU AG-ZN BATTERY WET-LIFE  
EXTENSION TEST**

**Propulsion and Power Division**

**B.J. Bragg**      **10/29/91**

**TEST RESULTS/CONCLUSIONS**

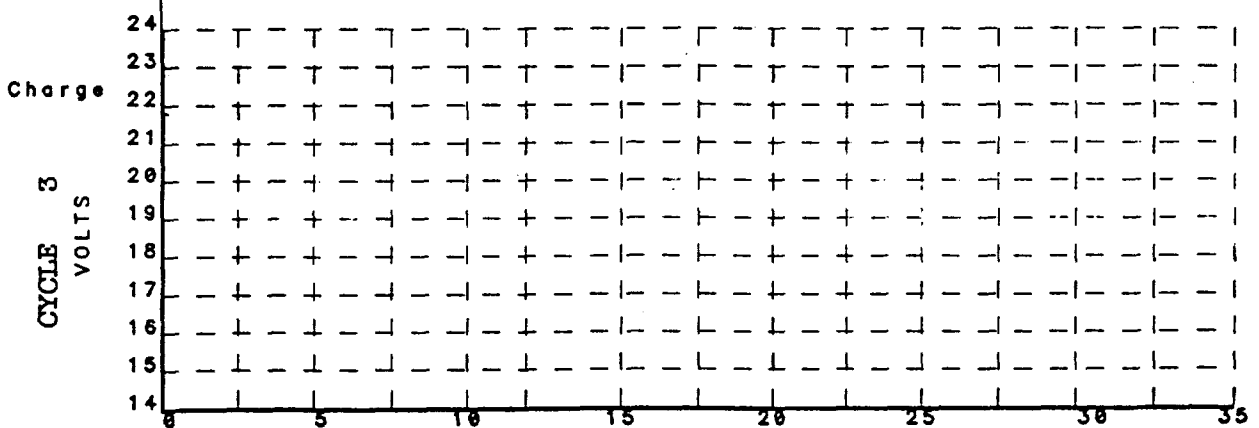
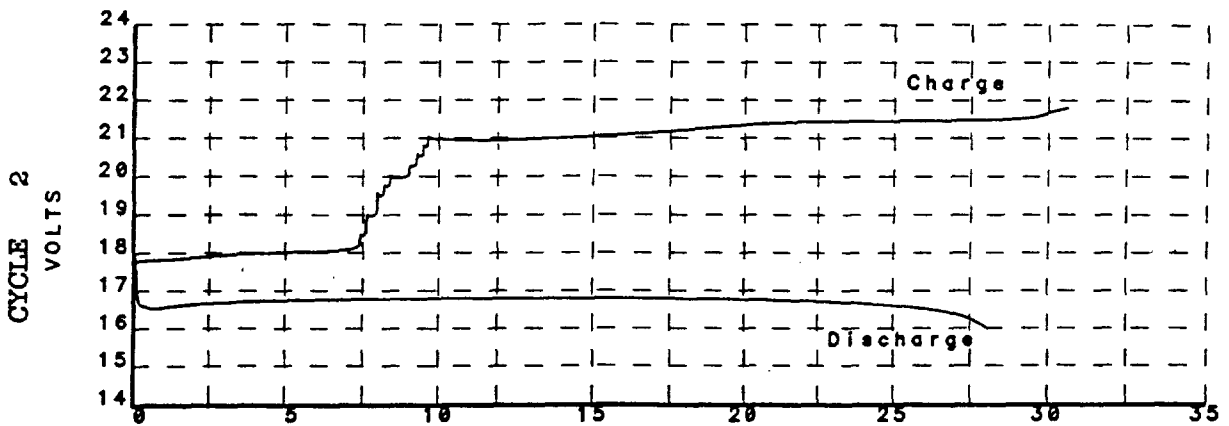
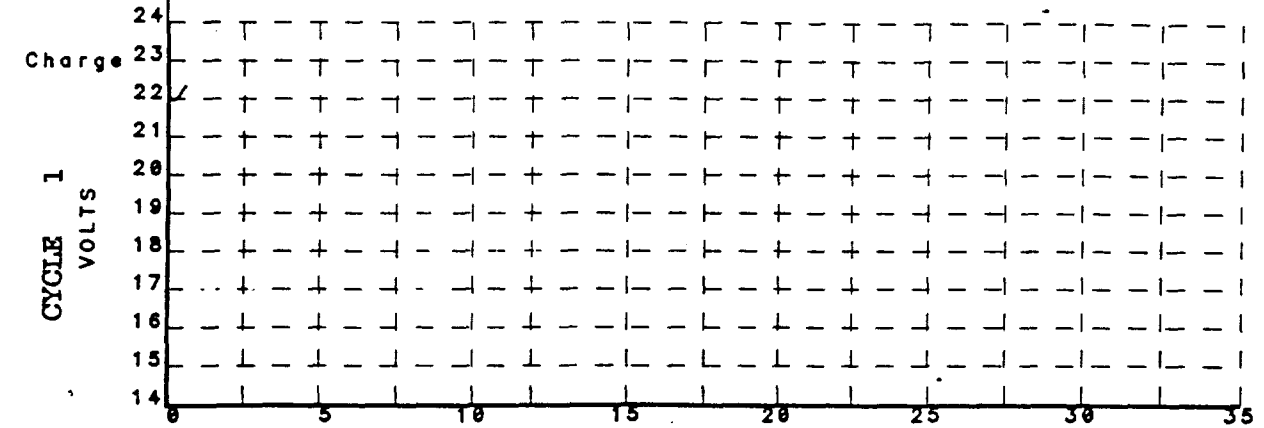
- **NINE BATTERIES HAVE BEEN TESTED FROM FOUR FLIGHT SHIPSETS FROM JAN '89 TO THE PRESENT**
- **ALL NINE HAVE SUCCESSFULLY PASSED THE 3-CYCLE REQUIREMENT AT 166 DAYS WET-LIFE**
- **THREE HAVE FAILED THE 3-CYCLE REQUIREMENT OF 226 DAYS**
- **FOUR HAVE PASSED THE 3-CYCLE REQUIREMENT OF 226 DAYS**
- **TWO 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 2F323, EMU 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  
 CHARGE CURRENT: 1.55 amps

BATTERY TYPE: EMU



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

(176 Day Wet-Life)

TEST 2P323, EMU SILVER-ALKALINE SECONDARY BATTERY EVALUATION

BATTERY SERIAL NO.: 1143

BATTERY MFG.: Yardney

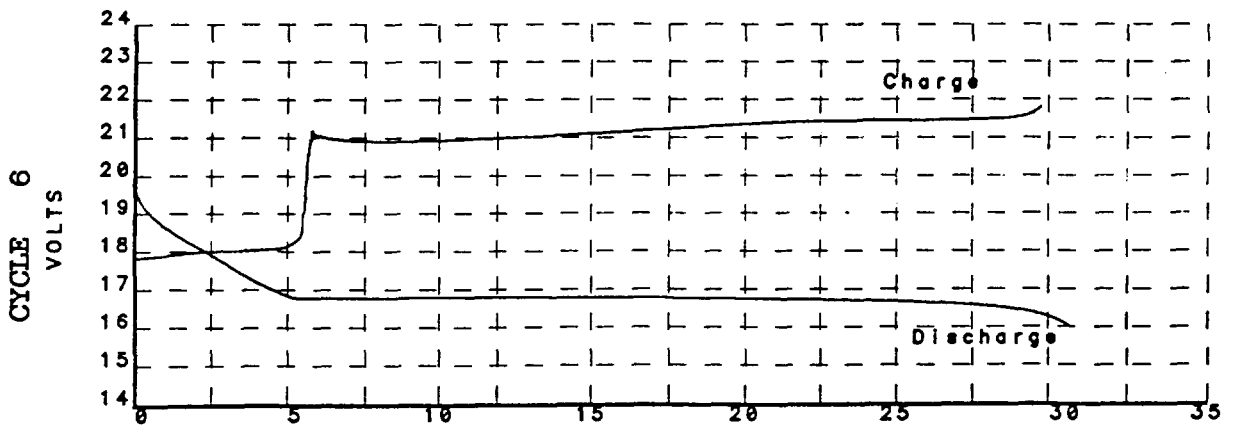
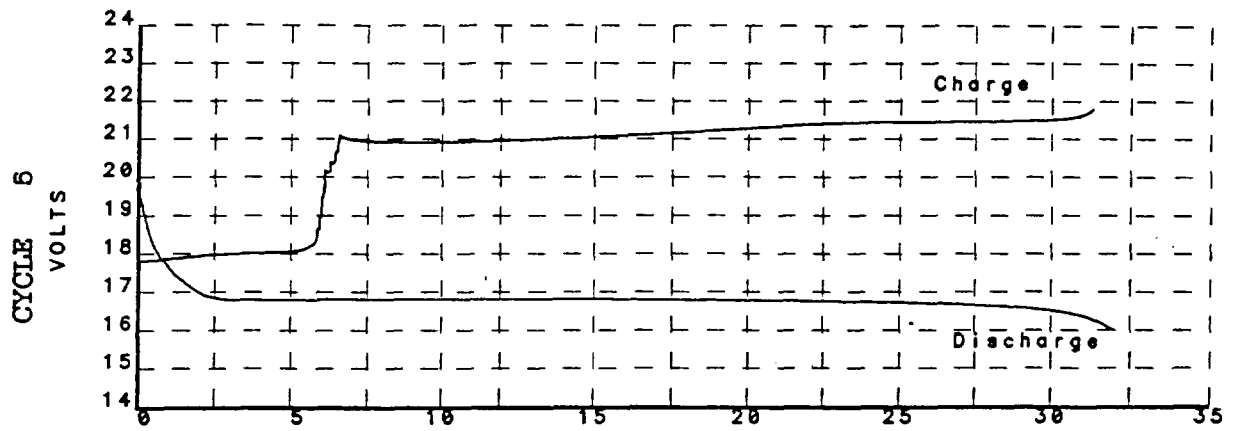
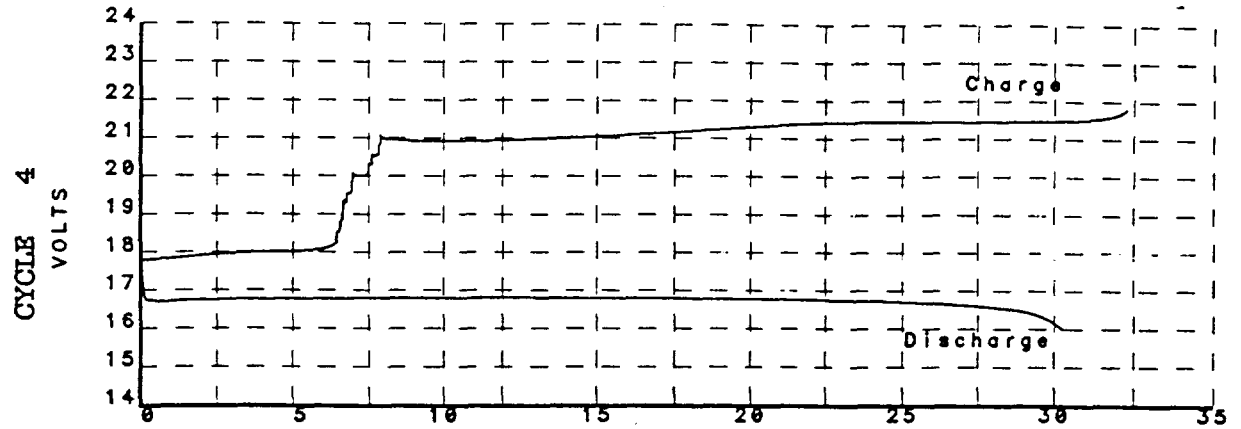
BATTERY TYPE: EMU

DEPTH OF DISCHARGE: 100%

TEST MGR.: C. M. WOOTEN

DISCHARGE CURRENT: 3.8 amps

CHARGE CURRENT: 1.55 amps



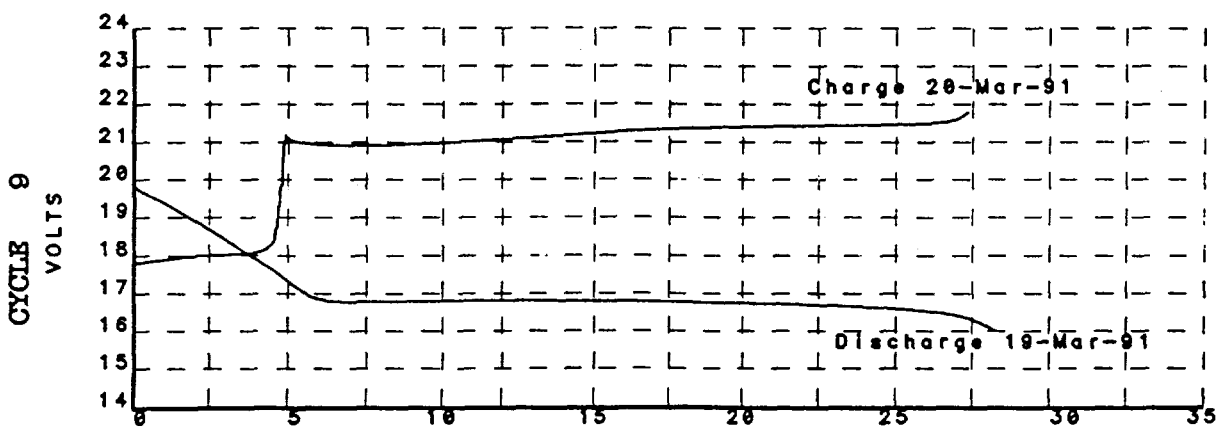
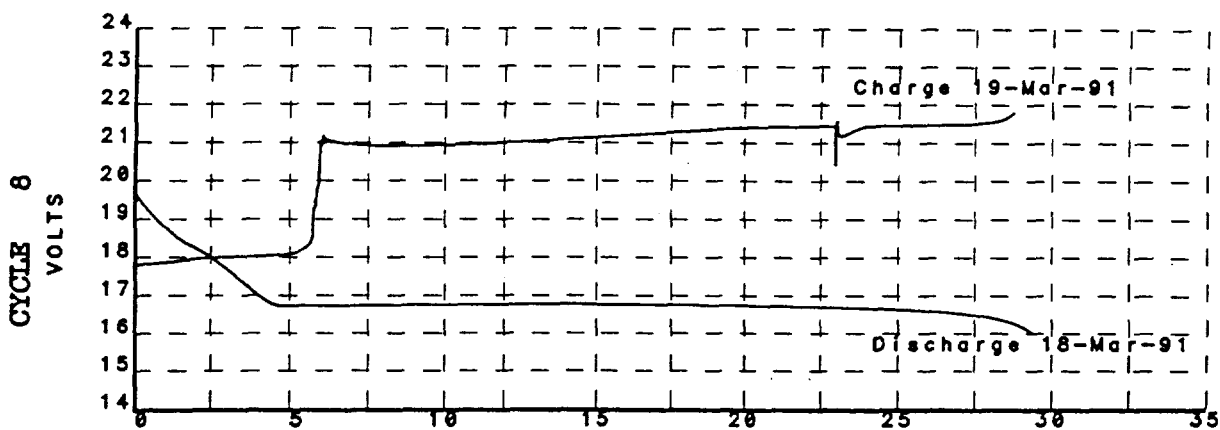
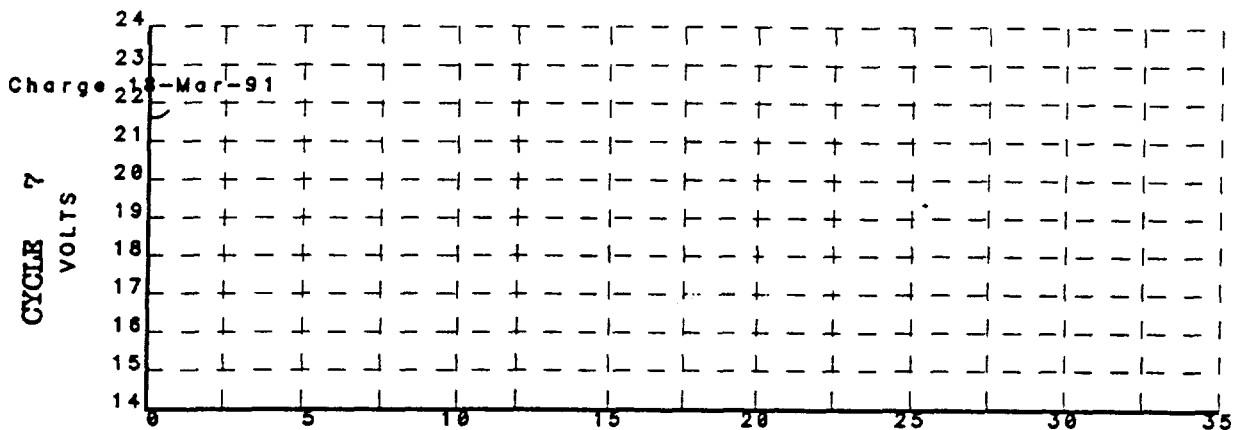
Cycle #	AMP HOURS	Type Test
4		Test Cycle
5		Test Cycle
6		Test Cycle

(176 Day Wet-Life)

TEST 2P323, EMU 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: EMU  
 CHARGE CURRENT: 1.55 amps



Cycle #	AMP HOURS	Type Test
7		Topping Charge
8		Test Cycle
9		Test Cycle

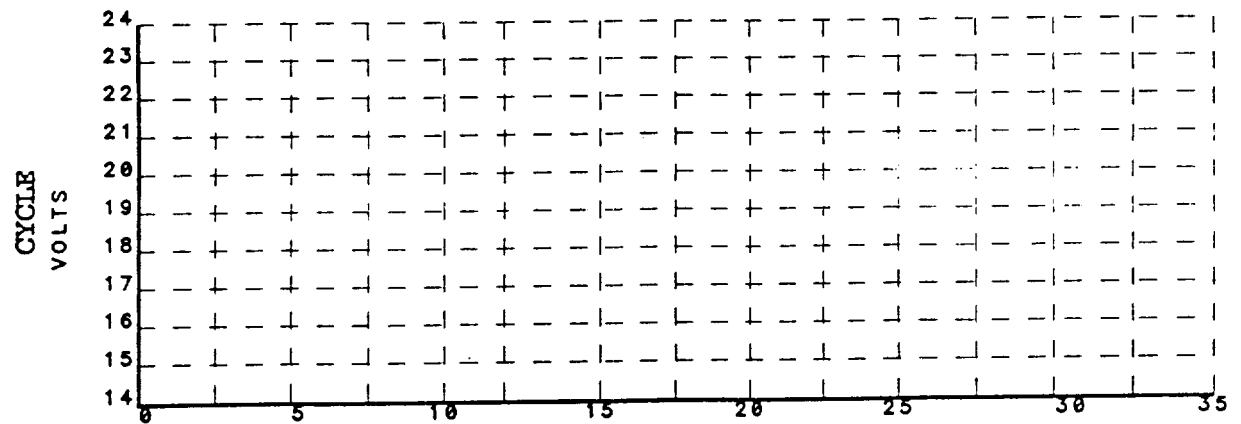
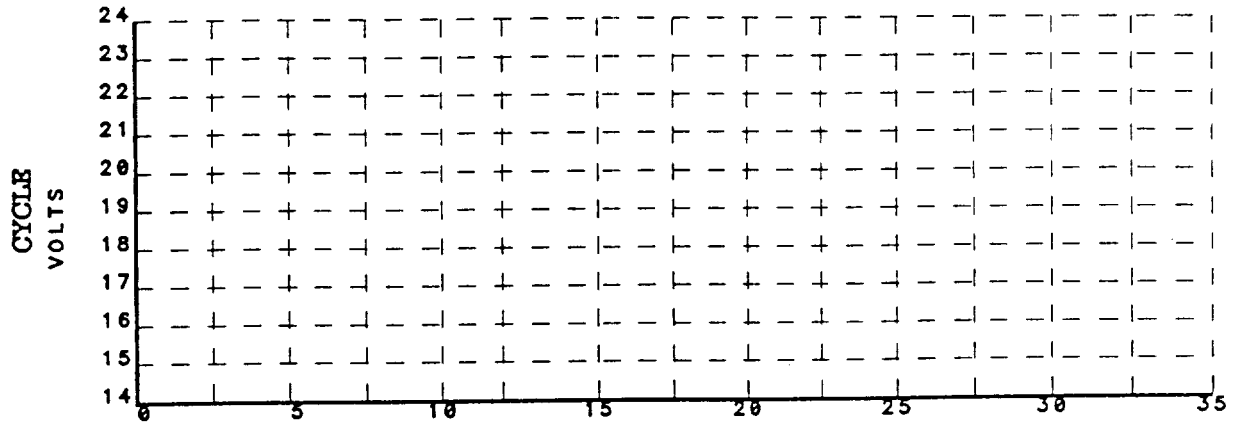
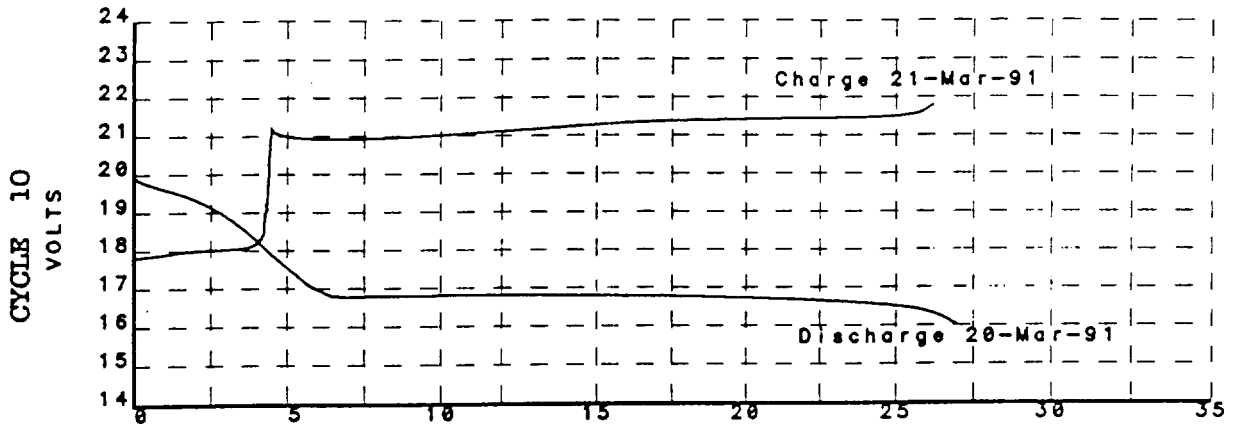
(226 Day Wet-Life)

TEST 2P323, EMU 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  
 CHARGE CURRENT: 1.55 amps

BATTERY TYPE: EMU



Cycle #                      Type Test  
 10                                  Test Cycle

(226 Day Wet-Life)

Test 2P323, EMJ Silver-Alkaline Secondary Battery Evaluation

Battery Serial No.: 1143

Battery Mfg.: Yardney

Battery Type: EMJ

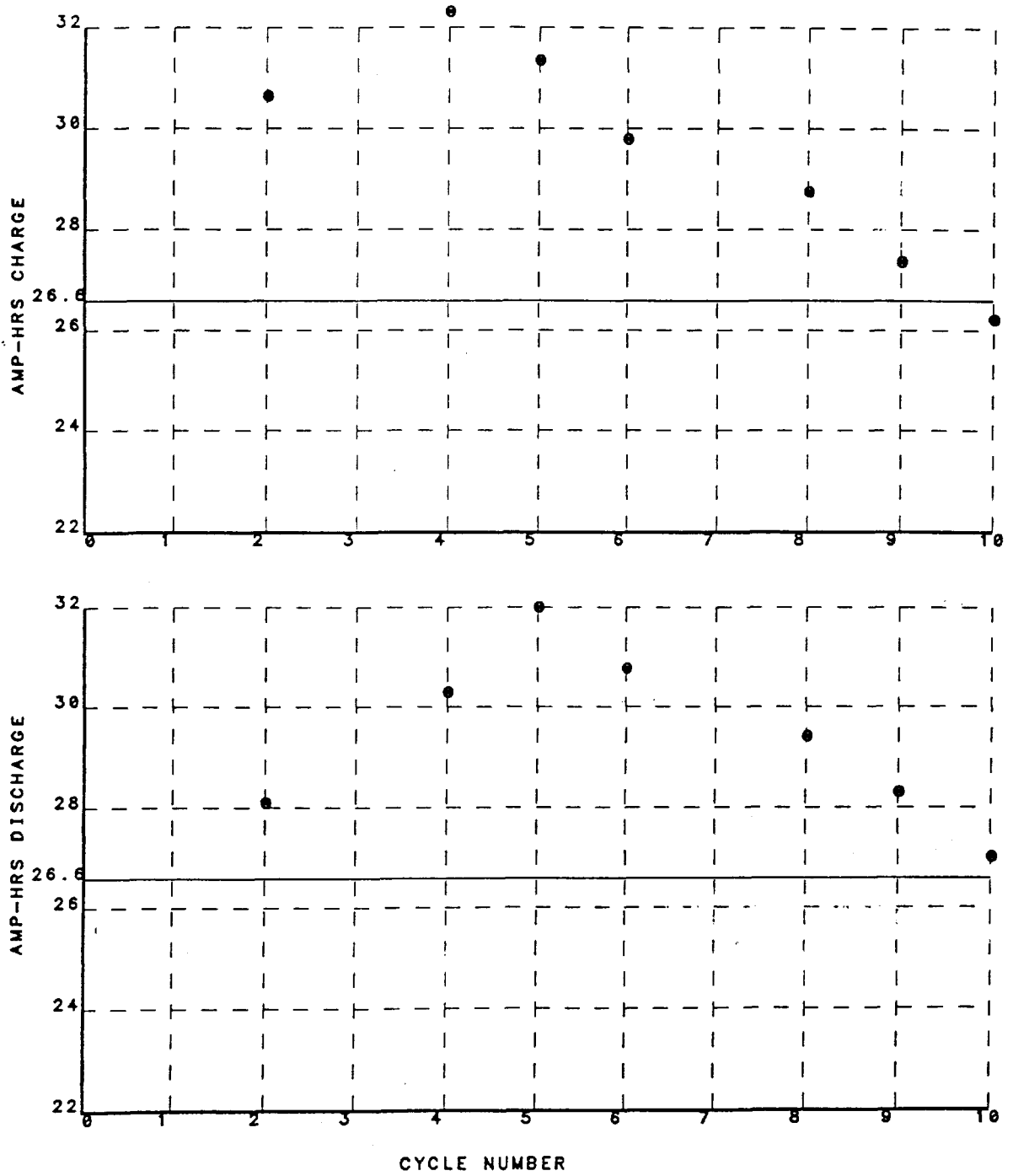
Depth of Discharge: 100%

Test Mgr.: C. M. Wooten

Discharge Current: 3.8 amps

Charge Current: 1.55 amps

Test End Date: 21-Mar-91



N92-22753

NASA Aerospace Battery Workshop 1991

High-Rate Li-MnO<sub>2</sub> 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

TFL 10/91



## 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:

SO<sub>2</sub>Cl<sub>2</sub>  
SOCl<sub>2</sub>  
SO<sub>2</sub>  
Lithium- (CF<sub>x</sub>)<sub>n</sub>  
CuO  
MnO<sub>2</sub>

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:

SOCl<sub>2</sub>  
SO<sub>2</sub>  
Lithium- (CF<sub>x</sub>)<sub>n</sub>  
MnO<sub>2</sub>

This resulted in the decision in 1982 to adopt the Li-MnO<sub>2</sub> 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-MnO<sub>2</sub>, such as high energy density, long shelf life, insignificant voltage delay and environmental safety, HOPPECKE succeeded in the development of high-rate Li-MnO<sub>2</sub> 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-MnO<sub>2</sub> 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 hermitically 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  $MnO_2$  (CMD), carbon and binder is pressed onto a metal grid. Very good electrochemical efficiencies of  $MnO_2$  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 ( $\text{LiClO}_4$ ). 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 halide, 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-MnO<sub>2</sub> cells compared to standard SO<sub>2</sub> 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 MnO<sub>2</sub> 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-MnO<sub>2</sub> cells for aerospace use

The high performance results and the safe electrochemical behaviour of the Li-MnO<sub>2</sub> 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.

#### Fig. 6

As a further extension of this technology, HOPPECKE is currently developing a 200 Ah high-rate Li-MnO<sub>2</sub> 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

Fig. 10 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 behaviour 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 behaviour 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 unexplainable behaviour of the cells was observed. This supports our view that Li-MnO<sub>2</sub> technology gives one of the safest lithium systems currently available.

## 6. Conclusion

- The electrochemical couple Li-MnO<sub>2</sub> is suitable for high rate applications
- HOPPECKE Li-MnO<sub>2</sub> 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-MnO<sub>2</sub> cells and batteries meet and often considerably exceed most military requirements
- First applications of HOPPECKE Li-MnO<sub>2</sub> technology in space missions already have been successful and the Li-MnO<sub>2</sub> system is a promising candidate for future space applications

Structure of a HOPPECKE LSC cell  
in coil type construction  
Schematic illustration

Fig. 1

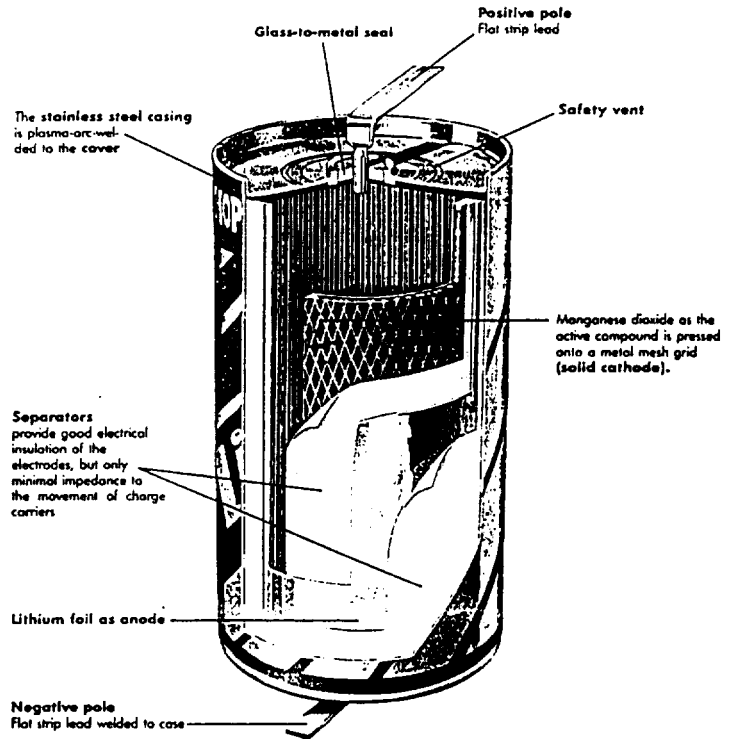


Fig. 2

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

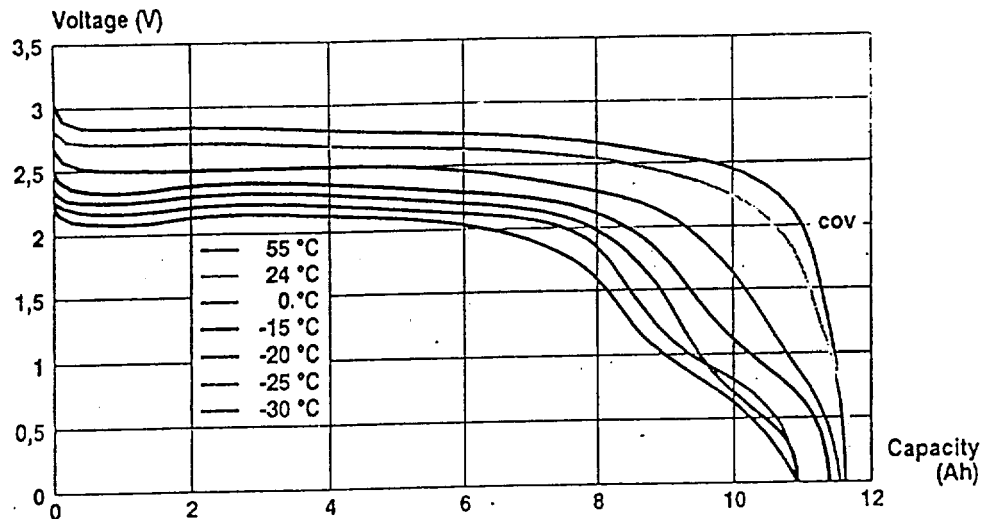


Fig. 3

LSC 3460 M: Performance and pulse response after 2 years storage at ambient conditions discharge current 2A at -30 °C

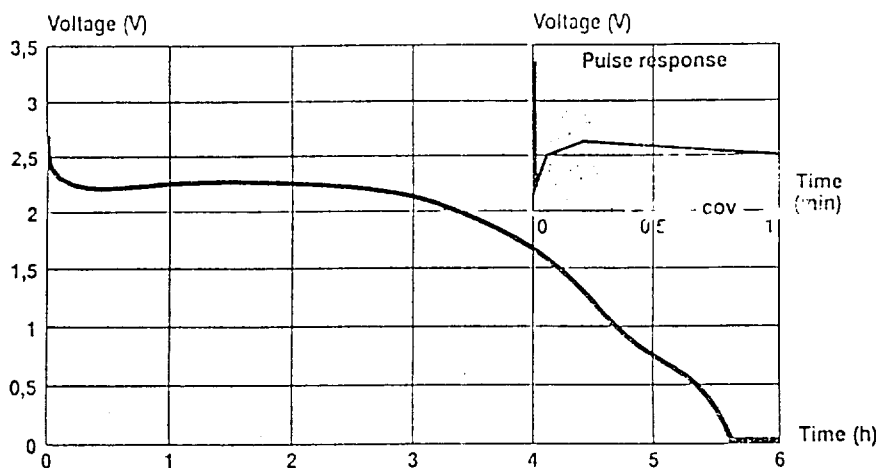


Fig. 4

Comparison of Li-MnO<sub>2</sub>-D-cells and Li-SO<sub>2</sub>-D-cells

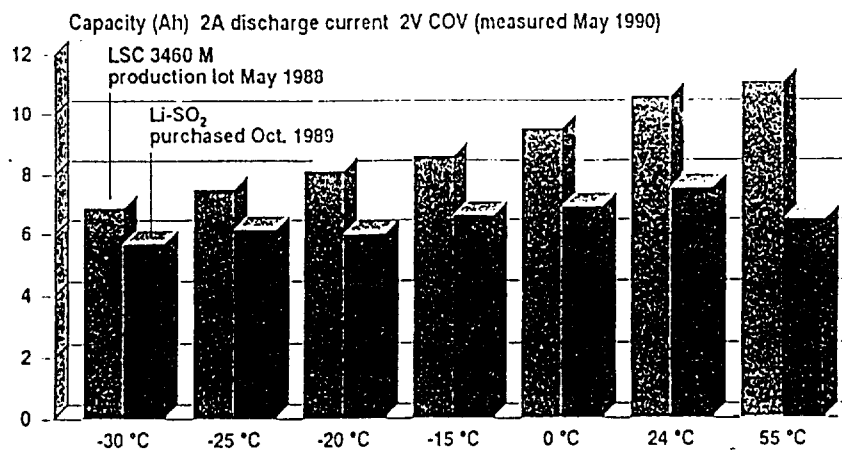


Fig. 5

LSC 3460 M  
Discharge and reverse discharge

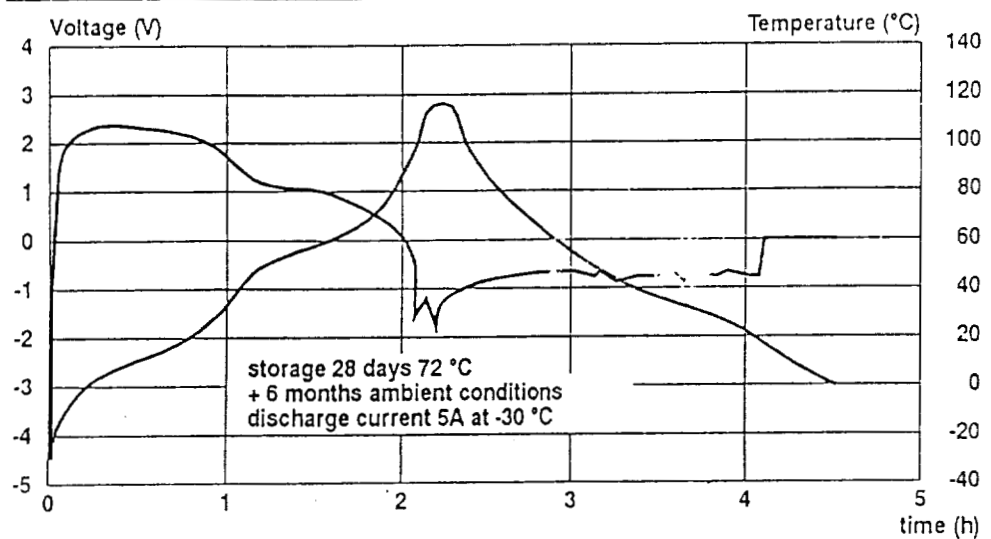
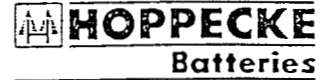


Fig. 6 HOPPECKE LSC cells in space applications

Mission	Application	Battery Systems	Approval status of Batteries
MIR 91	goggles experiment	14 V, 10 Ah and 5,6 V, 10 Ah	approved by ESA passed all mechanical tests
MIR 92	portable calculator	14 V, 4.5 Ah	concept approved by ESA delivered for mechanical testing
Cosmos 10	project biobox	28 V, 80 Ah	approval in process at ESA
Texus 23	microgravity experiment	30.8 V, 10 Ah	successful flight in Nov. 1989
MIR 92	video recorder supply	14 V, 20 Ah	delivered for prototype experiments in Feb. 1991
Cosmos 10	microgravity experiment	22.4 V, 4.5 Ah and 11.2 V, 10 Ah	will be delivered for prototype experiments in Nov. 1991

Fig. 7

200 Ah Li-MnO<sub>2</sub> - cell

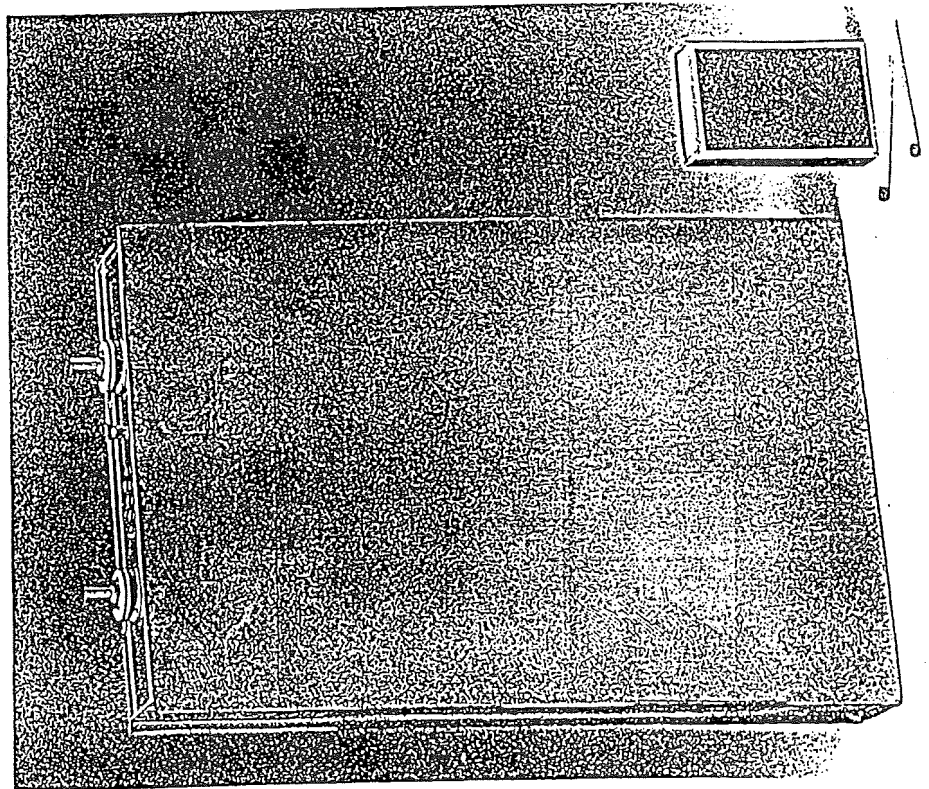


Fig. 8

200 Ah Li-MnO<sub>2</sub> - cell  
Cell cover with vent

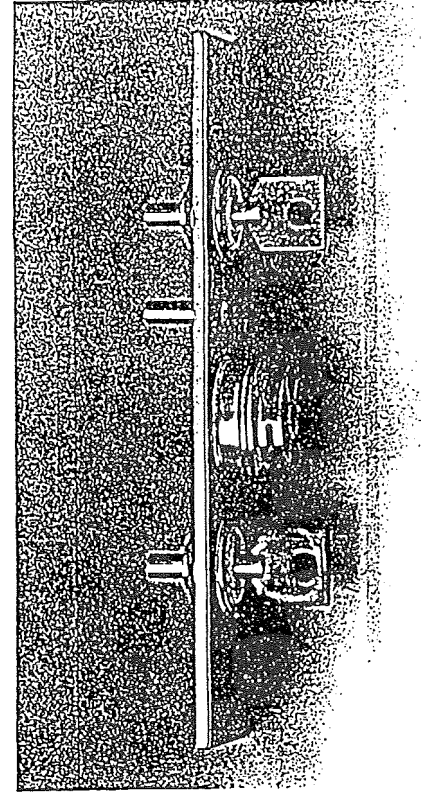
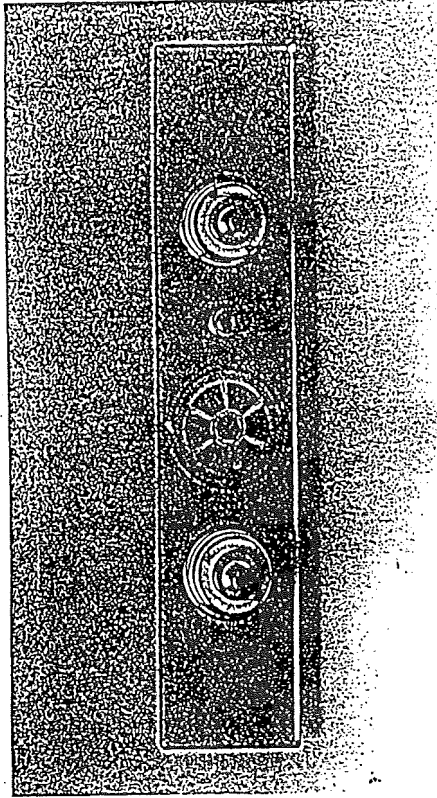
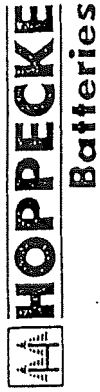


Fig. 9

200 Ah Li-MnO<sub>2</sub> - cell  
Discharge 40 A at room temperature

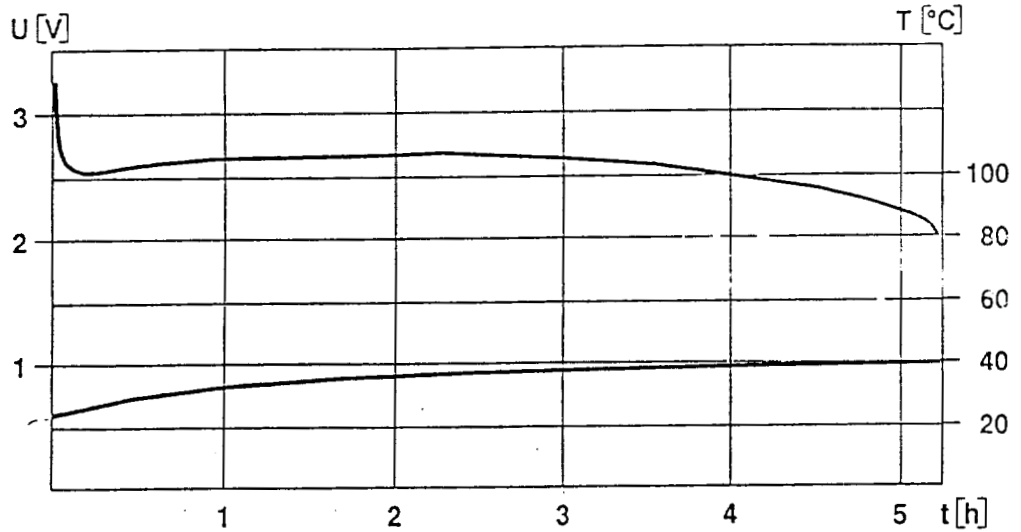


Fig. 10

200 Ah Li-MnO<sub>2</sub> - cell  
Discharge test under thermal  
worst case conditions

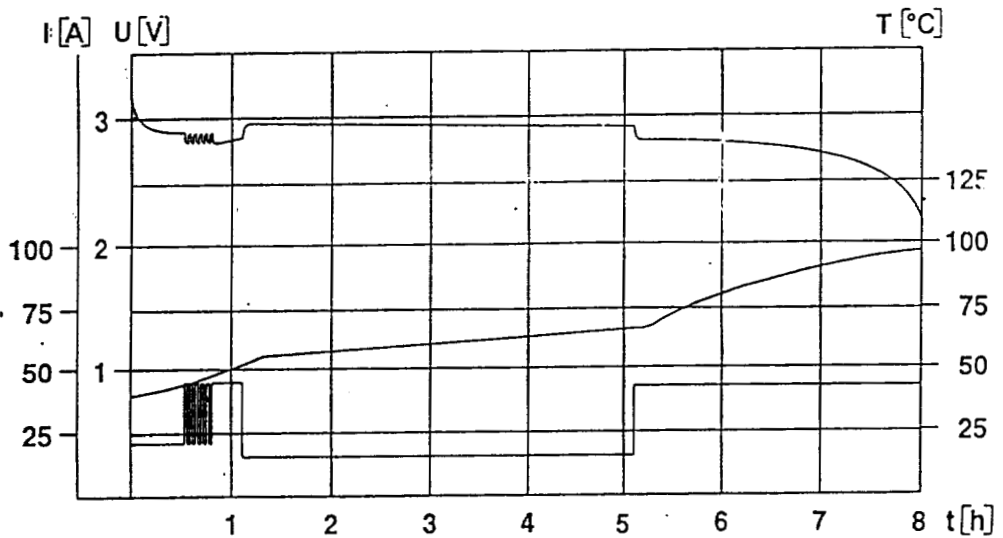
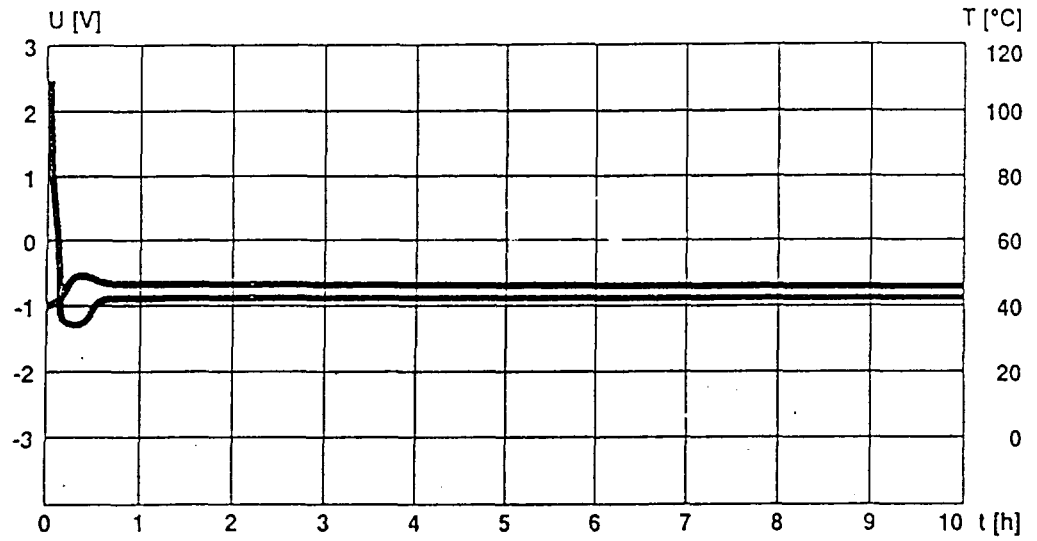


Fig. 11

200 Ah Li-MnO<sub>2</sub>- cell  
Overdischarge test at 40 °C  
I=20 A







CALORIMETRIC EVALUATION OF  
250 AHR Li/SOCl2 CELLS



STEPHEN F. DAWSON

JET PROPULSION LABORATORY,  
CALIFORNIA INSTITUTE OF TECHNOLOGY  
PASADENA, CALIFORNIA

ERIC DARCY

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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**OVERVIEW**

**CENTAUR 250 AHf Li/SOCl<sub>2</sub> 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**

**BATTERY SYSTEMS GROUP**

**OBJECTIVE**

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

**EXPERIMENTAL DESCRIPTION**

**HEAT GENERATION RATES FOR FULL SIZE 250 AH CENTAUR CELLS WERE MEASURED IN A HEAT 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 LiAlCl<sub>4</sub>/SOCl<sub>2</sub>**

**BINDER: BINDER PERCENTAGE (3.5 TO 6.5 %)**

**ELECTROLYTE ADDITIVE: PVC**

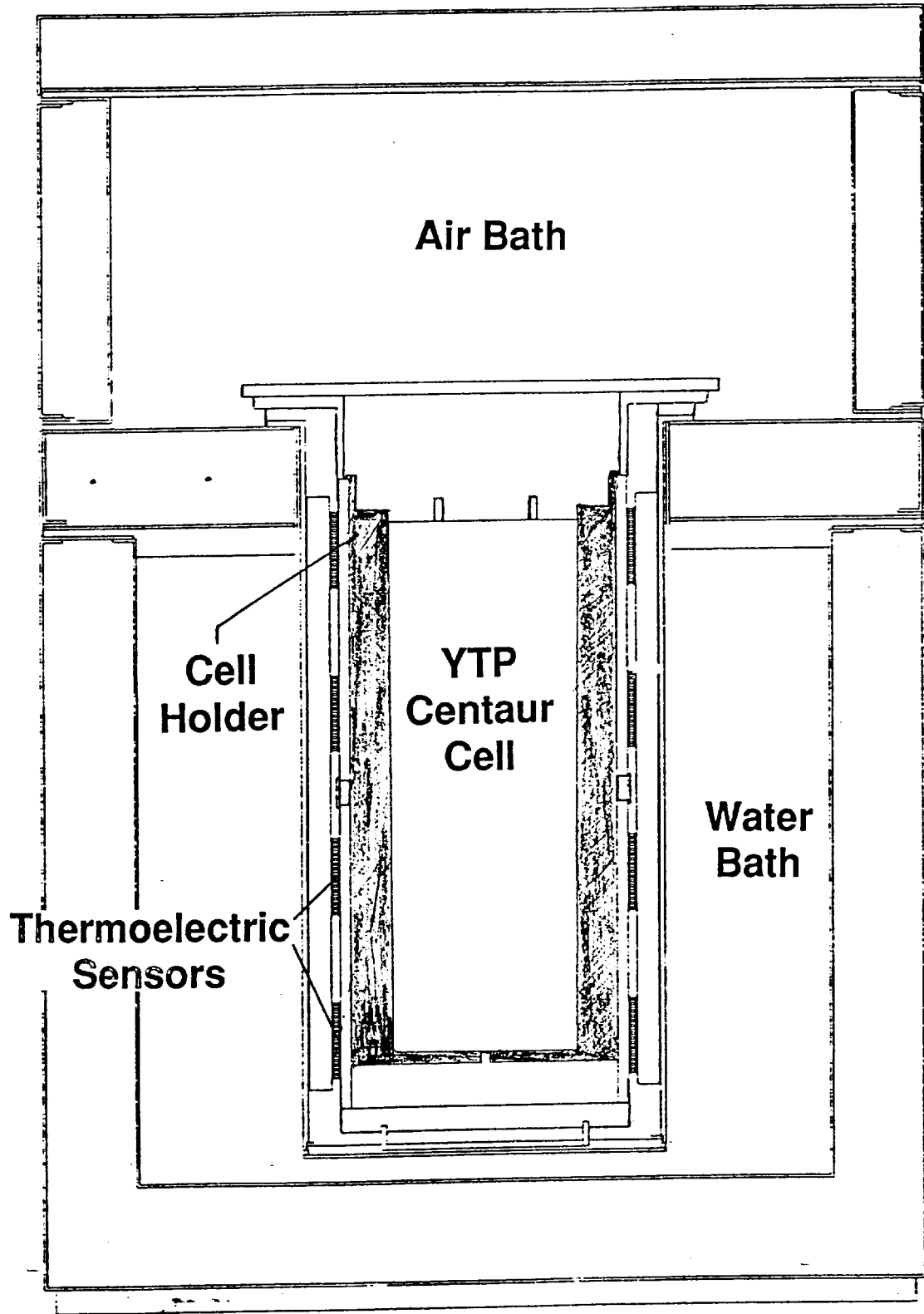
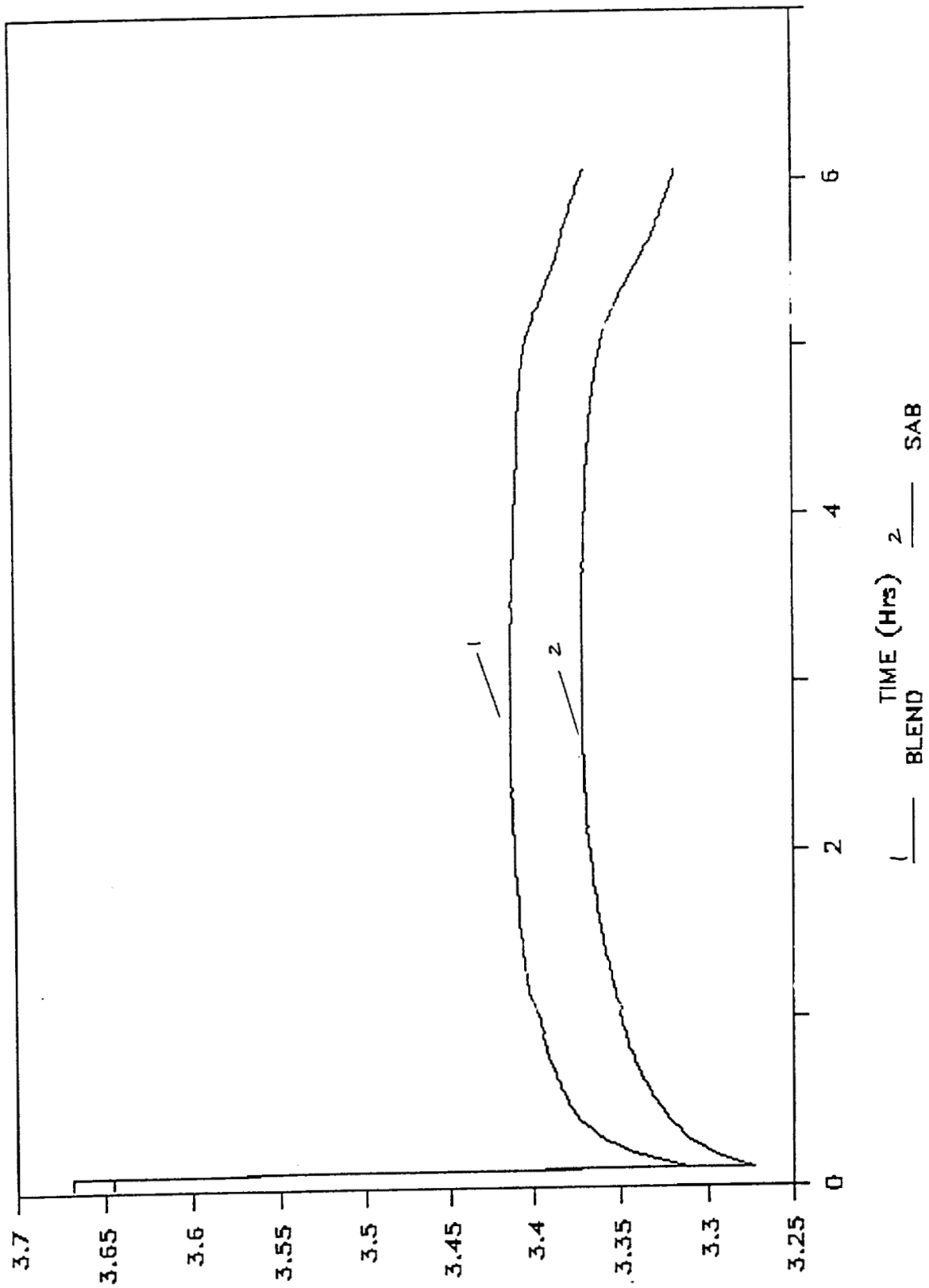


Fig. 1. Schematic of the cell in an aluminum cell holder in the calorimeter.

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  $\pm 0.005$  °C.

# VOLTAGE PERFORMANCE

SAB vs BLEND 250 AHrs 40 C



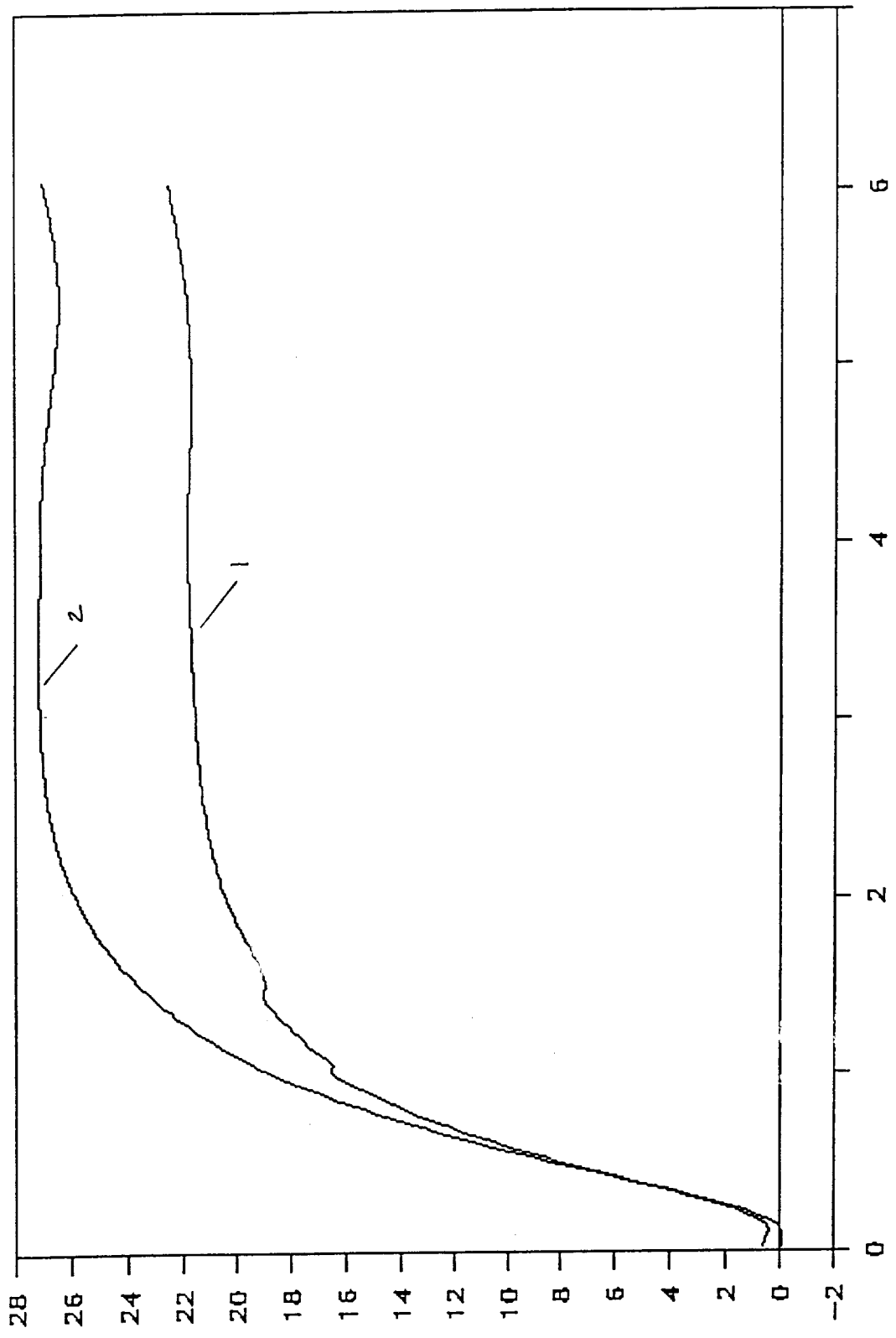
**JPL**

DISCHARGE PERFORMANCE OF STANDARD CARBON AND BLENDED CARBON ELECTRODES AT 40 C AND 42 AMP CONSTANT CURRENT TO 250 AH IS GIVEN. THE BLENDED CARBON ELECTRODE CELL SHOWS HIGHER VOLTAGE PERFORMANCE THROUGHOUT THE DISCHARGE.



# HEAT GENERATION

SAB vs BLEND 250 AHrs 40 C



1 — BLEND 2 — SAB

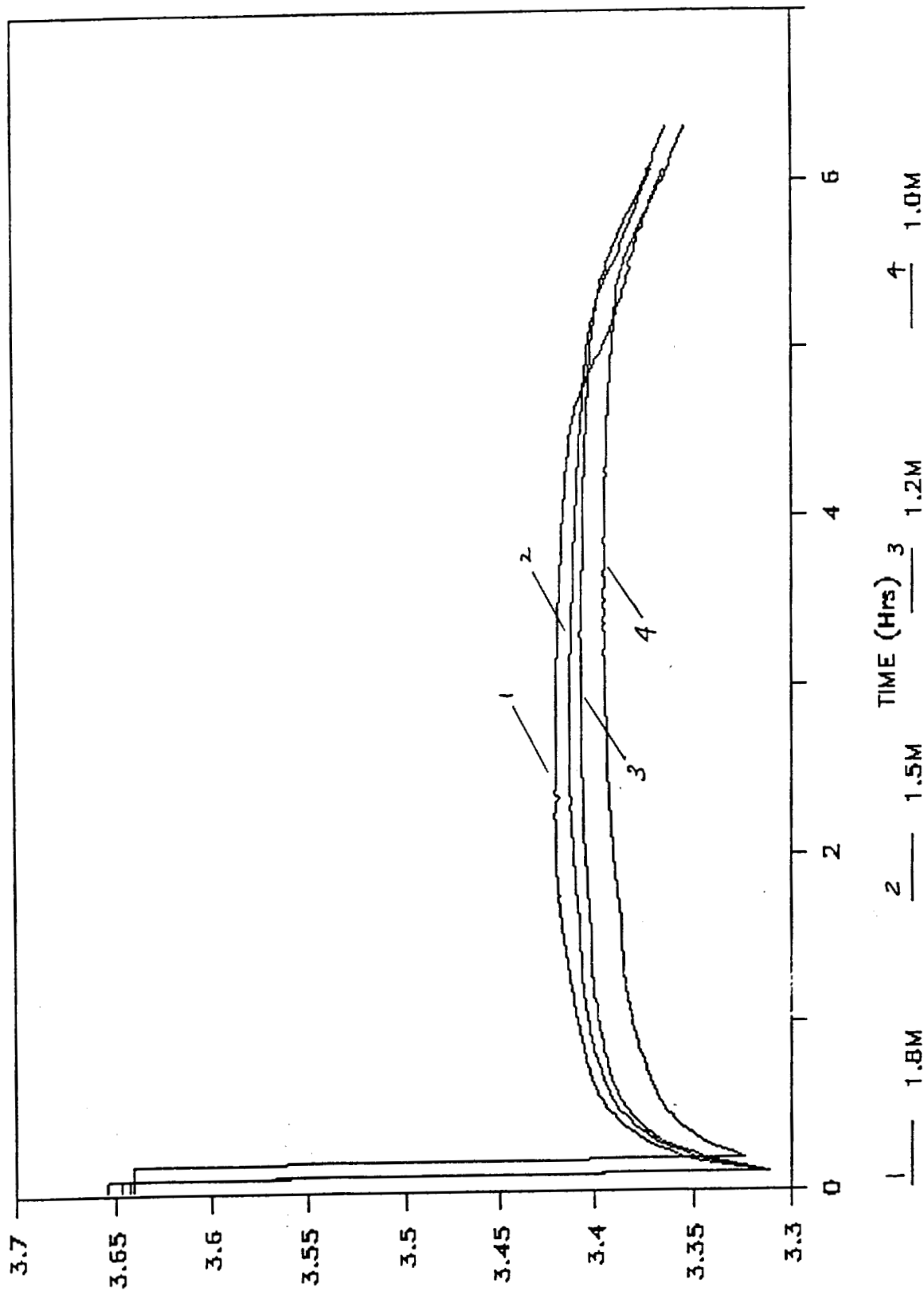
WATTS

**JPL**

HEAT GENERATION RATES ARE DISPLAYED FOR STANDARD AND BLENDED CARBON ELECTRODE CELLS. HIGHER HEAT GENERATION IS OBSERVED FOR THE STANDARD SAB CELLS.

# VOLTAGE PERFORMANCE

1.0-1.8M LIAICI4/SOCI2 250 AHrs 40 C

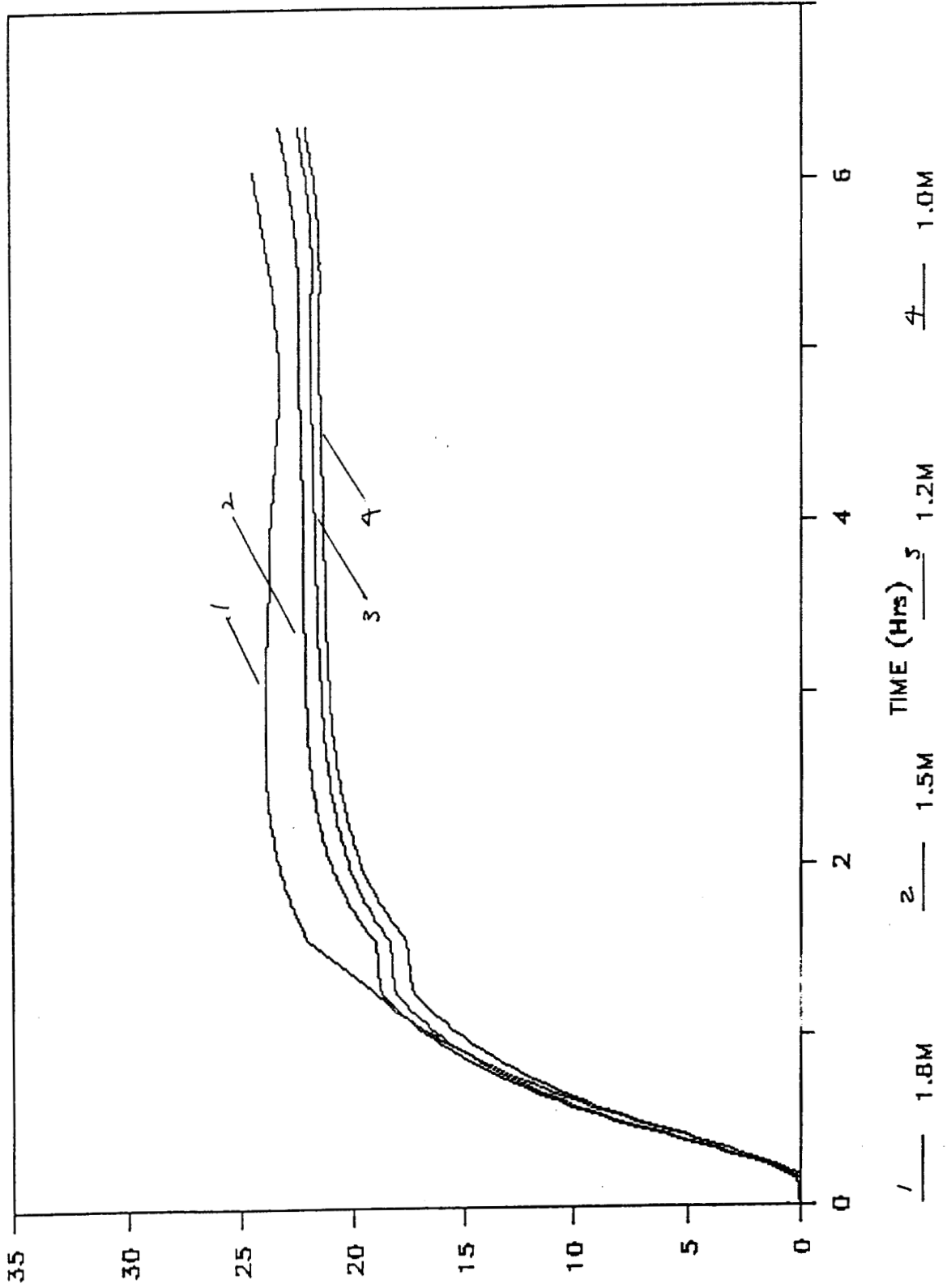


VOLTS

**JPL**

VOLTAGE PERFORMANCE THROUGH 250 AHIS FOR CELLS WITH ELECTROLYTE SALT CONCENTRATION FROM 1.0 TO 1.8 M  $\text{LiAlCl}_4/\text{SOCl}_2$  SHOW INCREASING VOLTAGE PERFORMANCE WITH INCREASING SALT CONCENTRATION.

HEAT GENERATION  
1.0-1.8M LAICI4/SOCI2 250 AHrs 40 C



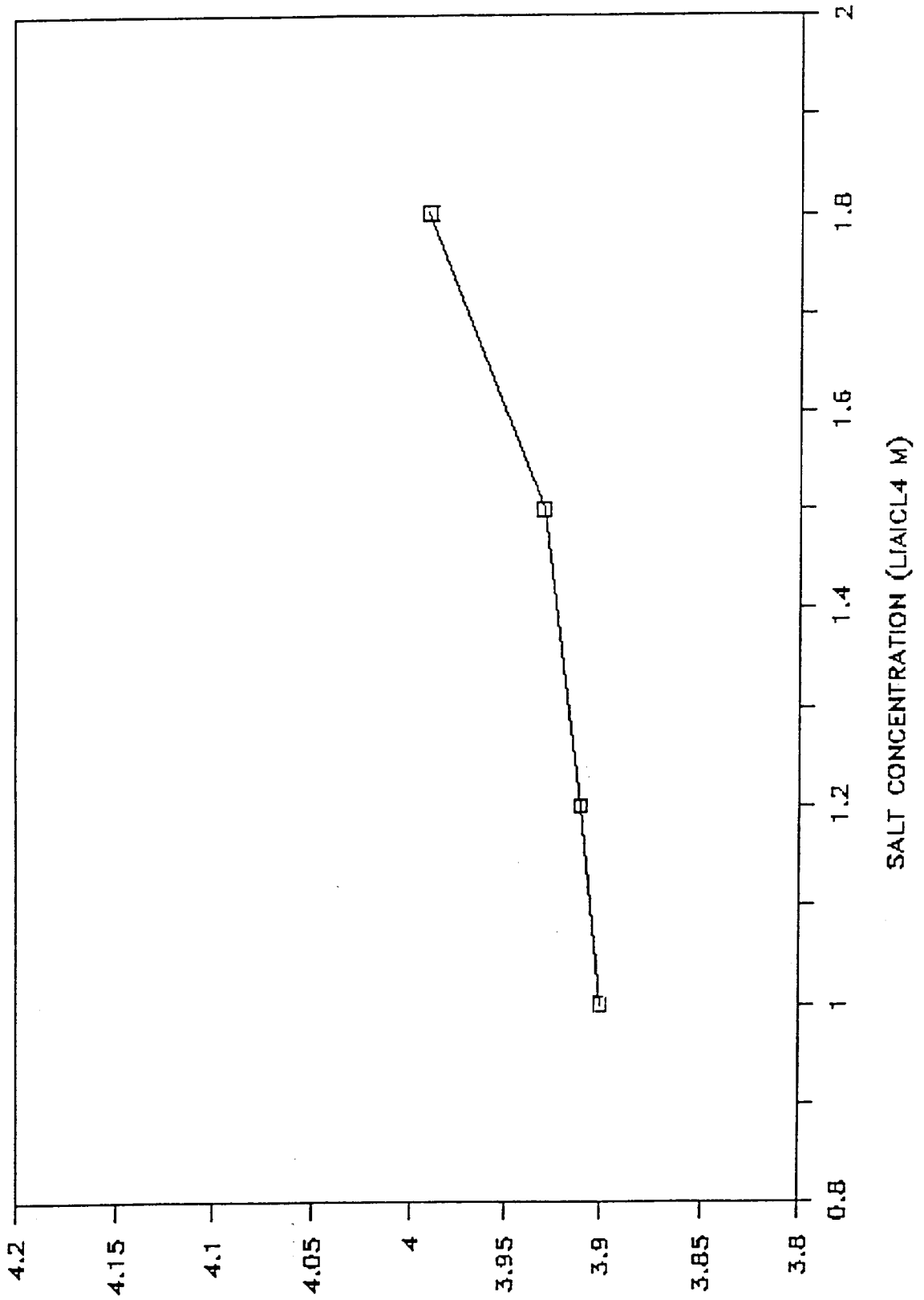
WATTS

**JPL**

HEAT GENERATION RATES INCREASE WITH HIGHER SALT CONCENTRATION.

# EFFECTIVE THERMAL POTENTIAL

1.0-1.8 Molar LiAlCl<sub>4</sub>/SOCl<sub>2</sub> 40 C



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:

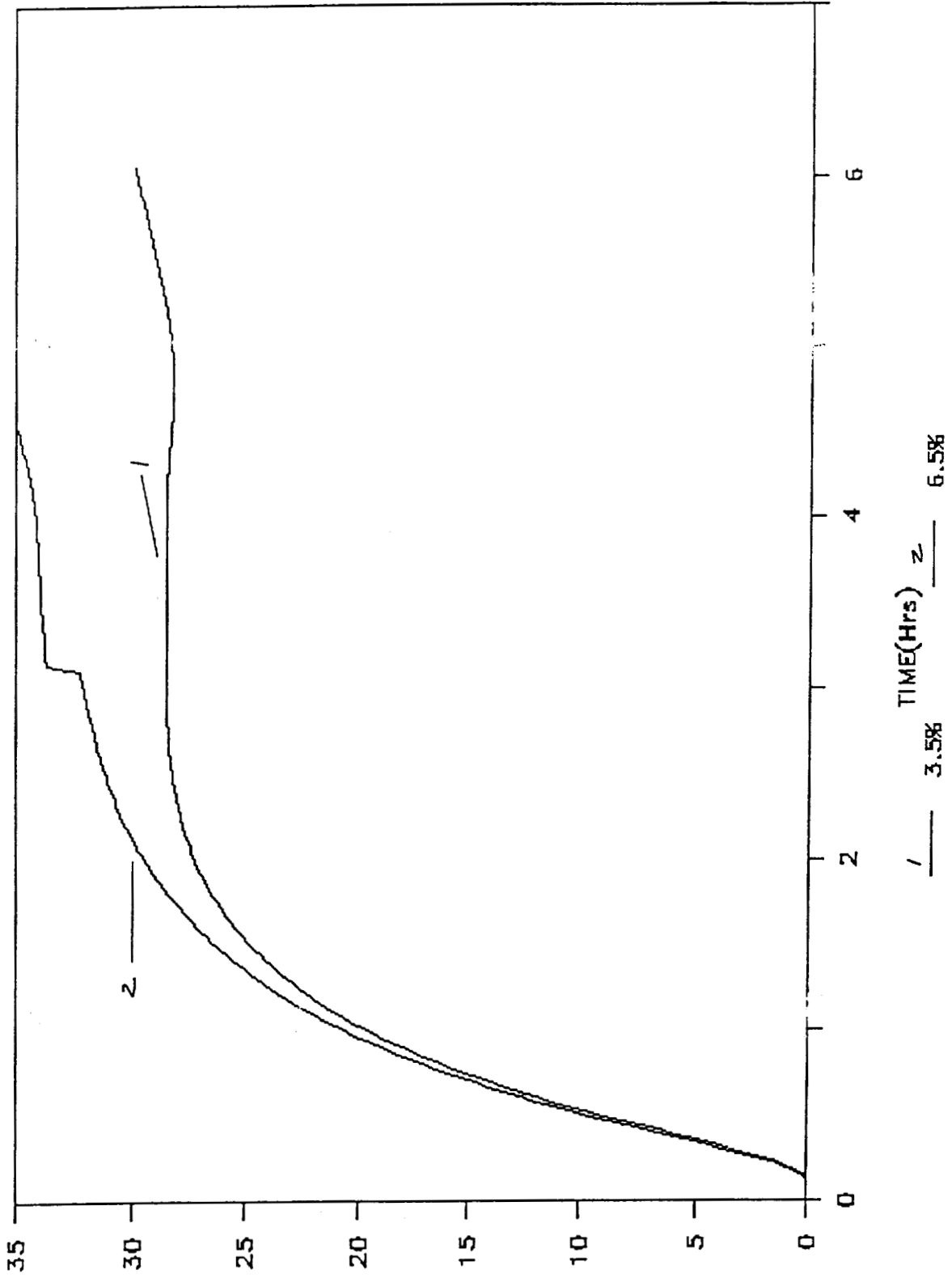
$$ETP = q / I + V_L$$

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

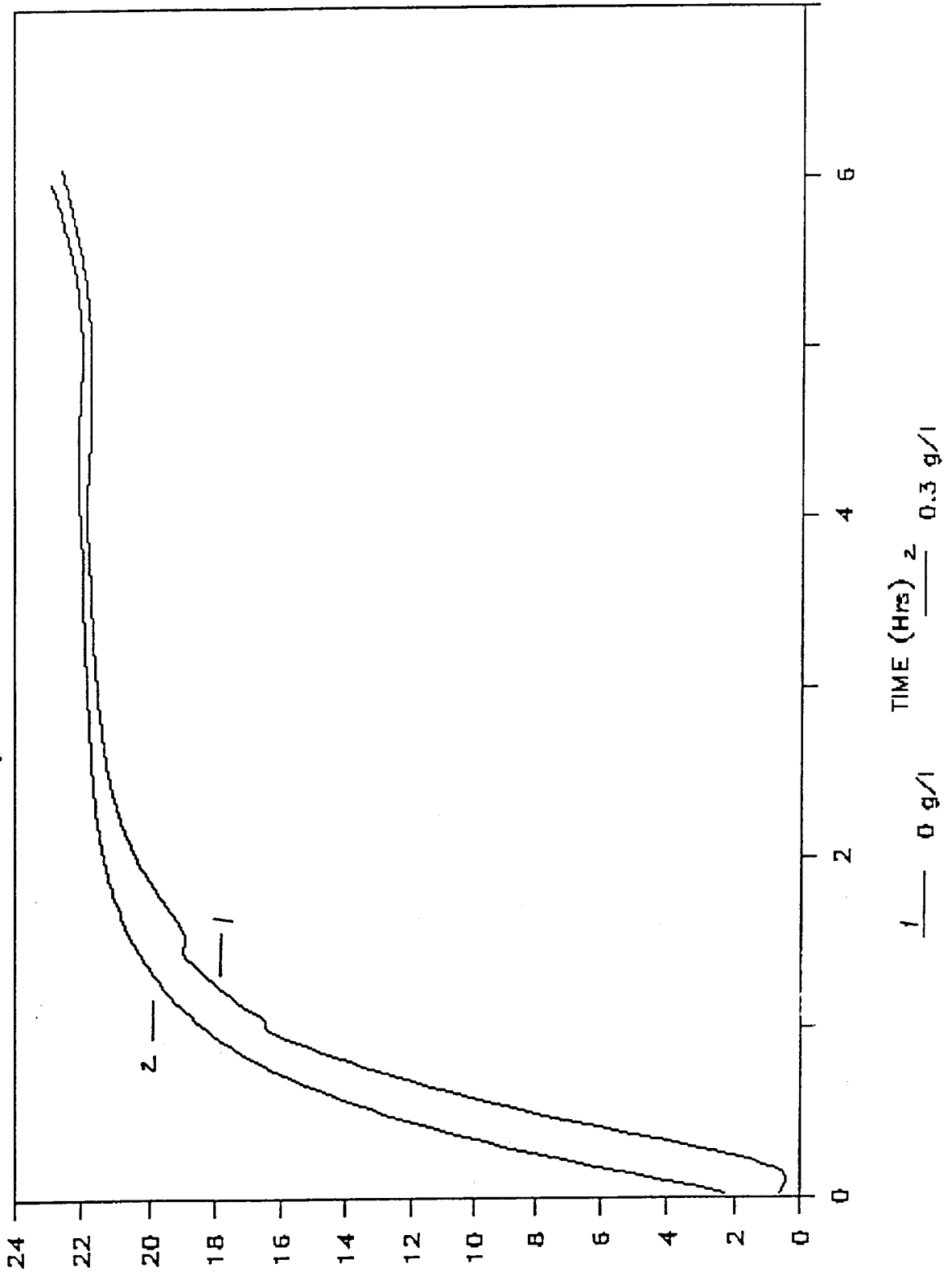


WATTS

**JPL**

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.

HEAT GENERATION  
0-0.3 g/l PVC 250 AHrs 40 C



WATTS

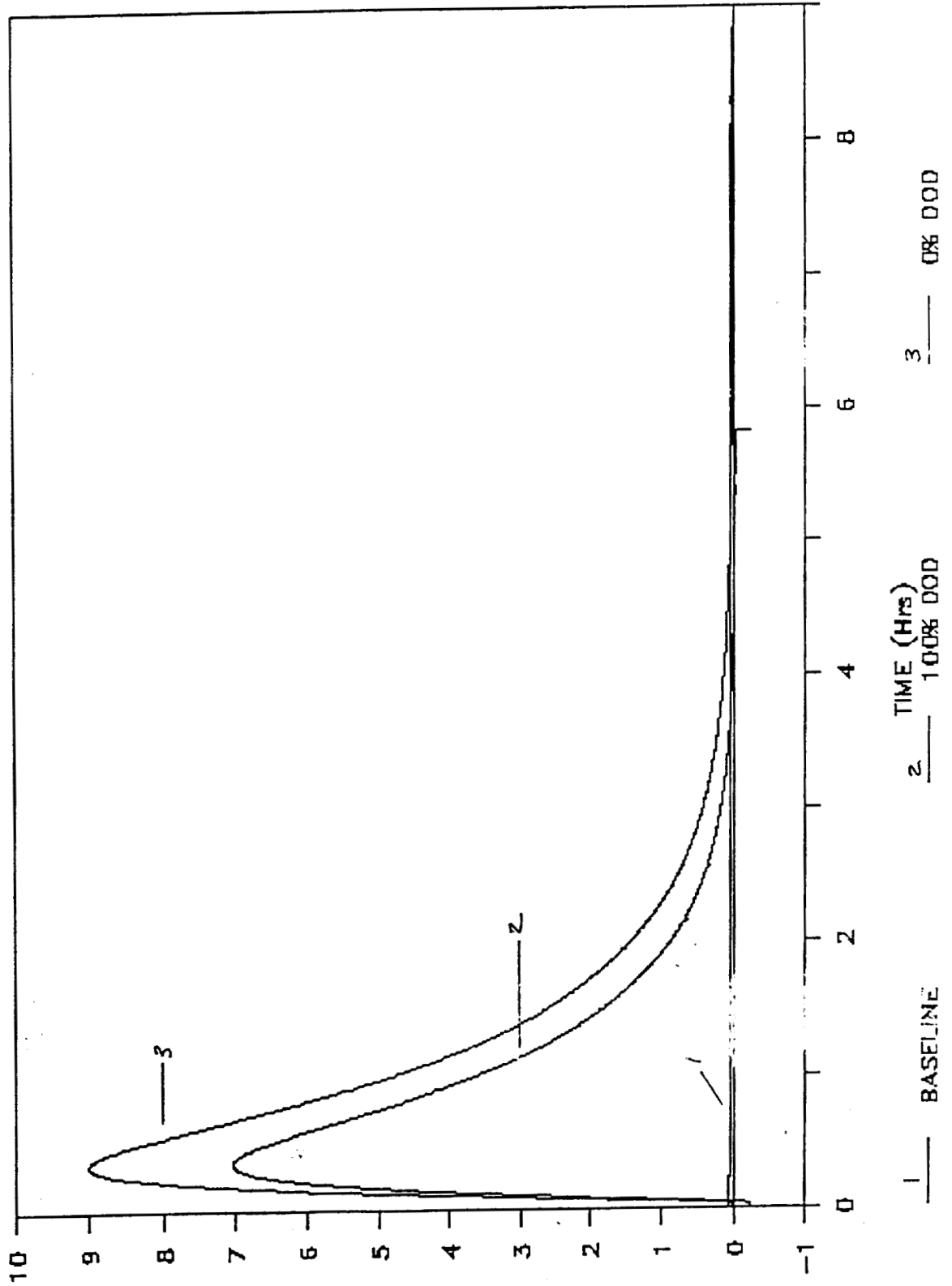
**JPL**

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INCREASED HEAT GENERATION IS OBSERVED FOR CELL CONTAINING 0.3 g/1 PVC OVER CELL WITHOUT PVC WHEN DISCHARGED WITH LITTLE OR NO STORAGE.

# HEAT CAPACITY

0-100% DOD, 40-25 C DROP



WATTS

**JPL**

HEAT CAPACITY FOR FRESH AND COMPLETELY DISCHARGED CELLS (315+ AHI) SHOW A 10% DROP  
IN THE  $C_p$  OF THE DISCHARGE CELL.

## CONCLUSION

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

DECREASING  $\text{LiAlCl}_4$  IN  $\text{SOCl}_2$  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.



Johnson Space Center - Houston, Texas

**Propulsion and Power Division**

**Bragg / Johnson**

**10/29/91**

# **Preliminary Test Results for Li-SOCl<sub>2</sub> High-Rate "D" Cells**

by

**B.J. Bragg**

and

**Paul Johnson**

**NASA Johnson Space Center**

**N 9 2 - 2 2 7 5 5**





<b>Propulsion and Power Division</b>	
<b>Bragg / Johnson</b>	<b>10/29/91</b>

## AGENDA

- Background
- Test Results
  - Weight, OCV, and Load Check
  - Shock Test
  - Vibration Test
  - Capacity Performance
  - Uninsulated Short Circuit
  - High Temperature Exposure
  - Overdischarge
- Conclusions



## Propulsion and Power Division

### Preliminary Test Results for Li-SOCl<sub>2</sub> High-Rate "D" Cells

Bragg / Johnson 10/29/91

#### BACKGROUND

- Objective - Evaluate the performance and abuse characteristics of 55 D-Size lithium-thionyl chloride (Li-SOCl<sub>2</sub>) 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.
  - Electrolyte - 1.8M LiAlCl<sub>4</sub> in SOCl<sub>2</sub> - 44-45 g
- Cells kept in cold storage at NASA-JSC until tested in June 1991.
- 55 cells delivered to JSC
  - 39 used in this test program
  - 14 cells discharged in calorimetry testing
  - 2 held as spares



<b>Preliminary Test Results for Li-SOCl2 High-Rate "D" Cells</b>	<b>Propulsion and Power Division</b>	
	<b>Bragg / Johnson</b>	<b>10/29/91</b>

### 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



<b>Preliminary Test Results for Li-SOCl<sub>2</sub> High-Rate "D" Cells</b>	<b>Propulsion and Power Division</b>	
	<b>Bragg / Johnson</b>	<b>10/29/91</b>

- **Vibration Test (3 Cells)**
- **Random vibration for 15 minutes in each of 3 mutually perpendicular axes according to the following spectrum:**

<u>Frequency (Hz)</u>	<u>Level</u>
20 to 80	+ 3 dB/ octave
80 to 350	0.1 g <sup>2</sup> / Hz
350 to 2000	-3 dB/ octave

- **Results: No change in OCV.**



<b>Preliminary Test Results for Li-SOCl<sub>2</sub> High-Rate "D" Cells</b>	<b>Propulsion and Power Division</b>	
	<b>Bragg / Johnson</b>	<b>10/29/91</b>

• 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

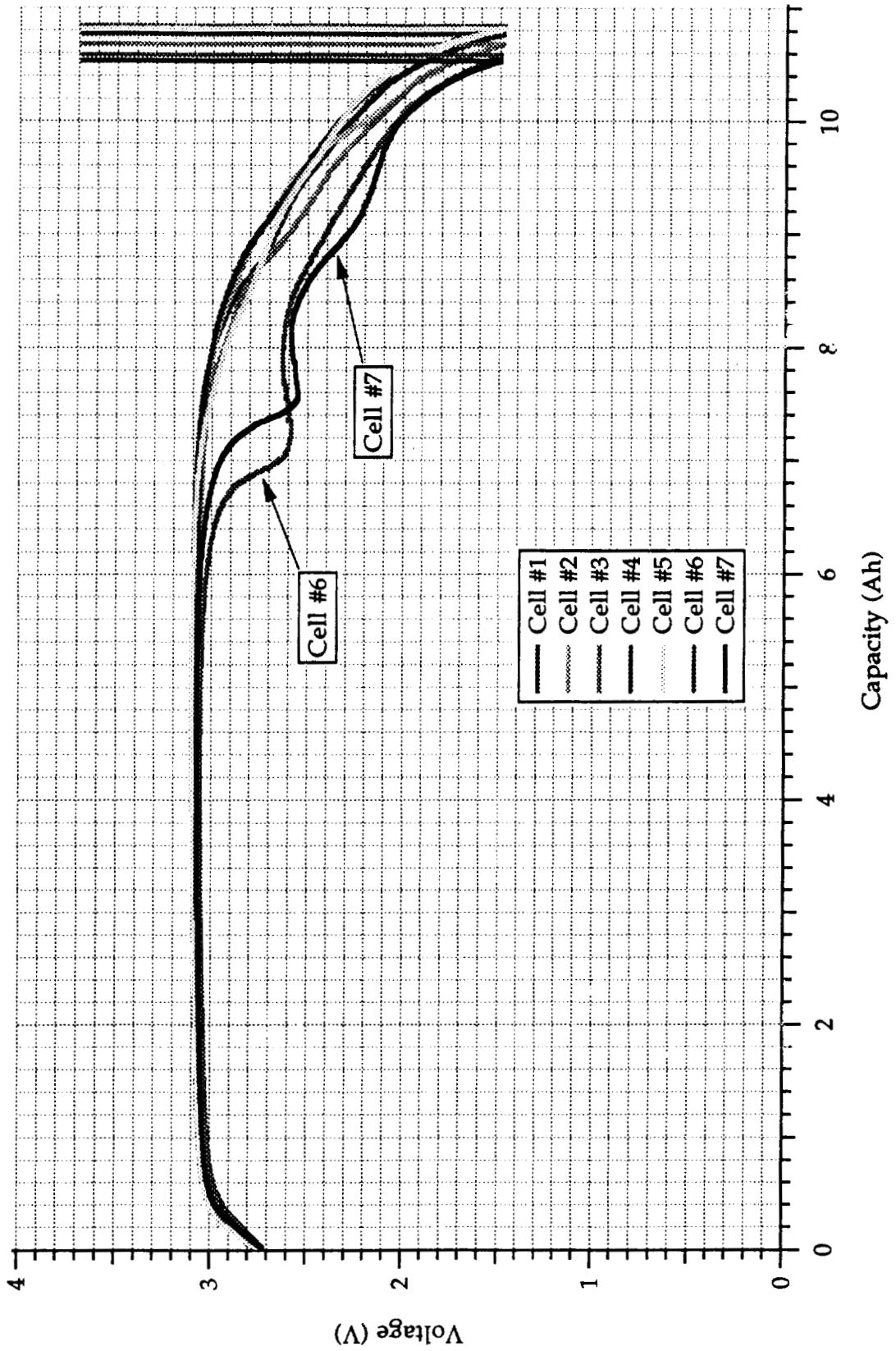
Room Temperature, 2 ohm load

- 11 Cells
- 10.42 - 11.11 Ah
- Avg. 10.7 Ah

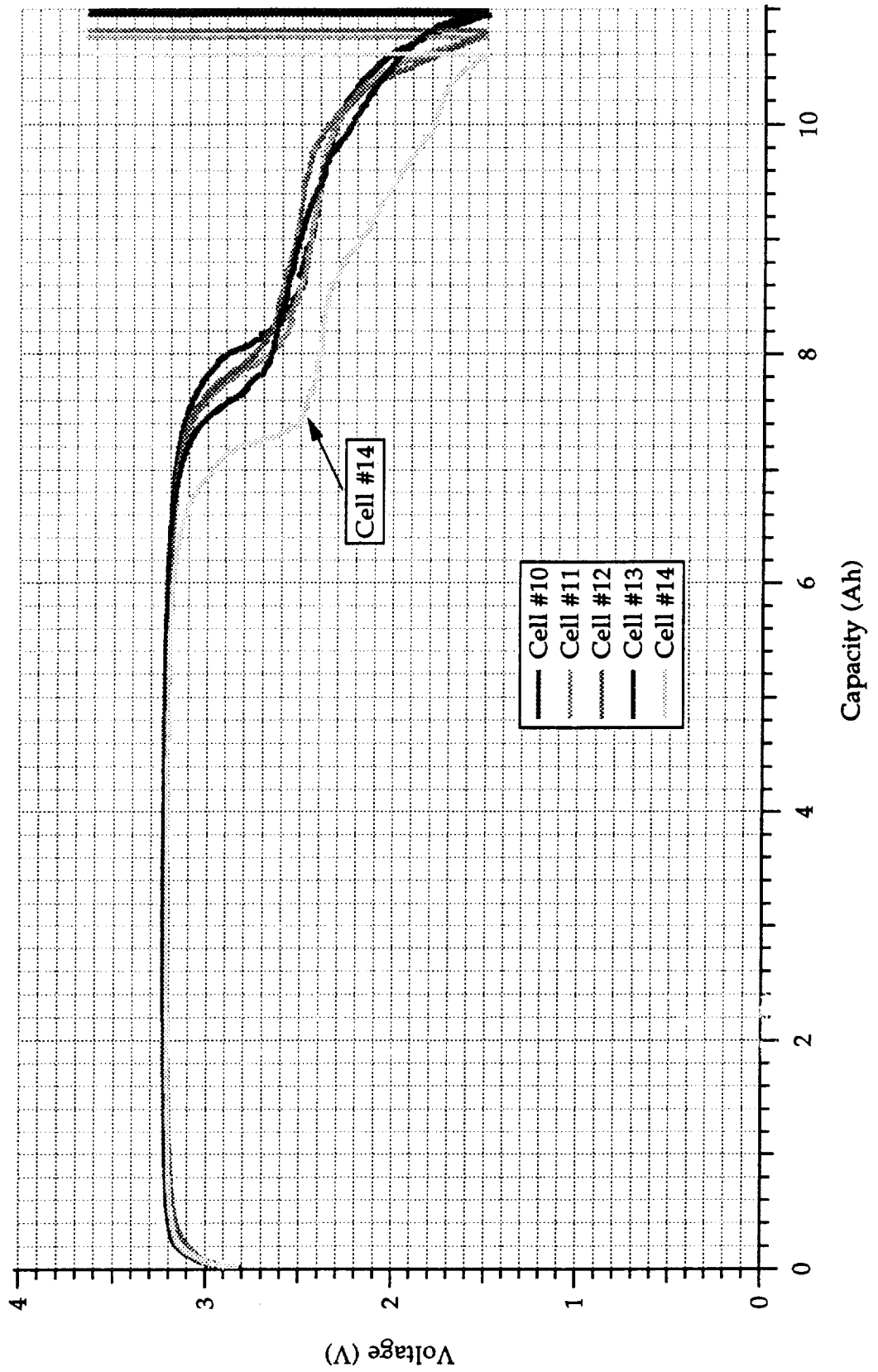
160°F, 2 ohm load

- 4 Cells
- 9.45 - 9.75 Ah
- Avg. 9.61 Ah

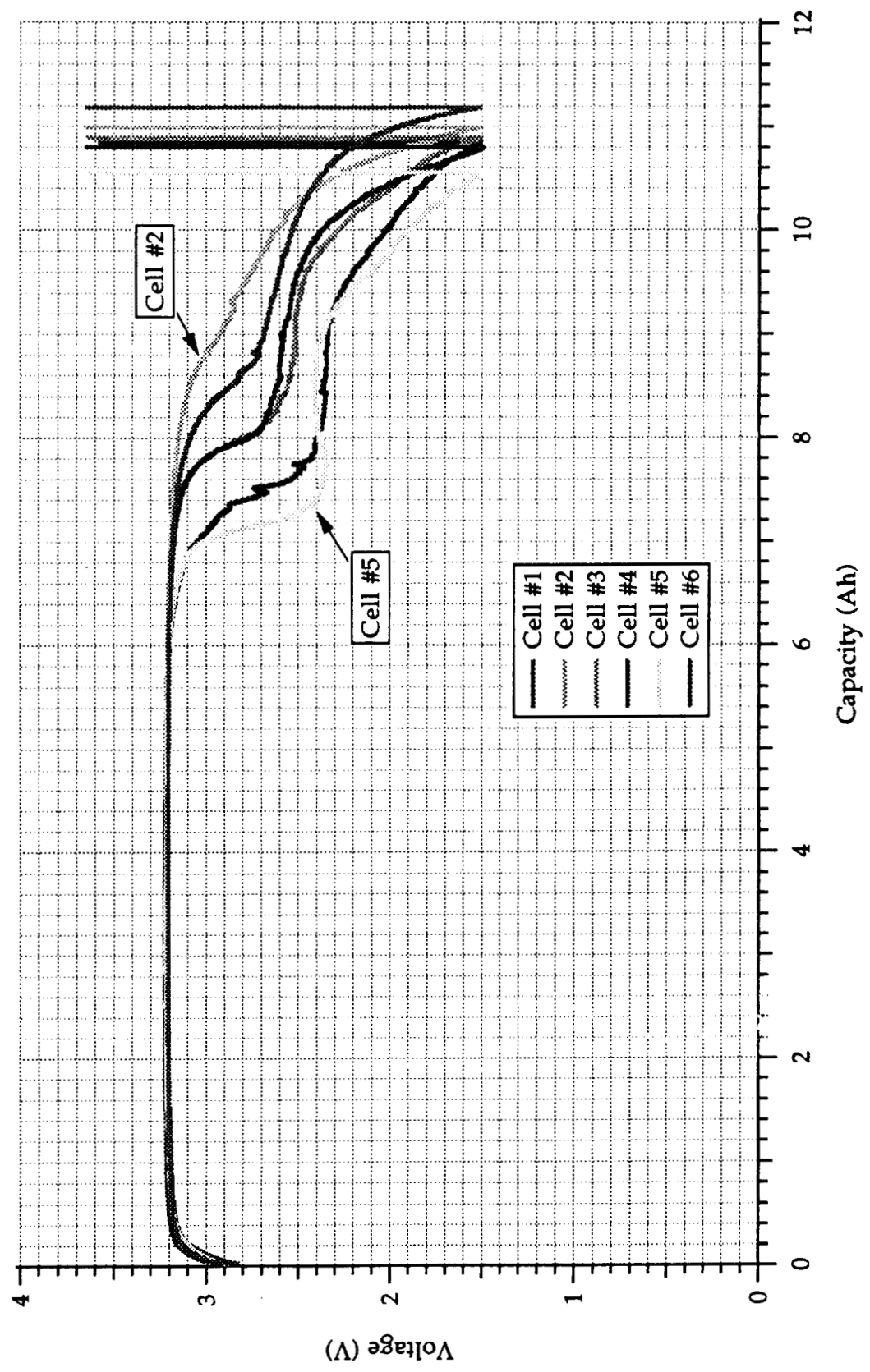
Li-SOCl<sub>2</sub> High Rate "D" Cell  
 One ohm discharge at room temperature to 1.5 volt



Li-SOCl<sub>2</sub> High Rate "D" Cell  
 Two ohm discharge at room temperature to 1.5 volt

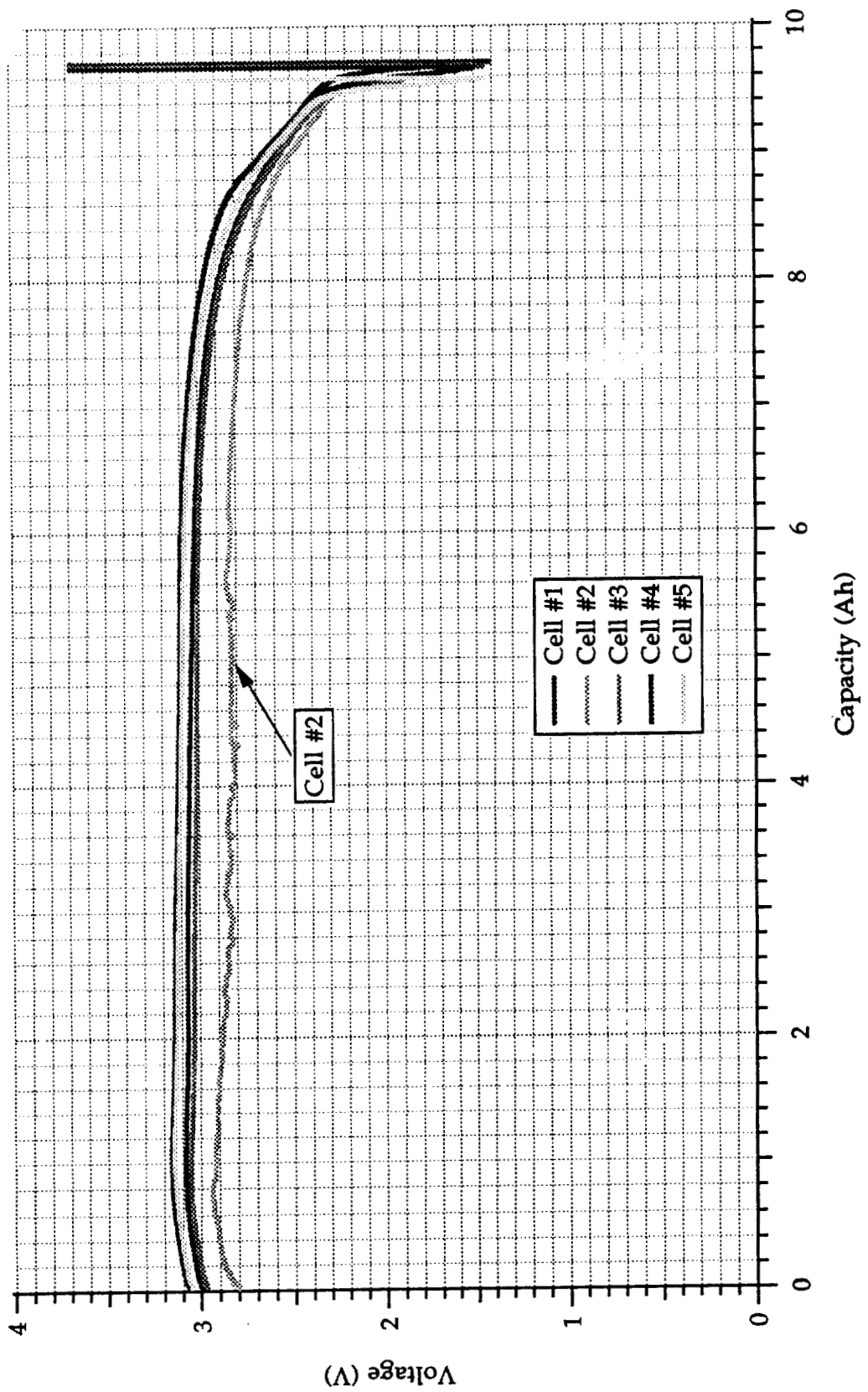


Li-SOCl<sub>2</sub> High Rate "D" Cell  
 Two ohm discharge at room temperature to 1.5 volt



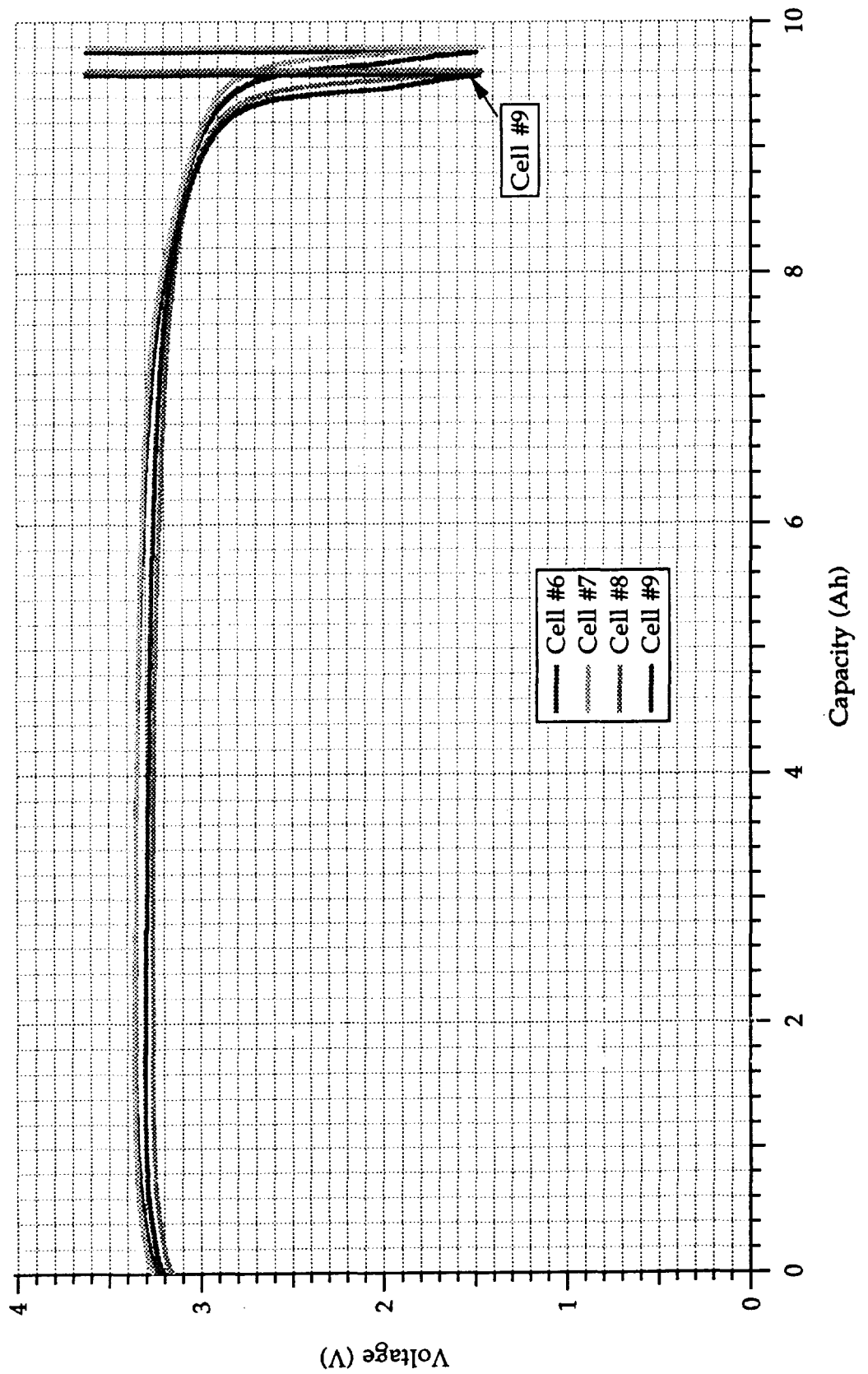


Li-SOCl<sub>2</sub> High Rate "D" Cell  
One ohm discharge at 160°F to 1.5 volt



# Li-SOCl<sub>2</sub> High Rate "D" Cell

Two ohm discharge at 160°F to 1.5 volt

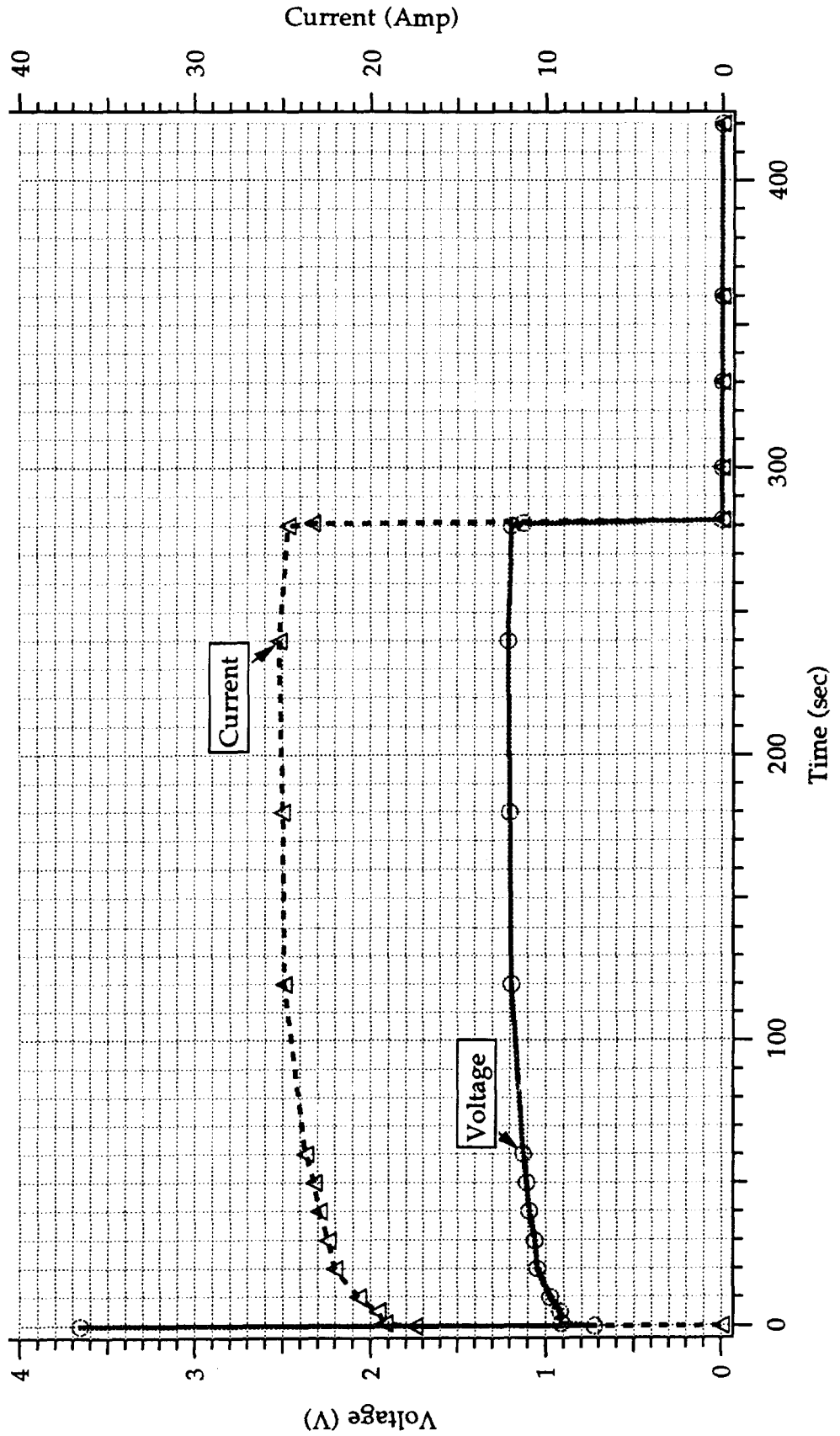




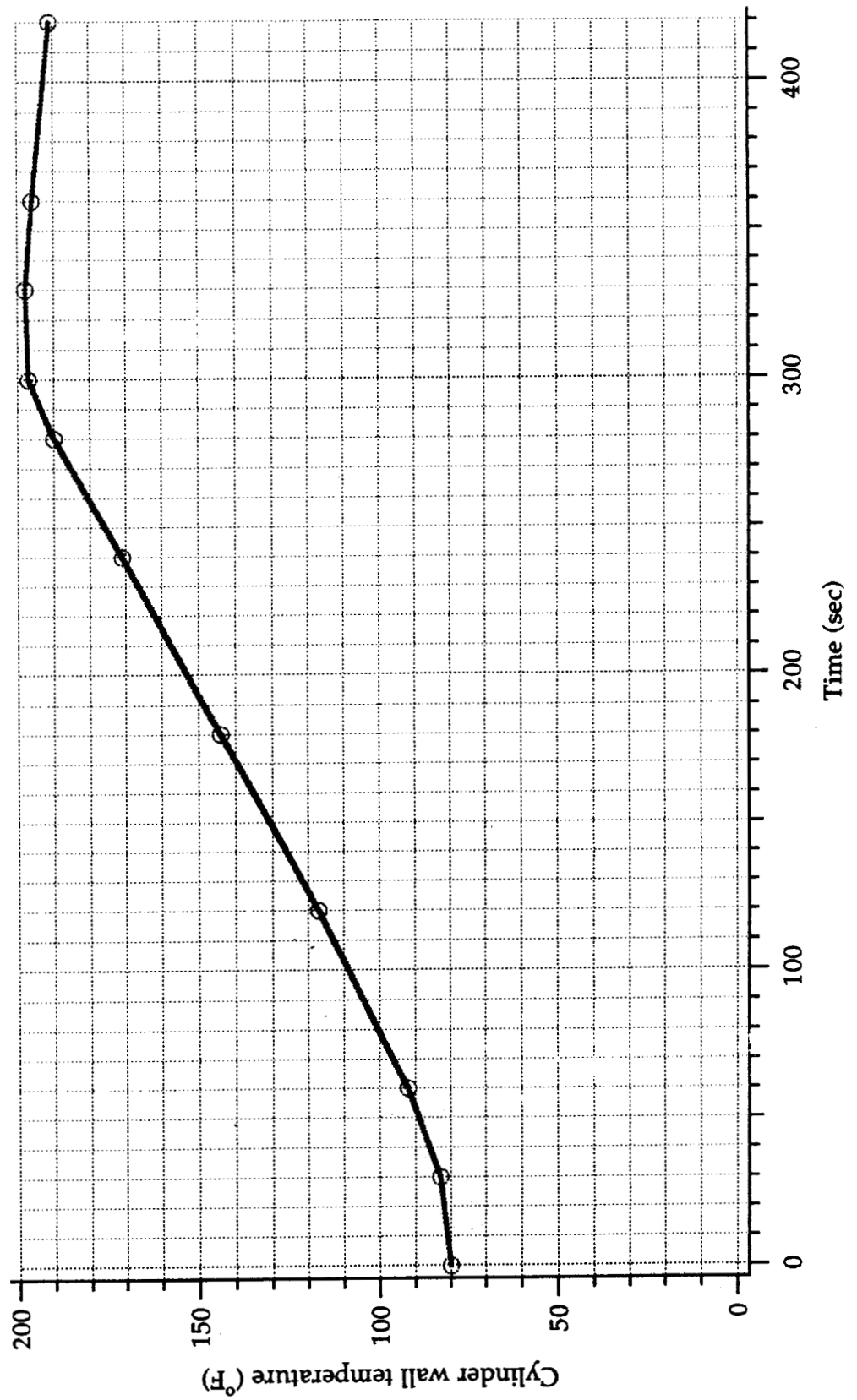
<b>Preliminary Test Results for Li-SOCl<sub>2</sub> High-Rate "D" Cells</b>	<b>Propulsion and Power Division</b>	
	<b>Bragg / Johnson</b>	<b>10/29/91</b>

- **Uninsulated Short Circuit (3 Cells)**
  - **Cell S/N 048396**
    - **Load : .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: .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-SOCl<sub>2</sub> High Rate "D" Cell  
 Uninsulated short circuit test  
 Cell S/N 048422 on 0.12 ohm load



Li-SOCl<sub>2</sub> High Rate "D" Cell  
Uninsulated short circuit test  
Cell S/N 048422 on 0.12 ohm load





<b>Preliminary Test Results for Li-SOCl<sub>2</sub> High-Rate "D" Cells</b>	<b>Propulsion and Power Division</b>
	<b>Bragg / Johnson</b>
	<b>10/29/91</b>

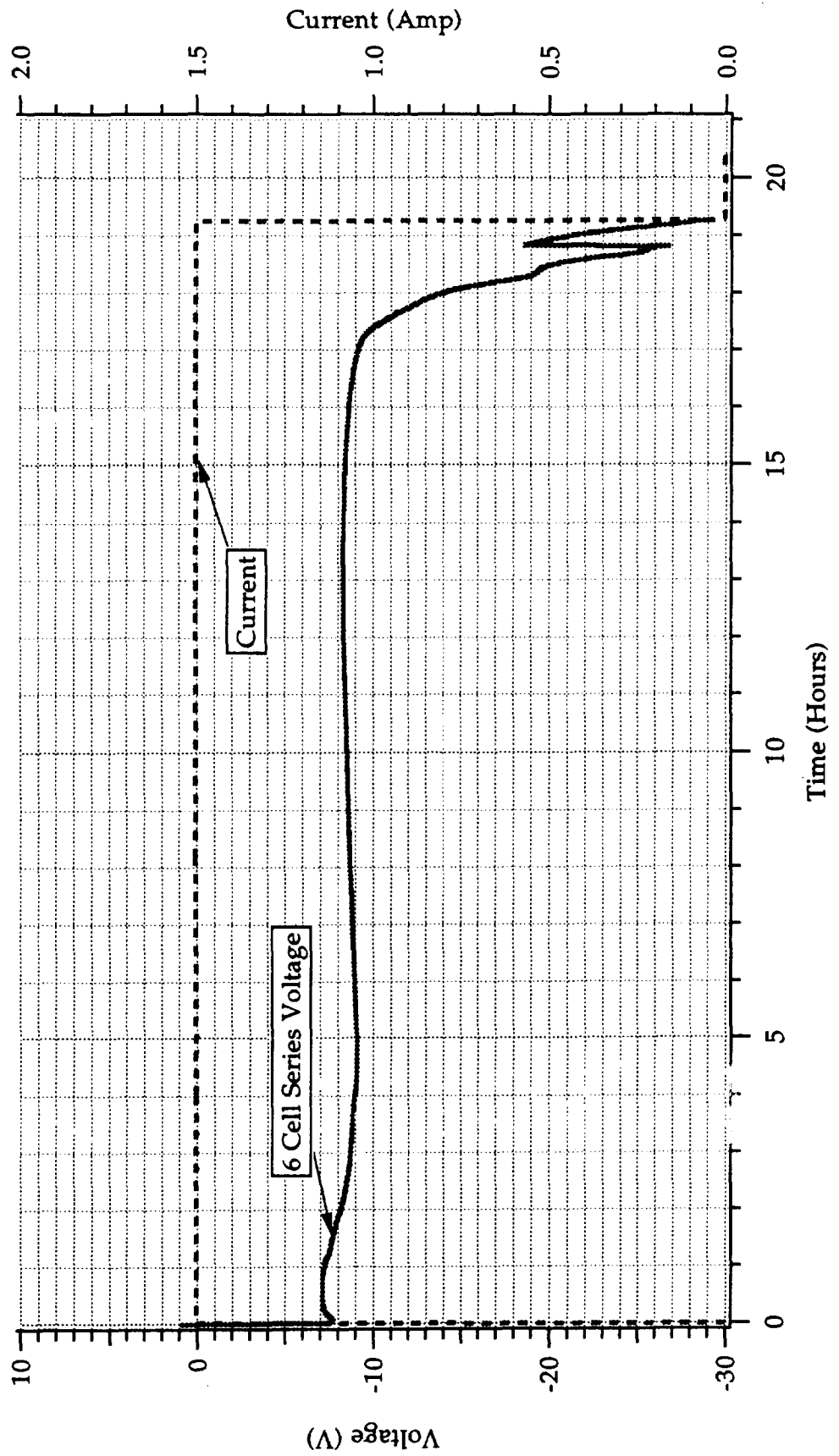
- Cell S/N 048439
  - Load: .120 ohm
  - Maximums: 1.21 VDC, 25 Amp, 130°F
  - Duration: 1 min 43 sec until internal lead fused.
  - Post-test: No OCV
- High Temperature Exposure
  - Cells tested for one hour at 225, 250, 275, and 300°F.
  - No leakage was found on any of the cells one week after high temperature exposure.



<b>Preliminary Test Results for Li-SOCl<sub>2</sub> High-Rate "D" Cells</b>	<b>Propulsion and Power Division</b>	
	<b>Bragg / Johnson</b>	<b>10/29/91</b>

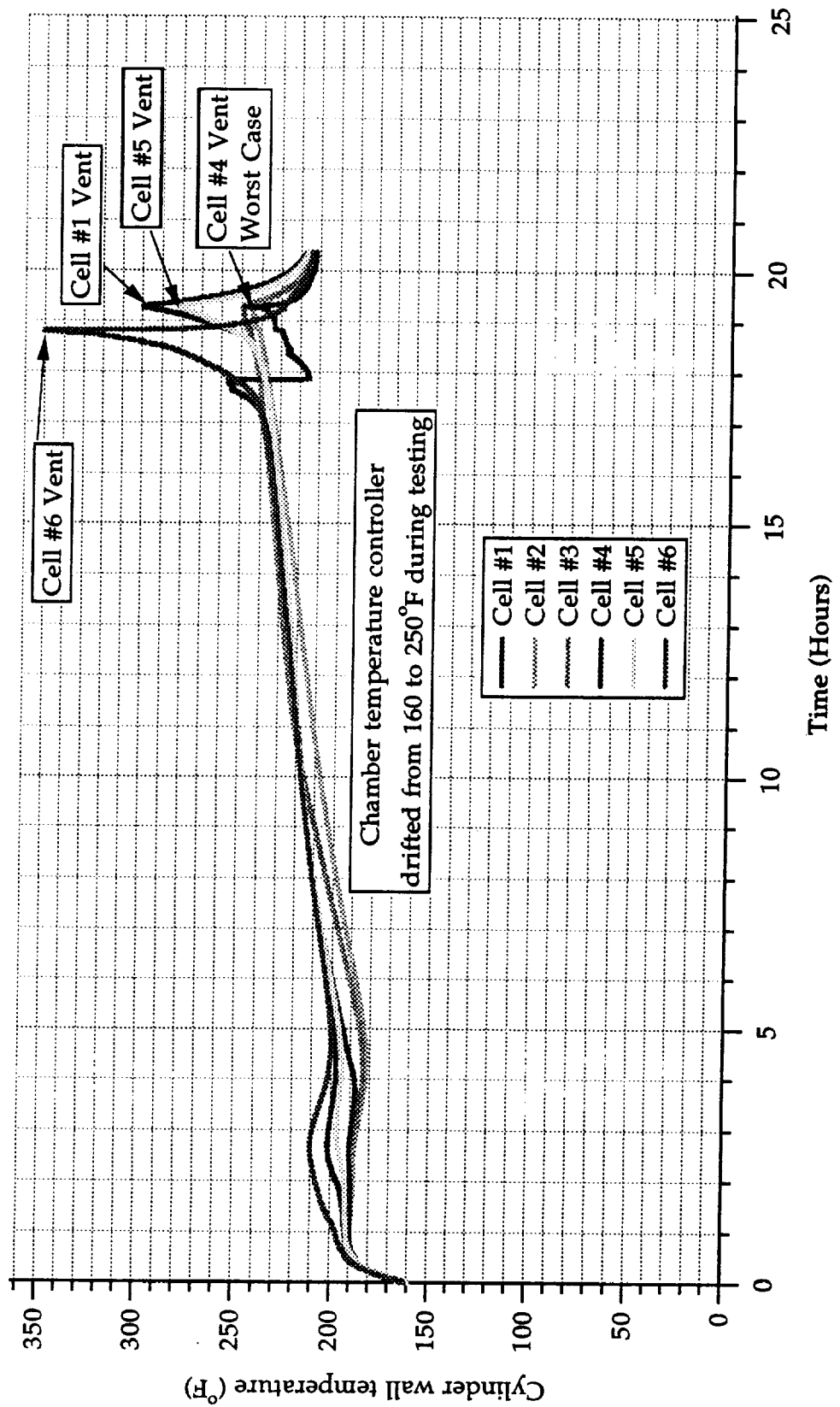
- **Overdischarge; 2 Weeks Post-Discharge (6 Cells)**
  - **With Shunt Diodes**
    - **1.5 A at 160°F**
    - **No cells vented, max temperature 209.4°F**
  - **Without Shunt Diodes**
    - **1.5 A at 160°F to 245°F: Chamber temp. control drifted during test.**
    - **One cell vented at 19 hours and 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-SOCl<sub>2</sub> High Rate "D" Cell  
Two week post-discharge overdischarge without shunt diodes  
1.5 A at 160°F

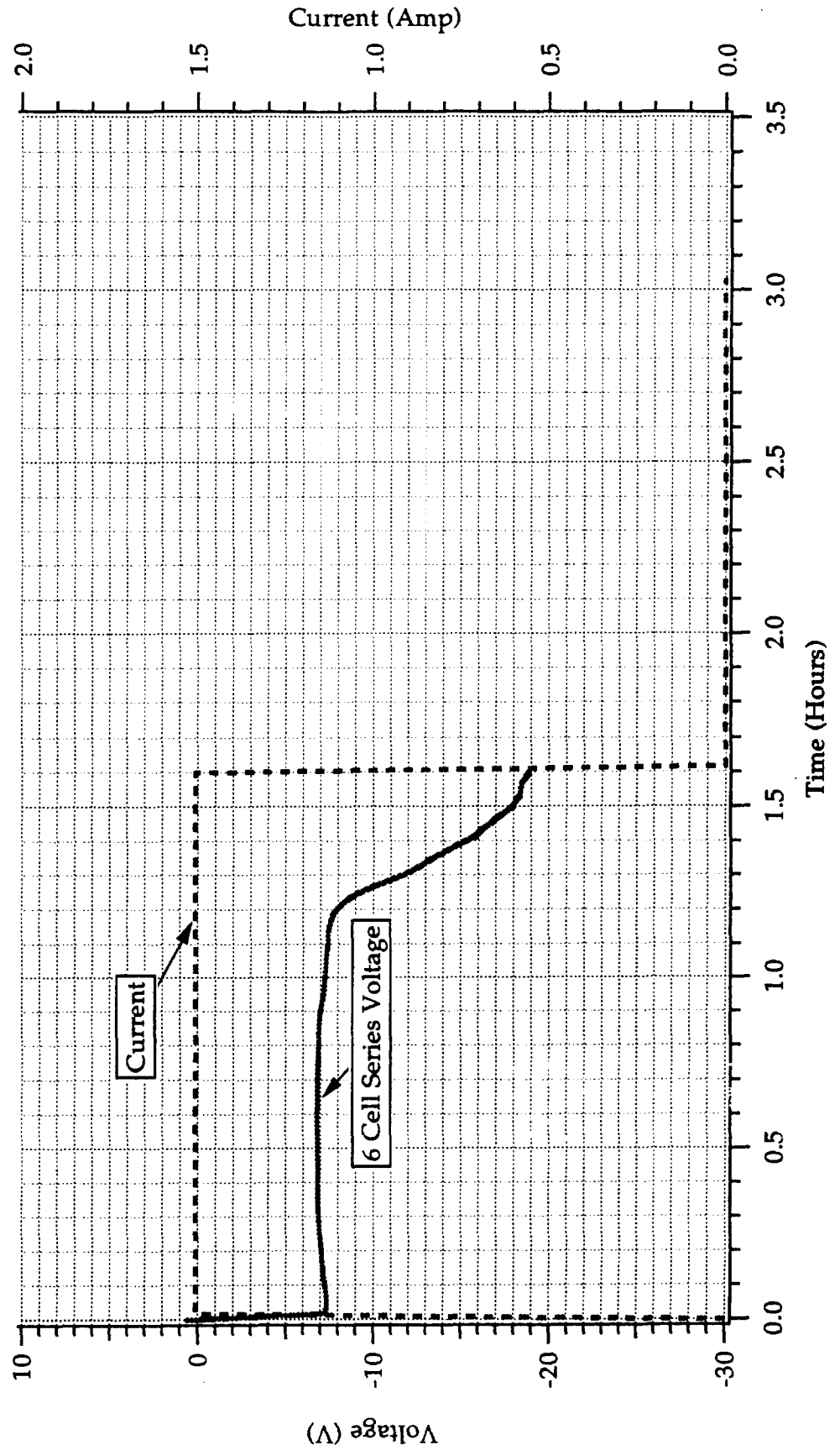




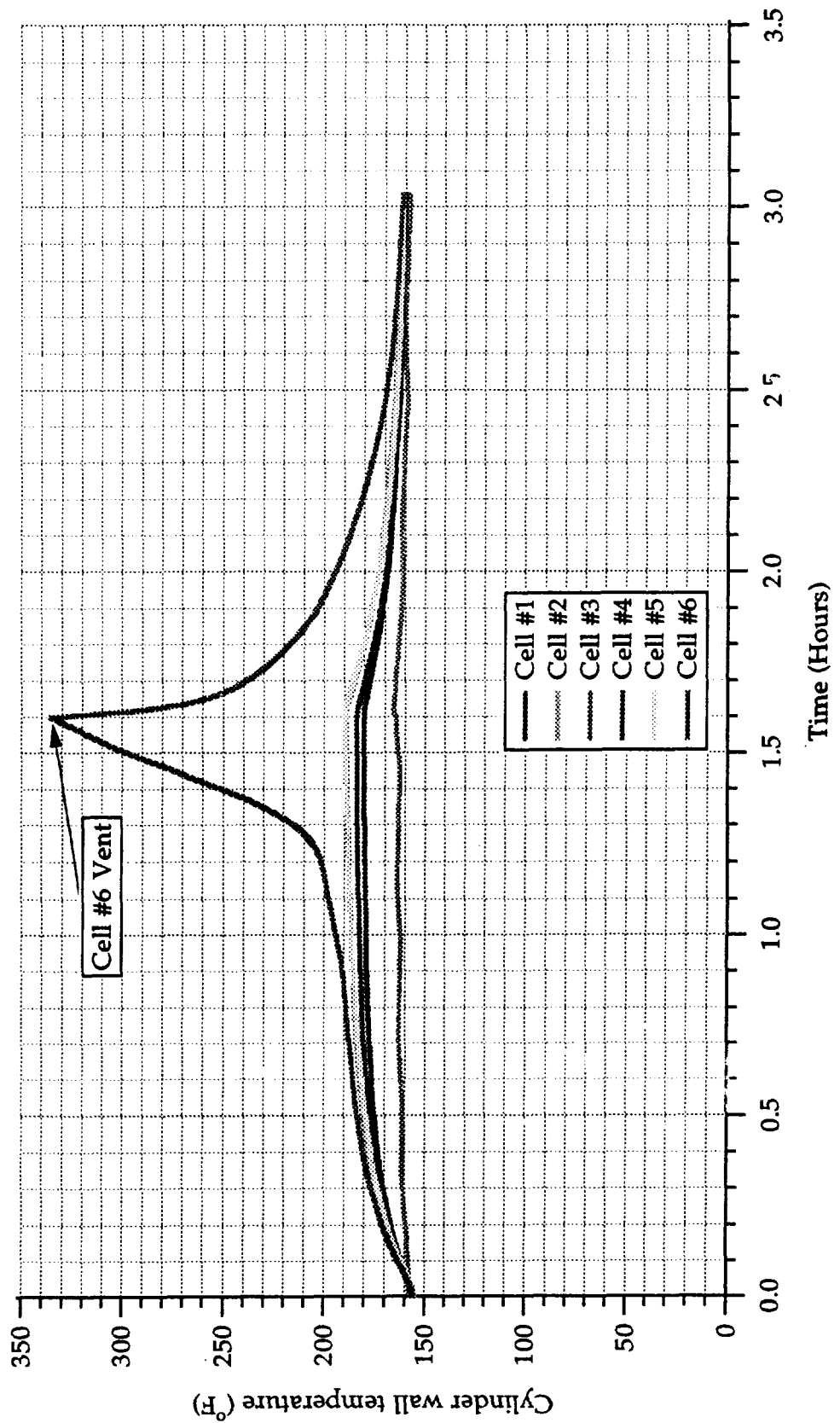
Li-SOCl<sub>2</sub> High Rate "D" Cell  
 Two week post-discharge overdischarge without shunt diodes  
 1.5 A at 160°F



Li-SOCl<sub>2</sub> High Rate "D" Cell  
Four week post-discharge without shunt diodes  
1.5 A at 160°F



Li-SOCl<sub>2</sub> High Rate "D" Cell  
 Four week post-discharge overdischarge without shunt diodes  
 1.5 A at 160° F





Preliminary Test Results for Li-SOCl <sub>2</sub> High-Rate "D" Cells	Propulsion and Power Division
	Bragg / Johnson 10/29/91

## 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*

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**RESULTS OF DEEP DOD LIFE CYCLE TESTS  
AT HIGH RATES ON 12Ah NiCd CELLS**

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**Paul E. Panneton and John R. Meyer**

**The Johns Hopkins University  
Applied Physics Laboratory  
Laurel, MD 20723**

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## **RESULTS OF DEEP DOD LIFE CYCLE TESTS AT HIGH RATES ON 12Ah NiCd CELLS**

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**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

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## 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

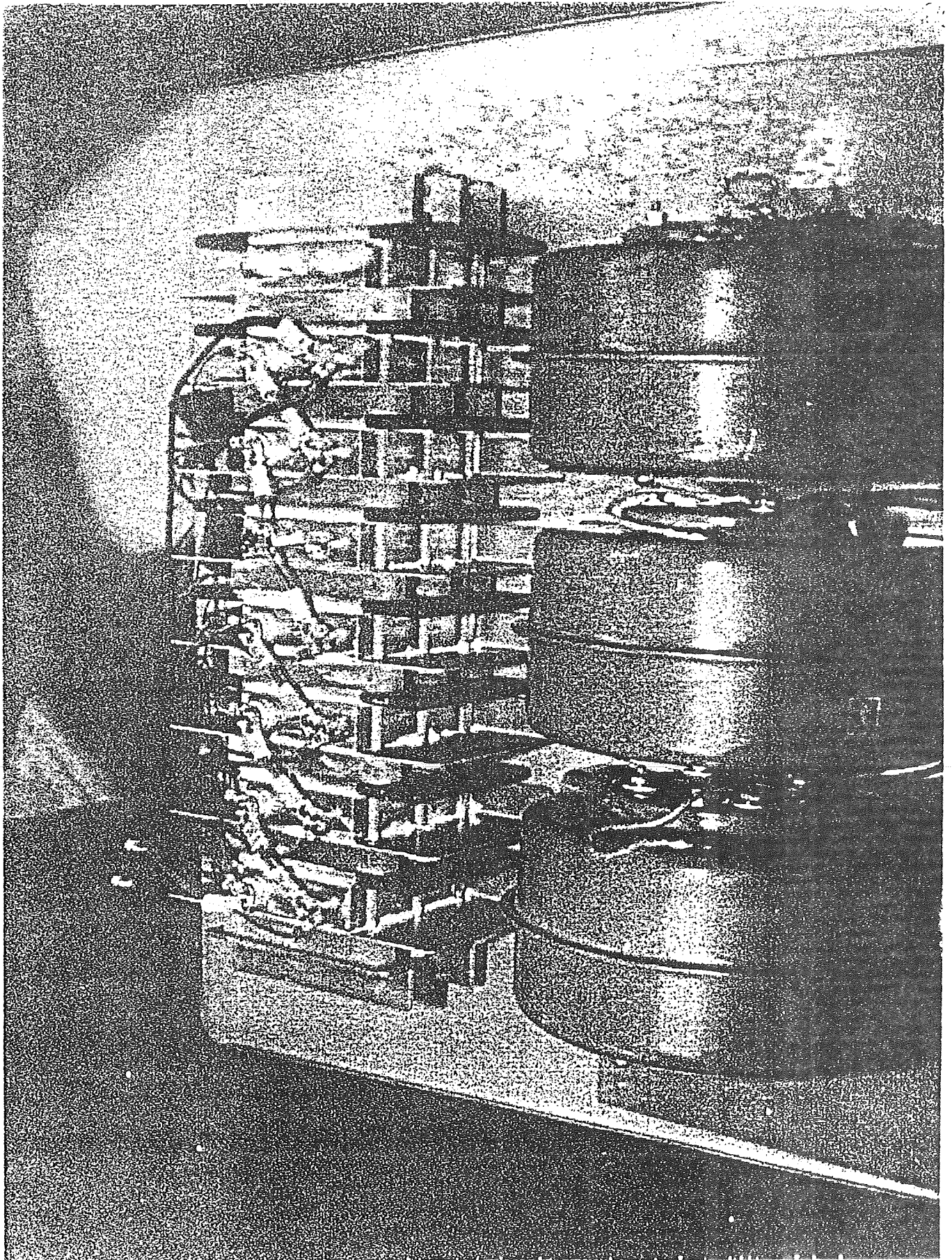


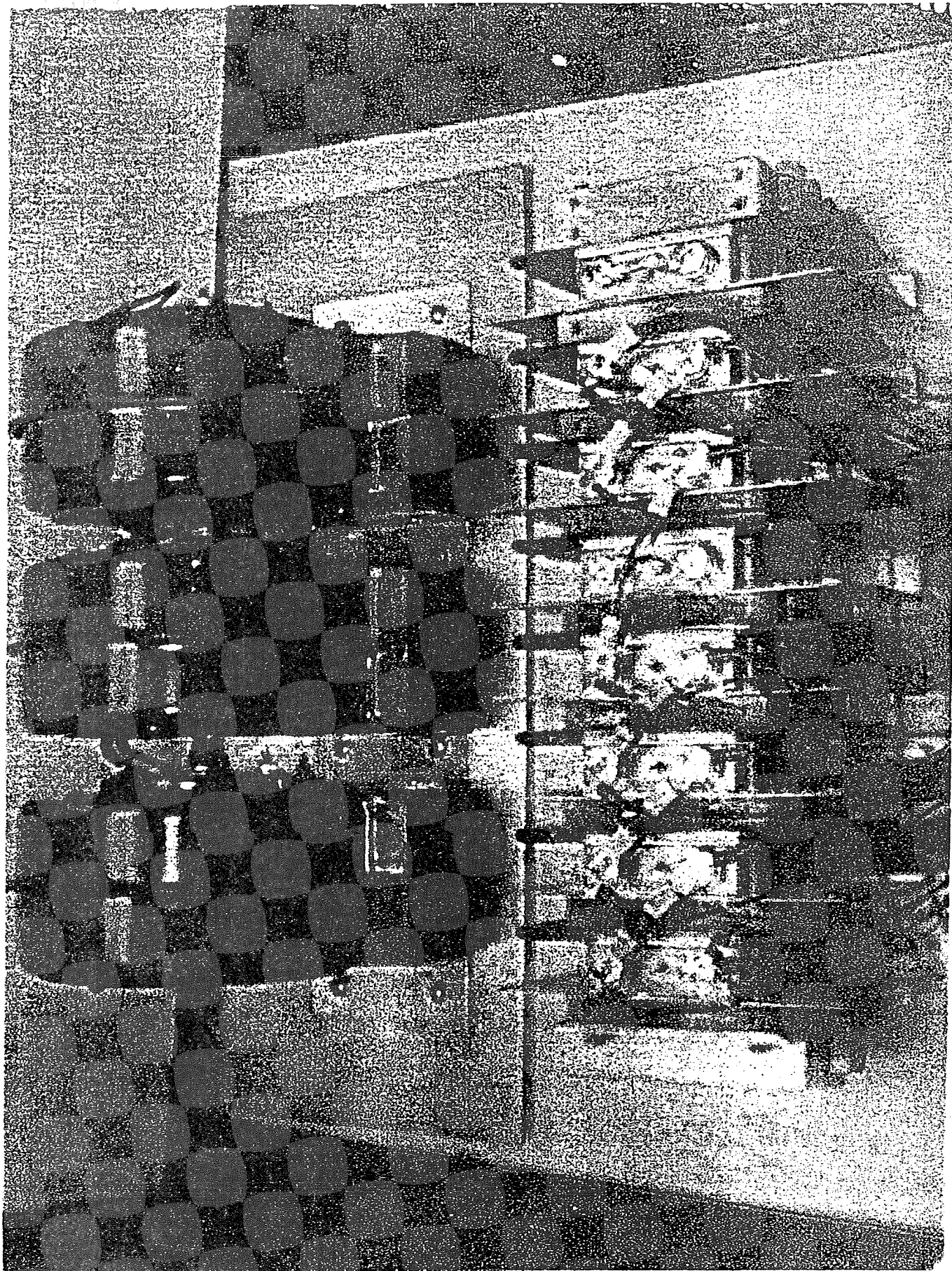
# **RESULTS OF DEEP DOD LIFE CYCLE TESTS AT HIGH RATES ON 12Ah NiCd CELLS**

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## **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**

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The test parameters were chosen to produce the:

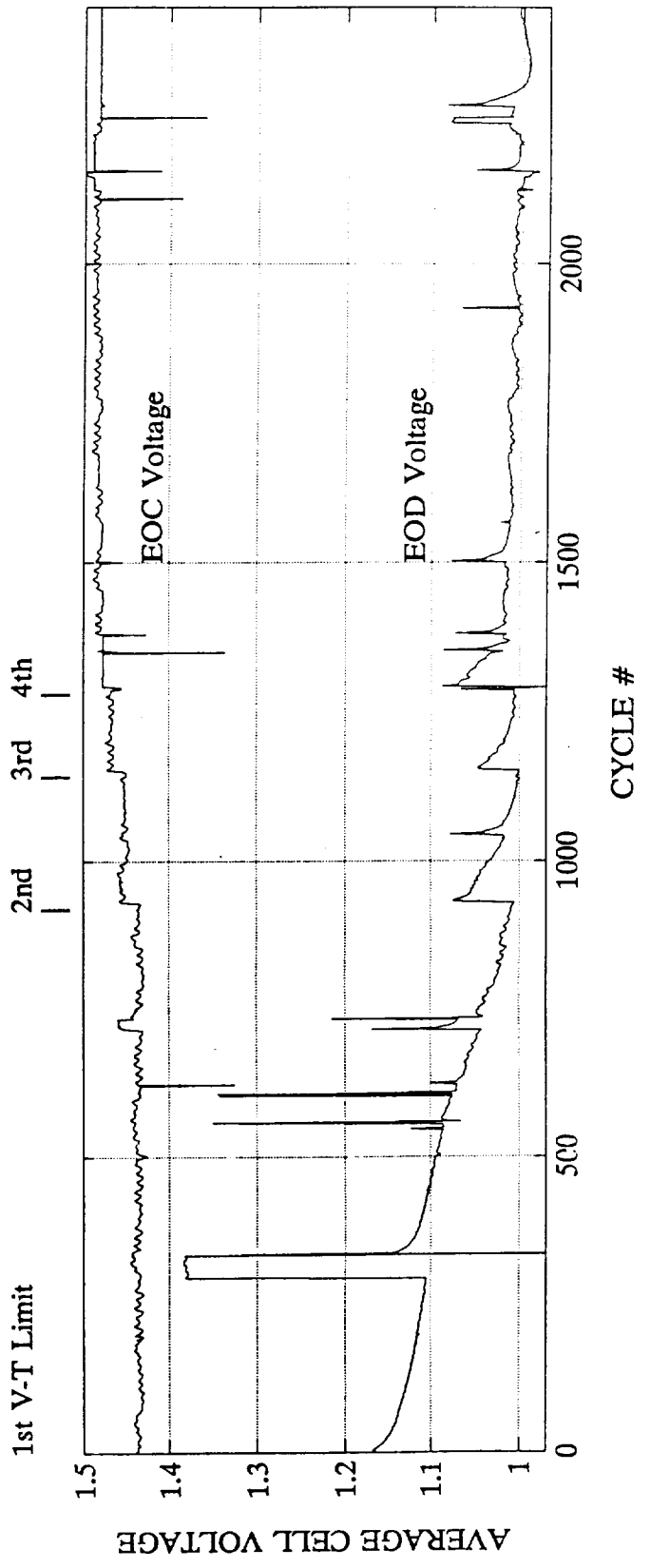
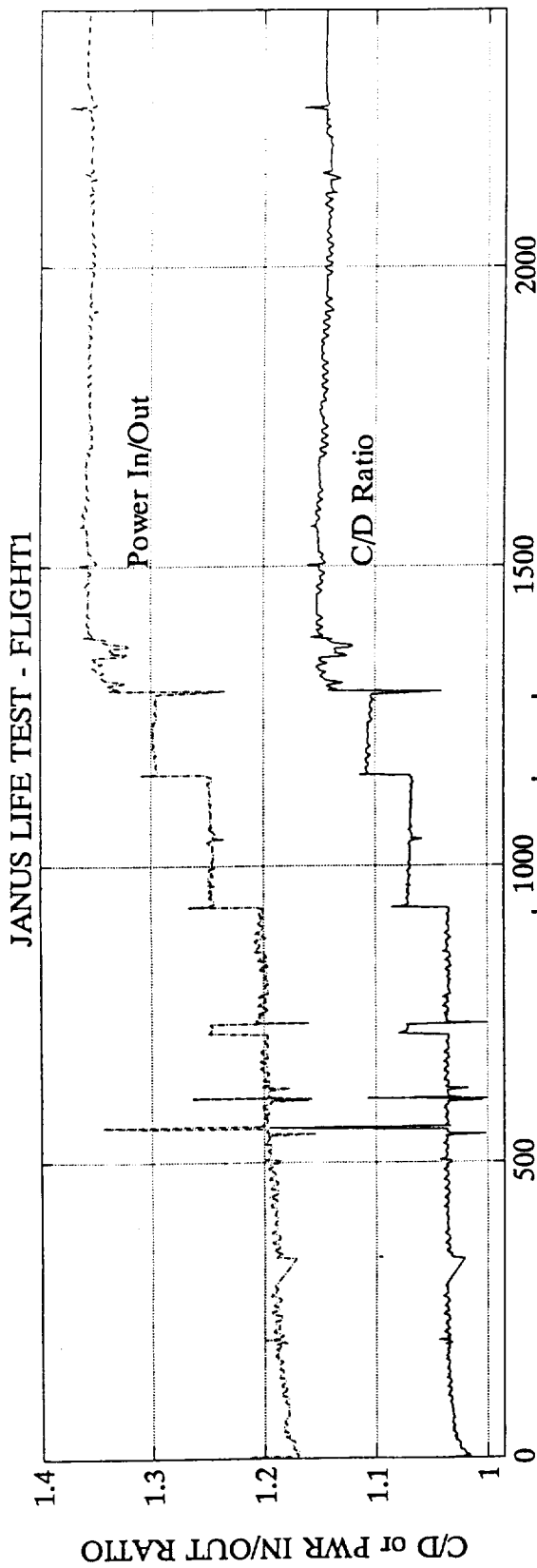
- Worst case eclipse, and
  - Lowest battery cell voltages
- 95 minute cycles at ambient temperature (20° to 30° C.)
- Discharge to 70% DOD (35 minutes - actual 69.44%)
    - C/3 rate for 15 minutes (unswitched loads)
    - 1.8C rate for 20 minutes (switched loads)
  - Charge for 60 minutes
    - 1C 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.

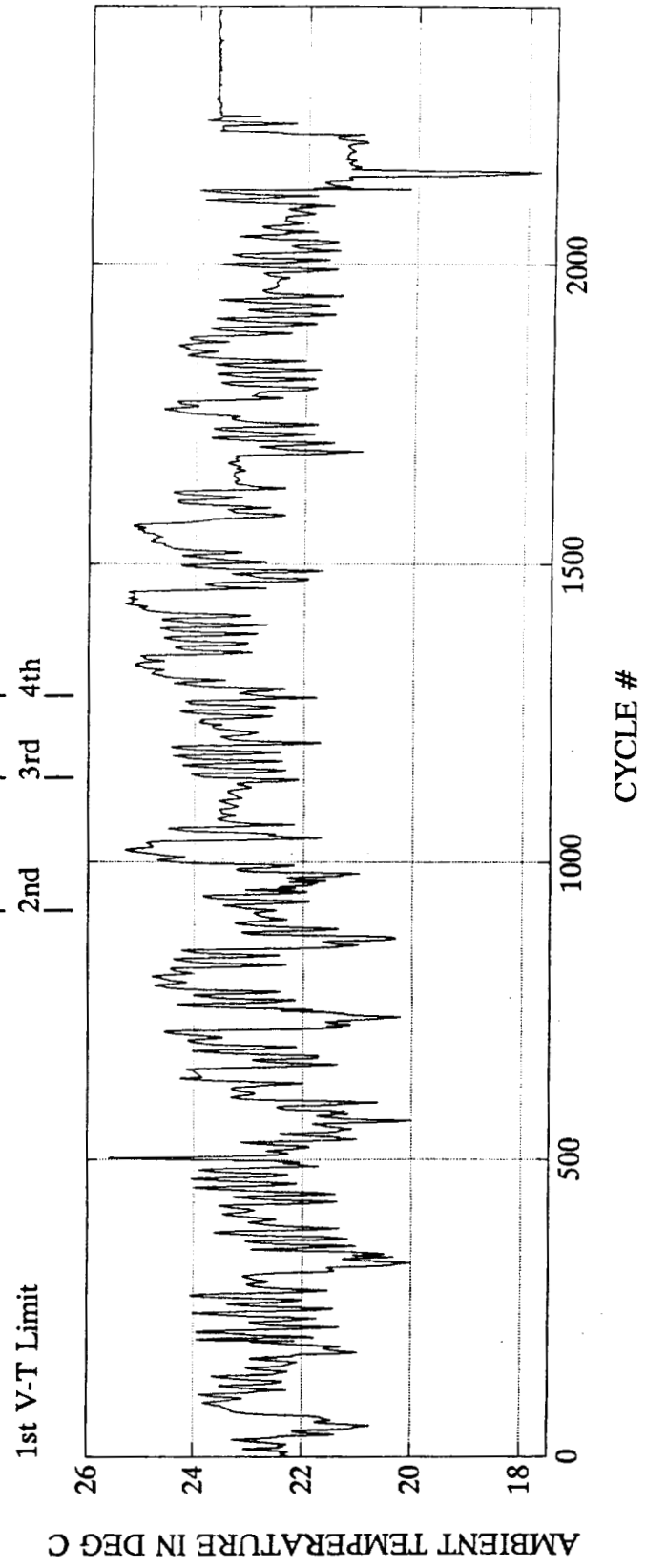
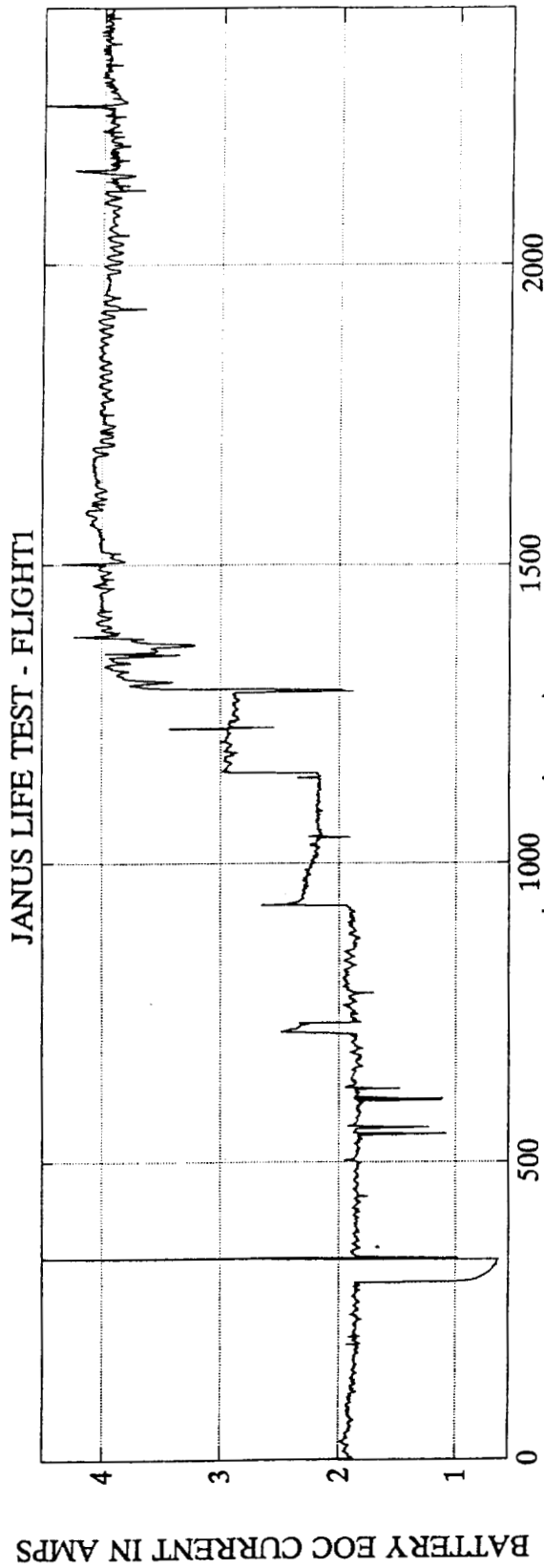


## RESULTS OF DEEP DOD LIFE CYCLE TESTS AT HIGH RATES ON 12Ah NiCd CELLS

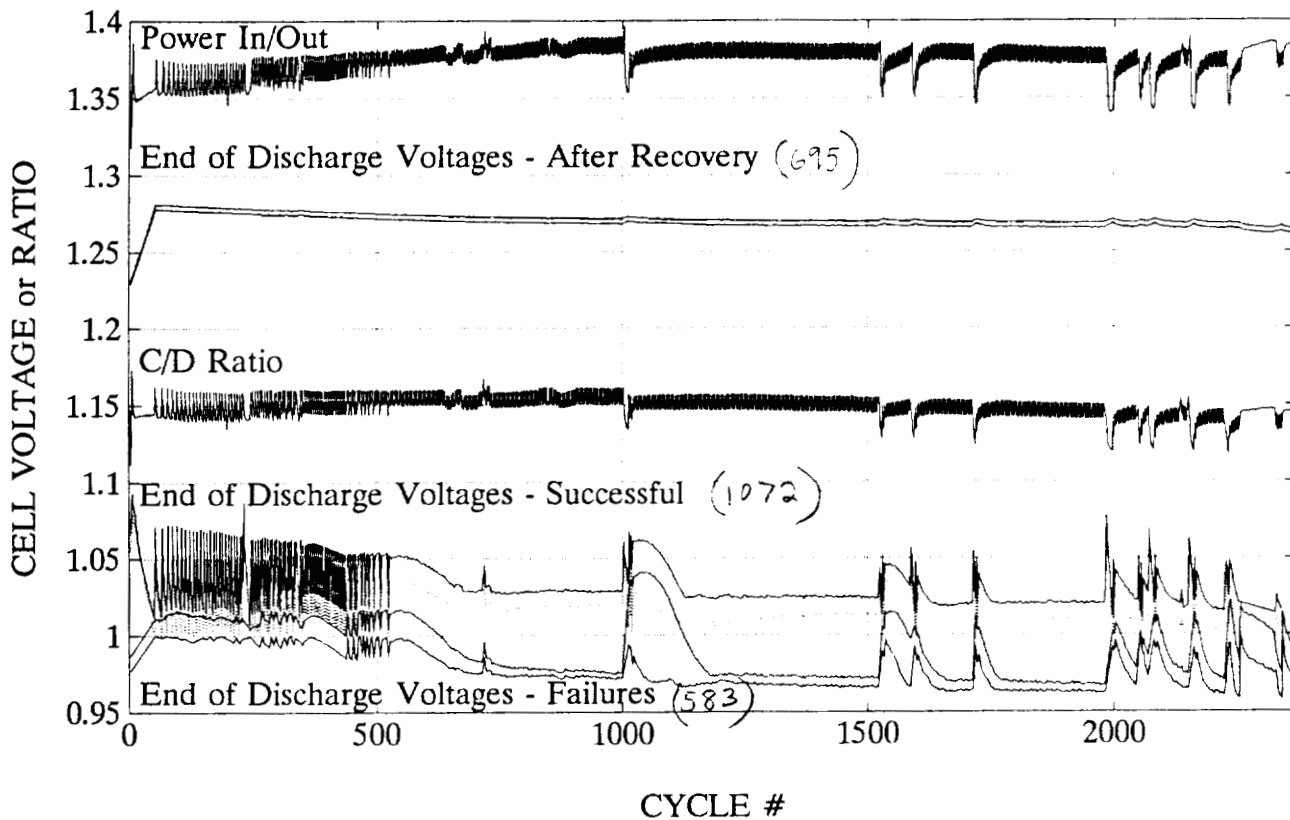
METHOD	REMARKS	# OF CYCLES	TOTAL 70% DOD	TOTAL 20% DOD
Contiguous 70% DOD Cycles. Raise VT Limit to Control C/D Ratio. 1V Cutoff.	C/D=1.036 <sup>4/10/78</sup>	913	913	
	C/D=1.069 <sup>4/27/78</sup>	219	1132	
	C/D=1.107 <sup>5/07/78</sup>	122	1254	
	C/D=1.146 <sup>5/10/78</sup>	1021	2275	
70% DOD Cycles Interspersed with 20% DOD Cycles. 1V Cutoff.	Above Cutoff	1072	3347	
	Below Cutoff	583	3930	
20% DOD Cycles	20% DOD Cycles	695		695
20% DOD Cycles	C/D=1.178	6104		6799
70% DOD Cycles	.95V Cutoff	100++	4030++	



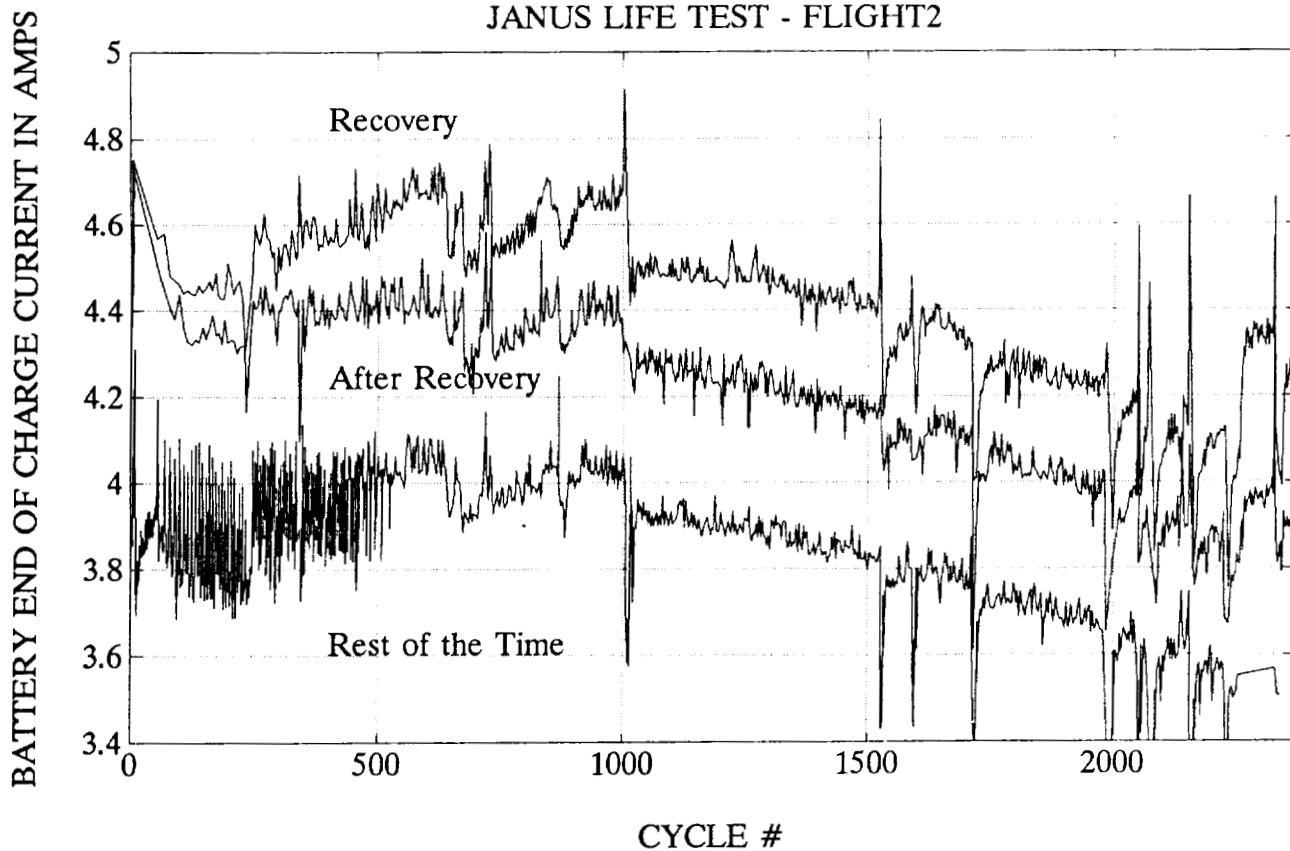




JANUS LIFE TEST - FLIGHT2

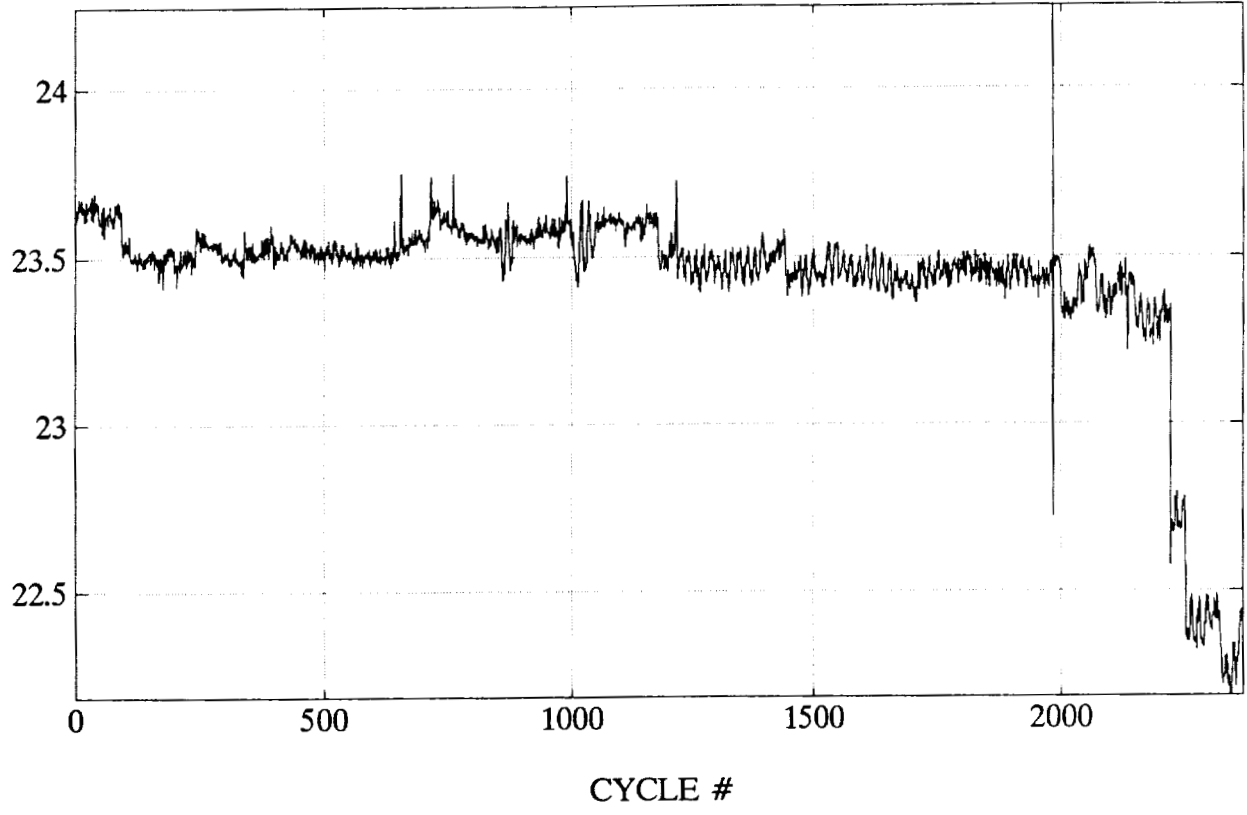


JANUS LIFE TEST - FLIGHT2



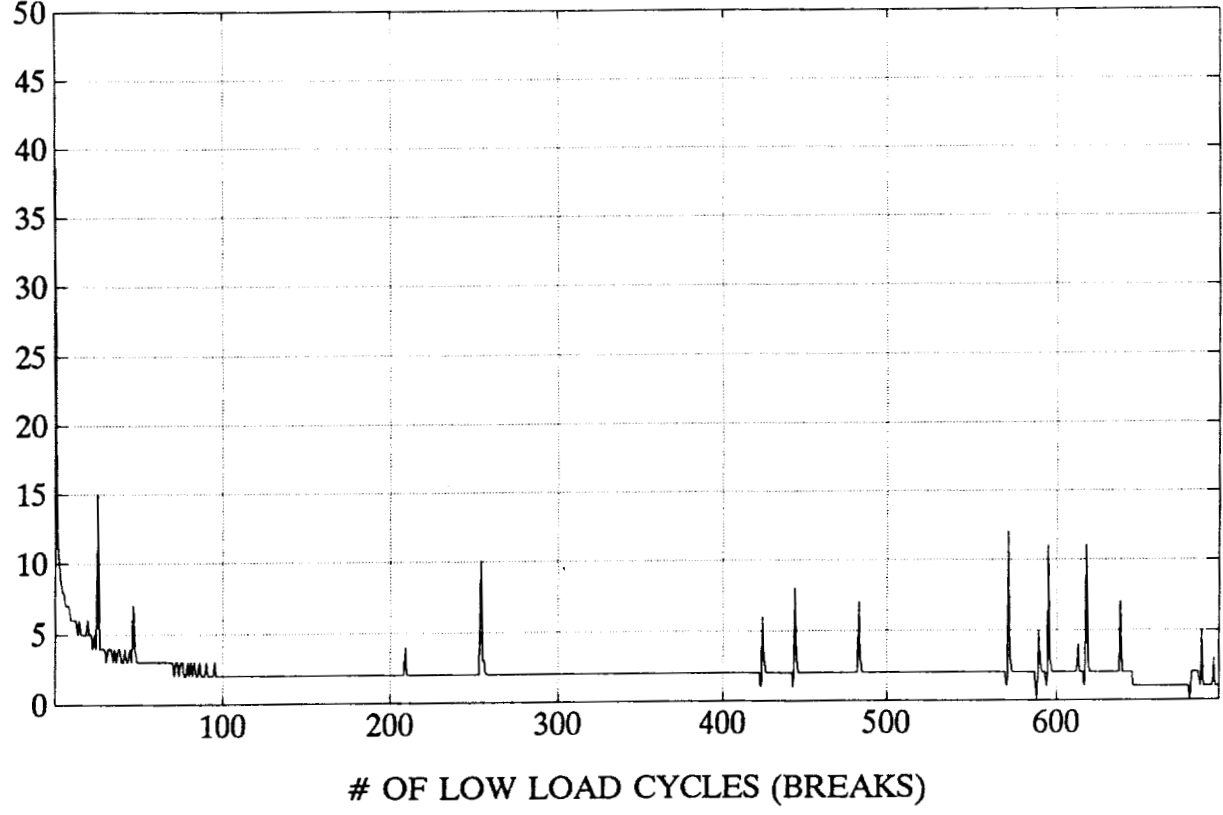
### JANUS LIFE TEST - FLIGHT2

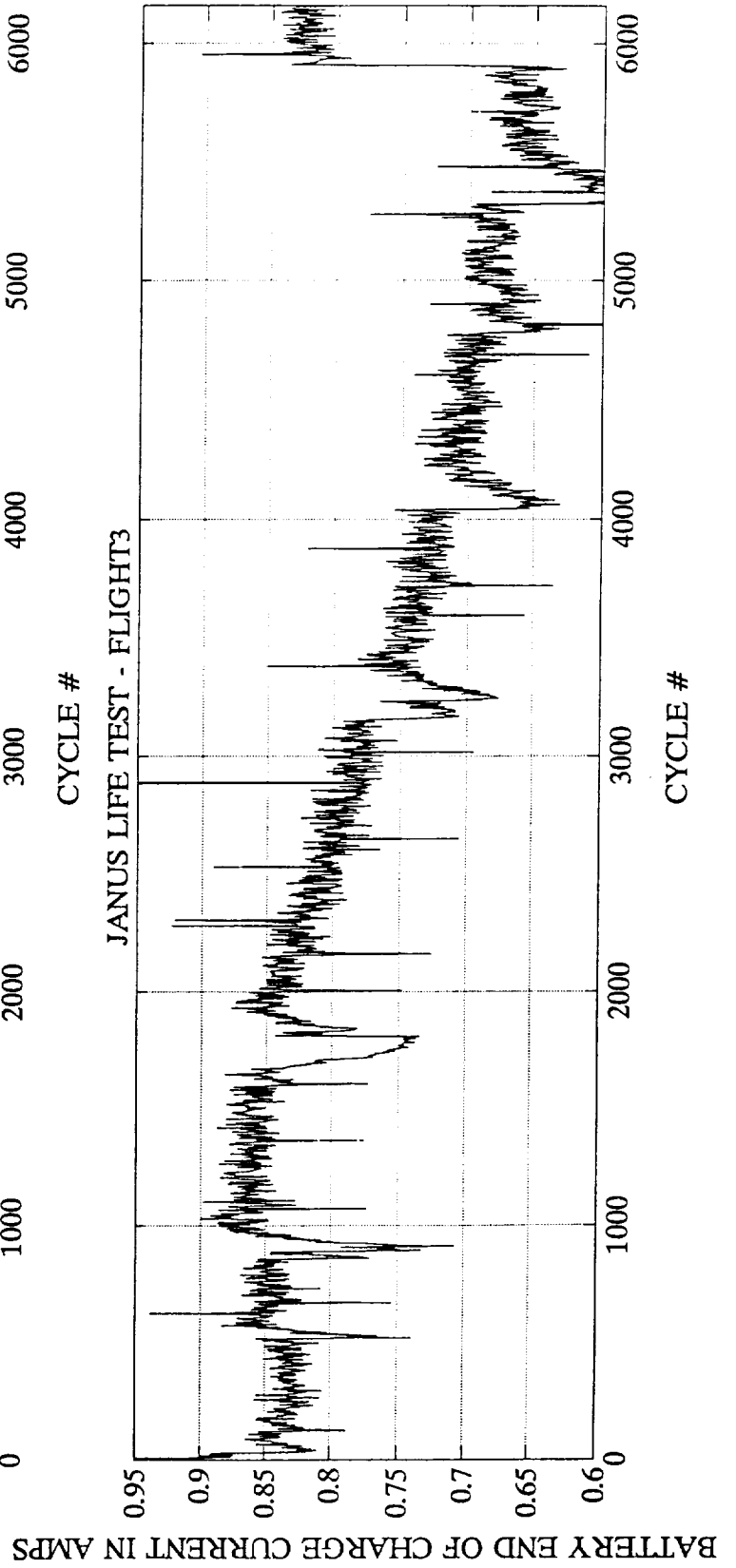
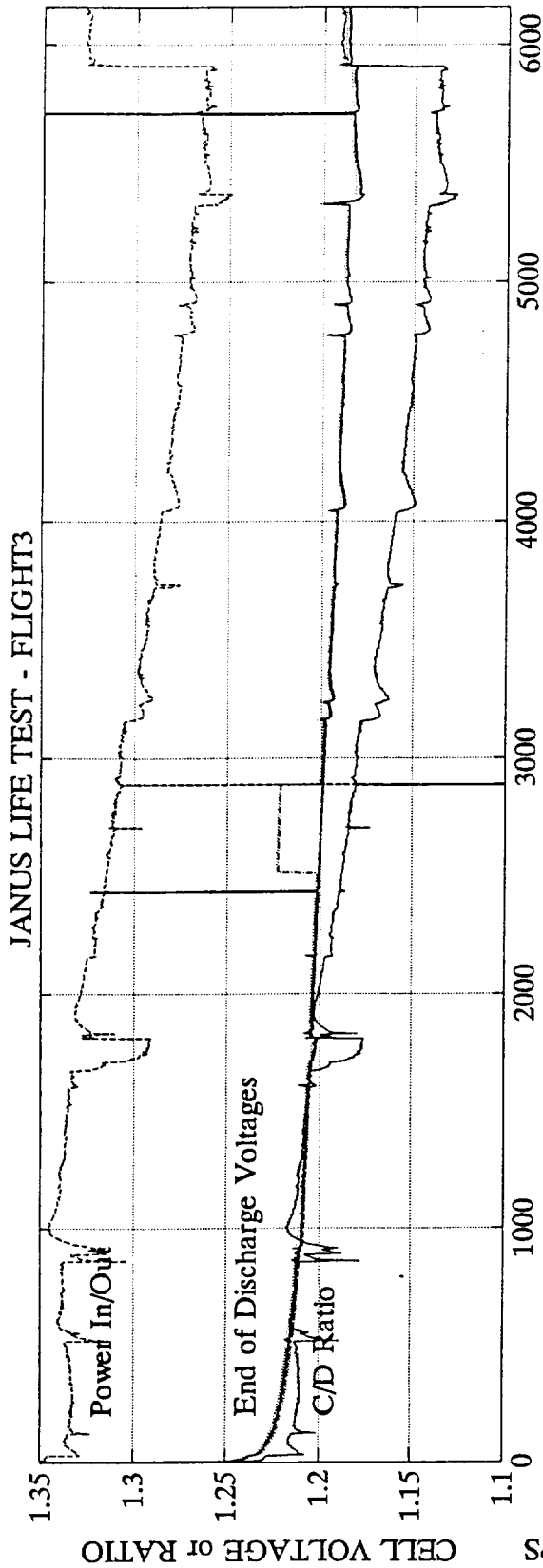
AVERAGE AMBIENT TEMPERATURE IN DEGREES C



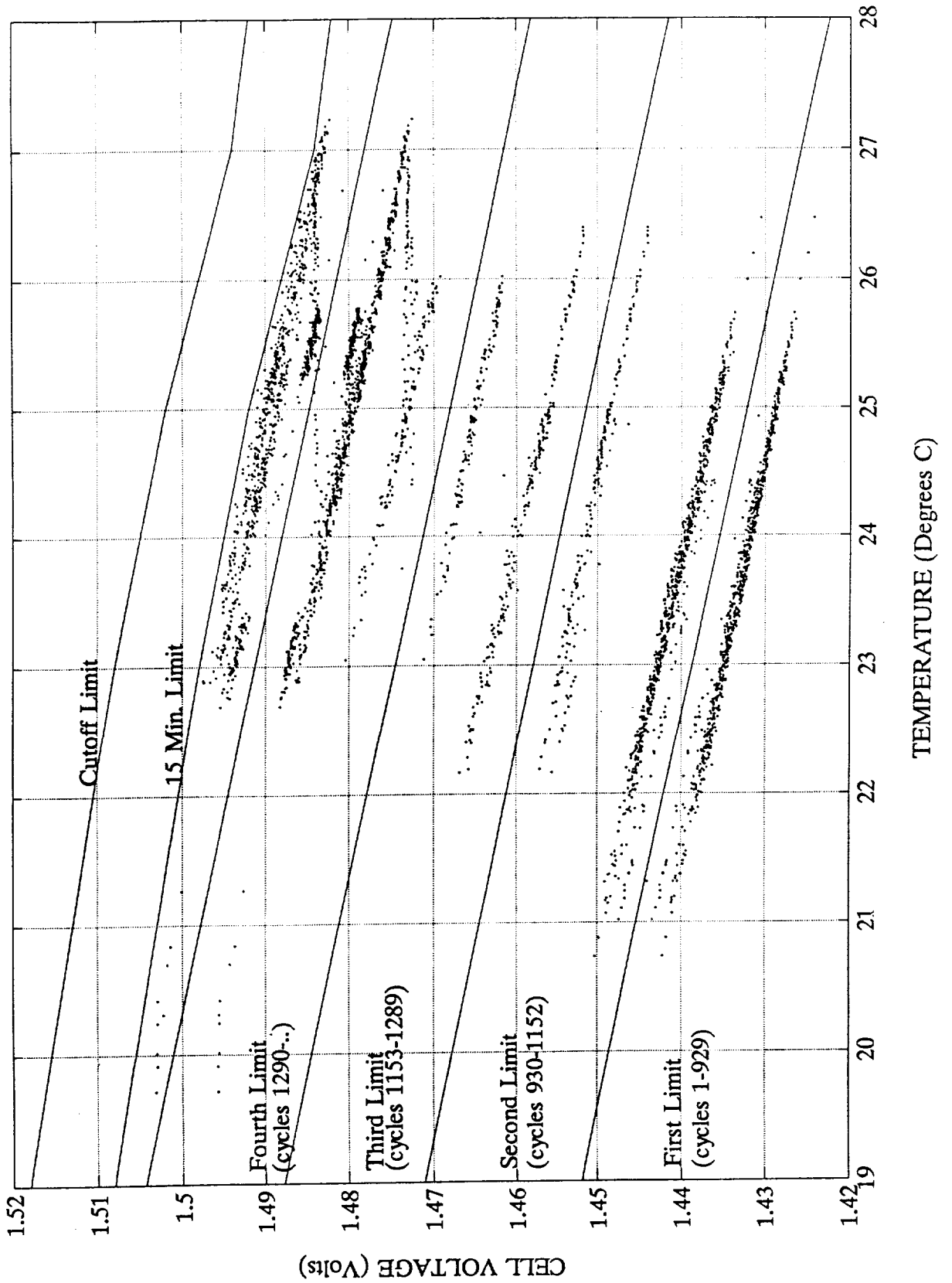
### JANUS SUMMARY - FLIGHT2

# OF HIGH LOAD CYCLES BETWEEN BREAKS

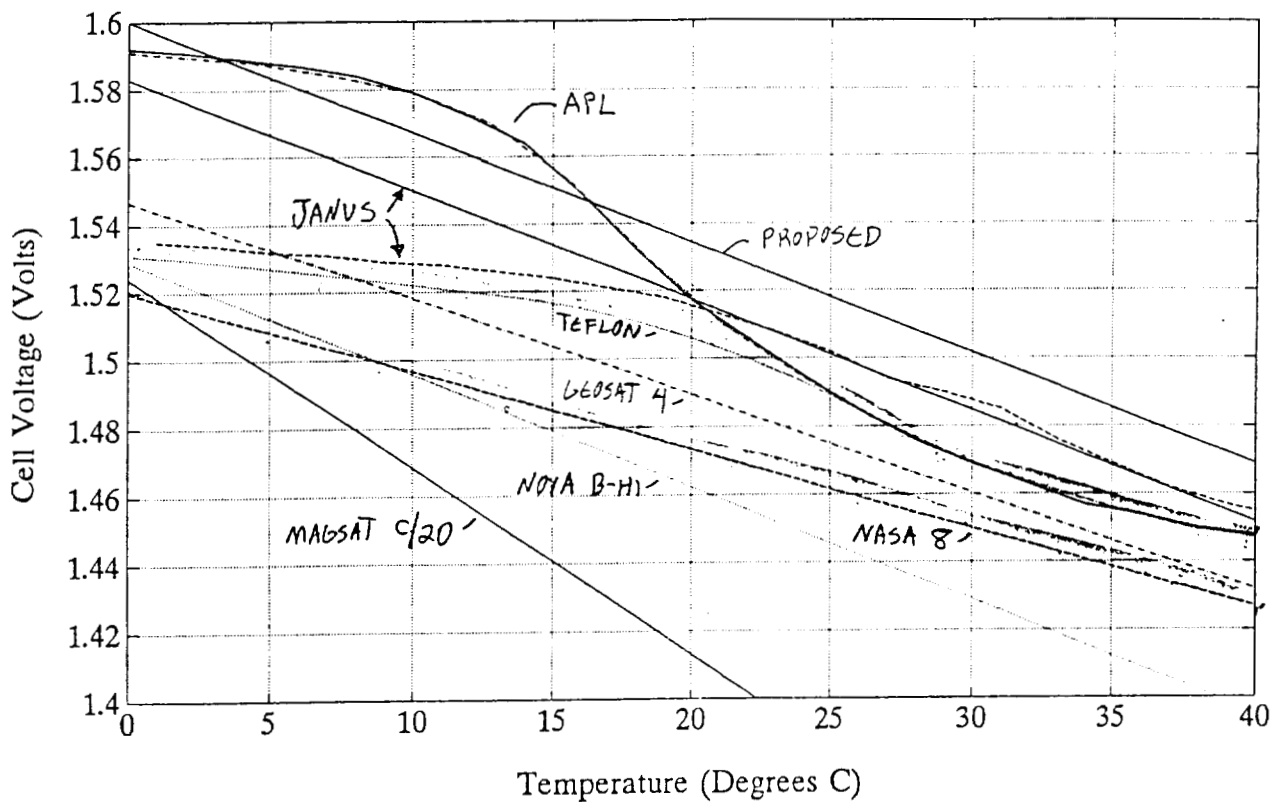




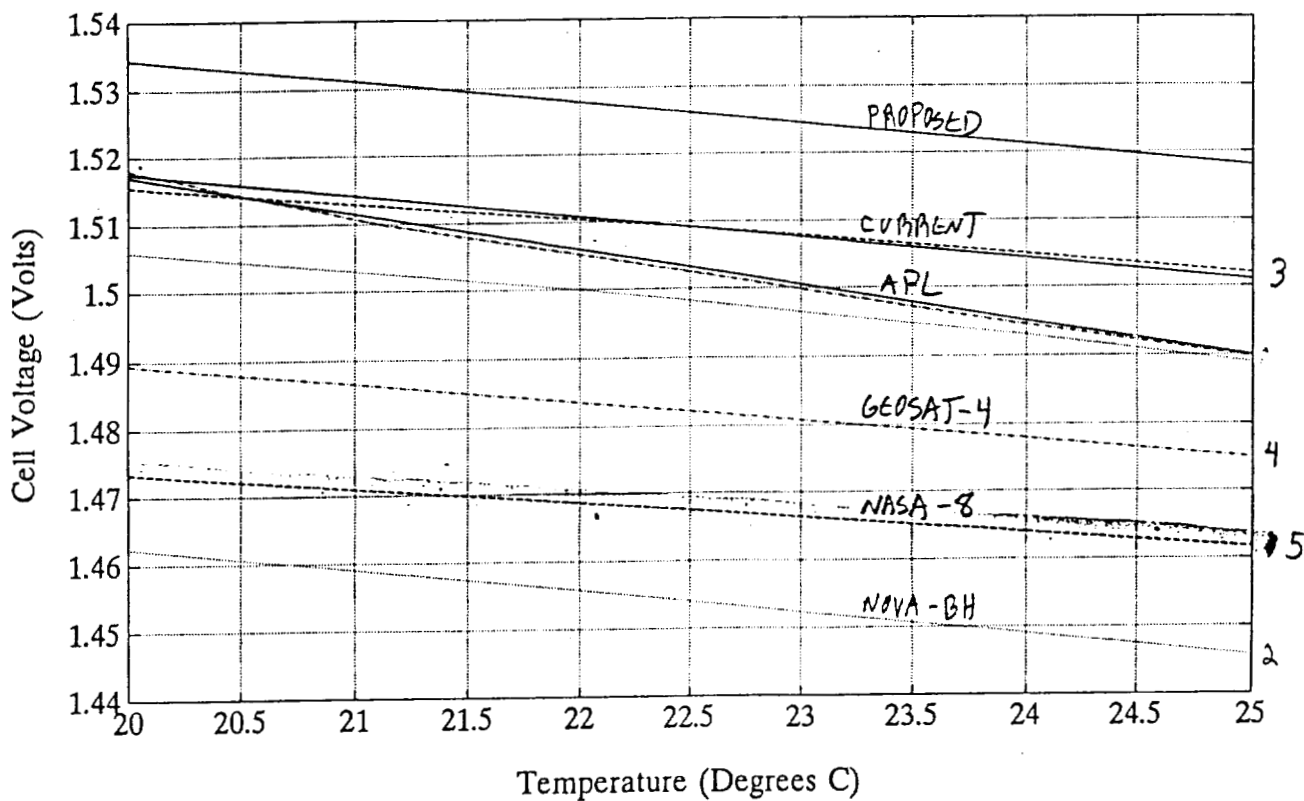
VOLTAGE-TEMPERATURE LIMITS for DEEP DOD LEO TEST

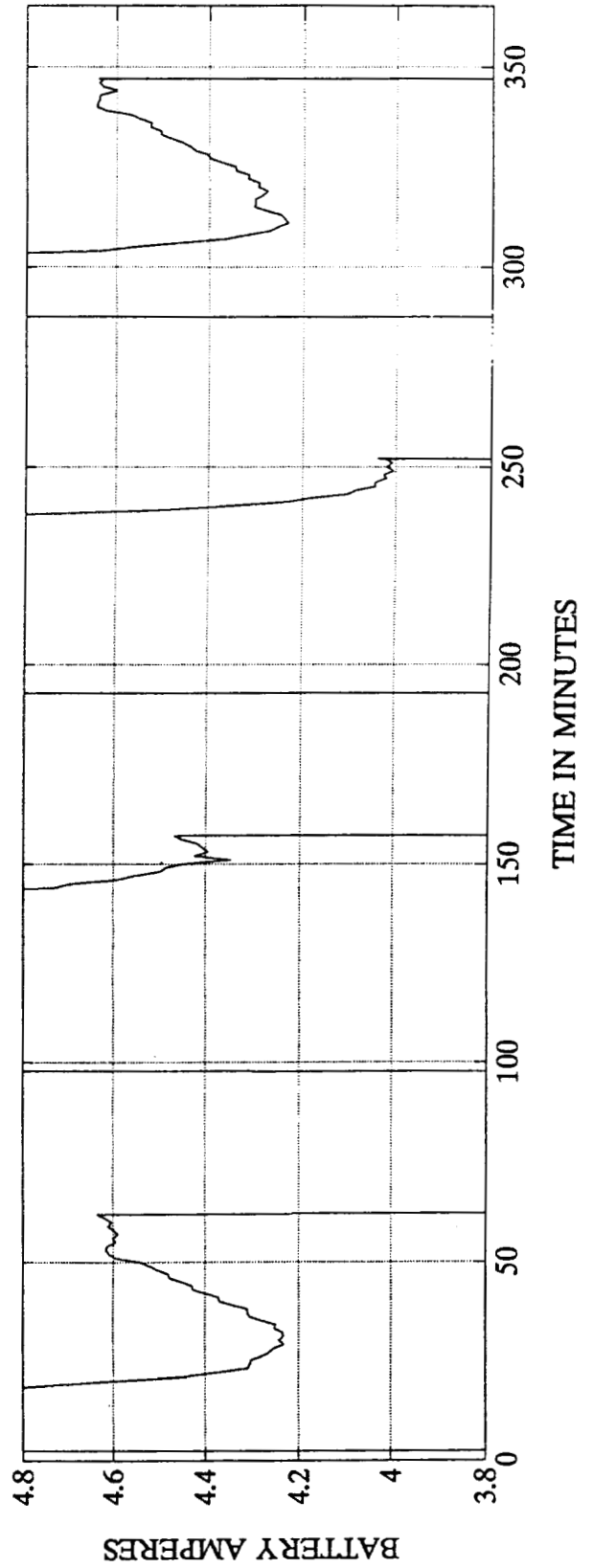
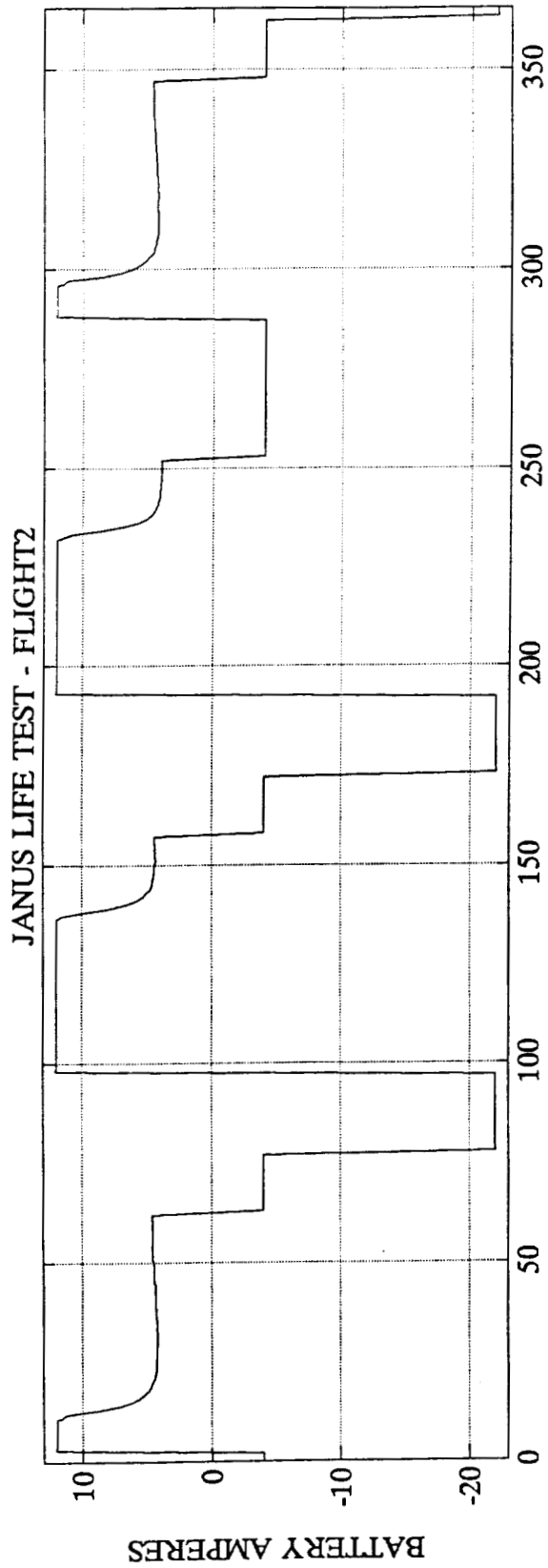


COMPARISON OF V-T LIMITS



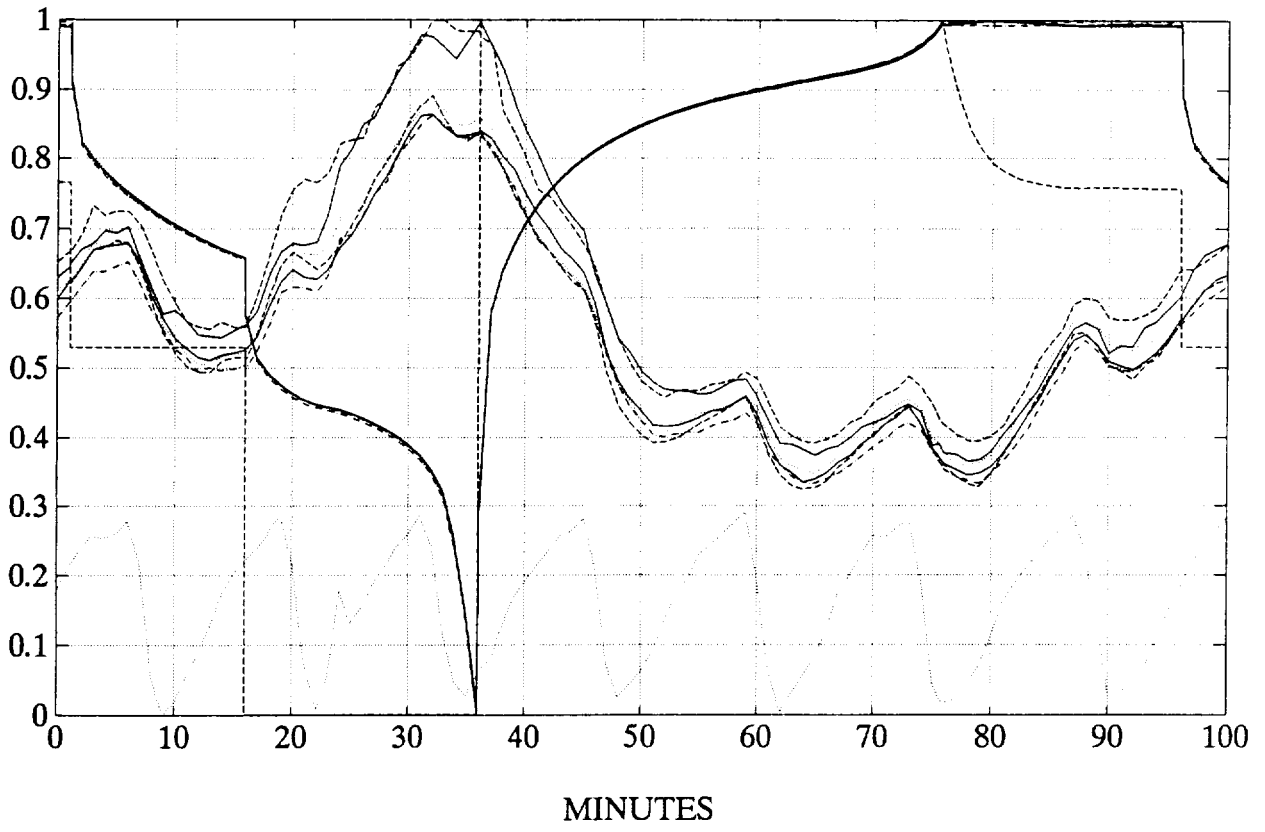
COMPARISON OF V-T LIMITS





CELL TEMPERATURES, VOLTAGES, AND CURRENT

T:0=22.8,1=27.2 V:0=0.96,1=1.49 I:0=-22.0,1=12.0







## **RESULTS OF DEEP DOD LIFE CYCLE TESTS AT HIGH RATES ON 12Ah NiCd CELLS**

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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

**NASA STANDARD 50 A.H. NICD CELL HISTORY**

**SYNOPSIS:** - CONCEPT, DESIGN & COMMITMENT FOR A NASA STANDARD NICKEL CADMIUM BATTERY CELL COALESCED 1975 - 1977

- NASA STANDARD 50 A.H. CELL FIRST MANUFACTURED 1977 - 1978

- 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

**NASA STANDARD NICKEL CADMIUM BATTERY CELL:**

**DEFINING DOCUMENTS: (NASA)**

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

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

**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 CELL (NOW OBSOLETE)
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

**NASA STANDARD 50 A.H. BATTERY CELL**

**CURRENT DESIGN ELEMENTS:**

- UNPASSIVATED POSITIVE PLATE (\*)
  - CADMIUM-TREATED POSITIVE PLATE (\*)
  - POSITIVE LOADING: 11.90 - 13.10 grams/dm<sup>2</sup> } strip type FD03
  - 16 POSITIVE PLATES PER CELL
  - POSITIVE PLATE SURFACE AREA = 22.75 dm<sup>2</sup>
  - TEFLONATED NEGATIVE PLATES
  - NEGATIVE PLATE LOADING: 15.10 - 16.30 grams/dm<sup>2</sup> (\*\*) } strip type FD04
  - 17 NEGATIVE PLATES PER CELL
- (\*) - EXCEPT FOR 50AB34, AS NOTED BEFORE (FD05)  
 (\*\*) - EXCEPT FOR 50AB34, WHICH IS LOADED 14.85 - 16.15 grams/dm<sup>2</sup> (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**

<u>PARA. NO.</u>	<u>TITLE</u>	<u>REGIME</u>	<u>REQUIREMENT</u>
3.0	SHORT	SHORT WITH 0.2 OHM RESISTORS	EOSV = 0.010V MAX
4.0, 8.0	74°F CAPACITY	CHARGE 24H @ 5 AMPS DISCHARGE @ 25 AMPS TO 1.00V RESISTIVE SHORT	V < 1.48V; P < 65 PSIG 3000 < CAP > 3900 A-M EOSV = 0.010V MAX
5.0	86°F CAPACITY	CHARGE 24H @ 5 AMPS DISCHARGE @ 25 AMPS TO 1.00V RESISTIVE SHORT	V < 1.47V; P < 65 PSIG CAP > 2400 A-M EOSV = 0.010V MAX
6.0	32°F OVRCHG	CHARGE 72H @ 2.5 AMPS DISCHARGE @ 25 AMPS TO 1.00V RESISTIVE SHORT	V < 1.53V; P < 75 PSIG CAP > 2700 A-M EOSV = 0.010V MAX
7.0	LOW RATE EFFICIENCY	CHARGE 20H @ 1.25 AMPS DISCHARGE @ 25 AMPS TO 1.00V RESISTIVE SHORT	CAP > 900 A-M
9.0	HIGH - RATE DISCHARGE	CHARGE 16H @ 5 AMPS DISCHARGE @ 150 AMPS FOR 30 SECONDS, THEN @ 25 AMPS TO 1.00V: RESISTIVE SHORT	EODV > 1.00V AFTER 30 SECONDS @ 150 AMPS 24 HOUR MAX SHORT
10.0	CHARGE RETENTION & IMPEDANCE	OPEN CIRCUIT FOR 24 HOURS MEASURE IMPEDANCE (HP 4328)	V > 1.17V AFTER 24 HOUR OPEN CIRCUIT 3 MILLIOHMS MAX

NASA STANDARD 50 A.H. BATTERY CELL: PLATE / CELL LOTS

<u>PLATE LOT</u>	<u>NOTES</u>	<u>CELL LOT / DISPOSITION</u>	<u>LOT SIZE</u>	<u>MISSION USE</u>
50AB20/21 LOT 1	-	50AB20/21 LOT 1	44 CELLS	50 A.H. QUAL BATTERY
50AB20/21 LOT 2	-	50AB20/21 LOT 2	101 CELLS	4 TEST BATTERIES
50AB20/21 LOT 3	-	50AB20/21 LOT 3	78 CELLS	2 TEST BATTERIES; 1 LANDSAT 4 FLIGHT BATTERY
50AB20/21 LOT 4	-	50AB20/21 LOT 4	52 CELLS	2 LANDSAT 4 FLIGHT BATTERIES
50AB20/21 LOT 5	-	50AB20/21 LOT 5	55 CELLS	2 LANDSAT 5 FLIGHT BATTERIES
50AB20/21 LOT 6	OVERLOADED	SCRAPPED	-	-
50AB20/21 LOT 7	-	50AB20/21 LOT 7	54 CELLS	1 LANDSAT 5 FLIGHT BATTERY; 1 LANDSAT SPARE BATTERY
50AB20/21 LOT 8A/8B	POSITIVE REJECTED, (PASSIVATED); 8B NEGATIVE USED FOR 50AB25 LOT 1 & 50AB20 LOT 13	-	-	-
50AB20/21 LOT 9	-	50AB20/21 LOT 9	92 CELLS	SCRAPPED. ERRATIC & HIGH VOLTAGE. CONTAMINATION?



NASA STANDARD 50 A.H. BATTERY CELL: PLATE / CELL LOTS

<u>PLATE LOT</u>	<u>NOTES</u>	<u>CELL LOT / DISPOSITION</u>	<u>LOT SIZE</u>	<u>MISSION USE</u>
50AB20/21 LOT 10	INSUFFICIENT MAT'L	-	-	-
50AB20/21 LOT 11	INSUFFICIENT MAT'L	-	-	-
50AB20/21 LOT 12	LOT 10 + LOT 11	50AB20/21 LOT 12	91 CELLS	2 ERBS FLIGHT BATTERIES; 1 ERBS CHARACTERIZATION BATTERY
-	LOT 11 POSITIVE	50AB20 LOT 13	21 CELLS	GSFC PRECHARGE EXPERIMENT
-	LOT 8 NEGATIVE			
50AB20 LOT 14	POSITIVE NOT CAD-MIUM TREATED	50AB25 LOT 1	12 CELLS	2536 SEPARATOR QUAL TEST CELLS
50AB20 LOT 14A/15B	BAD 2505 SEPARATOR	50AB20 LOT 14	78 CELLS	3 GRO TEST BATTERIES
50AB20 LOT 16	-	50AB20 LOT 15	7 CELLS	PRE-ACCEPT CELLS
		CHANGED TO 2536 SEPARATOR IN FLIGHT CELLS		
		50AB20 LOT 16	7 CELLS	PRE-ACCEPT CELLS
			81 CELLS	3 GRO FLIGHT SPARE BATTERIES
50AB20 LOT 17A/17B	-	50AB20 LOT 17	6 CELLS	PRE-ACCEPT CELLS
50AB20 LOT 18A/18B/18C	OVERLOADED	SCRAPPED	83 CELLS	3 GRO FLIGHT BATTERIES

NASA STANDARD 50 A.H. BATTERY CELL: PLATE / CELL LOTS

<u>PLATE LOT</u>	<u>NOTES</u>	<u>CELL LOT / DISPOSITION</u>	<u>LOT SIZE</u>	<u>MISSION USE</u>
50AB29 LOT 5	FROM 2536 TO G.F.E. 2505	50AB34 LOT 1	73 CELLS	3 GRO SPARE / TEST BATTERIES
50AB20 LOT 19A/B	POS. SCRAPPED	50AB35 LOT 1	81 CELLS	3 GRO FLIGHT BATTERIES
50AB20 LOT 20	NEG. SCRAPPED	50AB35 LOT 2	83 CELLS	3 UARS FLIGHT BATTERIES
50AB35 LOT 2A/2B	-	50AB25 LOT 2	77 CELLS	COMPLETED CELL ATP, DELIVERED TO GSFC COLD STORAGE
50AB35 LOT 3	JPL TEST CELLS	STOP WORK ORDER	-	-
50AB29 LOT 4	FROM 2536 TO G.F.E.	50AB34 LOT 2	4 CELLS	GSFC KOH FILL AMOUNT EXPERIMENT
50AB29 LOT 6	2505	50AB34 LOT 3	13 CELLS	
50AB35 LOT 4A/4B	-	50AB35 LOT 4	107 CELLS	3 EP FLIGHT BATTERIES; 1 EP SPARE BATTERY
50AB35 LOT 2A/2B	-	50AB35 LOT '2A'	7 CELLS	GAB 2538 SEPARATOR LIFE
50AB35 LOT 5A/5B	INSUFFICIENT MATERIAL	50AB25 LOT '3'	7 CELLS	TEST CELLS PLUS CONTROL CELLS
50AB35 LOT 6A/6B/6C	-	50AB39 LOT '1'	7 CELLS	-
		-	-	-
		50AB35 LOT 6	112 CELLS	3 TOPEX FLIGHT BATTERIES 1 TOPEX SPARE BATTERY

**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 SHOTDOWNS
- DESTRICT CELLS SHOW LOSS OF OVERCHARGE PROTECTION
- CONTAMINATION ?

**50AB20 LOT 13 / 50AB25 LOT 1**

- SEVERAL PERIODS OF EXCESSIVE SHOTDOWNS
- 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)**

<u>DATA</u>	<u>POSITIVE</u>			<u>NEGATIVE</u>		
	<u>6A</u>	<u>6B</u>	<u>6A</u>	<u>6B</u>	<u>6C</u>	
PLATE LOT	05103	05104	04801	04602	04601	
POST #	1-7	1-7	1-7	1-6	1,3-7	
SPIRALS						
AVERAGE LOADING (gm/dm <sup>2</sup> )	12.58	12.64	15.68	15.60	15.44	
AVERAGE PLATE THICKNESS (mills)	27.56	27.60	32.17	31.80	31.93	
SAMPLE PLATE WEIGHT (grams)	38.48	38.31	45.04	44.98	44.90	
100% PLATE WEIGHT (grams)	38.55	38.34	45.22	45.08	45.01	
ANTI-POLAR MASS (gm/dm <sup>2</sup> )	0.65	0.63	NA	NA	NA	
STRESS GROWTH (mills)	1.19	1.17	-	-	-	
STRESS RATING	-	-	3.35	2.83	3.08	
NICKEL ATTACK (%)	28.27	29.73	NA	NA	NA	
PLATE POROSITY (%)	31.93	32.47	33.41	32.73	33.32	
SAMPLE ECT (A-M)	3902	4052	7278	7403	7469	
100% ECT (A-M)	3946	4024	7343	7417	7486	
N/P RATIO	-	-	1.860	1.851	1.851	
CAPACITY STABILITY PERCENT	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**

CYCLE	GR1	GR2	GR3	GR4	GR5
1 R:	1.438 - 1.443	1.435 - 1.440	1.437 - 1.443	1.431 - 1.435	1.433 - 1.439
X:	1.44057	1.43729	1.44024	1.43281	1.43630
2 R:	1.442 - 1.449	1.435 - 1.443	1.437 - 1.443	1.441 - 1.446	1.433 - 1.442
X:	1.44590	1.43857	1.43995	1.44348	1.43804
3 R:	1.436 - 1.451	1.437 - 1.447	1.431 - 1.442	1.437 - 1.447	1.435 - 1.446
X:	1.44471	1.44148	1.43614	1.44238	1.44091
4 R:	1.440 - 1.447	1.434 - 1.443	1.433 - 1.441	1.437 - 1.443	1.432 - 1.444
X:	1.44333	1.43786	1.43648	1.43924	1.43857

**4.0 NEGATIVE PRECHARGE - 30 VENTS + 13 PSI [MINUTES TO VENT]**

TOTAL VENT TIME R:	2933 - 4687	3506 - 5279	3502 - 5014	3397 - 5621	3396-4356
X:	3788	4117	4026	4032	3846
AVG VENT TIME:	124.1	134.9	131.9	132.1	126.0

**6.0 PRESSURE STABILIZATION**

EOCV R:	1.451 - 1.457	1.439 - 1.449	1.442 - 1.448	1.441 - 1.449	1.437 - 1.448
X:	1.45400	1.44390	1.44452	1.44500	1.44365
EOCP R:	23 - 50	25 - 46	7 - 49	19 - 40	21 - 50
X:	39.7	35.3	34.9	31.4	35.9
CAP R:	3400 - 3525	3450 - 3575	3425 - 3575	3550 - 3750	3450 - 3650
X:	3455	3505	3496	3661	3538

**ALL CELLS ADJUSTED TO 160 mL**

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

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

**7.0 ROOM TEMPERATURE OVERCHARGE**

	<u>GR1</u>	<u>GR2</u>	<u>GR3</u>	<u>GR4</u>	<u>GR5</u>
EOCV R:	1.448 - 1.461	1.440 - 1.453	1.444 - 1.453	1.445 - 1.458	1.445 - 1.454
X:	1.45452	1.44685	1.44900	1.45176	1.44909
EOCP R:	11 - 36	12 - 36	9 - 41	9 - 30	9 - 35
X:	26.0	23.9	25.9	21.3	20.2
CAP R:	3450 - 3575	3425 - 3550	3400 - 3500	3475 - 3600	3400 - 3575
X:	3512	3490	3443	3546	3472

**9.0 BURN-IN CYCLES: - CAPACITY (A-M)**

<u>CYCLE</u>					
1 R:	3496 - 3650	3445 - 3554	3443 - 3539	3477 - 3593	3473 - 3604
X:	3569	3499	3482	3514	3520
2 R:	3433 - 3550	3298 - 3398	3375 - 3496	3412 - 3524	3384 - 3564
X:	3483	3353	3425	3463	3449
3 R:	3338 - 3450	3284 - 3399	3302 - 3439	3372 - 3489	3325 - 3495
X:	3387	3334	3360	3419	3393
4 R:	3282 - 3411	3219 - 3332	3206 - 3478	3283 - 3421	3258 - 3448
X:	3336	3267	3286	3331	3333
5 R:	3306 - 3418	3226 - 3340	3277 - 3404	3310 - 3454	3278 - 3447
X:	3350	3276	3332	3358	3347
6 R:	3286 - 3409	3218 - 3356	3239 - 3370	3262 - 3406	3253 - 3392
X:	3338	3287	3297	3307	3307
7 R:	3251 - 3378	3281 - 3410	3209 - 3333	3241 - 3389	3221 - 3377
X:	3307	3335	3278	3295	3283
8 R:	3233 - 3393	3251 - 3390	3255 - 3388	3373 - 3529	3259 - 3424
X:	3304	3309	3318	3427	3325
9 R:	3242 - 3367	3210 - 3340	3206 - 3338	3202 - 3360	3228 - 3374
X:	3294	3257	3268	3257	3298
10 R:	3211 - 3389	3187 - 3317	3196 - 3326	3234 - 3408	3216 - 3356
X:	3282	3242	3261	3290	3291

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

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

**10.0 ROOM TEMPERATURE OVERCHARGE**

	<u>GR1</u>	<u>GR2</u>	<u>GR3</u>	<u>GR4</u>	<u>GR5</u>
EOCV R:	1.447 - 1.465	1.439 - 1.453	1.437 - 1.459	1.447 - 1.461	1.433 - 1.454
X:	1.45881	1.44340	1.44686	1.45281	1.44596
EOCP R:	16 - 45	17 - 50	16 - 45	16 - 44	17 - 45
X:	32.0	31.0	32.0	30.2	30.3
CAP R:	3375 - 3500	3375 - 3475	3350 - 3450	3475 - 3625	3325 - 3475
X:	3433	3416	3386	3538	3388

**11.0 86°F CAPACITY SCREENING**

	<u>GR1</u>	<u>GR2</u>	<u>GR3</u>	<u>GR4</u>	<u>GR5</u>	<u>GR6</u>	<u>GR7</u>
EOCV R:	1.408 - 1.417	1.417 - 1.426	1.409 - 1.420	1.412 - 1.419	1.426 - 1.434	1.411 - 1.423	1.418 - 1.427
X:	1.41313	1.42094	1.41378	1.41558	1.42883	1.41880	1.42308
EOCP R:	(-1) - 10	2 - 10	2 - 12	1 - 9	3 - 11	0 - 17	1 - 11
X:	5.3	5.6	7.3	5.7	7.7	8.3	5.8
CAP R:	3198 - 3445	3256 - 3408	3131 - 3348	3145 - 3293	3278 - 3462	3240 - 3402	3241 - 3403
X:	3336	3314	3242	3201	3383	3302	3337

**12.0 32°F OVERCHARGE SCREENING**

32HRV R:	1.509 - 1.517	1.514 - 1.521	1.511 - 1.525	1.513 - 1.519	1.520 - 1.524	1.521 - 1.535	1.514 - 1.521
X:	1.51338	1.51719	1.51644	1.51600	1.52208	1.52860	1.51792
EOCV R:	1.501 - 1.507	1.498 - 1.507	1.498 - 1.508	1.502 - 1.508	1.505 - 1.509	1.505 - 1.513	1.501 - 1.507
X:	1.50400	1.50450	1.50306	1.50467	1.50667	1.50935	1.50483
EOCP R:	16 - 45	12 - 37	21 - 46	20 - 48	18 - 52	11 - 52	7 - 44
X:	32.3	25.6	34.2	33.8	35.4	31.9	26.1
CAP R:	3200 - 3434	3222 - 3361	3140 - 3241	3108 - 3238	3153 - 3340	3140 - 3315	3208 - 3349
X:	3331	3284	3191	3175	3284	3221	3275

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

**50AB35 LOT 4 ATP:**

**4.0 1st 74°F CAPACITY TEST**

	<u>GR1</u>	<u>GR2</u>	<u>GR3</u>	<u>GR4</u>	<u>GR5</u>	<u>GR6</u>	<u>GR7</u>
16HRV R:	1.451 - 1.456	1.459 - 1.463	1.457 - 1.467	1.455 - 1.459	1.463 - 1.468	1.460 - 1.467	1.468 - 1.472
X:	1.45431	1.46044	1.46194	1.45792	1.46558	1.46315	1.46967
20HRV R:	1.449 - 1.458	1.455 - 1.460	1.458 - 1.468	1.463 - 1.477	1.463 - 1.467	1.458 - 1.472	1.463 - 1.471
X:	1.45469	1.45713	1.46194	1.46783	1.46483	1.46615	1.46625
EOCV R:	1.448 - 1.456	1.456 - 1.460	1.456 - 1.466	1.457 - 1.464	1.461 - 1.466	1.456 - 1.469	1.462 - 1.469
X:	1.45431	1.45719	1.45989	1.45983	1.46375	1.46365	1.46500
EOCP R:	13 - 37	19 - 39	26 - 55	27 - 47	23 - 48	21 - 54	18 - 50
X:	29.9	29.9	41.2	35.7	38.6	37.6	34.4
CAP R:	3485 - 3595	3517 - 3658	3318 - 3670	3482 - 3592	3593 - 3670	3498 - 3642	3610 - 3700
X:	3543	3555	3572	3509	3623	3556	3656

**5.0 86°F CAPACITY**

EOCV R:	1.422 - 1.432	1.422 - 1.429	1.419 - 1.430	1.420 - 1.424	1.419 - 1.431	1.417 - 1.434	1.424 - 1.432
X:	1.42844	1.42513	1.42344	1.42125	1.42500	1.42520	1.427920
EOCP R:	4 - 16	5 - 14	6 - 17	5 - 14	6 - 14	4 - 19	5 - 15
X:	11.1	9.3	12.1	9.3	9.6	10.6	9.8
CAP R:	3252 - 3360	3279 - 3432	3313 - 3463	3218 - 3339	3301 - 3403	3202 - 3364	3321 - 3430
X:	3312	3324	3375	3256	3354	3263	3372

**6.0 32°F OVERCHARGE**

32HRV R:	1.520 - 1.527	1.521 - 1.528	1.518 - 1.530	1.520 - 1.525	1.522 - 1.527	1.525 - 1.535	1.521 - 1.527
X:	1.52519	1.52456	1.52328	1.52258	1.52450	1.52895	1.52358
EOCV R:	1.510 - 1.516	1.503 - 1.510	1.503 - 1.513	1.508 - 1.511	1.509 - 1.515	1.510 - 1.518	1.508 - 1.514
X:	1.51375	1.50788	1.50894	1.50983	1.51142	1.51345	1.51075
EOCP R:	15 - 51	16 - 41	27 - 53	21 - 57	23 - 59	14 - 55	24 - 52
X:	35.3	29.9	40.7	37.9	40.0	36.6	34.5
CAP R:	3265 - 3427	3301 - 3411	3230 - 3354	3177 - 3279	3301 - 3426	3225 - 3395	3213 - 3377
X:	3358	3368	3307	3215	3374	3302	3309



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

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

**7.0 LOW RATE EFFICIENCY**

	GR1	GR2	GR3	GR4	GR5	GR6	GR7
EOCV R:	1.373 - 1.376	1.374 - 1.375	1.374 - 1.377	1.375 - 1.376	1.375 - 1.376	1.375 - 1.376	1.375 - 1.377
X:	1.37419	1.37419	1.37578	1.37508	1.37550	1.37580	1.37600
CAP R:	877 - 902	859 - 874	896 - 915	904 - 923	847 - 862	901 - 914	901 - 919
X:	885	867	906	915	855	906	911

**8.0 2nd 74°F CAPACITY TEST**

16HRV R:	1.453 - 1.458	1.458 - 1.462	1.458 - 1.466	1.455 - 1.460	1.461 - 1.465	1.461 - 1.470	1.463 - 1.469
X:	1.45575	1.45981	1.46111	1.45792	1.46317	1.46620	1.46542
20HRV R:	1.451 - 1.459	1.458 - 1.463	1.455 - 1.466	1.458 - 1.467	1.462 - 1.468	1.461 - 1.474	1.461 - 1.469
X:	1.45619	1.45994	1.46000	1.46150	1.46500	1.46760	1.46392
EOCV R:	1.452 - 1.460	1.456 - 1.461	1.452 - 1.463	1.456 - 1.465	1.459 - 1.465	1.453 - 1.464	1.458 - 1.466
X:	1.45756	1.45825	1.45711	1.45917	1.46258	1.45855	1.46117
EOCP R:	17 - 45	24 - 41	30 - 55	29 - 51	31 - 53	25 - 60	26 - 51
X:	34.8	32.3	43.6	38.2	44.3	42.0	37.3
CAP R:	3706 - 3773	3669 - 3757	3679 - 3795	3640 - 3744	3688 - 3776	3729 - 3797	3720 - 3799
X:	3730	3706	3726	3678	3739	3769	3757

**NASA STANDARD 50 A.H. BATTERY CELL: TYPICAL DPA RESULTS**

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

	35 LOI 6	35 LOI 4	35 LOI 2	35 LOI 1	20 LOI 17	20 LOI 14	20 LOI 12	20 LOI 7	20 LOI 4	20 LOI 1	POST-PCG
TOTNEG	134.64	137.97	133.91	135.70	136.26	130.58	145.54	163.18	152.55	151.82	
TOTPCG	25.59	26.32	23.39	24.33	26.73	21.23	26.14	24.49	29.77	36.47	
OXYGEN PCG	17.06	23.22	17.12	18.44	20.34	19.10	21.11	18.50	RVN:12.50	RVN:12.33	
RESIDUAL PCG	8.53	3.10	6.27	5.89	6.39	2.13	5.03	5.99			
AVN	31.18	30.90	34.16	27.73	28.45	34.86	36.74	37.96	30.68	23.87	
POS 0.5	59.48	62.97	59.95	64.82	62.03	61.98	62.85	57.49	61.70	60.73	
POS 0.0	71.59	71.85	71.71	71.43	73.50	71.58	72.93	65.66	70.79	67.71	
TOTPOS	81.66	78.98	79.36	85.73	83.79	79.64	81.46	77.36	INC	INC	

	35 LOI 6	35 LOI 4	35 LOI 2	35 LOI 1	20 LOI 17	20 LOI 14	20 LOI 12	20 LOI 7	20 LOI 4	20 LOI 1	POST-ATP
TOTNEG	136.82	138.27	135.80	140.28	135.91	135.91	143.60	156.17	153.27	154.96	
TOTPCG	26.00	27.37	28.41	29.17	31.44	26.69	24.83	27.86	35.96	35.29	
OXYGEN PCG	18.32	21.18	20.95	23.19	25.17	23.36	20.95	23.00	RVN:15.67	RVN:15.50	
RESIDUAL PCG	7.68	6.19	7.46	5.98	6.27	3.33	3.88	4.86			
AVN	24.35	28.39	27.84	25.56	24.85	30.10	40.72	32.17	25.43	22.98	
POS 0.5	64.18	64.19	63.24	64.75	61.44	61.43	58.07	60.48	59.83	64.96	
POS 0.0	79.63	73.31	72.76	75.83	72.85	73.28	70.36	72.86	64.55	70.29	
TOTPOS	82.92	81.37	78.92	83.59	84.31	76.91	78.95	83.73	INC	INC	

FINAL FILL AMT (cc's)	160	160	161.8	158 - 161	163	162	160	165	165	170
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**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
- 50AB20 LOT 13 (NASA PRECHARGE EXPERIMENT)
- 50AB34 LOT 3 (NASA KOH FILL EXPERIMENT)

**WHEN THE DATA READS:**

- 1.509 / 1.507
- 15.6 / 13.1 / 7.4
- 3511 / 3602 / 3571

**IT MEANS:**

- PRE-ACCEPT DATA / FLIGHT CELL DATA
- NORMAL PCG / 50% OVERPCG / 50% UNDER PCG
- 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**

<u>CELL LOT</u>	<u>INTER-ELECTRODE SPACING (mills)</u>	<u>PACK WEIGHT (grams)</u>	<u>TEFLONATION (gm/dm<sup>2</sup>)</u>	<u>FINAL KOH FILL AMOUNT (cc's)</u>
50AB20/21 LOT 1	9.21	1336	0.226	170
LOT 2	9.52	1345	0.300	170
LOT 3	9.03	1321	0.358	170
LOT 4	9.21	1331	0.446	165
LOT 5	8.90	1339	0.358	172
LOT 7	8.97	1342	0.520	165
LOT 9	9.12	1372	0.176	150 - 153
LOT 12	8.76	1365	not avi	160
50AB20 LOT 13	9.02	not avi	not avi	166
50AB25 LOT 1	9.02	1313	0.286	150 - 160
50AB20 LOT 14	8.76	1347	0.325	162
LOT 15	8.98	1354	0.200	160
LOT 16	8.68	1355	0.297	150 / 153
LOT 17	8.82	1359	0.259	160 / 163
50AB34 LOT 1	8.97	1380	not recorded	163
50AB35 LOT 1	8.94	1350	0.218	158 - 161
LOT 2	9.12	1354	0.219	162
50AB25 LOT 2	8.98	1354	0.200	157
50AB34 LOT 2	not avi	not avi	not recorded	161
LOT 3	not avi	not avi	not recorded	161.5 / 148 / 174.5
50AB35 LOT 4	8.67	1375	0.177	160
50AB35 LOT 2a	9.12	1354	0.219	166
50AB25 LOT 3	9.12	1354	0.219	162
50AB39 LOT 1	9.12	1354	0.219	166
50AB35 LOT 6	8.23	1386	0.284	158 - 160

## NASA STANDARD 50 A.H. BATTERY CELL: PLATE DATA

<u>PLATE LOT</u>	<u>POSITIVE LOADING</u> <u>(gm/dm<sup>2</sup>)</u>	<u>100% ECT POS.</u> <u>CAPACITY (A-M)</u>	<u>N/P RATIO</u>
50AB20/21 LOT 1	12.69	3864	1.843
LOT 2	12.53	3880	1.864
LOT 3	12.63	3647	1.845
LOT 4	12.79	3784	1.843
LOT 5	12.96	3777	1.820
LOT 6	13.09	3958	-
LOT 7	12.80	3797	1.840
LOT 8	12.13	3791	-
LOT 9	13.17	4014	1.776
LOT 10	12.32	3846	1.966
LOT 11	12.16	3873	2.015
LOT 12	-	-	-
50AB20 LOT 13	12.16	3873	1.830
50AB25 LOT 1	12.16	3873	1.830
50AB20 LOT 14	12.70	3791	1.897
50AB20 LOT 15	12.56	3881	1.880
LOT 16	12.74	3738	1.967
LOT 17	12.84	3974	1.837
LOT 18A/18C	13.08	4039	-
LOT 19	not avl	-	-
LOT 20	12.65	-	-
50AB34 LOT 1	12.50	4055	1.840
50AB35 LOT 1	-	3782	1.977
LOT 2A/2B	12.76	3756	1.963
LOT 3	not recorded	not recorded	-
50AB34 LOT 2	12.70	3888	1.901
LOT 3	12.46	3966	1.935
50AB35 LOT 4A/4B	12.51	3802	1.967
50AB35 LOT 5	12.69	NA	NA
LOT 6A/B/C	12.61	3994	1.851

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**NASA STANDARD 50 A.H. BATTERY CELL: 95°F/86°F CAPACITY**

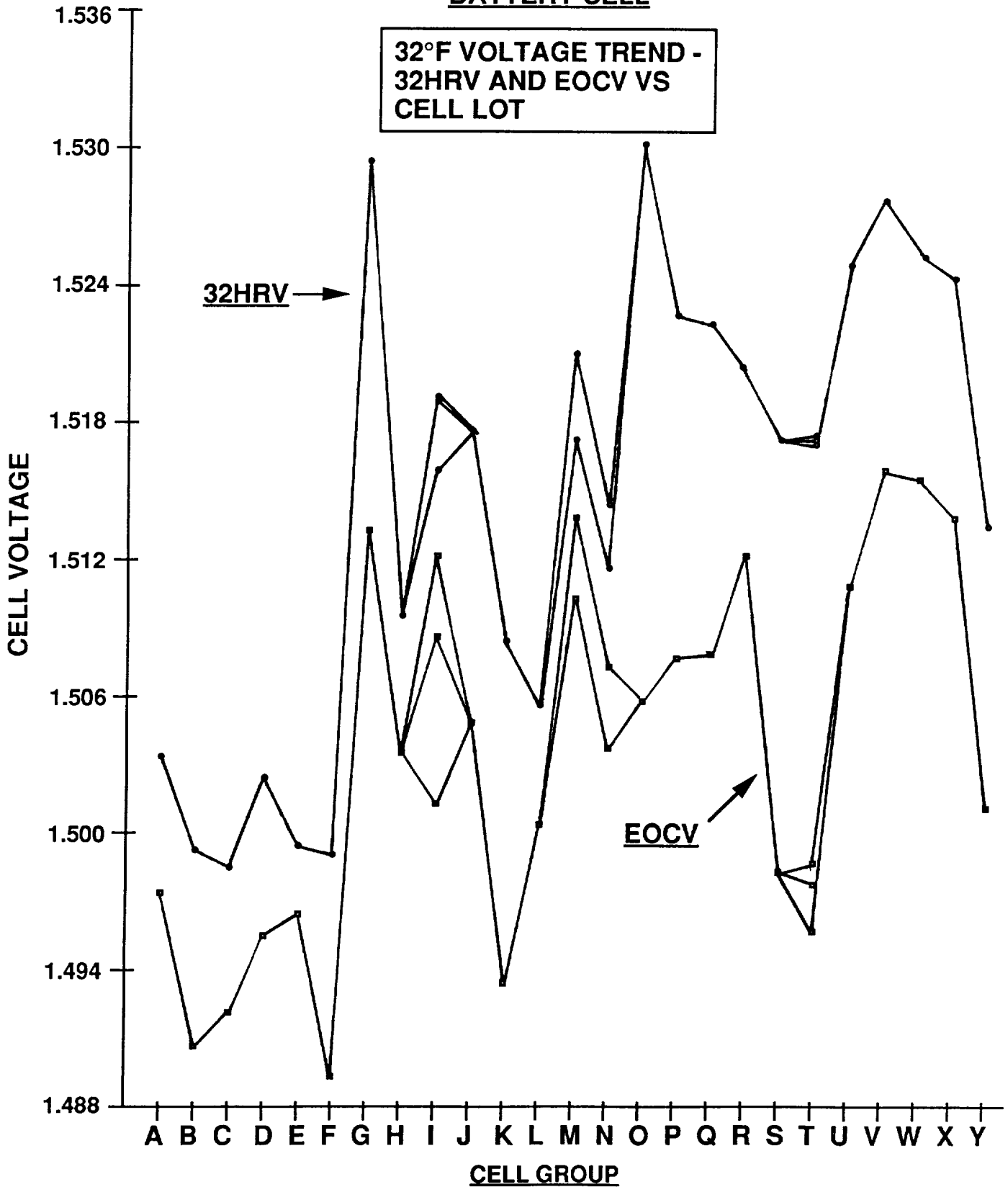
<u>CELL LOT</u>	<u>95°F EOCV</u>	<u>95°F CAPACITY (A-M)</u>	<u>86°F EOCV</u>	<u>86°F CAPACITY (A-M)</u>
50AB20/21 LOT 1	1.38842	3204		
LOT 2	1.39383	3286		
LOT 3	1.39230	3274		
LOT 4	1.39500	3445		
LOT 5	1.39202	3211		
LOT 7	1.39955	3434		
(3rd try) LOT 9	1.41401	3339		
LOT 12	1.39309	2695		
50AB20 LOT 13	1.38575/1.39075/1.39280	2503 / 2557 / 2658		
50AB25 LOT 1	1.40467	2903		
50AB20 LOT 14	1.38075	2118		
LOT 15	1.38833	2741		
LOT 16	1.40129 / 1.41133	3239 / 3349		
LOT 17	1.38340	2584		
50AB34 LOT 1			1.44011	3541
50AB35 LOT 1			1.41511	3342
LOT 2			1.42376	3617
50AB25 LOT 2			1.43813	3622
50AB34 LOT 2			1.42975	3467
LOT 3			1.41225	3304
50AB35 LOT 4			1.40825/1.40750/1.41050	3174 / 3107 / 3163
50AB35 LOT 2a			1.42522	3320
50AB25 LOT 3			1.41357	3344
50AB39 LOT 1			1.41829	3360
50AB35 LOT 6			1.42043	3368
			1.44246	3543

**NASA STANDARD 50 A.H. BATTERY CELL: 32°F CAPACITY**

<u>CELL LOT</u>	<u>32°F 32HRV</u>	<u>32°F EOCV</u>	<u>32°F EOCP [PSIG (-inHg)]</u>	<u>32°F CAPACITY (A-M)</u>
A 50AB20/21 LOT 1	1.50328	1.49740	52.5	3220
B LOT 2	1.49931	1.49067	49.8	3065
C LOT 3	1.49852	1.49225	44.2	3187
D LOT 4	1.50258	1.49566	44.0	3278
E LOT 5	1.49941	1.49650	44.3	2919
F LOT 7	1.49909	1.48940	53.9	3023
G (3rd try) LOT 9	1.52937	1.51341	16.1	3419
H LOT 12	1.50956	1.50369	25.2	3417
I 50AB20 LOT 13	1.51600/1.51900/1.51920	1.50125/1.50850/1.51220	9.4 / 5.3 / 7.6	3502 / 3631 / 3534
J 50AB25 LOT 1	1.51758	1.50492	21.9	3718
K 50AB20 LOT 14	1.50839	1.49335	(-1.3)	3255
L LOT 15	1.50567	1.50033	32.0	3112
M LOT 16	1.51714 / 1.52098	1.51029 / 1.51400	13.3 / 21.3	3547 / 3544
N LOT 17	1.51160 / 1.51429	1.50380 / 1.50733	5.4 / 15.1	3090 / 3133
O 50AB34 LOT 1	1.53015	1.50576	10.3	3488
P 50AB35 LOT 1	1.52285	1.50780	47.6	3636
Q LOT 2	1.52212	1.50801	50.0	3439
R 50AB25 LOT 2	1.52041	1.51213	32.4	3353
S 50AB34 LOT 2	1.51725	1.49800	11.0	3598
T LOT 3	1.51700/1.51750/1.51725	1.49775/1.49875/1.49575	13.8 / (-7.8) / 31.3	3632 / 3547 / 3542
U 50AB35 LOT 4	1.52492	1.51094	36.4	3320
V 50AB35 LOT 2a	1.52771	1.51600	75.0	3718
W 50AB25 LOT 3	1.52543	1.51557	56.6	3687
X 50AB39 LOT 1	1.52429	1.51386	60.0	3716
Y 50AB35 LOT 6	1.51374	1.50096	38.1	3387

**NASA STANDARD 50 A.H.  
BATTERY CELL**

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

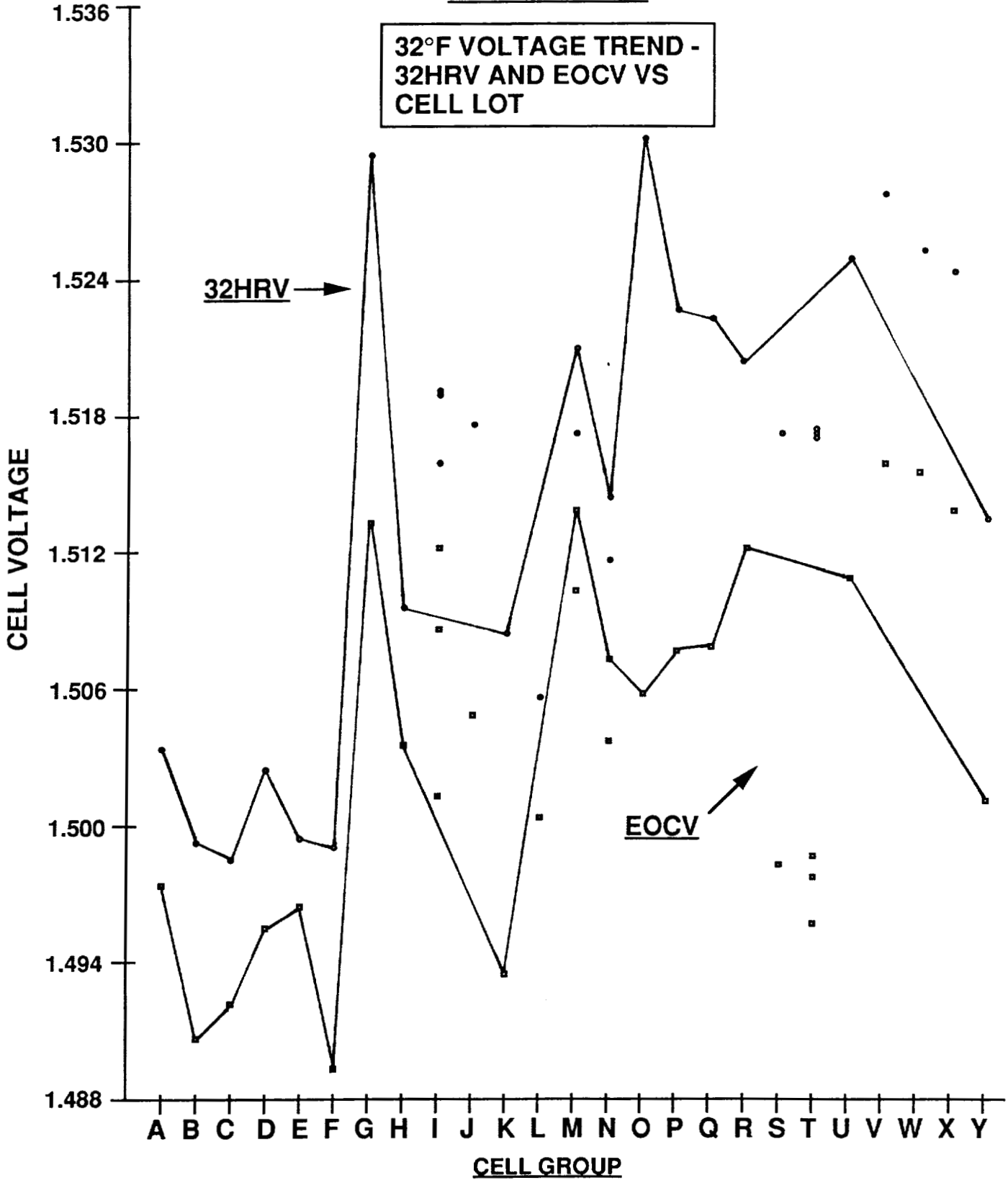


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**NASA STANDARD 50 A.H.  
BATTERY CELL**

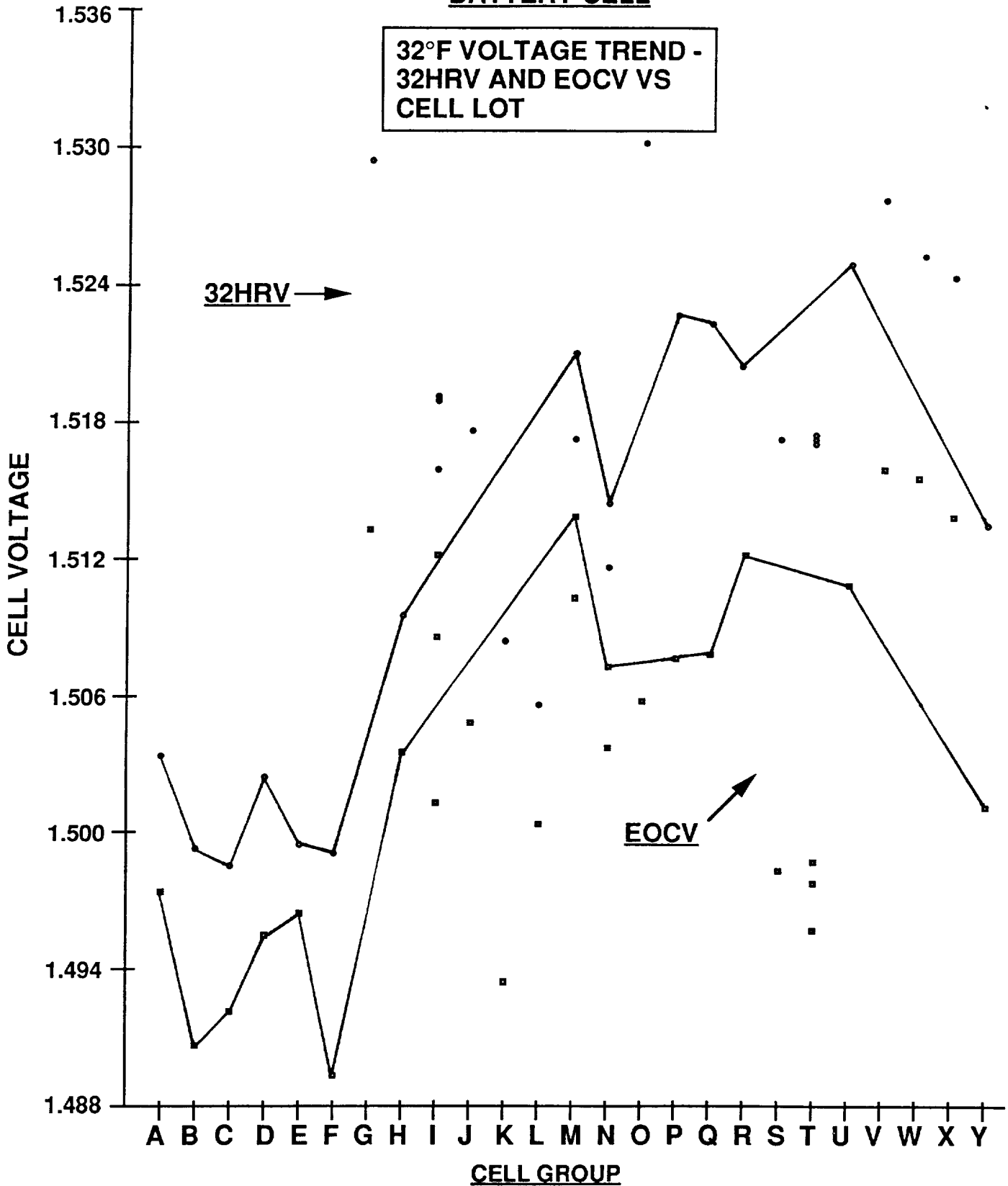
**32°F VOLTAGE TREND -  
32HRV AND EOCV VS  
CELL LOT**



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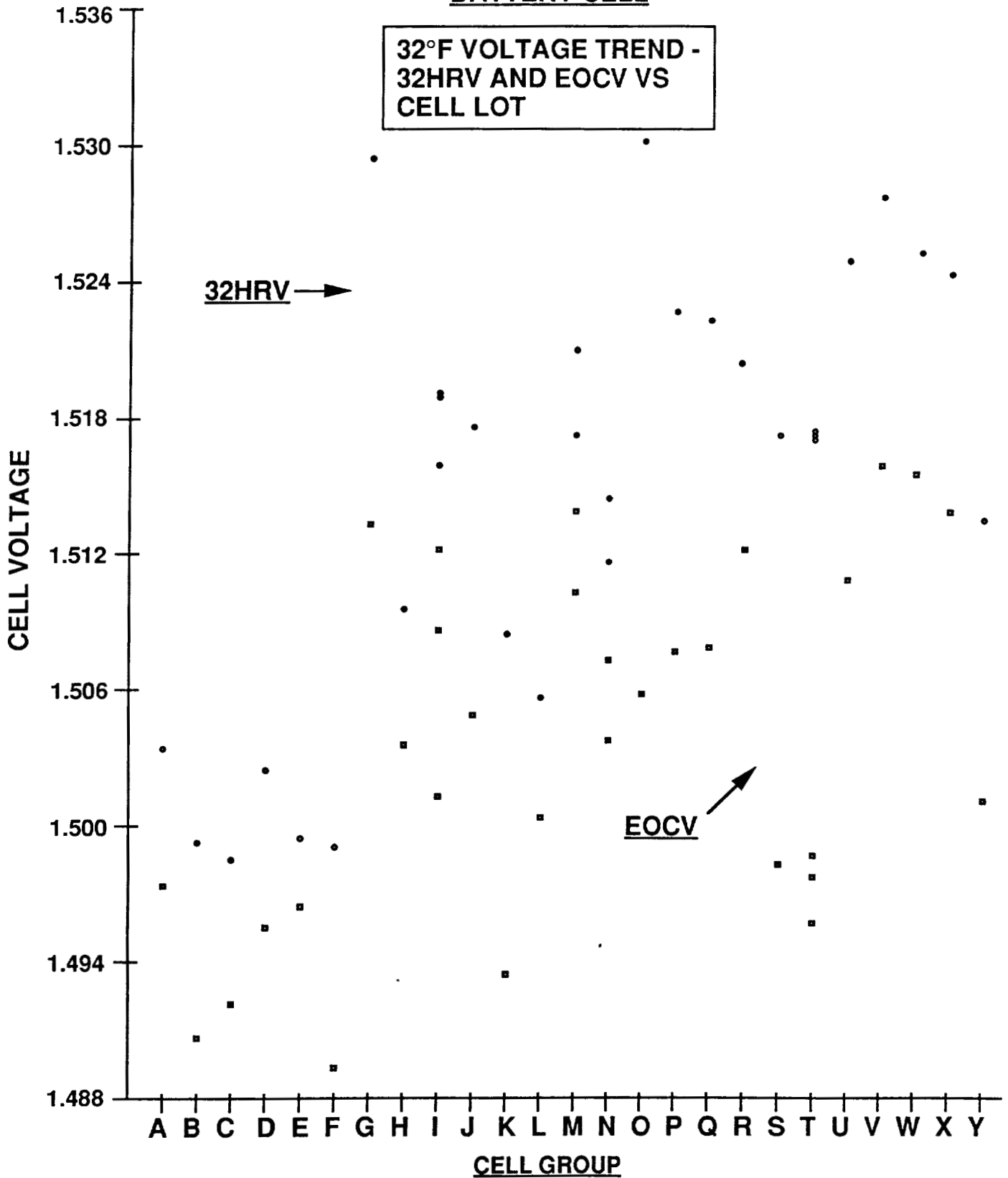
**NASA STANDARD 50 A.H.  
BATTERY CELL**

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



McDonnell Douglas Electronic Systems Company - Laser & Electronic Systems Division

**NASA STANDARD 50 A.H.  
BATTERY CELL**



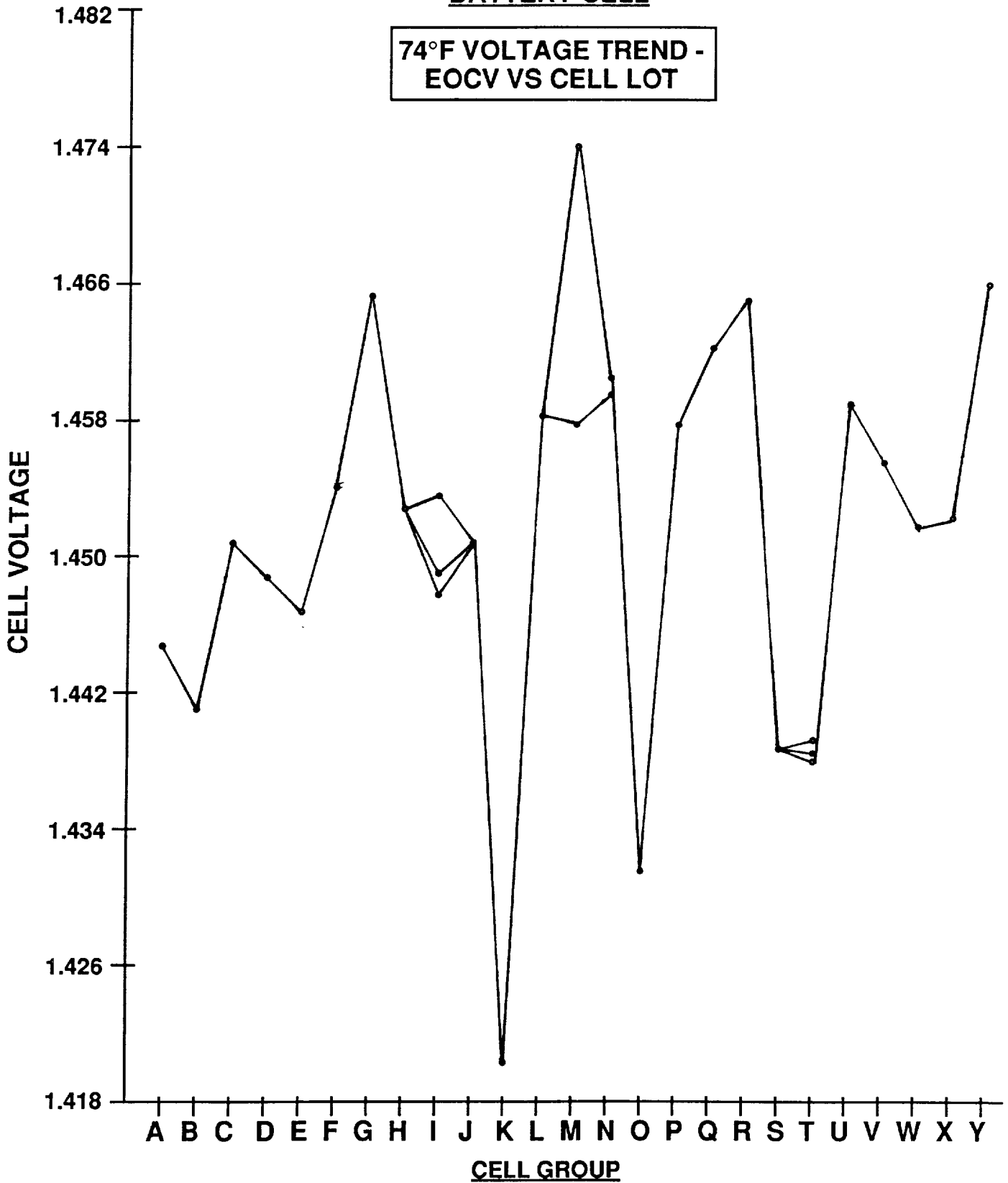
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**NASA STANDARD 50 A.H. BATTERY CELL: 2nd 74°F CAPACITY**

	<u>CELL LOT</u>	<u>74°F EOCV</u>	<u>74°F EOCP (PSIG)</u>	<u>74°F CAPACITY (A-M)</u>
A	50AB20/21 LOT 1	1.44484	33.9	3756
B	LOT 2	1.44103	34.1	3569
C	LOT 3	1.45081	44.1	3618
D	LOT 4	1.44886	34.0	3623
E	LOT 5	1.44680	27.7	3430
F	LOT 7	1.45406	51.2	3668
G	(6th try) LOT 9	1.46527	18.6	3803
H	LOT 12	1.45277	25.9	3597
I	50AB20 LOT 13	1.44892/1.44775/1.45340	12.8 / 8.5 / 10.0	3666 / 3559 / 3657
J	50AB25 LOT 1	1.45083	21.0	3478
K	50AB20 LOT 14	1.42013	2.2	3545
L	LOT 15	1.45833	26.0	3402
M	LOT 16	1.45771 / 1.47405	21.4 / 35.4	3654 / 3728
N	LOT 17	1.45940 / 1.46035	12.4 / 22.3	3687 / 3767
O	50AB34 LOT 1	1.43149	9.6	3907
P	50AB35 LOT 1	1.45764	48.0	3789
Q	LOT 2	1.46235	45.5	3730
R	50AB25 LOT 2	1.46501	43.0	3741
S	50AB34 LOT 2	1.43875	11.8	3901
T	LOT 3	1.43850/1.43925/1.43800	19.3 / 1.8 / 40.0	3897 / 3928 / 3873
U	50AB35 LOT 4	1.45893	39.0	3731
V	50AB35 LOT 2a	1.45557	41.3	3687
W	50AB25 LOT 3	1.45171	41.1	3715
X	50AB39 LOT 1	1.45229	48.0	3682
Y	50AB35 LOT 6	1.46612	43.2	3763

**NASA STANDARD 50 A.H.  
BATTERY CELL**

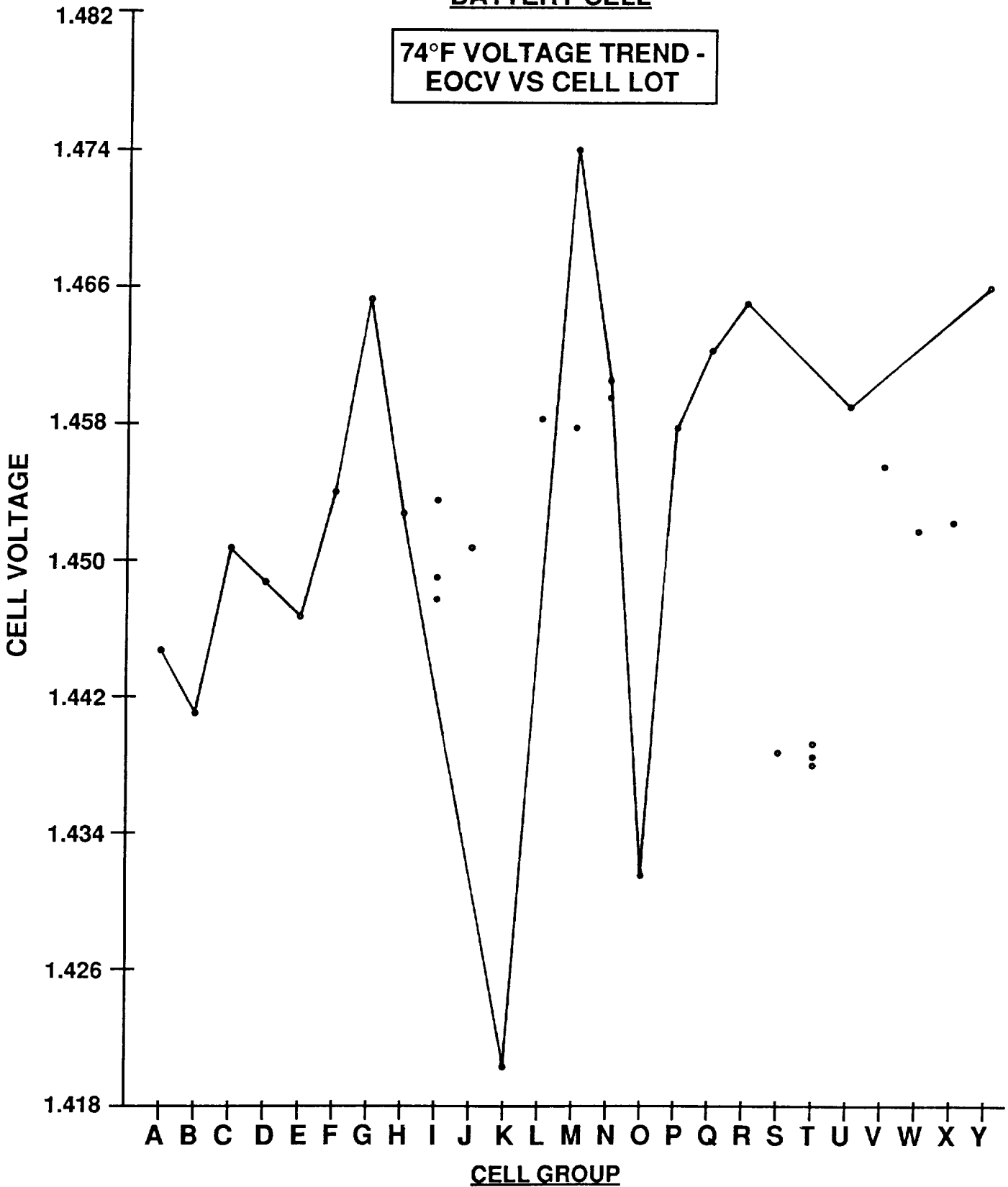
**74°F VOLTAGE TREND -  
EOCV VS CELL LOT**



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**NASA STANDARD 50 A.H.  
BATTERY CELL**

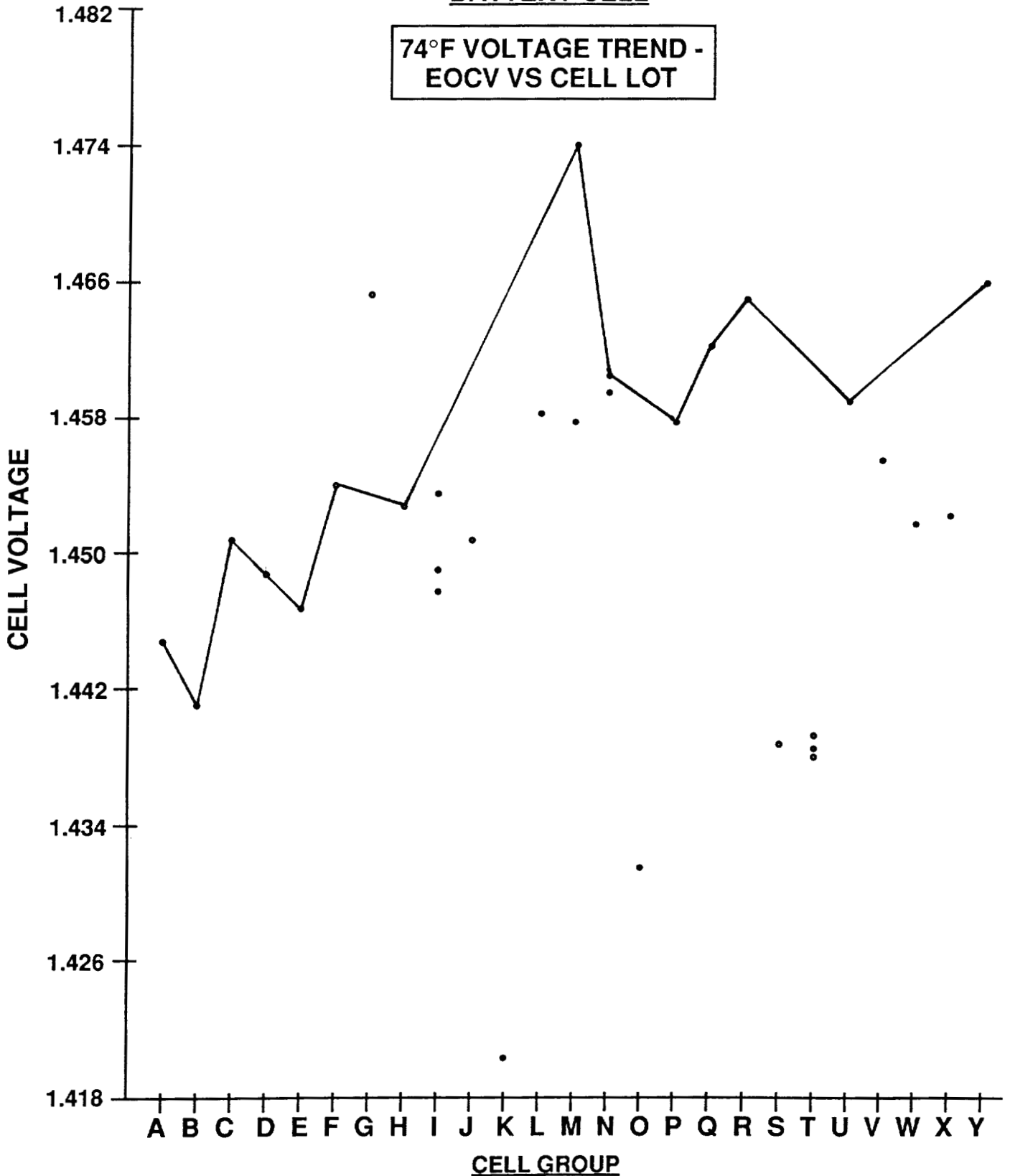
**74°F VOLTAGE TREND -  
EOCV VS CELL LOT**



McDonnell Douglas Electronic Systems Company - Laser & Electronic Systems Division

**NASA STANDARD 50 A.H.  
BATTERY CELL**

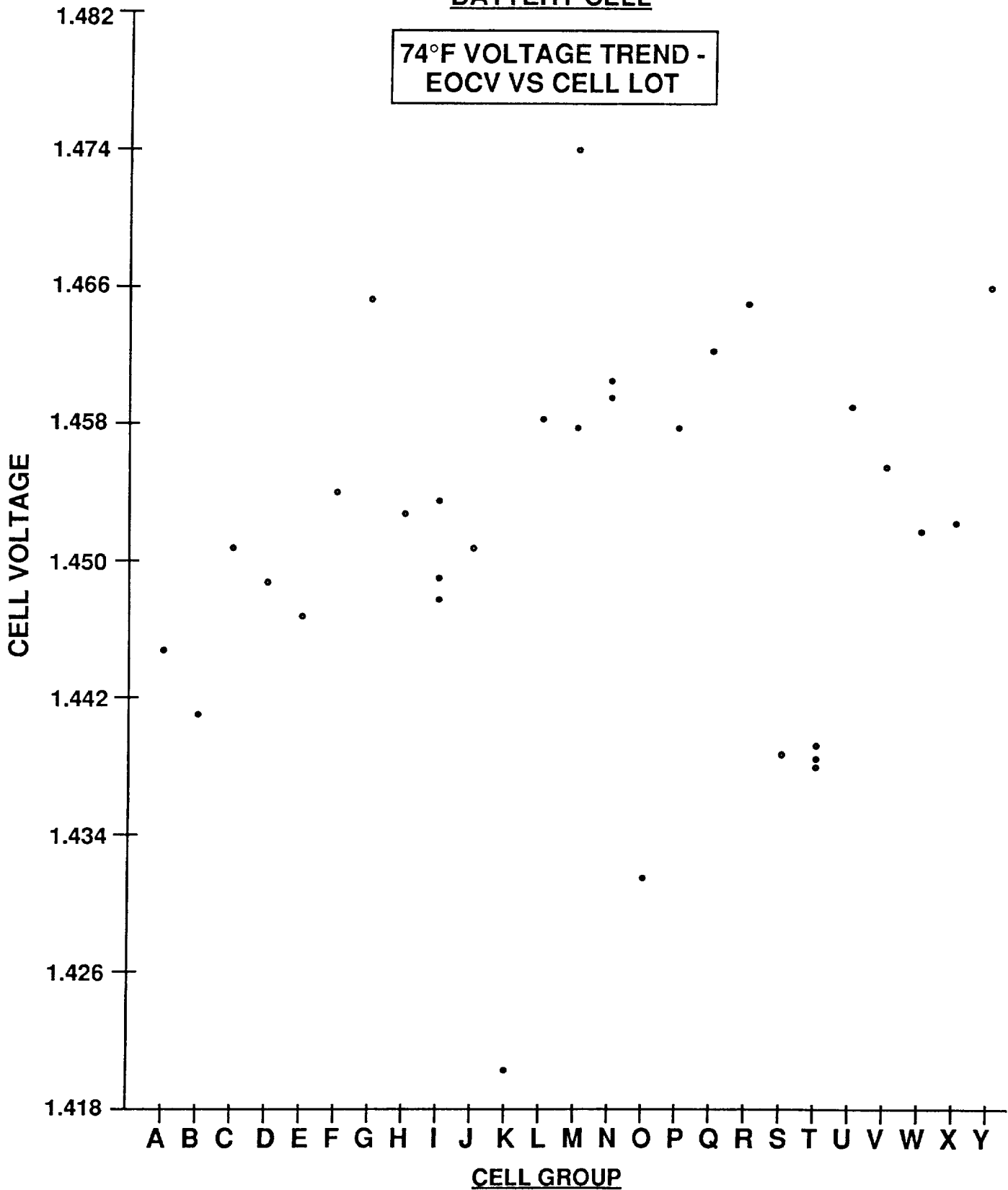
**74°F VOLTAGE TREND -  
EOCV VS CELL LOT**



McDonnell Douglas Electronic Systems Company - Laser & Electronic Systems Division

NASA STANDARD 50 A.H.  
BATTERY CELL

74°F VOLTAGE TREND -  
EOCV VS CELL LOT



McDonnell Douglas Electronic Systems Company - Laser & Electronic Systems Division



**NASA STANDARD 50 A.H. BATTERY CELL: DPA CELL DATA**

CELL LOT - S / N:	TOTAL NEGATIVE (AH)	OVERCHARGE PROTECTION (AH)	TOTAL PRECHARGE (AH)	SAMPLE POINT:		
				PCG	ATP	OTHER
50AB20/21 L1-32	151.82	23.87	36.47	X		
L1-29	154.96	22.98	35.29		X	
LOT 2-51	154.96	33.02	29.91	X		
L2-102	148.44	32.04	30.23			
L2-68	153.03	25.56	37.61		X	
LOT 3-25	148.68	32.97	25.73	X		
L3-2	155.45	15.97	38.72		X	
LOT 4-25	152.55	30.68	29.77	X		
L4-53	153.27	25.43	35.96		X	
LOT 5-25	151.10	23.91	35.87	X		
L5-50	158.59	27.68	28.78		X	
LOT 7-54	163.18	37.96	24.49	X		
L7-55	156.17	32.17	27.86		X	
LOT 9-25	137.08	25.65	28.04	X		
L9-93	131.76	11.55	38.70		X	
L9-52	135.14	5.83	43.60		X	
L9-51	131.27	17.40	32.72			EXP
LOT 12-92	143.60	36.74	26.14	X		
L12-25	145.54	40.72	24.83			
(OVER) LOT 13-13	134.42	34.92	17.29		X	
(NORMAL) L13-5	132.64	3.34	38.86			R/A
(OVER) L13-16	132.64	6.40	36.64			R/A
(UNDER) L13-20	132.64	8.94	33.82			R/A
50AB25 L1-6	132.64	7.46	36.90			R/A
LOT 1-11	132.64	17.58	30.78			R/A

**NASA STANDARD 50 A.H. BATTERY CELL: DPA CELL DATA**

CELL LOT - S / N:	TOTAL	OVERCHARGE	TOTAL	SAMPLE POINT:		
	NEGATIVE (AH)	PROTECTION (AH)	PRECHARGE (AH)	PCG	ATP	OTHER
50AB20 LOT 14-79	130.58	34.86	21.23	X		
L14-78	135.91	30.10	26.69		X	
LOT 15-7	137.86	34.70	25.27	X		P/A
L15-6	127.30	7.98	39.35			R/A
LOT 16-24	136.26	33.99	24.68	X		P/A
L16-16	135.14	27.12	27.87			500~
L16-84	134.90	26.11	28.42			500~
L16-88	135.91	33.40	24.07	X		
L16-1	136.13	29.77	29.31		X	P/A
LOT 17-90	139.73	33.65	26.52	X		
L17-87	136.26	28.45	26.73	X		
L17-81	137.00	26.62	29.95			
L17-69	135.91	24.85	31.44		X	F/A
50AB34 LOT 1-16	142.82	33.13	22.41	X		
L1-15	139.55	27.06	27.87		X	
50AB35 LOT 1-81	135.70	27.73	24.33	X		
L1-32	140.28	25.56	29.17		X	
LOT 2-36	133.91	34.16	23.39	X		
L2-63	135.80	27.84	28.41		X	
50AB25 LOT 2-37	138.01	30.85	24.72	X		
50AB34 LOT 3-20	139.26	31.64	24.65	X		
50AB35 LOT 4-39	137.97	30.90	26.32	X		
L4-108	138.27	28.39	27.37		X	
LOT 6-27	134.64	31.18	25.59	X		
L6-103	136.82	24.35	26.00		X	

**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**

**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 SHUTDOWNS 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  
GLENN KLEIN  
GUY RAMPPEL  
TRISH BROWN  
DR. GERRY HALPERT  
THOMAS YI  
KEN SCHWERT  
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.





**NASDA**  
NATIONAL SPACE DEVELOPMENT AGENCY OF JAPAN

## INTRODUCTION

- 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 —

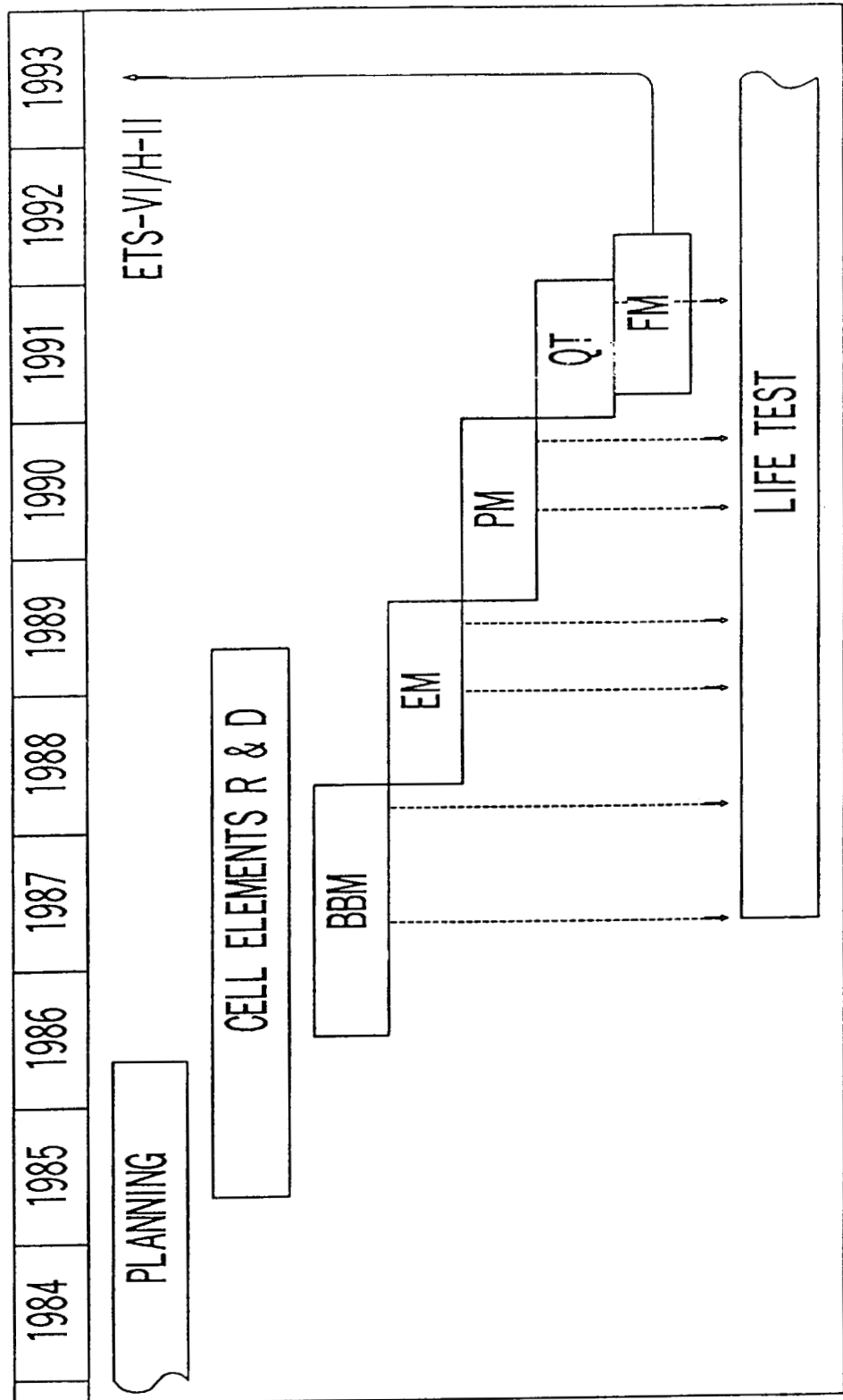
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INTRODUCTION  
CELL DESIGN  
INITIAL DATA  
BATTERY TEST FACILITY IN TSUKUBA SPACE CENTER  
EVALUATION OF CELL PARAMETERS  
•SEPARATOR •ELECTROLYTE •PRECHARGE  
TYPICAL LIFE DATA  
•GEO TEST •LEO TEST •BATTERY ASSY LEO TEST  
•ACCELERATED TEST  
ADVANCED CELL DESIGN  
CONCLUSION

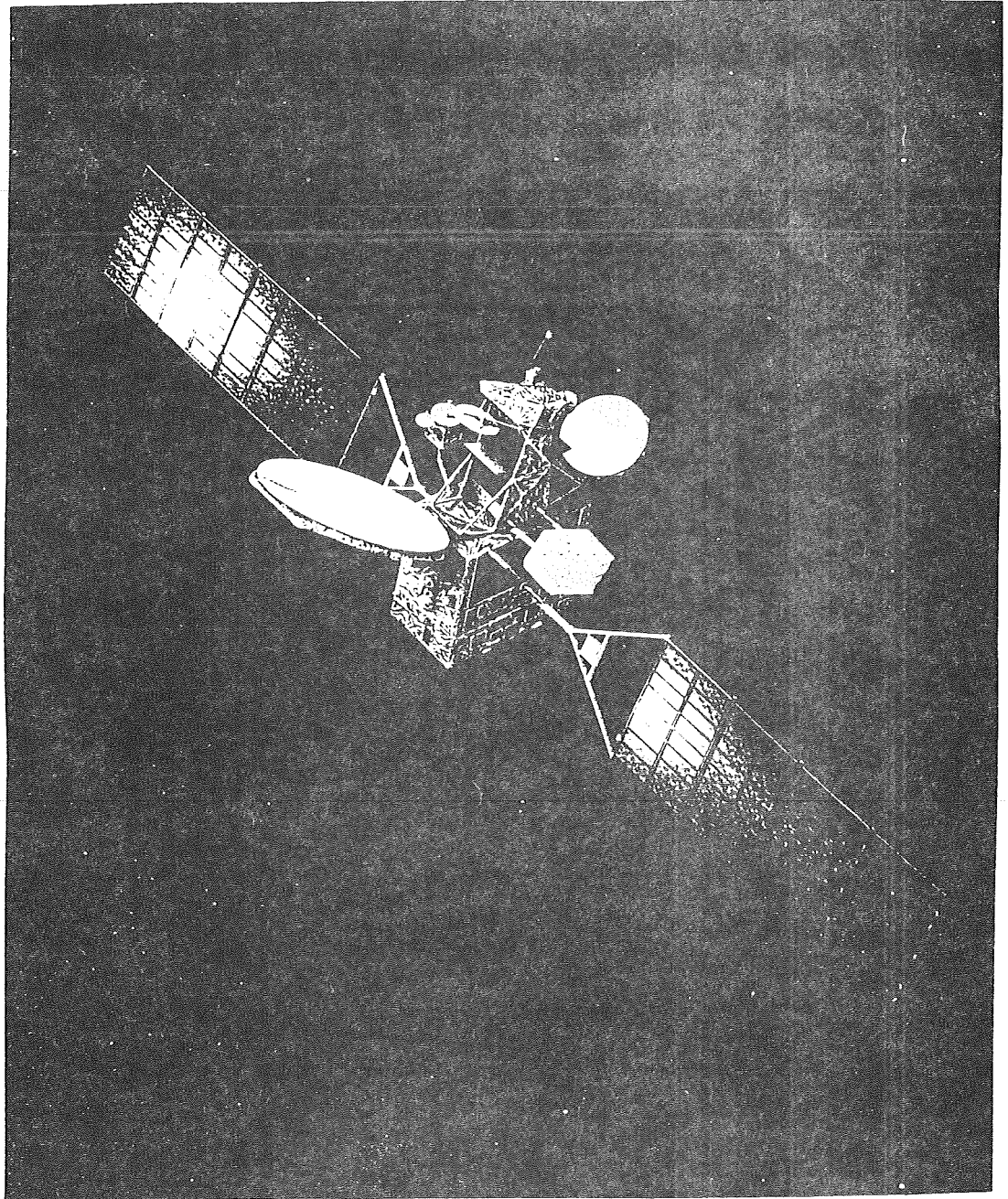




# MILESTONE OF 35AH Ni-Cd CELL DEVELOPMENT

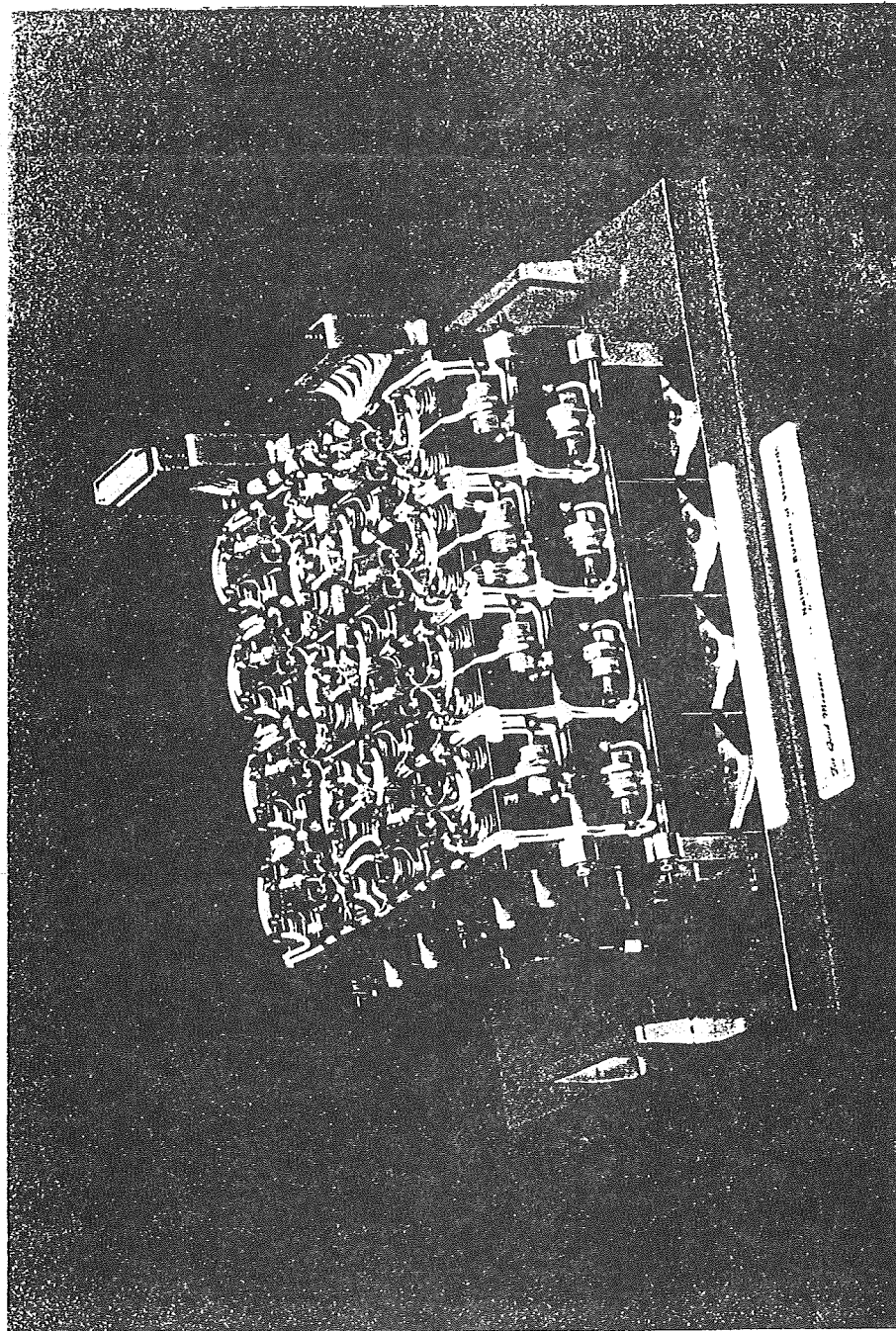


ENGINEERING TEST SATELLITE VI (ETS-VI)





# ETS-VI Ni-Cd BATTERY



\* Engineering Model

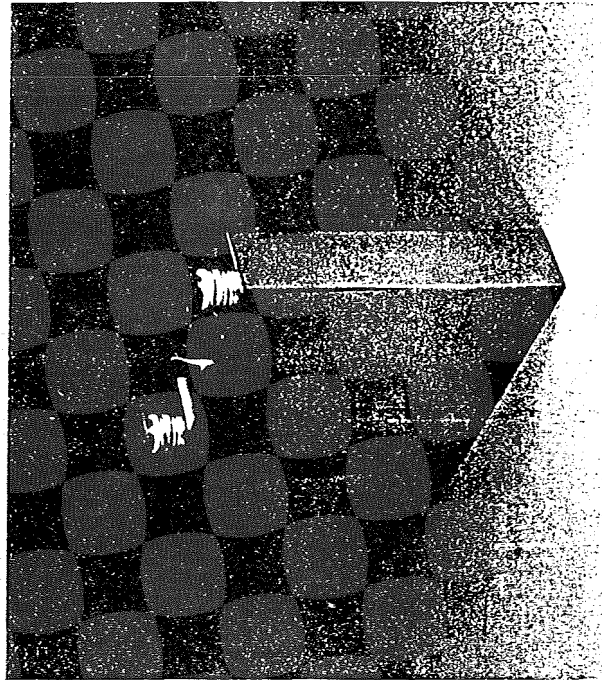


**NASDA**  
NATIONAL SPACE DEVELOPMENT AGENCY OF JAPAN

# 35 AH SPACE Ni-Cd CELL

## CELL MAJOR SPECIFICATIONS

Rated Capacity	35 AH	
Mission	GEO	10 Years, 1,000 cycles
	LEO	3 Years, 20,000 cycles
Weight	max. 1050 g	
Energy Density	40 WH/kg	
Mechanical Strength	Burst Pressure	35 kgf/cm <sup>2</sup>
	Pressure Cycling	50,000 cycles (0~3.5 kgf/cm <sup>2</sup> g)

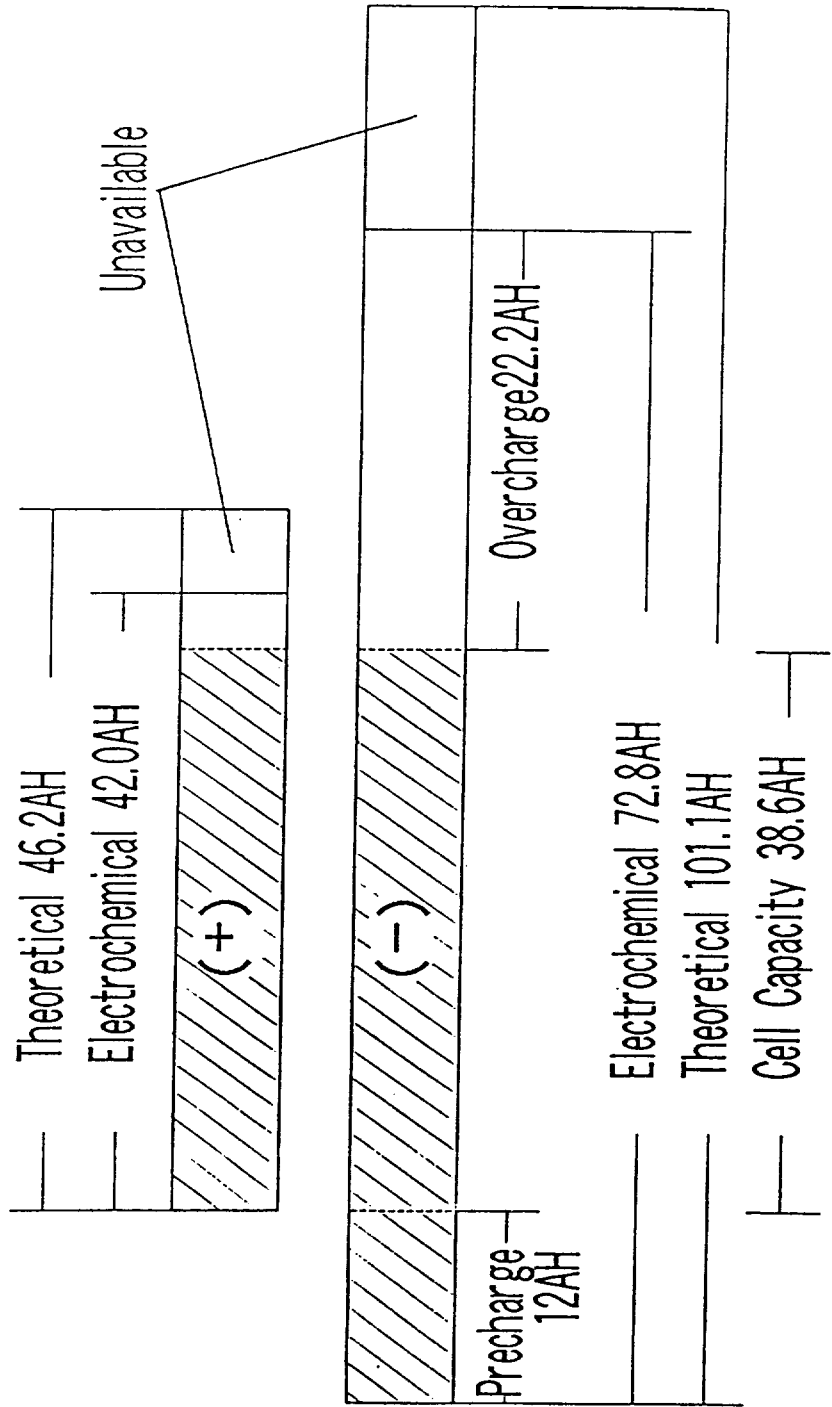


EXTERNAL VIEW OF Ni-Cd CELL

- 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.

	(+)	(-)
Electrode Dimension	104.4 x 100 x 0.63mm	104.4 x 100 x 0.80mm
Sinter Plate Porosity	85 %	86 %
Loading Level	2.4 g/cc-void	3.0 g/cc-void
Number of Plate	13	14
Electrode Capacity	42.0 AH	72.8 AH
Capacity Ratio		1.73
Separator	Nylon	
Precharge Capacity	12 AH	
Electrolyte	31%KOH 98g	
Cell Dimension	115.2H x 106.9W x 25.2Tmm (max.127Hmm)	
Cell Weight	max.1050g	
Cell Capacity	38.6AH	

# ELECTRODE CAPACITY DESIGN





**NASDA**  
NATIONAL SPACE DEVELOPMENT AGENCY OF JAPAN

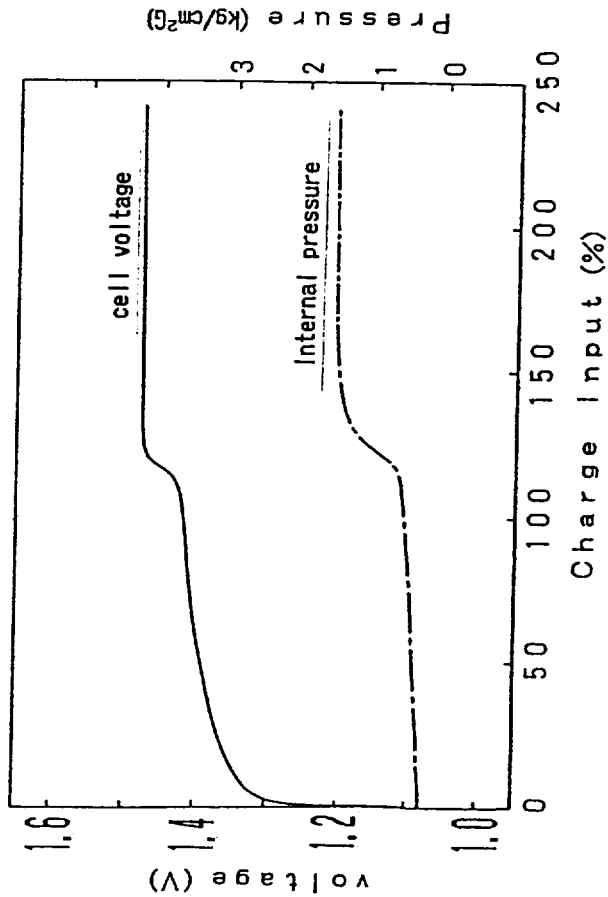
## CELL INITIAL DATA

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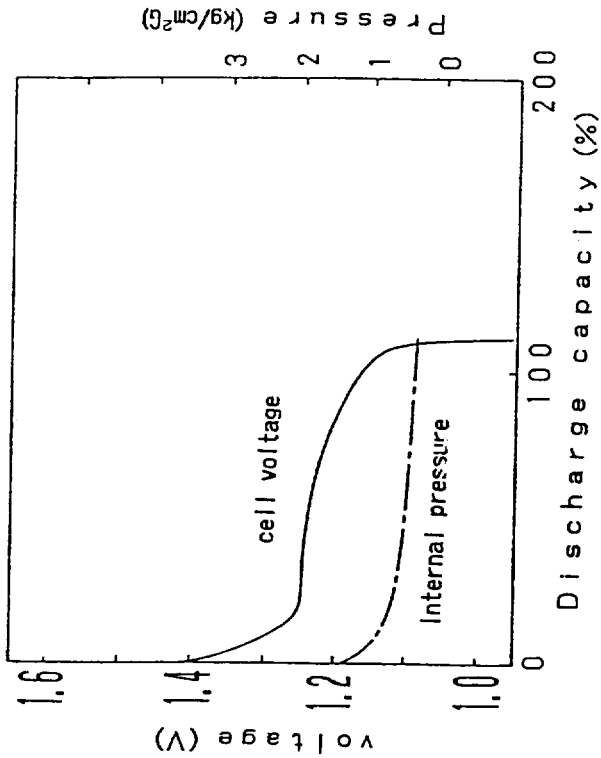
- The main initial tests of QT phase are as follows:
  - overcharge capacity test (-5°C, 20°C, 35°C)
  - high rate discharge test
  - internal impedance
  - alkaline leakage
  - open circuit voltage recovery
  - weight & dimensions check
  - some mechanical strength tests
- 94 sample cells have been used for these tests.
- Cell capacity, end of charge voltage, and weight data were distributed within narrow range.



CHARGE

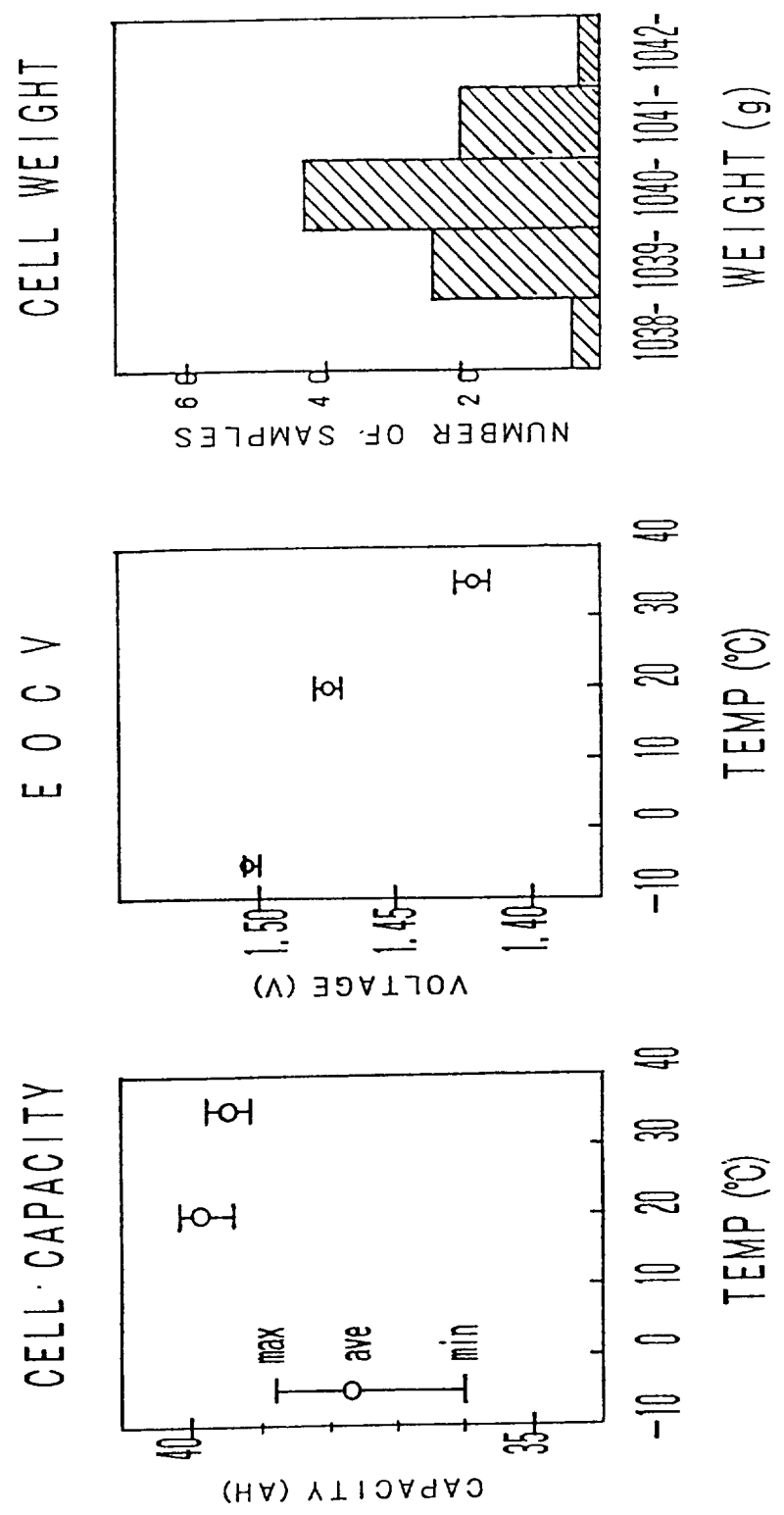


DISCHARGE



TEST CONDITION  
 CHARGE : 0.1C for 2.4 Hours  
 DISCHARGE : 0.5C to 1V  
 TEMP : 20°C

• 94 sample cells have been used for initial tests of QT-phase.  
 • Capacity, EOCV, & Weight data are within narrow range.



TEST CONDITION CHARGE : 0.1C for 24 Hours (in -5°C, 0.05C for 48 Hours)  
 DISCHARGE : 0.5C to 1V

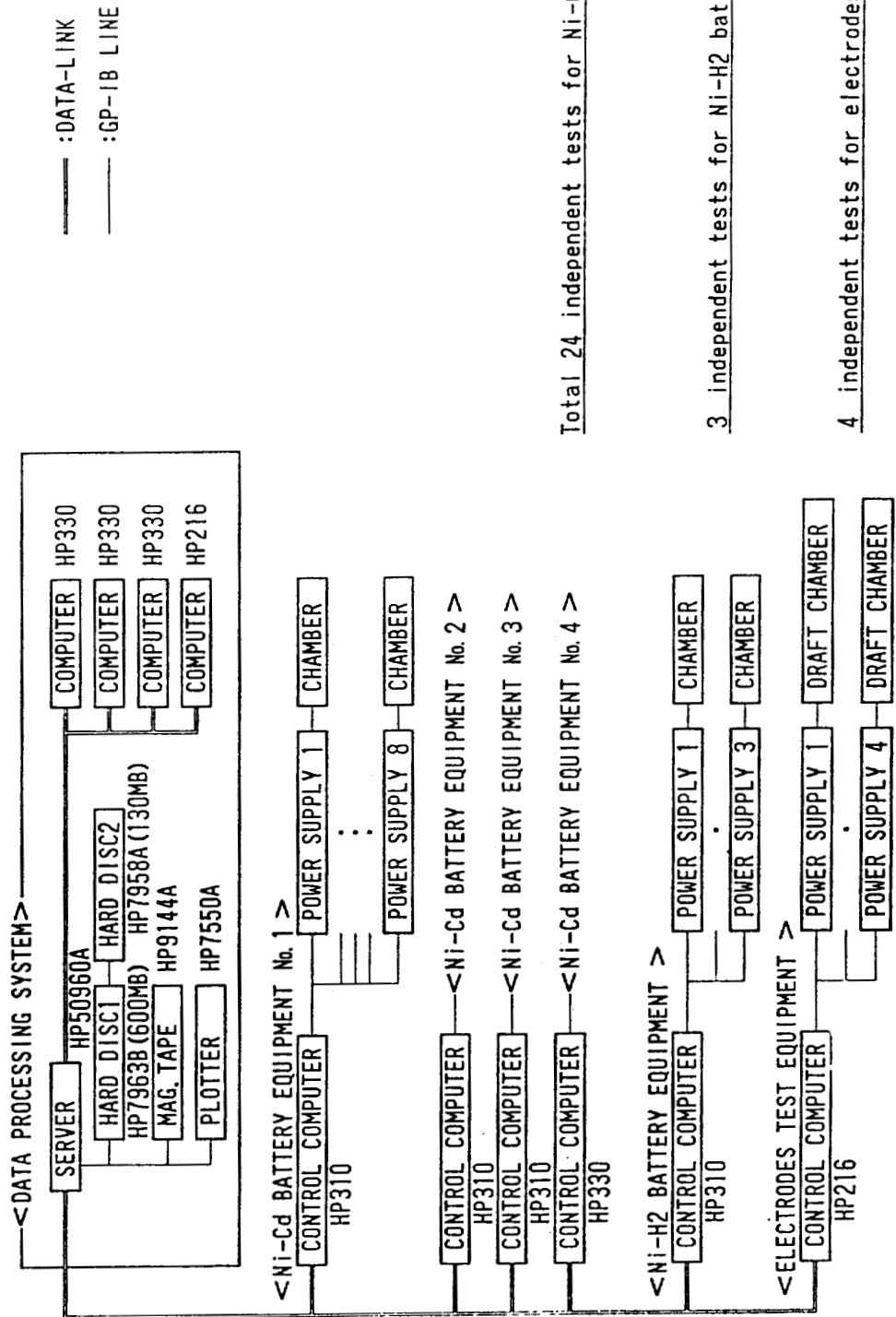


## BATTERY TEST FACILITY IN TSUKUBA SPACE CENTER

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- NASDA has a battery test facility in TKSC, which consists of 4 equipment for Ni-Cd batteries, and 1 equipment for Ni-H<sub>2</sub> batteries and for electrodes respectively.
- Each test equipment is independently controlled by each computer.
- Test data is transferred from each computer to a data server, 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  $\pm 2^{\circ}\text{C}$  range of the expected temp.
- Also cooling plates are available especially for battery assembly tests.

# BATTERY TEST SYSTEM IN TSUKUBA SPACE CENTER



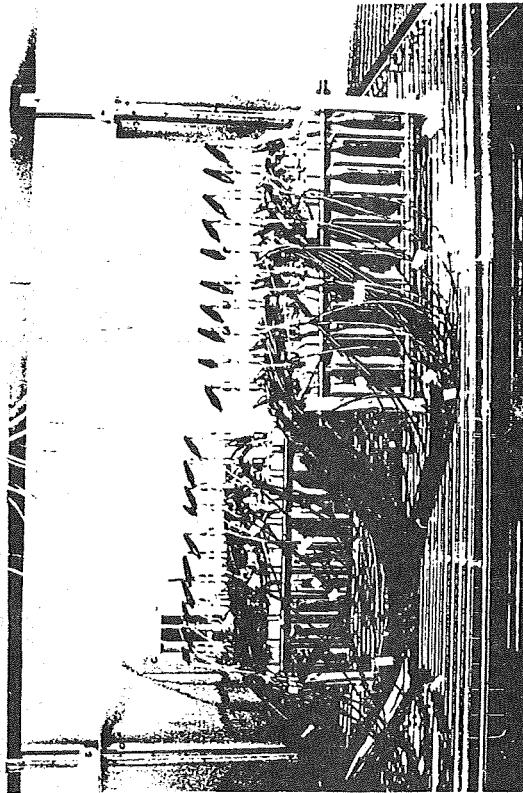
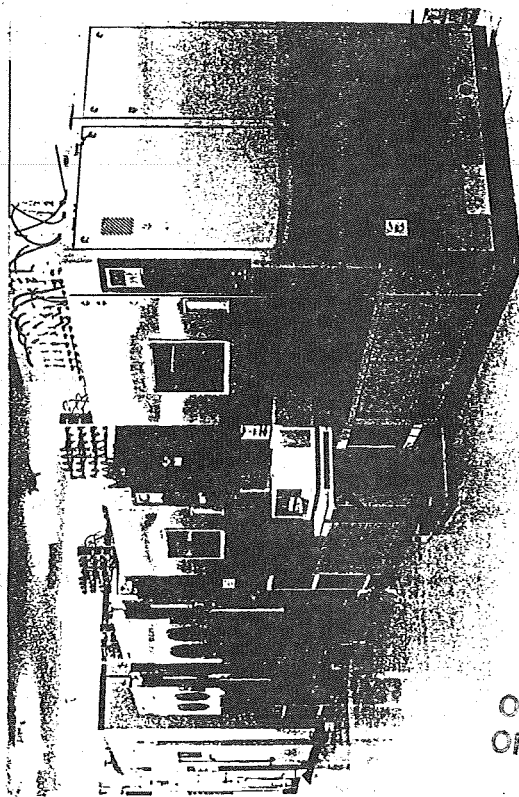
BATTERY TEST at NASDA TKSC



ORIGINAL PAGE IS  
OF POOR QUALITY



筑波宇宙センター Ni-Cd 電池寿命試験



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OF POOR QUALITY



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NATIONAL SPACE DEVELOPMENT AGENCY OF JAPAN

## LIFE TEST DATA

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- 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

Oct 8, 1991

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

\*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

TEST TYPE CONDITION	G E O	L E O	ACCELERATED
Charge	0.1C, 9 Hours	0.3C, 52.5 min	0.3C, 220min
Discharge	0.5C, 1.2 Hours	0.5C, 30 min	0.5C, 96min
DOD	60 %	25 %	80 %
Charge return	150 %	105 %	138 %
Reconditioning(*1)	every 4 5 cycles	DO NOT	DO NOT
Capacity test (*2)	every 4 5 cycles	about every 5000cycles	about every 1000cycles

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

\*2 : Capacity test is 0.5C discharge to 1 Volt, and then charge return is 0.1C for 16Hours.



## EVALUATION OF SEPARATOR

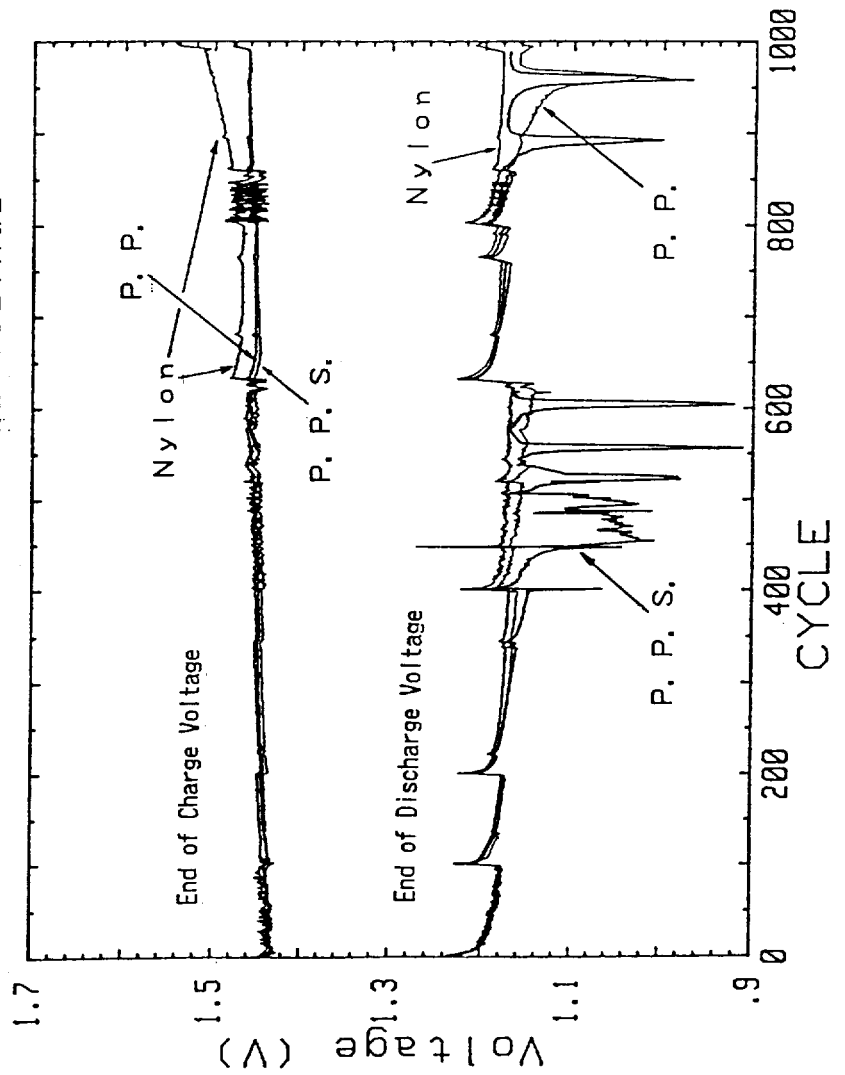
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- BBM cells have been used for this test.
- Candidates for the separator material were nylon, polypropylene (PP), and poly-phenylene sulfide (PPS).
- The test condition was accelerated cycling with higher temperature than for the other tests.
- As 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

# EVALUATION OF SEPARATORS

The current cells are using a nylon separator,  
 since PP & PPS separator cells could not keep normal EODV.

## CYCLE TREND OF CELL VOLTAGE



## SEPARATOR CANDIDATES

	Nylon	PP	PPS
Thickness	0.21 mm	0.21 mm	0.22 mm
Weight	87g/m <sup>2</sup>	79g/m <sup>2</sup>	84g/m <sup>2</sup>
Retention	32.6%	28.2%	32.0%

## TEST CONDITION

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

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

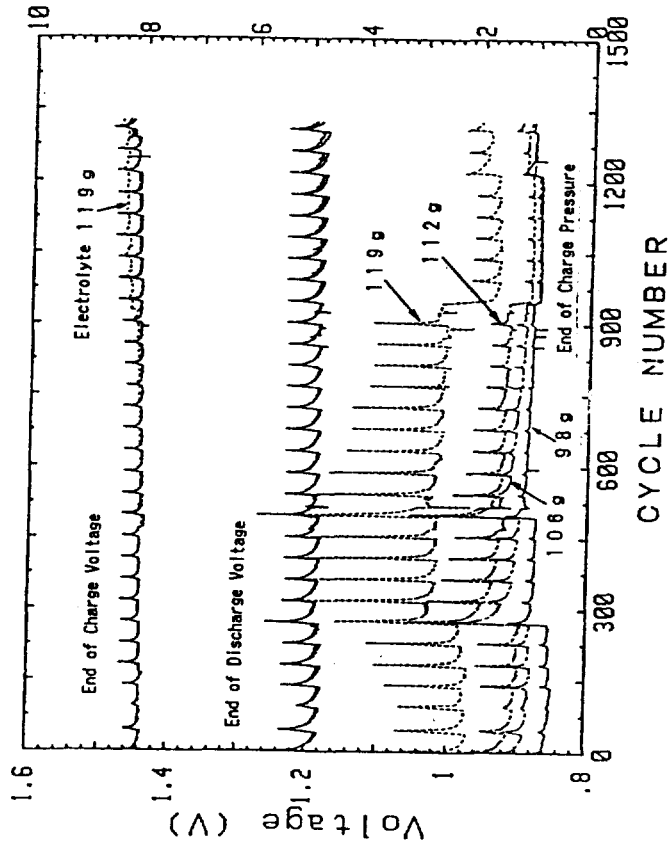
- When comparing the precharge under constant electrolyte at 106g, higher precharge caused the rising of EOCV and EOCP.
- We selected a 12AH precharge, because the 12AH-precharge cell has a lower EOCP, and is more stable in capacity than the 7AH-precharge cell.



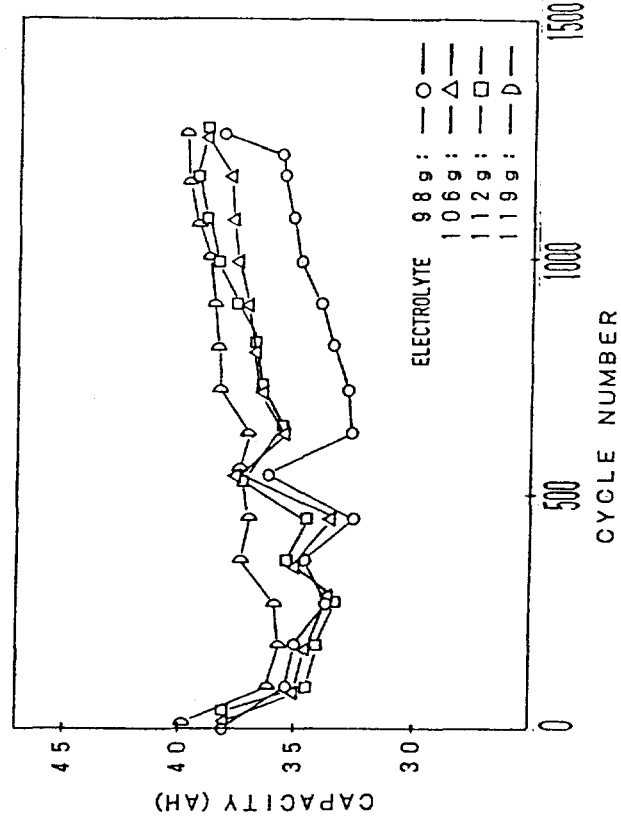
# EVALUATION OF ELECTROLYTE

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

## CYCLE TRENDS OF VOLTAGE & PRESSURE



## CYCLE TRENDS OF CAPACITY

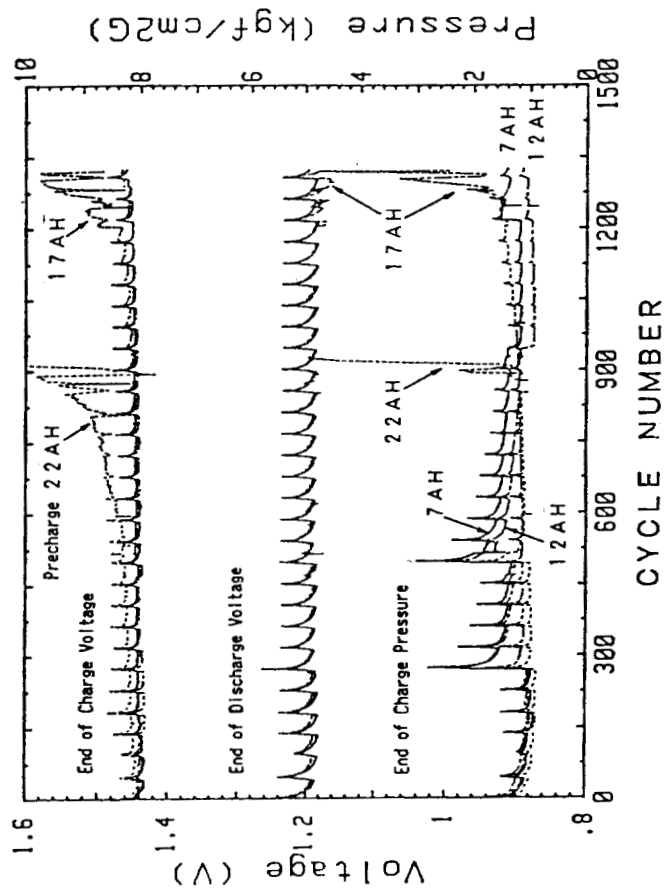


TEST CONDITION : SAME AS GEO TEST

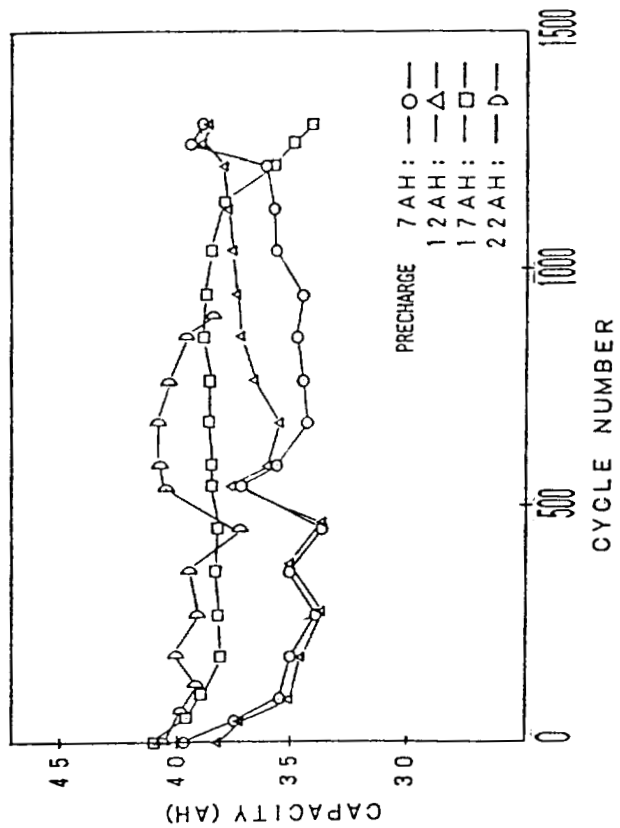
# EVALUATION OF PRECHARGE

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

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### 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.

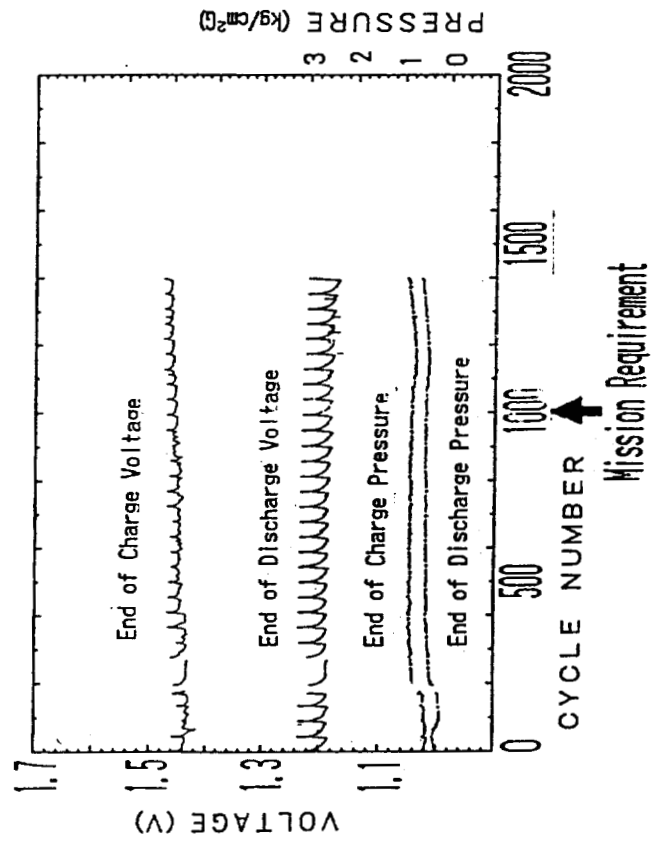
**Accelerated test**

- 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,

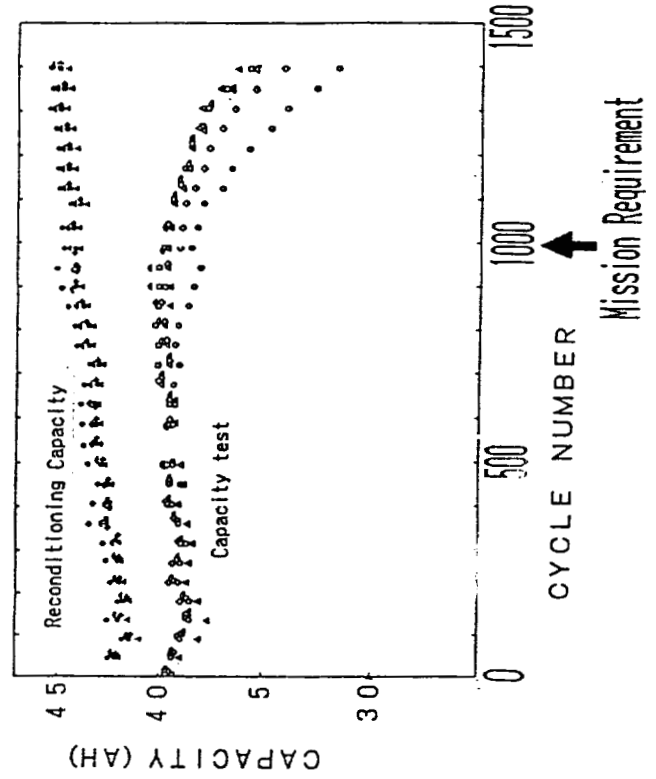


Cell voltage, pressure, and capacity is stable during the mission-required cycles

CYCLE TREND OF VOLTAGE & PRESSURE



CYCLE TREND OF CAPACITY

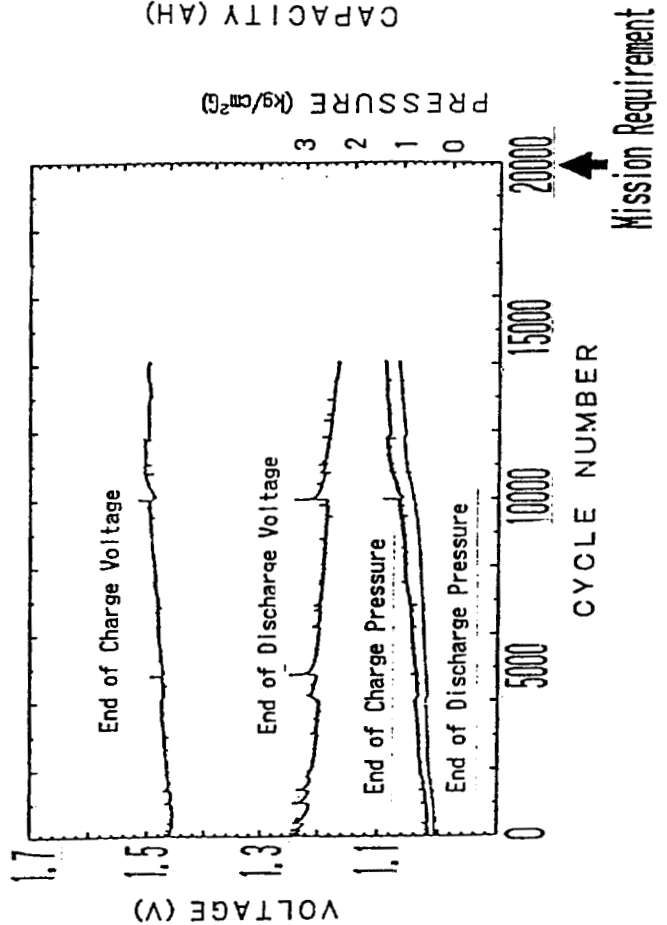




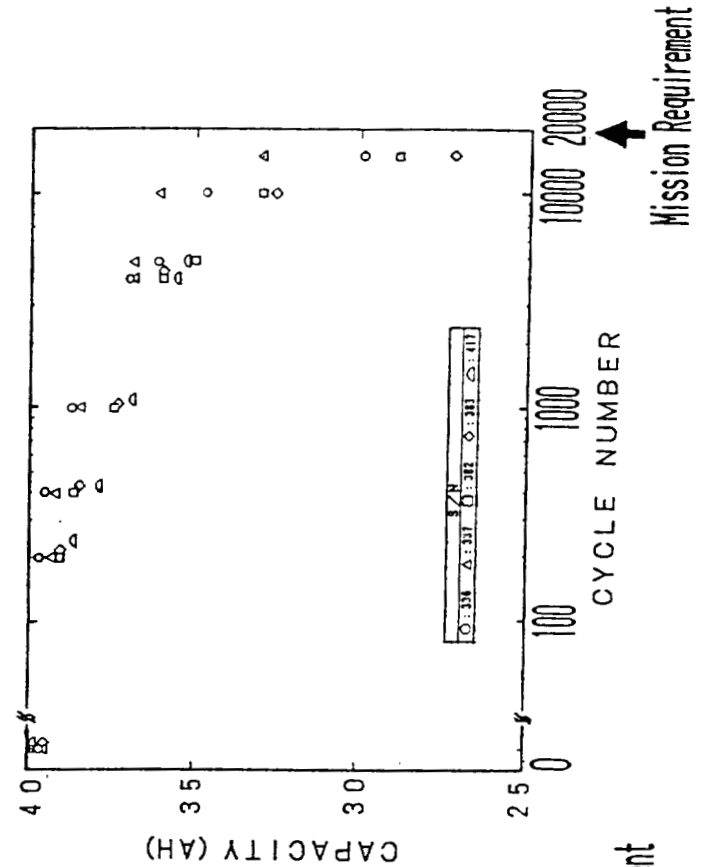
# TYPICAL LIFE DATA (LEO SIMULATION)

The expected result is over 20AH of capacity,  
and over 1.05V of EODV after 20,000 cycles.

### CYCLE TREND OF VOLTAGE & PRESSURE



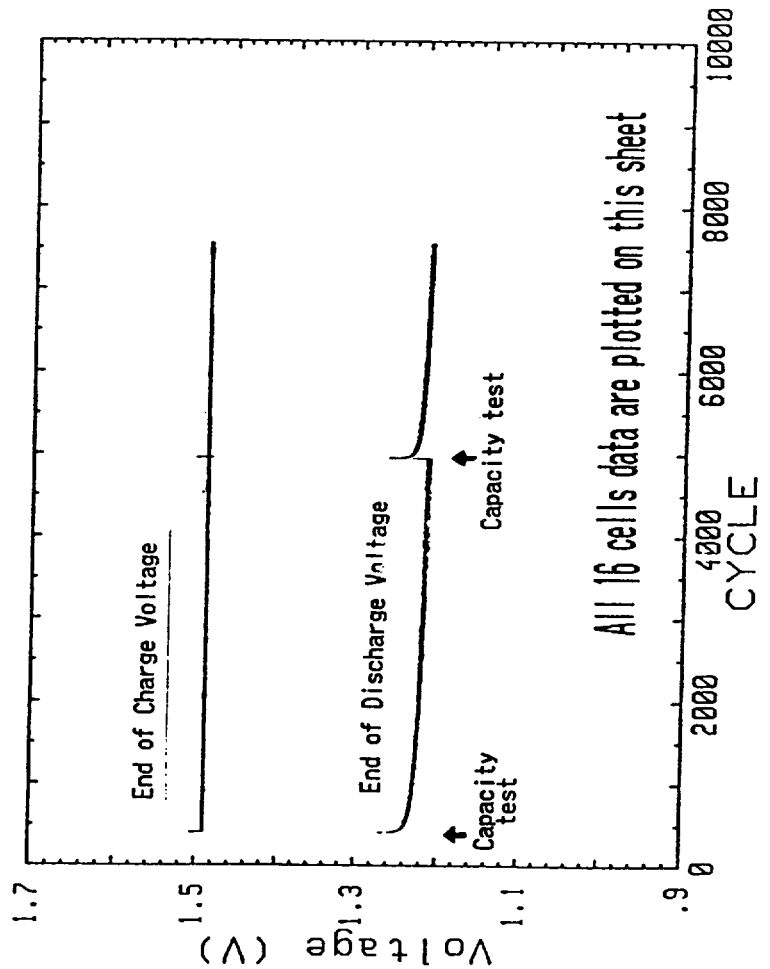
### CYCLE TREND OF CAPACITY



## TYPICAL LIFE DATA (BATTERY ASSY LEO)

The uniformity of EOCV & EODV of each cell was observed under constant voltage charging with battery assy.

### CYCLE TREND OF CELL VOLTAGE



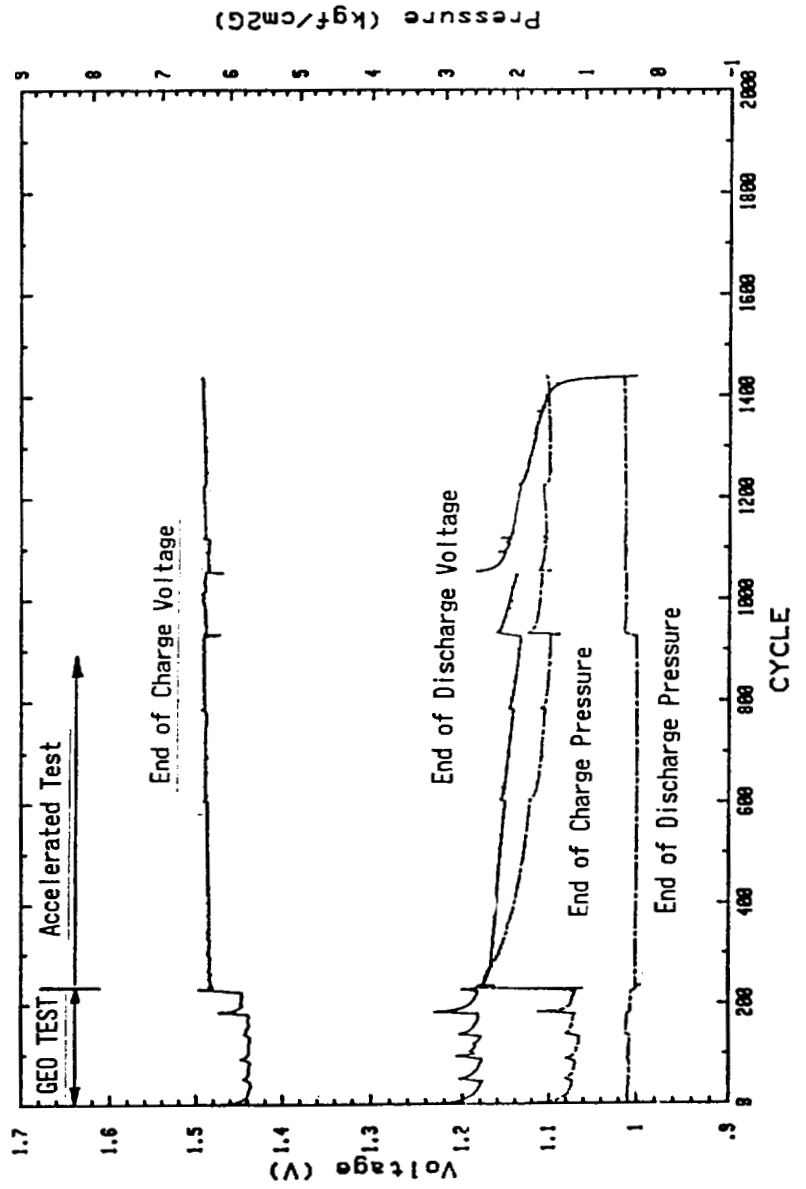
### TEST CONDITION

Charge (taper charge)  
 constant rate: 0.3C  
 limit voltage: 23.82V/16cells  
 charge time : 60min  
 Discharge : 0.33C, 36min  
 DOD : 20%  
 Temp : 5°C

**TYPICAL LIFE DATA (ACCELERATED CYCLE)**

The life of over 1,000 cycles was obtained  
in the case of DOD 80% cycling.

**CYCLE TREND OF VOLTAGE & PRESSURE**

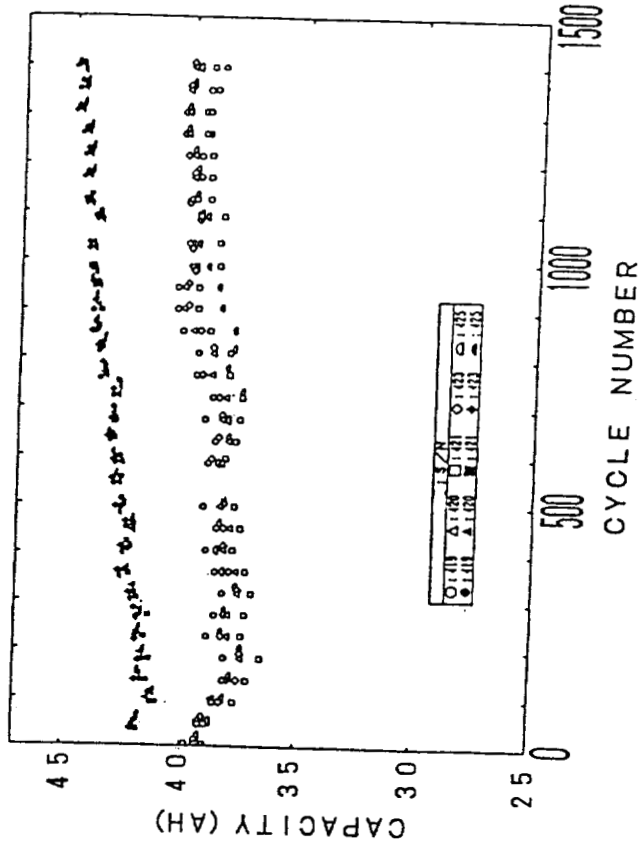
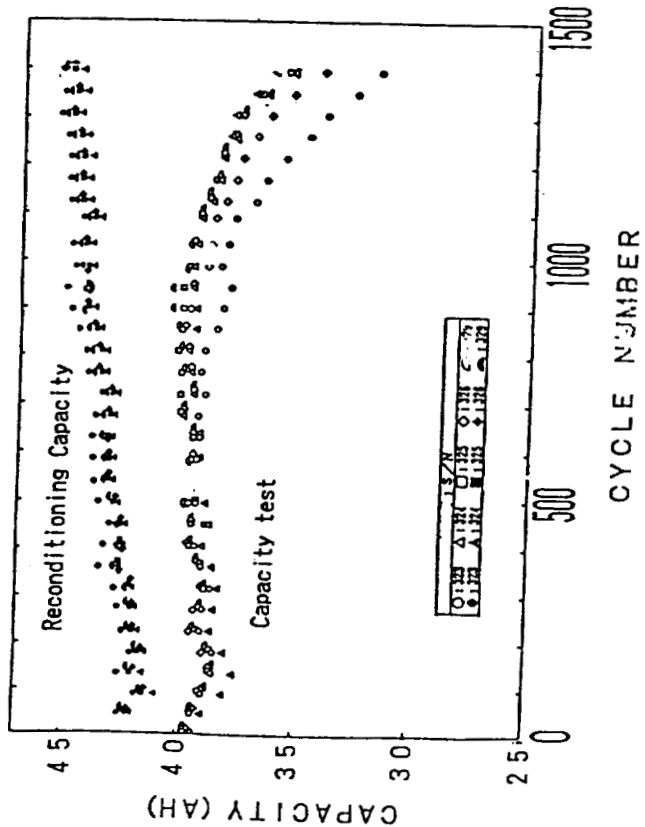


We have tried some treatments, and two methods of these treatments were good & effective for cell performance.

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 ADVANCED ALKALINE WASHING FOR SEPARATOR



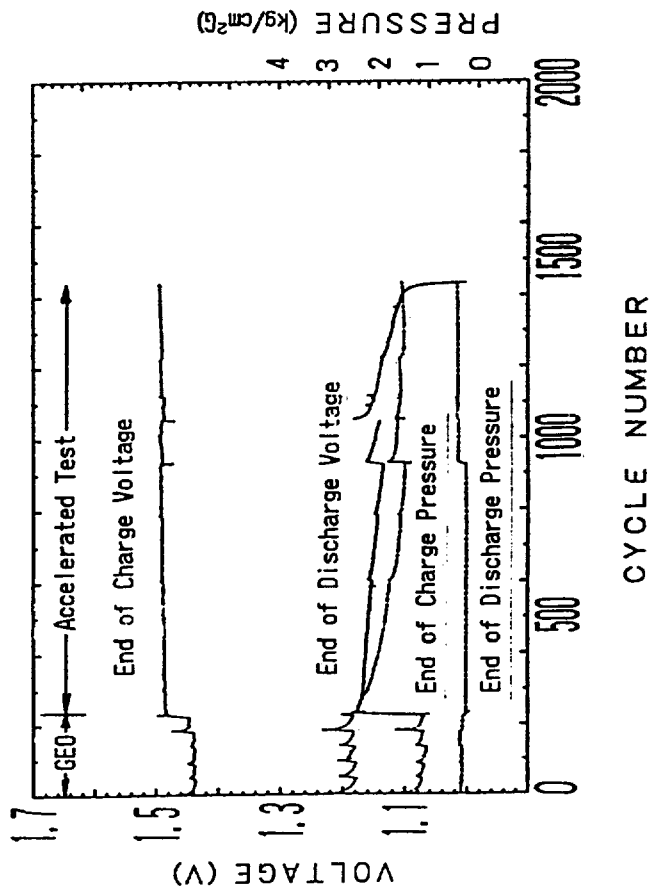
TEST CONDITION : SAME AS GEO SIMULATION



# ADVANCED CELL DESIGN (2)

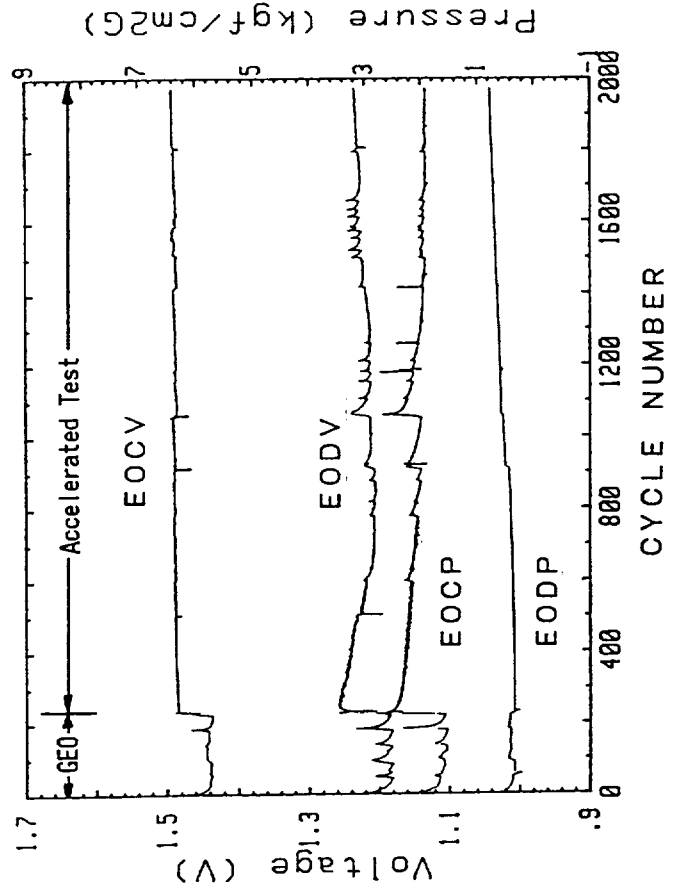
ORGANIC COMPOUND TREATMENT FOR NEGATIVE ELECTRODE  
IS EFFECTIVE FOR LIFE OF CELL

CURRENT DESIGN CELL



ADVANCED

NEGATIVE ELECTRODE TREATMENT



TEST CONDITION : SAME AS ACCELERATED CYCLING



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## 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-8 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.)

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- 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 80%) --- 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



## FUTURE PROGRAM

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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

**N 9 2 - 2 2 7 5 9**

## Analysis of Nickel-Cadmium Battery Reliability Data Containing Zero Failures

William K. Denson  
Reliability Analysis Center

Glenn 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 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)

1.25	9.1	2.8	1.7
4.5	9.1	7.9	1.5
2	8.4	2.5	1.5
20	8.4	7.8	1.3
.9	8.2	4.2	3.4
2.4	7	2.2	1
2.8	3	2.2	.8
22	7.7	2.2	.8
17.8	7.6	2.1	1.9
2	.6	2	1.7
.2	5.5	4	1.6
.9	7.4	6.3	.5
7.2	7.2	2.1	1.6
4.8	6	1.6	1.4
1.75	7.2	6.8	1.4
1.4	.3	6.8	1.3
.7	12.2	6.6	1.3
.8	11.2	3	1.2
14.6	12.2	1	1.2
11.5	2.8	1	1.1
13.6	6.7	1	1.1
14	6	6.3	1
5.75	4.4	5	.9
2.2	9.8	2.6	.9
10.6	9.7	6.2	.8
7.25	1	.8	.6
10.2	2.8	.8	.5
9.8	4.8	.8	.5
2.6	10.1	.5	.5
5	4.5	.6	.4
9	3.6	.2	.4
9.8	8.6	.2	.4
10.8	9.7	4.5	.4
10.8	4	6	.2
5	4.1	4.3	.2
9.5	4	4.3	.2
10.2	9.1	5.2	.2
4.5	3.85	5.2	.1
3	3.5	4	.1
9.9	8.9	3.1	
.4	.8	4.1	
5.6	3.2	1	
1	8.5	2.2	
9.6	3.96	2.2	
4	8.3	2.2	
1	8.3	3.2	
3	2.11	3	
3	8.2	.8	
8.5	2.8	1.8	

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;

$$h(t) = \left(\frac{\beta}{\alpha}\right) \left(\frac{t}{\alpha}\right)^{\beta-1}$$

To estimate the value of the characteristic life in the Weibull distribution, the following maximum likelihood estimator is typically used;

$$\alpha = \left[ \sum_{i=1}^n T_i^\beta / r \right]^{\frac{1}{\beta}}$$

where

- $T_i$  = Time to fail of the  $i^{\text{th}}$  part or survival time of the  $i^{\text{th}}$  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;

$$\alpha = \left[ 2 \sum_{i=1}^n T_i^\beta / \chi^2 (C; 2r + 2) \right]^{\frac{1}{\beta}}$$

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;

$\beta$	$\sum_{i=1}^n T_i^\beta$
1	793.02
2	6360.9
3	69923.6
4	948534
5	15012172
6	$2.64 \times 10^8$

The values of the Chi-square percentiles, taken from Chi-square tables are;

C (Confidence Level)	Chi-Square Percentile
.25	.5754
.50	1.386
.75	2.773
.90	4.605
.95	5.991
.975	7.378
.990	9.210
.995	10.60
.999	13.82

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)

$\beta$	C								
	.25	.50	.75	.90	.95	.975	.990	.995	.999
1	2756	1144	572	344	265	215	172	150	115
2	148	96	67	52	46	42	37	35	30
3	62	47	37	31	29	27	25	24	22
4	43	34	29	25	24	23	21	21	19
5	35	29	26	23	22	21	20	20	19
6	31	27	24	22	21	20	19	19	18

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 lives 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

Manufacturer	$\alpha$	$\beta$
1	120	4
2	50	4
3	170	2.3
4	80	1.0

While the characteristic life may be very high, of more interest may be the time to .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 .1% cumulative population failure, respectively.

TABLE 4: LOWER LIMIT OF TIME TO 1% FAILURE

$\beta$	C								
	.25	.50	.75	.90	.95	.975	.990	.995	.999
1	27.7	11.5	5.75	3.46	2.66	2.16	1.73	1.51	1.16
2	14.8	9.62	6.72	5.21	4.61	4.21	3.71	3.51	3.01
3	13.4	10.1	7.98	6.70	6.26	5.83	5.40	5.18	4.75
4	13.6	10.7	9.18	7.92	7.60	7.28	6.65	6.65	6.02
5	13.9	11.6	10.4	9.16	8.77	8.37	7.97	7.97	7.57
6	14.4	12.5	11.2	10.2	9.75	9.29	8.83	8.83	8.36

TABLE 5: LOWER LIMIT OF TIME TO .1% FAILURE

$\beta$	C								
	.25	.50	.75	.90	.95	.975	.990	.995	.999
1	2.76	1.14	.57	.34	.26	.22	.17	.15	.12
2	4.68	3.04	2.12	1.64	1.45	1.33	1.17	1.11	.94
3	6.20	4.70	3.70	3.10	2.90	2.70	2.50	2.40	2.20
4	7.43	6.04	5.16	4.45	4.27	4.09	3.73	3.73	3.38
5	8.79	7.28	6.53	5.78	5.53	5.27	5.02	5.02	4.77
6	9.80	8.54	7.49	6.95	6.64	6.32	6.00	6.00	5.69

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,  $\beta$ . 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 be 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.

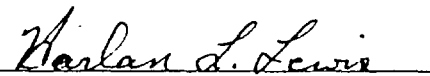
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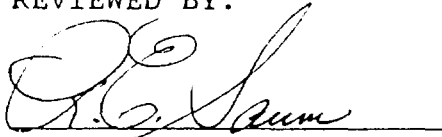
REPORT OF INVESTIGATIONS  
INTO CHARGE CADMIUM  
REACTIVITY: NICKEL-CADMIUM CELL  
ESD 91-86  
19 SEP 1991

PREPARED BY:



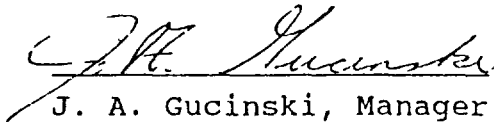
Harlan L. Lewis  
Material Science Lab

REVIEWED BY:



Robert E. Saum  
Environmental and Material  
Science Branch

APPROVED BY:



J. A. Gucinski, Manager  
Electrochemical Power  
Systems Division

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<sup>1</sup> 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 N<sub>2</sub> 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 N<sub>2</sub> 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 75C for 20 hours with pure O<sub>2</sub> 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)<sub>2</sub> state could be reoxidized to NiOOH or NiO<sub>2</sub>. 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:

Gas Sampling	S/N 28 Pellon 2536	S/N 9 Pellon 2536	S/N 95 Pellon 2505	S/N 7 Pellon 2505
Cell History	Baseline	One Year	Baseline	One Year
% H <sub>2</sub>	53.64	18.44	17.84	17.34
% He	14.48	6.97	33.08	24.81
% N <sub>2</sub>	30.45	62.95	48.44	55.74
% O <sub>2</sub>	1.43	11.64	0.64	2.11

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

$$n(\text{H}_2) = \frac{(2 \times 10^2 \text{ torr} \times 0.5364) \times 10 \text{ cc}}{6.24 \times 10^4 \text{ cc torr K}^{-1} \text{ mol}^{-1} \times 3 \times 10^2 \text{ K}} = 5.7 \times 10^{-5} \text{ mol}$$

for hydrogen gas. Similar calculations for all components yields the following:

Gas Sample	S/N 28	S/N 9	S/N 95	S/N 7
Measured P	150 torr	280 torr	380 torr	530 torr
Moles H <sub>2</sub>	5.7x10 <sup>-5</sup>	3.7x10 <sup>-5</sup>	4.8x10 <sup>-5</sup>	6.6x10 <sup>-5</sup>
Moles He	1.5 x10 <sup>-5</sup>	1.4x10 <sup>-5</sup>	8.9x10 <sup>-5</sup>	9.4x10 <sup>-5</sup>
Moles N <sub>2</sub>	3.2x10 <sup>-5</sup>	1.3x10 <sup>-5</sup>	1.3x10 <sup>-4</sup>	2.1x10 <sup>-4</sup>
Moles O <sub>2</sub>	1.5x10 <sup>-6</sup>	2.3x10 <sup>-5</sup>	1.7x10 <sup>-6</sup>	8.0x10 <sup>-5</sup>

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.

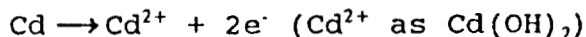
(3) The helium is probably present because it was inserted for leak detection.

(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  $N_2$  present is residual from the evacuation of air, then the  $O_2$  content should be about 20 percent of  $N_2$ . For S/N 28 and 95,  $O_2$  is much less than 20 percent of  $N_2$ , while in S/N 7 it is about 2X and in S/N 9 very much larger than the natural  $O_2/N_2$  ratio, indicating an initial (baseline)  $O_2$  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:

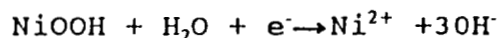
Each cell contained 11 positive and 12 negative plates. The analytical weights of  $Cd(OH)_2$  from three plates in S/N 28 for example were 7.84g, 8.40g, and 8.49g, giving an average of 8.24g  $Cd(OH)_2$  per plate. For 12 plates this is about 100g  $Cd(OH)_2$ . The cell reaction on discharge is



so the recovered cadmium hydroxide converts as

$$100g \text{ Cd(OH)}_2 \times \frac{1 \text{ mol Cd(OH)}_2}{146.4g \text{ Cd(OH)}_2} \times \frac{1 \text{ mol Cd}}{1 \text{ mol Cd(OH)}_2} \times \frac{2 \text{ mol } e^-}{1 \text{ mol Cd}} = 1.37 \text{ mol } e^-$$

For nickel, three plates analyzed of the eleven present gave an average of 5.38g  $Ni(OH)_2$  and 0.662g  $NiOOH$ . For eleven plates in the cell there were 59.2g  $Ni(OH)_2$  and 7.28g  $NiOOH$  total. The reaction is



and so the reduced  $Ni(OH)_2$  has consumed

$$59.2\text{g Ni(OH)}_2 \times \frac{1\text{mol Ni(OH)}_2}{92.7\text{g Ni(OH)}_2} \times \frac{1\text{mol NiOOH}}{1\text{mol Ni(OH)}_2} \times \frac{1\text{mol e}^-}{1\text{mol NiOOH}} = 0.639\text{mol e}^-$$

while the remaining NiOOH would consume

$$7.28\text{g NiOOH} \times \frac{1\text{mol NiOOH}}{91.7\text{g NiOOH}} \times \frac{1\text{mol e}^-}{1\text{mol NiOOH}} = 0.0729\text{mol e}^-$$

for a total of 0.718mol e<sup>-</sup>. 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<sup>2</sup> state that Cd does not react directly with alkaline solutions because Cd is not amphoteric like Zn; Cd cannot form the cadmate analog to the zincate ion (ZnO<sub>2</sub><sup>2-</sup>). However, Cd(OH)<sub>2</sub> apparently does dissolve in concentrated alkali as a [Cd(OH)<sub>4</sub>]<sup>2-</sup> ion. Mellor<sup>3</sup> reports that Cd forms Cd(OH)<sub>2</sub> in moist air. The conversion Cd → CdO → Cd(OH)<sub>2</sub> → [Cd(OH)<sub>4</sub>]<sup>2-</sup> 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 reactively 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)<sub>2</sub> (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 80C 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<sup>1</sup> 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 accidentally analyzed as Cd(OH)<sub>2</sub>, 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:

Cell Number	Discharged Cd (g)	Charged Cd (g)	Total Cd (g)	Charged Cd (%)
11	2.4960	0.1009	2.5969	3.88
15	2.3521	0.0934	2.4455	3.82
17	2.5026	0.1262	2.6288	4.80

\* 1/2 AA-Size

Next, the experiment was repeated using the procedure in 2b(2). In this case, the data obtained are:

Cell Number	Discharged Cd (g)	Charged Cd (g)	Total Cd (g)	Charged Cd (%)
22	2.4788	0.1209	2.5997	4.65
23	2.5518	0.1199	2.6717	4.49
24	2.6090	0.1083	2.7173	3.99

\* 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:

Cell Number	Discharged Cd (g)	Charged Cd (g)	Total Cd (g)	Charged Cd (%)
27	2.5434	0.0589	2.6023	2.26
27 <u>w</u> O <sub>2</sub>	2.4202	0.0382	2.4584	1.55
28	2.5416	0.0760	2.6176	2.90
28 <u>w</u> O <sub>2</sub>	2.4497	0.0169	2.4666	0.69
30	2.5707	0.0602	2.6309	2.29
30 <u>w</u> O <sub>2</sub>	2.4613	0.0518	2.5131	2.06

\* 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 O<sub>2</sub> 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 DPA<sup>1</sup>. The following table presents the analytical results:

Cell Number	Sample <u>w</u> Grid Charged Cd (%)	Sample <u>wo</u> Grid Charged Cd (%)	Difference (%)
15	2.28	3.82	40.3
17	3.18	4.80	33.8
22	2.37	4.65	49.0
23	1.95	4.49	56.6
24	1.69	3.99	57.6
27	0.55	2.26	75.7

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<sup>2+</sup> 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<sub>2</sub> was whether Ni(OH)<sub>2</sub> could be reoxidized to NiOOH or NiO<sub>2</sub> 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:

Cell Number	NiO <sub>2</sub> (%)
28	0.09
28 <u>w</u> O <sub>2</sub>	7.02
30	0.09
30 <u>w</u> O <sub>2</sub>	7.51

It appears that oxidation of Ni(OH)<sub>2</sub> is not only possible, but relatively easy. Consequently, any weight gain observed for a whole cell if O<sub>2</sub> 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<sub>2</sub>O<sub>3</sub> 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:

Cell Number	Plate Number	Charged Cd (g)	Charged Cd (%)
28 (2536)	3	0.0	0
	9	0.0	0
	13	0.0	0
95 (2505)	3	0.0	0
	9	0.0	0
	13	0.0	0
9 (2536)	3	0.026	0.36
	9	0.093	1.27
	13	0.298	3.77
7 (2505)	3	0.0	0
	9	0.0	0
	13	0.011	0.15

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<sup>2+</sup> occlusion in gelatinous Fe<sub>2</sub>O<sub>3</sub> · xH<sub>2</sub>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<sup>-1</sup> 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 $\text{cm}^{-1}$ , to 1274, 1180, and 1146 $\text{cm}^{-1}$  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 NWSOC 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<sup>1</sup> were examined to determine whether Cd metal could be converted to Cd(OH)<sub>2</sub> or CdO<sub>2</sub> 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  $Fe_2O_3 \cdot xH_2O$  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  $Fe_2O_3$ .

(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 IECEC 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.

## 6. Bibliography.

a. Halpert, G and Kunigahalli, V., "Procedures for Analysis of Nickel-Cadmium Cell Materials", Document X-711-74-279, Revision A, December 1980, NASA Goddard Space Flight Center, Greenbelt, MD 20771.

b. Cotton, F.A. and Wilkinson, G., Advanced Inorganic Chemistry, John Wiley and Sons, New York (1980), 592-600.

c. Mellor, J.W., Inorganic and Theoretical Chemistry (IV), Longmans, London (1963), 472-73.



## **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.

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*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 dependence 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 hydride 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  $1 \mu\text{g}/\text{m}^3$  or  $5 \mu\text{g}/\text{m}^3$  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.

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## WILSON & WILSON

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.

SUITE 500 1900 L STREET NW WASHINGTON DC 20036  
TELEPHONE 202-835-1571 FACSIMILE 202-296-2736



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

- o CURRENT OSHA EXPOSURE LIMIT IS 200 ug/m<sup>3</sup> -- ESTABLISHED IN 1972
- o GEP -- AND OTHER NiCd BATTERY MAKERS WORLD-WIDE -- ARE GENERALLY ENGINEERED TO 50 ug/m<sup>3</sup>
- o OSHA'S PROPOSED RULE-MAKING WOULD IMPOSE A MAXIMUM EXPOSURE OF EITHER 1 OR 5 ug/m<sup>3</sup>
- o OSHA'S RULE-MAKING IS EXPECTED TO BE PROMULGATED IN Q1 OR Q2 OF 1992

MRH1

## GATES ENERGY PRODUCTS

### POSITION

- o GEP HAS TAKEN LEADERSHIP ROLE IN SEEKING A REASONABLE SOLUTION
- o COST TO ENGINEER PLANT TO 25 ug/m<sup>3</sup> IS ESTIMATED TO BE AN ADDITIONAL:
  - \$20 MILLION CAPITAL
  - \$4 MILLION/YEAR OPERATING COST
- o MARGINS ARE UNDER SEVERE PRESSURE FROM FOREIGN COMPETITION; THESE COSTS WOULD MAKE US LESS COMPETITIVE
- o GEP IS NOT ABLE -- OR WILLING -- TO PAY THE ADDITIONAL COSTS TO MEET THE PROPOSED RULE, BASED ON SOUND BUSINESS PRACTICE
- o BOB SHILEY -- GEP PRESIDENT:
  - "IF THE REGULATION IS ESTABLISHED AT EITHER OF THOSE LEVELS (i.e., 1 OR 5 ug/m<sup>3</sup>, GATES WILL CEASE PRODUCTION OF NICKEL CADMIUM BATTERIES IN THE UNITED STATES"
- o 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
- o GEP IS DEVELOPING STATE-OF-THE-ART NiMH CELLS, AND CONVERTING FROM NiCd TO NiMH

MRH2

## GATES AEROSPACE BATTERIES

- (IF RULE IS ESTABLISHED AT LESS THAN 50 ug/m3)
- o GAB IS SUBJECT TO SAME CONSIDERATIONS AS GEP -- ADDED COSTS WILL MAKE US UNCOMPETITIVE
- o GAB WILL NOT MANUFACTURE NiCd CELLS AFTER GEP HAS PHASED OUT OF NiCd
- o ACTIVATION (FROM DRY STORAGE) OF WELDED CELLS DOES NOT PRESENT A CADMIUM HAZARD -- DRY STORAGE COULD PROVIDE A SCHEDULE BUFFER
- o OSHA RULE-MAKING THREATENS GAB'S ABILITY TO PROVIDE CONTINUING SUPPLY OF NiCd CELLS
- o 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
- o GATES AEROSPACE BATTERIES IS DEVELOPING NiMH CELLS TO REPLACE NiCd AEROSPACE CELLS -- RESULTS ARE VERY ENCOURAGING -- PAPER LATER TODAY

MRH3



**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.

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▪ 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.

HUGHES EDD POSITION ON PROPOSED NEW OSHA  
STANDARDS FOR AIRBORNE 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 air borne cadmium standards.

Our position on nickel cadmium cell technology is quite unique compared 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 ( $5 \text{ ug/m}^3$ ) 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*



N 9 2 - 2 2 7 6 1

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

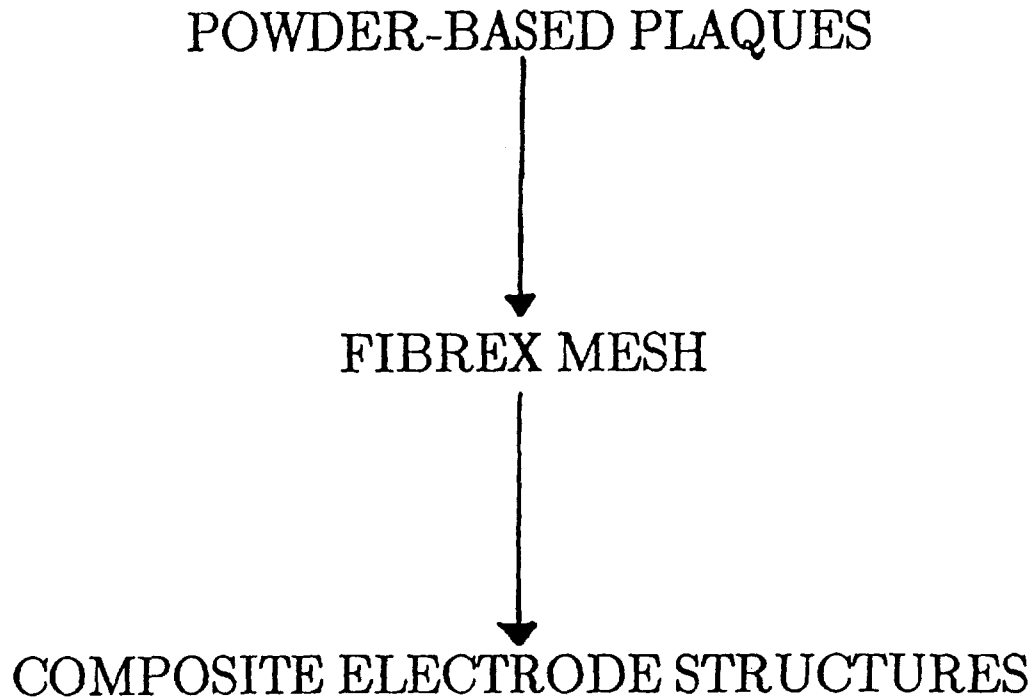
Peggy Reid

T.S. Lee

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# EVOLUTION OF ELECTRODE ARCHITECTURES

Nickel Hydroxide Half-Cell Reaction Studies



Tatarchuk and co-workers:

1. J. Electrochem. Soc., 137, 136 (1990).
2. J. Electrochem. Soc., 137, 1750 (1990).

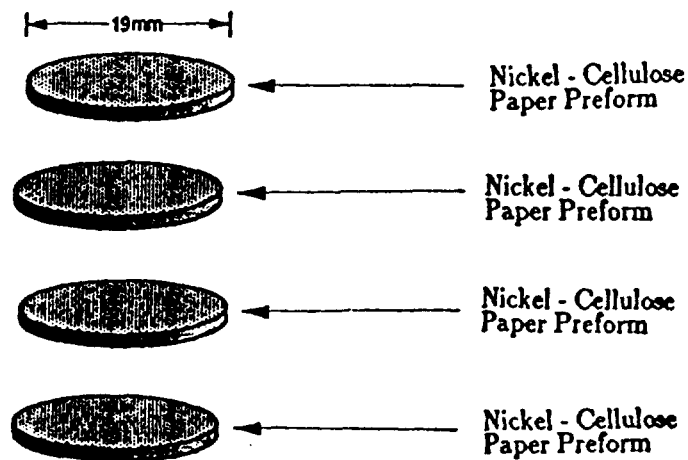
## Research Objective

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

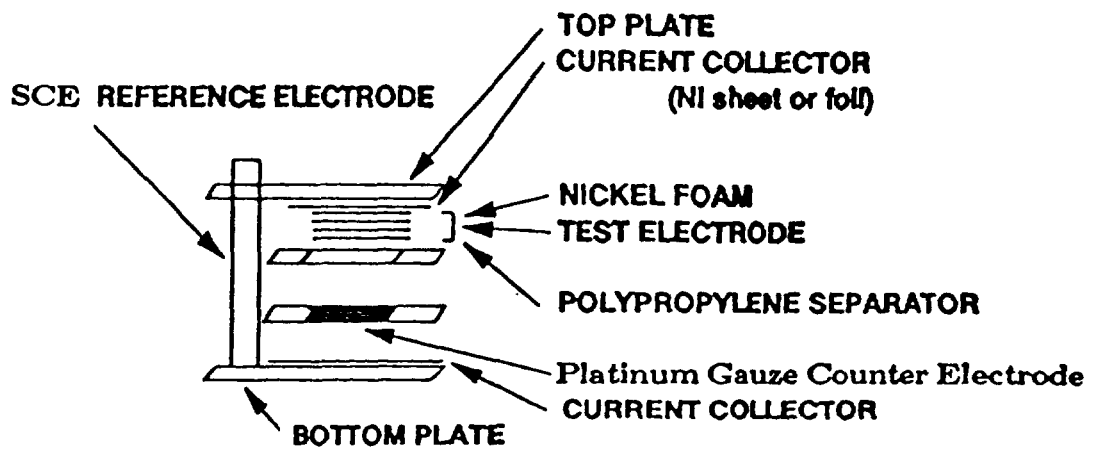
### Electrode Preparation



### 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  $m^2/g$  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 accessability 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

	<u>FIBREX</u>	<u>FIBREX+SS</u>	<u>FIBREX+Ni</u>	<u>SS</u>	<u>Ni</u>
BEFORE IMPREGNATION					
Thickness (mils)	35	35	35	19	19
Weight/Surf. Area ( $g/cm^2$ )	7.8	5.8	5.0	0.11	0.14
Density ( $g/cm^3$ )	0.49	0.55	0.55	0.33	0.35
Porosity (%)	94.4	93.7	93.7	95.8	95.8
AFTER IMPREGNATION					
WT of $Ni(OH)_2/cm^3$ of Void	0.42	0.21	0.67	1.12	0.66
Porosity (%)	80.9	86.7	74.1	66.0	75.9
Loading (vol %)	14.3	7.53	21.0	30.8	20.5

POLAROID  
F137 1139 C

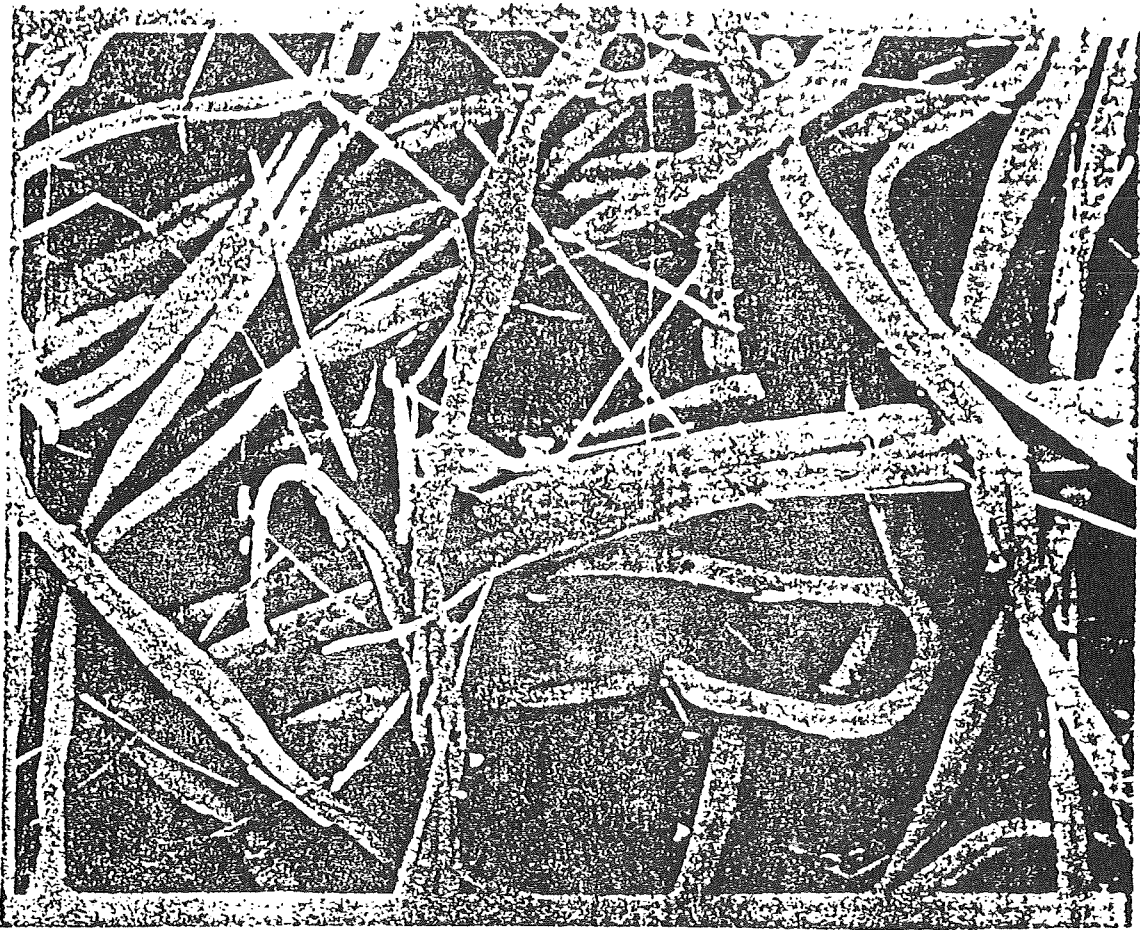


Figure 1. Electron micrograph of a FIBREX/nickel fiber composite electrode prior to impregnation.

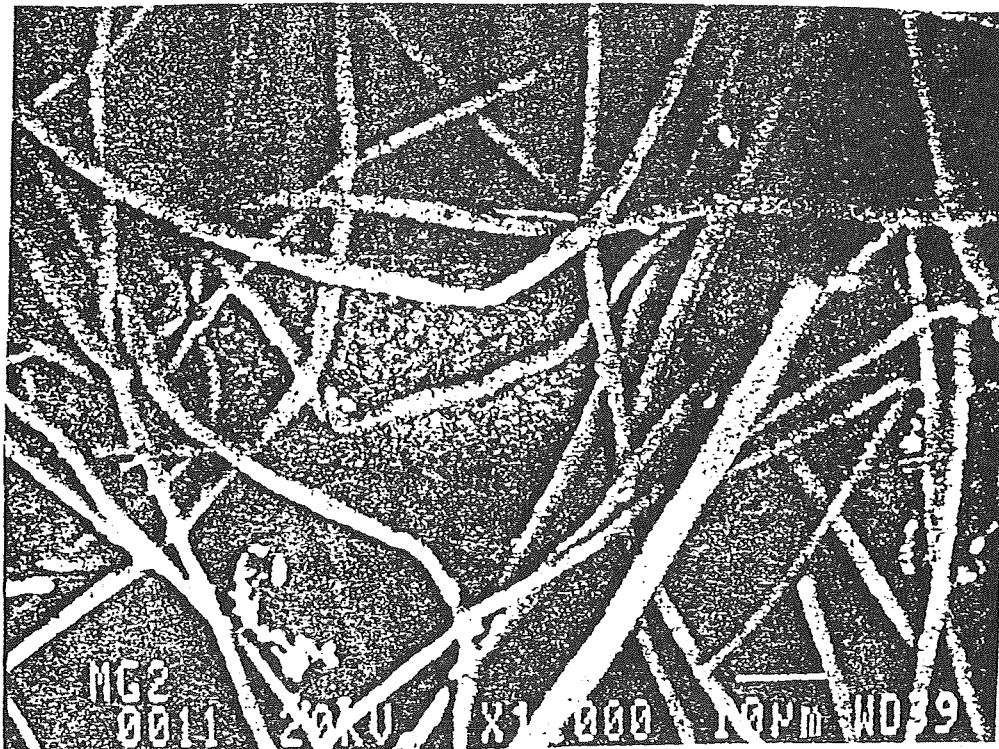


Figure 2. Electron micrograph showing the sinter bonded small diameter nickel fibers to the FIBREX mesh.

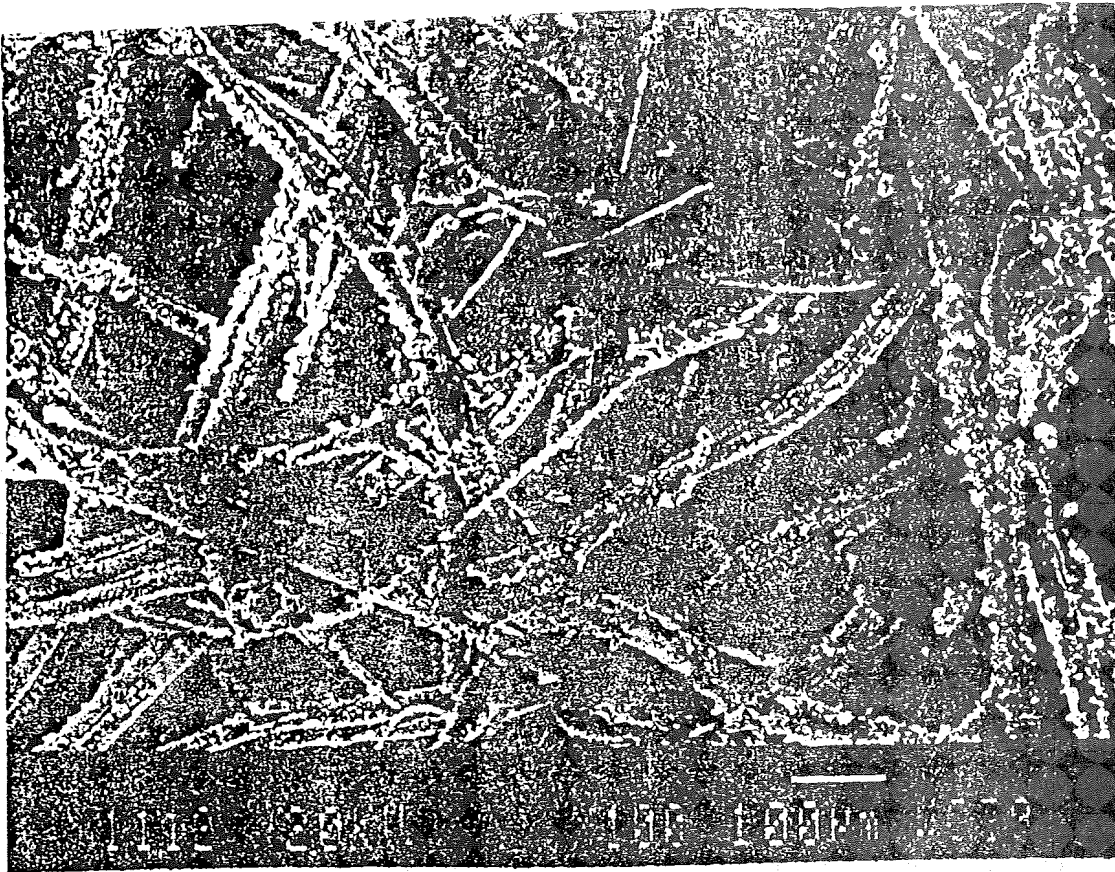


Figure 3. Electron micrograph of a FIBREX/nickel fiber composite electrode after aqueous impregnation galvanostatically at  $10 \text{ mA/cm}^2$  for 3 hours.

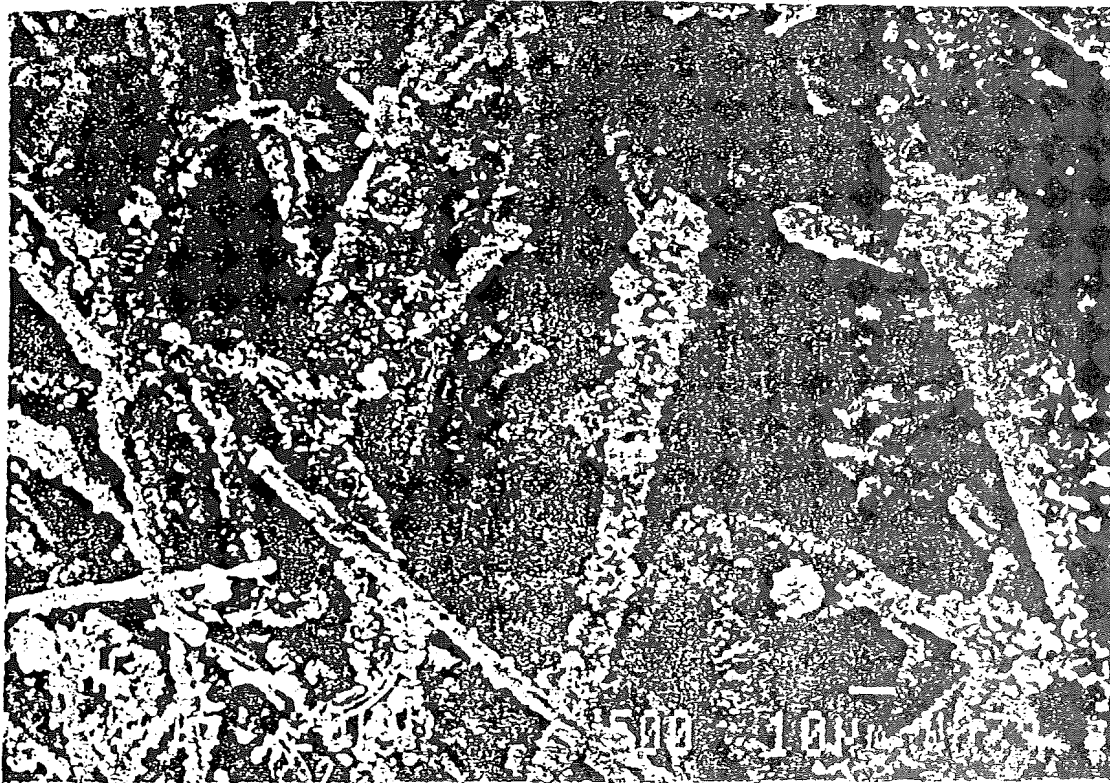
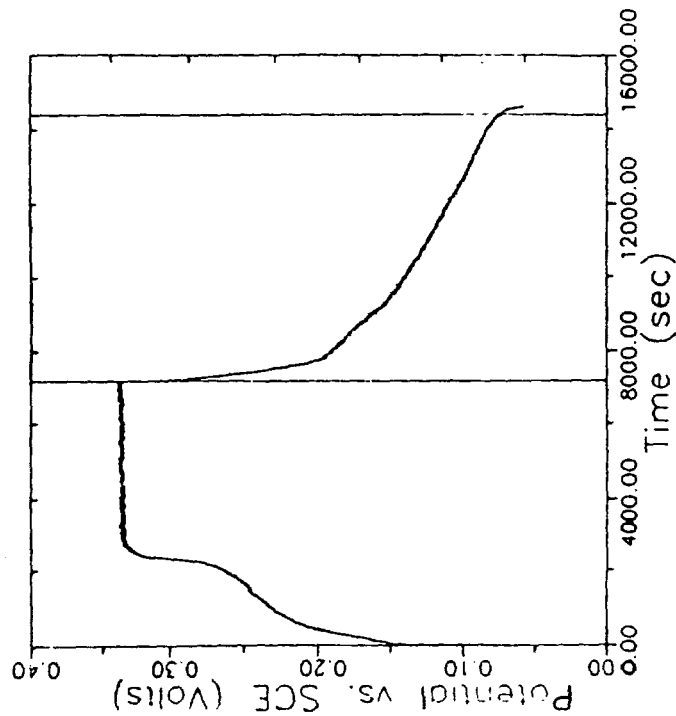


Figure 4. Electron micrograph of the same electrode as above but at higher magnification.

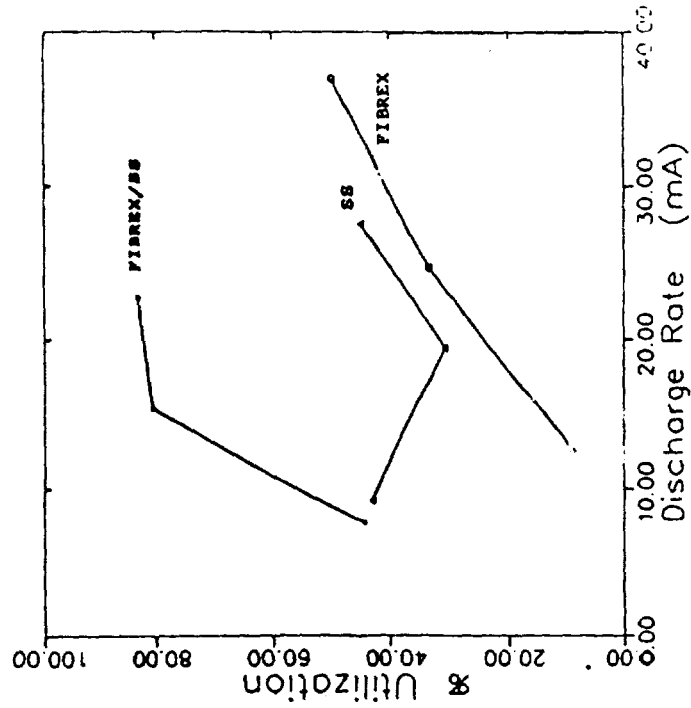
Potential vs. Time Curve for a Nickel Fiber Composite Electrode During Charge and Discharge.

Solution = 26 wt% KOH  
 Active Material Weight = 44 mg  
 Electrode Weight = 31 mg  
 Geometric Area = 2.8 cm<sup>2</sup>  
 Charge Rate = C/3  
 Discharge Rate = 3C/2



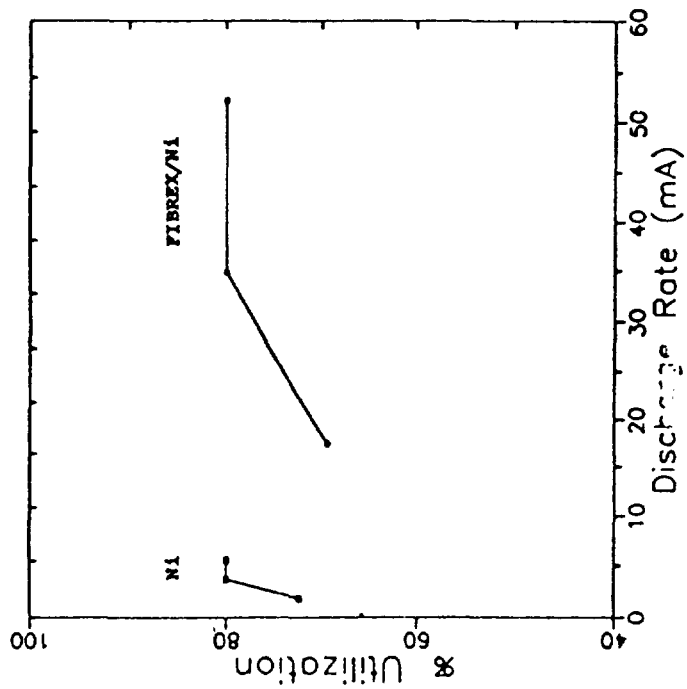
Plot of % Utilization vs. Discharge Rate for Different Composite Electrode Architecture

Solution = 26 wt% KOH  
 Active Material Weight = 53 mg (FIBREX/SS)/64 mg (SS)/85 mg (FIBREX/SS)  
 Electrode Weight = 27 mg (FIBREX/SS)/29 mg (SS)/125 mg (FIBREX/SS)  
 Geometric Area = 2.8 cm<sup>2</sup>  
 Charge Rate = C/2



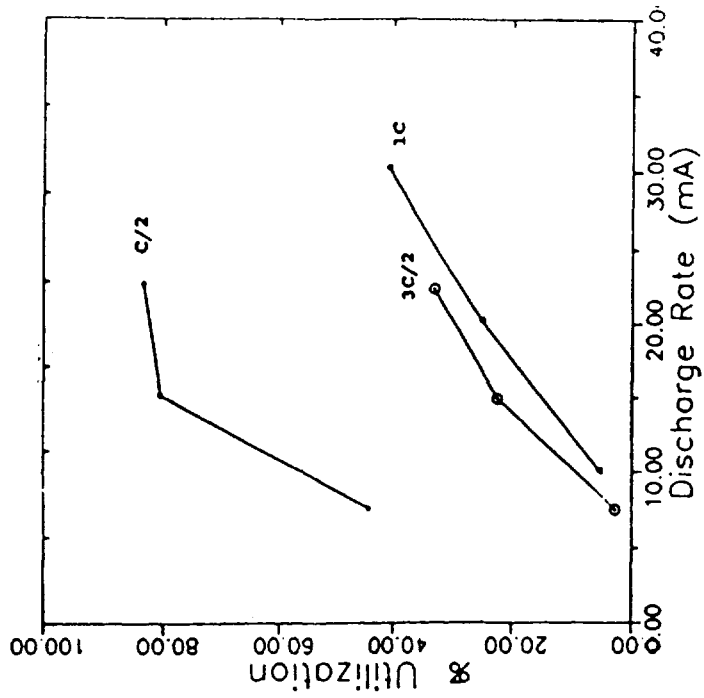
**Plot of % Utilization vs. Discharge Rate for a Nickel Fiber and a FIBREX/Nickel Fiber Composite Electrode.**

Solution = 26 wt% KOH  
 Active Material Weight = 44 mg (Ni) / 126 mg (FIBREX/Ni)  
 Electrode Weight = 31 mg (Ni) / 185 mg (FIBREX/Ni)  
 Geometric Area = 2.8 cm<sup>2</sup>  
 Charge Rate = C/2



**Plot of % Utilization vs. Discharge Rate for FIBREX/Stainless Steel Composite Electrode at Different Charge Rates.**

Solution = 26 wt% KOH  
 Active Material Weight = 53 mg (C/2)/70 mg (1C)/52 mg (3C)  
 Electrode Weight = 268 mg (C/2)/249 mg (1C)/326 mg (3C/2)  
 Geometric Area = 2.8 cm<sup>2</sup>



## 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-H<sub>2</sub> batteries.





**N92-22762**

**Composite Overwrapped Nickel-Hydrogen Pressure Vessels**

John Reagan, NASA Lewis Research Center  
Joe Lewis, TRW

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## COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

- o THE PURPOSE OF THIS PAPER IS TO STIMULATE INTEREST IN COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS.
  - o COMPOSITE OVERWRAPPED PRESSURE VESSELS SHOULD:
    - o BE MORE ECONOMICAL TO PRODUCE
    - o REQUIRE LESS SCHEDULE TIME TO PRODUCE
    - o BE MORE RELIABLE
    - o BE INHERENTLY MORE RESISTANT TO FATIGUE DAMAGE
    - o POTENTIALLY IMPROVE HEAT TRANSFER CHARACTERISTICS
    - o REDUCE MEMBRANE STRESS
    - o 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**

- o **HISTORY OF NICKEL-HYDROGEN PRESSURE VESSELS**
  - o **TECHNOLOGY IS FIFTEEN YEARS OLD**
  - o **EXCEPT FOR THE LAST TWO YEARS ALL KNOWN APPLICATIONS HAVE BEEN IN GEO ORBIT AT 600 PSI**
  - o **OVER THE LAST THREE YEARS APPLICATIONS HAVE MOVED TO LEO ORBITS WITH PRESSURE INCREASED TO EXCESS OF 1000 PSI**
    - o **DEPTH OF DISCHARGE HAS ALSO BEEN INCREASED FROM 10% TO PRESENT REQUESTS THAT ARE NOW APPROACHING 40%**
    - o **WEIGHT HAS BEEN REDUCED AT THE EXPENSE OF PRESSURE VESSEL WALL THICKNESS**
  - o **BOTH EUROPE AND JAPAN ARE PLANNING NICKEL-HYDROGEN BATTERIES FOR SPACE APPLICATIONS**

\*\*\*\*\*

**COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS**

- o **HISTORY (cont)**
  - o **INCONEL 718 HAS BEEN THE MATERIAL OF CHOICE SINCE EARLY DESIGNS**
    - o **ALL PRESENT DESIGNS KNOWN TO THE AUTHORS PRESENTLY USE OR ANTICIPATE THE USE OF INCONEL 718**
    - o **INCONEL 718 HAS PROVED TO BE VERY RELIABLE**
  - o **THE ADVANTAGES OF COMPOSITE OVERWRAPPED MATERIAL HAVE BEEN SUGGESTED SEVERAL TIMES BUT THE TECHNOLOGY HAS ALWAYS BEEN ELIMINATED EARLY ON DUE TO:**
    - o **FEAR OF ADVERSE THERMAL REACTIONS' EFFECTS**
    - o **UNKNOWN OF DESIGN**
    - o **LACK OF COMPOSITE OVERWRAPPED EXPERTS IN THE DESIGN PROCESS**
  - o **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

- o MATERIAL PROPERTIES DESIRED FOR PRESSURE VESSEL
    - o COMPATIBILITY WITH KOH
      - o GENERAL CORROSION
      - o FRACTURE CONTROL
    - o GOOD THERMAL CONDUCTIVITY
    - o HIGH STRENGTH-TO-WEIGHT RATIO
    - o HIGH CYCLE LIFE
      - o APPROXIMATELY 41,000 ACTUAL CYCLES FOR 15 YEAR SERVICE LIFE
        - o 164,000 ANALYTICAL CYCLES
- 

**Itemizes basic materials properties: thermal, corrosion, strength.**

## COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

- o APPROACHES TO ACHIEVING DESIRE PROPERTIES
  - o MONOLITHIC METAL CONSTRUCTION
    - o DIFFICULT TO OPTIMIZE PROPERTIES IN ONE ALLOY
    - o COMPROMISE OF SOME PROPERTY USUALLY REQUIRED
  - o COMPOSITE OVERWRAPPED CONSTRUCTION
    - o EACH DESIRED PROPERTY CAN BE OPTIMIZED IN DIFFERENT COMPONENTS OF COMPOSITE VESSEL
      - o COMPATIBILITY IN INNER LINER
      - o THERMAL CONDUCTIVITY IN OUTER LINER
      - o STRENGTH-TO-WEIGHT RATIO IN COMPOSITE OVERWRAP
      - o CYCLE LIFE IN INNER LINER

---

**Monolithic and Composite Overwrapped construction approach compared.**

## COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

- o POTENTIAL ADVANTAGES OF COMPOSITE PRESSURE VESSEL
    - o OPTIMIZED PROPERTIES
    - o POTENTIALLY LOWER COST
      - o COMPOSITE HIGH-PRESSURE GAS STORAGE VESSELS COST APPROXIMATELY 20% OF EQUIVALENT TITANIUM VESSEL
      - o POTENTIAL FOR ELIMINATION OF WELDS
    - o POTENTIALLY SHORTER MANUFACTURING SCHEDULE
      - o COMPOSITE VESSELS ARE BEING PRODUCED IN APPROXIMATELY ONE-THIRD TIME FOR EQUIVALENT TITANIUM VESSELS
    - o IMPROVED FRACTURE CONTROL CAPABILITY
      - o COMPOSITE VESSELS SHOW POTENTIAL FOR MILLIONS OF CYCLES BEFORE LEAKAGE
    - o POTENTIALLY LOWER WEIGHT
      - o COMPOSITE HIGH-PRESSURE GAS STORAGE VESSELS WEIGH APPROXIMATELY 20% OF WEIGHT OF EQUIVALENT TITANIUM VESSEL
    - o 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.**

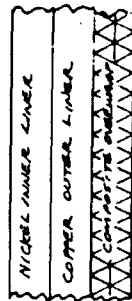
### COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

- o GRAPHITE/EPOXY OVERWRAPPED PRESSURE VESSEL WITH INCONEL X-750 LINER IS CURRENTLY FLYING ON B-1 BOMBER
- o 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

- o THERMAL CONDUCTIVITY OF SOME CANDIDATE MATERIALS
    - o COPPER: 226 BTU FT/HR FT<sup>2</sup>
    - o NICKEL: 50 BTU FT/HR FT<sup>2</sup>
    - o GRAPHITE: 48 BTU FT/HR FT<sup>2</sup>  
(PARALLEL TO FIBER)
    - o INCONEL 718: 6.5 BTU FT/HR FT<sup>2</sup>
    - o GRAPHITE/EPOXY: 0.1 BTU FT/HR FT<sup>2</sup>  
(TRANSVERSE TO FIBER)
- 

**Table showing recent successes using Graphite/Epoxy Composite Overwrapped technology in actual flight systems.**

#### COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

- o POTENTIAL LINER FABRICATION METHODS
  - o SPIN FORM AND CHEM-MILL
  - o ELECTROFORM AND CHEM-MILL
  - o FORGE AND CHEM-MILL

\*\*\*\*\*

#### COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

- o POTENTIAL ELIMINATION OF WELDS
  - o JOIN VESSEL COMPONENTS WITH ADHESIVES
  - o USE MECHANICAL CLOSURES WITH NON-STRUCTURAL SEALING WELDS

---

**Discussion of joining technology and the opportunity to: reduce risk in manufacturing, increase production, and improve reliability by adopting Composite Overwrapped technology.**

**COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS**

- o **FRACTURE CONTROL ISSUE FOR NICKEL-HYDROGEN PRESSURE VESSELS**
  - o **NDI METHODS FOR CRACKS ARE NOT SENSITIVE ENOUGH FOR 164,00 ANALYTICAL CYCLES**
  - o **ENVIRONMENTALLY AFFECTED SUSTAINED LOAD CRACK GROWTH DUE TO EFFECT OF KOH REDUCES CYCLE LIFE**

\*\*\*\*\*

**COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS**

- o **POTENTIAL FRACTURE CONTROL METHODOLOGY**
  - o **ELIMINATE STRUCTURAL WELDS**
  - o **ELIMINATE ALL CRACKS BY CHEM-MILLING INSIDE AND OUTSIDE SURFACES OF LINER**

---

**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.**

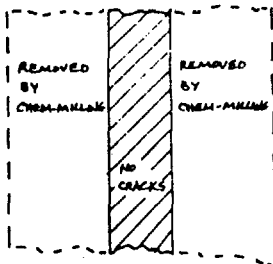
**COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS**

- o **NDI METHODOLOGY FOR WROUGHT METAL LINER**
  - o **WROUGHT METAL IS CONVENTIONALLY MACHINED TO A THICKNESS OF 0.030-0.040 INCH PER SURFACE GREATER THAN FINAL DESIRED THICKNESS**
  - o **BOTH SURFACES OF WROUGHT METAL ARE INSPECTED USING NSTS "SPECIAL" PENETRANT INSPECTION**
  - o **EXTRA 0.030-0.040 INCH THICKNESS IS CHEMICALLY MILLED FROM EACH SURFACE**
  - o **REMAINING MATERIAL IS "CRACK-FREE"**
    - o **CHEM-MILLING SOLUTIONS DO NOT GENERATE CRACKS**
      - o **NASA AND DoD SPECIFICATIONS REQUIRE "ETCHING" BEFORE PENETRANT INSPECTION**
    - o **ANY SURFACE CRACK IN ORIGINAL 0.030-0.040 INCH THICKNESS RESULT IN HOLES THROUGH FINAL THICKNESS**

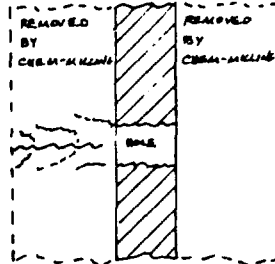
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**COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS**

- o **NDI METHODOLOGY**



**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.**

**COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS**

**FLIGHT HISTORY OF GRAPHITE-OVERWRAPPED PRESSURE VESSELS  
WITH THIN METALLIC LINERS**

PROGRAM	TYPE OF TANK	DATE FLOWN	FLUID	FIBER	OPERATING PRESSURE (PSIA)	BURST PRESSURE (PSIA)
WEDI	PRESSURANT	JAN. 1990	GN <sub>2</sub>	T-40	7,000	14,000
PEGASUS	PRESSURANT	APR. 1990	GN <sub>2</sub>	HT 46-9	2,500	5,000
ERIS	PRESSURANT	JAN. 1991	GN <sub>2</sub>	T-1000	9,400	24,000
ERIS	PROPELLANT	JAN. 1991	N <sub>2</sub> O/N <sub>2</sub> H <sub>4</sub>	HT 46-9	2,550	6,500
BRILLIANT PEBBLES	PRESSURANT	MAR. 1991	GN <sub>2</sub>	T-1000	9,000	20,000
PEGASUS MAPS	PROPELLANT	JULY 1991	HYDRAZINE	T-1000	464	696
	PRESSURANT	JULY 1991	GN <sub>2</sub>	T-1000	6,800	10,200
	PRESSURANT	JULY 1991	GN <sub>2</sub>	T-1000	5,800	8,700
MICROSAT	PRESSURANT	JULY 1991	GN <sub>2</sub>	T-1000	6,000	12,000

---

**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**
- 

**Presents cost and schedule information.**

THE LIAL/FES<sub>2</sub> BATTERY  
POWER SOURCE FOR THE FUTURE

D. BRISCOE, J. EMBREY, S. OWEIS, AND K. PRESS

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



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**The LiAl/FeS<sub>2</sub> 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<sub>2</sub> 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"<sup>(1)</sup>. 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<sub>2</sub>, or NiCl<sub>2</sub>), upper plateau (U.P.) Li(Al)/FeS<sub>2</sub> and H<sub>2</sub>O<sub>2</sub> 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<sub>2</sub> 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

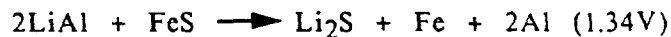
aluminum/iron disulfide batteries is three times that of nickel hydrogen with five times improvement in energy density (Wh/l) as shown in Figure 2.

**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<sup>(2)</sup>. 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

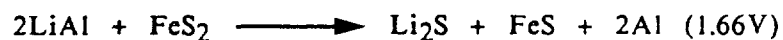


Failure to achieve good cycle life with this couple caused development emphasis to shift heavily in favor of the lower energy and less corrosive lithium aluminum/iron sulfide system. The discharge has a theoretical specific energy of 460 Wh/kg and can be written as



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<sub>2</sub> by Kaun and others. Success was achieved in 1986 by cycling only the upper plateau



with a theoretical specific energy of 490 Wh/kg. Over 1,000 cycles was demonstrated in LiAl/FeS<sub>2</sub> prismatic bicell configuration<sup>(3)</sup>. Further developments in 1988 of an electrochemical overcharge tolerance<sup>(4)</sup> and in 1990 of a peripheral seal material<sup>(5)</sup> make bipolar stack construction both workable and practical.

At SAFT, primary reserve thermal batteries containing bipolar LiAl/FeS<sub>2</sub> have been manufactured since 1978, and research and development on rechargeable prismatic LiAl/FeS and bipolar LiAl/FeS<sub>2</sub> has been conducted since 1990.

The LiAl/FeS<sub>2</sub> 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 FeS<sub>2</sub>. 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/FeS<sub>2</sub> 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/FeS<sub>2</sub> 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<sub>2</sub> 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<sup>2</sup> 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<sub>2</sub> 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<sub>2</sub> prismatic bicells (40 Ah), and LiAl/FeS<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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:

1. G. Halpert and A. Attia, "Advanced Electrochemical Concepts for NASA Applications," 24th IECEC Meeting, Washington, DC, August 6 - 11, 1989, Vol 3, pp 1429 - 1434.
2. P.A. Nelson, et al, "High Performance Batteries For Off-Peak Energy Storage and Electric Vehicle Propulsion," Argonne National Laboratory Report ANL-75-1.
3. T.D. Kaun, et al, "Lithium/Disulfide Cells Capable of Long Cycle Life," Proc. of the Symp. on Material and Processes for Lithium Batteries, ed., K.M. Abraham, Electrochem. Soc. Meeting, Vol 89-4, p. 373 (1989).
4. T.D. Kaun, T.F. Holifield, M. Nigohosian, and P.A. Nelson, "Development of Overcharge Tolerance in Li/FeS and Li/FeS<sub>2</sub> Cells," Proc. of the Symp. on Material and Processes for Lithium Batteries, ed., K.M. Abraham, Electrochem. Soc. Meeting, Vol 89-4, p. 383 (1989).
5. T.D. Kaun, M.J. Duoba, K.R. Gillie, and J.A. Smaga, "Sealing Li-Alloy/FeS<sub>2</sub> Cells for a Bipolar Battery," Proc. of the Symp. on Rechargeable Lithium Batteries, ed., S. Subbaro, Electrochem. Soc. Meeting, Vol 90-5, p. 315 (1990).



# ENERGY STORAGE REQUIREMENTS OF SIX ANTICIPATED SPACE MISSIONS

PRIORITY/ APPLICATIONS	CHARGE/ DISCHARGE DURATIONS	TYPICAL OPERATIONAL CYCLES REQUIRED		TYPICAL PEAK POWER AND ENERGY STORAGE REQUIRED (5 MINUTES)
		ACTUAL	*QUAL DESIRED	
1 OUTER PLANETARY ORBIT	C - 2.0HR D - 0.7HR	500	1000	0.50 C(1 KWH)
2 INNER PLANETARY ORBIT	C - 2.0HR D - 0.7HR	3000	6000	1.50 C(2 KWH)
**3 GEO	C - 22.8HR D - 1.2HR	1500	2000	1.50 C(5 KWH)
**4 PLANETARY ROVER	C - 12.0HR D - 3.0HR	300	600	1.30 C(3 KWH)
**5 LUNAR BASED	C - 11 DAYS D - 17 DAYS	80	160	0.02 C(5 MWH)
6 LEO	C - 1.0HR D - 0.6HR	30000	35000	1.10 C(25 KWH)

GEO: GEOSYNCHRONOUS ORBIT      LEO: LOW EARTH ORBIT      \*\* CANDIDATES FOR LIAL/FES2  
 \*QUAL: MINIMUM NUMBER OF CYCLES NEEDED TO QUALIFY FOR APPLICATION.  
 SOURCE: G. HALPERT AND A. ATTIA, JPL

Figure 1

**TECHNOLOGY PERFORMANCE COMPARISON  
GEOSYNCHRONOUS ORBIT**

	<u>NI-Cd</u>	<u>NI-H<sub>2</sub></u>	<u>PROJECTED BIPOLAR LiAl/FES<sub>2</sub></u>
<b>SPECIFIC ENERGY, WH/KG</b>	25 - 30	45 - 50	150
<b>ENERGY DENSITY, WH/L</b>	45	55	270
<b>CYCLE LIFE</b>	1000	1000	1000
- DOD (%)	70	70 - 80	80 - 100
<b>CALENDAR LIFE, YR</b>	15	15	10

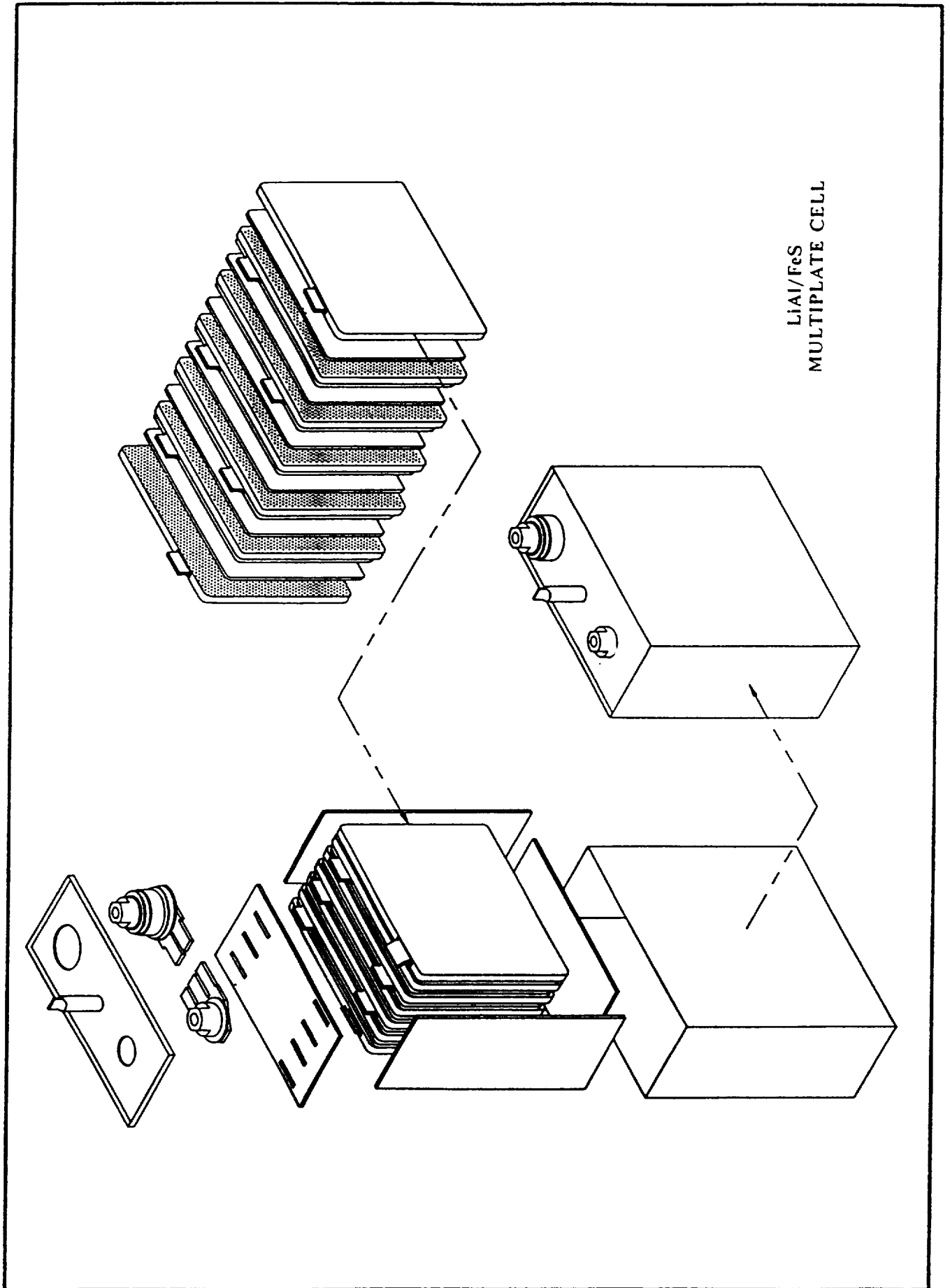
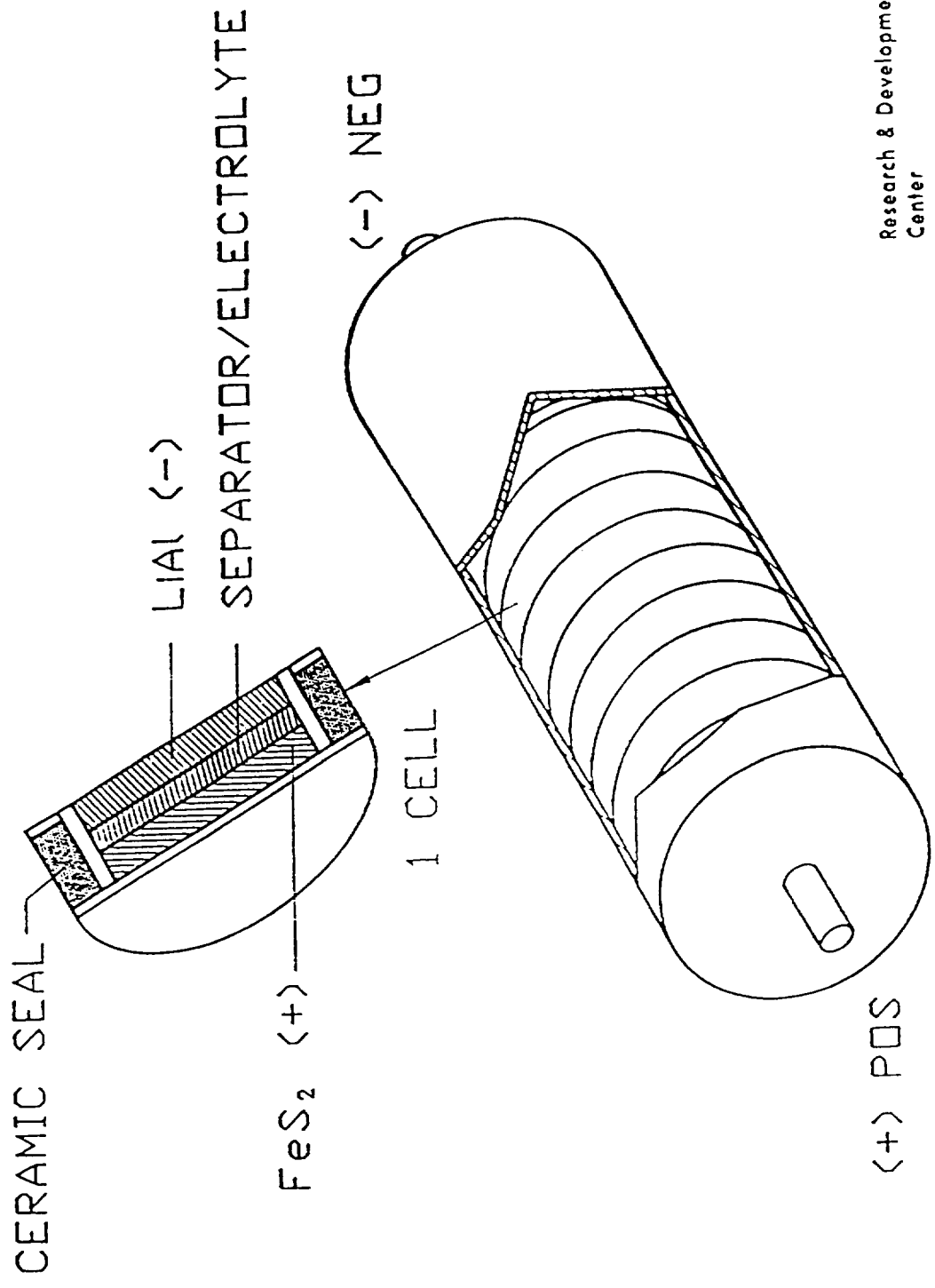


Figure 3

# BIPOLAR LiAl/FeS<sub>2</sub> MODULE CONCEPT DESIGN

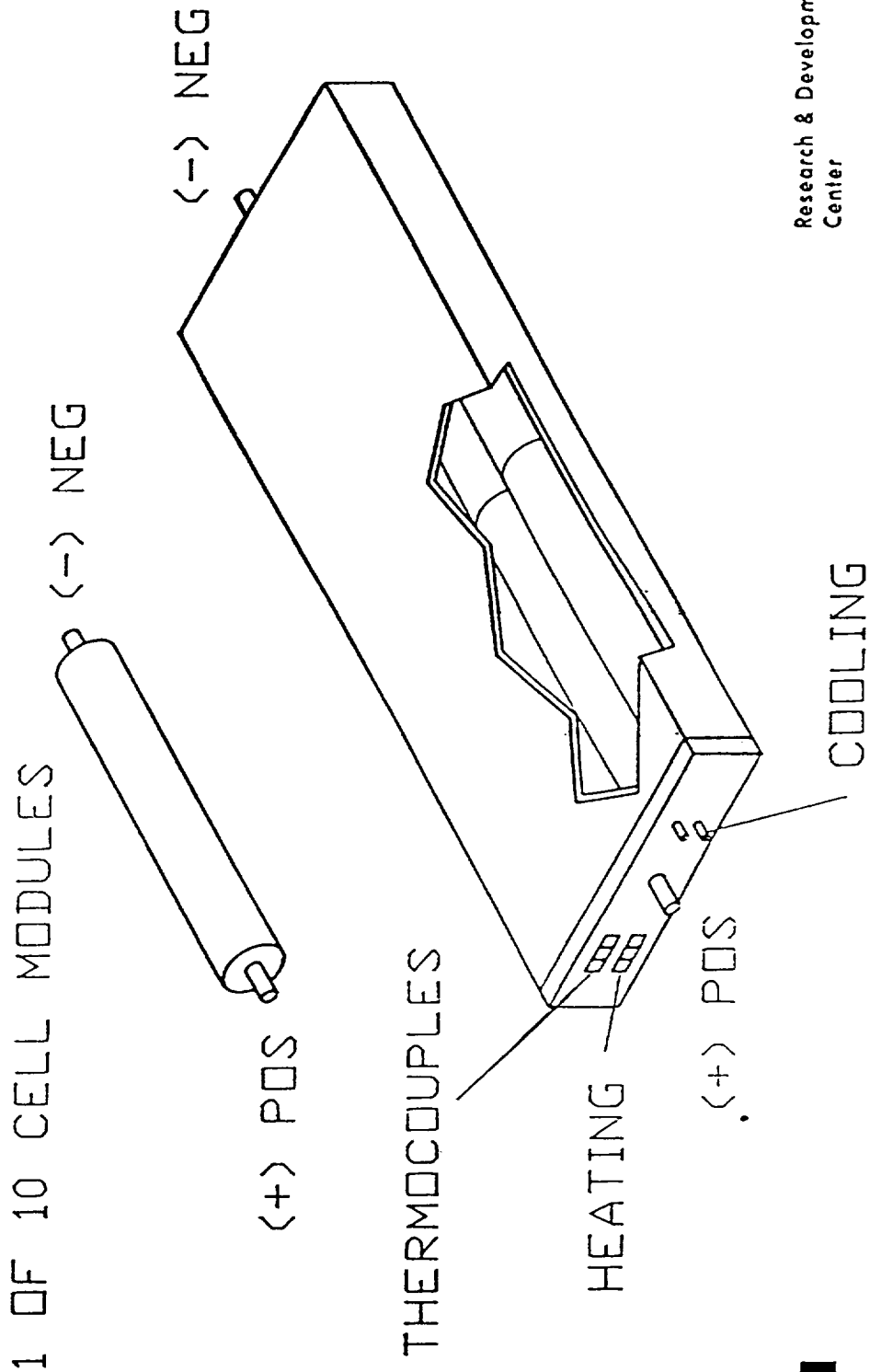


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Figure 4

# BIFILAR LiAl/FeS<sub>2</sub> BATTERY CONCEPT DESIGN



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Figure 5

# SAFT LiAl/FeS<sub>2</sub> BIPOLAR BATTERY

## DEVELOPMENT GOALS

	OPTIMIZED FOR <u>HIGH ENERGY</u>	OPTIMIZED FOR <u>HIGH POWER</u>
ENERGY, kWh	40	28
VOLTAGE, VOLTS	210 - 350	450 - 550
SPECIFIC ENERGY, WH/KG	150 (C/3)	39 (75C)
ENERGY DENSITY WH/L	270 (C/3)	56 (75C)
PEAK, SPECIFIC POWER, W/KG	340	2900
PEAK, POWER DENSITY, W/L	610	4164
CYCLE LIFE	1000	1000
DOD (%)	80	40
CALENDAR LIFE, YR	10	4



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# 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  
Huntsville, AL  
October 29-31, 1991

N92-22764

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# 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

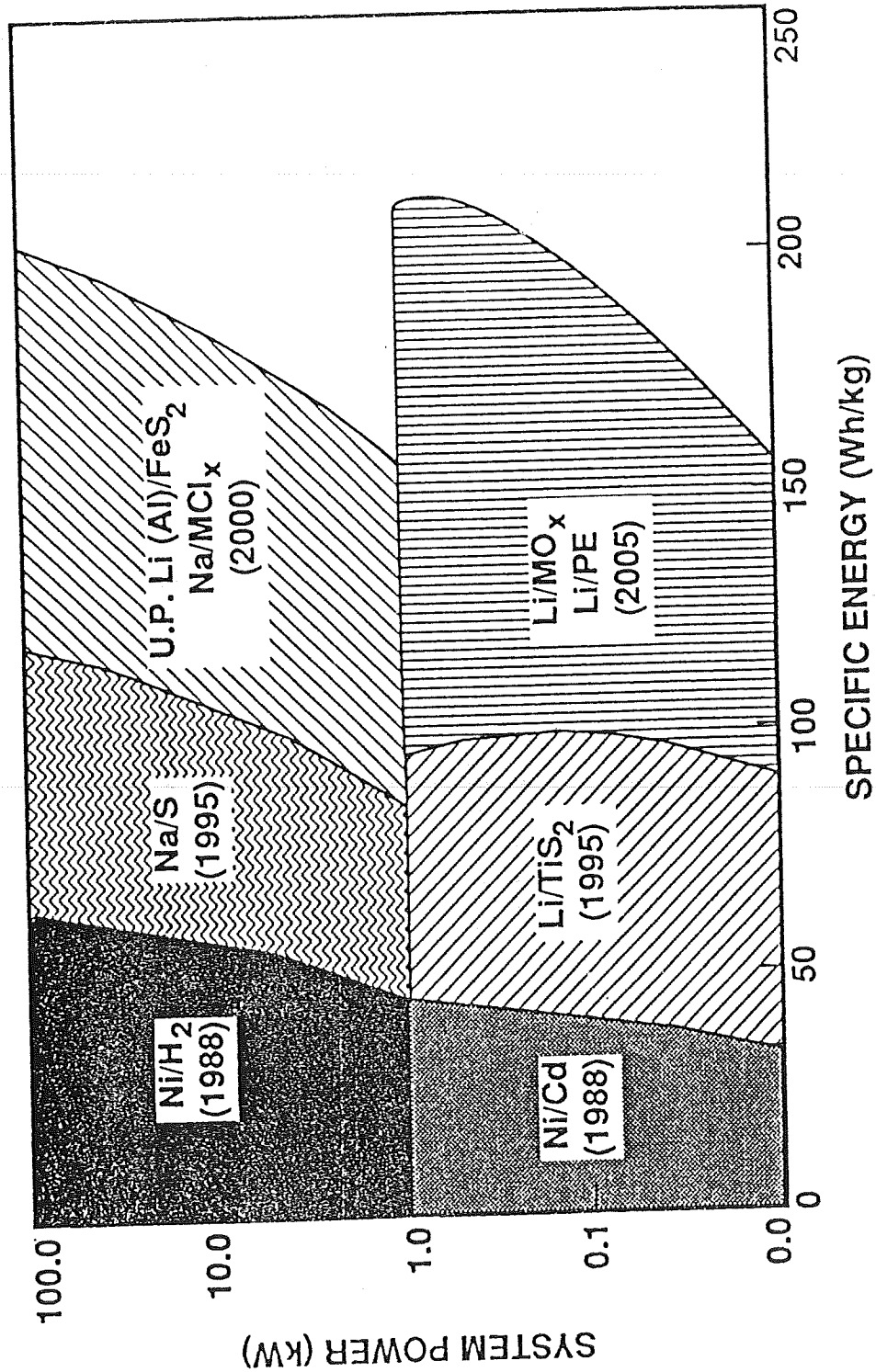
- TARGETS
  - 100 Wh/kg
  - 1000 CYCLES (50% DOD)
  - 5 YEAR ACTIVE STORAGE LIFE
  - SAFE



## **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**

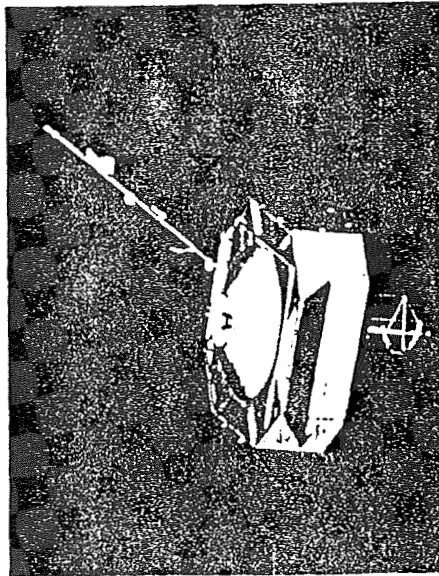
# JPL ADVANCED RECHARGEABLE BATTERY PERFORMANCE ENVELOPE



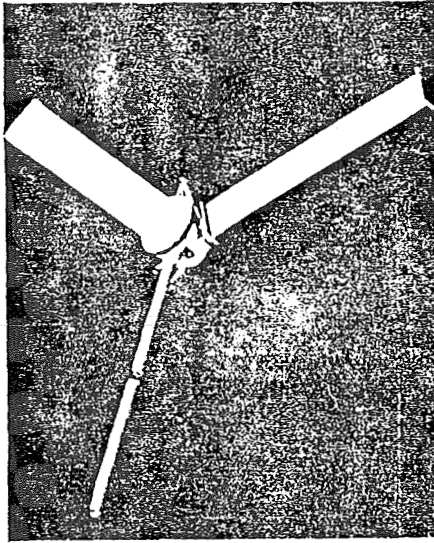
RECHARGEABLE LITHIUM CELL PROGRAM  
PROJECTED APPLICATIONS

**JPL**

PLANETARY ORBITERS  
(MERCURY ORBITER)



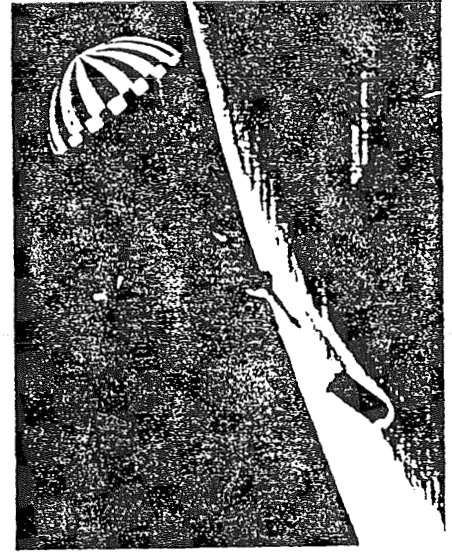
MISSIONS TO COMETS (COMET NUCLEUS  
SAMPLE RETURN TAIL PROBE)



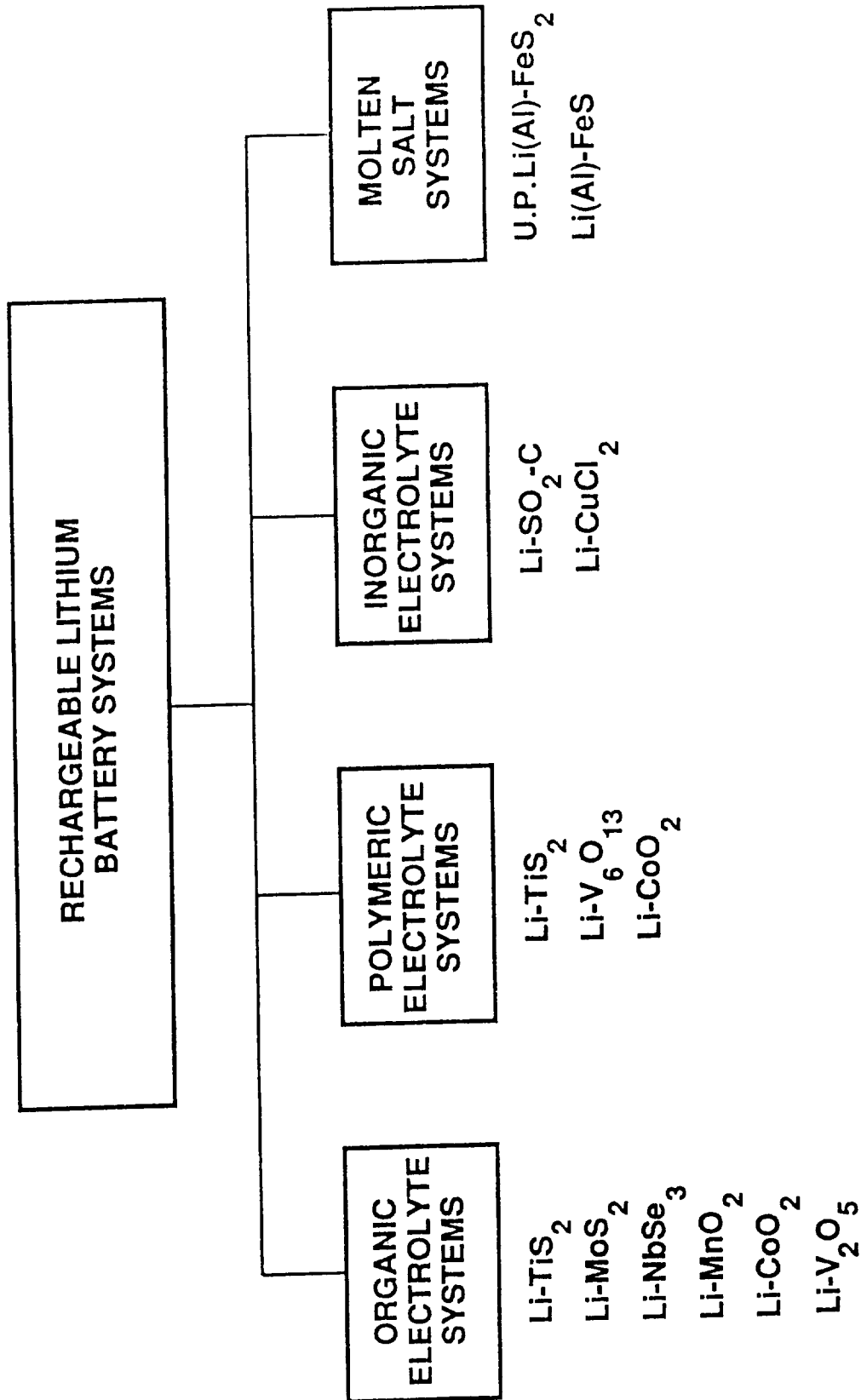
MARS ROVER



PENETRATORS  
(GLOBAL NETWORK MISSION)



# CLASSIFICATION OF SECONDARY LITHIUM CELLS



# SECONDARY LITHIUM CELLS/BATTERIES SPECIFIC ENERGY OF SELECTED CATHODE MATERIALS

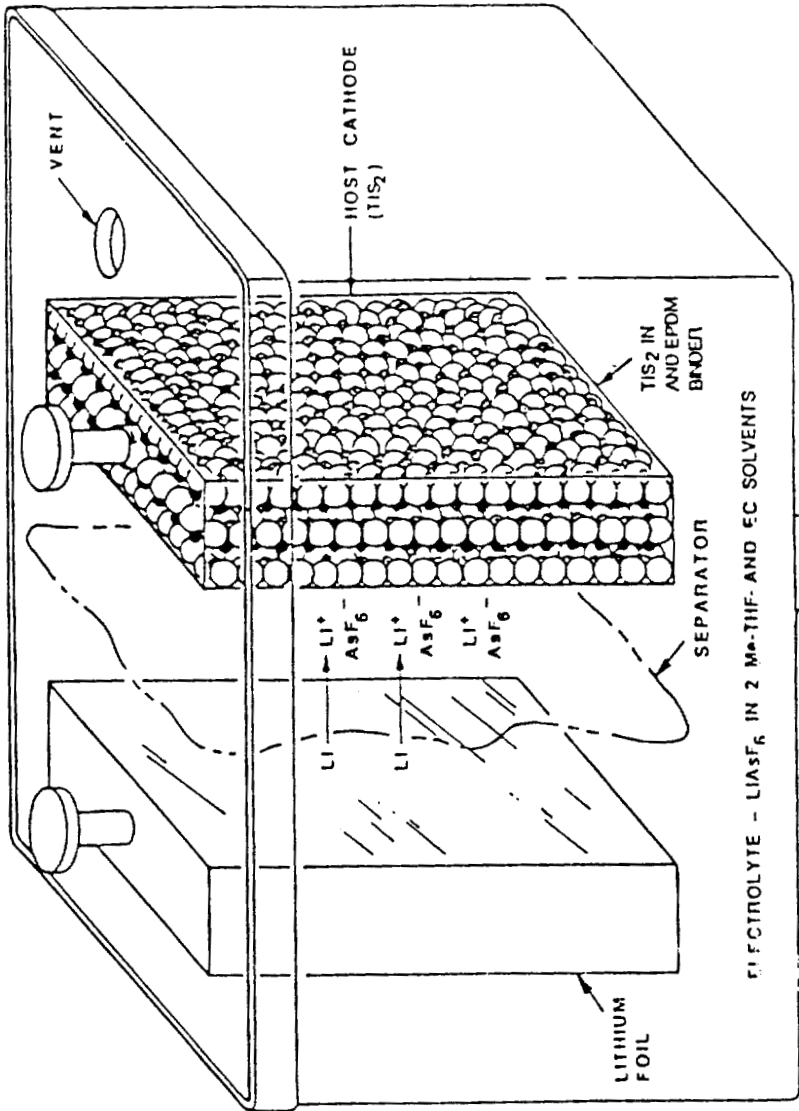
MATERIAL	AVE. V (Volt)	Li EQ.* PER mole	SPECIFIC ENERGY (Wh/kg) THEO.	EXP.**	CYCLE LIFE
<b>JPL STUDIES (EXPERIMENTAL CELLS)</b>					
Li-TiS <sub>2</sub>	2.1	0.9	473	417	300+
MoS <sub>2</sub>	1.9	2.0	717	421	50+
NbSe <sub>3</sub>	1.8	2.8	412	384	150+
V <sub>6</sub> O <sub>13</sub>	2.2	4.0	636	361	50+
<b>FROM LITERATURE (PROTOTYPE CELLS)</b>					
Li-TS <sub>2</sub>	2.1	0.8	473	378	200+
NbSe <sub>3</sub>	1.8	2.5	412	330	200+
MoS <sub>2</sub>	1.7	0.8	272	214	200+
MnO <sub>2</sub>	3.0	0.5	855	364	200+
CoO <sub>2</sub>	4.0	0.5	1094	465	50+
CuCl <sub>2</sub>	3.2	2.0	1125	665	140+
SO <sub>2</sub>	3.1	1.0	524	524	30+

\* EXPERIMENTALLY REVERSIBLE

\*\* EXPERIMENTALLY REVERSIBLE LITHIUM EQ./mole, BINDER AND  
CONDUCTING DILUENTS WERE TAKEN INTO CONSIDERATION

RECHARGEABLE AMBIENT-TEMPERATURE LITHIUM BATTERIES

**JPL** SCHEMATIC DIAGRAM OF A Li-TiS<sub>2</sub> CELL



CELL REACTIONS

DISCHARGE . . . LI INTERCALATION (INSERTION)  
 CHARGE . . . . . LI DE-INTERCALATION (REMOVAL)

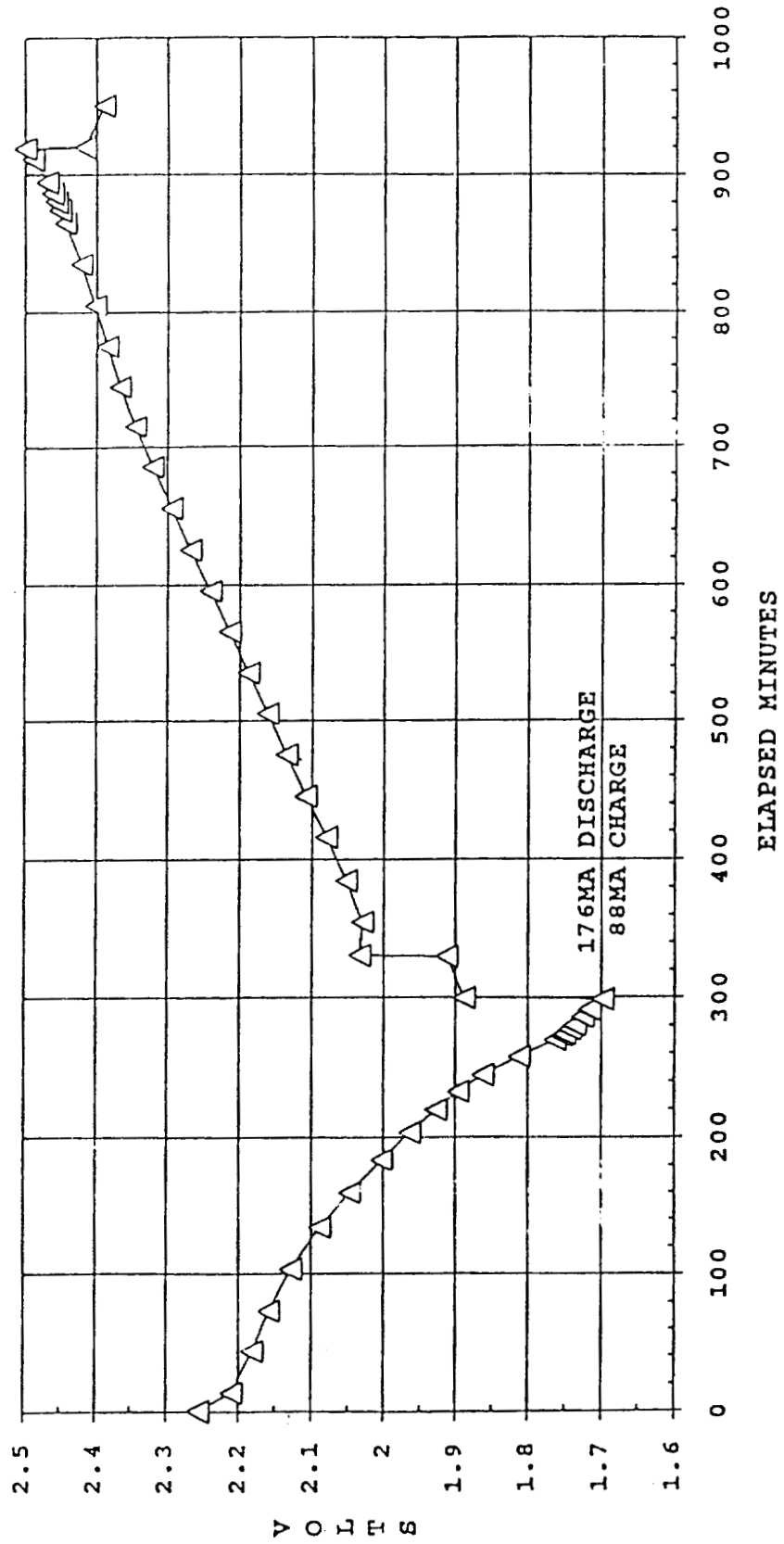


ELECTROLYTE

LITHIUM ARSENIC HEXAFLUORIDE (LiAsF<sub>6</sub>) - SALT  
 2-METHYL TETRA HYDROFURAN (2-MeTHF) WITH  
 ETHYLENE CARBONATE (EC) - MIXED SOLVENT

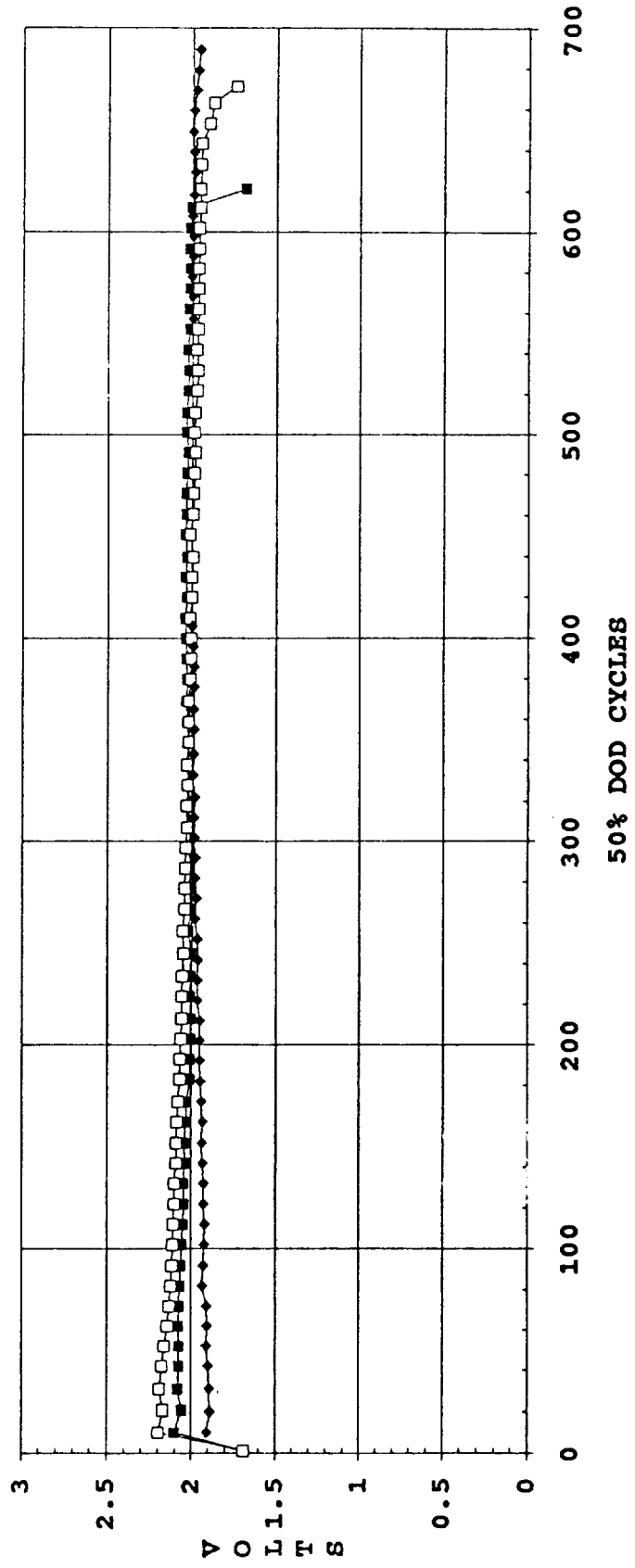


TYPICAL CHARGE/DISCHARGE CURVE FOR 1 Ah Li-TiS<sub>2</sub> CELL

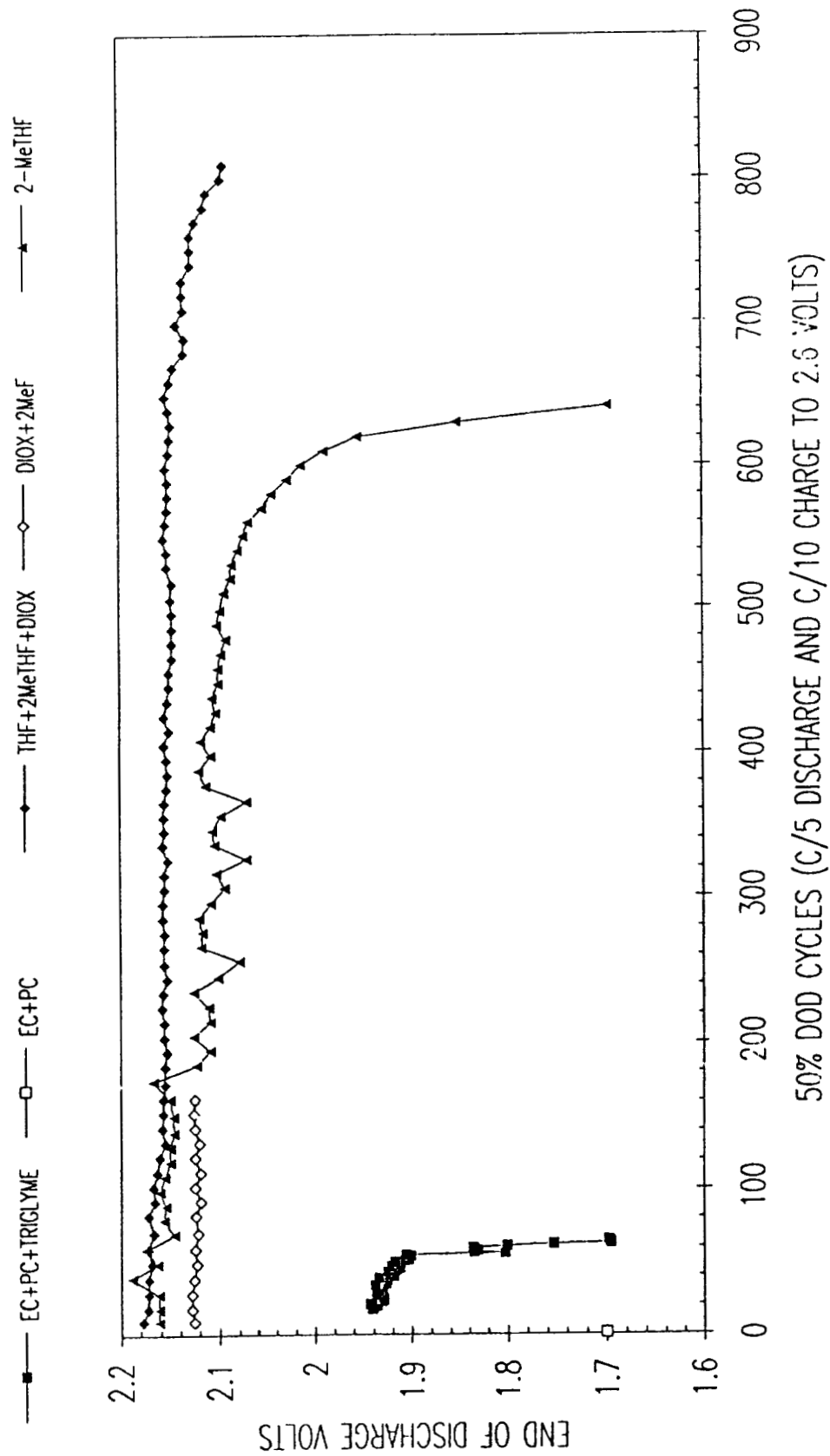


END-OF-DISCHARGE VOLTAGE VS CYCLES FOR JPL FABRICATED LITHIUM-TITANIUM  
DISULFIDE CELLS

■ 2-MeTHF      □ THF+2-MeTHF+2MeF      ◆ EC+2-MeTHF

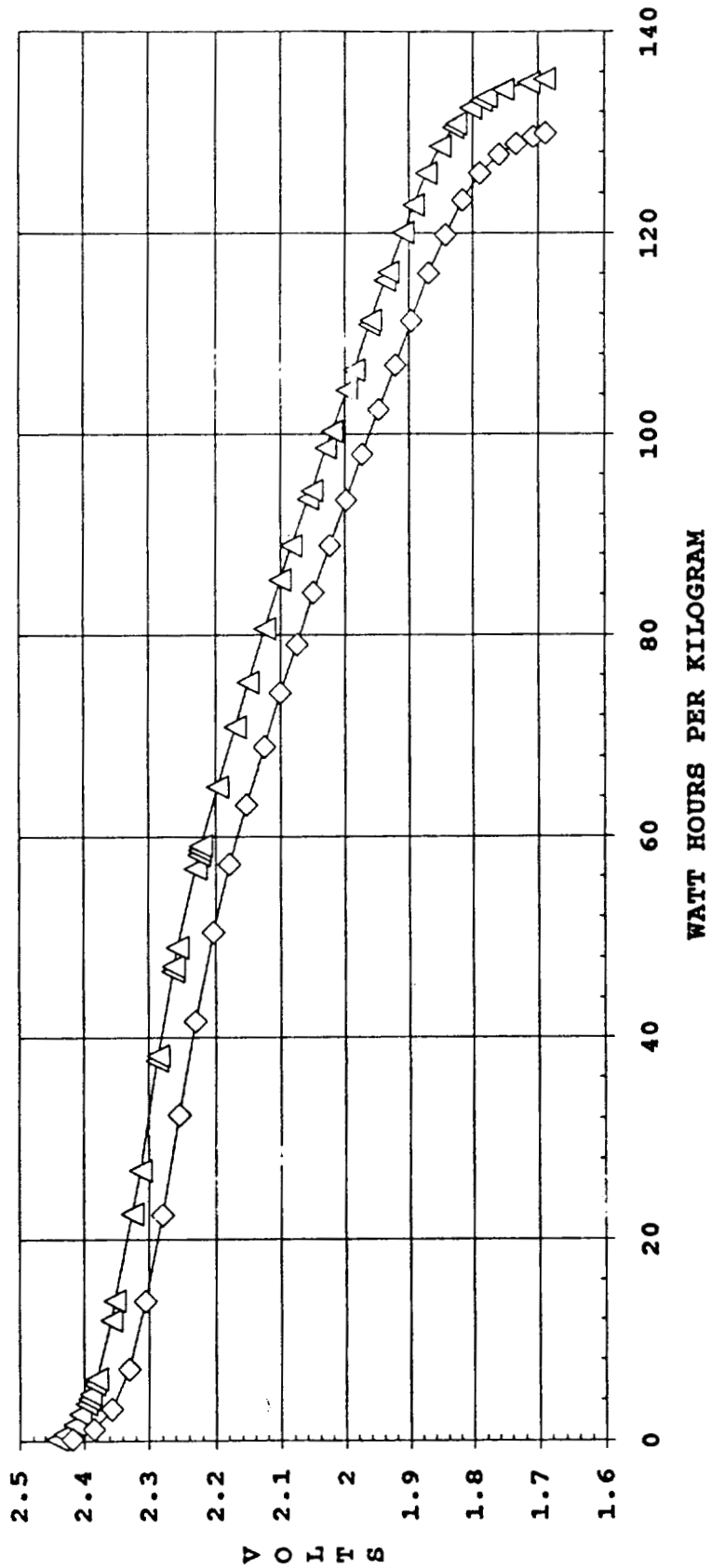


CYCLE LIFE PERFORMANCE OF 1 AHR LITHIUM-TITANIUM DISULFIDE CELLS WITH VARIOUS ELECTROLYTES

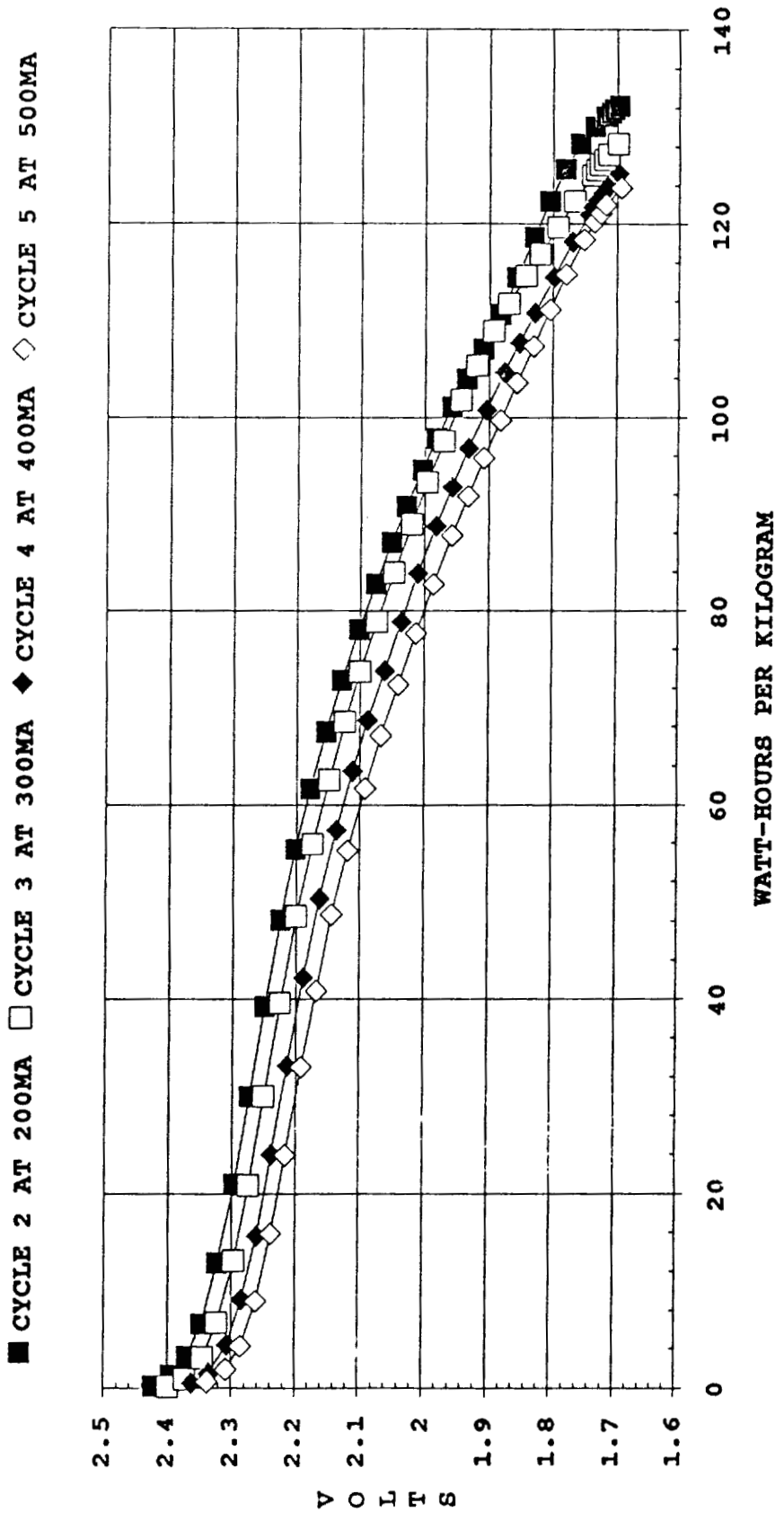


C/5 PERFORMANCE (200MA) OF AA 1 AMPERE-HOUR LITHIUM  
TITANIUM DISULFIDE CELL

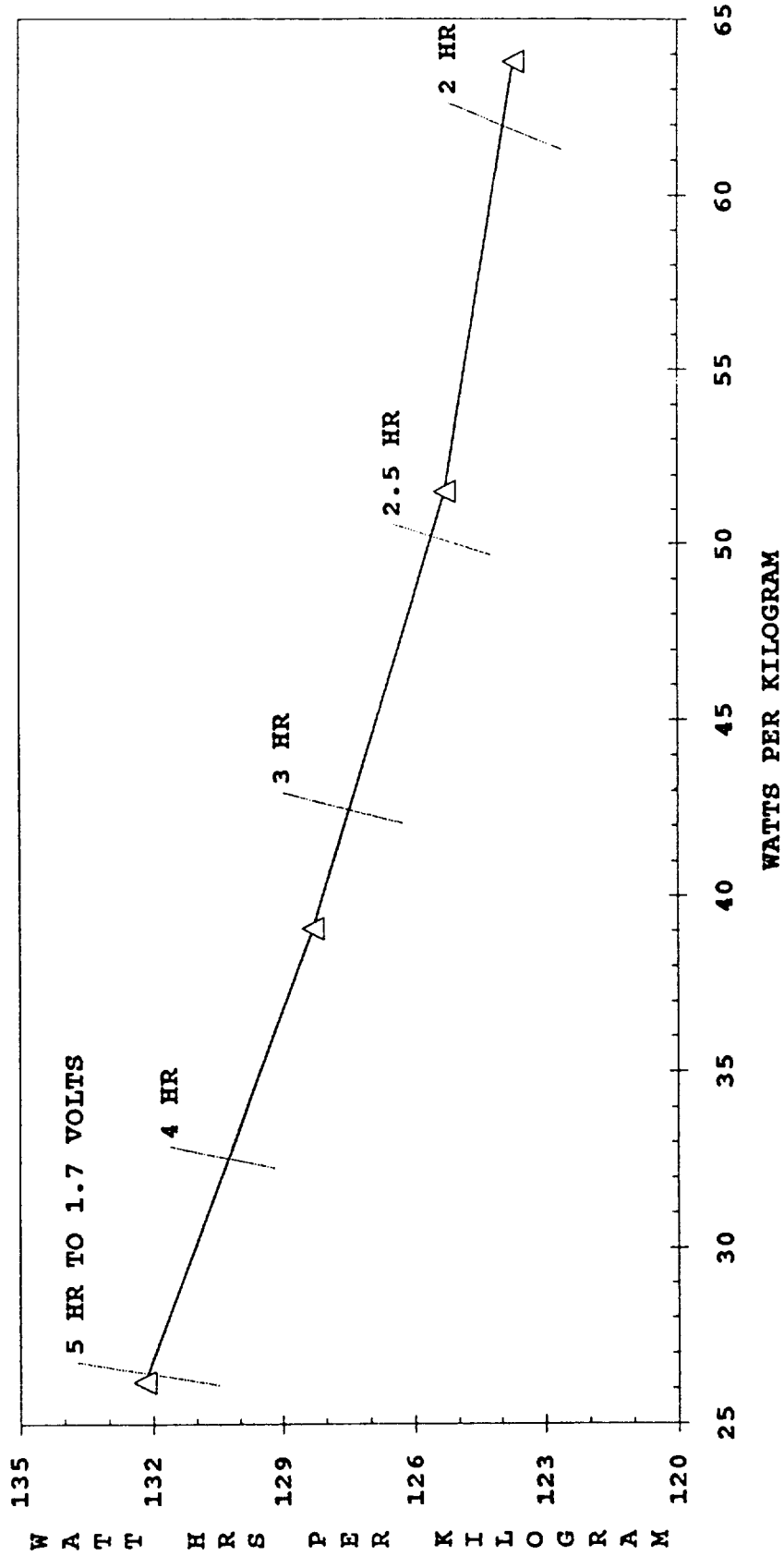
△ CYCLE 1 PERFORMANCE      ◇ AFTER 503 50% DOD CYCLES



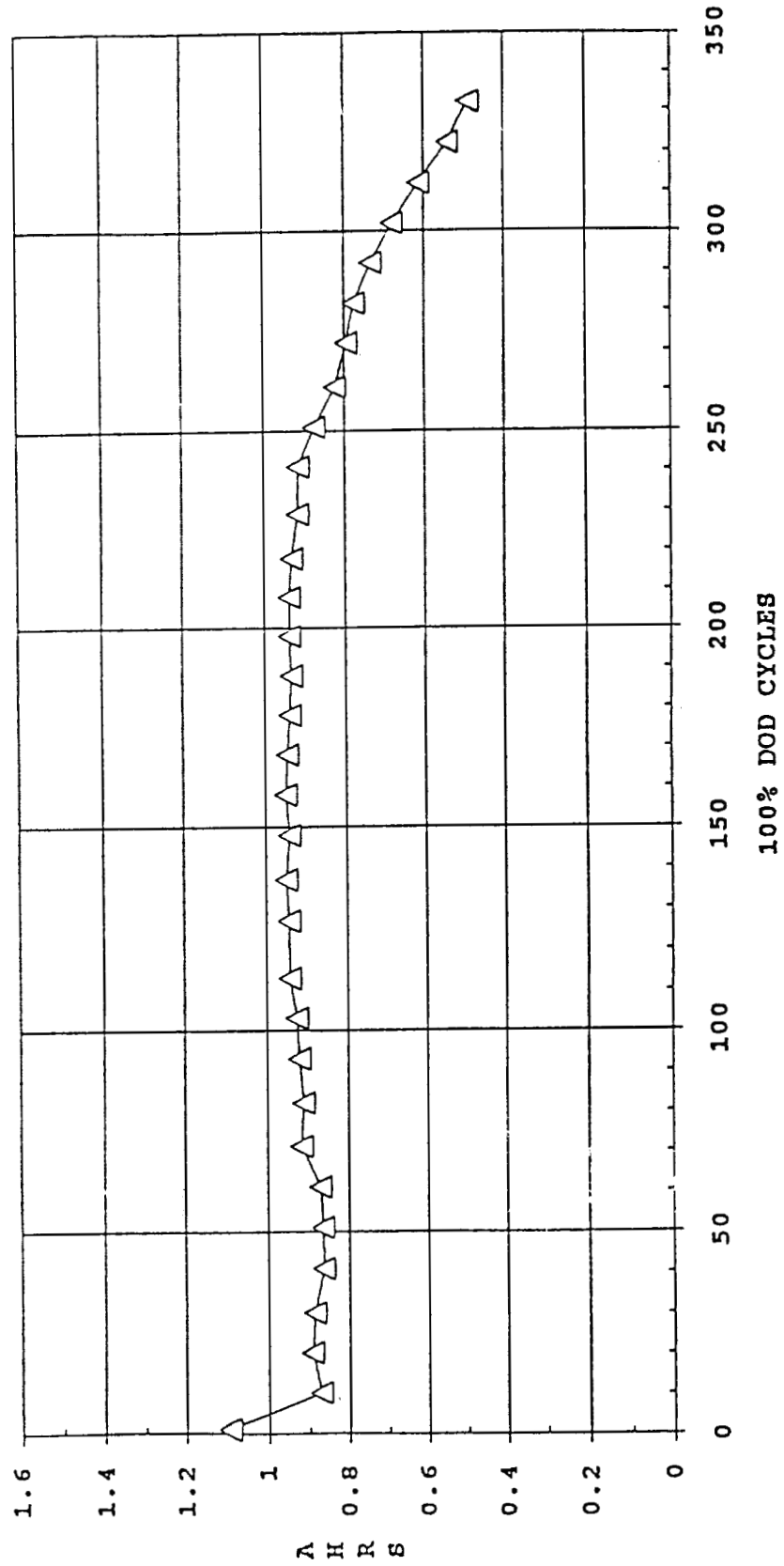
TYPICAL PERFORMANCE OF MANUFACTURED AA 1 AMPERE-HOUR LITHIUM  
TITANIUM DISULFIDE CELL



PERFORMANCE OF A TYPICAL MANUFACTURED AA 1 AMPERE-HOUR LITHIUM  
TITANIUM DISULFIDE CELL



CYCLE LIFE CHARACTERISTICS OF JPL 1 Ah Li-TiS<sub>2</sub> CELL  
AT 100% DOD

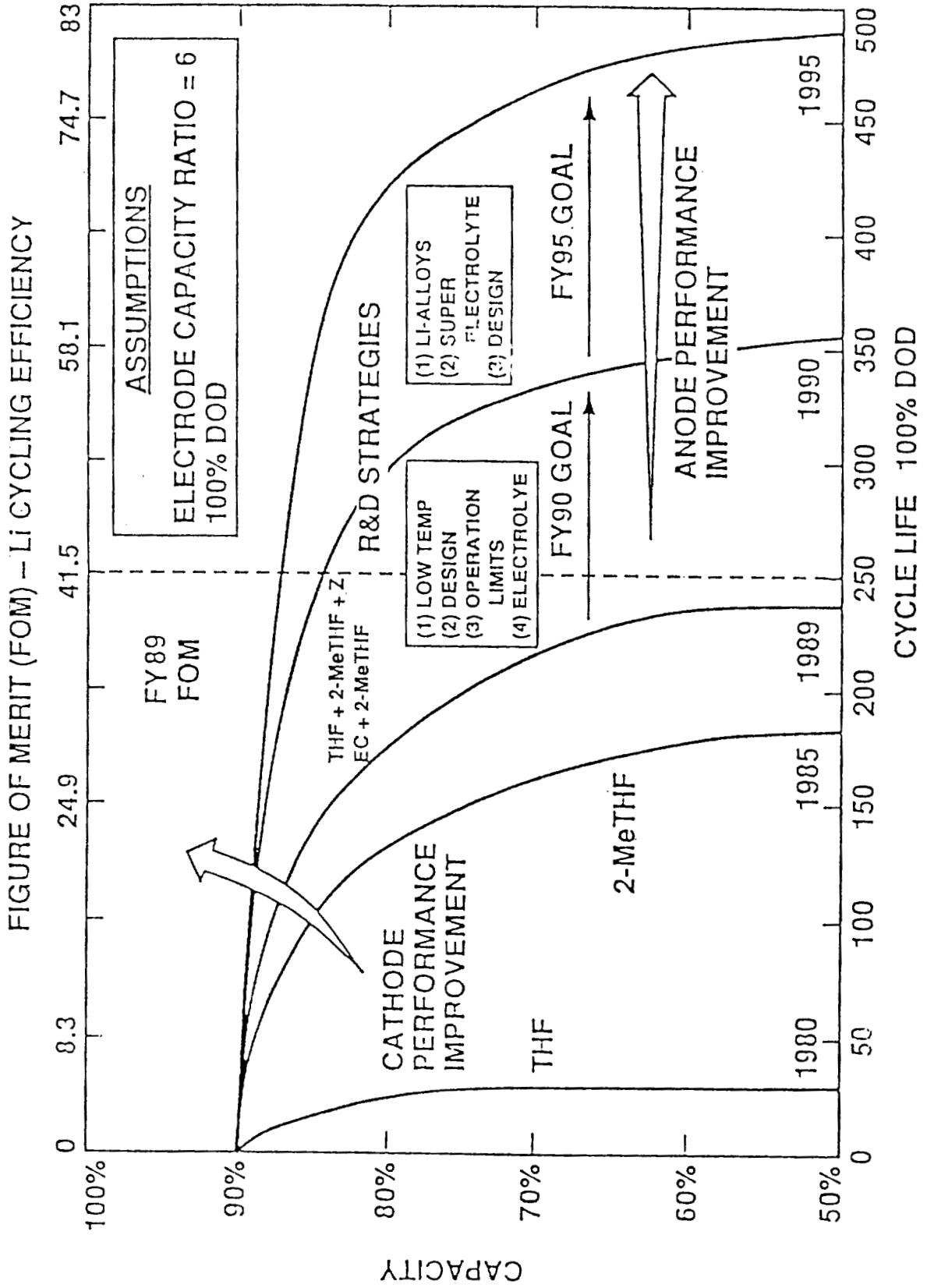


# JPL REQUIRED TECHNOLOGY IMPROVEMENTS

<u>PARAMETER</u>	<u>PRESENT STATUS</u>	<u>NASA REQUIREMENT</u>
CYCLE LIFE	335+ (100% DOD) 650+ (50% DOD)	500 (100% DOD) 1000 (50% DOD)
RATE CAPABILITY	C/5	C/2
CELL SIZE	1 Ah	30 Ah
OVERCHARGE/OVERDISCHARGE	SENSITIVE	TOLERANT
ACTIVE STORAGE	1 YEAR	5 YEARS



# RECHARGEABLE LITHIUM CELL PROGRAM JPL ADVANCES IN Li-TiS<sub>2</sub> CELL TECHNOLOGY





**ALTERNATE LI ANODE MATERIAL STUDIES**  
**EXPERIMENTAL EVALUATION OF SELECTED LI ALLOYS**

<u>Material</u>	<u>Stability*</u>	<u>Ave. E vs. Li</u> (mV)	<u>Reversibility**</u>		<u>Specific Energy***</u> (wh/Kg)	
			<u># OF Li</u> <u>Estimated</u>	<u>Experimental</u>	<u>Estimated</u>	<u>Experimental</u>
Li <sub>1.2</sub> Al	good	380	1.0	< 0.8	312	300
Li <sub>2.85</sub> Cd	poor	0	2.6	--	322	--
Li <sub>4.5</sub> Pb	good	388	3.5	< 1.5	254	167
Li <sub>0.15</sub> C	good	200	0.15	< 0.08	255	186
Li <sub>4.4</sub> Si	poor	--	--	--	--	--
Li <sub>4.3</sub> Sn	good	411	2.0	< 1.0	243	171
Li <sub>1.1</sub> Zn	good	191	0.6	< 0.12	220	62

\* Microcalorimetric and OCV measurements.

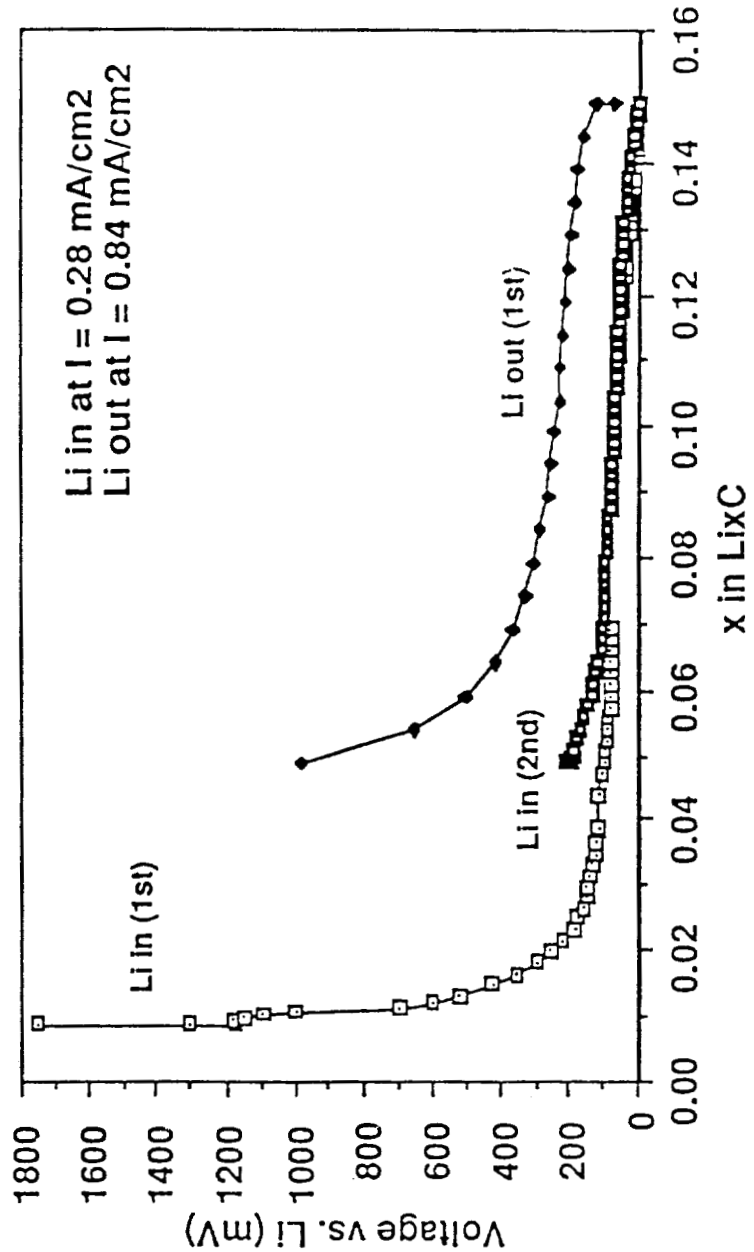
\*\* Galvanostatic cycling studies.

\*\*\* Calculated based on TIS2 cathode.

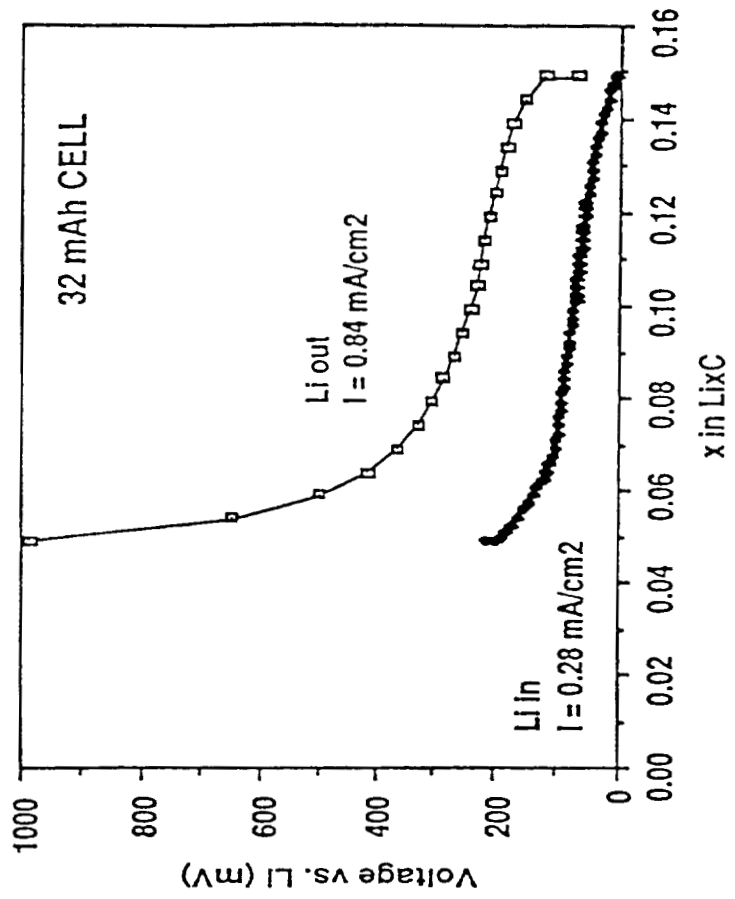
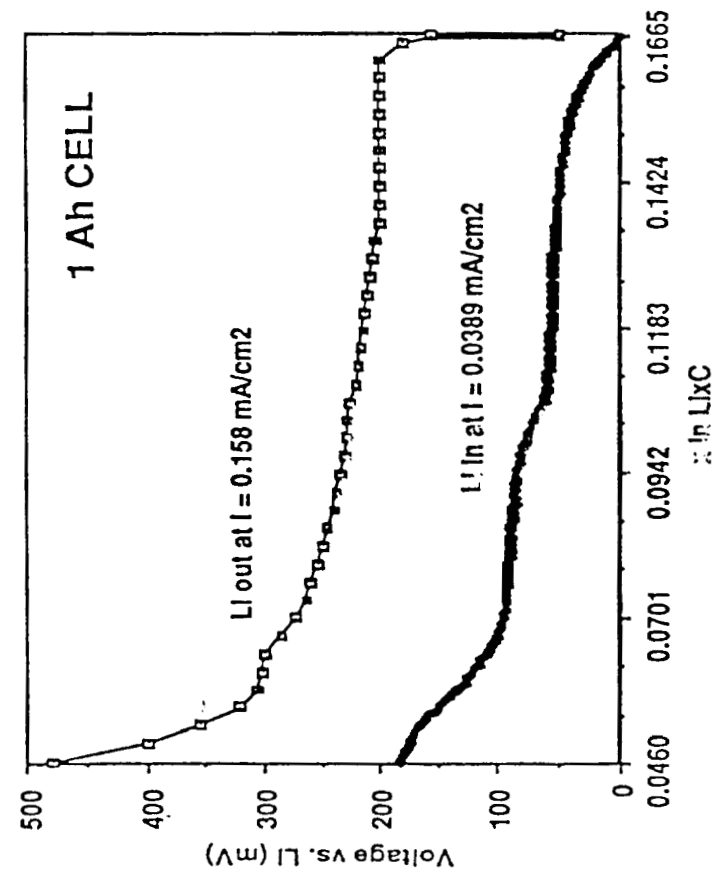
**SUMMARY OF FINDINGS:**

- o Li-Si & Li-Cd ALLOYS WERE FOUND TO BE UNSTABLE.
- o SELECTED Li-Al and Li-C ALLOY SYSTEMS FOR DETAILED ASSESSMENT.

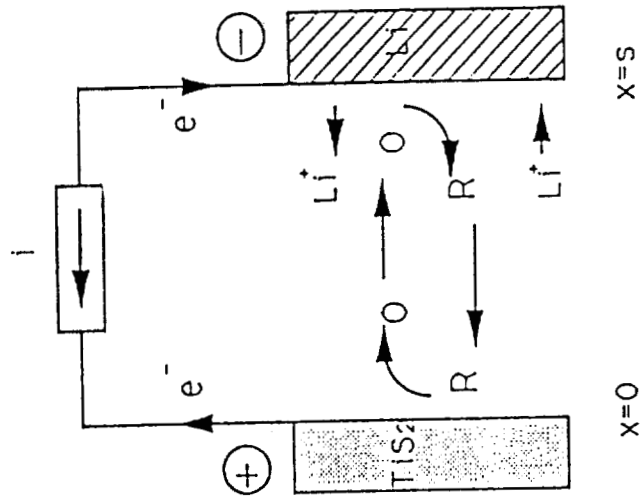
# ELECTROCHEMICAL INTERCALATION & DE-INTERCALATION OF Li IN $\text{Li}_x\text{C}$



**COMPARISON OF CHARGE & DISCHARGE CHARACTERISTICS OF 1 Ah & 32 mAh CELLS**



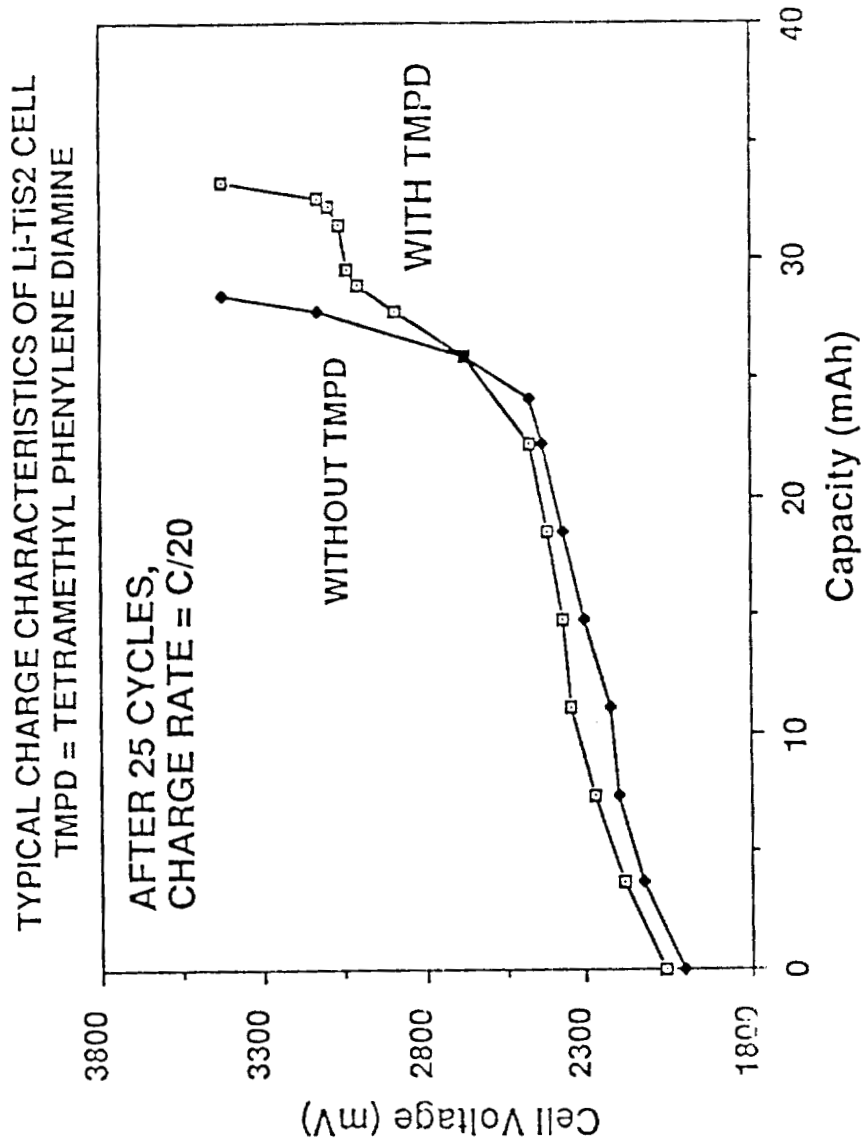
REDOX SHUTTLE APPROACH TO OVERCHARGE PROTECTION



CHEMICAL ENERGY CONVERSION (BATTERY) TECHNOLOGY

# JPL RECHARGEABLE LITHIUM CELL PROGRAM

STUDIES ON OVERCHARGE PROTECTION



## 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 RECHARGABLE 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)





**N92-22765**

**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 NiH<sub>2</sub> 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 NiH<sub>2</sub> 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

TABLE I: A comparison of nickel metal hydride, nickel cadmium and nickel hydrogen 22AH cell performance attributes.

The data tabulated compares two current well-established Aerospace NiCd & NiH<sub>2</sub> 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 NiH<sub>2</sub> 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/in<sup>3</sup>, versus the sintered cadmium electrode. On the other hand, the disadvantage the NiH<sub>2</sub> exhibits relative to the NIMH cell stems primar-

ily 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-

mentally 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 3.00AH and 3.15AH, 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

Performance Attribute	Nickel Cell Electrochemistry		
	NiCd (Note 1)	NiH <sub>2</sub> (Note 1)	NiMH (Note 2)
Midpoint Discharge Voltage (v)	1.20	1.24	1.24
Typical Capacity @ C/2 (AH)	27	22	22
Charge Retention (% , Note 3)	92	82	90
Cell Weight (Kg)	0.80	0.79	0.57
Specific Energy (WH/Kg)	33.0	34.5	47.9
Energy Density (WH/in <sup>3</sup> )	1.67	0.62	2.56

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

Cell Dimensions (Inches)	Nickel Cell Electrochemistry		
	NiCd (Note 1)	NiH <sub>2</sub> (Note 1)	NiMH (Note 2)
Overall Height	4.97	8.25	4.43
Case Height	4.55	5.94	4.01
Width	3.66	3.44(Dia)	2.98
Depth	0.95	N/A	0.89

Note 1: Gates Aerospace Batteries Product

Note 2: Actual Prototype Cell Data

Table III

NiMH Prismatic Cell Design Summary

Prismatic Cell Design (Note 1)

<b>Item</b>	<b>6AH</b>	<b>22AH</b>
<b>Positive Electrodes</b>		
Number . . . . .	14	15
Thickness (in) . . . . .	0.028	0.028
Capacity (AH) theoretical . . . . .	7.5	27.6
<b>Negative Electrodes</b>		
Number . . . . .	15	16
Thickness (in) . . . . .	0.0125	0.0125
Capacity (AH) . . . . .	11.5	42.2
<b>Separator</b> . . . . .	Nylon-2538	Nylon-2538
<b>Negative to Positive</b>		
<b>Capacity Ratio</b> . . . . .	<b>1.5</b>	<b>1.5</b>
<b>Electrolyte</b>		
Type . . . . .	KOH	KOH
Concentration (%) . . . . .	31	31
<b>Cell Dimensions (In)</b>		
Overall Height . . . . .	2.75	4.43
Case Height . . . . .	2.33	4.01
Width . . . . .	2.12	2.98
Depth . . . . .	0.82	0.89

*Note 1: Capacities are C/2 typicals at room temperature for prototype cells*

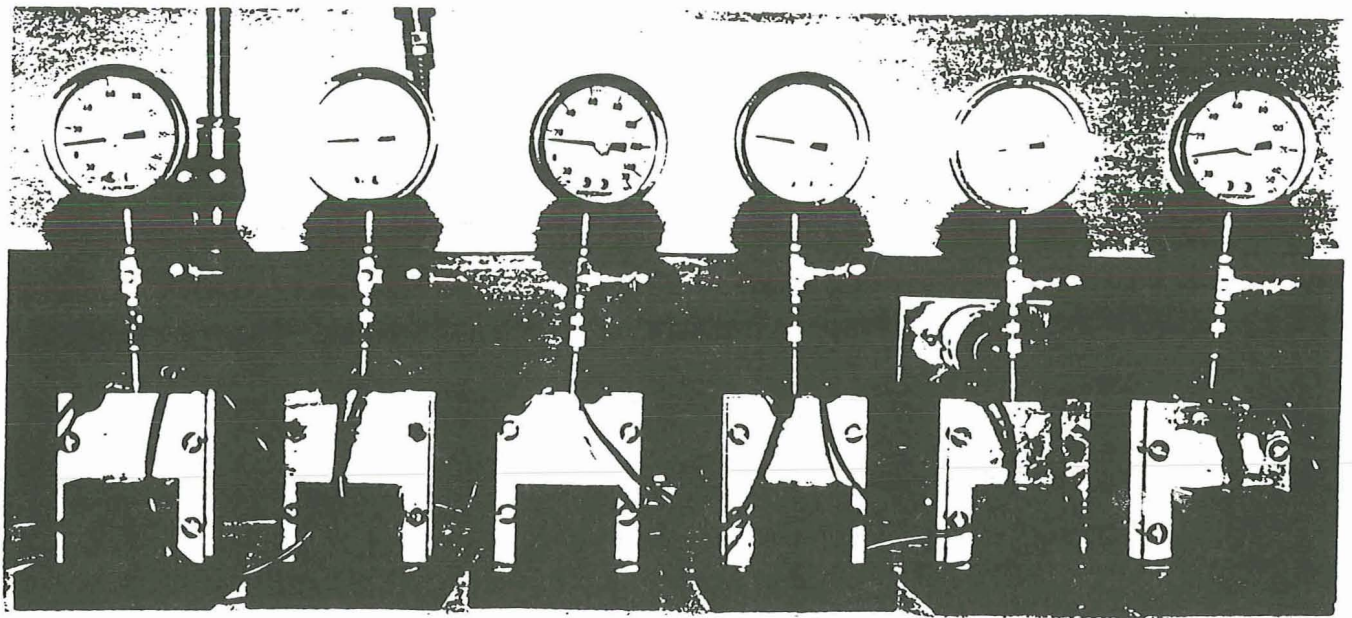


Figure 1 Prototype Aerospace Prismatic 6AH cells on cycle life test

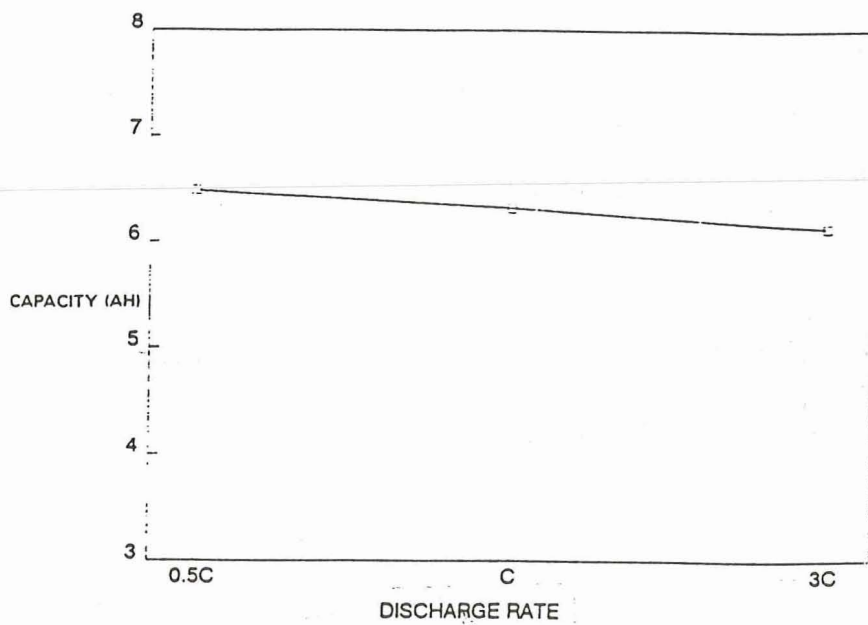


Figure 2 Prototype Aerospace Prismatic 6AH Cell Discharge Rate Capability

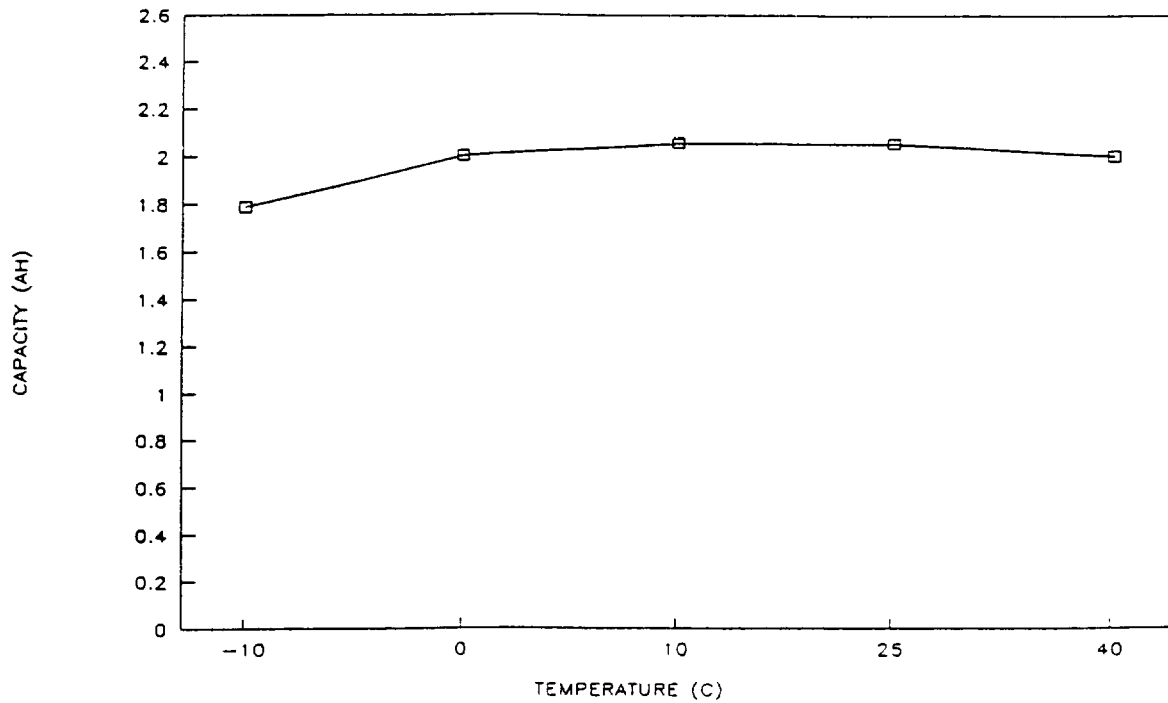


Figure 3 Cylindrical Cell Capacity vs. Temperature @ C Rate

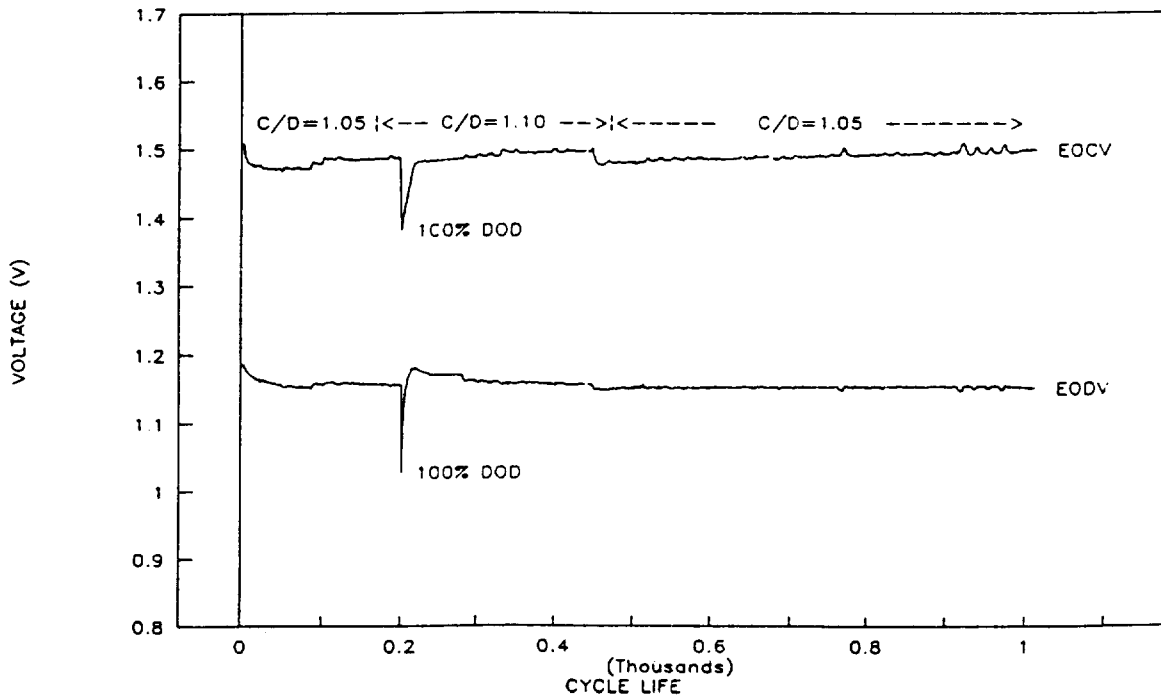
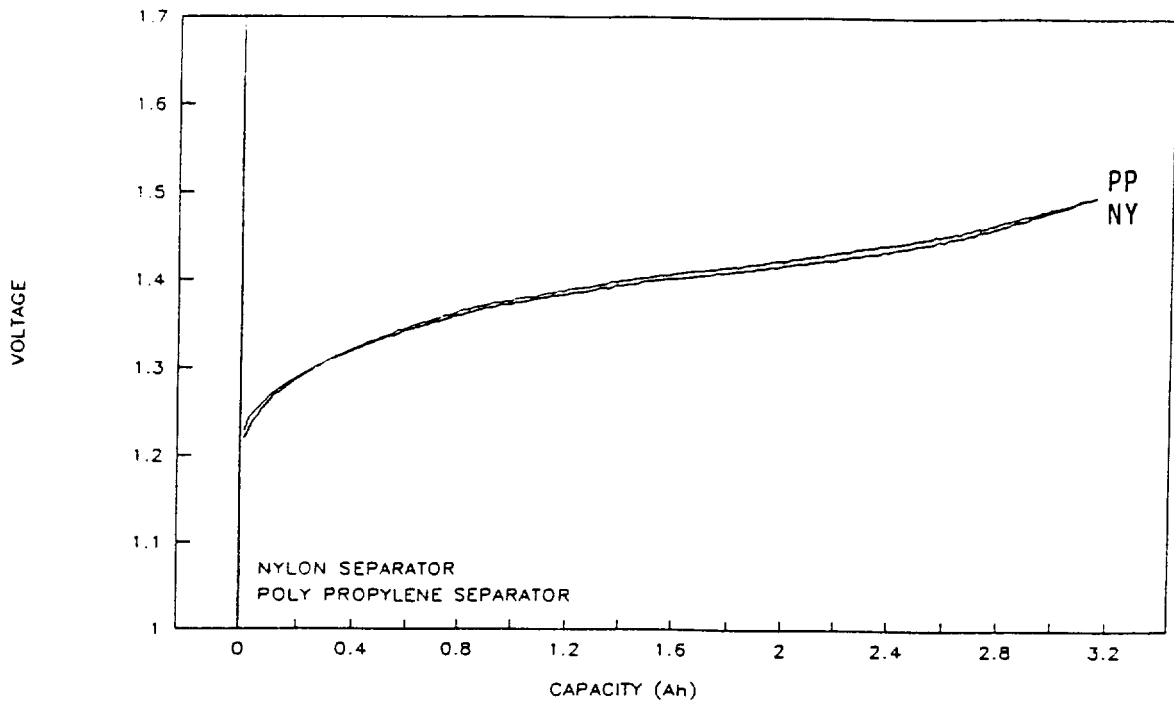
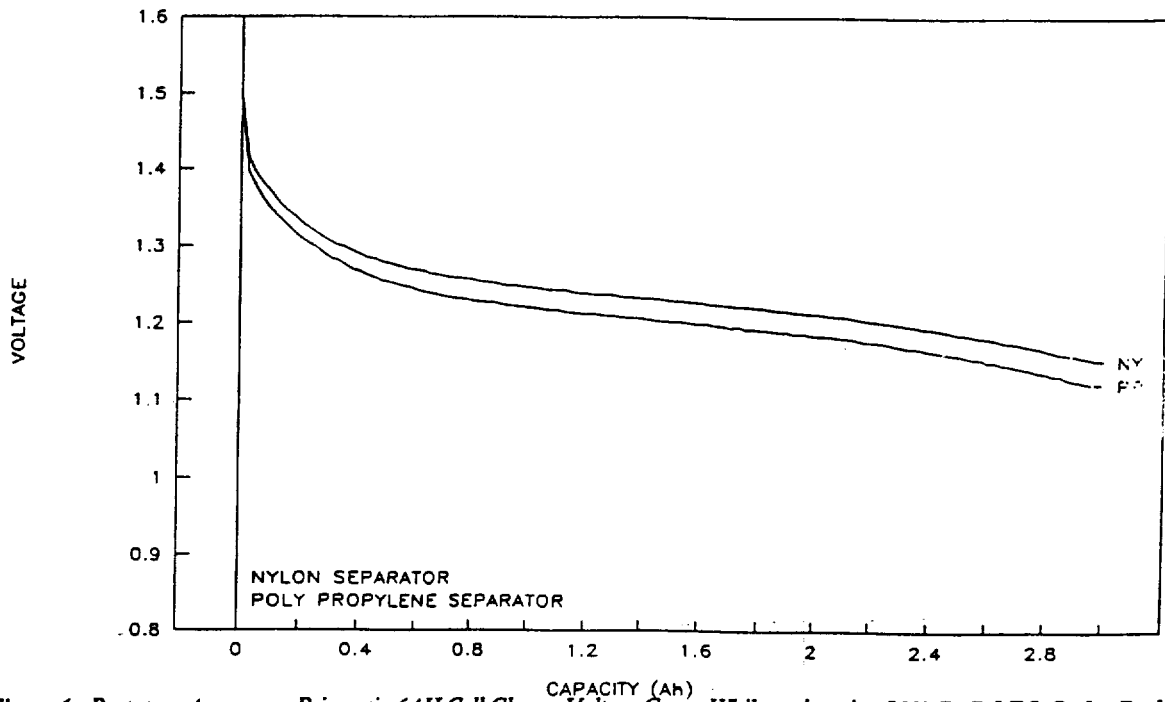


Figure 4 Prototype Aerospace Prismatic 6AH Cell EOCV and EODV Trends as a function of Number of 50% DoD LEO Cycles





**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

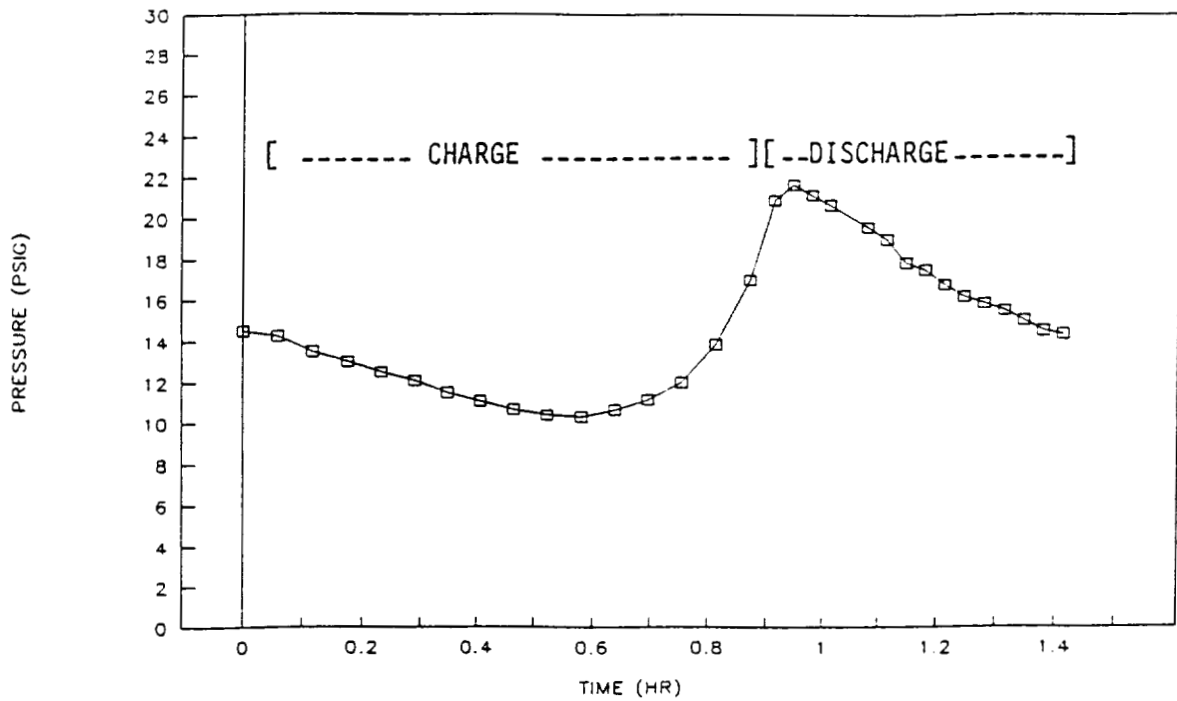


Figure 7 Prototype Aerospace Prismatic 6AH Cell Pressure Curve While undergoing 50% DoD LEO Cycle: Recharge Ratio = 1.05, Cycle 788

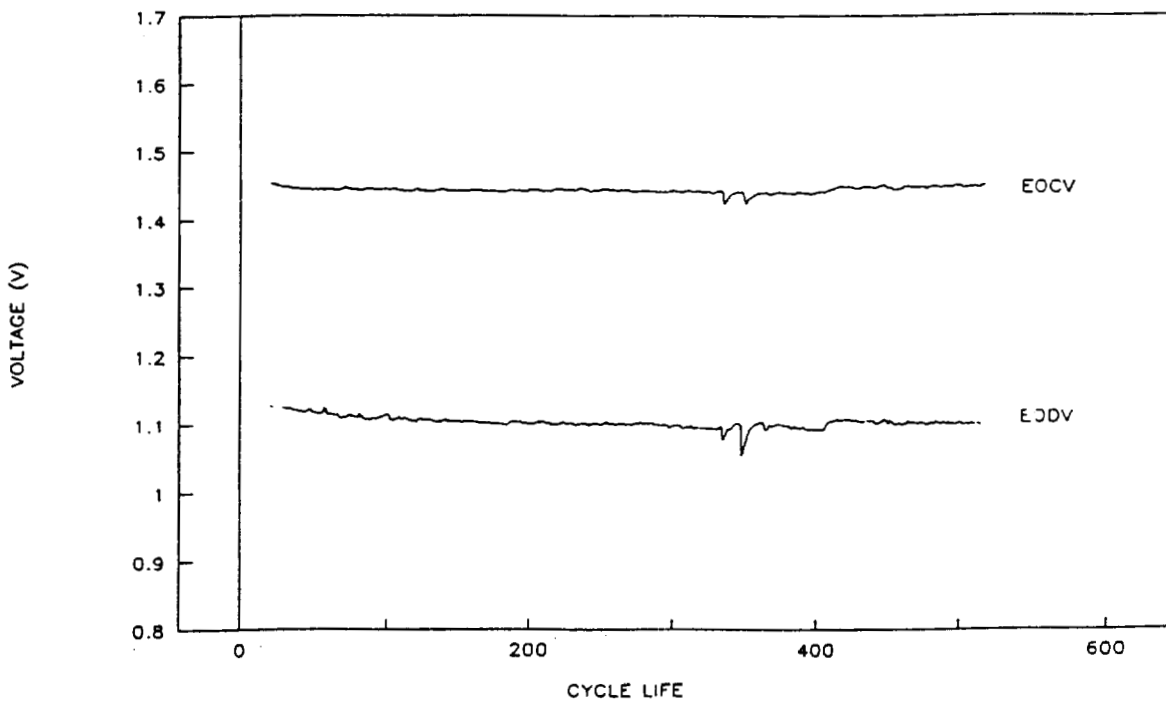
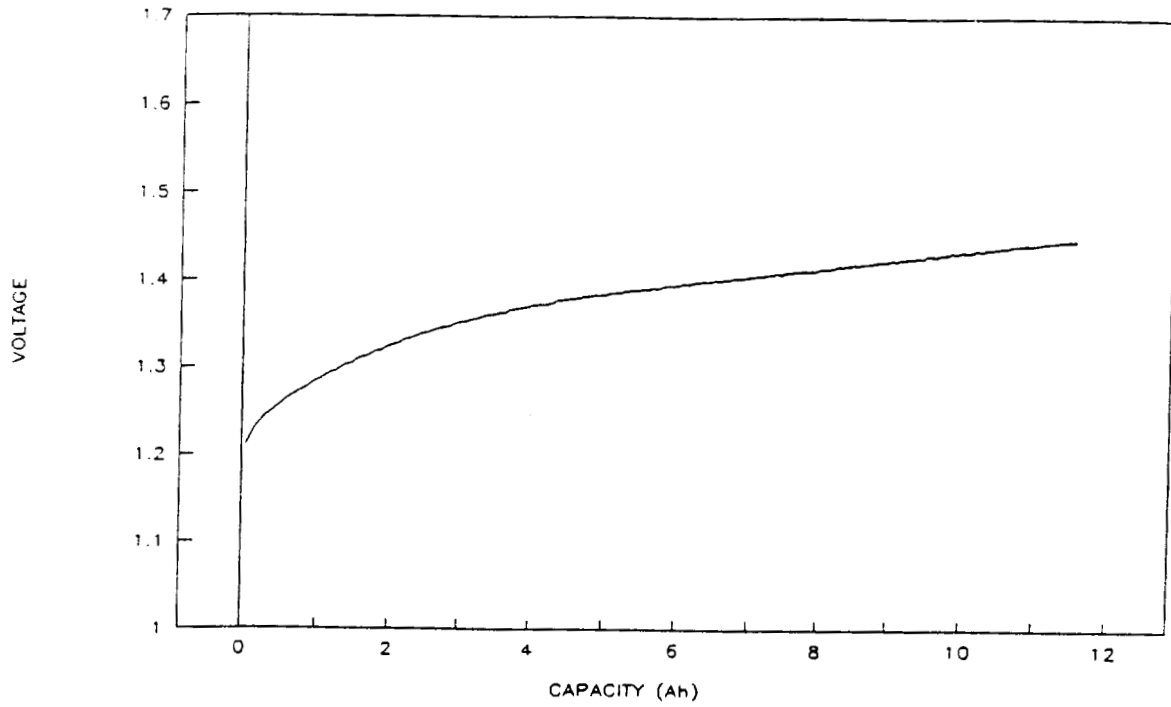
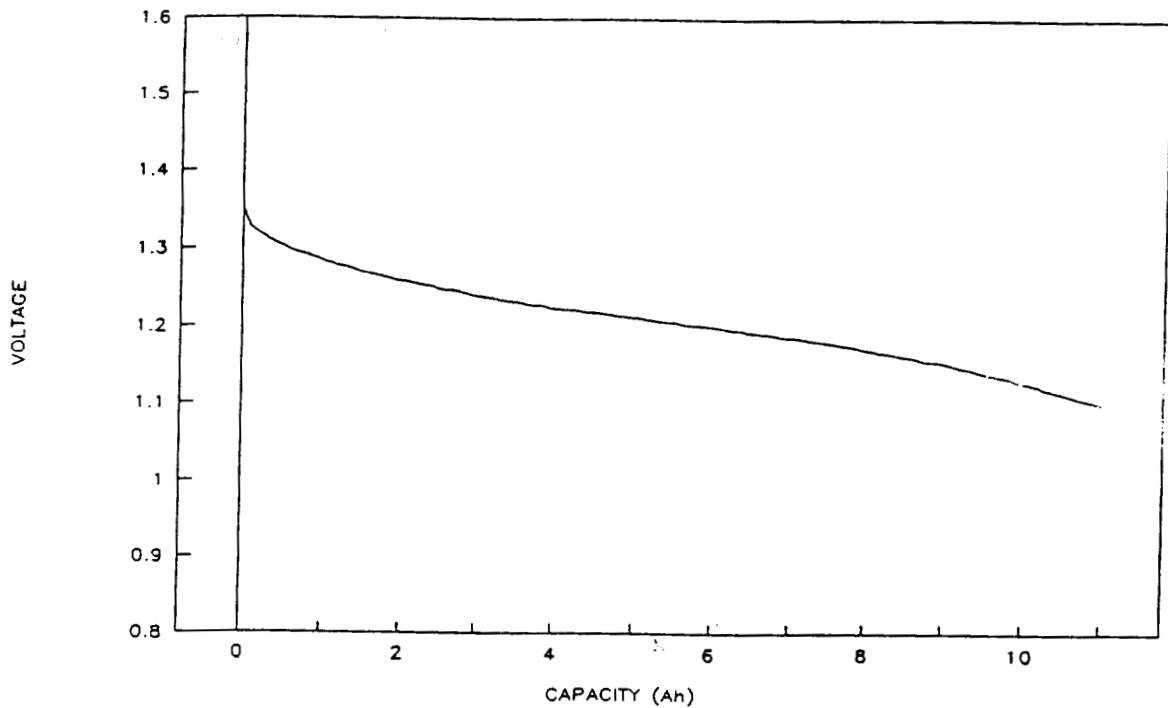


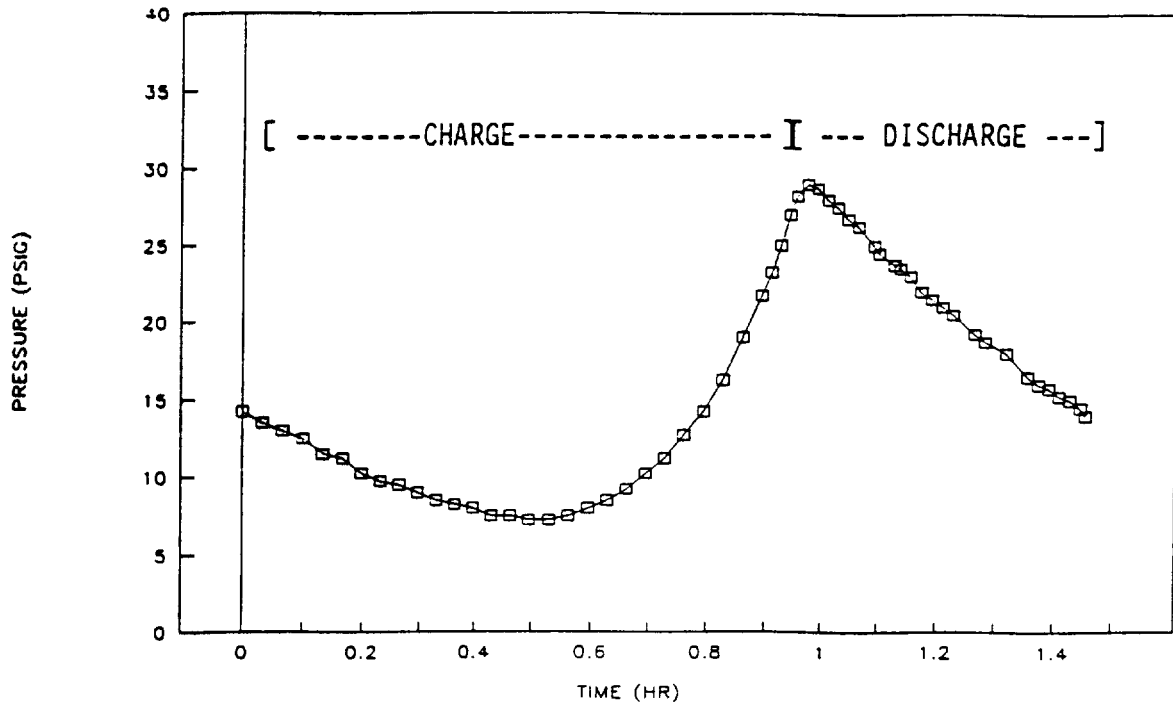
Figure 8 Prototype Aerospace Prismatic 22AH Cell EOCV and EODV Trends as a Function of Number of 50% DoD LEO Cycles



**Figure 9** Prototype Aerospace Prismatic 22AH Cell Charge Voltage Curve While Undergoing 50 % DoD LEO Cycle: R : charge Ratio = 1.05, Cycle 512



**Figure 10** Prototype Aerospace Prismatic 22AH Cell Discharge Voltage Curve While Undergoing 50% DoD LEO Cycle: R : 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

Figure 12

## 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 > NiH<sub>2</sub> and NiCd

Specific Energy > NiCd and NiH<sub>2</sub>

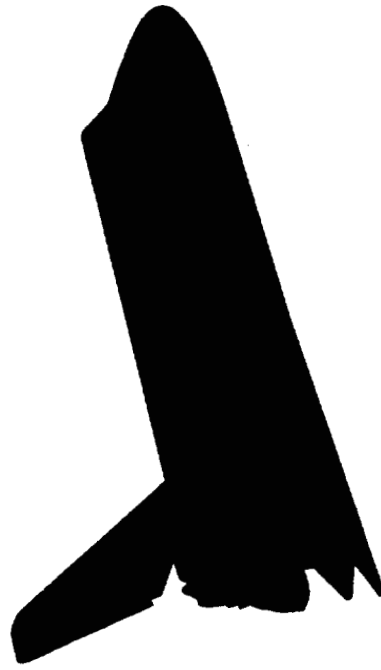
**N 9 2 - 2 2 7 6 6**

**Sealed Aerospace Metal-Hydride Batteries**

Dwaine Coates, Eagle Picher Industries

1991 NASA AEROSPACE BATTERY WORKSHOP

# SEALED AEROSPACE METAL-HYDRIDE BATTERIES



DWAINE 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

HERMETICALLY SEALED

OPERATE AT LOW PRESSURE

PRISMATIC GEOMETRY

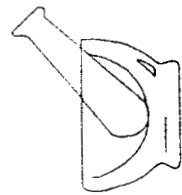
EXCELLENT OVERCHARGE

EXCELLENT OVERDISCHARGE

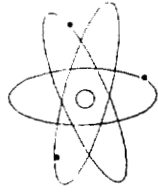
EXCELLENT THERMAL

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.



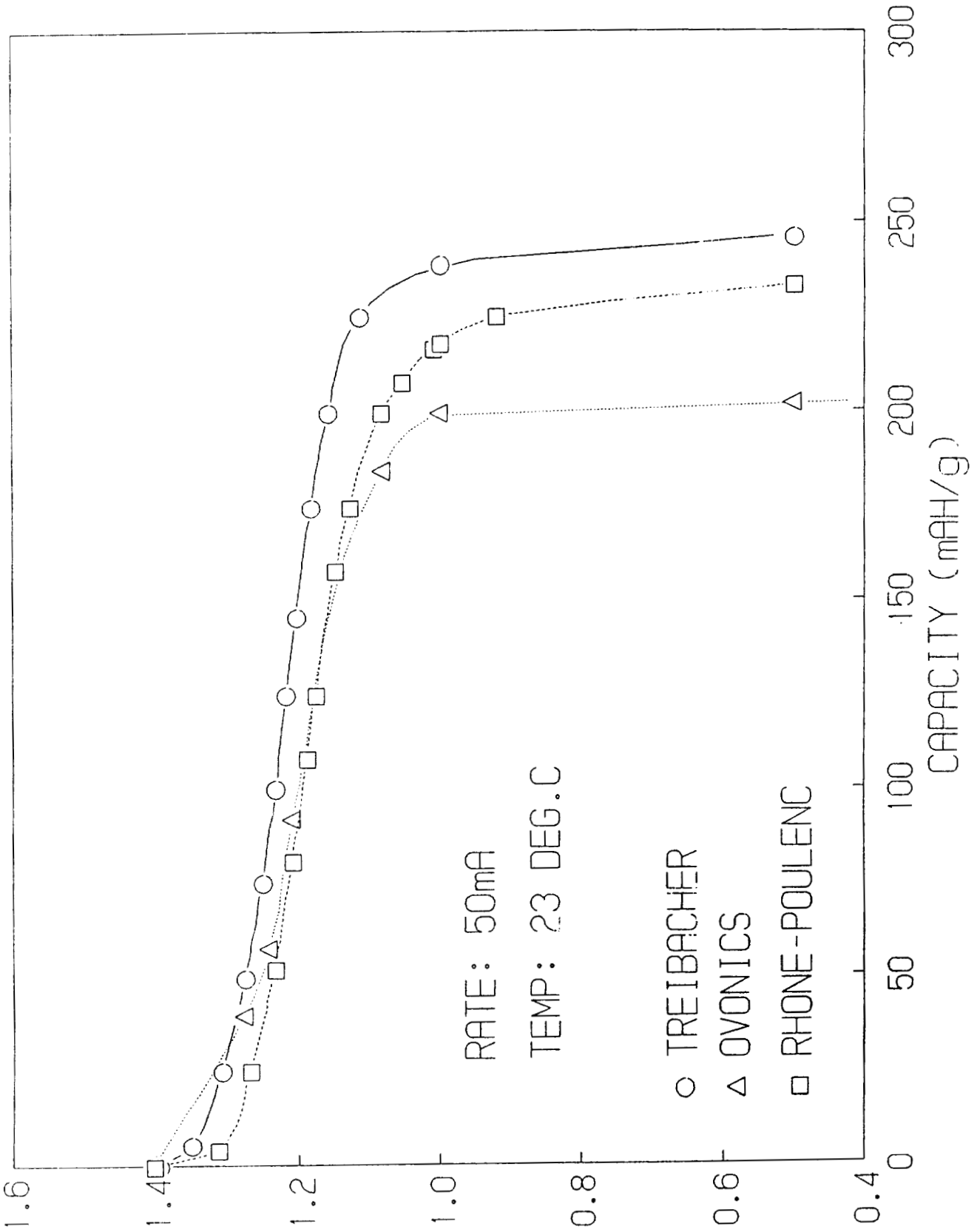
# SOURCES OF HYDRIDE MATERIALS AND ALLOYS



Morton International	Tricoastal Lanthanides
Treibacher-Austria	Crucible
Rhone-Poulenc	Goldschmidt AG
Nissho-Iwai America	Indian Rare Earths
Sumitomo	Molycorp/Unocal
Ergenics	REMACOR
HCl-Denver	Santoku Metal
Aesar/Johnson Matthey	Chori-Osaka
Baotou Research	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.

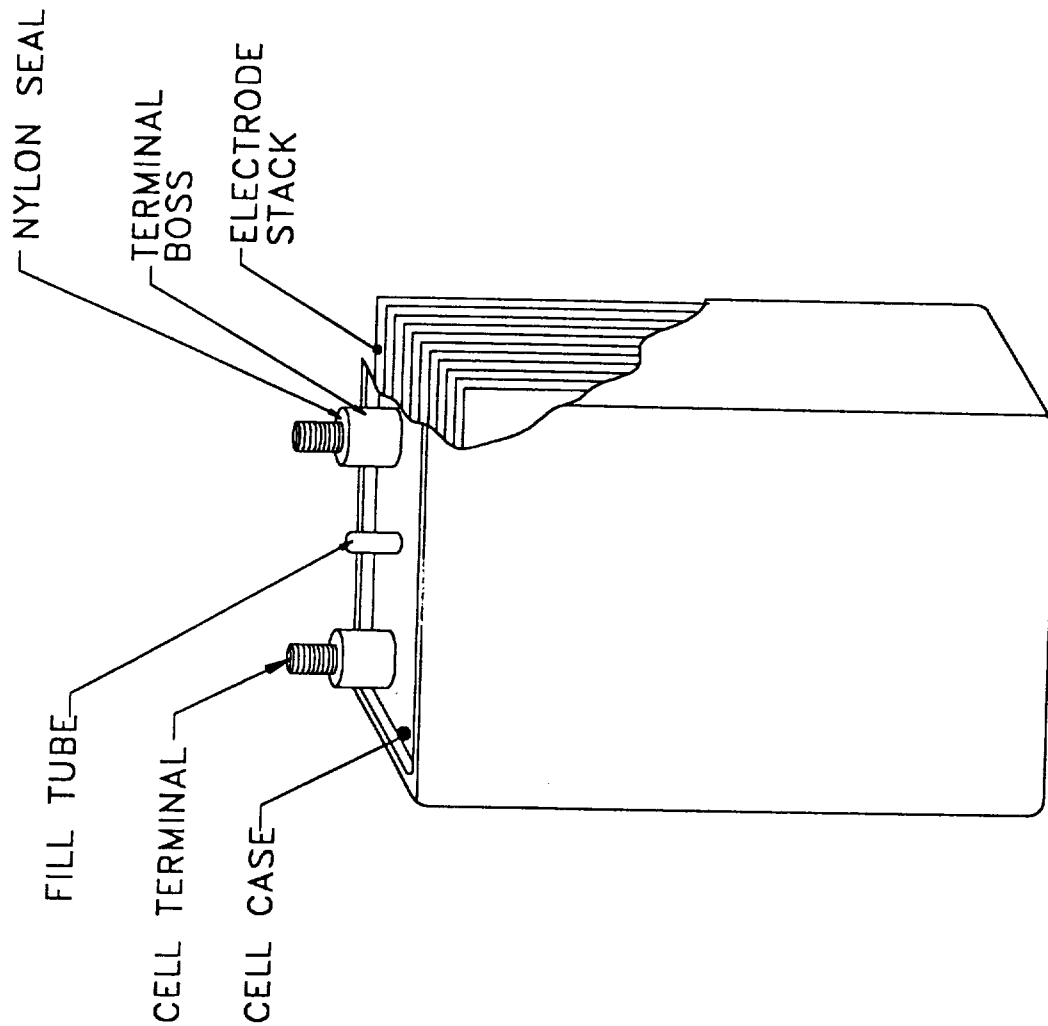
# METAL-HYDRIDE ENERGY DENSITY



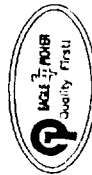
Eagle-Picher has evaluated materials from several of the sources previously listed. The chart shows comparative data for Ovonics material, Treibacher material and material from Rhone-Poulenc. The materials are in various stages of testing. Other materials are in-house but have not been evaluated yet. 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



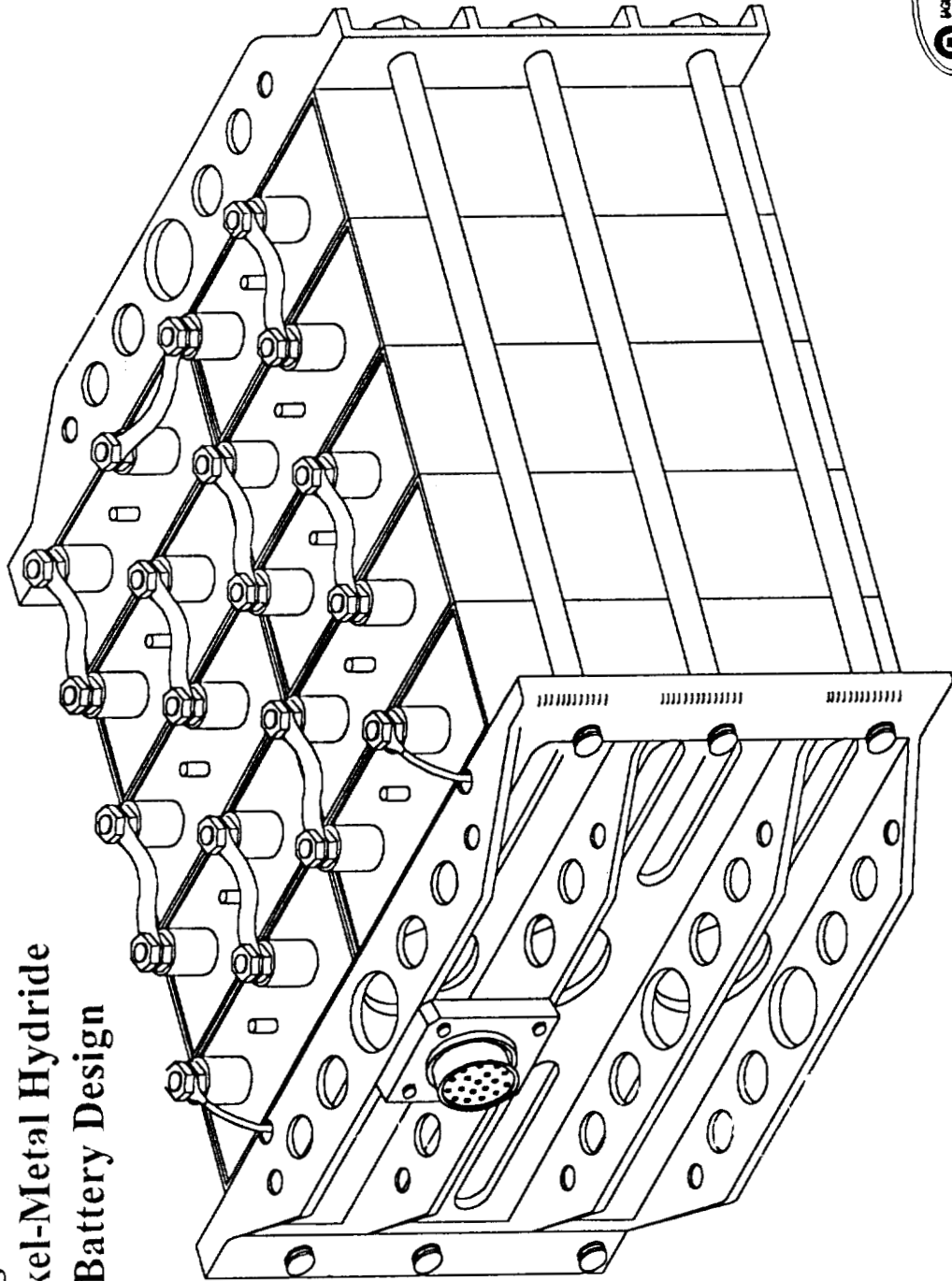
**Figure 2**  
Prismatic Aerospace  
Nickel-Metal  
Hydride Cell



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-Hydrde Batteries for Aerospace Applications

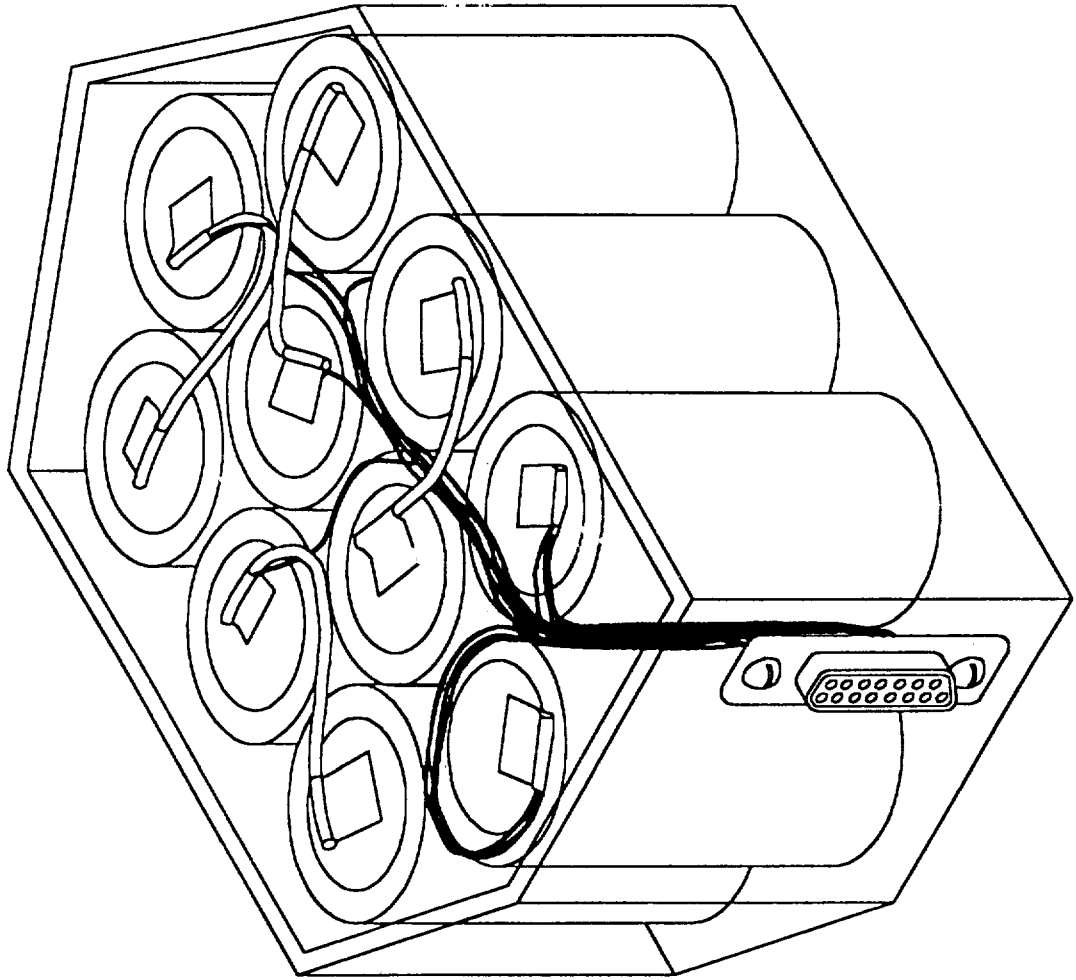
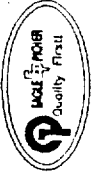
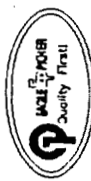
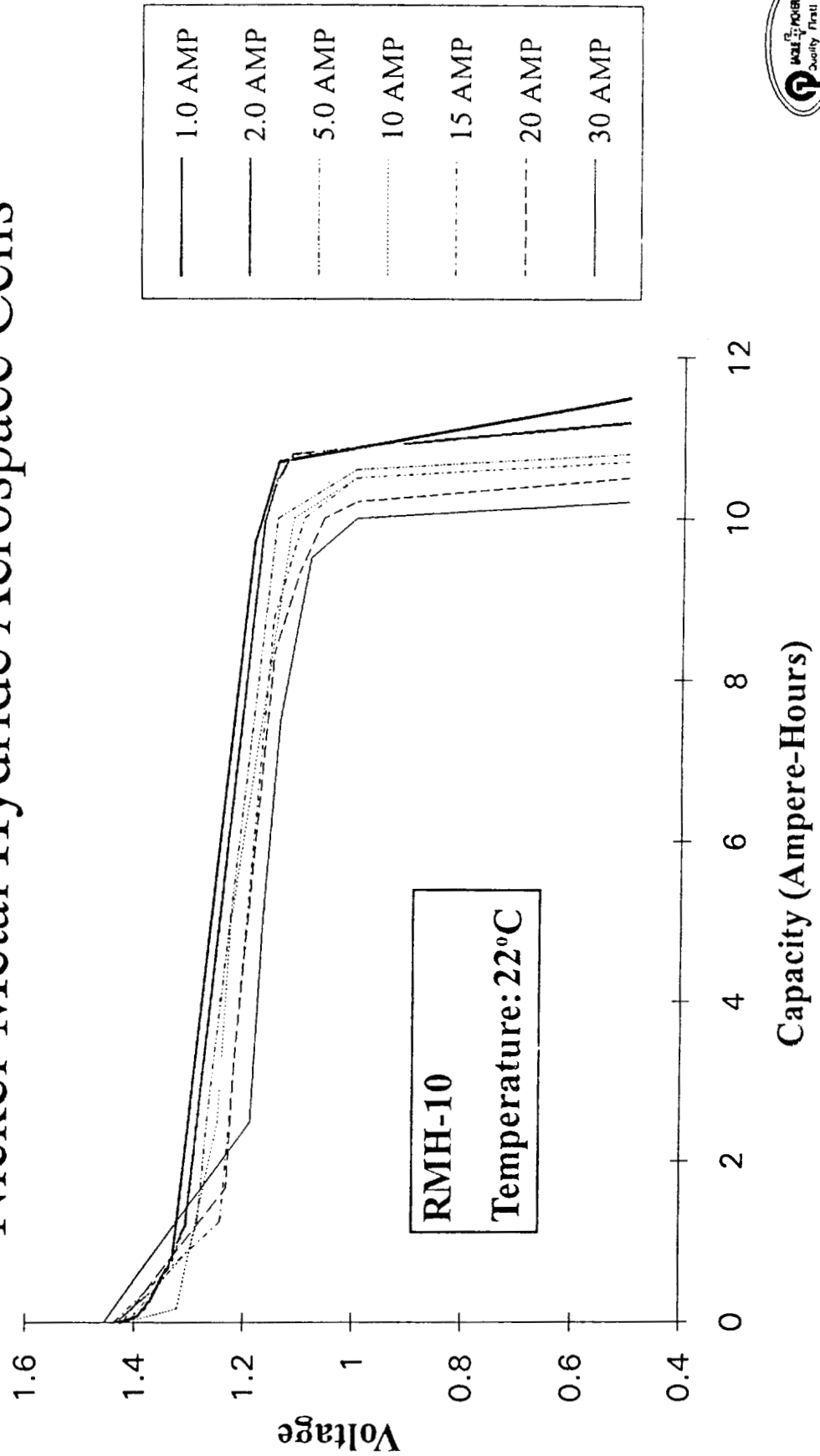


Figure 4  
Nickel-Metal Hydride  
Alternative Battery Design



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.

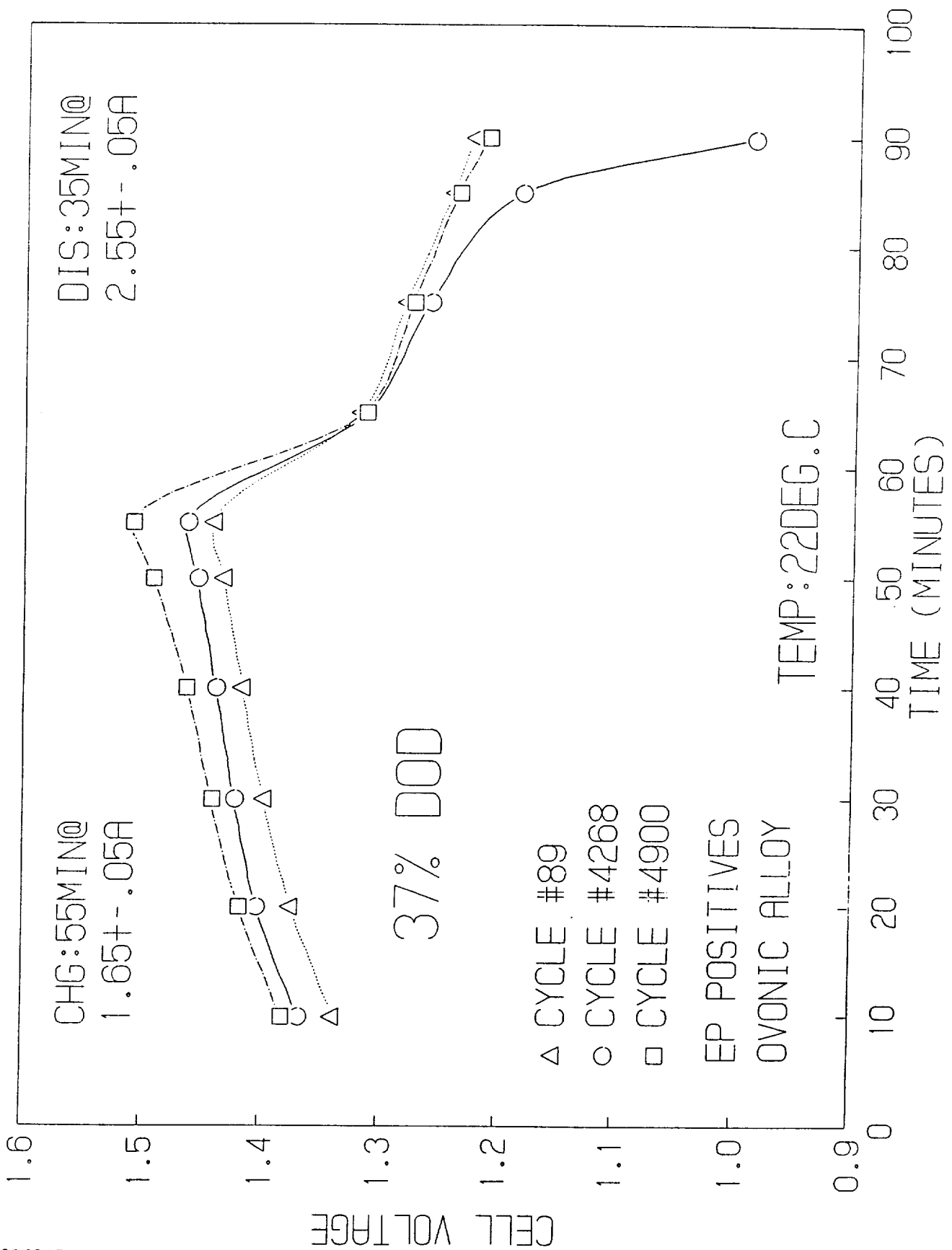
Figure 7  
**Nickel-Metal Hydride Aerospace Cells**



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.



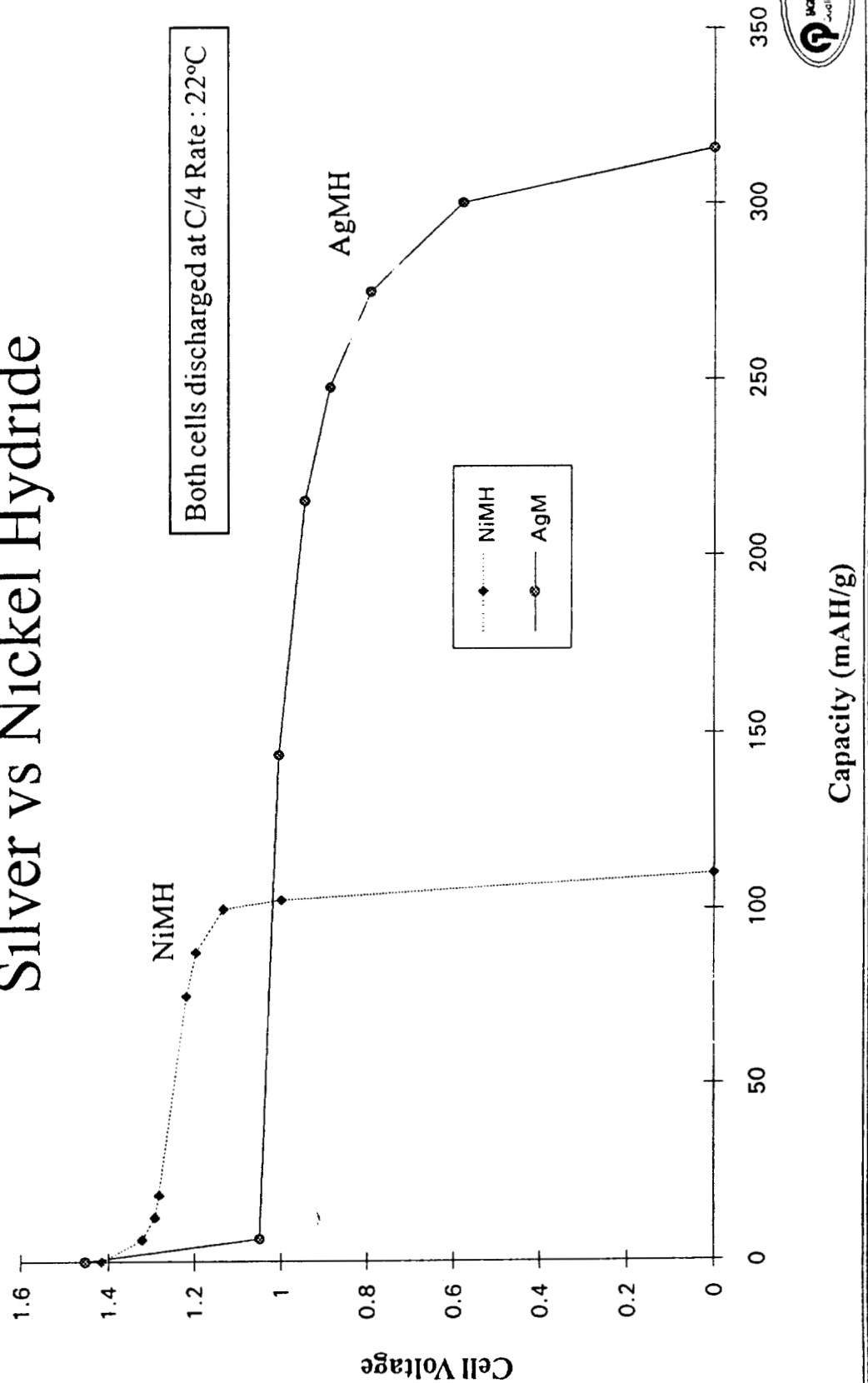
# NiMH LEO SIMULATION



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

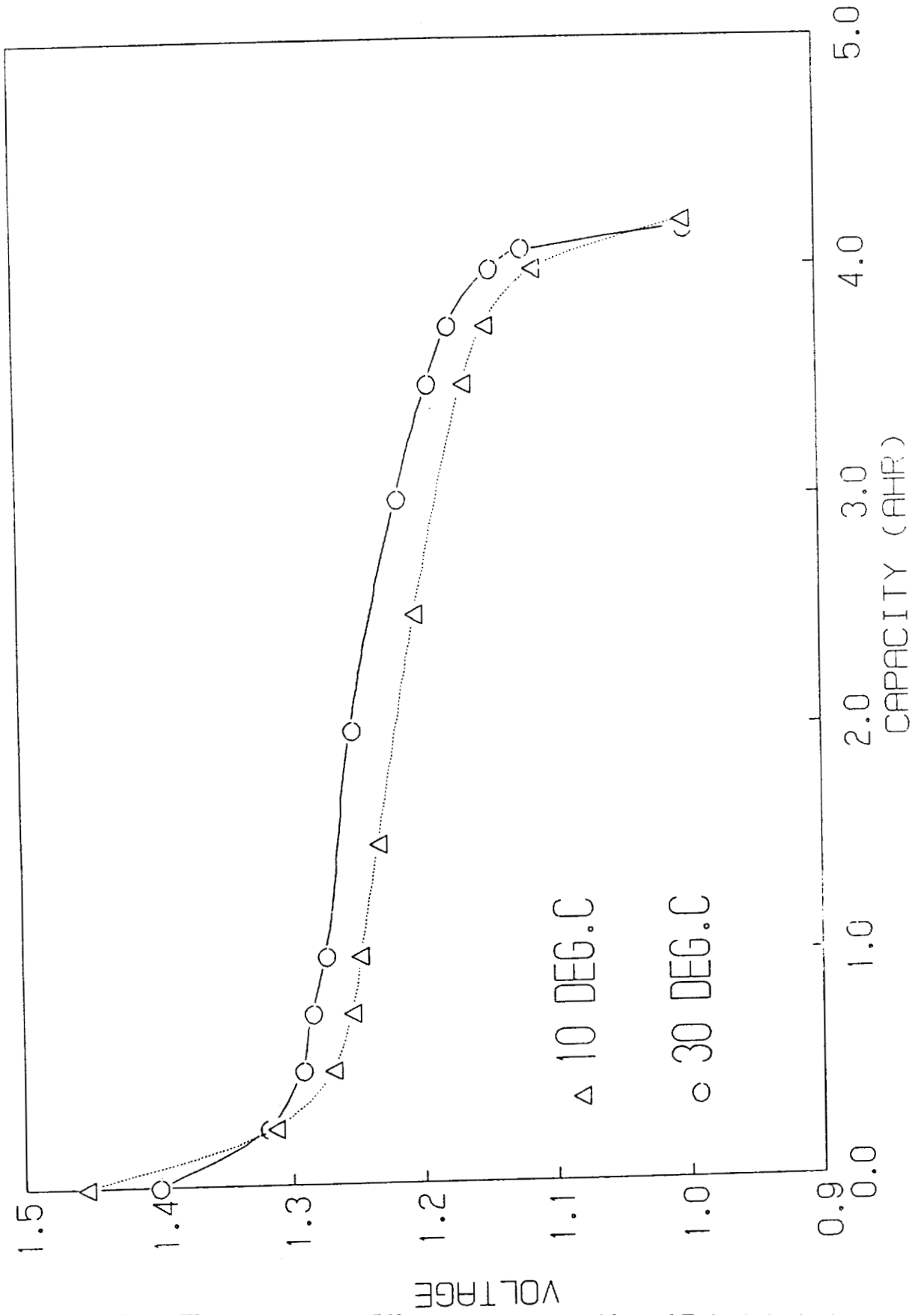
Figure 9  
Silver vs Nickel Hydride



This graph directly compares the nickel-metal hydride system with the silver-metal hydride system. The silver electrode has a much high 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.

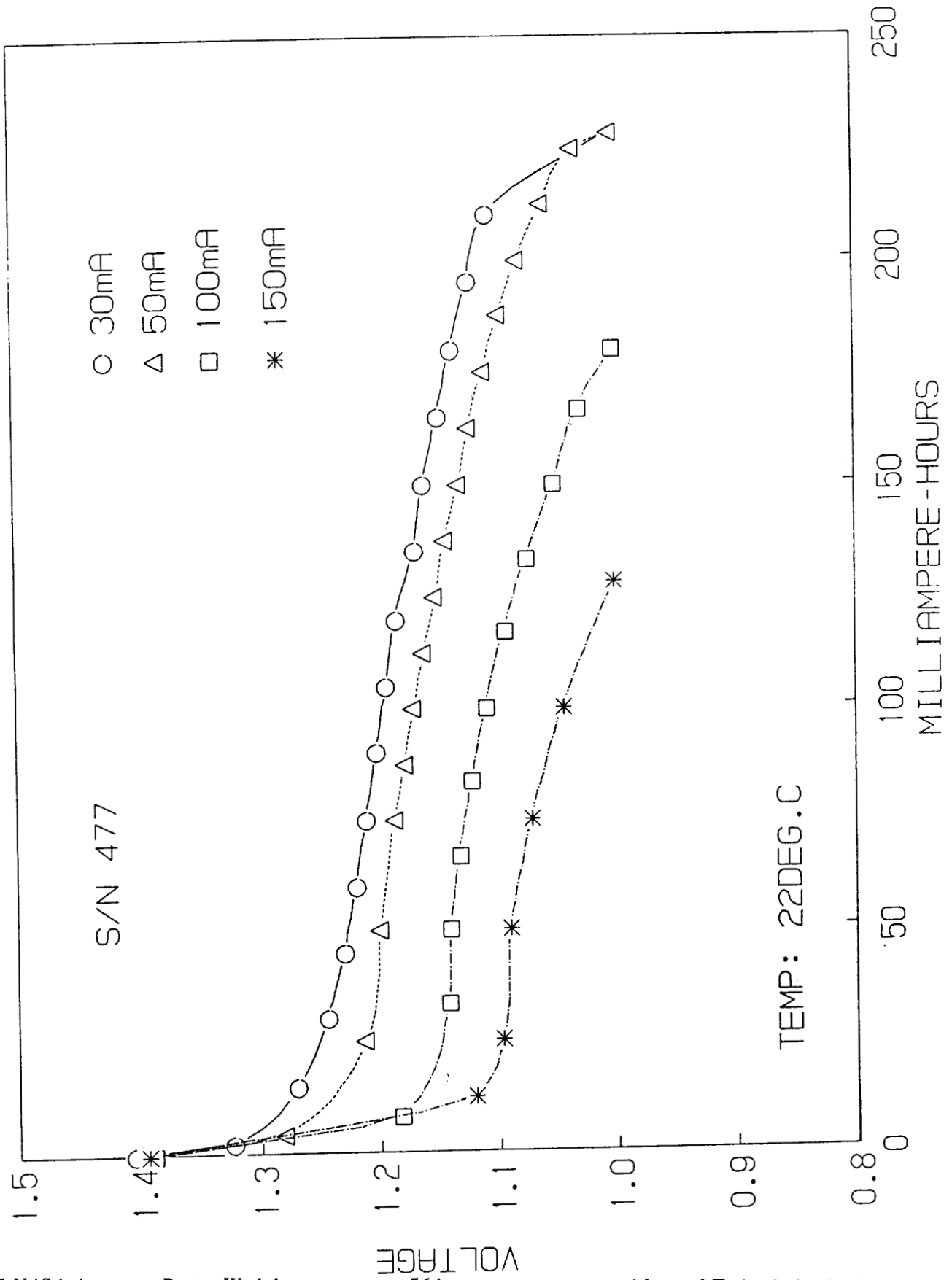
# NICKEL-METAL HYDRIDE DISCHARGE

1.0 AMP RATE



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 NiH<sub>2</sub>.

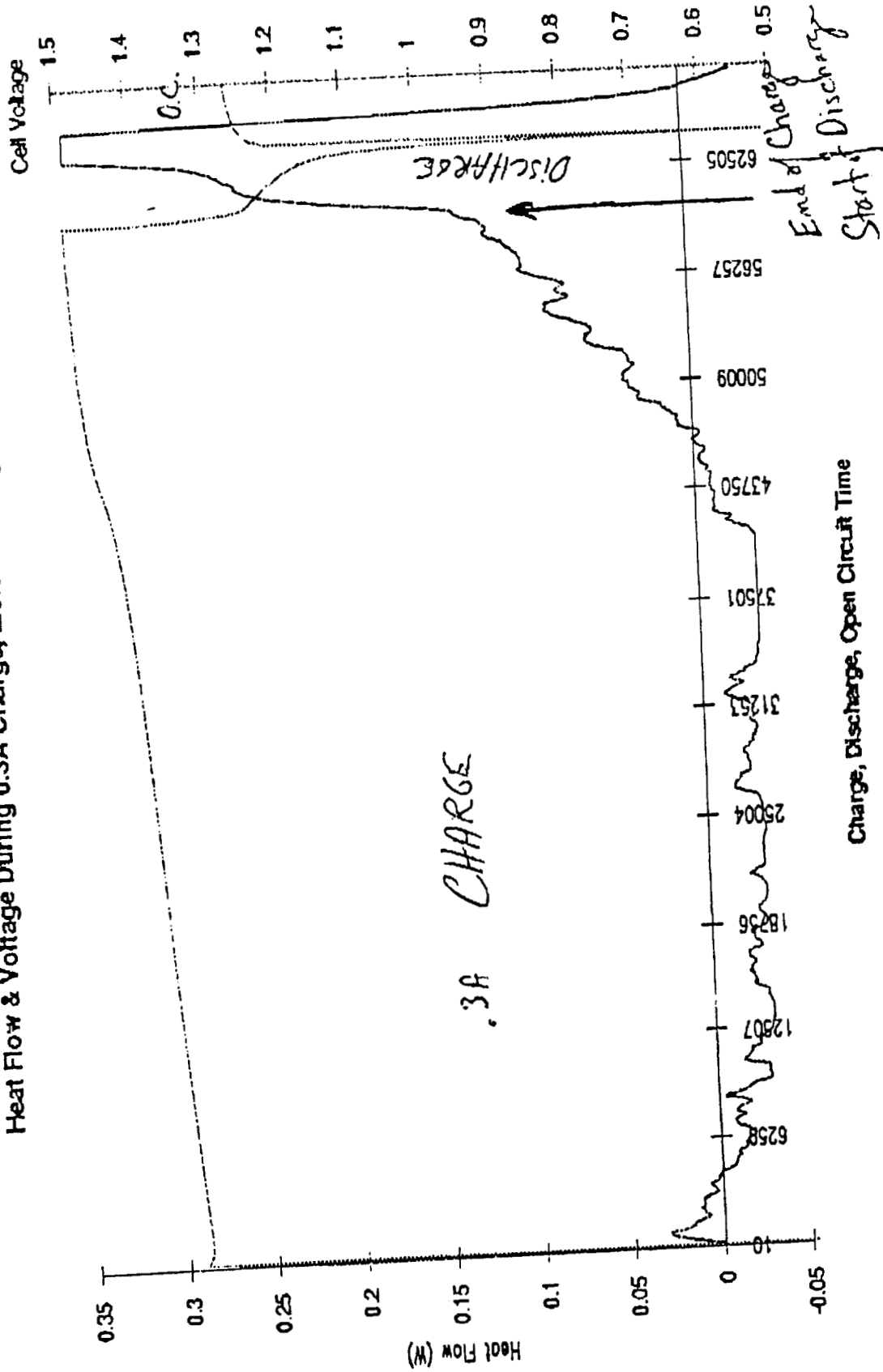
# NiMH BUTTON CELL



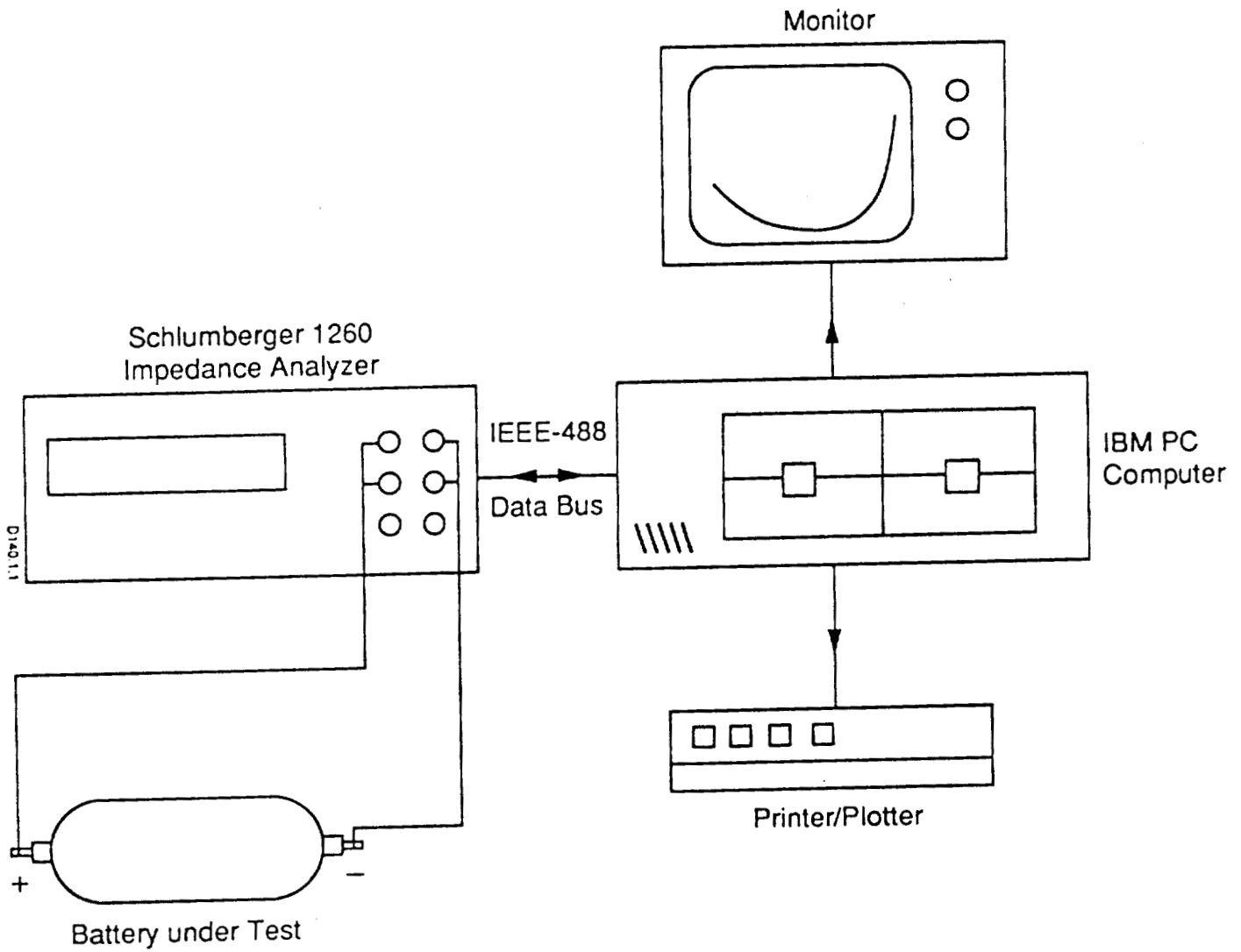
This data was included to illustrate the design versatility of the metal hydride system. Cells can be constructed in virtually any size or shape. This is a small diameter nickel-metal hydride button cell design. The cell is assembled and die-crimped such that it is a sealed cell. About 40 of these cells 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.



### Heat Flow & Voltage During 0.3A Charge, 2.5A Discharge, & Open Circuit



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

Cell Type	Capacity (Amp-Hrs)	No. of Cells Measured	Storage Time (Years)	No. of Aging Cycles	Type of Life Test
NiH <sub>2</sub>	30	1	7	10,800	Real-Time LEO
"	30	1	0	10,800	"
"	30	2	0	3,800	"
"	30	9	0	38,000	Real-Time LEO
"	30	9*	7	1,500	Real-Time LEO
"	50	1	5-6	0	None
"	50	4	0	23,309	Proprietary
"	50	18	0	62,000	Accel. LEO
"	65	2	0	0	Real-Time GEO
"	65	4	0	600	"
"	76	4	?	0	Proprietary
"	76	2	?	3,057	Proprietary
"	76	2	?	23,309	Proprietary
"	76	4	?	43,000	Accel. LEO
"	76	8	0	3,801	Real-Time LEO
NiMH	4	2	0.33	0	"
"	4	2	0	3,801	"
"	8	2	0	2,001	"
"	C-cell	3	0	0	"
"	C-cell	1	1	0	"

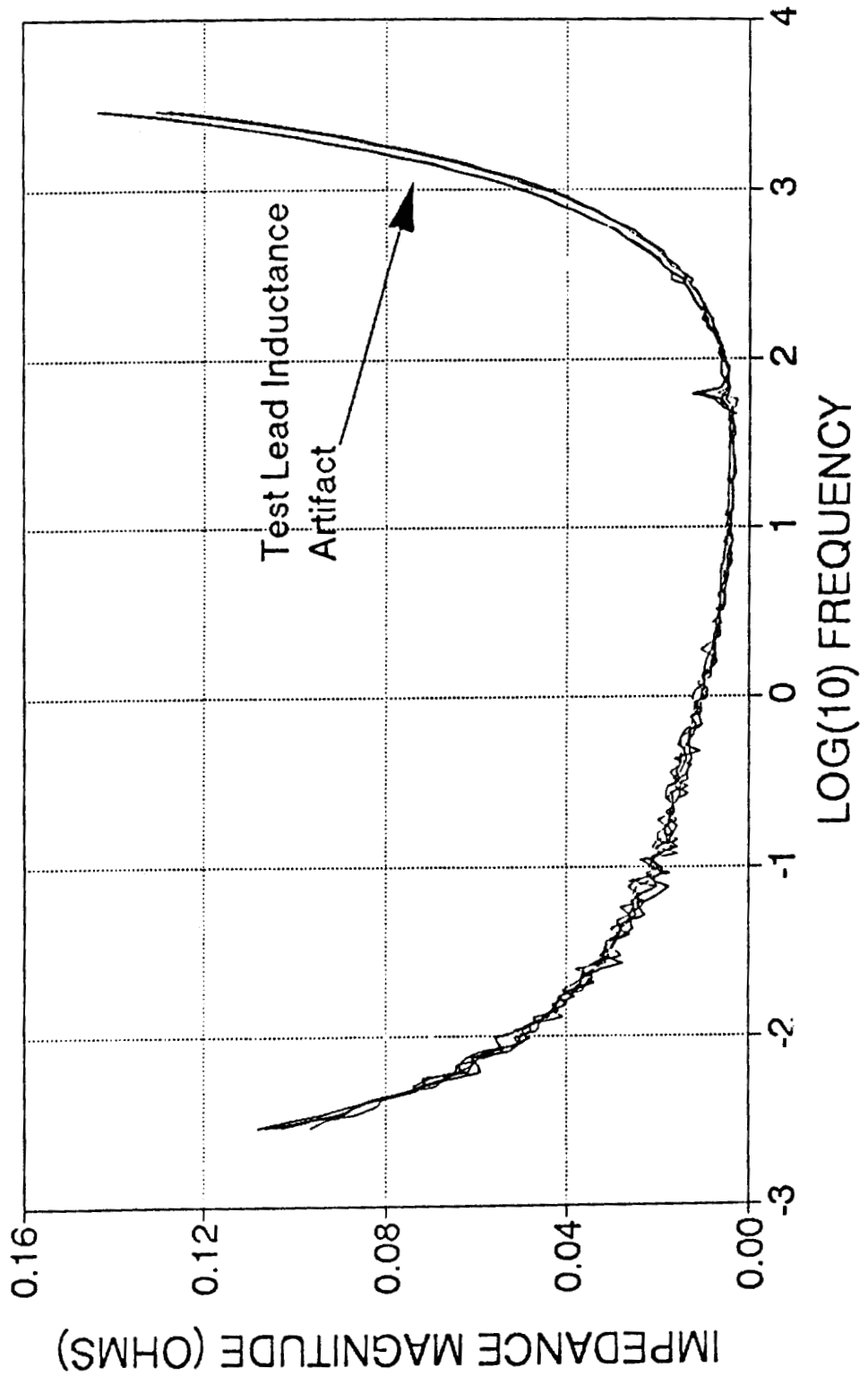
Best Aging Comparisons

\* A number of fabrication variations

D140.2.2

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 sizes ranging from 3.5 amp-hours to 76 amp-hours.

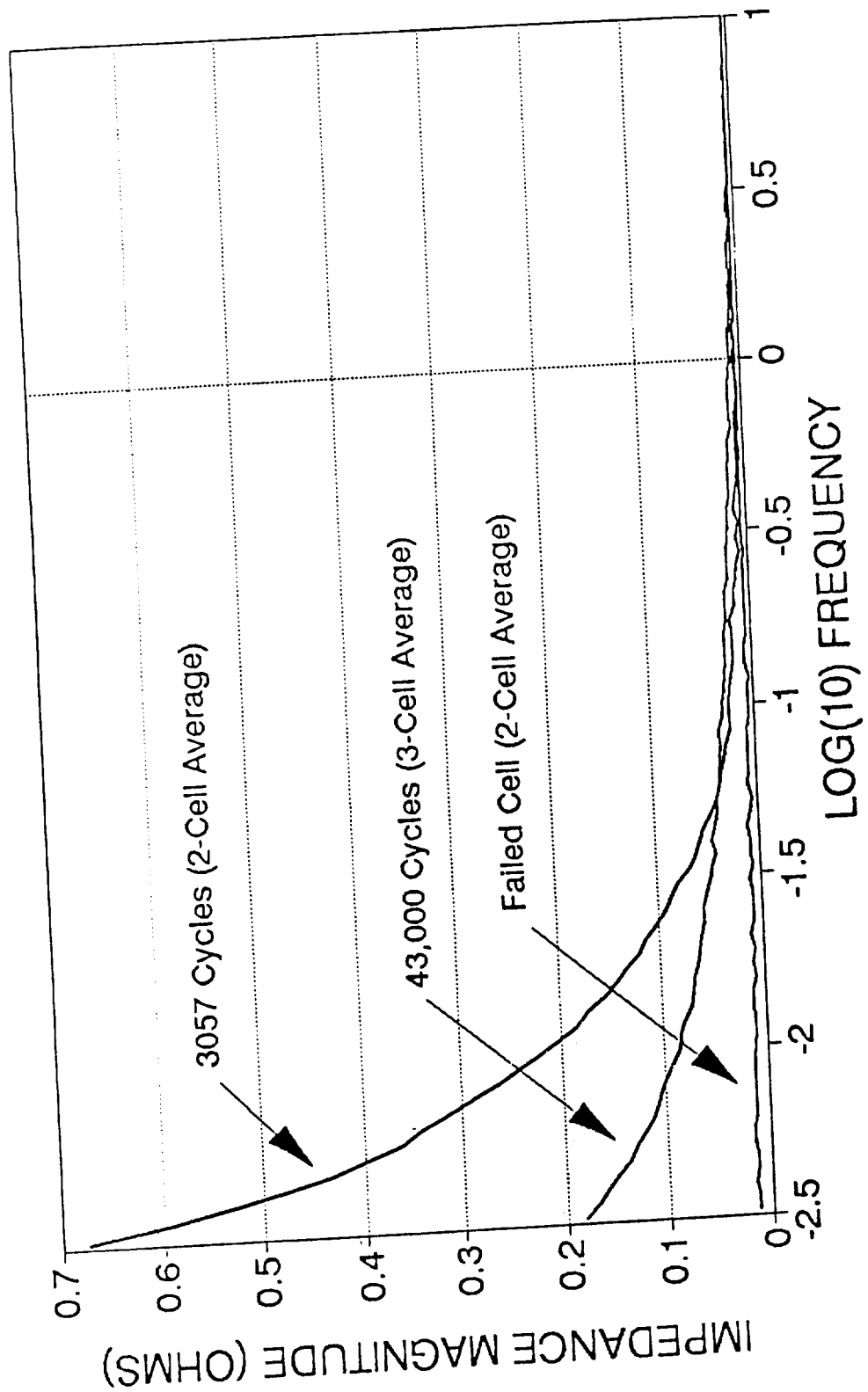
5 REPEATED MEASUREMENTS OF A 50 AMP-HR  
NICKEL HYDROGEN CELL (62,000 CYCLES)



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.

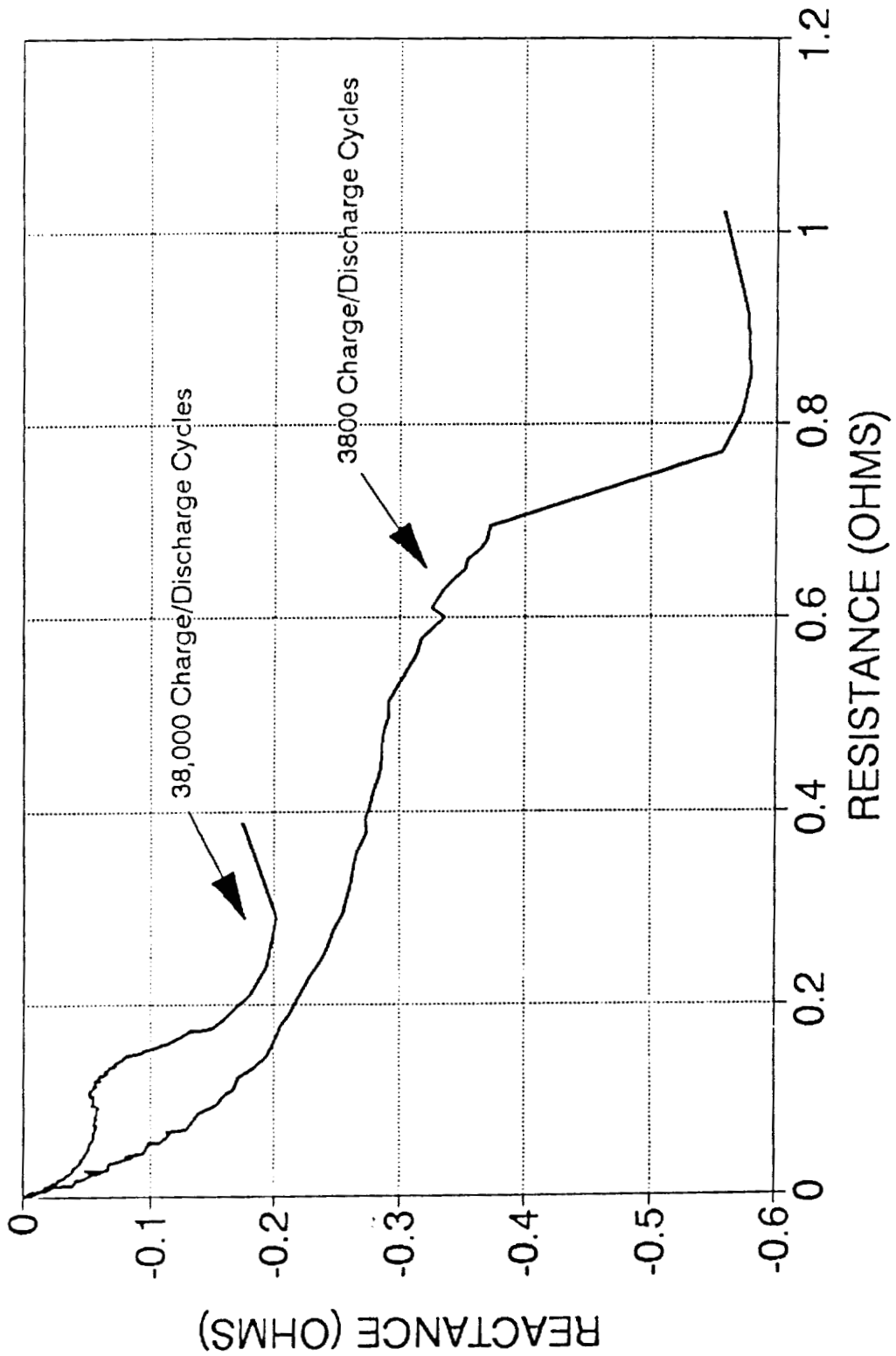


RAW IMPEDANCE DATA FOR 76 AMP-HR  
NICKEL HYDROGEN CELLS



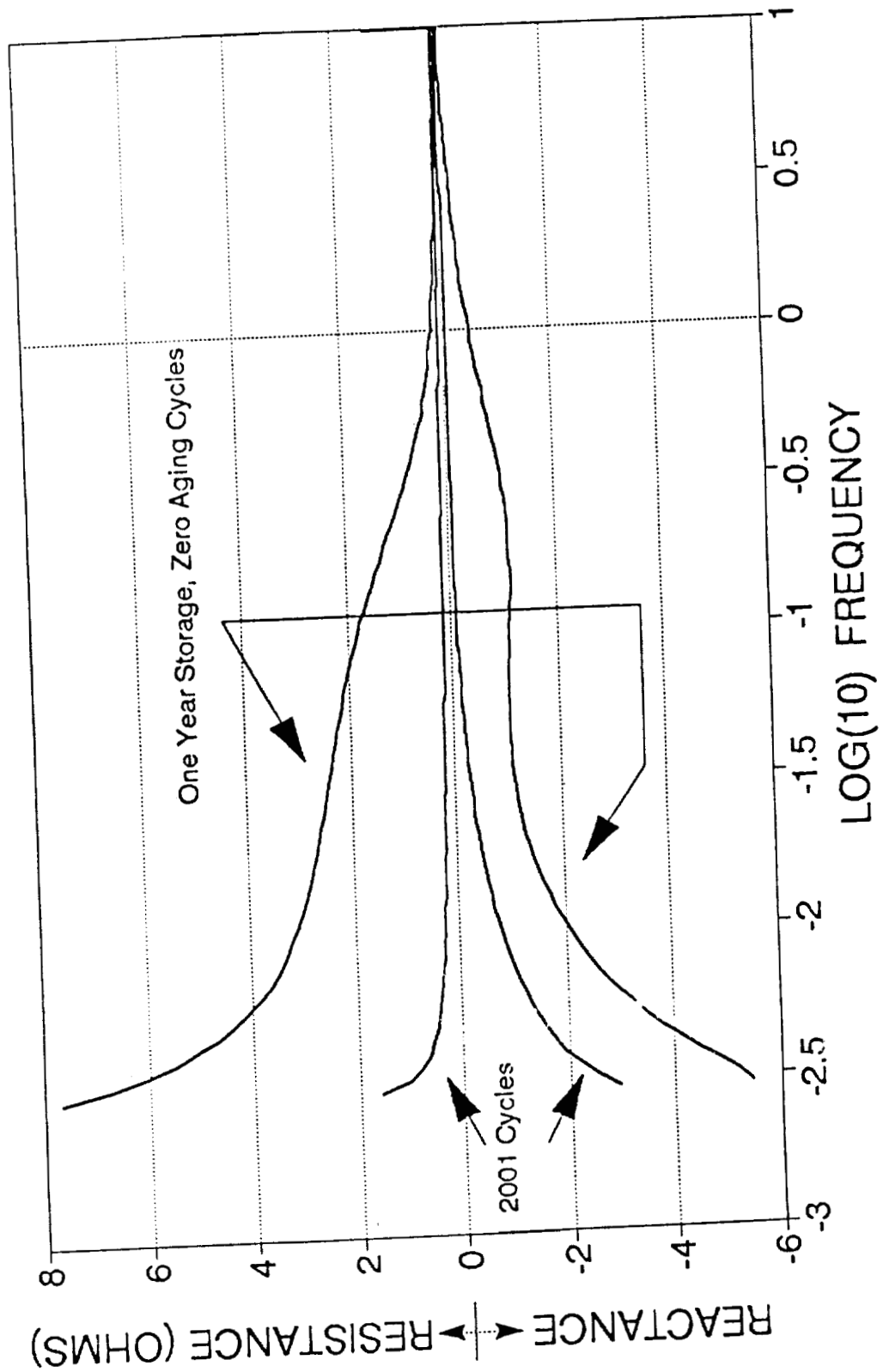
A plot of impedance versus the base ten log of frequency shows some interesting characteristics in the low frequency region below 1 Hertz. This is the Warburg region where the availability of charge carriers is diffusion controlled. The AC impedance in this frequency range decreases with the age of the 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



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



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

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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.

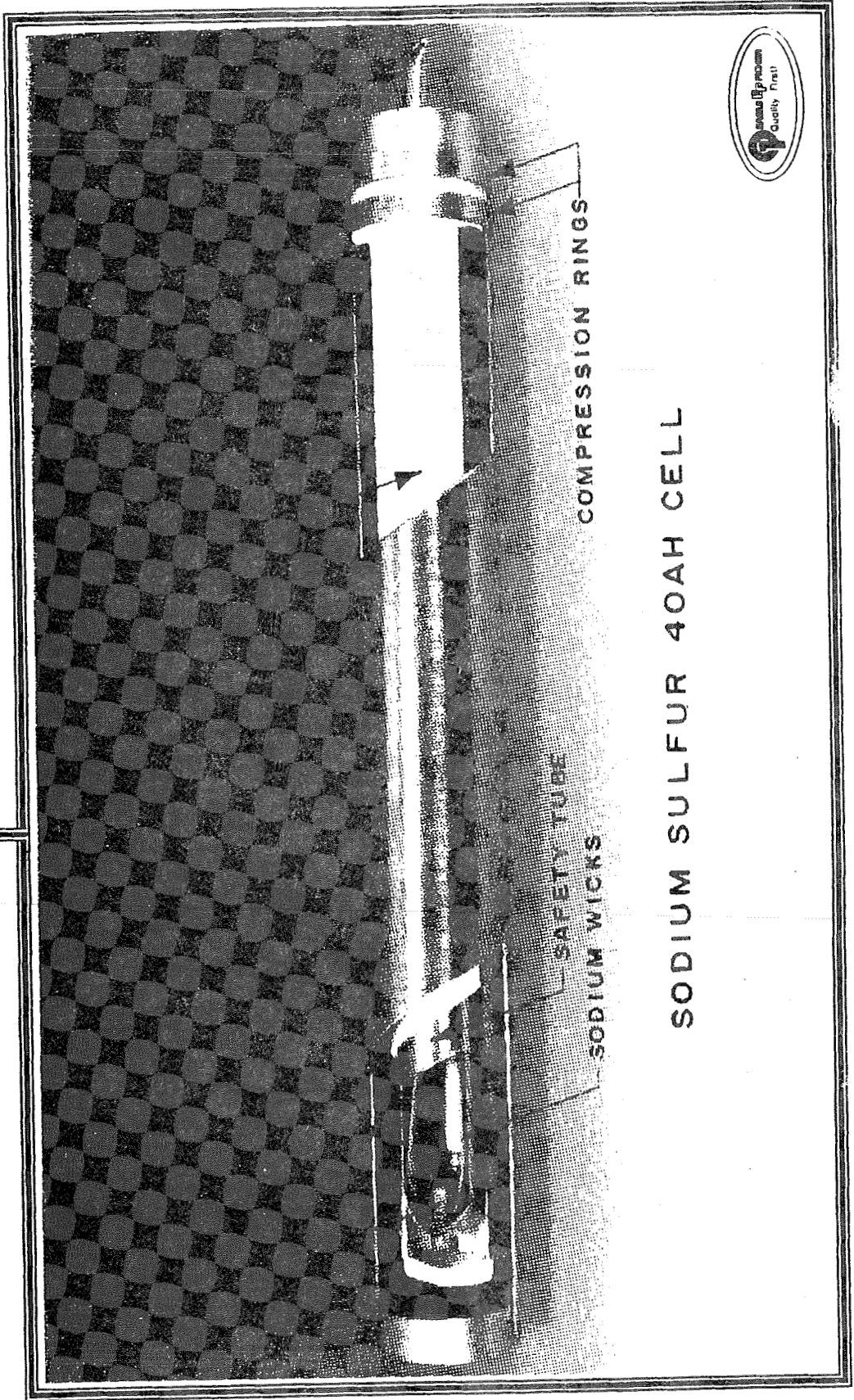
The results of six months of testing a 250 watt-hour sodium sulfur space battery look very promising. With over 1,000 LEO cycles conducted on this first battery, the next generation battery is being designed. This next design will focus on achieving greater energy densities associated with the sodium sulfur chemistry.

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ELECTRONICS DIVISION  
JOPLIN, MO

HERMAL-ORDNANCE OPERATION

# Na-S BATTERIES



SODIUM SULFUR 40AH CELL



# Na-S BATTERIES

CELL DESIGN	A	B	C	D
DISCHARGE RATE	75 AMPS	75 AMPS	75 AMPS	75 AMPS
DISCHARGE TIME	33 MIN	32 MIN	35 MIN	35 MIN
AVE. VOLTS (DIS)	1.20 VOLTS	1.24 VOLTS	1.39 VOLTS	1.56 VOLTS
Whrs DISCHARGE	49.5 Whrs	49.9 Whrs	61.1 Whrs	67.7 Whrs
AVE. CHARGE RATE	33.5 AMPS	33.2 AMPS	34.81 AMPS	40.24 AMPS
CHARGE TIME	73 MIN	73 MIN	73.9 MIN	65.2 MIN
AVE. VOLTS (CHG)	2.44 VOLTS	2.43 VOLTS	2.44 VOLTS	2.39 VOLTS
Whrs CHARGE	98.6 Whrs	98.3 Whrs	104.6 Whrs	104.6 Whrs
EFFICIENCY				
(Whrs DIS/Whrs CHG)	50.20%	50.70%	58.40%	64.70%
SPECIFIC ENERGY	72.6 Whrs/Kg	73.1 Whrs/Kg	87.4 Whrs/Kg	98.6 Whrs/Kg
ENERGY DENSITY	159.2 Whrs/l	160.5 Whrs/l	196.0 Whrs/l	217.4 Whrs/l
END OF DISCHARGE				
RESISTANCE (mOhms)	8.8 mOhms	8.8 mOhms	6.4 mOhms	6.1 mOhms
F1 (%)	30.00	31.42	21.61	14.08

Note: F1 is a measure of the percent nonavailable theoretical cell capacity.



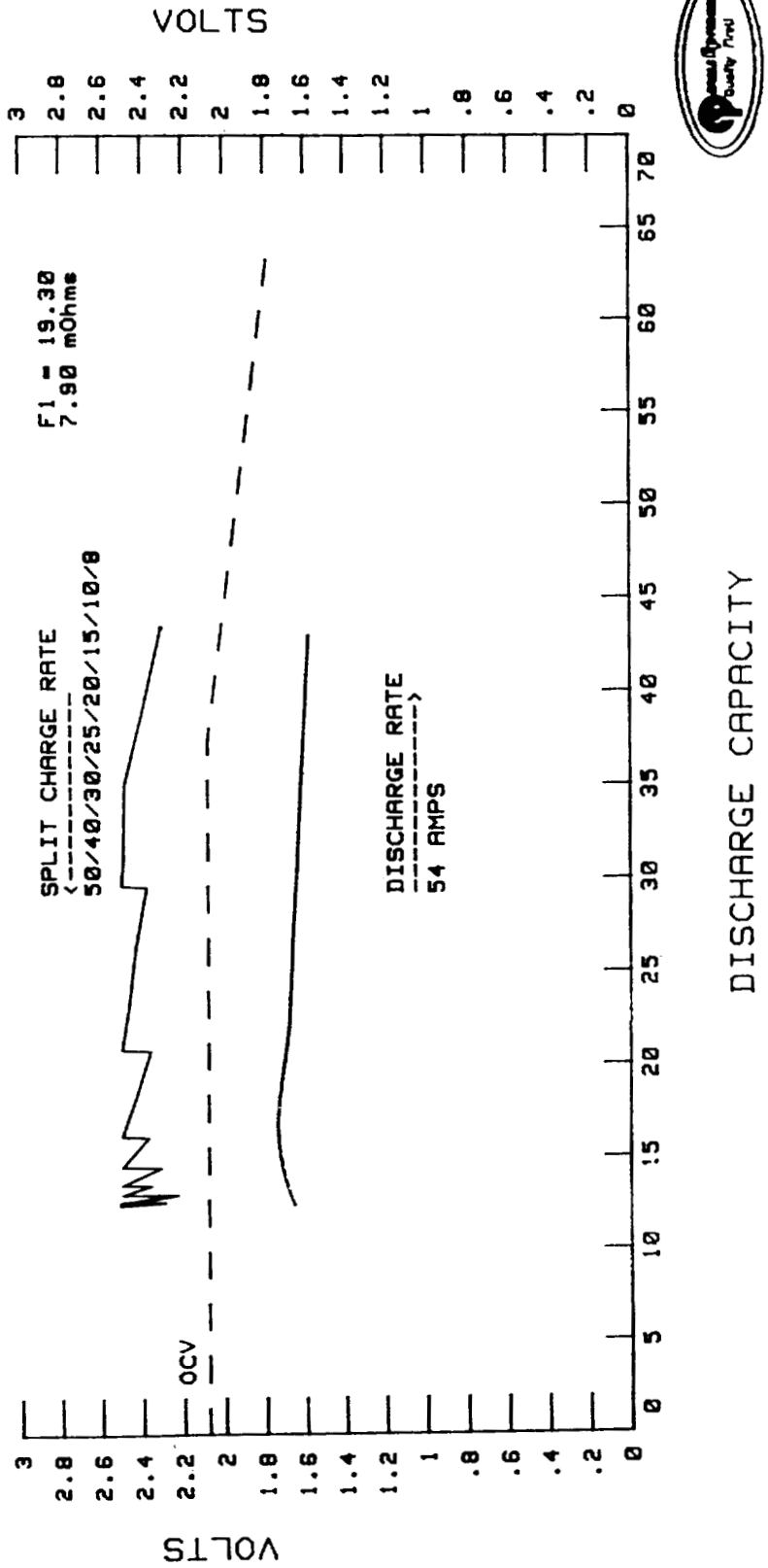
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# Na-S BATTERIES

TD-75 CYCLE 1828 (LEO 60% DOD)

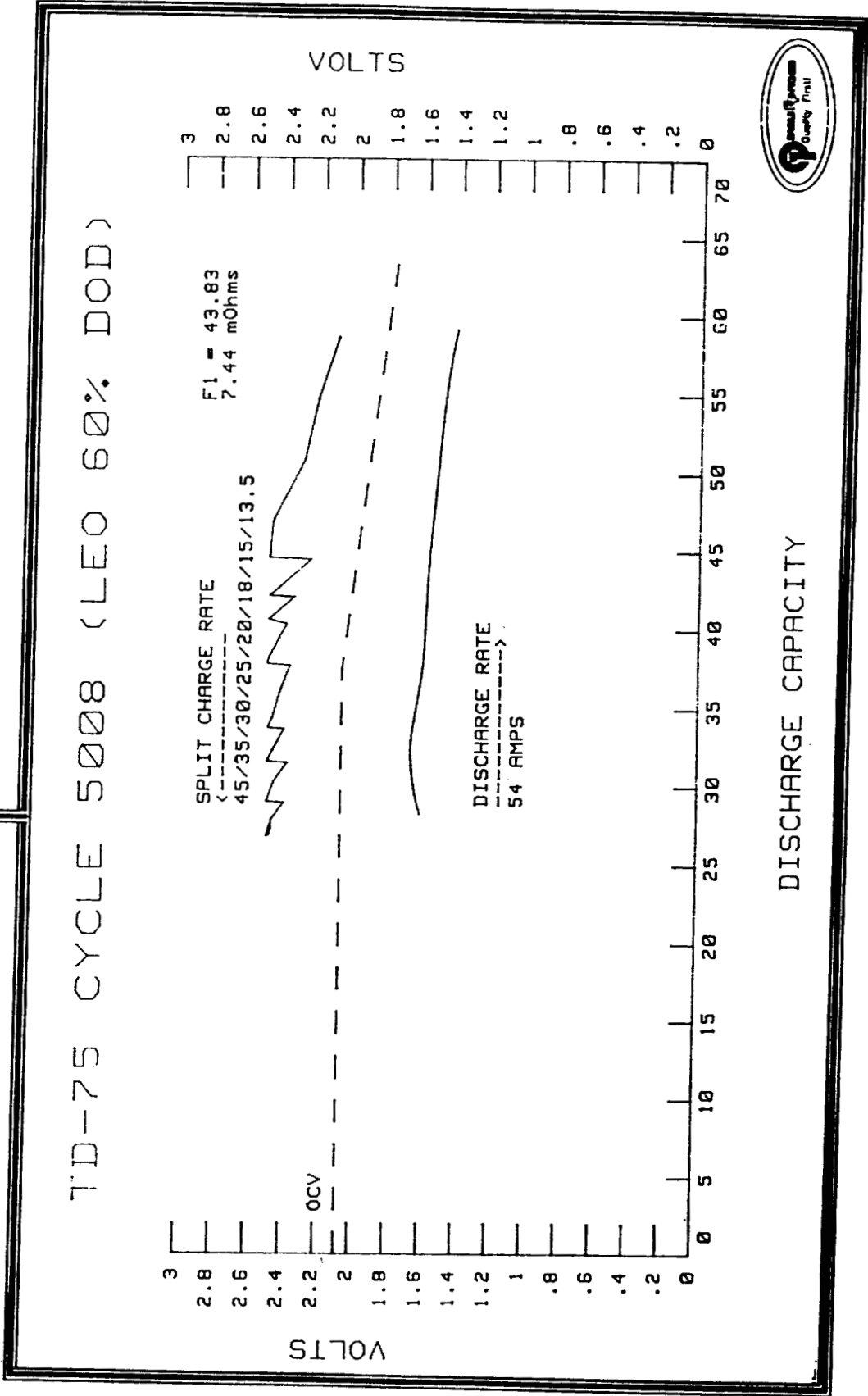


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# Na-S BATTERIES



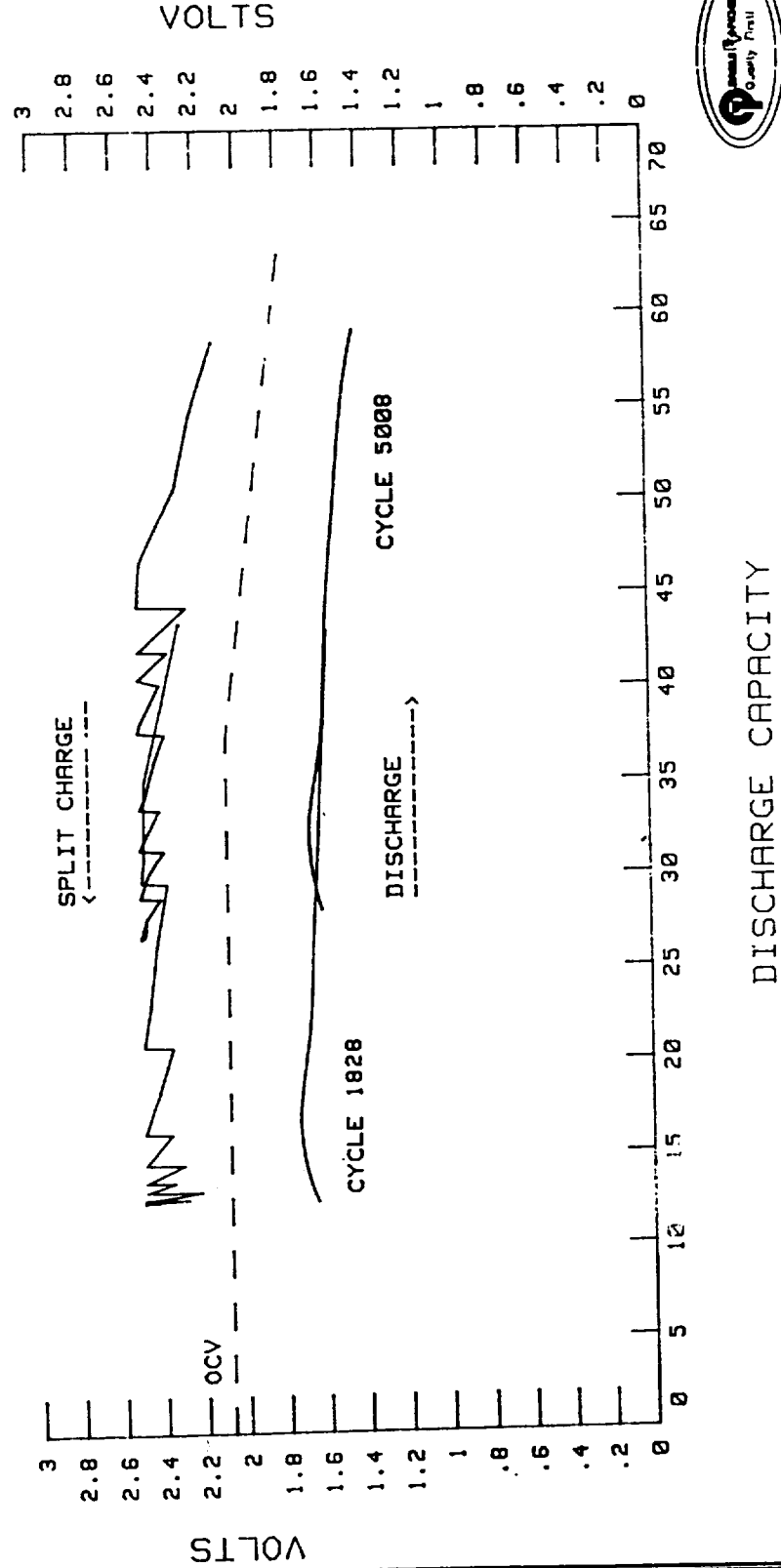
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# Na-S BATTERIES

TD-75 (LEO 60% DOD)





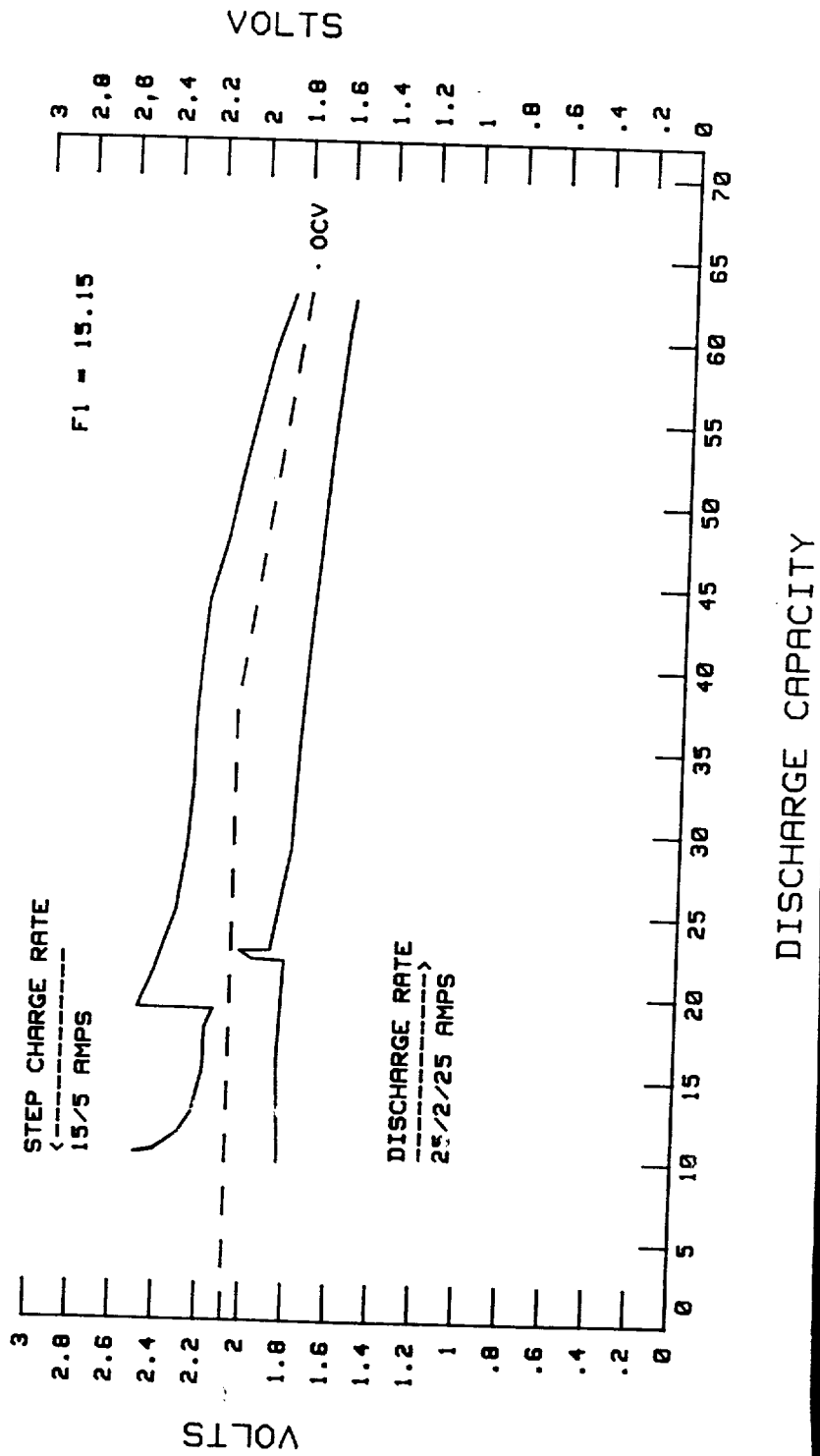
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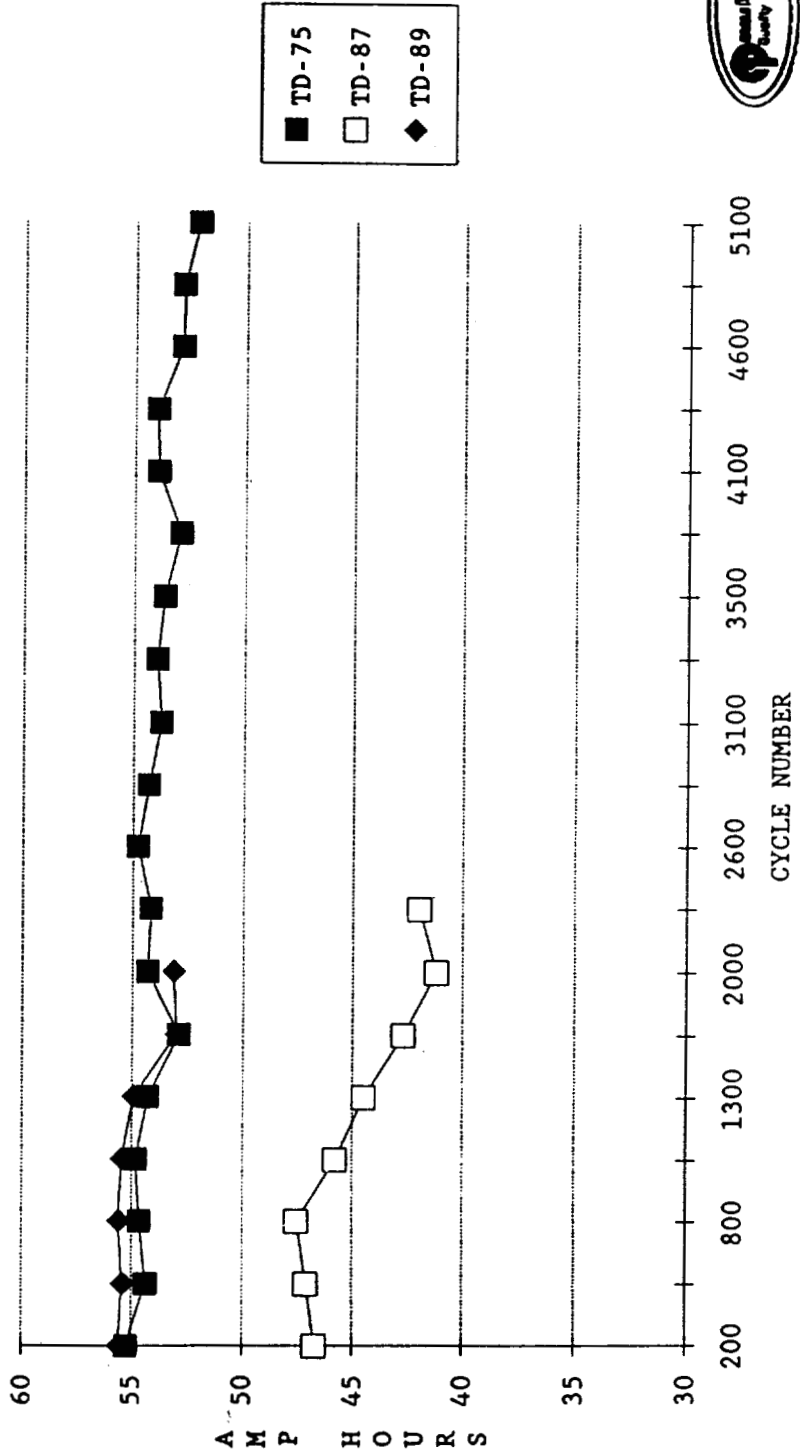
# Na-S BATTERIES

CELL CYCLE 4935



**Na-S BATTERIES**

CAPACITY VS. CYCLE LIFE



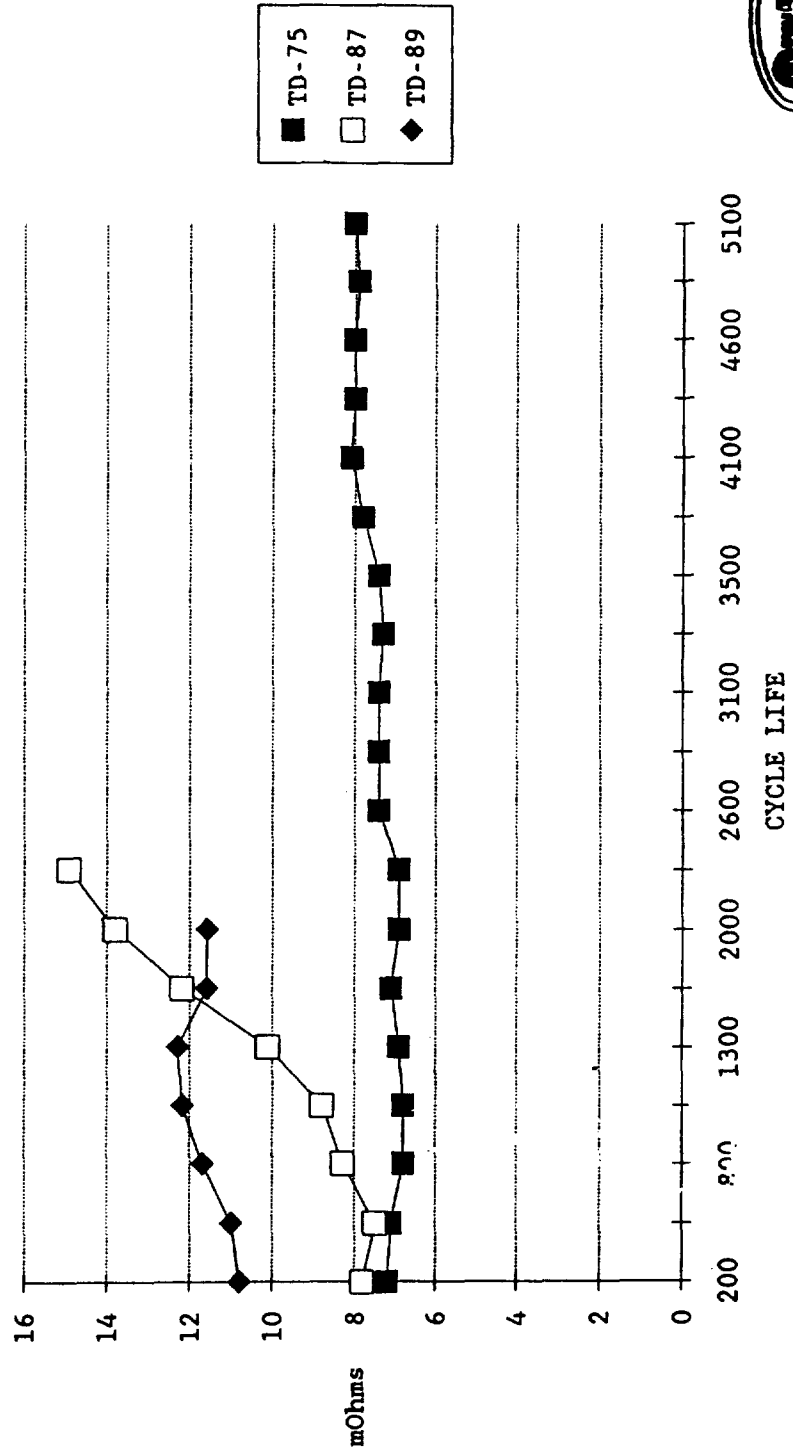
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RESISTANCE (EOD) VS. CYCLE LIFE





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# **Na-S BATTERIES**

## **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: .0075 ohms**



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# **Na-S BATTERIES**

## **IMPROVED CELL TECHNOLOGY AVAILABLE NOW**

**55AH CELLS DISCHARGED TO 60% DOD AT "C" RATE**

**AVERAGE VOLTS WHILE DISCHARGING: 1.75**

**AVERAGE VOLTS DURING CHARGE: 2.40**

**SPECIFIC ENERGY: 100 WH / KG**

**ENERGY DENSITY: 225 WH / l**

**E.O.D. RESISTANCE: .005 ohms**



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**Na-S BATTERIES**

**CELL - TO - BATTERY TRANSITION**

- 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**



# **Na-S BATTERIES**

## **CELL - TO - BATTERY TRANSITION ( CONTINUED )**

- 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**





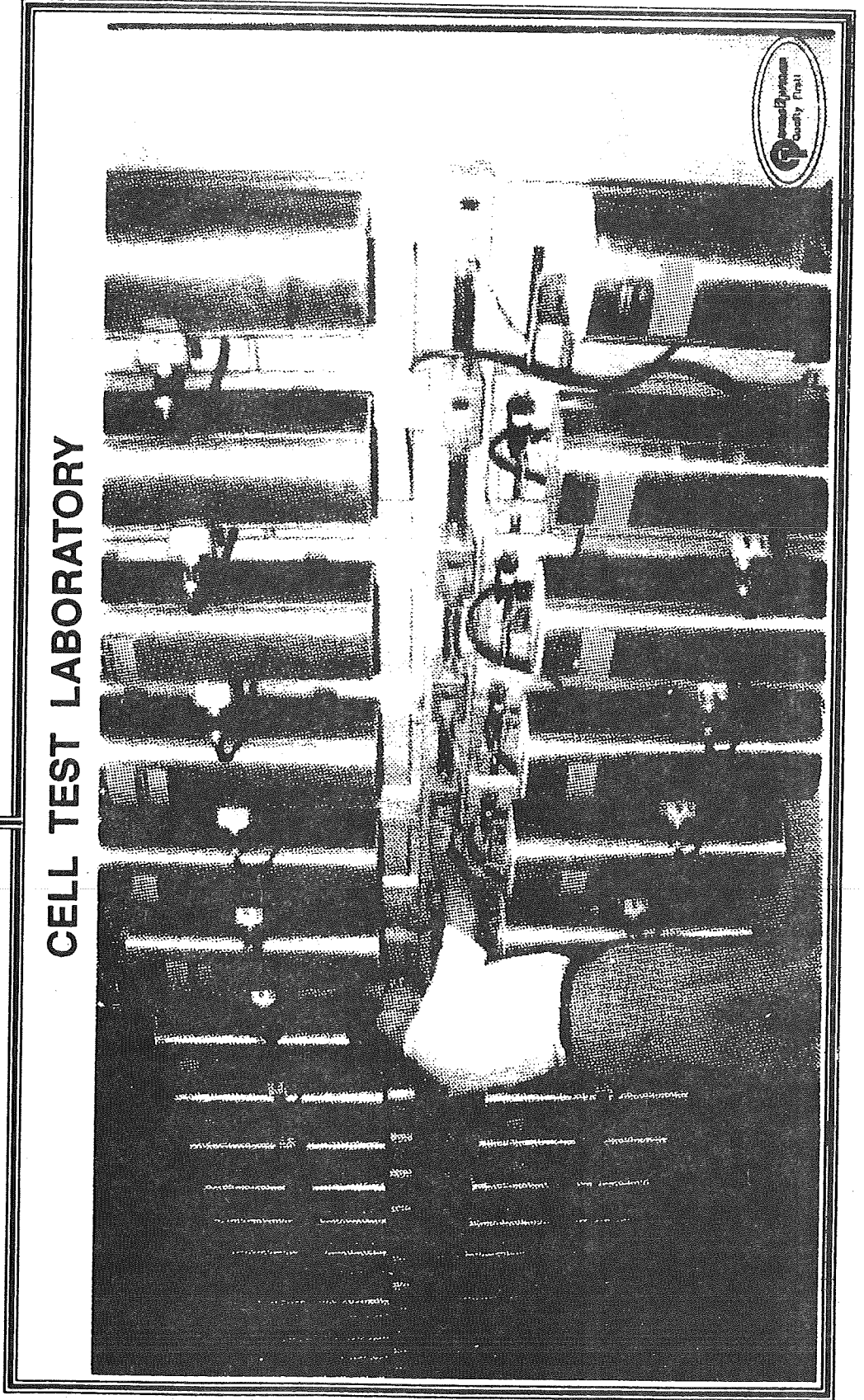
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**Na-S BATTERIES**

**CELL TEST LABORATORY**



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JOPLIN, MO**

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**Na-S BATTERIES**

**THE NEXT GENERATION SPACE BATTERIES**

**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.**



**EAGLE EP PICHER**

**ELECTRONICS DIVISION  
JOPLIN, MO**

**THERMAL-ORDNANCE OPERATION**

**Na-S BATTERIES**

**BATTERY STATUS**

**ENTRY LEVEL BATTERY EFFORTS FUNDED INTERNALLY**

**UNIT APPROACHING 1000 CYCLES**

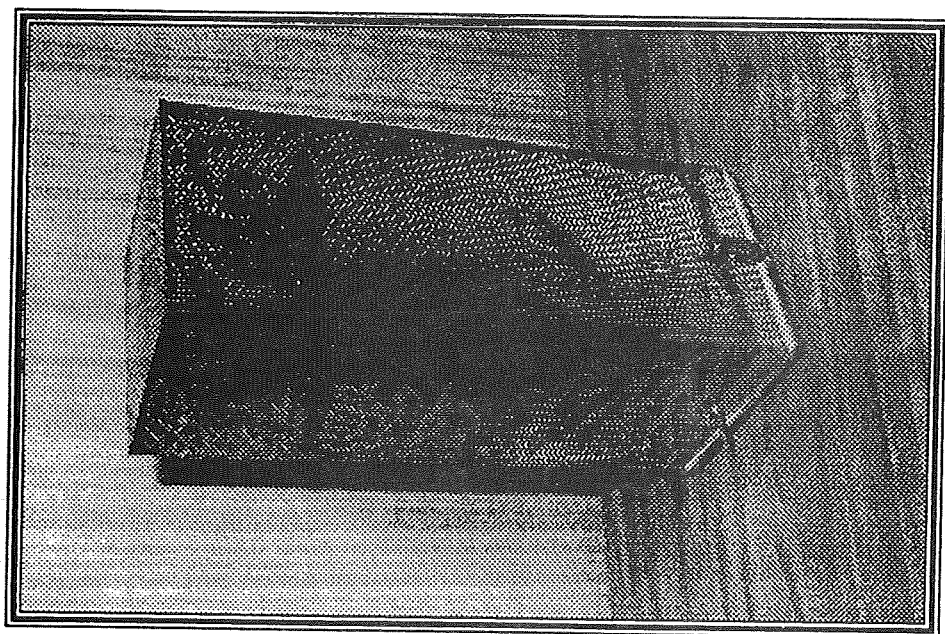
**CONSTANT CURRENT CHARGE / DISCHARGE  
NOMINAL 60% DOD (= 30 A.H.)**

**CYCLE CONTROLLED BY FIRST CELL TO ACHIEVE PRE-SET VALUES  
(OTHERWISE BY CYCLE DEFINITION ONLY)**

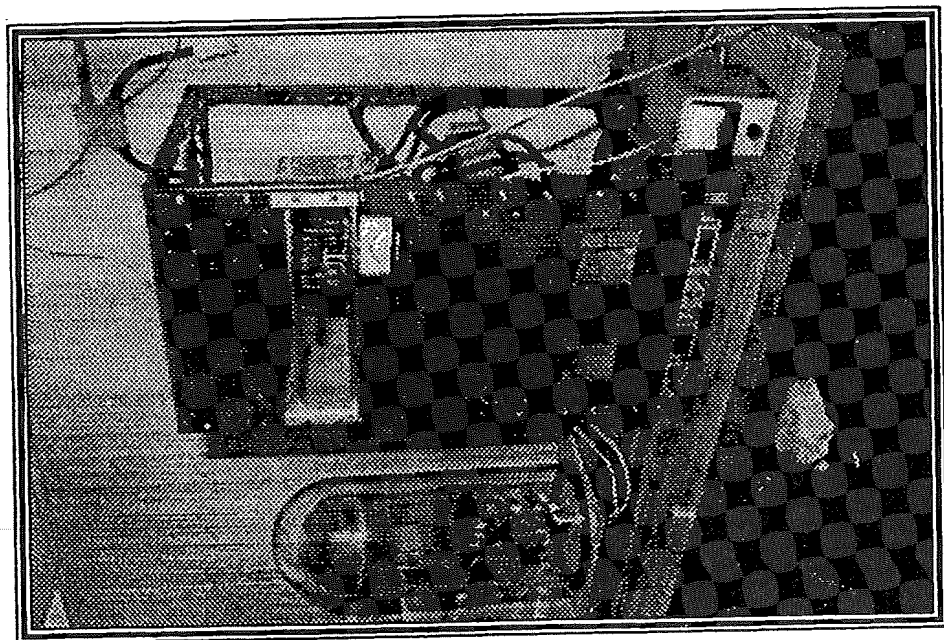
**CALENDAR LIFE NOW FIVE MONTHS**



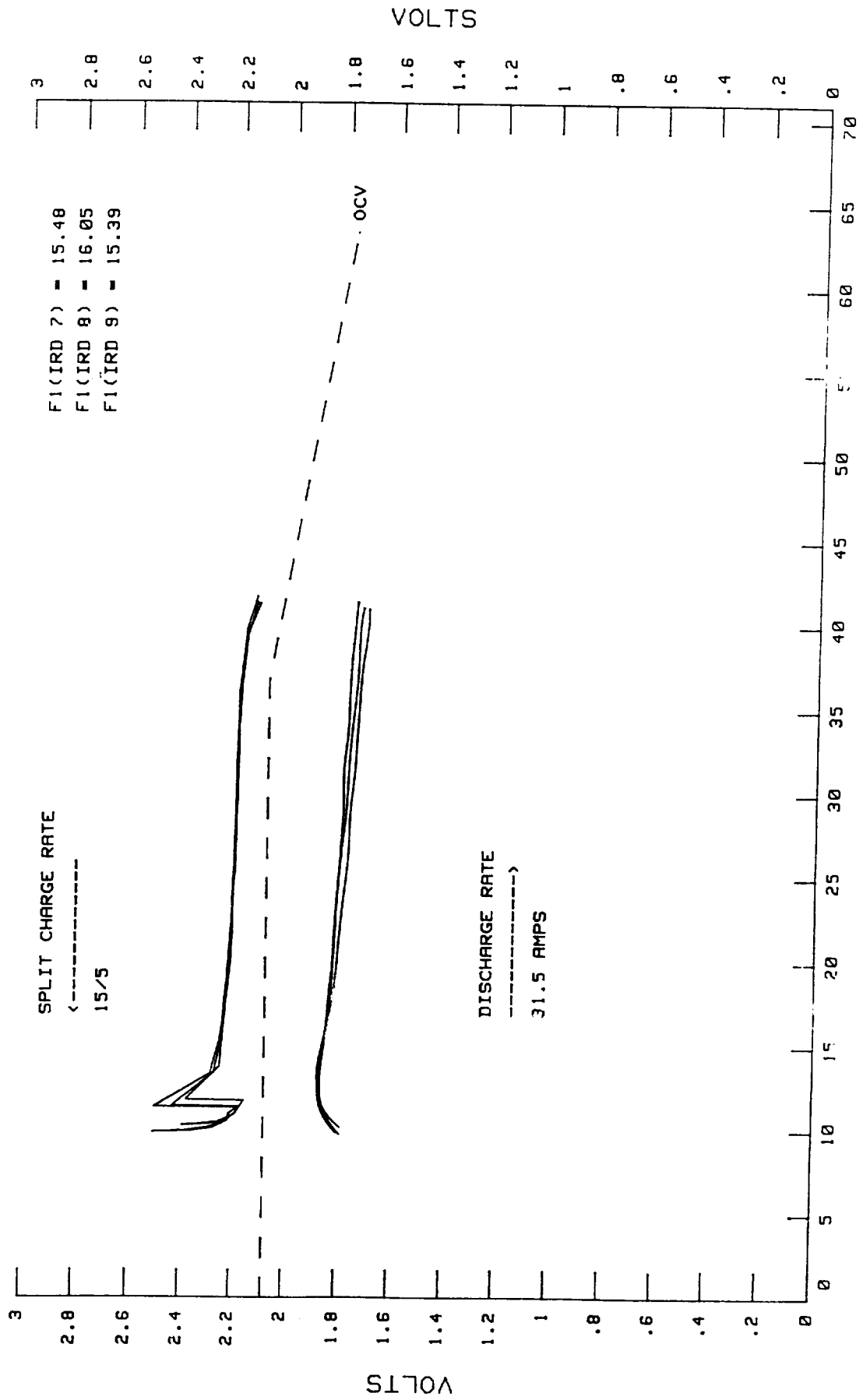
# Sodium Sulfur Battery



Battery Test Set-up



# IRD BATTERY (CYCLE 32)



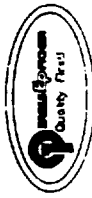
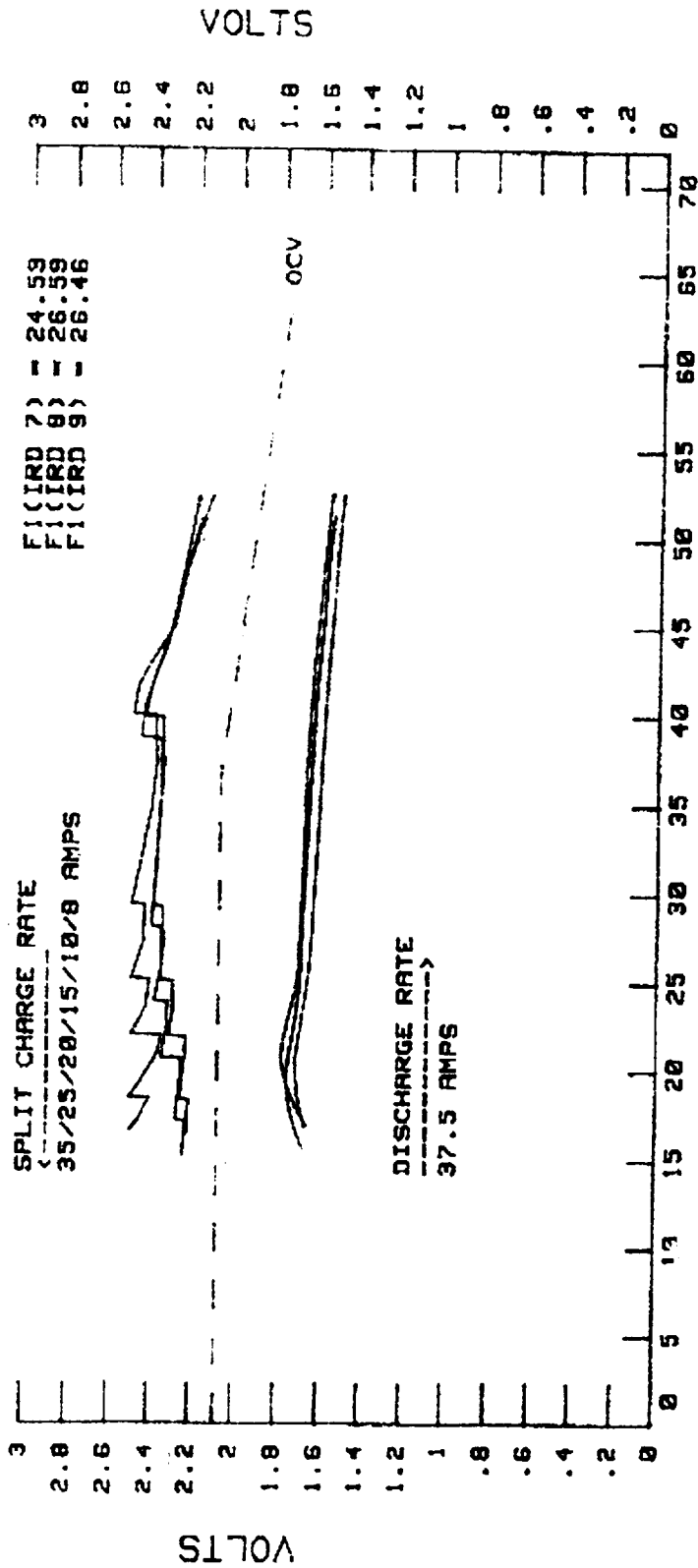
**EAGLE**  **PICHER**

ELECTRONICS DIVISION  
JOPLIN, MO

THERMAL-ORDNANCE OPERATION

# Na-S BATTERIES

IRD BATTERY (CYCLE 918)



# **Na-S BATTERIES**

## **BATTERY DESCRIPTION**

- 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**

**N 9 2 - 2 2 7 6 8**

**OCTOBER 30, 1991  
THE 1991 NASA AEROSPACE BATTERY WORKSHOP**

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**BATTERY SYSTEMS GROUP**

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## OUTLINE

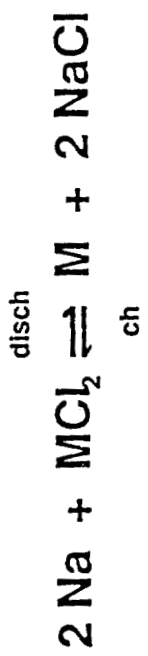
- CONFIGURATION AND ADVANTAGES
- CAPABILITIES OF THE SYSTEMS
- STUDIES AT JPL
- AREAS OF FURTHER STUDY

## SODIUM - METAL CHLORIDE BATTERIES

- CONFIGURATION



- CELL REACTION



- METAL CHLORIDES

FERROUS CHLORIDE  
NICKEL CHLORIDE

- OPERATING TEMPERATURES :  $\geq 250^\circ\text{C}$

## COMPARISON WITH Na - S

### ADVANTAGES

- LOWER OPERATING TEMPERATURES ( $\geq 250^{\circ}\text{C}$ )
- WIDER RANGE OF OPERATING TEMPERATURES ( 180 - 425 $^{\circ}\text{C}$ )
- SAFETY IN THE EVENT OF INTERNAL SHORT AND TEMPERATURE EXCURSIONS
- FAILS SHORT CIRCUIT (NO NEED FOR BYPASS)
- BUILT-IN OVERCHARGE MECHANISM
- TOLERANCE TO OVERDISCHARGE
- ASSEMBLY IN THE D'CHARGED STATE WITH LITTLE OR NO SODIUM

### DISADVANTAGES

- MORPHOLOGICAL CHANGES AT THE CATHODE
- LOWER POWER DENSITIES



# 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/cm<sup>2</sup>)

- 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

# CAPABILITIES OF THE SYSTEMS

## PERFORMANCE OF $MCl_2$ CELLS AND BATTERIES

PARAMETER ↓ TYPE	PARAMETER →	CAPACITY Amp. Hr	PRACTICAL ENERGY DENSITY @ 5 hr RATE		SPECIFIC POWER @2/3 OCV AND 70%DOD W / Kg
			Wh / Kg	Wh / l	
BETA 33 CELL 33 mm dia and 160-200 mm long	$FeCl_2$	42	142	260	139
	$NiCl_2$	40	124	310	150
BETA 55 CELL 55 dia and 230-300 mm long	$FeCl_2$	140	110	172	-
	$NiCl_2$	100	109	155	-
BETA 55 BATTERY	$FeCl_2$	15 KWh	88	103	-
	$NiCl_2$	30 KWh	88	95	-

A. R. Tilley and R. N. Bull, 22<sup>nd</sup> IECEC; 1078 (1987)

## ENVIRONMENTAL TESTS ON Na/MCl<sub>2</sub> 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

R. J. WEDLAKE AND A. R. TILLEY, B. ELECTROCHEM., 4, 41 (1988)



## Na / NiCl<sub>2</sub> 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

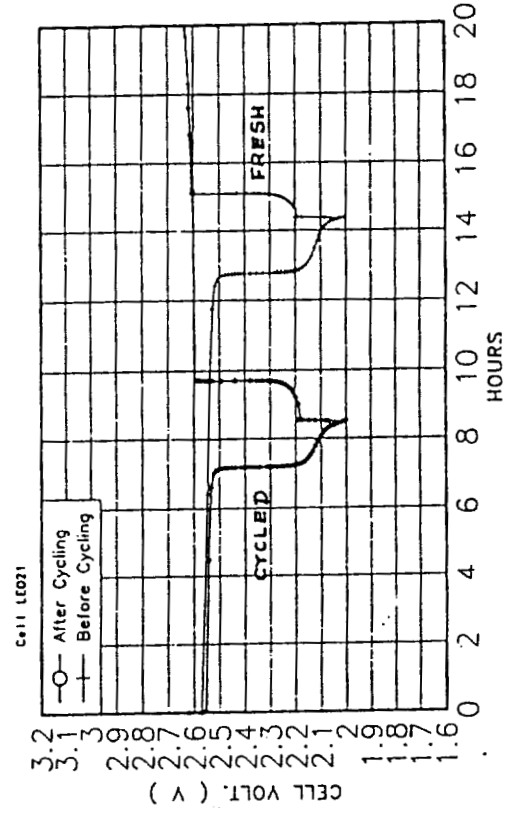


Fig. 8 CELL CAPACITY AT 1 A RATE BEFORE & AFTER 2810 CYCLES

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  $\text{FeCl}_2$  AND  $\text{NiCl}_2$
- 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 $\text{FeCl}_2$ REDUCTION

- EVIDENCE FOR TWO - STEP REACTION MECHANISM FROM CYCLIC VOLTAMMETRY  
 $\text{Na}_6\text{FeCl}_8$  INTERMEDIATE

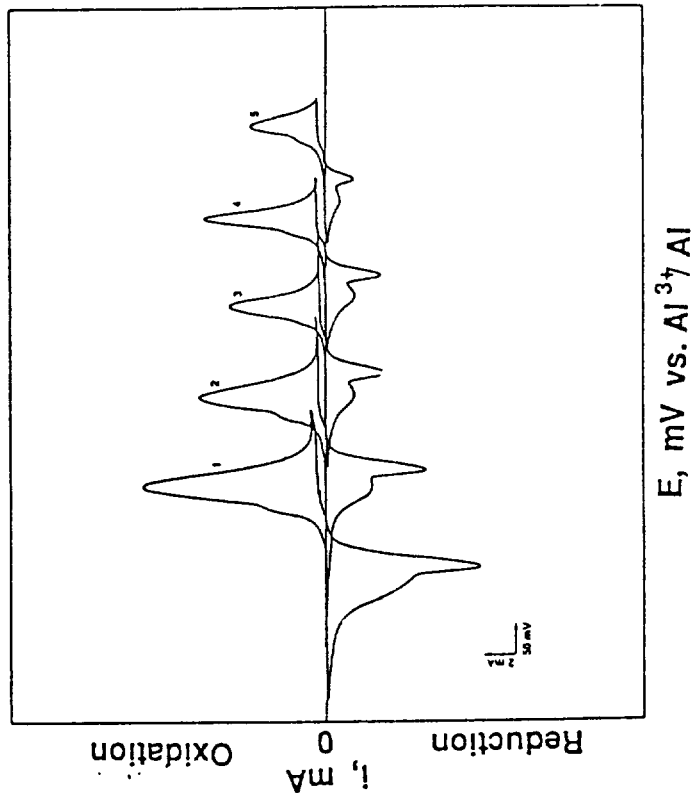
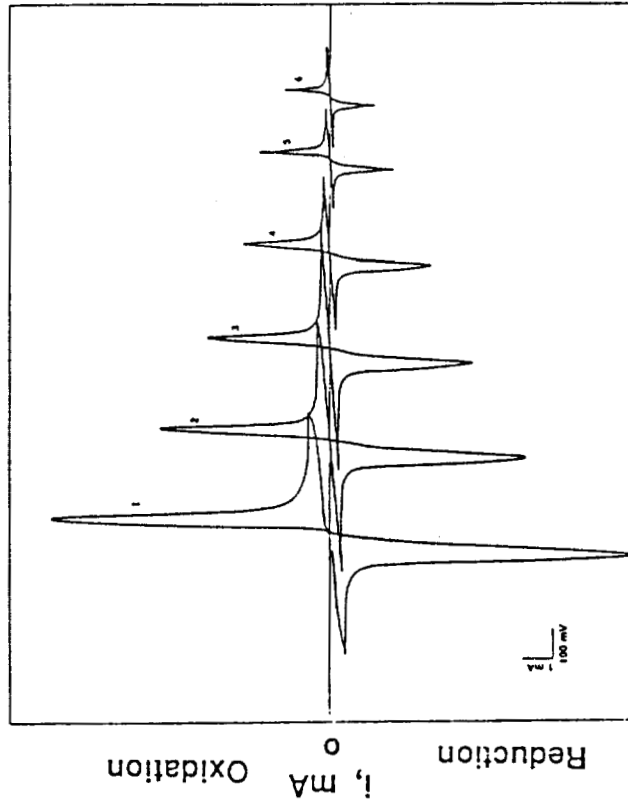


Fig. 3. Cyclic voltammograms of Fe electrode (area:  $0.05 \text{ cm}^2$ ) in  $\text{NaAlCl}_4$  at  $220^\circ\text{C}$  at scan rates of 1.) 20, 2.) 10, 3.) 5, 4.) 2, and 5.) 1 mV/s. Scale on the y axis is 1 mA/cm (reduced to half) for curves 4 and 5.

- Ni ADDITIONS FOR OVERCHARGE PROTECTION OF  $\text{FeCl}_2$

# MECHANISM OF $\text{NiCl}_2$ REDUCTION

- SINGLE - STEP REACTION SCHEME CONFIRMED BY CYCLIC VOLTAMMETRY



Cyclic voltammetric curves of Ni electrode in  $\text{NaAlCl}_4$  at  $220^\circ\text{C}$  at different scan rates of 1) 50, 2) 20, 3) 10, 4) 5, 5) 2 and 6) 1 mV/s.

$E$ , mV vs.  $\text{Al}^{3+}/\text{Al}$

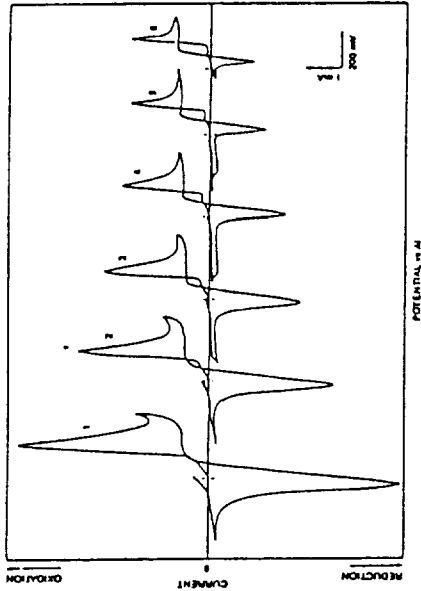
- GOOD REVERSIBILITY

**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, Al and Ag UNLIKELY.
- .. High oxidation currents.

**Co**



Voltammograms of Co ( $E_0$ : 870 mV) at 1) 50, 2) 20, 3) 10, 4) 5, 5) 2 and 6) 1 mV/s.

• **COPPER EXHIBITS TWO - STEP OXIDATION (SECOND STEP FORMS SOLUBLE CHLORIDE)**

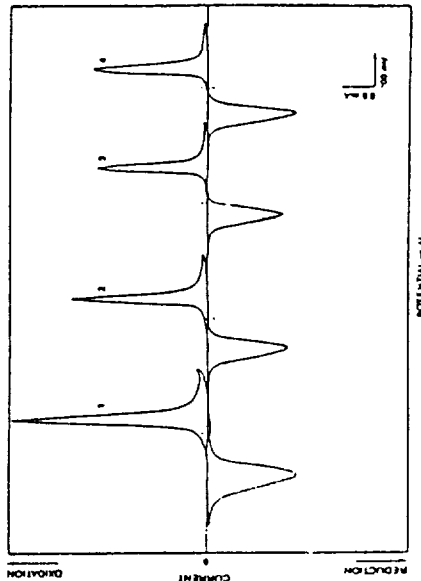
• .. Unlikely.

**Mo**

• **COBALT AND MOLYBDENUM ARE LIKELY CATHODE MATERIALS**

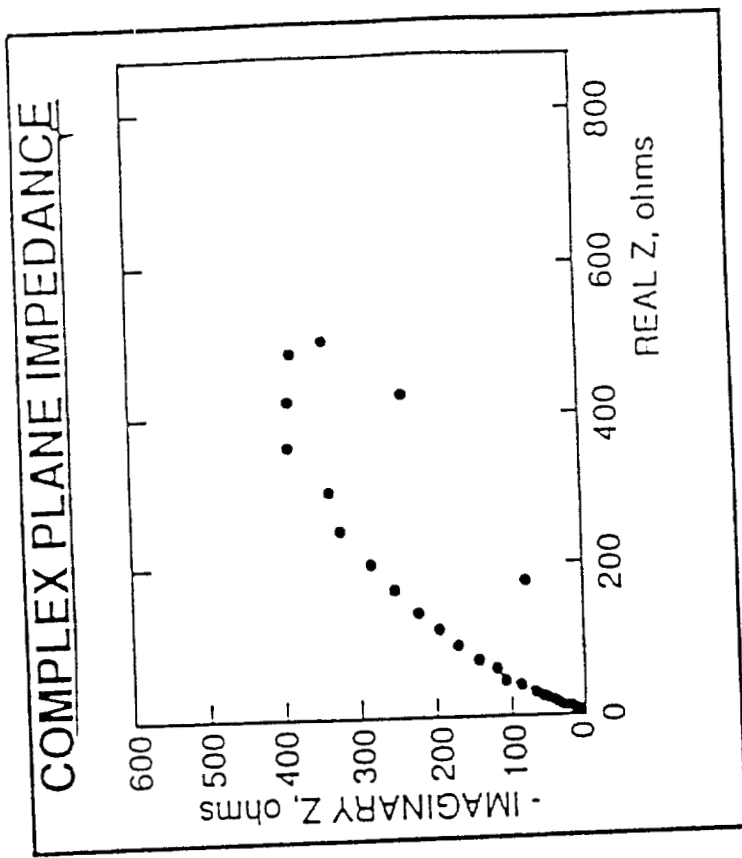
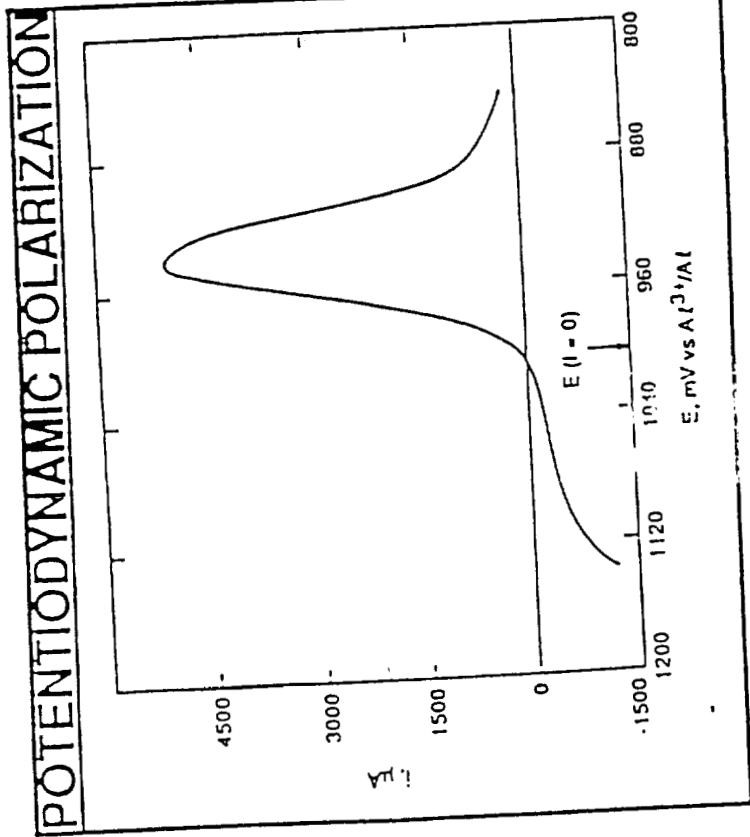
• .. Low oxidation currents.

• **MOLYBDENUM IS A STABLE CURRENT COLLECTOR FOR NiCl<sub>2</sub>.**



Voltammograms of Mo ( $E_0$ : 997 mV) at 1) 50, 2) 20, 3) 10 and 4) 5 mV/s (Scale on Y-axis doubled for curve 4).

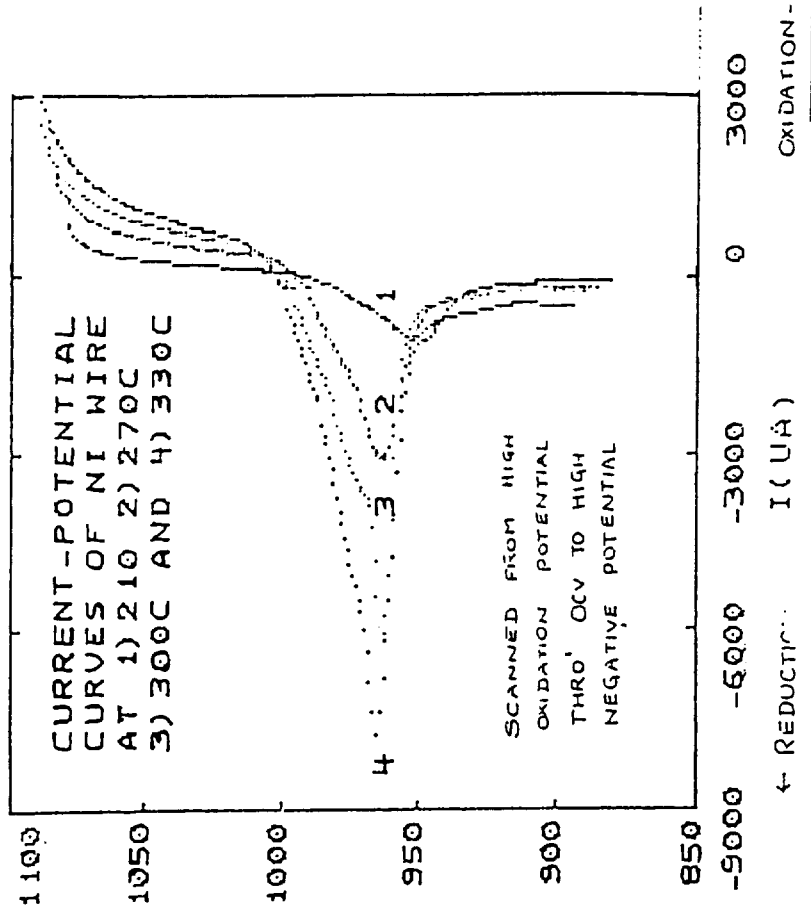
# PASSIVATION OF NiCl<sub>2</sub>



- PASSIVATION DURING REDUCTION BY NaCl PRECIPITATION
- PASSIVATION IS MORE PROMINENT THAN IN FeCl<sub>2</sub>

## PASSIVATION OF NiCl<sub>2</sub>

- 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

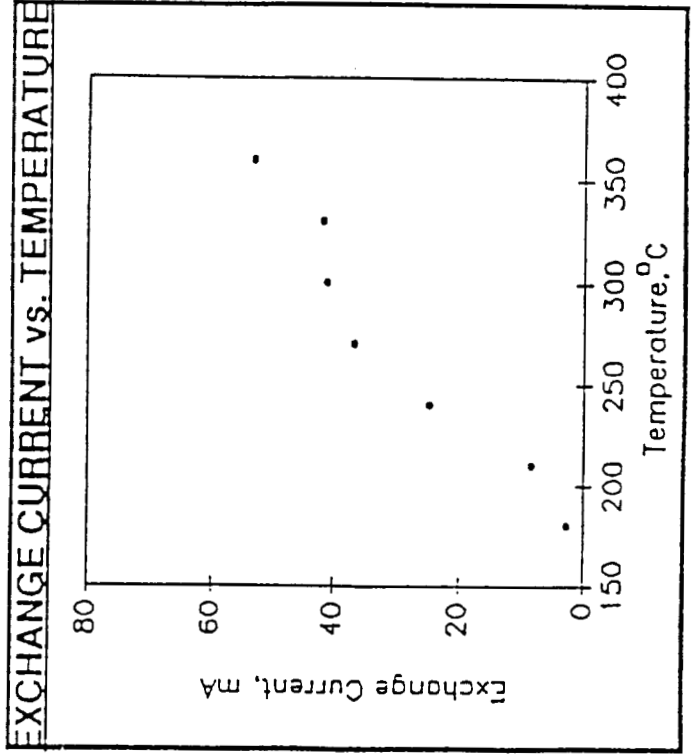


BATTERY SYSTEMS GROUP



## KINETICS OF $MCl_2$ REDUCTION

- HIGH EXCHANGE CURRENT DENSITIES ( $1 \text{ mA/cm}^2$ ) FOR BOTH  $FeCl_2$  AND  $NiCl_2$ .
- 10 % INCREASE IN THE EXCHANGE CURRENT DENSITY OF  $NiCl_2$  FOR EACH  $10^\circ\text{C}$  RISE IN THE OPERATING TEMPERATURE.
- OPTIMUM TEMPERATURE FOR  $NiCl_2 \geq 250^\circ\text{C}$ .



## ADDITIVE REQUIRED FOR NiCl<sub>2</sub>

- DECLINE IN CAPACITY PREMATURELY
- EFFECT MORE PROMINENT AT HIGHER POROSITIES
- LOSS OF SINTERED STRUCTURE DUE TO AN AGGLOMERATION OF Ni PARTICLES

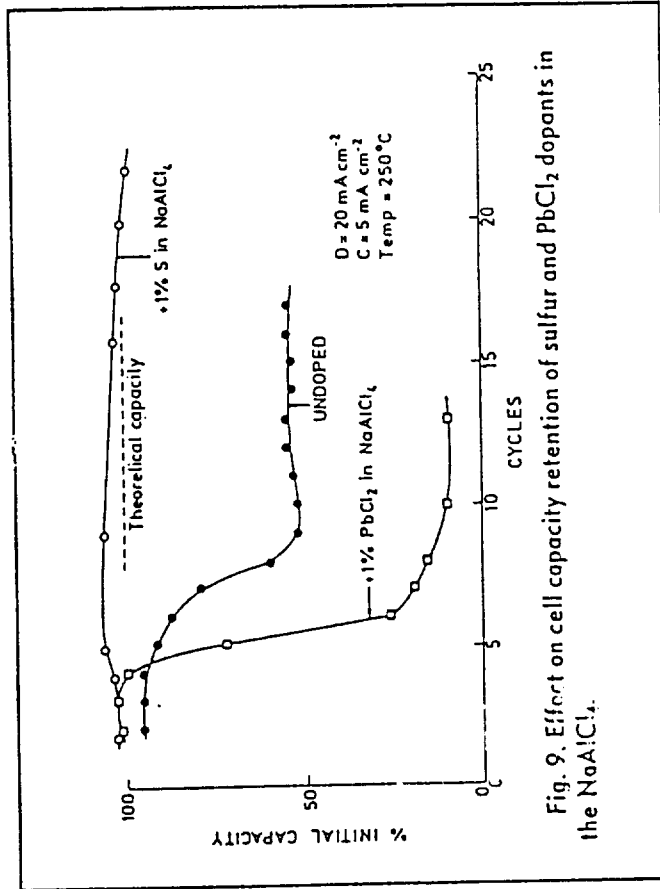


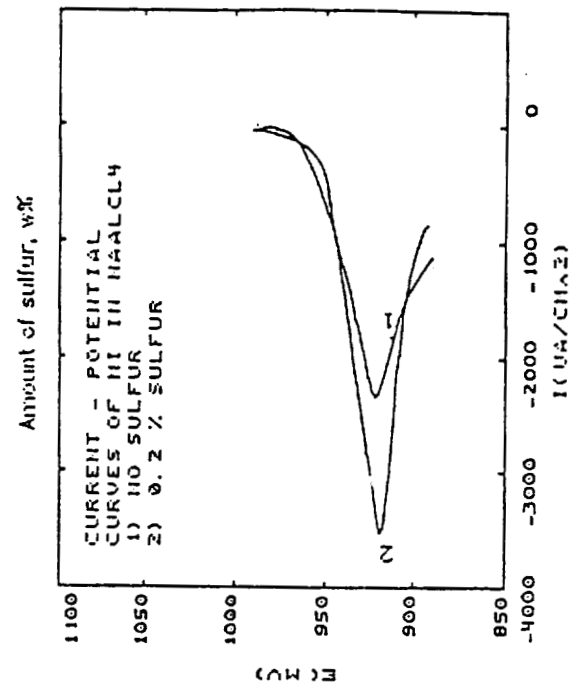
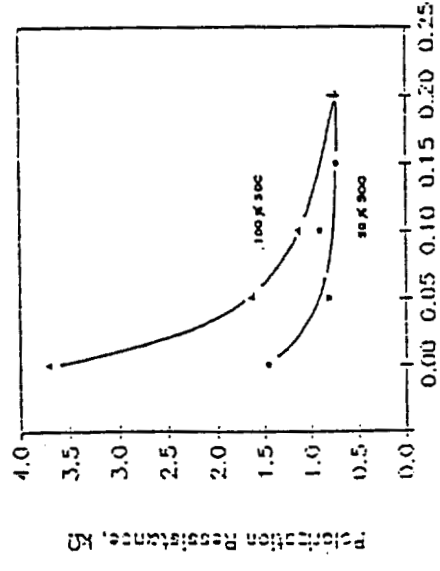
Fig. 9. Effect on cell capacity retention of sulfur and PbCl<sub>2</sub> dopants in the NaAlCl<sub>4</sub>.

R. J. Bones, D. A. Teagle, S. D. Brooker and F. L. Cullen  
 J. Electrochem. Soc., 136, 1274 (1989).

- SULFUR REDUCES MORPHOLOGICAL CHANGE

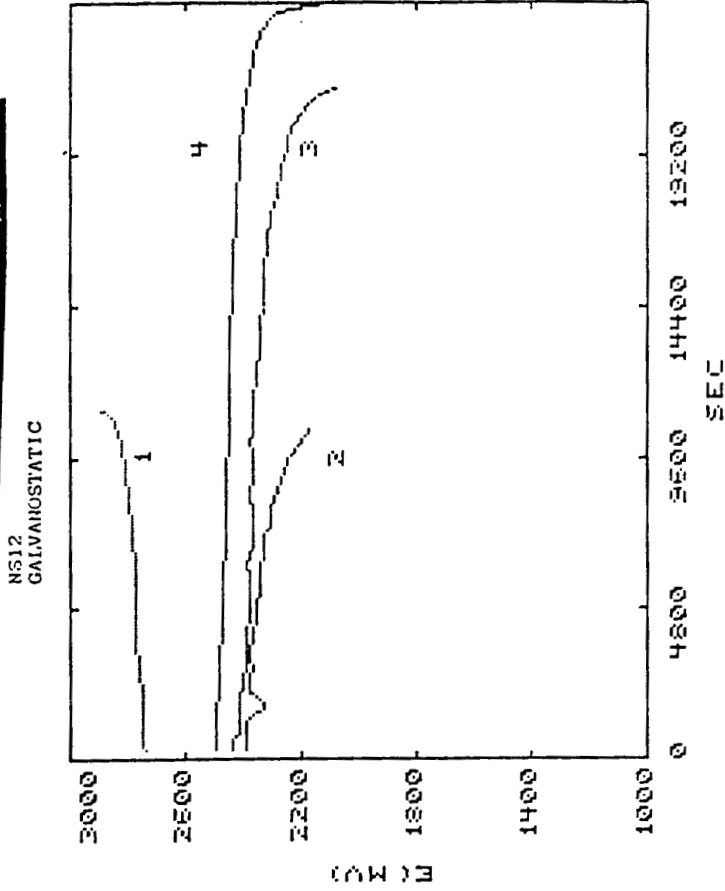
# EFFECT OF SULFUR ON NiCl<sub>2</sub> KINETICS

- HIGHER PEAK CURRENTS IN CYCLIC VOLTAMMETRIC CURVES
- IMPROVEMENT IN RECHARGEABILITY
- ENHANCED KINETICS OF NiCl<sub>2</sub> 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



# FABRICATION PARAMETERS VS. ENERGY DENSITY

- OPTIMIZE CONVERSION EFFICIENCY (RATIO OF NaCl : M) AND ELECTRODE POROSITY

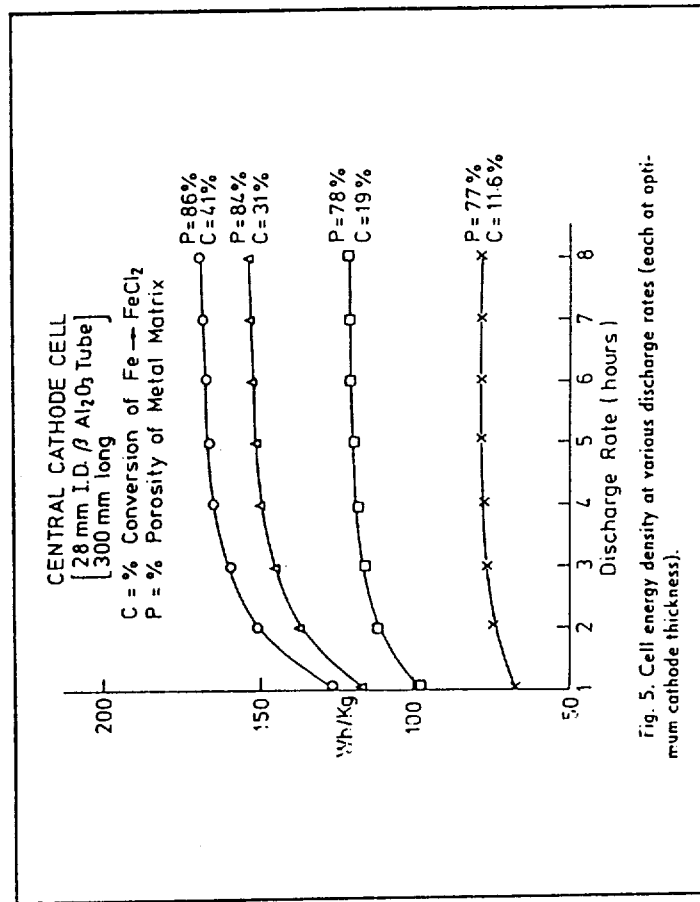


Fig. 5. Cell energy density at various discharge rates (each at optimum cathode thickness).

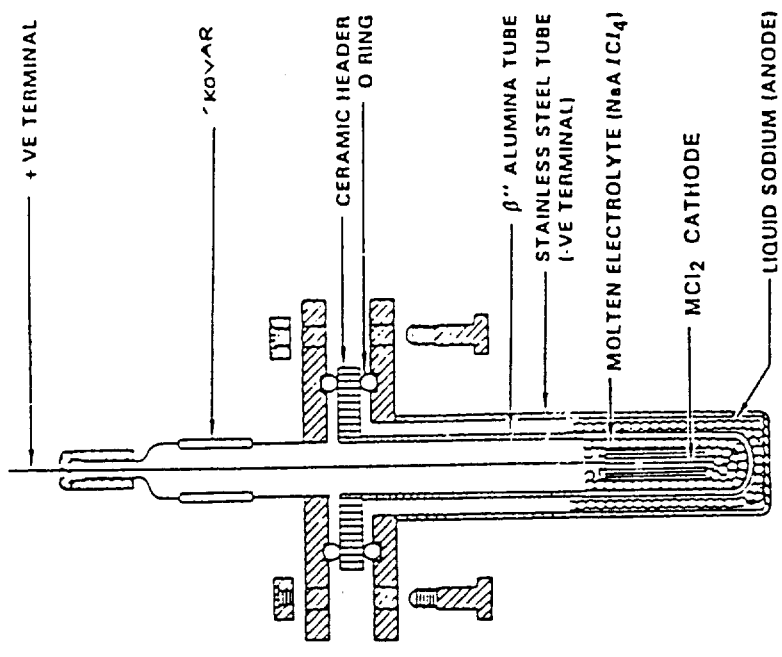
R. J. Bones, J. Coetzer, R. C. Galloway  
and D. A. Teagle, J. Electrochem., Soc.,  
134, 2379 (1987).

- 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



**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

ACTIVITY	88 89 90 91 92 93 94 95 96 97 98 99 2000	
SCREENING STUDIES	<div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">Evaluate organic and inorganic cathodes</div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">Down select to Na/MCl<sub>2</sub></div>	IDENTIFY SYSTEM CAPABLE OF PROVIDING > 1000 CYCLES AND 150 Wh/Kg
ELECTROCHEMICAL CHARACTERIZATION OF MCl <sub>2</sub>	<div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">Short term studies performance and reversibility</div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">Identify suitable materials</div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">Identify and overcome rate limiting processes</div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">Down select to Na/MCl<sub>2</sub></div>	ESTABLISH MECHANISMS DETERMINE REACTION KINETICS AND IDENTIFY RATE LIMITING PROCESSES
COMPONENT DEVELOPMENT	<div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">Develop 5 Ah TEST CELL</div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">Study of performing enhancing additives</div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">Develop cathode fabrication process</div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">Identify cell failure mechanism</div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">Charge methods</div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">Optimize and improve design</div>	DEFINE DESIGN REQUIREMENTS FOR 20-25 Ah CELLS
PERFORMANCE AND SAFETY EVALUATION	<div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">Develop performance data base</div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">Evaluate safety and environmental effects</div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">Identify failure modes</div>	DEMONSTRATE CYCLE LIFE AND PERFORMANCE IN OPTIMIZED 20-25 Ah CELL
PROTO TYPE	<div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">Develop eng model cell</div> <div style="border: 1px solid black; padding: 2px;">Demo 1000 cycles and 150 Wh/Kg</div>	FINAL DEMONSTRATION





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## PUBLICATIONS FROM JPL ACTIVITIES

1. "AEROSPACE APPLICATIONS OF SODIUM BATTERIES USING NOVEL CATHODE MATERIALS",  
PROC. OF 24<sup>th</sup> IECEC, WASHINGTON D.C., AUG. 1989.
2. "ORGANIC CATHODE MATERIALS IN SODIUM BATTERIES"  
J. APPLIED ELECTROCHEMISTRY, 20 , 357 - 364 (1990).
3. "ADVANCED RECHARGEABLE SODIUM BATTERIES WITH NOVEL CATHODES"  
J. POWER SOURCES, 29, 301 - 309 (1990).
4. "ELECTROCHEMISTRY OF METAL CHLORIDES IN SODIUM BATTERIES".  
J. ELECTROCHEM. SOC., 137, 2991 - 2997 (1990).
5. "ALTERNATE CATHODES FOR SODIUM - METAL CHLORIDE BATTERIES"  
J. ELECTROCHEM. SOC., 138, 883 -884 (1991).
6. "SODIUM - METAL CHLORIDE BATTERY RESEARCH AT JPL"  
PROC. SERT CONF., APRIL 1991.
7. "PROGRESS AND RECENT DEVELOPMENTS IN SODIUM - METAL CHLORIDE BATTERIES"  
PROC. 26<sup>th</sup> IECEC, BOSTON, MA, AUG. 1991.

## CONCLUSIONS

- RAPID DEVELOPMENT IN THE TECHNOLOGY OF Na /  $\text{MCl}_2$  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  $\sim 100$  Wh/Kg HAVE BEEN DEMONSTRATED IN BOTH Na /  $\text{FeCl}_2$  AND Na /  $\text{NiCl}_2$  CELLS.
- OPTIMIZATION OF POROUS CATHODE AND SOLID ELECTROLYTE GEOMETRIES ARE ESSENTIAL FOR FURTHER ENHANCING THE PERFORMANCE.
- FUNDAMENTAL STUDIES CONFIRM THE CAPABILITIES OF THESE SYSTEMS.  $\text{NiCl}_2$  EMERGES AS THE CANDIDATE CATHODE MATERIAL FOR HIGH POWER DENSITY APPLICATIONS SUCH AS ELECTRIC VEHICLE AND SPACE.



N 9 2 - 2 2 7 6 9

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

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**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**

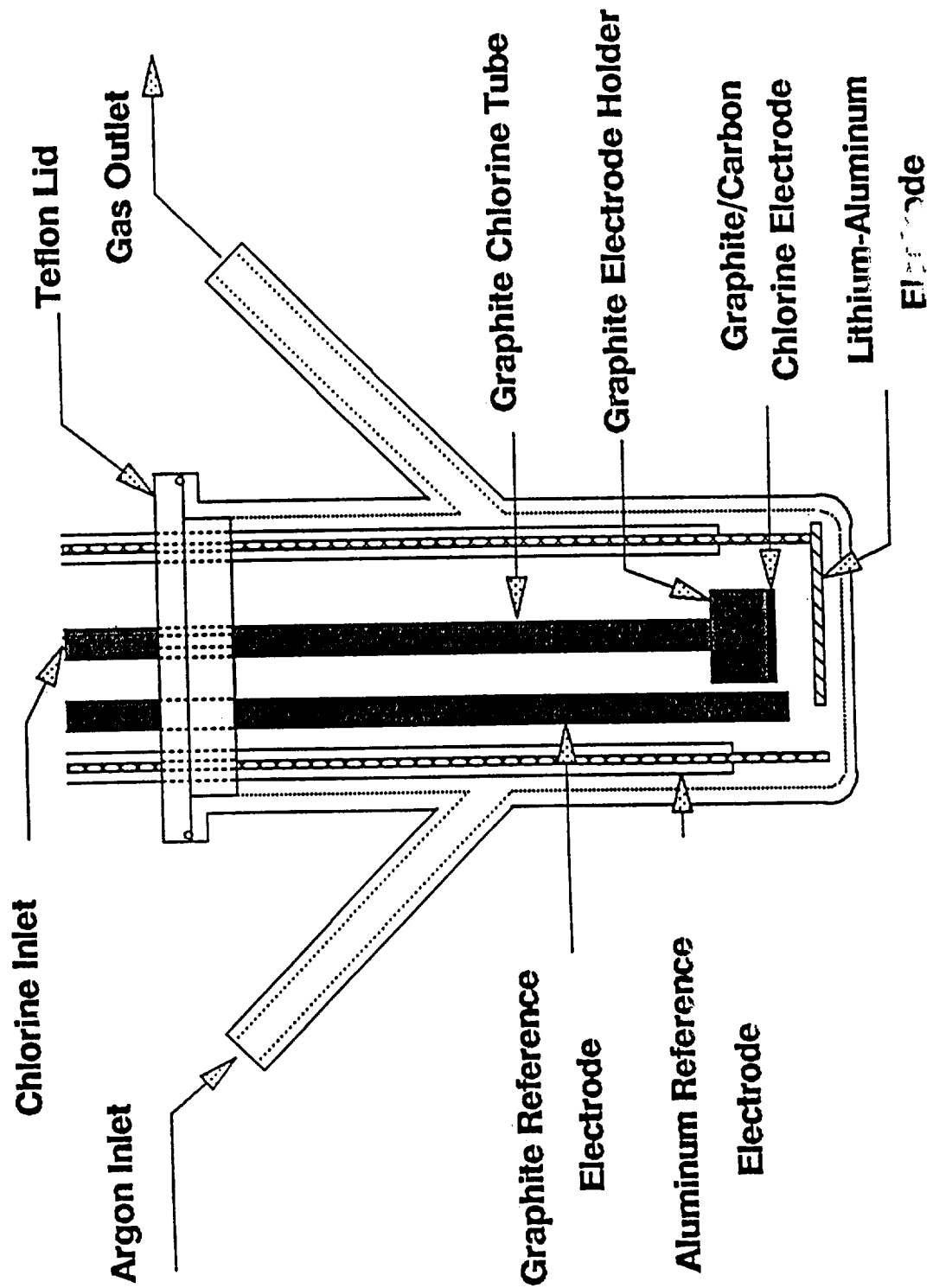
**CELL STACK DEVELOPMENT**

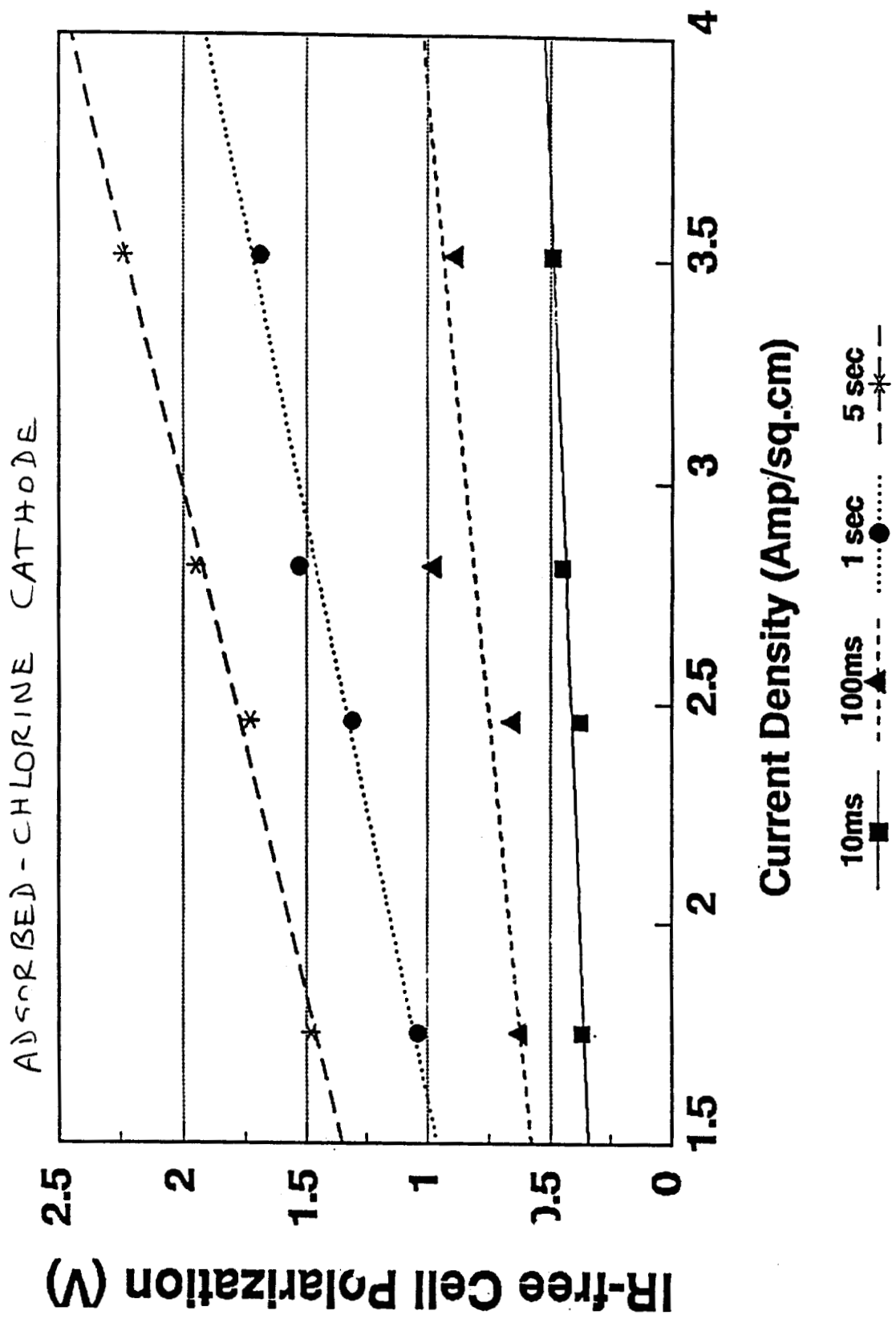
**SUMMARY**



# **CHLORINE CATHODES**

- **Uniform Pore Size Distribution**
- **Good Permeability to Chlorine**
- **Activated Surface**
- **Electrochemical Activation**





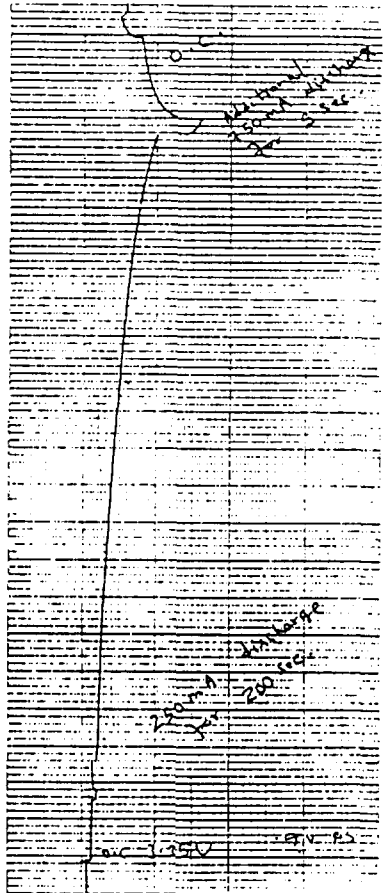
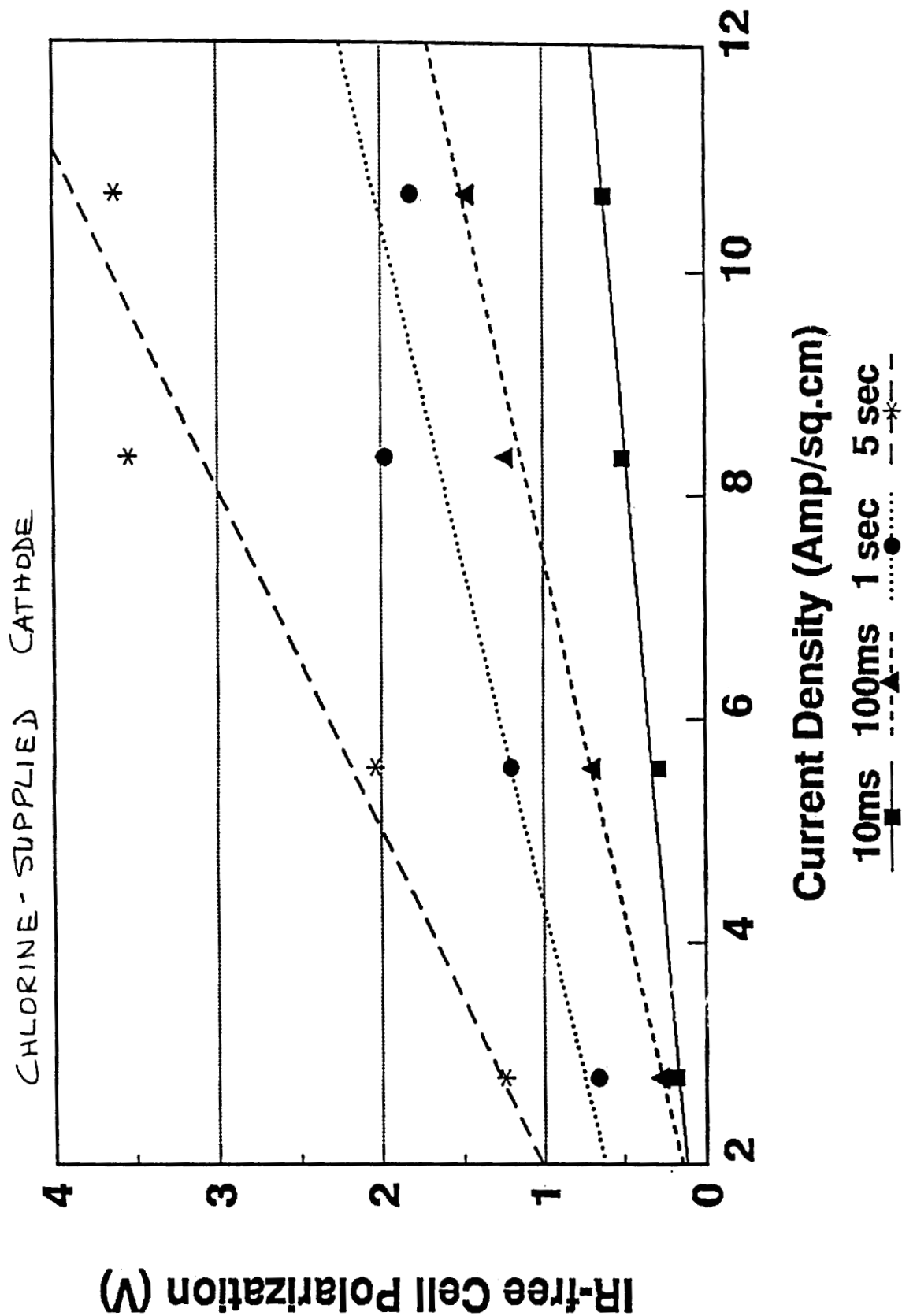
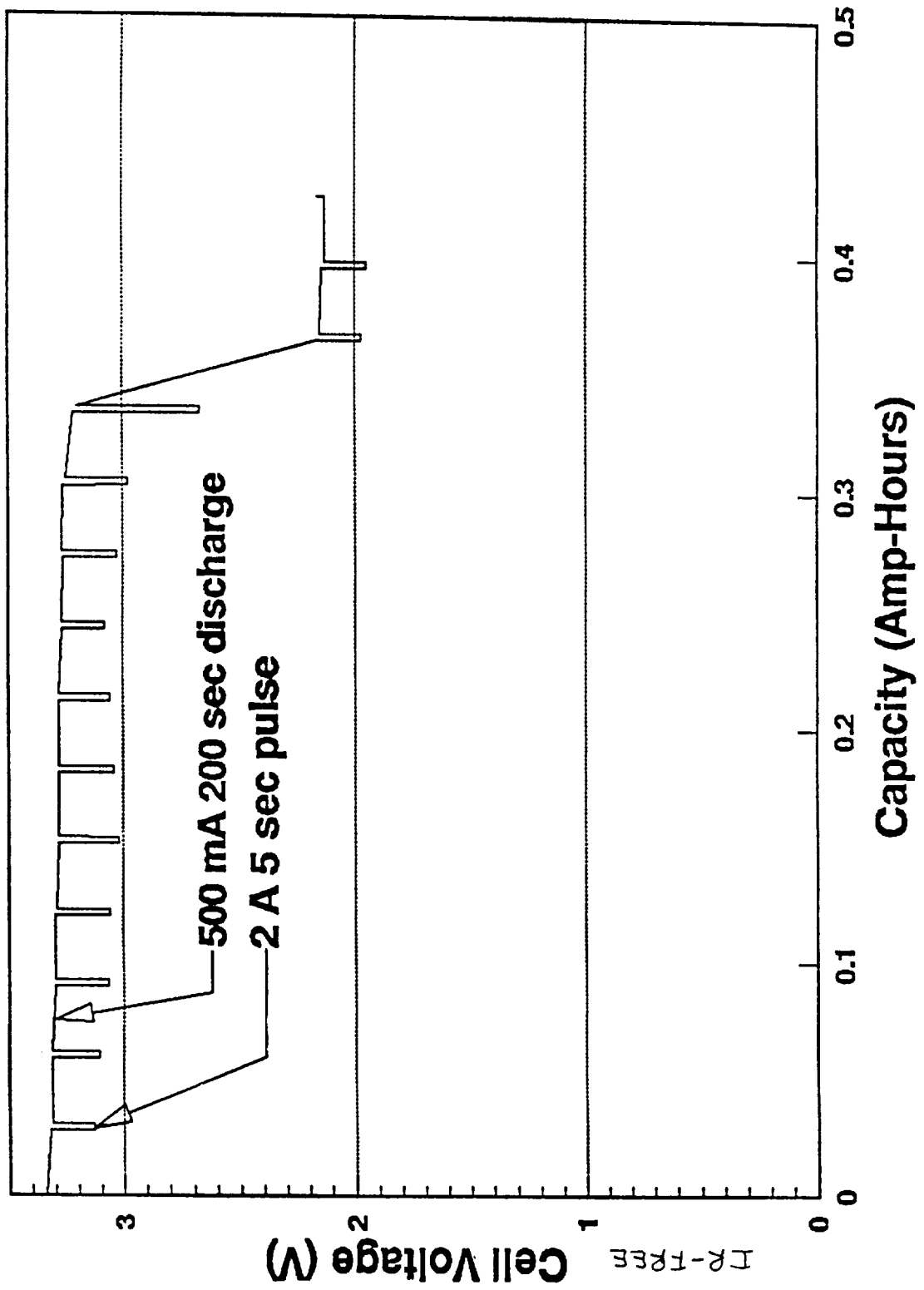


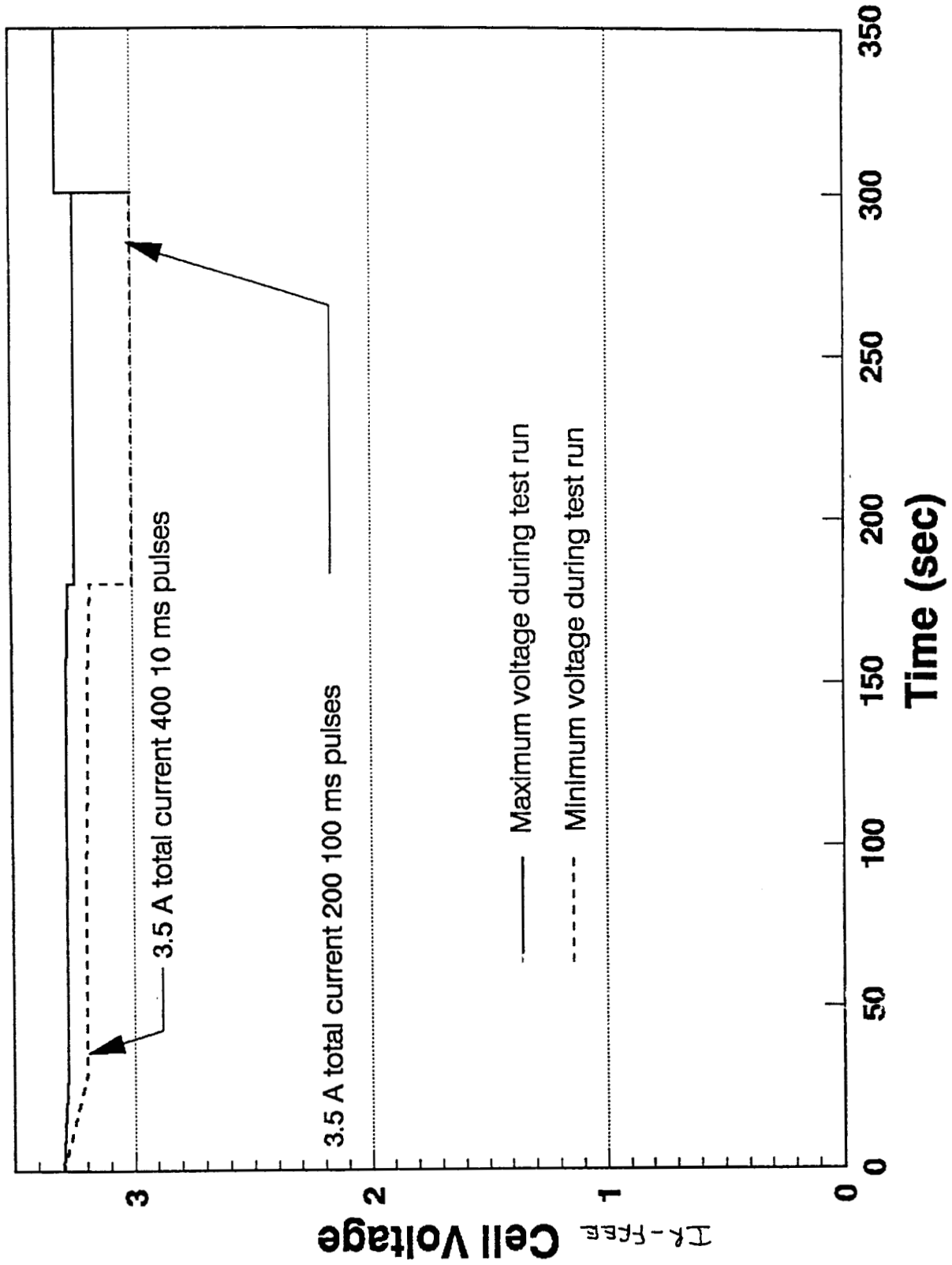
Fig. 5 Discharge characteristics for a Li-Al/carbon 8-9-2 absorbed chlorine cell under test cycle 1 regime, 250 mA for 200 sec followed by 1 A current



Li-Al / CHLORINE CELL 450°C



Li-Al/CHLORINE CELL, 450°C



# **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**

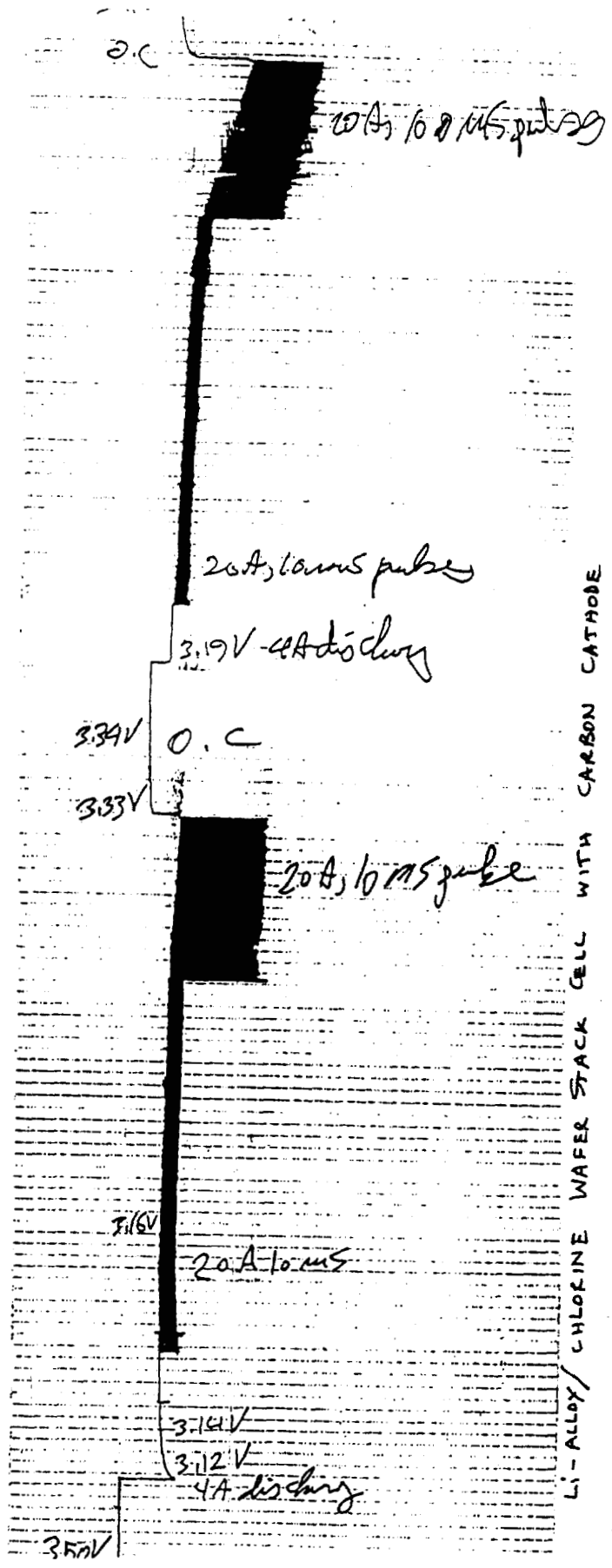
**UNIT CELL DEVELOPMENT**

**CELL STACK DEVELOPMENT**

**SUMMARY**

# Cell Development

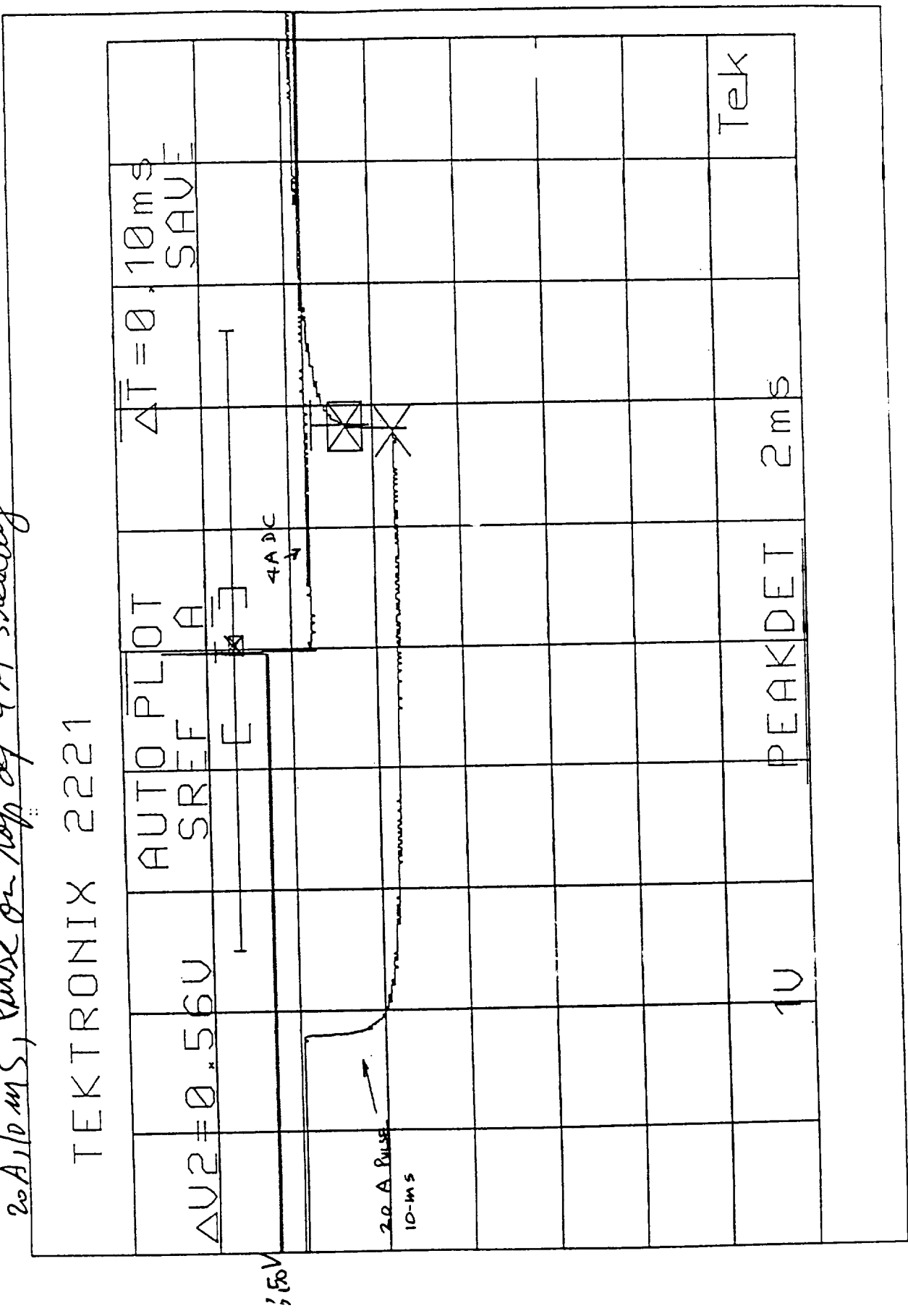
- **Test Hardware**
- Glass Enclosure Cell
- Anode Wafer in Stainless Steel or Ni Cup, Nickel leads
- Cathode rests on EB salt wafer backed by graphite current collector
- Chlorine fed to the wafer-ambient pressure
- **Test Regime**
- Steady discharge load + 400 10 ms pulses + 200 100 ms pulses



LI-ALLOY/ CHLORINE WAFER STACK CELL WITH CARBON CATHODE  
 INC. U.S.A. MADE IN CANADA

Cell # 12-92 (1) Oct 19/90

(Tray 1)  
20 A, 10 ms, Pulse on top of 4A steady



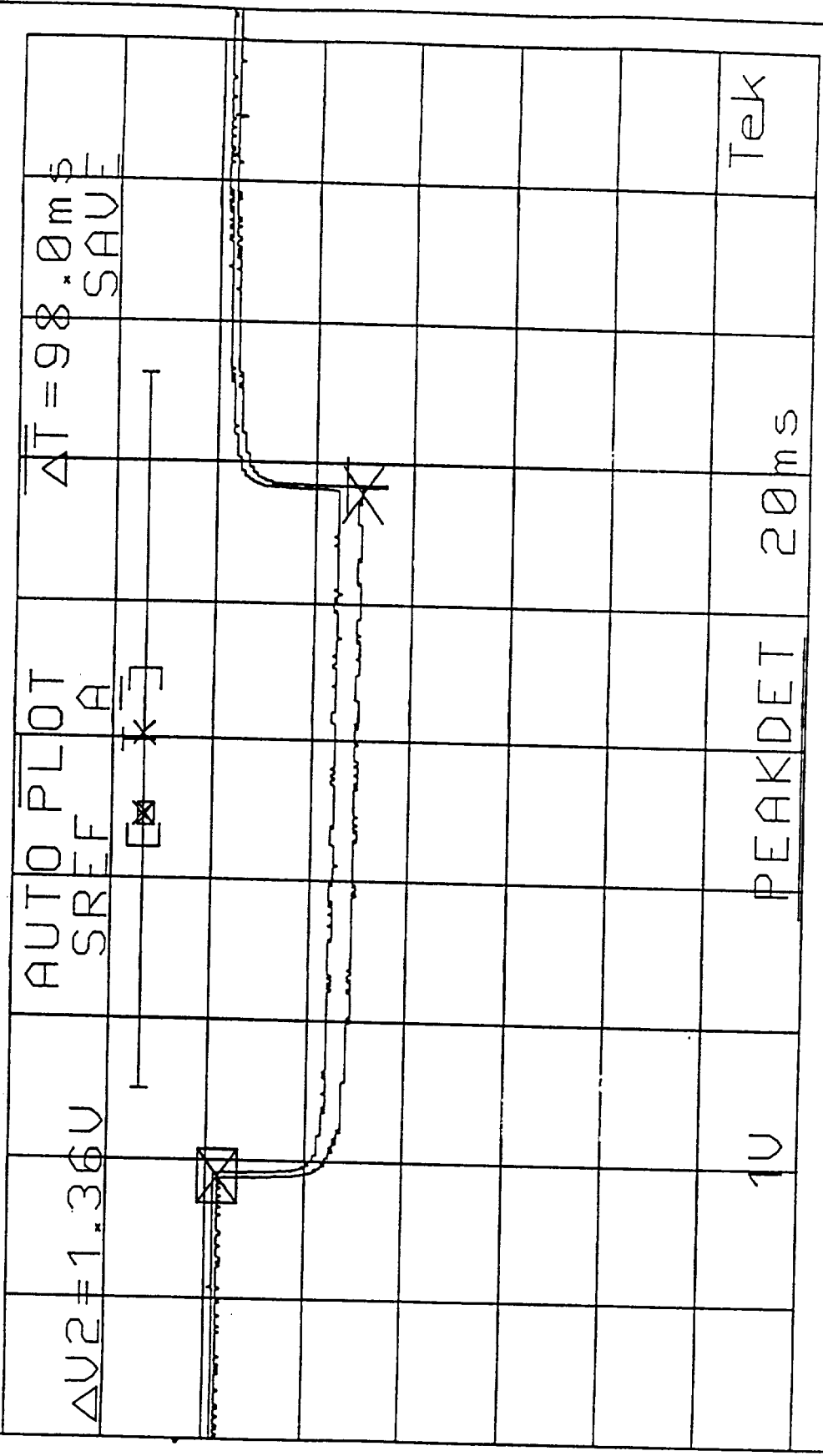
80 CELL # 16-1 C

(unobs)

USA 17/7C

20 A, 100 ms pulse on top of 4 A steady (200th pulse (bottom))

TEKTRONIX 2221



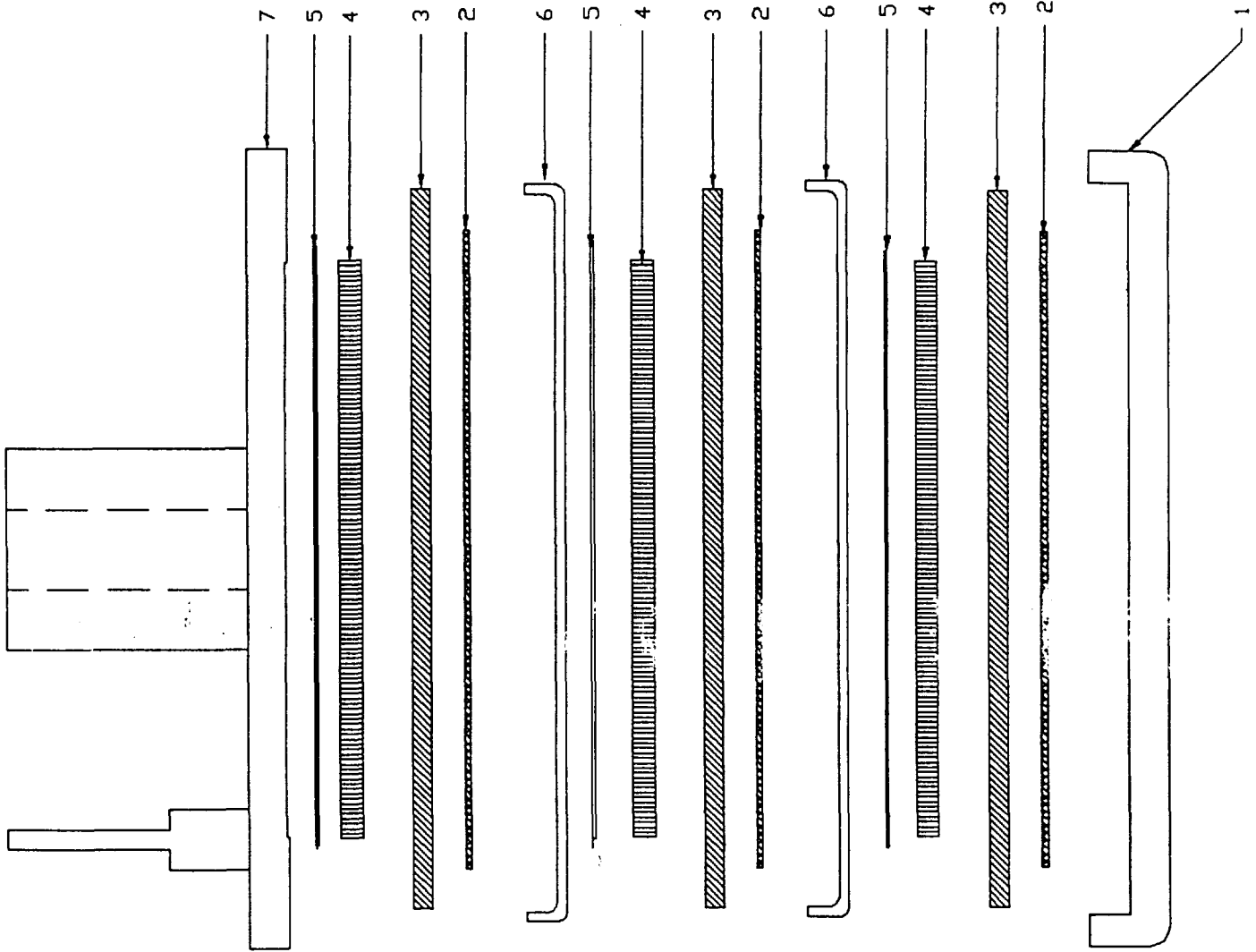
**INTRODUCTION**

**CHLORINE CATHODES**

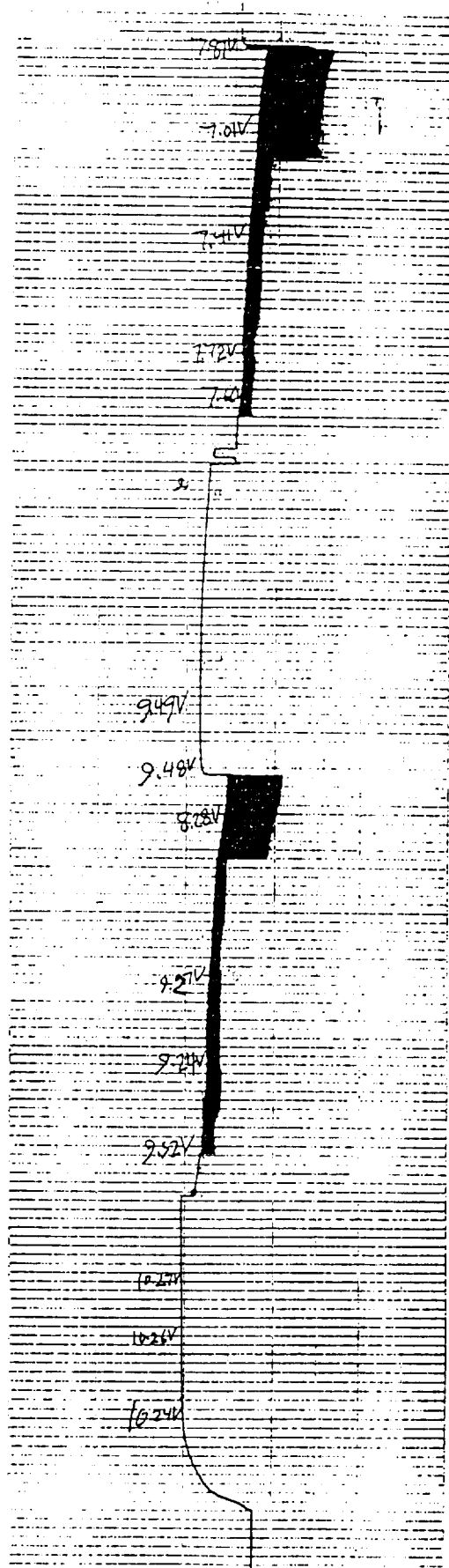
**UNIT CELL DEVELOPMENT**

**CELL STACK DEVELOPMENT**

**SUMMARY**



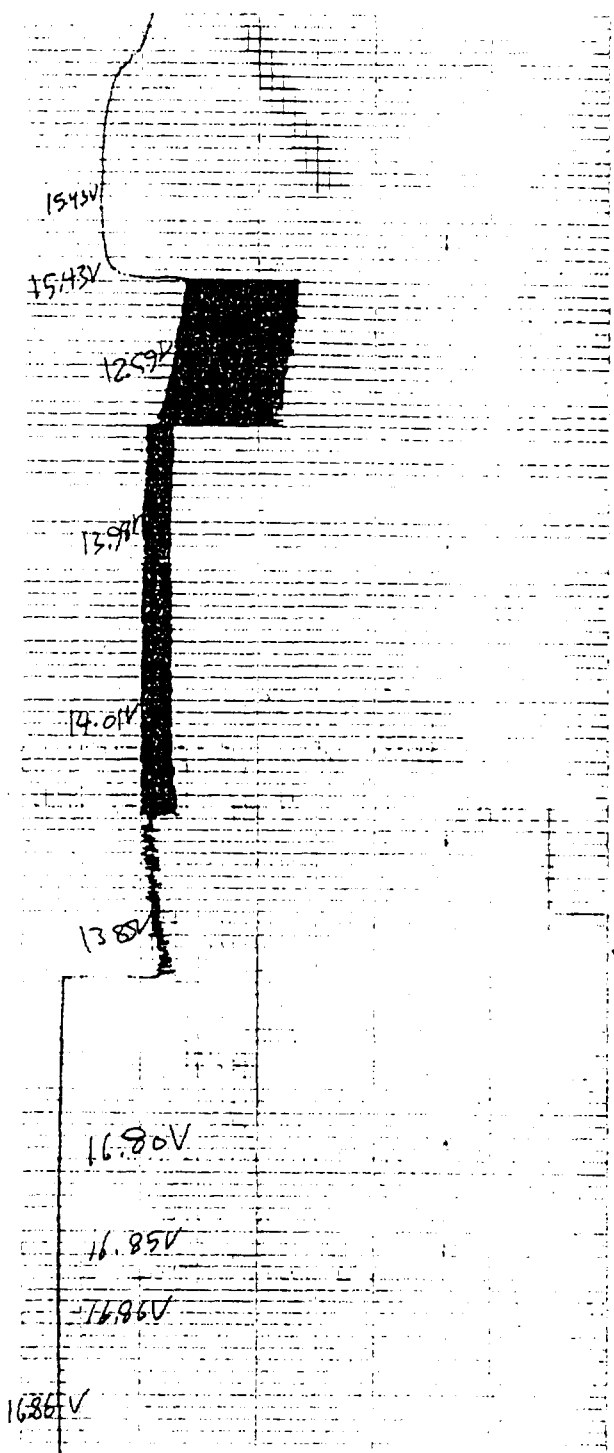
1. Anode Current Collector
2. Li-Al Anode
3. Salt Wafer
4. Carbon Cathode
5. Grafoil
6. Nickel Cup
7. Cathode Current Collector with Chlorine Feed Tube



3- CELL STACK U/ CHLORINE SYSTEM

NAPLES MO. U.S.A. MADE IN CANADA CHART NO. 1237  
 LIFE TIME ANGUS INDIANAPOLIS MO. U.S.A. MADE IN CANADA CHART NO. 1237





5 CELL STACK Li ALLOY / CHLORINE SYSTEM

STEERING AND/OR INDEPENDENT ENG. U.S.A. MADE IN CANADA

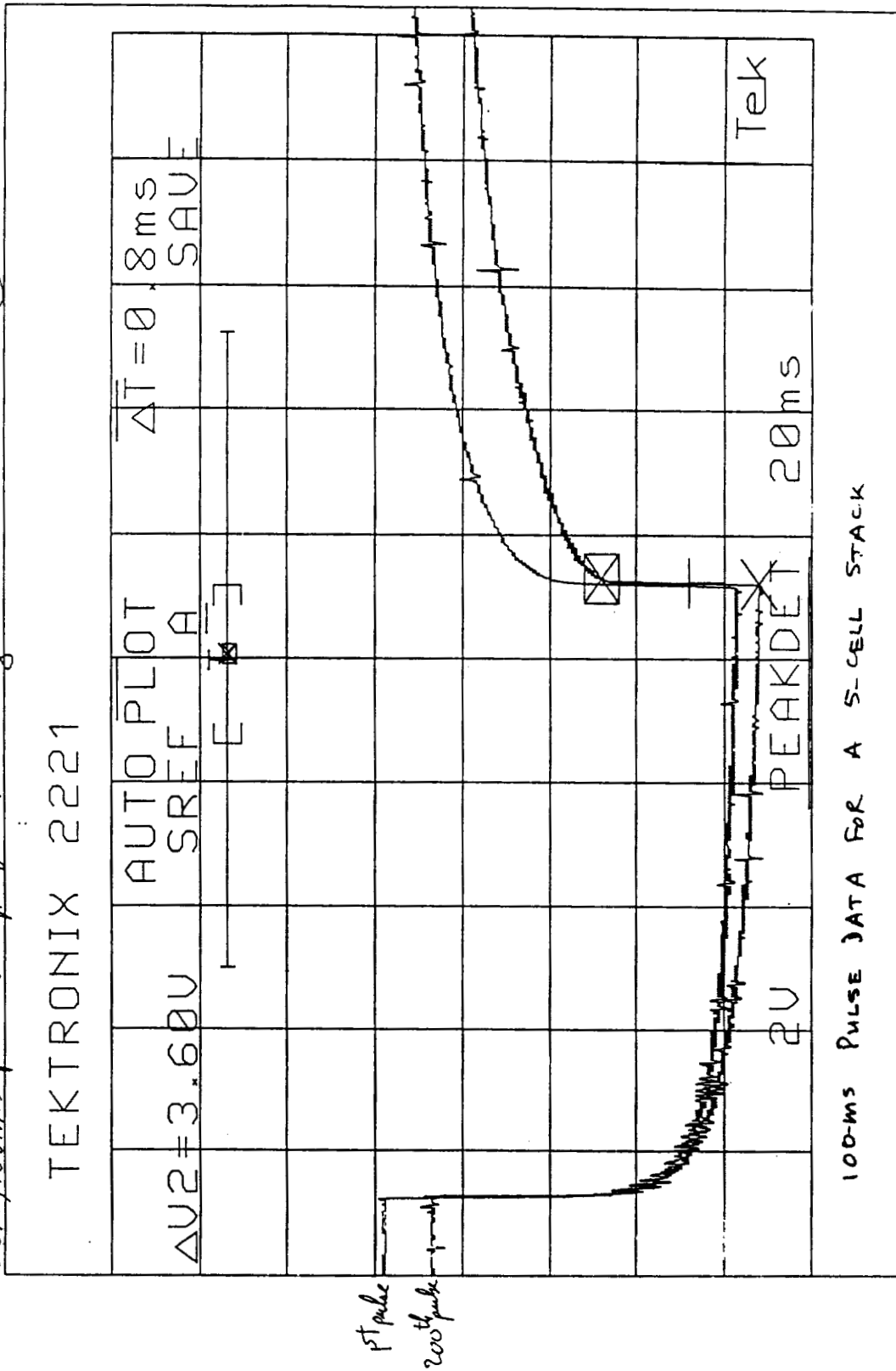
cell #12 - 146

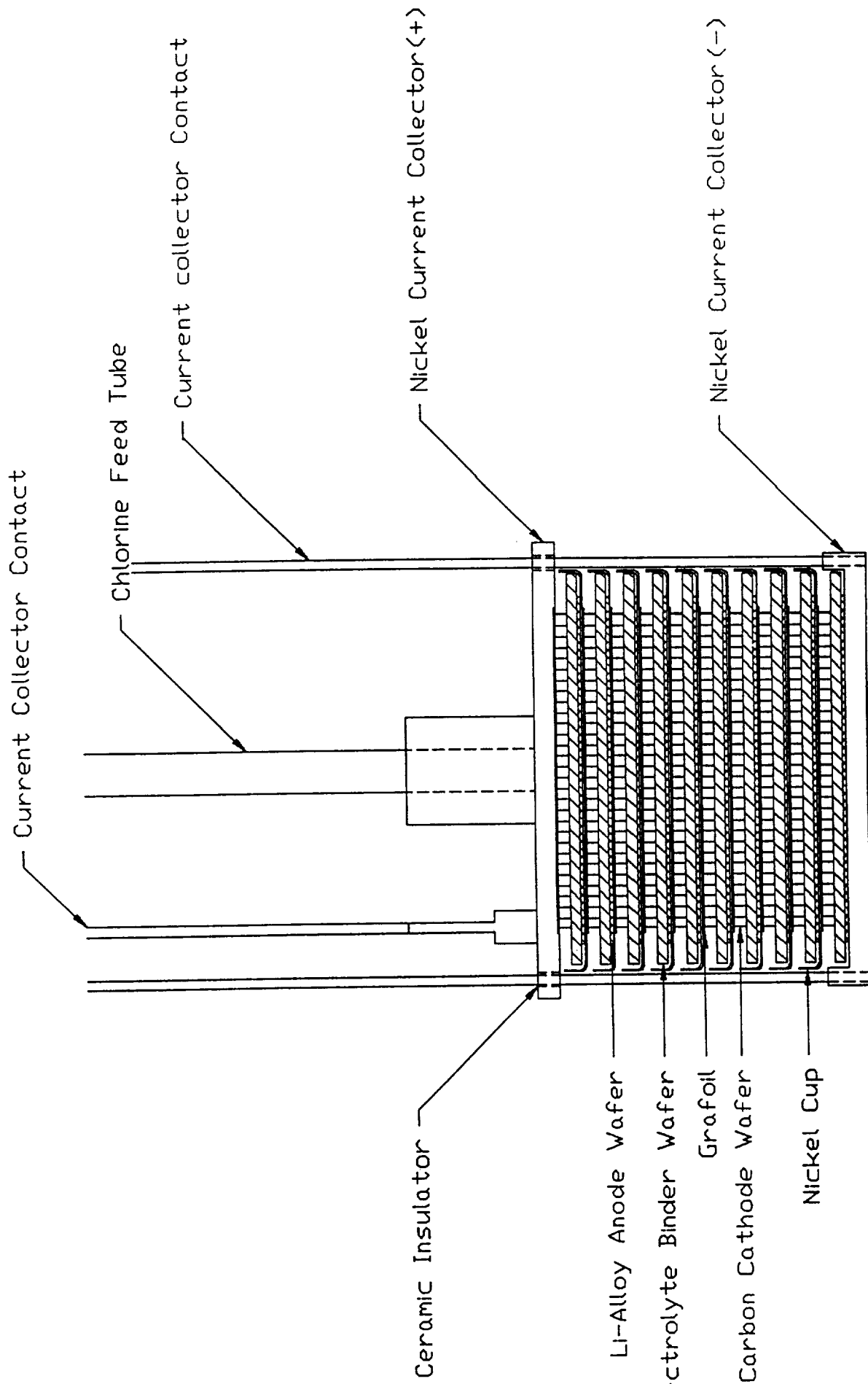
(trial 1)

11/17/79

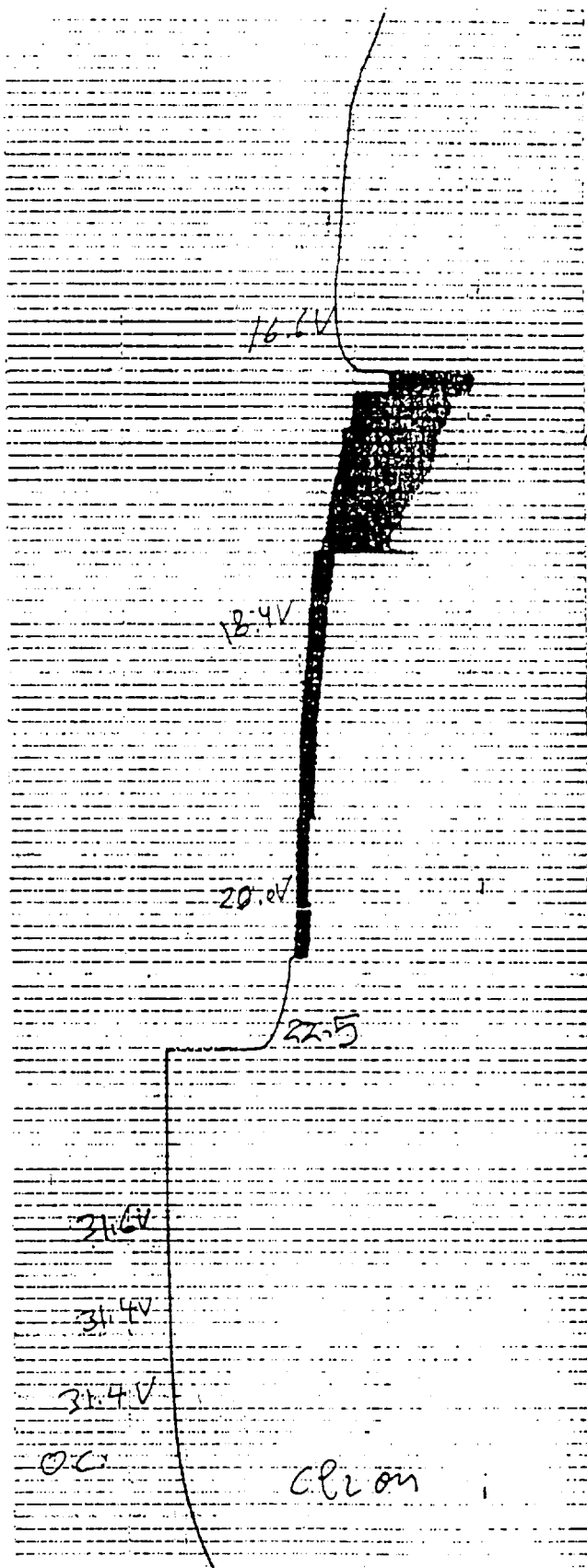
20A, 100ms pulses on top of 4A discharge

(2)





UNCLASSIFIED



Li-Al/CHLORINE SYSTEM 10 CELL STACK - DISCHARGE PROFILE

MADE IN CANADA    COMPANY NO. 19819    CITIZENS ARMS INDIANAPOLIS, IND., U.S.A. MADE IN CANADA    CHART No. 5905    ELECTRIC 5446

# BATTERY DESIGN PARAMETERS

<b>Delivered Energy</b>	56 Wh
<b>Output Voltage</b>	96 V
<b>No. of Cells</b>	40
<b>Open Circuit Voltage</b>	134 V
<b>Capacity</b>	0.56 Ah
<b>Weight</b>	1.34 kg
<b>Volume</b>	1.32 L
<b>Current Density</b>	0.25 A/sq. cm
<b>Pulsing</b>	1.00 A/sq.cm

**POWER DENSITY**  
**4A DC, 24A PULSE REGIME**

	<b>kW/kg</b> <b>10 ms</b>	<b>kW/kg</b> <b>100 ms</b>	<b>kW/L</b> <b>10 ms</b>	<b>kW/L</b> <b>100 ms</b>
<b>Cell</b>	3.9	3.2	4.3	3.5
<b>Stack (5-cell)</b>	3.9	3.1	4.3	3.4
<b>Battery</b>	1.7	1.4	1.7	1.4

**ENERGY DENSITY**  
**4A DC, 24 A PULSE REGIME**

	<b>Wh/kg</b>	<b>Wh/L</b>
<b>CELL</b>		
<b>1 cycle</b>	<b>102</b>	<b>112</b>
<b>2 cycle</b>	<b>183</b>	<b>201</b>
<b>STACK</b>	<b>95</b>	<b>104</b>
<b>BATTERY</b>	<b>42</b>	<b>43</b>

**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*

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JOHNSON CONTROLS BATTERY GROUP, INC.  
P. O. BOX 591  
MILWAUKEE, WI 53201

NICKEL HYDROGEN COMMON PRESSURE VESSEL BATTERY DEVELOPMENT  
KENNETH R. JONES & JEFFREY P. ZAGRODNIK  
(414-783-2604) / (414-783-2605)

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 amphoters 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 fail 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 CO<sub>2</sub> 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:**

[1] IECEC paper, The NASA Research and Technology Program On Batteries, Gary L. Bennett, 25th IECEC, August 1990 (Page 80).

[2] IECEC paper, Some Initial Tests Carried Out On Nickel Hydrogen Cells With Regard To Their Usage On The Olympus Space Craft, P. Leggett and A. Sepers, 20th IECEC, August 1985 (Page 1.331).

2



FIGURE 1: 26-CELL CPV BATTERY AND IPV EQUIVALENT

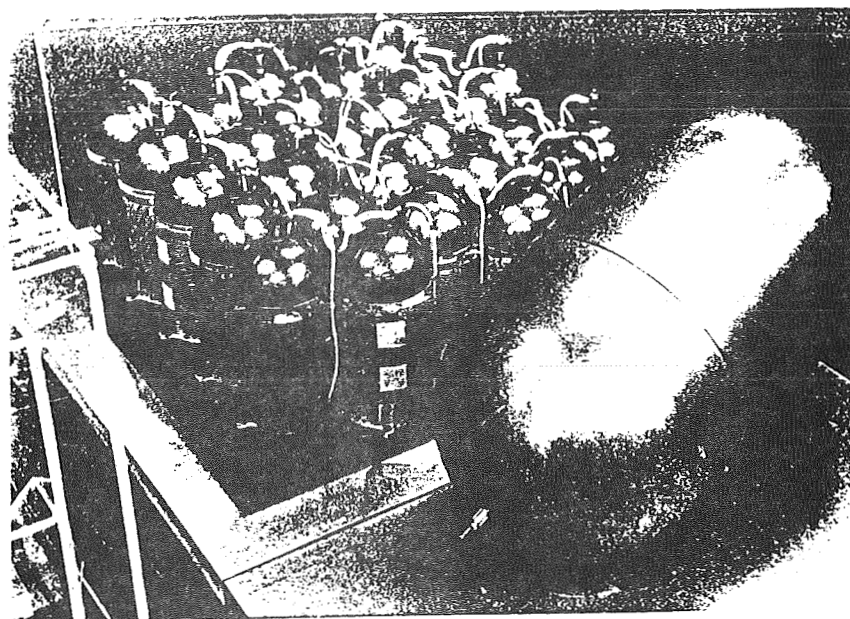
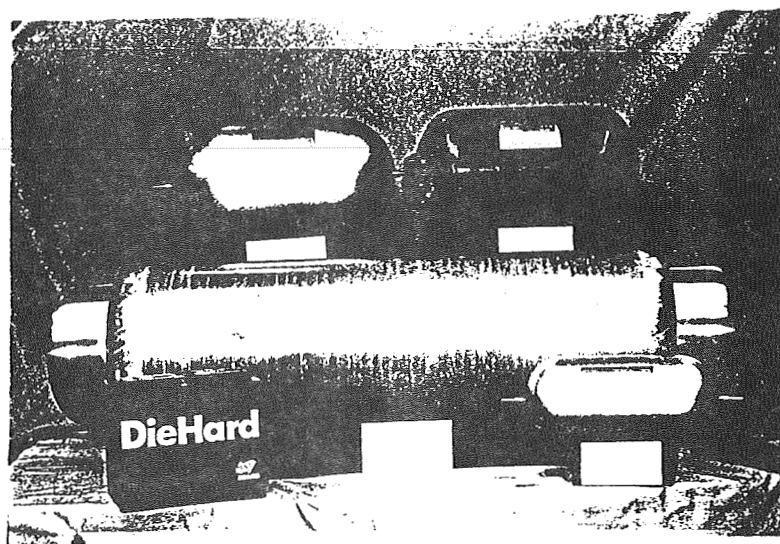


FIGURE 2: VARIETY OF CPV BATTERIES CURRENTLY IN PRODUCTION



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FIGURE 3: 5" CIRCULAR CPV CELL

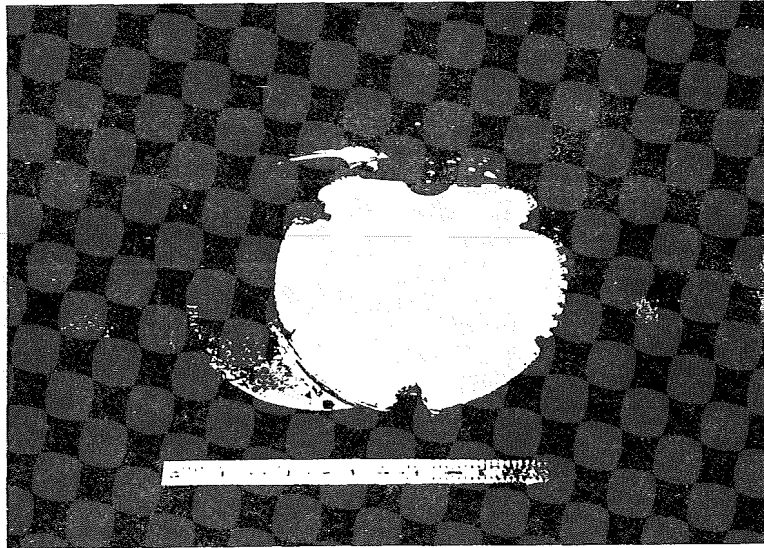
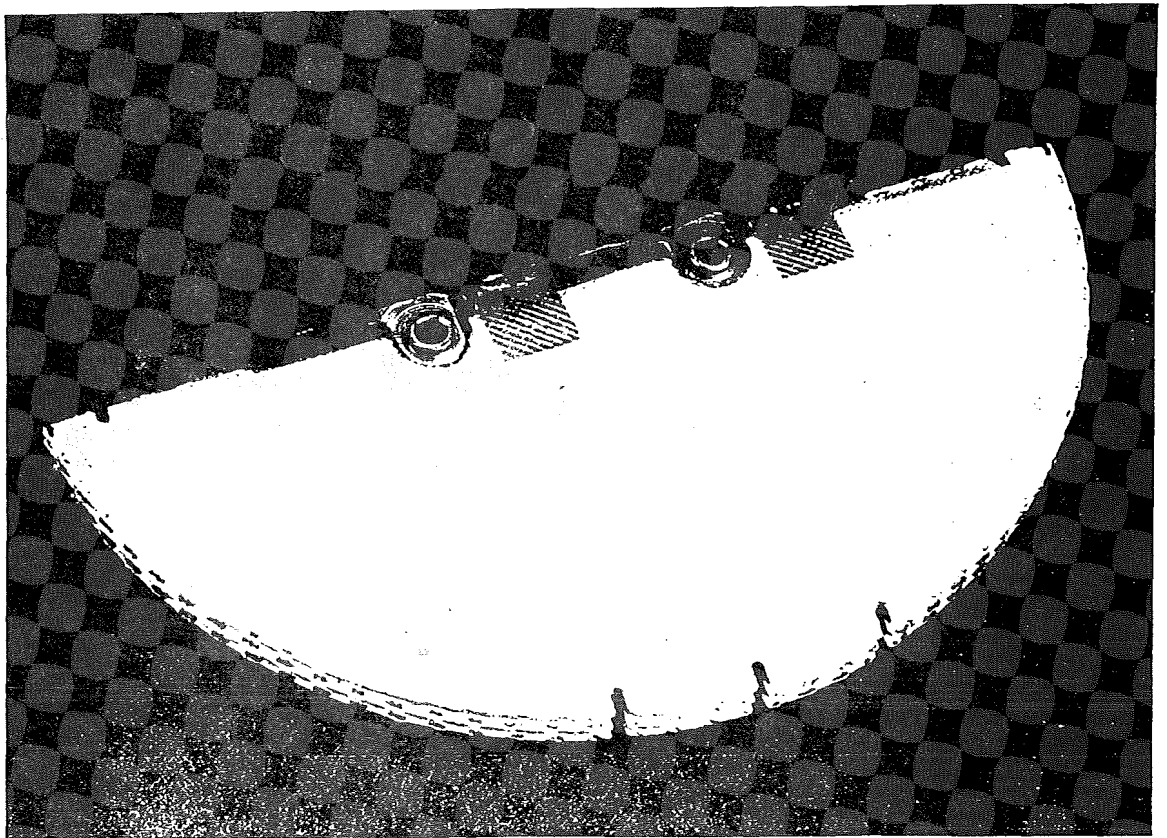


FIGURE 4: 10" SEMI-CIRCULAR CPV CELL



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FIGURE 5: RECTANGULAR CPV CELL MODULE AND COMPONENTS

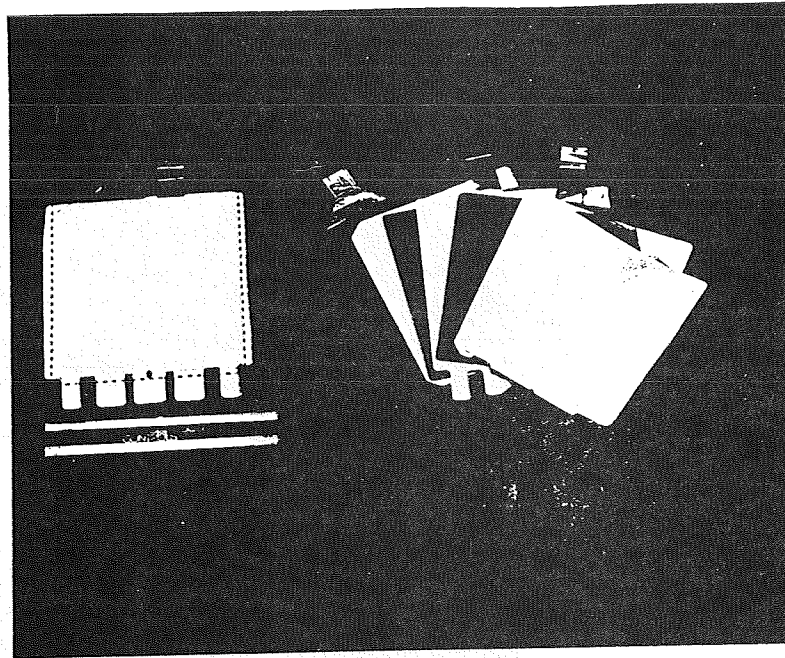


FIGURE 6:

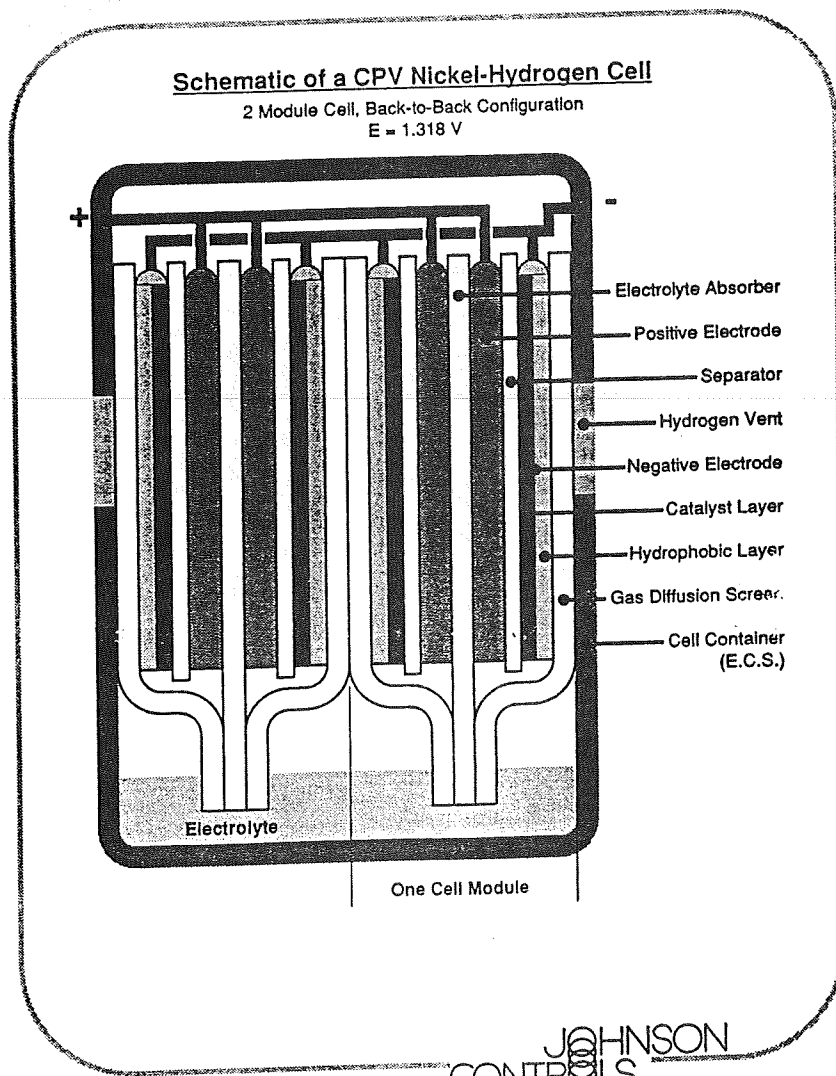
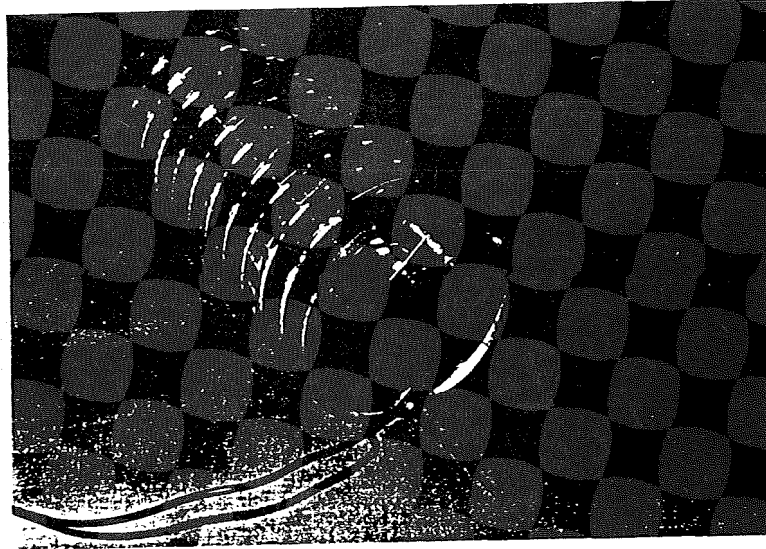


FIGURE 7: 22 CELL CPV LEO BATTERY STACK





**A NICKEL- HYDROGEN COMMON PRESSURE VESSEL  
SPACEFLIGHT EXPERIMENT**

**J.C.GARNER  
NAVAL RESEARCH LABORATORY  
SPACE SYSTEMS DEVELOPMENT DEPARTMENT  
4555 OVERLOOK AVENUE  
S.W. WASHINGTON D.C. 20375**

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## 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**

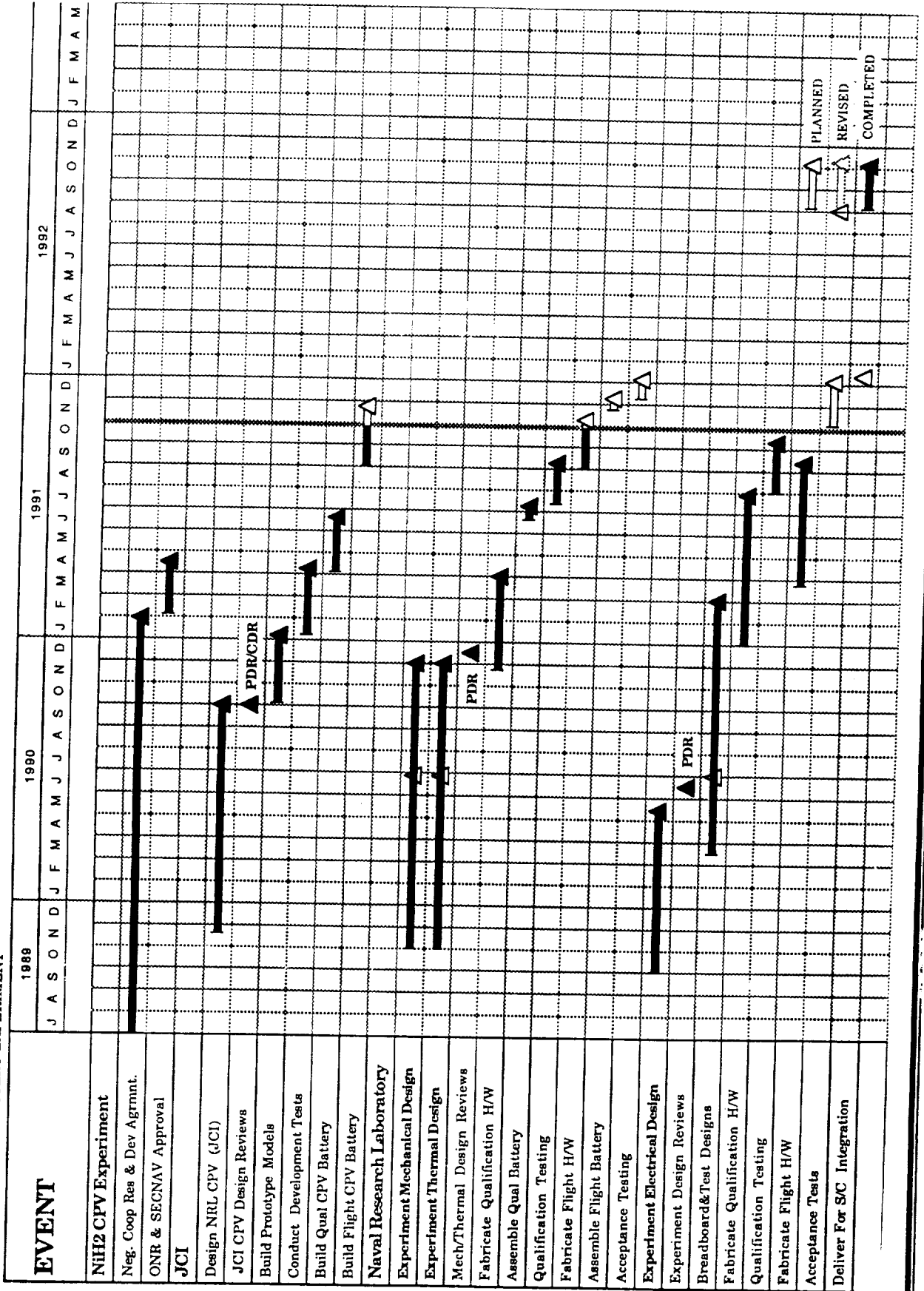
- **COOPERATIVE RESEARCH AND DEVELOPMENT AGREEMENT (CRDA)  
SIGNED BY NRL AND JCI**
- **NO FUNDS EXCHANGED BETWEEN PARTIES**
- **JCI TO PROVIDE TWO NIH2 CPV BATTERIES, ONE FOR QUALIFICATION  
TEST, ONE FOR FLIGHT**
- **NRL TO PROVIDE QUALIFICATION/ACCEPTANCE TESTS, SPACECRAFT  
INTEGRATION, AND FLIGHT DATA**



# A NiH2 CPV BATTERY SPACEFLIGHT EXPERIMENT SCHEDULE

NASA BATTERY WKSHP 31 OCTOBER 1991

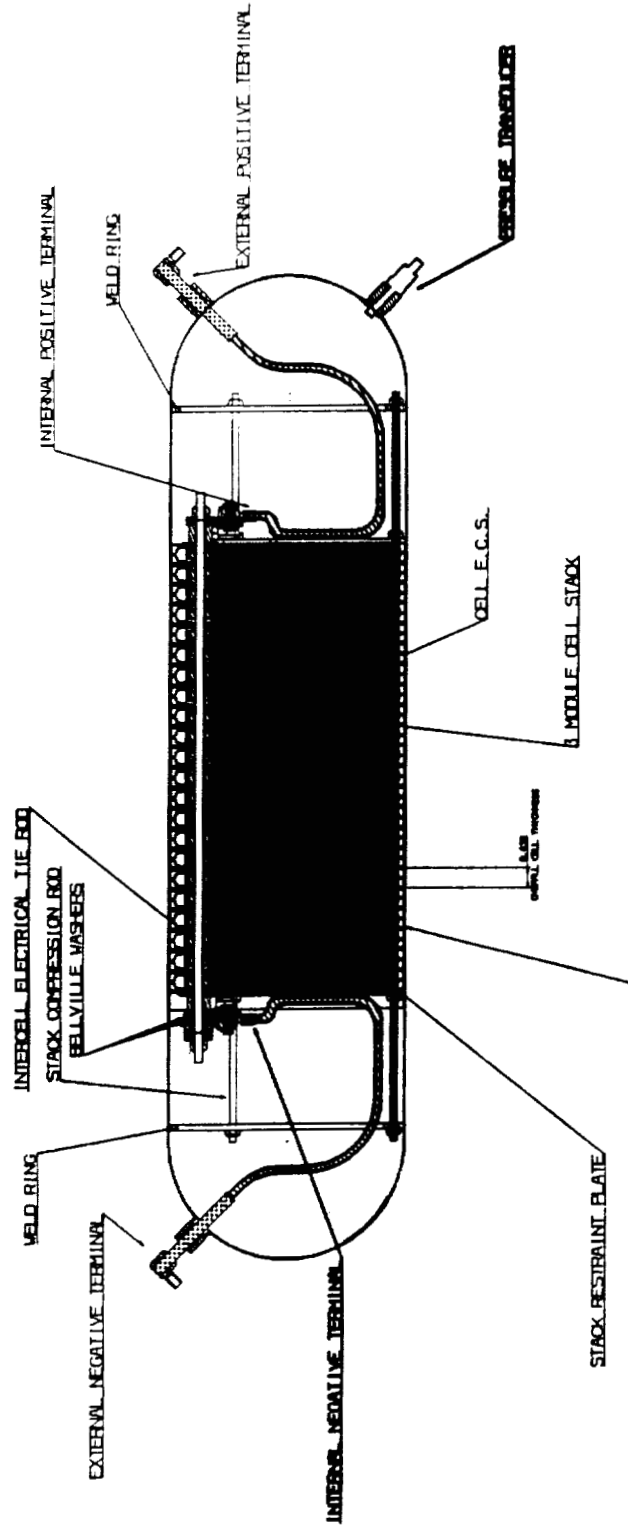
NRL/JCI NiH2 CPV BATTERY EXPERIMENT



**EXPERIMENT DETAILS**

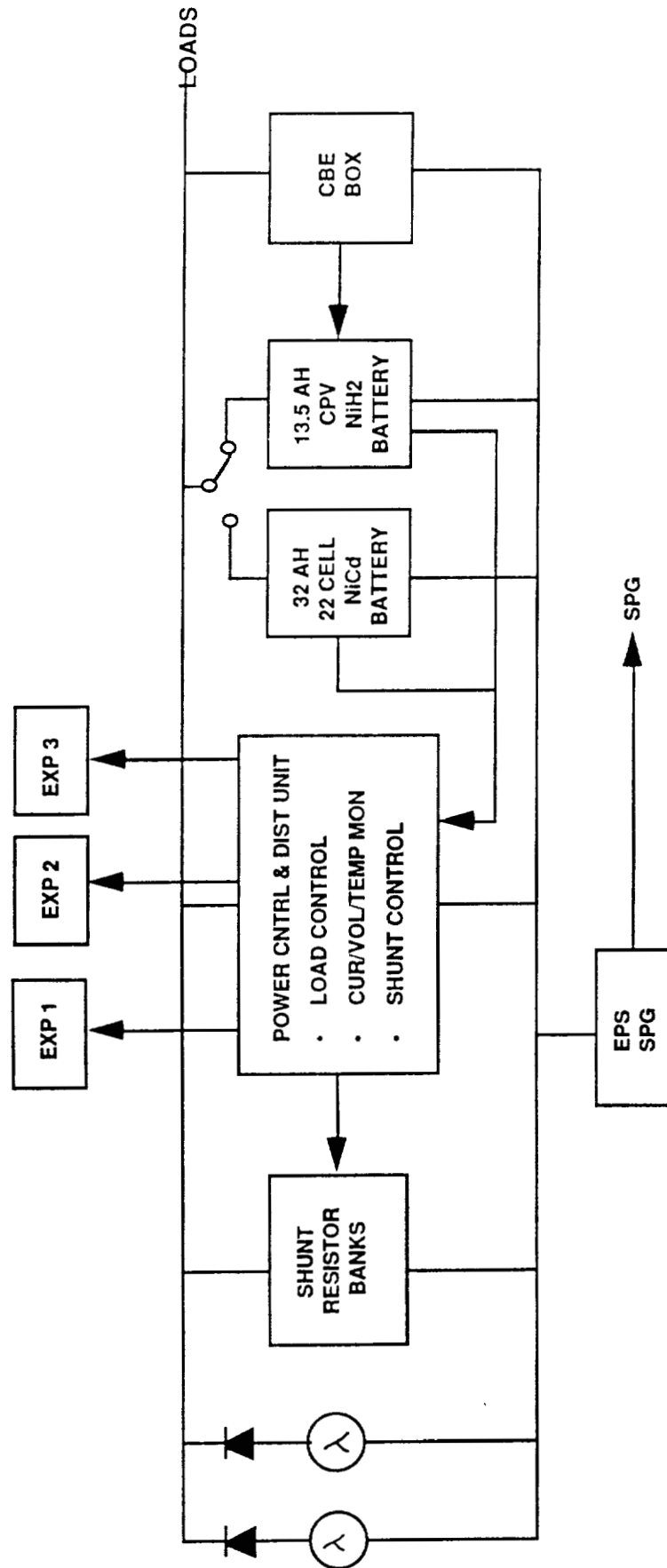
- **LAUNCH CY 92**
- **240 MINUTE ORBIT**
- **MAXIMUM ECLIPSE PERIOD 45 MINUTES**
- **BATTERY SIZED TO SUPPORT A 50% DEPTH OF DISCHARGE**
- **EXPERIMENT DURATION 3+ YEARS**
- **DATA WILL INCLUDE:**
  - BATTERY VOLTAGE**
  - CHARGE/DISCHARGE CURRENT**
  - BATTERY TEMPERATURE**
  - PRESSURE BY TWO METHODS**
  - (PRESSURE TRANSDUCER & STRAIN GAUGE.)**

# JOHNSON CONTROLS INC 5" DIA NiH2 CPV BATTERY FEATURES

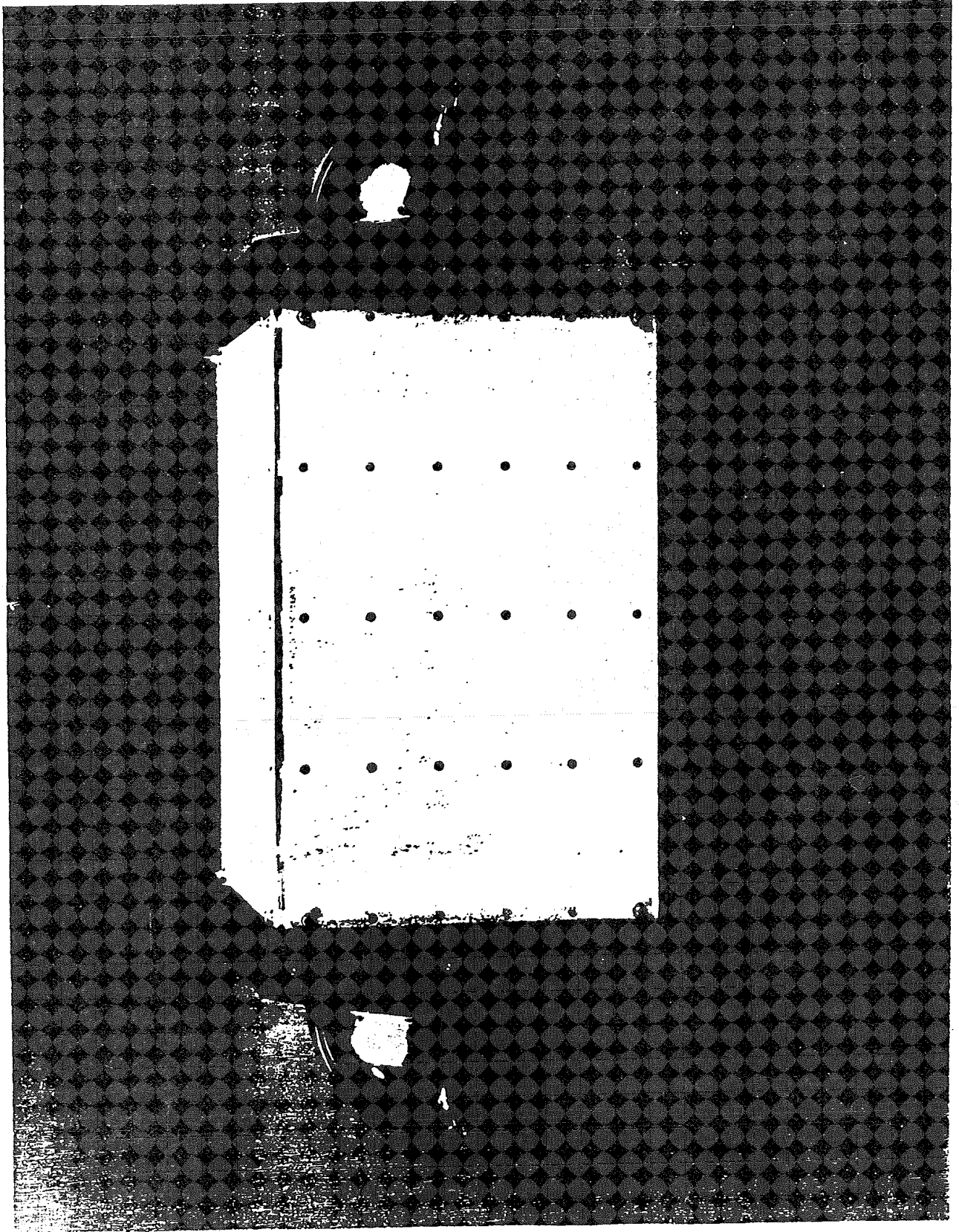


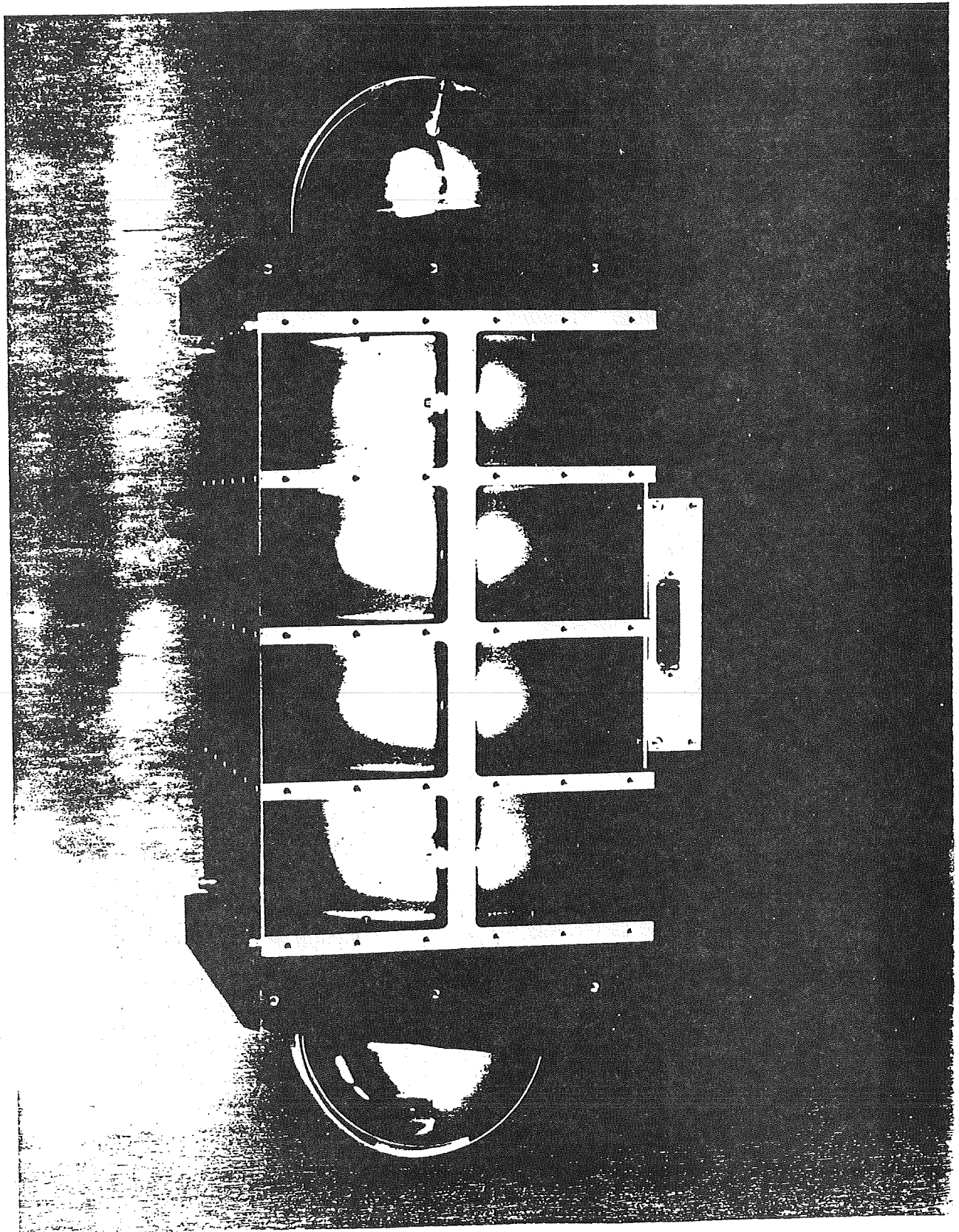
- **NOMINAL CAPACITY:** 10.7 Ah
- **THEORETICAL CAPACITY:** 13.4 Ah
- **NUMBER OF CELLS:** 22
- **WEIGHT:** 6.80 kg (15.0 lbs)
- **NO. MODULES/CELL:** 3
- **PRESSURE VESSEL:** INCONEL 718
- **LENGTH - 20.7"**
- **DIAMETER - 5.0"**

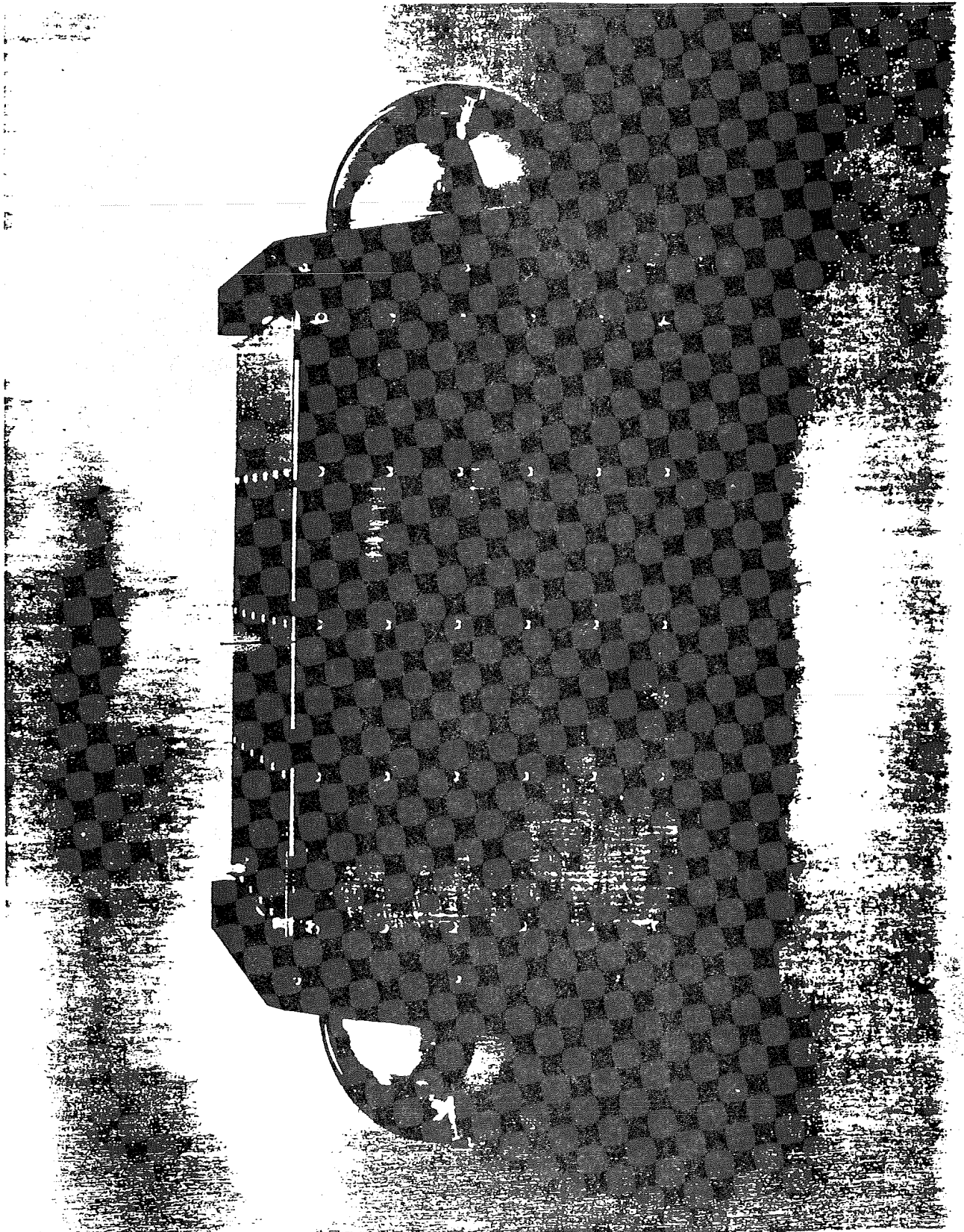
**NiH2 CPV BATTERY WITH S/C ELECTRICAL POWER SUBSYSTEM**

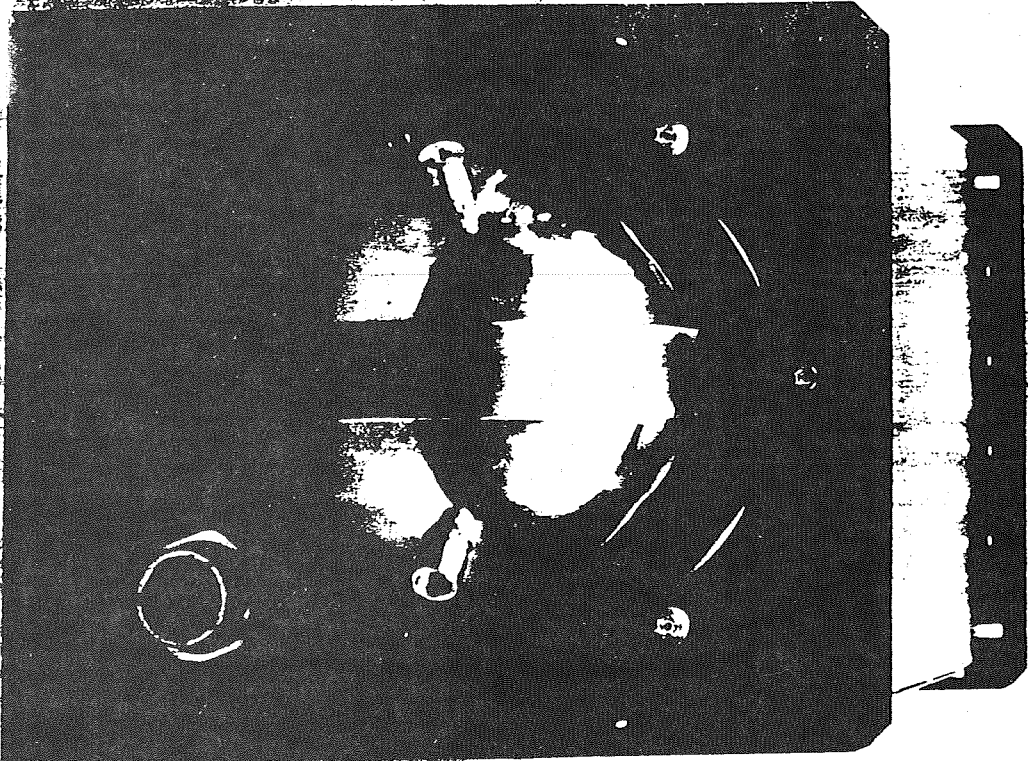


- NiH2 CPV BATTERY ON-LINE BATTERY
- NiCd BATTERY BACK-UP
- NiH2 CPV BATTERY USES EITHER A-H INTEGRATION OR CONSTANT CURRENT CHARGING
- CBE ELECTRONICS PROVIDES AUTOMATIC SWITCHOVER TO NiCd









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## CPV Designs Developed and Tested

### 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.

**CPV Designs Developed and Tested****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 Designs Developed and Tested**

**CPV (2.5 V) vs. IPV: "Same Energy" Analysis**  
**(Cell Level)**

1. Example: 80 Ah (IPV) vs. 40 Ah (CPV)

2. Discharge:

	<u>Rate C/2</u>	<u>Ah</u>	<u>Energy</u>
IPV	40 A	80.0 Ah	102.4 Wh
CPV	0 A	40.0 Ah	102.4 Wh

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 Designs Developed and Tested

### 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 Designs Developed and Tested**

CPV (2.5 V) vs. IPV: "Same Energy" Analysis  
(Battery Level) (cont.)

4. Given this difference in reliability equip the IPV battery with diodes:

	<u>Mass</u>	<u>Energy Density (gravimetric)</u>
IPV	66.3 kg (w/diodes) per batt.	43.7 Wh/kg
CPV	<u>60.6</u> kg (no diodes) per batt.	47.8 Wh/kg
	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 Designs Developed and Tested****CPV Design Comparison**

	<u>RNHC-6-1</u>	<u>RNHC-12-1</u>	<u>RNHC-35-9</u>	<u>RNHC-40-3</u> ( <u>Proto.</u> )
<b>Design:</b>	Two 6 Ahr Stacks In Series	Two 12 Ahr Stacks In Series	Two 35 Ahr Stacks In Series	Two 40 Ahr Stacks In Series
<b>Rated Cap. (C):</b>	6 Ah	12 Ah	35 Ah	40 Ah
<b>Positive Electrodes:</b>	Same Standard Technology			
<b># of Pos. Elect. Per Stack:</b>	10 (2.4" dia.)	10 (3.4" dia.)	26 (3.4" dia.)	32 (3.4" dia.)
<b>Plate Config.:</b>	Mantech	Intelsat	Mantech	Intelsat



**CPV Designs Developed and Tested****CPV Design Comparison (cont.)**

<u>RNHC-6-1</u>	<u>RNHC-12-1</u>	<u>RNHC-35-9</u>	<u>RNHC-40-3</u> ( <u>Proto.</u> )
-----------------	------------------	------------------	---------------------------------------

Separator:	Zircar	Asbestos	Zircar	Asbestos
------------	--------	----------	--------	----------

Negative Elect.: -----Platinum/Teflon Catalyst Over Patented Nickel Grid -----  
w/Reduced Pt

Electrolyte Management:	Non-Recirc.	Non-Recirc.	Recirc.	Non-Recirc.
	No Weld Ring	-----Open Spoke Weld Ring-----		

Design MEOP:	500 psig	480 psig	950 psig	950 psig
--------------	----------	----------	----------	----------

**CPV Designs Developed and Tested**

CPV Design Comparison (cont.)

	<u>RNHC-6-1</u>	<u>RNHC-12-1</u>	<u>RNHC-35-9</u>	<u>RNHC-40-3</u> (Proto.)
Capacity (C/2 Discharge to 2.0 volts, 10 deg. C):	7.6 Ah	15.0 Ah	38.9 Ah	45.4 Ah
Max. Length:	6.75"	9.0"	11.6"	10.0"
Max. Diameter:	2.55"	3.51"	3.51"	3.51"
Cell Mass: (S.G. = Strain Gage)	663 g	1022 g w/S.G.	2000 g w/S.G.	1850 g w/S.G.
Energy Density: (Gravimetric)	28.7 Wh/kg	36.7 Wh/kg	48.6 Wh/kg	61.4 Wh/kg

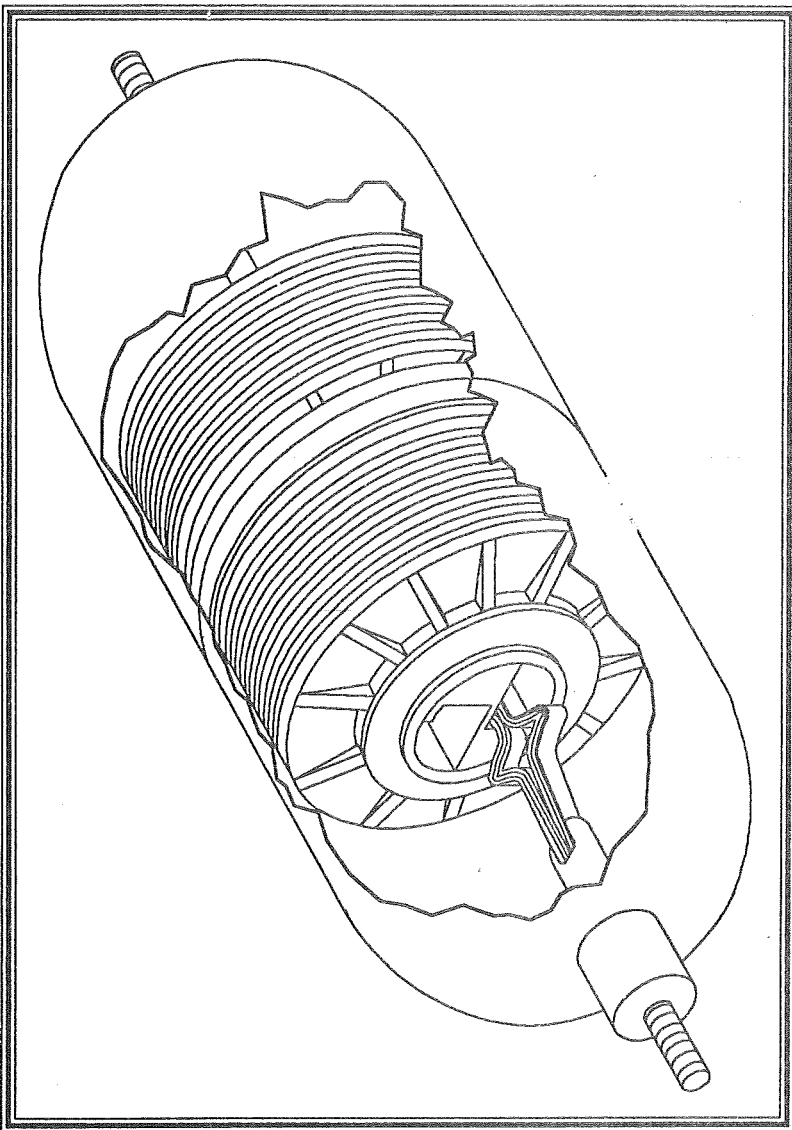
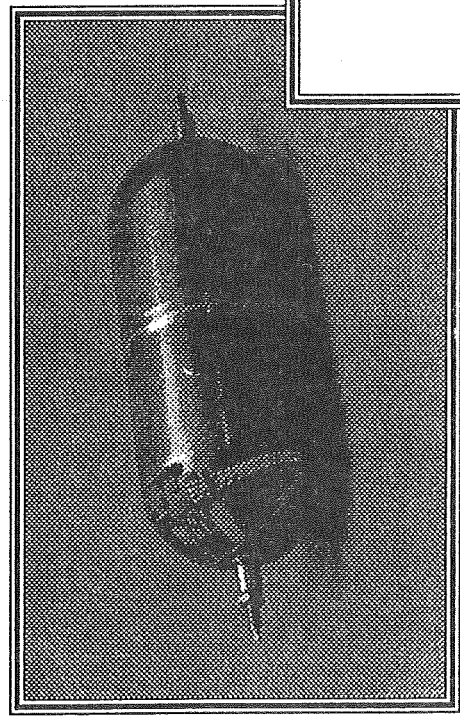




**EAGLE EP PITCHER**  
ELECTRONICS DIVISION  
Joplin, MO

ADVANCED SYSTEMS OPERATION

**CPV Designs Developed and Tested**



**\*RNHC-35-9**  
**&**  
**\*RNHC-40-3**

\*See Design Details

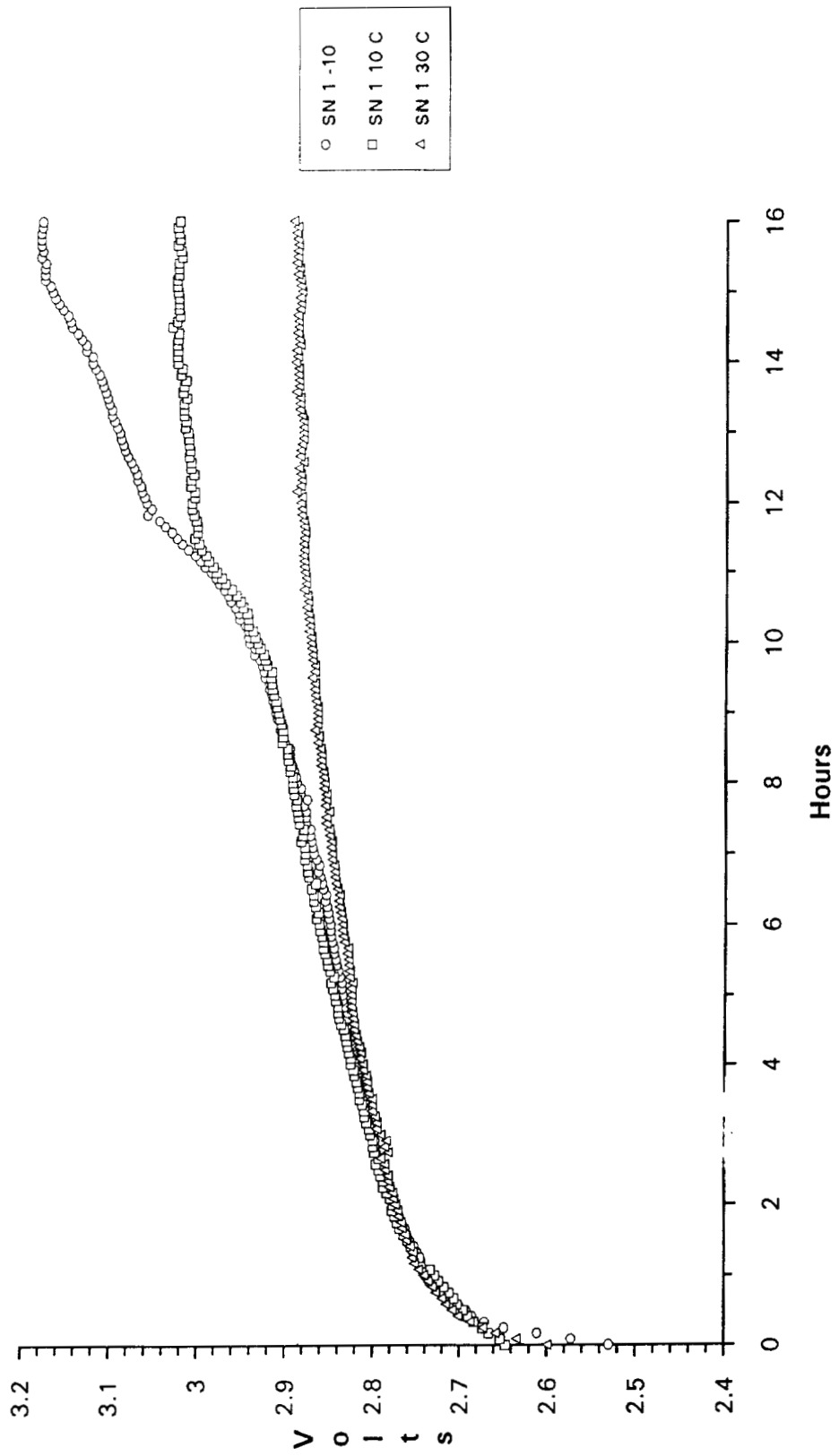
**RNHC-6-1 (CPV): Characterization Testing: Performance Summary**

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

# CPV Designs Developed and Tested

**RNHC-6-1 (CPV) Characterization Tests: Comparison of Charge Voltage: -10°, 10° & 30°C: Charge 0.6 Amps for 16 Hours**





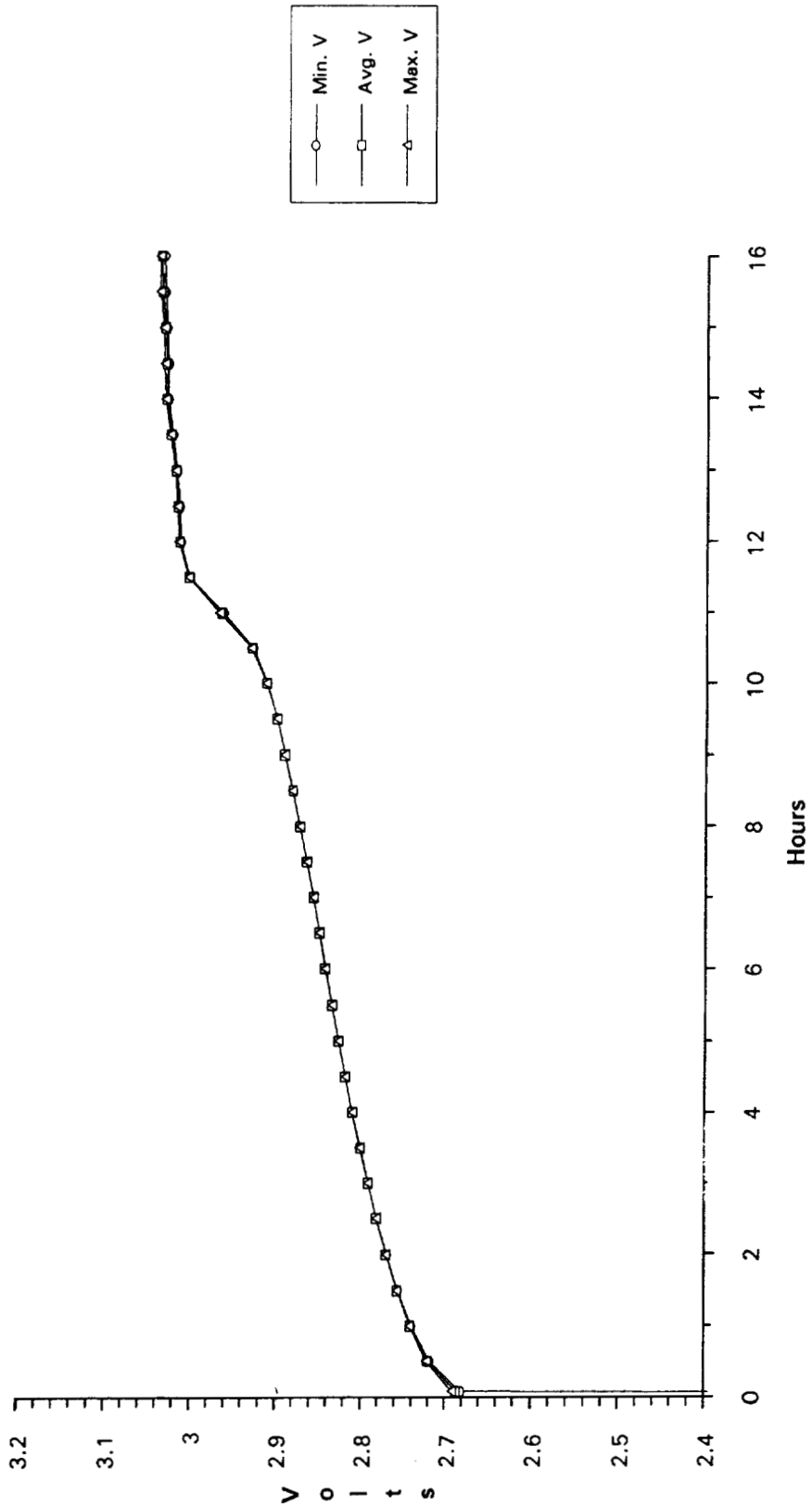




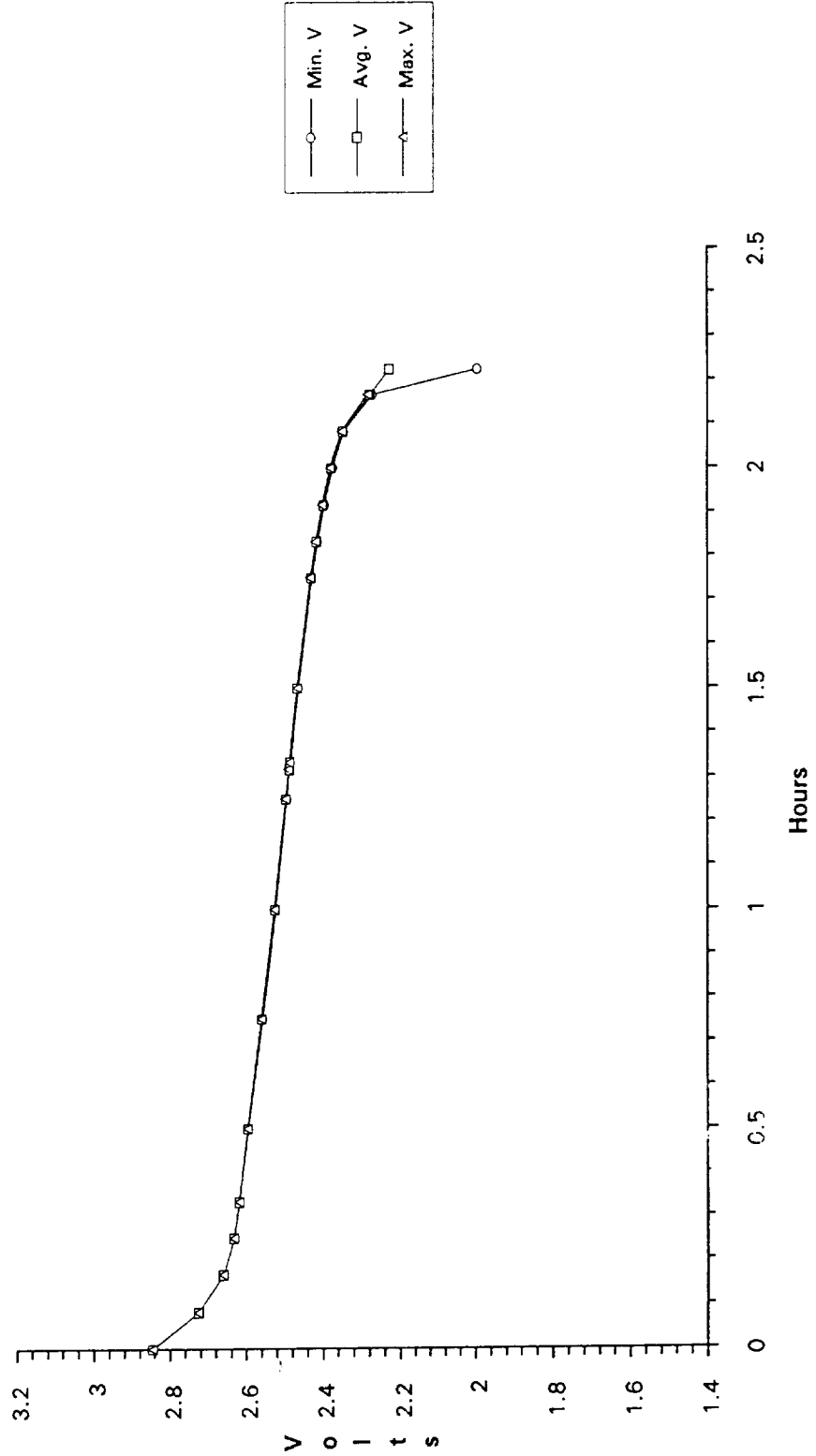
**RNHC-12-1 (CPV) Characterization Testing:****Performance Summary**

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**



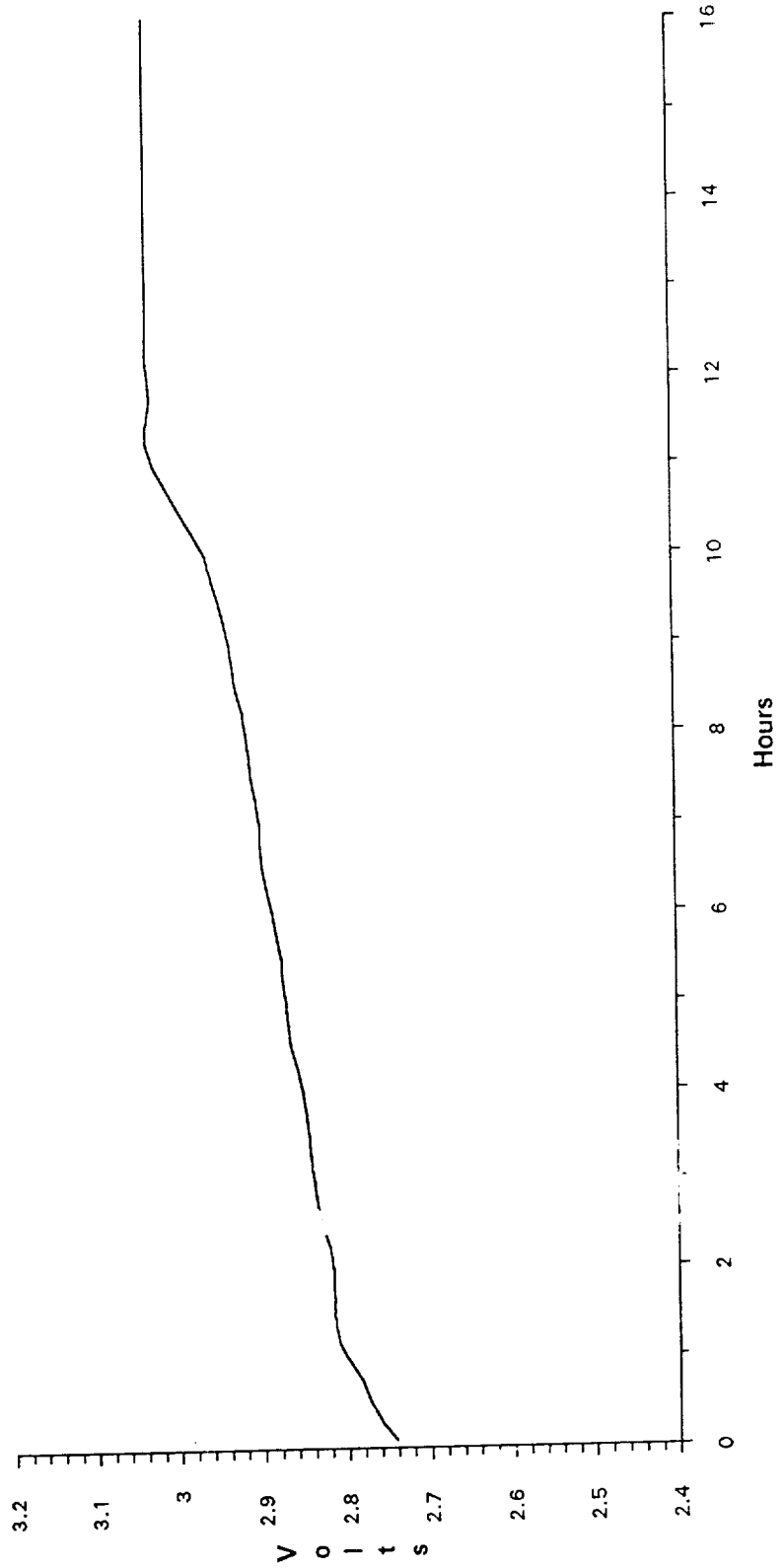
**RNHHC-35-9 (CPV): Characterization Testing:**

**Performance Summary**

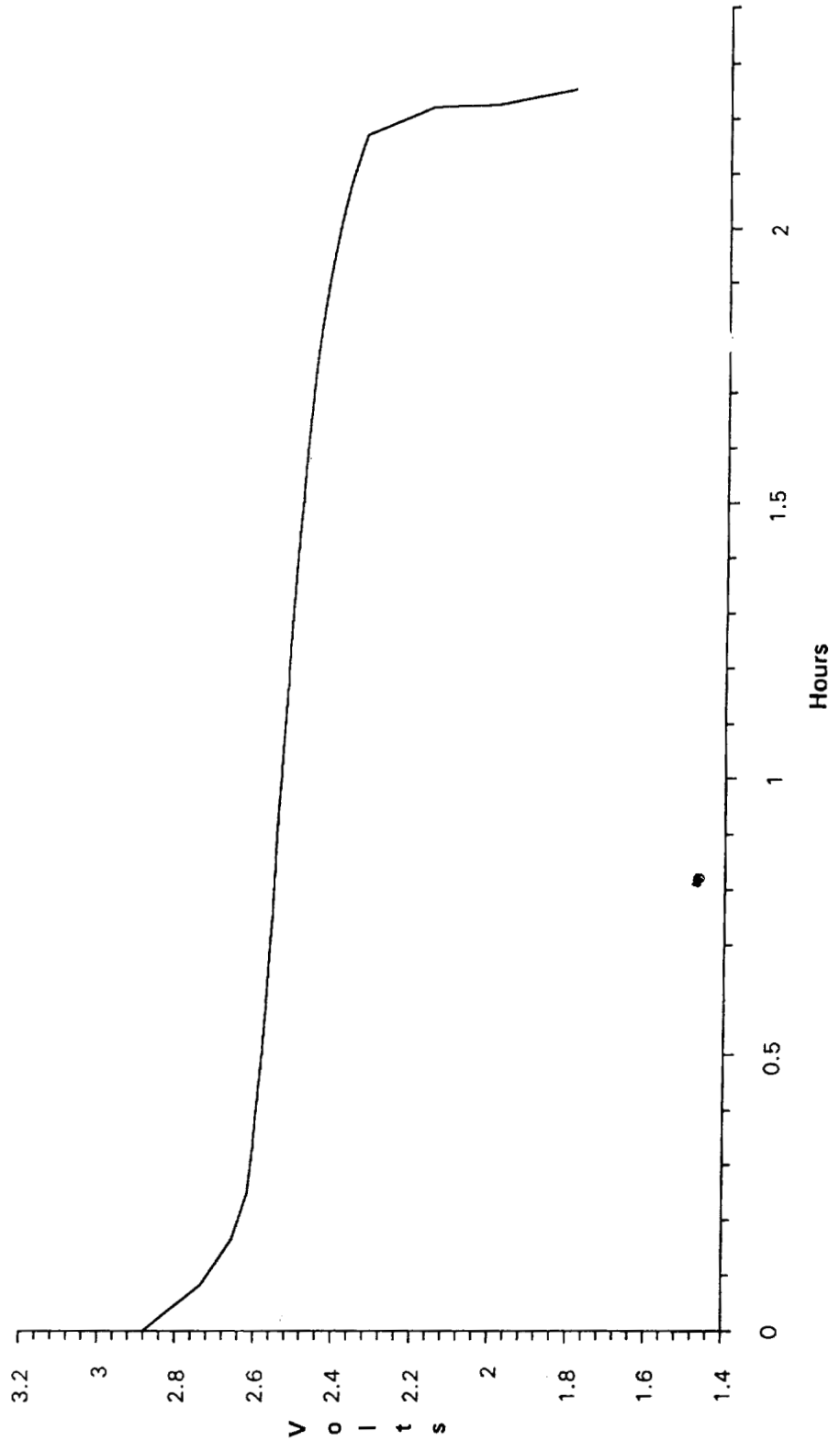
1. 10°C Std. Cap. Test  
Charge 3.5 Amps for 16 hrs.  
Discharge 17.5 Amps to 2.0 V  
Cap. to 2.2 V: ..... 38.80 Ah  
Cap. to 2.0 V: ..... 38.88 Ah

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**



**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%





**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)

**CPV Designs Developed and Tested**

**RNHC-40-3 (Prototype) (CPV): Characterization Testing/Life Test:  
 Performance Summary**

**(Cont.)**

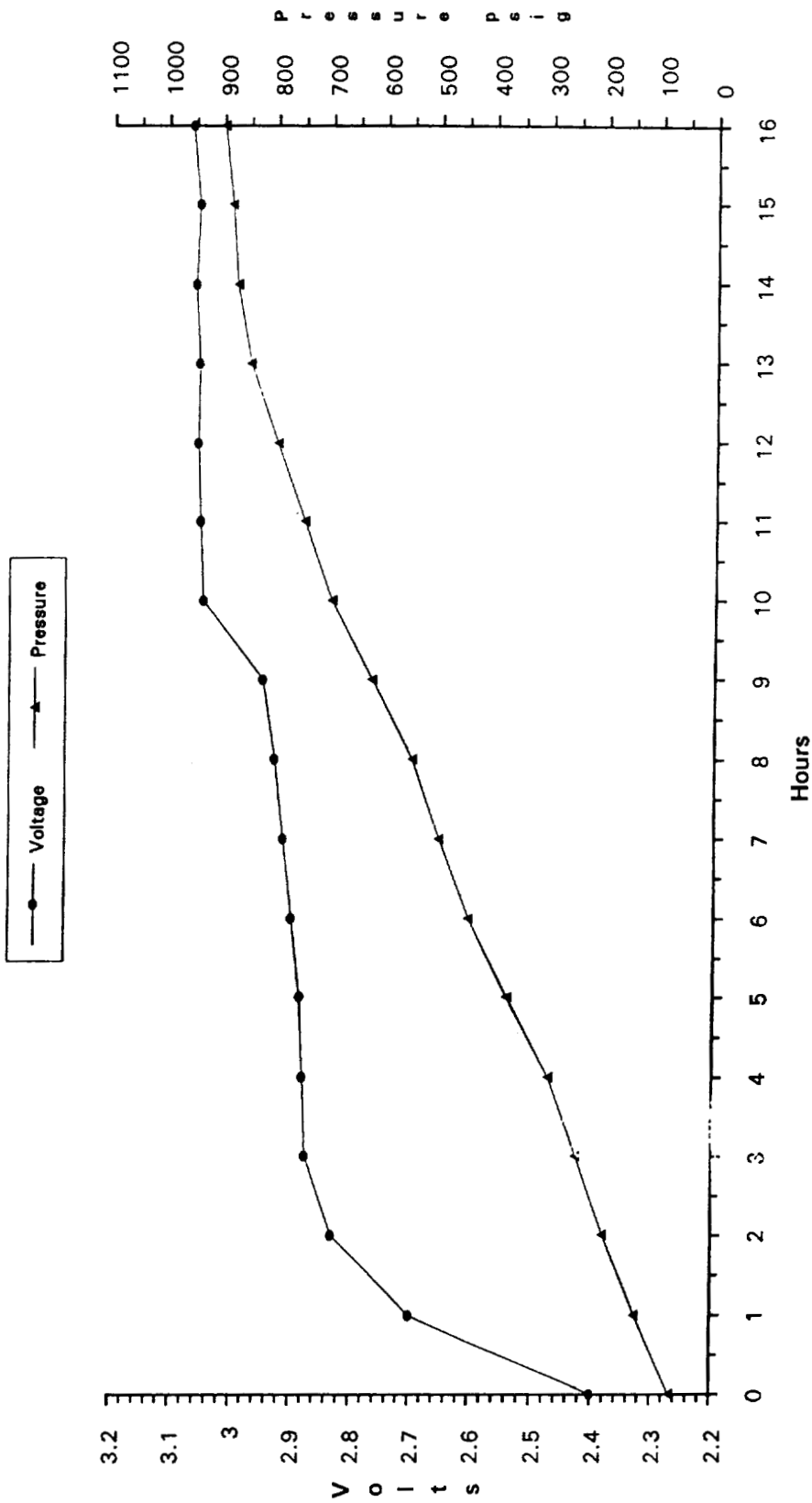
**Capacity Retention Results: Life Test**

Date (M/YY)	Cycle Number	Ini.Cap. Ah	Post 72 hr. (Ah)	Cap. Ret. %	Temp. °C
6-84	Accept. Test	45.4	36.6	80.6	10.0
8-87	8,201	54.7	46.3	84.6	10.0
10-87	8,303	54.5	48.2	88.4	5.0
4-89	9,592	46.1	39.7	86.1	12.5
6-89	10,003	47.3	40.4	85.4	10.0
12-89	11,546	45.6	39.2	86.0	8.6
7-91	13,425	41.7	35.5	85.1	9.7



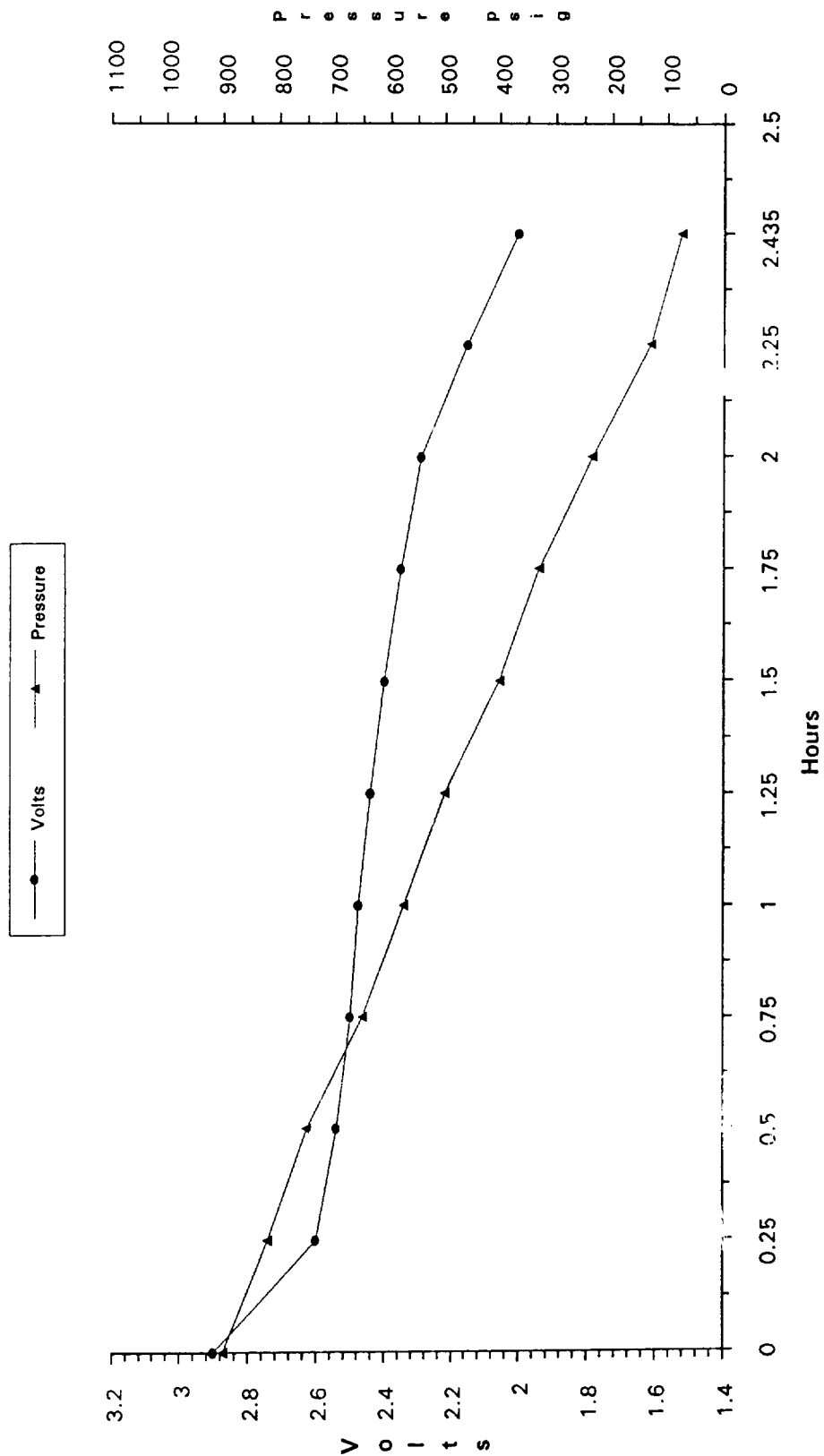
**CPV Designs Developed and Tested**

**RNHC-40-3 (Proto.) (CPV) Life Test: Approximately 10°C:  
Cycle # 15,266: Charge 4.0 Amps for 16 Hours**



**CPV Designs Developed and Tested**

**RNHC-40-3 (Proto.) (CPV) Life Test: Approximately 10°C:  
 Cycle # 15,266: Discharge 20.0 Amps to 2.0 V**





N92-22773

1991 NASA BATTERY WORKSHOP  
HUNTSVILLE, ALABAMA

HEAT GENERATION DURING OVERCHARGE OF  
NI/H<sub>2</sub> CELLS

H. VAIDYANATHAN, W. H. KELLY, AND M. W. EARL

COMSAT LABORATORIES  
CLARKSBURG, MD. 20871-9475

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Abstract

Heat Generation During Overcharge of Ni/H<sub>2</sub> 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/H<sub>2</sub> cell was measured using a radiative-type calorimeter. A flight configuration-type Ni/H<sub>2</sub> 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:

$$mC_p \frac{dT}{dt} = Q_{diss} + Q_{in} - Q_{out}$$

where  $m$  = mass of the cell  
 $C_p$  = thermal capacity of the cell  
 $Q_{out}$  = measured heat using the calibration curve for the calorimeter and cell temperature  
 $Q_{in}$  = heat input to the cell via the heater tape  
 $Q_{diss}$  = 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/H<sub>2</sub> CELL**
- **DETERMINATION OF INSTANTANEOUS HEAT DISSIPATION USING A RADIATIVE TYPE CALORIMETER**
- **ENDOTHERMIC TO EXOTHERMIC TRANSITION DURING CHARGE**
- **HEAT DISSIPATION DURING OVERCHARGE AND DISCHARGE**



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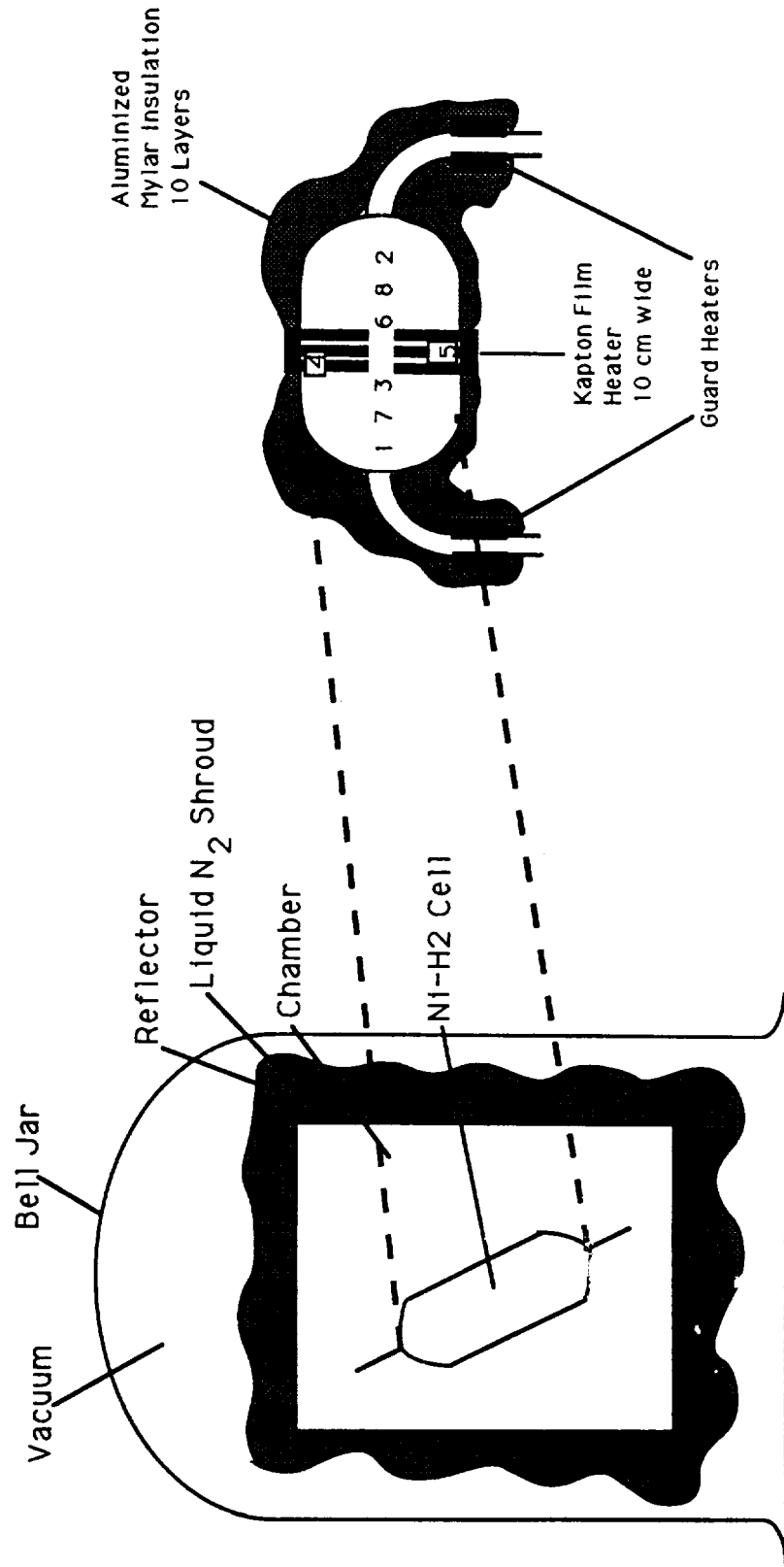
## LITERATURE DATA

- |   |  |
|---|--|
| C. J. JOHNSON<br>ELECTROCHEMICAL SOCIETY,<br>FALL, 1989 | NI/H <sub>2</sub> CELL, CONDUCTION TYPE,<br>SILICON OIL BATH, ISOTHERMAL CONDITIONS                      |
| H. KAWAMOTO AND ET. AL.<br>J ECS 136,1355, 1989         | NA/S CELL, FURNACE, HEAT TRANSFER BY<br>CONVECTION AND RADIATION   |
| R. COHEN AND ET. AL.<br>J ECS 137,2649, 1990            | Ca/SO CL <sub>2</sub> CELL, CONDUCTION TYPE,<br>WATER BATH. CARBON CLOTH AS CONDUCTOR.<br>FACTOR = 1W/°C |
| ERIC DARCY<br>1990 NASA BATTERY<br>WORKSHOP             | Li/BCX AND Li/SO CL <sub>2</sub><br>CONDUCTION TYPE, DROP CALORIMETRY<br>WATER BATH. AI AS CONDUCTOR     |

## **CALORIMETER**

- HEAT TRANSFER BY RADIATION
- LIQUID N<sub>2</sub> COOLED CHAMBER OF 0.5 M<sup>3</sup> (TEMP = -184°C)
- CHAMBER ENCLOSED IN A VACUUM JAR (10<sup>-6</sup> MM OF HG)
- CELL HEATED BY HEATER TAPE
- CELL LEADS HEATED
- 6 THERMOCOUPLES TO MEASURE THE TEMPERATURE OF THE CHAMBER
- 2 THERMOCOUPLES TO MEASURE TEMPERATURE OF CELL LEADS
- 8 THERMOCOUPLES TO MEASURE CELL TEMPERATURE

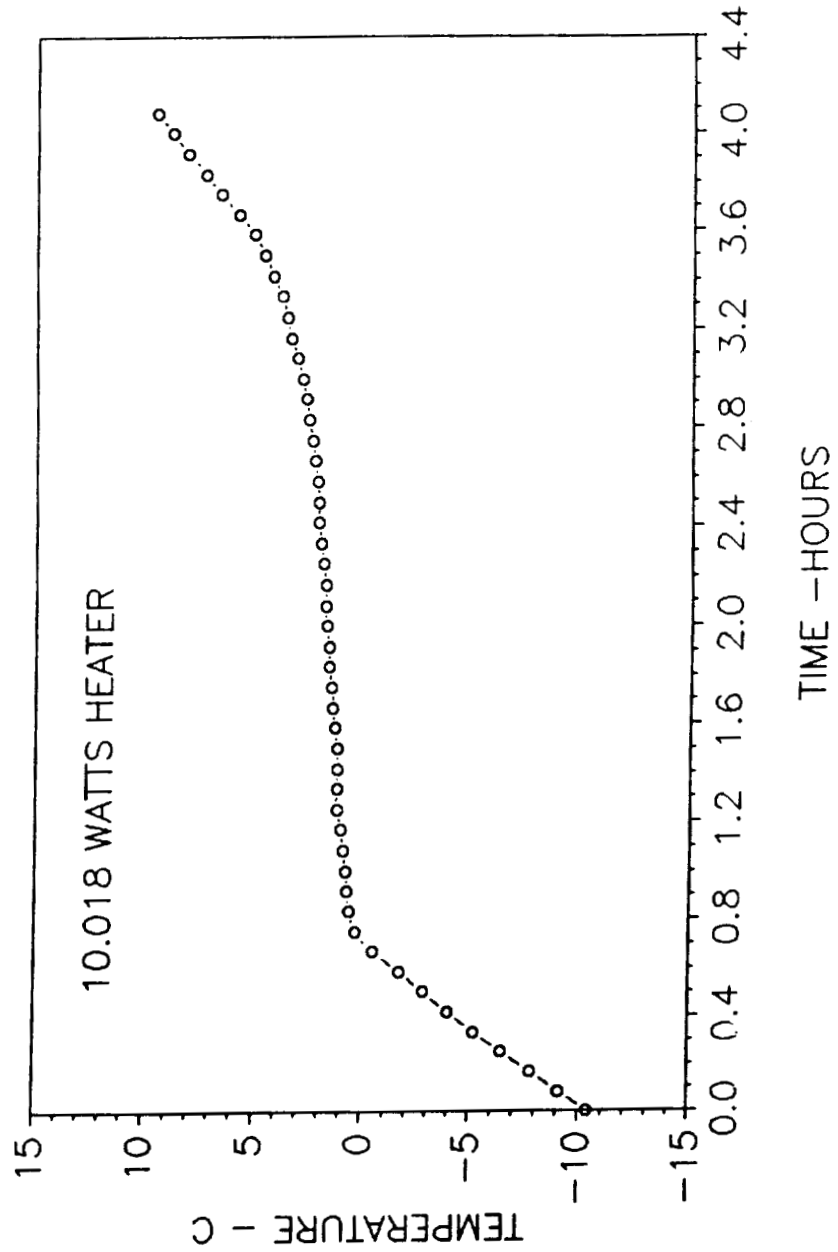
## CALORIMETER



## **CALIBRATION AND MEASUREMENT**

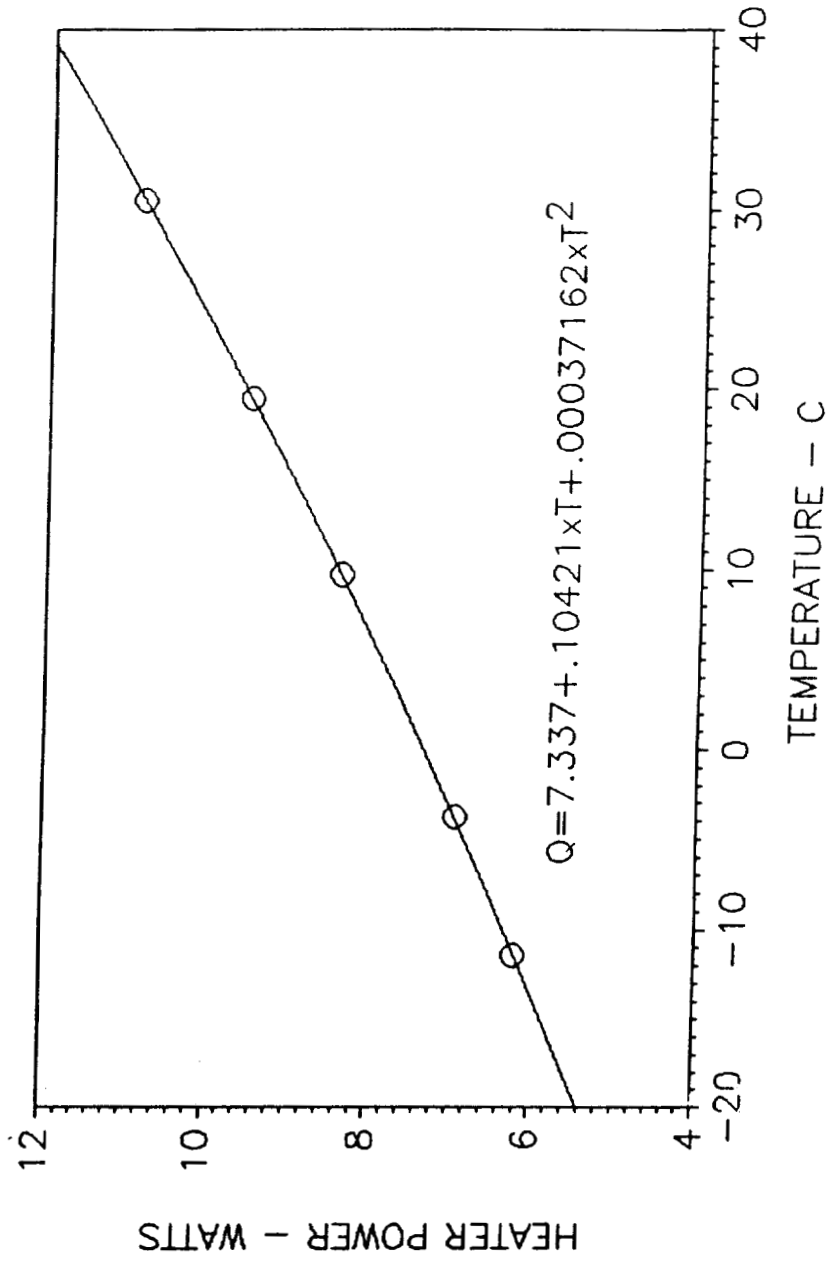
- **SPECIFIC HEAT DETERMINATION OF AL CYLINDER 958 J/KG°C**
- **HEAT OF FUSION OF WATER, 75.6 CAL/GM**
- **CELL INSTALLED IN THE DISCHARGED STATE**
- **7W OF HEATER POWER TO MAINTAIN CELL AT 0°C**
- **CELL TEMPERATURE MONITORED CONTINUOUSLY**
- **CELL THERMAL CAPACITY DETERMINATION, 1631 J/°C**

**CELL CALIBRATION**  
**ALUMINUM CYLINDER - 100 GRAMS H<sub>2</sub>O**





**BATTERY CELL CALIBRATION - (1-6 CELL)**  
**NO CHARGE - HEATER POWER ONLY**



## THERMAL ANALYSIS

- HEAT DISSIPATION CALCULATED USING ENTHALPY VOLTAGE

$$Q \text{ (discharge)} = -I (E_H - E_L)$$

$$Q \text{ (charge)} = -I (\eta_{EH} - E_L)$$

- FACTOR ANALYSIS TECHNIQUE (STATISTICAL APPROACH)

$$Q = C_1 + C_2 Y_1 + C_3 Y_1^2 \dots C_n Y_1^m$$

$Y_n$  = independent variable,  $C_n$  = dimensional constant



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## GOVERNING EQUATIONS

$$m \text{ cp } \frac{dT}{dt} = Q_{\text{diss}} + Q_{\text{in}} - Q_{\text{out}}$$

cp = thermal capacity of the cell

m = mass of the cell

$Q_{\text{in}}$  = cell heater power = current x voltage

$Q_{\text{out}}$  = calculated using the equation formulated from experimental values of cell temperature

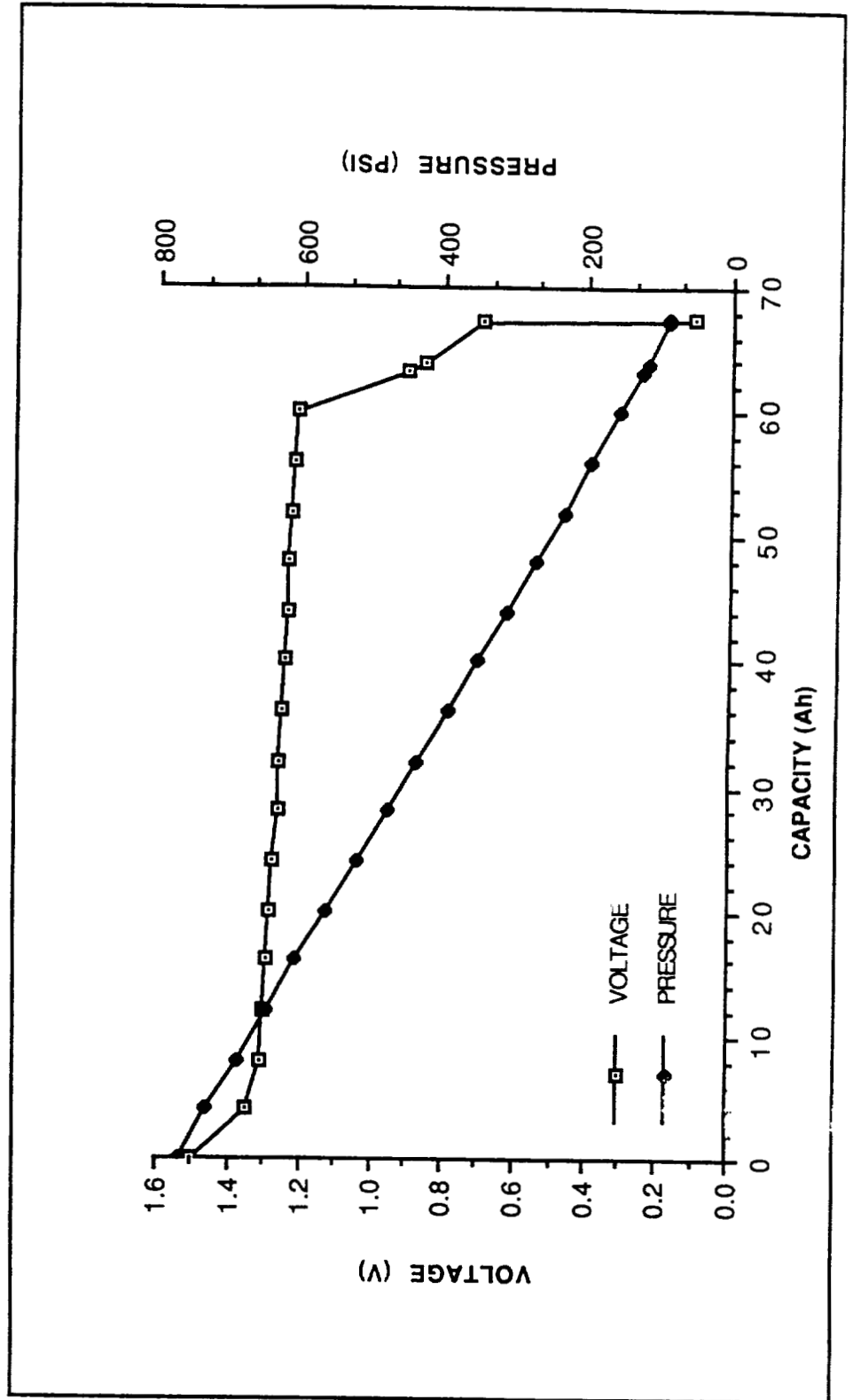
$$= 7.337 + 1.0421T + 0.00037162 T^2$$

$Q_{\text{diss}}$  = heat dissipation

CALCULATION OF THERMAL CAPACITY

<u>MATERIAL</u>	<u>SPECIFIC HEAT</u> <u>J/gm °C</u>	<u>M X Cp</u> <u>JOULE/°C</u>
POLYPROPYLENE SCREEN	1.88	66.928
POSITIVE	0.7	353.92
NEGATIVE	0.6	42.24
ZIRCAR	0.67	59.496
KOH-31%	3.24	845.64
INCONEL	0.44	120.428
NICKEL	0.46	87.63
ALUMINUM	0.96	80.352
POLYSULFONE	1.004	30.8228
POLYPROPYLENE	1.88	39.856
MISCELL.	1	5.3
<b>TOTAL</b>		<b>1732.6128</b>

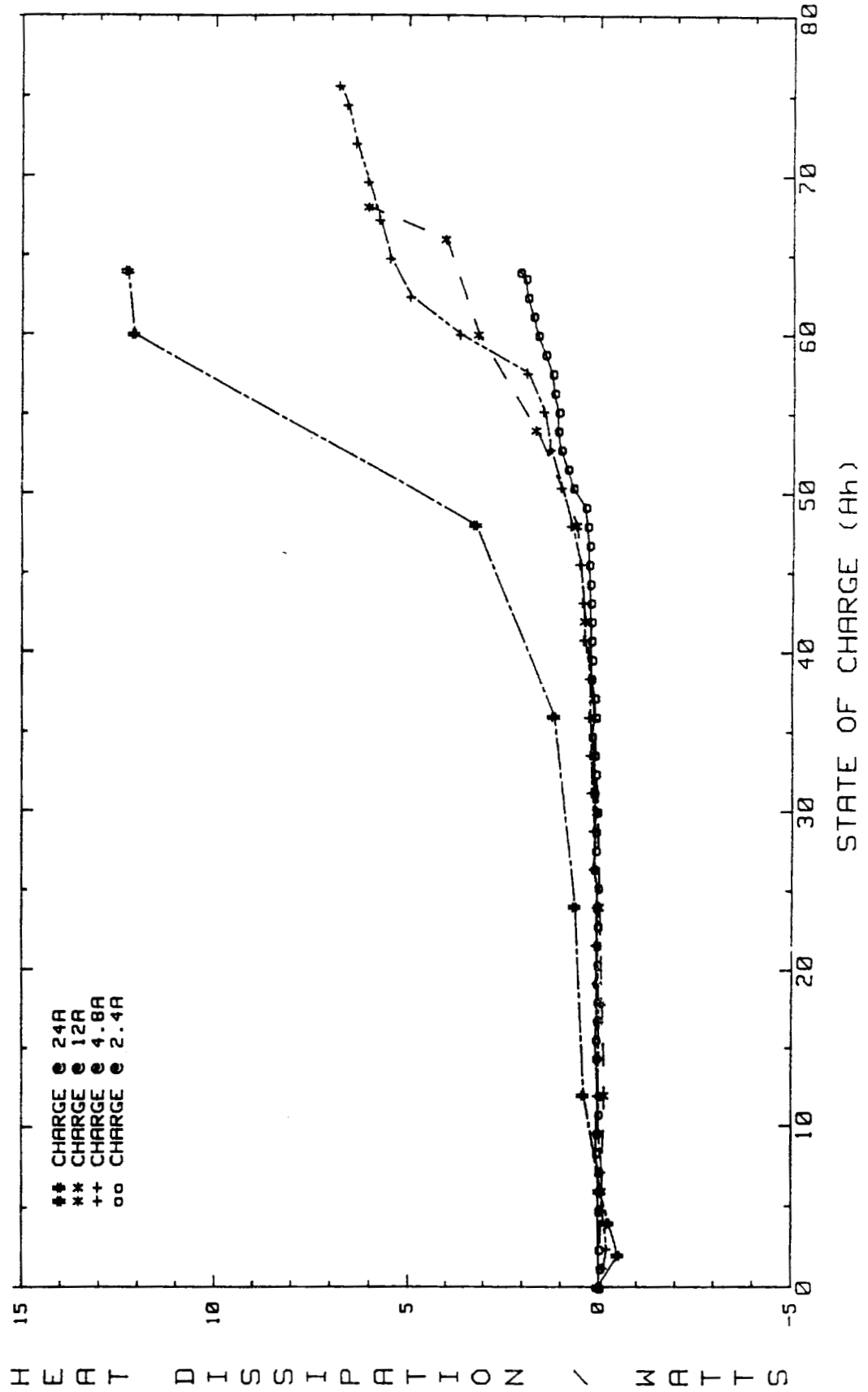
**VOLTAGE PROFILE OF I-VI S/N 12-1304**  
**DURING C/2 DISCHARGE**



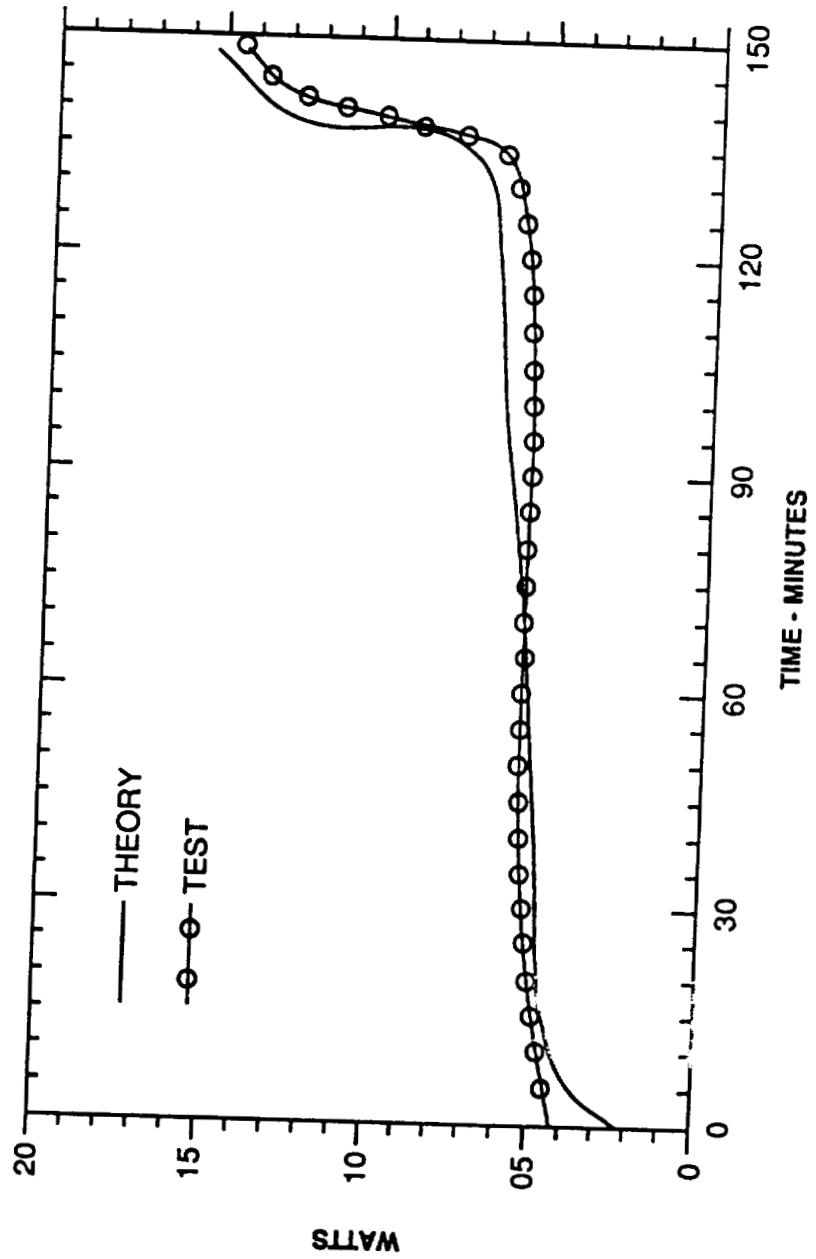
## TEMPERATURE DISTRIBUTION

<u>STATE OF CHARGE</u>	<u>CELL DOMES</u>		<u>STACK AVERAGE OF 4</u>	<u>ΔT DOME TO STACK</u>	
	<u>1</u>	<u>2</u>			
	<u>°C</u>	<u>°C</u>	<u>°C</u>	<u>°C</u>	
<b>4.8A Charge</b>	Mid-Charge	-3.75	-3.78	-2.6	1.165
	EOC	15.5	15.87	17.25	1.74
<b>12A Charge</b>	Mid-Charge	-5.47	-5.57	-4.64	0.88
	EOC	2.89	3.41	4.61	1.48
<b>24A Charge</b>	Mid-Charge	-3.02	-4.19	-3.73	0.13
	EOC	6.66	7.35	10.62	3.62
<b>24A Discharge</b>	Mid-Discharge	-8.98	-7.16	.7	1.07
	EOD	3.61	5.24	5.81	2.39

**HEAT DISSIPATION AT VARIOUS RATES OF CHARGE**

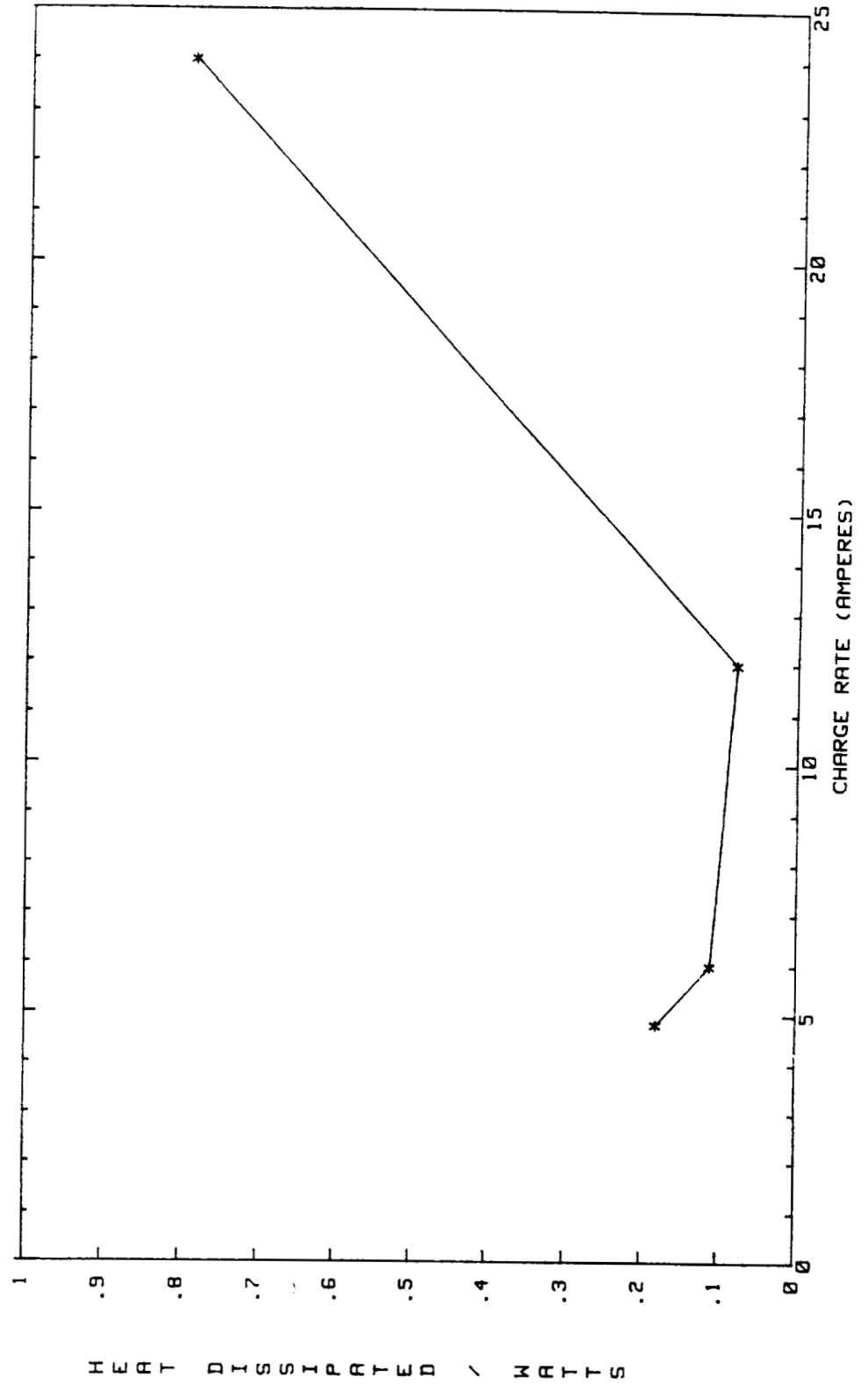


## HEAT DISSIPATION DURING DISCHARGE AT C/2





**VARIATION OF HEAT DISSIPATION AT 50% CHARGED STATE**



**COMPARISON OF CALCULATED AND EXPERIMENTAL  
HEAT DISSIPATION AT C/10 CHARGE**

CHARGE INPUT AH	CALCULATED HEAT WATTS	EXPERIMENTAL HEAT WATTS
2.4	-0.575	-0.222
9.6	-0.32	-0.145
14.4	-0.219	+0.005
19.2	-0.143	+0.04
24.0	-0.095	+0.06
28.8	+0.39	+0.124
38.4	+0.47	+0.238



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## 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

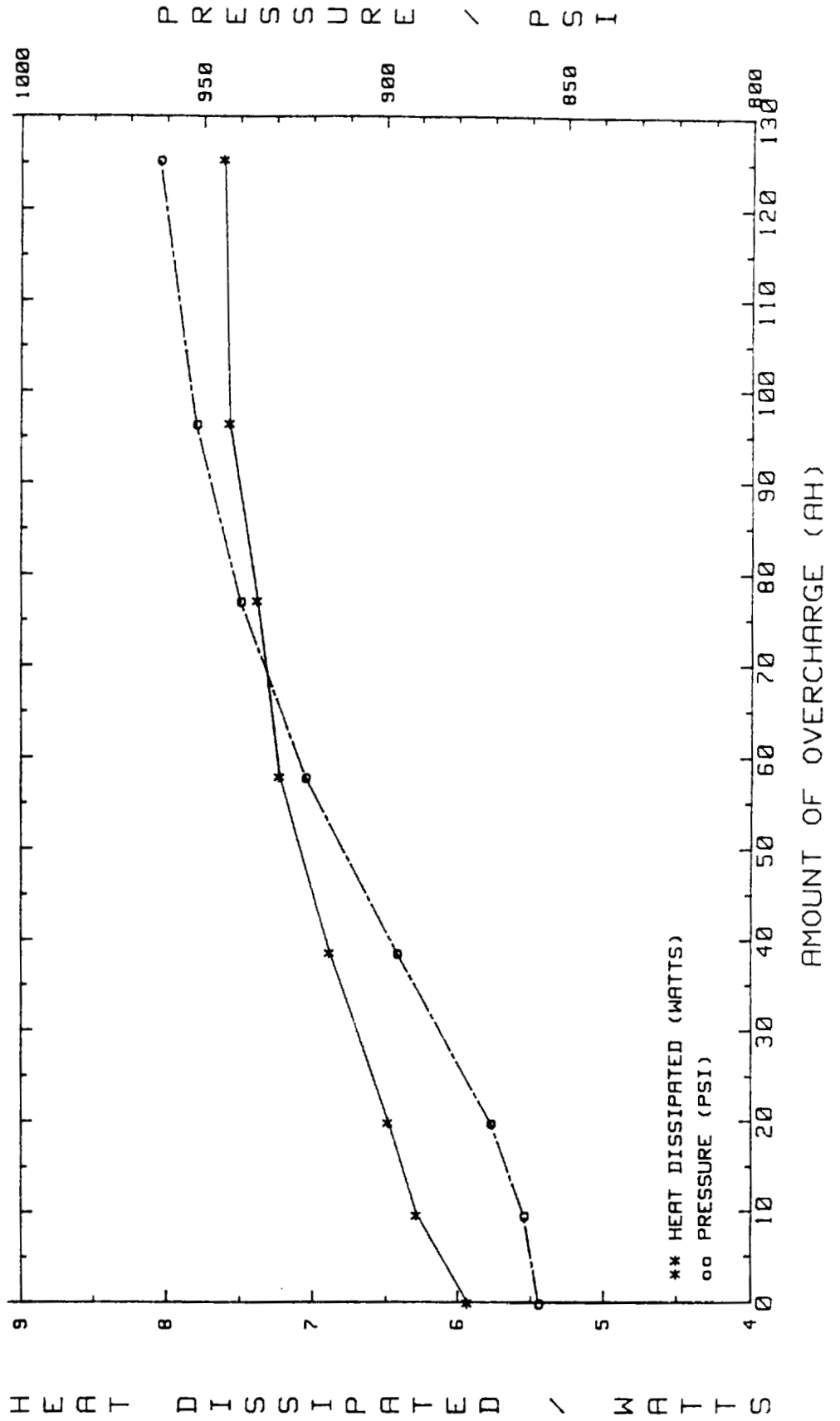
## EXPLANATION FOR INCONSISTENCY

- **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**

**HEAT DISSIPATION DURING TRICKLE CHARGE AT C/100**

<u>TEMPERATURE</u> °C	<u>MEASURED HEAT</u> WATTS	<u>CALCULATED HEAT</u> WATTS
6.8	1.08	0.9021
4.8	1.017	0.9039
1.37	0.7552	0.910
-1.07	0.748	0.9176
-22.6	0.766	0.9746

**RELATIONSHIP BETWEEN HEAT GENERATION AND PRESSURE INCREASE DURING C/10 OVERCHARGE AT -3 +/- 30 C**



**HEAT DISSIPATION DURING OPEN CIRCUIT STAND**

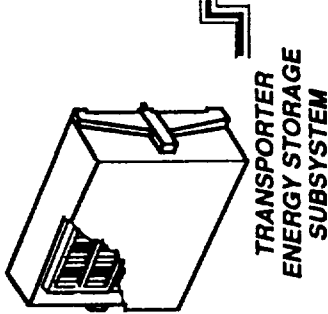
<u>CHARGE RATE PROCEEDING THE OPEN CIRCUIT STAND</u>	<u>TEMPERATURE (°C)</u>	<u>CELL PRESSURE (PSI)</u>	<u>HEAT DISSIPATED (WATTS)</u>
C/10	1.7	826	0.85
C/20	6.0	830	1.11
C/4	6.3	839	1.68
C/2	13.7	854	1.91

## **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 UNACCURATE VALUES FOR  $E_H$  AND CHARGE EFFICIENCY**







MDESC - L&ES

# NICKEL-HYDROGEN BATTERY DESIGN FOR THE TRANSPORTER ENERGY STORAGE SUBSYSTEM (TESS)

N 9 2 - 2 2 7 7 4

BY

JOHN R. LAPINSKI  
MDESC-L&ES

& DEBORAH S. BOURLAND  
NASA-JSC

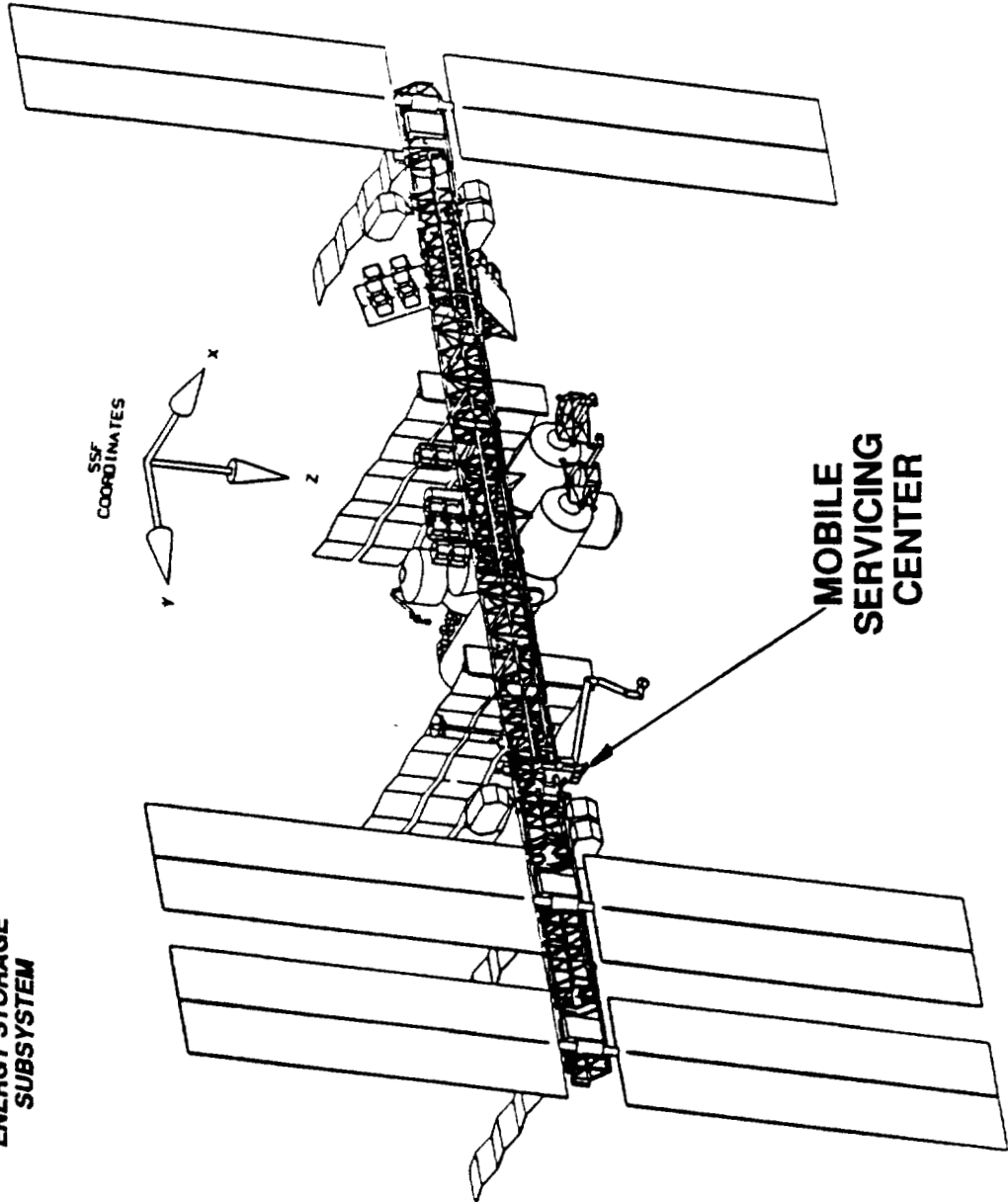
# SPACE STATION FREEDOM - PMC

MDESC - L&ES



- 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

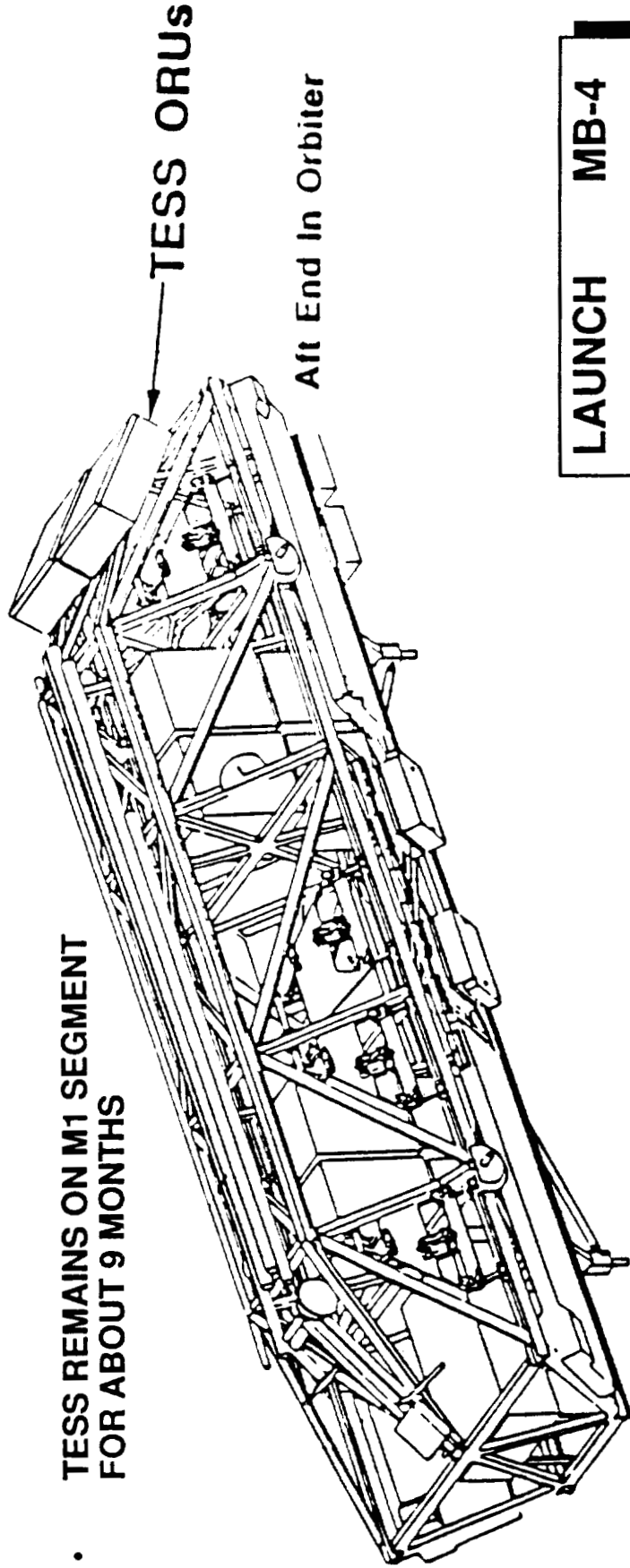
MDESC - L&ES



TRANSPORTER  
ENERGY STORAGE  
SUBSYSTEM

- TESS BATTERY LAUNCHED  
DISCHARGED AND OPEN  
CIRCUIT

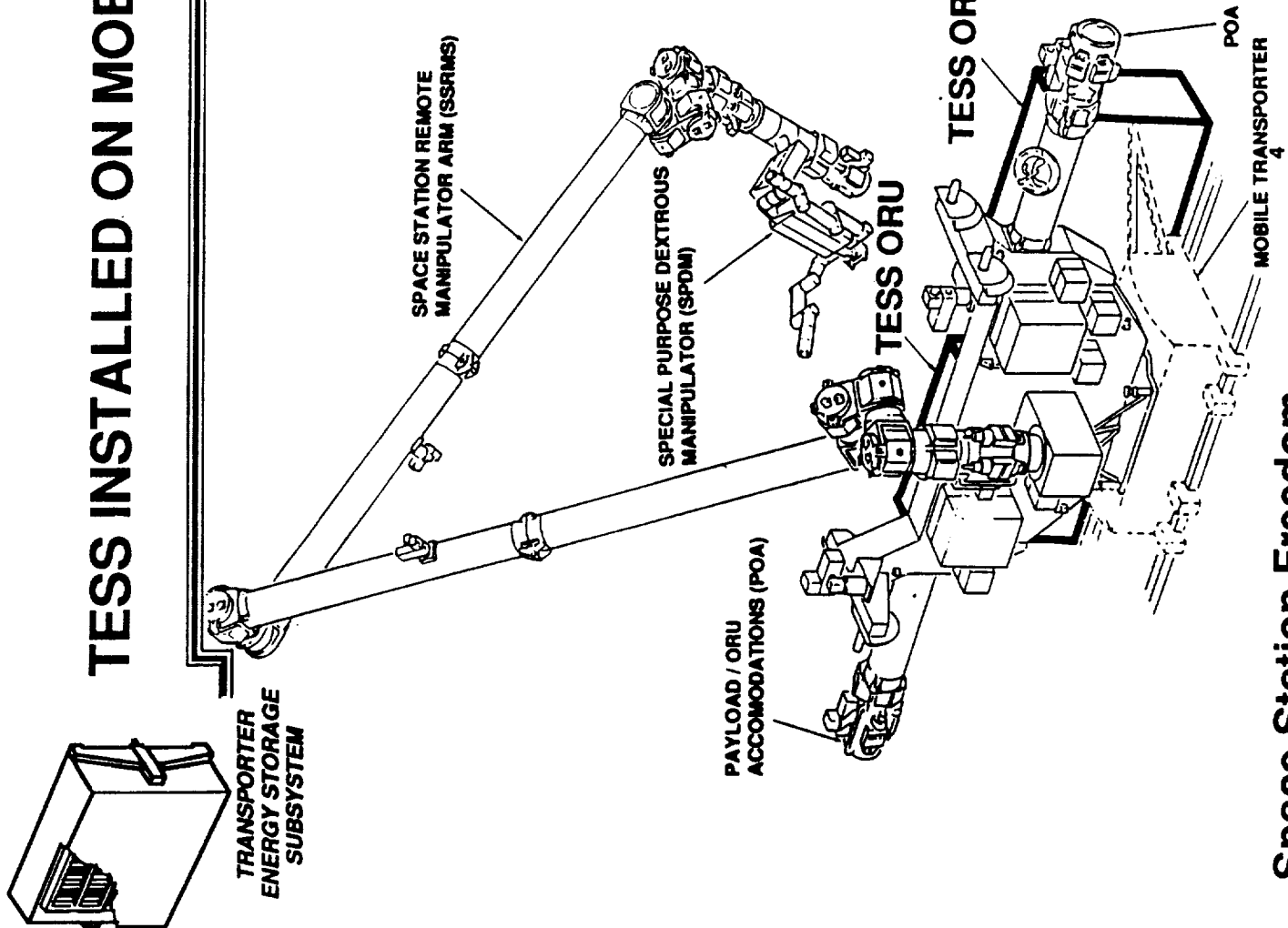
- TESS REMAINS ON M1 SEGMENT  
FOR ABOUT 9 MONTHS



LAUNCH	MB-4
SEGMENT	M1

# TESS INSTALLED ON MOBILE SERVICING CENTER

MDESC - L&ES

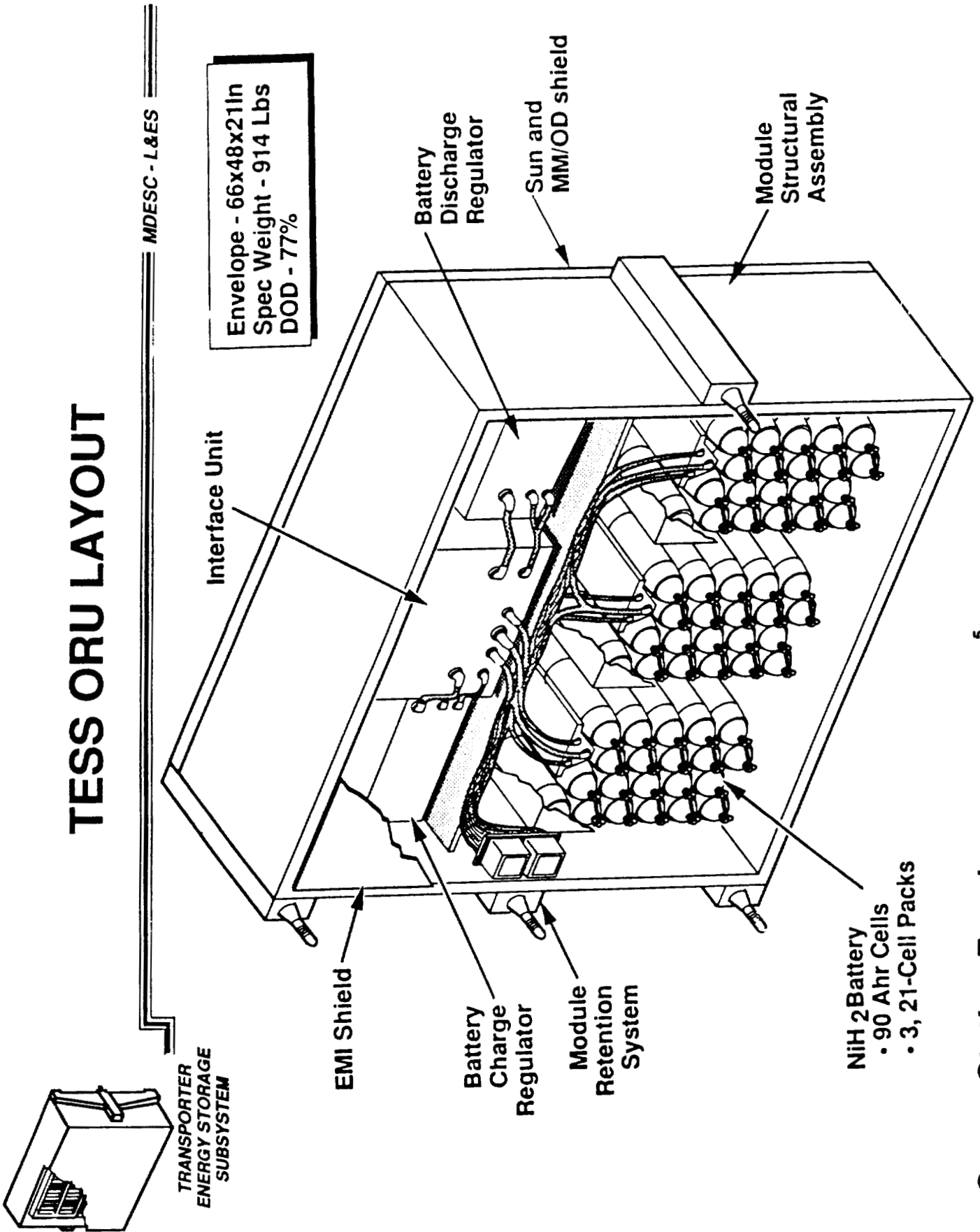


- TESS INSTALLED ON MOBILE TRANSPORTER DURING MB-7 EVA OPERATIONS.
- TESS PROVIDES ABOUT 3.3 HOURS OF MSC TRANSLATION
- TESS PROVIDES REGULATED 120 VOLTS:
  - 10 KW-HR OF ENERGY
  - 3000 WATTS AVERAGE POWER
  - 6000 WATTS PEAK POWER

# TESS ORU LAYOUT

MDESC - L&ES

Envelope - 66x48x21In  
 Spec Weight - 914 Lbs  
 DOD - 77%





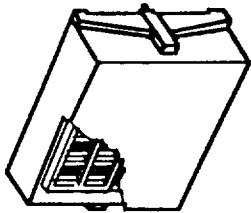
TRANSPORTER  
ENERGY STORAGE  
SUBSYSTEM

# BATTERY DESIGN REQUIREMENTS

MDESC - L&ES

011291

- 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 REDUNDANCY, FAIL DEGRADE, FAIL SAFE



TRANSPORTER  
ENERGY STORAGE  
SUBSYSTEM

# BATTERY DESIGN REQUIREMENTS (CONTINUED)

MDESC - L&ES

- **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**





TRANSPORTER  
ENERGY STORAGE  
SUBSYSTEM

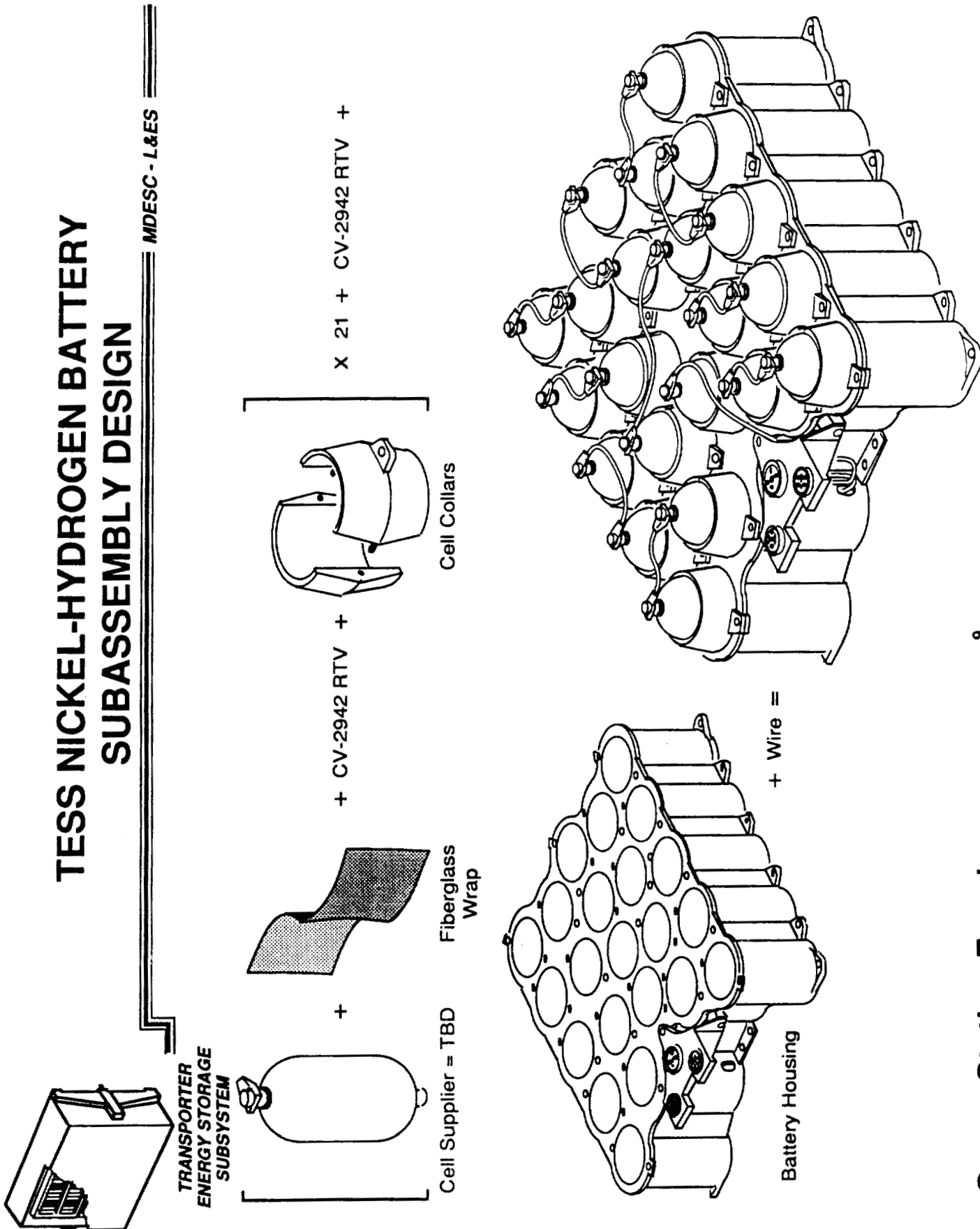
## TESS BATTERY DESIGN

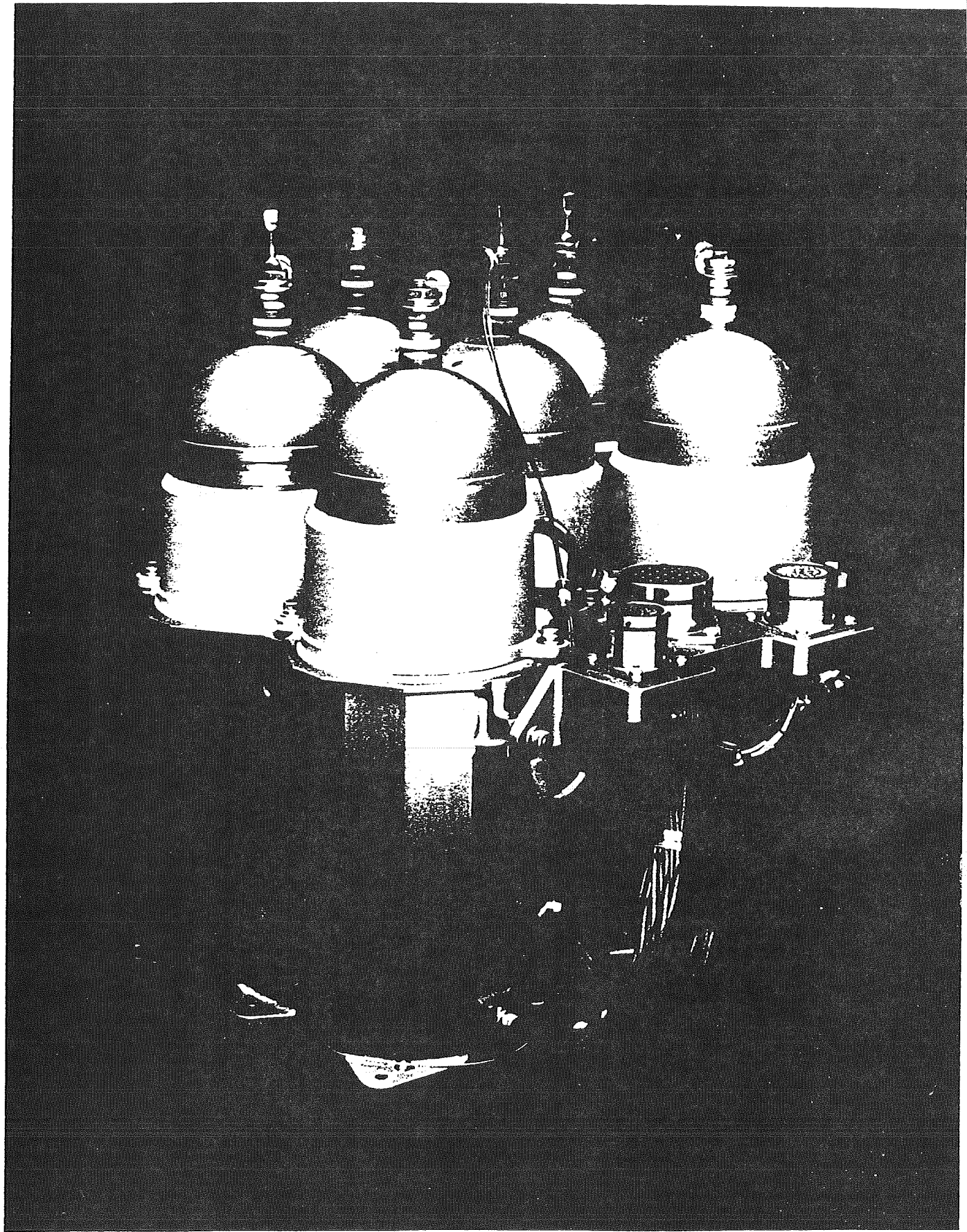
MDESC - L&ES

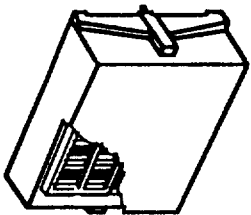
- TWO 63-CELL NICKEL HYDROGEN BATTERIES
  - THREE 21-CELL SUBASSEMBLIES, CONNECTED IN SERIES
  - 90 AMP-HR HUBBLE SPACE TELESCOPE (HST) CELLS, MODIFIED
- 21-CELL SUBASSEMBLY
  - WEIGHT: 149 LBS INCLUDING MM/OD COVERS
  - SIZE: 14.9 W x 23.7 L x 13.0 H (INCHES)
  - 3 ELECTRICAL CONNECTORS: POWER, INSTRUMENTATION, 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

MDESC - L&ES





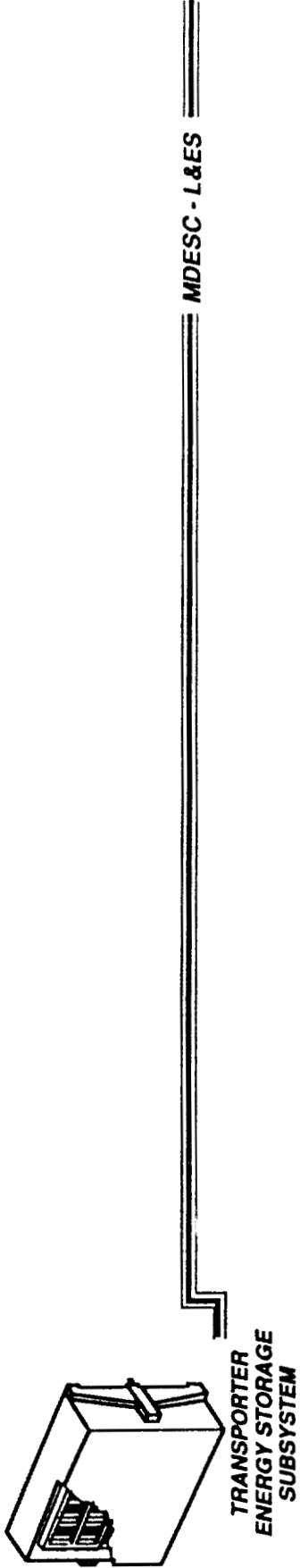


TRANSPORTER  
ENERGY STORAGE  
SUBSYSTEM

## PROOF-OF-PRINCIPLE TESTING OF 6-CELL BATTERY

MDESC - L&ES

- 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



# GROUND RULES FOR DOWNSIZING TESS

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TRANSPORTER  
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- 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.
 

	<u>WAS</u>	<u>NOW</u>
- ENERGY LEVEL	10 KWHR	3.4 KWHR
- NOMINAL POWER	3000 W	2300 W
- PEAK POWER	6000 W	3500 W
- TRANSLATION TIME	3.33 HRS	1.50 HRS
- NUMBER OF MISSIONS	150	50
- MAINTAIN CURRENT LEVEL OF TESS RELIABILITY.
  - FAIL DEGRADE, FAIL SAFE

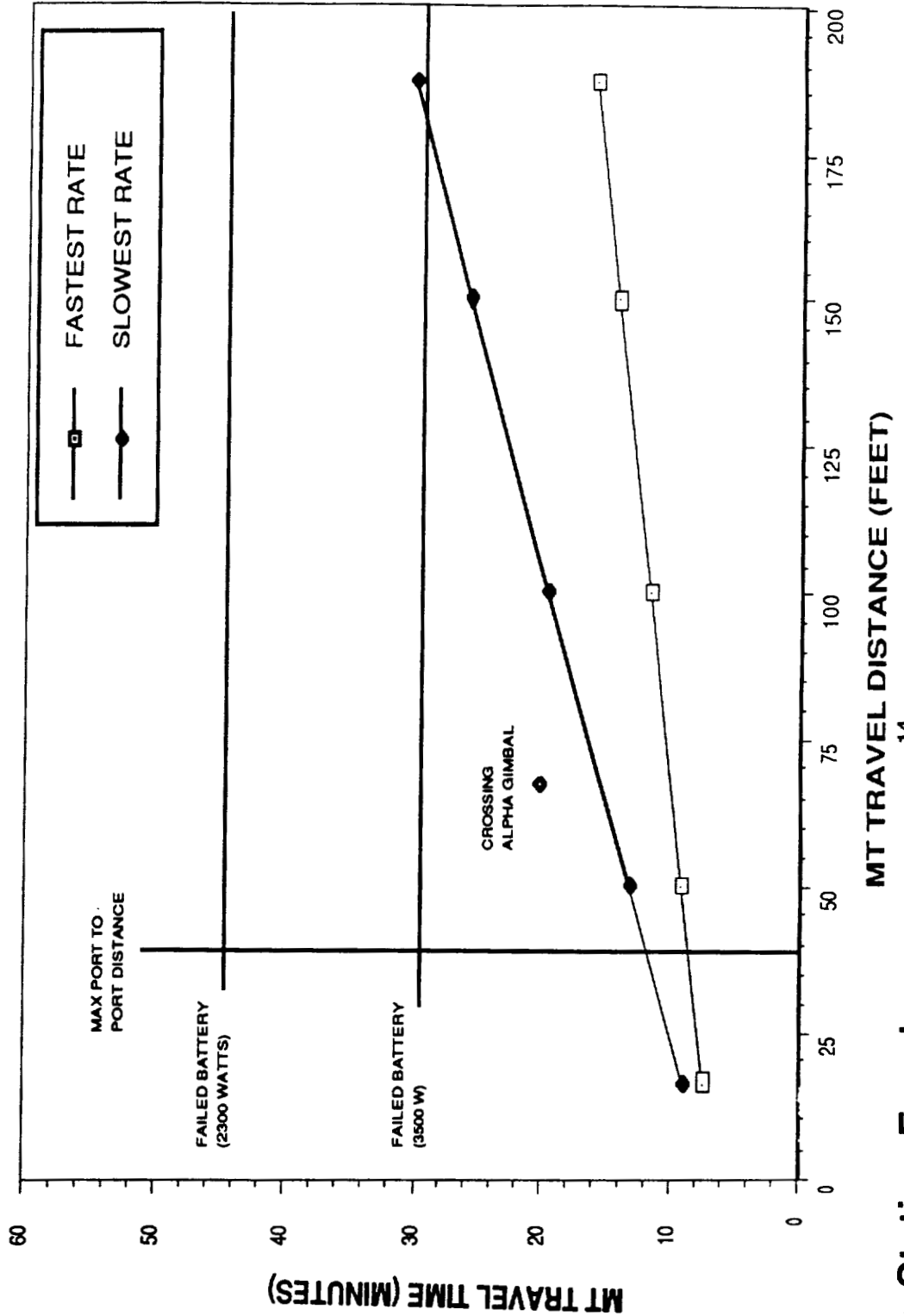


TRANSPORTER  
ENERGY STORAGE  
SUBSYSTEM

# TRAVEL DISTANCE FOR MT BASED ON TESS SIZE

MDESC - L&ES

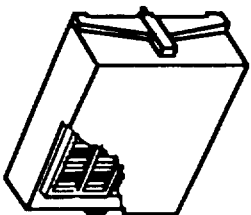
BASED ON FAILED BATTERY CONDITION FOR AVERAGE & PEAK LOADS



Space Station Freedom

14

McDonnell Douglas • GE • Honeywell • IBM • Lockheed



TRANSPORTER  
ENERGY STORAGE  
SUBSYSTEM

# TESS TRANSLATION OUTPUT CAPABILITY

MDESC - L&ES

ASSUMING ONE EVA/EVR MISSION PER DAY.

<b>TIMELINE - HOURS</b>	6, 8, OR 12	24
<b>EVA/EVR MISSION</b>	<b>COOLDOWN/RECHARGE/ PREP FOR NEXT EVA/EVR</b>	
<b>TESS</b> <ul style="list-style-type: none"> <li>• SUPPLIES 1.5 HRS OF MT TRANSLATION.</li> <li>• SMALL AMOUNT OF COOLDOWN OR CHARGING DURING MBS OPERATIONS.</li> <li>• POSSIBLE INCREASE OF MT TRANSLATION TIME TO 2 HRS.</li> </ul>	<b>TESS</b> <ul style="list-style-type: none"> <li>• COOLS AND RECHARGES AS NECESSARY TO BE AVAILABLE FOR NEXT DAY'S ACTIVITIES.</li> </ul>	

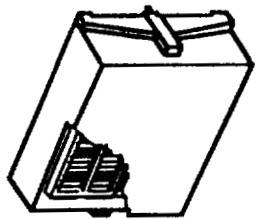
NOTE: TRANSLATION TIMES WILL BE CUT IN HALF FOR FAILED BATTERY CONDITION

**Space Station Freedom**

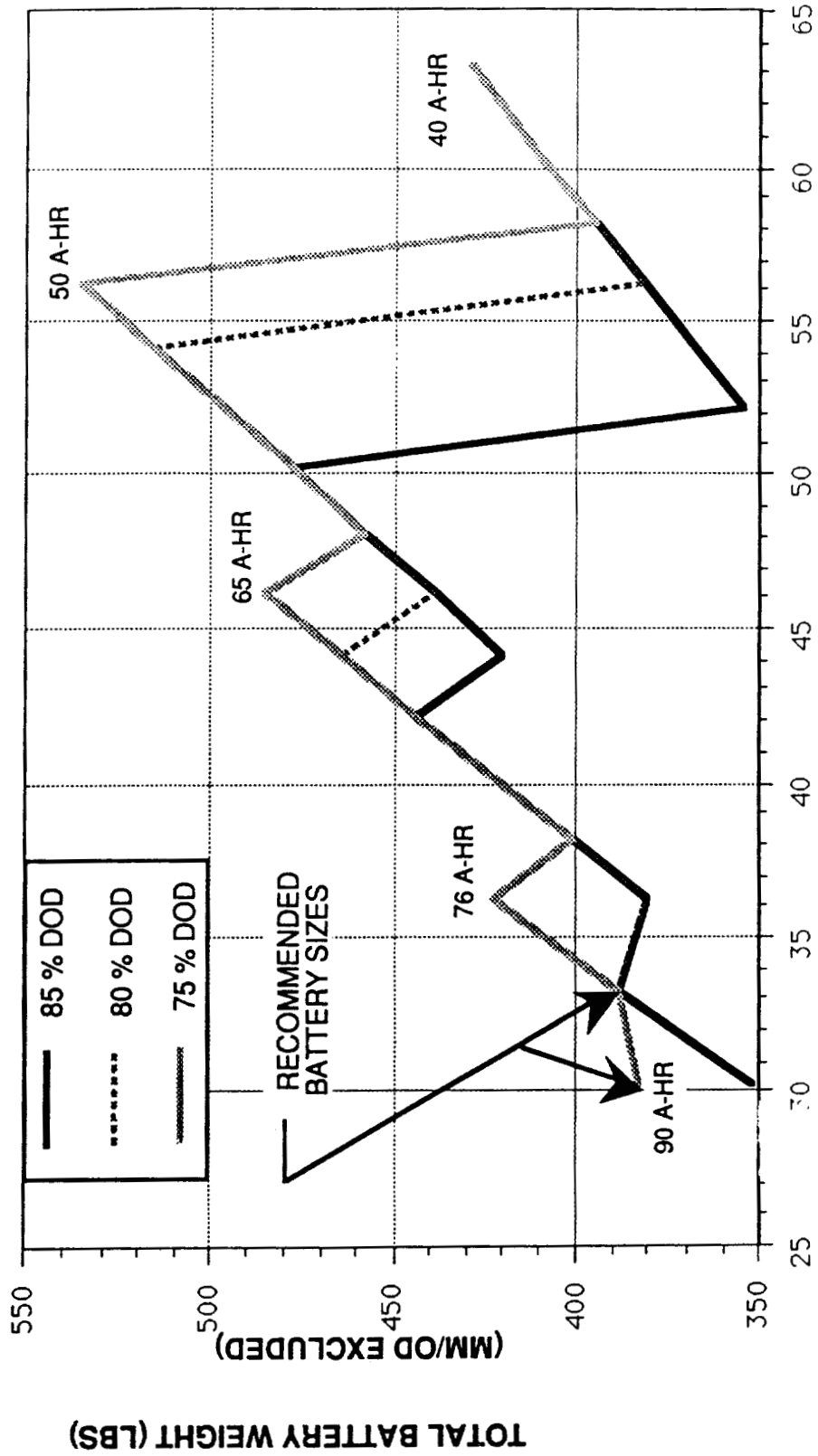


# BATTERY SIZING BASED ON MAXIMUM DOD

MDESC - L&ES



TRANSPORTER  
ENERGY STORAGE  
SUBSYSTEM



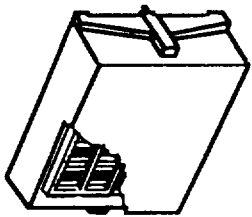
NUMBER OF NIH2 CELLS

Space Station Freedom

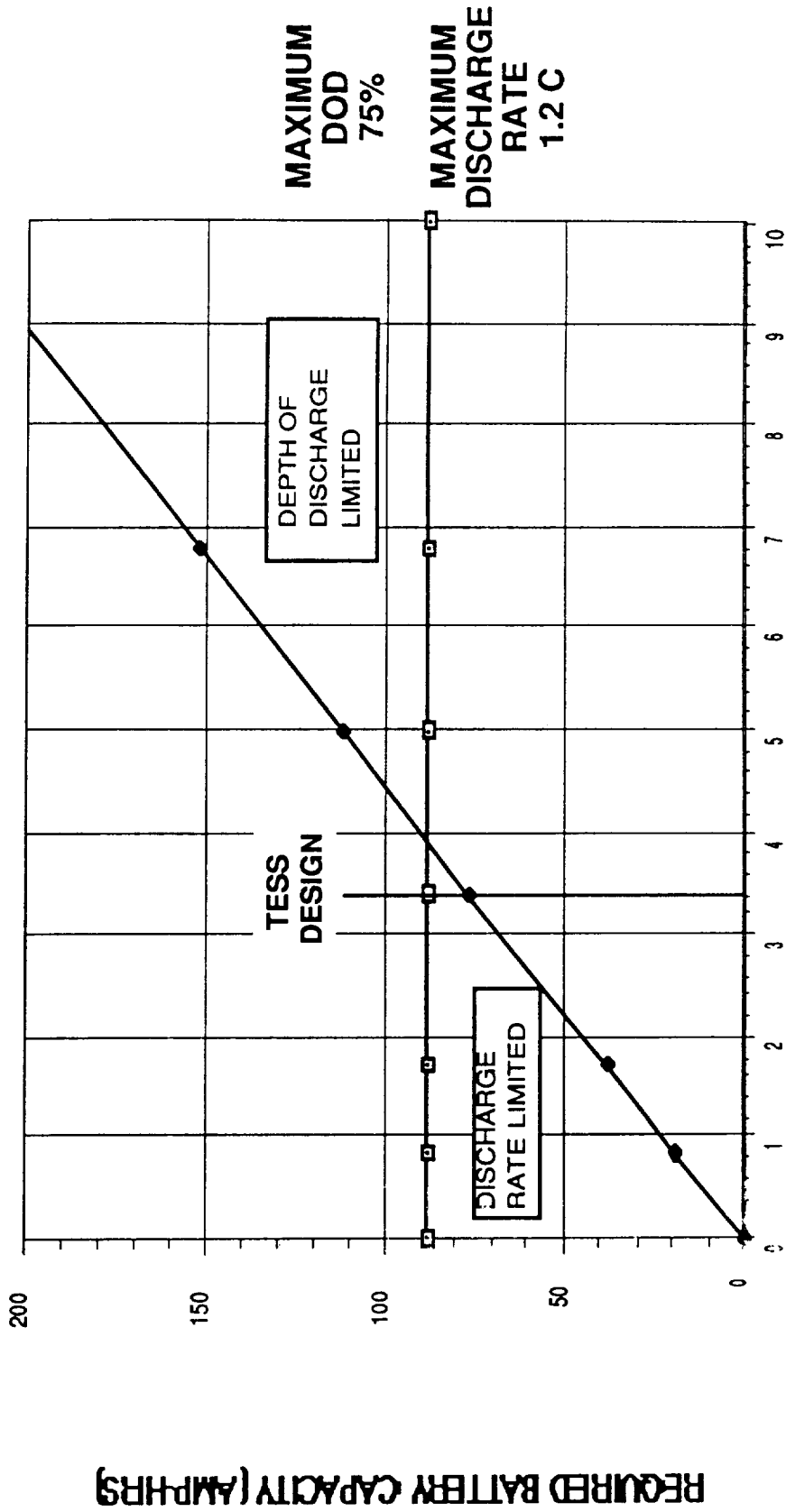
# TESS BATTERY WILL BE DISCHARGE RATE LIMITED

MDESC - L&ES

AVERAGE POWER 2300 W  
 PEAK POWER 3500 W  
 33 NIH2 CELL BATTERY



TRANSPORTER  
 ENERGY STORAGE  
 SUBSYSTEM



TESS BATTERY ENERGY (KW-HRS)

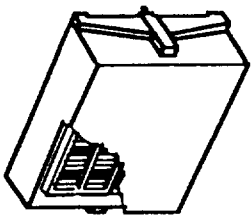


**TRANSPORTER  
ENERGY STORAGE  
SUBSYSTEM**

## **DOWNSIZED TESS SOLUTION FOR MBS REDESIGN**

**MDESC - L&ES**

- **REMOVE ONE TESS ORU**
- **REMOVE 63- CELL, 90 AMP-HR NIH2 BATTERY**
- **ADD TWO 33-CELL, 90 AMP-HR NIH2 BATTERIES**
- **CONNECT BATTERIES IN PARALLEL TO OBTAIN REDUNDANCY**



TRANSPORTER  
ENERGY STORAGE  
SUBSYSTEM

## RELATED NIH2 BATTERY CELL TESTING AT NASA-JSC

MDESC - L&ES

- OBTAINED 8 HUBBLE SPACE TELESCOPE CELLS FROM NASA-MARSHALL SPACE FLIGHT CENTER
- PAIR CELLS 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
  - STANDRY PERIODS OF CONSTANT TRICKLE CHARGE
- TEST PREPARATION IN PROGRESS



N92-22775

NICKEL HYDROGEN CELL DESIGN  
*A DESIGNER'S ASPECT*

Raymond Rehm

Nickel Hydrogen Battery Cells

October 30, 1991

Gates Energy Products  
Gates Aerospace Batteries

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## 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 restriction's 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 compres-

sion 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.

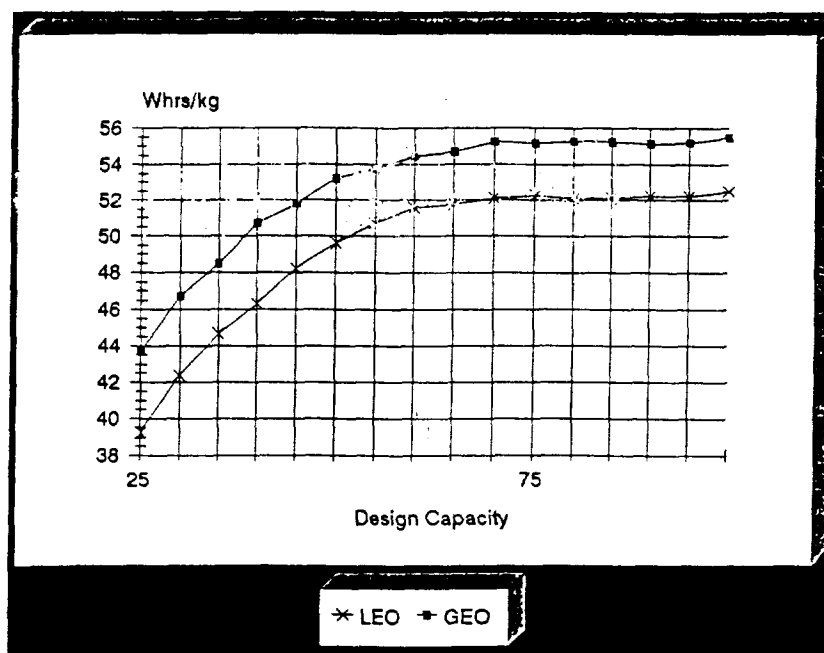


Figure 1 Specific Energy for Gates 3.5" Cells  
1991 NASA Aerospace Battery Workshop

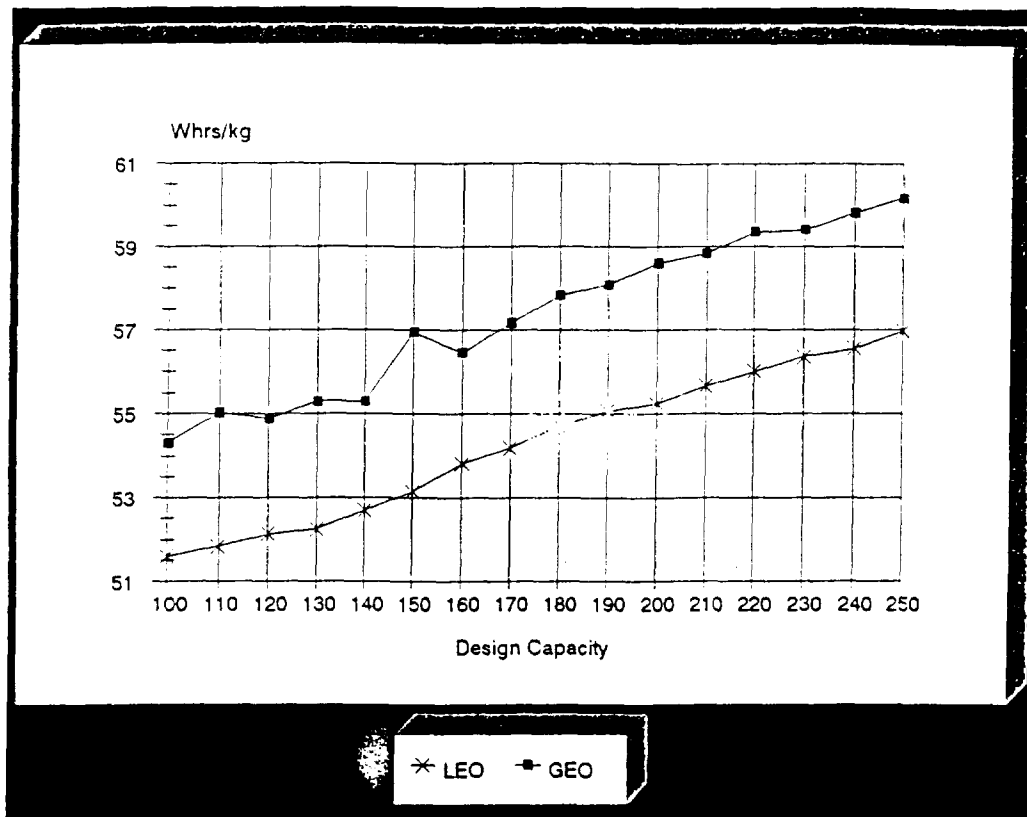


Figure 2. Specific Energy for Gates 4.5" Cells

### 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 be-

tween 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 NiH<sub>2</sub> 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 10°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.

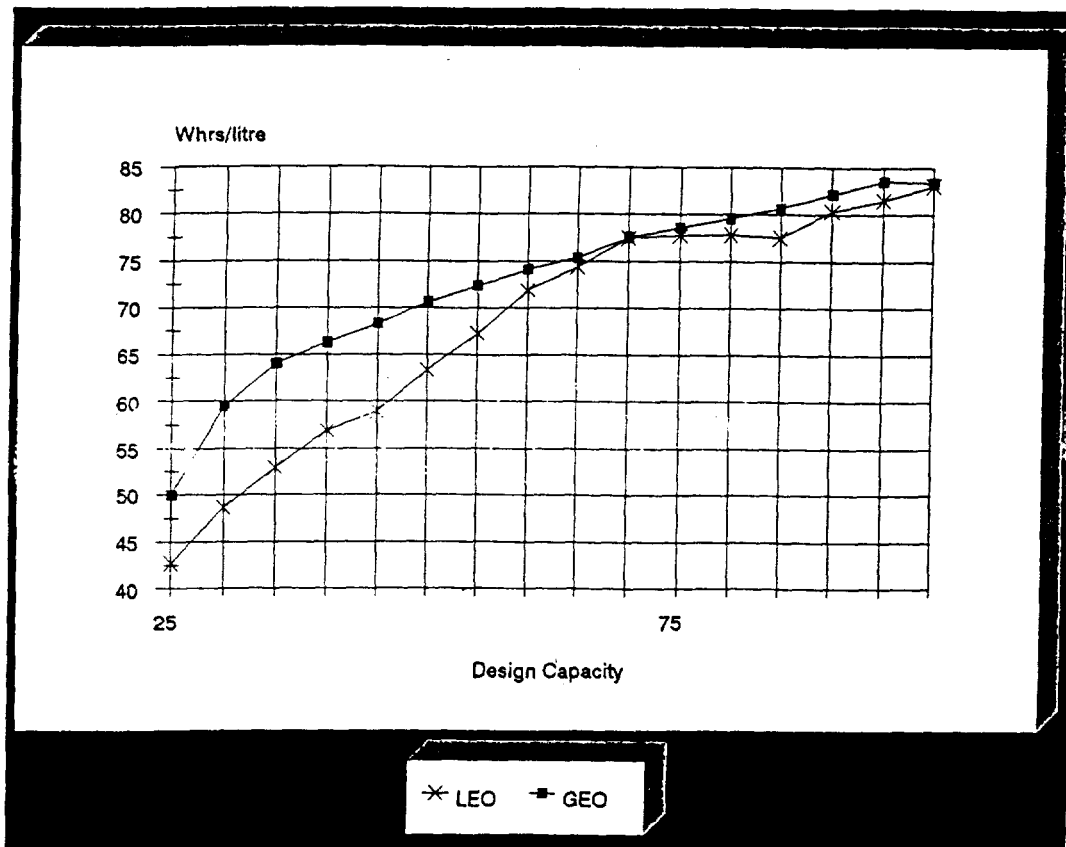


Figure 3. Energy Density of Gates 3.5" Cells

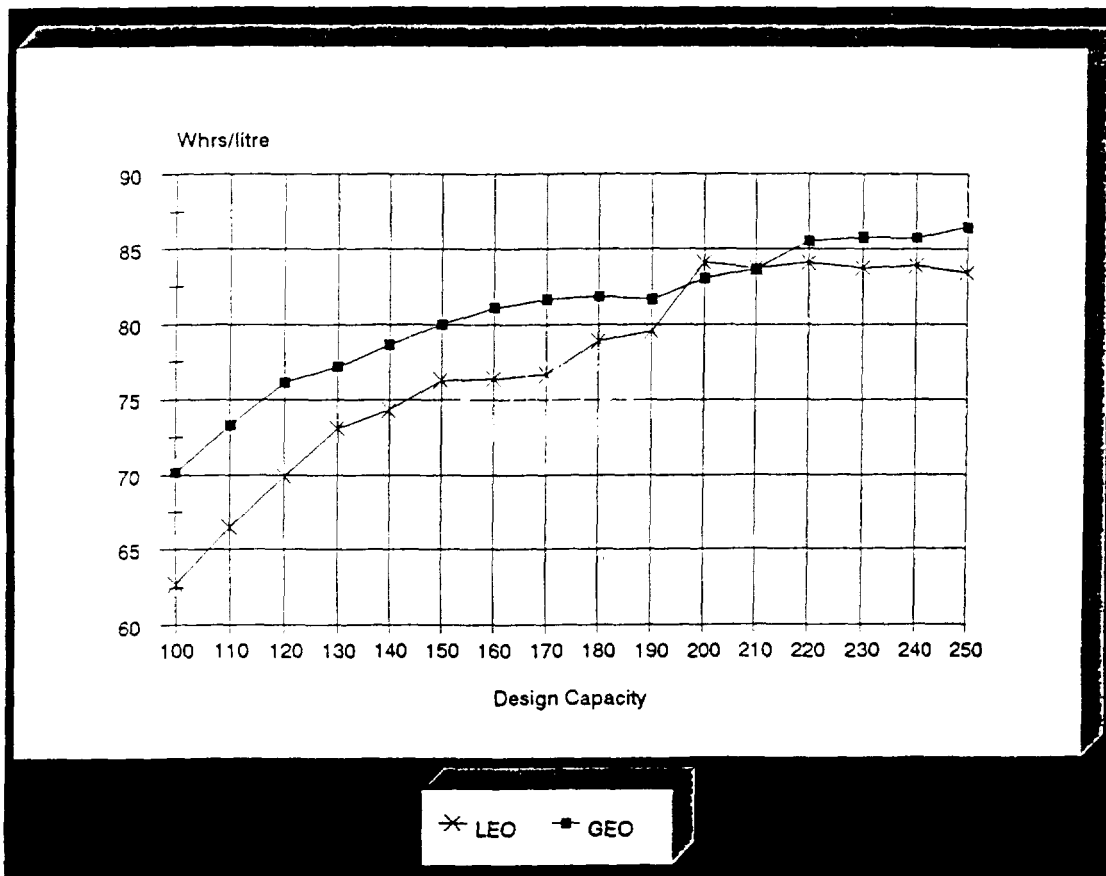


Figure 4. Energy Density of Gates 4.5" Cells

## 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**

**N92-22776**

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# **EOS OVERALL PROGRAM**

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## **THREE PHASE PROGRAM**

**LIFE EVALUATION TEST PHASE  
ACCEPTANCE TESTS  
CHARACTERIZATION TESTS  
FIVE YEAR LEO LIFE TEST**

**ENGINEERING PROTOTYPE (WORKHORSE) HARDWARE  
FOUR COMPLETE BATTERIES  
FULL QUALIFICATION**

**PRIME FLIGHT HARDWARE  
FIVE COMPLETE BATTERIES**

## 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

## CELL DESCRIPTION (Cont)

VENDOR COMPARISON	VENDOR A	VENDOR B
CELL WEIGHT (LOT AVE.) GRAMS	1476	1515
CELL LENGTH (DOME TO DOME)	7.820	6.991
TERMINAL SEAL	ZIEGLER	CERAMIC
ELECTRODE CONFIGURATION	BACK-BACK	RECIRCULAT.
PLAQUE	SLURRY	SINTER
ELECTROLYTE - % KOH	31.0	31.0
PRECHARGE	NICKEL	HYDROGEN
WALL WICK	YES	YES
CATALYZED	YES	NO
PRESSURE VESSEL THICKNESS (INCHES)	0.023	0.024
BURST PRESSURE (PSIG)	2900	2700
PREDICTED MEOP (PSIG)	705	800
BURST FACTOR	4.1	3.38



## ACCEPTANCE TESTS

---

THREE (MINIMUM) BURN IN CYCLES, C/2 @ 10C  
 SEVEN CAPACITY CHARGE/DISCHARGE CYCLES (WITH LETDOWN)

DISCHARGE RATE	TEMPERATURE (DEG C)		
	-5	0	10
C/2		1	1
C	1		3
			20
			1

THREE OVERCHARGE TESTS (-5C, 10C, 25C)  
 CHARGE @ C/20 FOR 48 HOURS  
 DISCHARGE @ C/2

ONE PULSE DISCHARGE TEST (10C)  
 2C FOR 20 SECONDS  
 DISCHARGE @ C/2

ONE CHARGE RETENTION TEST (10C)  
 72 HOUR OC STAND  
 DISCHARGE @ C/2

## CHARACTERIZATION TESTS

---

TWO (MINIMUM) CONDITIONING CYCLES, C/2 @ 10C  
ELEVEN CAPACITY CHARGE/DISCHARGE CYCLES

DISCHARGE RATE	TEMPERATURE (DEG C)						
	-10	-5	0	5	10	20	
C/2	1	1	1	2	1	1	1
C	1		1	1			

ONE OVERCHARGE TESTS (-10C)  
CHARGE @ C/20 FOR 48 HOURS  
DISCHARGE @ C/2

TWO CHARGE RETENTION TESTS (10C)  
72 HOUR OC STAND  
DISCHARGE @ C/2

TWELVE VOLTAGE/TEMPERATURE CHARACTERIZATION TESTS  
THREE SEPARATE V/T LEVELS  
FOUR TEST TEMPERATURES (-10C, 0C, 10C, 20C)

## 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)



N92-22777



GATES AEROSPACE BATTERIES

---

# FAULT TREE ANALYSIS

## NiH<sub>2</sub> AEROSPACE CELLS

### FOR LEO MISSION

Glenn C. Klein  
Gates Aerospace Batteries

Donald E. Rash, Jr.  
Reliability Analysis Center

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# FAULT TREE ANALYSIS, NiH<sub>2</sub> 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.

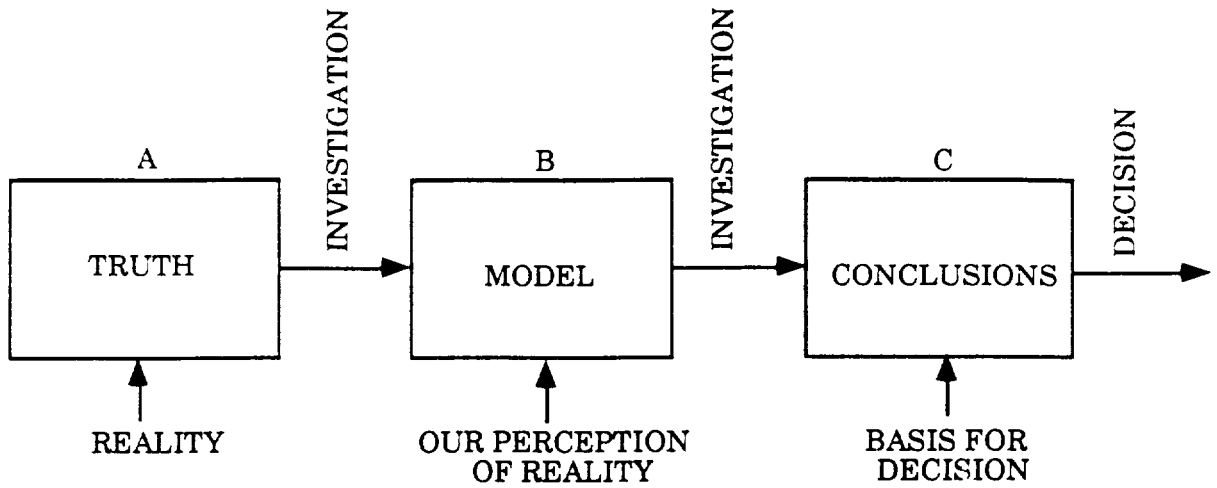


FIGURE 1: RELATIONSHIP BETWEEN REALITY, SYSTEM MODEL, AND DECISION PROCESS

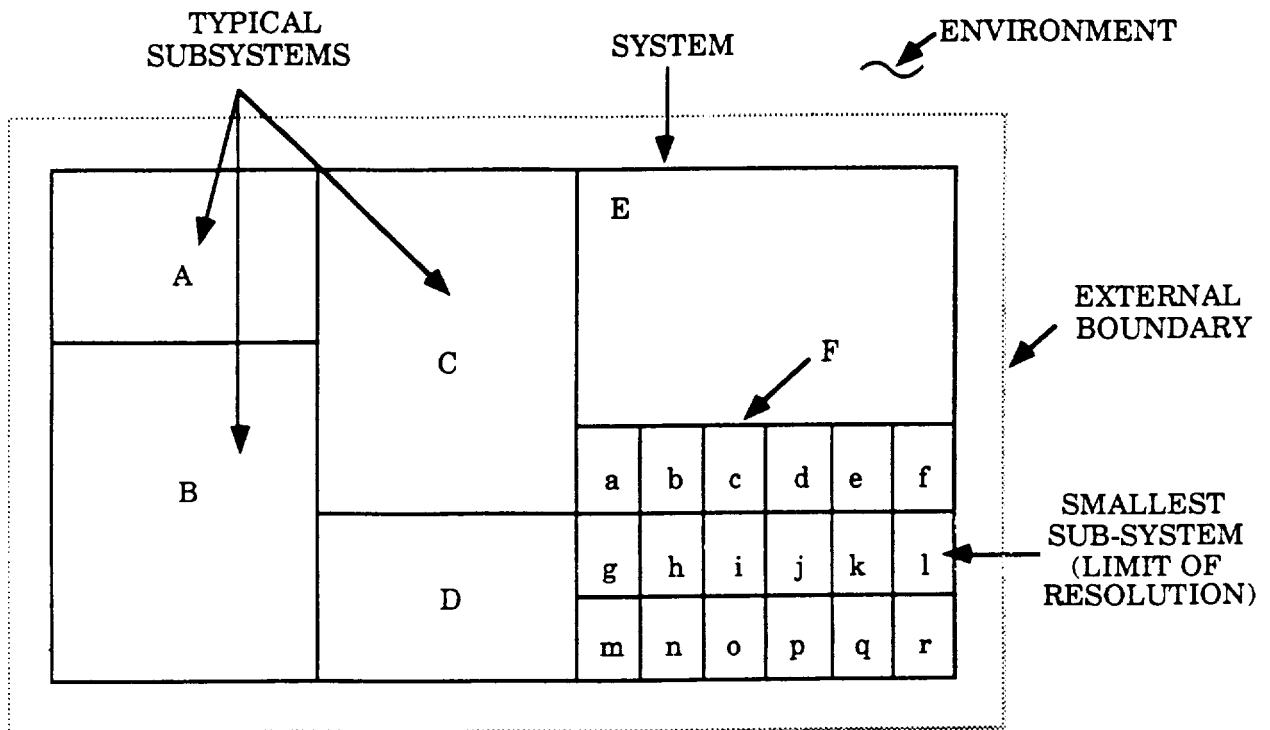


FIGURE 2: SYSTEM DEFINITION: EXTERNAL AND INTERNAL BOUNDARIES



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 NiH<sub>2</sub> 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 NiH<sub>2</sub> 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

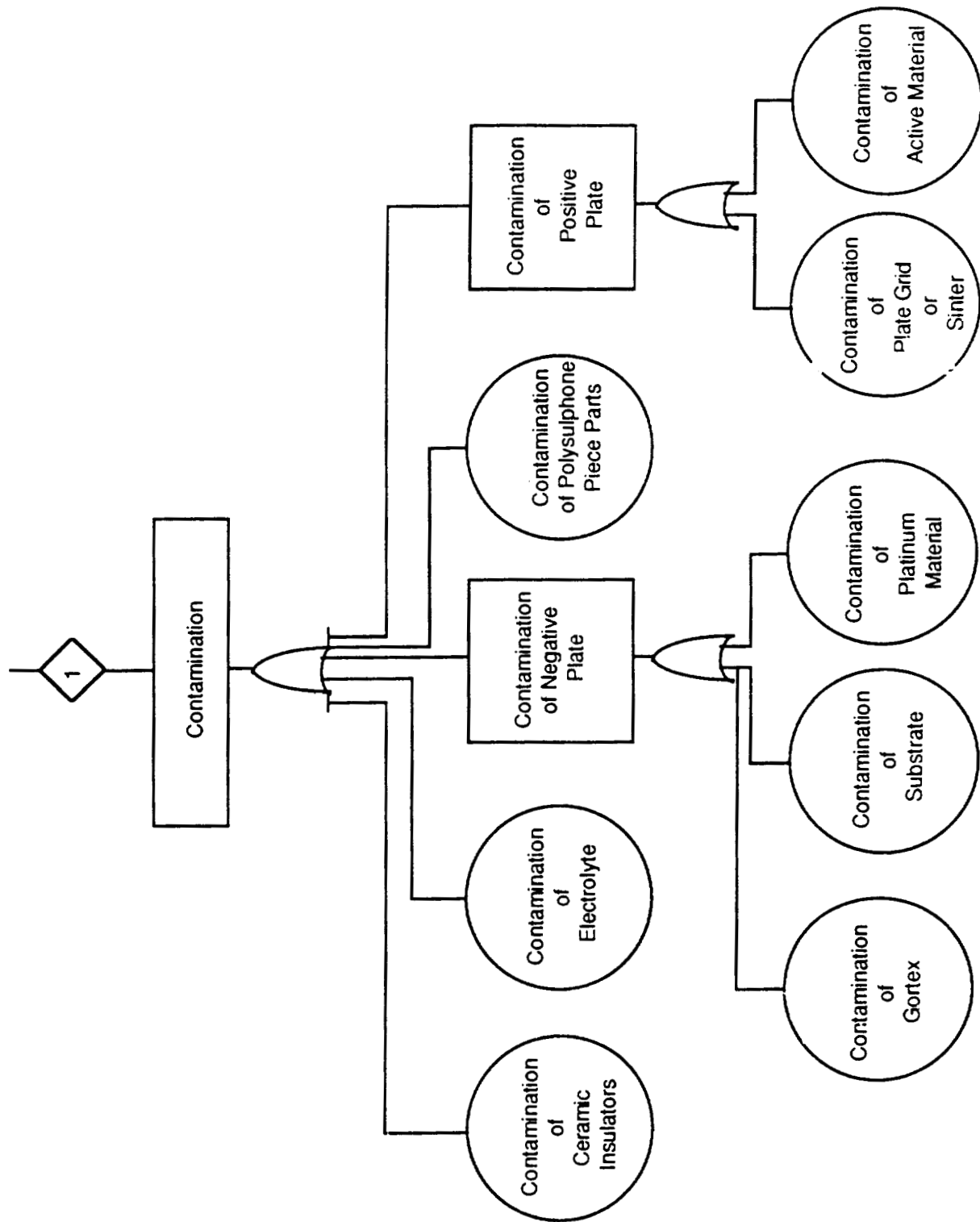


FIGURE 3: FAULT TREE SYMBOLOGY

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 NiH<sub>2</sub> 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 NiH<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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.

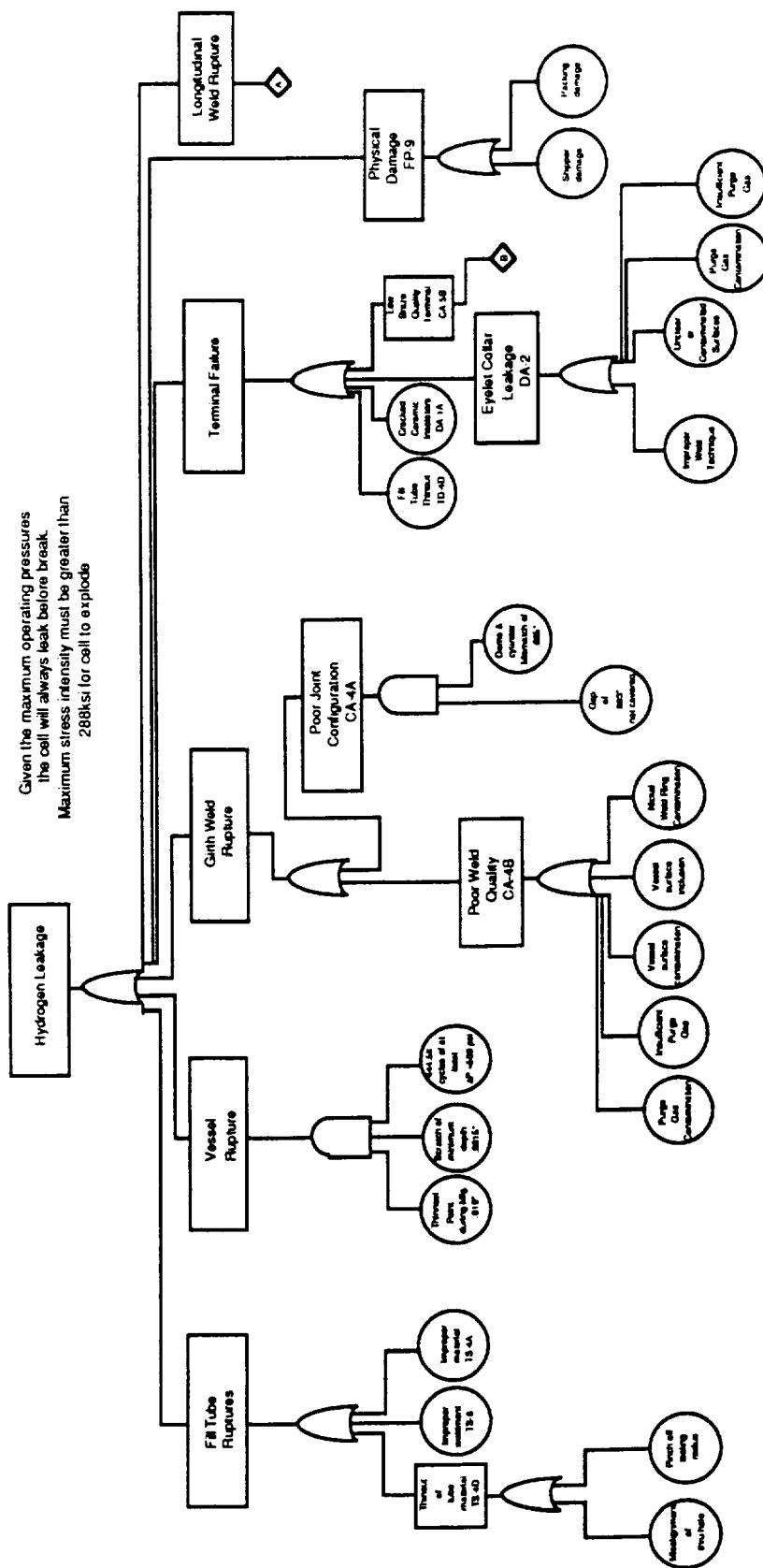


FIGURE 4

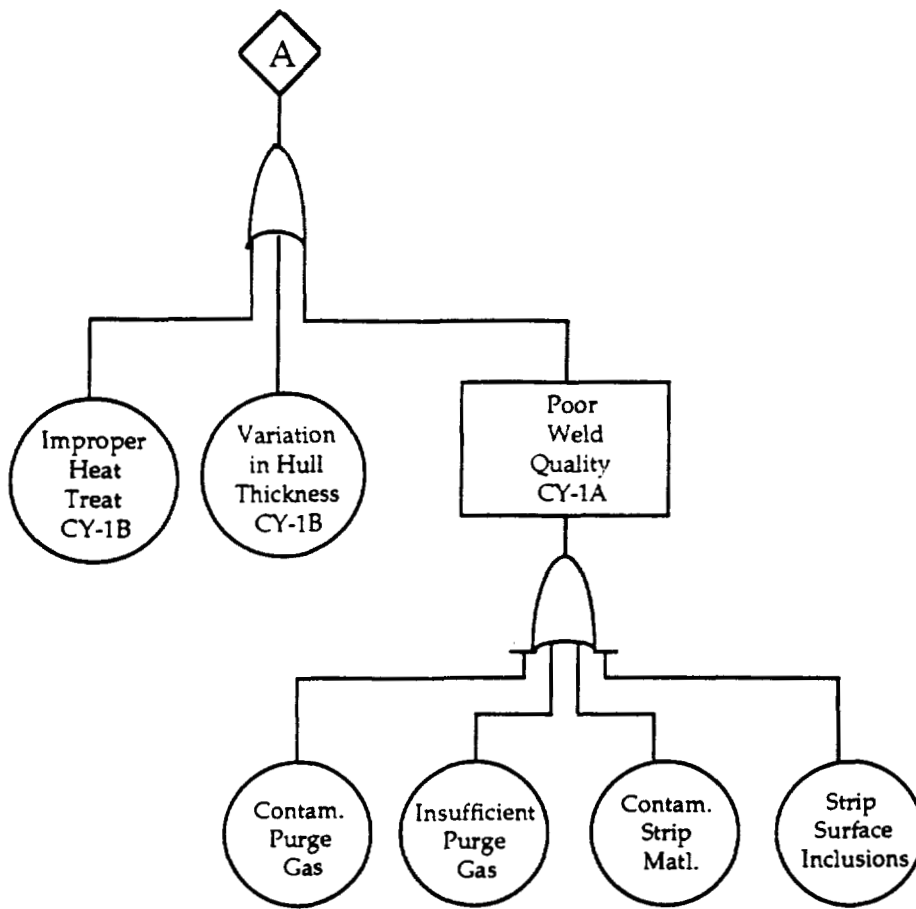


FIGURE 5

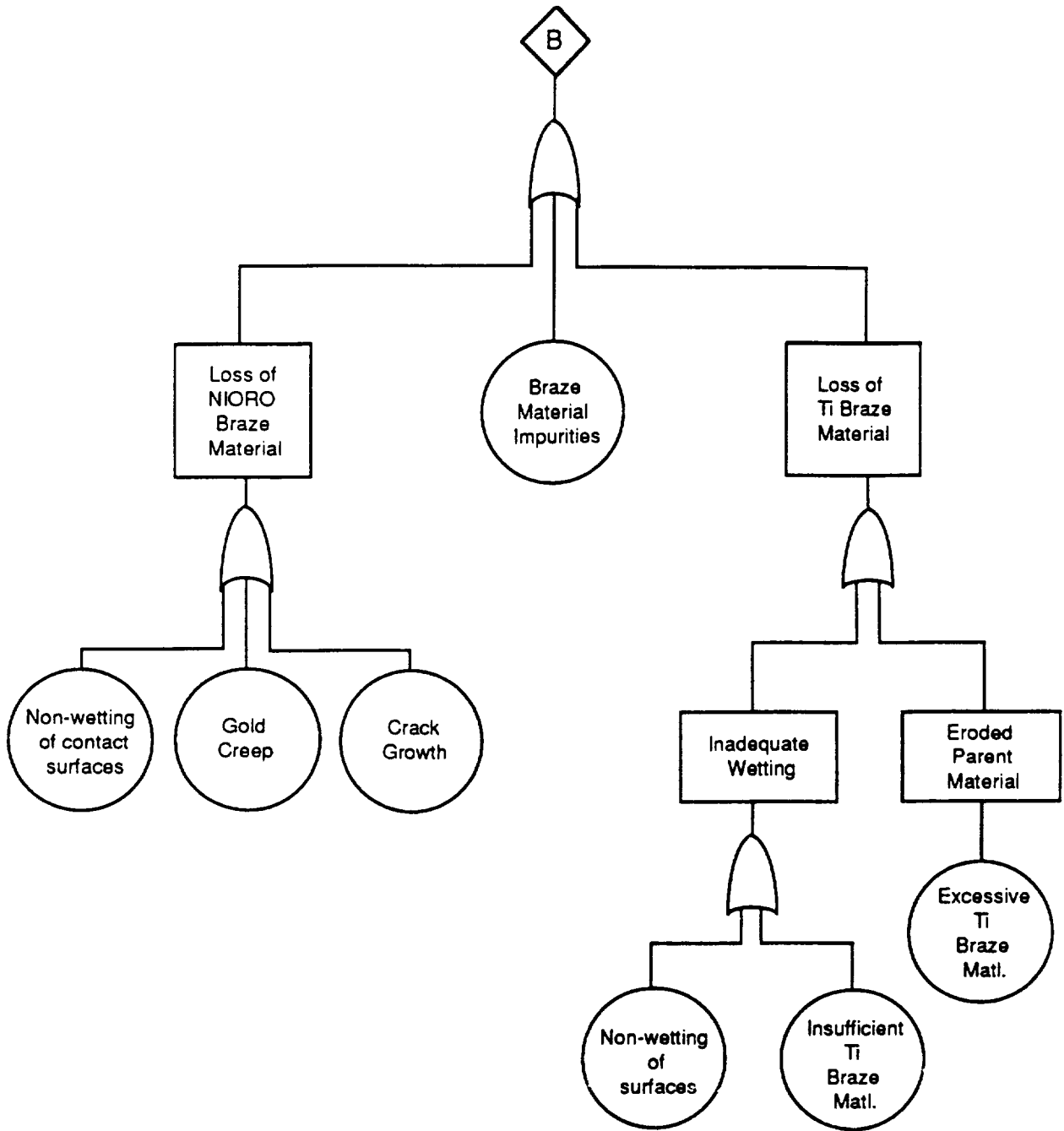


FIGURE 6



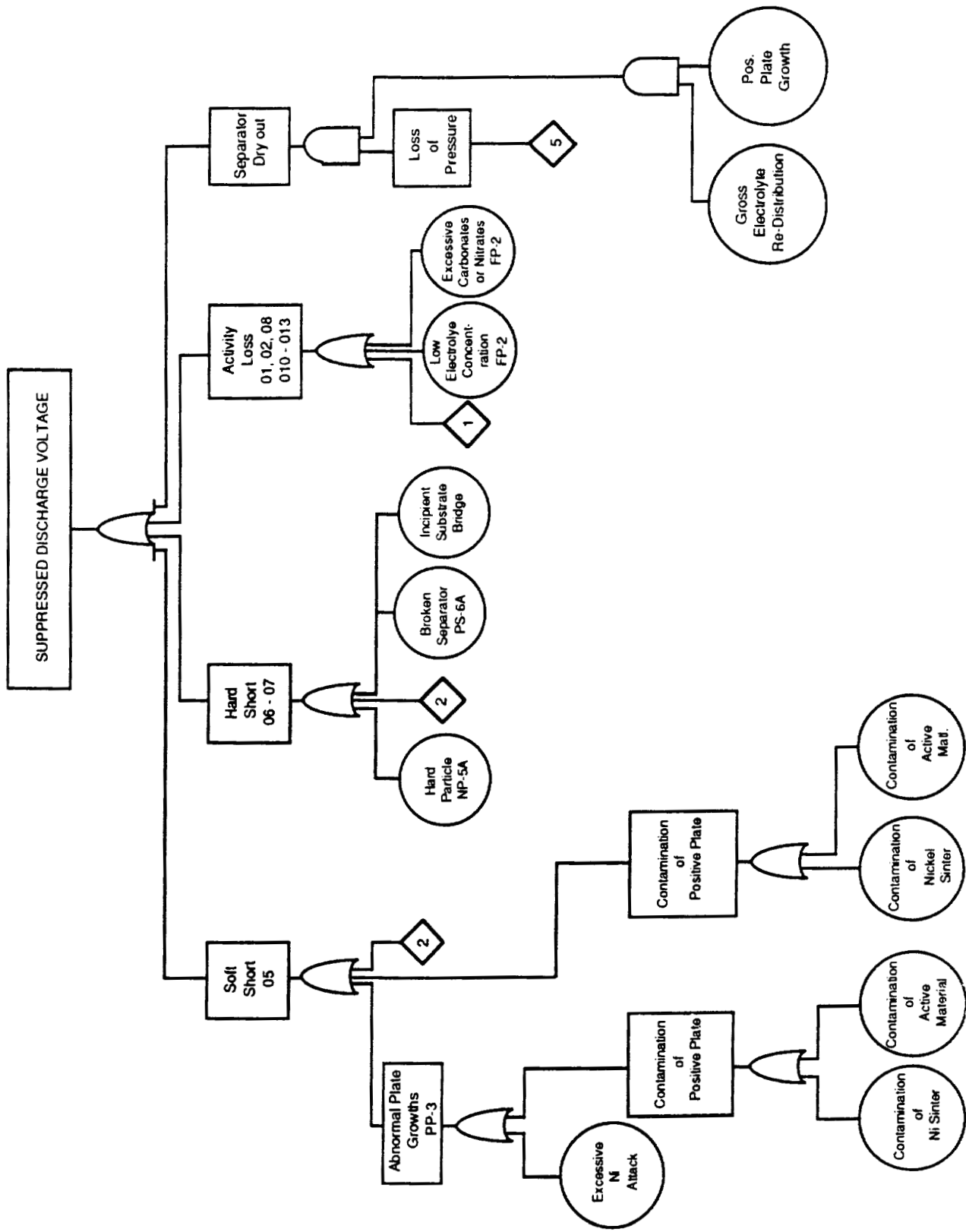


FIGURE 7

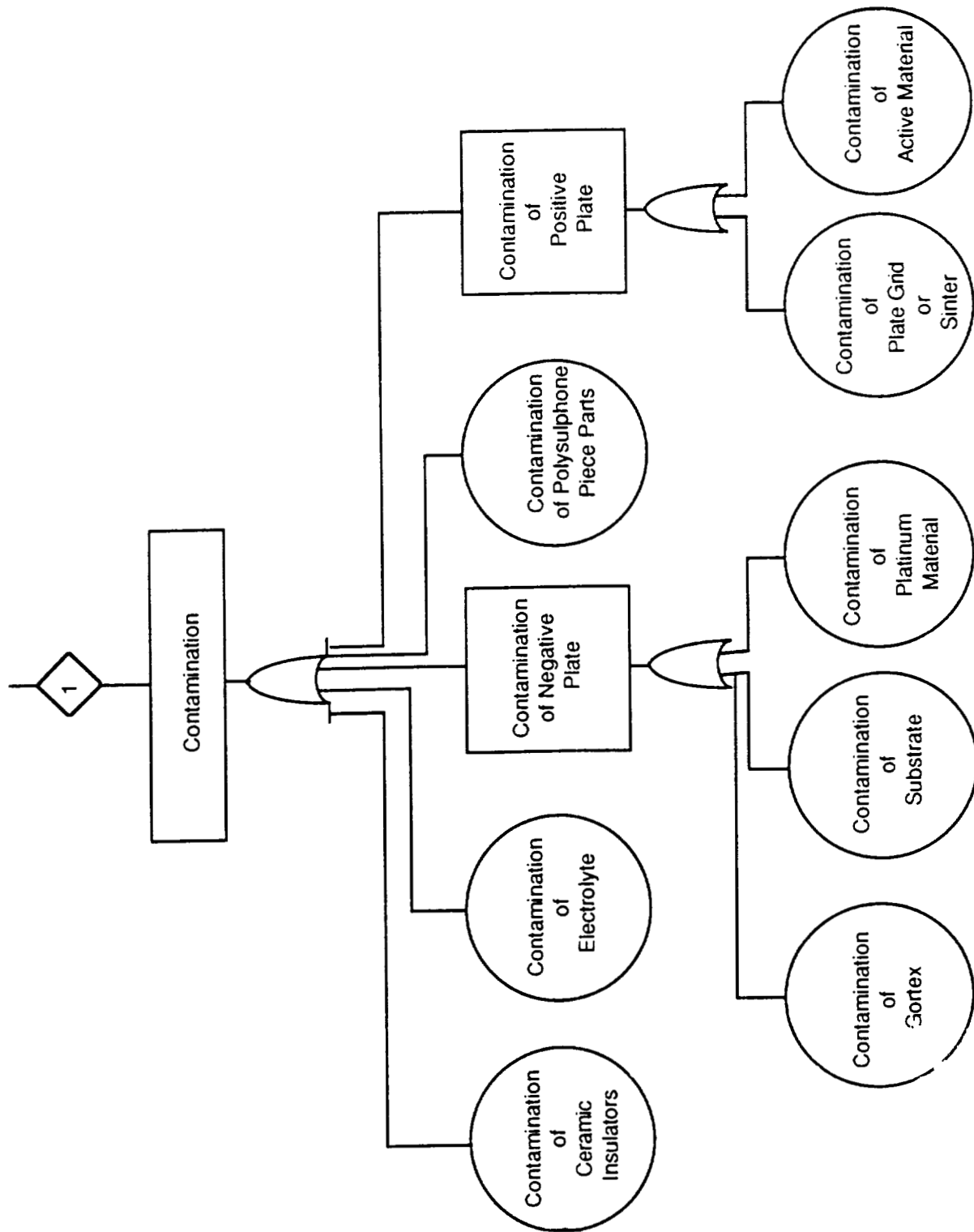


FIGURE 8

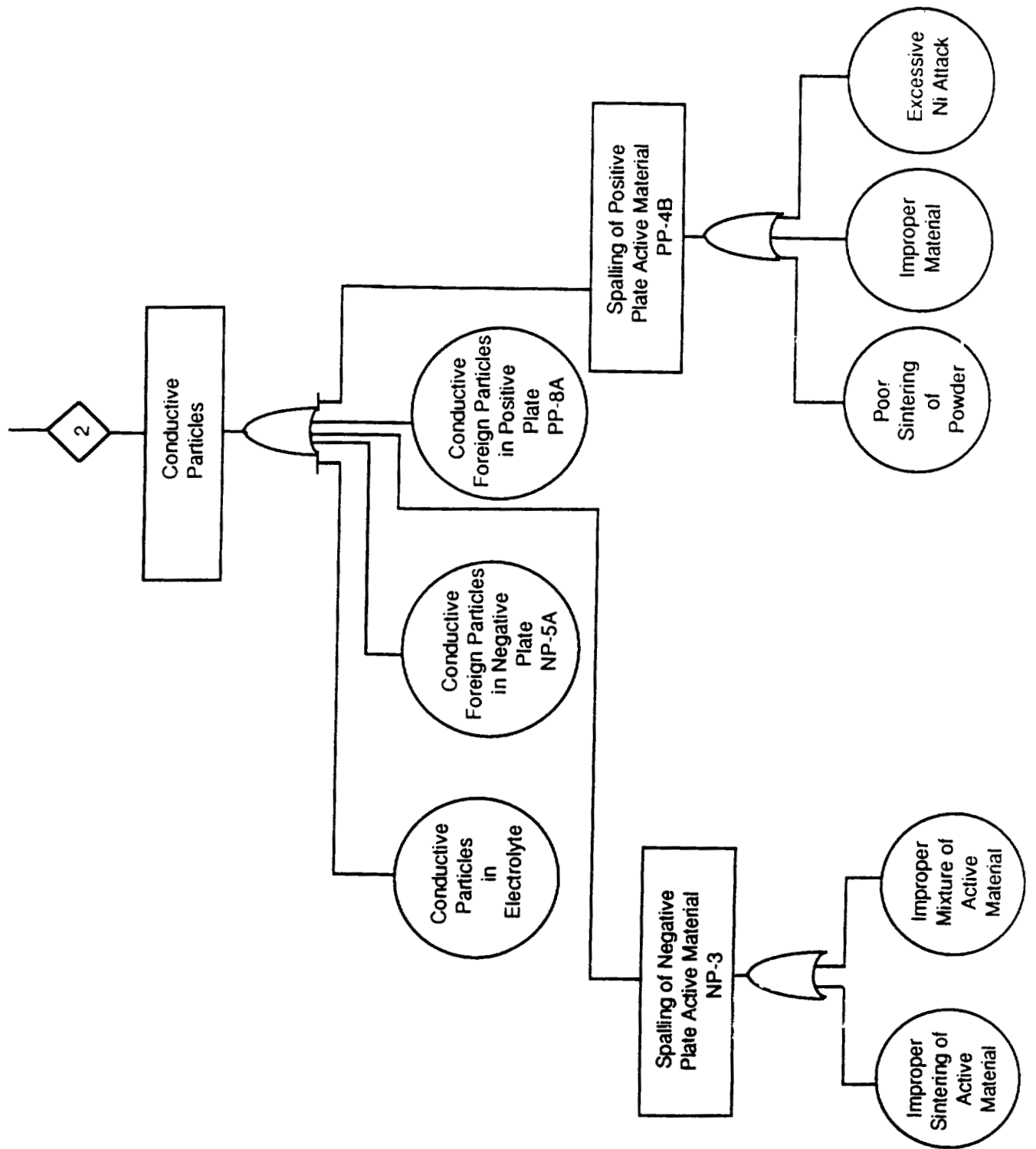


FIGURE 9

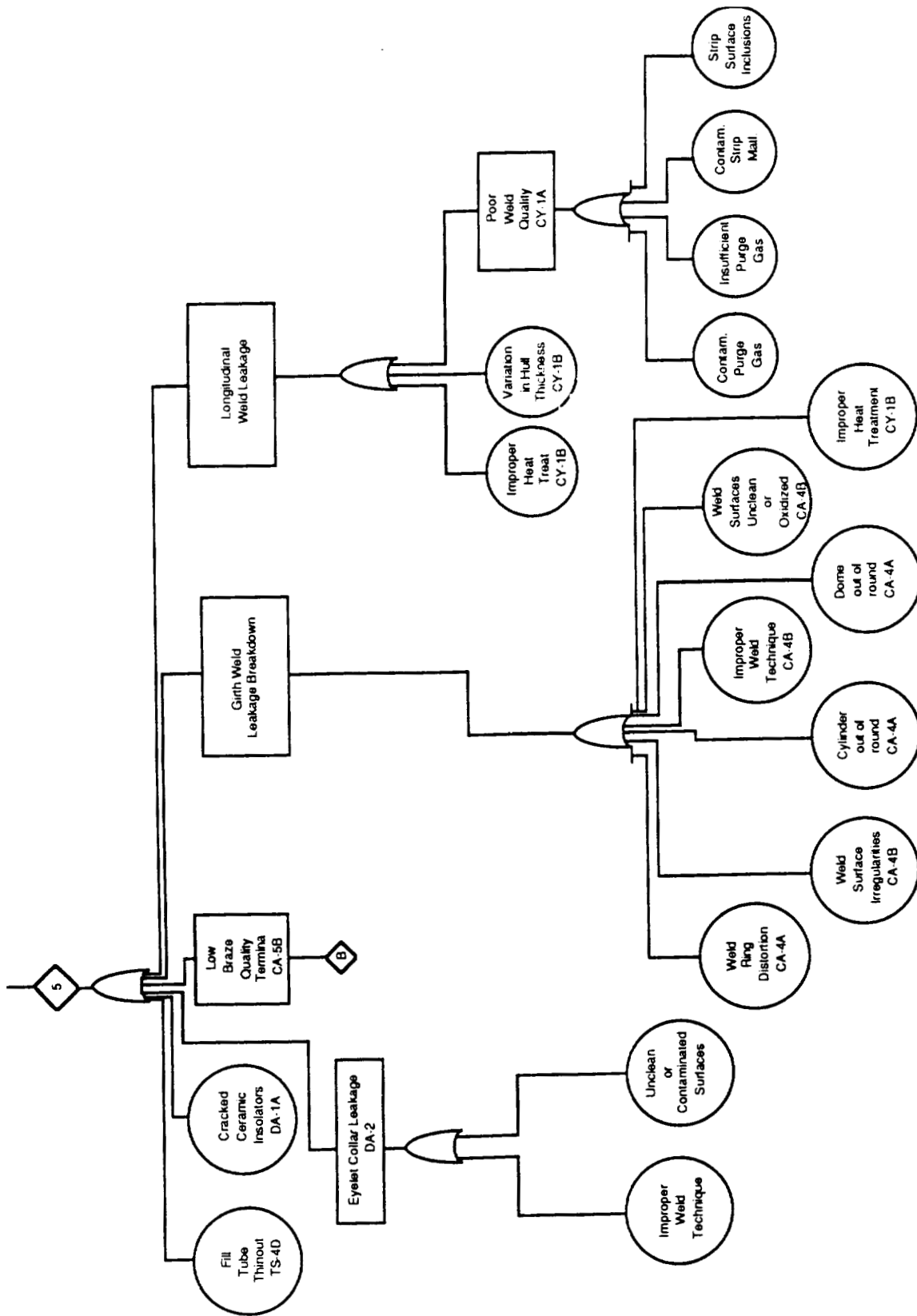


FIGURE 10

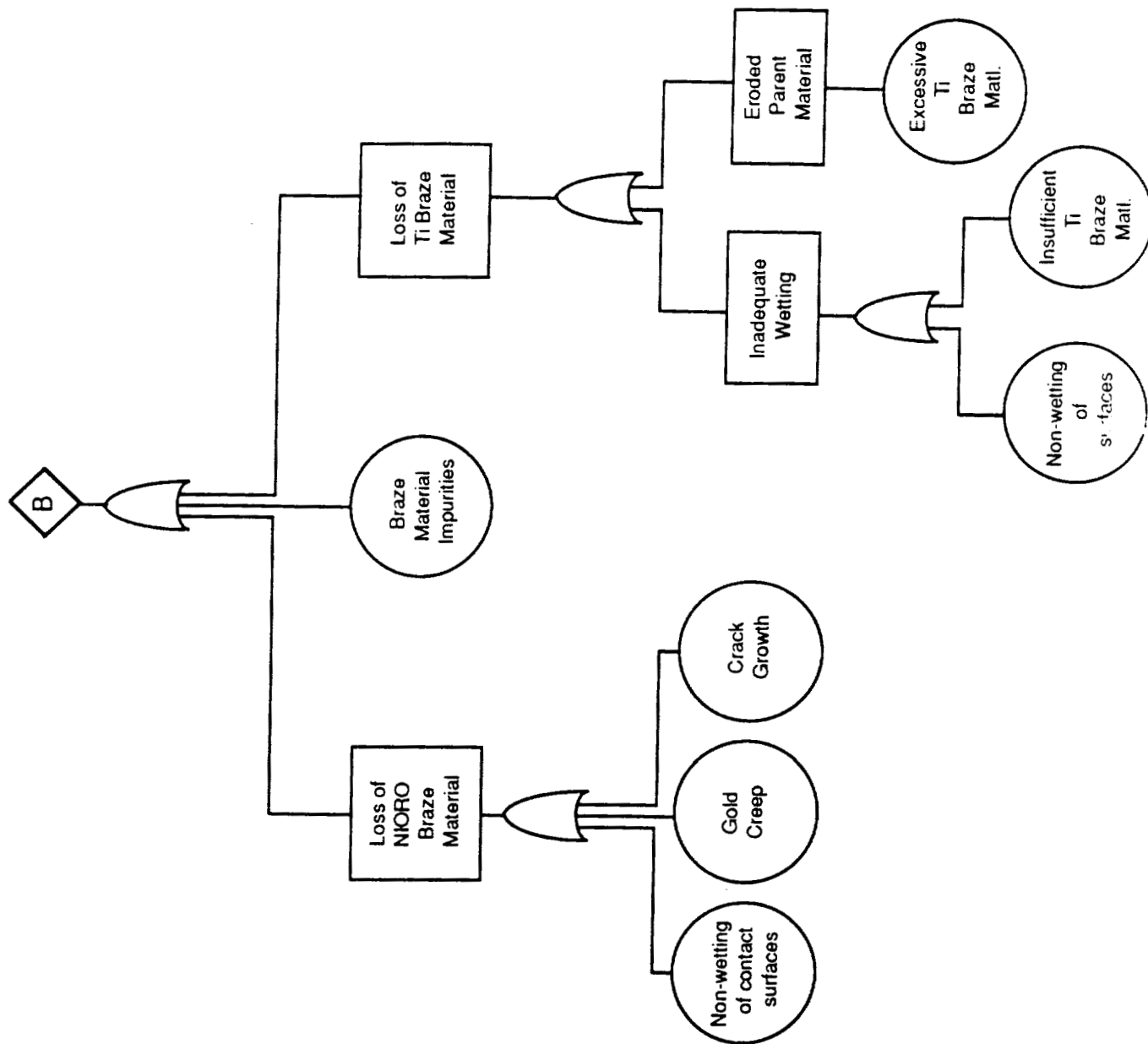


FIGURE 11

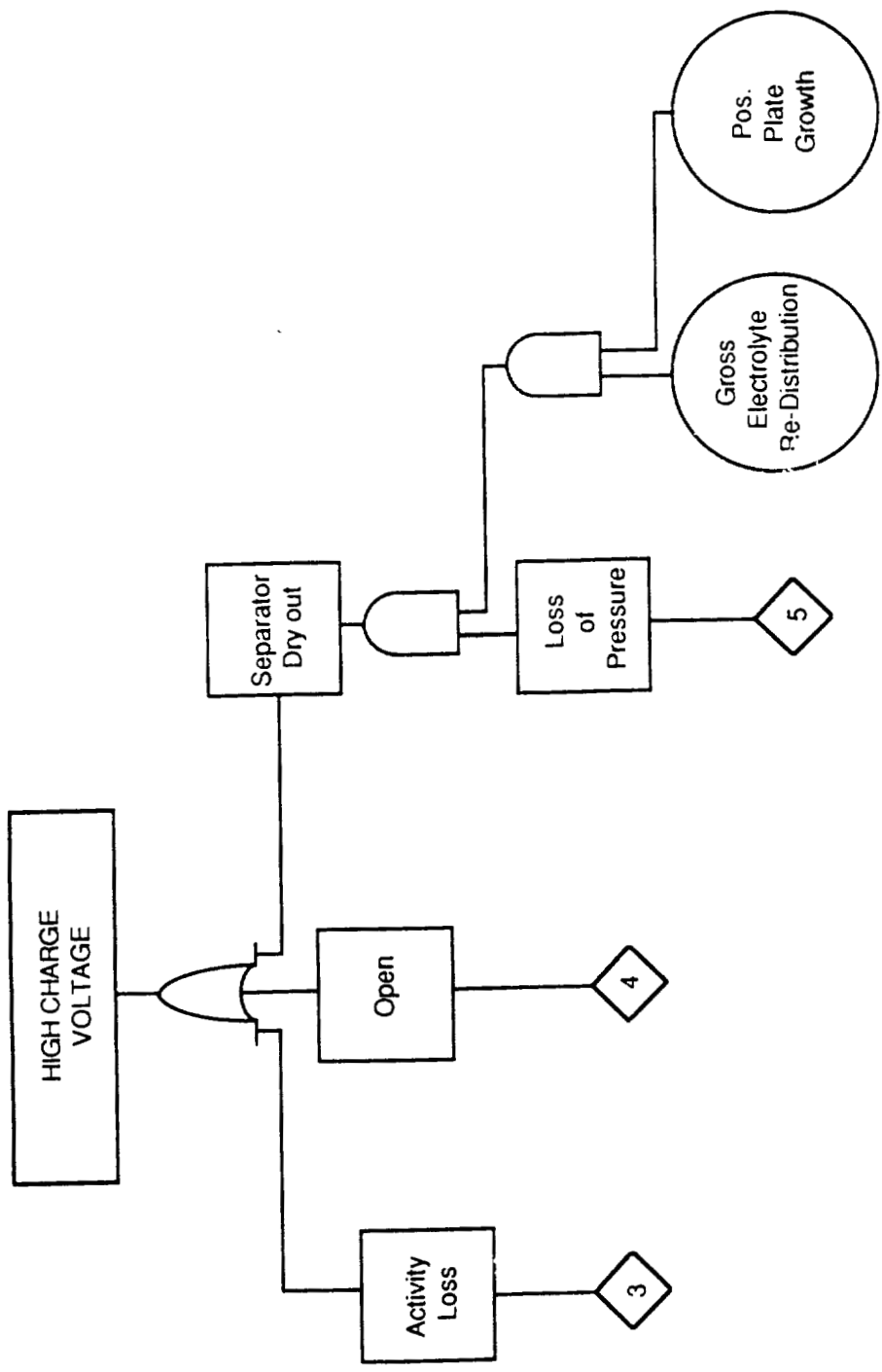


FIGURE 12

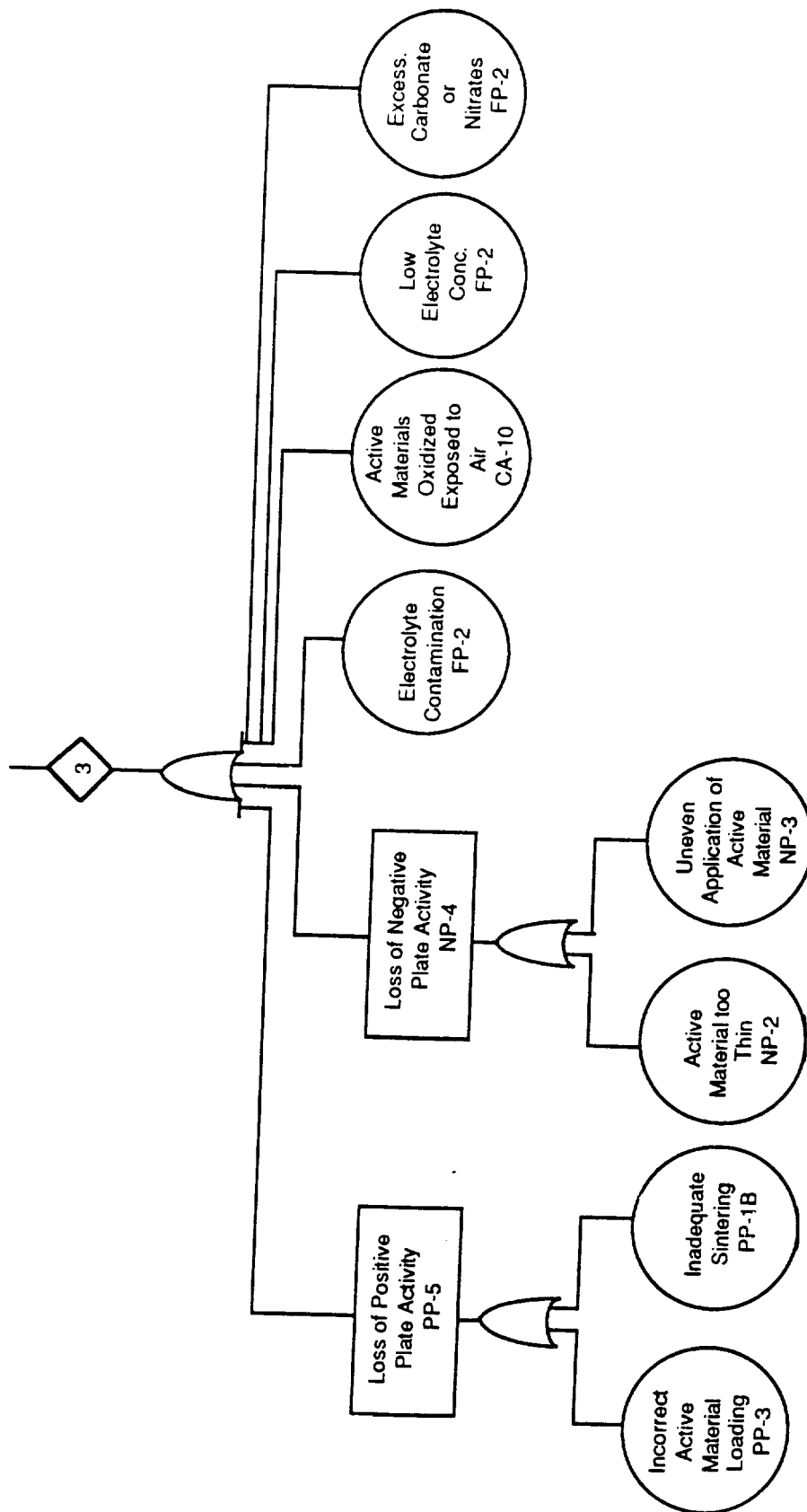


FIGURE 13

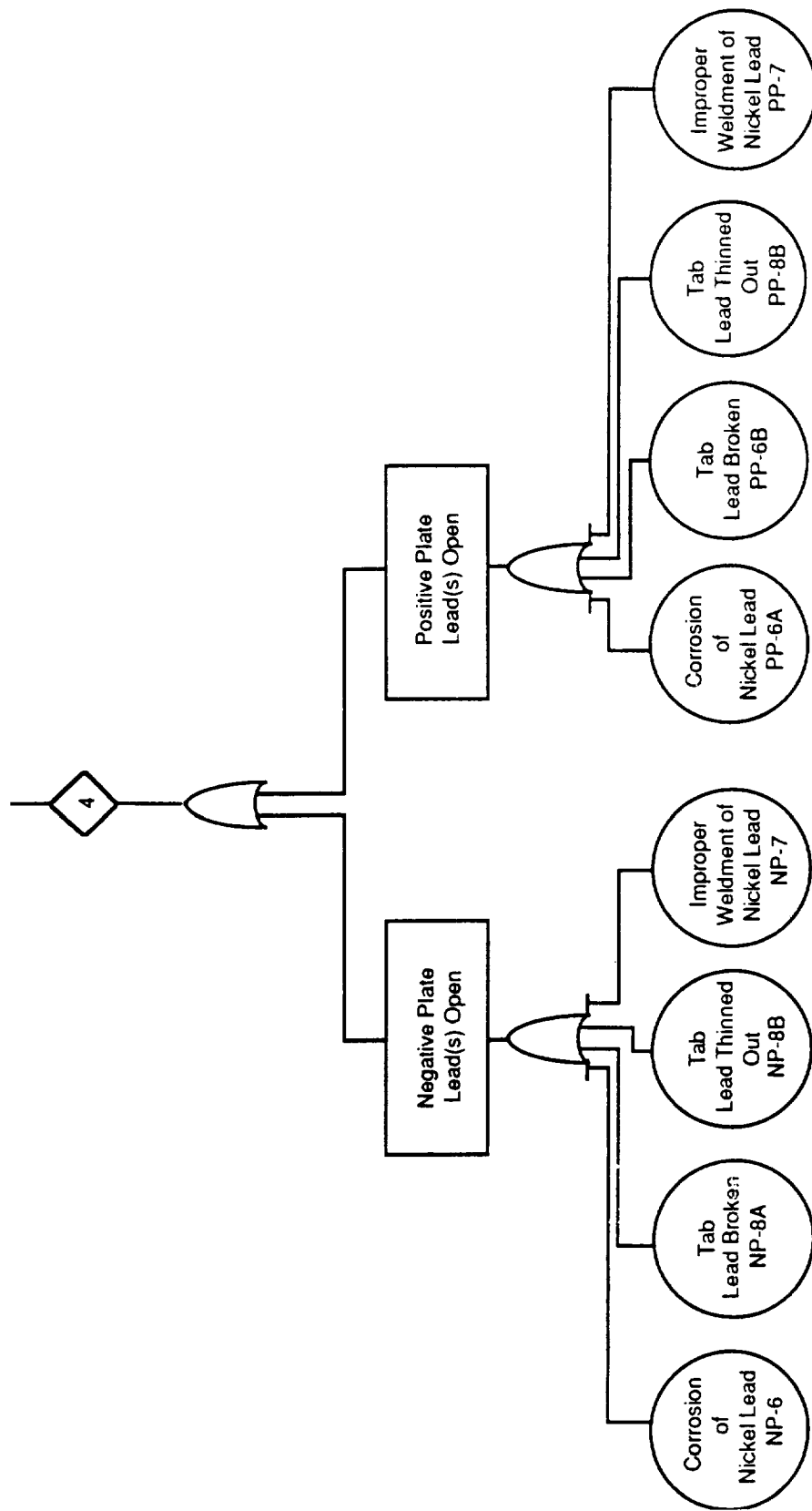


FIGURE 14



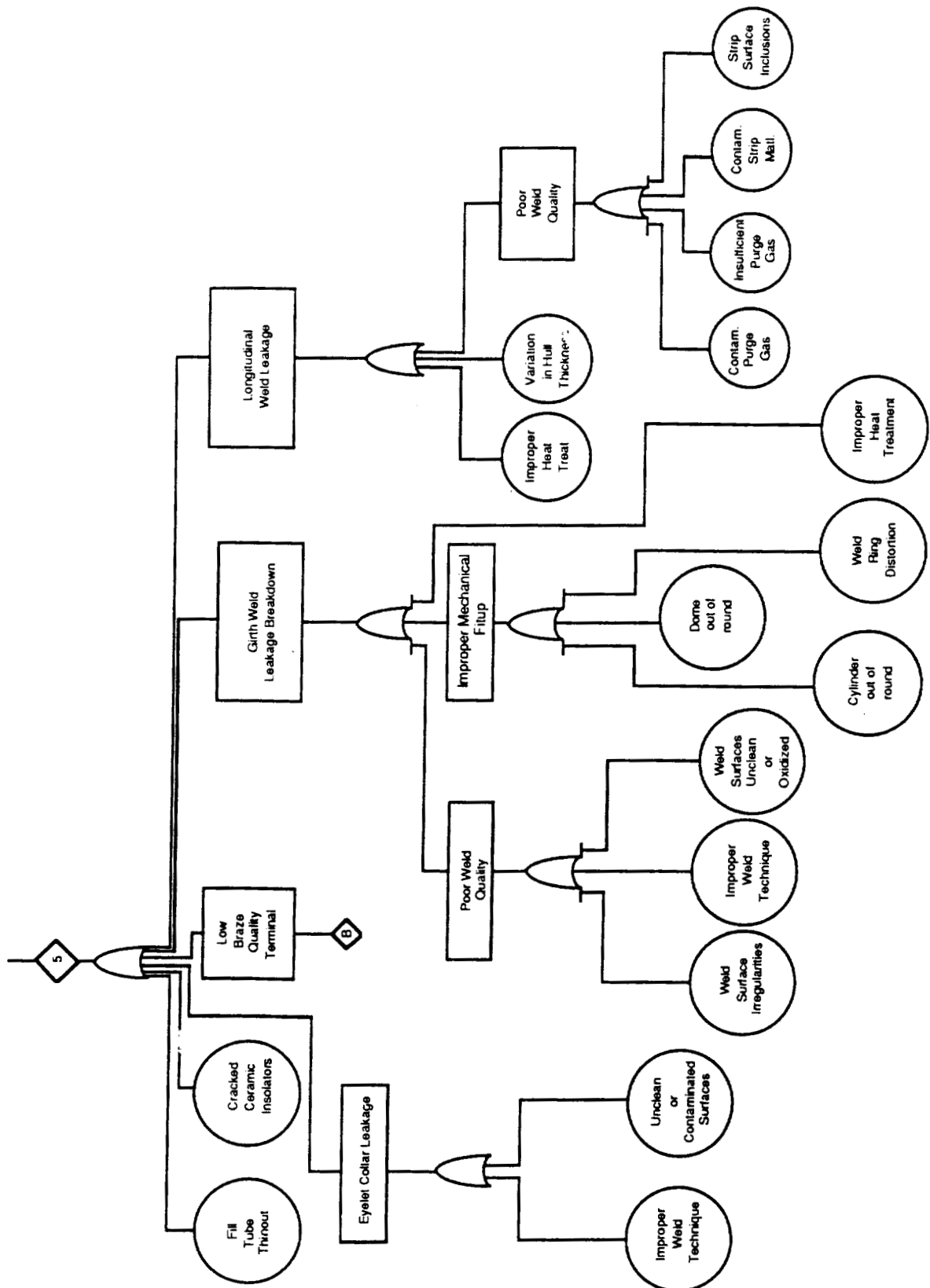


FIGURE 15

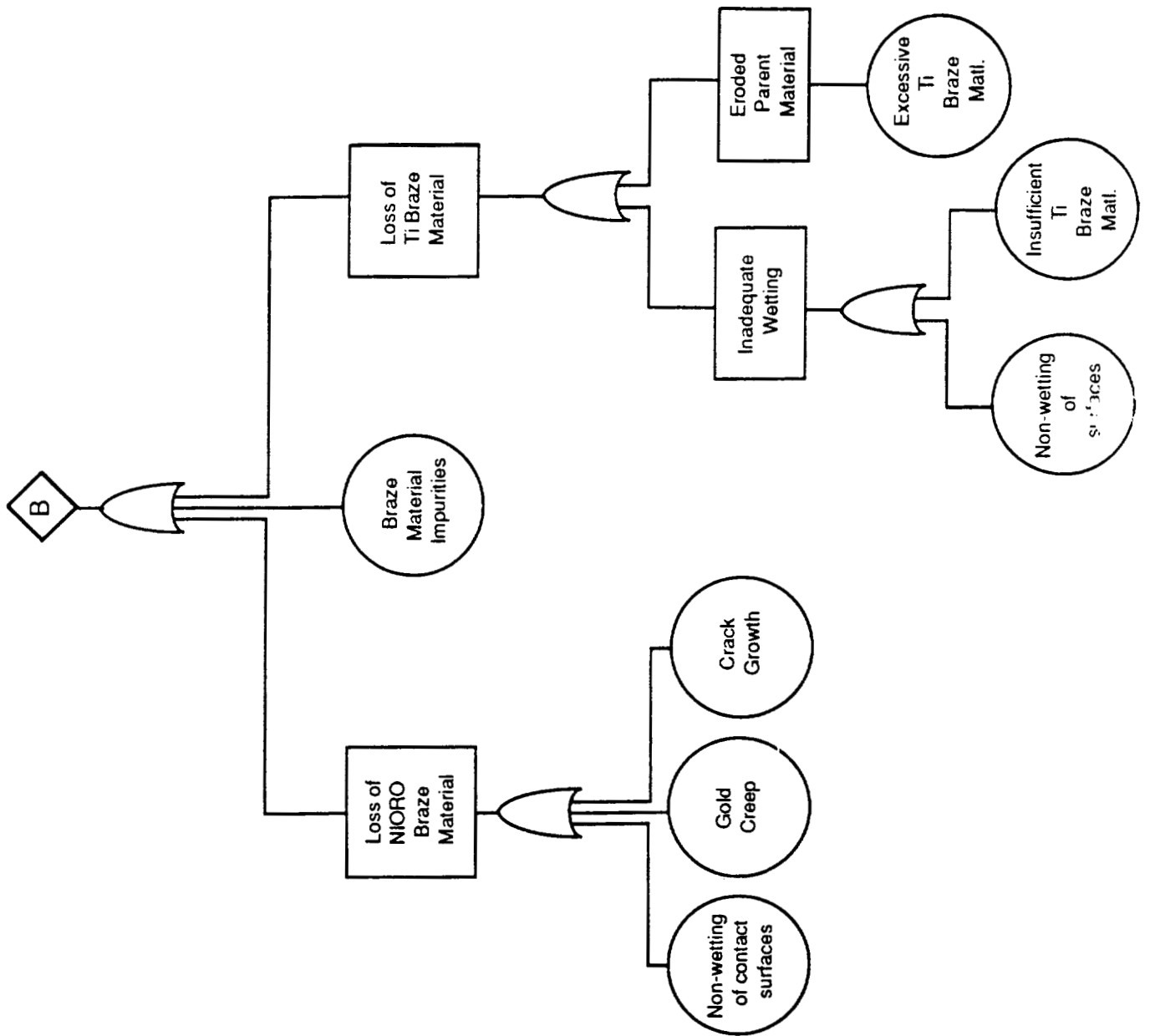


FIGURE 16

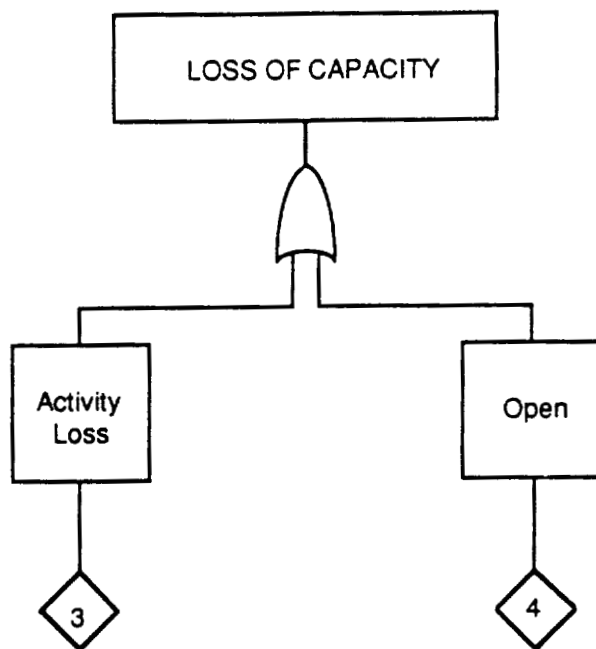


FIGURE 17

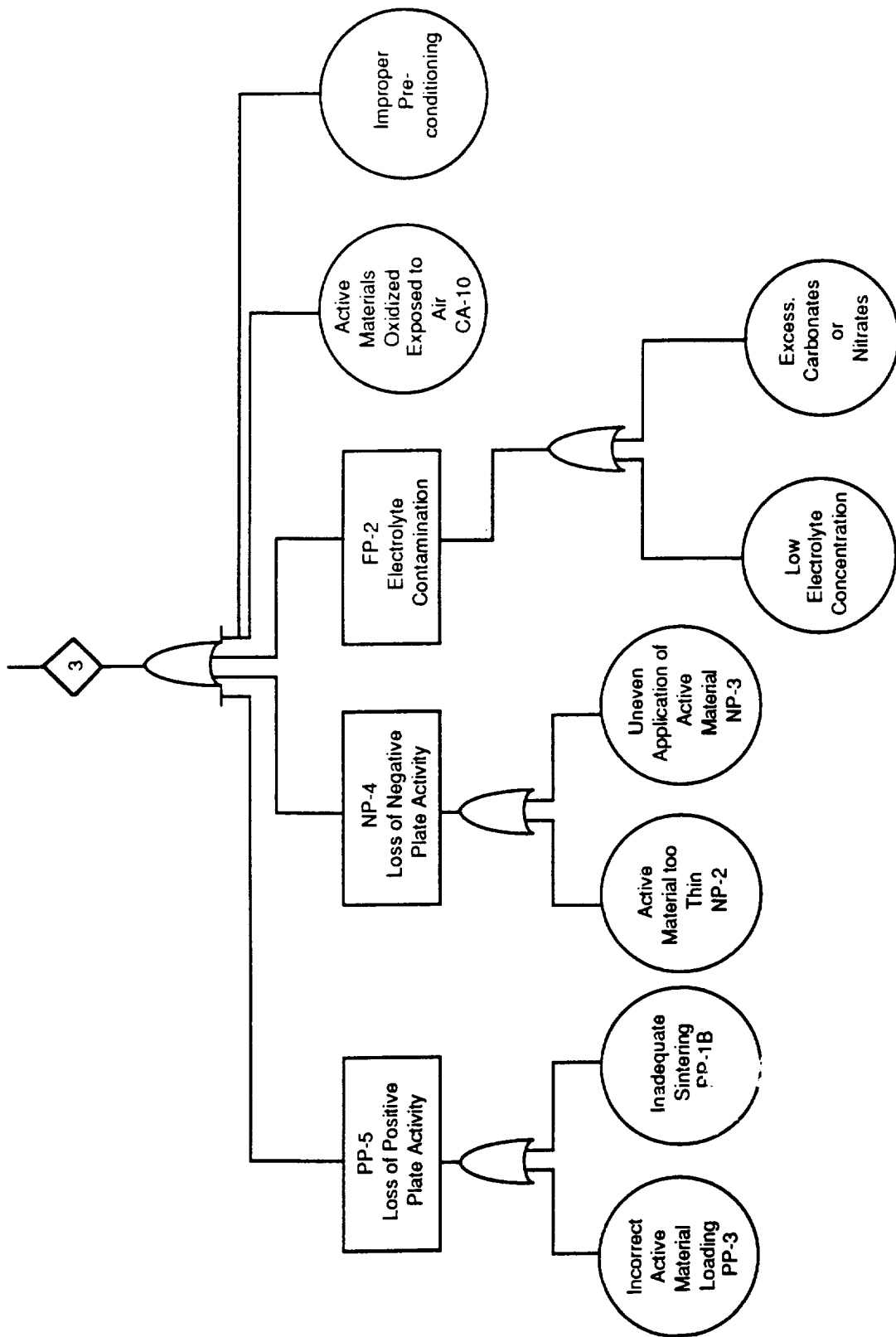


FIGURE 18

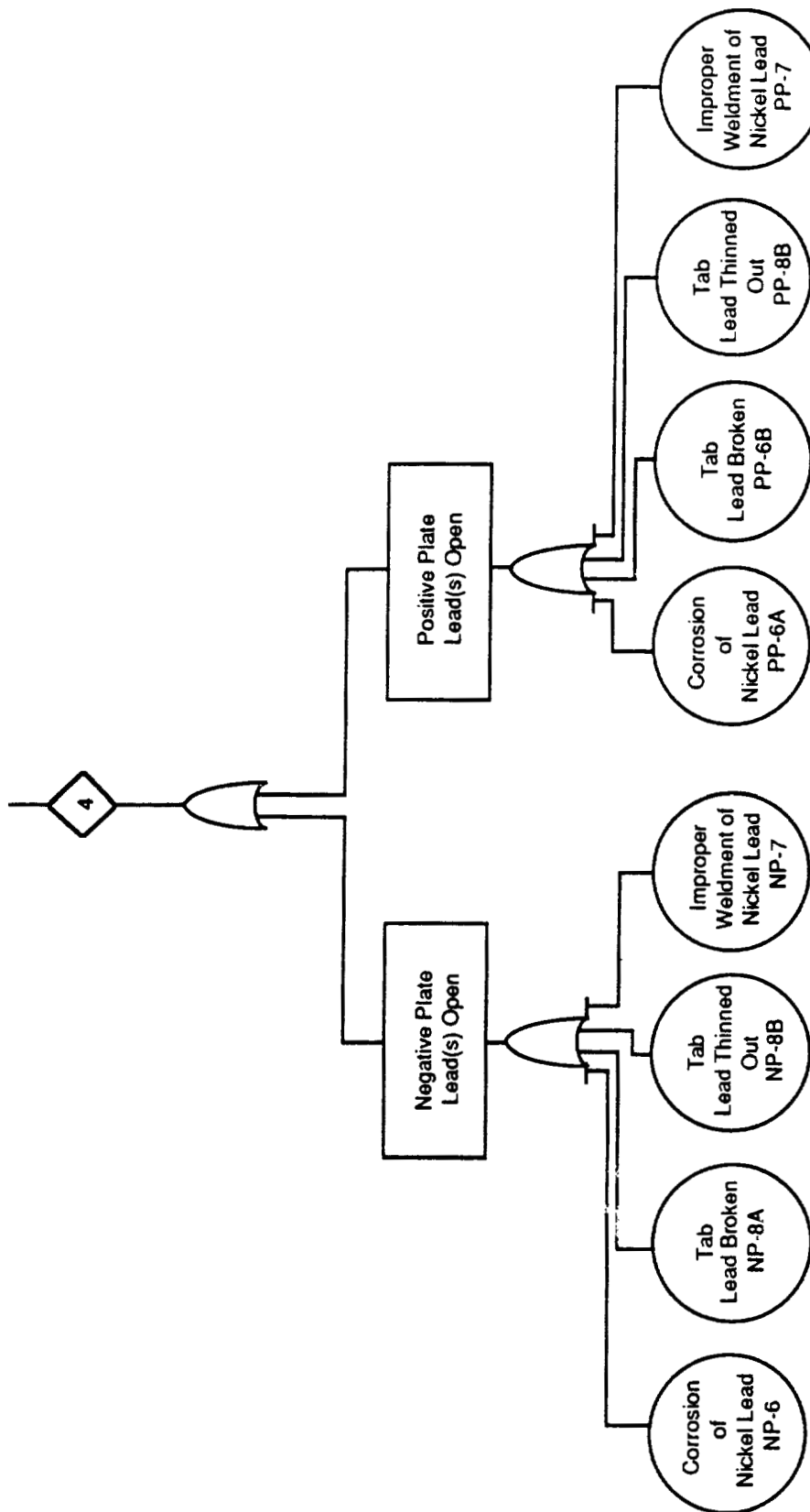


FIGURE 19

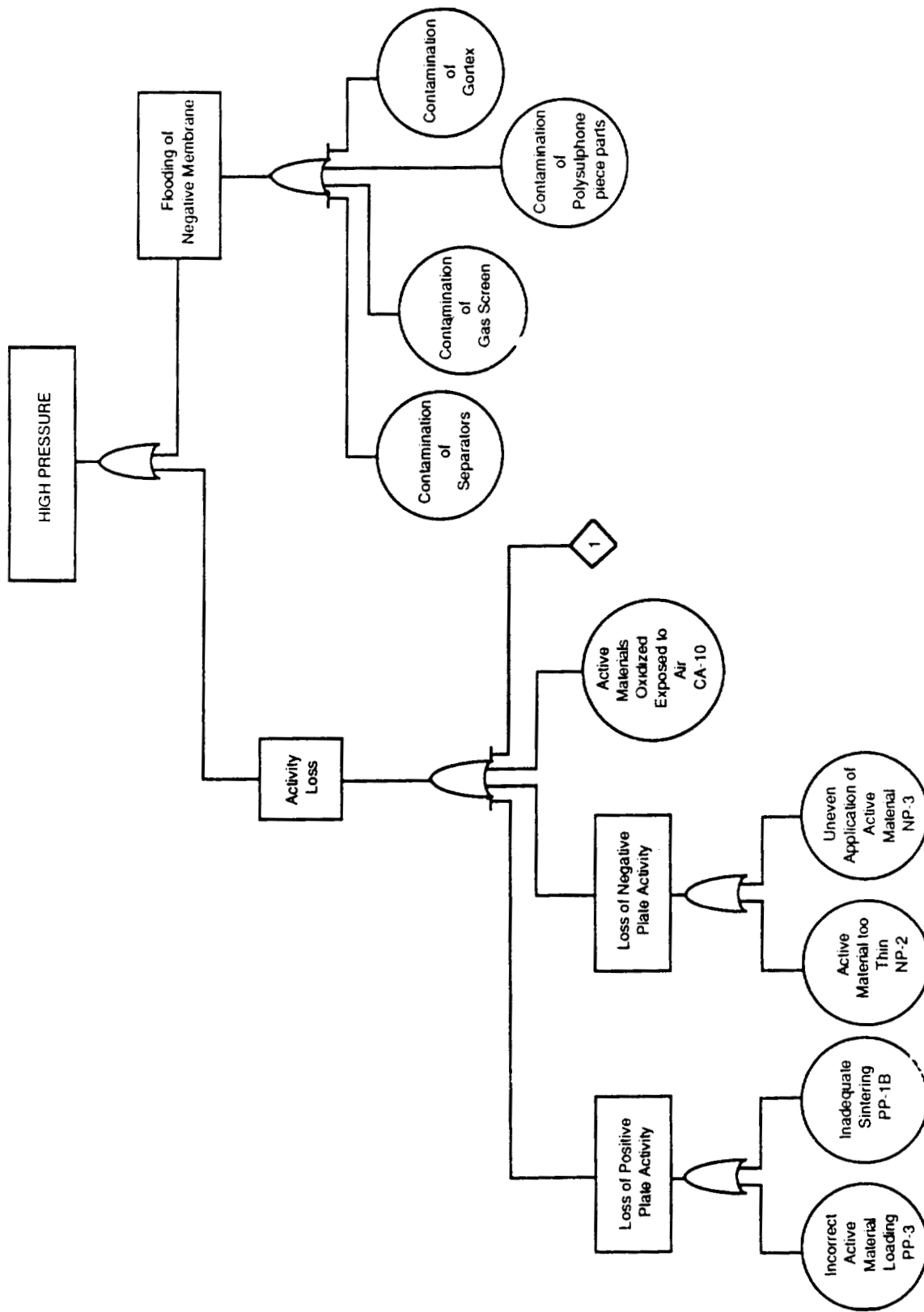


FIGURE 20

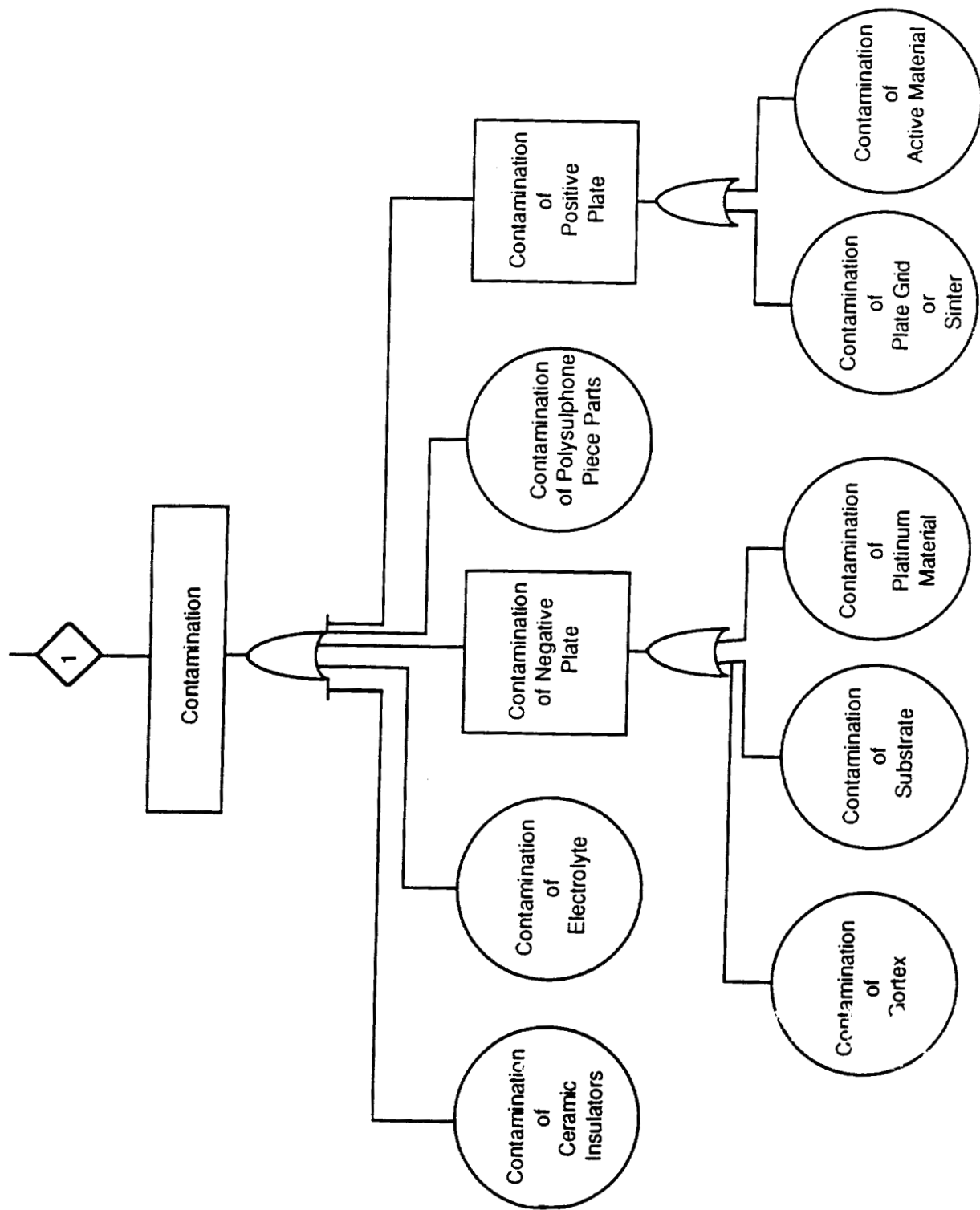


FIGURE 21

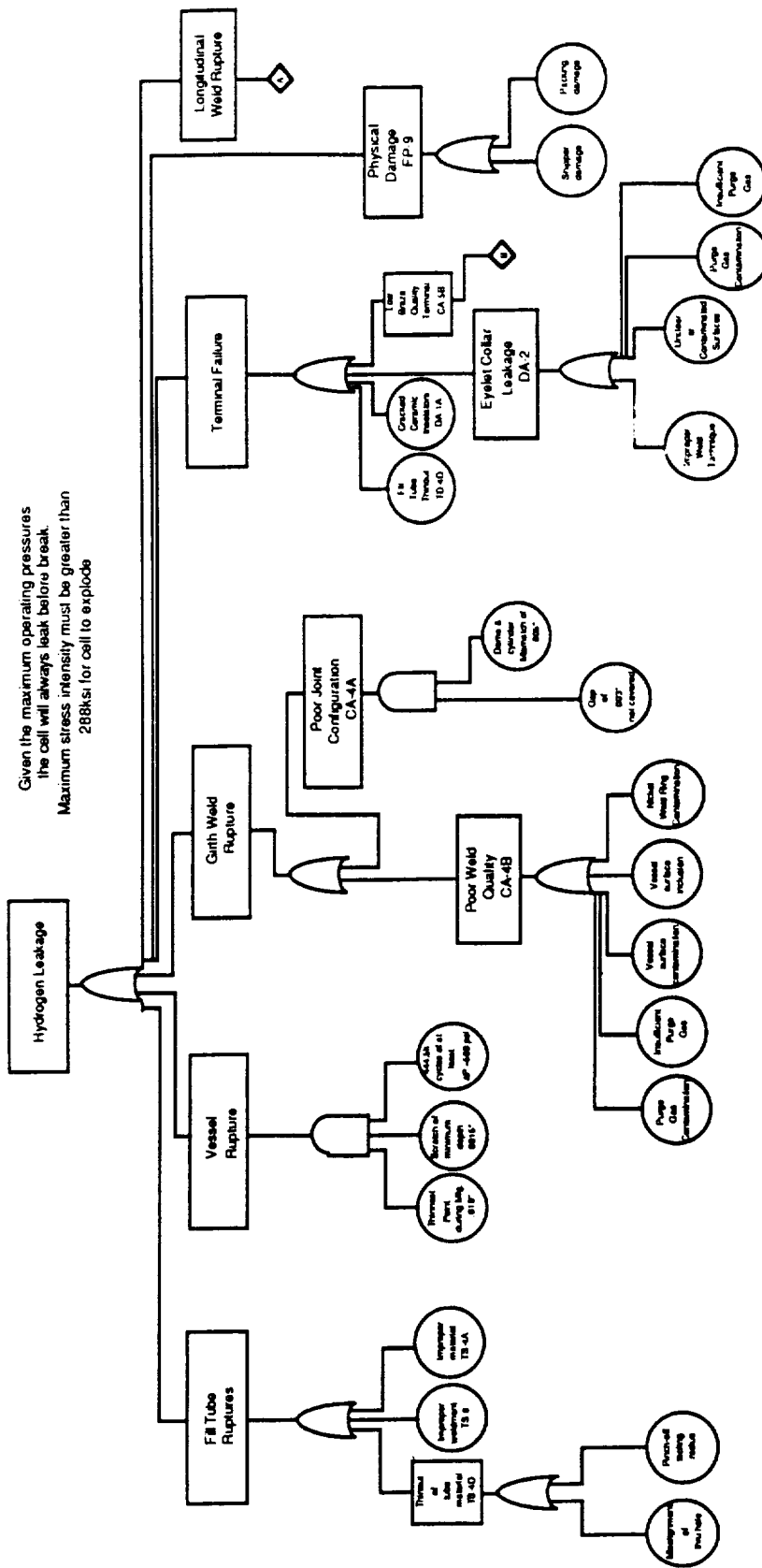


FIGURE 22



## Failure Modes and Effects Analysis on Gates NiH<sub>2</sub> Battery for LEO Mission

FMEA NO. CA-4B  
 Critical Item (Yes/No) Yes  
 Item Name: Girth weld  
 Part Number: 149C1930AJ1  
 Quantity: 1  
 Hardware Location: (Internal)  
 System: NiH<sub>2</sub> Battery  
 Subsystem: Cell assembly  
 Reference Designator: \_\_\_\_\_  
 Hardware (Including Redundancy)  
 Operating Verification:  
 (A) Checkout  
     (1) Prelaunch      PASS  
     (2) On Orbit      FAIL  
 (B) Detectability      PASS  
 (Appropriate Mission Phases)

Document Number: RAC NiH<sub>2</sub> 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): TDB

Reliability Analysis Center	Gates Battery
Prepared By: <u>D. Rash</u>	Approved By: _____
Approved By: <u>G. Ebel</u>	Approved By: _____

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/operation pressure & safety factor of 4 for burst/operating cycles  
 (Note: Rational for Acceptability is applicable to CIL Items only) (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 analysis; 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<sub>2</sub> cells in LEO Mission identifies and analyzes five specific Top-Level failure events; quantification of this Fault Tree has already begun.

### **References**

- 1) Fault Tree Handbook, NUREG-0492, U.S. Nuclear Regulator Commission, Washington, DC, (1981)
- 2) Fault Tree Analysis Application Guide, Reliability Analysis Center, Rome, NY, (1990).





# 50 Ah Ni H2 CELL LIFE TEST RESULTS

by

Thierry JAMIN

CNES - Toulouse Space Center, France

and

Olivier PUIG

SAFT Aerospace department

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# HISTORIC

- DEVELOPMENT OF A MEDIUM CAPACITY RANGE (30 - 50 Ah) IPV SAFT Ni H<sub>2</sub> CELL (1985 - 1988)
- SHORT TERM QUALIFICATION TESTING REALISED BY MID 1988

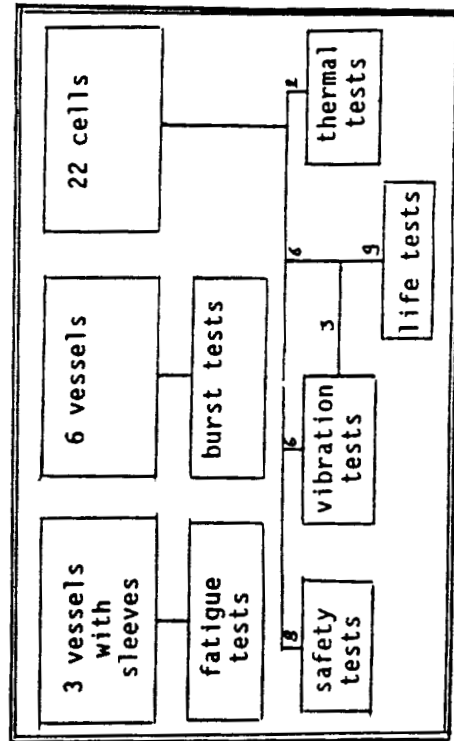
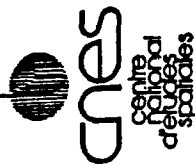


Table 1 : Qualification Test Programm



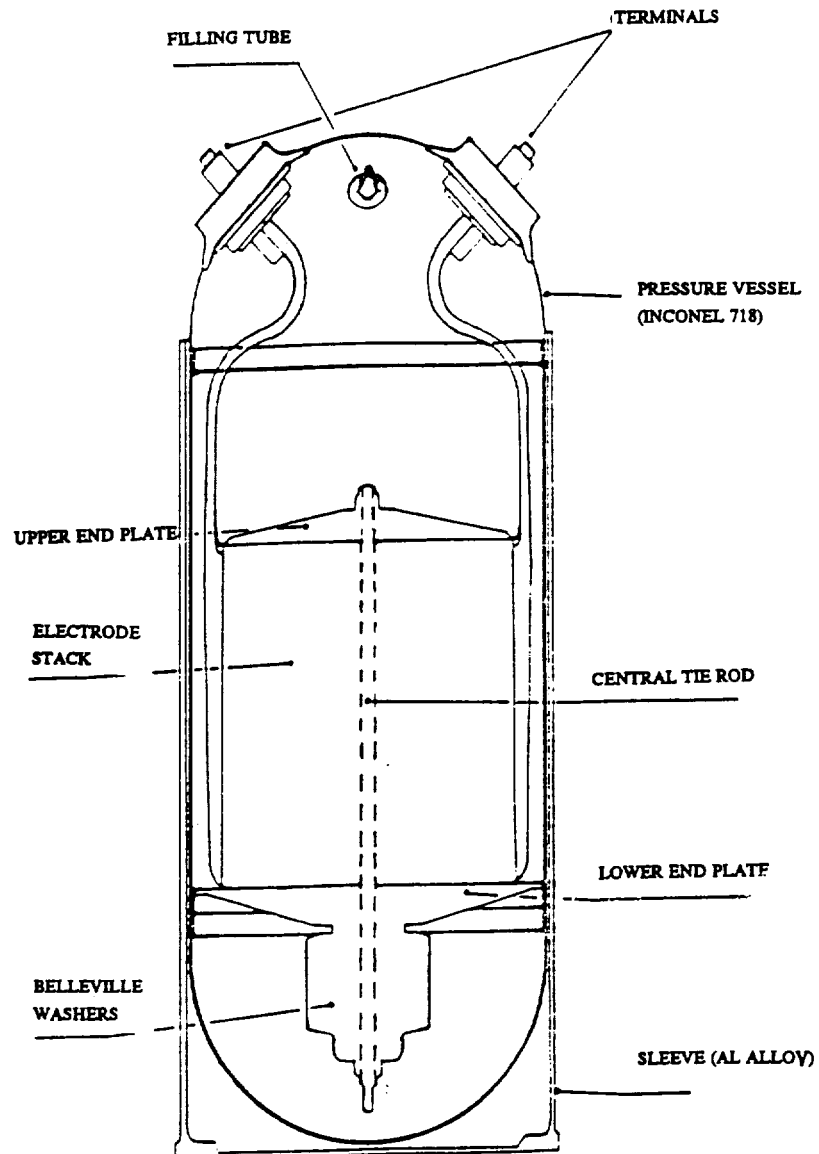
## **SAFT 50 Ah CELL DESIGN (VHS BL SERIE)**

### **MECHANICAL/VESSEL DESIGN**

- PRESSURE VESSEL MADE OF HEAT TREATED INCONEL 718 PARTS.
- VESSEL DIAEMETER 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 ( I TERMINALS PLAN)
- TIG WELDING TECHNIQUE FOR ALL JONCTIONS.
- MOP : 1070 PSI/SAFETY FACTOR : 2,5.

# SAFT 50 Ah CELL DESIGN

## (VHS BL SERIE)



1991 MSFC - Battery Workshop - 29-31/10/91



## **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 COLECTOR : EXPANDED NICKEL GRID.
- CATALYST : PT CHARCOAL + TEFLONISED BINDER.
- HYDROPHOBIC BACK LAYER : MICROPOROUS PTFE.



## **SAFT 50 Ah CELL DESIGN (VHS BL SERIE)**

### ELECTROCHEMICAL/STACK DESIGN (suite)

#### **SEPARATOR**

- MULTILAYERED NON WOVEN POLYAMID FELT.

#### **GAS - SCREEN**

- WOVEN NYLON MATERIAL.

#### **ELECTROLYTE**

- 31 % w KOH (BEFORE ACTIVATION)

### THERMAL DESIGN

#### **SINGLE PIECE SLEEVE TO BASEPLATE**

- LIGHT AL. ALLOY.

#### **GAP INTERFILLER**

- POLYMERIC RESIN.

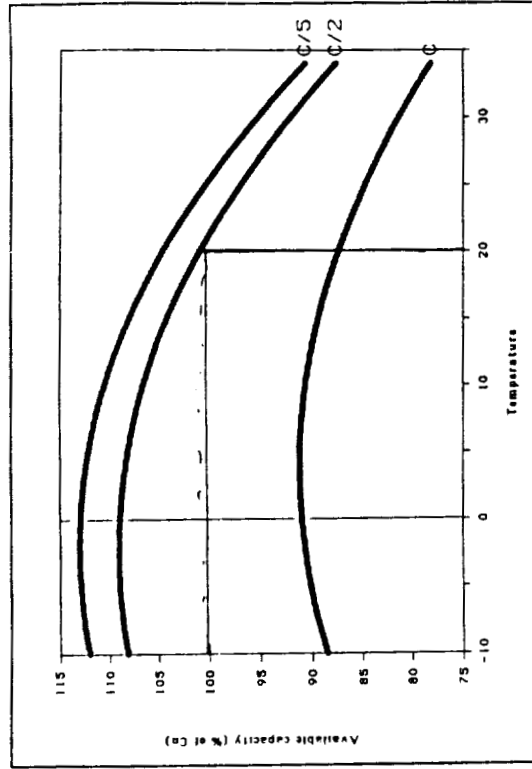


# SAFT 50 Ah CELL DESIGN (VHS BL SERIE)

## ELECTRICAL CHARACTERISTICS

CAPACITY	51,5 Ah
ENERGY DENSITY	48 Wh/Kg
VOLUMIC ENERGY	70 Wh/L
INTERNAL RESISTANCE	< 3 mΩ

MEAN VALUES ON THE QUALIFICATION LOT.



Available Capacity



## 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

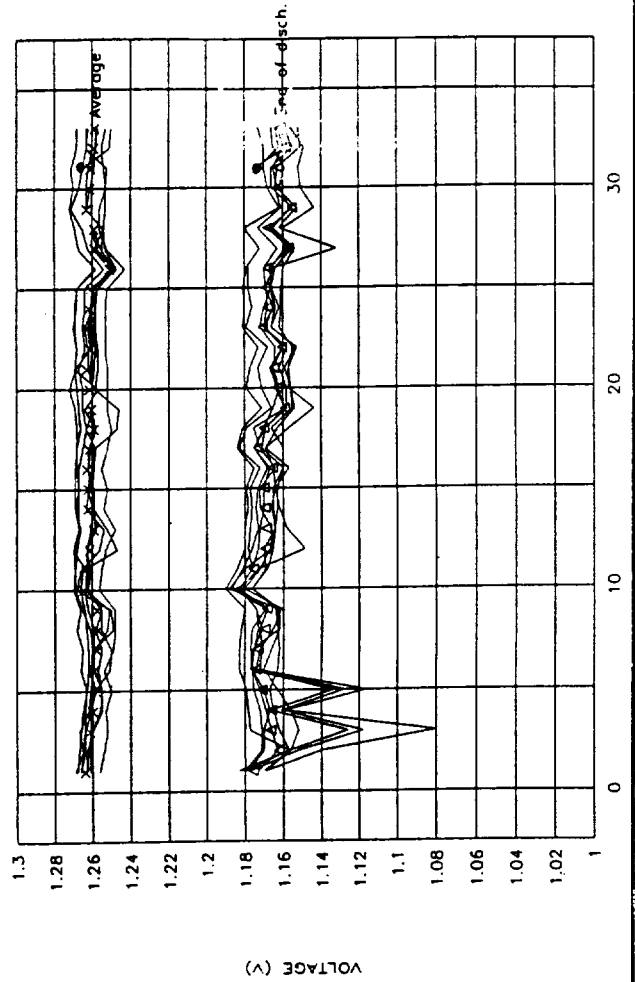
- DISCHARGE REGIM	C/1.7
- DOD	70 %
- CHARGE REGIM	C/14
- RETURN FACTOR	1.15 - 1.17
- REGIM:	C/200 - C/100
- REFERENCE TEMPERATURE	10°C

# SAFT 50 Ah CELL LIFE TEST

## RESULTS

### DISCHARGE VOLTAGE EVOLUTION

- STABILITY FOR MEAN DISCHARGE VOLTAGE (1,26 V).
- SLIGHT DECREASE FOR EOD VOLTAGE : 1,16 V/EOL.

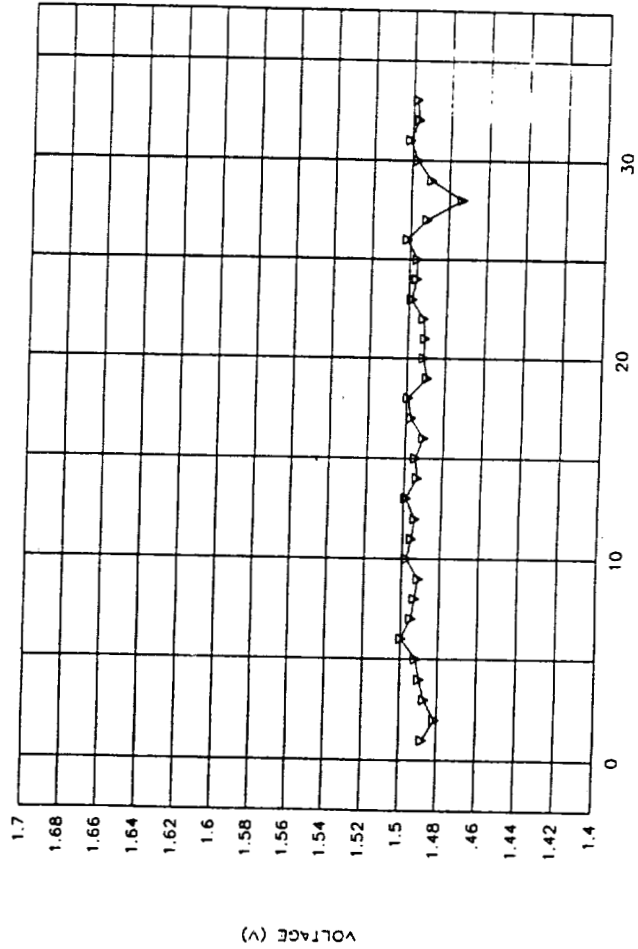




# SAFT 50 Ah CELL LIFE TEST RESULTS

## END OF CHARGE VOLTAGE EVOLUTION

- NO APPARENT DEGRADATION (1,5 V)

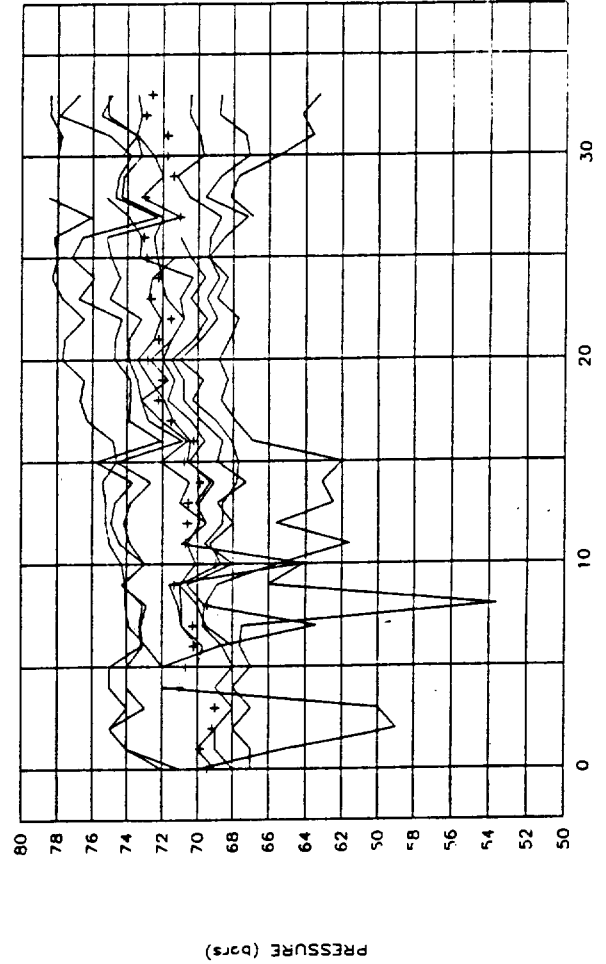




# SAFT 50 Ah CELL LIFE TEST RESULTS

## END OF CHARGE PRESSURE EVOLUTION REFERENCE CYCLE

- NO PRESSURE STABILITY ALONG THE WHOLE TEST.
- AT MAXIMUM CYCLING PRESSURE  $\bar{P}$  IS 4 BARS.







## SAFT 50 Ah CELL LIFE TEST RESULTS

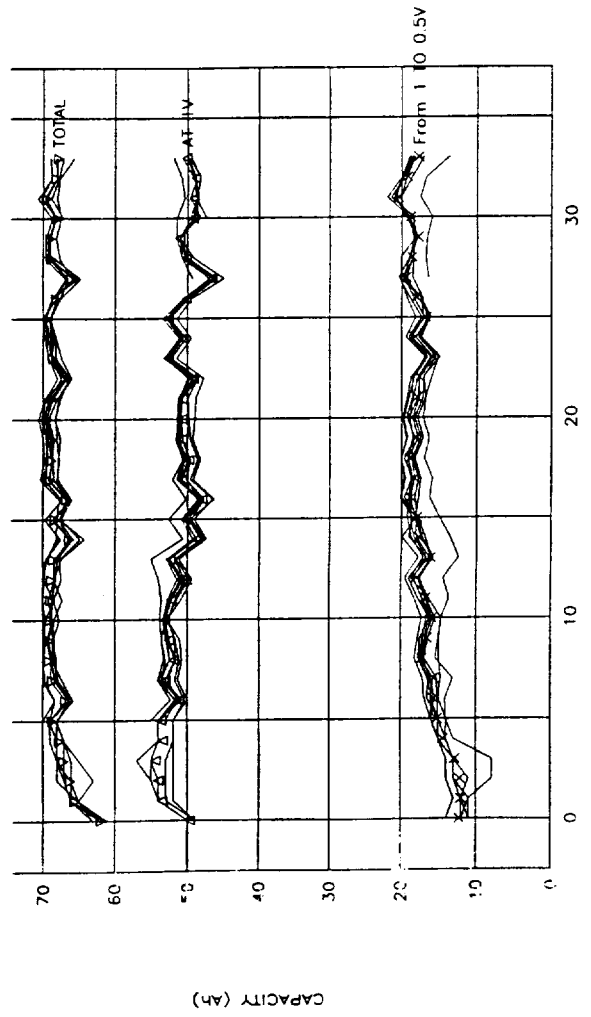
### STANDARD CAPACITY MEASUREMENT

- 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.

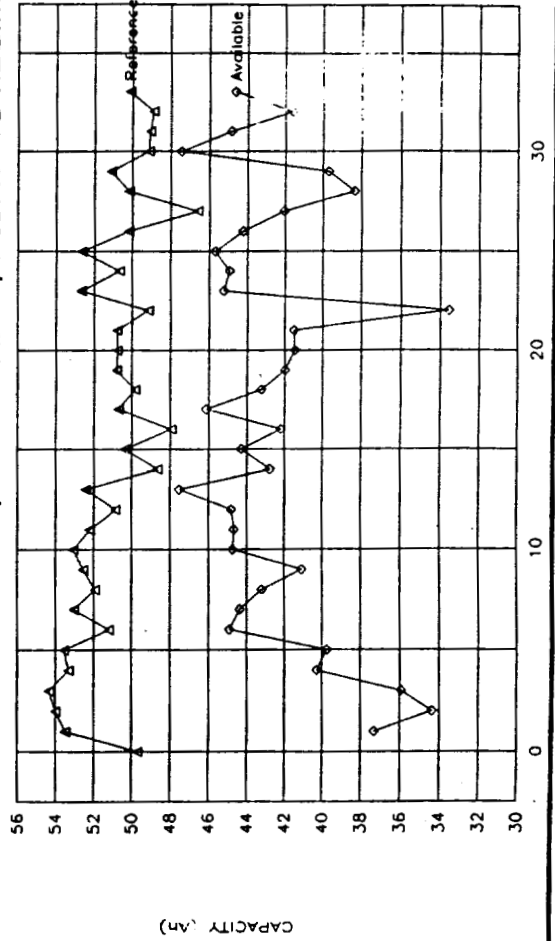




# SAFT 50 Ah CELL LIFE TEST RESULTS

## COMPARISON BETWEEN ON CYCLE AVAILABLE CAPACITY AND STANDARD CAPACITY

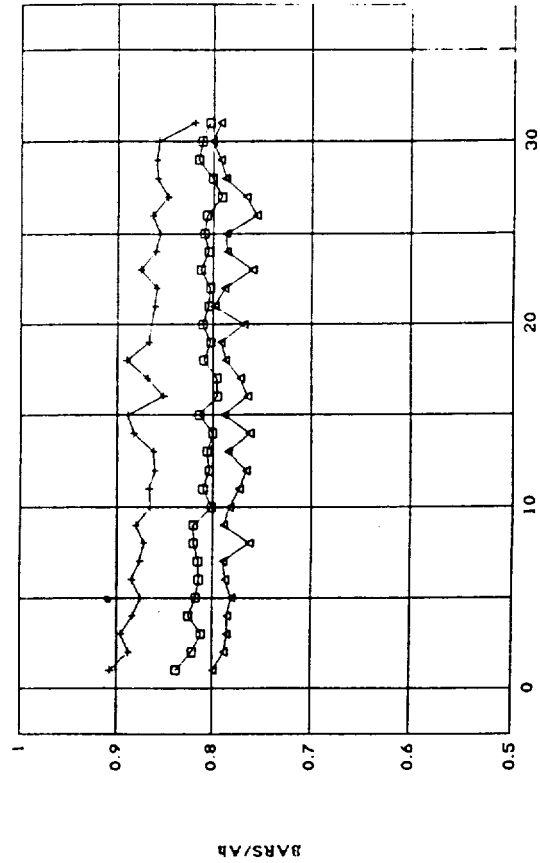
- CAPACITY AT 1 V UNDER CYCLING DISCHARGE REGIM REPRESENTS 80 TO 95 % (WRT STANDARD CAPACITY).
- DEPENDS ON STATE OF CHARGE (AND K VALUE, FLOATING REGIM, TEMPERATURE).



# SAFT 50 Ah CELL LIFE TEST RESULTS

## COULOMBIC EFFICIENCY EVOLUTION FOR REFERENCE CYCLE

- SMALL DISCHARGE EFFICIENCY DIMINUTION/TO COUPLE WITH MAX PRESSURE EVOLUTION.





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## 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.

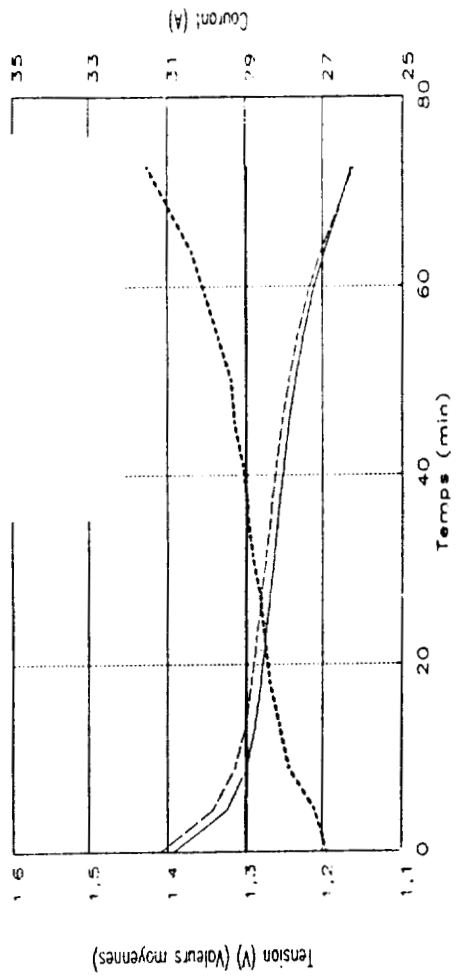


# SAFT 50 Ah CELL LIFE TEST RESULTS

## 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.

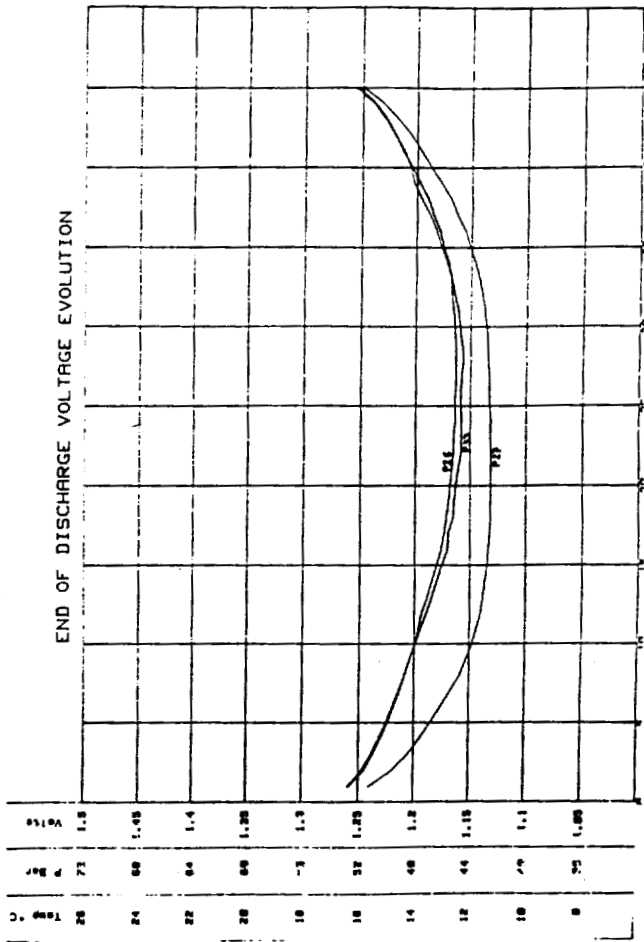




# SAFT 50 Ah CELL LIFE TEST RESULTS

## RECONDITIONNING EFFECT

- CELL 9 WASN'T RECONDITIONED AFTER SEASON 26.
- DIRECT EFFECT IS OBSERVED ON SEASON 27.

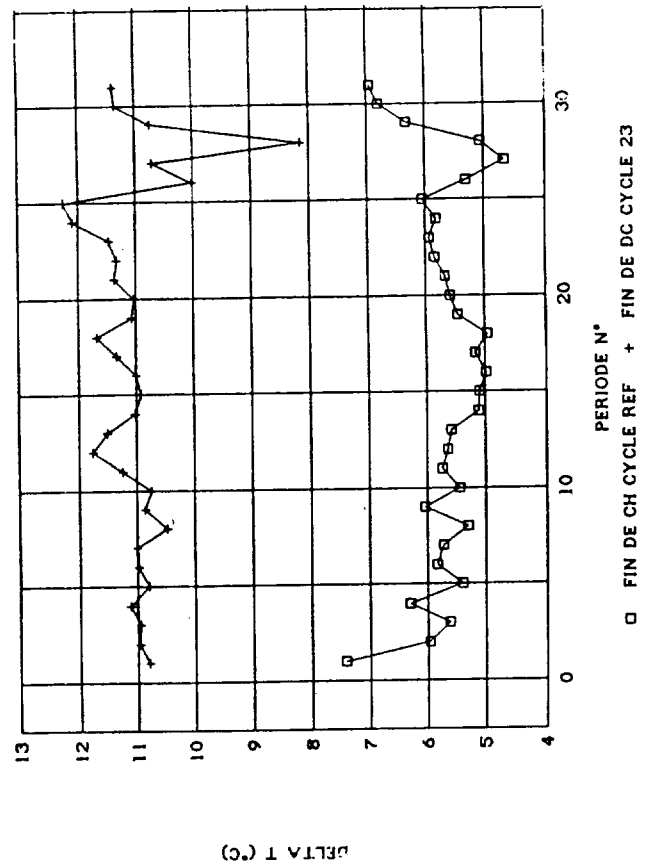




# SAFT 50 Ah CELL LIFE TEST RESULTS

## TEMPERATURE EVOLUTION

- CONDUCTION GRADIENT BETWEEN CELL/SLEEVE WALL AND BASEPLATE ARE SLIGHTLY RISING AS AN AGEING EFFECT WITH CYCLES.



1991 NASA Aerospace Battery Workshop - 23/07/89

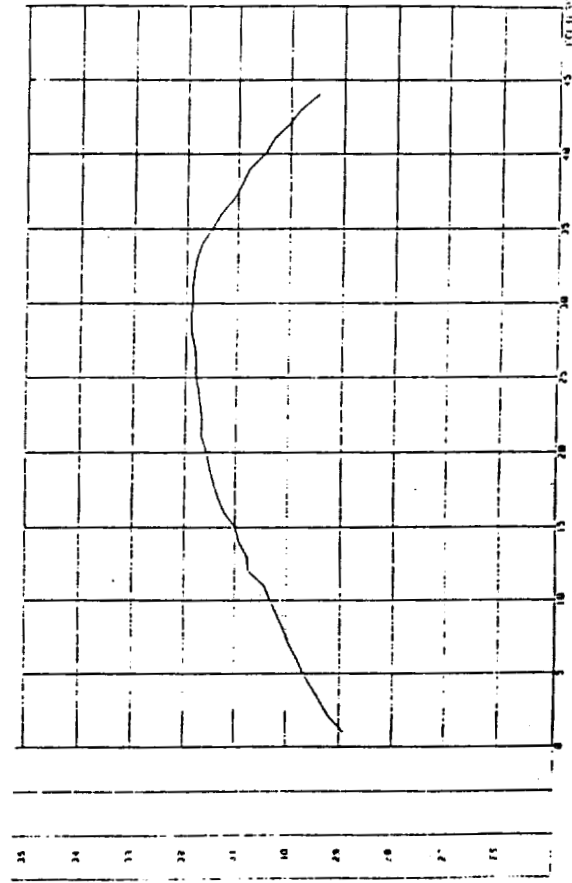




# SAFT 50 Ah CELL LIFE TEST RESULTS

## 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 EXCESS 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

- AN OTHER 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.
- START UP : BEGINNING OF 1992.
- FIVE YEARS LIFE TEST.







Electronics Division  
Joplin, MO

ADVANCED SYSTEMS OPERATION

# 1991 NASA AEROSPACE BATTERY WORKSHOP

## 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
- \* MULTIPLE 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



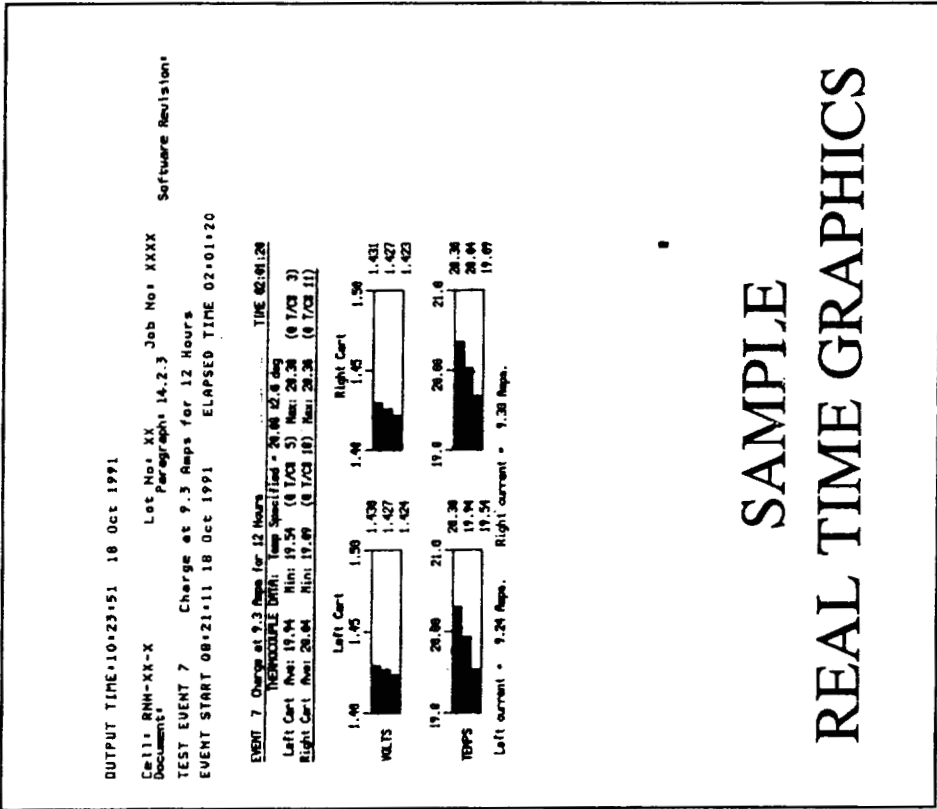


ADVANCED SYSTEMS OPERATION

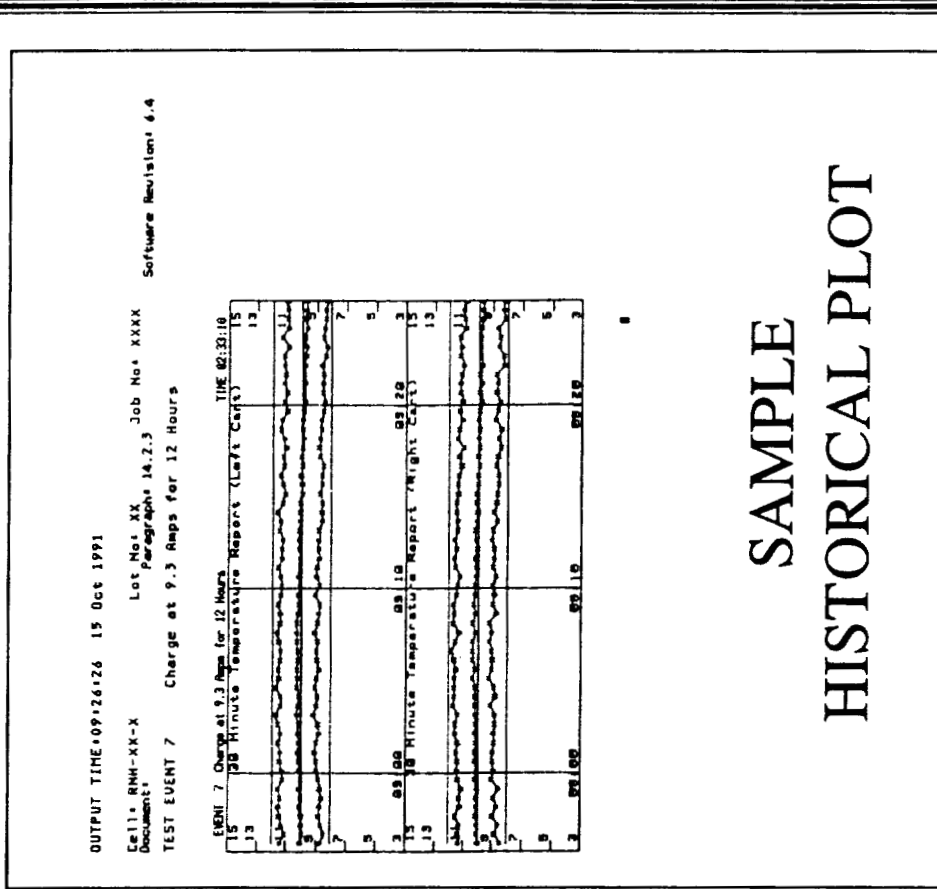


Electronics Division  
Joplin, MO

1991 NASA AEROSPACE BATTERY WORKSHOP



SAMPLE  
REAL TIME GRAPHICS



SAMPLE  
HISTORICAL PLOT



OUTPUT TIME: 18:40:19 14 Oct 1991  
 Cell: RHN-XX-X Let No: XX Paragraph: 14.2.3 Job No: XXXX Software Revision: 6.4  
 Document: ATP-XXX Rev X  
 TEST EVENT 7 Charge at 9.5 Ramps for 12 Hours  
 EVENT START 14:40:14 14 Oct 1991 ELAPSED TIME 02:00:00

CELL VOLTAGES	CELL VOLTAGES	CELL VOLTAGES	CELL VOLTAGES
11 1.424	21 1.424	31 1.425	41 1.425
12 1.424	22 1.427	32 1.427	42 1.427
13 1.425	23 1.427	33 1.427	43 1.427
14 1.425	24 1.427	34 1.427	44 1.427
15 1.427	25 1.427	35 1.427	45 1.427
16 1.427	26 1.427	36 1.427	46 1.427
17 1.427	27 1.427	37 1.427	47 1.427
18 1.427	28 1.427	38 1.427	48 1.427
19 1.427	29 1.427	39 1.427	49 1.427
20 1.427	30 1.427	40 1.427	50 1.427

Stress Gages:  
 1 0.000000 2 0.000000 3 0.000000 4 0.000000 5 0.000000 6 0.000000 7 0.000000 8 0.000000  
 9 0.000000 10 0.000000 11 0.000000 12 0.000000 13 0.000000 14 0.000000 15 0.000000

Thermistors:  
 1 2.2964 2 2.2962 3 2.2917 4 2.2917

Excitation Voltages: 15.766000

SAMPLE  
 CELL LEVEL  
 PRINTOUT

Post-Thermal Vac Testing  
 Battery: SRR-XXXXX Paragraph: 6.16.3.5 Software Revision: 6.14  
 Document: ATP-XXX Rev X  
 TEST EVENT 5 Nameplate - Initial Charge - Step 2  
 EVENT START 08:47:04 24 Jul 1991 ELAPSED TIME 11:00:00

CELL CHANNELS	CELL CHANNELS	CELL CHANNELS	CELL CHANNELS
1 1.514	2 1.511	3 1.514	4 1.513
5 1.515	6 1.511	7 1.513	8 1.512
9 1.515	10 1.511	11 1.513	12 1.514
13 1.515	14 1.511	15 1.513	16 1.512
17 1.515	18 1.511	19 1.513	20 1.514
21 1.515	22 1.511	23 1.513	24 1.514
25 1.515	26 1.511	27 1.513	28 1.514
29 1.515	30 1.511	31 1.513	32 1.514
33 1.515	34 1.511	35 1.513	36 1.514
37 1.515	38 1.511	39 1.513	40 1.514
41 1.515	42 1.511	43 1.513	44 1.514
45 1.515	46 1.511	47 1.513	48 1.514
49 1.515	50 1.511	51 1.513	52 1.514

T/C Data (Deg C):  
 1 9.20 2 9.11 3 8.40 4 10.42 5 10.42 6 9.97  
 7 10.38 8 9.14 9 10.42 10 10.42 11 10.42 12 10.42  
 13 10.42 14 10.42 15 10.42 16 10.42 17 10.42 18 10.42  
 19 10.42 20 10.42 21 10.42 22 10.42 23 10.42 24 10.42  
 25 10.42 26 10.42 27 10.42 28 10.42 29 10.42 30 10.42  
 31 10.42 32 10.42 33 10.42 34 10.42 35 10.42 36 10.42  
 37 10.42 38 10.42 39 10.42 40 10.42 41 10.42 42 10.42  
 43 10.42 44 10.42 45 10.42 46 10.42 47 10.42 48 10.42  
 49 10.42 50 10.42 51 10.42 52 10.42

Strain Gages:  
 1 3.30404 (793.0) 2 3.37333 (857.4) 3 3.32104 (845.0)  
 4 3.40944 (860.3) 5 3.40944 (860.3) 6 3.40944 (860.3)  
 7 3.40944 (860.3) 8 3.40944 (860.3) 9 3.40944 (860.3)  
 10 3.40944 (860.3) 11 3.40944 (860.3) 12 3.40944 (860.3)  
 13 3.40944 (860.3) 14 3.40944 (860.3) 15 3.40944 (860.3)  
 16 3.40944 (860.3) 17 3.40944 (860.3) 18 3.40944 (860.3)  
 19 3.40944 (860.3) 20 3.40944 (860.3) 21 3.40944 (860.3)  
 22 3.40944 (860.3) 23 3.40944 (860.3) 24 3.40944 (860.3)  
 25 3.40944 (860.3) 26 3.40944 (860.3) 27 3.40944 (860.3)  
 28 3.40944 (860.3) 29 3.40944 (860.3) 30 3.40944 (860.3)  
 31 3.40944 (860.3) 32 3.40944 (860.3) 33 3.40944 (860.3)  
 34 3.40944 (860.3) 35 3.40944 (860.3) 36 3.40944 (860.3)  
 37 3.40944 (860.3) 38 3.40944 (860.3) 39 3.40944 (860.3)  
 40 3.40944 (860.3) 41 3.40944 (860.3) 42 3.40944 (860.3)  
 43 3.40944 (860.3) 44 3.40944 (860.3) 45 3.40944 (860.3)  
 46 3.40944 (860.3) 47 3.40944 (860.3) 48 3.40944 (860.3)  
 49 3.40944 (860.3) 50 3.40944 (860.3) 51 3.40944 (860.3)  
 52 3.40944 (860.3)

Thermistors:  
 1 3.3275.4 (11.41) 2 3.3275.4 (11.29) 3 3.3275.4 (11.29)  
 4 3.3275.4 (11.41) 5 3.3275.4 (11.29) 6 3.3275.4 (11.29)  
 7 3.3275.4 (11.41) 8 3.3275.4 (11.29) 9 3.3275.4 (11.29)  
 10 3.3275.4 (11.41) 11 3.3275.4 (11.29) 12 3.3275.4 (11.29)  
 13 3.3275.4 (11.41) 14 3.3275.4 (11.29) 15 3.3275.4 (11.29)  
 16 3.3275.4 (11.41) 17 3.3275.4 (11.29) 18 3.3275.4 (11.29)  
 19 3.3275.4 (11.41) 20 3.3275.4 (11.29) 21 3.3275.4 (11.29)  
 22 3.3275.4 (11.41) 23 3.3275.4 (11.29) 24 3.3275.4 (11.29)  
 25 3.3275.4 (11.41) 26 3.3275.4 (11.29) 27 3.3275.4 (11.29)  
 28 3.3275.4 (11.41) 29 3.3275.4 (11.29) 30 3.3275.4 (11.29)  
 31 3.3275.4 (11.41) 32 3.3275.4 (11.29) 33 3.3275.4 (11.29)  
 34 3.3275.4 (11.41) 35 3.3275.4 (11.29) 36 3.3275.4 (11.29)  
 37 3.3275.4 (11.41) 38 3.3275.4 (11.29) 39 3.3275.4 (11.29)  
 40 3.3275.4 (11.41) 41 3.3275.4 (11.29) 42 3.3275.4 (11.29)  
 43 3.3275.4 (11.41) 44 3.3275.4 (11.29) 45 3.3275.4 (11.29)  
 46 3.3275.4 (11.41) 47 3.3275.4 (11.29) 48 3.3275.4 (11.29)  
 49 3.3275.4 (11.41) 50 3.3275.4 (11.29) 51 3.3275.4 (11.29)  
 52 3.3275.4 (11.41)

Excit. Voltages:  
 1 3.50.065 2 3.57333 (857.4) 3 3.52104 (845.0)  
 4 3.50.065 5 3.57333 (857.4) 6 3.52104 (845.0)  
 7 3.50.065 8 3.57333 (857.4) 9 3.52104 (845.0)  
 10 3.50.065 11 3.57333 (857.4) 12 3.52104 (845.0)  
 13 3.50.065 14 3.57333 (857.4) 15 3.52104 (845.0)  
 16 3.50.065 17 3.57333 (857.4) 18 3.52104 (845.0)  
 19 3.50.065 20 3.57333 (857.4) 21 3.52104 (845.0)  
 22 3.50.065 23 3.57333 (857.4) 24 3.52104 (845.0)  
 25 3.50.065 26 3.57333 (857.4) 27 3.52104 (845.0)  
 28 3.50.065 29 3.57333 (857.4) 30 3.52104 (845.0)  
 31 3.50.065 32 3.57333 (857.4) 33 3.52104 (845.0)  
 34 3.50.065 35 3.57333 (857.4) 36 3.52104 (845.0)  
 37 3.50.065 38 3.57333 (857.4) 39 3.52104 (845.0)  
 40 3.50.065 41 3.57333 (857.4) 42 3.52104 (845.0)  
 43 3.50.065 44 3.57333 (857.4) 45 3.52104 (845.0)  
 46 3.50.065 47 3.57333 (857.4) 48 3.52104 (845.0)  
 49 3.50.065 50 3.57333 (857.4) 51 3.52104 (845.0)  
 52 3.50.065

SAMPLE  
 BATTERY LEVEL  
 PRINTOUT



# 1991 NASA AEROSPACE BATTERY WORKSHOP

Activation and Conditioning / Cell Selection  
 Cell: RNH-KX-X Lot Nos. 14  
 Document: EP-PP-XXX Rev X Paragraph: 3.2.2  
 TEST EVENT 32 Cell Matching Discharge  
 Time to bypass at 1.000 volt

Software Revision: 6.4

Cell #	Min V	Max V	Cell #	Min V	Max V	Cell #	Min V	Max V
1	376.10	94.8	376.10	94.8	94.8	106	376.10	94.8
2	376.10	94.8	376.10	94.8	94.8	107	376.10	94.8
3	376.10	94.8	376.10	94.8	94.8	108	376.10	94.8
4	376.10	94.8	376.10	94.8	94.8	109	376.10	94.8
5	376.10	94.8	376.10	94.8	94.8	110	376.10	94.8
6	376.10	94.8	376.10	94.8	94.8	111	376.10	94.8
7	376.10	94.8	376.10	94.8	94.8	112	376.10	94.8
8	376.10	94.8	376.10	94.8	94.8	113	376.10	94.8
9	376.10	94.8	376.10	94.8	94.8	114	376.10	94.8
10	376.10	94.8	376.10	94.8	94.8	115	376.10	94.8
11	376.10	94.8	376.10	94.8	94.8	116	376.10	94.8
12	376.10	94.8	376.10	94.8	94.8	117	376.10	94.8
13	376.10	94.8	376.10	94.8	94.8	118	376.10	94.8
14	376.10	94.8	376.10	94.8	94.8	119	376.10	94.8
15	376.10	94.8	376.10	94.8	94.8	120	376.10	94.8
16	376.10	94.8	376.10	94.8	94.8	121	376.10	94.8
17	376.10	94.8	376.10	94.8	94.8	122	376.10	94.8
18	376.10	94.8	376.10	94.8	94.8	123	376.10	94.8
19	376.10	94.8	376.10	94.8	94.8	124	376.10	94.8
20	376.10	94.8	376.10	94.8	94.8	125	376.10	94.8
21	376.10	94.8	376.10	94.8	94.8	126	376.10	94.8
22	376.10	94.8	376.10	94.8	94.8	127	376.10	94.8
23	376.10	94.8	376.10	94.8	94.8	128	376.10	94.8
24	376.10	94.8	376.10	94.8	94.8	129	376.10	94.8
25	376.10	94.8	376.10	94.8	94.8	130	376.10	94.8
26	376.10	94.8	376.10	94.8	94.8	131	376.10	94.8
27	376.10	94.8	376.10	94.8	94.8	132	376.10	94.8
28	376.10	94.8	376.10	94.8	94.8	133	376.10	94.8
29	376.10	94.8	376.10	94.8	94.8	134	376.10	94.8
30	376.10	94.8	376.10	94.8	94.8	135	376.10	94.8
31	376.10	94.8	376.10	94.8	94.8	136	376.10	94.8
32	376.10	94.8	376.10	94.8	94.8	137	376.10	94.8
33	376.10	94.8	376.10	94.8	94.8	138	376.10	94.8
34	376.10	94.8	376.10	94.8	94.8	139	376.10	94.8
35	376.10	94.8	376.10	94.8	94.8	140	376.10	94.8
36	376.10	94.8	376.10	94.8	94.8	141	376.10	94.8
37	376.10	94.8	376.10	94.8	94.8	142	376.10	94.8
38	376.10	94.8	376.10	94.8	94.8	143	376.10	94.8
39	376.10	94.8	376.10	94.8	94.8	144	376.10	94.8
40	376.10	94.8	376.10	94.8	94.8	145	376.10	94.8
41	376.10	94.8	376.10	94.8	94.8	146	376.10	94.8
42	376.10	94.8	376.10	94.8	94.8	147	376.10	94.8
43	376.10	94.8	376.10	94.8	94.8	148	376.10	94.8
44	376.10	94.8	376.10	94.8	94.8	149	376.10	94.8
45	376.10	94.8	376.10	94.8	94.8	150	376.10	94.8
46	376.10	94.8	376.10	94.8	94.8	151	376.10	94.8
47	376.10	94.8	376.10	94.8	94.8	152	376.10	94.8
48	376.10	94.8	376.10	94.8	94.8	153	376.10	94.8
49	376.10	94.8	376.10	94.8	94.8	154	376.10	94.8
50	376.10	94.8	376.10	94.8	94.8	155	376.10	94.8
51	376.10	94.8	376.10	94.8	94.8	156	376.10	94.8
52	376.10	94.8	376.10	94.8	94.8	157	376.10	94.8
53	376.10	94.8	376.10	94.8	94.8	158	376.10	94.8
54	376.10	94.8	376.10	94.8	94.8	159	376.10	94.8
55	376.10	94.8	376.10	94.8	94.8	160	376.10	94.8
56	376.10	94.8	376.10	94.8	94.8	161	376.10	94.8
57	376.10	94.8	376.10	94.8	94.8	162	376.10	94.8
58	376.10	94.8	376.10	94.8	94.8	163	376.10	94.8
59	376.10	94.8	376.10	94.8	94.8	164	376.10	94.8
60	376.10	94.8	376.10	94.8	94.8	165	376.10	94.8
61	376.10	94.8	376.10	94.8	94.8	166	376.10	94.8
62	376.10	94.8	376.10	94.8	94.8	167	376.10	94.8
63	376.10	94.8	376.10	94.8	94.8	168	376.10	94.8
64	376.10	94.8	376.10	94.8	94.8	169	376.10	94.8
65	376.10	94.8	376.10	94.8	94.8	170	376.10	94.8
66	376.10	94.8	376.10	94.8	94.8	171	376.10	94.8
67	376.10	94.8	376.10	94.8	94.8	172	376.10	94.8
68	376.10	94.8	376.10	94.8	94.8	173	376.10	94.8
69	376.10	94.8	376.10	94.8	94.8	174	376.10	94.8
70	376.10	94.8	376.10	94.8	94.8	175	376.10	94.8
71	376.10	94.8	376.10	94.8	94.8	176	376.10	94.8
72	376.10	94.8	376.10	94.8	94.8	177	376.10	94.8
73	376.10	94.8	376.10	94.8	94.8	178	376.10	94.8
74	376.10	94.8	376.10	94.8	94.8	179	376.10	94.8
75	376.10	94.8	376.10	94.8	94.8	180	376.10	94.8
76	376.10	94.8	376.10	94.8	94.8	181	376.10	94.8
77	376.10	94.8	376.10	94.8	94.8	182	376.10	94.8
78	376.10	94.8	376.10	94.8	94.8	183	376.10	94.8
79	376.10	94.8	376.10	94.8	94.8	184	376.10	94.8
80	376.10	94.8	376.10	94.8	94.8	185	376.10	94.8
81	376.10	94.8	376.10	94.8	94.8	186	376.10	94.8
82	376.10	94.8	376.10	94.8	94.8	187	376.10	94.8
83	376.10	94.8	376.10	94.8	94.8	188	376.10	94.8
84	376.10	94.8	376.10	94.8	94.8	189	376.10	94.8
85	376.10	94.8	376.10	94.8	94.8	190	376.10	94.8
86	376.10	94.8	376.10	94.8	94.8	191	376.10	94.8
87	376.10	94.8	376.10	94.8	94.8	192	376.10	94.8
88	376.10	94.8	376.10	94.8	94.8	193	376.10	94.8
89	376.10	94.8	376.10	94.8	94.8	194	376.10	94.8
90	376.10	94.8	376.10	94.8	94.8	195	376.10	94.8
91	376.10	94.8	376.10	94.8	94.8	196	376.10	94.8
92	376.10	94.8	376.10	94.8	94.8	197	376.10	94.8
93	376.10	94.8	376.10	94.8	94.8	198	376.10	94.8
94	376.10	94.8	376.10	94.8	94.8	199	376.10	94.8
95	376.10	94.8	376.10	94.8	94.8	200	376.10	94.8
96	376.10	94.8	376.10	94.8	94.8	201	376.10	94.8
97	376.10	94.8	376.10	94.8	94.8	202	376.10	94.8
98	376.10	94.8	376.10	94.8	94.8	203	376.10	94.8
99	376.10	94.8	376.10	94.8	94.8	204	376.10	94.8
100	376.10	94.8	376.10	94.8	94.8	205	376.10	94.8
101	376.10	94.8	376.10	94.8	94.8	206	376.10	94.8
102	376.10	94.8	376.10	94.8	94.8	207	376.10	94.8
103	376.10	94.8	376.10	94.8	94.8	208	376.10	94.8
104	376.10	94.8	376.10	94.8	94.8	209	376.10	94.8
105	376.10	94.8	376.10	94.8	94.8	210	376.10	94.8
106	376.10	94.8	376.10	94.8	94.8	211	376.10	94.8
107	376.10	94.8	376.10	94.8	94.8	212	376.10	94.8
108	376.10	94.8	376.10	94.8	94.8	213	376.10	94.8
109	376.10	94.8	376.10	94.8	94.8	214	376.10	94.8
110	376.10	94.8	376.10	94.8	94.8	215	376.10	94.8
111	376.10	94.8	376.10	94.8	94.8	216	376.10	94.8
112	376.10	94.8	376.10	94.8	94.8	217	376.10	94.8
113	376.10	94.8	376.10	94.8	94.8	218	376.10	94.8
114	376.10	94.8	376.10	94.8	94.8	219	376.10	94.8
115	376.10	94.8	376.10	94.8	94.8	220	376.10	94.8
116	376.10	94.8	376.10	94.8	94.8	221	376.10	94.8
117	376.10	94.8	376.10	94.8	94.8	222	376.10	94.8
118	376.10	94.8	376.10	94.8	94.8	223	376.10	94.8
119	376.10	94.8	376.10	94.8	94.8	224	376.10	94.8
120	376.10	94.8	376.10	94.8	94.8	225	376.10	94.8
121	376.10	94.8	376.10	94.8	94.8	226	376.10	94.8
122	376.10	94.8	376.10	94.8	94.8	227	376.10	94.8
123	376.10	94.8	376.10	94.8	94.8	228	376.10	94.8
124	376.10	94.8	376.10	94.8	94.8	229	376.10	94.8
125	376.10	94.8	376.10	94.8	94.8	230	376.10	94.8
126	376.10	94.8	376.10	94.8	94.8	231	376.10	94.8
127	376.10	94.8	376.10	94.8	94.8	232	376.10	94.8
128	376.10	94.8	376.10	94.8	94.8	233	376.10	94.8
129	376.10	94.8	376.10	94.8	94.8	234	376.10	94.8
130	376.10	94.8	376.10	94.8	94.8	235	376.10	94.8
131	376.10	94.8	376.10	94.8	94.8	236	376.10	94.8
132	376.10	94.8	376.10	94.8	94.8	237	376.10	94.8
133	376.10	94.8	376.10	94.8	94.8	238	376.10	94.8
134	376.10	94.8	376.10	94.8	94.8	239	376.10	94.8
135	376.10	94.8	376.10	94.8	94.8			



Electronics Division  
Joplin, MO

ADVANCED SYSTEMS OPERATION

# 1991 NASA AEROSPACE BATTERY WORKSHOP

## 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 INTER-FACES BUFFER
  - \* HEWLETT PACKARD 3852A DATA ACQUISITION AND CONTROL UNIT
  - \* HEWLETT PACKARD 3853A DACU EXTENDER
  - \* ELECTRONIC MEASUREMENT INCORPORATED EMHP-150-200 POWER SUPPLY



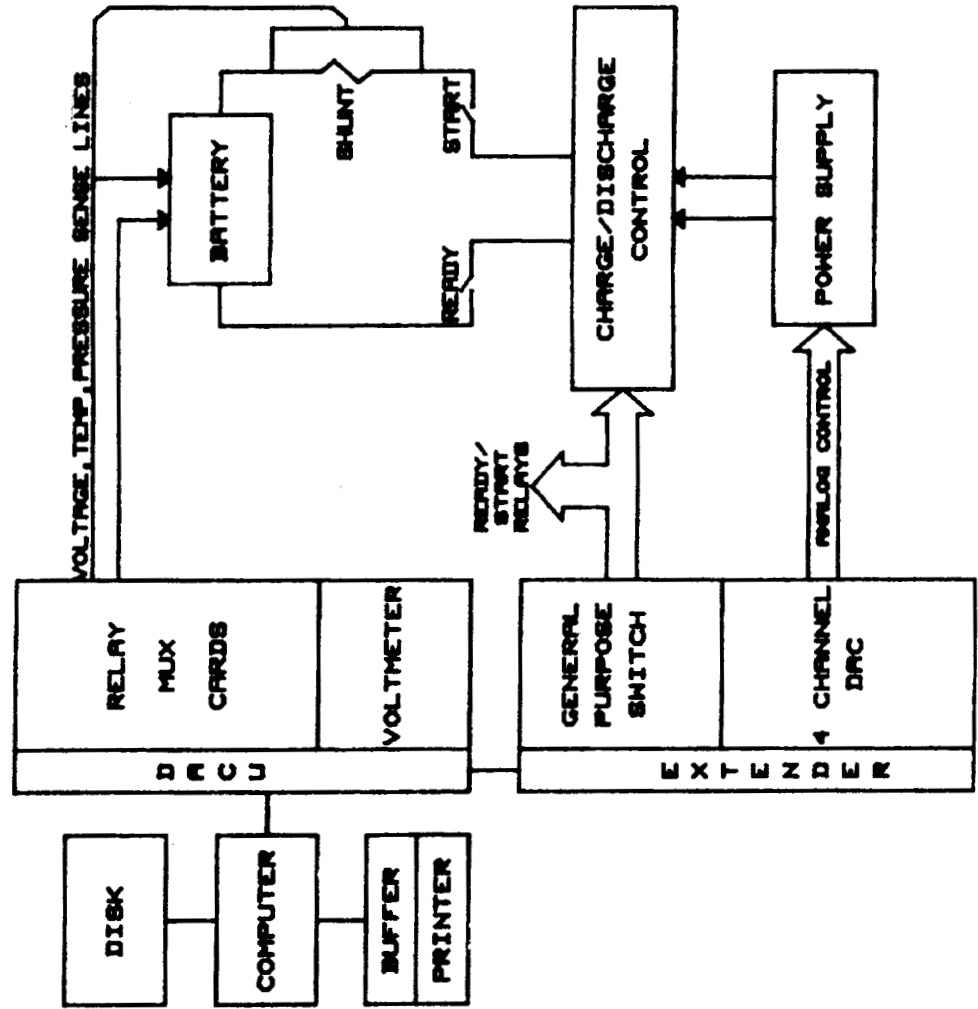


**STANDARD BATTERY LEVEL TESTING**

- \* 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 INTER-FACES BUFFER
  - \* HEWLETT PACKARD 3852A DATA ACQUISITION AND CONTROL UNIT
  - \* HEWLETT PACKARD 3853A DACU EXTENDER
  - \* ELECTRONIC MEASUREMENT INCORPORATED EMHP-80-250 POWER SUPPLY



STANDARD BATTERY LEVEL TEST SYSTEM



**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

Record	Event	Description
1		Stabilization at 10C
2	1	Start of Cycle (from 1 to max. of 20)
3	2	Charge at 9.3 Amps for 12 Hours
4	3	Discharge at 36 Amps (W/Pulse) to 0.5 Volts
5	4	Drain Cells to 0.1 V/Cell
6	5	Open Circuit for Decision to Continue Cycles
7		End of Cycle
8	6	Charge at 4 Amps for 36 Hours
9	7	Discharge at 36 A to 0.5 V/Cell
10	8	Drain Cells to 0.1 V/Cell
11	9	Open Circuit for Test Verification
12		End of Test

Sample Procedure File

Program: ATPXXX

Document: ATP-XXX Rev X Paragraph: 14.2.2  
 Event: 2 (Charge) Charge at 9.3 Amps for 12 Hours

Nominal 10.0 Abort Warn 1 Warn 2  
 Temperature: ±10.0 ± 2.0 ± 3.0 (Degrees C)  
 Time Volts  
 Termination: 12:00:00 n/a  
 Warning : Voltage > 1.520  
 Current : Nominal 9.30 Abort Warn  
 ±04.65 ±0.070  
 Print-outs : 5 Minute mark  
 Interval of 00:30:00  
 Operator command  
 Maximum voltage and time of some

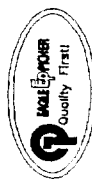
Sample Procedure File

Program: ATPXXX

Document: ATP-XXX Rev X Paragraph: 14.2.3  
 Event: 3 (Discharge) Discharge at 36 Amps (W/Pulse) to 0.5 Volts

Nominal 10.0 Abort Warn 1 Warn 2  
 Temperature: ±10.0 ± 2.0 ± 3.0 (Degrees C)  
 Time Volts  
 Termination: n/a .500  
 Current : Nominal 36.00 Abort Warn  
 @ 01:30:10 : 85.00 ±18.00 ±0.100  
 @ 01:30:40 : 36.00 ±42.50 ±0.100  
 ±18.00 ±0.100  
 Print-outs : 00:05:00 00:10:00 00:15:00  
 30 Minute intervals till .85% of capacity  
 5 Minute intervals thereafter  
 00:26:00 00:27:00  
 01:30:10 01:30:30  
 01:30:40  
 Operator command  
 Termination  
 Time to .500 volts  
 Time to .700 volts  
 Time to 1.000 volts  
 Time to 1.200 volts

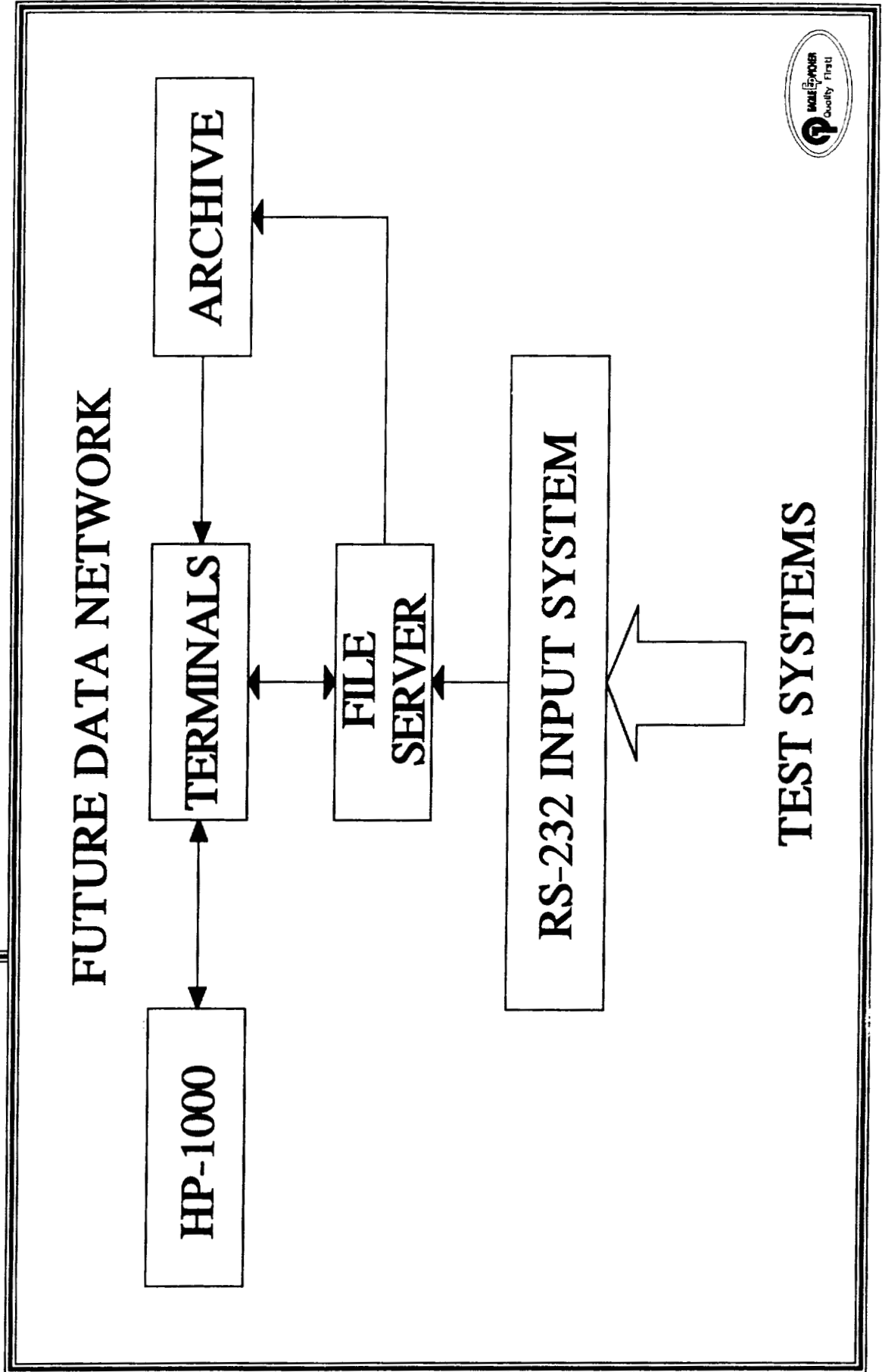
SAMPLE TEST DEFINITION SHEETS



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**

**John E. Lowery**

**National Aeronautics and Space Administration**

**George C. Marshall Space Flight Center**

**Information and Electronic Systems Laboratory**

**Marshall Space Flight Center, AL 35812**

## **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  $\text{CoHO}_2$  is formed from Nickel active material.**
- **$\text{CoHO}_2$  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 useable 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,  $\text{CoHO}_2$  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.

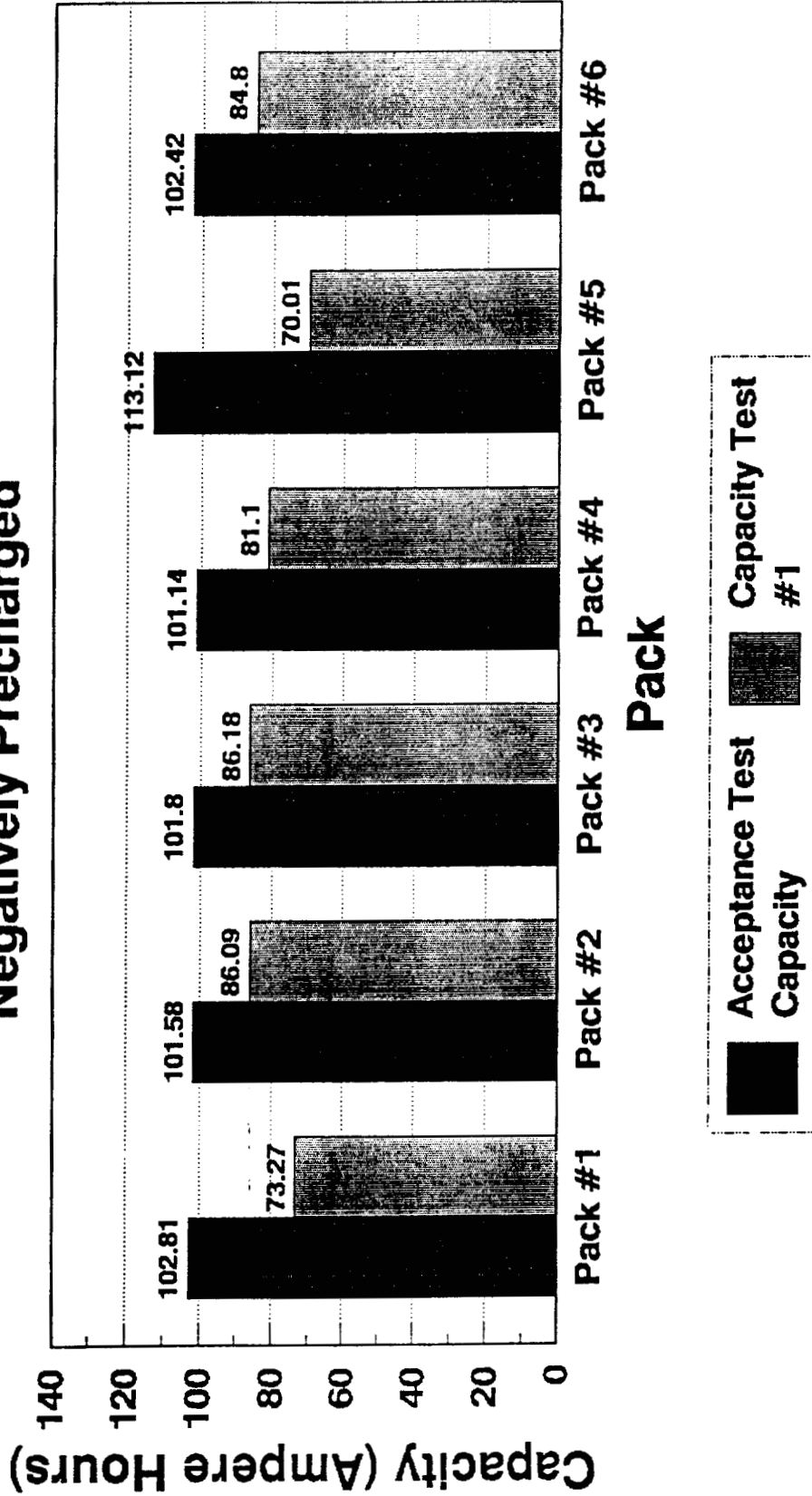
Subject test cells utilized in this test bed are Eagle-Picher RNH 90-3 cells remaining after completion of the Hubble Space Telescope (HST) program. There are 24 cells from three different cell builds (TM-1, FSM and FM-1) divided into six groups of four cells. Each cell has a cylindrical individual pressure 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



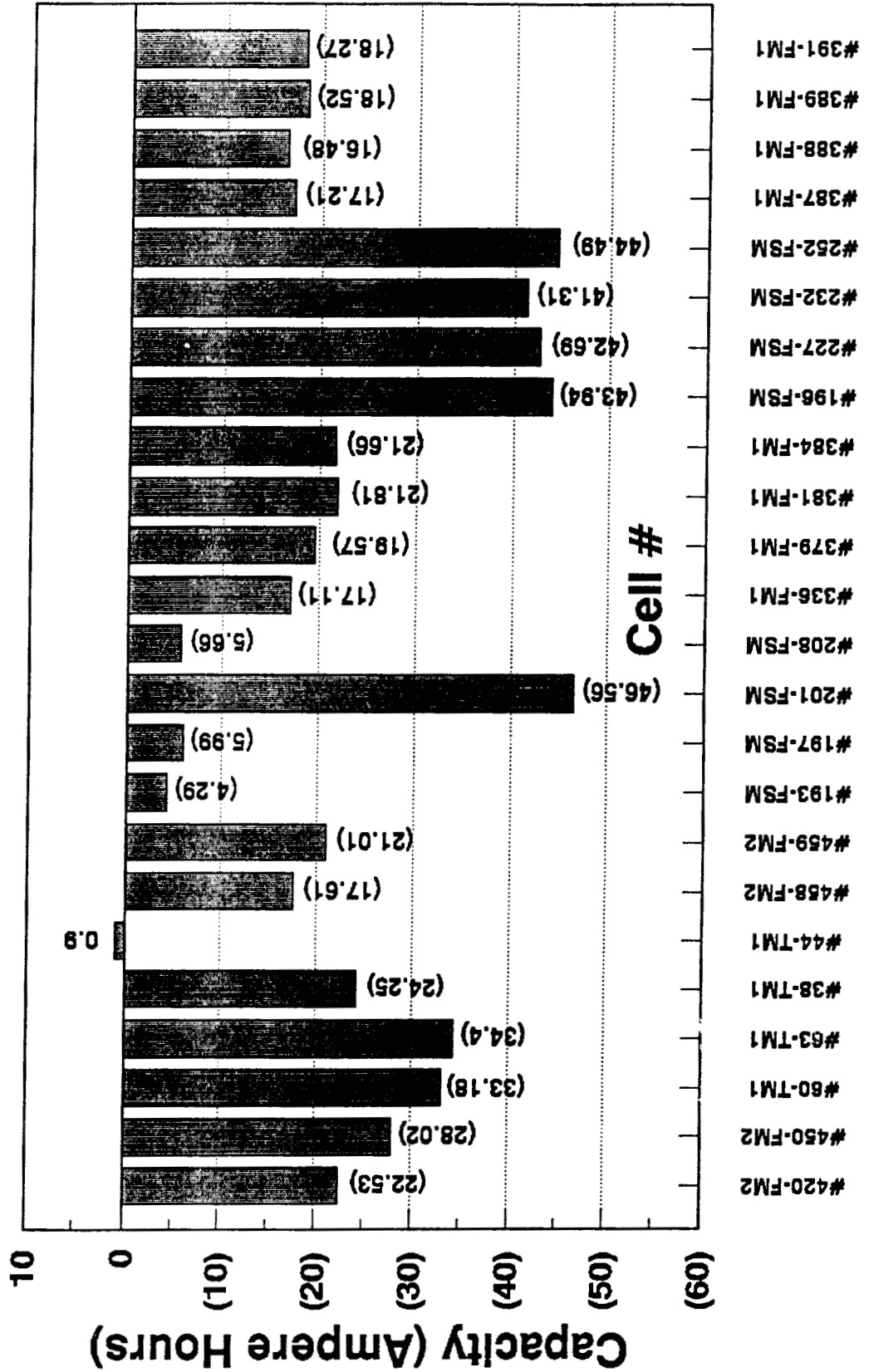
Acceptance Test Capacity, June 1989 - 1.2 Volts.  
 First Capacity Test, June 1991 - 1.0 Volts.

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



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.

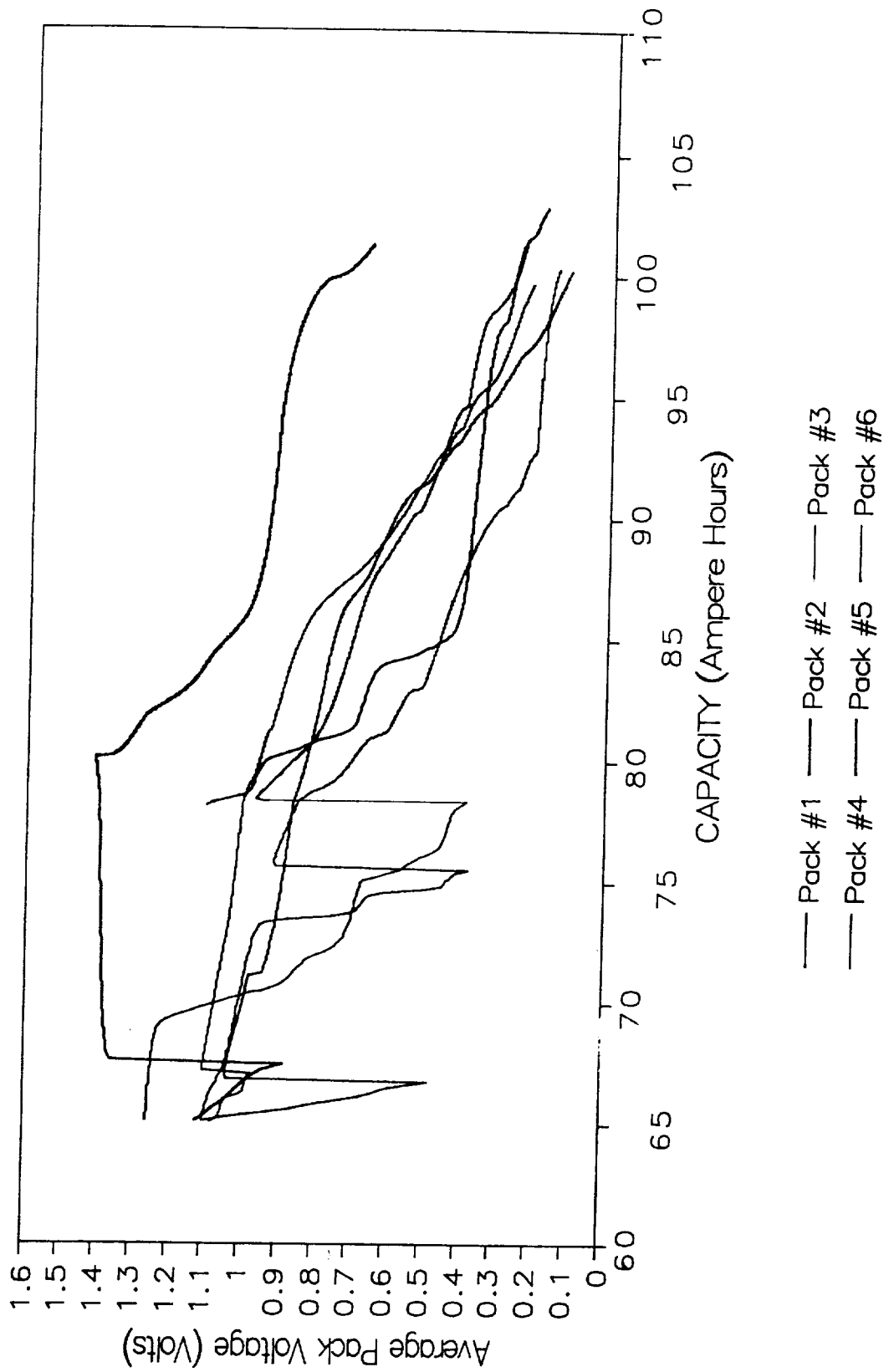
CAPACITY SUMMARY EPI RNH 90-3 (HST CELL)

Capacity Test #1, June 12, 1991, After baseline charge.

Pac #	Cell #	Lot	Serial #	Begin Pressure	Ending Pressure	Begin Voltage	Ahrs Cap to 1.0 V	Psi/Ahr
1	1	FM2	420	1126.24	538.28	1.407	78.3	7.51
	2	FM2	450	1297.7	513.6	1.41	75.27	10.42
	3	TM1	60	1069.82	410.35	1.406	69.52	9.49
	4	TM1	63	1139.43	449.91	1.407	70	9.85
2	1	TM1	38	1142.25	240.4	1.407	77.25	11.67
	2	TM1	44	978.1	11.16	1.396	102.8	9.41
	3	FM2	458	1223.57	441	1.412	84.1	9.31
	4	FM2	459	1058.99	357.2	1.41	80.2	8.75
3	1	FSM	193	1208.38	319.4	1.411	93.1	9.55
	2	FSM	197	1276.76	435.6	1.411	92.4	9.10
	3	FSM	201	1268.72	603.98	1.416	67.9	9.79
	4	FSM	208	1032.92	200.2	1.411	91.31	9.12
4	1	FM1	336	1054.24	322.7	1.41	82.1	8.91
	2	FM1	379	1103.08	345.5	1.411	82.1	9.23
	3	FM1	381	1115.41	392.7	1.412	79.4	9.10
	4	FM1	384	1150.47	387	1.411	80.8	9.45
5	1	FSM	196	1184.19	512.13	1.413	69.52	9.67
	2	FSM	227	1083.53	462.89	1.419	70.98	8.74
	3	FSM	232	1139.49	480.81	1.417	70.98	9.28
	4	FSM	252	1407.79	755.97	1.42	68.55	9.51
6	1	FM1	387	1142.51	331.2	1.412	85.5	9.49
	2	FM1	388	1111.73	305.1	1.409	85.4	9.45
	3	FM1	389	1212.22	418.3	1.413	84.4	9.41
	4	FM1	391	1108.53	333	1.411	83.9	9.24

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.

# Shifted Capacity EPI RNH 90-3

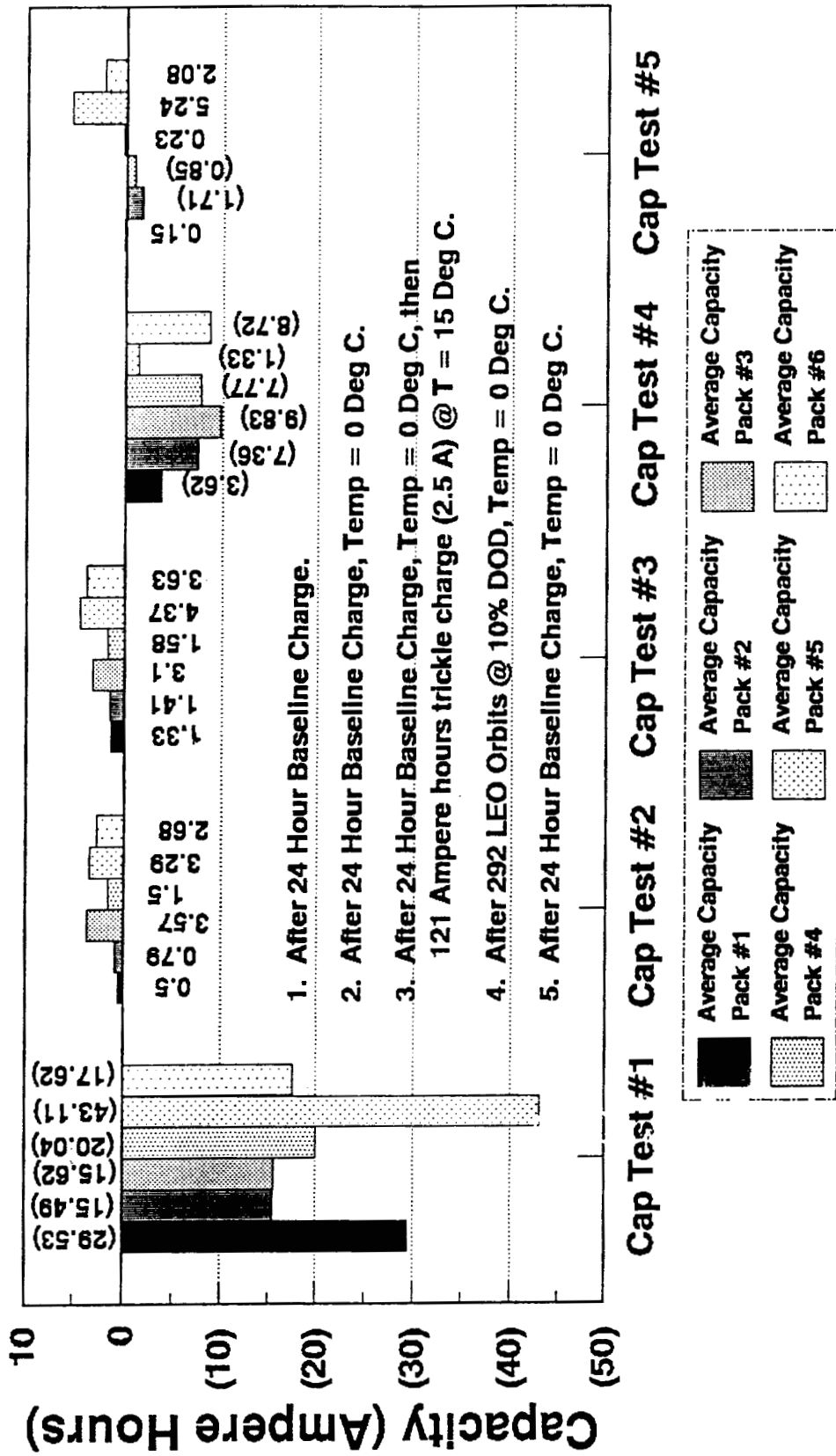


This graph is an attempt to ascertain a shift in capacity to a lower voltage plateau. The graph shows the average cell voltage at the end of the first capacity test as the pack entered reconditioning. The C/6 load was maintained as long as possible until all cells were below 1.0 volts before reconditioning. 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



Acceptance Test Capacity, June 1989 - 1.2 Volts.  
 Other Capacity Test's, - 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 fourth capacity test was run 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.**

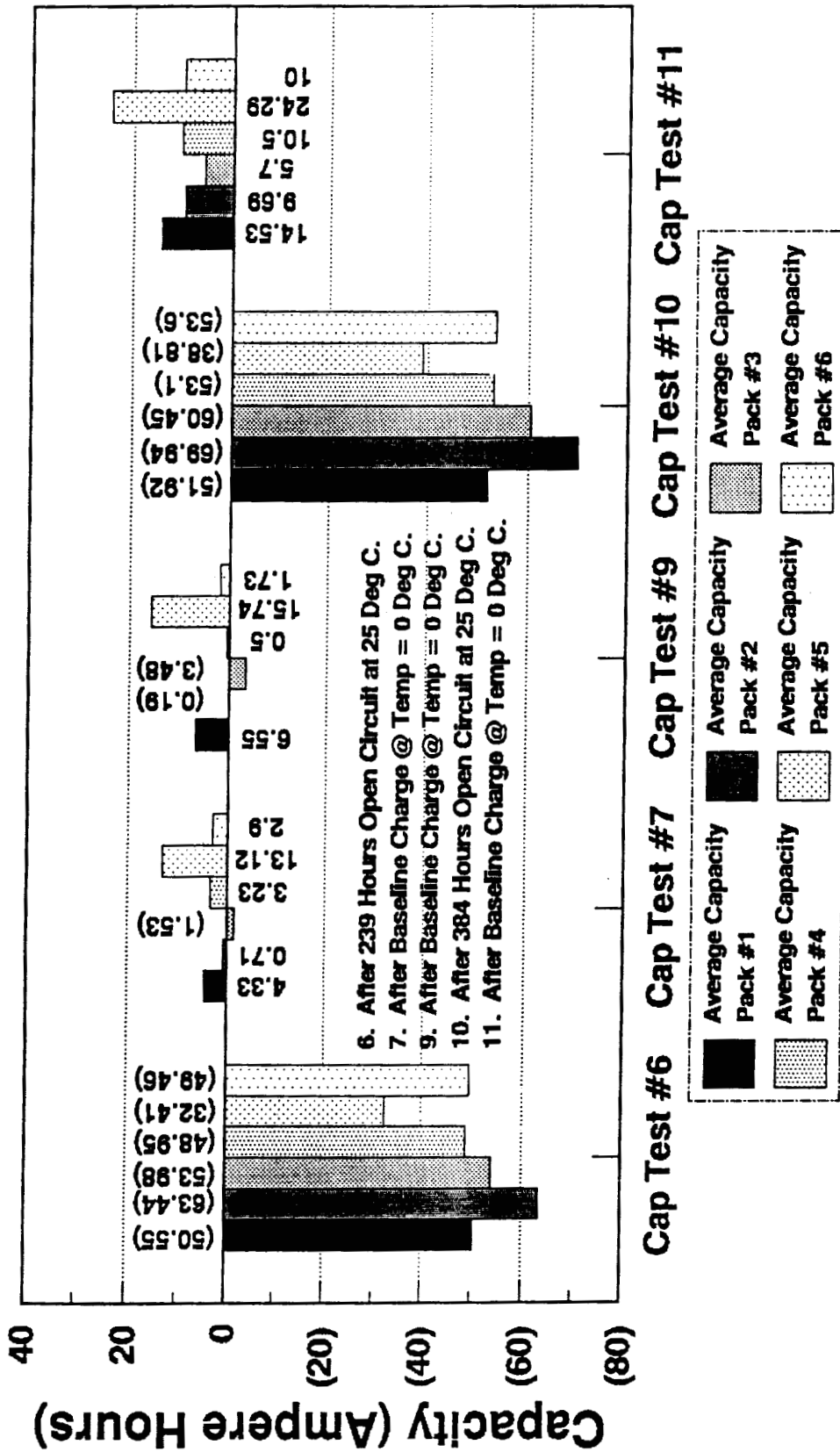
**Allow Cells to Stand Open Circuit for 1 Hour.**

**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



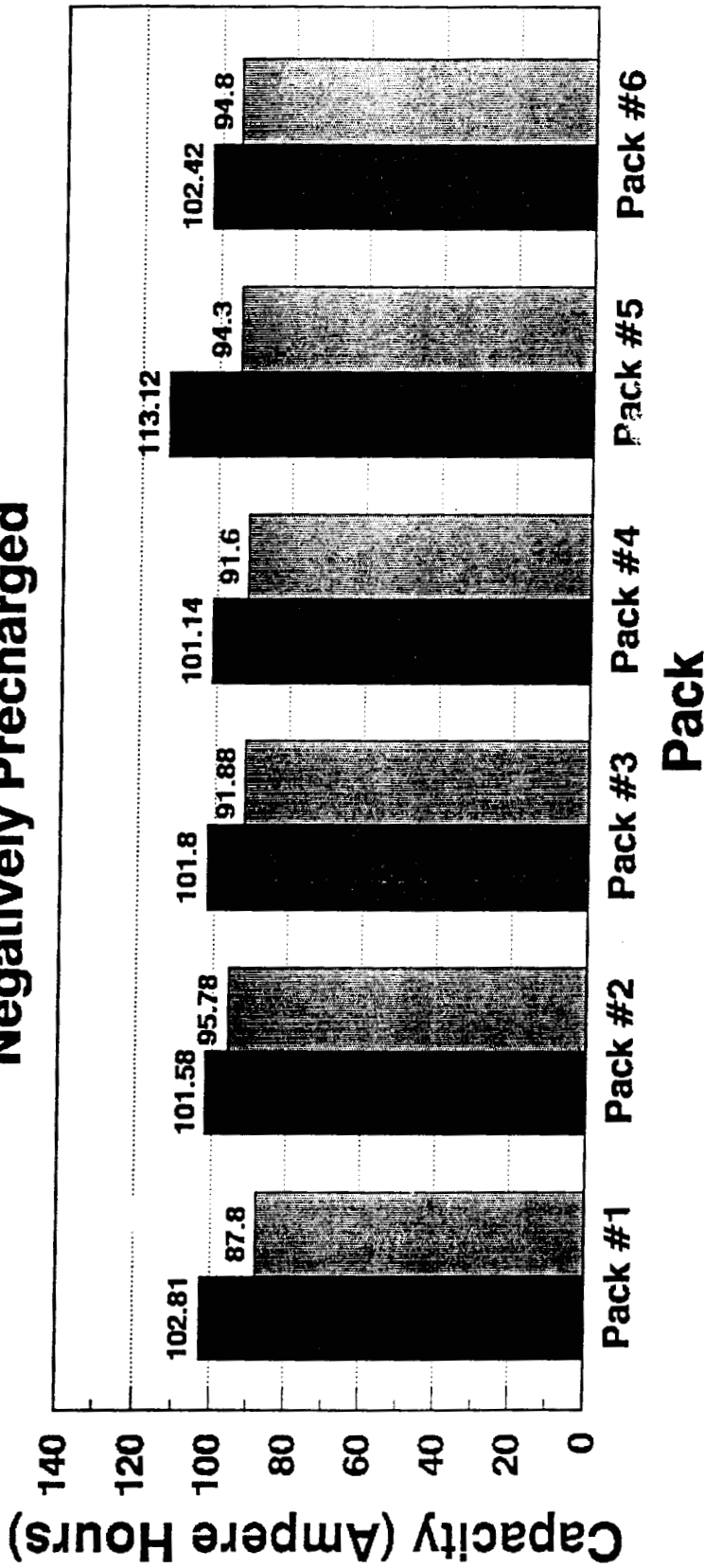
Acceptance Test Capacity, June 1989 - 1.2 Volts.  
 Other Capacity Tests, - 1.0 Volts.

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  
 Capacity Test #11

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.



## List of Attendees

Dr. Shyam D. Argade  
Technochem Company  
203-A Creek Ridge Rd.  
Greensboro, NC 27406-4419  
919-370-9440

Carolyn Ausborn  
Ausborn & Brewer, Inc.  
University of Alabama - Huntsville  
Johnson Research Center, Annex D  
POB 700  
Huntsville, AL 35804  
205-895-6846

Caroline Bastien  
SAFT  
156 Avenue De Metz  
93230 Romainville, France  
33-1-49-42-3417

Carl Baxam  
Tracor Battery Technology Center  
3368 Style Ave.  
Laurel, MD 20724  
301-251-4877

Bob Bechtel  
Marshall Space Flight Center  
MS EB12  
Marshall Space Flight Center, AL 35812  
205-544-3294

Wayne S. Bishop  
W.J. Schafer Associates, Inc.  
Suite 511  
5100 Springfield Pk.  
Dayton, OH 45431-1231  
513-253-9572

B. J. Bragg  
Johnson Space Center  
MS EP5  
NASA Rd. 1  
Houston, TX 77058  
713-483-9060

Jeff Brewer  
Marshall Space Flight Center  
MS EB12  
Marshall Space Flight Center, AL 35812  
205-544-3345

J. Douglass Briscoe  
SAFT R & D Center  
109 Beaver Court  
Cockeysville, MD 21030  
301-771-3200

Harry Brown  
Naval Weapons Support Center - Crane  
Code 3056  
Crane, IN 47522  
812-854-1593

David Burns  
Marshall Space Flight Center  
MS EB13  
Marshall Space Flight Center, AL 35812

Ed Buzzelli  
Westinghouse Science & Technology Center  
1310 Beulah Rd.  
Pittsburgh, PA 15235  
412-256-1952

Gerald W. Byers  
Martin Marietta  
MS B4383  
POB 179  
Denver, CO 80201  
303-971-4812

Robert B. Byrnes  
Dept. of the Army  
27 Kelvin Dr.  
Stafford, VA 22554  
703-659-8286

John E. Casey  
Lockheed Engineering & Sciences Co.  
2400 NASA Rd. 1, C51  
Houston, TX 77058-3711  
713-483-0446

Alan Cash  
Teledyne Brown Engineering  
MS 50  
300 Sparkman Dr. NW  
Huntsville, AL 35807  
205-726-3506

Bob Champion  
McDonnell Douglas Space Systems Co.  
Suite 320  
1100 Hercules  
Houston, TX 77058  
713-283-4805

Wing F. Chiu  
McDonnell Douglas Space Systems Co.  
Suite 320  
1100 Hercules  
Houston, TX 77058  
713-283-4806

Dwaine Coates  
Eagle Picher Industries, Inc.  
1215 West B Street  
Joplin, MO 64802  
417-623-8000

Betty Colhoun  
Goddard Space Flight Center  
Code 440.9  
Greenbelt, MD 20771  
301-286-7691

Louis Csorba  
United Airlines  
3150 Longview Dr.  
San Bruno, CA 94066  
415-876-3088

Dr. Marsha E. Daman  
Space Systems / Loral  
3825 Fabian Way  
Palo Alto, CA 94303  
415-852-4254

Ivan Danzig  
U.S. Army  
6812 Wild Rose Court  
Springfield, VA 22152  
703-644-5797

Eric C. Darcy  
Johnson Space Center  
MS EP5  
NASA Rd. 1  
Houston, TX 77058  
713-483-9055

**PRECEDING PAGE BLANK NOT FILMED**

Stephen F. Dawson  
Jet Propulsion Laboratory  
4800 Oak Grove Dr.  
Pasadena, CA 91109  
818-354-4329

James A. DeGruson  
Eagle Picher Industries, Inc.  
C & Porter St.  
Joplin, MO 64802  
417-623-8000 EXT491

Frank Deligiannis  
Jet Propulsion Laboratory  
MS 277-104  
4800 Oak Grove Dr.  
Pasadena, CA 91109  
818-354-0404

William K. Denson  
Reliability Analysis Center  
POB 4700  
Rome, NY 13440-8200  
315-339-7038

Lloyd Doering  
USA Strategic Defense Command  
POB 1500  
Huntsville, AL 35807-3801  
205-955-4387

Rajiv Doreswamy  
Marshall Space Flight Center  
MS EB12  
Marshall Space Flight Center, AL 35812  
205-544-3366

Paul J. Dozier  
U.S. Army Missile Command  
Weapon System Mgt. Directorate  
AMSMI-WS  
Redstone Arsenal, AL 35898  
205-876-1323

Steven J. Ebel  
WGL  
10000 Wehrle Dr.  
Clarence, NY 14031  
716-759-6901

Ted Edge  
Marshall Space Flight Center  
MS EB11  
Marshall Space Flight Center, AL 35812  
205-544-3381

John Edwards  
Boeing Commercial Airplane Co.  
MS 6U-HR  
POB 3707  
Seattle, WA 98124-2207  
206-477-0435

Blake A. Emmerich  
Zircar Products, Inc  
110 N. Main St.  
Florida, NY 10921  
914-651-4481 EXT229

Rolan Farmer  
Eagle Picher Industries, Inc.  
3820 South Hancock Expressway  
Colorado Springs, CO 80911  
719-392-4266

Richard E. Ferro  
Auburn University  
Department of Chemical Engineering  
230 Ross Hall  
Auburn University, AL 36849-5127  
205-844-2026

Ed Fitzgerald  
Teledyne Brown Engineering  
MS 70  
300 Sparkman Dr. NW  
Huntsville, AL 35807  
205-726-2865

John Fordyce  
WGL Battery Division  
10000 Wehrle Dr.  
Clarence, NY 14031  
716-759-2828

Richard Fredo  
Lockheed Technical Operations Co.  
Goddard Space Flight Center  
Code 440.8  
Greenbelt, MD 20771  
301-286-6949

Kenneth H. Fuhr  
Martin Marietta  
MS 8048  
POB 179  
Denver, CO 80201  
303-977-4495

J.C. Garner  
Naval Research Laboratory  
Code 8112  
4555 Overlook Ave. SW  
Washington, DC 20375-5000  
202-767-9075

Pete George  
Marshall Space Flight Center  
MS EB12  
Marshall Space Flight Center, AL 35812  
205-544-3331

Joseph A. Gillis  
MDAC / GSFC - NASA  
Goddard Space Flight Center  
Code 405  
Greenbelt, MD 20770  
301-286-9867

Steve Girard  
Eagle Picher Industries, Inc.  
1215 West B Street  
Joplin, MO 64801  
417-623-8000

Richard D. Glover  
Ames - Dryden  
POB 273  
Edwards, CA 93523  
805-258-3680

Linda Godfrey  
United Airlines - SFO EG  
San Francisco International Airport  
San Francisco, CA 94128-3800  
415-876-3740

Eugena Goggans  
Marshall Space Flight Center  
MS EB13  
Marshall Space Flight Center, AL 35812  
205-544-3386

Lester Gordy  
U.S. Army  
8219 Running Creek Ct.  
Springfield, VA 22153  
703-455-4220

Jacques Goulard  
SAFT  
156 Avenue De Metz  
93230 Romainville, France  
33-1-49-42-3417

John G. Gray  
Boeing Co.  
MS 81-09  
POB 3999  
Seattle, WA 98124  
206-773-3655

Shahid Habib  
NASA Headquarters  
Code QE  
Washington, DC 20546  
202-453-8052

Doug Hafen  
Lockheed Missiles & Space Co., Inc.  
B/551 O/79-10  
POB 3504  
Sunnyvale, CA 94089-3504  
408-743-7220

Charles Hall  
Marshall Space Flight Center  
MS EB12  
Marshall Space Flight Center, AL 35812  
205-544-3330

David Hall  
Marshall Space Flight Center  
MS EB12  
Marshall Space Flight Center, AL 35812  
205-544-4215

Steve Hall  
Naval Weapons Support Center - Crane  
Code 30561, Bldg. 2949  
Crane, IN 47522-5000  
812-854-1593

Dr. H.J. Harms  
Hoppecke Batteries  
POB 1140  
5790 Brilon 2  
Germany  
011-49-2963-61-448

Mike Harrison  
Gates Aerospace Batteries  
POB 147115  
Gainesville, FL 32614-7115  
904-462-4742

Gary L. Hartjen  
Rockwell International  
MS LB-31  
6633 Canoga Ave.  
Canoga Park, CA 91303  
818-700-2202

Jeff Hayden  
Eagel-Picher Industries, Inc.  
3820 South Hancock Expressway  
Colorado Springs, CO 80911  
719-392-4266

Richard Hazen  
TRW  
Bldg. R11, Rm. 1850  
One Space Park  
Redondo Beach, CA 90277  
213-813-6827

Ed Hendee  
Telesat Canada  
1601 Telesat Court  
Gloucester, Ontario  
Canada K1B 5P4  
613-748-0123 EXT 2366

Lt. Bob Highley  
U.S. Air Force  
PL/STPP  
Kirtland AFB, NM 87117-6008  
505-846-7805

Carole A. Hill  
Aerospace Corporation  
MS 2-275 Bldg. A-6  
POB 92957  
Los Angeles, CA 90009-2957  
213-336-0175

Albert Himy  
Navy / Westinghouse  
POB 18249  
Pittsburgh, PA 15236  
412-382-7883

Lt. Shaun House  
U.S. Air Force  
PL/STPP  
Kirtland AFB, NM 87117-6008  
505-846-1700

Oscar Hsu  
Freudenberg Nonwovens  
221 Jackson St  
Lowell, MA 01852  
508-454-0461

Lorna Jackson  
Marshall Space Flight Center  
MS EB12  
Marshall Space Flight Center, AL 35812  
205-544-3318

Robert A. Jamieson  
Aerospace Corporation  
MS M3/718  
2350 E. El Segundo Blvd.  
El Segundo, CA 90245-4691  
213-336-0520

Thierry Jamin  
CNES  
18 Avenue Edouard Belin  
31055 Toulouse Cedex  
France  
CNES/CST/TE/AE/SE/AC  
61 27 49 38

Dr. Chris Johnson  
Boeing Defense & Space  
MS 8C-61  
POB 3999  
Seattle, WA 98124  
206-773-5058

Kenneth R. Jones  
Johnson Controls  
12500 W. Silver Spring  
Butler, WI 53007  
414-783-2600

Dr. Wade H. Jordan  
US Army  
1 Mountain Top Rd.  
Front Royal, VA 22630  
703-635-9311

Carlos Judkins  
Boeing  
12623 88th Pl. NE  
Kirkland, WA 98034  
206-773-2456

David Jung  
Goddard Space Flight Center  
Code 711.5  
Greenbelt, MD 20771  
301-286-6104

Nolimits Kamimori  
National Space Development Agency of Japan  
Tukuba Space Center  
2-1-1 Sengen, Tsukuba, Ibaraki, 305 Japan  
81-298-52-2285

Ken Kaufman  
Lockheed Engineering & Sciences Co.  
2400 NASA Rd. 1, B17  
Houston, TX 77058-3711  
713-333-7880

Bobby Kennedy  
Marshall Space Flight Center  
MS EB13  
Marshall Space Flight Center, AL 35812  
205-544-3384

Marcie Kennedy  
Marshall Space Flight Center  
MS EB12  
Marshall Space Flight Center, AL 35812  
205-544-3724

Glenn Klein  
Gates Aerospace Batteries  
POB 147115  
Gainesville, FL 32614-7115  
904-462-3569

Roy Lanier  
Marshall Space Flight Center  
MS EB11  
Marshall Space Flight Center, AL 35812  
205-544-3301

John R. Lapinski  
McDonnell Douglas Electronic Systems  
MS 106 3323  
POB 516  
St. Louis, MO 63166-0516  
314-233-2404

John Lear  
Grumman Space & Electronics  
MS T01-12  
South Oysterbay Rd.  
Bethpage, NY 11714-3588  
516-575-5460

Eric J. Lecomte  
ETCA  
POB 4097  
B-6000 Charleroi  
Belgium  
32 71 44 23 30

Mario R. Lembo  
Hoppecke Batteries  
10 Park Place  
Butler, NJ 07436  
201-492-0045

Dr. Harlan Lewis  
Naval Weapons Support Center - Crane  
Code 3059  
Crane, IN 47522  
812-854-1431

Joe Lewis  
TRW  
MS 01-2260  
Redondo Beach, CA 90278  
213-813-9433

Del Linenberger  
Ball Aerospace  
MS CO-6B  
POB 1062  
Boulder, CO 80306  
303-939-4797

Eric Lowery  
Marshall Space Flight Center  
MS EB12  
Marshall Space Flight Center, AL 35812  
205-544-0080

Steve Luna  
Marshall Space Flight Center  
MS EB12  
Marshall Space Flight Center, AL 35812  
205-544-3402

Chuck Lurie  
TRW  
MS R4/1028  
One Space Park  
Redondo Beach, CA 90278  
213-813-4888

Dr. Tyler X. Mahy  
U.S. Government  
c/o OTS-2S83 NHB  
Washington, DC 20505  
703-874-0739

Cheryl A. Malloy  
Kennedy Space Center  
MS CS-EED-32  
Kennedy Space Center, FL 32899  
407-867-3466

Michelle Manzo  
Lewis Research Center  
MS 309-1  
21000 Brookpark Rd.  
Cleveland, OH 44135  
216-433-5261

Lynn Marcoux  
Marcoux Engineering, Inc.  
2837 Featherhill Dr.  
Orange, CA 92667  
714-998-3048

Nehemiah Margalit  
Tracor Battery Technology Center  
4294 Mainsail Dr.  
Burke, VA 22015  
301-251-4881

James Marusek  
Naval Weapons Support Center – Crane  
Code 305C  
Crane, IN 47522-5000  
812-854-1593

Dean W. Maurer  
AT&T  
379 Princeton-Hightstown Rd.  
Cranbury, NJ 08512  
609-448-0687

Bryon T. Maynard  
Kennedy Space Center  
MS CS-TMO-2  
Kennedy Space Center, FL 32899  
407-867-2223

Kurt McCall  
Marshall Space Flight Center  
MS EB12  
Marshall Space Flight Center, AL 35812  
205-961-4501

Mike McIntosh  
Marshall Space Flight Center  
MS CN01M  
Marshall Space Flight Center, AL 35812  
205-544-5737

Glen Merry  
MATSI, Inc.  
Suite S-007  
430 10th St. NW  
Atlanta, GA 30318  
404-876-8009

George Methlie  
2120 Natahoa Ct.  
Falls Church, VA 22043  
703-533-1449

Joseph F. Mibelli  
JFM Engineering  
7880 NW 56th St.  
Miami, FL 33166  
305-592-2272

Ron Miller  
Goddard Space Flight Center  
Code 405  
Greenbelt, MD 20771  
301-286-6331

Tom Miller  
Lewis Research Center  
MS 500-222  
21000 Brookpark Rd.  
Cleveland, OH 44035  
216-433-6300

James J. Moran  
Vitro Corporation  
600 Maryland Ave., SW  
Suite 300, West Wing  
Washington, DC 20024  
202-646-6334

Dr. Dan Mulville  
NASA Headquarters  
Code QE  
Washington, DC 20546  
202-453-1867

Tohru Nagao  
The Yokohama Rubber Co., Ltd.  
2-1 Oiwake, Hiratsuka-City  
Kanaga Pref. 254, Japan  
0463-32-2716

Ken Nakatani  
Sanyo Electric Co., Ltd.  
222-1 Kaminaizen, Sumoto-City  
Hyogo, Japan  
0799-24-4111

Dave Nawrocki  
Lockheed Missiles & Space Co., Inc.  
808 Loyalton  
Campbell, CA 95008  
408-743-0170

Al Norton, Jr.  
Marshall Space Flight Center  
MS EB13  
Marshall Space Flight Center, AL 35812  
205-544-3362

Pat O'Donnell  
Lewis Research Center  
MS 309-1  
21000 Brookpark Rd.  
Cleveland, OH 44135  
216-433-5248

Paul E. Panneton  
Johns Hopkins University / APL  
23-214  
Johns Hopkins Rd.  
Laurel, MD 20723  
301-953-5649

Craig Partlo  
Hughes Aircraft  
Bldg. S-75, MS CHSE  
16800 E. CentreTech Parkway  
Aurora, CO 80011-9046  
303-341-3821

David F. Pickett  
Hughes Aircraft Co.  
Electron Dynamic Division  
MS 231/1040  
POB 2999  
Torrance, CA 90509  
213-517-7601

Gopal Rao  
Goddard Space Flight Center  
Code 711.5  
Greenbelt, MD 20771  
301-286-6654

David P. Roller  
Alliant Techsystems, Inc.  
Power Sources Center  
104 Rock Rd.  
Horsham, PA 19044  
215-674-3800

Dr. Ruch  
Hoppecke Batteries  
POB 11 40  
W-5790 Brilon 2  
Germany  
011-49-2963-61-386

David F. Schmidt  
Gates Aerospace Batteries  
POB 147115  
Gainesville, FL 32614-7115  
904-462-4752



Todd Schutt  
Marshall Space Flight Center  
MS EB12  
Marshall Space Flight Center, AL 35812  
205-544-2027

Dr. Pinakin M. Shah  
Alliant Techsystems, Inc.  
Power Sources Center  
104 Rock Rd.  
Horsham, PA 19044  
215-674-3800

John J. Smithrick  
Lewis Research Center  
MS 302-1  
21000 Brookpark Rd.  
Cleveland, OH 44135  
216-433-5255

Daniel G. Soltis  
Sverdrup Technology Inc.  
Lewis Research Center  
MS AAC/2  
21000 Brookpark Rd.  
Cleveland, OH 44135  
216-977-7081

Dan Standlee  
Eagle Picher Industries, Inc.  
1215 West B Street  
Joplin, MO 64802  
417-623-8000 EXT301

Sal Di Stefano  
Jet Propulsion Laboratory  
MS 277-212  
4800 Oak Grove Drive  
Pasadena, CA 91109  
818-354-6320

Ken Stephens  
Marshall Space Flight Center  
MS EB11  
Marshall Space Flight Center, AL 35812  
205-544-6616

Joseph Stockel  
Office of Research & Development  
Washington, DC 20505  
703-351-2065

S. Surampudi  
Jet Propulsion Laboratory  
4800 Oak Grove Drive  
Pasadena, CA 91109  
818-354-0352

Dr. Greg M. Swain  
Auburn University  
Department of Chemical Engineering  
230 Ross Hall  
Auburn University, AL 36849-5127  
205-844-2026

Mike Takao  
Sanyo Energy (USA) Corporation  
200 Riser Rd.  
Little Ferry, NJ 07643  
201-641-2333 EXT416

Steve Tesney  
Marshall Space Flight Center  
MS EB12  
Marshall Space Flight Center, AL 35812  
205-544-3400

Lawrence H. Thaller  
Aerospace Corporation  
MS M2/275  
POB 92957  
Los Angeles, CA 90009  
213-336-5180

David L. Thaxton  
Marshall Space Flight Center  
MS CN23  
Marshall Space Flight Center, AL 35812  
205-544-8371

Daniel L. Thomas  
University of Alabama - Huntsville  
Department of Chemical Engineering  
Huntsville, AL 35899  
205-895-6266

Lawrence Tinker  
Gates Aerospace Batteries  
POB 147115  
Gainesville, FL 32614-7115  
904-462-4715

Mark R. Toft  
McDonnell Douglas Electronic Systems  
MS 106 3323  
POB 516  
St. Louis, MO 63166-0516  
314-233-8649

Walter A. Tracinski  
Hughes Aircraft Company  
POB 2999  
Torrance, CA 90509  
310-517-7616

Dr. Hari Vaidyanathan  
COMSAT Laboratories  
22300 Comsat Dr.  
Clarksburg, MD 20871  
301-428-4507

Michael Viens  
Goddard Space Flight Center  
Code 313  
Greenbelt, MD 20771-0001  
301-286-2049

Harry Wajsgas  
Goddard Space Flight Center  
Code 711.1  
Greenbelt, MD 20771  
301-286-7477

Dick Walk  
Tracor Battery Technology Center  
1601 Research Blvd.  
Rockville, MD 20850  
301-251-4875

John Weeks  
Kennedy Space Center  
MS TV-ETD-22  
Kennedy Space Center, FL 32899  
407-861-3720

Lt. Randall White  
USAF SSD / SDES  
HQ SSD (AFSC) / SDES  
POB 92960  
Los Angeles Air Force Base  
Los Angeles, CA 90009-2960  
213-363-2533

Greg Whitlow  
SAFT R & D Center  
109 Beaver Court  
Cockeysville, MD 21030  
301-771-3200

Tom Whitt  
Marshall Space Flight Center  
MS EB12  
Marshall Space Flight Center, AL 35812  
205-544-3313

Teresa K. Williams  
Hughes Aircraft  
MS CHSS  
16800 E. CentreTech Parkway  
Aurora, CO 80011  
303-344-6000

Doug Willowby  
Marshall Space Flight Center  
MS EB12  
Marshall Space Flight Center, AL 35812  
205-544-3334

Bob Wilson  
Wilson & Wilson  
1133 15th St. NW  
Suite 1200  
Washington, DC 20036  
202-835-1571

Dennis Wingo  
University of Alabama - Huntsville  
Research Institute M-65  
Huntsville, AL 35899  
205-895-6620

Cliff Wooten

Rt. 1, Box 305-A  
Monticello, GA 31064  
404-468-2723

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