NASA Conference Publication 3140

The 1991 NASA Aerospace Battery Workshop

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

NASA

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The 1991 NASA Aerospace Battery Workshop

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

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

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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

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_2 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_2 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_2, and Li-SO_2 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 $Zn\text{-}O_2$ 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 ($\sim$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 $LiSOCl_2$, and the Wilson Greatbatch, Ltd. Li-CSC.

The NASA Aerospace Flight Battery Systems Program also supports the development of a pair of $Zn\text{-}O_2$ 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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AUSBORN & BREWER, INC.

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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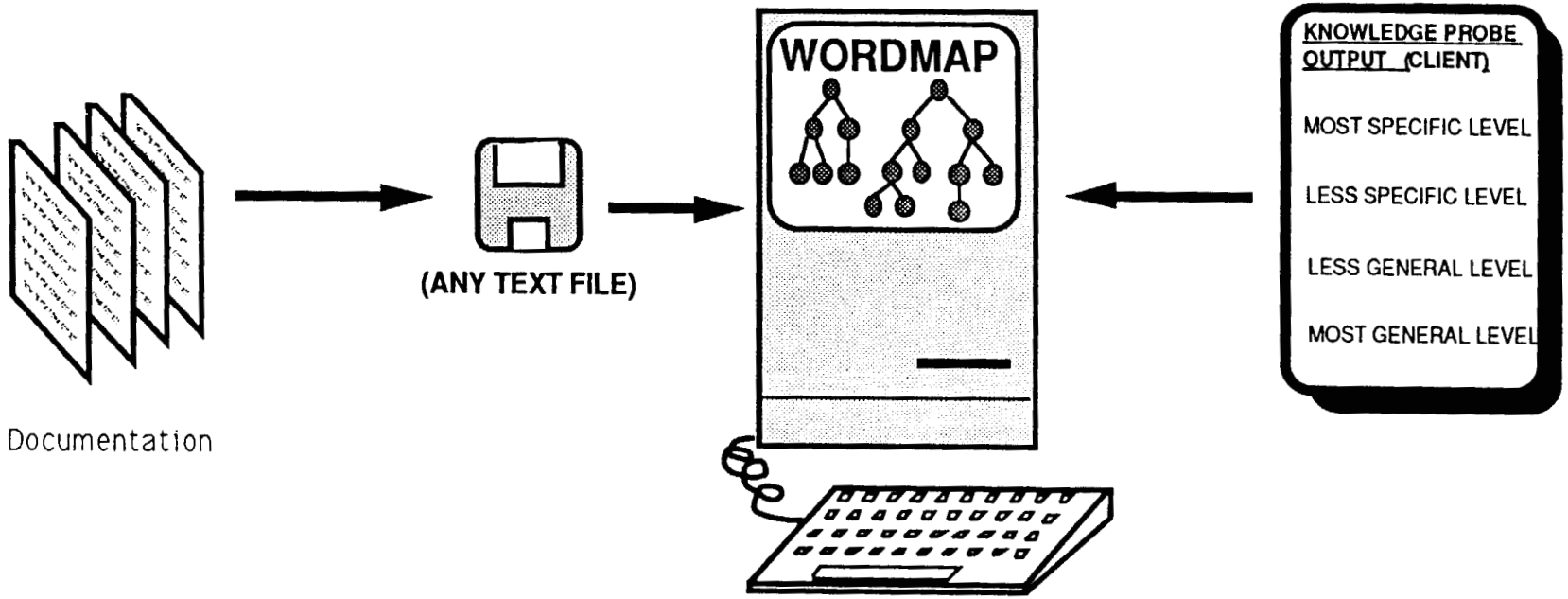
WORDMAP: Document Analysis Tool



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

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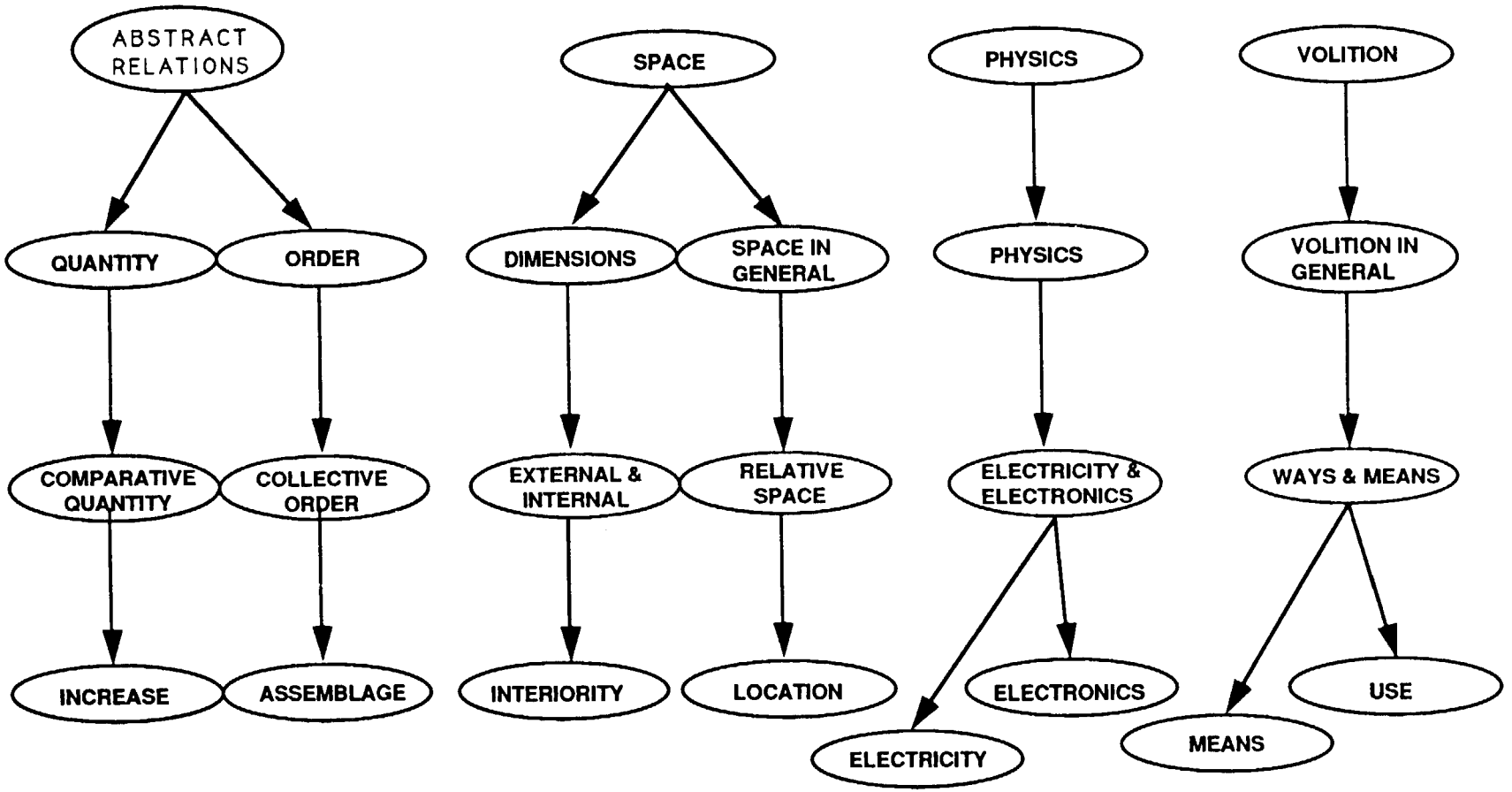
Battery Technology Example



INNOVATIVE KNOWLEDGE ENGINEERING

PROFILE OF A CELL TEST DATABASE AND A CORRESPONDING RELIABILITY DATABASE

George R. Brearley
Glenn C. Klein

Gates Energy Products
Gates Aerospace Batteries

Abstract

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

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

Reduction in Test Discrepancies

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

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

MACHINE: Numerous equipment additions include 1] Failsafe Devices for preventing cell reversal, for ensuring proper transitions of test procedure, audible warning devices; and, usage of data loggers; 2] charge/discharge status indicators; 3] refurbishment of existing equipment and adoption of customized en-

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. 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.

Reduction in Performance Variation

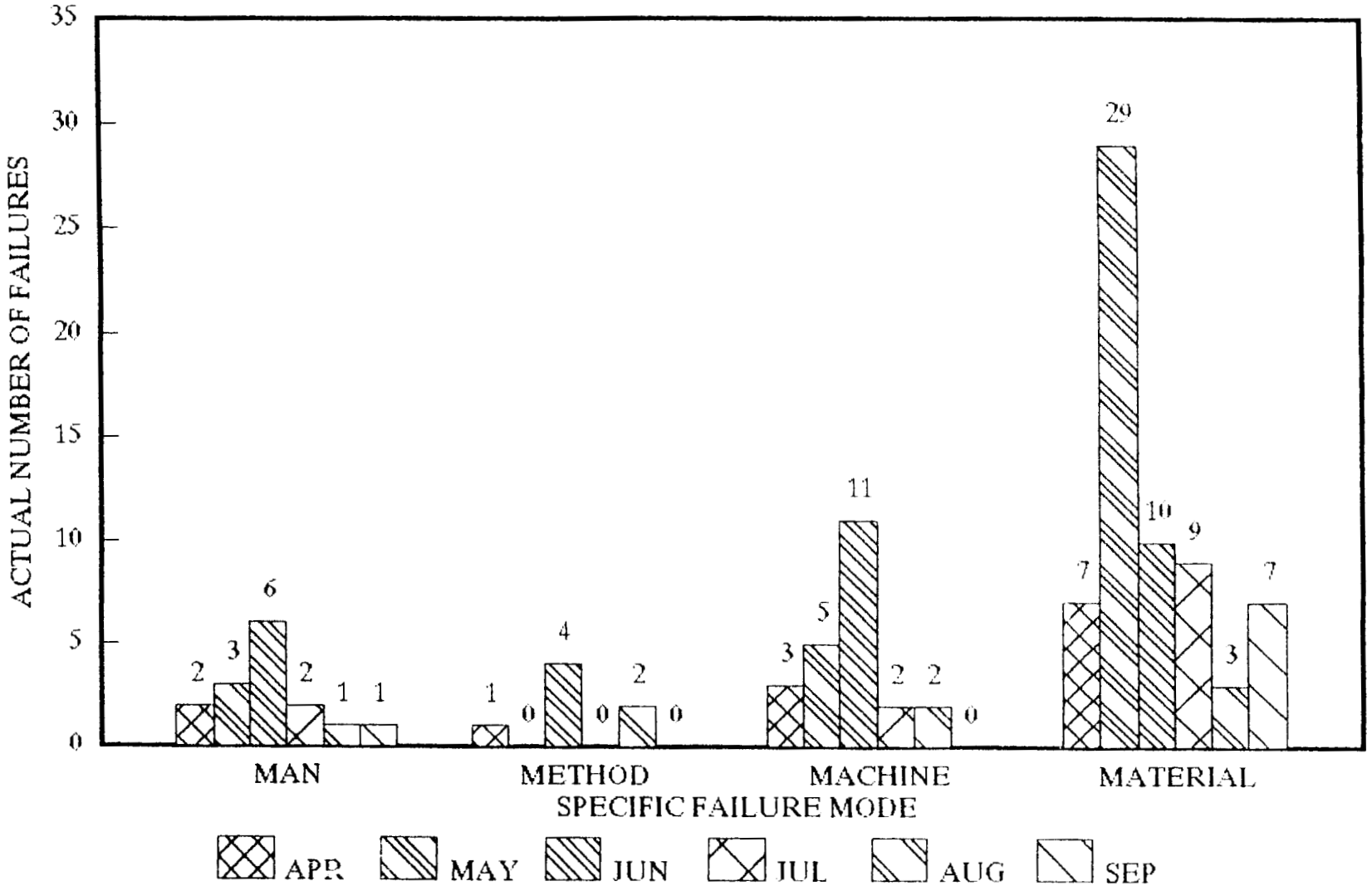
Further reduction of variation within the Test Unit is hampered somewhat by the currently imposed contractual obligations and restrictions. Whether we consider performance variation within a lot or consider lot-to-lot performance variation, two additional steps must be taken. These steps include the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

Classification of Test Discrepancies

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

TEST FAILURES BY CATEGORY (1991)

(Atp + Pre−Atp Failures)



NOTE: INFORMATION TAKEN FROM GAR DATABASE

Created by: Richard Calloway

CHART 1

TABLE 1

Acceptance Testing: NiCd Discrepancy Definitions

	CELL RESPONSE DISCREPANCIES	TEST CONTROL DISCREPANCIES
CRITICAL	1. Overvoltages > 25mV 2. Pressures ≥ 80 PSIG	1. Cell Case Temperature excursion ≥ 10° C [and never above 30° 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
MAJOR	1. Overvoltages > 10mV but ≤ 25mV 2. Overpressures > 5 PSIA 3. Capacities ≥ 2.0% below specification 4. Cell Impedance over specification 5. Pulse Disc : minimum voltage not met	1. Cell Case Temp. excursion > 5° C but < 10° C 2. Resistor on cell during charge 3. Charge rate > 10% above specification 4. Discharge rate > 20% above specification 5. Delta pressures > 3 PSIG
MINOR	1. Overvoltages ≤ 10mV 2. Overpressures ≤ 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	1. Cell Case Temperature excursion ≤ 5° C 2. Charge rate ≤ 10% above specification 3. Discharge rate ≤ 20% above specification 4. Insufficient shortdown voltage (EOSV) 5. Interrupted Burn-in cycle ≥ 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 occurence 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_2 Discrepancy Definitions

	CELL RESPONSE DISCREPANCIES	TEST CONTROL DISCREPANCIES
CRITICAL	1. Overvoltages > 25mV 2. Pressures ≥ 20% above MOP 3. Hydrogen leakage	1. Cell Case Temperature excursion ≥ 10° C [and never above 40° 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
MAJOR	1. Overvoltages > 10mV ≤ 25mV 2. Overpressures > 50 PSIA 3. Capacities ≥ 2.0% below specification 4. Cell Impedance over specification 5. Max. Allowable Strain Gage voltage is violated	1. Cell Case Temp. excursion > 5° C but < 10° C 2. Resistor on cell during charge 3. Charge rate > 10% above specification 4. Discharge rate > 20% above specification
MINOR	1. Overvoltages ≤ 10mV 2. Overpressures ≤ 50 PSIA 3. Capacities < 2.0% below specification 4. Capacity over "Max Allowable" spec. 5. Average Capacity out-of-specification 6. Capacity Range out-of-specification 7. EOCV Range out-of-specification	1. Cell Case Temperature excursion ≤ 5° C 2. Charge rate ≤ 10% above specification 3. Discharge rate ≤ 20% above specification 4. Insufficient shortdown voltage (EOSV) 5. Improper Open-Circuit time 6. Interrupted test sequence: < 30 minutes on charge cycle, < 10 minutes on discharge cycle 7. Improper Open-Circuit time 8. Incomplete/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 occurence 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)

TEST	DATA REQ'D.	PERFORMANCE STD
Set Neg. Pre-Chg.	time to first vent	normality of times & review of lot-to-lot data
	time to last vent	normality of times & review of lot-to-lot data
	0_2 weight loss	$\pm$0.5 amp-hour (0_2 equivalent) from lot average
Room Temp. O/C [after KOH adj.]	EOCP	range of 20 to 45 PSIG & delta P $\leq$ +3 PSI in last 8 hours
72° F Capacity	EOCP	range of 20 to 45 PSIG
	EOCV	$\pm$12mV from lot average
	Capacity	$\pm$3.0% from lot average
32° F Test	EOCP	range of 10 to 35 PSIG
	EOCV	$\pm$12 mV from lot average
	Capacity	$\pm$3.0% from lot average

TABLE 4

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

TEST	DATA REQ'D.	PERFORMANCE STD
Each capacity test	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
Each overcharge test	EOCV dispersion	± 12mV from lot average
	EOCP ranges	20-45 PSIG @ 75° F; 10-35 PSIG @ 32° F
	EOCP	delta P $\leq$ + 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

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 toleranced tighter than the Customer Specification. This is the first step in identifying and reducing Common Causes and the accompanying variation, or performance dispersion. Tables 3 & 4 contain the Engineering Alerts to be applied to NiCd Pre-ATP and to NiCd ATP performance testing. These are non-normalized limitations for several reasons: [1] this removes one more crutch or excuse for non-performance; and, [2] software sub-routines for real time normalization of multiple data points appears counterproductive and very demanding of computer memory. Similar Engineering Alerts for NiH2 performance testings are being developed and will be implemented following successful implementation of those for the NiCd cell product line. Necessarily, the entire program is dependent upon the continued implementation of computerized control and data loggers.

Reduction of Lot-to-Lot Performance Variation

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

Conclusions and Recommendations

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

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

3. Engineering Alerts are proposed for internal usage and are already being implemented on the NiCd product line.

A Computerized Aircraft Battery Servicing Facility

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

The 1991 NASA Aerospace Battery Workshop

Marshall Space Flight Center
Huntsville, Alabama

October 29-31, 1991

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 MA-8	24540-007 27797-001	10 24	2 3	2 3
PA-30	ARC-10H120-21 CA-24A	10H120-21 27312-001	10 24	2 2	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 CA-9-20 CA-121	31463-001 28974-01C 19150-01C	3 24 12	9 5 6	3 5 6

AESL Overview

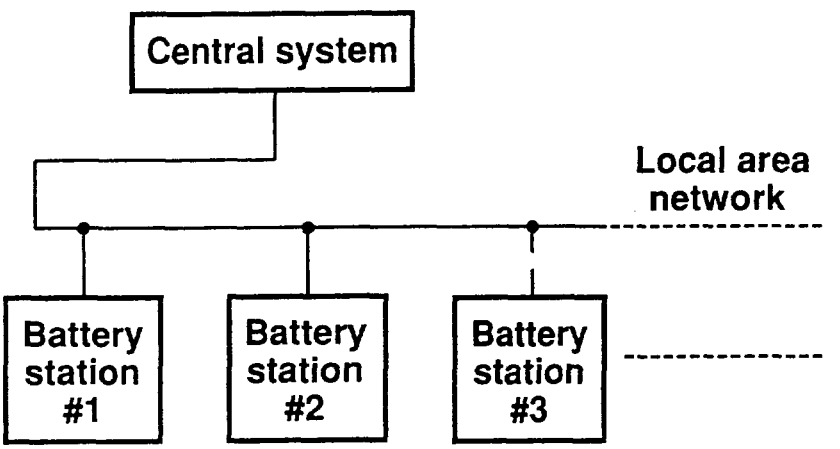
The AESL is a distributed digital system consisting of a central system and battery servicing stations connected by a high-speed serial data bus. The entire system is located in two adjoining rooms; the bus length is approximately 100 ft.

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)

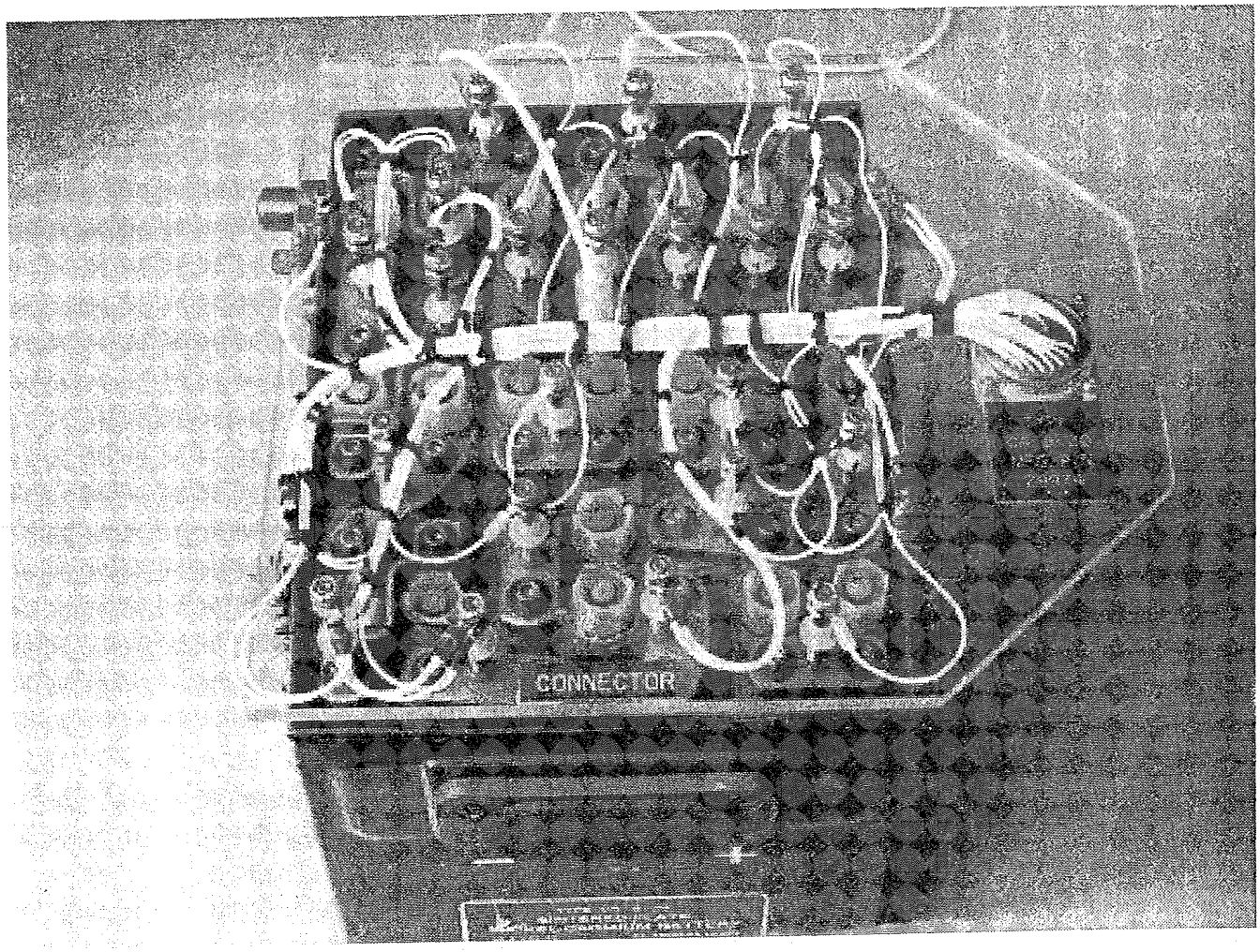
The battery station benches are 34-in. wide modular wooden structures which can be moved through a standard doorway with a pallet mover. The following components are mounted to the bench:

Charger – analzyer	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 Terminal connector Printer connector Load bank control connector	Mounted under left side of work surface
Right connector panel Battery cable connector Monitor plate connector	Mounted under right side of work surface
Controller assembly Cardcage Floppy diskette drive Current leakage box Accessory power box	Mounted on lower shelf

Monitor Plate Attached to CA-9-20

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

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



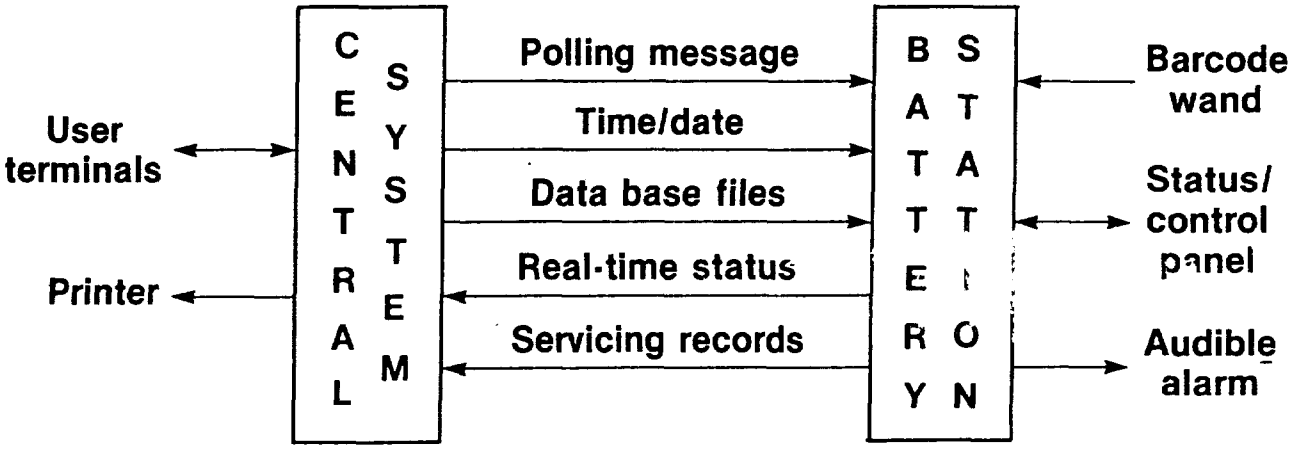
The operator initiates a servicing task by positioning the case temperature probes, attaching the monitor plate and power cable, installing the hot vapor sensor, selecting the task, and reading the barcode tag on the side of the battery. The database files necessary to support the servicing of this battery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

NASA AD87-449



Analog Subsystem Channels

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

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

Analog Subsystem Channels

NASA
D91-467

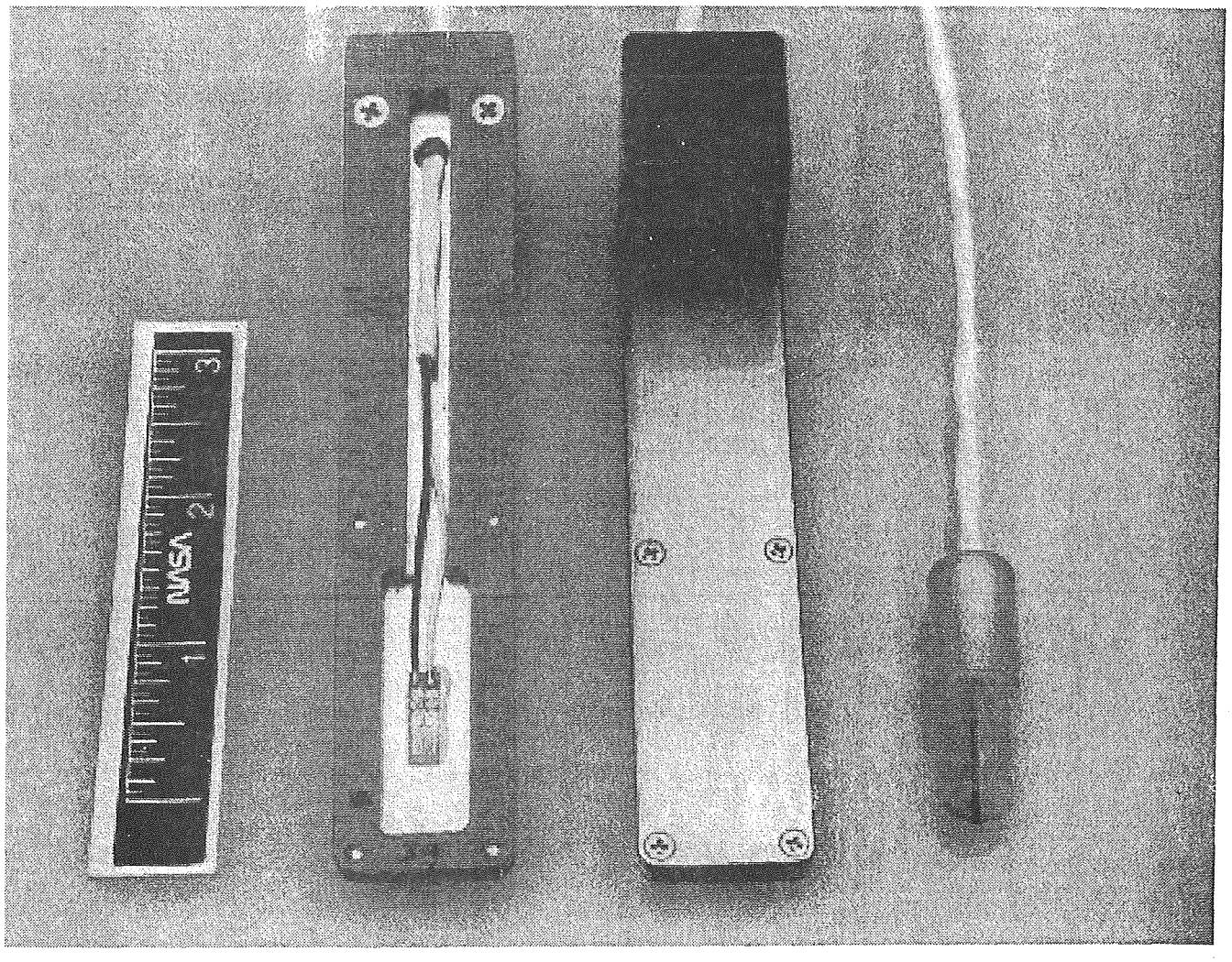
- **30 cell voltages**
- **1 battery monitor plate voltage**
- **1 battery cable voltage**
- **1 charger–analyzer current**
- **5 temperature probes**
- **1 case leakage current**
- **1 programmable load bank voltage**
- **1 programmable load bank current**
- **1 programmable load bank temperature probe**

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.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

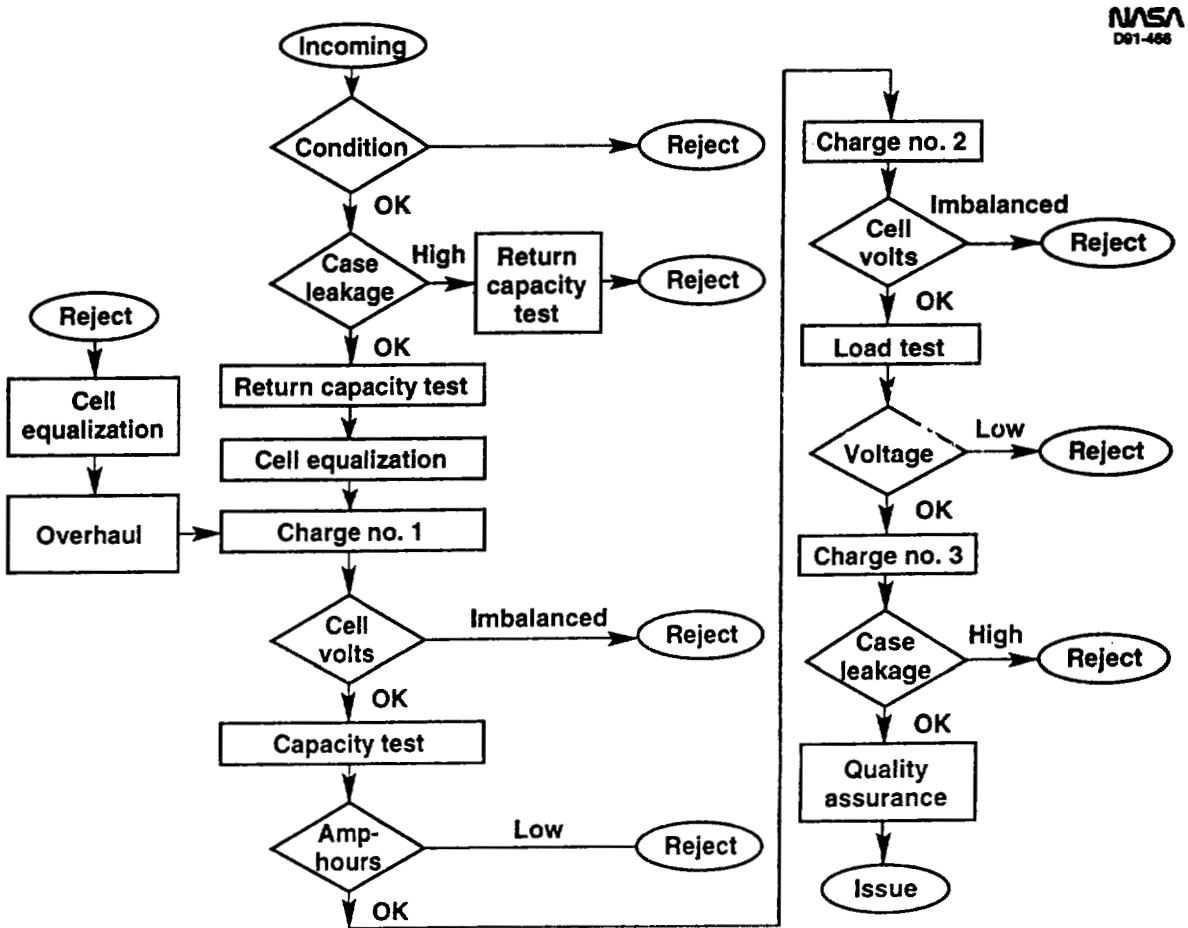


Servicing Procedure

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.

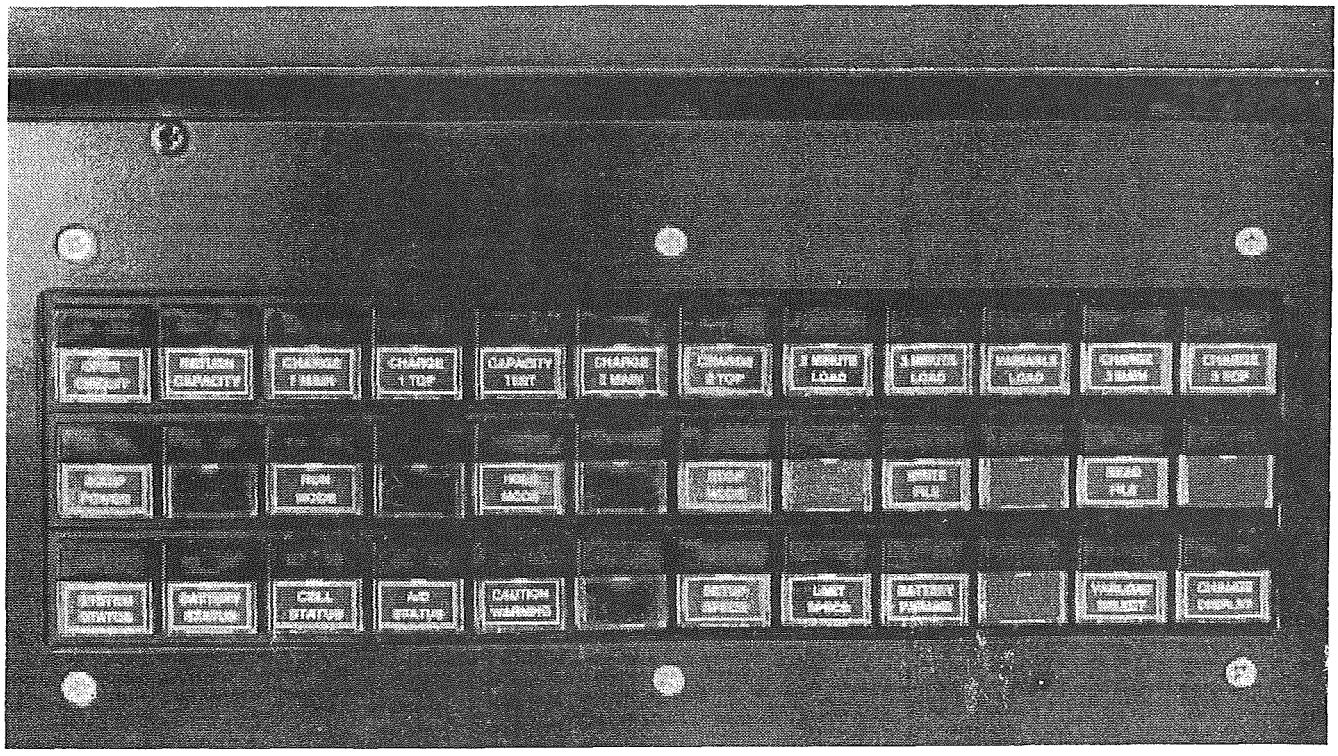


Pushbuttons Panel

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 operatior 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 botttom row of pushbuttons is used to control the display unit.



Shutdown Criteria

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

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

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

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

Shutdown Criteria

NASA
D91-465

- **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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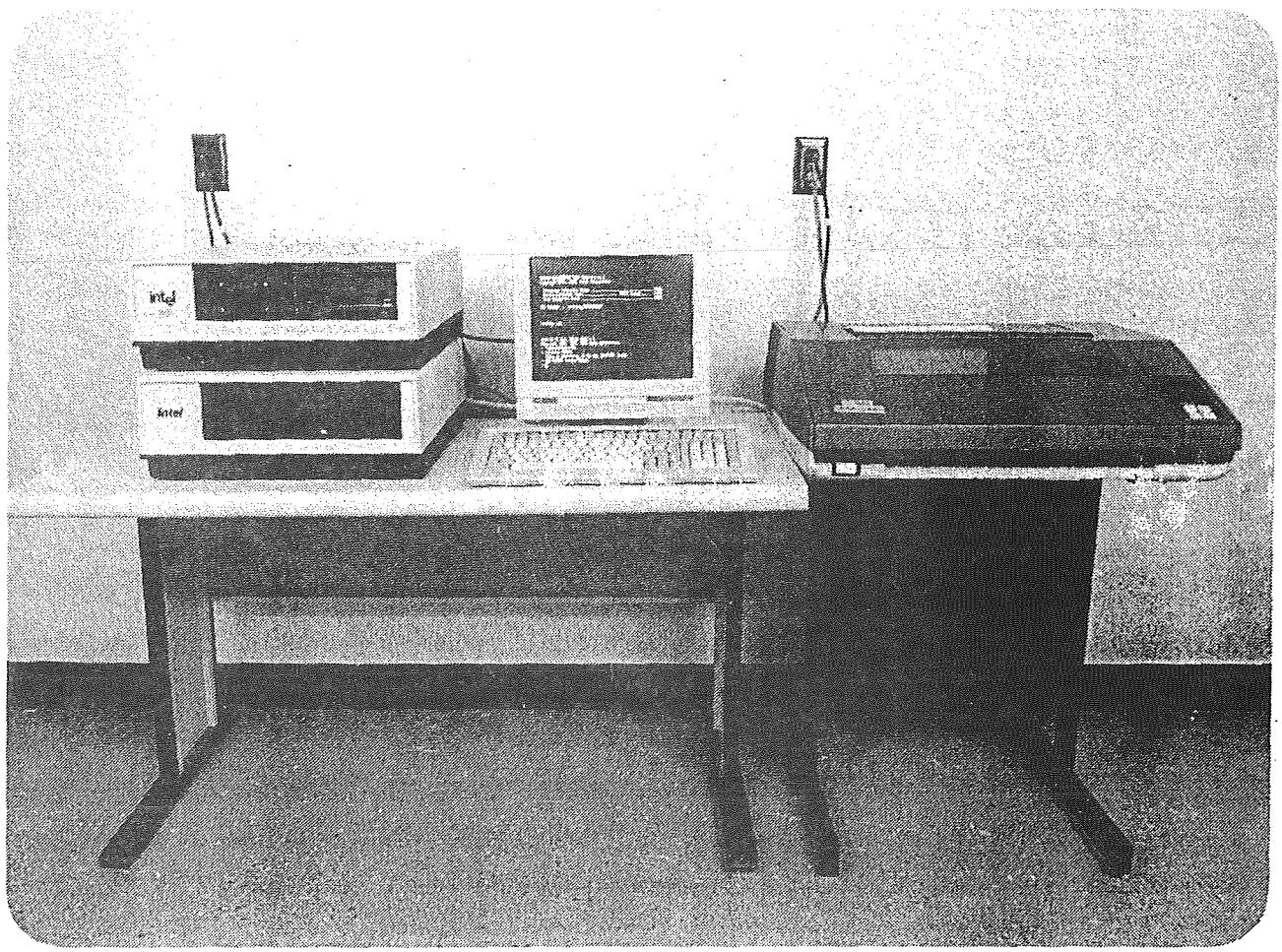
NASA
AD88-1077



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 discretes 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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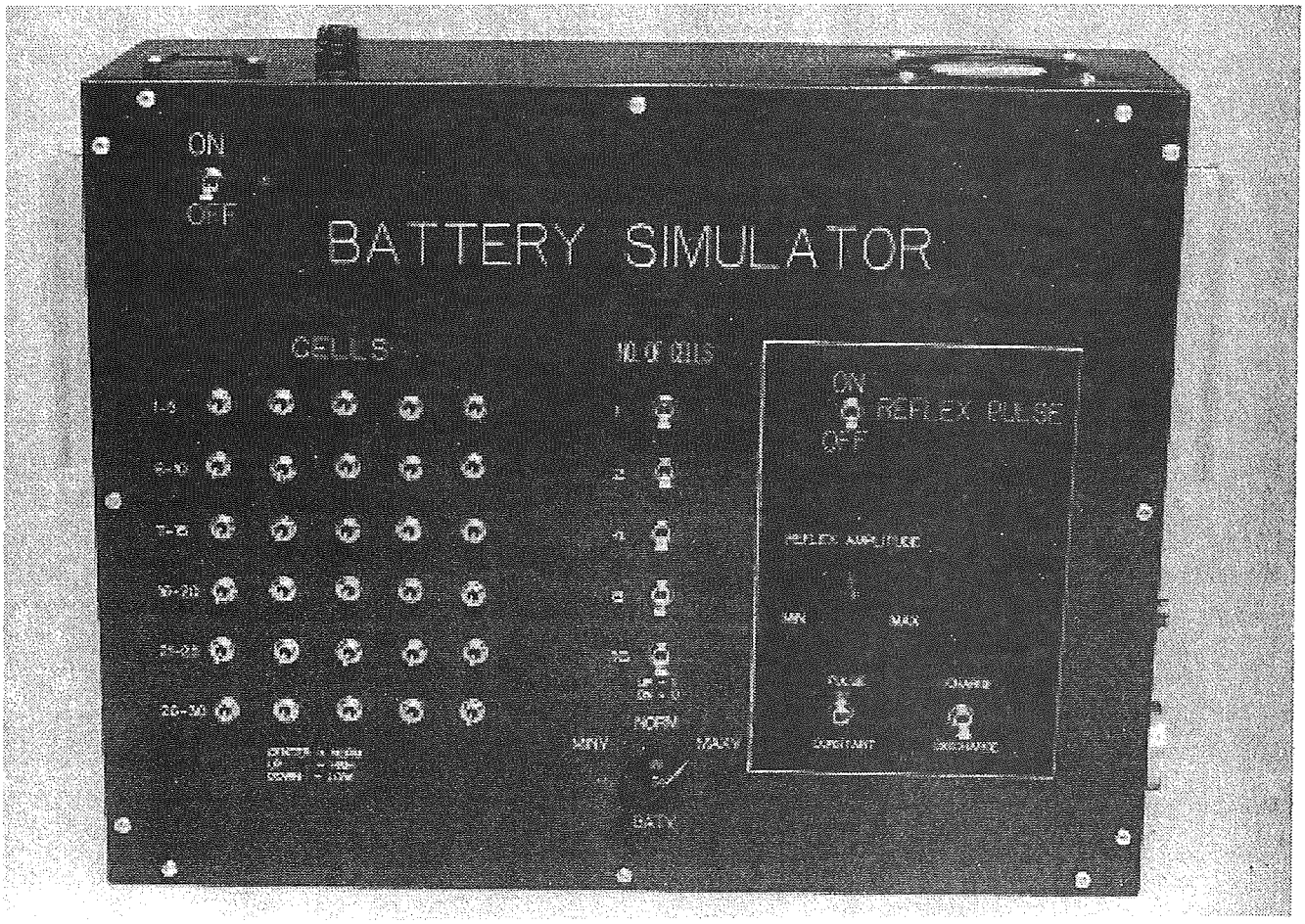


Project Timeline

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

NASA
D91-483

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

PL BATTERY PROGRAM: OVERVIEW

- NICKEL HYDROGEN
  - LEO TESTING
  - EMBRITTLEMENT TESTING
- SODIUM SULFUR
  - FLIGHT EXPERIMENT
  - HOT LAUNCH EVALUATION
- SOLID STATE POLYMERS
  - GEO BATTERY DEVELOPMENT
  - PULSE POWER BATTERY SBIR
  - IN-HOUSE EVALUATION

BATT-2

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

PL BATTERY PROGRAM:

- NICKEL HYDROGEN
  - LEO TESTING
  - EMBRITTLEMENT TESTING

The Phillips Laboratory Nickel Hydrogen testing effort consists of a LEO Life Test Program, a Pulse Test Program, and a Hydrogen Embrittlement Investigation.

NIH2 TEST PROGRAM: OBJECTIVES

- DEMONSTRATE NIH2 PERFORMANCE IN LEO
- DEVELOP A STATISTICALLY SIGNIFICANT BATTERY CELL DATABASE
- DEMONSTRATE THAT DATA BASE FOR 3.5 IN CELLS CAN BE APPLIED TO 4.5 IN CELLS
- DEMONSTRATE NIH2 CELL PERFORMANCE IN PULSE APPLICATIONS

The objectives of the LEO Life Test Program are to: demonstrate NiH2 performance in low earth orbit, develop a statistically significant battery cell 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 10C	3.5 IN DIAM -5C	4.5 IN DIAM 10C
LEO				
25%	(EPI-CS/GEP)			10*
	YARD	5		
40%	HUGHES	10	10	5
	YARD	10	10	
	EPI-J	7		8
	GATES	10	10	8
60%	HUGHES	10		
PULSE				
40%	EPI-J	10		
STORAGE	(EPI-CS/GEP)			10*
TOTAL CELLS		92 - 3.5 INCH		41 - 4.5 INCH

NIH2-9A

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

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

BATT-8A

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 propogation in Inconel 718.

HYDROGEN EMBRITTLEMENT TEST: APPROACH

PHASE I: EMBRITTLEMENT INVESTIGATION

- SAMPLES CUT FROM 3 SPENT CELLS FROM LEO LIFE TEST (EP-13,000 CYCLES, YARD-3,770 CYCLES, GATES-4,300 CYCLES). ALL 60% DOD. INCONEL 718 CASES.
- TENSILE SPECIMENS CUT PARALLEL TO LONG AXIS OF YARDNEY CELL
- 13 STRIPS CUT FROM OTHER TWO CELLS IN A CIRCUMFERENTIAL DIRECTION. WERE THEN BENT INTO U SHAPES AND PLACED IN A 1000 psig HYDROGEN ENVIRONMENT FOR 200 HOURS. 8 SAMPLES (6 OF WHICH WERE SCRIBED AT THE OUTER SURFACE OF THE U-BEND TO A DEPTH OF 0.0002-0.0005 IN) WERE THEN EXPOSED FOR AN ADDITIONAL 200-400 HOURS

In Phase I, samples were cut from three spent cells that had undergone LEO cycling (varying from 3,770-13,000 cycles) at 60% DOD. All cases were Inconel 718. Several specimens were cut parallel to the long axis of one of the cells and subjected to tensile testing. Thirteen strips were cut from the other two cells in a circumferential direction, bent into U shapes and placed in 1000 psig hydrogen for 200 hours. Eight samples were then exposed for an additional 200-400 hours.

HYDROGEN EMBRITTLEMENT TEST: RESULTS

PHASE I:

- TENSILE DUCTILITY OF INCONEL 718 DECREASED AFTER LONG EXPOSURE TO NIH2 CELL ENVIRONMENT. FRACTURE MODE REMAINED DUCTILE.
- ONE FAILURE OBSERVED IN U-BEND SPECIMENS AFTER 200 HOURS. DETERMINED TO BE CAUSED BY APPLIED BENDING STRESS, HYDROGEN ENVIRONMENT, AND SURFACE DEFECT CAUSED BY IMPROPER MACHINING
- INCONEL 718 THAT HAS BEEN EXPOSED TO THE NIH2 CELL ENVIRONMENT APPEARS TO BE MORE SUSCEPTIBLE TO HYDROGEN EMBRITTLEMENT THAN VIRGIN INCONEL 718. THRESHOLD INTENSITY FACTOR COULD BE DECREASED FROM 22 ksi$\sqrt{in}$ FOR VIRGIN INCONEL TO BELOW 17 ksi$\sqrt{in}$ FOR MATERIAL EXPOSED TO HYDROGEN FOR LONG TIMEFRAMES

BATT-2C

Initial results indicate that the tensile ductility of Inconel 718 decreased after long exposure to the NiH2 cell environment. However, the fracture mode remained ductile. One failure was observed in the group of u-bend specimens after 200 hours exposure. However, the failure was determined to have been caused by a combination of the applied bending stress, the hydrogen environment, and a surface defect that was introduced as a result of improper machining during the process of cutting the sample from the cell. Inconel 718 that has been exposed to the NiH2 battery environment appears to be more susceptible to hydrogen embrittlement than virgin material.

HYDROGEN EMBRITTLEMENT TEST: RESULTS (CONT)

PHASE I:

- MAXIMUM APPLIED STRESS INTENSITY FACTOR FOR CELL SHELL IS APPROX 15 ksi$\sqrt{in}$, 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.

BATT-22

The maximum applied stress intensity factor fo. the cell shell has been calculated at approximately 15 ksi in, which may be very close to the threshold stress intensity factor of the Inconel material exposed to hydrogen over long periods of time. Therefore, it is recommended that additional tests be conducted to determine the threshold stress intensity factor value of shell material to warrant safe operation of the cells.

HYDROGEN EMBRITTLEMENT TEST: APPROACH

PHASE II: CRACK PROPOGATION RATES

- SAMPLES CUT FROM SPENT CELLS FROM LEO LIFE TEST. ALL INCONEL 718 CASES
- U-BEND SPECIMENS WITH PRECRACKS EMPLOYED TO ESTIMATE THE CRACK PROPOGATION RATE OF INCONEL 718 IN 1000 psig HYDROGEN. KOH ALSO PRESENT IN TEST ENVIRONMENT
- SOLENOID USED TO PLACE EACH SAMPLE UNDER A CYCLIC LOAD PROFILE

NOTE: PHASE II IS STILL IN PROGRESS

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

PL BATTERY PROGRAM:

- SODIUM SULFUR
  - FLIGHT EXPERIMENT
  - HOT LAUNCH EVALUATION

The Phillips Laboratory Sodium Sulfur development and testing effort consists of a flight test of a 16 cell GEO NaS battery and an evaluation of the hot launch capabilities of NaS cells.

NaS FLIGHT EXPERIMENT: OBJECTIVES

- VERIFY NaS TECHNOLOGY IN ZERO-G
- VERIFY NaS CELL DESIGN FOR GEO APPLICATIONS
- MONITOR THERMAL CONTROL PROCESSES
- ENABLE TRANSITION OF NaS TECHNOLOGY

BATT-3

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

BATT-3A

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

- 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

BATT-4

The flight experiment will utilize a 16 cell, 28 volt, 40 amp-hr GEO battery under development at Wright Patterson AFB. This battery will be delivered GFE to Phillips Lab for integration onto the Air Forces's P91-1 satellite which will fly in 1995. A separate ground test unit will duplicate the experiment concurrently on the ground.

NaS HOT LAUNCH EVALUATION: OBJECTIVES

- EVALUATE CELL PERFORMANCE UNDER HOT LAUNCH CONDITIONS. HOT LAUNCH IS A LAUNCH IN WHICH THE CELLS ARE AT OPERATING TEMPERATURE

- TO EVALUATE STRUCTURAL INTEGRITY OF CELLS UNDER HOT LAUNCH CONDITIONS

BATT-6

The purpose of the Sodium Sulfur Hot Launch Evaluation is to investigatte 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.

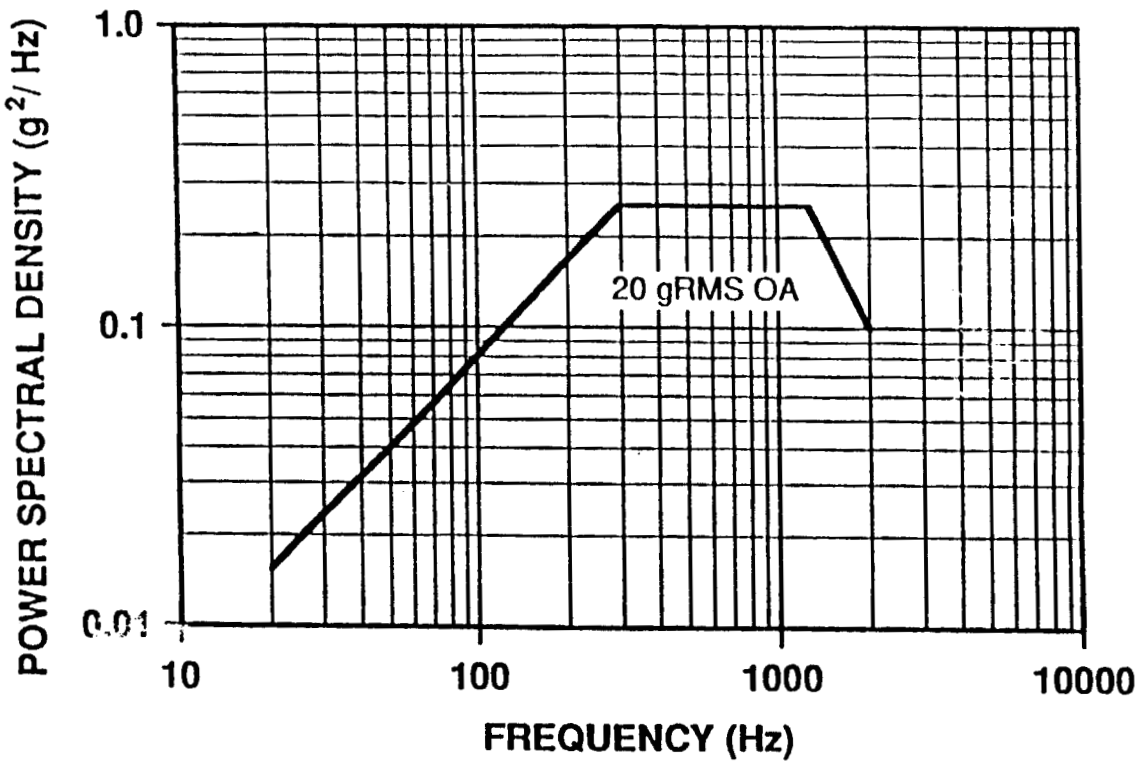
NaS HOT LAUNCH EVALUATION: TEST PLAN

- 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 th etest 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.

C-2

NaS HOT LAUNCH EVALUATION: VIBRATION ENVIRONMENT



BATT-90

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

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

BATT-6C

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

PL BATTERY PROGRAM:

- SOLID STATE POLYMERS
  - GEO BATTERY DEVELOPMENT
  - PULSE POWER BATTERY SBIR
  - IN-HOUSE EVALUATION

SATI-2H

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
- SCALBILITY AND PRODUCIBILITY ANALYSIS
- CELL PERFORMANCE TESTING AND ANALYSIS

STATUS:

- FY92 NEW START
- 2 YR BAA EFFORT FOLLOWED BY EXPANDED PROGRAM

BATT-7

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

SOLID STATE BATTERIES: PULSE POWER BATTERY DEVEL

GOAL:

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

APPROACH:

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

STATUS:

- PHASE I SBIR NEARING COMPLETION

BATT-6

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 poly-acrylonitrile 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

BATT-8

An in-house program at Phillips Lab will also assess the capabilities and limitations of current solid state cells, thus providing valuable information for use on our GEO battery development program. The approach will be to procure cells from several manufacturers, cycle them until failure, and perform a series of tests to determine the failure modes/mechanisms.

BATTERY and CELL TESTING at Marshall Space Flight Center

Marshall Space Flight Center
Huntsville, Alabama
35812

Tom Whitt and Lorna Jackson

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

EB12/MSFC

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

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

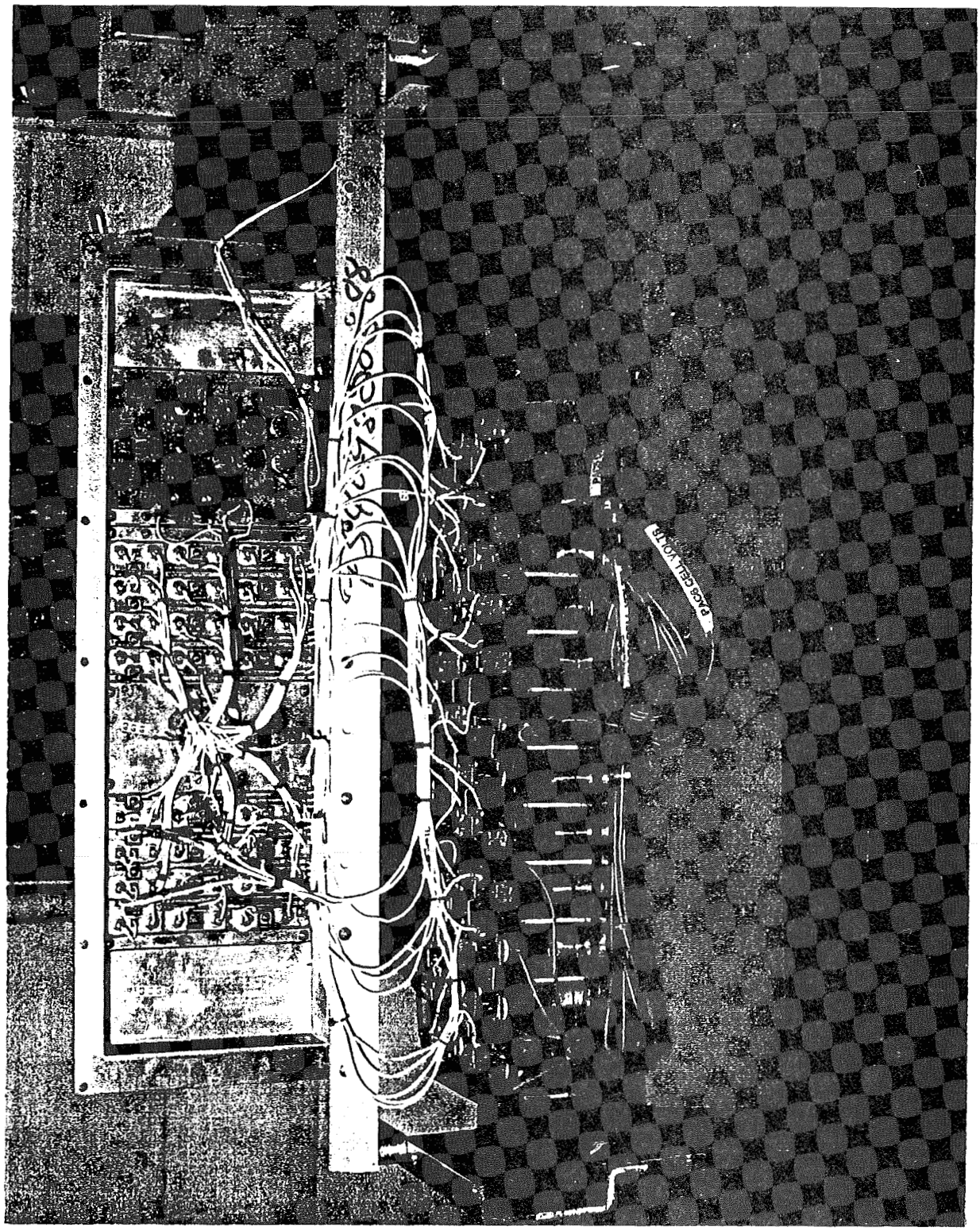
HST NiCd Six, 4-Cell Packs

- 55 ampere-hour cells developed by Eagle-Picher Inc. RSN-55-15, Type 44 Cells
- These were the baseline cells for HST before their replacement by Ni-H2 batteries.
- Characterize cell behavior and demonstrate life capability of the originally designed HST batteries.
- Completed over 27,000 LEO cycles
- The cells met the 3 year HST capacity requirement even after 59 months of cycling.

EB12/MSFC

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_2 batteries. The packs are configured into six packs of four cells each. The system was designed for the cells to operate at a depth of discharge equivalent to 16 percent of nameplate capacity of 55 ampere-hours during normal cycling. On line since 1990, this test will be used to characterize cell behavior and demonstrate life capability of the originally designed HST batteries.

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



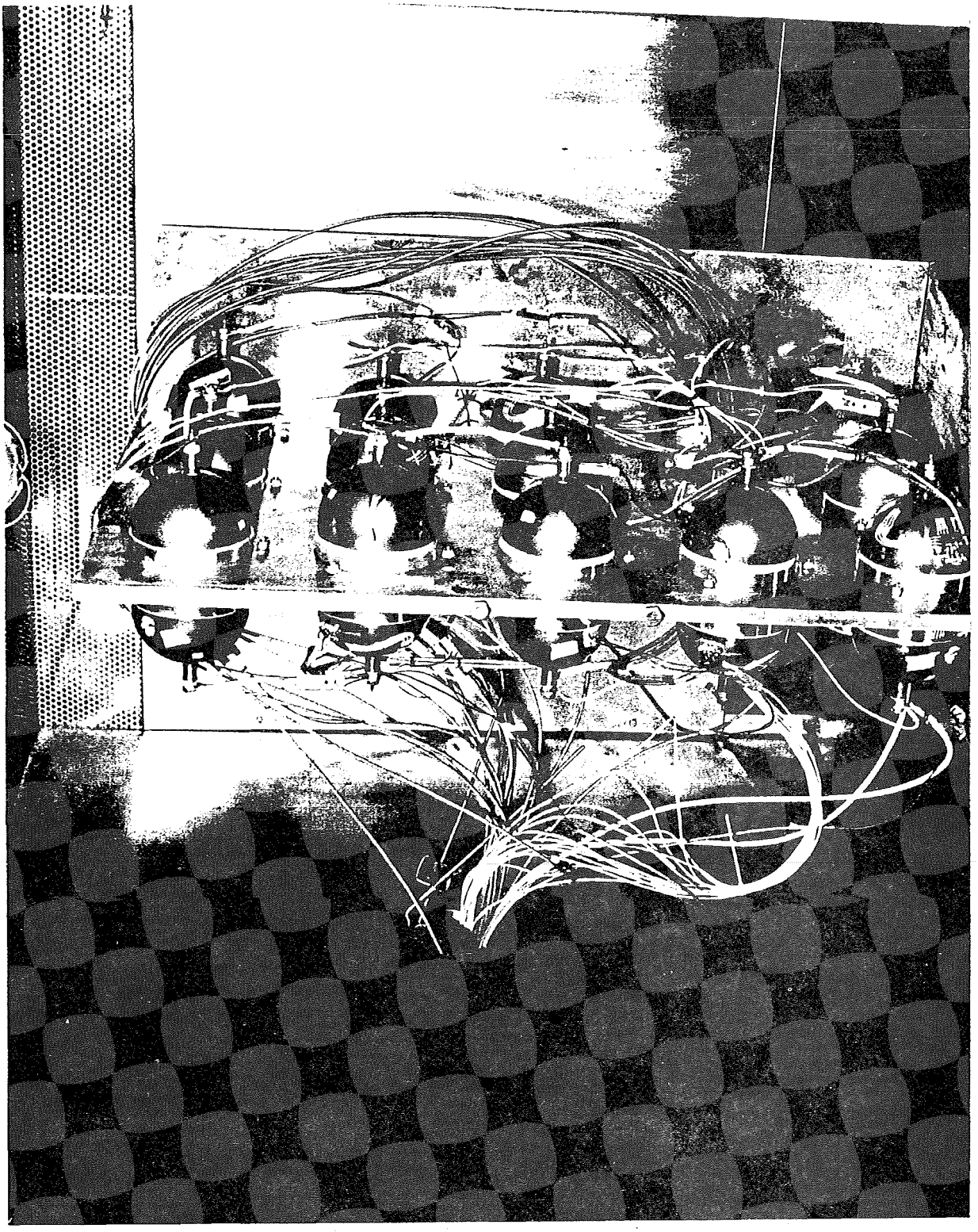
HST Ni-Cd Six, 4-Cell Packs

HST Ni-H2 14 Cell Pack

- 30 ampere-hour cells developed by Eagle Picher Inc. RNH-30-1 (COMSAT design)
- On test since 1986, to build data base for Ni-H2 LEO operation at shallow DODs
- Completed over 26,000 LEO cycles at 13% DOD.
- Capacity after 4.5 years of cycling was 22 Ah.

EB12/MSFC

HST Ni-H2 Fourteen Cell Pack - Fourteen Eagle-Picher RNH-30-1 (30 ampere-hour capacity) cells of COMSAT design on test since 1986 (First Ni-H_2 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_2 cells in anticipation of a decision to fly Ni-H_2 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_2 LEO operation at shallow depths of discharge.



HST Ni-H_2 Fourteen Cell Pack

Ni-H2 12 Cell Pack

- 33 ampere-hour (Ah) cells developed by Eagle Picher Inc. RNH-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.

EB12/MSFC

Ni-H2 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.

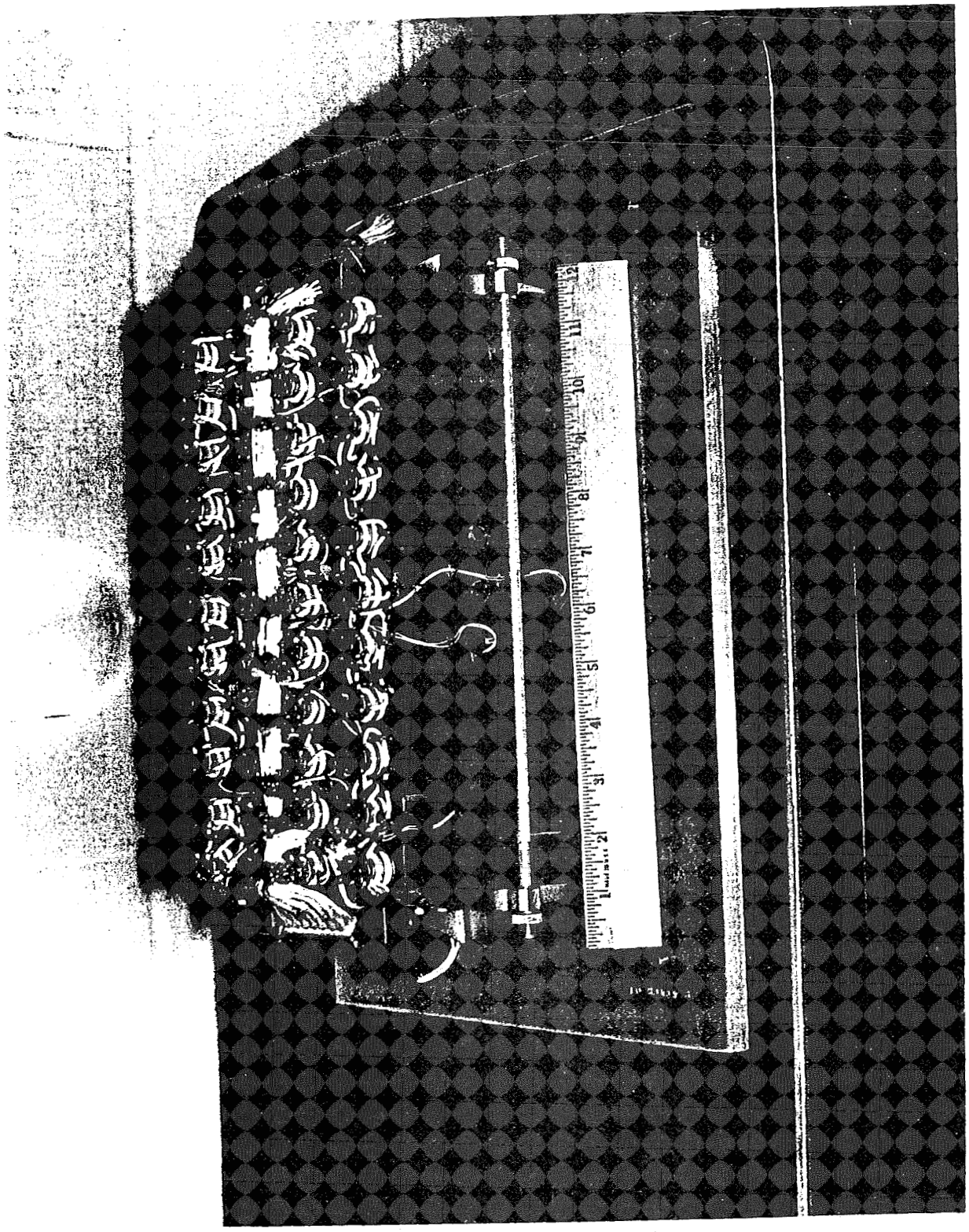
CRRES Ni-Cd Testing

- 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

EB12/MSFC

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.



CRRES Flight Spare Battery

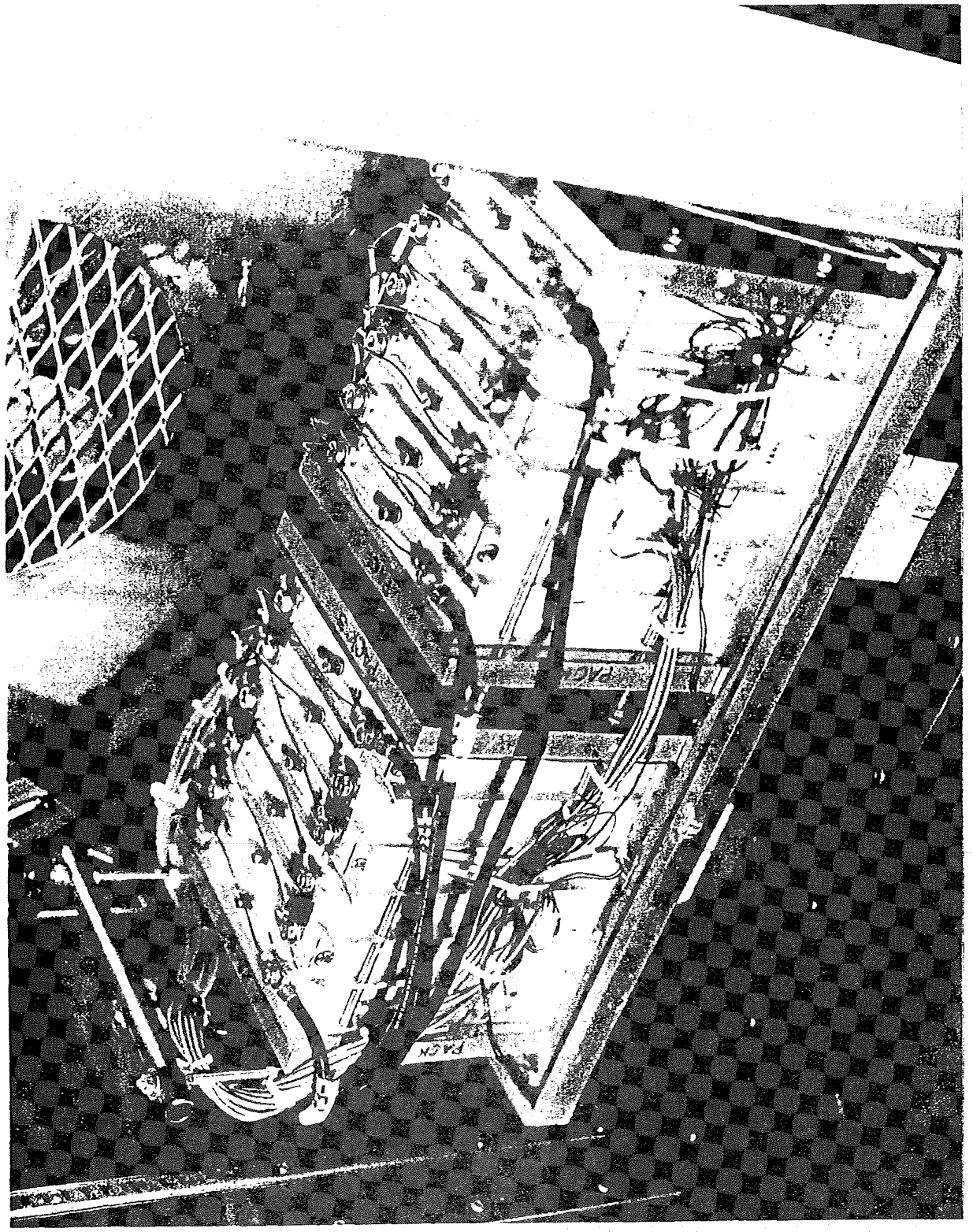
Silver-Zinc Pack Testing
Four, 6-Cell Packs

- 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 Dicharges" (295 Ah)
- 19 Deep Discharges and over 8200 LEO cycles
- Total capacity after 18 months of cycling was 295 Ah.

EB12/MSFC

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).



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

HST Ni-H2 4-Cell Packs

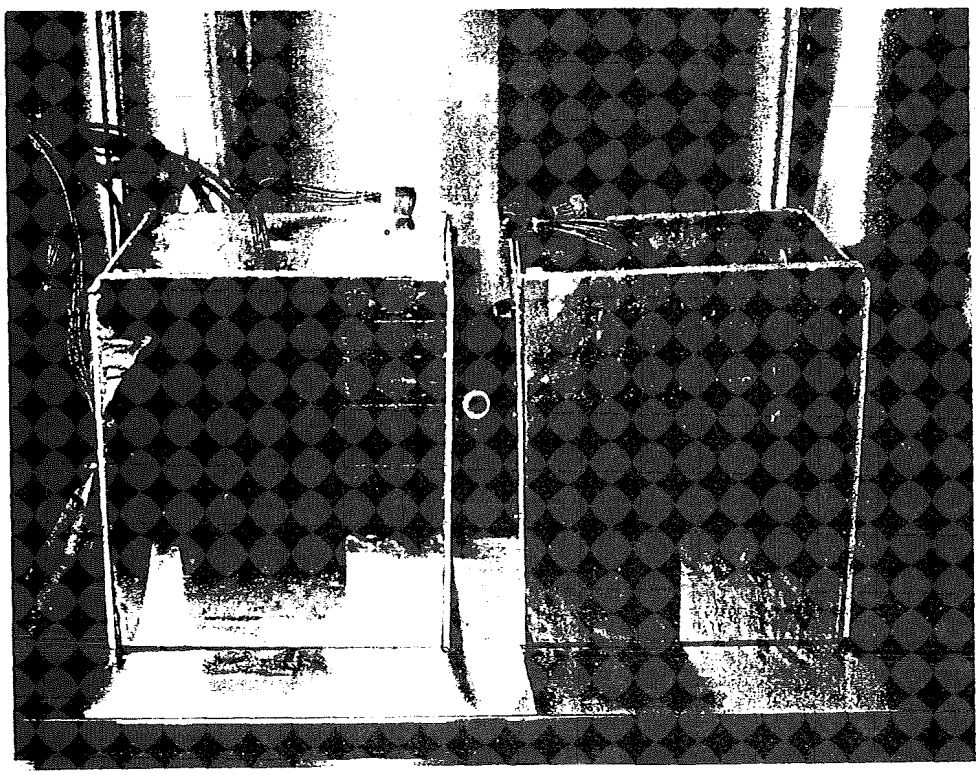
- 88 ampere-hour cells developed by Eagle Picher Inc. for the HST project. RNH-90-3
- One 4-cell pack of TM1 cells, One 4-cell pack of TM2 cells, and One 4-cell pack of FSM cells
- Packs used for parametric testing. First of the HST cells to arrive at MSFC for testing.
- Testing parallels HST system test with ability to investigate proposed changes or duplicate recent occurrences without affecting integrity of system test.
- Months on test TM1- 34 TM2- 32 FSM- 30

EB12/MSFC

HST Ni-H2 Three, 4-Cell Packs - Three four cell packs of Eagle-Picher RNH-90-3 cells from different lots (4 Flight Spare Module (FSM) Lot Cells, 4 Test Module 1 (TM1) Lot Cells and 4 Test Module 2 (TM2) Lot Cells) following an Hubble Space Telescope (HST) low earth orbit (LEO) (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.

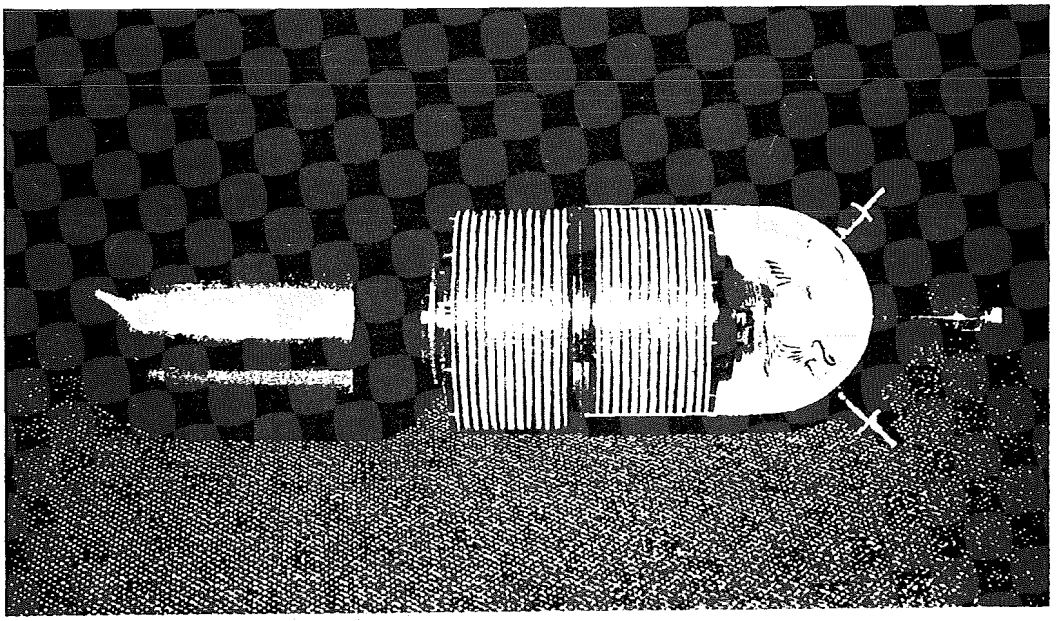
The packs provided early data on the operation of HST Ni-H_2 cells cycled according to a Voltage versus Temperature (VT) curve already in place for use on the HST with Ni-Cd batteries. The test bed uses programmable power supplies and load banks with digital system control and data collection while solar array decay, seasonal sun intensity, off nominal roll and other parameters are variable. These cells were used for parametric testing on Ni-H_2 cells of HST design. This test will continue HST LEO cycling when not performing system evaluation tests.

HST Ni-H_2 Three, 4-Cell Packs



Eagle Picher RNH-90-3

Developed for the Hubble Space Telescope



Testing of RNH-90-3 Cells

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

EB12/MSFC

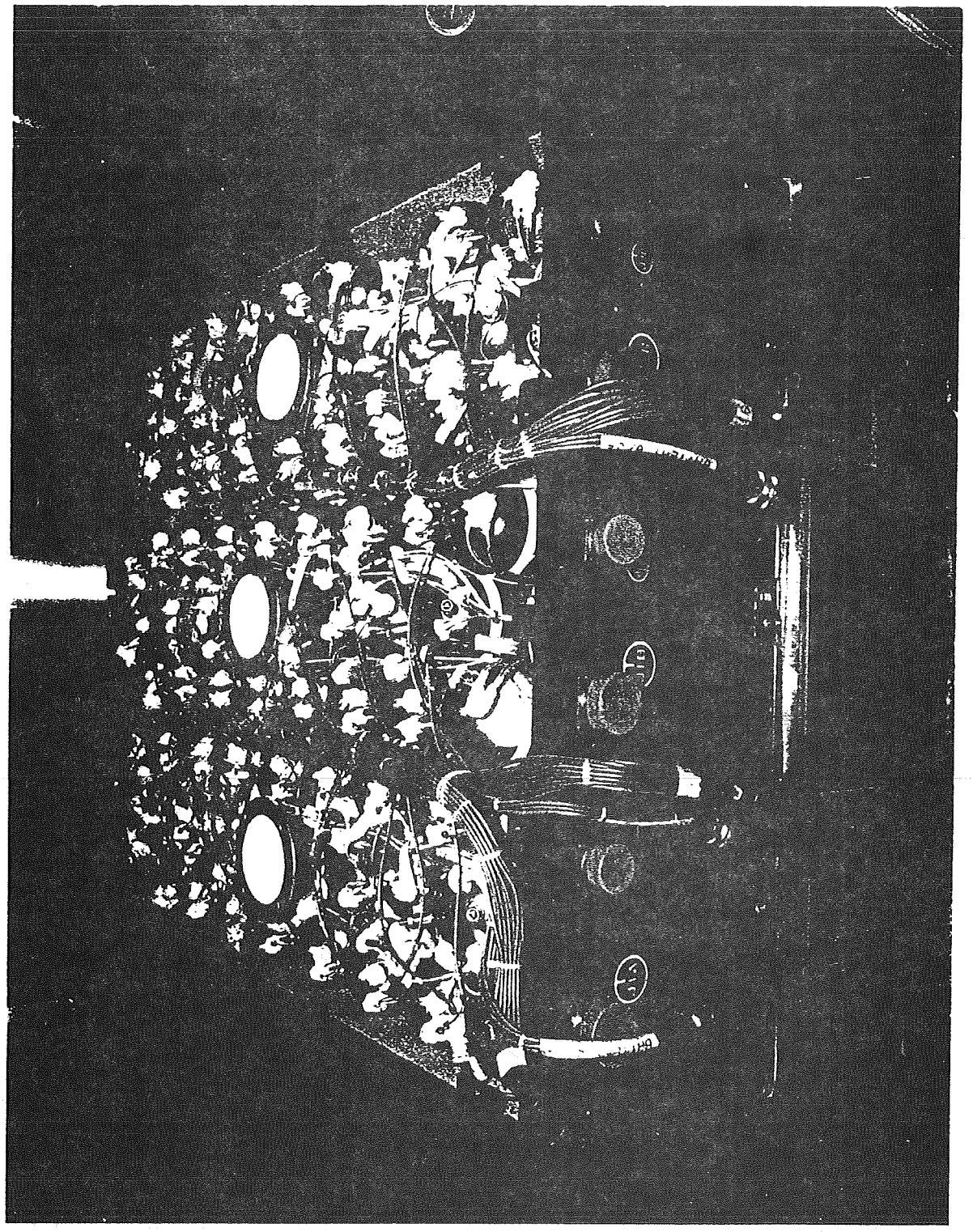
HST Ni-H2 Six Battery Test

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

EB12/MSFC

HST Ni-H2 Six Battery System Simulation - A full scale Hubble Space Telescope (HST) Ni-H_2 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_2 modules in a low earth orbit (LEO) power system; these modules are operating at the current HST Charge Current Control (CCC) levels in a $0^{o}C$ environment.

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



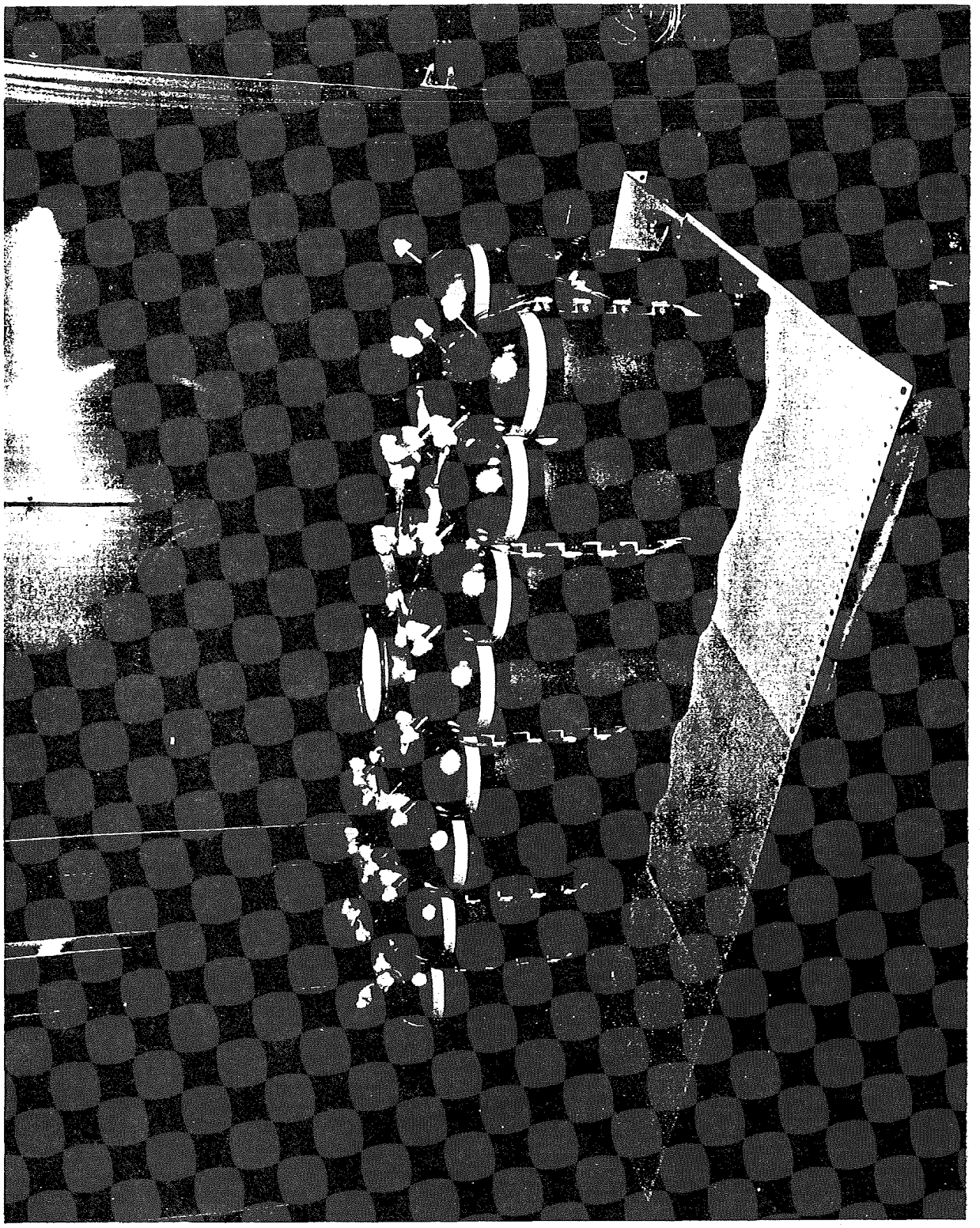
HST Ni-H_2 Three Battery Module

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

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.



HST Ni-H_2 "Flight Spare" Battery

Ni-H2 Two, 2 Cell Packs

- 88 ampere-hour cells developed by Eagle Picher Inc. for the HST project. RNH-90-3
- Previously used in the HST 4 Cell Pack Testing.
- 1 pack with 26% KOH / 1 pack at 31% KOH
- Compare performance of the KOH concentrations at high DODs (20-50%) in a LEO cycling profile
- 24 months of testing at the higher DODs

EB12/MSFC

Ni-H2 Two, 2-Cell Packs - Four test cells from the Hubble Space Telescope (HST) engineering lot of cells (Eagle-Picher RNH-90-3) are divided into two packs of two cells dependent upon their electrolyte concentration (2 cells with 26% KOH, Pack #1; and 2 cells with 31% KOH, Pack #2). On line since 1988, this test was set up to research the behavior of Ni-H_2 cells of HST design, having differing electrolyte concentrations, when operated at high depths of discharge (20% - 50%) in a low earth orbit cycling program. This test utilizes cells which were previously used in the HST three, 4-cell pack testing program. These cells are currently cycling according to a parametric test matrix which will be completed in 1992.

EAGLE PICHER RNH-90-3 CELLS CYCLING AT 22% & 33% DODs

- 88 ampere-hour cells developed by Eagle Picher Inc. for the HST project.
- Four 4-cell packs cycling at 22% DOD
  Two 4-cell packs cycling at 33% DOD
- Gather data to determine best charge control method to use for Ni-H2 cells at moderate DODs.
- Study the effect of reconditioning on Ni-H2 cells.
- Demonstrate the ability of the HST design to provide extended life cycle at DODs required by AXAF, Space Station, etc.

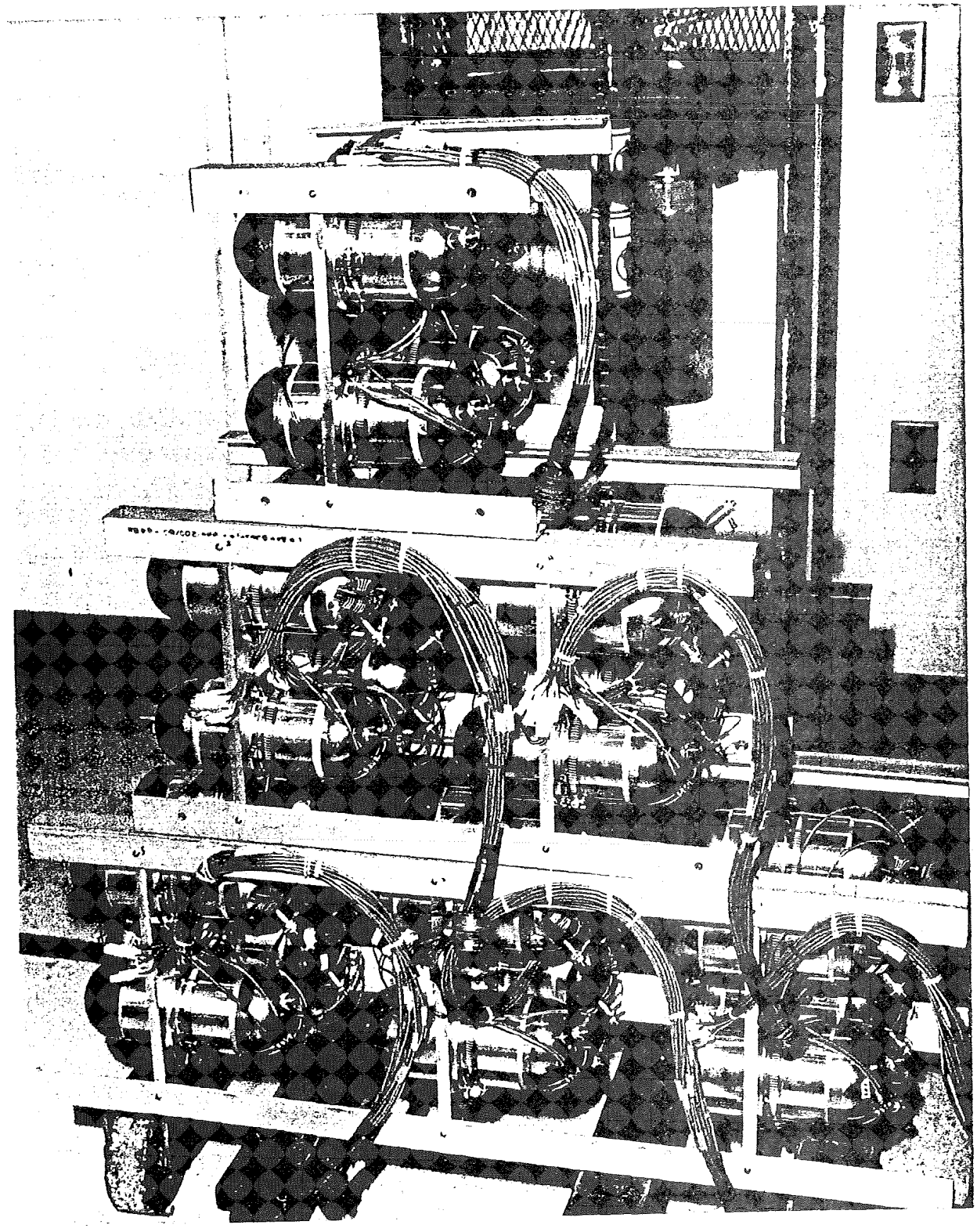
EB12/MSFC

Six, Ni-H2 4-Cell Packs - This test utilizes 24 Eagle-Picher RNH-90-3 Ni-H_2 cells from the Hubble Space Telescope (HST) program. The cells are low earth orbit (LEO) cycling on a 61/35 orbit. On line since May of 1991, the purpose of this test is to evaluate the performance and operating characteristics of the HST cell at moderate depths of discharge (DOD's) and investigate the long term effects of periodic reconditioning.

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

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

Six, Ni-H_2 4-Cell Packs



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Testing of Eagle Picher RNH-90-3
at MSFC

Summary

TEST	# of Cells	Cycling DOD	Project(s)	Months of testing
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
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SUMMARY OF LDEF BATTERY ANALYSES

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ABSTRACT

Tests and analyses of NiCd, $LiSO_2$ and LiCF batteries flown on the Long Duration Experiment Flight (LDEF) includes results from NASA, Aerospace and commercial labs. The $LiSO_2$ 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_2), 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 fo Space Exposure	Li/SO2	12	2	64%
A 0187-1	Clam Shell Elect-Micromeorites	Li/SO2	7.5	1	59%
A 0187-1	Clam Shell Elect-Micromeorites	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 Counductive. 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 $0 \pm 5\ ^{o}C$. The average temperature of LDEF flight batteries was $15 \pm 10\ ^{o}C$, 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.

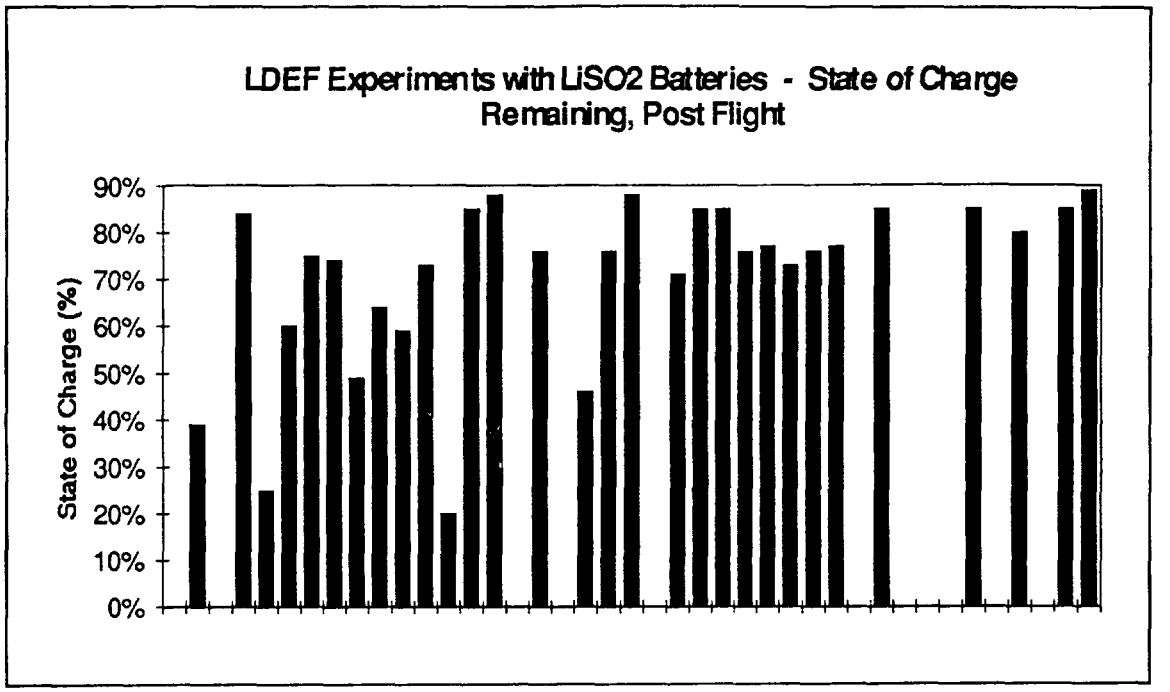

Figure 1. State of Charge Remaining in Li/SO_2 Batteries Returned from LDEF Flight.

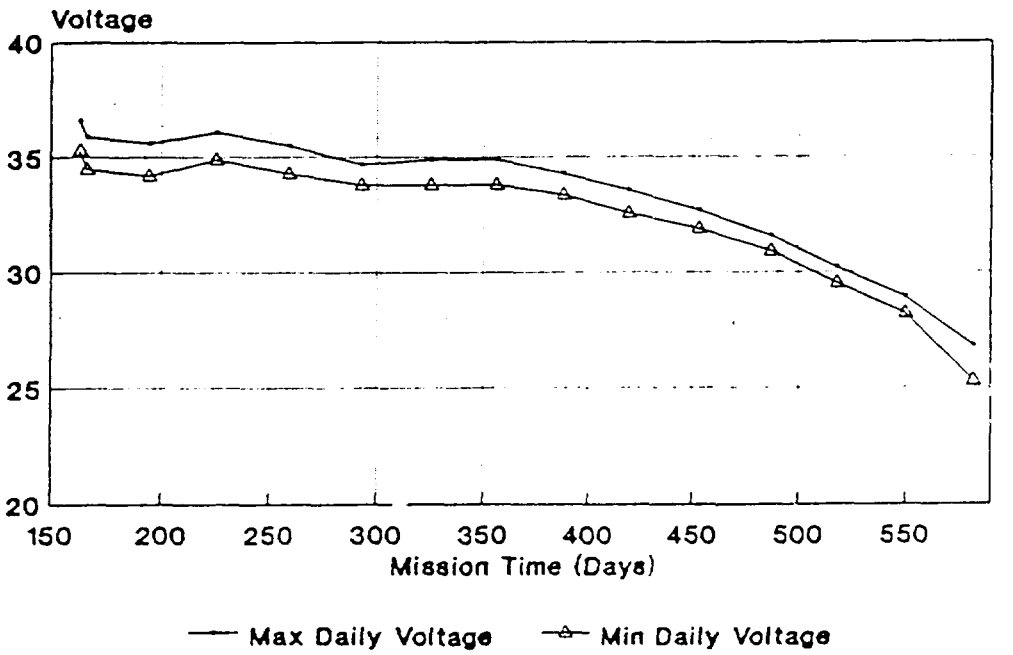

Figure 2. Gradual Degradation of Voltage with Flight Duration for Li/CF Batteries

TESTS AND ANALYSES ON THE NICKEL CADMIUM BATTERY

One nickel cadmium battery was flown on the Low Temperature Heat Pipe Experiment Package (Experiment #S1001). Analysis and test of the battery has been conducted by S. Tiller and D. Sullivan of NASA Goddard Space Flight Center (7). The battery consisted of two 9-cell packs, which were mounted onto a 0.75 inch thick aluminum baseplate. Prior to flight, power analysis for the 12-Ah NiCd battery indicated a need for 2 to3 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.

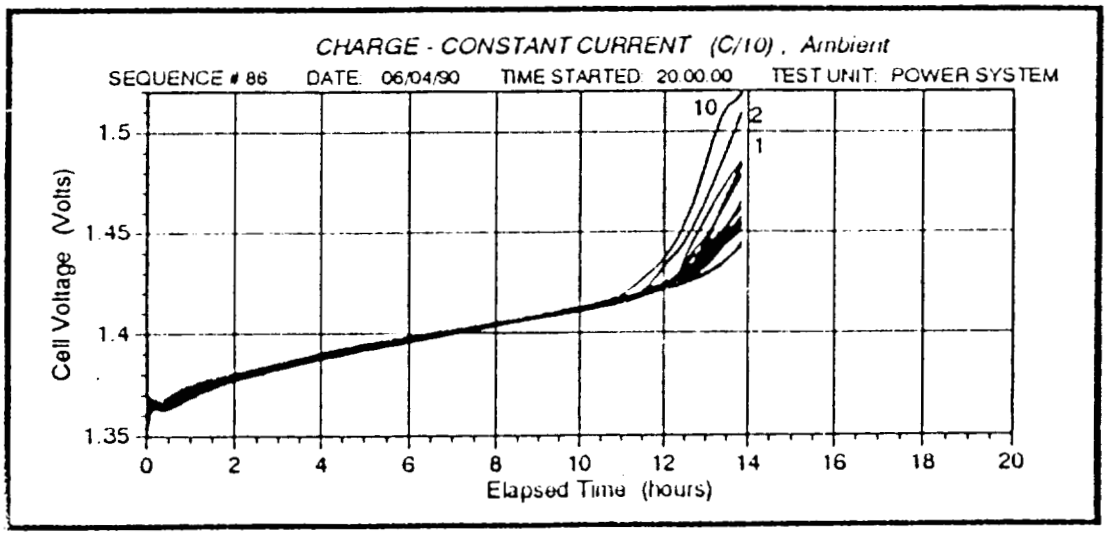

Figure 3. Constant Current Charge Indicates Loss of Overcharge Protection

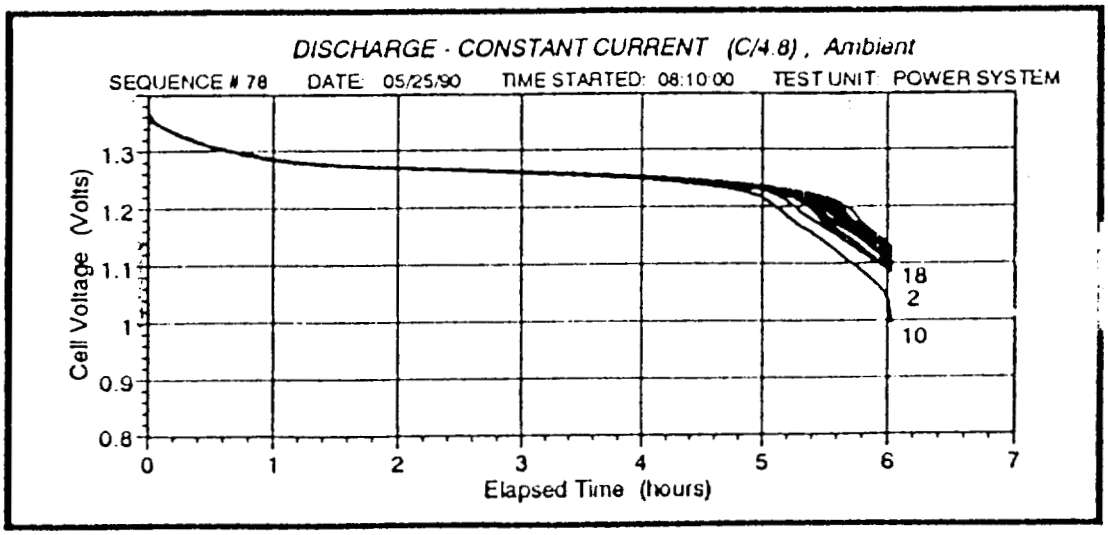

Figure 4. Constant Current Discharge Produces Low Capacity, Post Flight

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2. Raman, "Experimentation and Destructive Physical Analysis for the Space-Exposed Lithium-Sulfur Dioxide (Li/SO2) Batteries From the Long Duration Exposure Facility (LDEF)", SAFT America Inc., 1991, Attachment 1, p. 39.

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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

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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 $Li/(CFx)_n$ CELLS

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NASA AEROSPACE BATTERY WORKSHOP

OCTOBER 29-31, 1991

MARSHALL SPACE FLIGHT CENTER

HUNTSVILLE, AL

ABSTRACT

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

INTRODUCTION

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

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

WET CATHODES VOLUME BEFORE DISCHARGE

	Volume *(Cm^3)
PC/DME	0.261
GBL	0.251

CATHODES FROM DISCHARGED CELLS

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

ΔVolume* (%)

	32°F	120°F
PC/DME	36	1
GBL	36	2

75°F Discharge Across a 15,000 ohm Load

ΔVolume* (%)

PC/DME	27
GBL	28

* ± 1%

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.

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

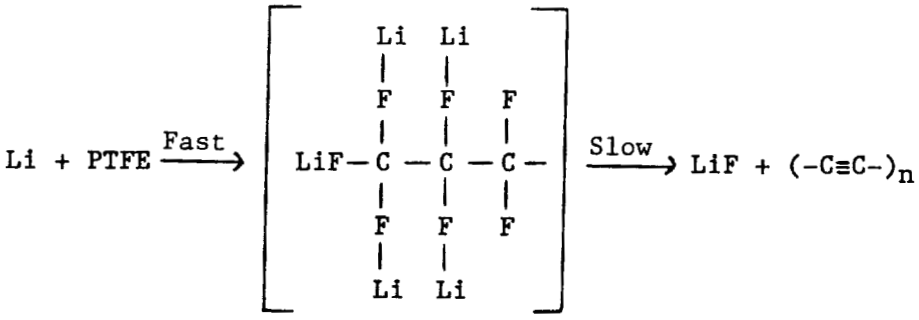
PROPOSED MECHANISMS

$(CF_x)_n$

$$n\,Li + (CF)_n \longrightarrow [CFLi]_n^* \longrightarrow nLiF + nC$$

* 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?

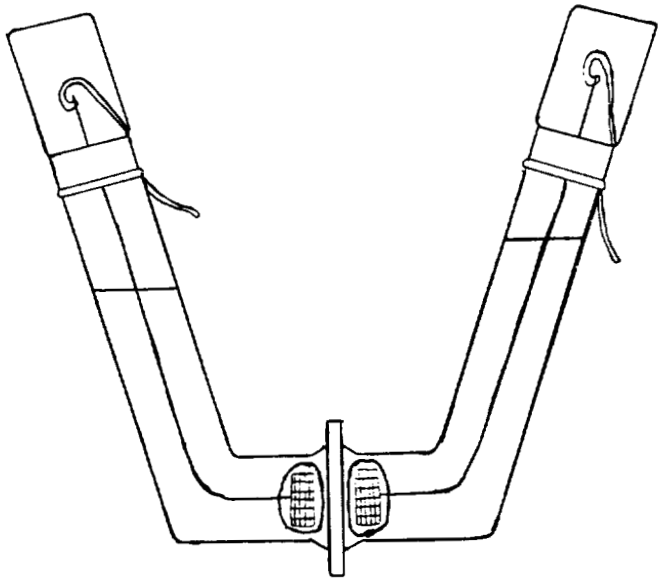
ROLE OF CARBON

(Reaction Mechanism)

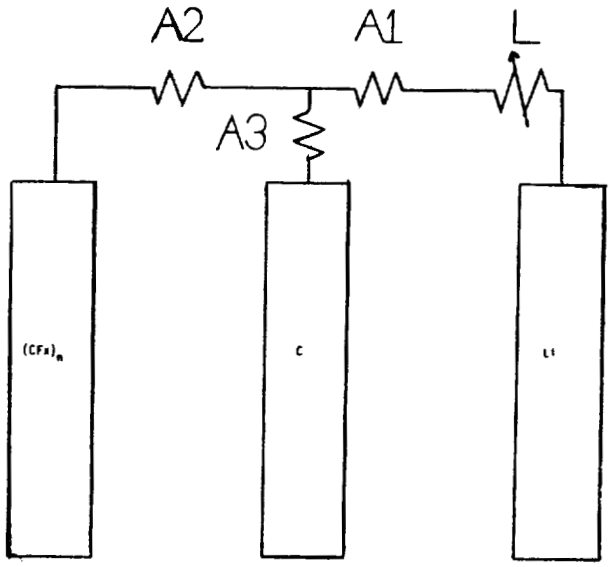
Reaction mechanisms proposed, in the literature, for the $(CFx)_n$ electrode reduction by lithium assume lithium ion penetration to reaction sites between layers of active material via an intermediate. A similar mechanism is proposed for the reduction of PTFE by lithium metal.

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

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



"Lithium passage through carbon" cell.



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

A1 - Resistor used to measure total current flow.
A2 - Resistor used to measure current flow to $(CFx)_n$.
A3 - Resistor used to measure current flow to carbon.
L - Resistive load controlling current flow.

ROLE OF CARBON

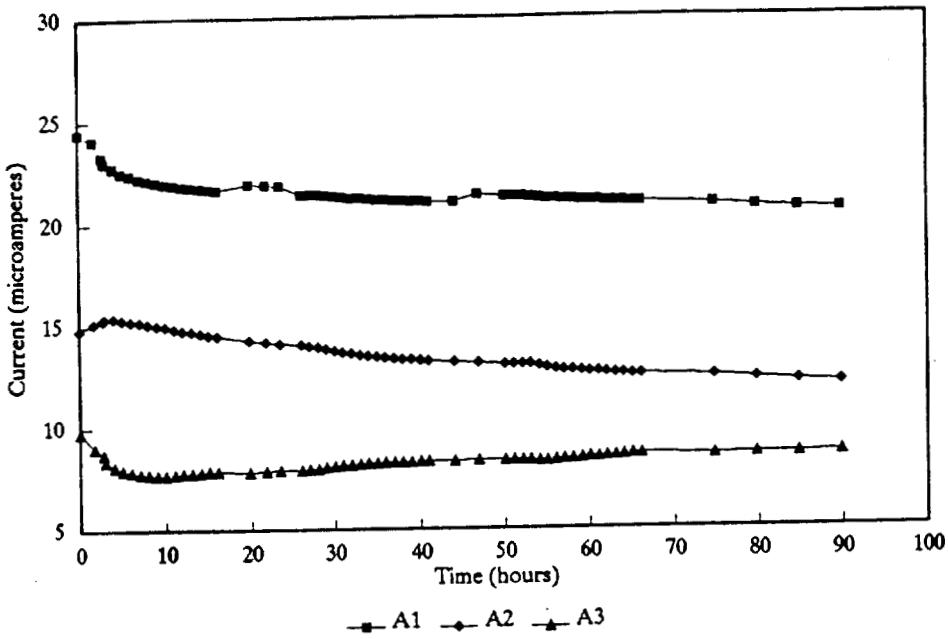
(Experimental)

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

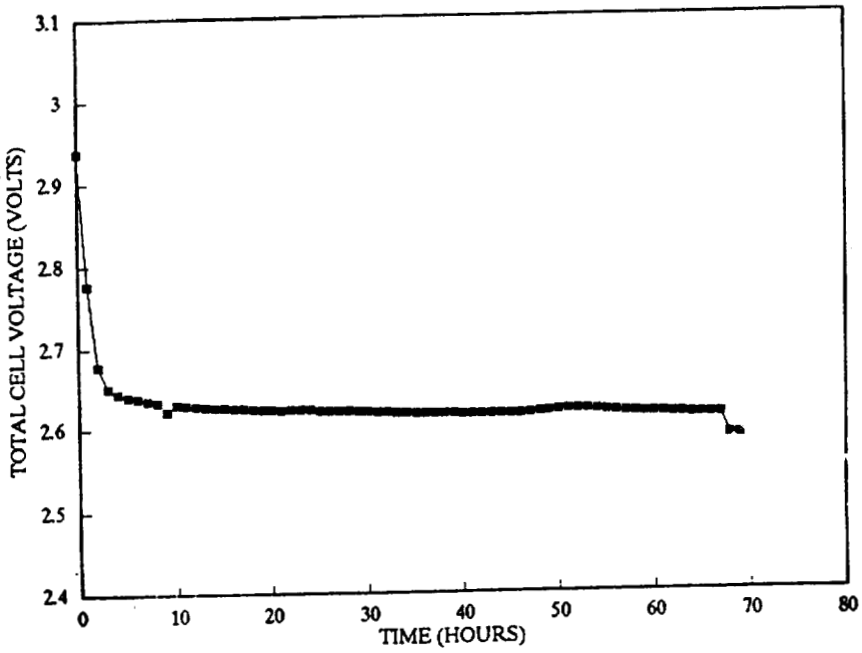
This cell was discharged through a large resistance, L and the currents flowing from the lithium, to the carbon and to the $(CF_x)_n$ electrodes were measured through smaller calibrated resistors A1, A3 and A2, respectively, using DVMs. The voltage between the two electrodes, Li and $(CF_x)_n$ was also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

Initial results with a 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.



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)

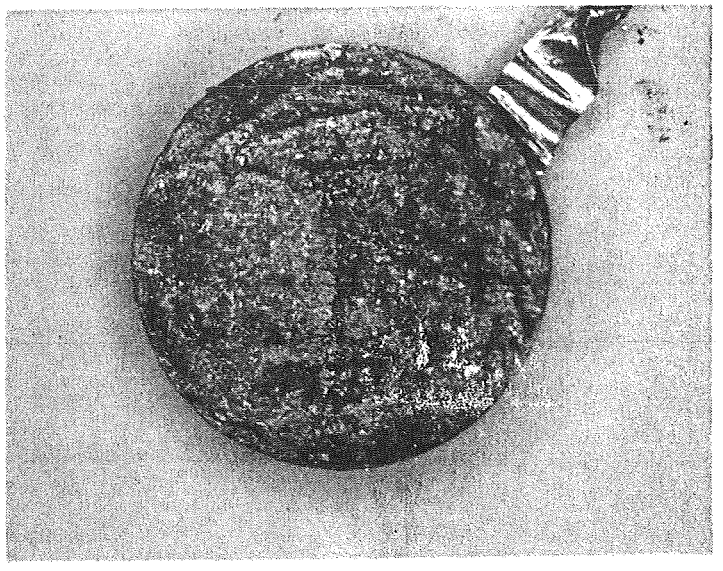
Results obtained with the PC solution varied some with the piece of carbon used. In the case of one cell similar results to those obtained with DMSI were obtained.

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 primarily 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.

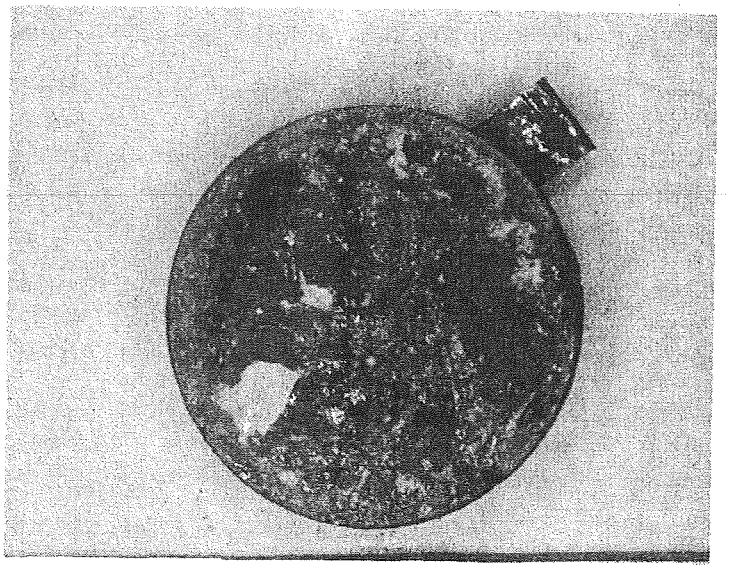
Such behavior indicates carbon loading with lithium while the cell is discharging. Hence, if one assumes that $(CFx)_n$ is fully covered with discharge product, even if slightly cracked, then the observed discharge voltages could be attributed to mixed potentials involving lithium loading on carbon and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

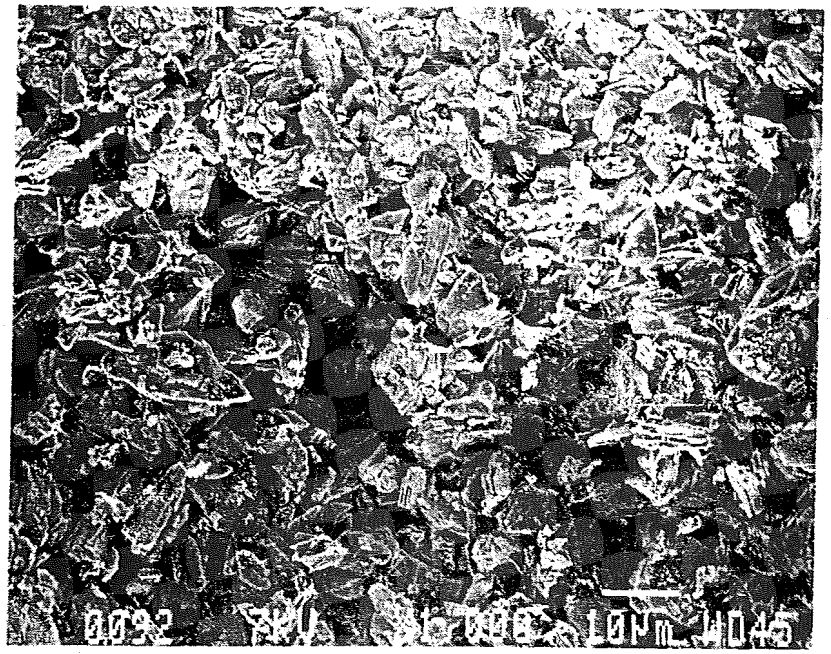
Visual and microscopic examination of specially made "electrodes" gave better insite into the swelling mechanism.

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

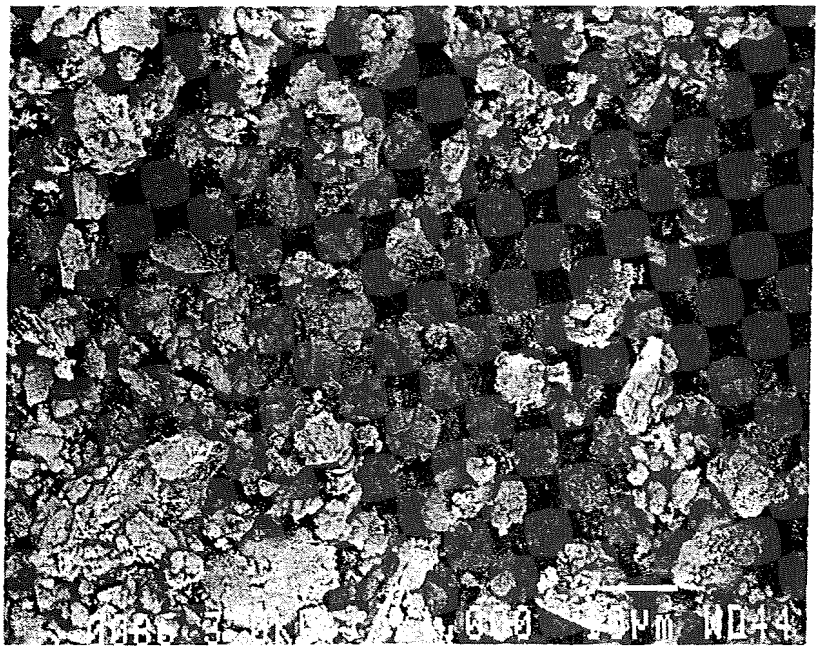
Surprisingly, partially discharged material on the surface of these electrodes hardened into a porous matrix and had to be scraped for further observation. Scraping of such partially discharged electrodes revealed a gray upper layer of partially discharged material on the top of the electrode and a dull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

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 <u>through</u> 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 Li/$(CFx)_n$ cells is the formation and three dimensional expansion of the fused particle matrix.

Lithium reaction with carbon in the $(CFx)_n$ electrode provides for an acceptable explanation for lithium ion migration during discharge and might explain observed voltages during discharge.

AKNOWLEDGEMENT

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

N92-22748

PRIMARY ZINC-AIR BATTERIES FOR SPACE POWER

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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^2, while the maximum continuous current density is 50 mA/cm^2.

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^2) to be delivered and the utilization (%) achieved at a given current density. Figure 4 shows typical anode utilization data for a zinc-air button cell and for three sizes of alkaline cylindrical cells, all of which use similar anodes. The tailoff in the zinc-air cell curve is the result of air access restrictions to the cathode. The much lower utilizations for the alkaline cells are the result of the cylindrical geometry and the moisture uptake of the manganese dioxide cathode. We assumed AA utilizations for the initial designs, to be conservative, but those achieved in practice were more in agreement with the zinc-air curve, as extrapolated linearly.

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

electrolyte weepage. A microporous polymeric separator placed against the cathode surface prevents internal shorting.

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

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

$$s = i \bullet L^2/1100.$$

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:

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

$$Vav\ (V) = 1.29 - 0.0058i.$$

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^2, 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^2) 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^2) 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.

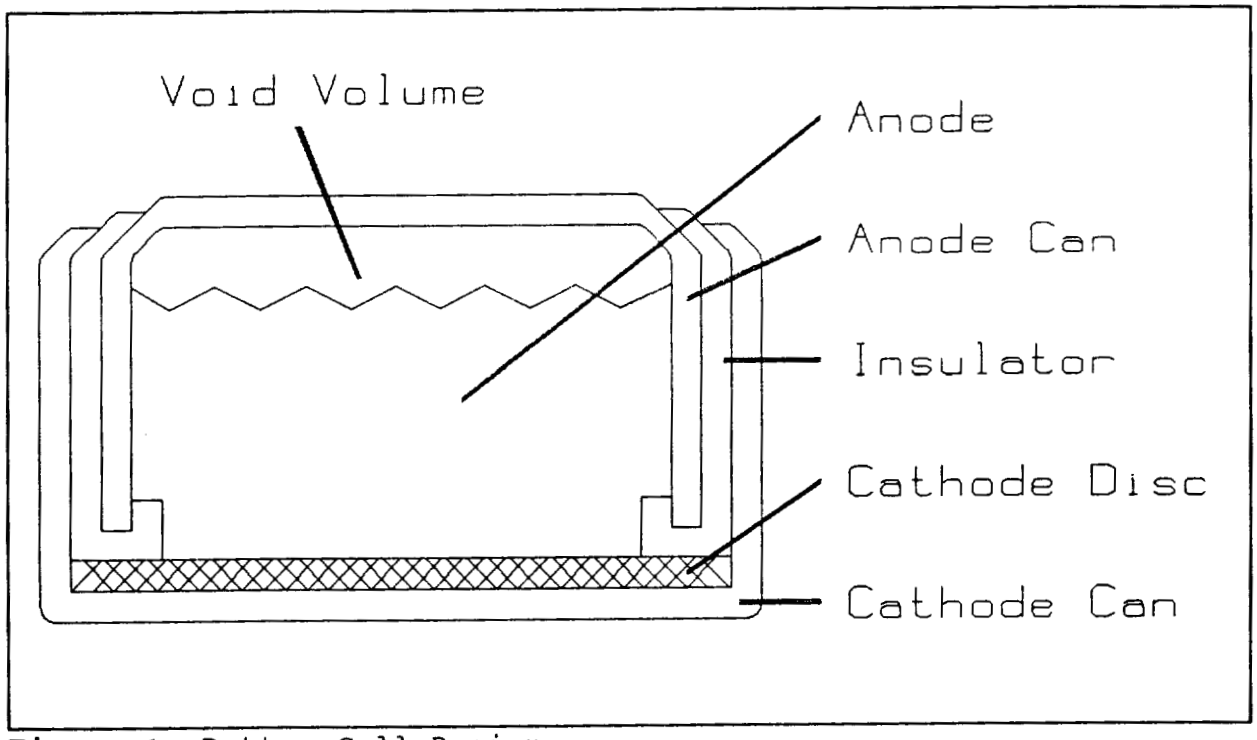

Figure 1: Button Cell Design

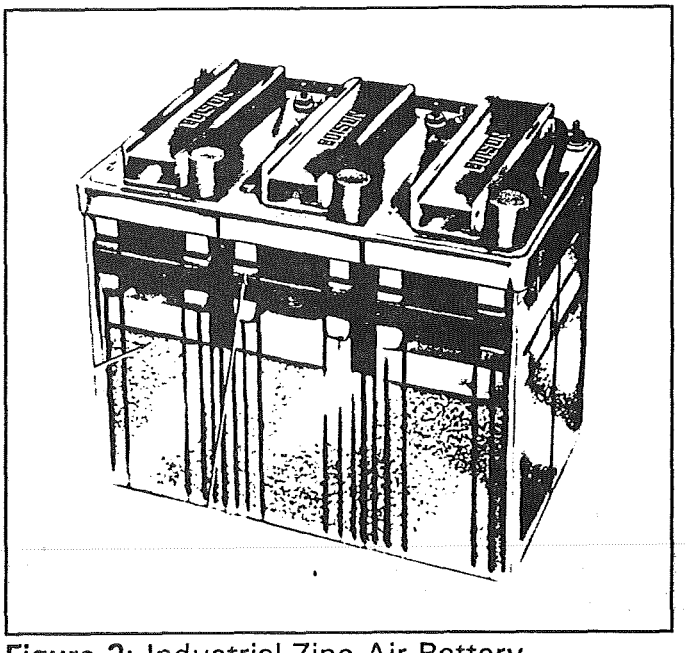

Figure 2: Industrial Zinc-Air Battery

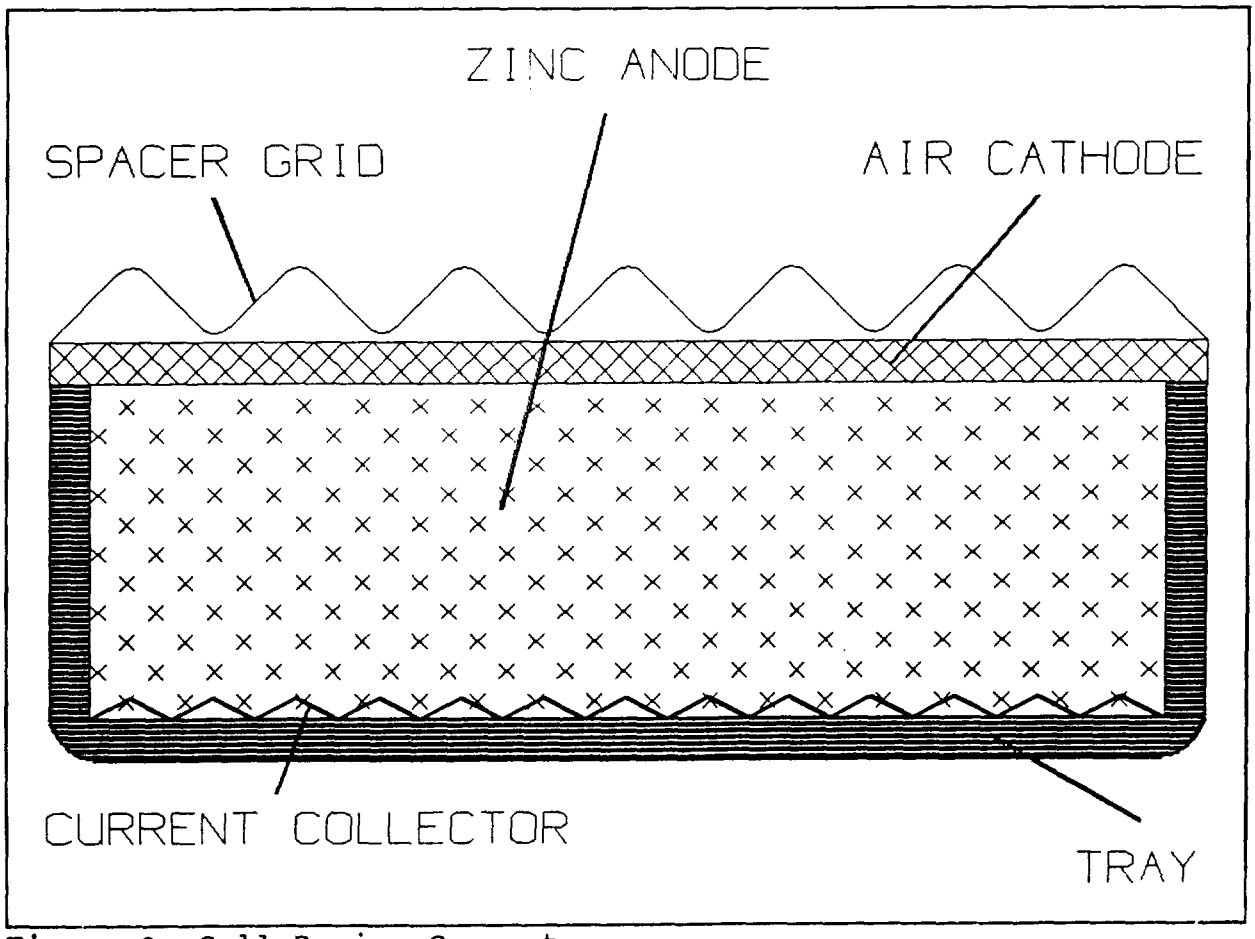

Figure 3: Cell Design Concept

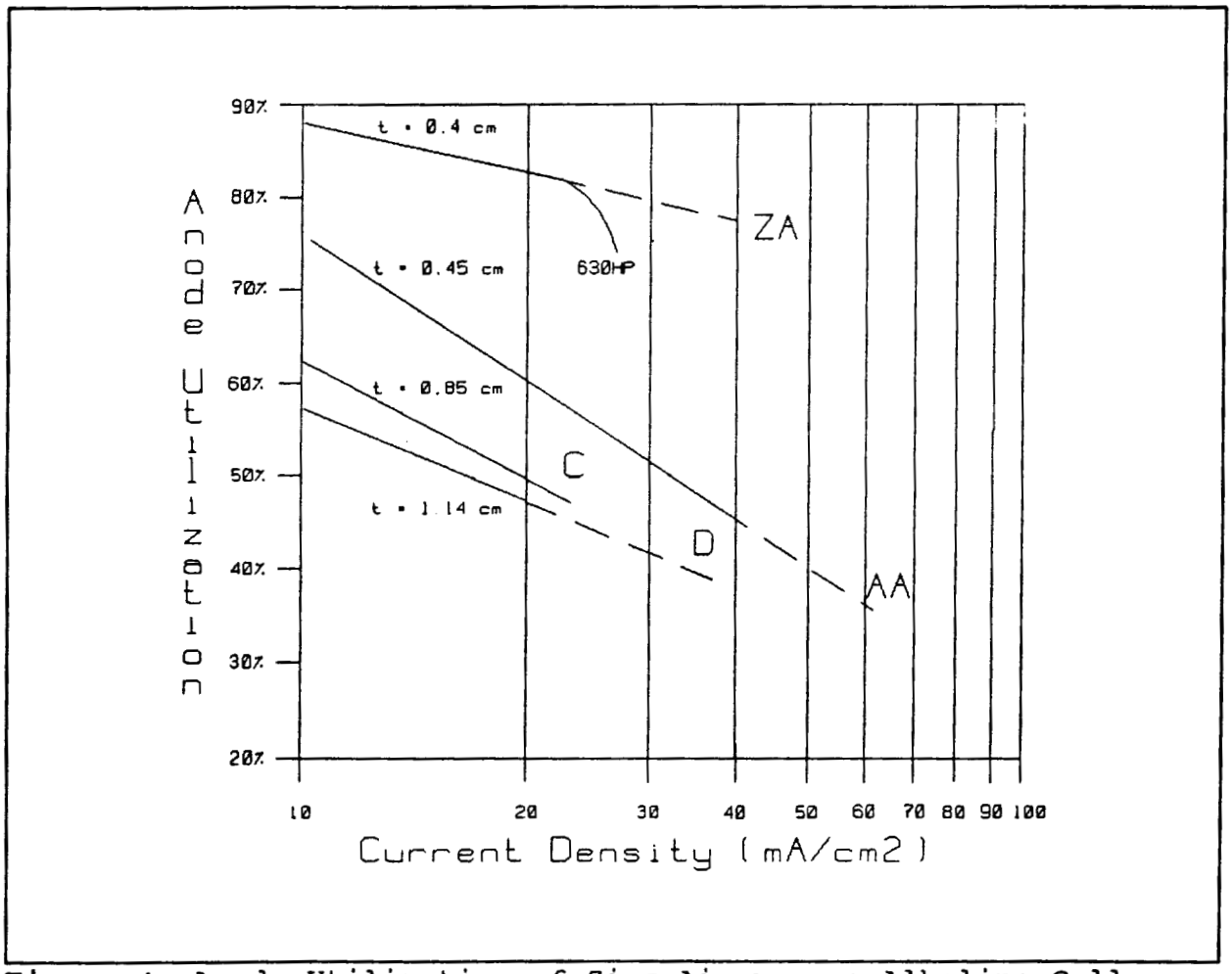

Figure 4: Anode Utilization of Zinc-Air versus Alkaline Cells

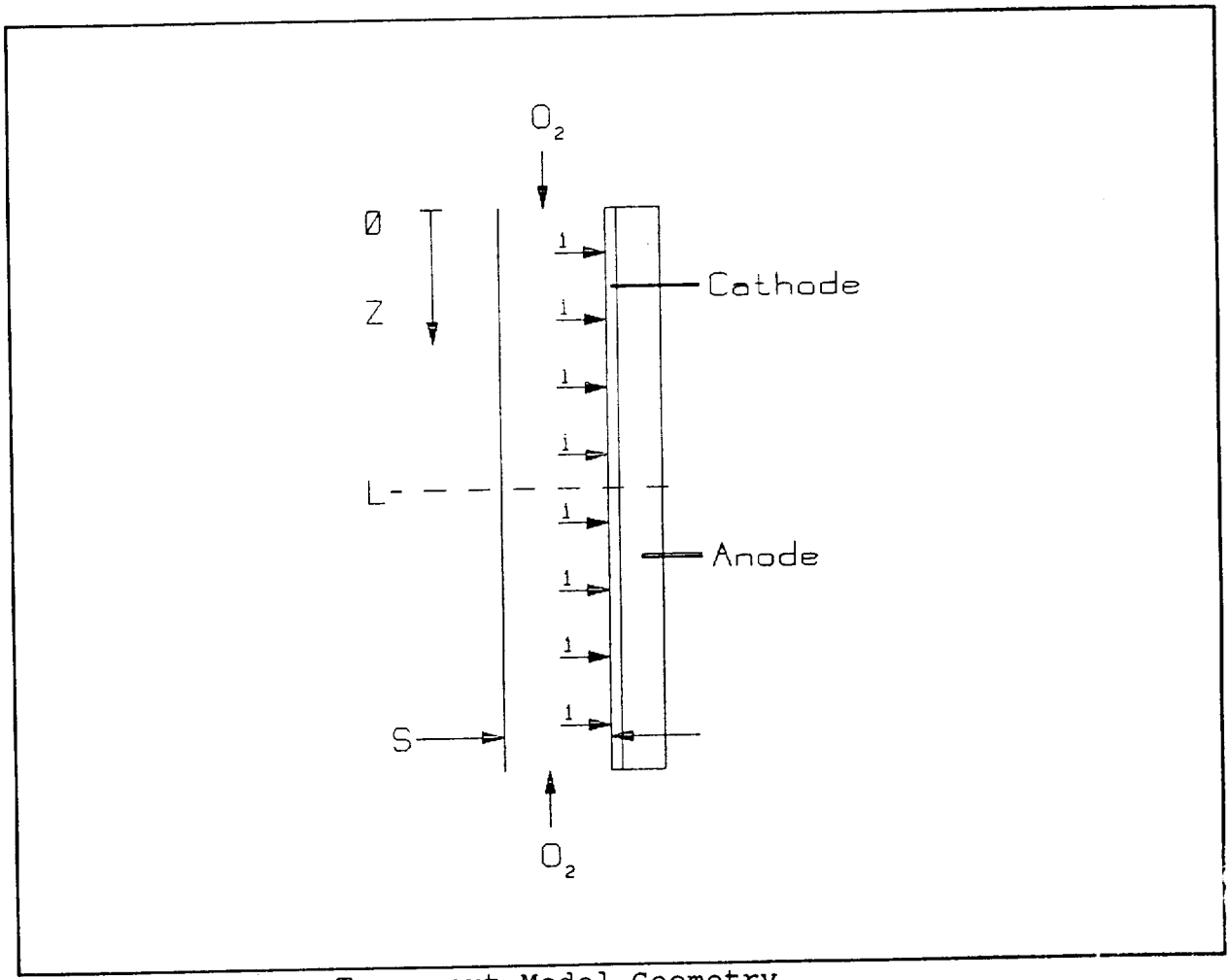

Figure 5: Oxygen Transport Model Geometry

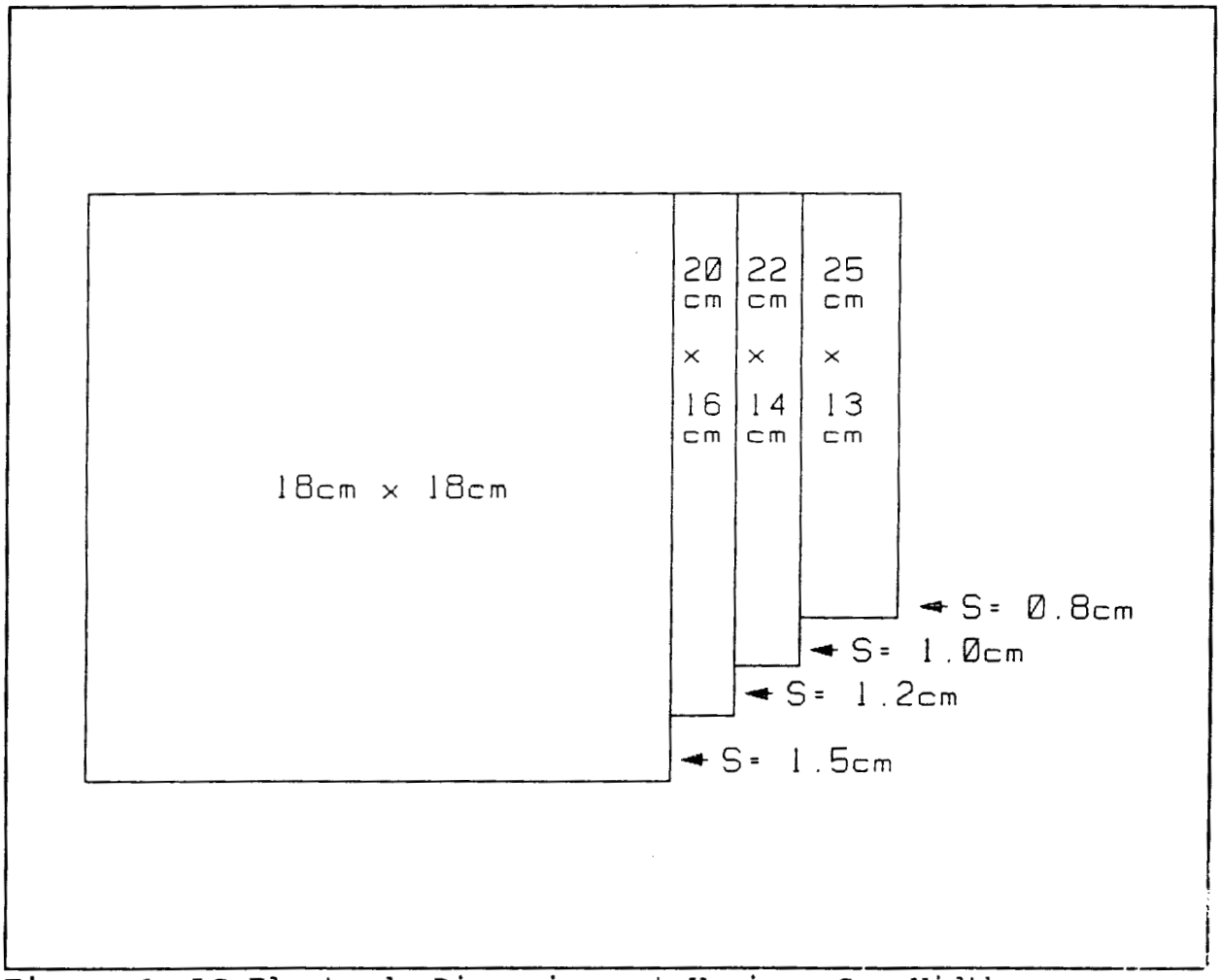

Figure 6: LC Electrode Dimensions at Various Gap Widths

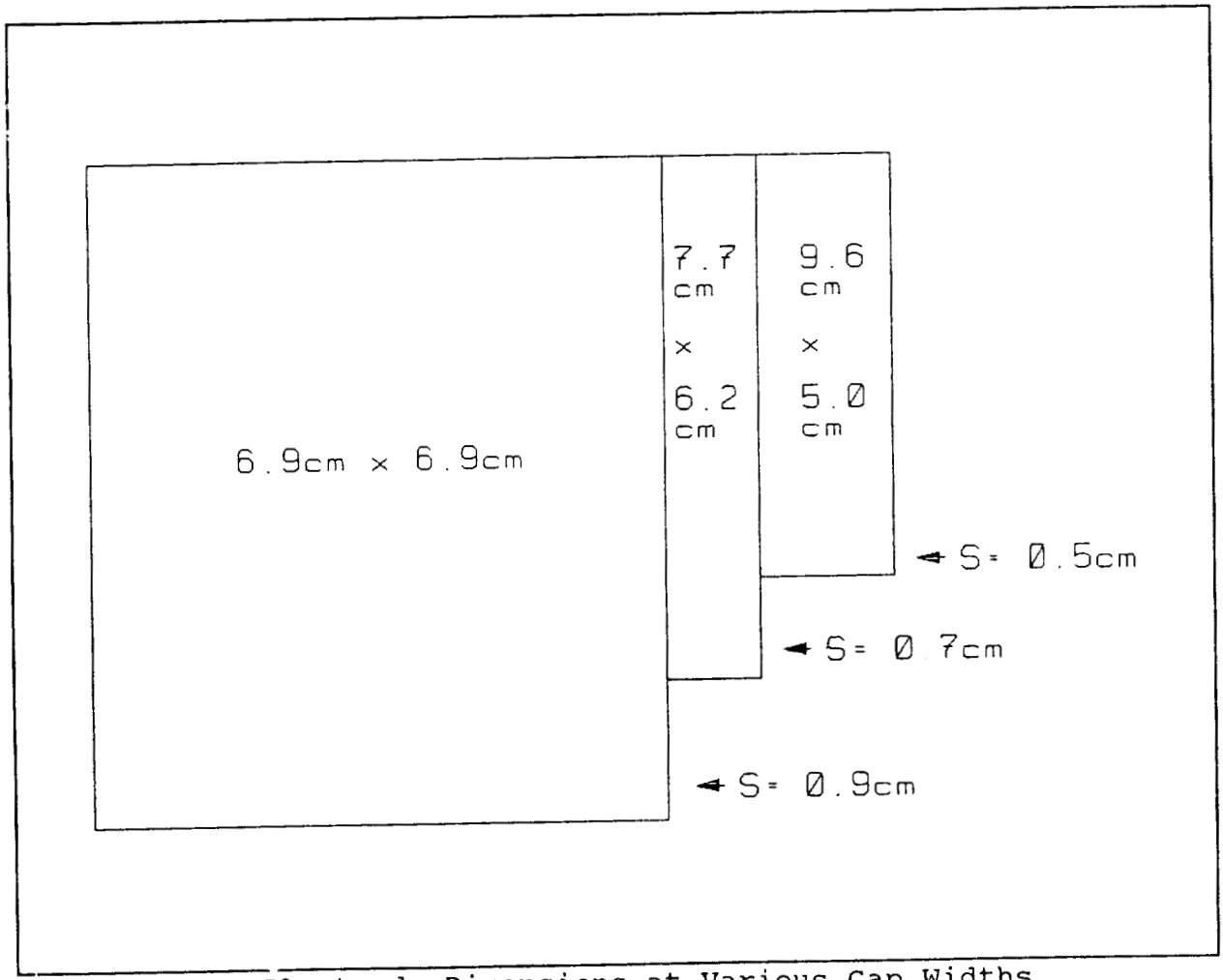

Figure 7: HR Electrode Dimensions at Various Gap Widths

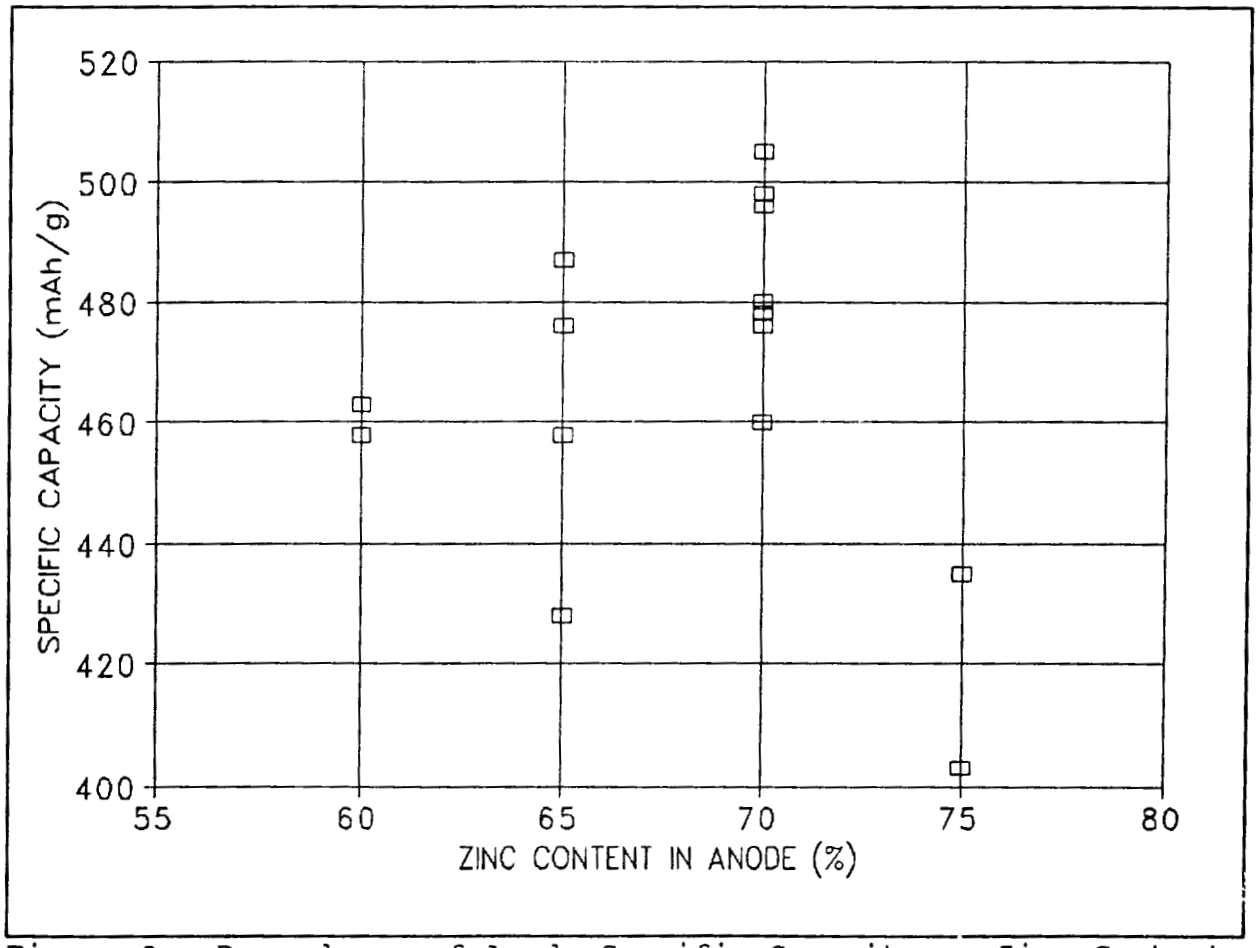

Figure 8: Dependence of Anode Specific Capacity on Zinc Content

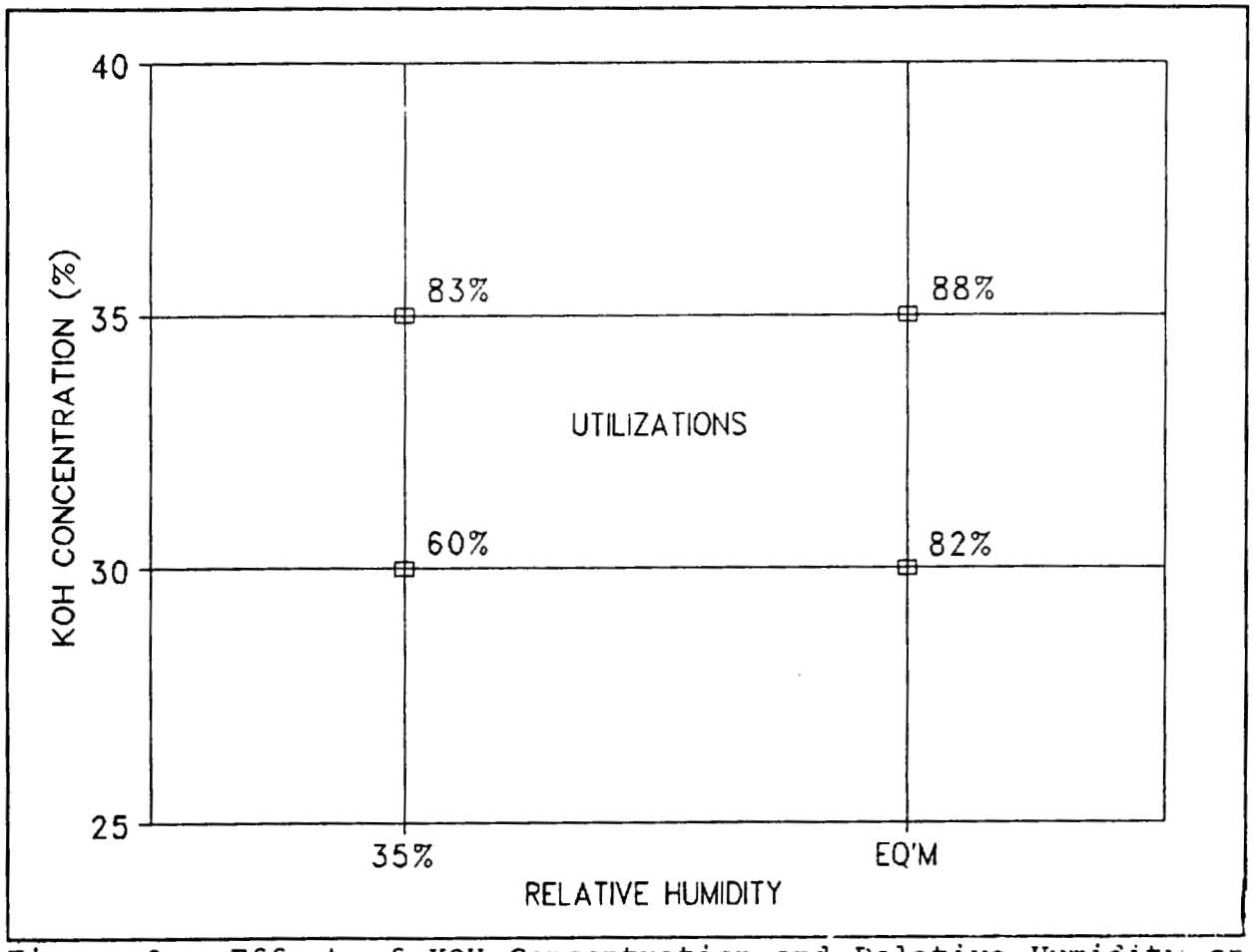

Figure 9: Effect of KOH Concentration and Relative Humidity on Anode Utilization

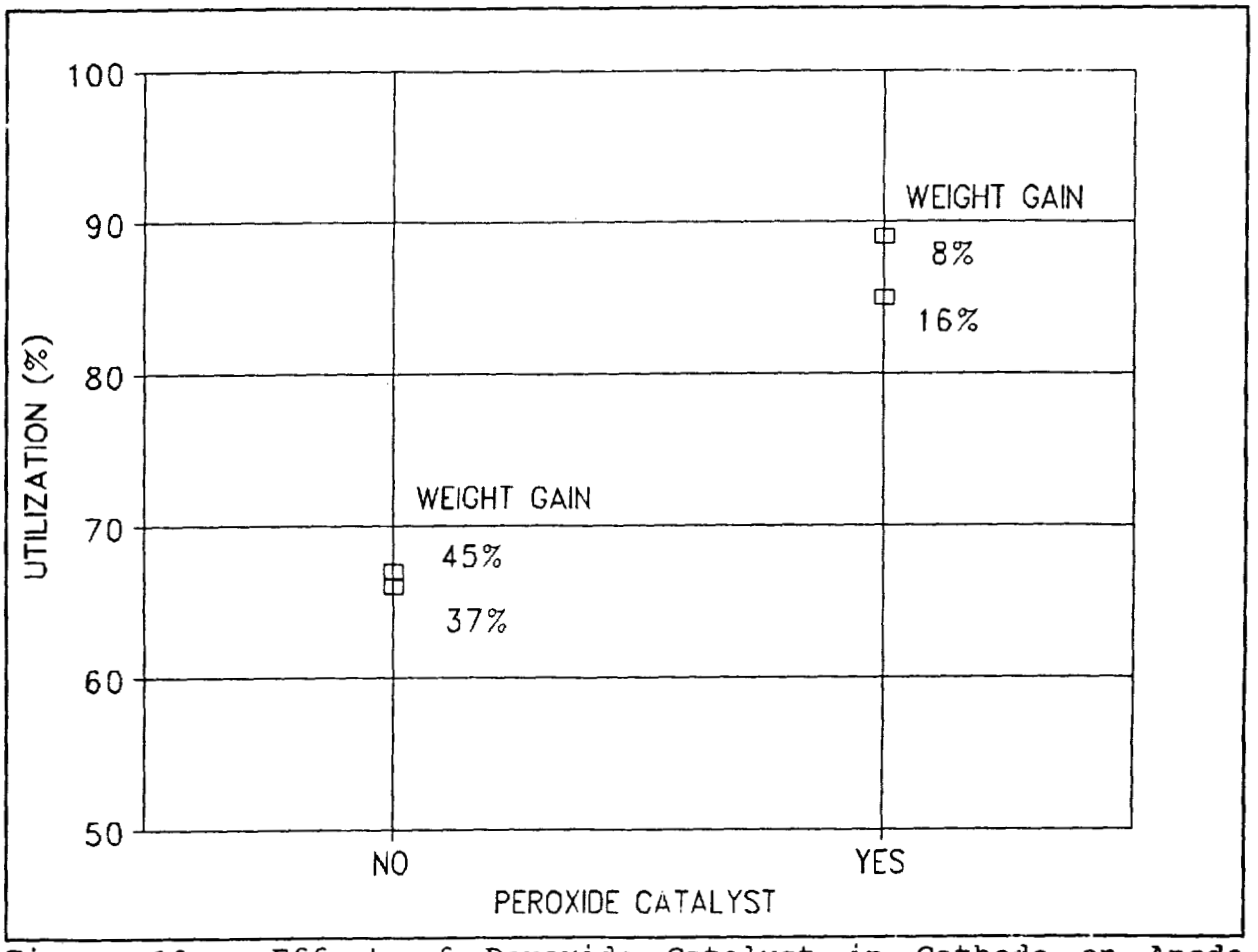

Figure 10: Effect of Peroxide Catalyst in Cathode on Anode Utilization

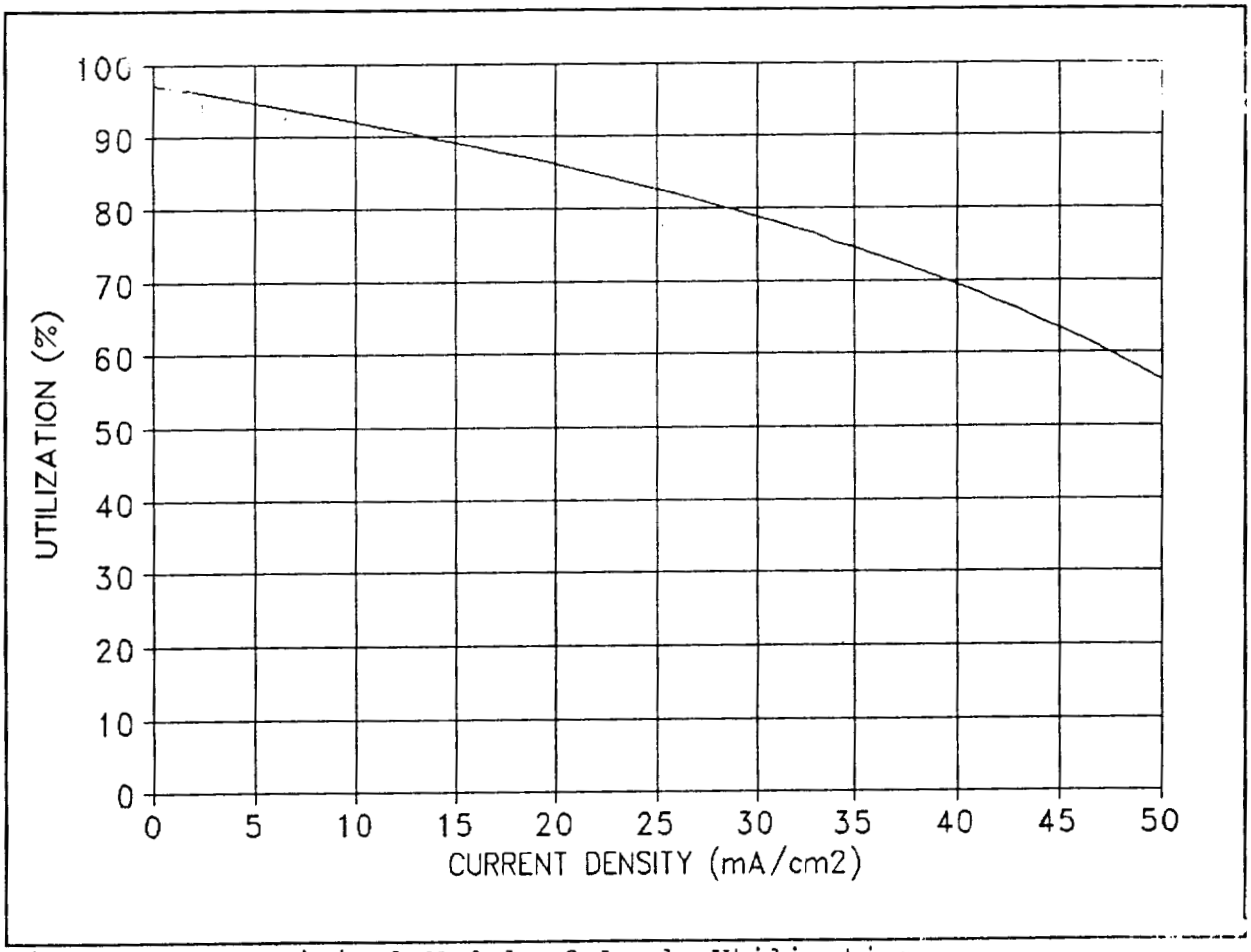

Figure 11: Empirical Model of Anode Utilization

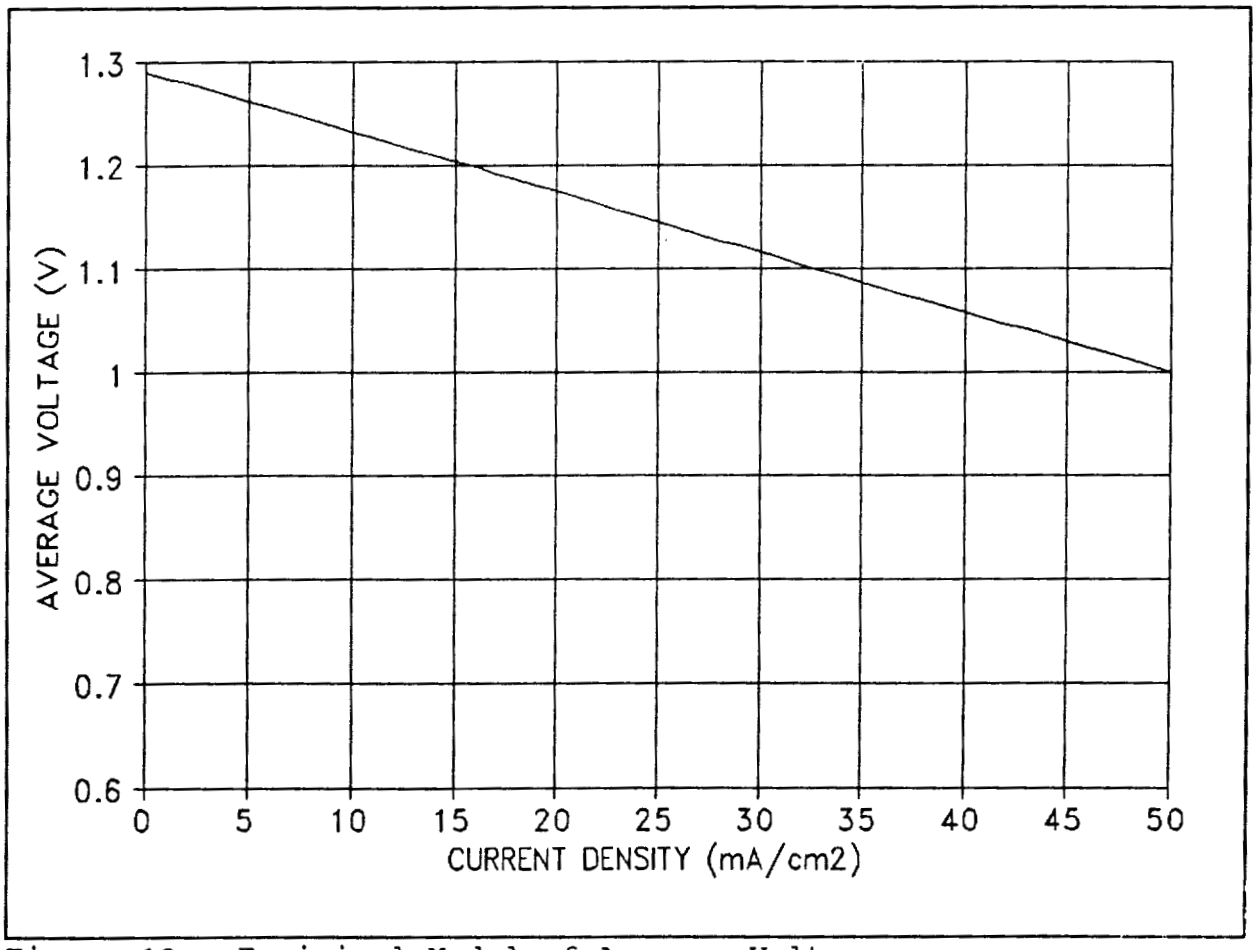

Figure 12: Empirical Model of Average Voltage

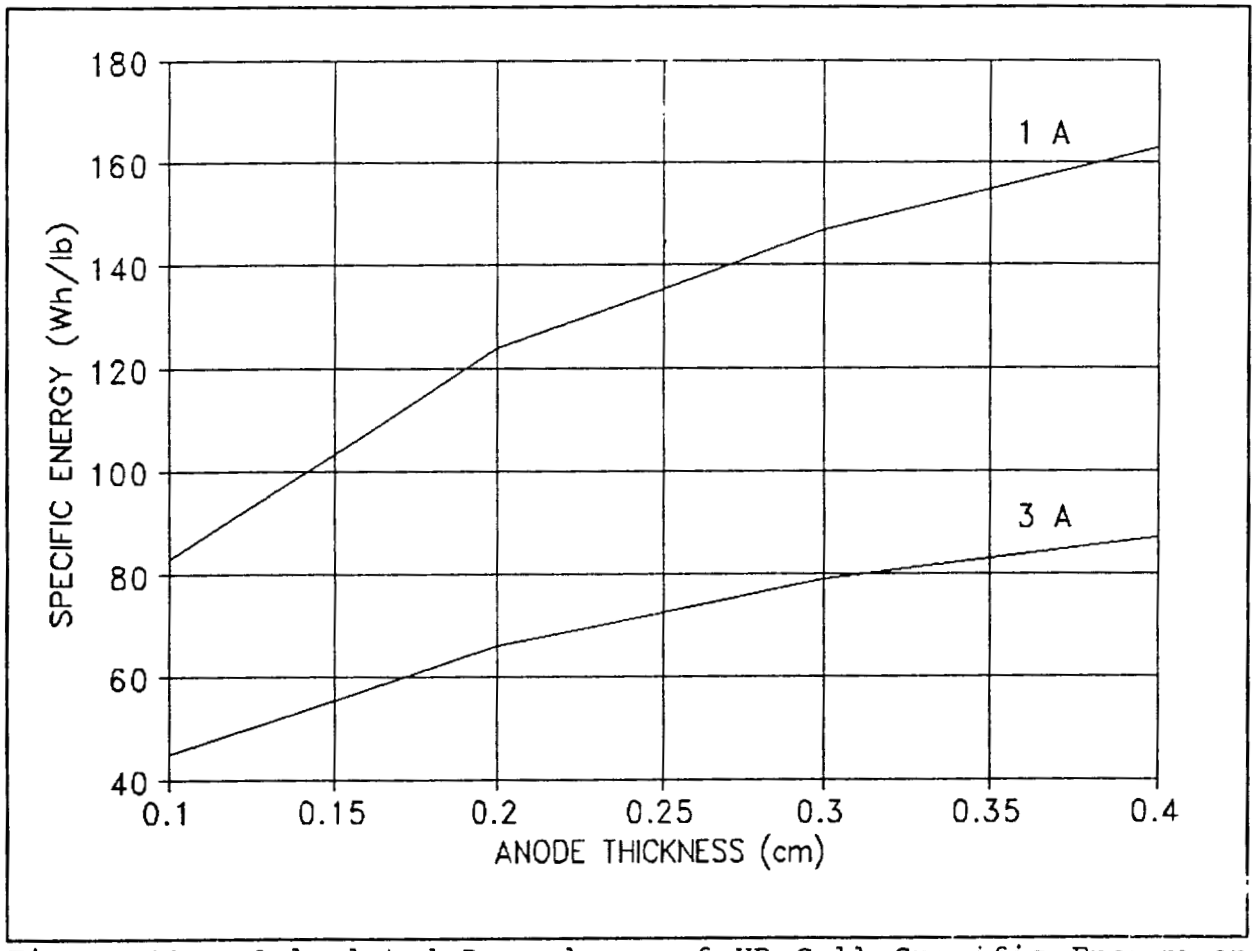

Figure 13: Calculated Dependence of HR Cell Specific Energy on Anode Thickness

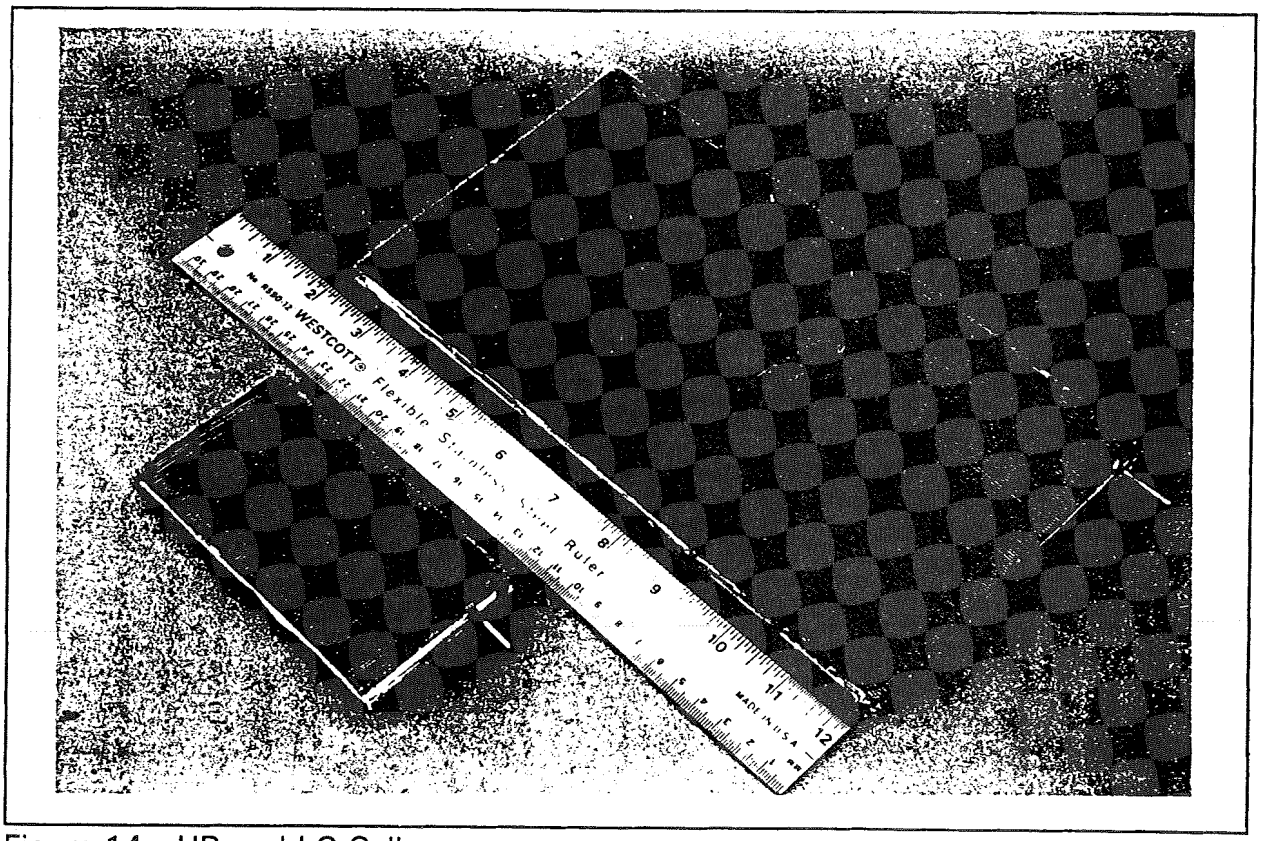

Figure 14: HR and LC Cells

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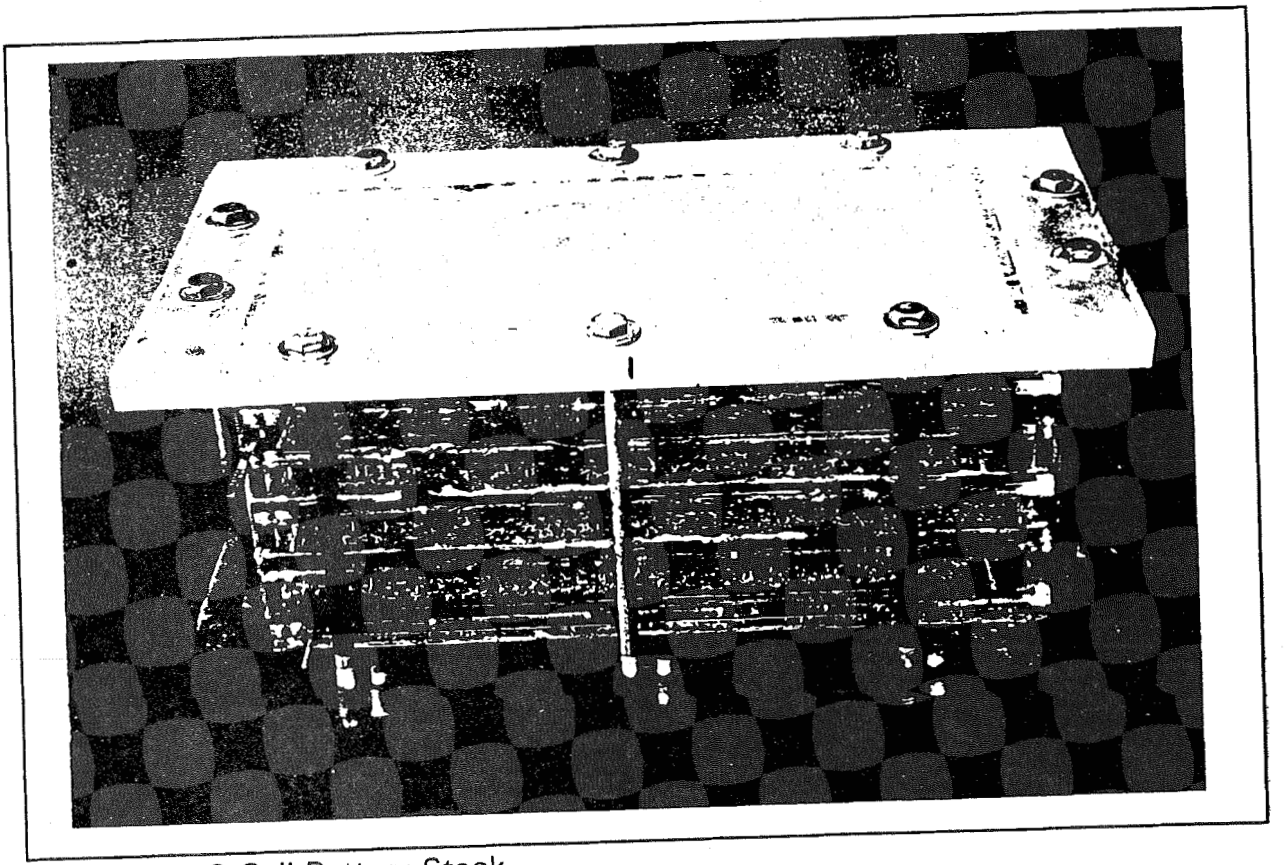

Figure 15: LC Cell Battery Stack

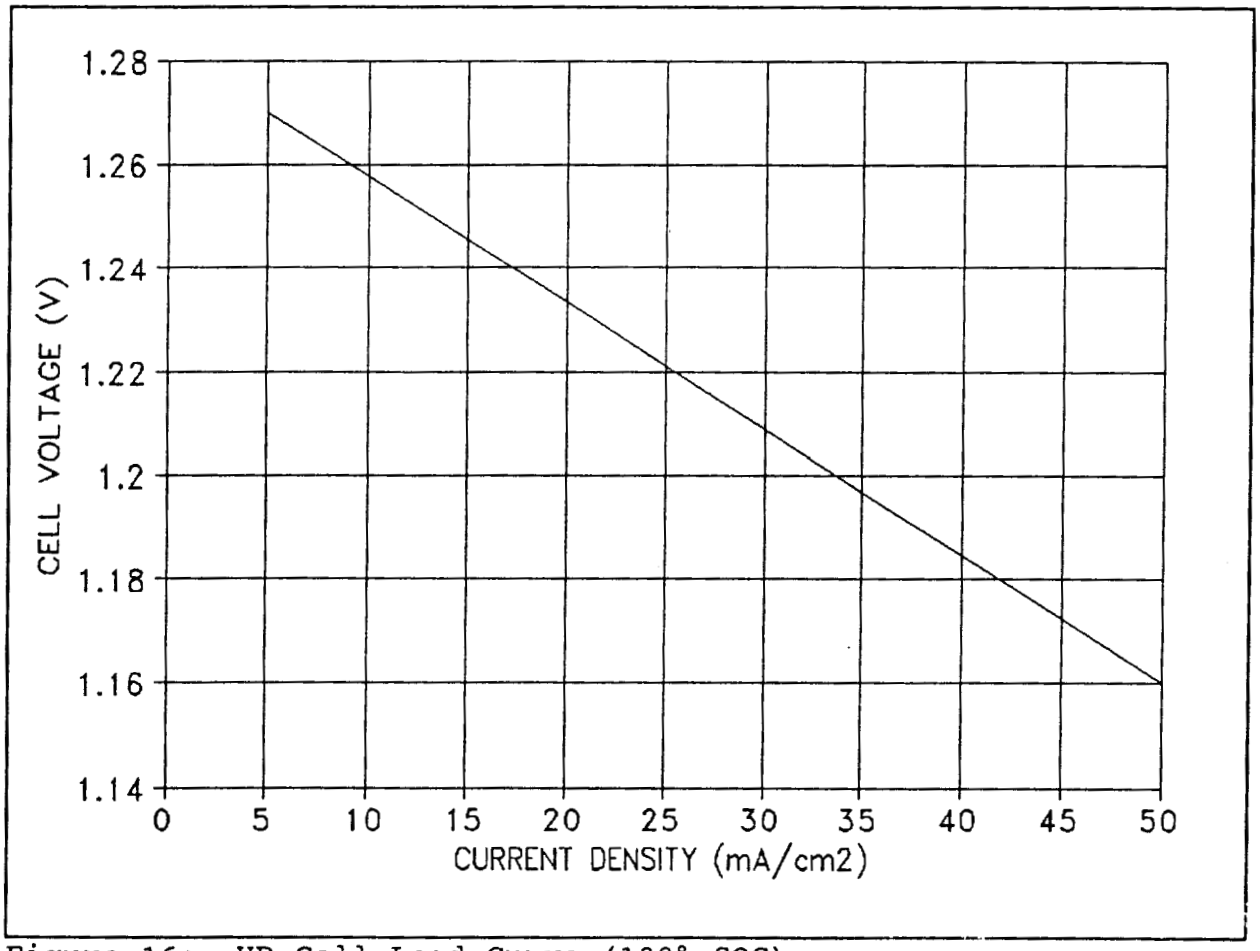

Figure 16: HR Cell Load Curve (100% SOC)

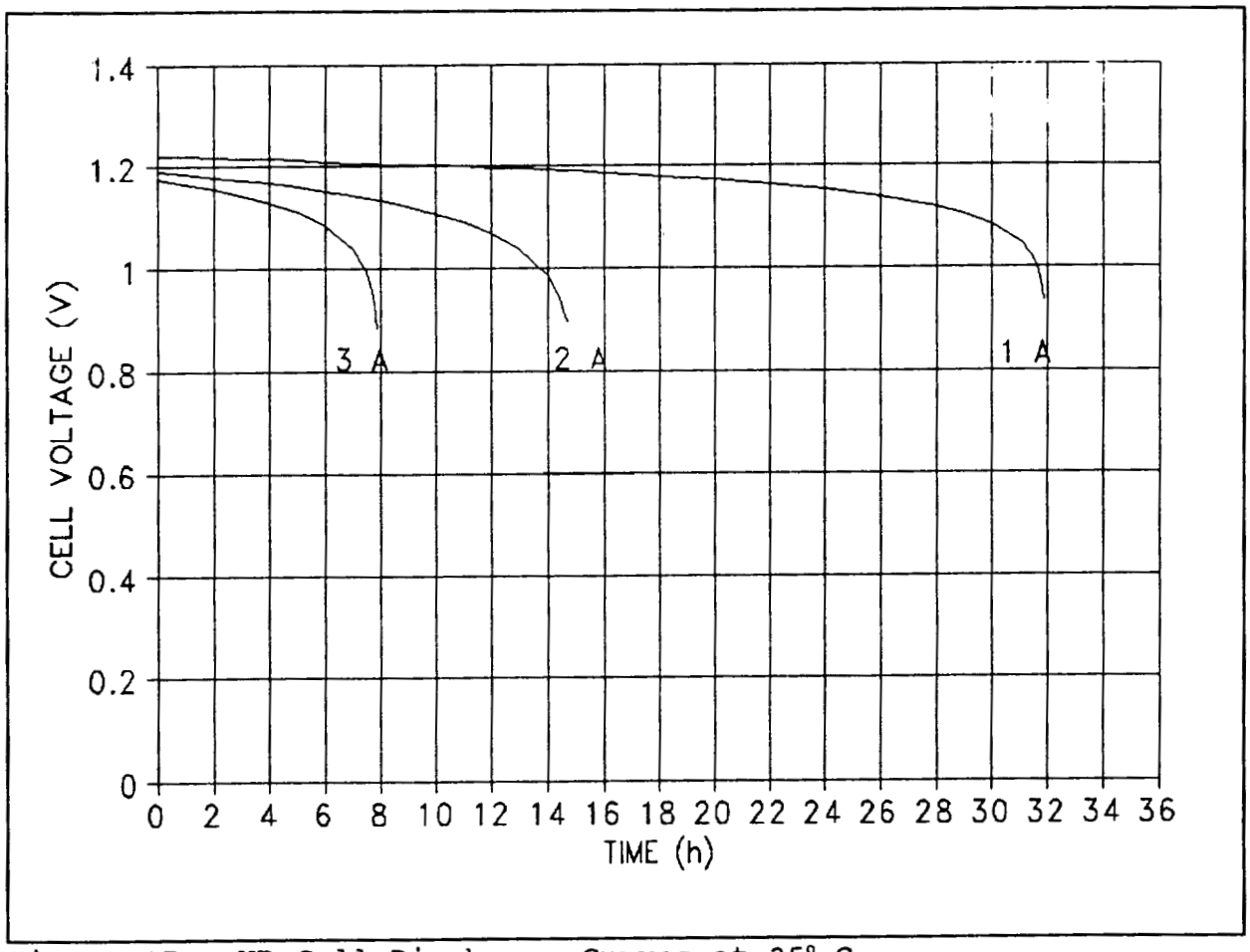

Figure 17: HR Cell Discharge Curves at 25° C

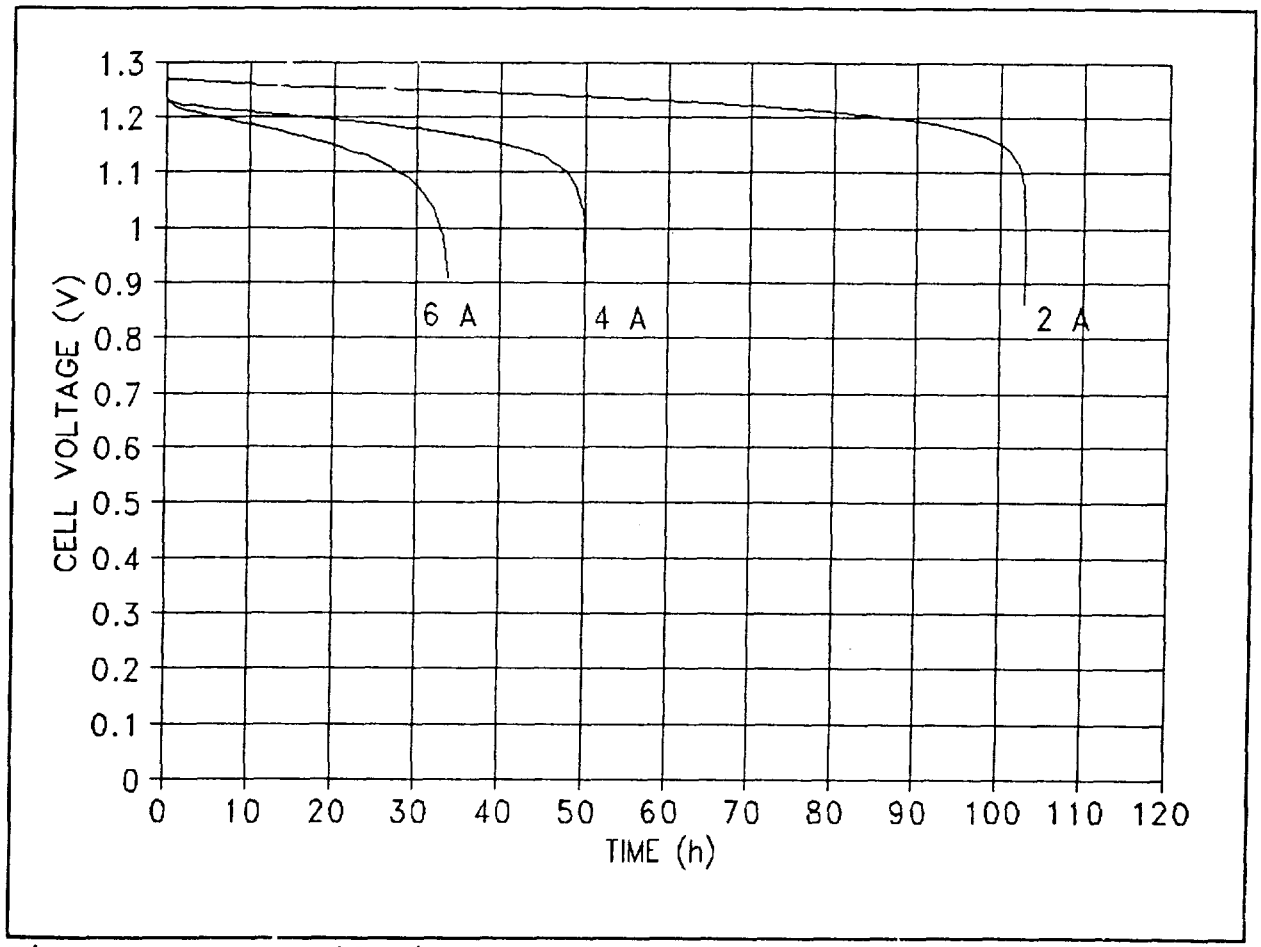

Figure 18: LC Cell Discharge Curves at 25° C

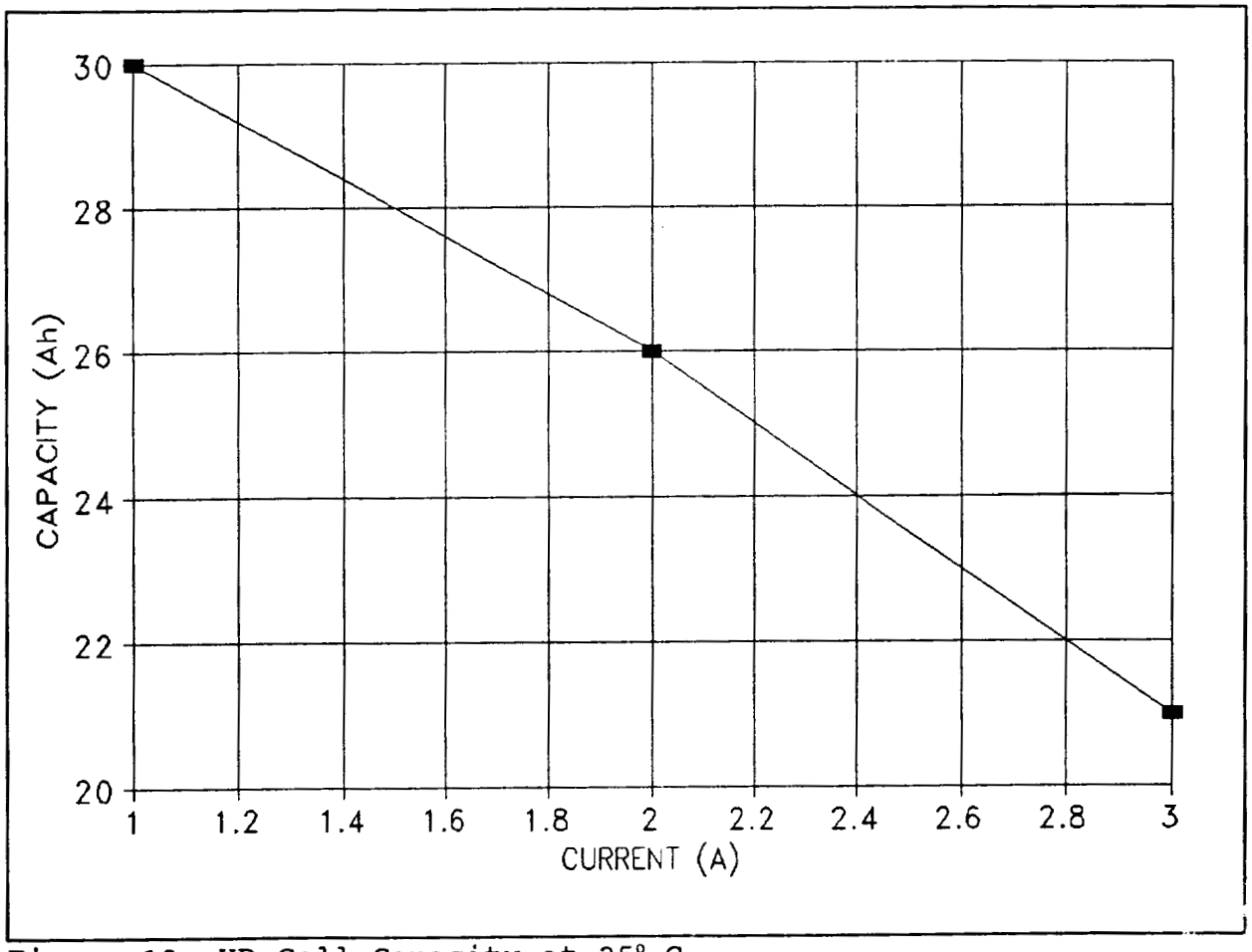

Figure 19: HR Cell Capacity at 25° C

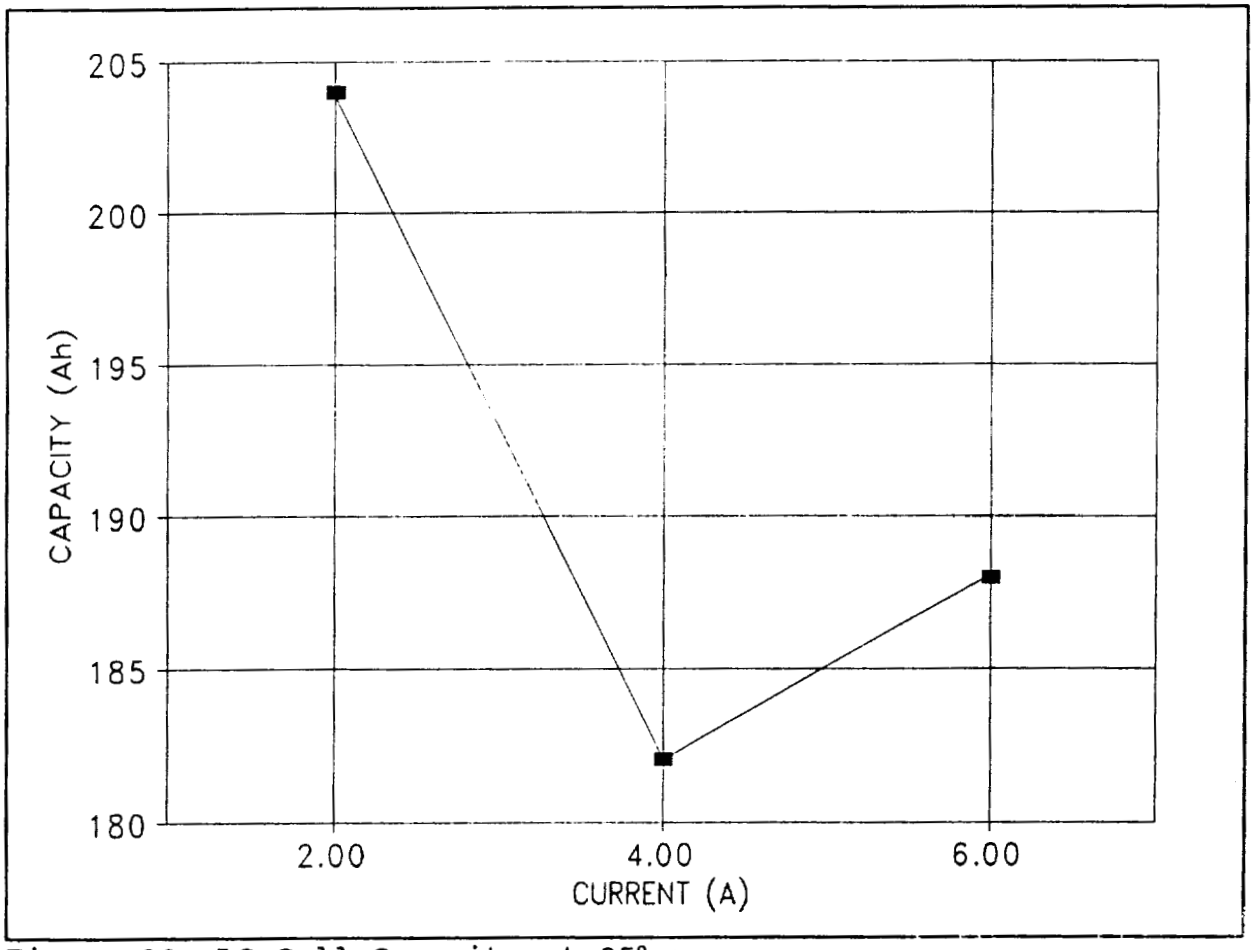

Figure 20: LC Cell Capacity at 25° c

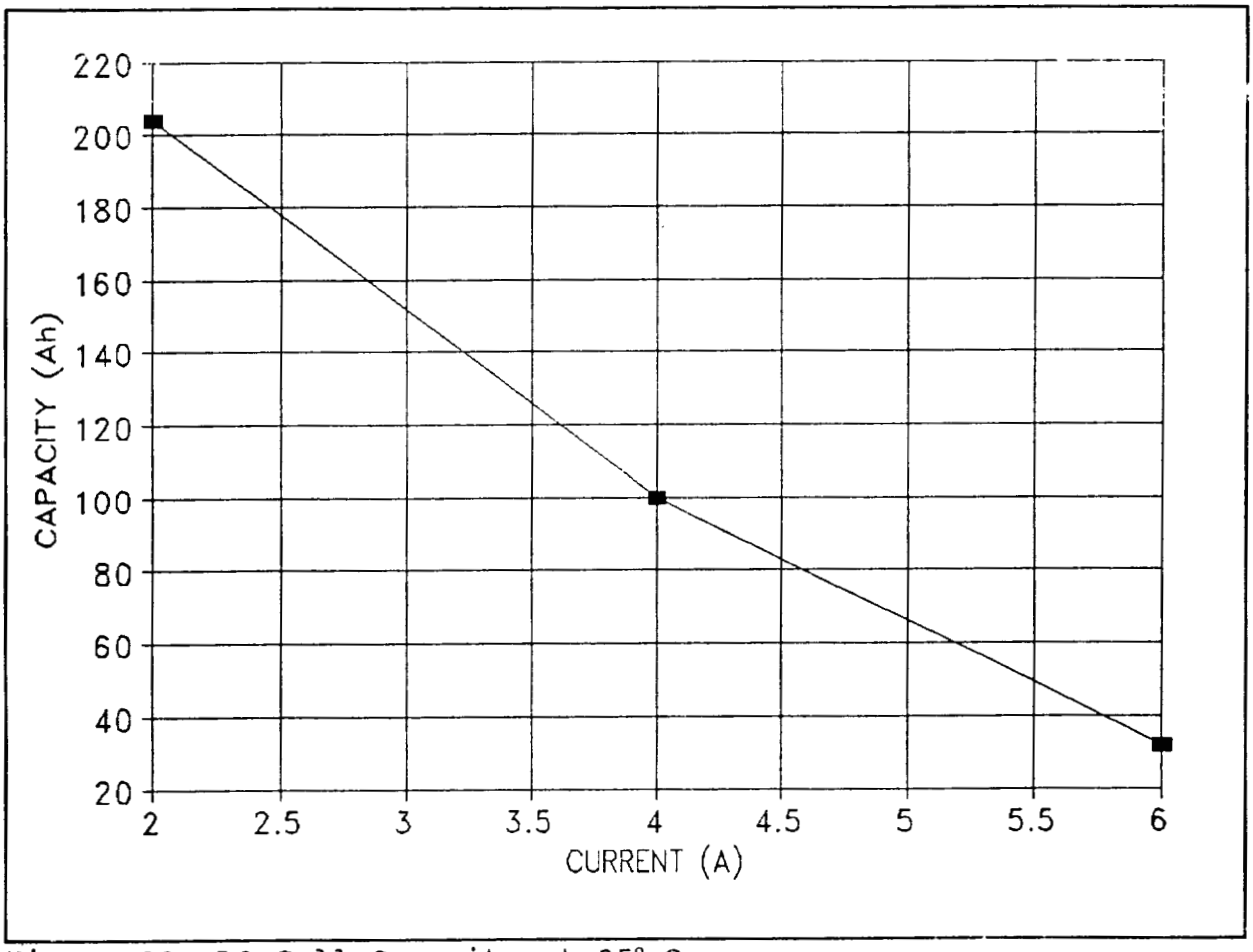

Figure 20: LC Cell Capacity at 25° C

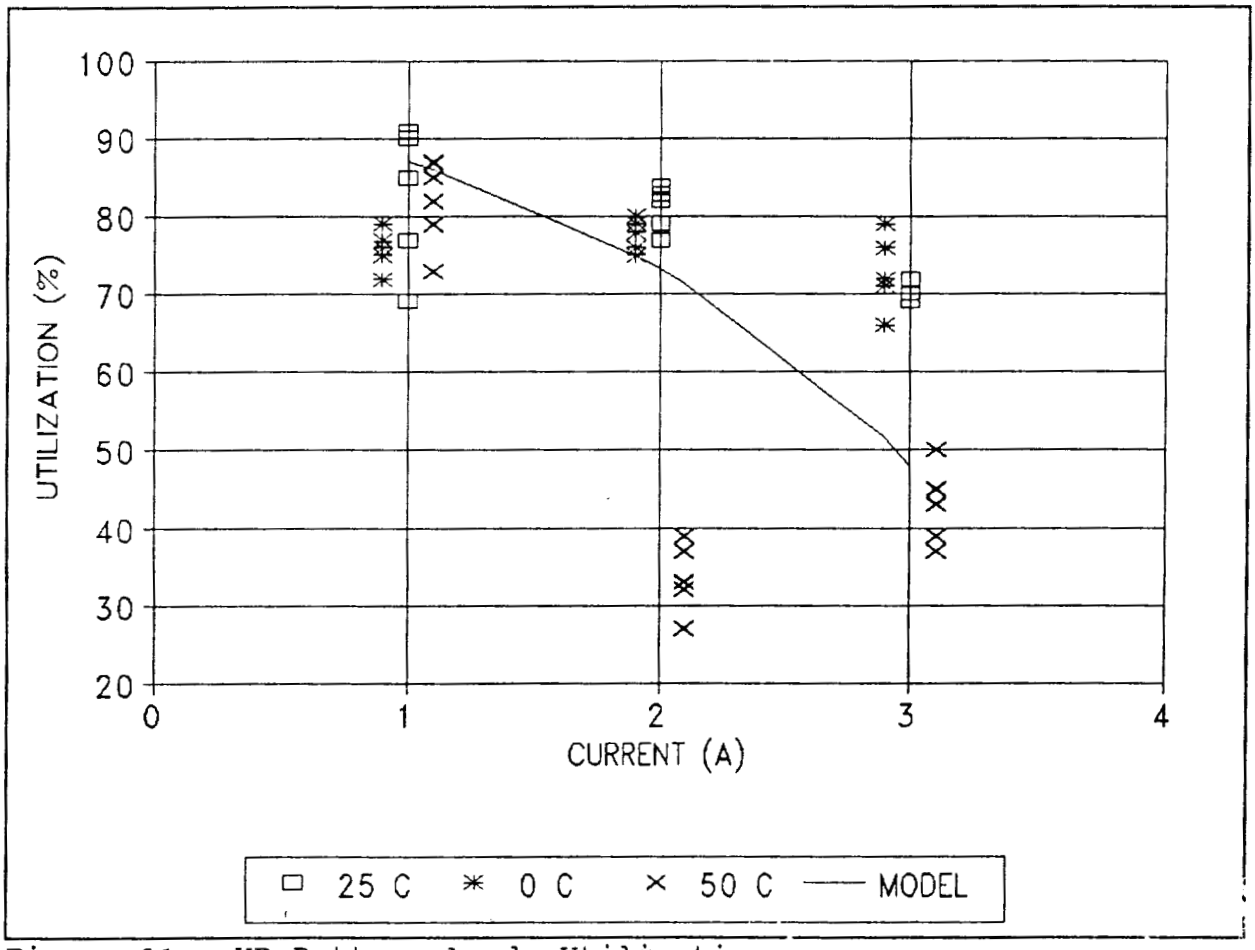

Figure 21: HR Battery Anode Utilization

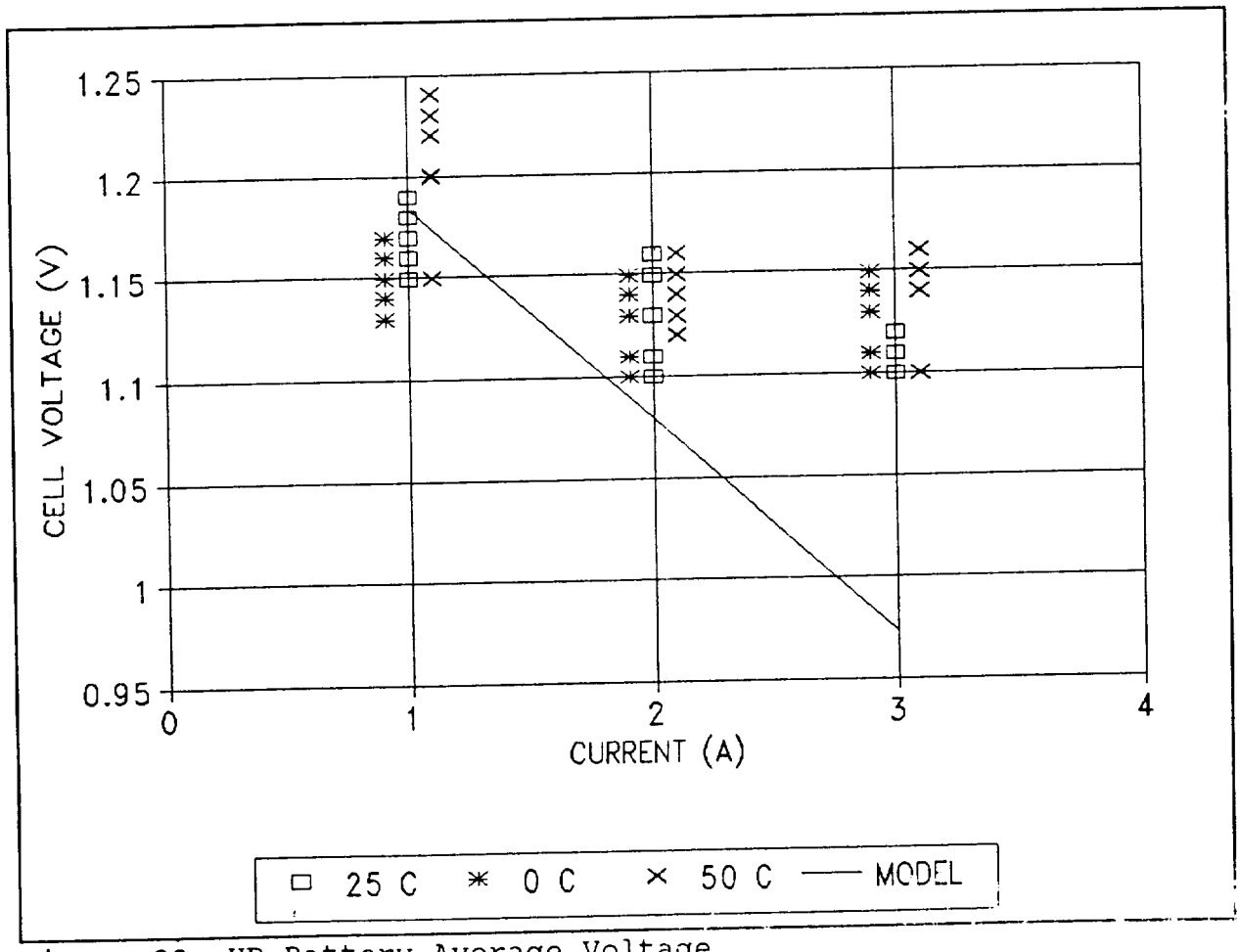

Figure 22: HR Battery Average Voltage

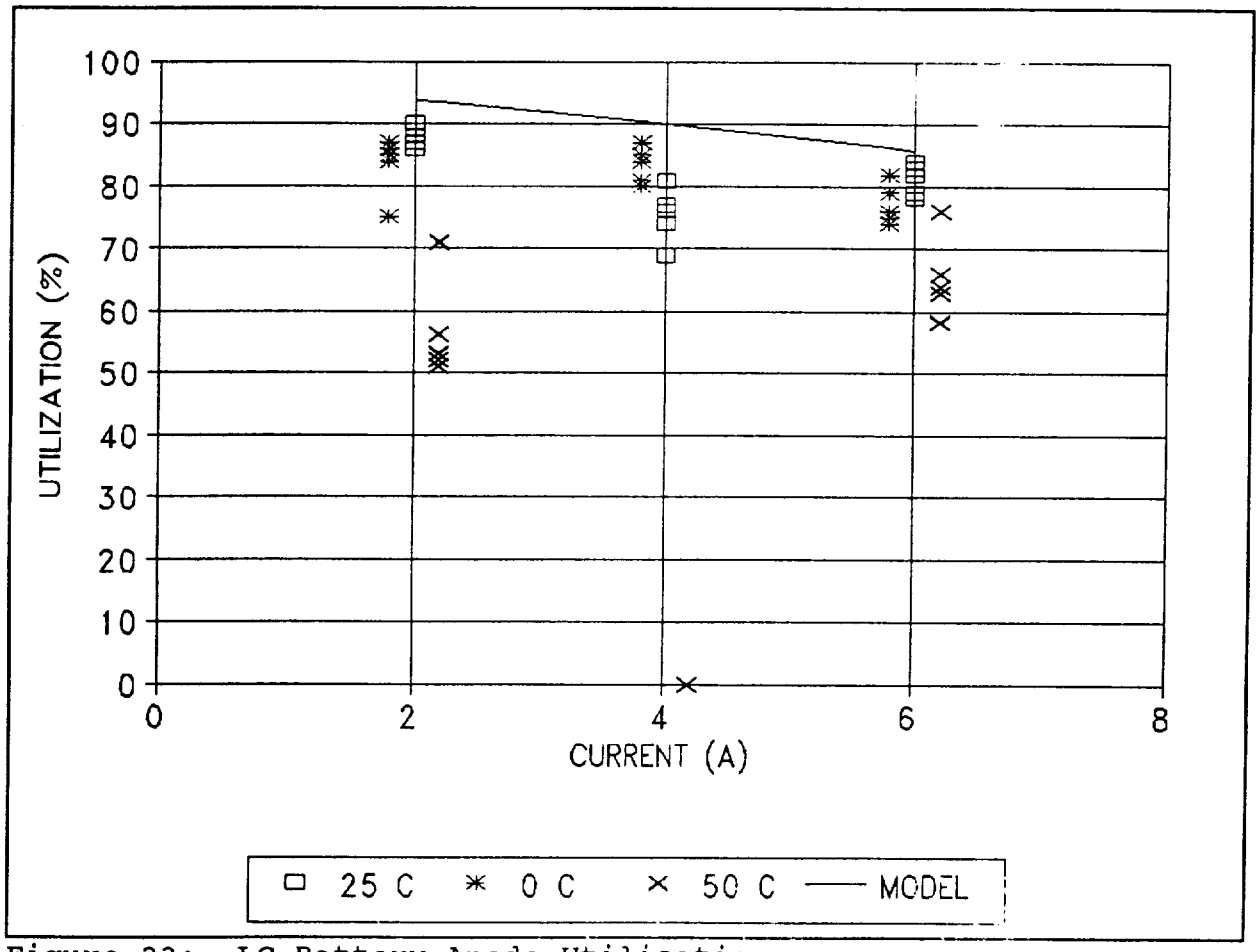

Figure 23: LC Battery Anode Utilization

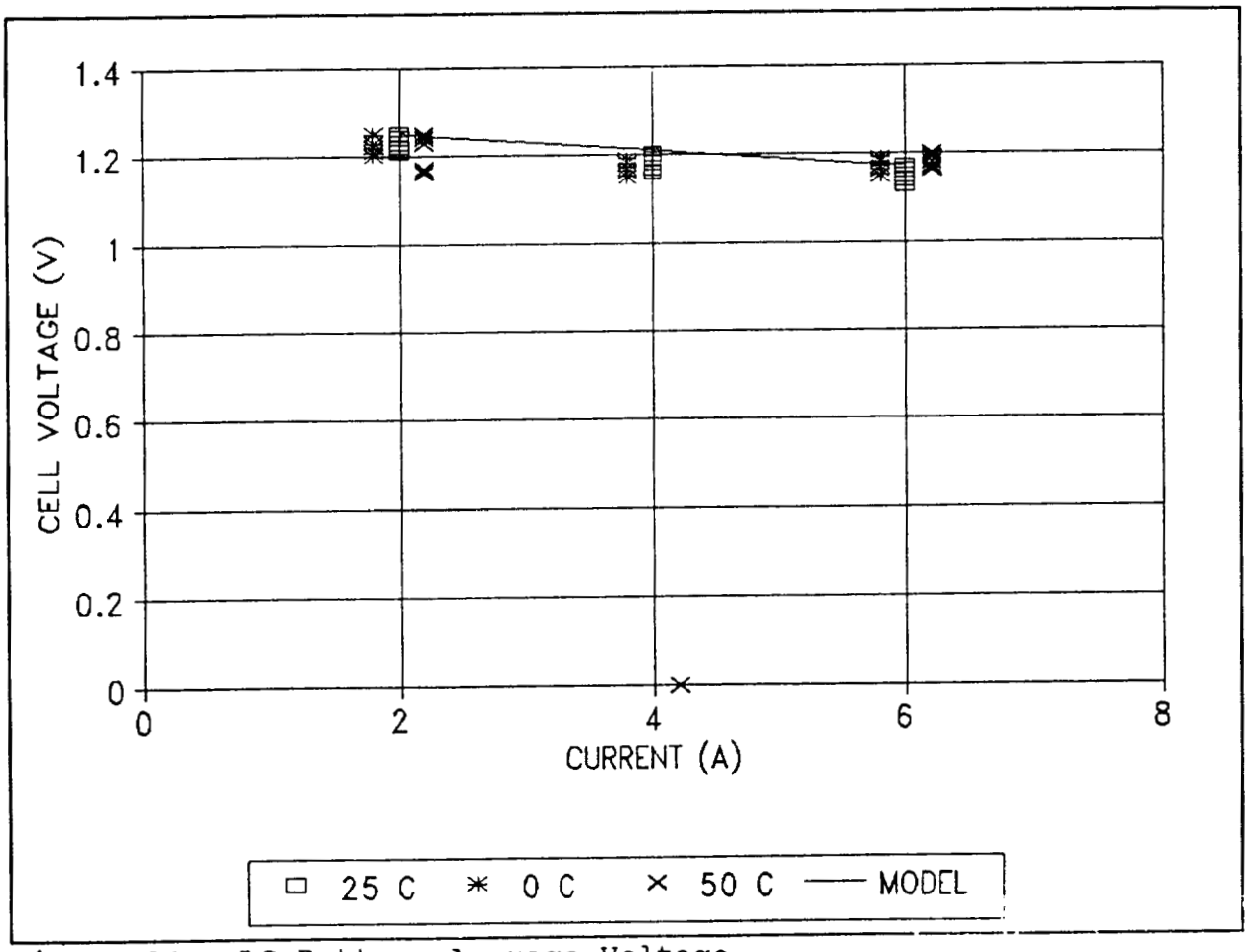

Figure 24: LC Battery Average Voltage

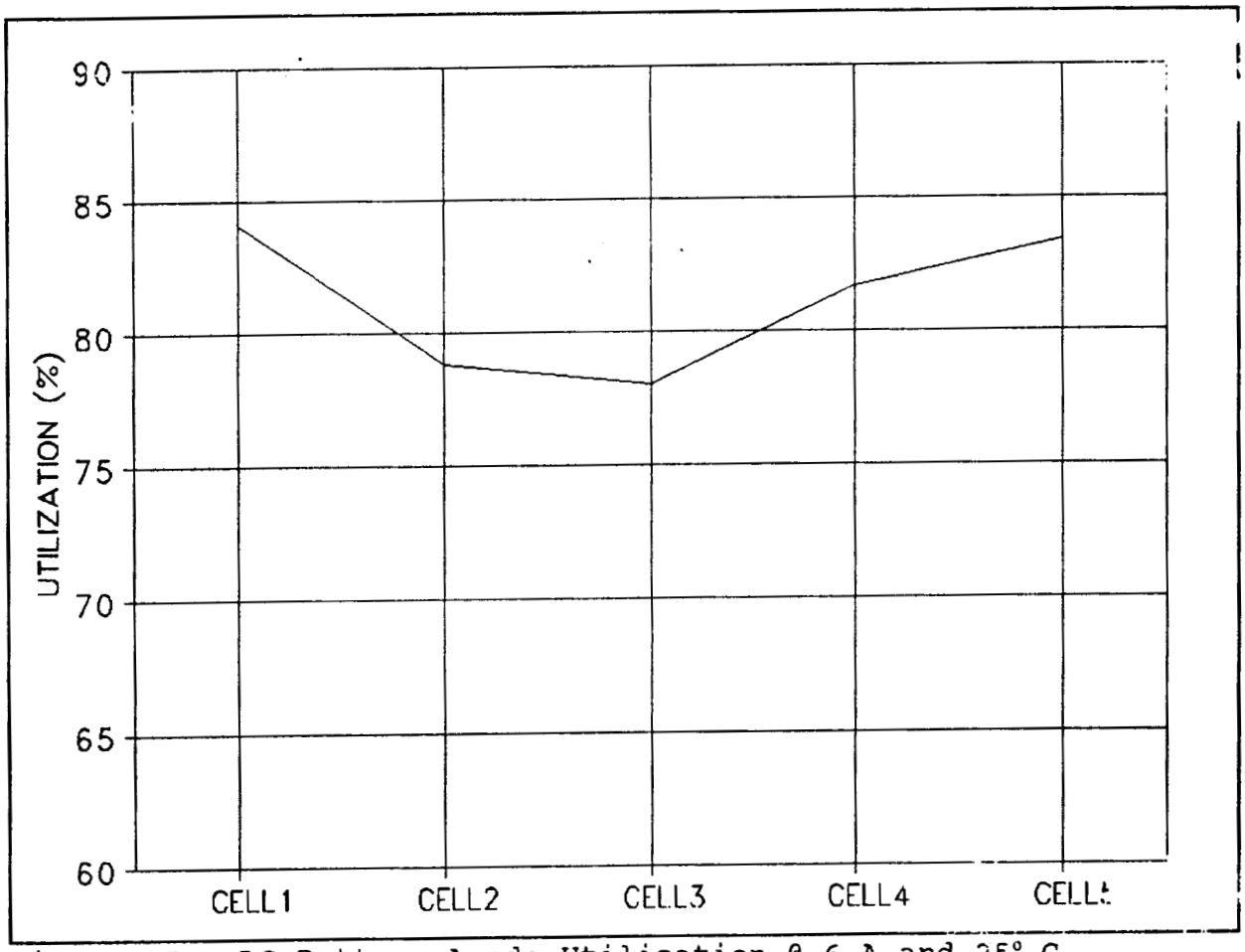

Figure 25: LC Battery Anode Utilization @ 6 A and 25° C

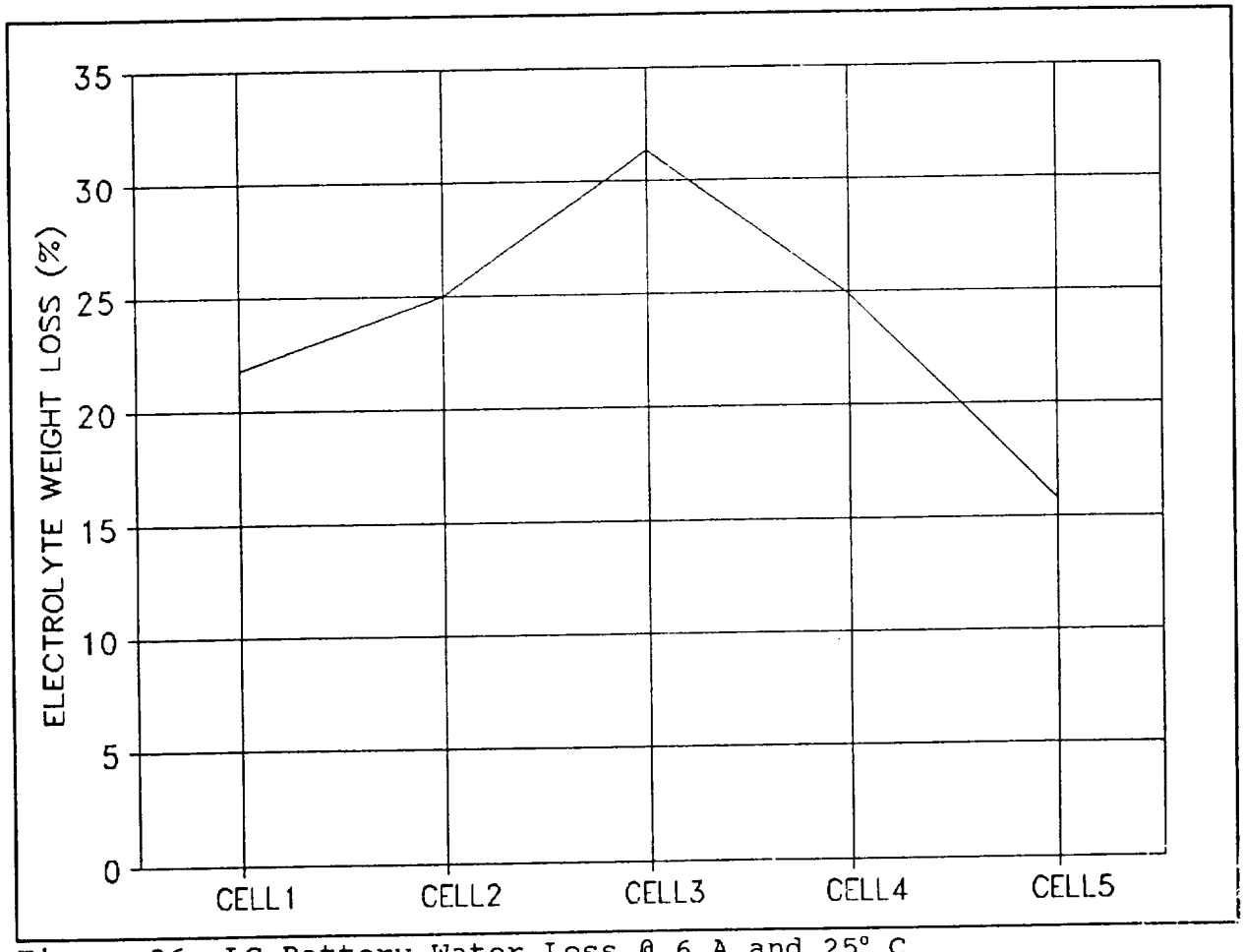

Figure 26: LC Battery Water Loss @ 6 A and 25° C

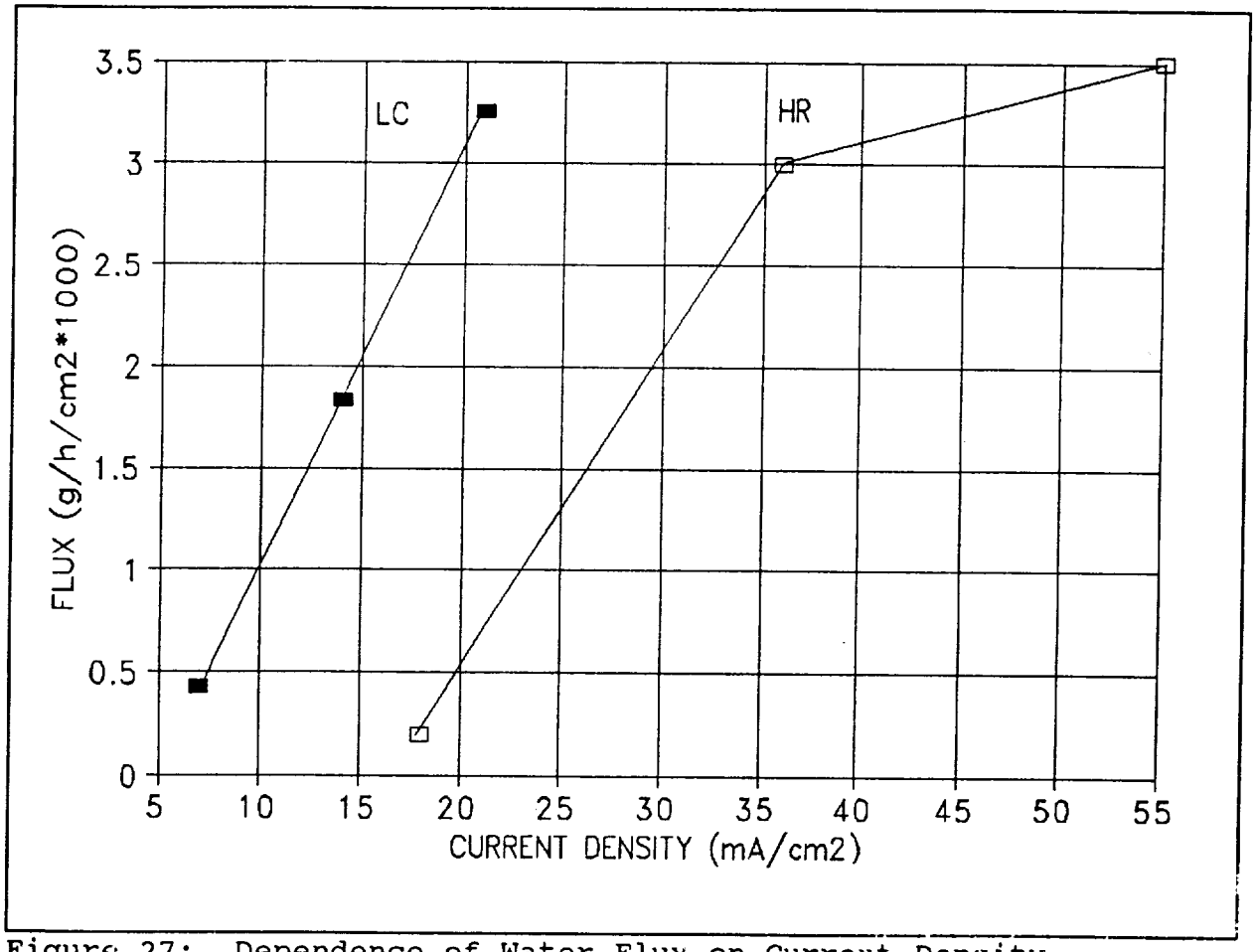

Figure 27: Dependence of Water Flux on Current Density

N92-22749

RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

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

ABSTRACT

Dynamic impedance tests have been performed on a 180Ah $LiSOCl_2$ 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 $LiSOCl_2$ 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 $LiSOCl_2$ 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 $LiSOCl_2$ 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 $LiSOCl_2$ 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 modelized 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 : $R_2 = 41 - 6 = 35m\Omega$. 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 = 32nH and C = 137μF.

R_1 varies slightly with T° and I_{DC} = as I or T° 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 modelized by an RC parallel cell, added to Model 1.

R_3 is given by the value of the plateau : R3 = 30 - 6 = 24mΩ.
C_2 is given by the value of the impedance at F = 2KHz.

Model 2 also applies at high temperatures, with R_3 = 0mΩ (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 symetrical.

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 = 4.3mΩ
L2 = 1.2μH
As $R_4 << R_1$, R_4 can be neglected

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RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

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ETCA (BELGIUM)

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INTRODUCTION

* THE ELECTRICAL POWER GENERATION OF THE HERMES SPACE PLANE COMPRISES :

- THE MAIN ELECTRICAL POWER GENERATION :

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

- THE SECONDARY ELECTRICAL POWER GENERATION :

  2 LITHIUM BATTERIES TO PROVIDE ELECTRICAL ENERGY AS AUXILARY SOURCES IN NOMINAL MODES AND BACK-UP SOURCES FOR EMERGENCY RE-ENTRY

SAFT DIVISION ESPACE SPACE DEPARTMENT

RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

ETCA

INTRODUCTION

* A SHORT TERM WORK CONTRACT WAS AWARDED BY AEROSPATIALE TO SAFT TO DEMONSTRATE THE FEASIBILITY OF A $LiSOCl_2$ BATTERY DESIGN, AS PART OF THE HERMES SPACE PLANE PRELIMINARY DEVELOPMENT WORK.

* THE PROPOSED $LiSOCl_2$ BATTERY CONSISTS OF 28 CELLS OF 180 AH CONNECTED IN SERIES

  TOTAL ENERGY = 16.6 KWH

  TOTAL MASS = 60 KG (132 LB)

  TOTAL VOLUME : 54 L

SAFT DIVISION ESPACE SPACE DEPARTMENT

RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

ETCA

INTRODUCTION

* SUMMARY OF THE ELECTRICAL CHARACTERISTICS OF EACH BATTERY

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

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INTRODUCTION

* DYNAMIC IMPEDANCE TESTS HAVE BEEN PERFORMED ON A 180 AH $LiSOCl_2$ CELL :

  - A RISE TIME TEST WAS PERFORMED TO SHOW THE ABILITY OF THE CELL TO MEET THE RISE TIME REQUIREMENT

  - RESPONSE TESTS WERE PERFORMED IN ORDER TO BUILD A MATHEMATICAL ELECTRICAL MODEL OF THE $LiSOCl_2$ BATTERY

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

ETCA IS INVOLVED IN THE HERMES PROGRAM AS THE POWER SYSTEM CONTRACTOR.

SAFT DIVISION ESPACE SPACE DEPARTMENT

RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

ETCA

TEST DESCRIPTIONS

* RISE TIME TEST :

- DISCHARGE AT 40A, VOLTAGE MEASUREMENT DURING THE FIRST 200 µs OF THE DISCHARGE.
- 13 DAYS REST PERIOD, DURING WHICH A 50mA DISCHARGE CURRENT IS IMPOSED IN ORDER TO AVOID THE PASSIVATION EFFECT.
- DISCHARGE AT 40A, VOLTAGE MEASUREMENT DURING THE FIRST 200 µs OF THE DISCHARGE.

SAFT DIVISION ESPACE SPACE DEPARTMENT

RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

ETCA

TEST DESCRIPTIONS

* **RESPONSE TESTS**

THEY CONSISTED OF STEP RESPONSE AND FREQUENCY RESPONSE TESTS

- STEP RESPONSE TEST : THE CELL VOLTAGE TO A NEGATIVE AND POSITIVE 10A STEP WAS MEASURED STARTING FROM VARIOUS CURRENTS, AT VARIOUS DOD's AND CELL TEMPERATURES.

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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RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

ETCA

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 $LiSOCl_2$ 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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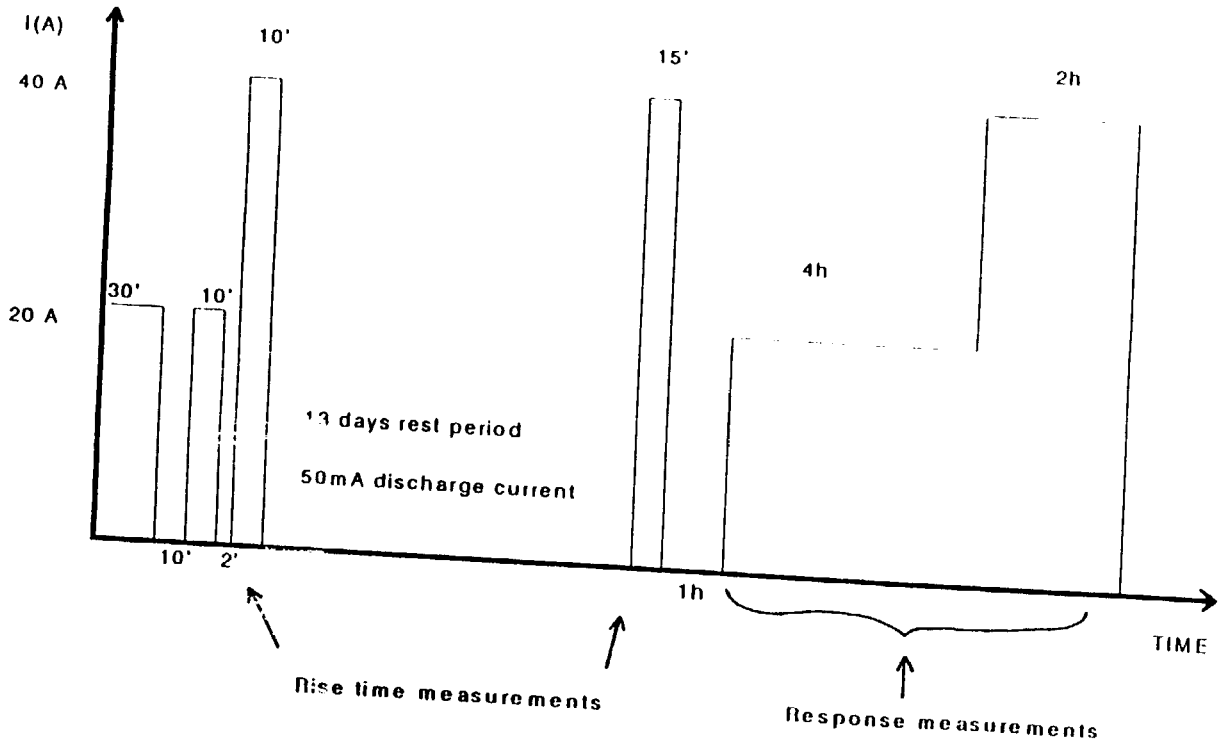
RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

ETCA

TEST SEQUENCE

THE CELL WAS DISCHARGED UNDER THE FOLLOWING PROFILE (T = 40°C)



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RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

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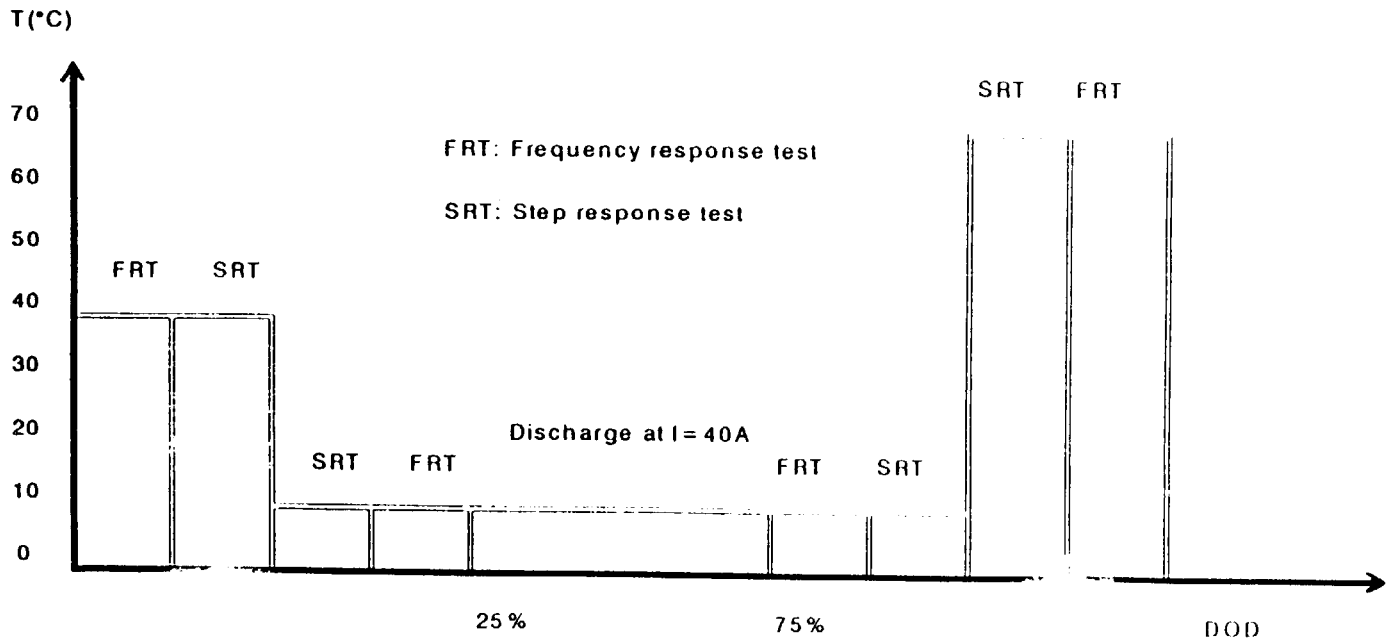
TEST SEQUENCE

RESPONSE TESTS SEQUENCE



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RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

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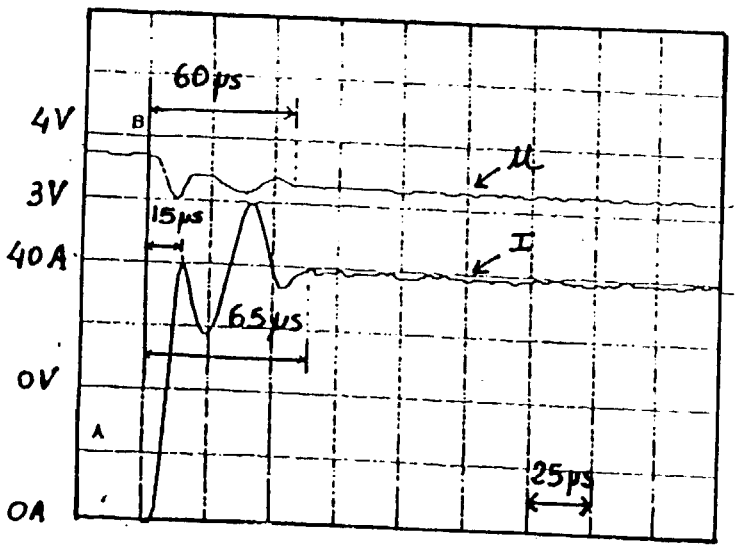
TEST RESULTS

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 60µS AND ALWAYS STAYED SUPERIOR TO 3V (U BATTERY ≥ 84V)

* NO DELAY EFFECT

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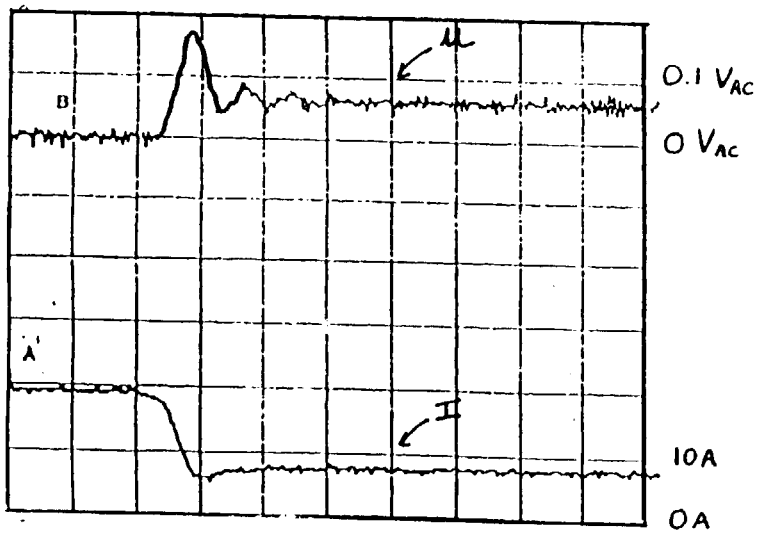
RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

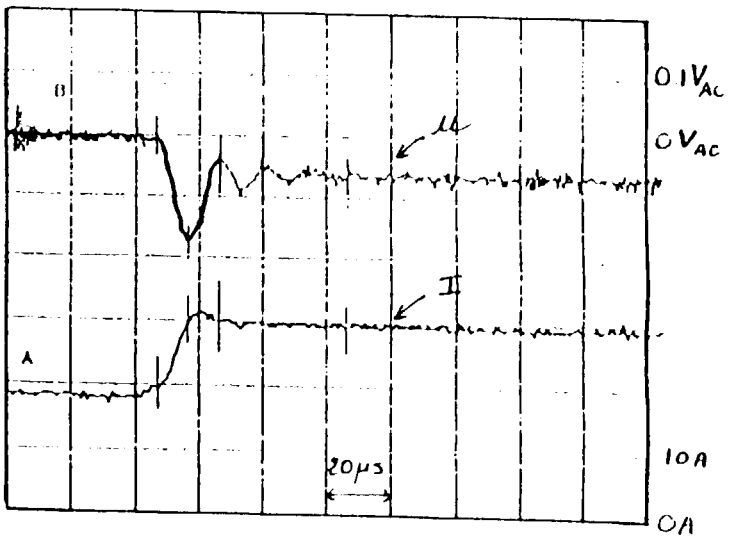
ETCA

TEST RESULTS

STEP RESPONSE TEST

AT T = 43°C, DOD = 25%, I = 20A





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RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

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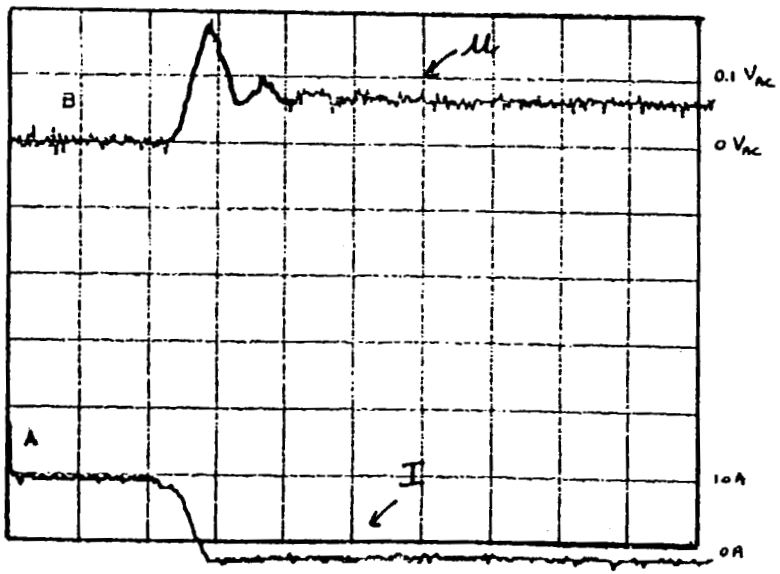
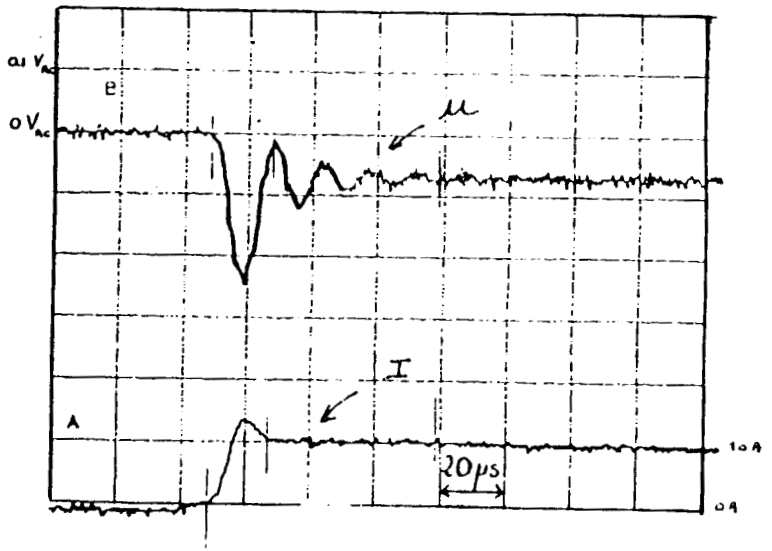
TEST RESULTS

STEP RESPONSE TEST

AT T = 43°C , DOD = 25%, I = 0A





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TEST RESULTS

STEP RESPONSE TESTS

- DYNAMIC RESPONSE (0 TO 70 µs) :

  * WHEN 40 < T < 70°C, NEGATIVE STEP RESPONSE IS IDENTICAL FOR ALL CURRENT AND DOD.

  * WHEN T < 40°C, THE VOLTAGE VARIATION DUE TO THE 10A STEP INCREASES AND VARIES WITH THE DOD.

  * THE POSITIVE STEP RESPONSE IS THE OPPOSITE OF THE NEGATIVE STEP RESPONSE FOR I > 10 A.

  * FOR I ≤ 10 A, THE VOLTAGE VARIATION DUE TO THE POSITIVE 10 A LOAD STEP, IS HIGHER

  * THE VOLTAGE ALWAYS STABILIZED WITHIN 70 µs WITH ΔV ALWAYS INFERIOR TO 0.13V.

- STATIC RESPONSE :

  * AFTER τ = 70µs, THE VOLTAGE SLOWLY VARIES WITH TIME BEFORE REACHING ITS NOMINAL VALUE

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RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

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TEST RESULTS

GENERAL OBSERVATIONS ON DYNAMIC RESPONSES OF $LiSOCl_2$ 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

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RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

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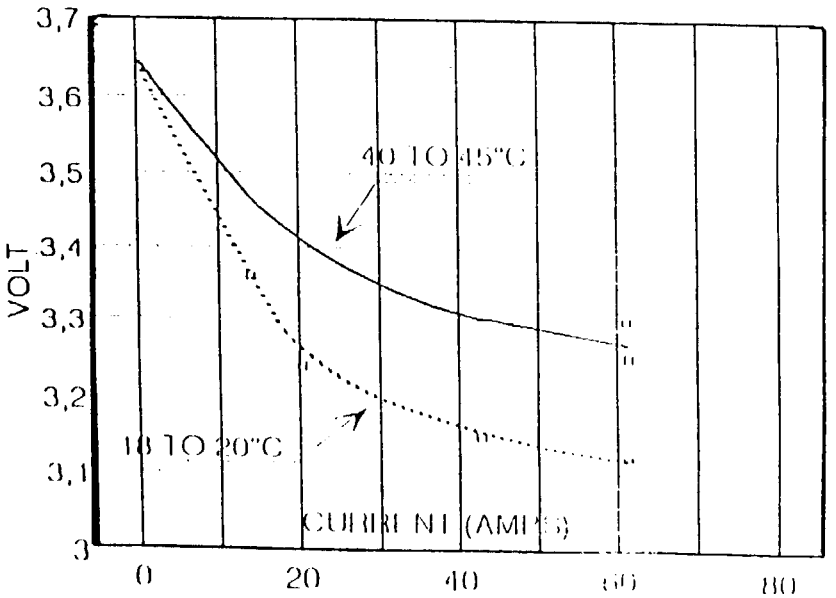
TEST RESULTS

STATIC RESPONSES OF $LiSOCl_2$ CELLS

VLS 250 AM AVERAGE VOLTAGE Vs CURRENT FOR VARIOUS TEMPERATURES



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RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

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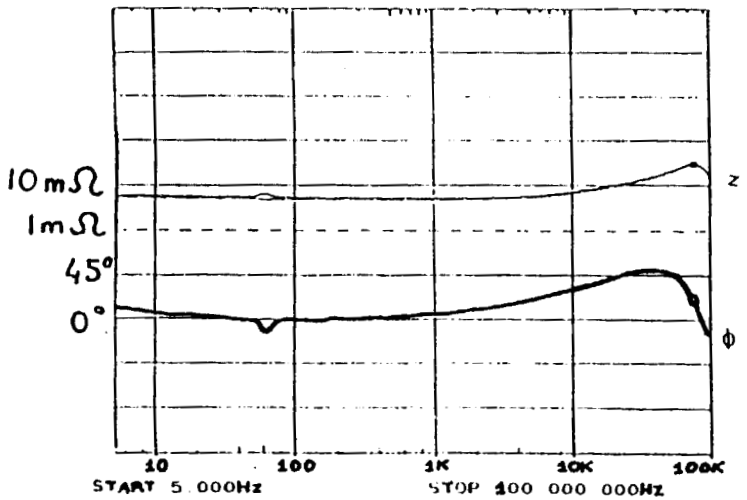
TEST RESULTS

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

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RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

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TEST RESULTS

CELL DISCHARGE

DELIVERED ENERGY : 612.1 WH (400 WH/KG)

DELIVERED CAPACITY : 204.8 AH

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RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

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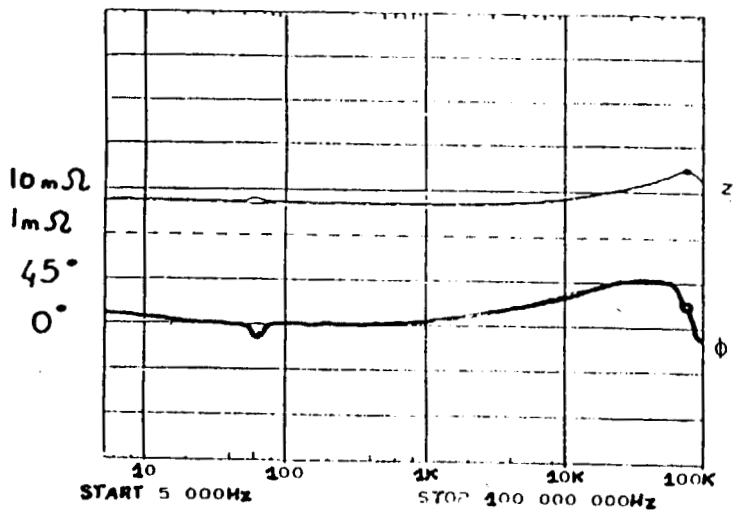
ELECTRICAL MODELIZATION

CELL ELECTRICAL MODELIZATION BASED ON FREQUENCY RESPONSE TEST

MODEL 1 : $T \geq 40°C$



* PLATEAU AT 6 mΩ

  → SERIES RESISTANCE : R_1

* RESONANCE AT 76 KHz, 41 mΩ

  → RLC PARALLEL CIRCUIT : R_2 = 35 mΩ

  $1/2\pi\sqrt{LC}$ = 76 KHz

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RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

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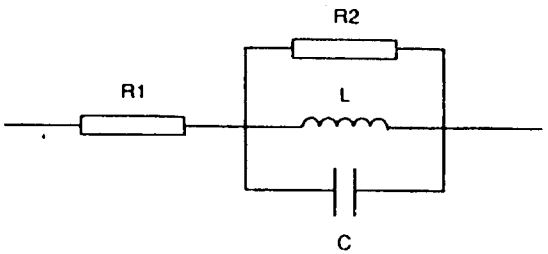
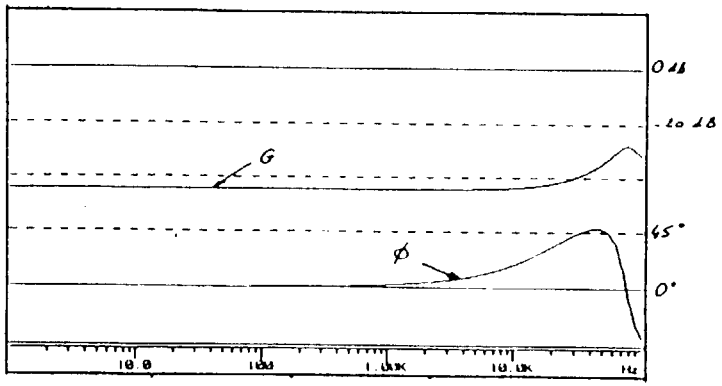
ELECTRICAL MODELIZATION

MODEL 1 : T ≥ 40°C



SIMULATION RESULT



R_1 = 6 mΩ TO 10 mΩ
(R_1 INCREASES AS T° AND/OR DC CURRENT DECREASES)

R_2 = 35 mΩ
L = 32 µH
C = 137 µF

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RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

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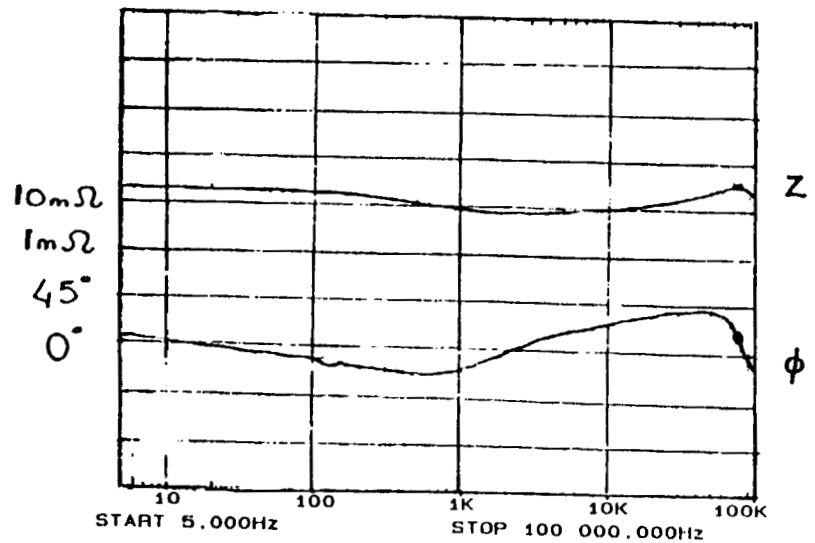
ELECTRICAL MODELIZATION

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

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RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

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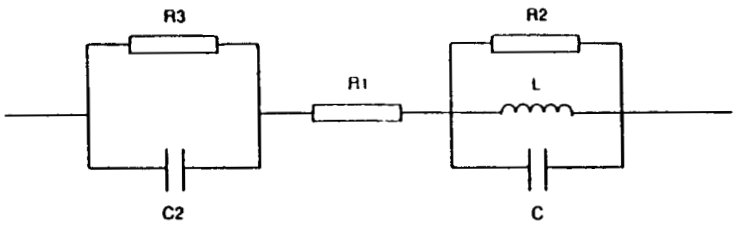
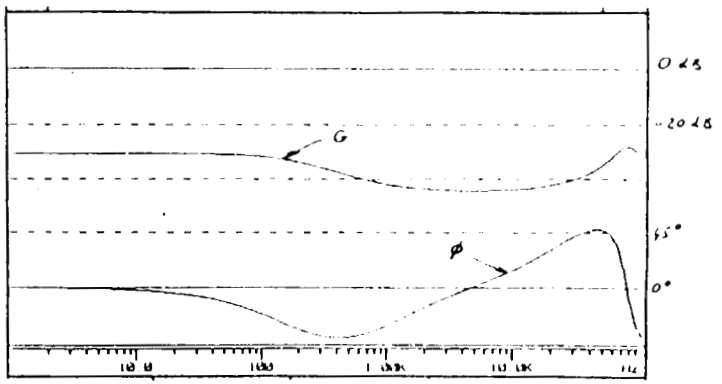
ELECTRICAL MODELIZATION

MODEL 2 ; T < 40°C



SIMULATION RESULT



R_3 = 0 mΩ TO 24 mΩ
(R_3 INCREASES AS T° AND/OR DC CURRENT DECREASES)

C_2 = 35.4 mF

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RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

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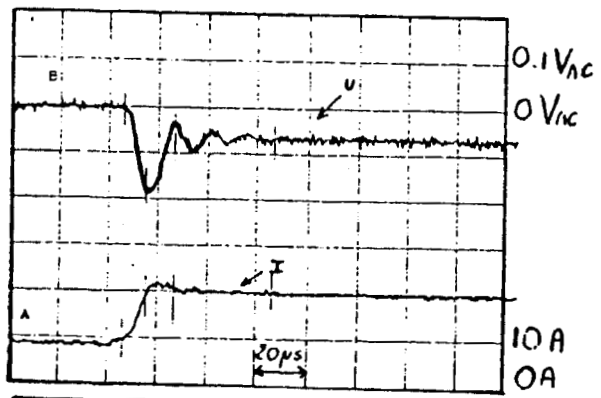
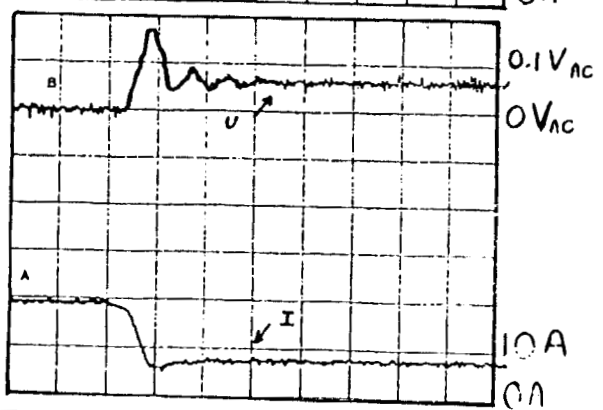
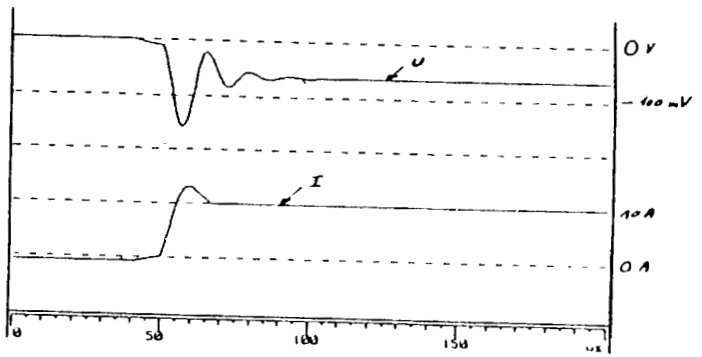
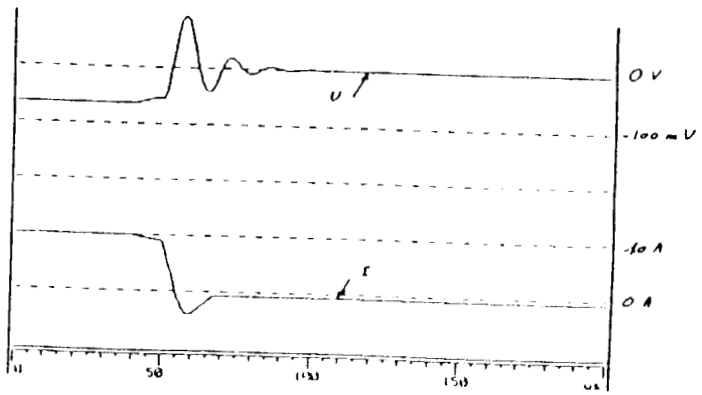
ELECTRICAL MODELIZATION

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









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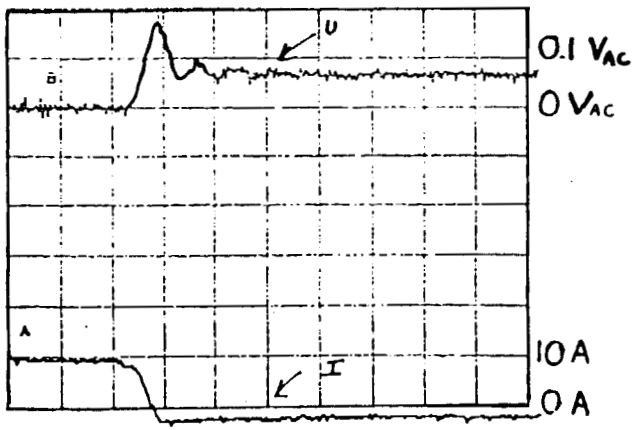
RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

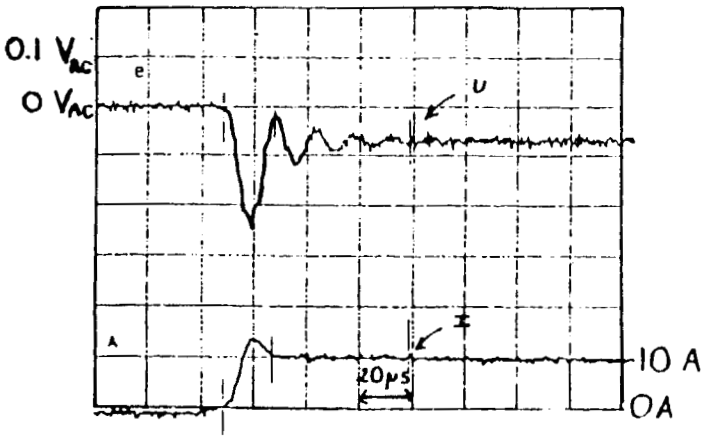
ETCA

ELECTRICAL MODELIZATION

MODEL VALIDATION WITH STEP RESPONSE RESULTS (I_{DC} < 10A)

FOR I < 10A, THE POSITIVE AND NEGATIVE STEP RESPONSES ARE NOT SYMETRICAL.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.

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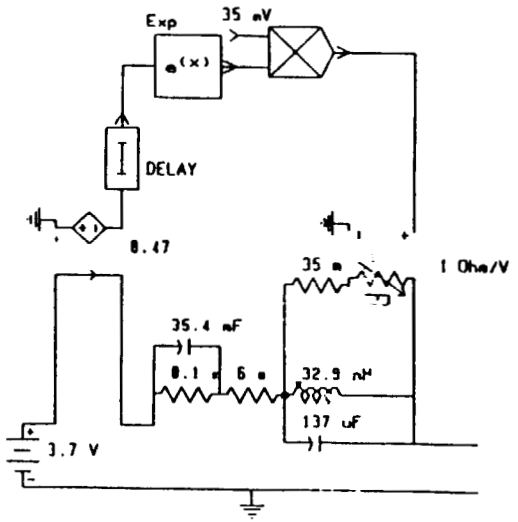
RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

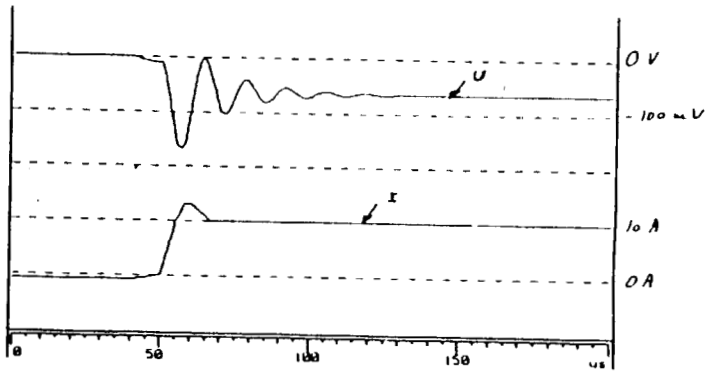
ETCA

ELECTRICAL MODELIZATION

MODEL 3 : MODEL2 + RESISTOR (R)



SIMULATION RESULT



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RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

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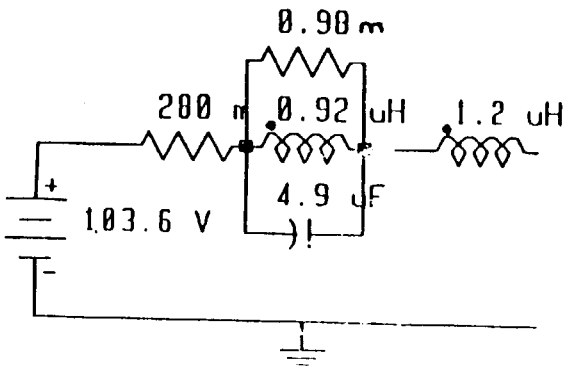
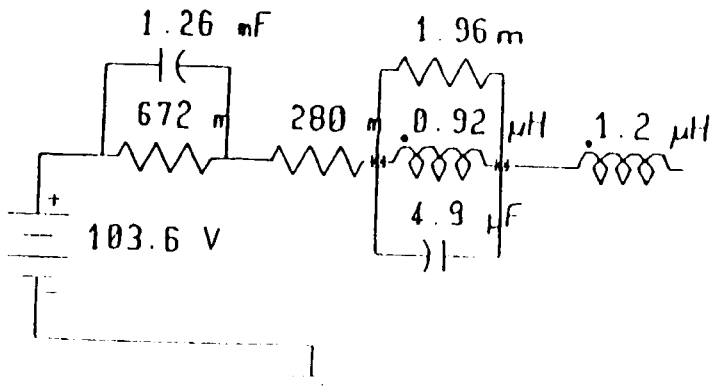
ELECTRICAL MODELIZATION

BATTERY ELECTRICAL MODELIZATION

T > 40°C



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



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RISE TIME AND RESPONSE MEASUREMENTS ON A $LiSOCl_2$ CELL

ETCA

CONCLUSION

* THE 180 Ah $LiSOCl_2$ CELL HAS SHOWN THE ABILITY TO DELIVER 40A WITHIN LESS THAN 60 µs IN THE SPECIFIED VOLTAGE RANGE (> 3 VOLTS).
* NO DELAY EFFECT WAS NOTICED AFTER 13 DAYS DURING WHICH A 50mA PERMANENT CURRENT WAS DISCHARGED.
* SEVERAL ELECTRICAL MODELS HAVE BEEN PRESENTED WHICH SIMULATE THE DYNAMIC BEHAVIOUR OF THE CELL FOR DIFFERENT CONDITIONS OF TEMPERATURE, CURRENT AND DOD.
* TWO MODELS OF THE 28 $LiSOCl_2$ CELL BATTERY ARE PROPOSED TO BE USED FOR THE MATHEMATICAL ANALYSIS OF THE HERMES POWER SYSTEM AND FOR AN ELECTRICAL SIMULATOR SPECIFICATION.

NASA 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

INTERNAL/EXTERNAL SHORT CIRCUIT PROTECTION FOR LI D CELLS

Propulsion and Power Division

B.J. Bragg | 10/29/91

AGENDA

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

INTERNAL/EXTERNAL SHORT CIRCUIT PROTECTION FOR LI D CELLS

Propulsion and Power Division
B.J. Bragg | 10/29/91

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

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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

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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

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- 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

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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

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INCORPORATION INTO LITHIUM D CELLS

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

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

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

INTERNAL/EXTERNAL SHORT CIRCUIT PROTECTION FOR LI D CELLS

Propulsion and Power Division

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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

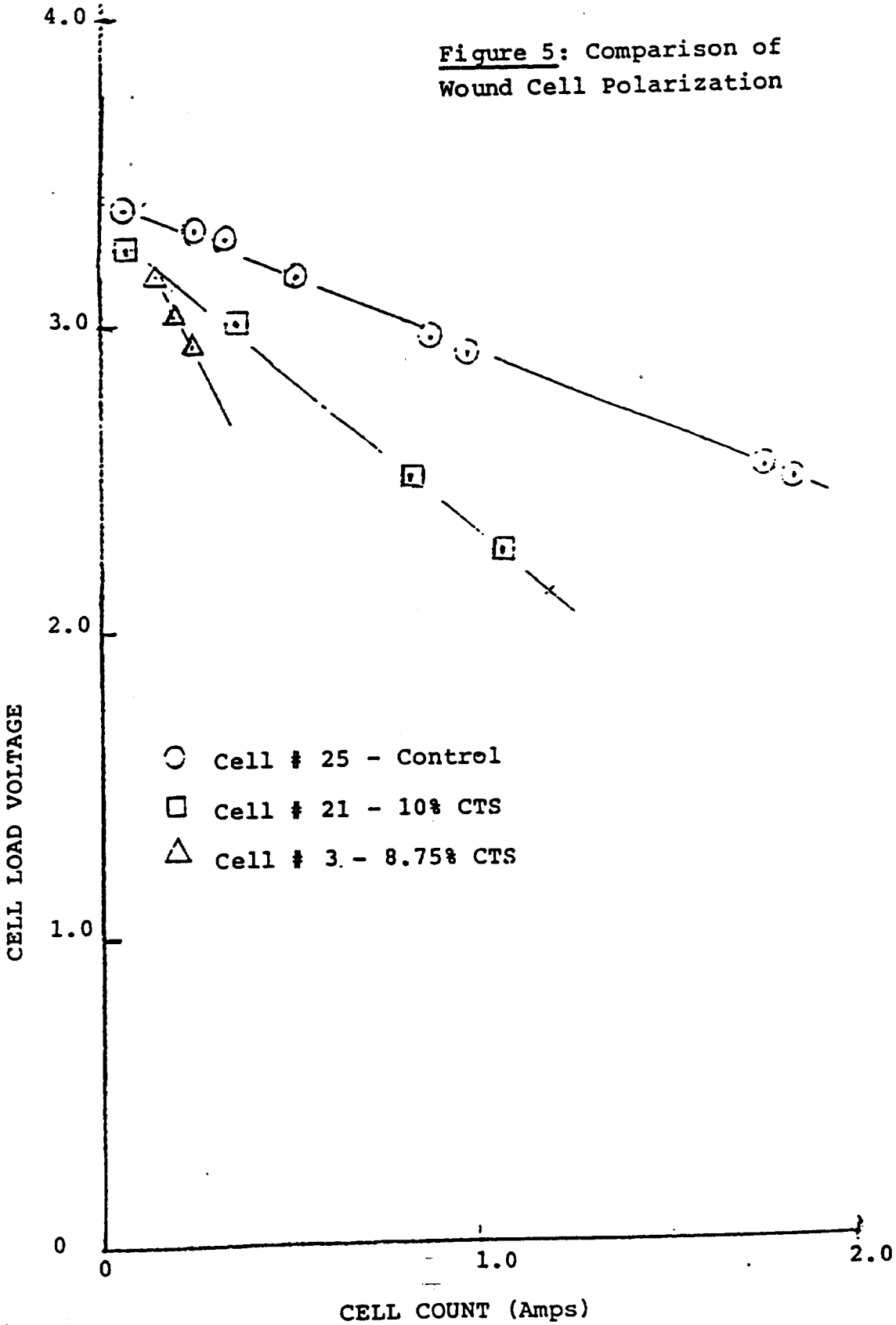
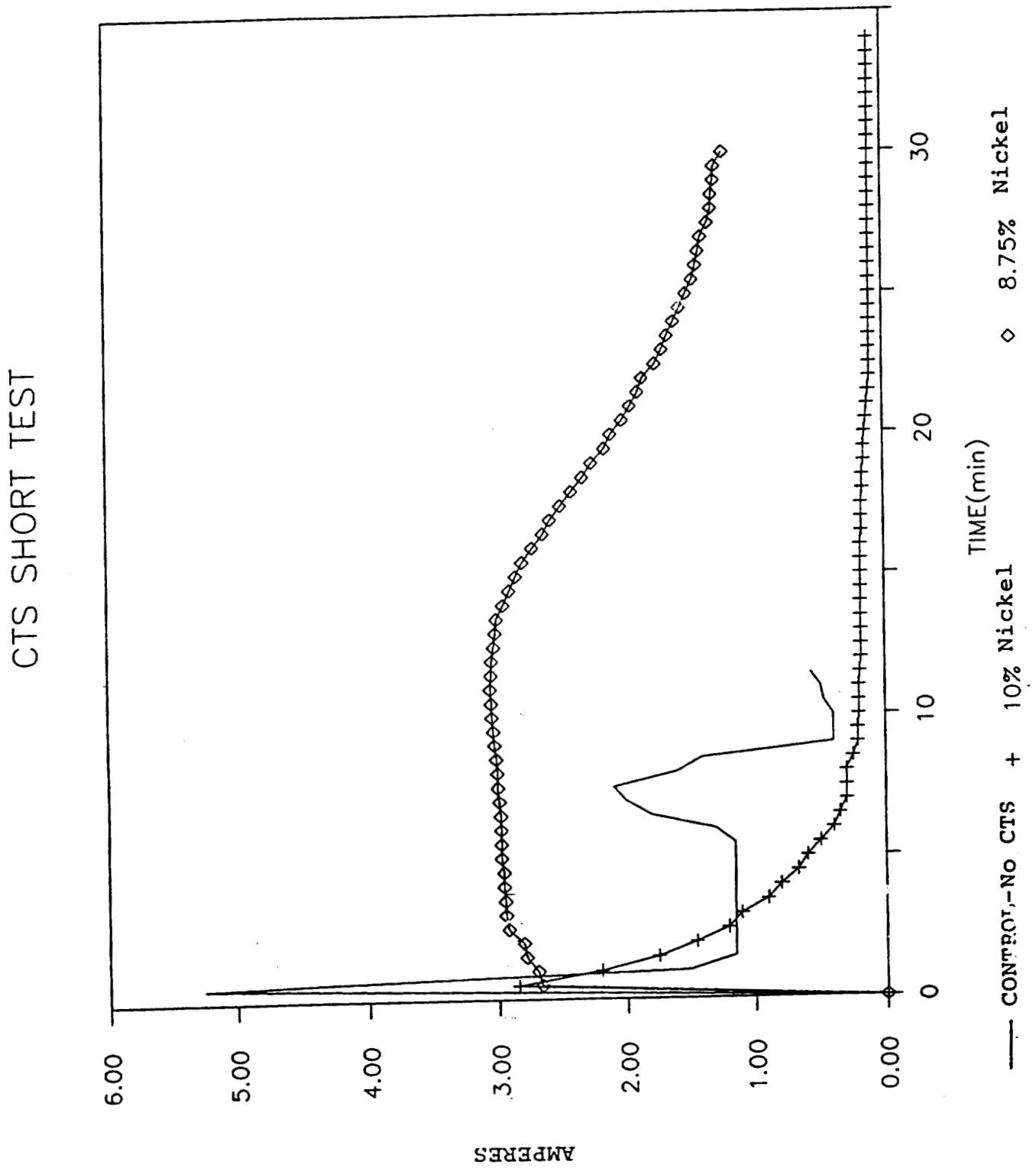
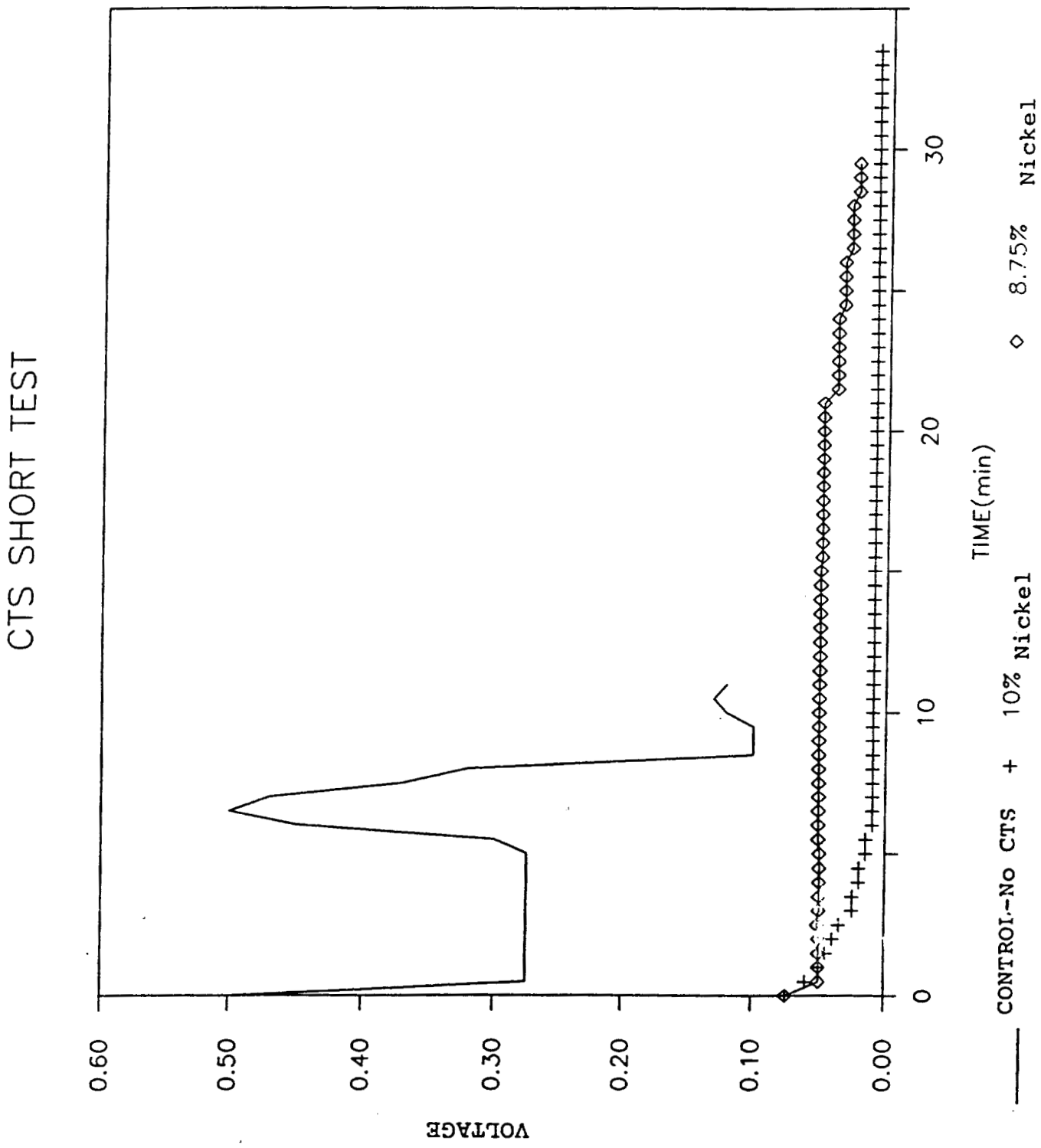
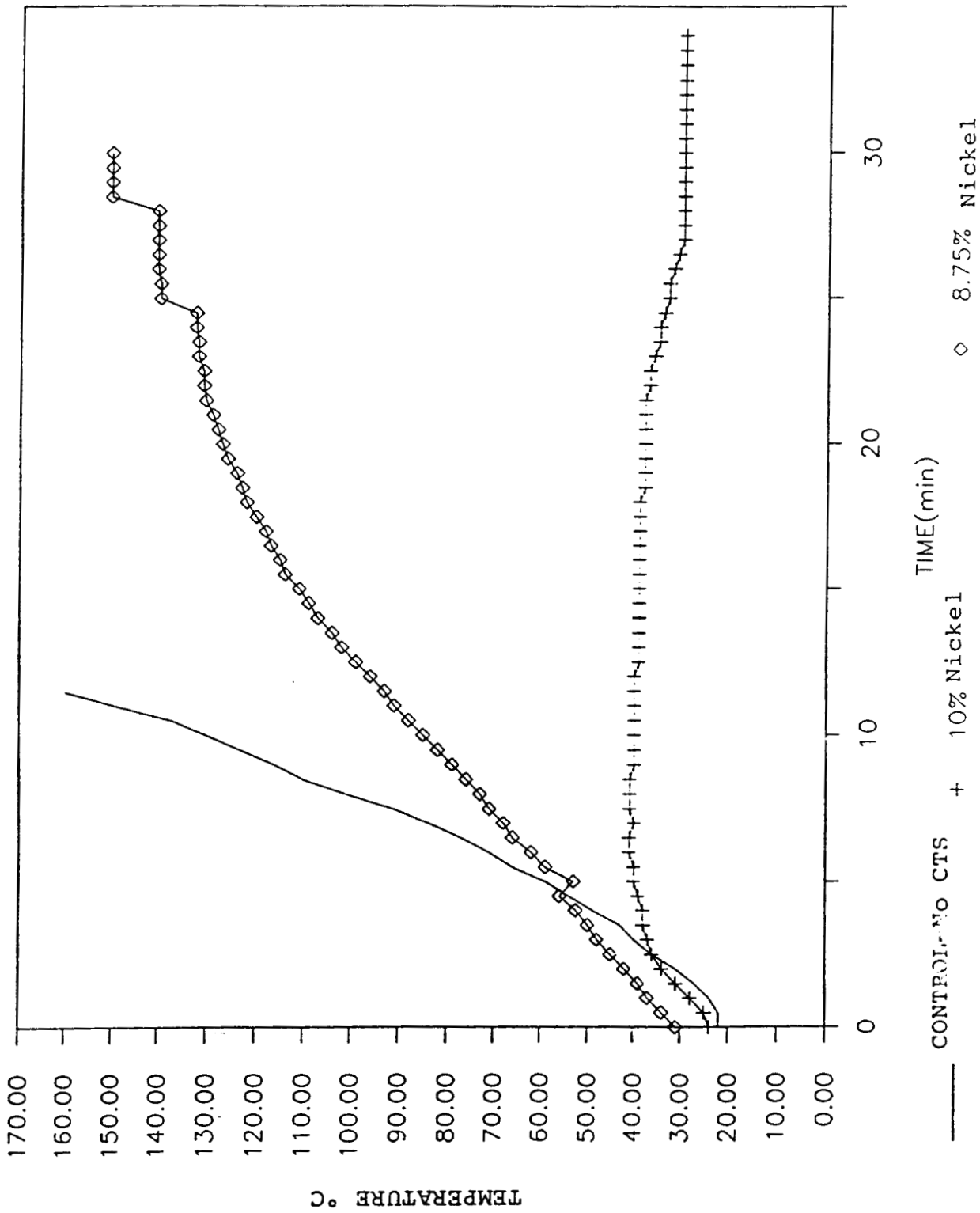


Figure 5: Comparison of Wound Cell Polarization


CTS SHORT TEST
AMPERES
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
10
20
30
TIME(min)
CONTROL-No CTS + 10% Nickel
◇ 8.75% Nickel
Yardney Technical Products, Inc., NAS 9-18279


CTS SHORT TEST
VOLTAGE
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
10
20
30
TIME(min)
CONTROL-No CTS + 10% Nickel ◇ 8.75% Nickel
Yardney Technical Products, Inc., NAS 9-18279


CTS SHORT TEST
TEMPERATURE °C
170.00
160.00
150.00
140.00
130.00
120.00
110.00
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0
10
20
30
TIME(min)
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_2 cell battery pack. In addition, the cells meet the requirements for the Li/BCX cells used for extra-vehicular activities by the crew of the shuttle. One of the major qualifying tests is the ability of the cells to withstand exposure to high temperature (149°C) without leaking. Electrical performance and thermal abuse test data will be presented for the cells.

Li/BCX Battery for the NASA AN/PRC-112 Survival Radio

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

and

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

Objectives

Overall Objective

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

Requirements

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

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

- extend operational life by a factor of four compared to operation using a Li/SO_2 battery

Background

- The AN/PRC-112 is an army radio which was designed with a Li/SO_2 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.

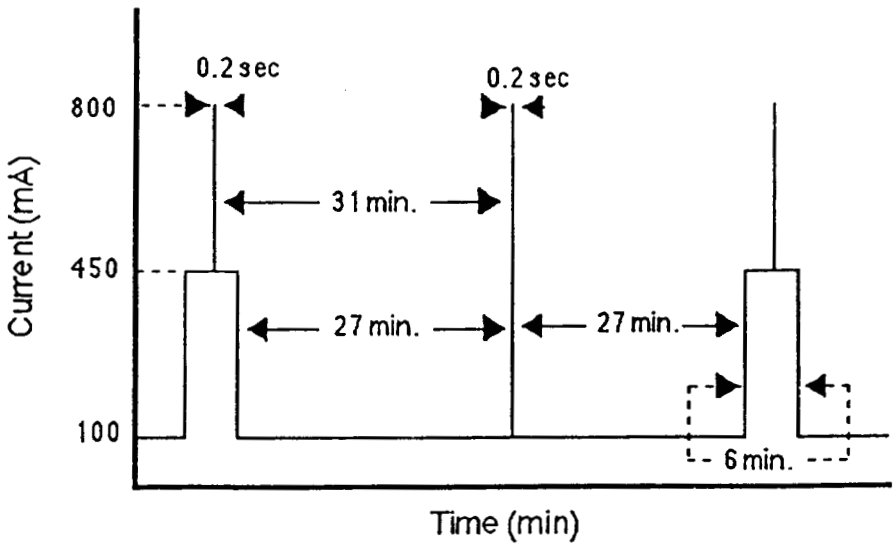
- The previously NASA qualified Li/BCX C cell had insufficient power capability to meet the survival radio electrical requirements. A higher power version was needed.

- 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^3
working electrode surface area	110 cm^2
chemistry	Li/BrCl + $SOCl_2$
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.

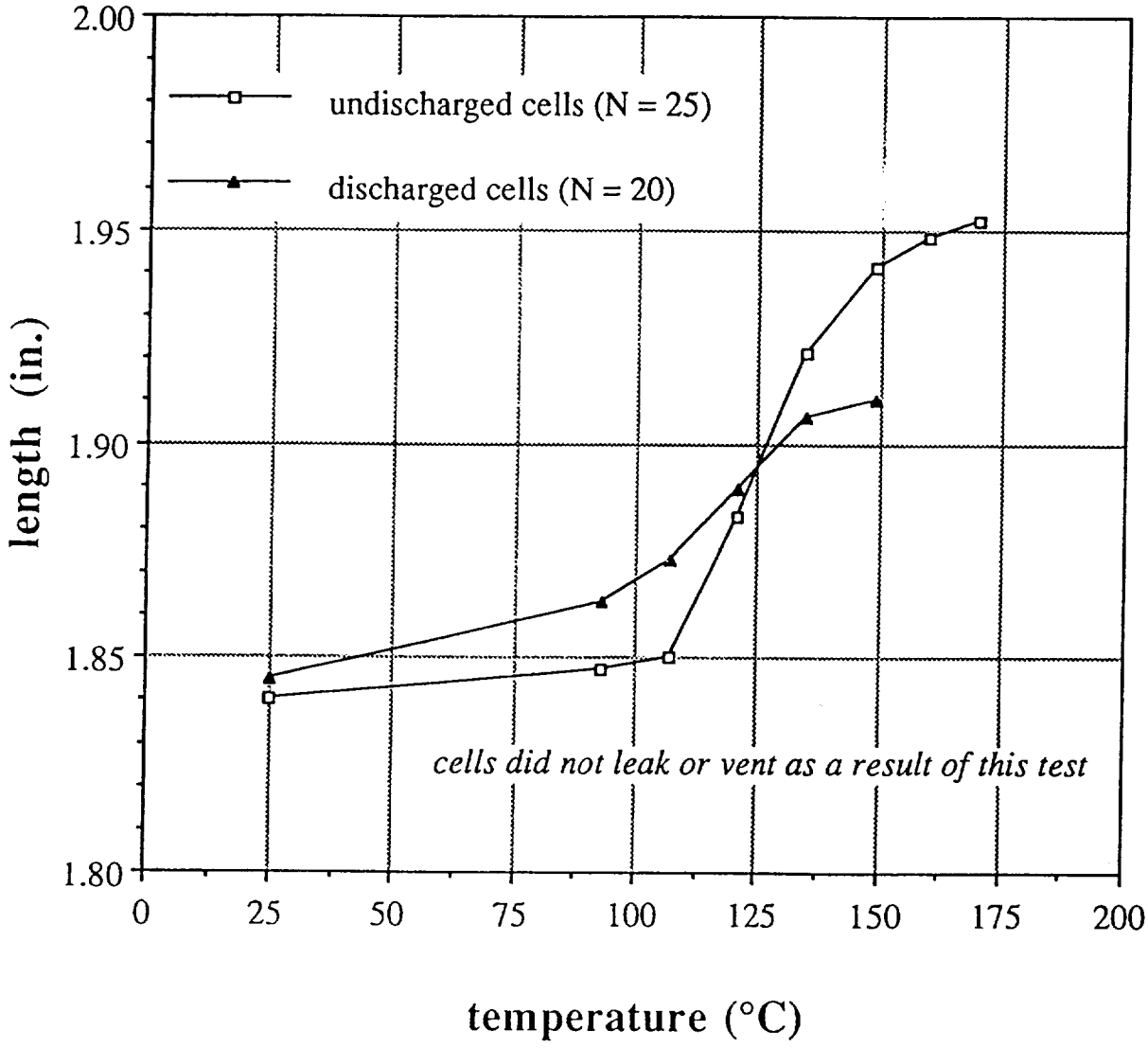
Electrical Abuse Testing

- 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

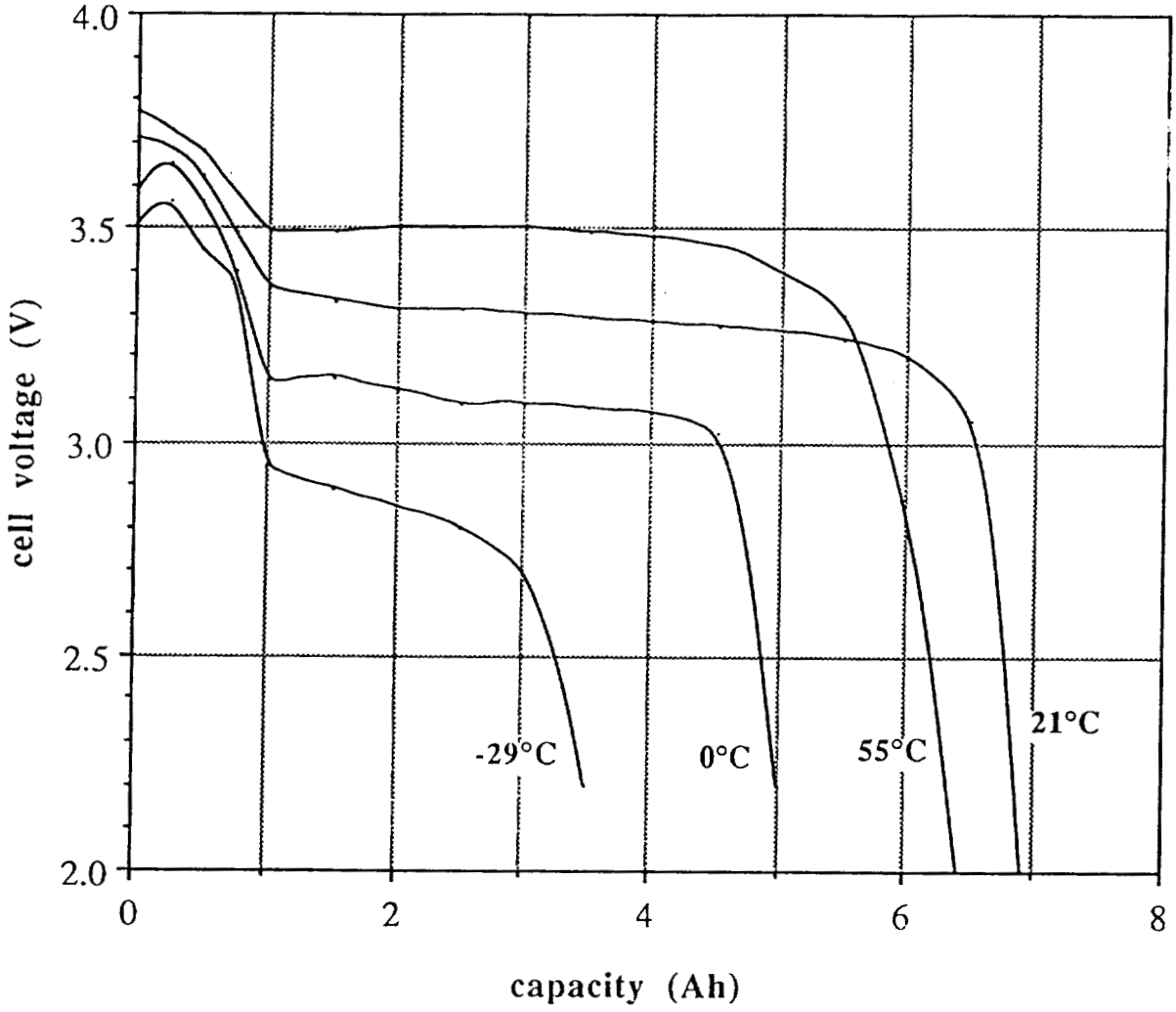
- 52 cells tested
- average initial current: 5.8 A
- average peak temperature: 87°C
- average time to peak temperature: 30 minutes
- no vents, leaks, or ruptures

Force Overdischarge Testing

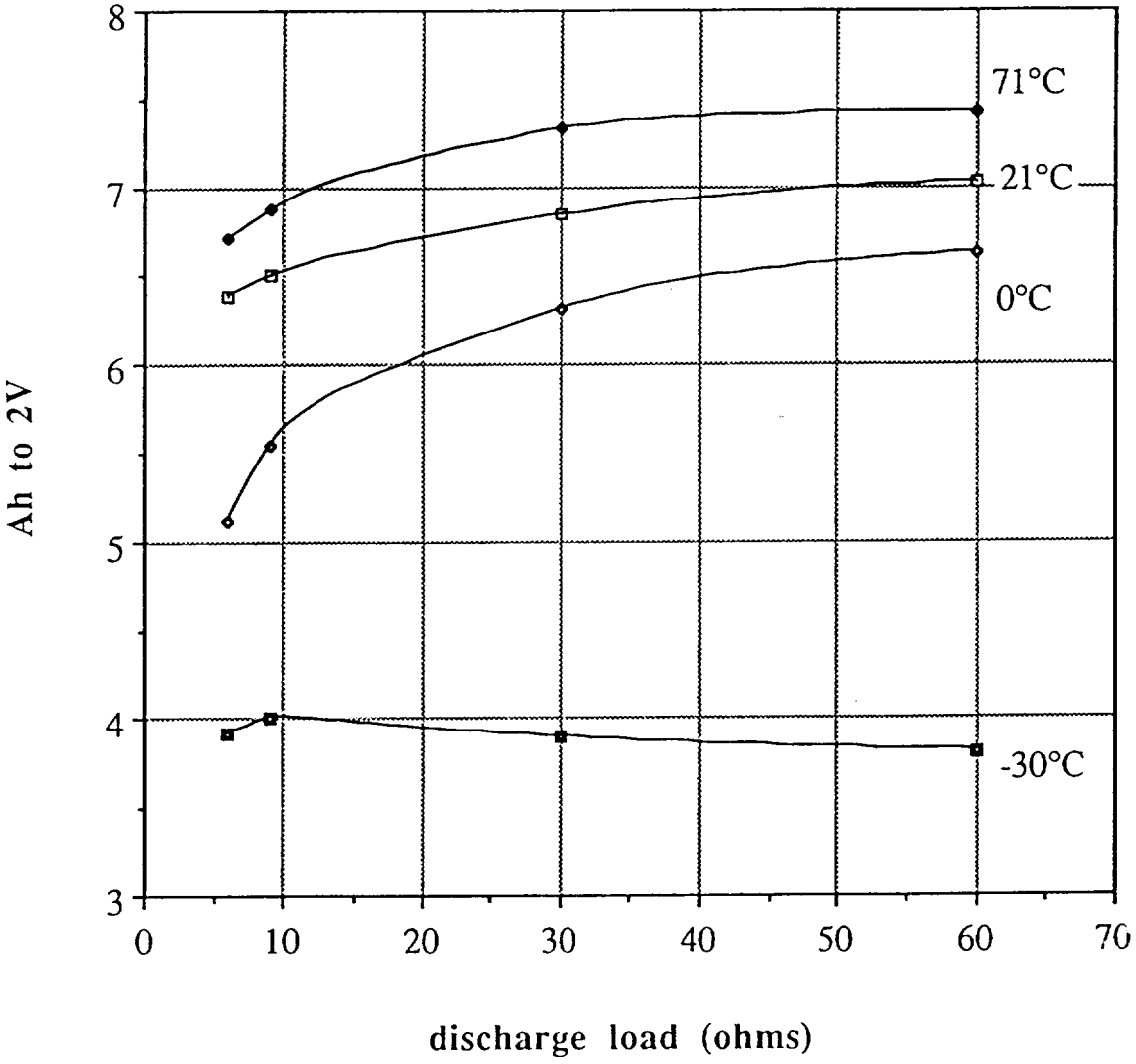
In general...

- 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

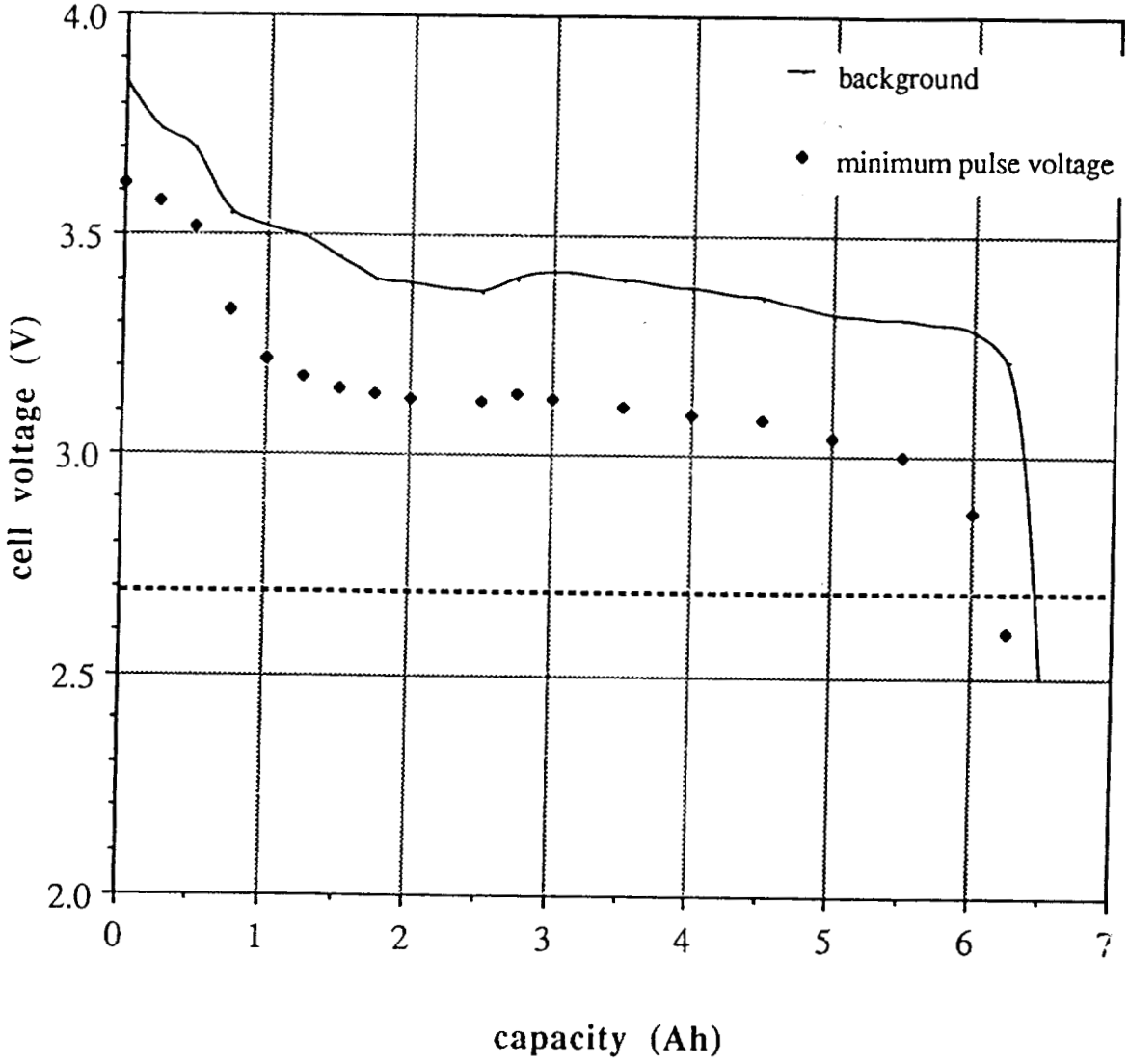
Li/BCX (149) C-CELL DISCHARGE RESULTS UNDER 6Ω LOADS AT VARIOUS TEMPERATURES



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

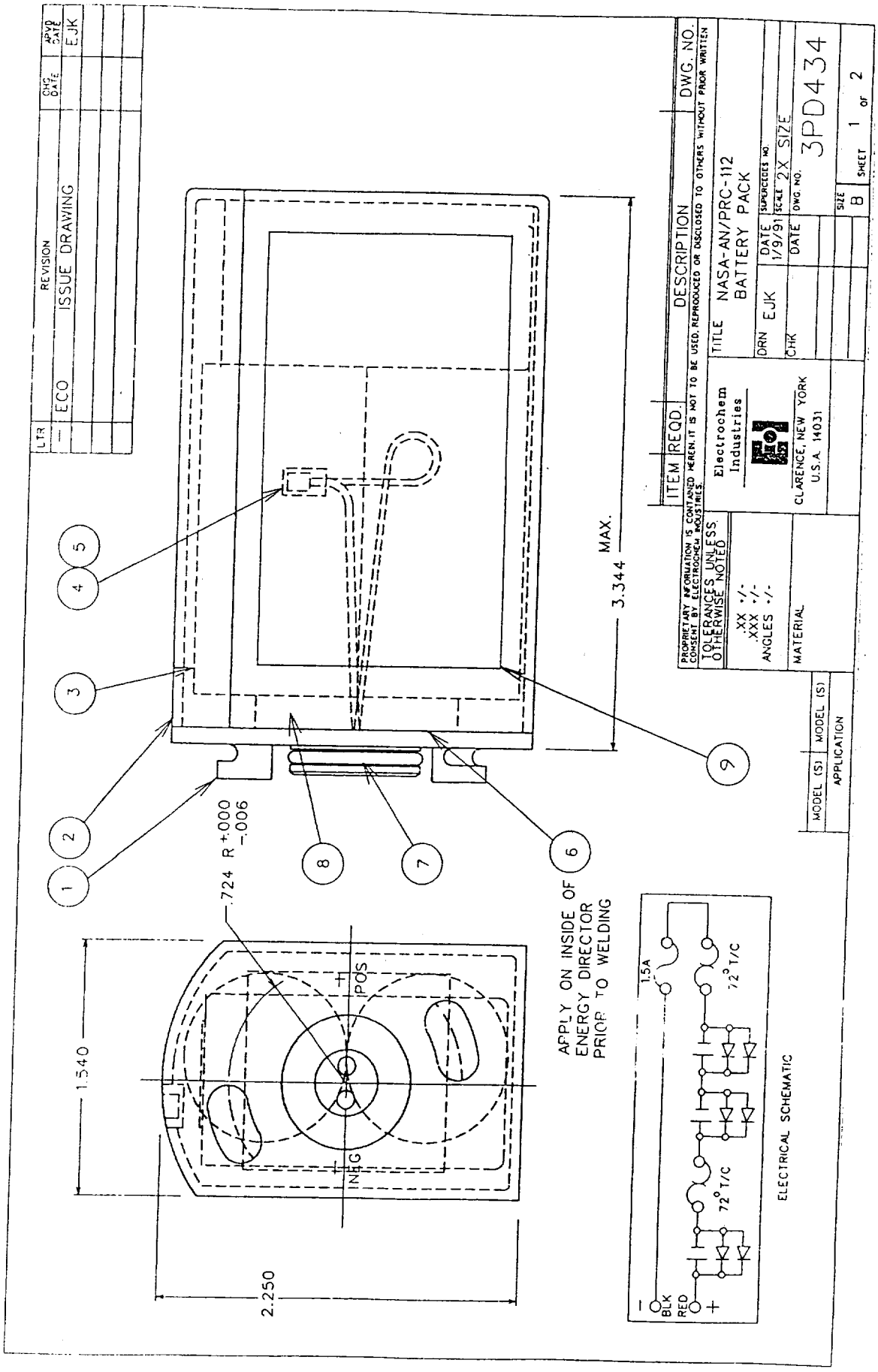
- Designed to accommodate three "universal" Li/BCX C cells in series.

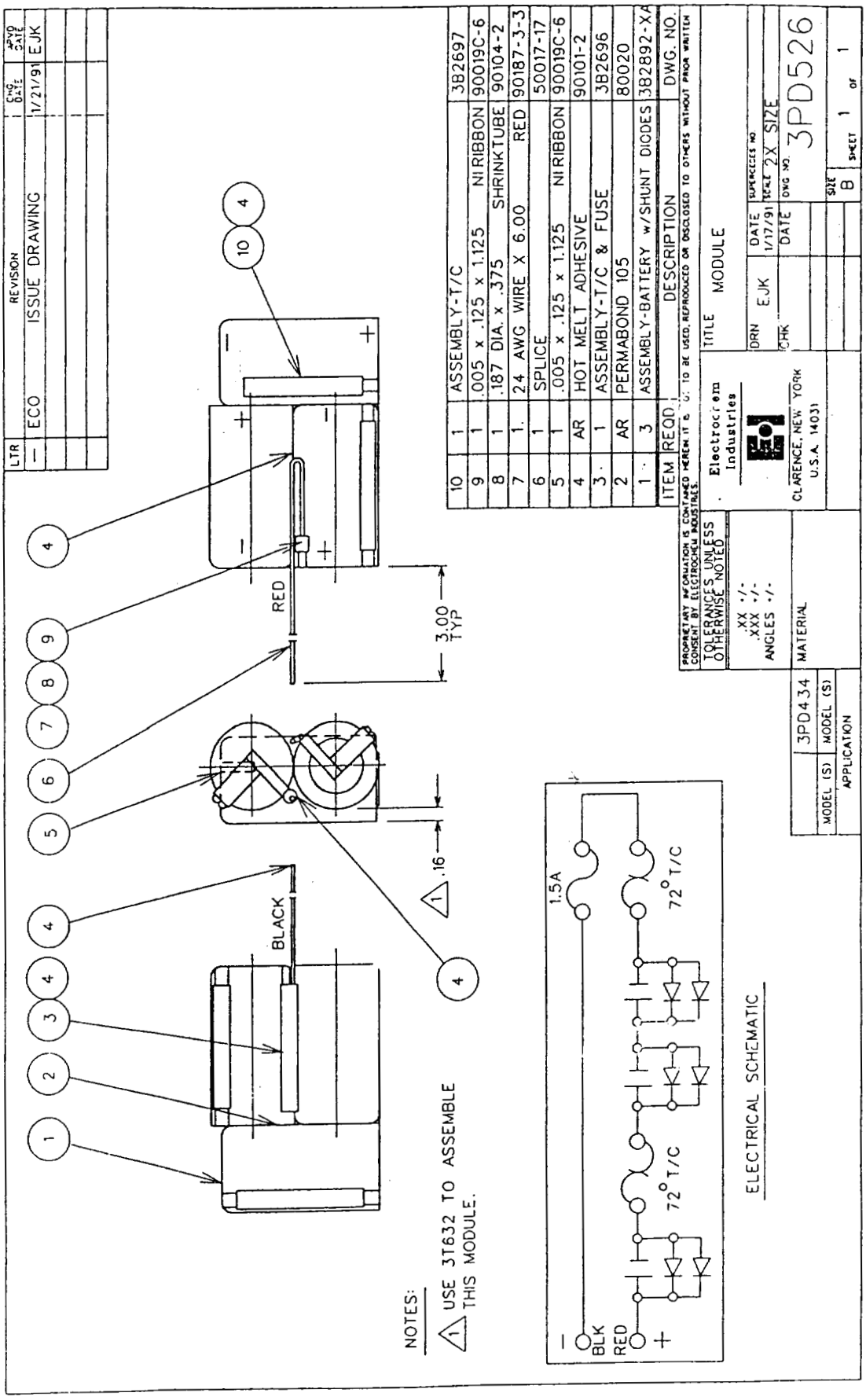
- Safety features to include a 4A fast-blow fuse built into each cell, two shunt diodes in parallel with each cell, two thermal fuses rated at 72°C in the battery, and one 1.5A fast-blow fuse in the negative leg of the battery.

- Battery weight to be 280 g max.

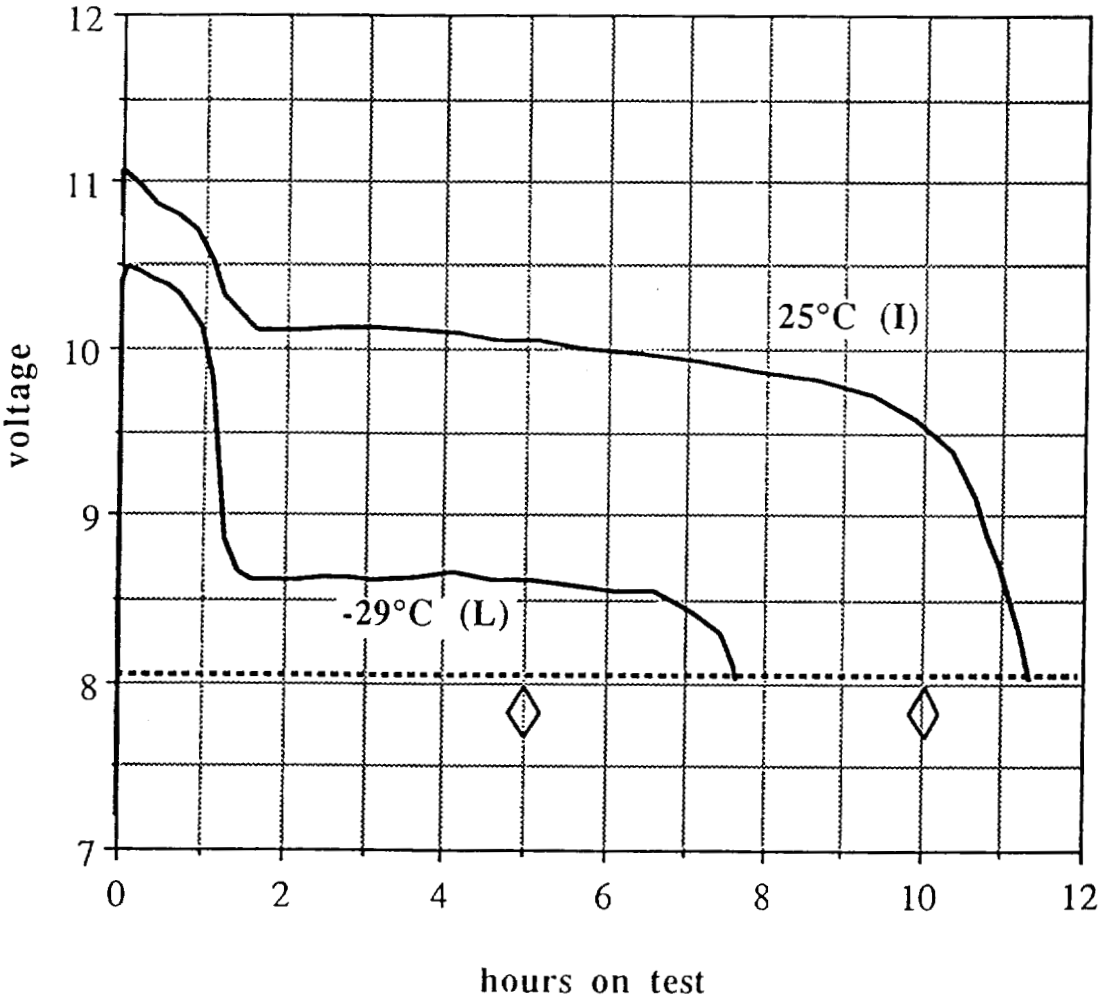
- under 0.5A load at room temperature and higher the battery must attain an 8V minimum operating voltage within 5 sec.

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

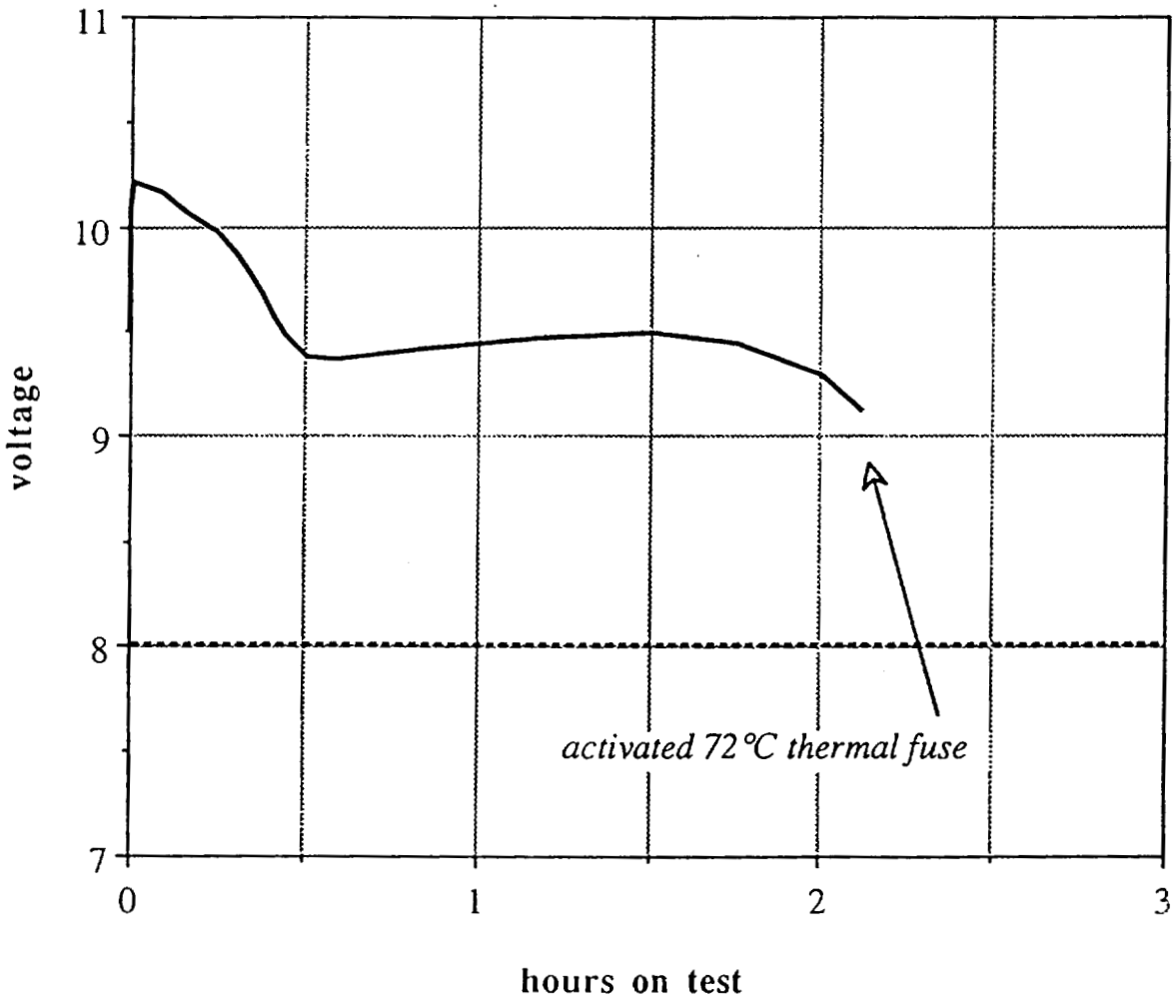

LTR
REVISION
CHG DATE
APVD DATE
—
ECO
ISSUE DRAWING
EJK
DESCRIPTION
DWG. NO.
ITEM REQD.
PROPRIETARY INFORMATION IS CONTAINED HEREIN. IT IS NOT TO BE USED, REPRODUCED OR DISCLOSED TO OTHERS WITHOUT PRIOR WRITTEN CONSENT BY ELECTROCHEM INDUSTRIES.
TOLERANCES UNLESS OTHERWISE NOTED
.XX +/-
.XXX +/-
ANGLES +/-
MATERIAL
Electrochem Industries
CLARENCE, NEW YORK U.S.A. 14031
TITLE
NASA-AN/PRC-112 BATTERY PACK
DRN EJK
DATE 1/9/91
CHK
DATE
SUPERCEDES NO.
SCALE 2X SIZE
DWG. NO.
3PD434
SIZE B
SHEET 1 OF 2
MODEL (S)
MODEL (S)
APPLICATION
MAX.
3.344
.724 R +.000 -.006
1.540
2.250
POS
NEG
APPLY ON INSIDE OF ENERGY DIRECTOR PRIOR TO WELDING
1.5A
72° T/C
72° T/C
BLK
RED
ELECTRICAL SCHEMATIC


REVISION
LTR
ECO
ISSUE DRAWING
ENG DATE
1/21/91
APVD DATE
EJK
ITEM REQD
DESCRIPTION
DWG. NO.
10 1 ASSEMBLY-T/C 3B2697
9 1 .005 x .125 x 1.125 NI RIBBON 90019C-6
8 1 .187 DIA. x .375 SHRINK TUBE 90104-2
7 1. 24 AWG WIRE X 6.00 RED 90187-3-3
6 1 SPLICE 50017-17
5 1 .005 x .125 x 1.125 NI RIBBON 90019C-6
4 AR HOT MELT ADHESIVE 90101-2
3 1 ASSEMBLY-T/C & FUSE 3B2696
2 AR PERMABOND 105 80020
1 3 ASSEMBLY-BATTERY w/SHUNT DIODES 3B2892-XA
PROPRIETARY INFORMATION IS CONTAINED HEREIN IT IS TO BE USED, REPRODUCED OR DISCLOSED TO OTHERS WITHOUT PRIOR WRITTEN CONSENT BY ELECTROCHEM INDUSTRIES.
TOLERANCES UNLESS OTHERWISE NOTED
.XX +/-
.XXX +/-
ANGLES +/-
Electrochem Industries
CLARENCE, NEW YORK
U.S.A. 14031
TITLE MODULE
DRN EJK DATE 1/17/91
CHK DATE
SUPERCEDES NO
SCALE 2X SIZE
DWG NO. 3PD526
SIZE B
SHEET 1 OF 1
3PD434
MODEL (S)
MODEL (S)
APPLICATION
MATERIAL
NOTES:
1 USE 3T632 TO ASSEMBLE THIS MODULE.
BLACK
RED
3.00 TYP
.16
1.5A
BLK
RED
72° T/C
72° T/C
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 ± 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 ± 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 g^2/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 1.4×10^{-5} cc/sec
  - batteries passed, average leak rate was 5.8×10^{-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_2 battery.

- Qualification testing will be complete during the second half of Nov91.

NASA 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

NASA Johnson Space Center | Engineering Directorate

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 STANDARD (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 >/= 7 HOURS; >/=26.6 AH)

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EMU AG-ZN BATTERY WET-LIFE EXTENSION TEST

Propulsion and Power Division

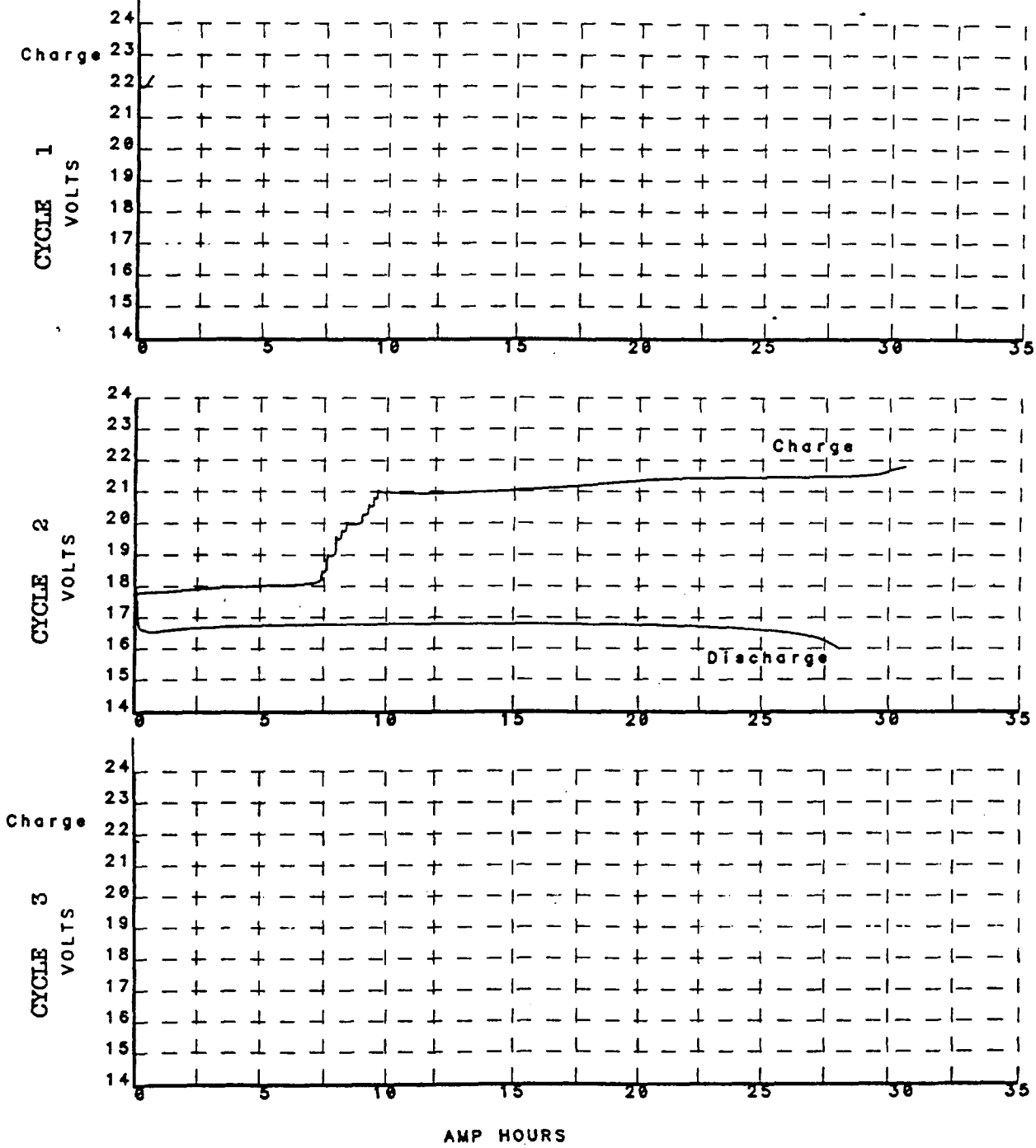
B.J. Bragg | 10/29/91

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

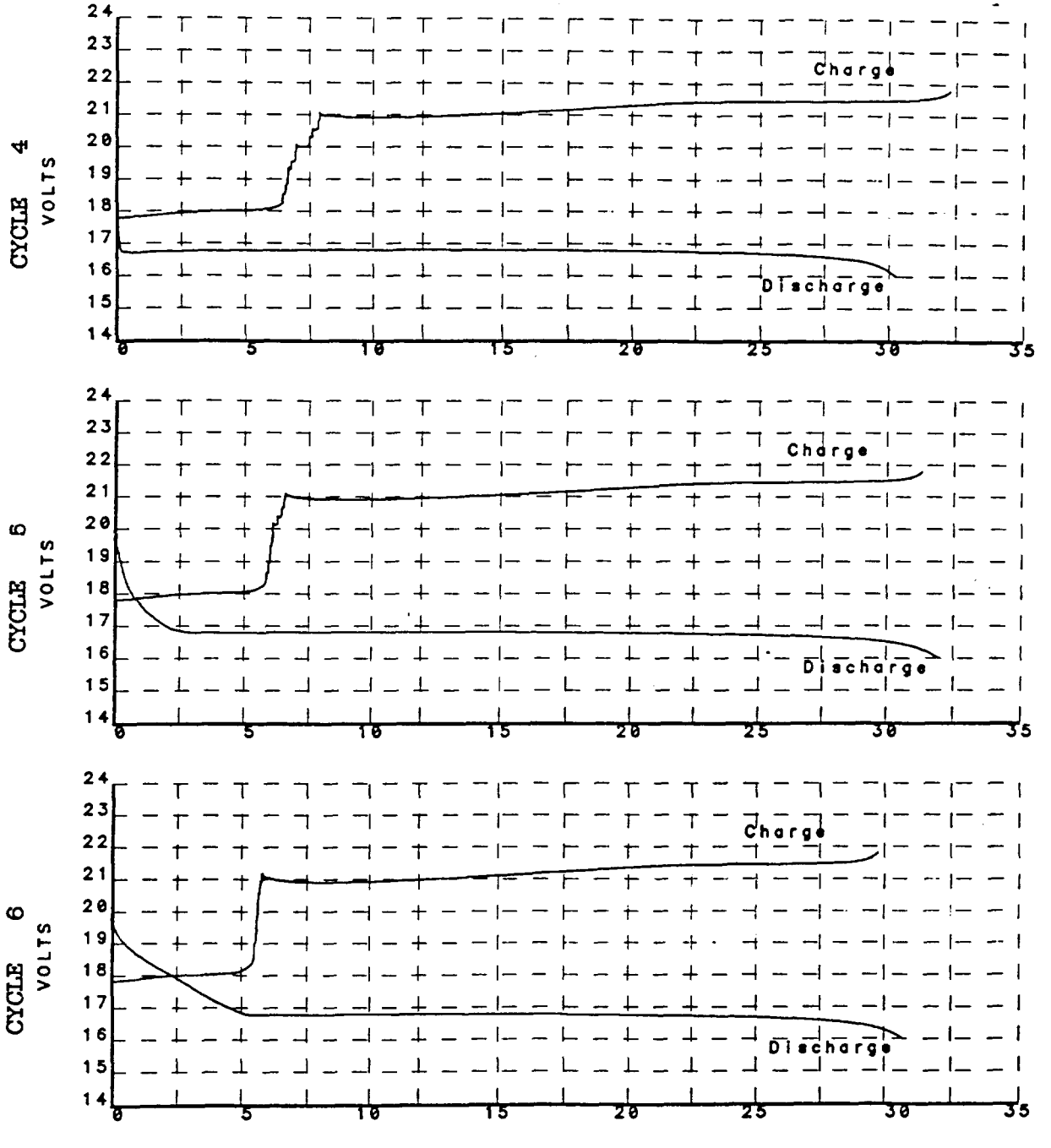
(176 Day Wet-Life)

TEST 2P323, EMU SILVER-ALKALINE SECONDARY BATTERY EVALUATION

BATTERY SERIAL NO.: 1143
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

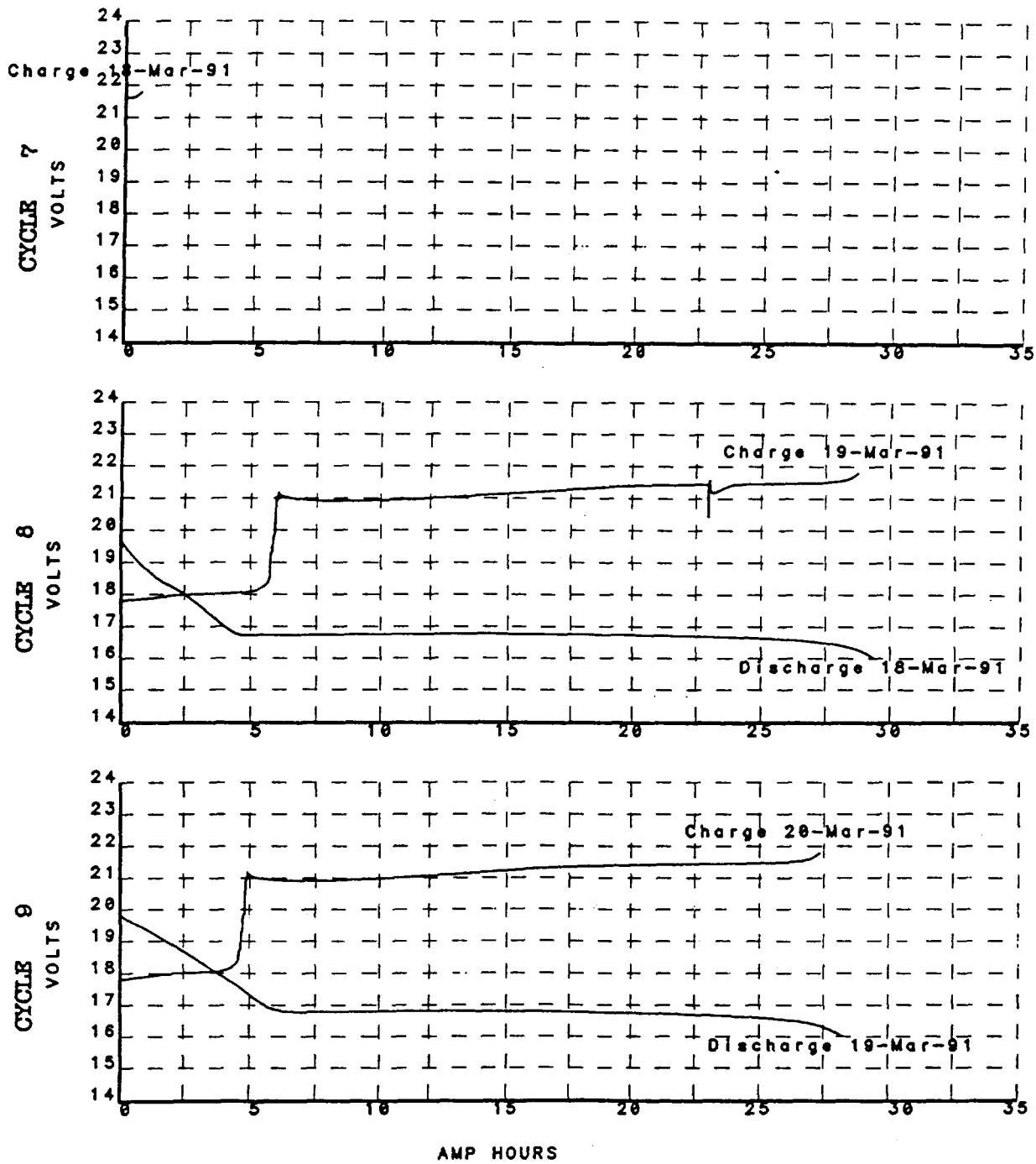


Cycle #	Type Test
4	Test Cycle
5	Test Cycle
6	Test Cycle

(176 Day Wet-Life)

TEST 2P323, EMU SILVER-ALKALINE SECONDARY BATTERY EVALUATION

BATTERY SERIAL NO.: 1143
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

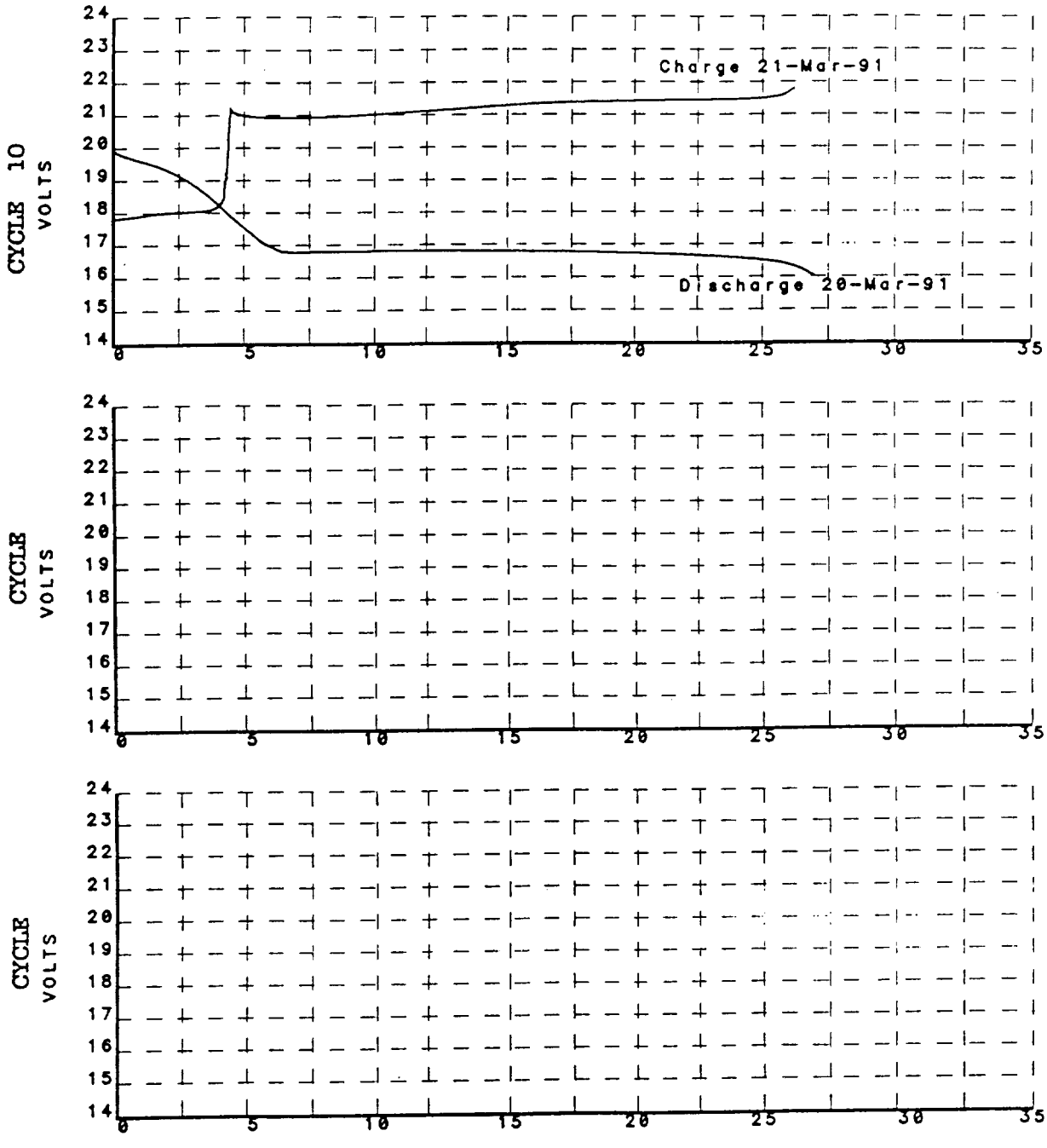


Cycle #	Type Test
7	Topping Charge
8	Test Cycle
9	Test Cycle

(226 Day Wet-Life)

TEST 2P323, EMU SILVER-ALKALINE SECONDARY BATTERY EVALUATION

BATTERY SERIAL NO.: 1143
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

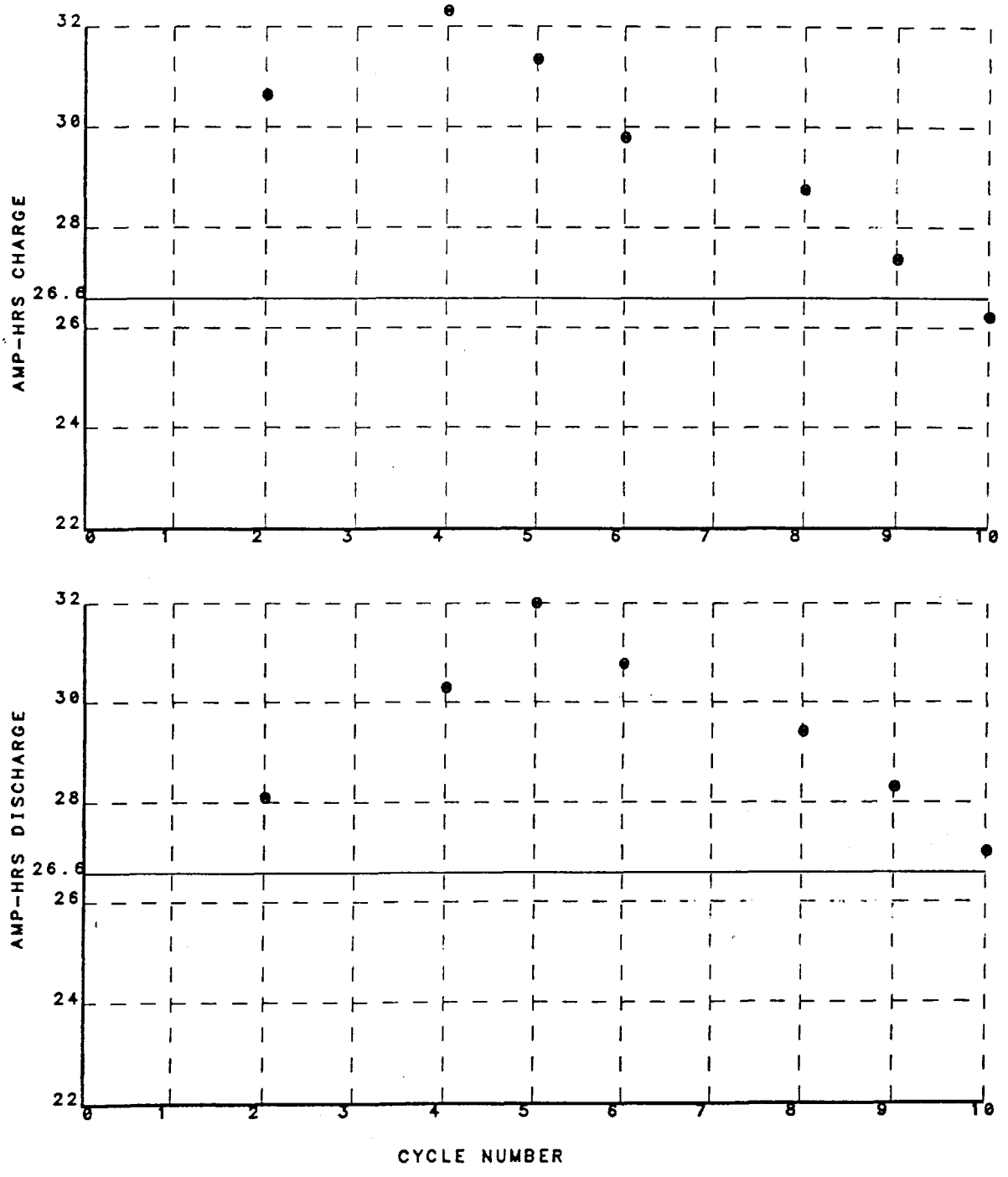


Cycle #	Type Test
10	Test Cycle

(226 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
Test End Date: 21-Mar-91



NASA Aerospace Battery Workshop 1991

High-Rate Li-MnO_2 Cells for Aerospace Use

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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:

Lithium- SO_2Cl_2, $SOCl_2$, SO_2, $(CF_x)_n$, CuO, MnO_2

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:

Lithium- $SOCl_2$, SO_2, $(CF_x)_n$, MnO_2

This resulted in the decision in 1982 to adopt the Li-MnO_2 system for high-rate applications.

The reason for this was that it appeared the most promising system in its overall characteristics. With the main goal to achieve the good properties of the couple Li-MnO_2 such as high energy density, long shelf life, insignificant voltage delay and environmental safety, HOPPECKE succeeded in the development of high-rate Li-MnO_2 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_2 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 lithiumperchlorate ($LiClO_4$). 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_2 cells compared to standard SO_2 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_2 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 sudded exothermic reactions or violent explosions occur.

5. Space applications

HOPPECKE high-rate Li-MnO_2 cells for aerospace use

The high performance results and the safe electrochemical behaviour of the Li-MnO_2 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_2 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 batterey 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 densitiy 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 inexplainable behaviour of the cells was observed. This supports our view that Li-MnO_2 technology gives one of the safest lithium systems currently available.

6. Conclusion

- The electrochemical couple Li-MnO_2 is suitable for high rate applications
- HOPPECKE Li-MnO_2 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_2 cells and batteries meet and often considerably exceed most military requirements
- First applications of HOPPECKE Li-MnO_2 technology in space missions already have been succesful and the Li-MnO_2 system is a promising candidate for future space applications

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

Fig. 1

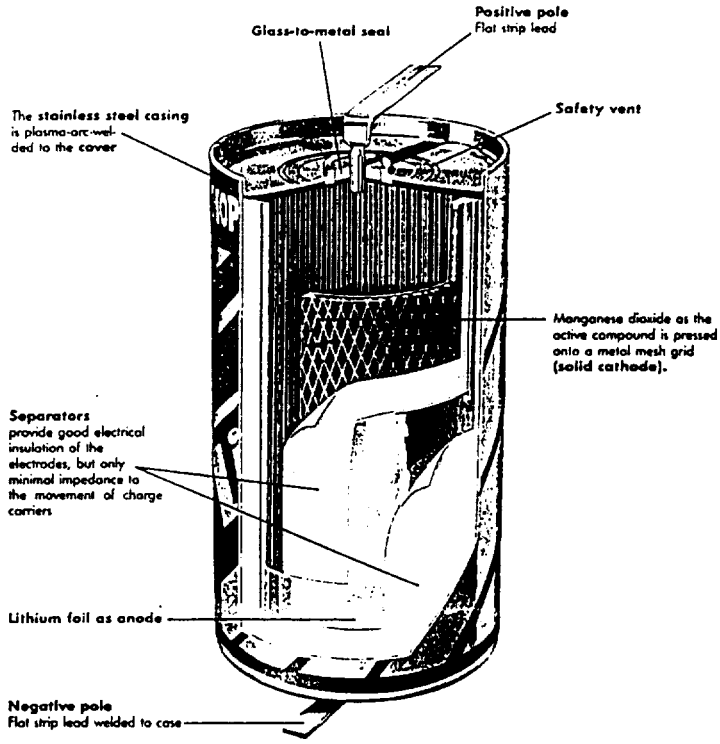


Fig. 2

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

HOPPECKE Batteries

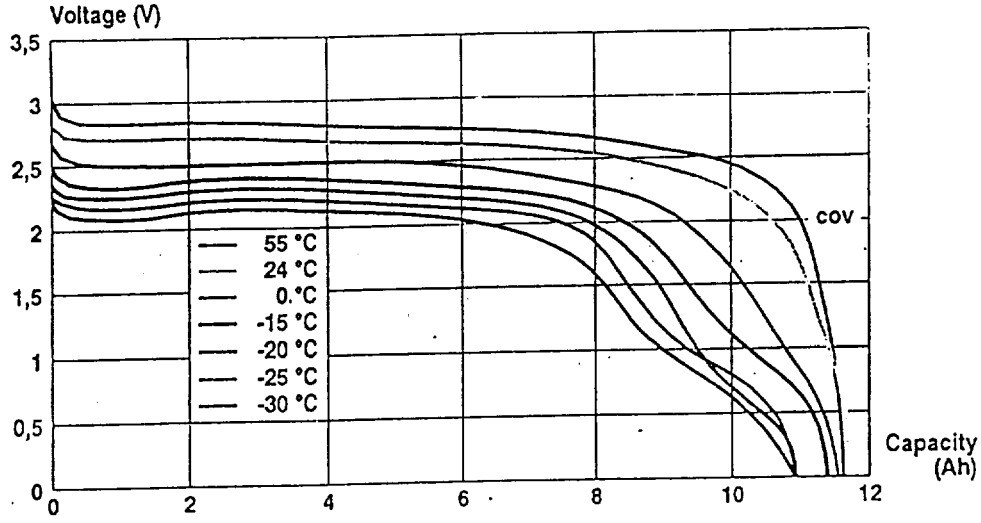


Fig. 3

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

HOPPECKE Batteries

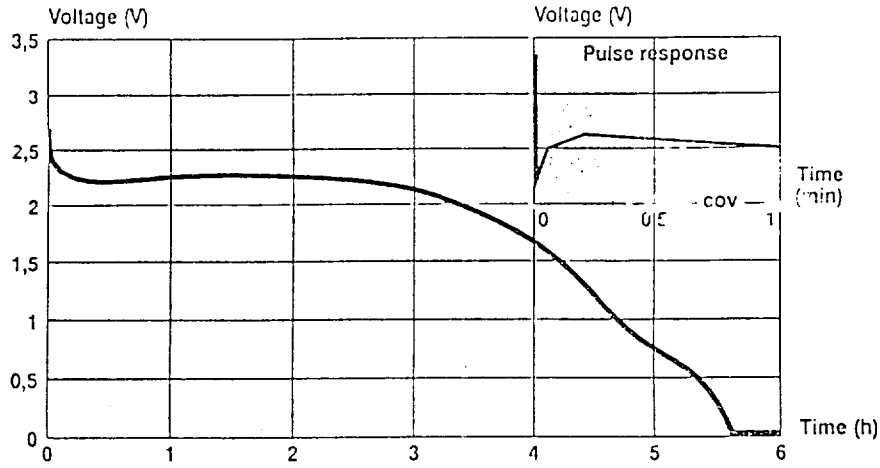


Fig. 4

Comparison of Li-MnO_2-D-cells
and Li-SO_2-D-cells

HOPPECKE Batteries

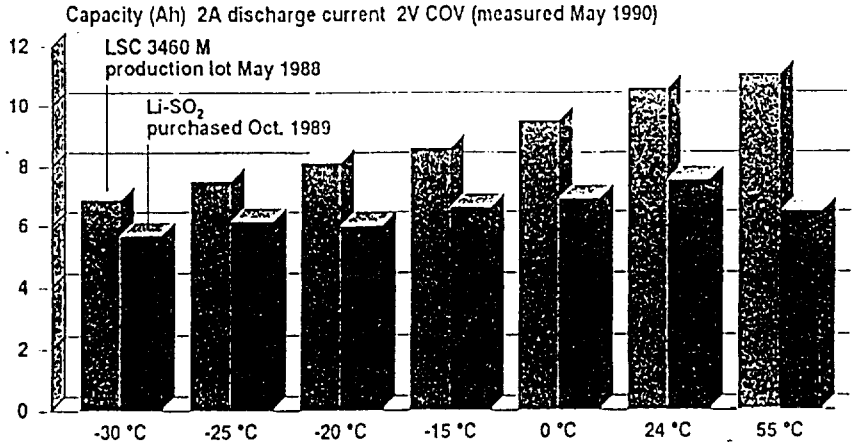


Fig. 5

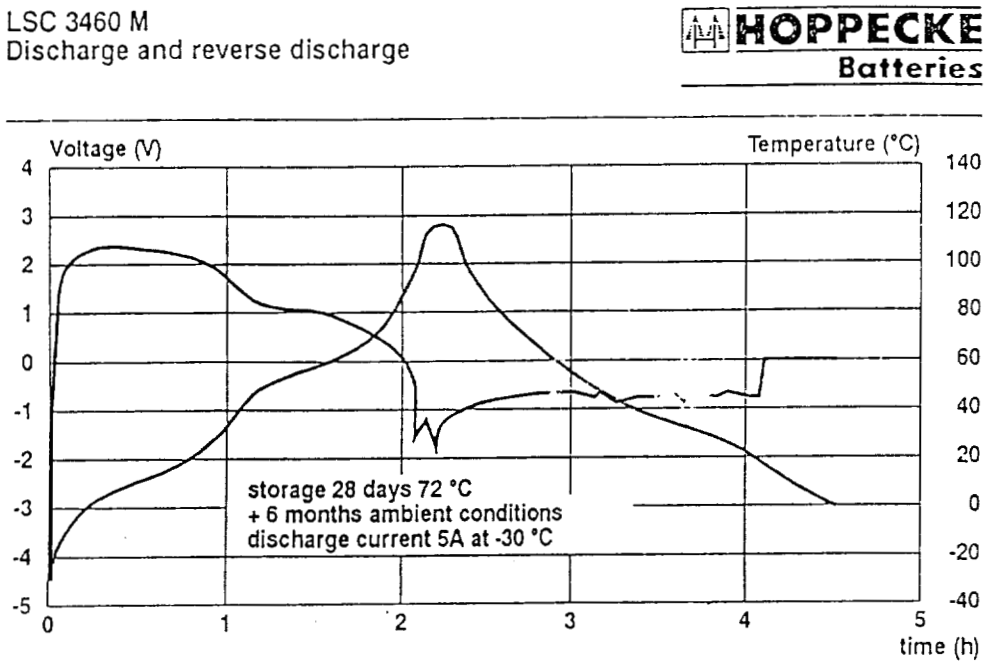


Fig. 6 HOPPECKE LSC cells in space applications

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_2 - cell

HOPPECKE Batteries

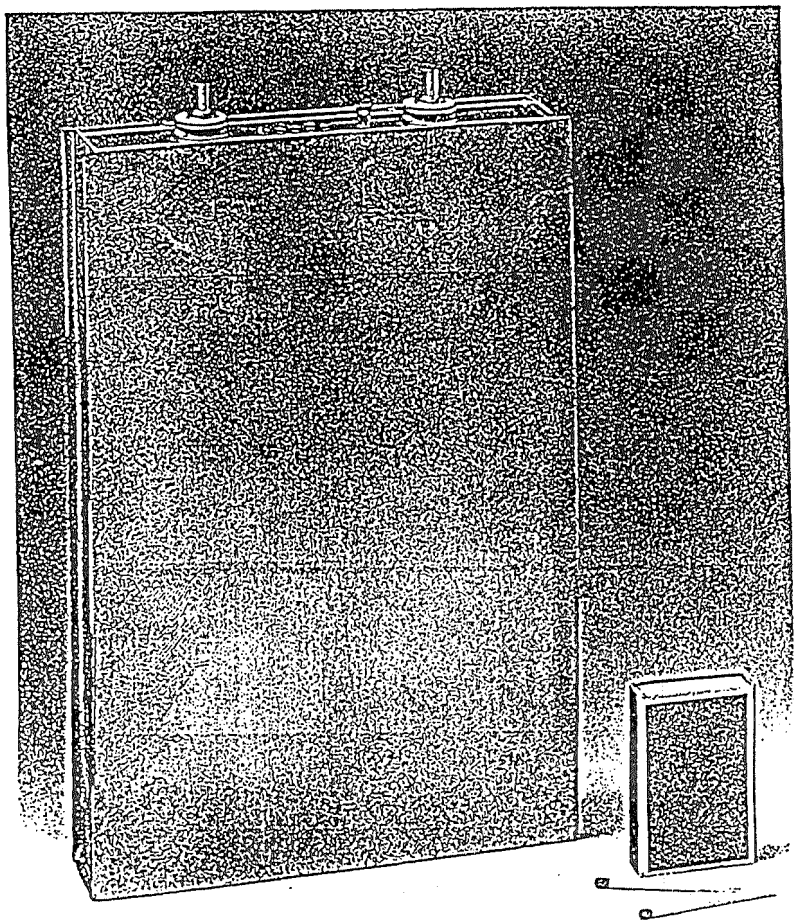


Fig. 8

200 Ah Li-MnO_2 - cell
Cell cover with vent

HOPPECKE Batteries

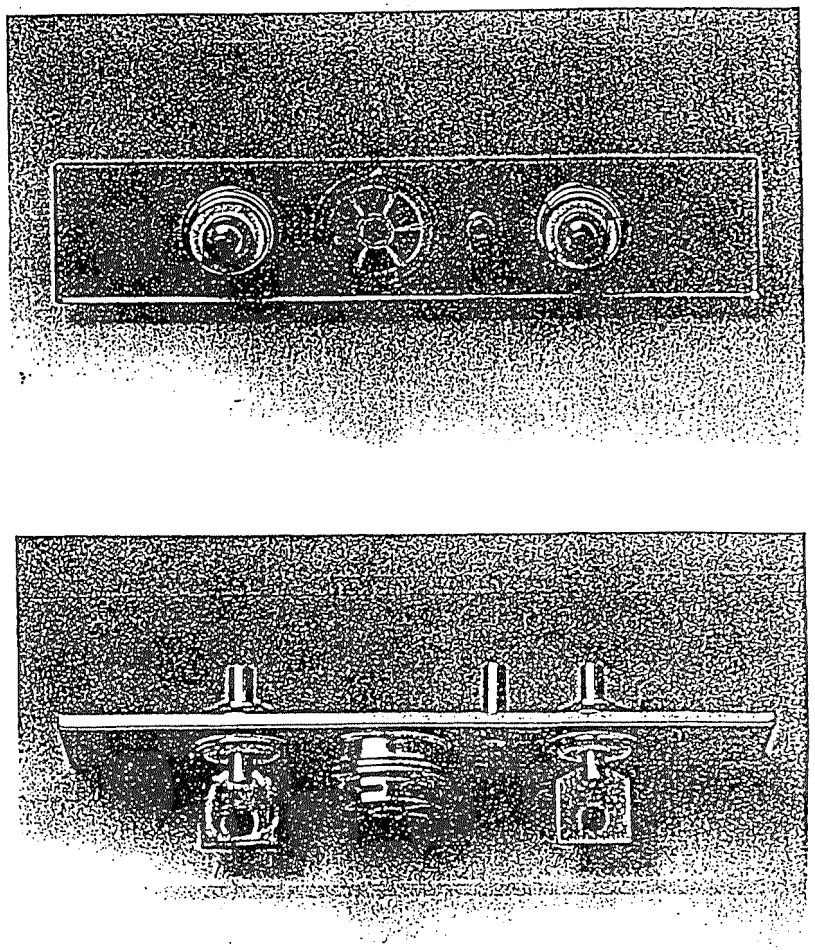


Fig. 9

200 Ah Li-MnO_2 - cell
Discharge 40 A at room temperature

HOPPECKE Batteries

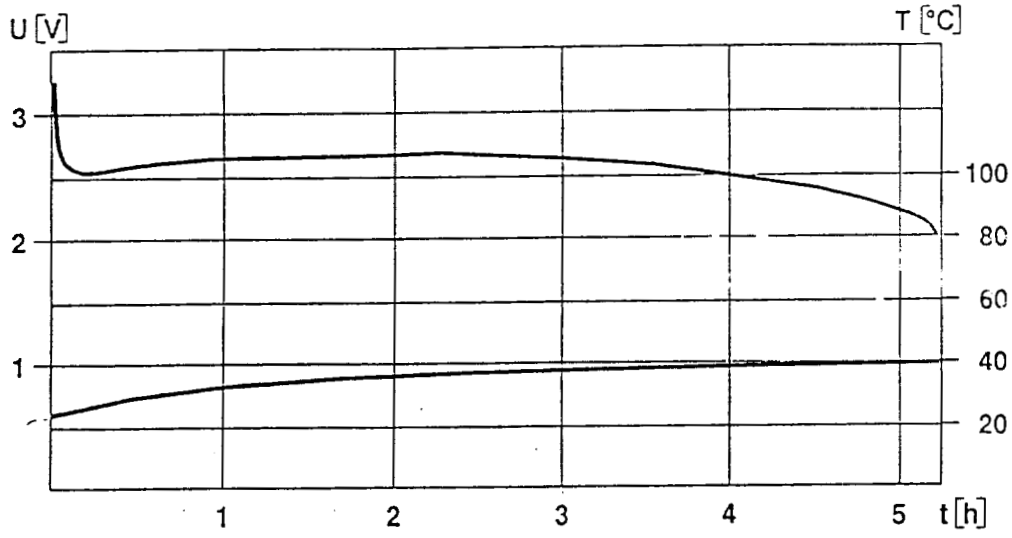


Fig. 10

200 Ah Li-MnO_2 - cell
Discharge test under thermal
worst case conditions

HOPPECKE Batteries

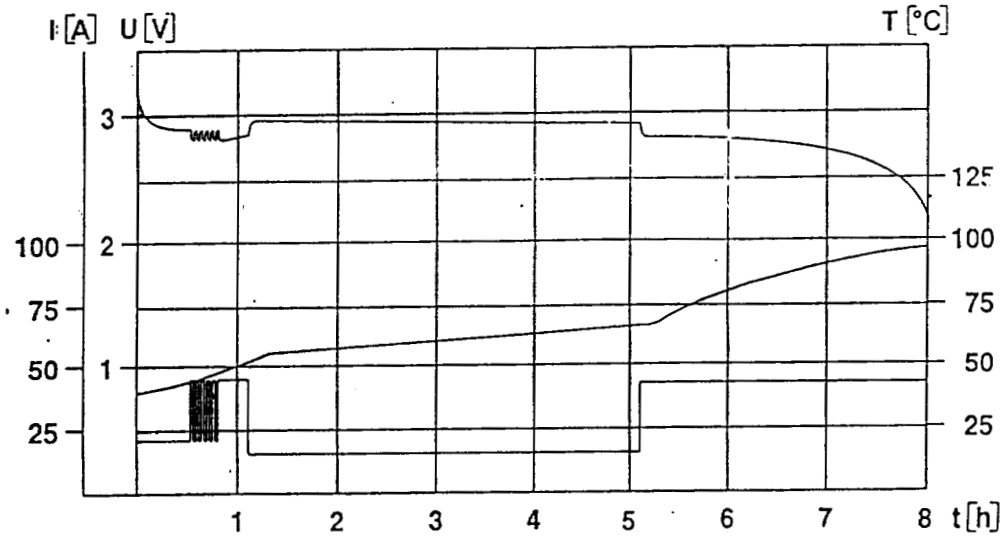
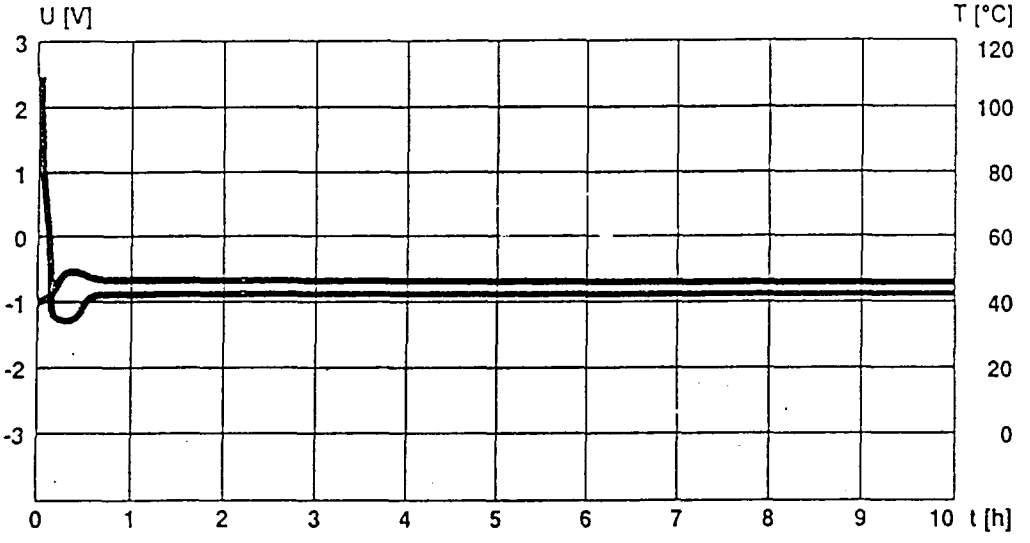


Fig. 11

200 Ah Li-MnO_2- cell
Overdischarge test at 40 °C
I=20 A

HOPPECKE
Batteries



Q-3

CALORIMETRIC EVALUATION OF 250 AHR Li/SOCl2 CELLS

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ERIC DARCY

NASA JOHSON SPACE CENTER

1991 NASA AEROSPACE BATTERY WORKSHOP
U.S. SPACE AND ROCKET CENTER

29-31 OCTOBER 1991, HUNTSVILLE, ALABAMA

JPL

OVERVIEW

CENTAUR 250 AHr Li/$SOCl_2$ 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

JPL

OBJECTIVE

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

EXPERIMENTAL DESCRIPTION

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

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

HEAT CAPACITY
DROP CALORIMETRY, 15 C DELTA, 25 C

DESIGN OPTIONS
CARBON: SAB AND HIGH SURFACE AREA CARBONS
SALT CONCENTRATION: 1.0 TO 1.8 M $LiAlCl_4/SOCl_2$
BINDER: BINDER PERCENTAGE (3.5 TO 6.5 %)
ELECTROLYTE ADDITIVE: PVC

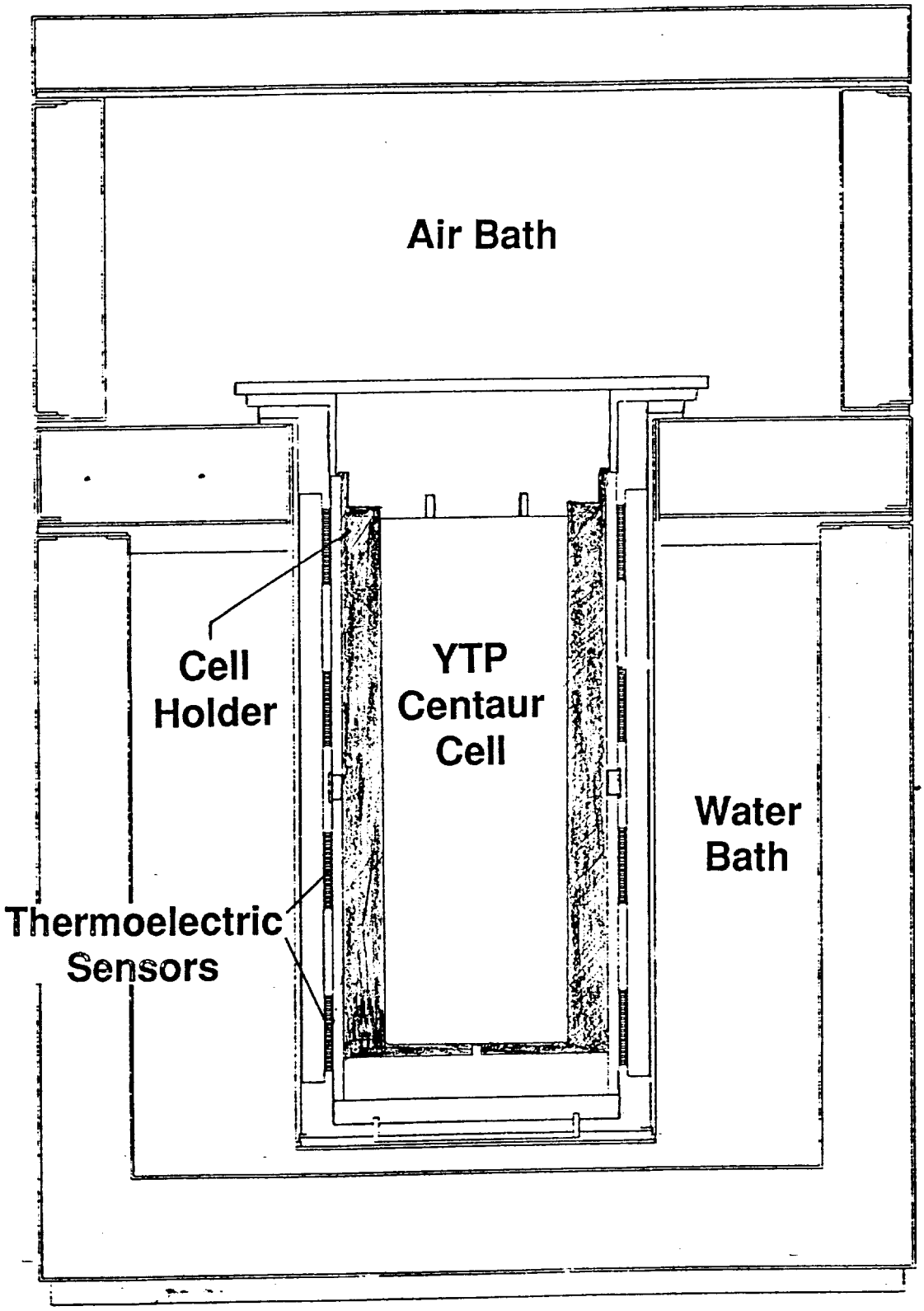
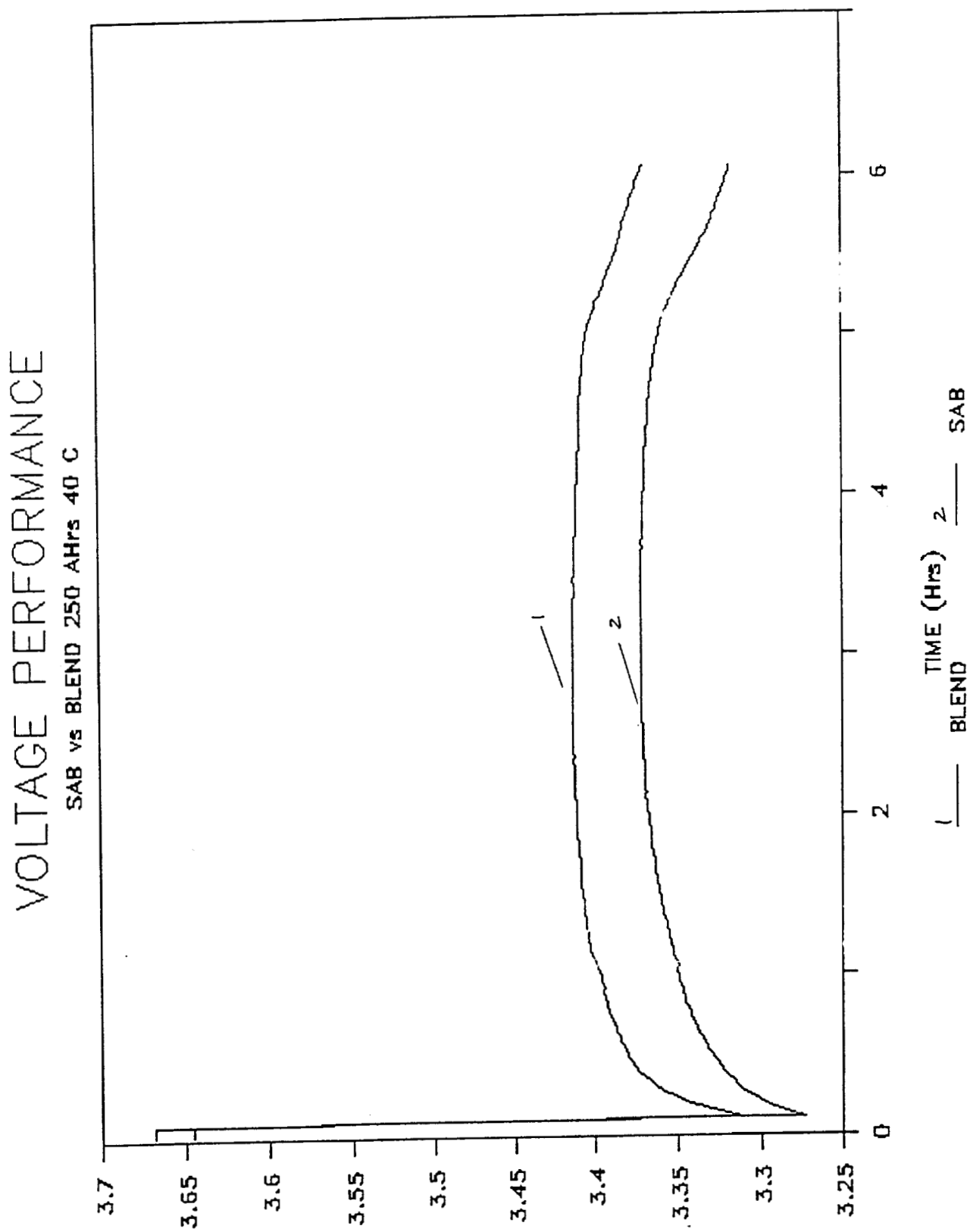


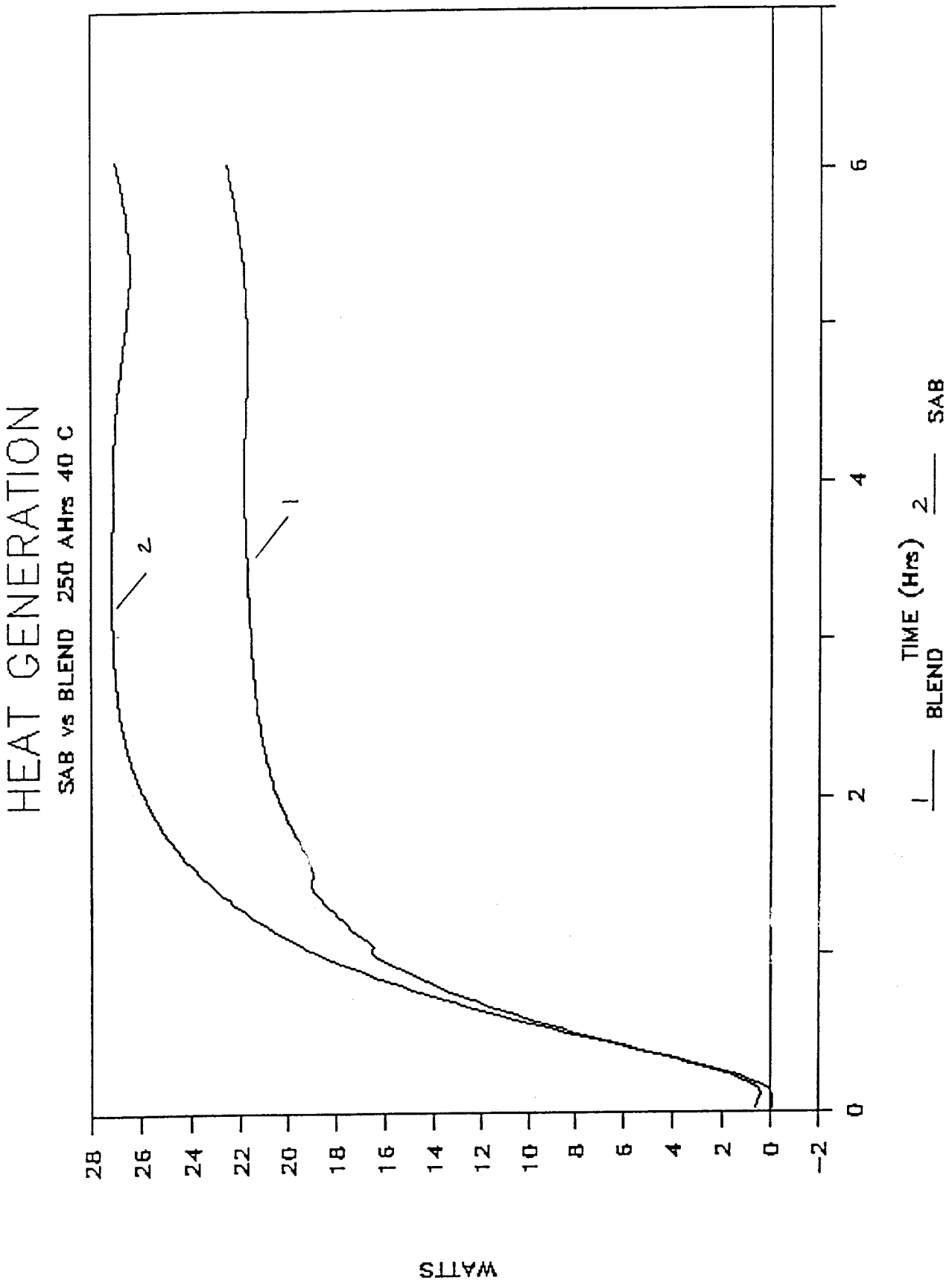
Fig. 1. Schematic of the cell in an aluminum cell holder in the calorimeter.

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 ± 0.005 °C.


VOLTAGE PERFORMANCE
SAB vs BLEND 250 AHrs 40 C
VOLTS
3.7
3.65
3.6
3.55
3.5
3.45
3.4
3.35
3.3
3.25
0
2
4
6
TIME (Hrs)
1 BLEND
2 SAB
1
2

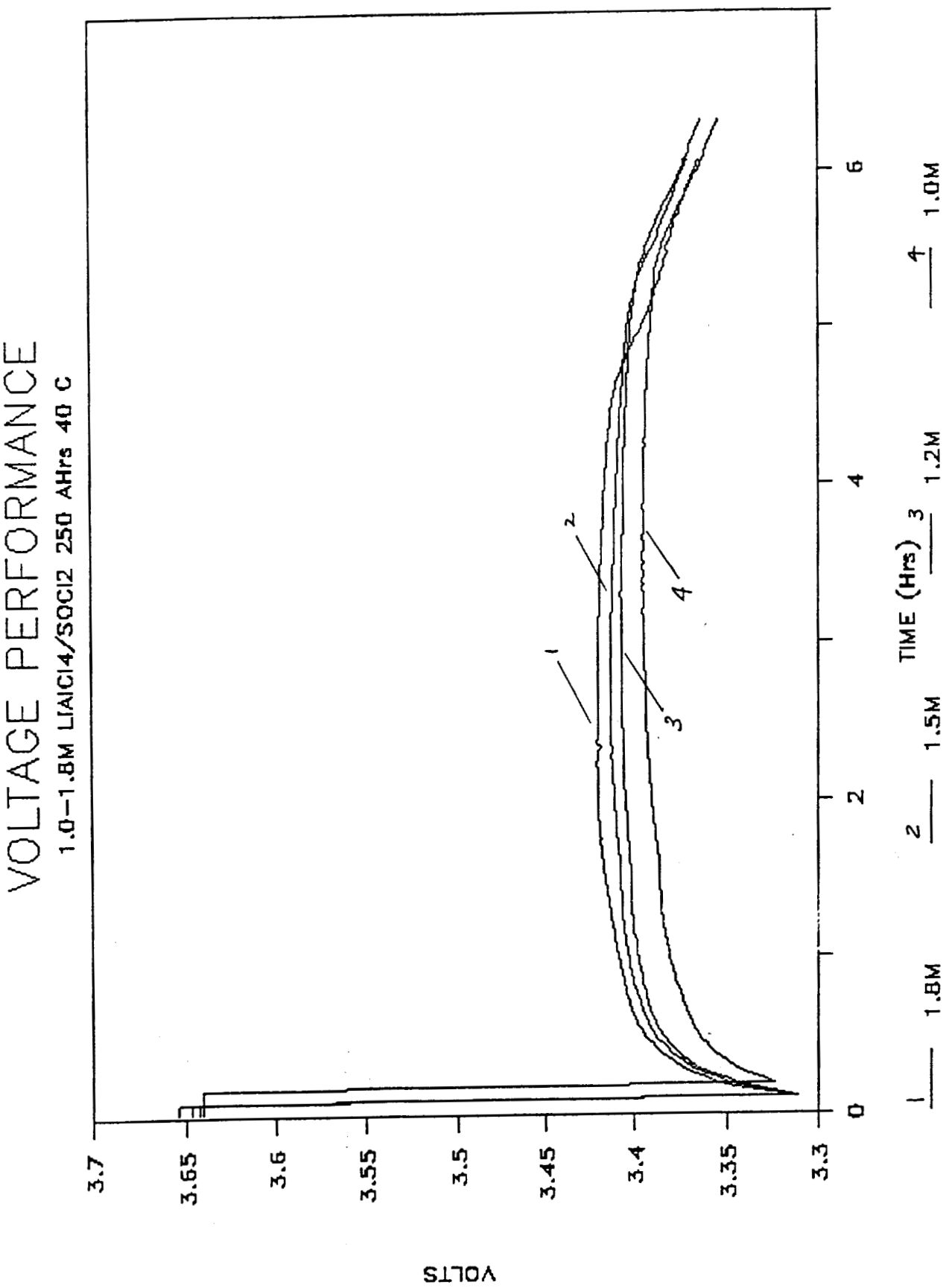
JPL

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


HEAT GENERATION
SAB vs BLEND 250 AHrs 40 C
WATTS
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
-2
0
2
4
6
TIME (Hrs)
1 BLEND
2 SAB
1
2

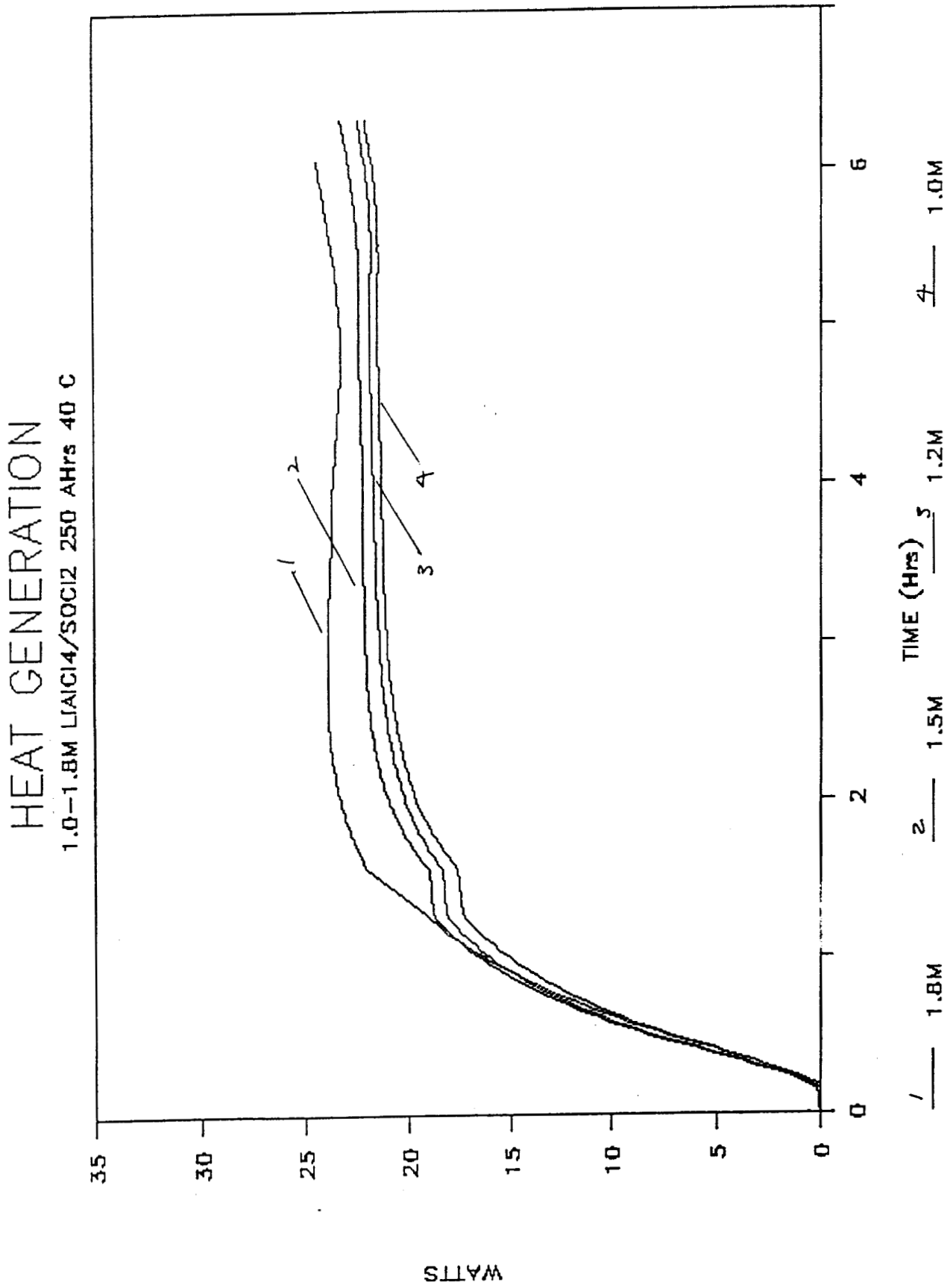
JPL

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 LiAlCl4/SOCl2 250 AHrs 40 C
VOLTS
3.7
3.65
3.6
3.55
3.5
3.45
3.4
3.35
3.3
0
2
4
6
TIME (Hrs)
1
2
3
4
1.8M
1.5M
1.2M
1.0M

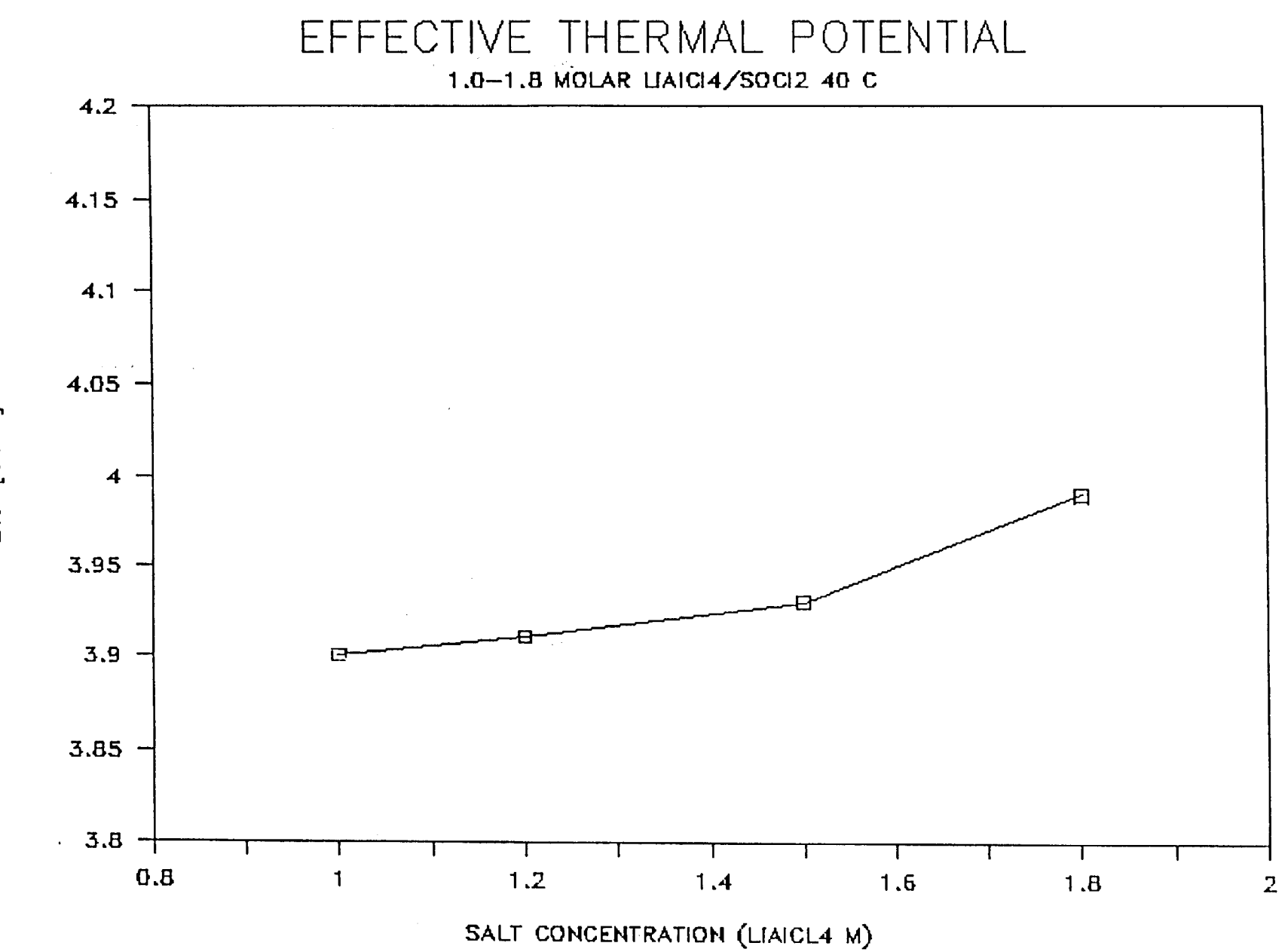
JPL

VOLTAGE PERFORMANCE THROUGH 250 AHrs FOR CELLS WITH ELECTROLYTE SALT CONCENTRATION FROM 1.0 TO 1.8 M $LiAlCl_4/SOCl_2$ SHOW INCREASING VOLTAGE PERFORMANCE WITH INCREASING SALT CONCENTRATION.


HEAT GENERATION
1.0–1.8M LiAlCl4/SOCl2 250 AHrs 40 C
WATTS
35
30
25
20
15
10
5
0
0
2
4
6
TIME (Hrs)
1 1.8M
2 1.5M
3 1.2M
4 1.0M
1
2
3
4

JPL

HEAT GENERATION RATES INCREASE WITH HIGHER SALT CONCENTRATION.


EFFECTIVE THERMAL POTENTIAL
1.0–1.8 MOLAR LIAICI4/SOCI2 40 C
ETP (40 C)
4.2
4.15
4.1
4.05
4
3.95
3.9
3.85
3.8
0.8
1
1.2
1.4
1.6
1.8
2
SALT CONCENTRATION (LIAICL4 M)

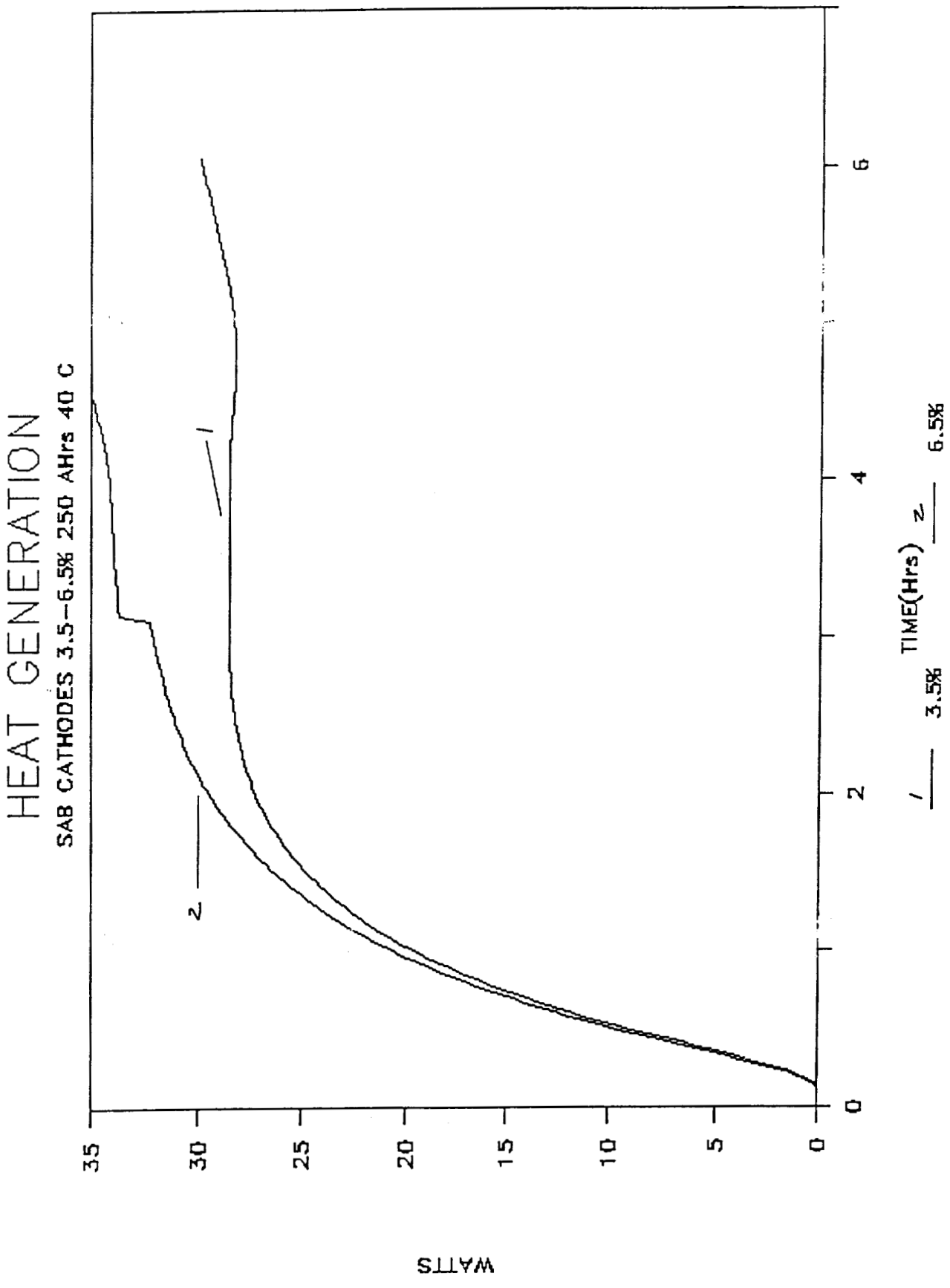
JPL

EFFECTIVE THERMAL POTENTIALS (ETP) ARE SHOWN AS A FUNCTION OF CELL SALT CONCENTRATION. ETP VALUES ARE GENERATED FROM INSTANTANEOUS HEATS, LOAD CURRENT, AND LOAD VOLTAGE BY THE FOLLOWING EQUATION:

$$ETP=q/I+V_L$$

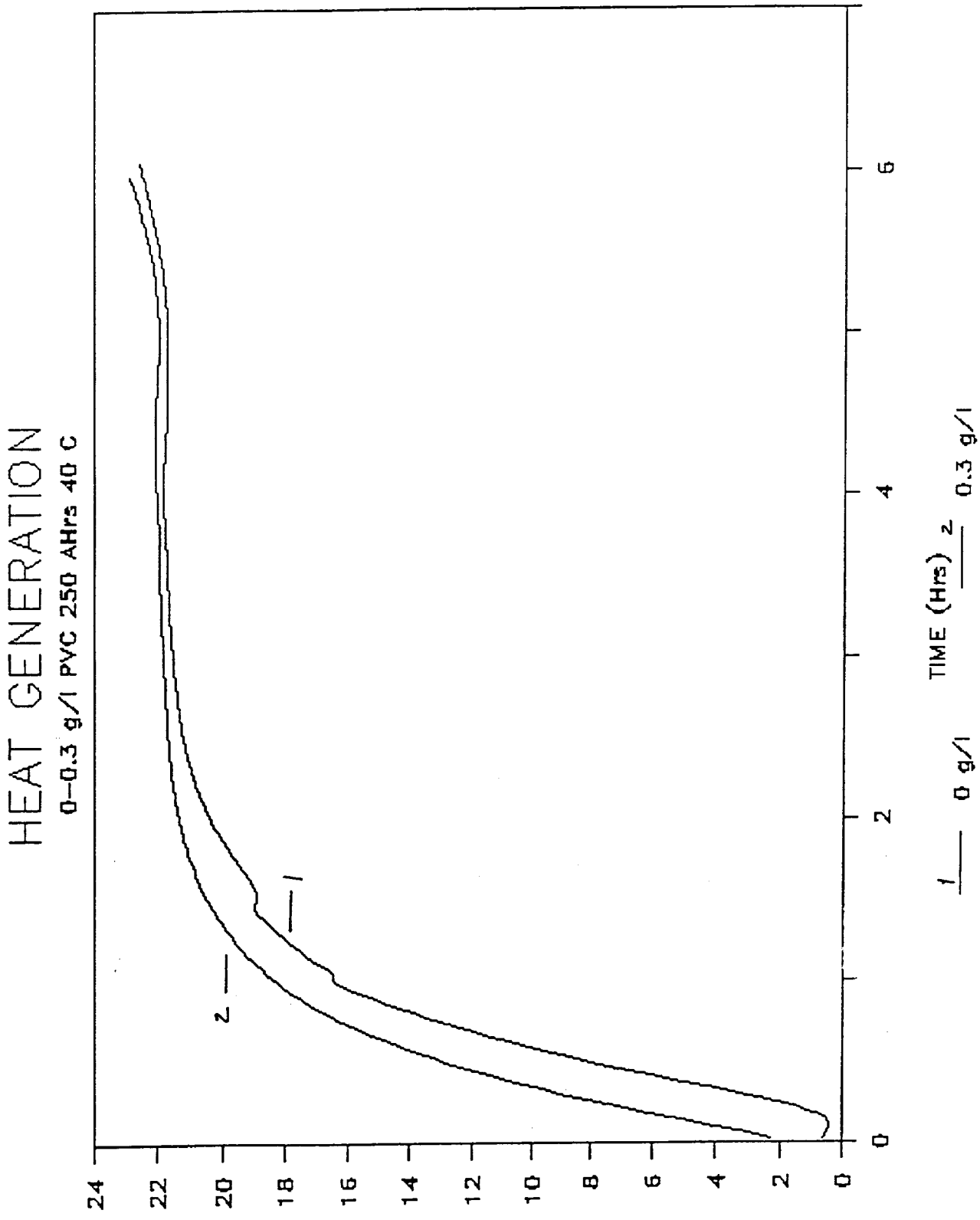
WHERE: q= HEAT GENERATION (WATTS)
I= DISCHARGE CURRENT
V_L= LOAD VOLTAGE

ETP IS A RELATIVE MEASURE OF THE HEAT GENERATION OF THE CELL AND MAY BE USED FOR ENGINEERING COMPARISON.


HEAT GENERATION
SAB CATHODES 3.5-6.5% 250 AHrs 40 C
WATTS
TIME(Hrs)
1 3.5%
2 6.5%
0
5
10
15
20
25
30
35
0
2
4
6
1
2

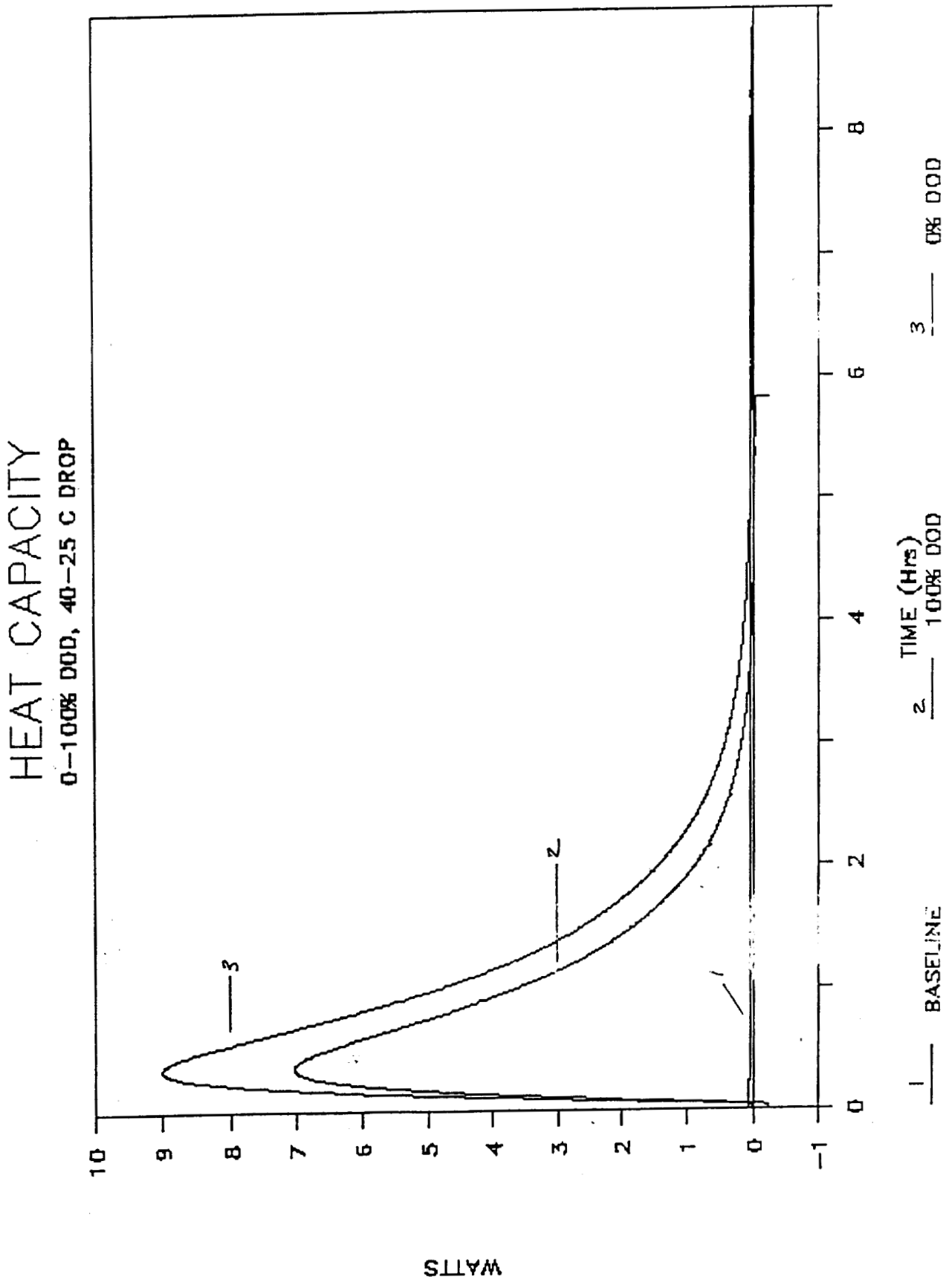
JPL

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
24
22
20
18
16
14
12
10
8
6
4
2
0
0
2
4
6
TIME (Hrs)
1 — 0 g/l
2 — 0.3 g/l
1
2

JPL

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


HEAT CAPACITY
0-100% DOD, 40-25 C DROP
WATTS
TIME (Hrs)
1 BASELINE
2 100% DOD
3 0% DOD

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

JPL

CONCLUSION

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

DECREASING $LiAlCl_4$ IN $SOCl_2$ 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-$SOCl_2$ High-Rate "D" Cells

by

B.J. Bragg

and

Paul Johnson

NASA Johnson Space Center

	Propulsion and Power Division	
	Bragg / Johnson	10/29/91

AGENDA

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

Johnson Space Center - Houston, Texas

Preliminary Test Results for Li-SOCl2 High-Rate "D" Cells

Propulsion and Power Division

Bragg / Johnson

10/29/91

BACKGROUND

- Objective - Evaluate the performance and abuse characteristics of 55 D-Size lithium-thionyl chloride (Li-SOCl2) cells at relatively high rates.
- Cells developed by Electrochem Industries, Inc. under contract to the Jet Propulsion Laboratory.
- Cells manufactured in October 1989.
  - Li wt, - 3.44 g
  - Li anode area - 530 sq. cm
  - 1 anode tab - 0.25" w X 0.005" thk.
  - Cathode (carbon) wt. - 5.2 g
  - Cathode thk. - 0.025 "
  - 2 cathode tabs - 0.125"w X 0.005"thk.
  - Electrolyte - 1.8M LiAlCl4 in SOCl2 - 44-45 g
- 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

Johnson Space Center - Houston, Texas

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

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 ± 1 millisecond rise and a 1 ± 1 millisecond decay.
  - Results: No change in OCV

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

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

Frequency (Hz)	Level
20 to 80	+ 3 dB/ octave
80 to 350	0.1 g2 / Hz
350 to 2000	-3 dB/ octave

  - Results: No change in OCV.

Johnson Space Center - Houston, Texas

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

- Capacity Performance (32 Cells)
  - Ah to 1.5 VDC

<u>-40°F, 2 ohm load</u>

- 5 Cells
- 4.10 - 4.98 Ah
- Avg. 4.52 Ah

<u>Room Temperature, 1 ohm load</u>

- 7 Cells
- 10.38 - 10.75 Ah
- Avg. 10.57 Ah

<u>Room Temperature, 2 ohm load</u>

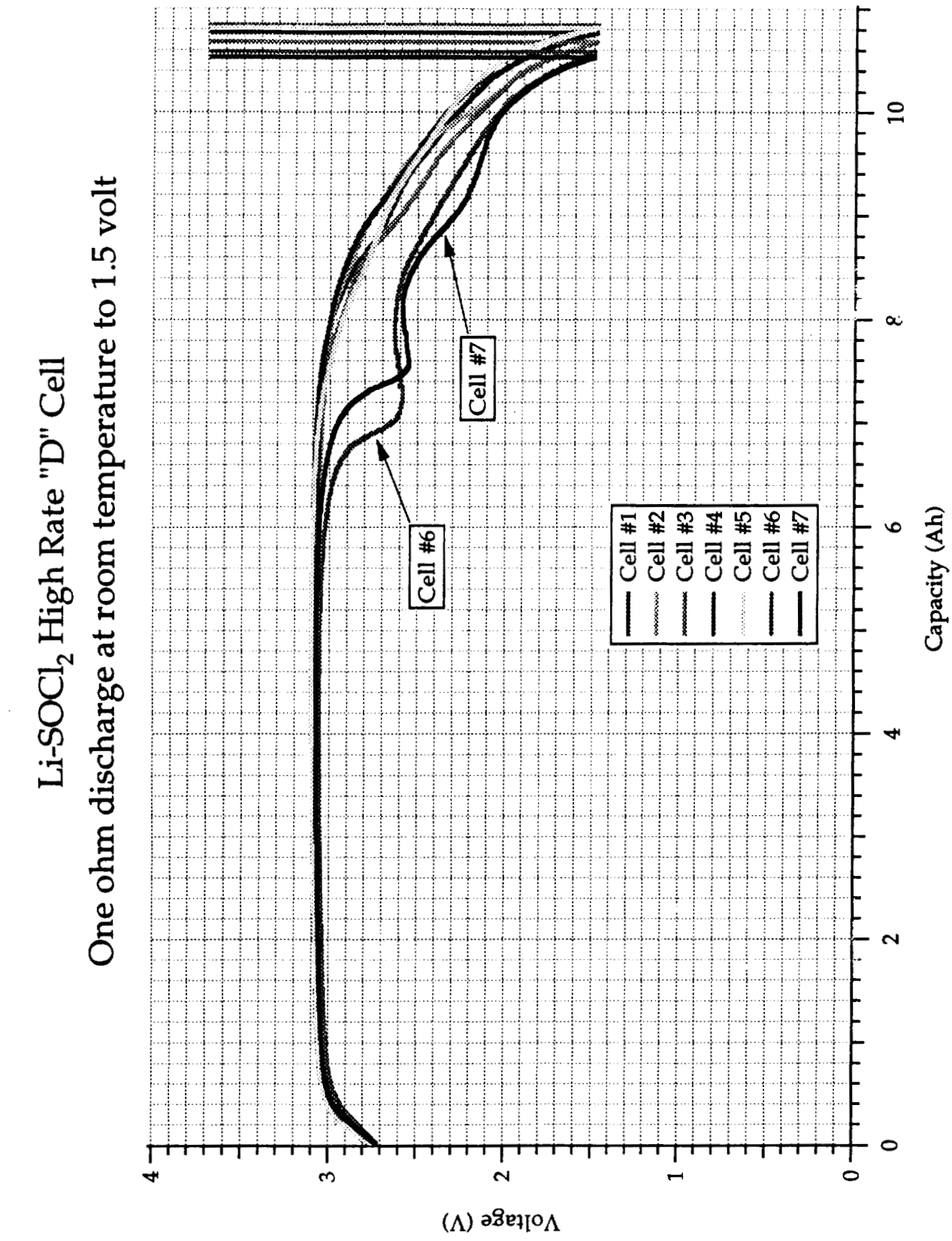
- 11 Cells
- 10.42 - 11.11 Ah
- Avg. 10.7 Ah

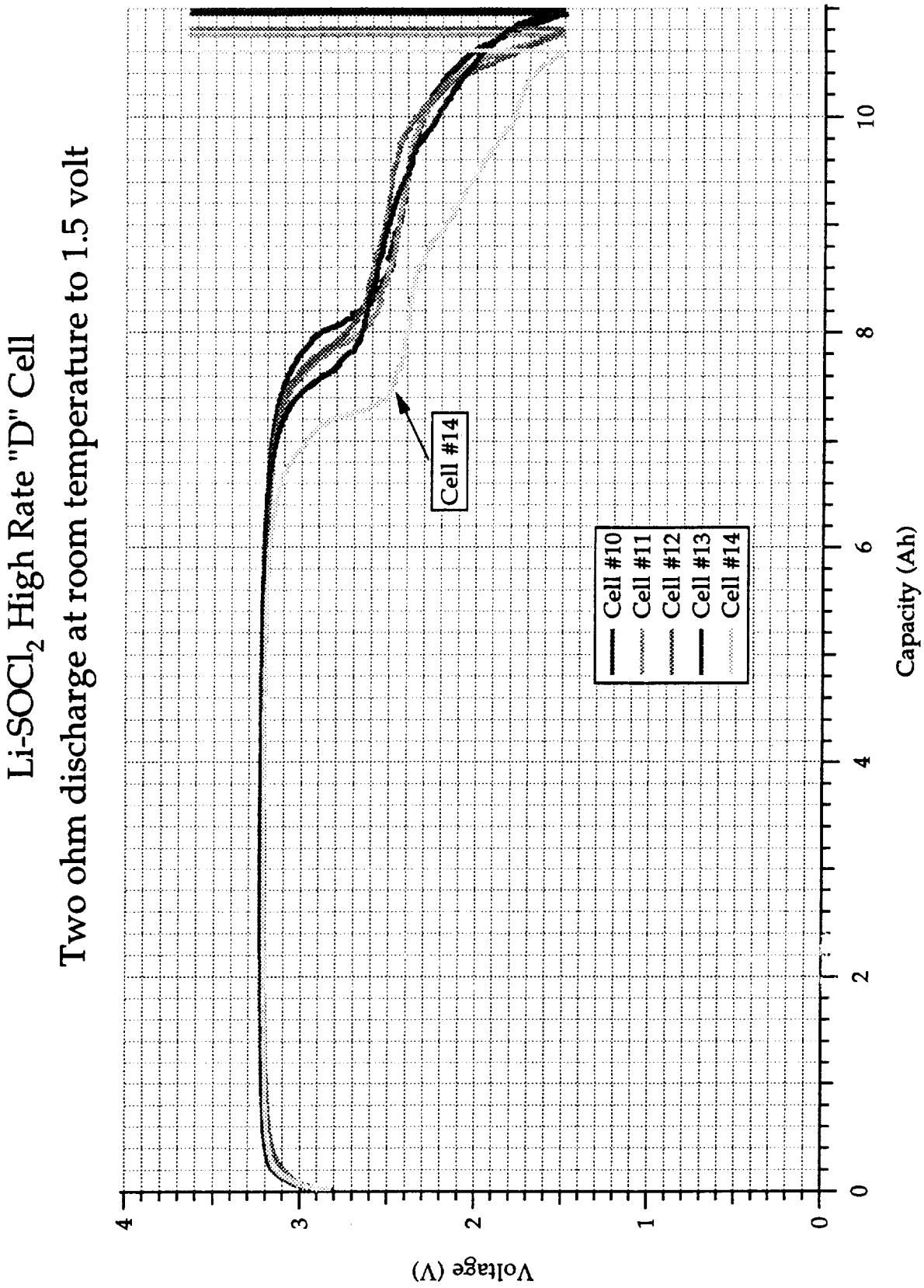
<u>160°F, 1 ohm load</u>

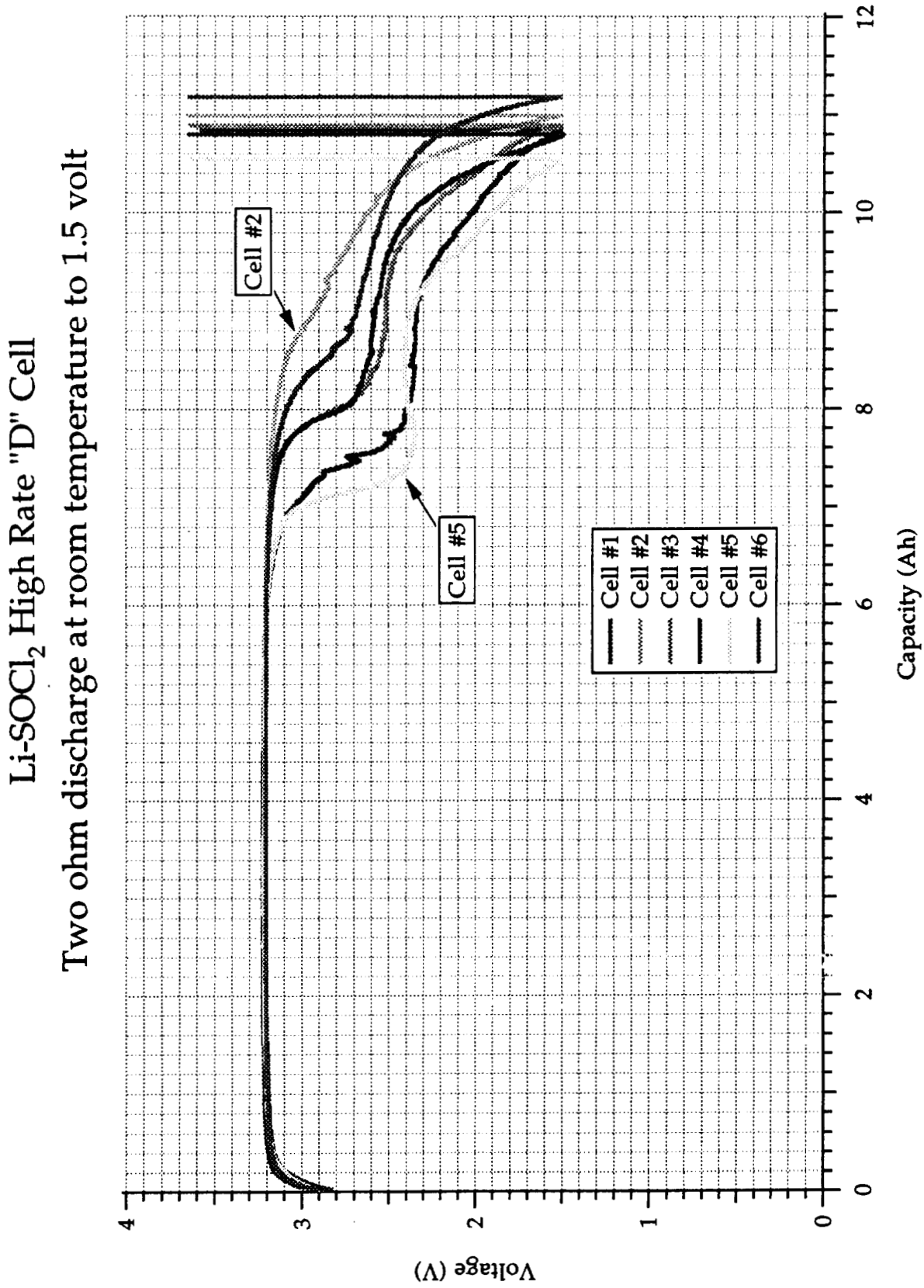
- 5 Cells
- 9.48 - 9.61 Ah
- Avg. 9.55 Ah

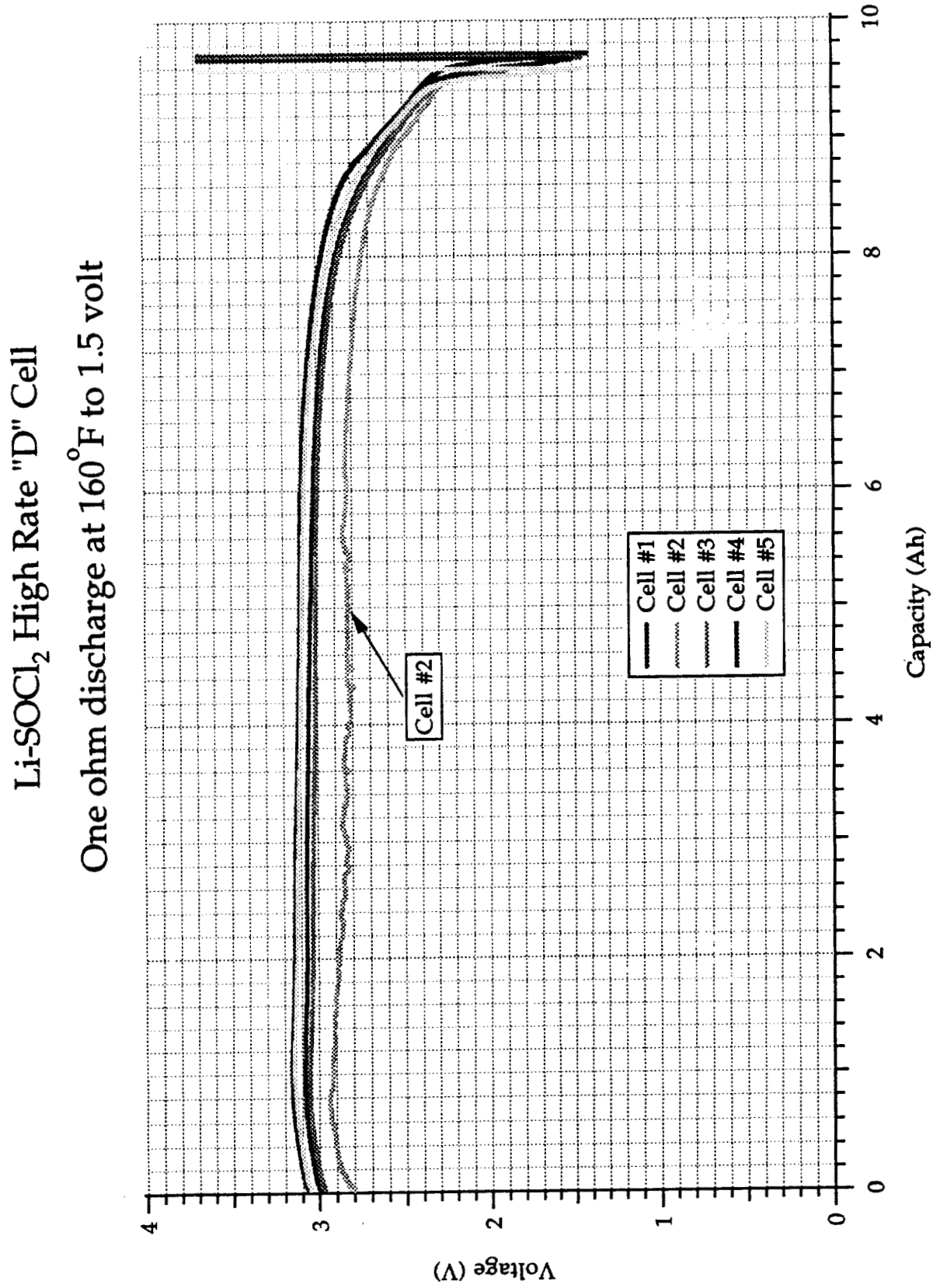
<u>160°F, 2 ohm load</u>

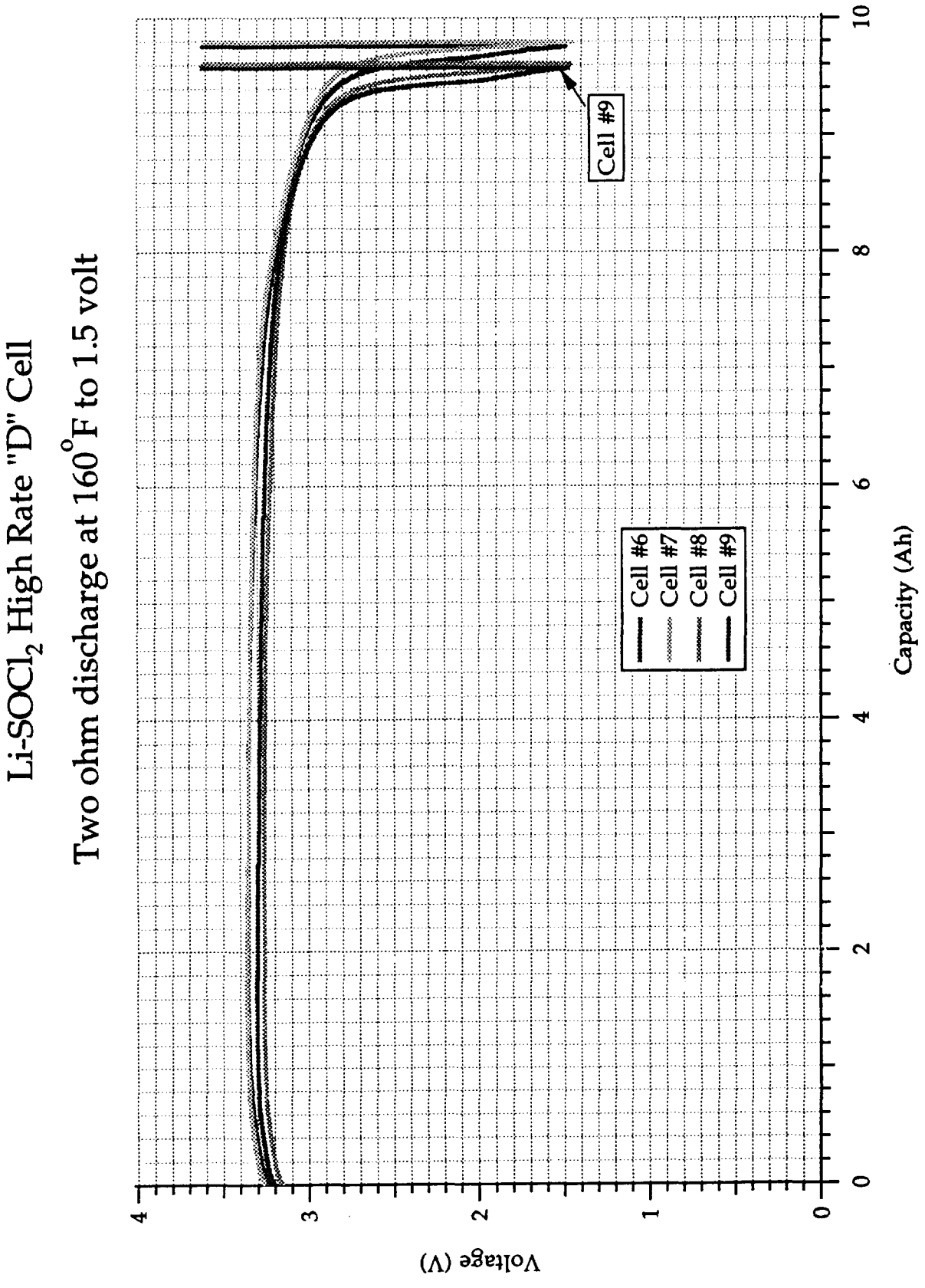
- 4 Cells
- 9.45 - 9.75 Ah
- Avg. 9.61 Ah


Li-SOCl2 High Rate "D" Cell
One ohm discharge at room temperature to 1.5 volt
Voltage (V)
Capacity (Ah)
Cell #1
Cell #2
Cell #3
Cell #4
Cell #5
Cell #6
Cell #7
Cell #6
Cell #7
0
1
2
3
4
0
2
4
6
8
10


Li-SOCl2 High Rate "D" Cell
Two ohm discharge at room temperature to 1.5 volt
Cell #14
Cell #10
Cell #11
Cell #12
Cell #13
Cell #14
Voltage (V)
Capacity (Ah)
0
1
2
3
4
0
2
4
6
8
10

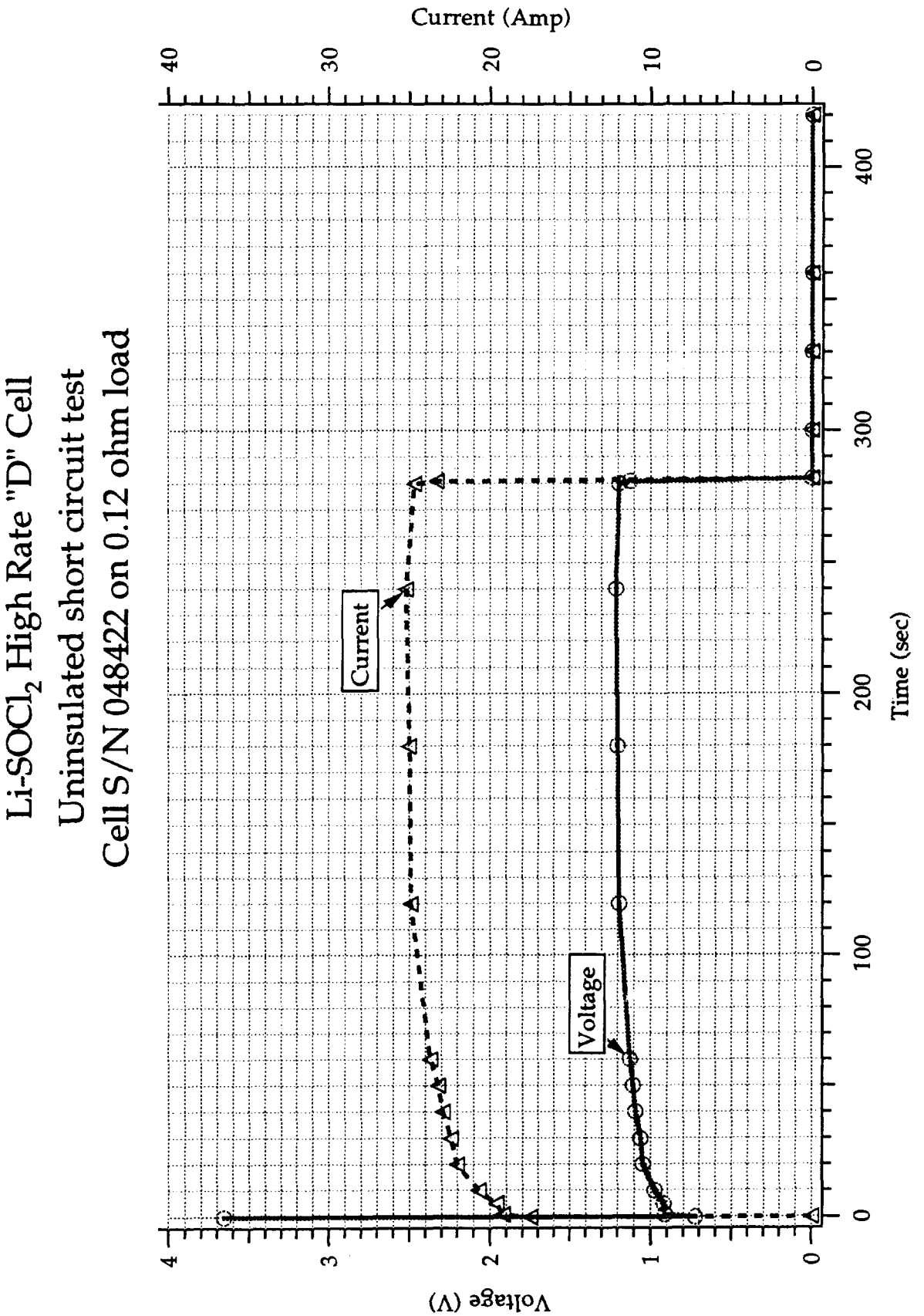

Li-SOCl2 High Rate "D" Cell
Two ohm discharge at room temperature to 1.5 volt
Cell #2
Cell #5
Cell #1
Cell #2
Cell #3
Cell #4
Cell #5
Cell #6
Voltage (V)
Capacity (Ah)
0
1
2
3
4
0
2
4
6
8
10
12

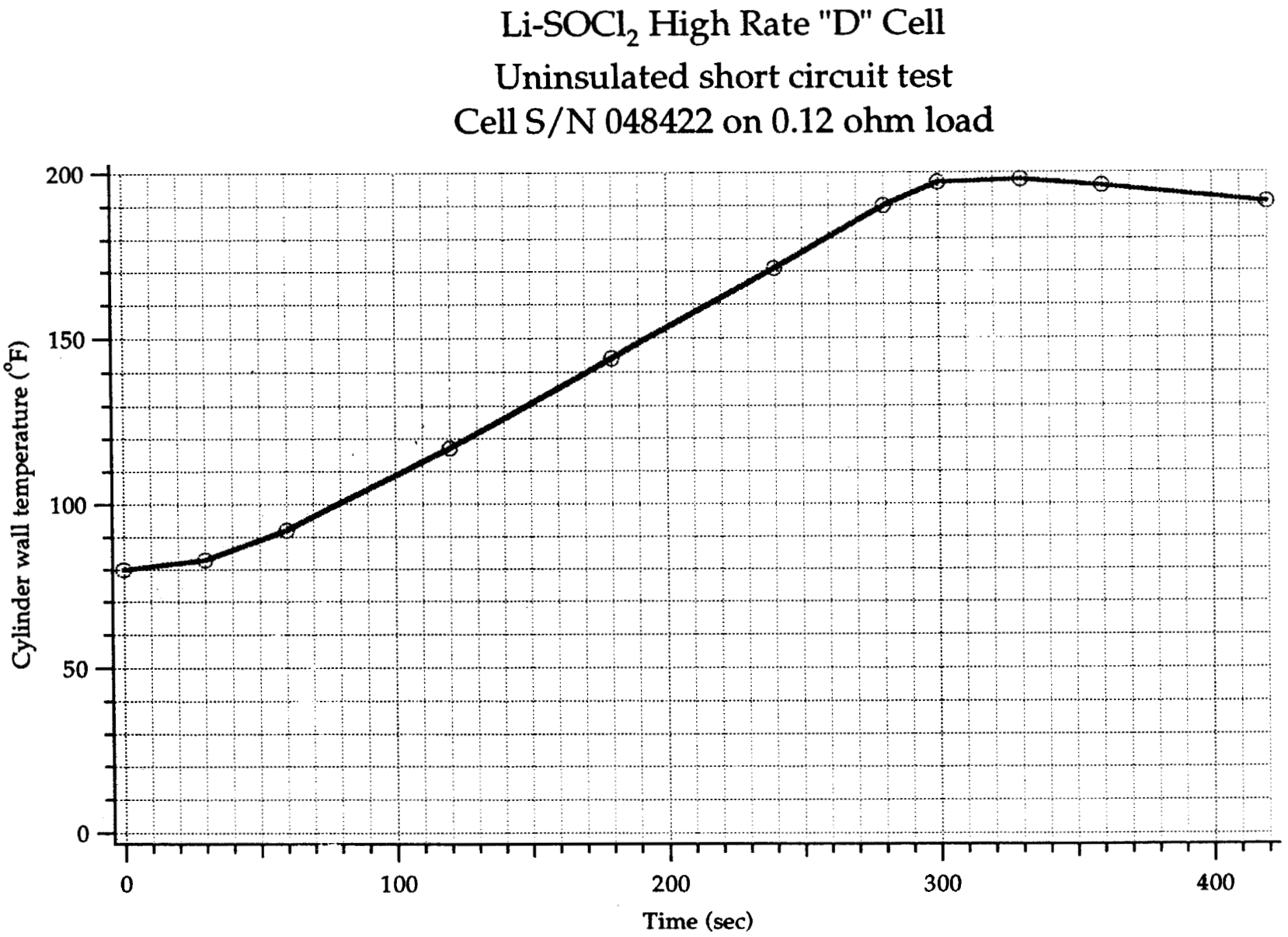

Li-SOCl2 High Rate "D" Cell
One ohm discharge at 160°F to 1.5 volt
Voltage (V)
Capacity (Ah)
Cell #1
Cell #2
Cell #3
Cell #4
Cell #5
Cell #2
0
1
2
3
4
0
2
4
6
8
10


Li-SOCl2 High Rate "D" Cell
Two ohm discharge at 160°F to 1.5 volt
Voltage (V)
Capacity (Ah)
Cell #6
Cell #7
Cell #8
Cell #9
Cell #9
0
1
2
3
4
0
2
4
6
8
10

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

- 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-SOCl2 High Rate "D" Cell
Uninsulated short circuit test
Cell S/N 048422 on 0.12 ohm load
Current (Amp)
40
30
20
10
0
Current
Voltage
Voltage (V)
4
3
2
1
0
0
100
200
300
400
Time (sec)


Li-SOCl2 High Rate "D" Cell
Uninsulated short circuit test
Cell S/N 048422 on 0.12 ohm load
Cylinder wall temperature (°F)
200
150
100
50
0
0
100
200
300
400
Time (sec)

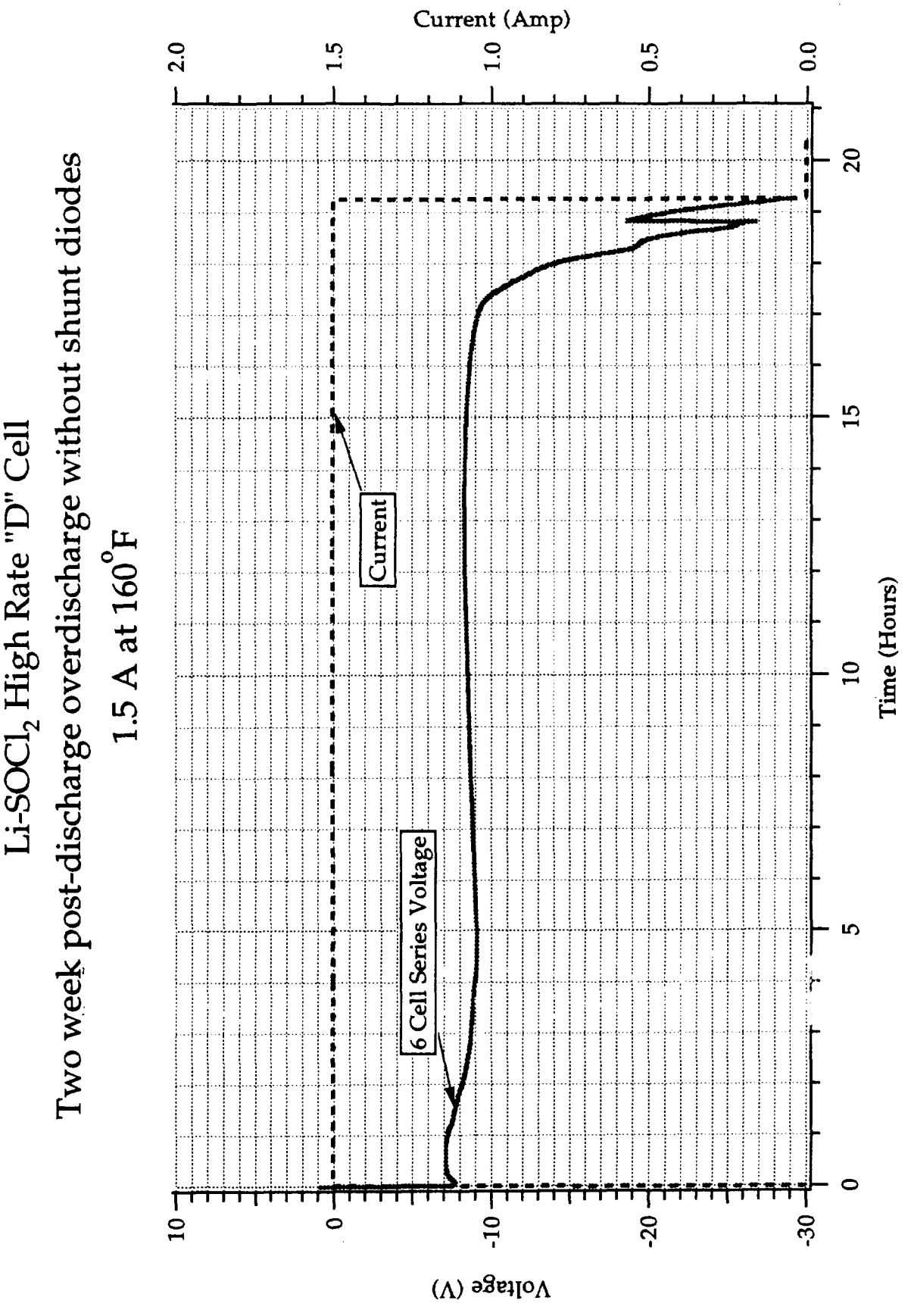
Preliminary Test Results for Li-SOCl2 High-Rate "D" Cells	Propulsion and Power Division	
	Bragg / Johnson	10/29/91

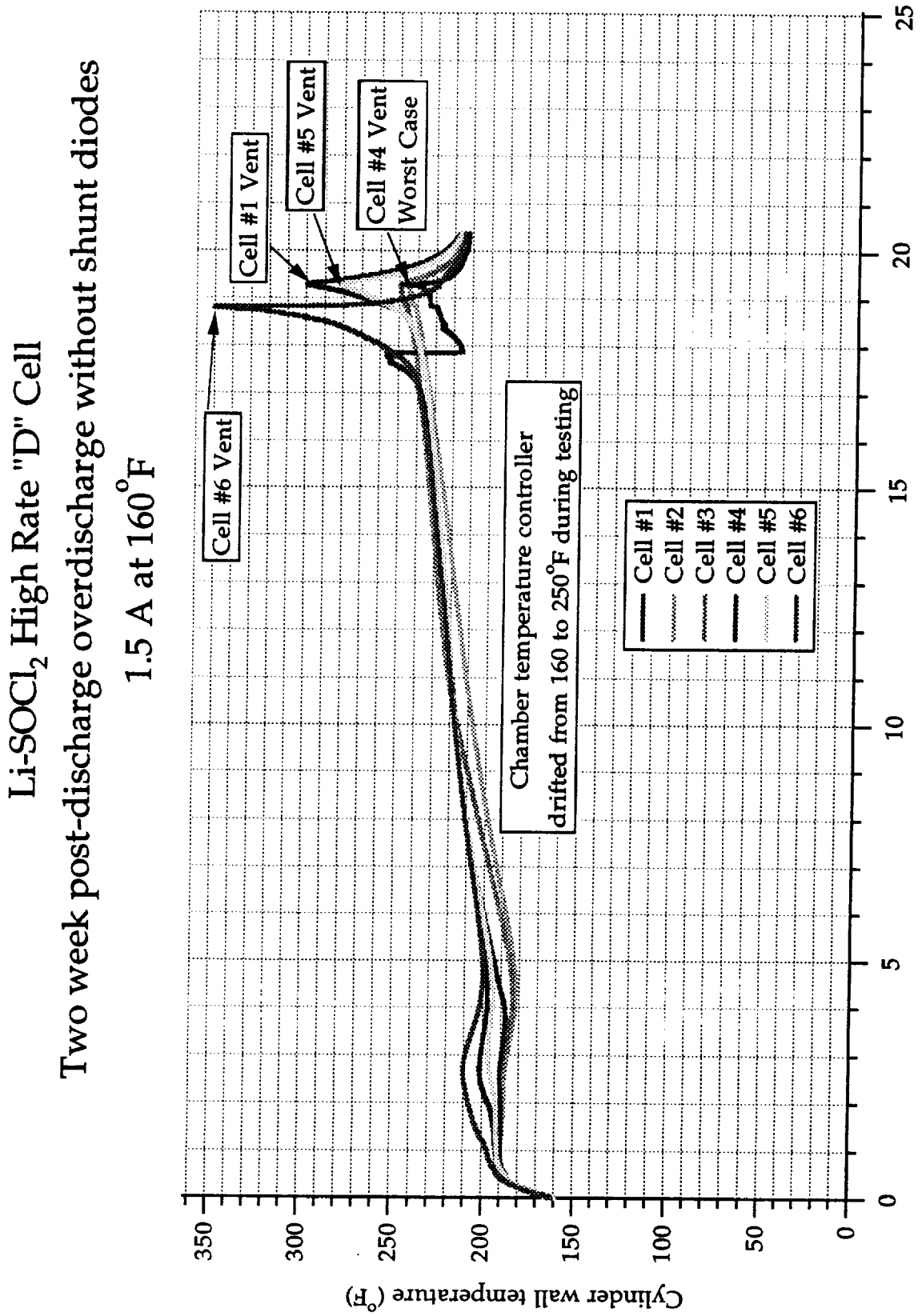
- Cell S/N 048439
  - Load: .120 ohm
  - Maximums: 1.21 VDC, 25 Amp, 130°F
  - Duration: 1 min 43 sec until internal lead fused.
  - Post-test: No OCV

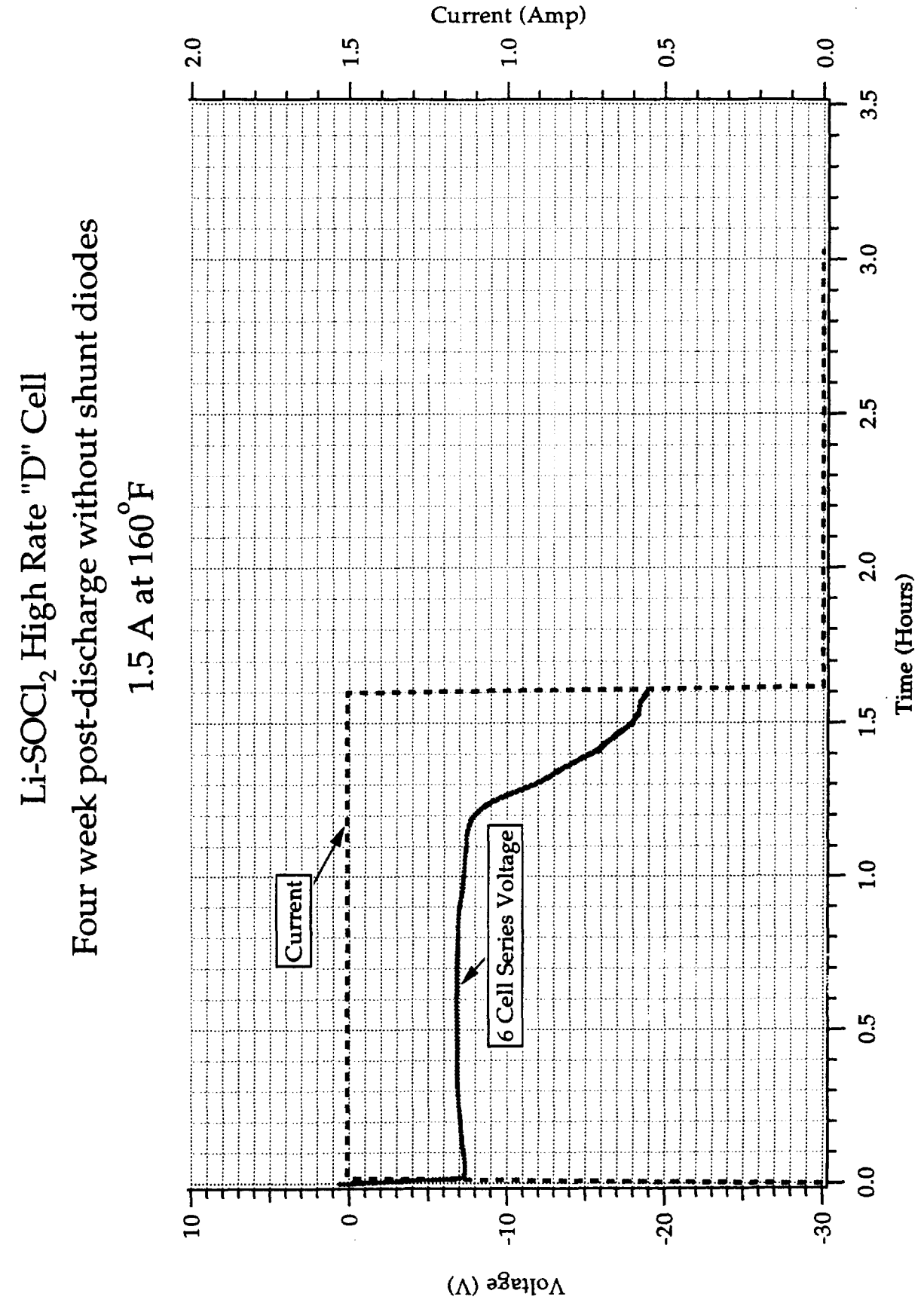
- High Temperature Exposure
  - Cells tested for one hour at 225, 250, 275, and 300°F.
  - No leakage was found on any of the cells one week after high temperature exposure.

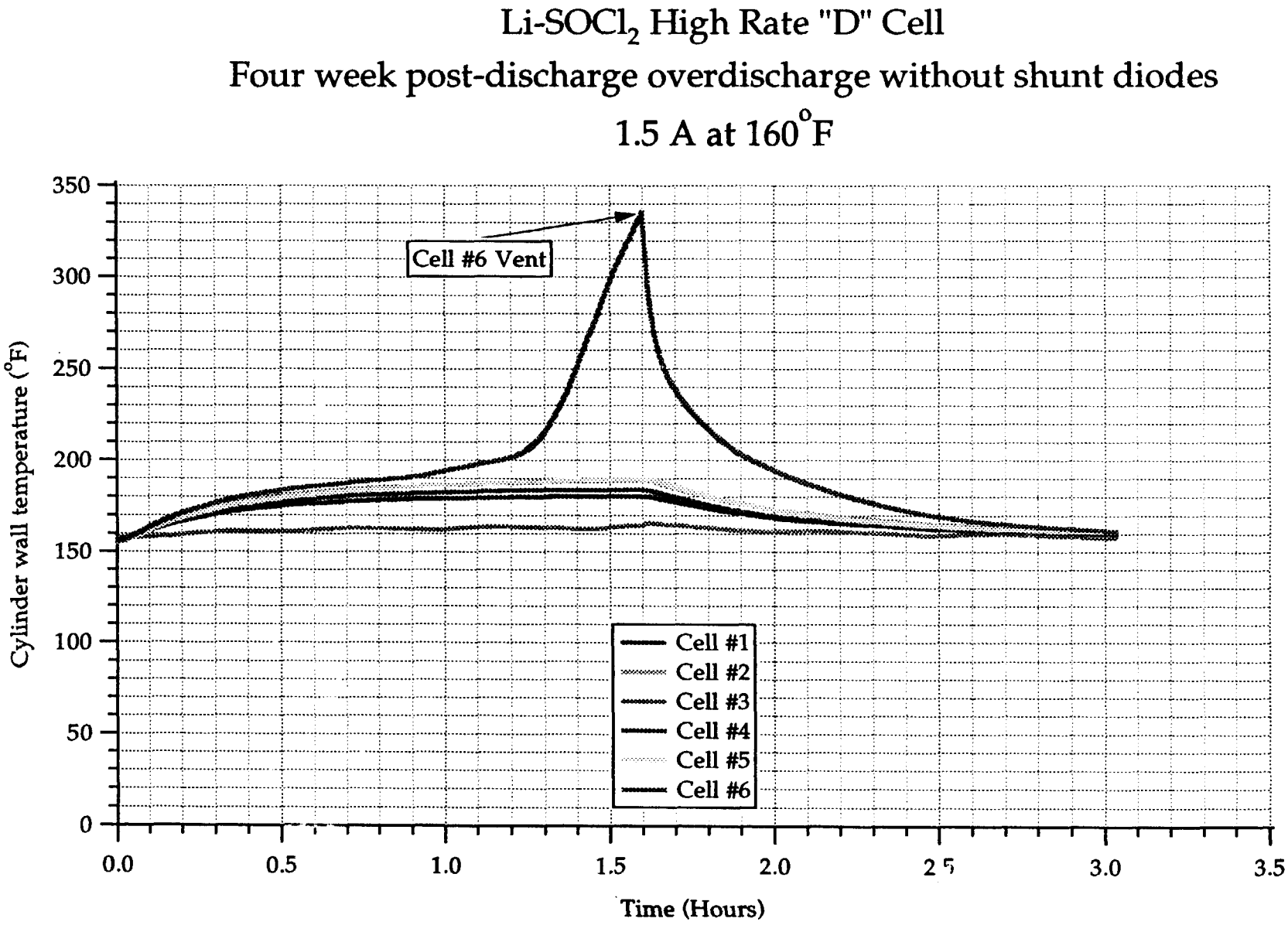
Preliminary Test Results for Li-SOCl2 High-Rate "D" Cells	Propulsion and Power Division	
	Bragg / Johnson	10/29/91

- Overdischarge; 2 Weeks Post-Discharge (6 Cells)
  - With Shunt Diodes
    - 1.5 A at 160°F
    - No cells vented, max temperature 209.4°F
  - Without Shunt Diodes
    - 1.5 A at 160°F to 245°F: Chamber temp. control drifted during test.
    - One cell vented at 19 hours and 3 cells at 19.25 hours, max temperature 348.7°F
- Overdischarge; 4 Weeks Post-Discharge (6 Cells)
  - With Shunt Diodes
    - 1.5 A at 160°F
    - No cells vented, max temperature 226.4°F
  - Without Shunt Diodes
    - 1.5 A at 160°F
    - One cell vented at 1.6 hours, max temperature 328.8°F


Li-SOCl2 High Rate "D" Cell
Two week post-discharge overdischarge without shunt diodes
1.5 A at 160°F
Current (Amp)
2.0
1.5
1.0
0.5
0.0
Current
6 Cell Series Voltage
10
0
-10
-20
-30
Voltage (V)
0
5
10
15
20
Time (Hours)


Li-SOCl2 High Rate "D" Cell
Two week post-discharge overdischarge without shunt diodes
1.5 A at 160°F
Cell #6 Vent
Cell #1 Vent
Cell #5 Vent
Cell #4 Vent
Worst Case
Chamber temperature controller
drifted from 160 to 250°F during testing
Cell #1
Cell #2
Cell #3
Cell #4
Cell #5
Cell #6
Cylinder wall temperature (°F)
Time (Hours)
0
50
100
150
200
250
300
350
0
5
10
15
20
25


Li-SOCl2 High Rate "D" Cell
Four week post-discharge without shunt diodes
1.5 A at 160°F
Current (Amp)
2.0
1.5
1.0
0.5
0.0
Current
6 Cell Series Voltage
10
0
-10
-20
-30
Voltage (V)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Time (Hours)


Li-SOCl2 High Rate "D" Cell
Four week post-discharge overdischarge without shunt diodes
1.5 A at 160°F
Cell #6 Vent
Cell #1
Cell #2
Cell #3
Cell #4
Cell #5
Cell #6
Cylinder wall temperature (°F)
Time (Hours)
350
300
250
200
150
100
50
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5

Preliminary Test Results for Li-SOCl2 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

N92-22756

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

Paul E. Panneton and John R. Meyer

The Johns Hopkins University
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Laurel, MD 20723

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

This presentation reviews a 12Ah NiCd LEO lifecycle test that induced 47% more deep DOD cycles by mixing them with shallow DOD cycles. This test also showed how aggressive recharging to a C/D ratio of 1.15 nearly doubled performance over cycling below a C/D of 1.11.

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

JHU/APL spacecraft program - JANUS MISSION II

- ☞ 2 year Low Earth Orbit (LEO) mission
- ☞ Size and weight critical

Electrical Power System (EPS)

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

NiCd Battery

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

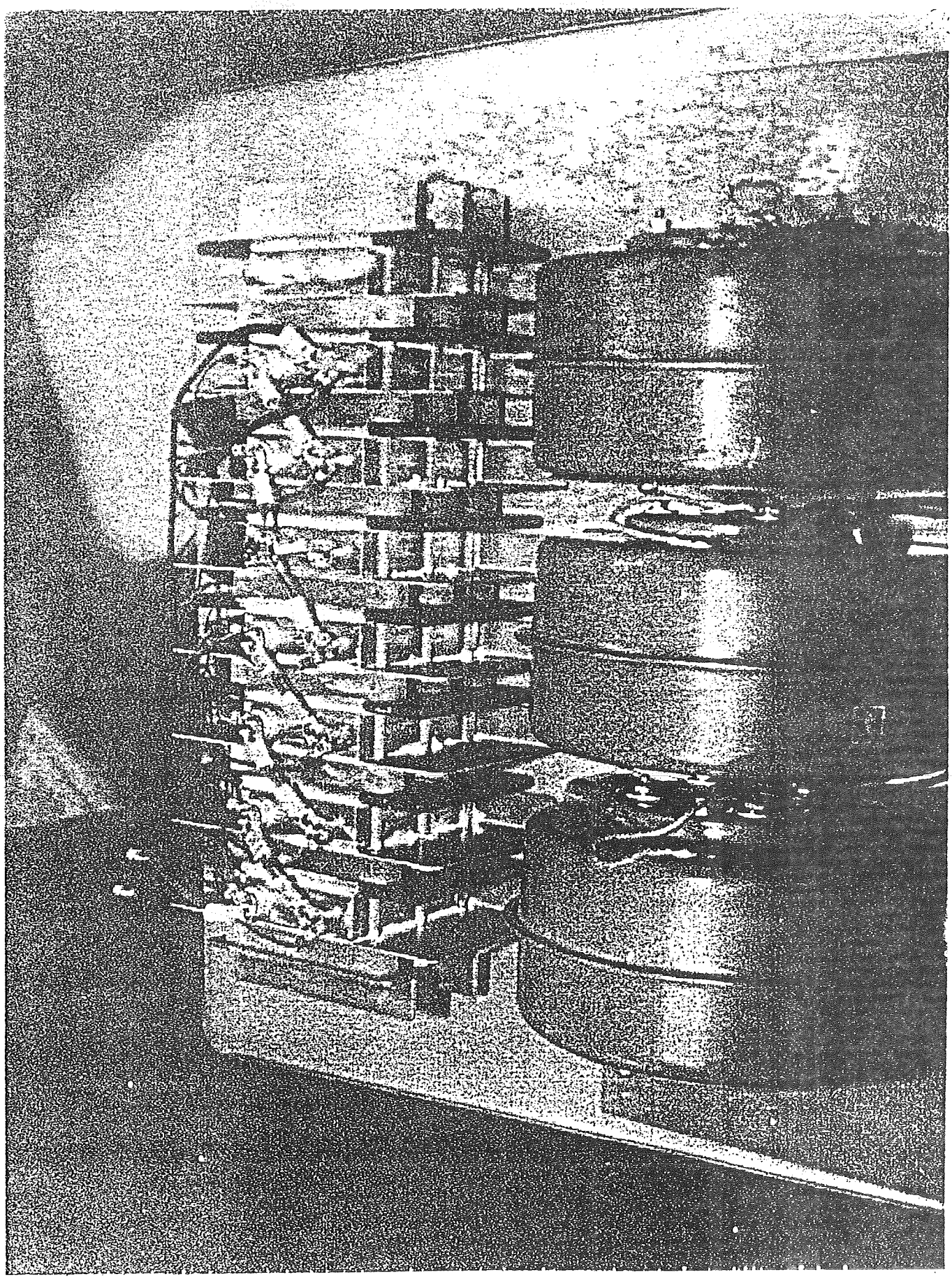
⇒ **Lifecycle test**

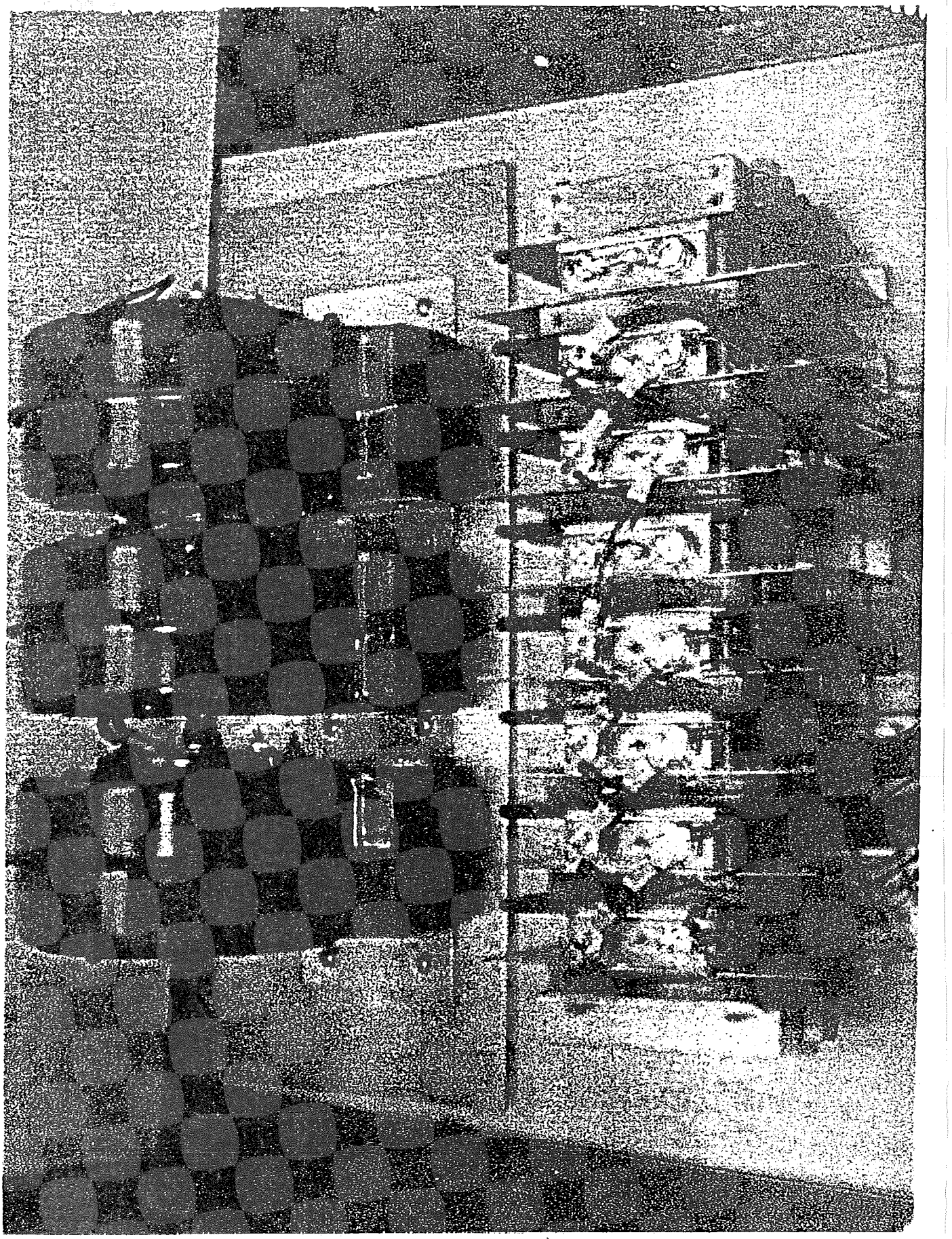
RESULTS OF DEEP DOD LIFE CYCLE TESTS AT HIGH RATES ON 12Ah NiCd CELLS

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

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

  - All cells were from the same lot
  - Filled in April 1988
  - Short circuited
  - Put in sealed plastic bags
  - Refrigerated at 5° Centigrade





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

The test parameters were chosen to produce the:

- Worst case eclipse, and
- Lowest battery cell voltages

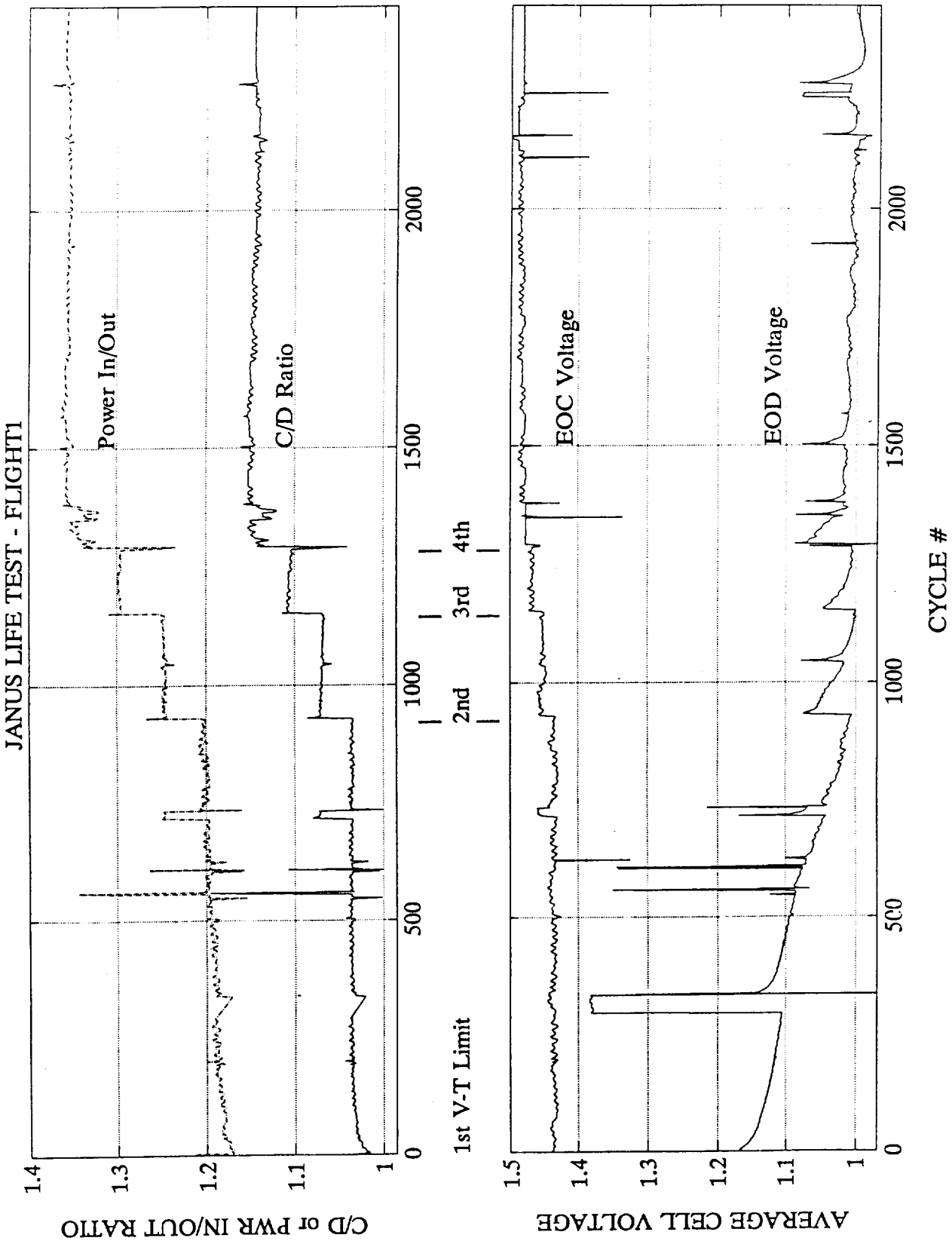
95 minute cycles at ambient temperature (20° to 30° C.)

- Discharge to 70% DOD (35 minutes - actual 69.44%)
  - -- C/3 rate for 15 minutes (unswitched loads)
  - -- 1.8C rate for 20 minutes (switched loads)
- Charge for 60 minutes
  - -- 1C rate until reach V-T limit
  - -- V-T controlled taper

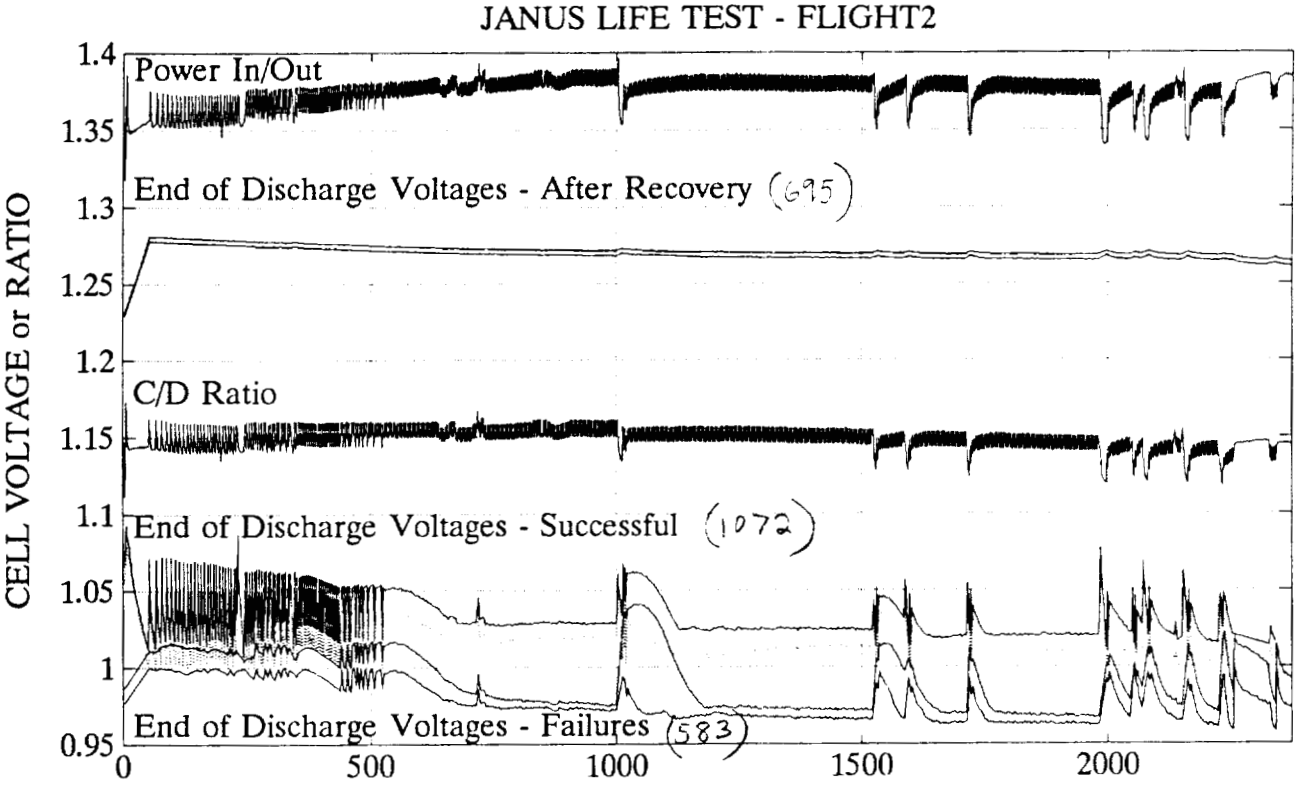
Relatively high end-of-charge (EOC) rates were required to fully recharge the battery in the short amount of time allowed.

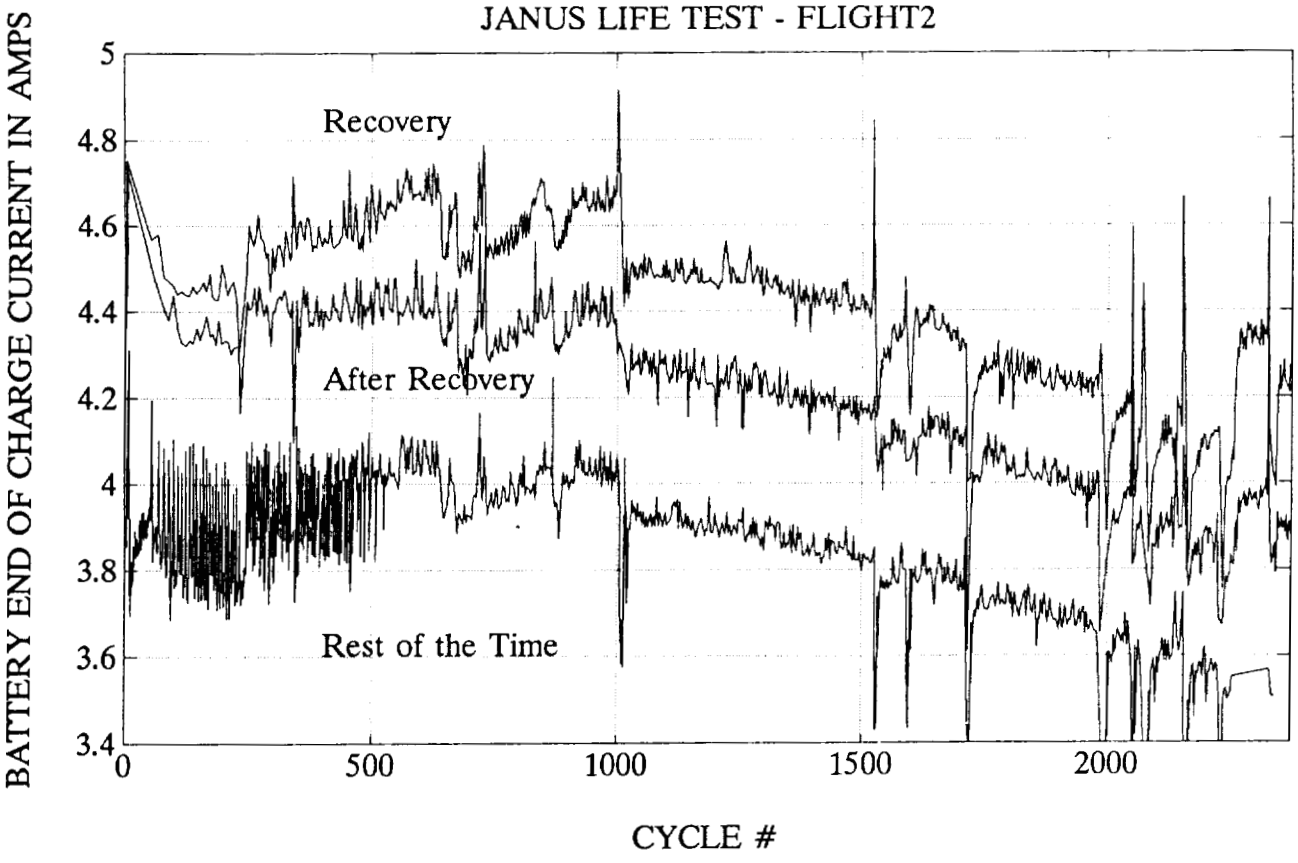
RESULTS OF DEEP DOD LIFE CYCLE TESTS AT HIGH RATES ON 12Ah NiCd CELLS

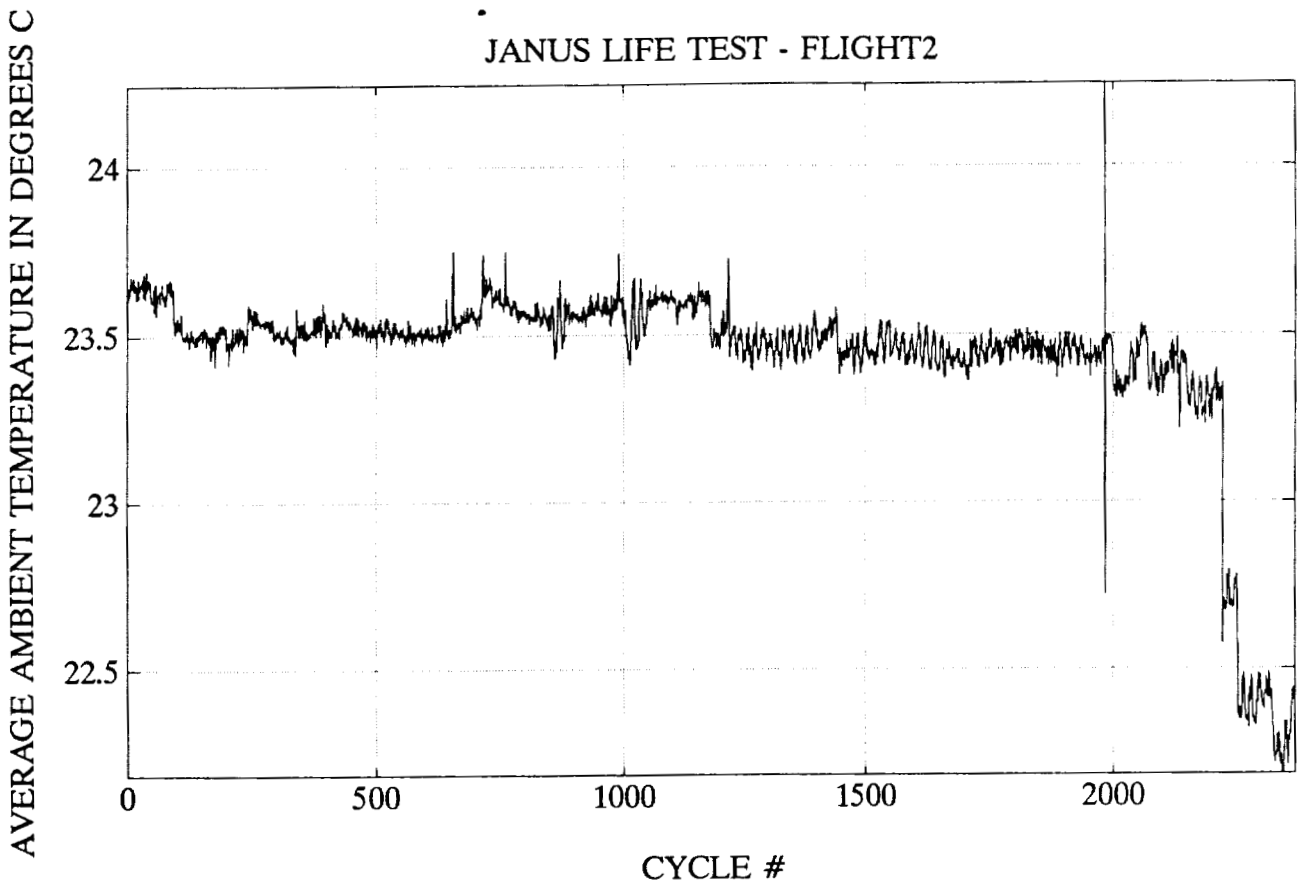
METHOD	REMARKS	# OF CYCLES	TOTAL 70% DOD	TOTAL 20% DOD
Contiguous 70% DOD Cycles. Raise VT Limit to Control C/D Ratio. 1V Cutoff.	C/D=1.036 NWA	913	913	
	C/D=1.069 NASA	219	1132	
	C/D=1.107 CLOSE!	122	1254	
	C/D=1.146 APL LIMIT	1021	2275	
70% DOD Cycles Interspersed with 20% DOD Cycles. 1V Cutoff.	Above Cutoff	1072	3347	
	Below Cutoff	583	3930	
	20% DOD Cycles	695		695
20% DOD Cycles	C/D=1.178	6104		6799
70% DOD Cycles	.95V Cutoff	100++	4030++	

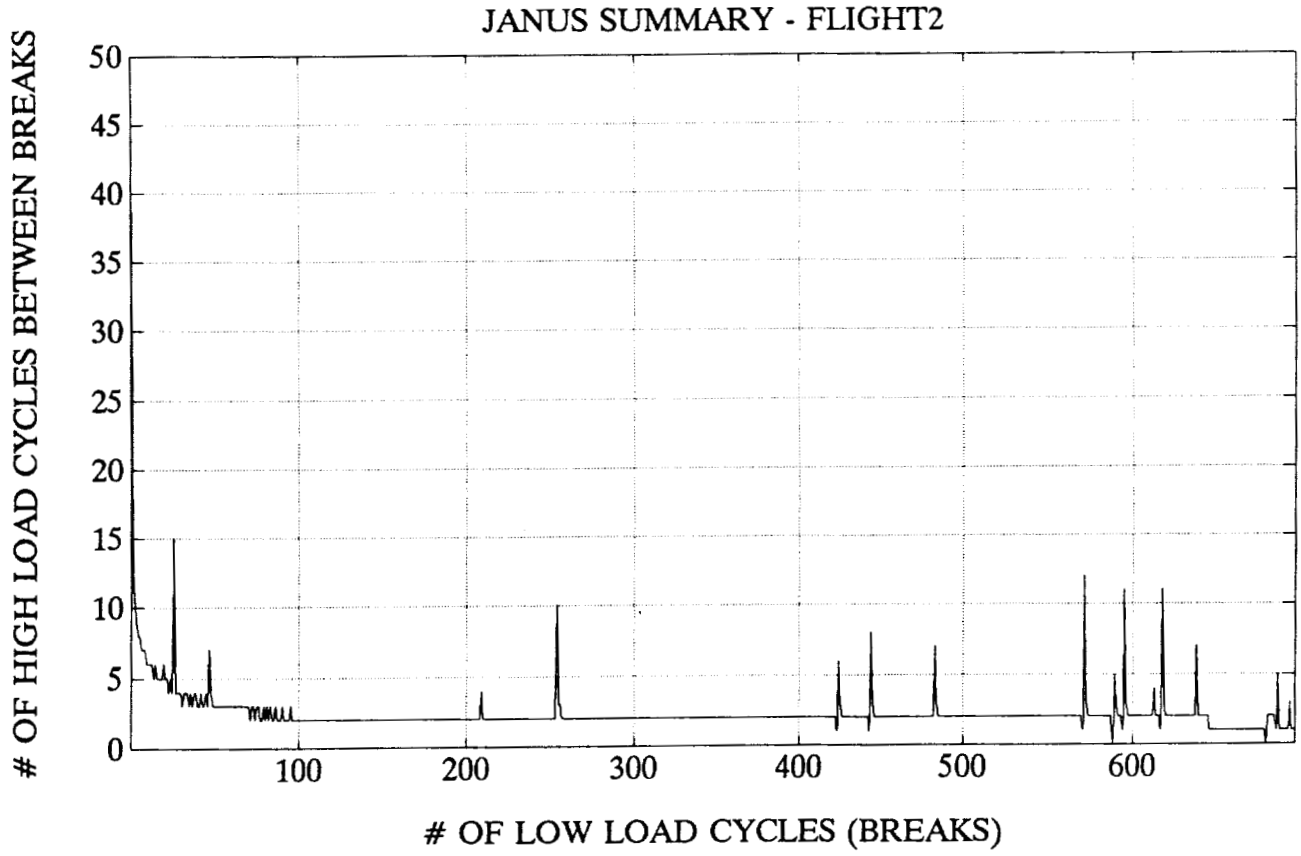

JANUS LIFE TEST - FLIGHT1
Power In/Out
C/D Ratio
C/D or PWR IN/OUT RATIO
1.4
1.3
1.2
1.1
1
0
500
1000
1500
2000
1st V-T Limit
2nd
3rd
4th
EOC Voltage
EOD Voltage
AVERAGE CELL VOLTAGE
1.5
1.4
1.3
1.2
1.1
1
0
500
1000
1500
2000
CYCLE #

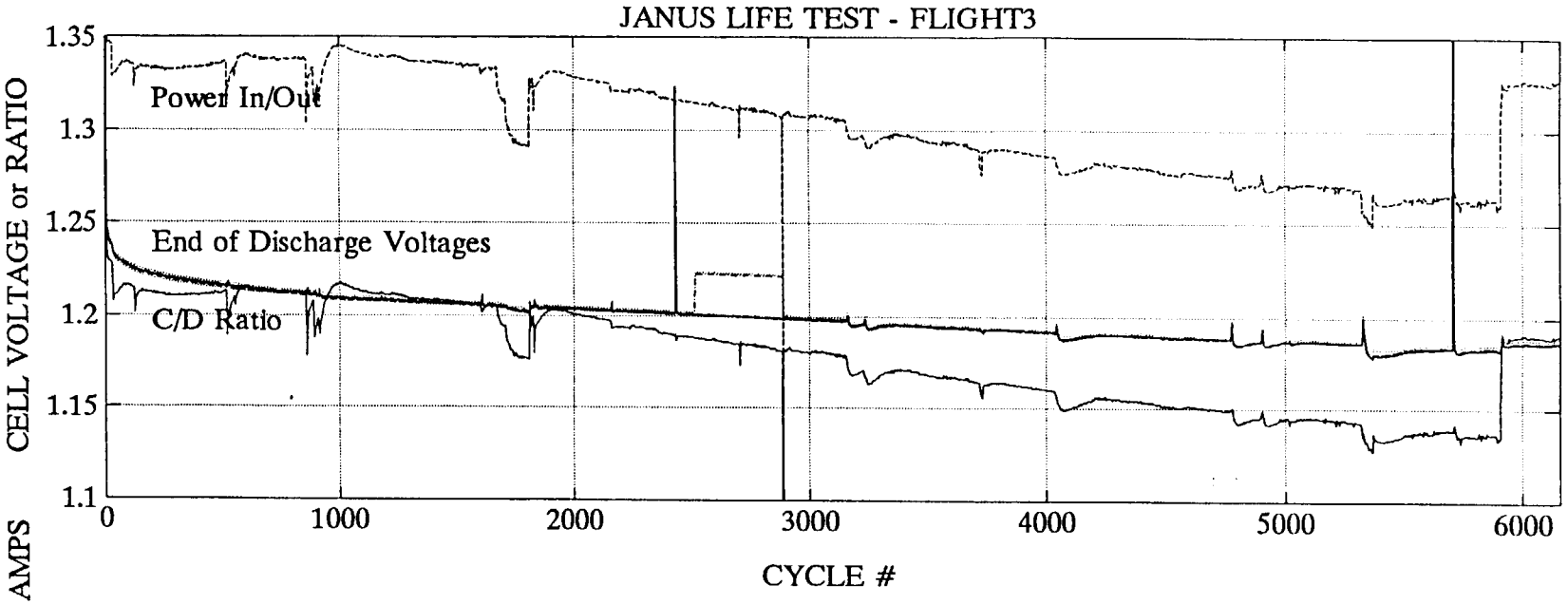
JANUS LIFE TEST - FLIGHT1
BATTERY EOC CURRENT IN AMPS
AMBIENT TEMPERATURE IN DEG C
CYCLE #
1st V-T Limit
2nd
3rd
4th
0
500
1000
1500
2000
1
2
3
4
18
20
22
24
26

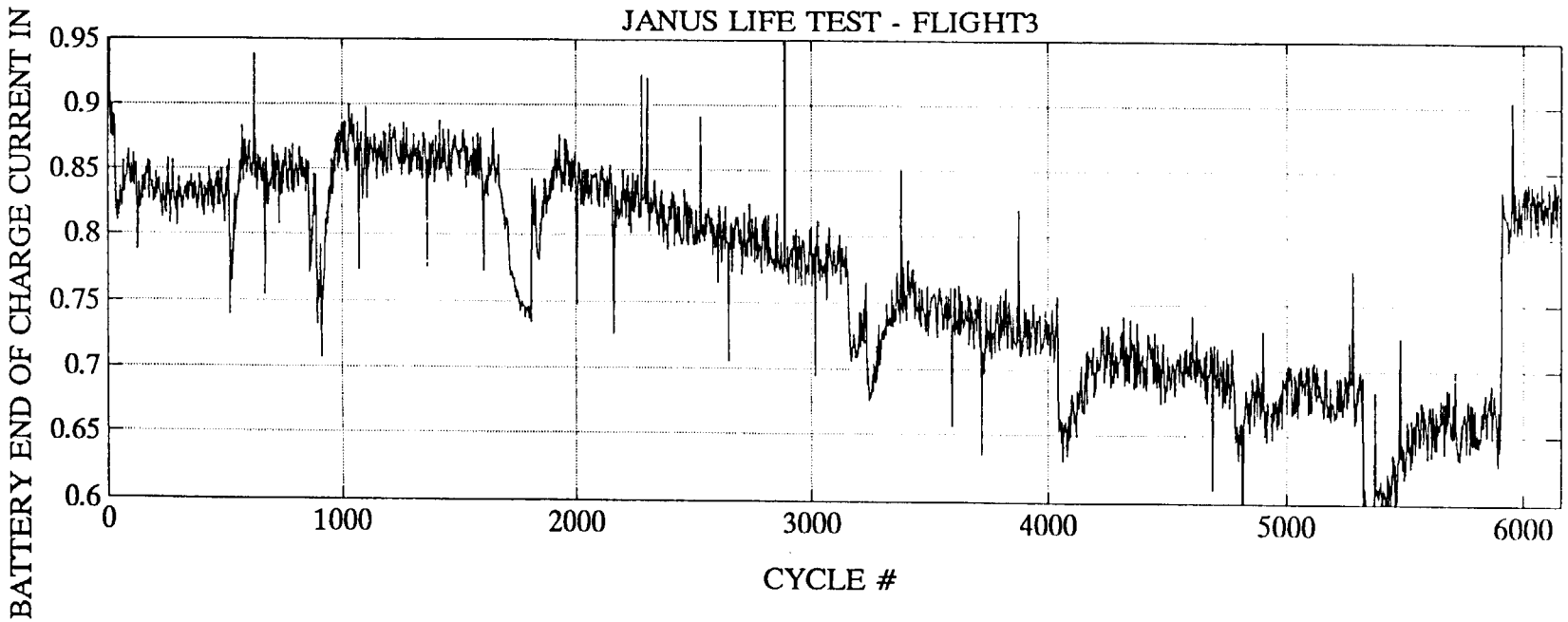

JANUS LIFE TEST - FLIGHT2
Power In/Out
End of Discharge Voltages - After Recovery (695)
C/D Ratio
End of Discharge Voltages - Successful (1072)
End of Discharge Voltages - Failures (583)
CELL VOLTAGE or RATIO
CYCLE #
1.4
1.35
1.3
1.25
1.2
1.15
1.1
1.05
1
0.95
0
500
1000
1500
2000

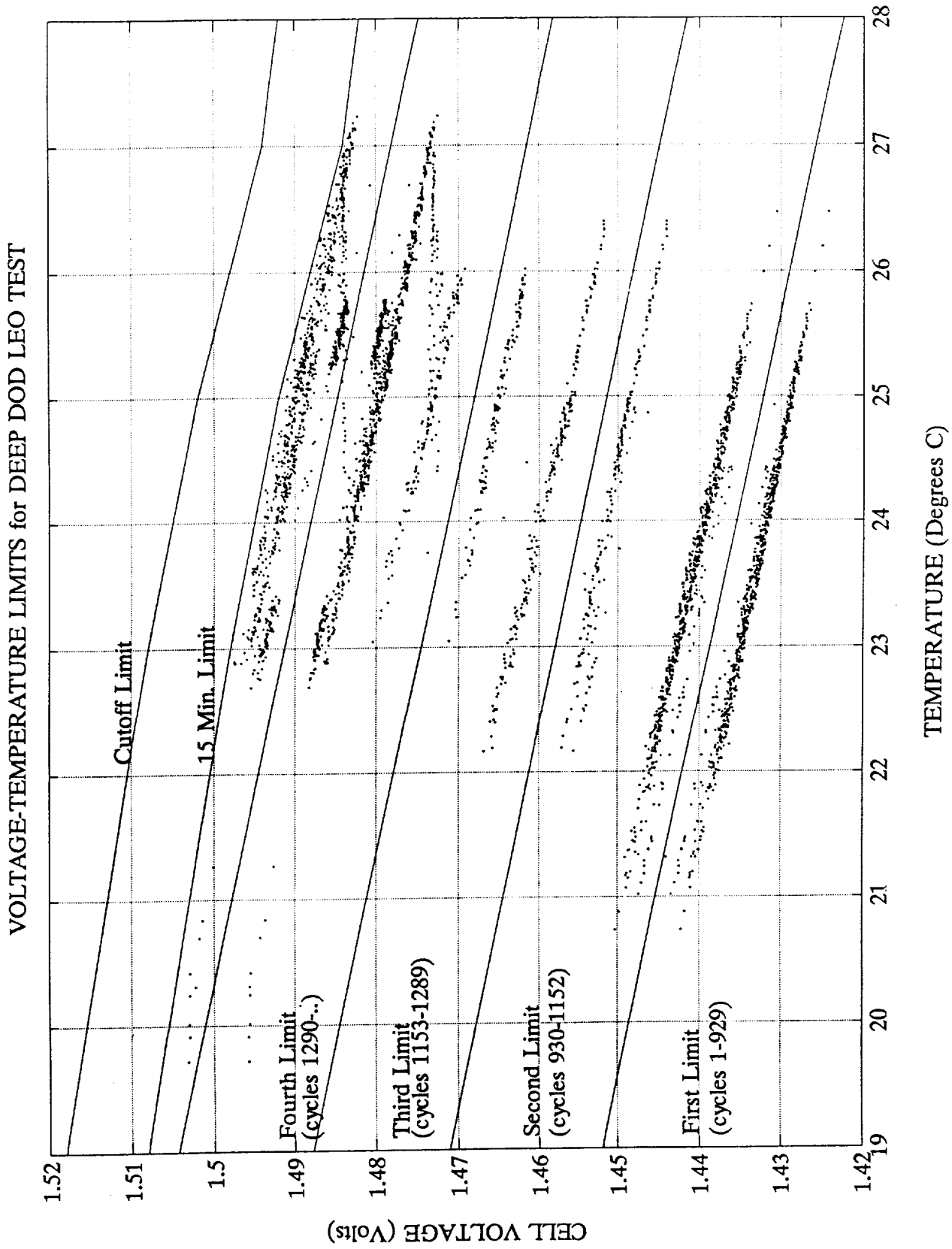

JANUS LIFE TEST - FLIGHT2
Recovery
After Recovery
Rest of the Time
BATTERY END OF CHARGE CURRENT IN AMPS
CYCLE #
5
4.8
4.6
4.4
4.2
4
3.8
3.6
3.4
0
500
1000
1500
2000

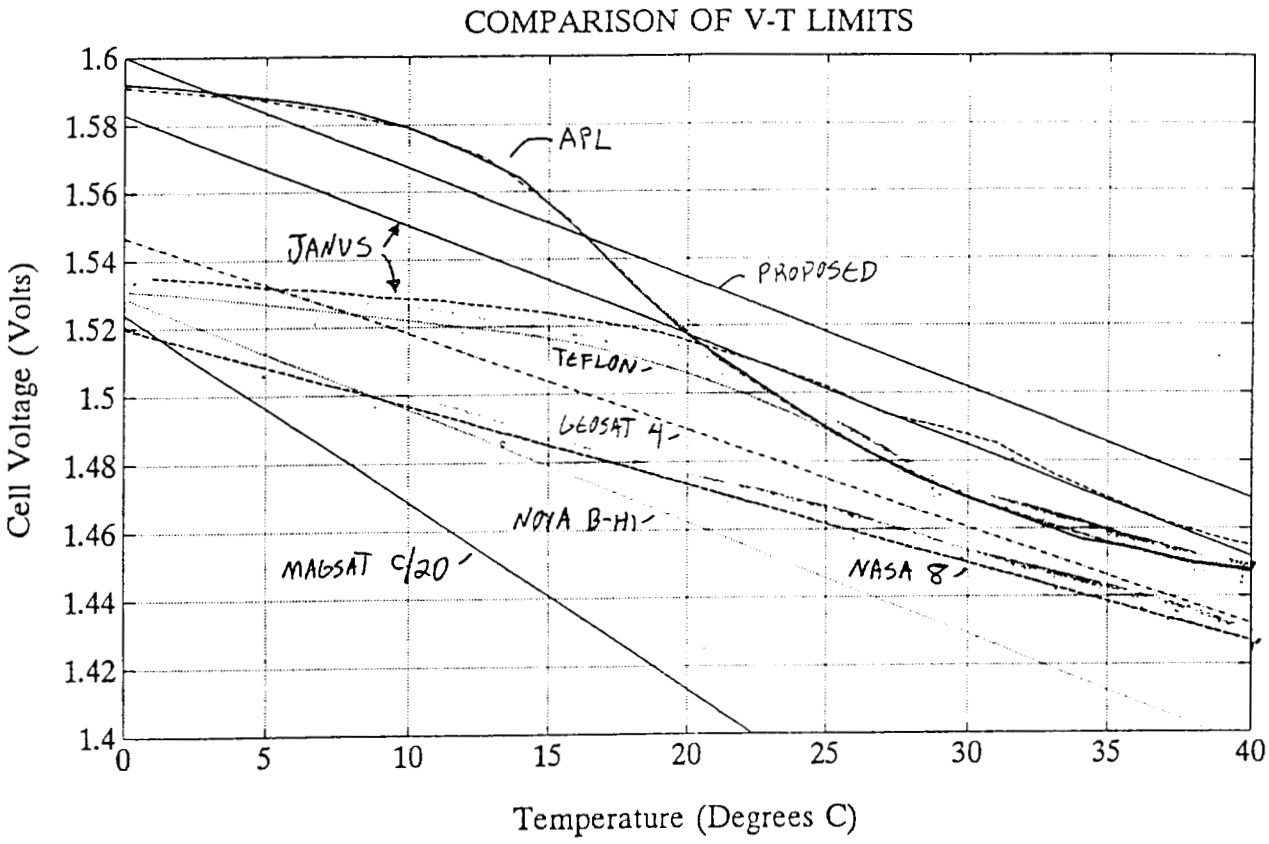

JANUS LIFE TEST - FLIGHT2
AVERAGE AMBIENT TEMPERATURE IN DEGREES C
24
23.5
23
22.5
0
500
1000
1500
2000
CYCLE #

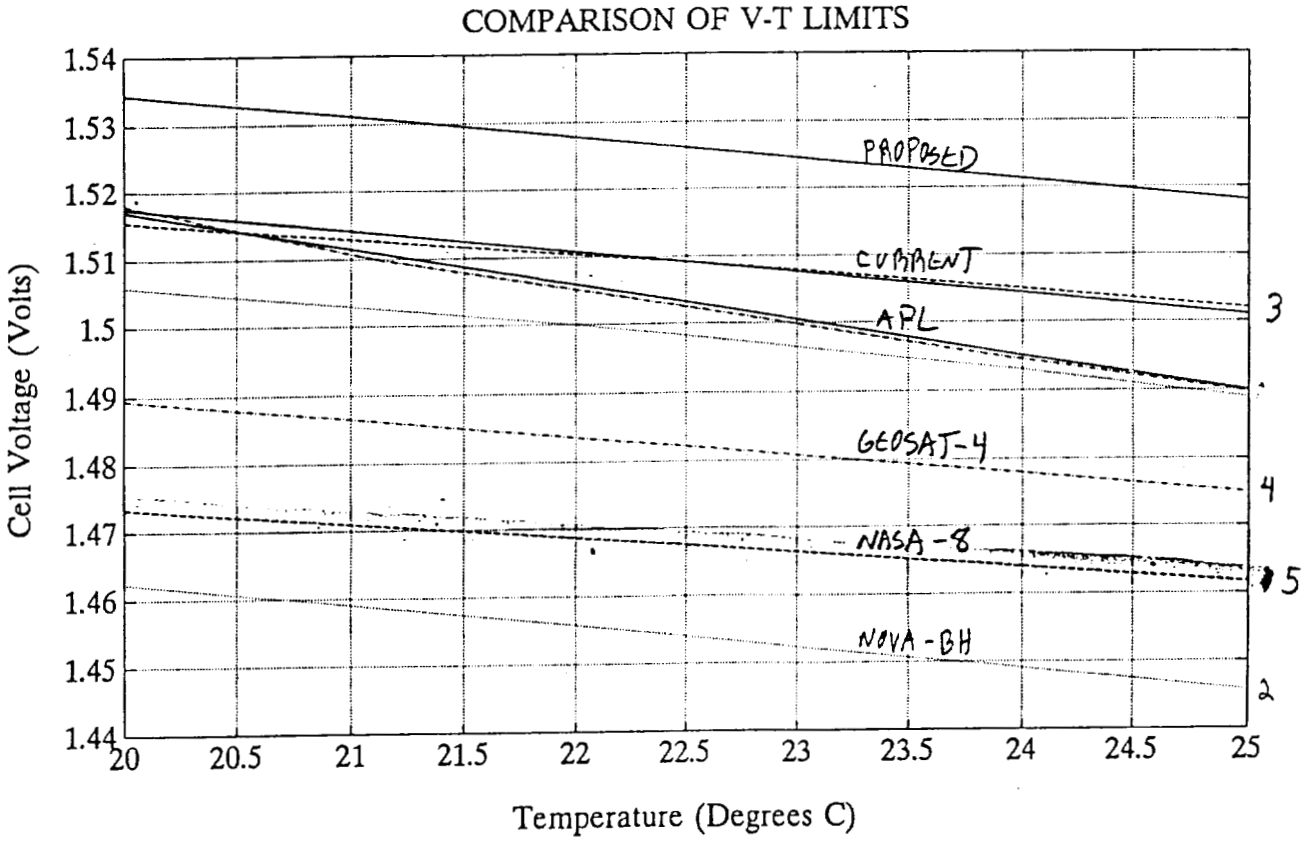

JANUS SUMMARY - FLIGHT2
OF HIGH LOAD CYCLES BETWEEN BREAKS
50
45
40
35
30
25
20
15
10
5
0
100
200
300
400
500
600
OF LOW LOAD CYCLES (BREAKS)

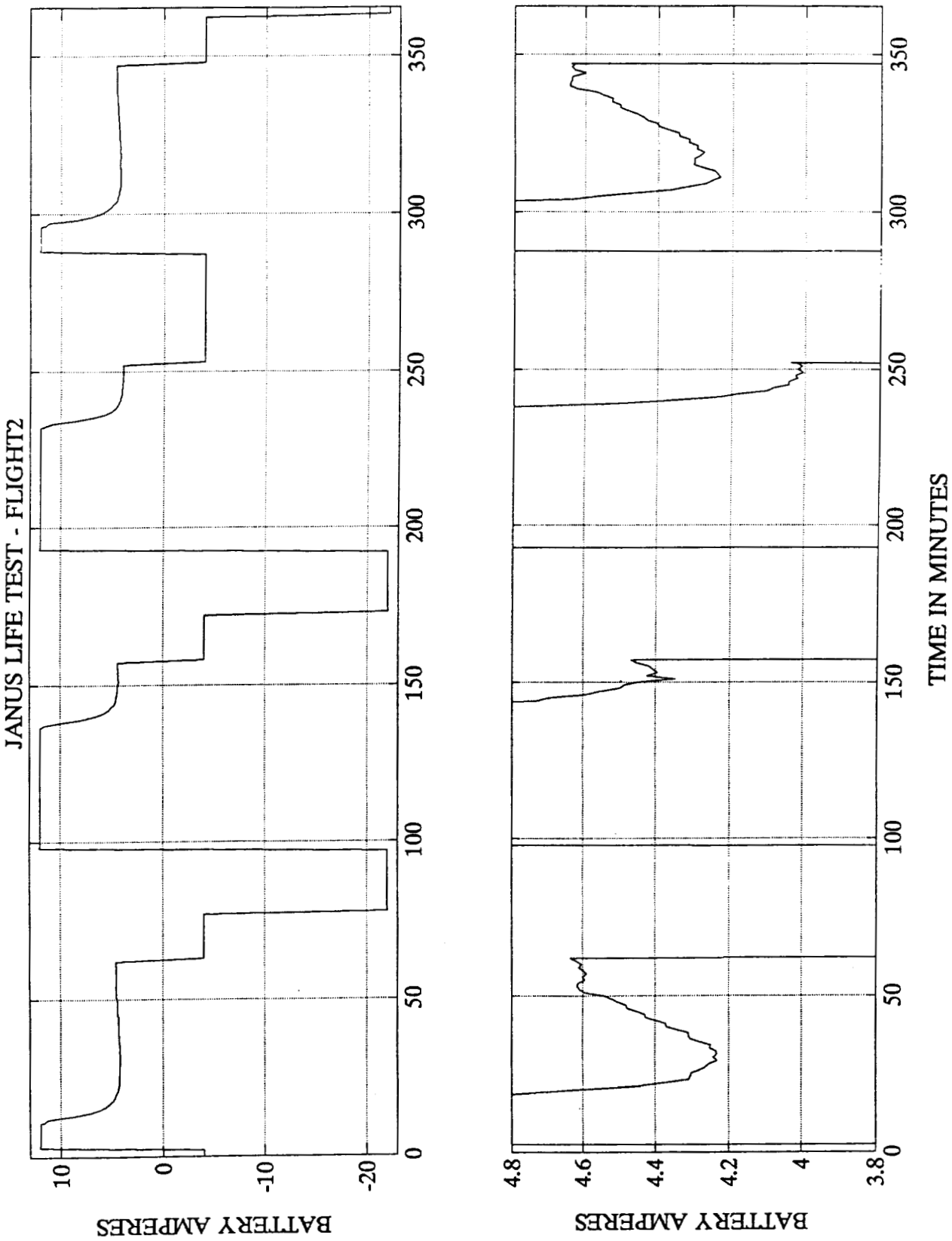

JANUS LIFE TEST - FLIGHT3
CELL VOLTAGE or RATIO
Power In/Out
End of Discharge Voltages
C/D Ratio
1.35
1.3
1.25
1.2
1.15
1.1
0
1000
2000
3000
4000
5000
6000
CYCLE #

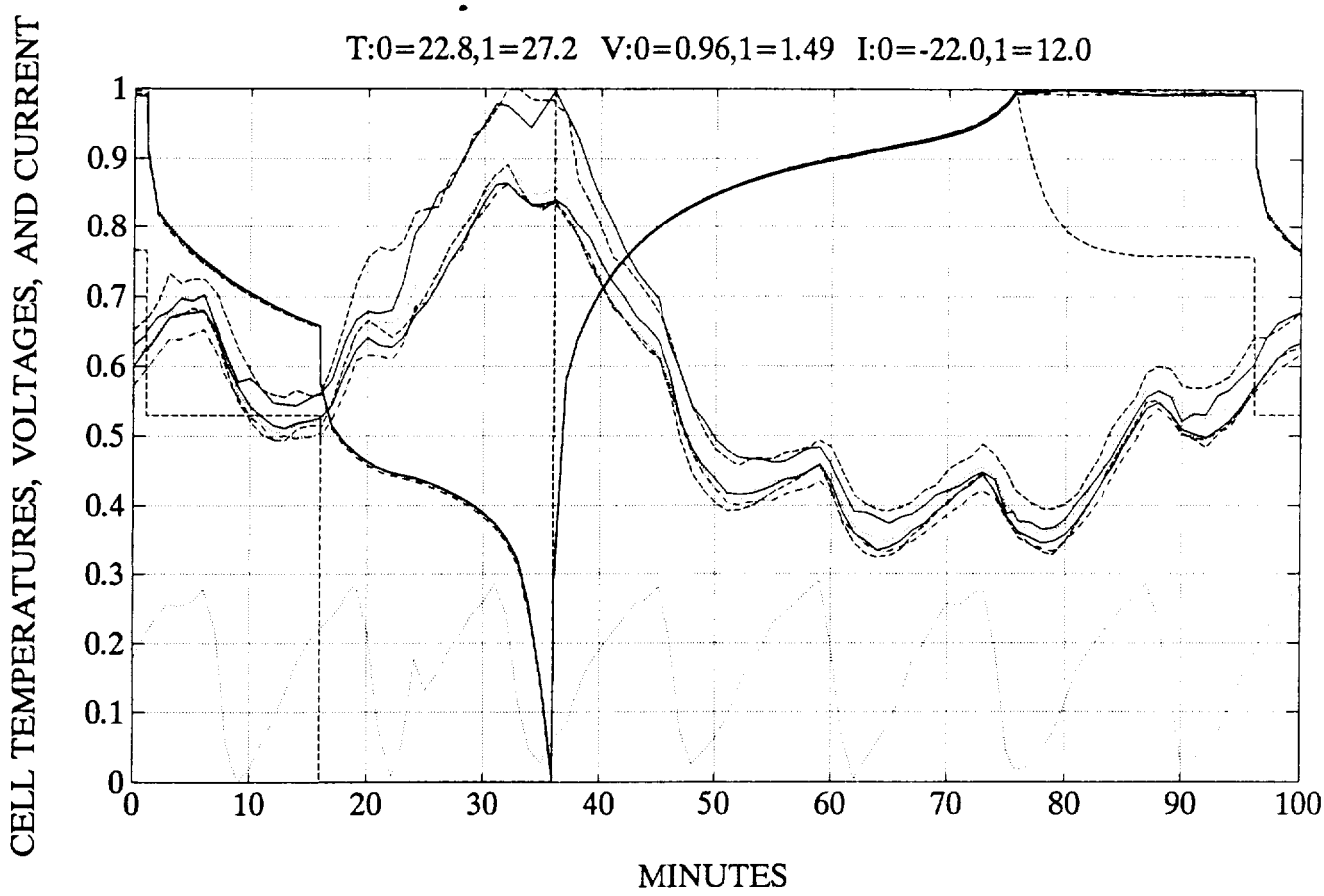

JANUS LIFE TEST - FLIGHT3
BATTERY END OF CHARGE CURRENT IN AMPS
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0
1000
2000
3000
4000
5000
6000
CYCLE #


VOLTAGE-TEMPERATURE LIMITS for DEEP DOD LEO TEST
Cutoff Limit
15 Min. Limit
Fourth Limit
(cycles 1290-..)
Third Limit
(cycles 1153-1289)
Second Limit
(cycles 930-1152)
First Limit
(cycles 1-929)
CELL VOLTAGE (Volts)
TEMPERATURE (Degrees C)
1.52
1.51
1.5
1.49
1.48
1.47
1.46
1.45
1.44
1.43
1.42
19
20
21
22
23
24
25
26
27
28


COMPARISON OF V-T LIMITS
Cell Voltage (Volts)
Temperature (Degrees C)
APL
JANUS
PROPOSED
TEFLON
GEOSAT 4
NOVA B-H1
MAGSAT C/20
NASA 8
1.6
1.58
1.56
1.54
1.52
1.5
1.48
1.46
1.44
1.42
1.4
0
5
10
15
20
25
30
35
40


COMPARISON OF V-T LIMITS
Cell Voltage (Volts)
Temperature (Degrees C)
PROPOSED
CURRENT
APL
GEOSAT-4
NASA-8
NOVA-BH
3
4
5
2
1.54
1.53
1.52
1.51
1.5
1.49
1.48
1.47
1.46
1.45
1.44
20
20.5
21
21.5
22
22.5
23
23.5
24
24.5
25


JANUS LIFE TEST - FLIGHT2
BATTERY AMPERES
10
0
-10
-20
0
50
100
150
200
250
300
350
BATTERY AMPERES
4.8
4.6
4.4
4.2
4
3.8
0
50
100
150
200
250
300
350
TIME IN MINUTES


T:0=22.8,1=27.2 V:0=0.96,1=1.49 I:0=-22.0,1=12.0
CELL TEMPERATURES, VOLTAGES, AND CURRENT
MINUTES
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
80
90
100

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

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.

MDESC-L&ES

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

SYSNOPSIS: - 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:

	LAUNCH:
- LANDSAT 4	7/82
- LANDSAT 5	3/84
- EARTH RADIATION BUDGET SATELLITE (ERBS)	10/84
- GAMMA RAY OBSERVATORY (GRO)	3/91
- UPPER ATMOSPHERE RESEARCH SATELLITE (UARS)	9/91
- EXPLORER PLATFORM (EP)	(1/92)
- OCEAN TOPOGRAPHY EXPERIMENT / POSEIDON (TOPEX)	(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 STORAGECELLS
NHB 8073.1	NASA SPECIFICATION FOR MANUFACTURING AND PERFORMANCE REQUIREMENTS OF NASA STANDARD AEROSPACE NICKEL-CADMIUM CELLS

EXECUTIVE DOCUMENTS: (GE/GAB)

232A2222AA-84	APPLICABLE QUALITY PLAN FOR NASA STANDARD NiCd CELLS (MASTER MCD)
232A2222AA-87	APPLICABLE QUALITY PLAN FOR NASA STANDARD NiCd CELLS (MASTER MCD)
232A2222AA-88	TEMPLATE FOR JOB-SPECIFIC MCD's

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^2

strip type FD03

- 16 POSITIVE PLATES PER CELL
- POSITIVE PLATE SURFACE AREA = 22.75 dm^2

- TEFLONATED NEGATIVE PLATES
- NEGATIVE PLATE LOADING: 15.10 - 16.30 grams/dm^2(**)
- 17 NEGATIVE PLATES PER CELL

strip type FD04

(*) - EXCEPT FOR 50AB34, AS NOTED BEFORE (FD05)
(**) - EXCEPT FOR 50AB34, WHICH IS LOADED 14.85 - 16.15 grams/dm^2(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

PARA. NO.	TITLE	REGIME	REQUIREMENT
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

PLATE LOT	NOTES	CELL LOT / DISPOSITION	LOT SIZE	MISSION USE
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

PLATE LOT	NOTES	CELL LOT / DISPOSITION	LOT SIZE	MISSION USE
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	50AB25 LOT 1	12 CELLS	2536 SEPARATOR QUAL TEST CELLS
50AB20 LOT 14	POSITIVE NOT CADMIUM TREATED	50AB20 LOT 14	78 CELLS	3 GRO TEST BATTERIES
50AB20 LOT 15A/15B	BAD 2505 SEPARATOR	50AB20 LOT 15 CHANGED TO 2536 SEPARATOR IN FLIGHT CELLS	7 CELLS	PRE-ACCEPT CELLS
50AB20 LOT 16	-	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
			83 CELLS	3 GRO FLIGHT BATTERIES
50AB20 LOT 18A/ 18B/18C	OVERLOADED	SCRAPPED	-	-

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

PLATE LOT	NOTES	CELL LOT / DISPOSITION	LOT SIZE	MISSION USE
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 2A/2B	-	50AB35 LOT 2	83 CELLS	3 UARS FLIGHT BATTERIES
50AB20 LOT 15	REBUILT USING 2536	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
50AB29 LOT 6	2505	50AB34 LOT 3	13 CELLS	EXPERIMENT
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
		50AB25 LOT '3'	7 CELLS	TEST CELLS PLUS CONTROL
		50AB39 LOT '1'	7 CELLS	CELLS
50AB35 LOT 5A/5B	INSUFFICIENT MATERIAL	-	-	-
50AB35 LOT 6A/6B/6C	-	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 SHORTDOWNS
- DESTRUCT CELLS SHOW LOSS OF OVERCHARGE PROTECTION
- CONTAMINATION ?

50AB20 LOT 13 / 50AB25 LOT 1

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

50AB20 LOT 14

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

50AB20 LOT 17

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

50AB34 LOT 1 / 50AB35 LOT 1

- BOTH LOTS REQUIRED ADDITIONAL PRECHARGING

NASA STANDARD 50 A.H. BATTERY CELL: TYPICAL PLATE SUMMARY

50AB35 LOT 6 (TOPEX)

DATA	POSITIVE		NEGATIVE		
PLATE LOT	6A	6B	6A	6B	6C
POST #	05103	05104	04801	04602	04601
SPIRALS	1 - 7	1 - 7	1 - 7	1 - 6	1,3 - 7
AVERAGE LOADING (gm/dm2)	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/dm2)	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

		GR1	GR2	GR3	GR4	GR5
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)

CYCLE						
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

		GR1	GR2	GR3	GR4	GR5
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

		GR1	GR2	GR3	GR4	GR5	GR6	GR7
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

		GR1	GR2	GR3	GR4	GR5	GR6	GR7
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 LOT 6	35 LOT 4	35 LOT 2	35 LOT 1	20 LOT 17	20 LOT 14	20 LOT 12	20 LOT 7	20 LOT 4	20 LOT 1	
TOTNEG	134.64	137.97	133.91	135.70	136.26	130.58	145.54	163.18	152.55	151.82	POST-PCG
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 LOT 6	35 LOT 4	35 LOT 2	35 LOT 1	20 LOT 17	20 LOT 14	20 LOT 12	20 LOT 7	20 LOT 4	20 LOT 1	
TOTNEG	136.82	138.27	135.80	140.28	135.91	135.91	143.60	156.17	153.27	154.96	POST-ATP
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 AM'T (cc's)	160	160	161.8	158 - 161	163	162	160	165	165	170	

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:	WHEN THE DATA READS:	IT MEANS:
50AB20 LOT 16 AND LOT 17	1.509 / 1.507	PRE-ACCEPT DATA / FLIGHT CELL DATA
50AB20 LOT 13 (NASA PRECHARGE EXPERIMENT)	15.6 / 13.1 / 7.4	NORMAL PCG / 50% OVERPCG / 50% UNDER PCG
50AB34 LOT 3 (NASA KOH FILL EXPERIMENT)	3511 / 3602 / 3571	NORMAL KOH FILL / KOH UNDER-FILL / KOH OVER-FILL (161.5 / 148 / 174.5 cc's) (0.85 / 0.77 / 0.93 fill index)

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

CELL LOT	INTER-ELECTRODE SPACING (mills)	PACK WEIGHT (grams)	TEFLONATION (gm/dm2)	FINAL KOH FILL AMOUNT (cc's)
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 avl	160
50AB20 LOT 13	9.02	not avl	not avl	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 avl	not avl	not recorded	161
LOT 3	not avl	not avl	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

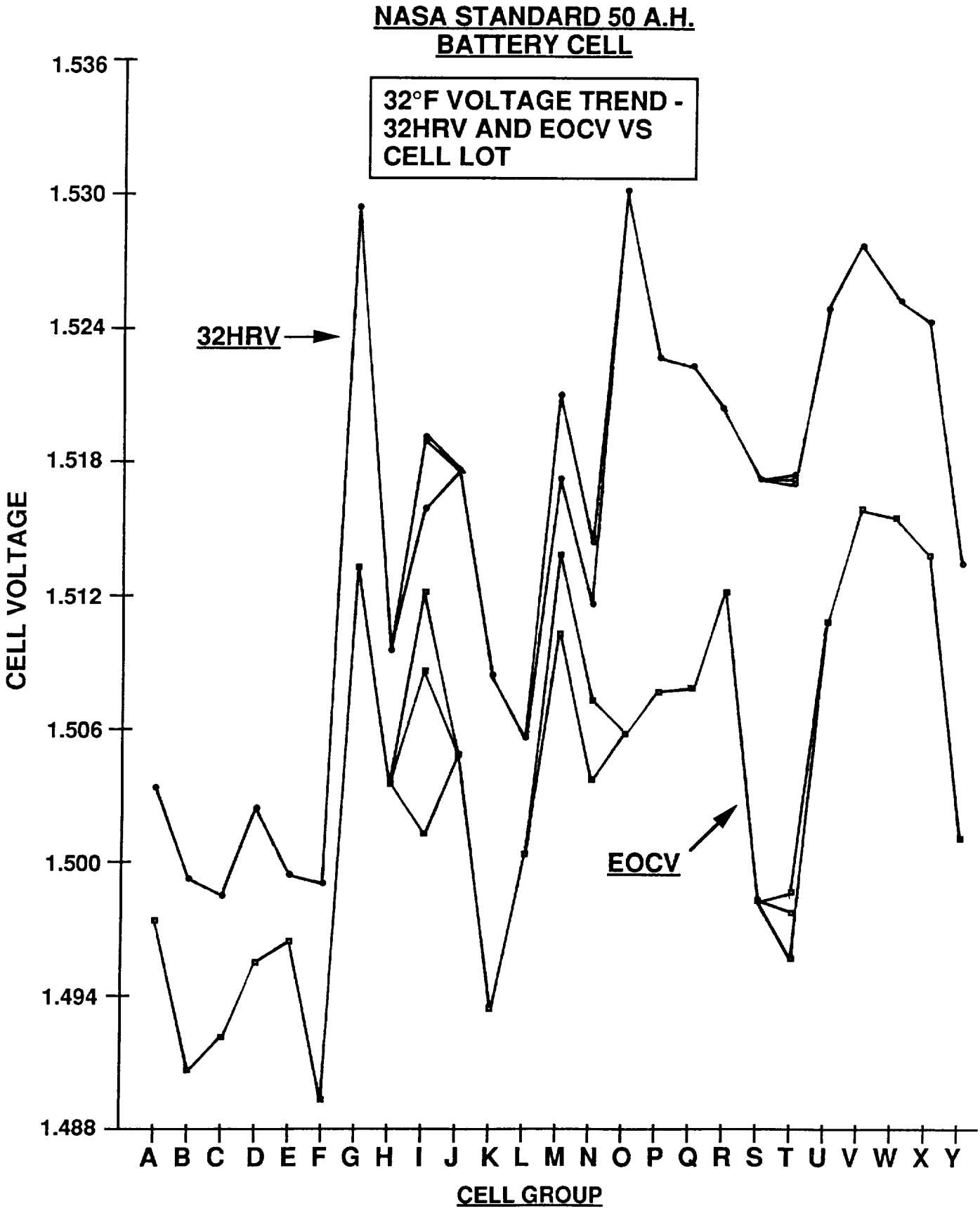
PLATE LOT	POSITIVE LOADING (gm/dm2)	100% ECT POS. CAPACITY (A-M)	N/P RATIO
50AB20/21 LOT 1	12.69	3864	1.843
LOT 2	12.53	3880	1.864
LOT 3	12.63	3647	1.845
LOT 4	12.79	3784	1.843
LOT 5	12.96	3777	1.820
LOT 6	13.09	3958	-
LOT 7	12.80	3797	1.840
LOT 8	12.13	3791	-
LOT 9	13.17	4014	1.776
LOT 10	12.32	3846	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

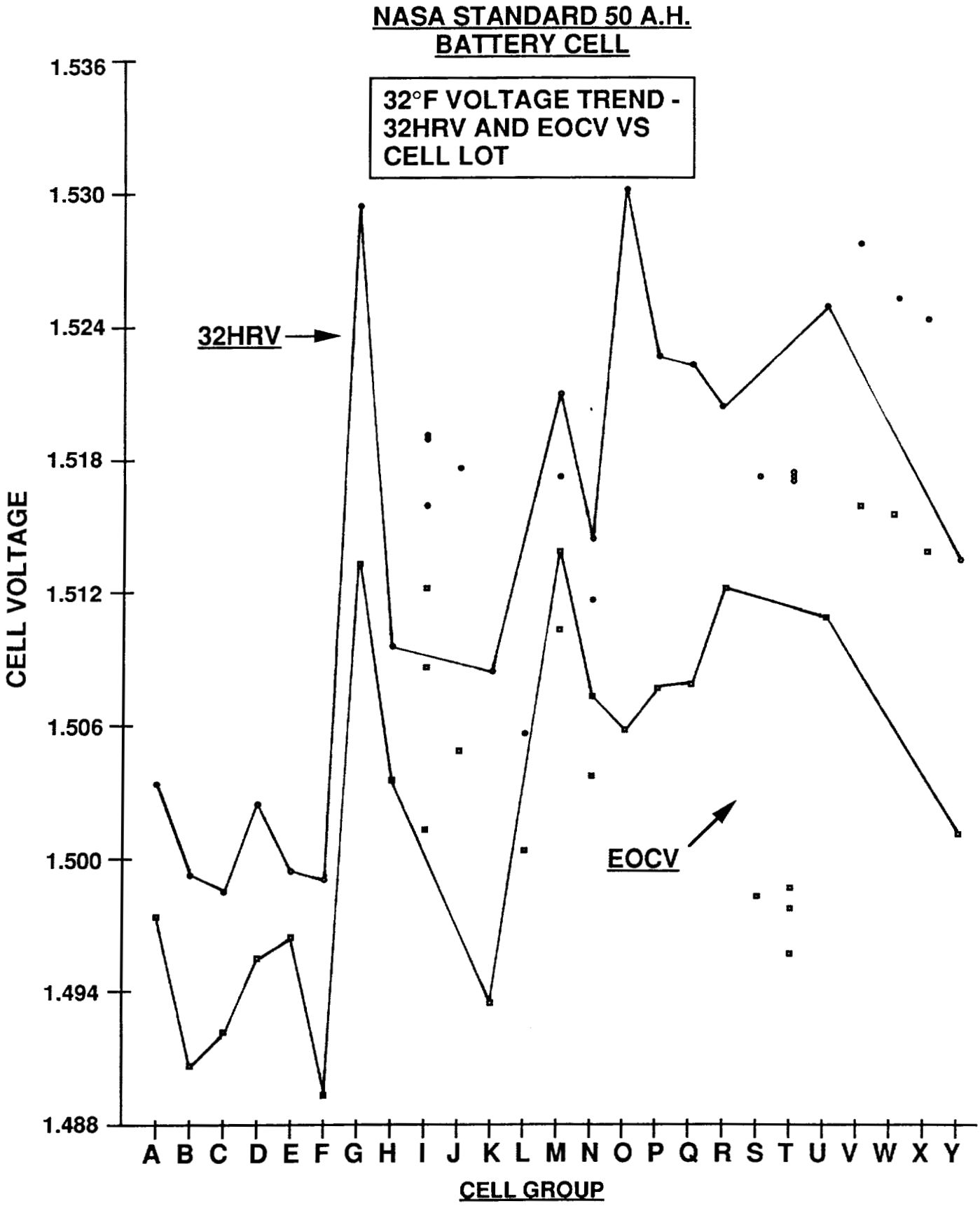
NASA STANDARD 50 A.H. BATTERY CELL: 95°F/86°F CAPACITY

CELL LOT	95°F EOCV	95°F CAPACITY (A-M)	86°F EOCV	86°F CAPACITY (A-M)
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	1.44011	3541
50AB34 LOT 1			1.41511	3342
50AB35 LOT 1			1.42376	3617
LOT 2			1.43813	3622
50AB25 LOT 2			1.42975	3467
50AB34 LOT 2			1.41225	3304
LOT 3			1.40825/1.40750/1.41050	3174 / 3107 / 3163
50AB35 LOT 4			1.42522	3320
50AB35 LOT 2a			1.41357	3344
50AB25 LOT 3			1.41829	3360
50AB39 LOT 1			1.42043	3368
50AB35 LOT 6			1.44246	3543

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

	CELL LOT	32°F 32HRV	32°F EOCV	32°F EOCP [PSIG (-inHg)]	32°F CAPACITY (A-M)
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
32HRV
EOCV
CELL VOLTAGE
1.536
1.530
1.524
1.518
1.512
1.506
1.500
1.494
1.488
A B C D E F G H I J K L M N O P Q R S T U V W X Y
CELL GROUP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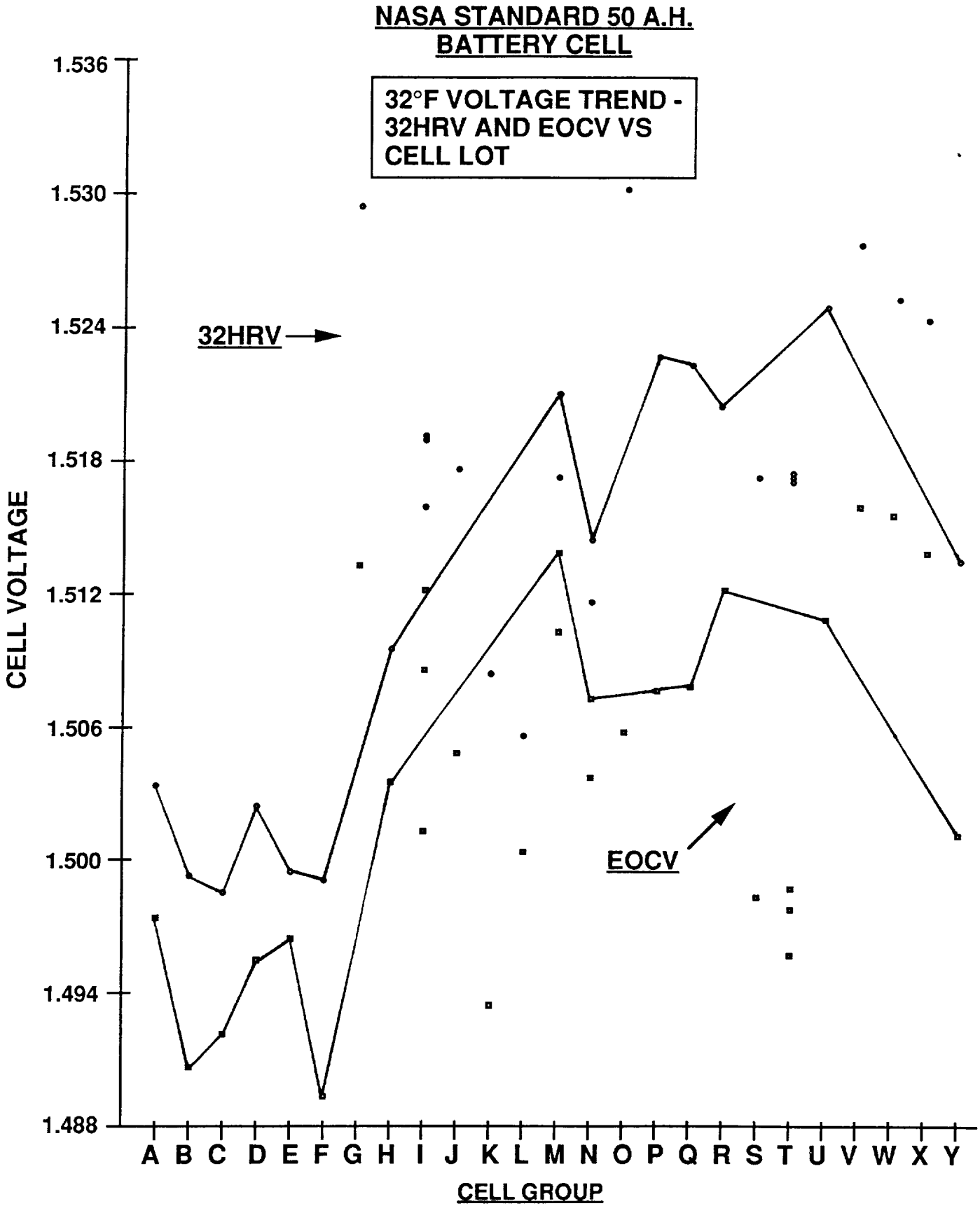
BATTERY CELL
32°F VOLTAGE TREND -
32HRV AND EOCV VS
CELL LOT
32HRV
EOCV
CELL VOLTAGE
1.536
1.530
1.524
1.518
1.512
1.506
1.500
1.494
1.488
A B C D E F G H I J K L M N O P Q R S T U V W X Y
CELL GROUP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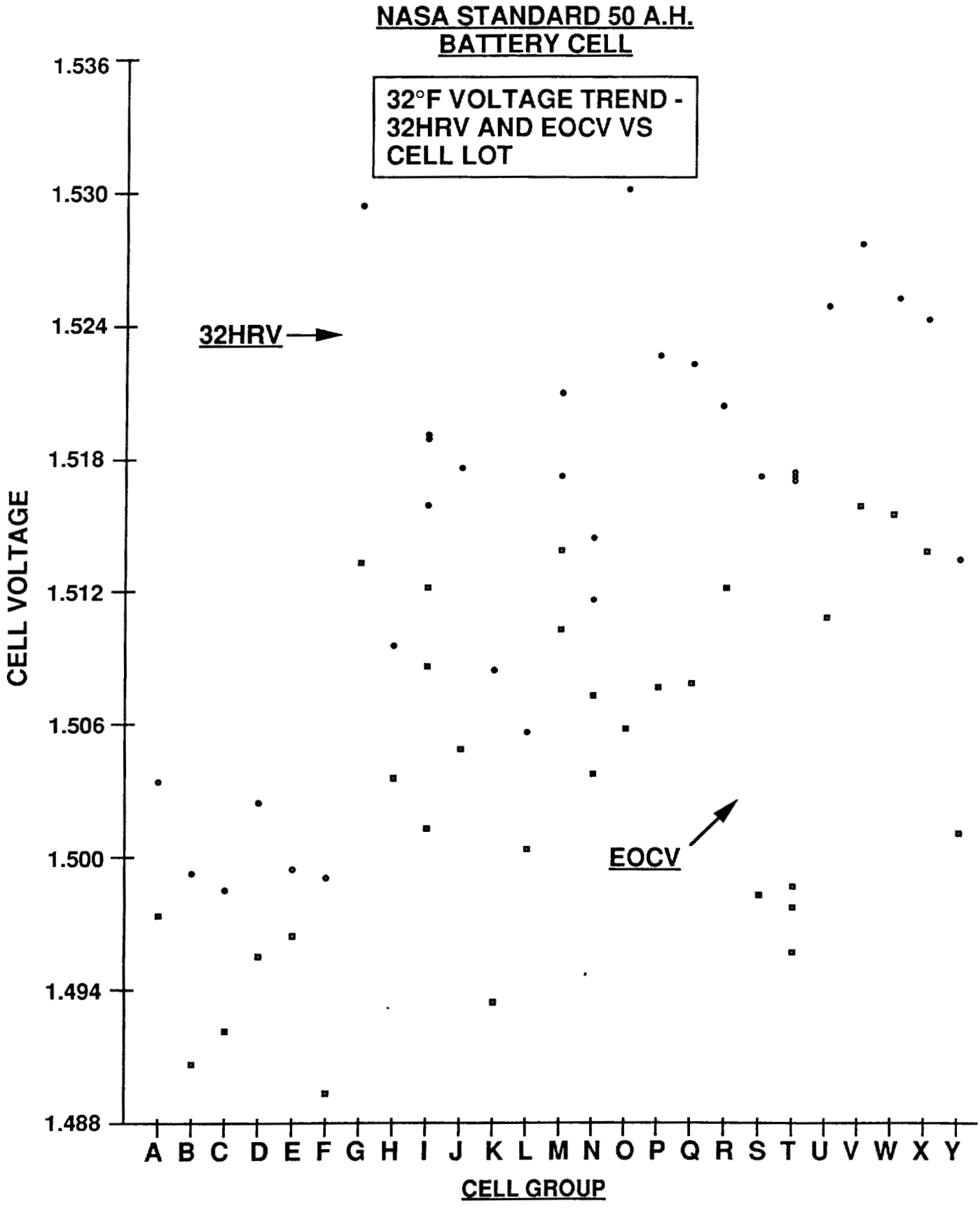
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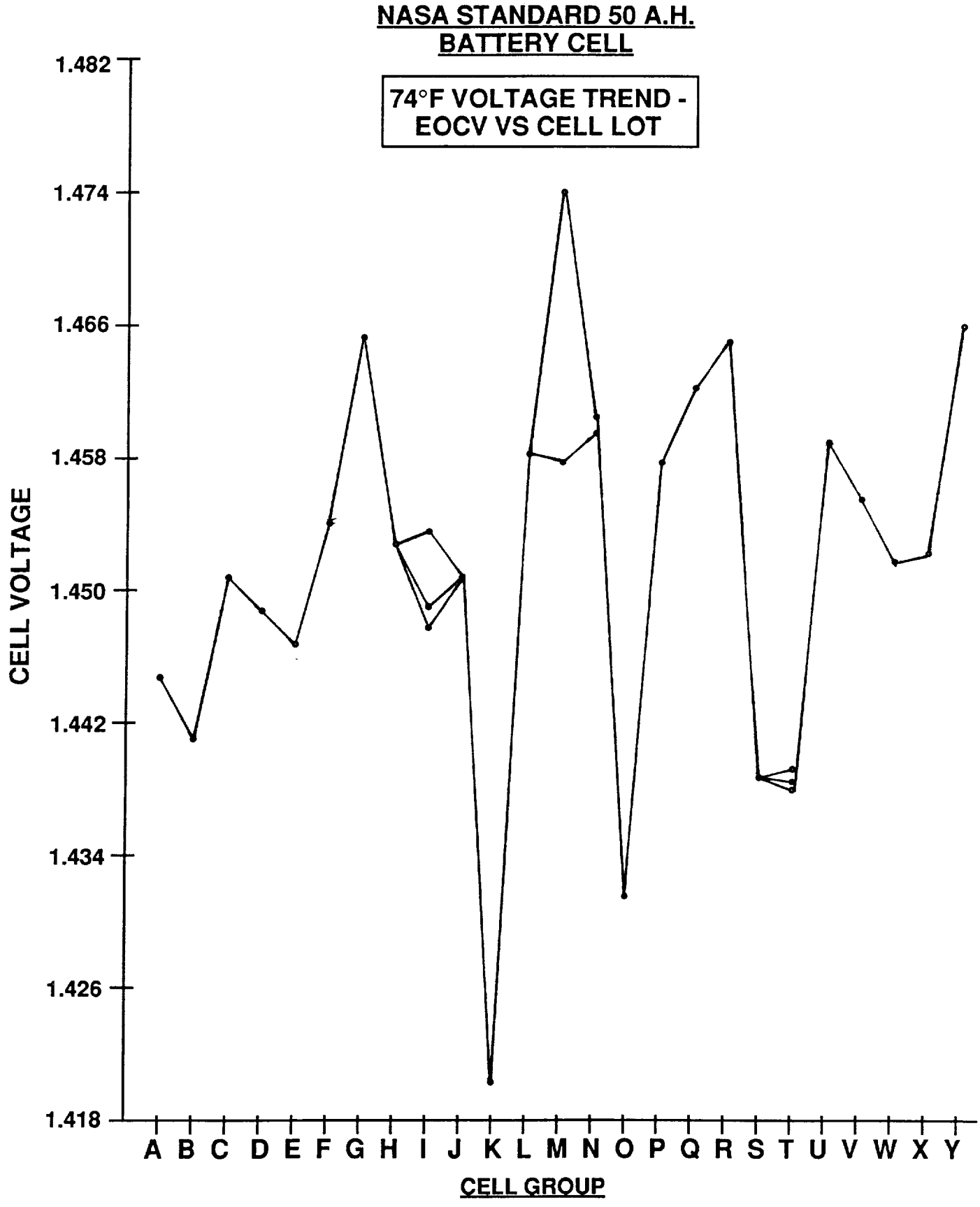
CELL VOLTAGE
32HRV
EOCV
A B C D E F G H I J K L M N O P Q R S T U V W X Y
CELL GROUP

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

	CELL LOT	74°F EOCV	74°F EOCP (PSIG)	74°F CAPACITY (A-M)
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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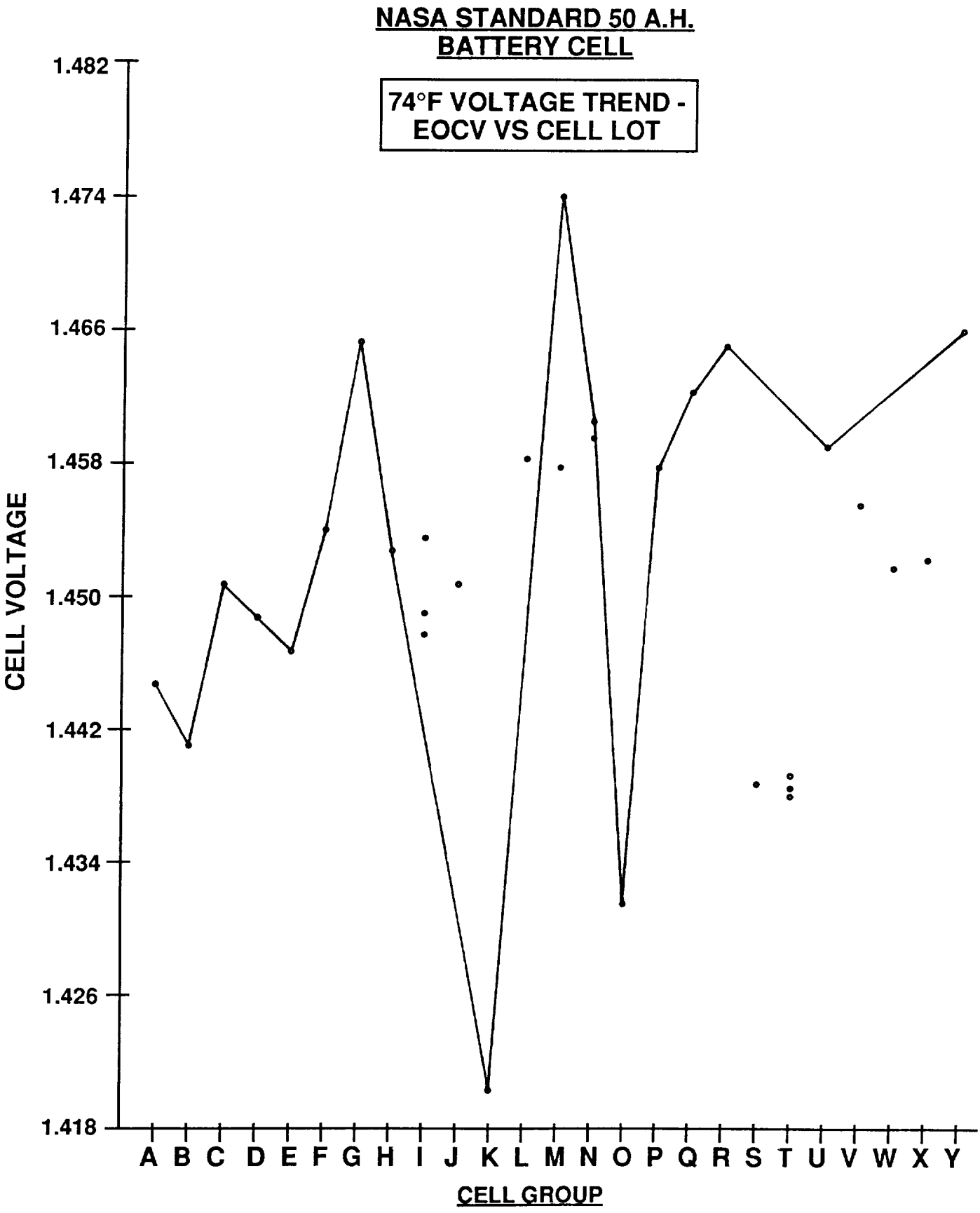
BATTERY CELL
74°F VOLTAGE TREND -
EOCV VS CELL LOT
CELL VOLTAGE
1.482
1.474
1.466
1.458
1.450
1.442
1.434
1.426
1.418
A B C D E F G H I J K L M N O P Q R S T U V W X Y
CELL GROUP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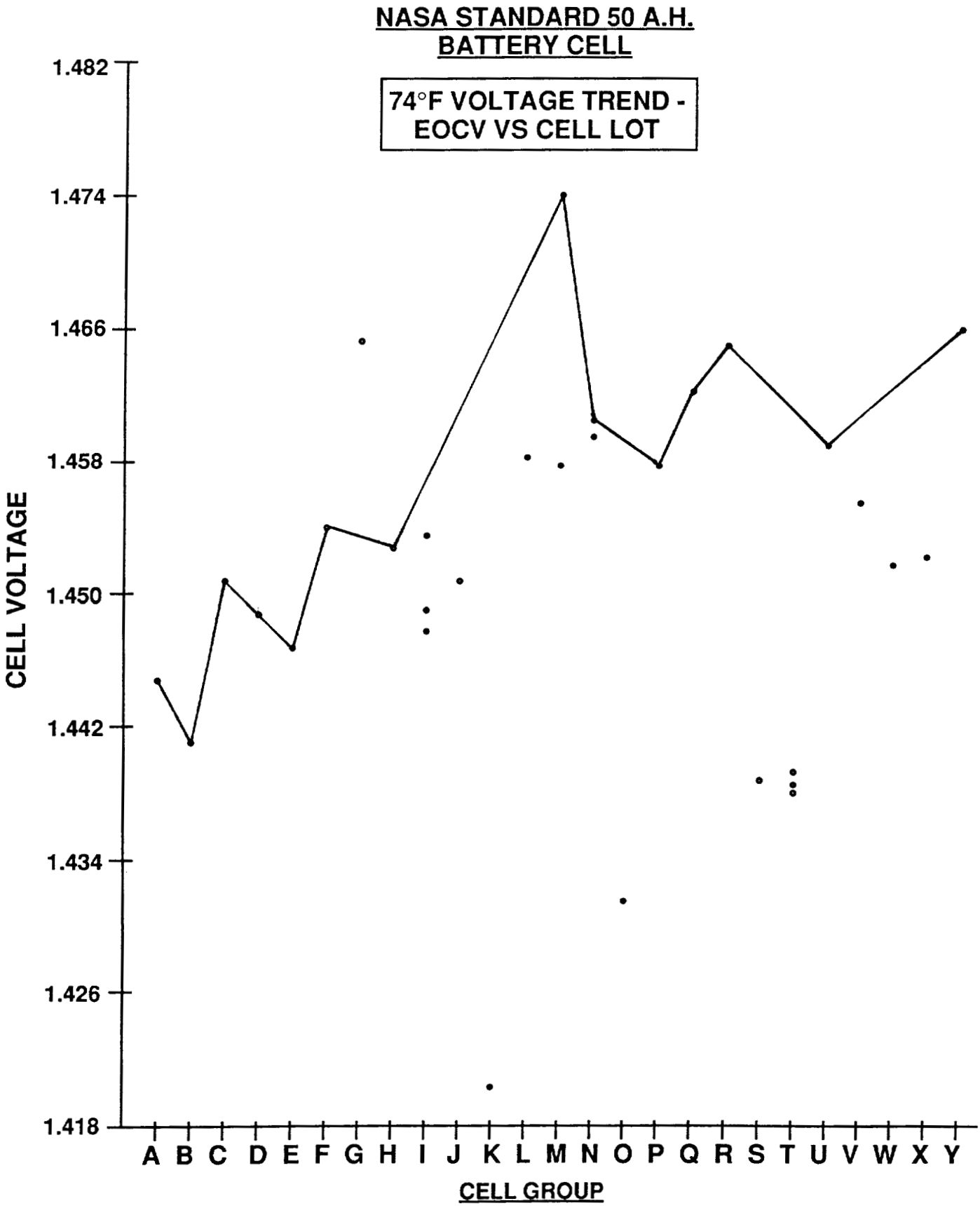
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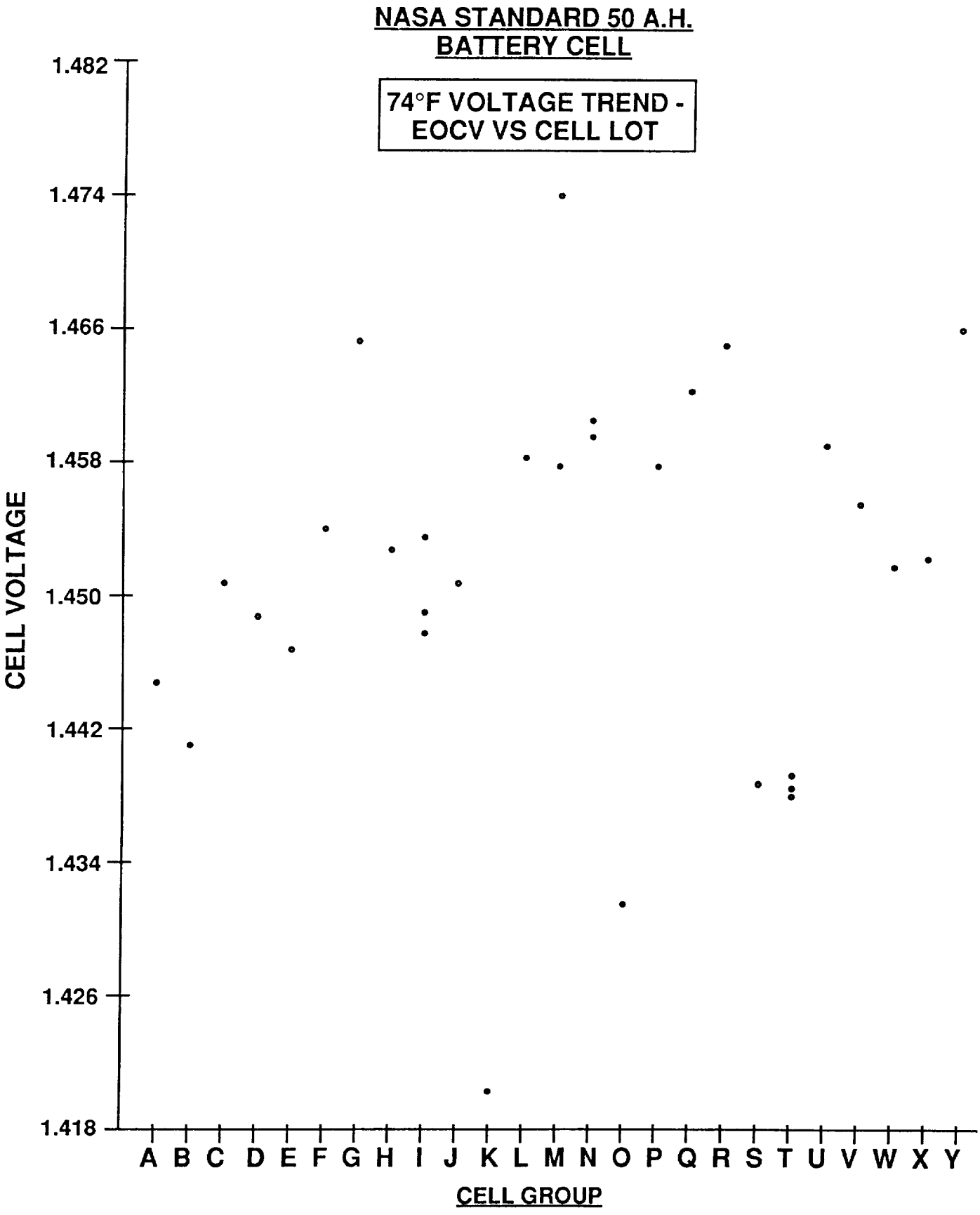
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A B C D E F G H I J K L M N O P Q R S T U V W X Y
CELL GROUP

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	X		
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		X	
(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 NEGATIVE (AH)	OVERCHARGE PROTECTION (AH)	TOTAL PRECHARGE (AH)	SAMPLE POINT: 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	
LOT 17-90	139.73	33.65	26.52	X		P/A
L17-87	136.26	28.45	26.73	X		
L17-81	137.00	26.62	29.95			F/A
L17-69	135.91	24.85	31.44		X	
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	

C-5

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 SHORTDOWNS SHOULD BE AVOIDED

9. EOCV HAS INCREASED AT BOTH 32°F AND 74°F

NASA STANDARD 50 A.H. NICKEL CADMIUM BATTERY CELL

CELL-LEVEL PERFORMANCE HISTORY

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

DAN DELL	GATES AEROSPACE BATTERIES
GLENN KLEIN	GATES AEROSPACE BATTERIES
GUY RAMPEL	GATES AEROSPACE BATTERIES
TRISH BROWN	GATES AEROSPACE BATTERIES
DR. GERRY HALPERT	JET PROPULSION LABORATORY
THOMAS YI	NASA - GODDARD SPACE FLIGHT CENTER
KEN SCHWER	NASA - GODDARD SPACE FLIGHT CENTER
DON WEBB	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

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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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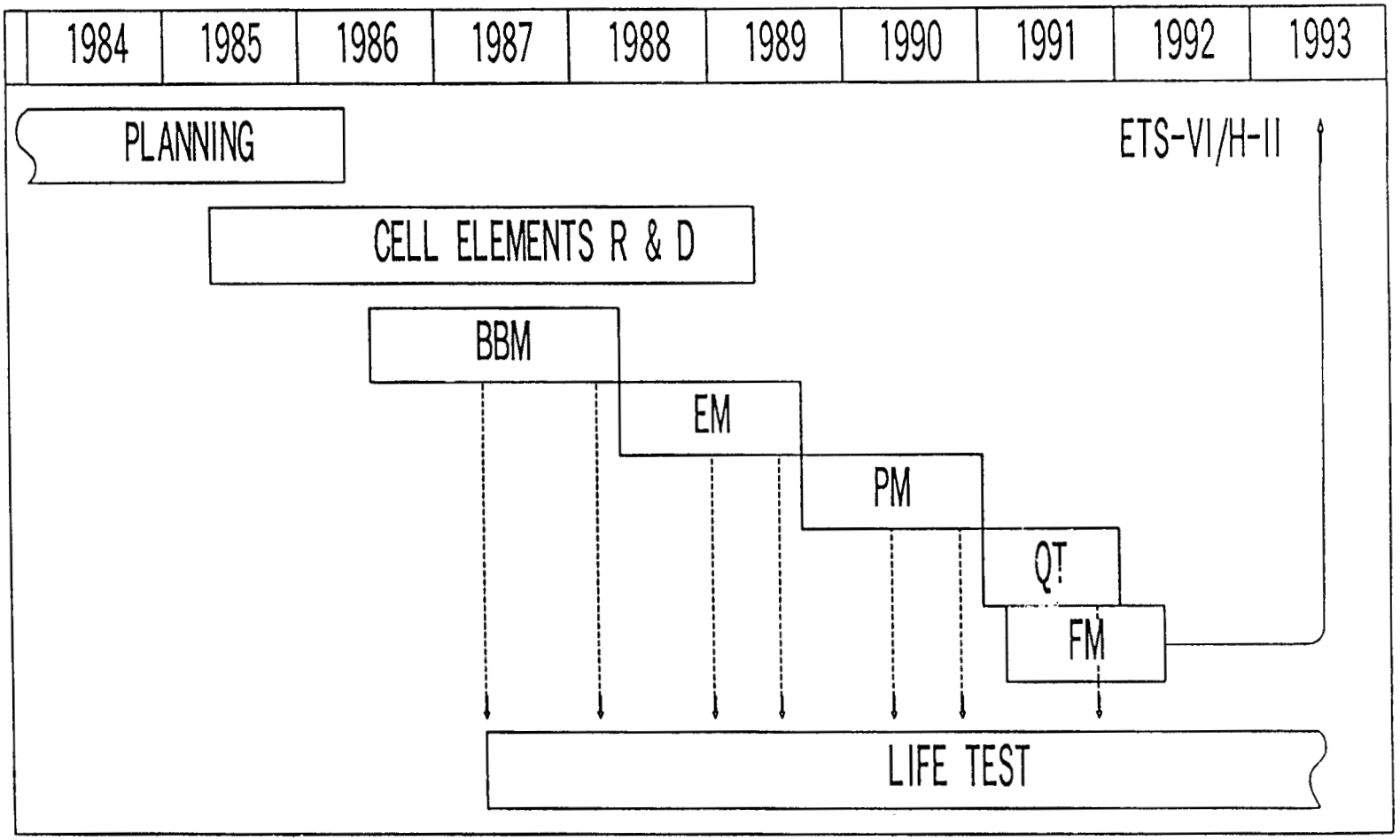
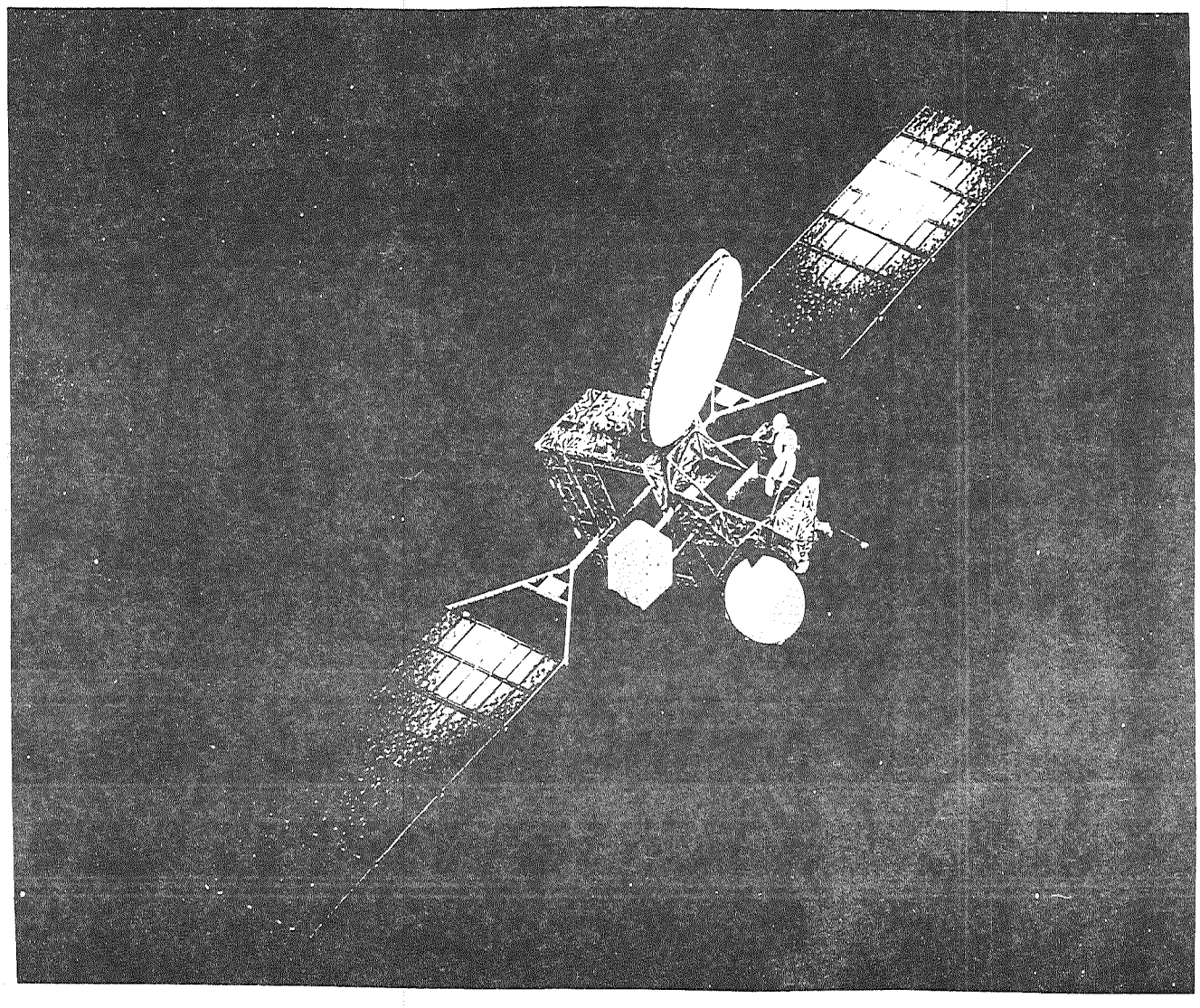
MILESTONE OF 35AH Ni-Cd CELL DEVELOPMENT



ENGINEERING TEST SATELLITE VI (ETS–VI)



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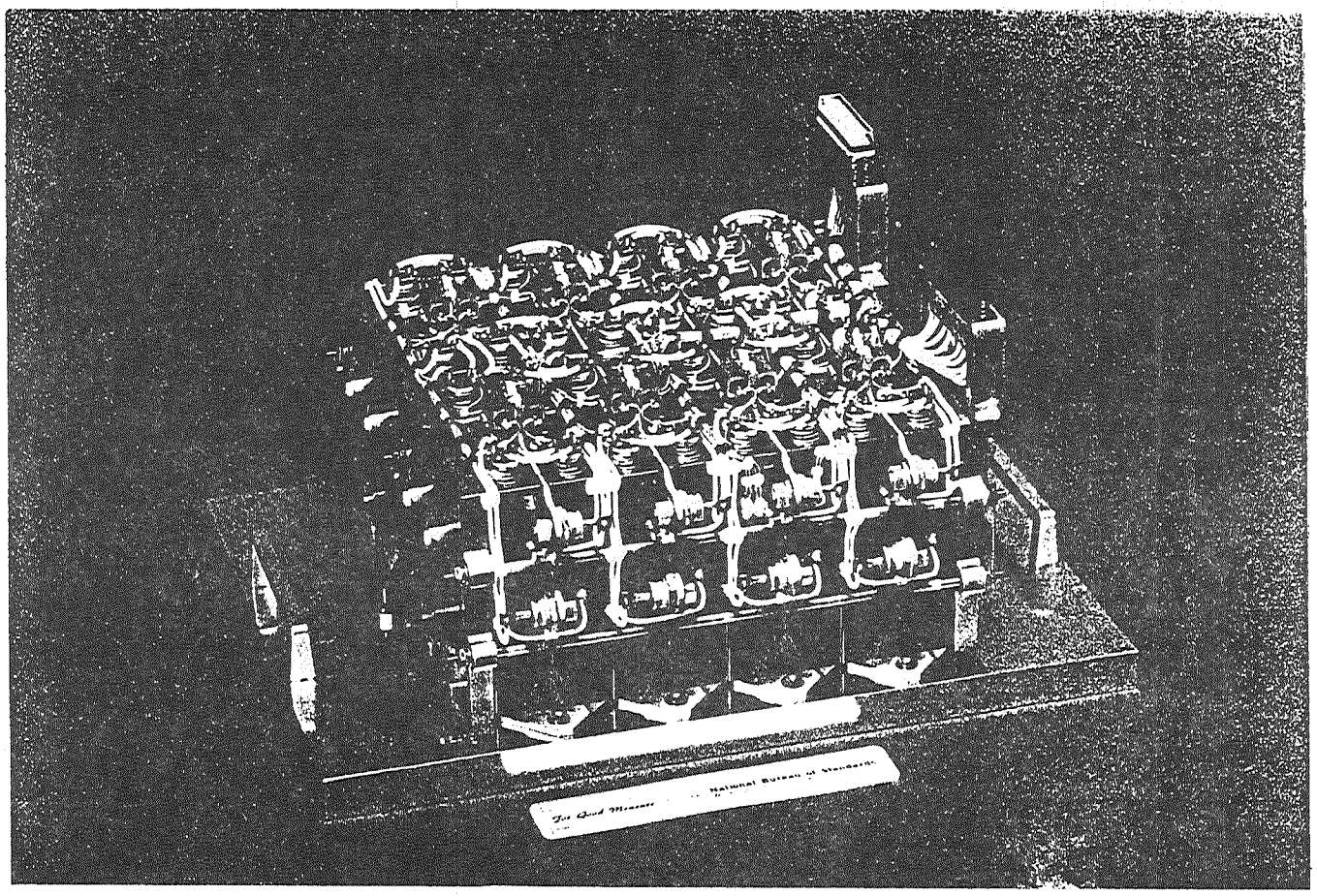
ETS－Ⅵ Ni-Cd BATTERY



＊Engineering Model

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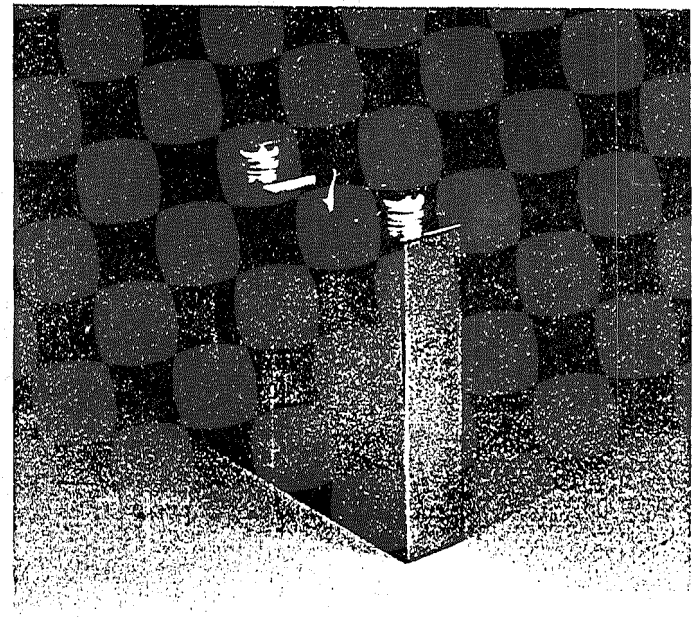
35AH SPACE Ni-Cd CELL

CELL MAJOR SPECIFICATIONS

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



EXTERNAL VIEW OF Ni-Cd CELL

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CELL DESIGN

- 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.

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CELL DESIGN

	(+)	(−)
Electrode Dimension	104.4 × 100 × 0.63mm	104.4 × 100 × 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 × 106.9W × 25.2Tmm (max.127Hmm)	
Cell Weight	max.1050g	
Cell Capacity	38.6AH	

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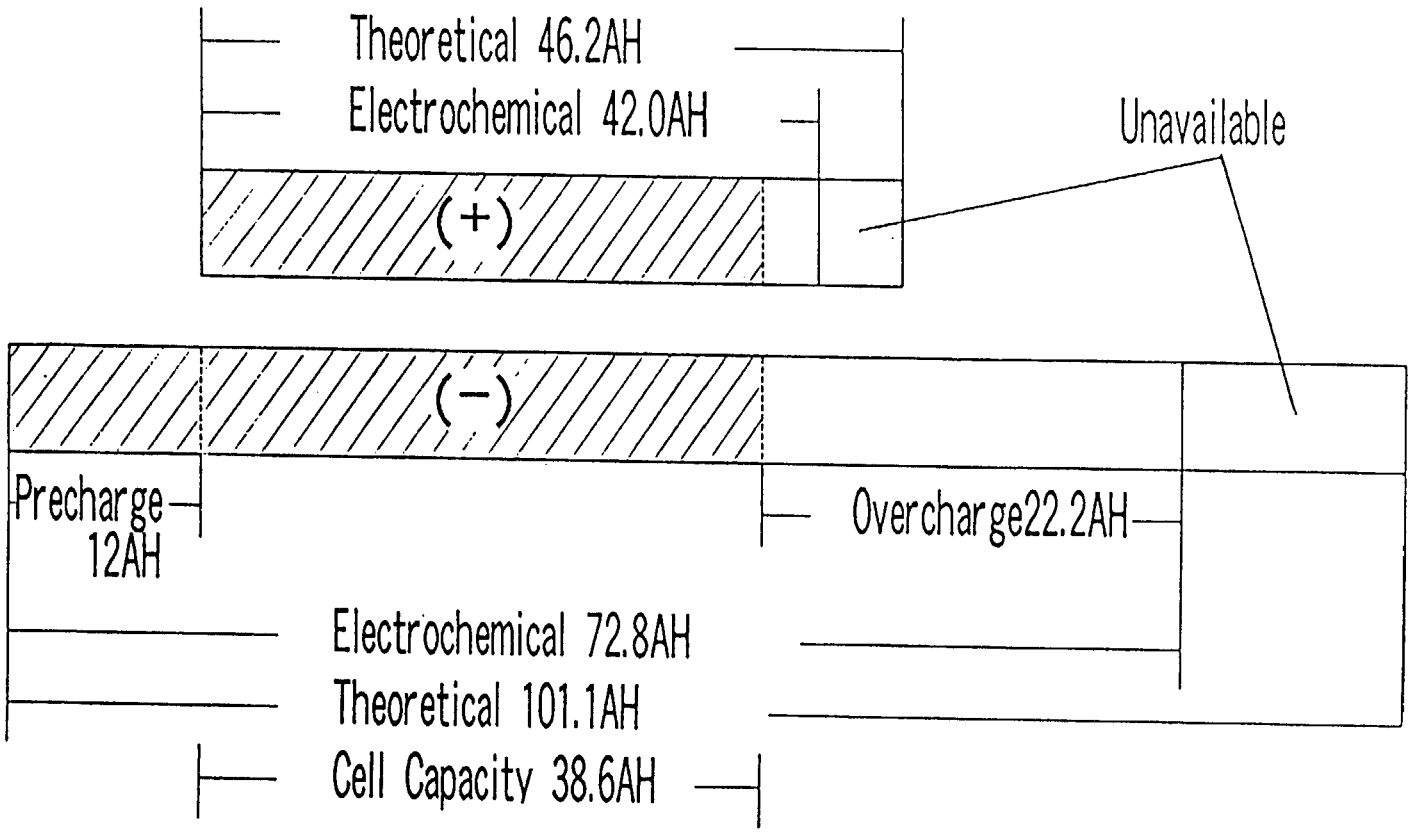
ELECTRODE CAPACITY DESIGN



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CELL INITIAL DATA

- The main initial tests of QT phase are as follows:
  - overcharge capacity test (-5℃, 20℃, 35℃)
  - 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.

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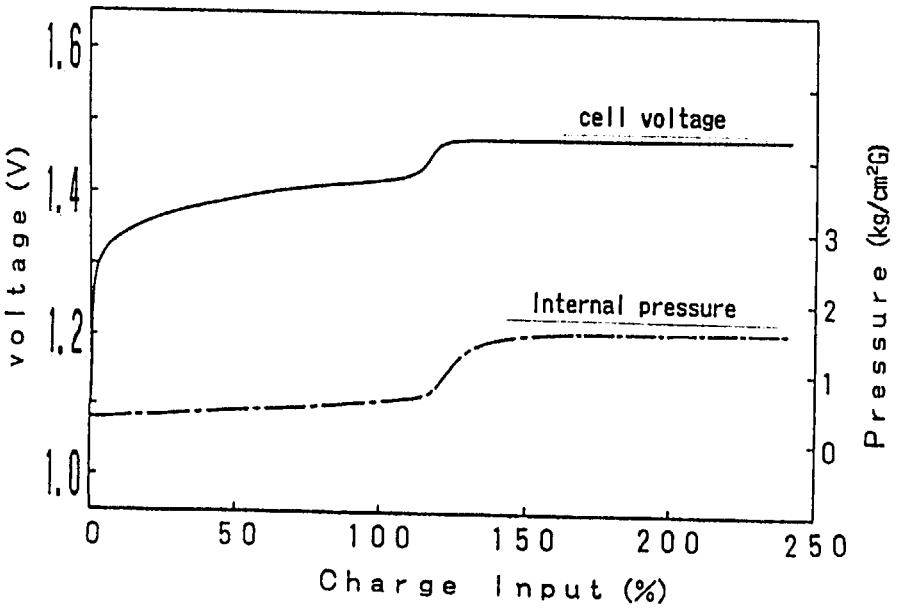
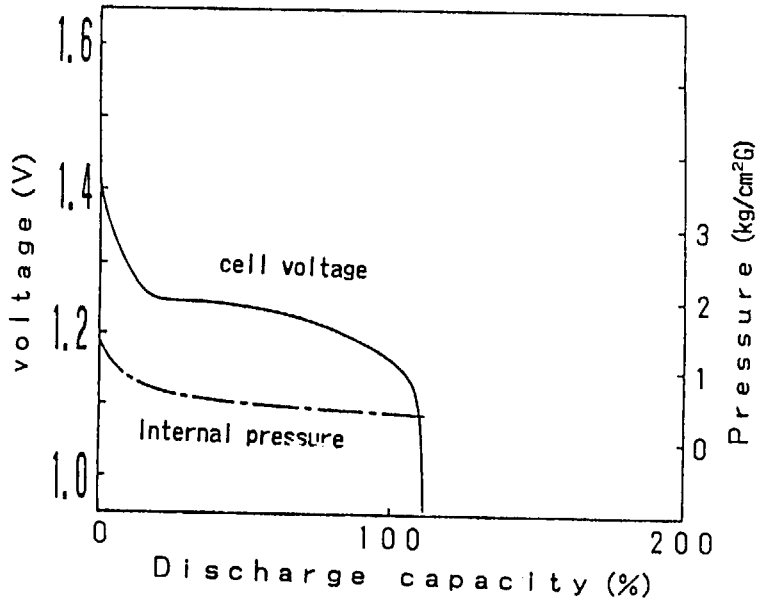
Ni-Cd CELL INITIAL DATA

CHARGE



DISCHARGE



TEST CONDITION
CHARGE : 0.1C for 24 Hours
DISCHARGE : 0.5C to 1V
TEMP : 20℃

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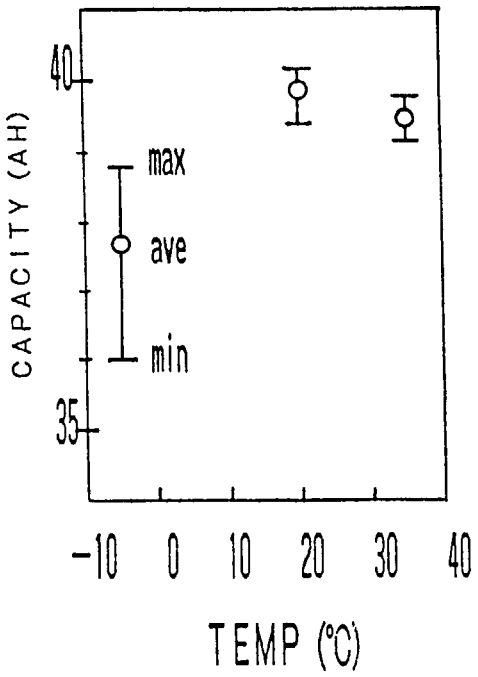
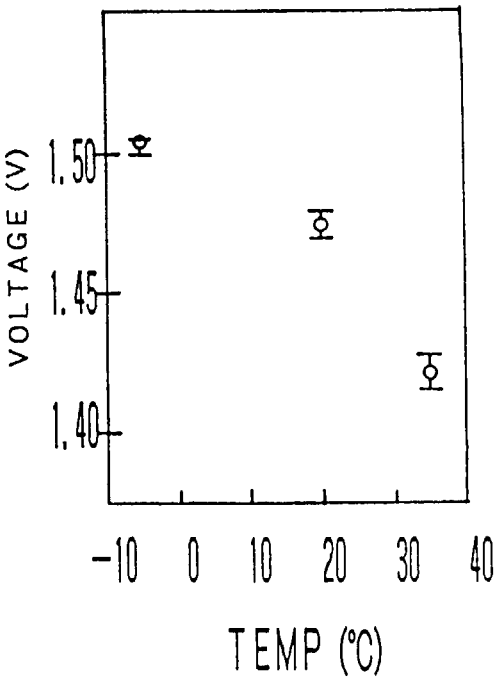
Ni-Cd CELL INITIAL DATA

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

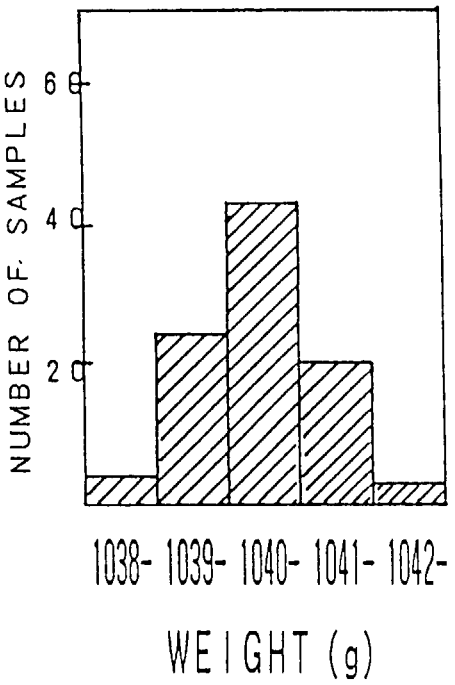
CELL CAPACITY



E O C V



CELL WEIGHT



TEST CONDITION CHARGE : 0.1C for 24 Hours (In −5℃, 0.05C for 48 Hours)
DISCHARGE : 0.5C to 1V

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BATTERY TEST FACILITY IN TSUKUBA SPACE CENTER

- NASDA has a battery test facility in TKSC, which consists of 4 equipment for Ni-Cd batteries, and 1 equipment for Ni-H2 batteries and for electrodes respectively.
- Each test equipment is independently controlled by each computer.
- Test data is transfered 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 ±2℃ range of the expected temp.
- Also cooling plates are available especially for battery assembly tests.

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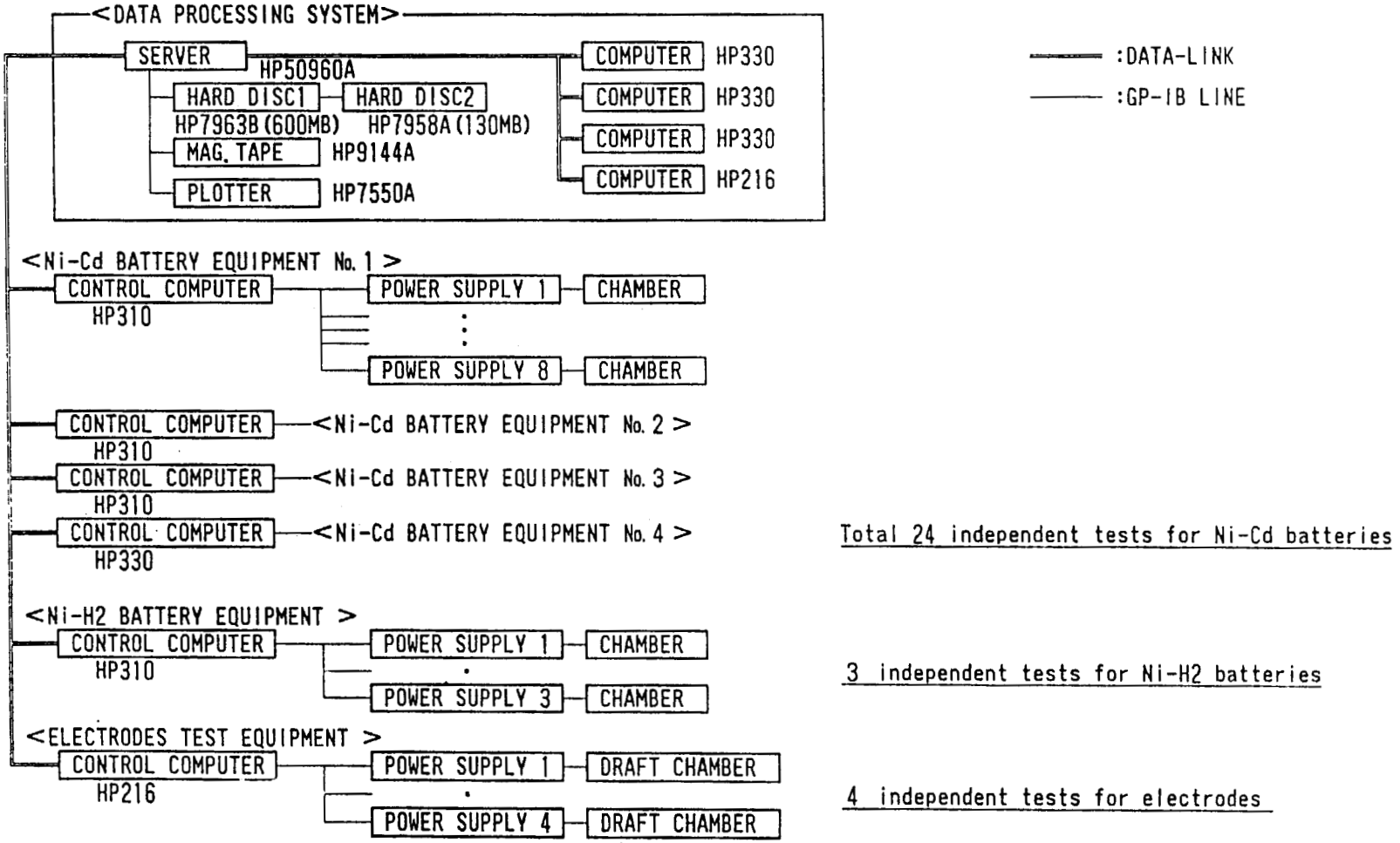
BATTERY TEST SYSTEM IN TSUKUBA SPACE CENTER



Total 24 independent tests for Ni-Cd batteries

3 independent tests for Ni-H2 batteries

4 independent tests for electrodes

BATTERY TEST at NASDA TKSC

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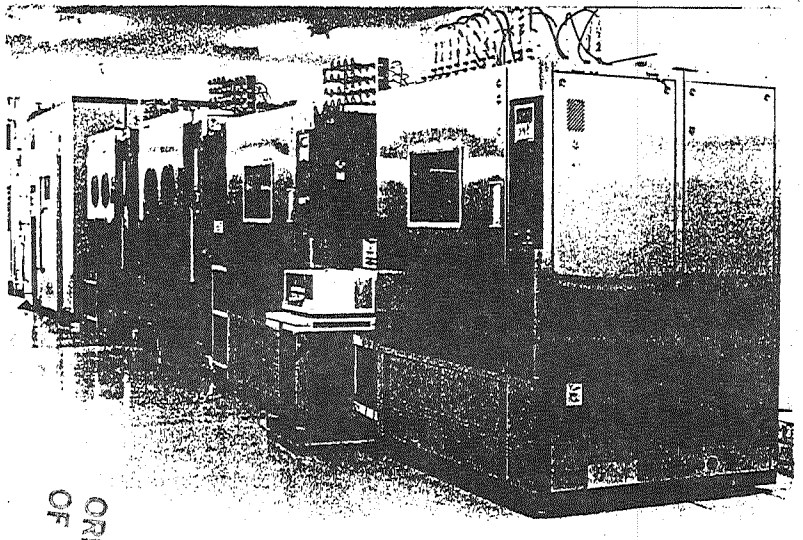
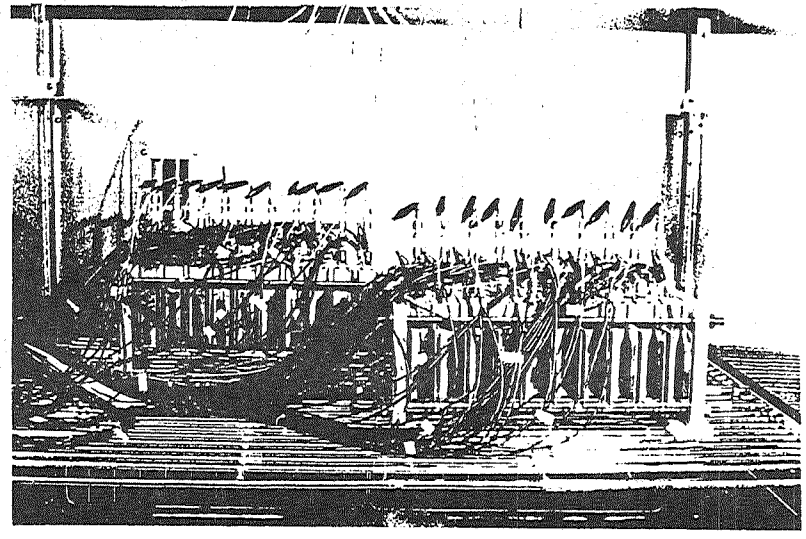
筑波宇宙センター　Ni-Cd 電池寿命試験





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LIFE TEST DATA

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

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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℃	1186 (Finished)
2	BBM	LEO	25%	20℃	17334
3	BBM (*2)	ACCELERATED	60%	30℃	1429 (Finished)
4	EM1	GEO	60%	20℃	1530
5	EM1	LEO	25%	20℃	15235
6	EM2	GEO	60%	20℃	1350
7	EM2	LEO	25%	20℃	12517
8	EM2	TRICKLE CHG	——	20℃	677 day
9	EM2 ASSY	LEO	20%	5℃	7560
10	PM1	ACCELERATED	80%	20℃	1968
11	PM2	GEO	60%	20℃	370
12	PM2	LEO	25%	20℃	2795
13	PM2	TRICKLE CHG	——	20℃	175 day
14	PM2 ASSY	GEO	50%	20℃	210

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

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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 45 cycles	DO NOT	DO NOT
Capacity test (*2)	every 45 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.

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EVALUATION OF SEPARATOR

- 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

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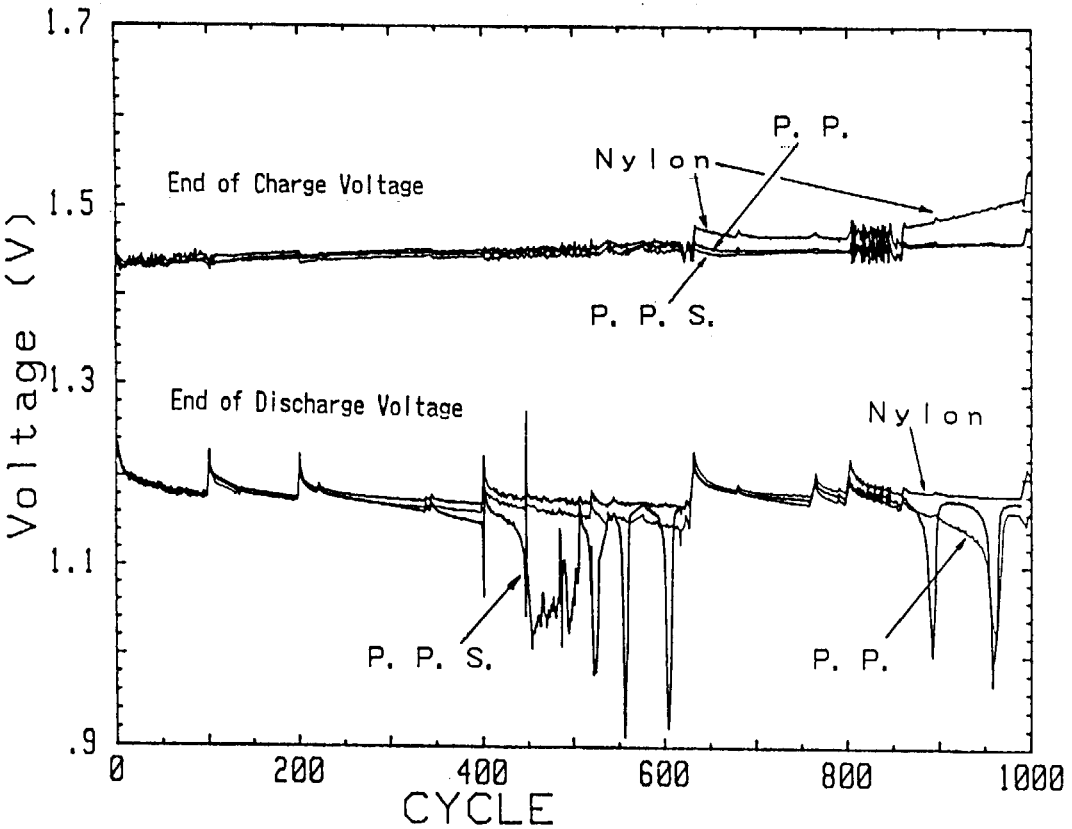
EVALUATION OF SEPARATORS

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/m²	79g/m²	84g/m²
Retention	326%	282%	320%

TEST CONDITION

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

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EVALUATION OF ELECTROLYTE & PRECHARGE

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.

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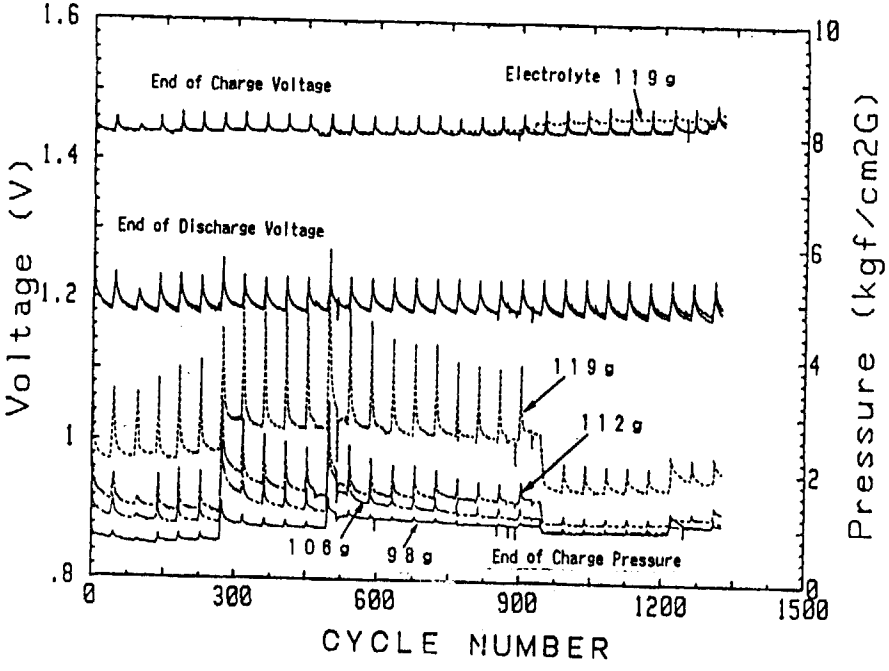
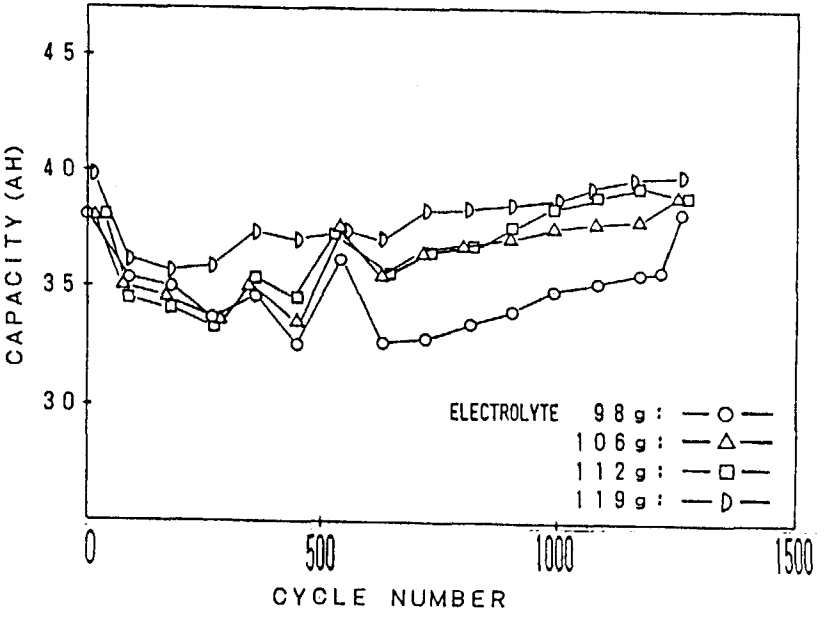
EVALUATION OF ELECTROLYTE

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

CYCLE TREND OF VOLTAGE & PRESSURE



CYCLE TREND OF CAPACITY



TEST CONDITION : SAME AS GEO TEST

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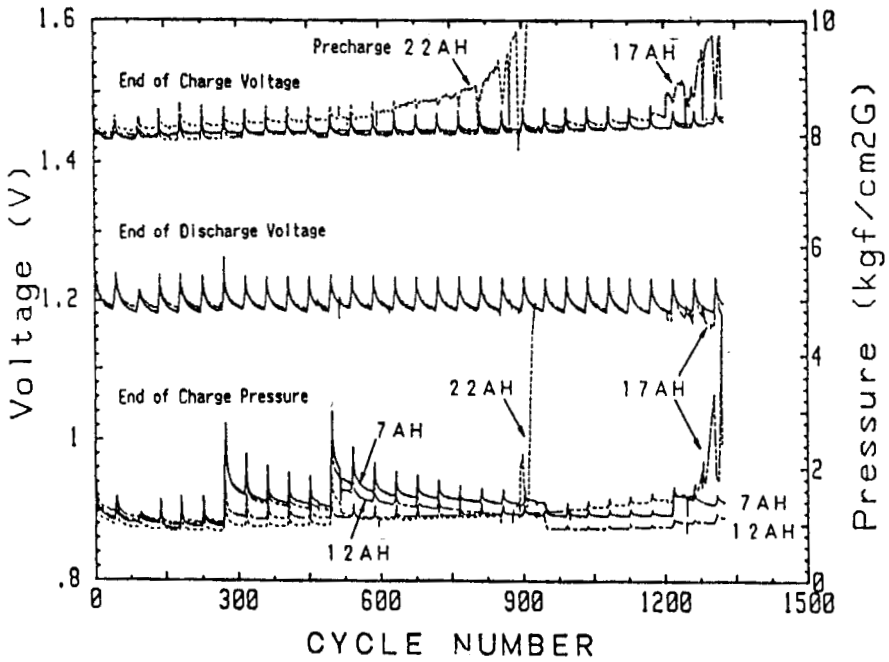
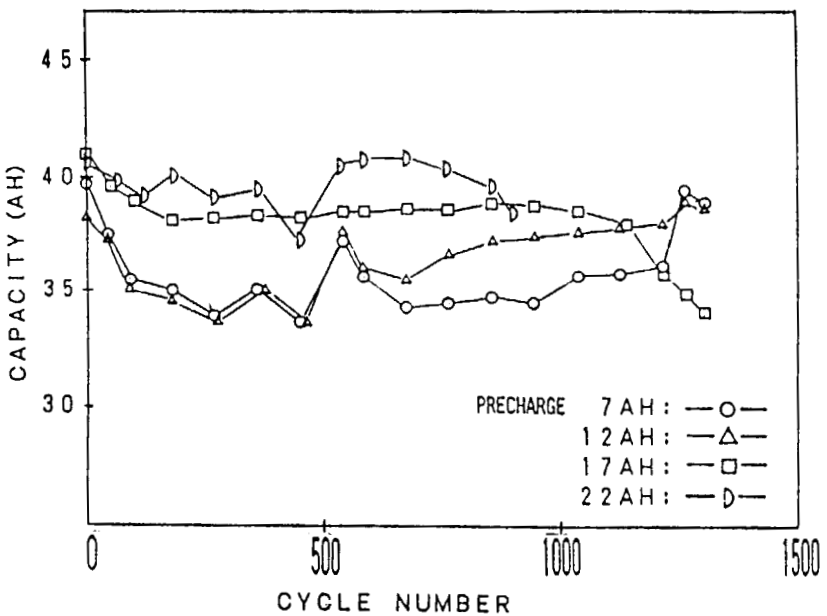
EVALUATION OF PRECHARGE

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

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TYPICAL LIFE DATA

GEO test

- EM1 cells data is presented as typical GEO life data.
- Voltage & pressure data were stable, but the capacity degradation was observed after about 1,000cycles.
- 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.

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TYPICAL LIFE DATA (cont.)

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% bacause 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.

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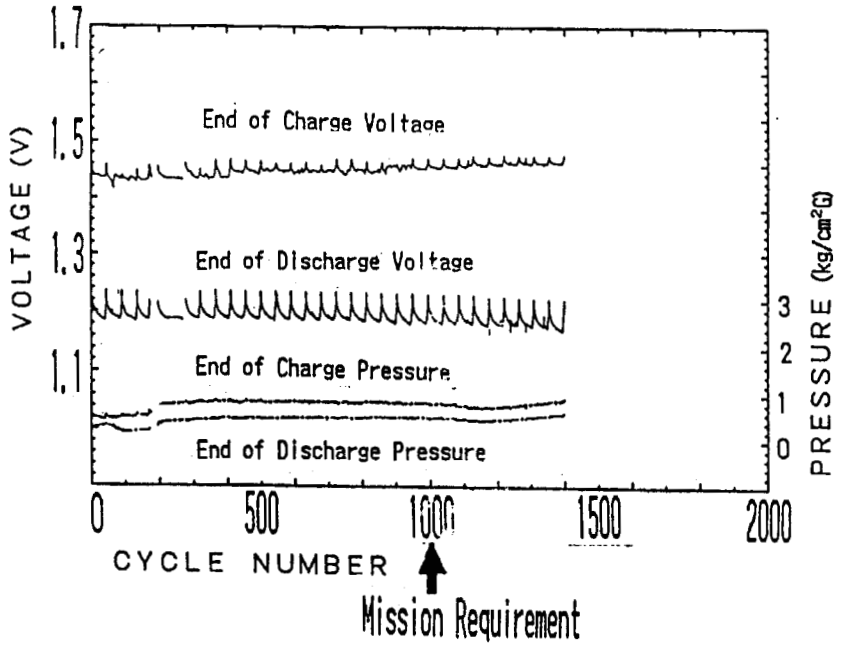
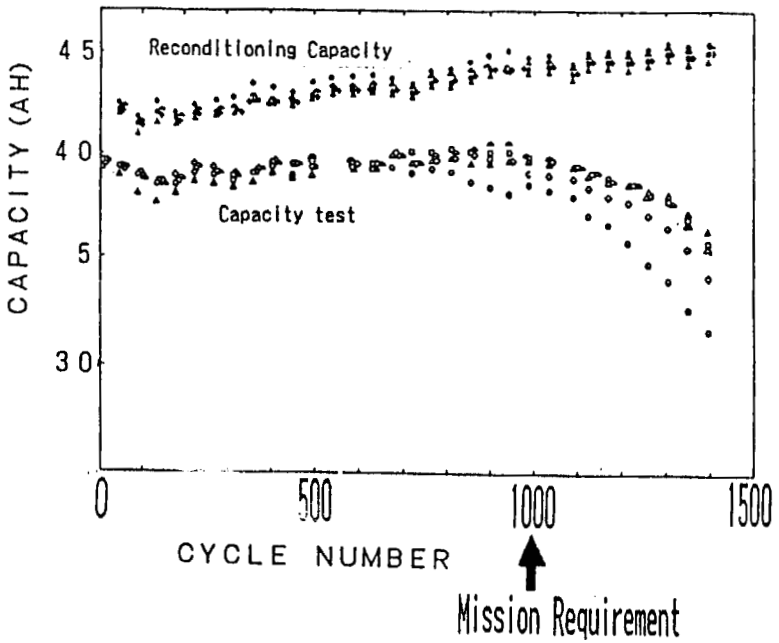
TYPICAL LIFE DATA (GEO SIMULATION)

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

CYCLE TREND OF VOLTAGE & PRESSURE



CYCLE TREND OF CAPACITY



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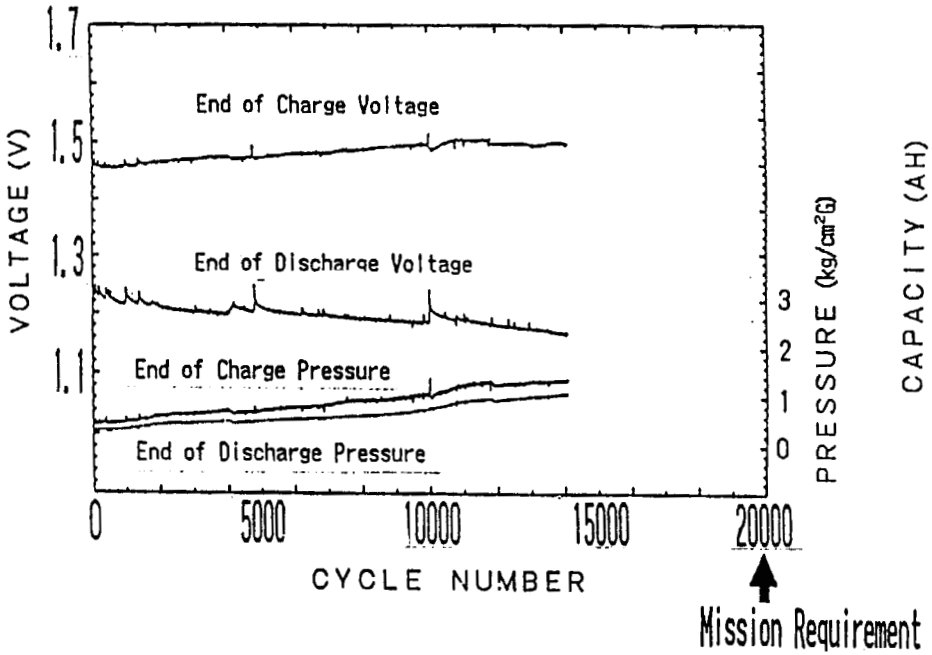
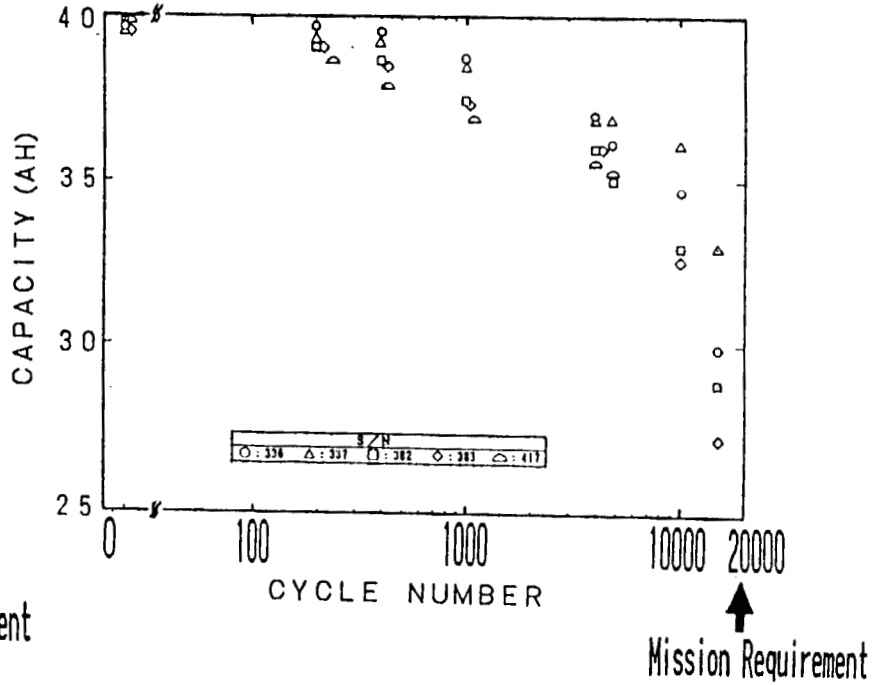
TYPICAL LIFE DATA (LEO SIMULATION)

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



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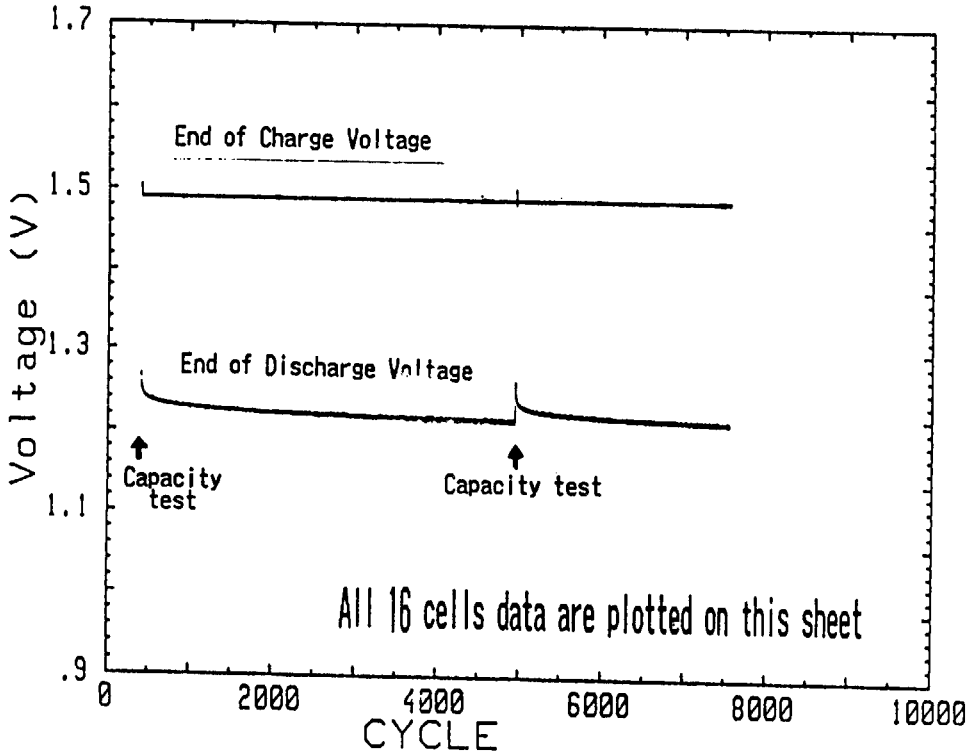
TYPICAL LIFE DATA (BATTERY ASSY LEO)

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℃

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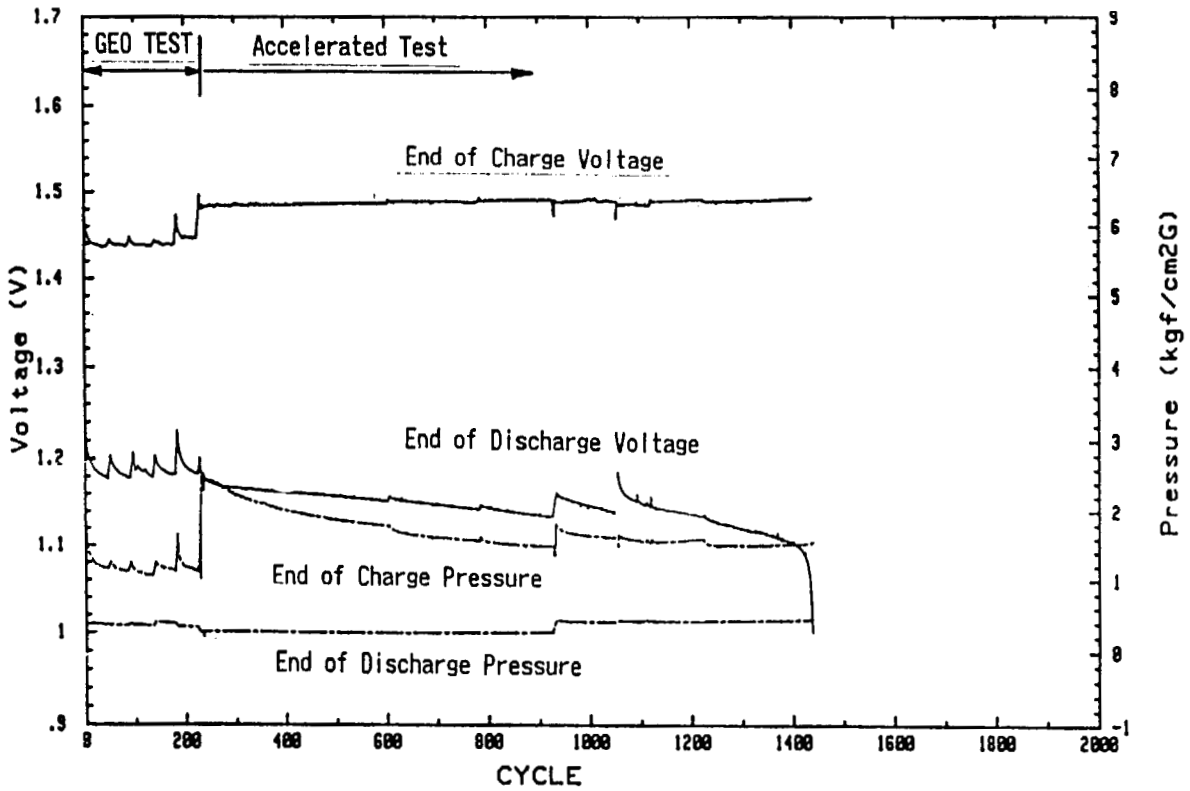
TYPICAL LIFE DATA (ACCELERATED CYCLE)

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

CYCLE TREND OF VOLTAGE & PRESSURE



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ADVANCED CELL DESIGN

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.

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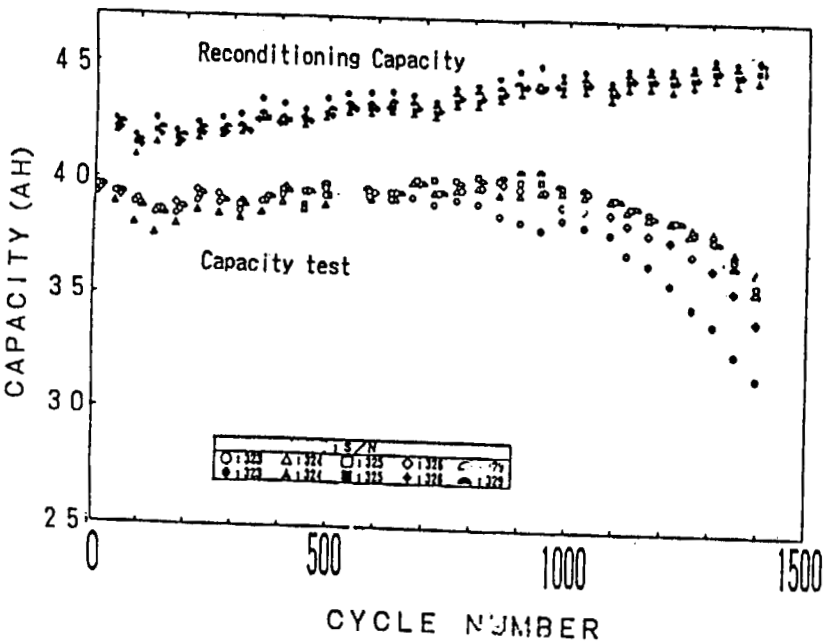
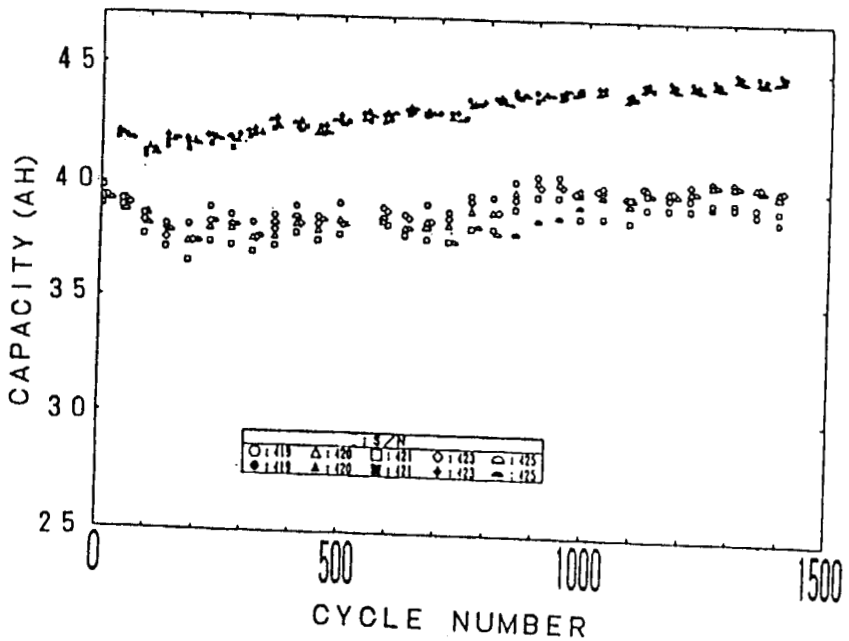
ADVANCED CELL DESIGN (1)

ALKALINE WASHING FOR SEPARATOR IS EFFECTIVE FOR STABILITY OF CAPACITY.

CURRENT DESIGN CELL → ADVANCED → ALKALINE WASHING FOR SEPARATOR





TEST CONDITION : SAME AS GEO SIMULATION

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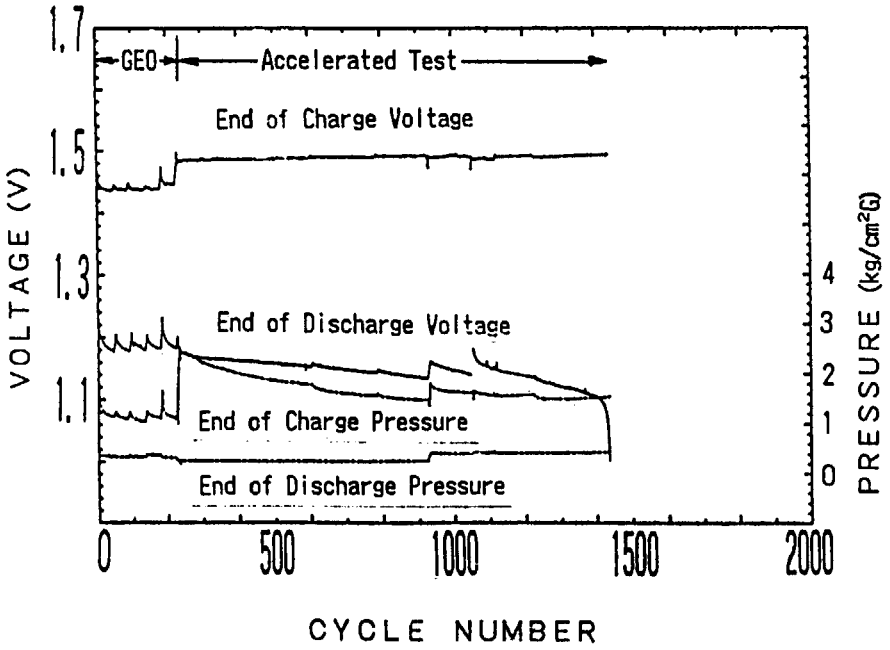
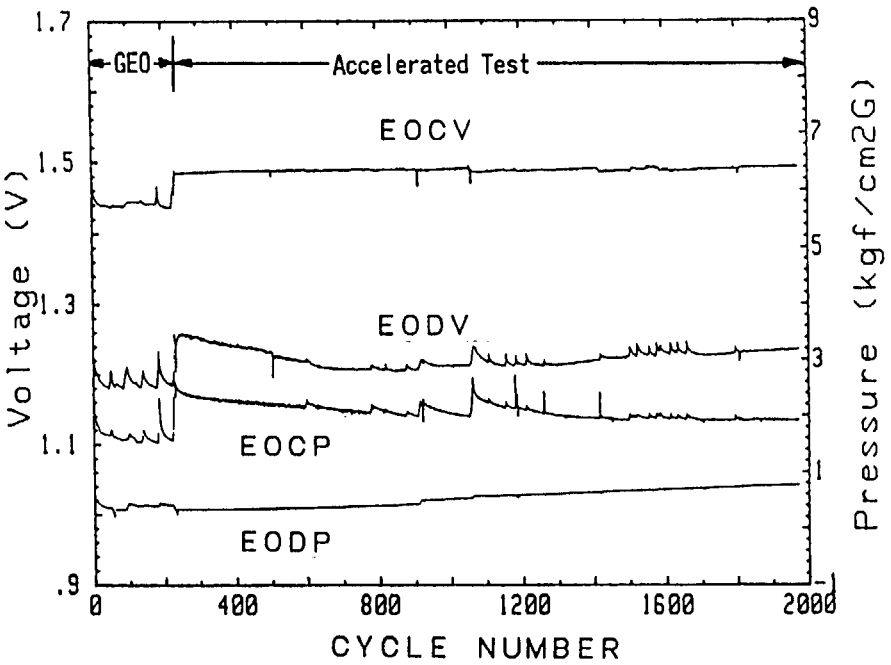
ADVANCED CELL DESIGN (2)

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-6 confidently.
- Presently the LEO test is at about 15,000 cycles, of course, we expect to achieve the 20,000 cycles successfully, since we want to use these cells for the LEO mission of ADEOS which is our test satellite launched in 1995.

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CONCLUSION (cont.)

- It was verified that two treatments were effective for the cell performance.
- But these methods were not adopted for flight cell design of ETS-6, since there is not enough data in the time when the flight cell design might be decided.
- We will adopt it for future cell design.

Our future program on Ni-Cd cells is as follows:

1. Inprovement of 35AH cells (and use in ADEOS)
2. Development of 25AH cells based on 35AH cells
3. Development of 50AH cells with another design

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SUMMARY

1. High energy density of 40WH/kg with current design was developed

2. The life of current design cell is as follows:
   - GEO Test (DOD 60%) --- over 1,400 cycles
   - LEO Test (DOD 25%) --- over 15,000 cycles
   - Accelerated Test (DOD 80%) --- 1,400 cycles

3. The following methods are effective for increasing the cycle life in the advanced cell design.
   - Alkaline washing for separator
   - Organic compound treatment for negative electrode

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FUTURE PROGRAM

1. Inprovement 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

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Glenn C. Klein
Gates Aerospace Batteries

Analysis of Nickel-Cadmium Battery Reliability Data Containing Zero Failures

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Reliability Analysis Center

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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

α = characteristic life, time to 63% population failure
β = 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^{th} part or survival time of the i^{th} part if it has not failed
r = Number of failures
n = Total population of parts

Since the data collected and presented in Table 1 indicates r=0, a characteristic life of infinity implied by this estimate is clearly erroneous. The fact that no failures have been observed indicates only that enough time has not elapsed to experience failures. As stated previously, the appropriate analysis methodology to use under these conditions is to apply confidence limits to derive worst case reliability values. From this, lower bound estimates of lifetimes can be made within a given confidence level. To accomplish this, the Chi-square distribution can be utilized. The lower confidence limit for the Weibull distribution in the case where no failures have occurred is;

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

where

χ^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;

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

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 β values listed. For example, the α lower

limit of 52 at 90% confidence is only valid if a β of 2 represented the original population.

TABLE 2: LOWER LIMIT OF α (YEARS)

β	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 α in Table 2 may appear to be unrealistically high for low confidence levels and low β values, they are included to illustrate the dependency of characteristic life to these values.

The characteristic lifes listed in Table 2 are therefore the lower confidence limit of the actual failure distribution. For example, assuming a beta of 4, one can be 90% certain that the characteristic life is greater than 25 years, or 99.9% certain it is greater than 19 years.

To estimate typical β 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 α and β values were derived. From this data, the range of β values were observed to be between 1 and 4. Although the characteristic life α from this data is a function of cycles, its absolute value is not important for the purposes of this analysis since extraction of typical β values was the primary concern. Based on this information, a conservative β value of 4 can be used in lieu of empirical β's for Gates NiCd cells. If time-to-failure data becomes available, the chosen value of β can be modified.

TABLE 3: WEIBULL ANALYSIS RESULTS

Manufacturer	α	β
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 α. 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

β	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

β	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, β. The

shape parameter β is a critical factor in lower bound life estimations and since the data used in this methodology is survival data only, the β cannot derived from empirical data. Therefore to adequately use the analysis methodology outlined in this paper, a β 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

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REPORT OF INVESTIGATIONS INTO CHARGED CADMIUM REACTIVITY: NICKEL-CADMIUM CELLS

Ref: (a) Comparison of Physical and Chemical States of Two Separator Type Ni-Cd Cells From a Satellite Simulation Program, Presentation at 25th Annual IECEC Meeting

1. Introduction.

a. In August 1990, a presentation was given, reference (a), at the 25th Annual IECEC meeting in Reno, Nevada on the results of Destructive Physical Analysis (DPA) on two successive sets of Ni-Cd cells. The cells were of two different separator types, Pellon 2505 and 2536. One cell of each separator type was analyzed on two occasions; the first pair were analyzed October-November 1988 to establish baseline data on essentially new cells; the second pair were analyzed in January-February 1990 after the cells had been on charge-discharge cycling for a year in connection with a satellite simulation study at Naval Weapons Support Center Crane (NWSCC).

b. During the report presentation, several questions arose concerning the gas composition found in the cells, the absence of charged cadmium in the analytical data presented, and the appearance of dried-out portions on the Cd plates in the one-year cell S/N 7 which utilized Pellon 2505 as its separator material. It is the intention of this report to respond to the stated concerns and to clarify the observational results.

2. Procedures.

a. Gas Compositions. The data presented in reference (a) for gas compositions in the cell head spaces were given as percent of total, and it was stated that the actual cell pressures were much less than one atmosphere. In the Results section following, the original data are converted to mole quantities for clarification.

b. Cadmium Analysis. The absence of residual quantities of cadmium metal in the analytical data from the anode analysis utilizing the 1980 Revision A NASA Goddard[1] 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_2 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_2 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_2 bubbling through the solution. The intent was to provide insofar as possible a ready environment for alkaline solution oxidation of residual Cd in the plates. After this treatment, the plates were extracted and dried as before, and analyzed along with the control half-plates for charged and discharged cadmium. The nickel plates from the cells utilized in this paragraph were treated exactly the same to determine whether the nickel in the $Ni(OH)_2$ state could be reoxidized to NiOOH or NiO_2. 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_2	53.64	18.44	17.84	17.34
% He	14.48	6.97	33.08	24.81
% N_2	30.45	62.95	48.44	55.74
% O_2	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

$$n(H_2) = \frac{(2\times10^2\text{torr} \times 0.5364) \times 10\text{cc}}{6.24\times10^4\text{cc torr K}^{-1}\text{ mol}^{-1} \times 3\times10^2\text{K}} = 5.7\times10^{-5}\text{mol}$$

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_2	5.7×10^{-5}	3.7×10^{-5}	4.8×10^{-5}	6.6×10^{-5}
Moles He	1.5×10^{-5}	1.4×10^{-5}	8.9×10^{-5}	9.4×10^{-5}
Moles N_2	3.2×10^{-5}	1.3×10^{-5}	1.3×10^{-4}	2.1×10^{-4}
Moles O_2	1.5×10^{-6}	2.3×10^{-5}	1.7×10^{-6}	8.0×10^{-5}

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 then 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

$$Cd \longrightarrow Cd^{2+} + 2e^- \ (Cd^{2+} \text{ as } Cd(OH)_2)$$

so the recovered cadmium hydroxide converts as

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

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

$$NiOOH + H_2O + e^- \longrightarrow Ni^{2+} + 3OH^-$$

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

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

while the remaining NiOOH would consume

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

for a total of 0.718mol e^-. The ratio of Cd to NiOOH is almost 2:1 in terms of electron exchange, so the positive electrode (Ni) should be the limiting electrode. However, if upon complete discharge of a cell no Cd is found during DPA, but NiOOH is observed, then it is probable that the cell would have behaved as though it was negative plate limited if driven to reversal.

c. Cadmium Reactivity. The previous calculations raise an immediate question as to why no cadmium metal was found in the analysis. There are several possible explanations:

(1) Cd metal could dissolve in the electrolyte once air is admitted to the cell. It has been observed in these labs that the Cd plates from AA-size cells become warm to the touch during cell disassembly in ambient air and it is known that Zn plates from Ag/Zn batteries will ignite in air if saturated with KOH. The Ni and Cd plates within the cell are exposed to an air atmosphere once the cell has been tapped for gas analysis, and transfer to a nitrogen-purged glove box occurred immediately after gas sampling. Cotton and Wilkinson[2] state that Cd does not react directly with alkaline solutions because Cd is not amphoteric like Zn; Cd cannot form the cadmiate analog to the zincate ion (ZnO_2^{-2}). However, $Cd(OH)_2$ apparently does dissolve in concentrated alkali as a $[Cd(OH)_4]^{2-}$ ion. Mellor[3] reports that Cd forms $Cd(OH)_2$ in moist air. The conversion $Cd \longrightarrow CdO \longrightarrow Cd(OH)_2 \longrightarrow [Cd(OH)_4]^{2-}$ is thus possible. However, when tests were performed in this lab where mossy Cd was immersed in 36 percent KOH and allowed to stand in contact with ambient air for two hours, the samples showed no significant weight loss for Cd. Nevertheless, the observation that plates coated with concentrated KOH and exposed to ambient air become warm indicates that a chemical reaction does occur, and electrochemically prepared Cd may be 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 $Cd(OH)_2$ (discharged material) from Cd metal (charged material) in the negative plate. Again, it is known that Zn plates from silver-zinc batteries suffer the problem of solution of Zn in ammonium acetate-ammonium hydroxide solution. However, when mossy Cd metal was stirred with heating for 2 hours at 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[1] no reagent blank is specified in the Cd metal titration. It has been found that a reagent error amounting to 60 to 70 percent of the total titer for Cd metal must be accounted in this analysis. This would explain why some analysts might report Cd presence from this procedure if it is determined in an analysis where reagent blank corrections are not utilized.

(4) The total Cd analysis performed for the four cells analyzed thus far has accounted for 97 to 99 percent of the weight recorded for the whole plate, for a total of 12 plates analyzed. If a significant analytical error were occurring where Cd metal was being accidently analyzed as $Cd(OH)_2$, then the total analytical weight would be greater than the actual plate weight by 10 to 15 percent at least, since two hydroxy groups are 30 percent of the weight of cadmium. But in fact, in all the cells analyzed, the accumulated weight did not vary from the actual weight by more than +3 percent and in some cases the variation was negative.

d. Cadmium Analysis. The next step was to determine whether charged Cd could be found if Cd plates from another cell type which were known to contain excess charged Cd were dissected and great care were taken to exclude air during cell dissection and plate handling up through the soxhlet extraction of KOH. The procedure is described in Section 2b(1). The analytical results, following that procedure, are as follows:

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 w O_2	2.4202	0.0382	2.4584	1.55
28	2.5416	0.0760	2.6176	2.90
28 w O_2	2.4497	0.0169	2.4666	0.69
30	2.5707	0.0602	2.6309	2.29
30 w O_2	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_2 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[1]. The following table presents the analytical results:

Cell Number	Sample w Grid Charged Cd (%)	Sample wo 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^{2+} ions, even after repeated washings to a filtrate volume of 500ml. Thus an analytical procedure which requires solution of grid substrate containing iron will inherently lower the amount of charged Cd found during analysis.

e. Nickel Reoxidation. A final question which arose during the attempted oxidation of Cd with O_2 was whether $Ni(OH)_2$ could be reoxidized to NiOOH or NiO_2 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_2(%)
28	0.09
28 w O_2	7.02
30	0.09
30 w O_2	7.51

It appears that oxidation of $Ni(OH)_2$ is not only possible, but relatively easy. Consequently, any weight gain observed for a whole cell if O_2 is deliberately used to estimate residual Cd in that cell before DPA may just as well be due to nickel re-oxidation. And in fact, the possibility that iron in the grids can be converted to Fe_2O_3 must also be considered, and we have obtained some evidence which suggests that occurs as well.

f. Analysis Summary. In summary, the following statements may be made:

(1) If there is residual charged Cd in a cell, it does not react so easily with ambient air under alkaline conditions that analysis should give zero Cd. In the original analysis of cells with S/N's 28, 95, 7, and 9, the individual cell results were:

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^{2+} occlusion in gelatinous $Fe_2O_3 \cdot xH_2O$ formed when the entire negative grid and plate material are dissolved in nitric acid in the charged Cd analysis procedures.

g. Infrared Characterization of Separators. The infrared scans of the two separator materials, Pellon 2505 and 2536, are very similar, as expected. However there is a prominent peak at $934cm^{-1}$ in the 2536 spectrum which is absent from the 2505 spectrum. The spectra of S/N's 28 and 9 both exhibit this peak,

and have been identified throughout the analyses as Pellon 2536, while spectra of S/N's 95 and 7, which have been identified with Pellon 2505, are missing this peak. There are, in addition, position shifts in peaks in the 2505 material at 1263, 1170, and 1122cm^{-1}, to 1274, 1180, and 1146cm^{-1} respectively for 2536 which are consistent in both separator sets identified by S/N's 2505 and 2536. Thus, that separator material identified with S/N 7 in which the Cd plates had appeared dried out and discolored is unambiguously Pellon 2505.

Conclusions.

a. As a consequence of the presentation discussed in the introduction to this report, four areas of concern arose in the Ni-Cd community with regard to the reported DPA results on the first four nickel-cadmium cells from a satellite simulation study analyzed at NWSCC in 1988-1989 and 1989-1990. An investigation of the procedures and results which were the basis of those concerns has been completed and the results have been detailed in the preceding sections. The analytical problems and their resolution were developed as follows:

(1) The analysis data of head space gases for the four cells have been converted to mole quantities, using estimations of the head space and sampling device volumes. These are within ten percent of actual volumes but are deliberately estimated large. From the data it can be concluded that the analytical values were consistent with expectations based on the cell preparation procedures and subsequent cycling history.

(2) Calculations based on the analytical values of cadmium and nickel contents of one of the four cells have shown that the mole ratio of cadmium to nickel, in terms of electron exchange, is about 2:1. Therefore, the cells were constructed to be nickel (positive electrode) limiting. But in fact in three of the four cells no residual (charged) cadmium metal was found after complete discharge, while residual NiOOH was found in significant quantities. Indeed, even in the single cell where residual Cd was found, the ratio of residual NiOOH to Cd was 4:1 based on moles of electrons. Consequently, even if the cells were manufactured to be cadmium-rich, if driven to reversal, they would operate as if they were negative-limited.

(3) Several of the steps in the DPA procedure[1] were examined to determine whether Cd metal could be converted to $Cd(OH)_2$ or CdO_2 prior to the analytical processes for its determination. The results were negative in the sense that the actual procedural steps did not appear to be at fault.

(4) Next, several Ni-Cd cells of another size which were known to contain residual Cd at full discharge were analyzed after being subjected to conditions where it was possible for Cd

to be oxidized to Cd^{2+} prior to the chemical characterization. Only in circumstances where the negative plates were deliberately oxidized for 24 hours in alkaline solution at elevated temperature was a decrease in the Cd content observed in comparison electrode strips. Even then, residual analyzable Cd was still present in significant quantities.

(5) During these last studies, it was found that the DPA procedure incorporated an inherent loss of analyzable Cd if grids with significant iron content were dissolved in acid during the analysis. In that event, gelatinous Fe_2O_3 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.

The following is a brief summary of NASA's position with respect to the cadmium issue.

The proposed regulation by the Occupational Safety and Health Administration (OSHA) on the permissible exposure level (PEL) to cadmium has the potential to adversely affect NASA flight programs. This is due to the high dependance on cadmium for flight batteries in many NASA programs. For the past 25 years, nickel-cadmium (Ni-Cd) batteries have been the energy source for a vast majority of NASA missions. Ni-Cd technology also is currently planned for use on many future missions.

The only qualified supplier for NASA Standard Ni-Cd batteries has just recently announced it will cease production of these cells in the United States if the PEL is enacted as proposed. If this takes place, there will be no alternative but to consider other less-desirable options. One option is to develop new technologies such as nickel-metal 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 $\mu g/m^3$ or 5 $\mu g/m^3$ 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.

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

All of the federal bodies mentioned above believe OSHA has failed that crucial test. After several meetings with OSHA, it appears that OSHA itself agrees that the industries cannot meet the levels put forth in their proposal through engineering controls and work practices. However, OSHA has proposed standards of either 1 or 5 micrograms of cadmium per cubic meter of air, well below the level of 50 micrograms per cubic meter currently considered generally feasible in the industry.

OSHA's approach will create international competitiveness inequities and is contrary to current case law. The Cadmium Council believes that the effects upon employment and the balance of trade deficit will be substantial if OSHA is successful in implementing this new regulation.

Independent studies predict that imposition of the new OSHA standards would result in the closure of three U.S. nickel-cadmium battery manufacturing facilities comprising 55% of U.S. sales and 99% of U.S.-owned facilities, with the loss of more than 2300 jobs in the United States.

In addition, because the U.S. firm which manufactures over 90% of all nickel-cadmium battery cells for space vehicles and satellites would be among those closed, power supplies for the U.S. civilian and military space effort would have to be obtained, if possible, from foreign suppliers, further contributing to employment and trade losses.

The cost impact of the proposed rule would result in almost all U.S. nickel-cadmium batteries being manufactured off-shore, following the example of VCR's and other small electronic products.

As for the health risk argument, OSHA has developed risk assessments for cancer and renal dysfunction which the Office of Management and Budget has criticized as unreasonable.

Finally, OSHA has ignored the fact that most other industrialized nations have cadmium health standards in the range from 20 to 50 micrograms per cubic meter and that with those standards in place, no major health problems have been observed.

Toward that end, members of The Cadmium Council and other major trade associations would appreciate any action you, the Presidents' Council on Competitiveness or the National Space Council might take to urge OSHA to follow its legal guidelines.

Respectfully Submitted,

ROBERT DALE WILSON
Attorney At Law

CC: Mr. John Sununu
Mr. Alan Hubbard

GATES ENERGY PRODUCTS

BACKGROUND

- CURRENT OSHA EXPOSURE LIMIT IS 200 ug/m3 -- ESTABLISHED IN 1972
- GEP -- AND OTHER NiCd BATTERY MAKERS WORLD-WIDE -- ARE GENERALLY ENGINEERED TO 50 ug/m3
- OSHA'S PROPOSED RULE-MAKING WOULD IMPOSE A MAXIMUM EXPOSURE OF EITHER 1 OR 5 ug/m3
- OSHA'S RULE-MAKING IS EXPECTED TO BE PROMULGATED IN Q1 OR Q2 OF 1992

MRH1

GATES ENERGY PRODUCTS

POSITION

- GEP HAS TAKEN LEADERSHIP ROLE IN SEEKING A REASONABLE SOLUTION
- COST TO ENGINEER PLANT TO 25 ug/m3 IS ESTIMATED TO BE AN ADDITIONAL: $20 MILLION CAPITAL
  $4 MILLION/YEAR OPERATING COST
- MARGINS ARE UNDER SEVERE PRESSURE FROM FOREIGN COMPETITION; THESE COSTS WOULD MAKE US LESS COMPETITIVE
- GEP IS NOT ABLE -- OR WILLING -- TO PAY THE ADDITIONAL COSTS TO MEET THE PROPOSED RULE, BASED ON SOUND BUSINESS PRACTICE
- BOB SHILEY -- GEP PRESIDENT:
  "IF THE REGULATION IS ESTABLISHED AT EITHER OF THOSE LEVELS (i.e., 1 OR 5 ug/m3, GATES WILL CEASE PRODUCTION OF NICKEL CADMIUM BATTERIES IN THE UNITED STATES"
- GEP REQUIRES A NUMERICAL WORKPLACE STANDARD TO ALLOW US TO CONTINUE IN BUSINESS, OR SUFFICIENT TIME FROM OSHA TO PHASE OUT OF THE MANUFACTURE OF NiCd BATTERIES
- GEP IS DEVELOPING STATE-OF-THE-ART NiMH CELLS, AND CONVERTING FROM NiCd TO NiMH

MRH2

GATES AEROSPACE BATTERIES

(IF RULE IS ESTABLISHED AT LESS THAN 50 ug/m3)

- GAB IS SUBJECT TO SAME CONSIDERATIONS AS GEP -- ADDED COSTS WILL MAKE US UNCOMPETITIVE
- GAB WILL NOT MANUFACTURE NiCd CELLS AFTER GEP HAS PHASED OUT OF NiCd
- ACTIVATION (FROM DRY STORAGE) OF WELDED CELLS DOES NOT PRESENT A CADMIUM HAZARD -- DRY STORAGE COULD PROVIDE A SCHEDULE BUFFER
- OSHA RULE-MAKING THREATENS GAB'S ABILITY TO PROVIDE CONTINUING SUPPLY OF NiCd CELLS
- CUSTOMERS ARE ADVISED TO WATCH THE RULE-MAKING CLOSELY TO ENSURE THAT THEIR PROGRAM NEEDS ARE COVERED:
  - -- ACCELERATE PRODUCTION AND DRY STORE (IF OSHA ALLOWS TIME)
  - -- OTHER SOURCES (FOREIGN)
  - -- OTHER COUPLES - NiH2
    - NiMH
- GATES AEROSPACE BATTERIES IS DEVELOPING NiMH CELLS TO REPLACE NiCd AEROSPACE CELLS -- RESULTS ARE VERY ENCOURAGING -- PAPER LATER TODAY

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.

- EPI NICKEL-CADMIUM PLANS

  EPI's current plans are to continue in the Nickel-Cadmium business.

  1. Standard issued in 92 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 ($5\ ug/m^3$) 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 Distric (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 numberous reasons. First of all we could not, in good consience, 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 stardards are still the enforced rule. Going around the regulation also implies that we do not agree with the health risks and are imposing our own standards. We are not qualified to do this.

Advanced Technologies Session

Organizers: ***Sal Di Stefano***
Jet Propulsion Laboratory

Ed Buzzelli
Westinghouse Science & Technology Center

A New Composite Electrode Architecture For Energy Storage Devices

R.E. Ferro, G.M. Swain and B.J. Tatarchuk

Department of Chemical Engineering and
the Space Power Institute
Auburn University, AL 36849

Acknowledgements

NASA-LeRC Electrochemical Technology Branch
Contract # NAG3-1154

Doris Britton
Patricia O'Donnell
Peggy Reid

T.S. Lee

EVOLUTION OF ELECTRODE ARCHITECTURES

Nickel Hydroxide Half-Cell Reaction Studies

POWDER-BASED PLAQUES

FIBREX MESH

COMPOSITE ELECTRODE STRUCTURES

Tatarchuk and co-workers:

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.)

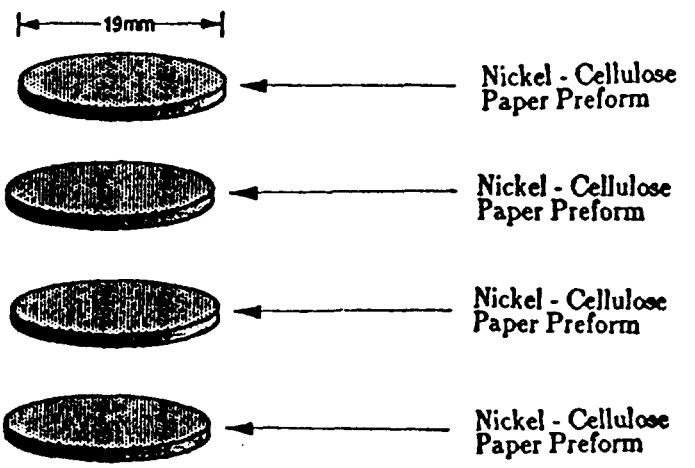
2. Nickel FIBREX mesh/ stainless steel fibers (2 um dia.)

3. Stainless steel fibers

4. Nickel FIBREX mesh/ nickel fibers (2 um dia.)

5. Nickel fibers

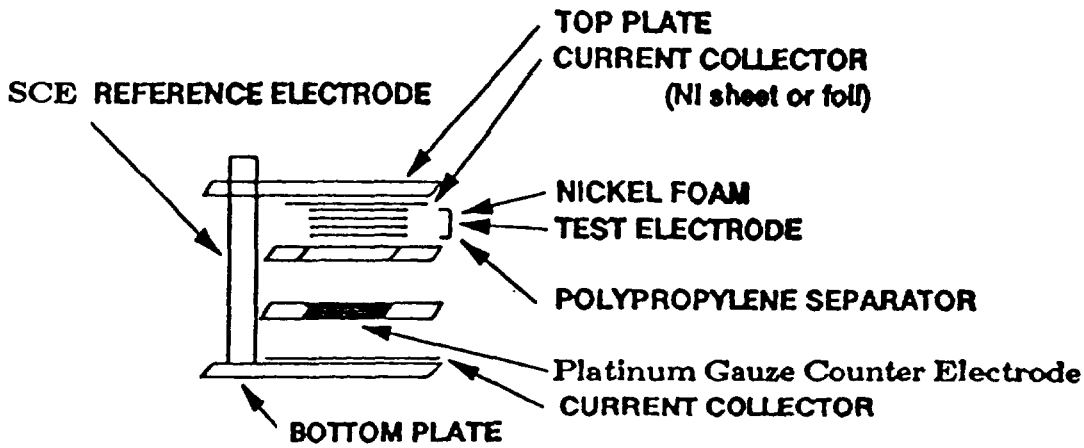
Electrode Preparation



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 acessibility 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

	FIBREX	FIBREX+SS	FIBREX+Ni	SS	Ni
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

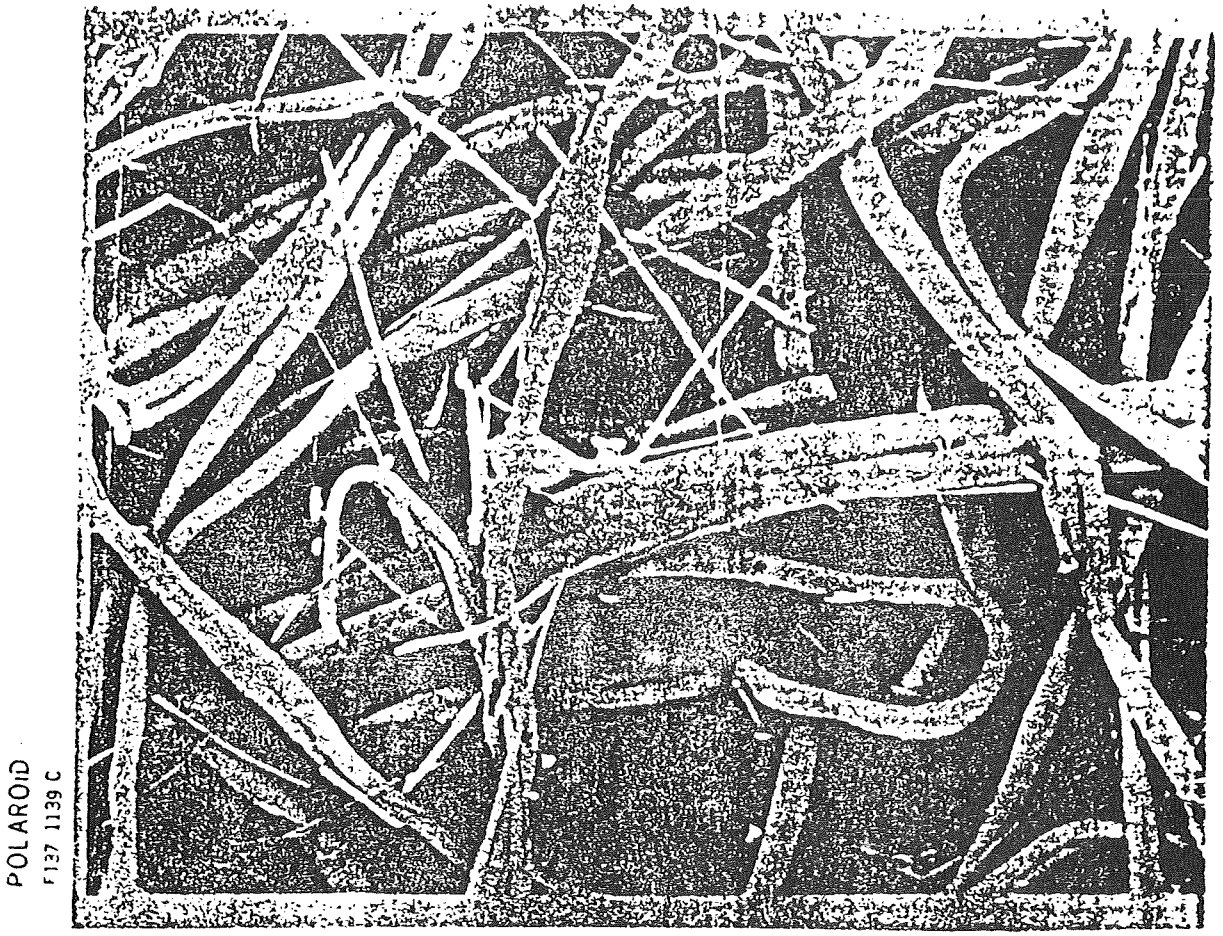


Figure 1. Electron micrograph of a FIBREX/nickel fiber composite electrode prior to impregnation.

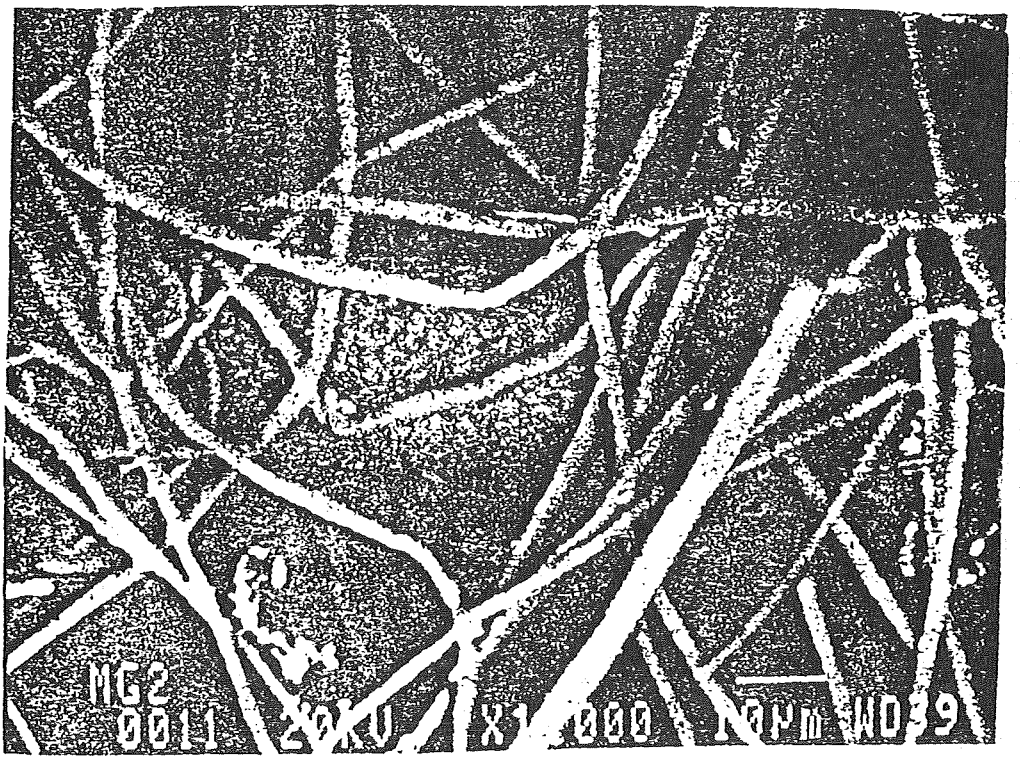


Figure 2. Electron micrograph showing the sinter bonded small diameter nickel fibers to the FIBREX mesh.

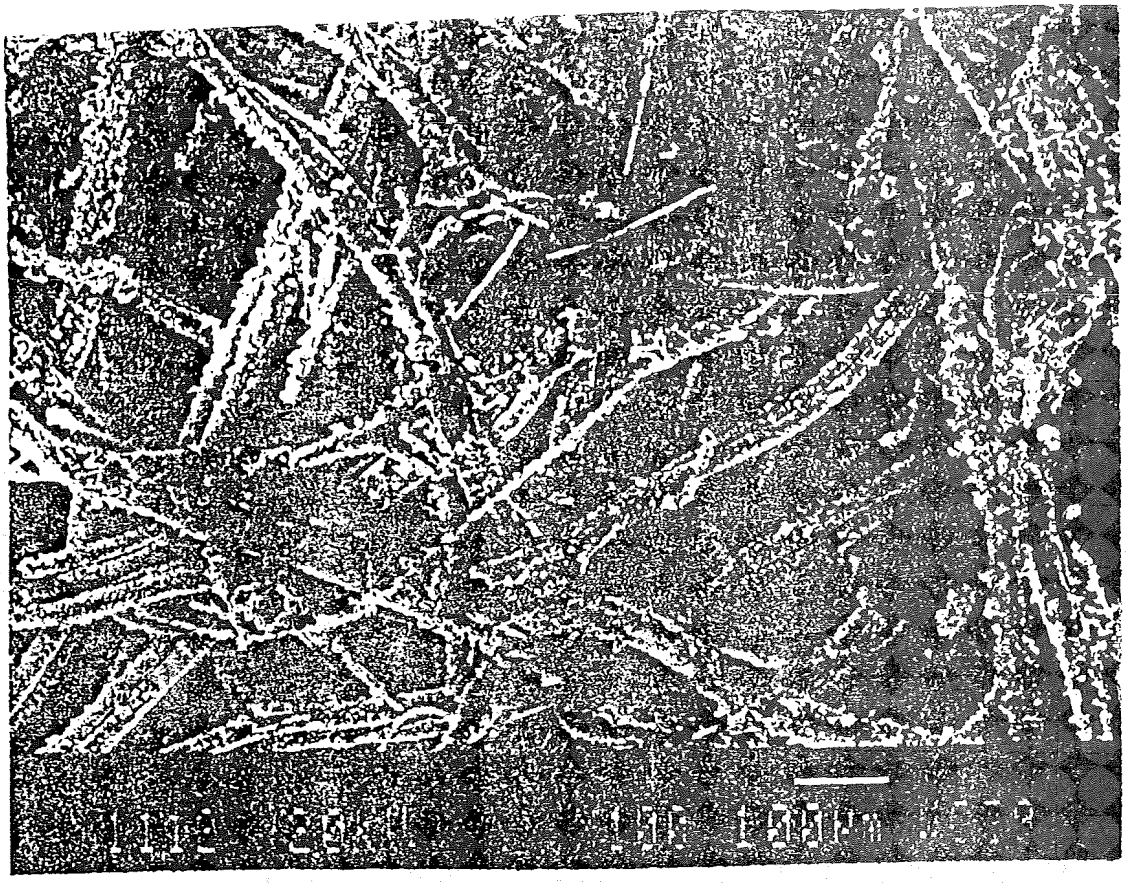


Figure 3. Electron micrograph of a FIBREX/nickel fiber composite electrode after aqueous impregnation galvanostatically at 10 mA/cm^2. for 3 hours.

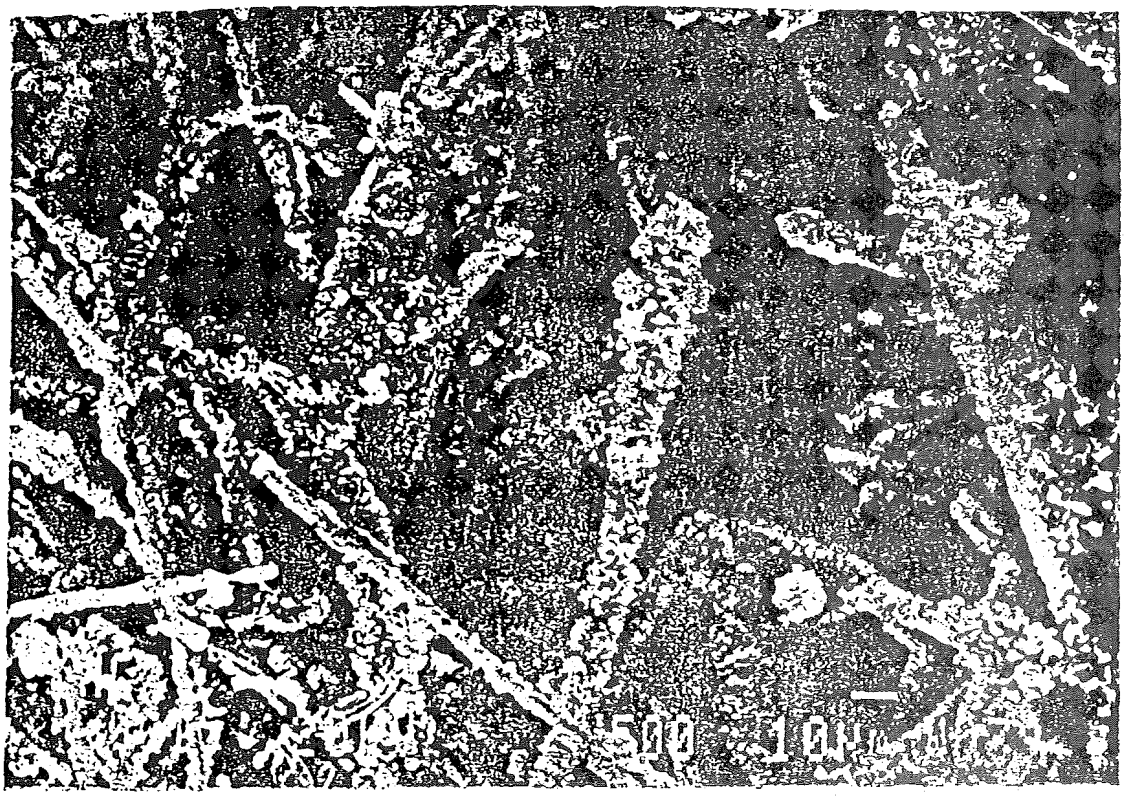
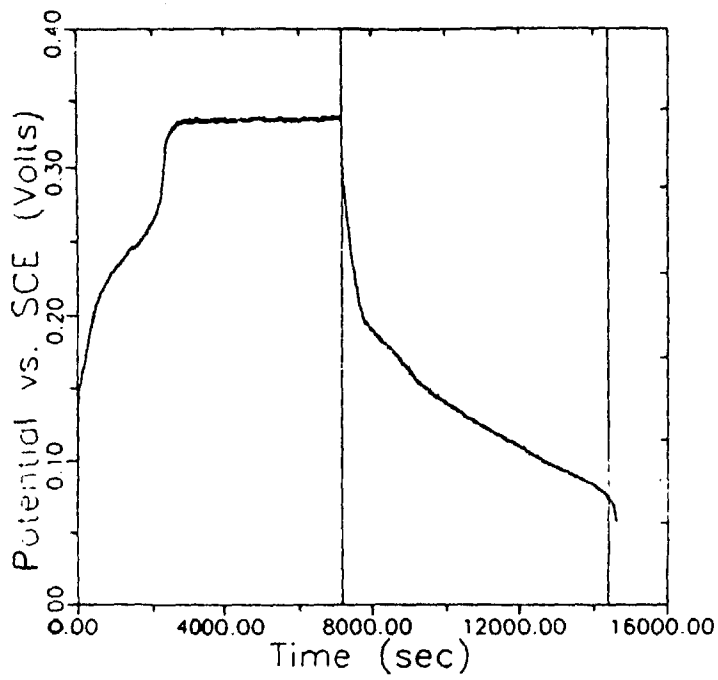


Figure 4. Electron micrograph of the same electrode as above but at higher magnification.

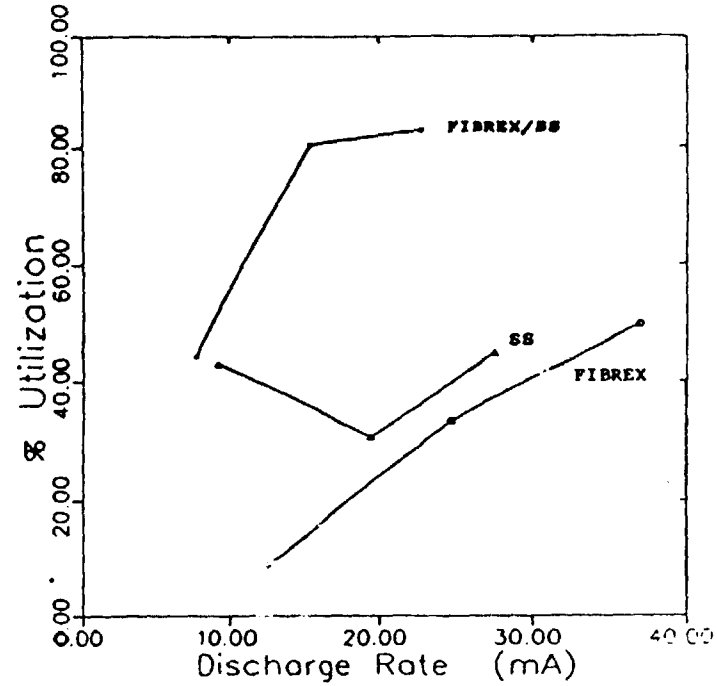
Potential vs. Time Curve for a Nickel Fiber Composite Electrode During Charge and Discharge.

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



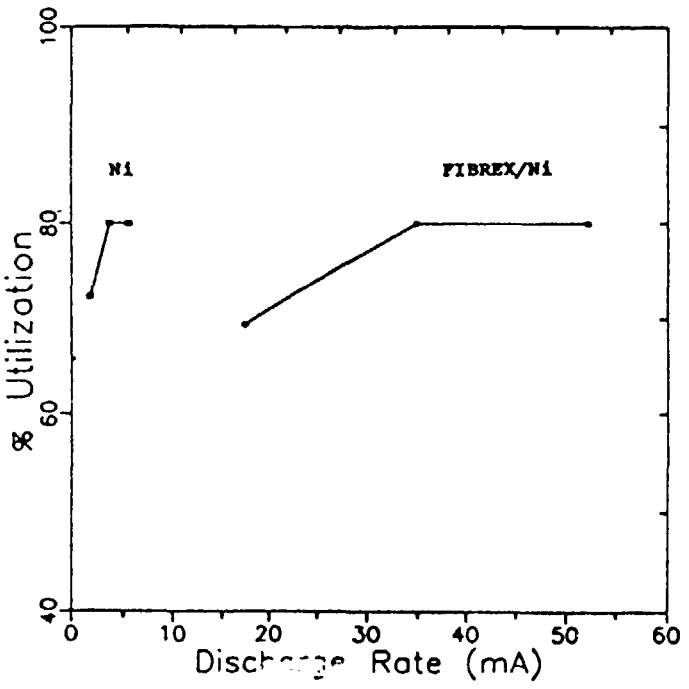
Plot of % Utilization vs. Discharge Rate for Different Composite Electrode Architecture

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



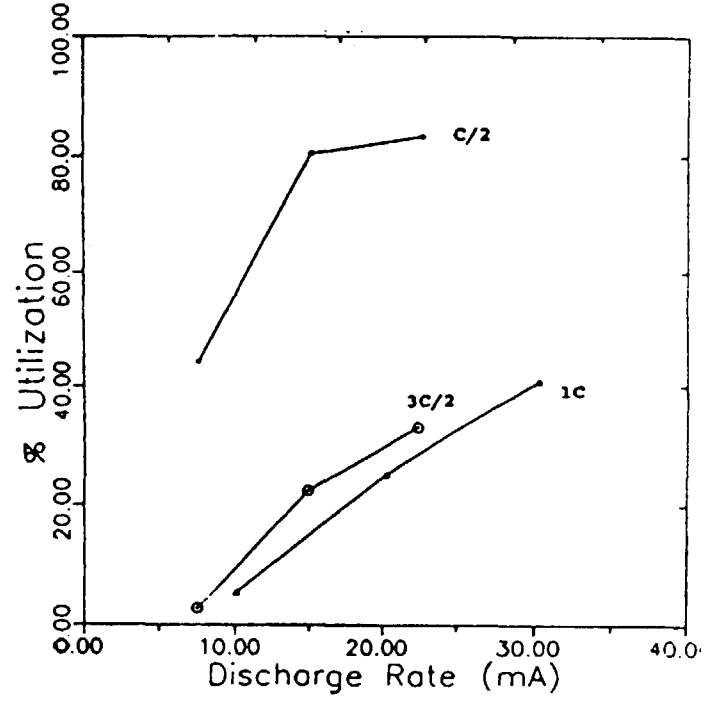
Plot of % Utilization vs. Discharge Rate for a Nickel Fiber and a FIBREX/Nickel Fiber Composite Electrode.

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^2
Charge Rate = C/2



Plot of % Utilization vs. Discharge Rate fo FIBREX/Stainless Steel Composite Electro Different Charge Rates.

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



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 <u>good</u> indicator of the condition of the electrode/active material microstructure and morphology. <u>Conformal deposition</u> 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_2 batteries.

Composite Overwrapped Nickel-Hydrogen Pressure Vessels

John Reagan, NASA Lewis Research Center
Joe Lewis, TRW

COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

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

States purpose of paper - stimulate interest in Composite Overwrapped pressure vessel technology as applied to Nickel-Hydrogen Battery pressure vessels. Includes technical and economic forces that could be utilized in such a design.

COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

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

COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

- HISTORY (cont)
  - INCONEL 718 HAS BEEN THE MATERIAL OF CHOICE SINCE EARLY DESIGNS
    - ALL PRESENT DESIGNS KNOWN TO THE AUTHORS PRESENTLY USE OR ANTICIPATE THE USE OF INCONEL 718
    - INCONEL 718 HAS PROVED TO BE VERY RELIABLE
  - THE ADVANTAGES OF COMPOSITE OVERWRAPPED MATERIAL HAVE BEEN SUGGESTED SEVERAL TIMES BUT THE TECHNOLOGY HAS ALWAYS BEEN ELIMINATED EARLY ON DUE TO:
    - FEAR OF ADVERSE THERMAL REACTIONS' EFFECTS
    - UNKNOWNS OF DESIGN
    - LACK OF COMPOSITE OVERWRAPPED EXPERTS IN THE DESIGN PROCESS
  - DESIGNERS HAVE ACKNOWLEDGED THE ABILITY OF COMPOSITE OVERWRAPPED TECHNOLOGY TO REDUCE THE OVERALL STRESS IN THE CRITICAL GIRTH WELD(S) AREA

Presents the history of Nickel Hydrogen Pressure Vessels over the last 15 years including materials, operating conditions, and market expansion to internationals.

Discusses minor interest in Composite Overwrap technology as applied to Nickel-Hydrogen Batteries to date.

COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

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

Itemizes basic materials properties: thermal, corrosion, strength.

COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

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

Monolithic and Composite Overwrapped construction approach compared.

COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

- POTENTIAL ADVANTAGES OF COMPOSITE PRESSURE VESSEL
  - OPTIMIZED PROPERTIES
  - POTENTIALLY LOWER COST
    - COMPOSITE HIGH-PRESSURE GAS STORAGE VESSELS COST APPROXIMATELY 20% OF EQUIVALENT TITANIUM VESSEL
    - POTENTIAL FOR ELIMINATION OF WELDS
  - POTENTIALLY SHORTER MANUFACTURING SCHEDULE
    - COMPOSITE VESSELS ARE BEING PRODUCED IN APPROXIMATELY ONE-THIRD TIME FOR EQUIVALENT TITANIUM VESSELS
  - IMPROVED FRACTURE CONTROL CAPABILITY
    - COMPOSITE VESSELS SHOW POTENTIAL FOR MILLIONS OF CYCLES BEFORE LEAKAGE
  - POTENTIALLY LOWER WEIGHT
    - COMPOSITE HIGH-PRESSURE GAS STORAGE VESSELS WEIGH APPROXIMATELY 20% OF WEIGHT OF EQUIVALENT TITANIUM VESSEL
  - PRECISE CONTROL OF VESSEL WALL GROWTH DUE TO PRESSURE WITH MINIMAL EFFECT ON WEIGHT

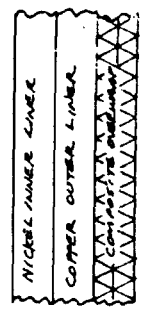
Detailed description of the advantages of Composite Overwrapped Pressure vessels showing weight savings, manufacturing schedule reductions, and improved fatigue life.

COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

- GRAPHITE/EPOXY OVERWRAPPED PRESSURE VESSEL WITH INCONEL X-750 LINER IS CURRENTLY FLYING ON B-1 BOMBER
- NO KNOWN REASON WHY INCONEL 718 LINERS OR LINERS OF ANY DUCTILE NICKEL ALLOY COULD NOT BE OVERWRAPPED WITH GRAPHITE/EPOXY

COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

OPTIMIZED PROPERTIES



SCHEMATIC SECTION
OF VESSEL WALL

Discussion of B-1 application, wide range of usable materials, and a sketch of a possible optimized design.

COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

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

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

COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

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

COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

- POTENTIAL ELIMINATION OF WELDS
  - JOIN VESSEL COMPONENTS WITH ADHESIVES
  - 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

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

COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

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

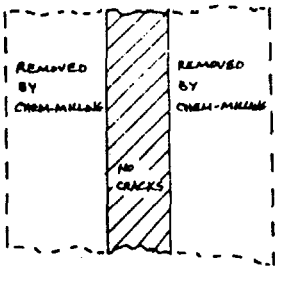
Fracture Control problems in present designs are addressed and possible solutions proposed. Emphasis is on the improvement possibilities with Composite Overwrapped technology in the area of a large analytical increase in total pressure vessel life.

COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

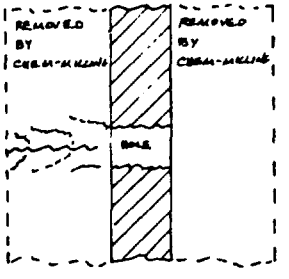
- NDI METHODOLOGY FOR WROUGHT METAL LINER
  - WROUGHT METAL IS CONVENTIONALLY MACHINED TO A THICKNESS OF 0.030-0.040 INCH PER SURFACE GREATER THAN FINAL DESIRED THICKNESS
  - BOTH SURFACES OF WROUGHT METAL ARE INSPECTED USING NSTS "SPECIAL" PENETRANT INSPECTION
  - EXTRA 0.030-0.040 INCH THICKNESS IS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

COMPOSITE OVERWRAPPED NICKEL-HYDROGEN PRESSURE VESSELS

- NDI METHODOLOGY



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)
NEDI	PRESSURANT	JAN. 1990	GN_2	T-40	7,000	14,000
PEGASUS	PRESSURANT	APR. 1990	GN_2	HT 46-9	2,500	5,000
ERIS	PRESSURANT	JAN. 1991	GHe	T-1000	9,400	24,000
ERIS	PROPELLANT	JAN. 1991	NTO/MMH	HT 46-9	2,550	6,500
BRILLIANT PEBBLES	PRESSURANT	MAR. 1991	GHe	T-1000	9,000	23,000
PEGASUS HAPS	PROPELLANT	JULY 1991	HYDRAZINE	T-1000	464	696
	PRESSURANT	JULY 1991	GHe	T-1000	6,000	10,200
	PRESSURANT	JULY 1991	GN_2	T-1000	5,000	8,700
MICROSAT	PRESSURANT	JULY 1991	GN_2	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 OVERWRAP 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_2 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

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SAFT

Research & Development Center

The LiAl/FeS_2 Battery

Power Source for the Future

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Abstract:

Advanced high power density rechargeable batteries are currently under development at SAFT. These batteries have the potential of greatly increasing the power and energy densities available for space applications. Depending on whether the system is optimized for high power or high energy, values up to 150 Wh/kg and 2,100 W/kg (including hardware) are projected. This is due to the fact that the system employs a high conductivity molten salt electrolyte. The electrolyte also serves as a separator layer with unlimited freeze thaw capabilities. Life of 1,000 cycles and ten calendar years is projected. The electrochemistry consists of a lithium aluminum alloy negative electrode, iron disulfide positive electrode, and magnesium oxide powder immobilized molten salt electrolyte. Processed powders are cold compacted into circular discs which are assembled into bipolar cell hardware with peripheral ceramic seals. The culmination of SAFT's development work will be a high energy battery of 40 kWh and a high power battery of 28 kWh.

Introduction:

Advanced rechargeable high energy batteries are desirable for a number of applications where the performance of present day lead acid batteries is

inadequate. Such applications as electric vehicle propulsion, utility load leveling, military and space demand high power and energy from reliable power sources. Rechargeable high temperature electrochemistries employing molten salt electrolytes and high energy electrodes offer promise for fulfilling present and future requirements in lower weight and volume packages.

Today, SAFT is developing LiAl/FeS_2 batteries in sealed bipolar configuration having superior energy and power densities. Such batteries promise to give improved performance with lower weight for future space applications.

Space Power Systems:

At the 1989 IECEC conference, a paper was presented entitled: "Advanced Electrochemical Concepts for NASA Applications"[1]. Presented in that paper were the results of a Jet Propulsion Laboratory survey of 23 electrochemical systems for space applications. The highest ranked advanced systems for operation in planetary inner-orbit spacecraft included Na/beta"alumina/z (where z = S, $FeCl_2$, or $NiCl_2$), upper plateau (U.P.) Li(Al)/FeS_2 and H_2O_2 alkaline regenerative fuel cell (RFC). The achievable specific energy for these as operational batteries was estimated to be 130, 180, and 100 Wh/kg respectively. Energy storage requirements of six anticipated space missions are tabulated as shown in Figure 1. GEO, planetary rover, and lunar based applications were designated as shown to be good candidates for LiAl/FeS_2 primarily because of moderate cycles and large energy requirements.

As compared to present state-of-the-art nickel/cadmium and nickel/hydrogen batteries, the projected specific energy (Wh/kg) for bipolar constructed lithium

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

Lithium/Metal Sulfide System Description:

During the 1970s, work was performed at Argonne National Laboratory (ANL) to develop batteries for electric vehicle propulsion and utility load leveling[2]. Both lithium aluminum/iron disulfide and iron sulfide couples were investigated. The complete discharge (two plateaus) of lithium aluminum/iron disulfide can be written as

$$4LiAl + FeS_2 \longrightarrow 2Li_2S + Fe + 4Al$$

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

$$2LiAl + FeS \longrightarrow Li_2S + Fe + 2Al \quad (1.34V)$$

Full scale prismatic multiplate cells and small batteries were built at Eagle Pitcher, Gould, and ANL.

In the 1980s, some work was continued at ANL on $LiAl/FeS_2$ by Kaun and others. Success was achieved in 1986 by cycling only the upper plateau

$$2LiAl + FeS_2 \longrightarrow Li_2S + FeS + 2Al \quad (1.66V)$$

with a theoretical specific energy of 490 Wh/kg. Over 1,000 cycles was demonstrated in $LiAl/FeS_2$ prismatic bicell configuration[3]. Further developments in 1988 of an electrochemical overcharge tolerance[4] and in 1990 of a peripheral seal material[5] make bipolar stack construction both workable and practical.

At SAFT, primary reserve thermal batteries containing bipolar LiAl/FeS_2 have been manufactured since 1978, and research and development on rechargeable prismatic LiAl/FeS and bipolar LiAl/FeS_2 has been conducted since 1990.

The LiAl/FeS_2 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_2. 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_2 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 negligable 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_2 batteries designed for military application. Installed in missiles, guided bombs, and projectiles, these batteries withstand severe environments of shock, vibration, and acceleration in both non-operating and operating conditions. The dense paste-like electrolyte/separator is not subject to cracking typical of solid ceramic separators. For secondary applications, this separator property provides unlimited freeze thaw capability.

An advantage over ambient temperature batteries is that the electrochemistry is always operating at optimum temperature independent of environmental changes.

Development Goals:

Currently, SAFT is working on development of two batteries utilizing LiAl/FeS_2 electrochemistry in bipolar construction. One battery will be optimized for high energy utilizing thick electrodes at moderate current densities to achieve 150 Wh/kg with power of 340 W/kg. This battery is being developed for electric vehicle propulsion. The second battery will be optimized for high power utilizing thin electrodes at high current densities up to 5.0 amperes/cm^2 to achieve extremely high specific power of 2.9 kW/kg at a relatively low specific energy of 39 Wh/kg. This battery will provide high power for an electric weapon application. A comparison of development goals for these batteries is shown in Figure 6.

Development Status:

At SAFT, bipolar primary thermal batteries have been made since the 1950s. In 1978, SAFT introduced the LiAl/FeS_2 technology developed by ANL into thermal batteries. Since 1990, work on rechargeable lithium metal sulfide technology has been conducted at SAFT's Baltimore facility. This work included LiAl/FeS prismatic multiplate cells (200 Ah), LiAl/FeS_2 prismatic bicells (40 Ah), and LiAl/FeS_2 bipolar cells (0.3 to 3.2 Ah).

A number of recent accomplishments are noteworthy. Specific energy of 89 Wh/kg was achieved for LiAl/FeS prismatic multiplate cells tested at the C/3 rate.

Battery hardware was developed to accommodate 27 multiplate cells. Bipolar LiAl/FeS_2 cells and batteries have achieved 2,100 W/kg, and 6,700 W/l, at very high rates of charge (3C) and discharge (75C).

Development Issues:

A target of 1993 has been set to develop a 7 kW high power bipolar LiAl/FeS_2 scaleable module for test. A 5 kWh high energy module is targeted for development by 1994.

In order to achieve these development goals, work must progress towards improvement and scale up of peripheral seals, chemical equalization, and corrosion resistant materials at the cell and cell stack level. Engineering of stack pressure/restraint and current collection systems and methods for electrical isolation need development.

At the battery level, development of an optimized thermal management system that is reliable and producible at minimum cost is essential. The high battery volumes required for electric vehicles require development of a recycling program.

References:

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_2 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_2 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
			Actual	*Qual	Desired	(5 Minutes)
1	Outer Planetary Orbit	C - 2.0hr D - 0.7hr	500	1000	2000	0.50 C(1 kWh)
2	Inner Planetary Orbit	C - 2.0hr D - 0.7hr	3000	6000	10000	1.50 C(2 kWh)
**3	GEO	C - 22.8hr D - 1.2hr	1500	2000	4000	1.50 C(5 kWh)
**4	Planetary Rover	C - 12.0hr D - 3.0hr	300	600	800	1.30 C(3 kWh)
**5	Lunar Based	C - 11 days D - 17 days	80	160	350	0.02 C(5 MWh)
6	LEO	C - 1.0hr D - 0.6hr	30000	35000	50000	1.10 C(25 kWh)

GEO: Geosychronous Orbit LEO: Low Earth Orbit ** Candidates for LiAl/FeS_2
*Qual: Minimum number of cycles needed to qualify for application.
Source: G. Halpert and A. Attia, JPL

Figure 1

TECHNOLOGY PERFORMANCE COMPARISON
GEOSYNCHRONOUS ORBIT

	Ni-Cd	Ni-H_2	Projected Bipolar LiAl/FeS_2
Specific Energy, Wh/kg	25 -30	45 - 50	150
Energy Density, Wh/L	45	55	270
Cycle Life	1000	1000	1000
- DOD (%)	70	70 - 80	80 - 100
Calendar Life, YR	15	15	10

Figure 2

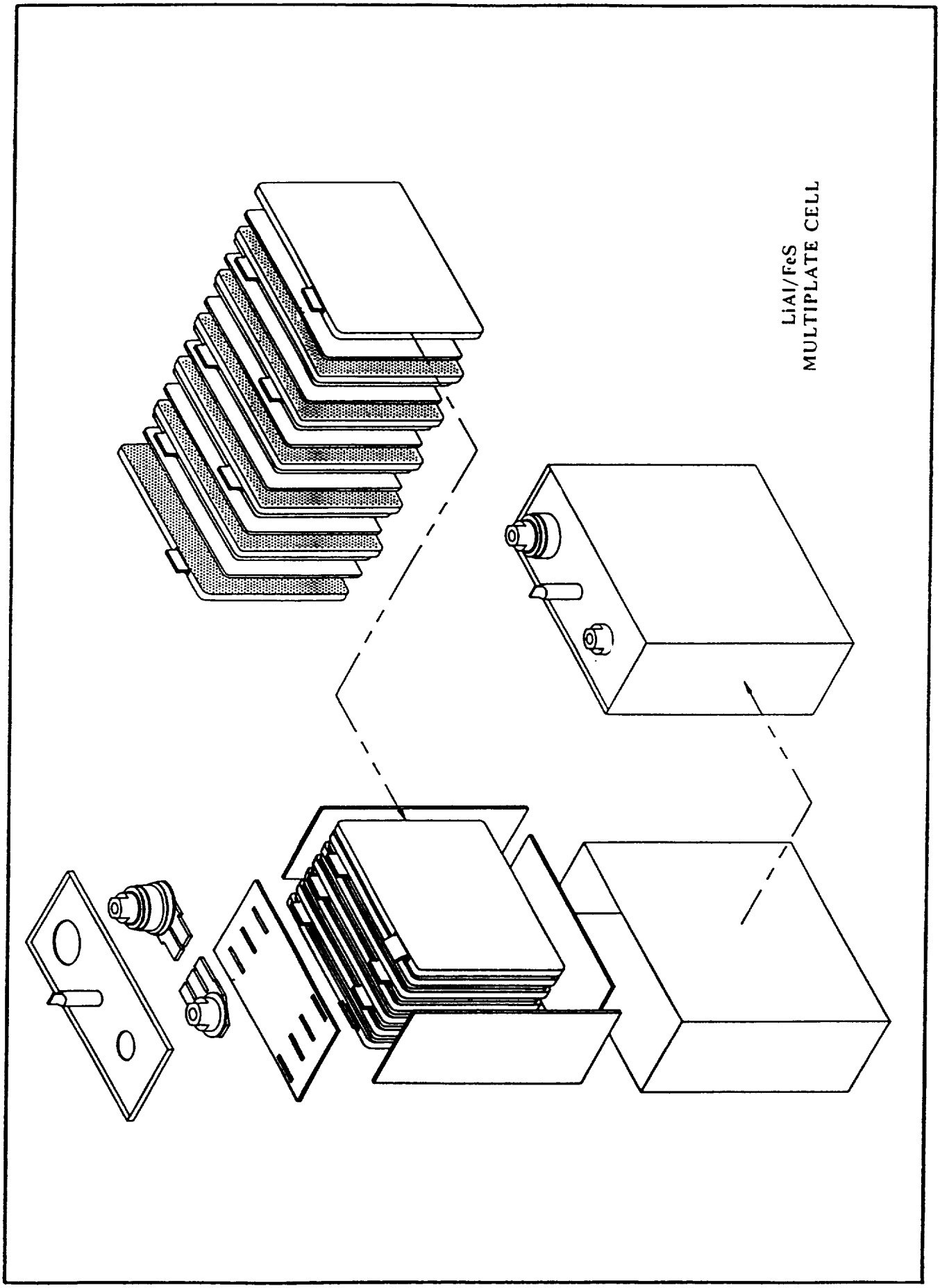

Figure 3

BIPOLAR LiAl/FeS2 MODULE CONCEPT DESIGN

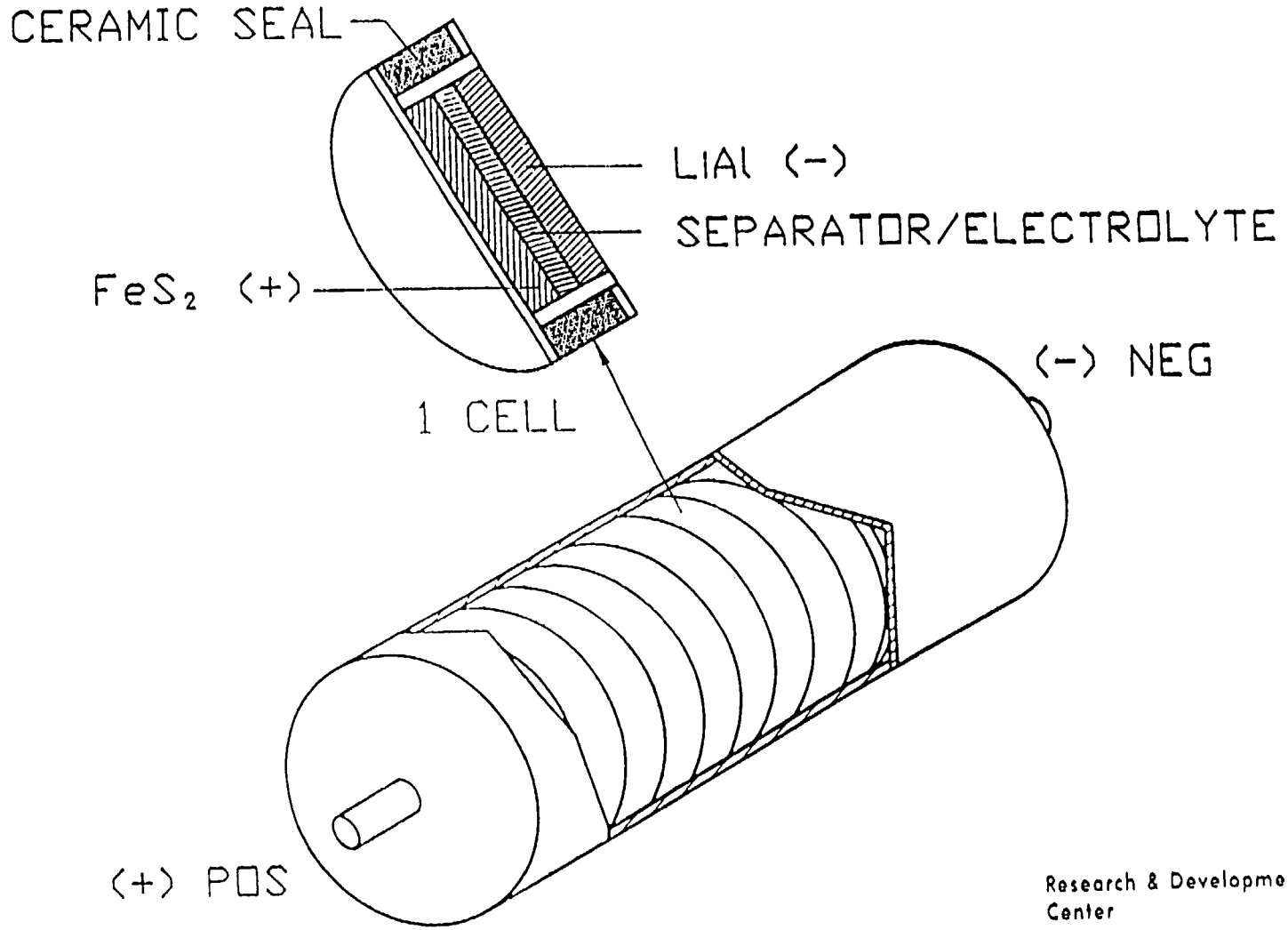

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Figure 4

BIPOLAR LiAl/FeS2 BATTERY CONCEPT DESIGN

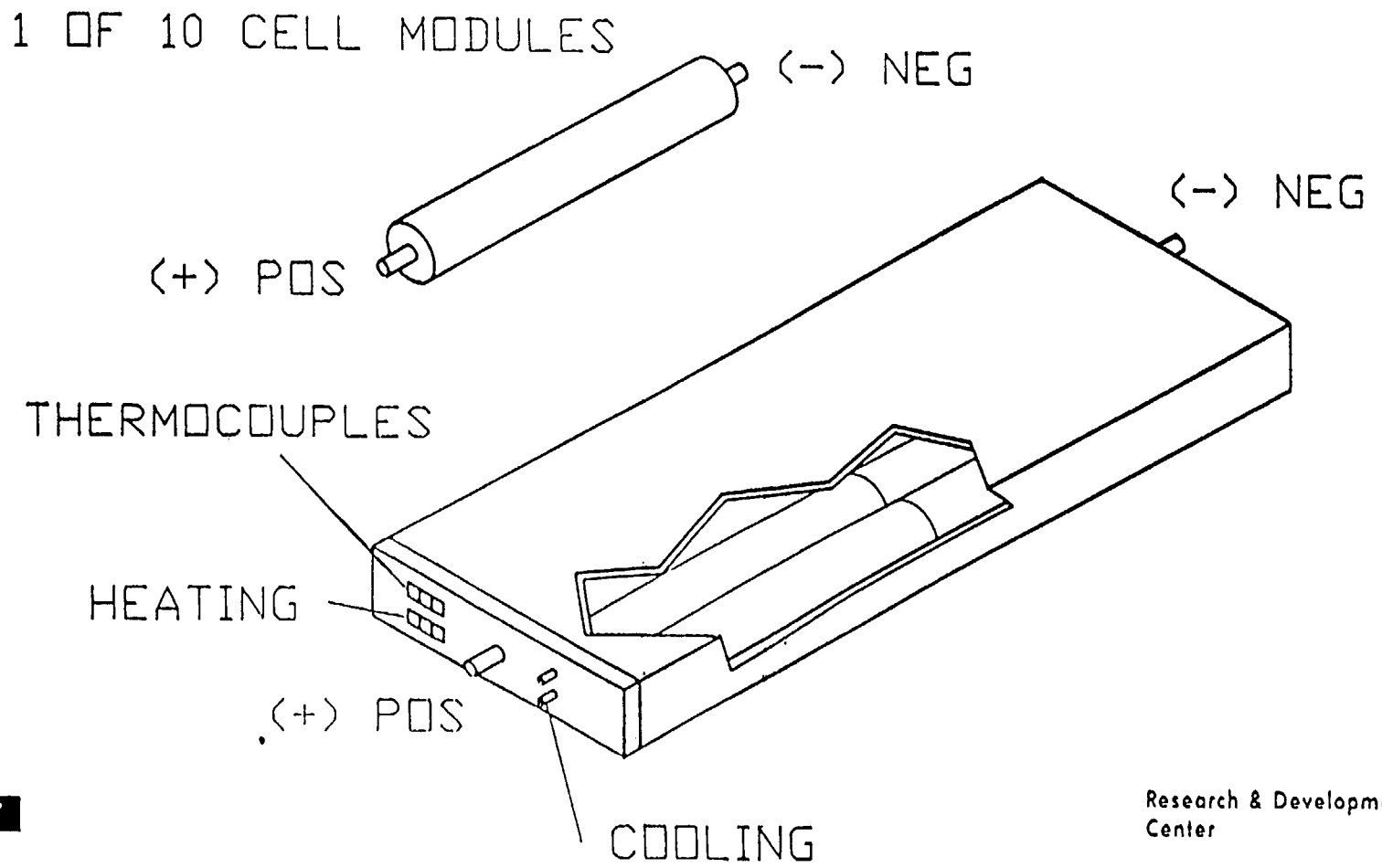

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Figure 5

SAFT LiAl/FeS_2 BIPOLAR BATTERY

Development Goals

	Optimized for High Energy	Optimized for High Power
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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Figure 6

SECONDARY LITHIUM CELLS FOR SPACE APPLICATIONS

JPL

S. SURAMPUDI, D. H. SHEN, C.-K. HUANG,
S. R. NARAYANAN, A. ATTIA, G. HALPERT

1991 NASA Aerospace Battery Workshop
U. S. Space and Rocket Center
Huntville, AL
October 29-31, 1991

JPL

SECONDARY LITHIUM CELLS/BATTERIES
OUTLINE

(1) JPL PROGRAM GOAL

(2) SPACE APPLICATIONS

(3) JPL PROGRESS

(4) SUMMARY

(5) ACKNOWLEDGEMENTS

JPL

SECONDARY LITHIUM CELLS/BATTERIES
PROGRAM GOAL

- DEMONSTRATE THE FEASIBILITYOF AMBIENT TEMPERATURE SECONDARY LITHIUM CELL TECHNOLOGY BY 1994

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

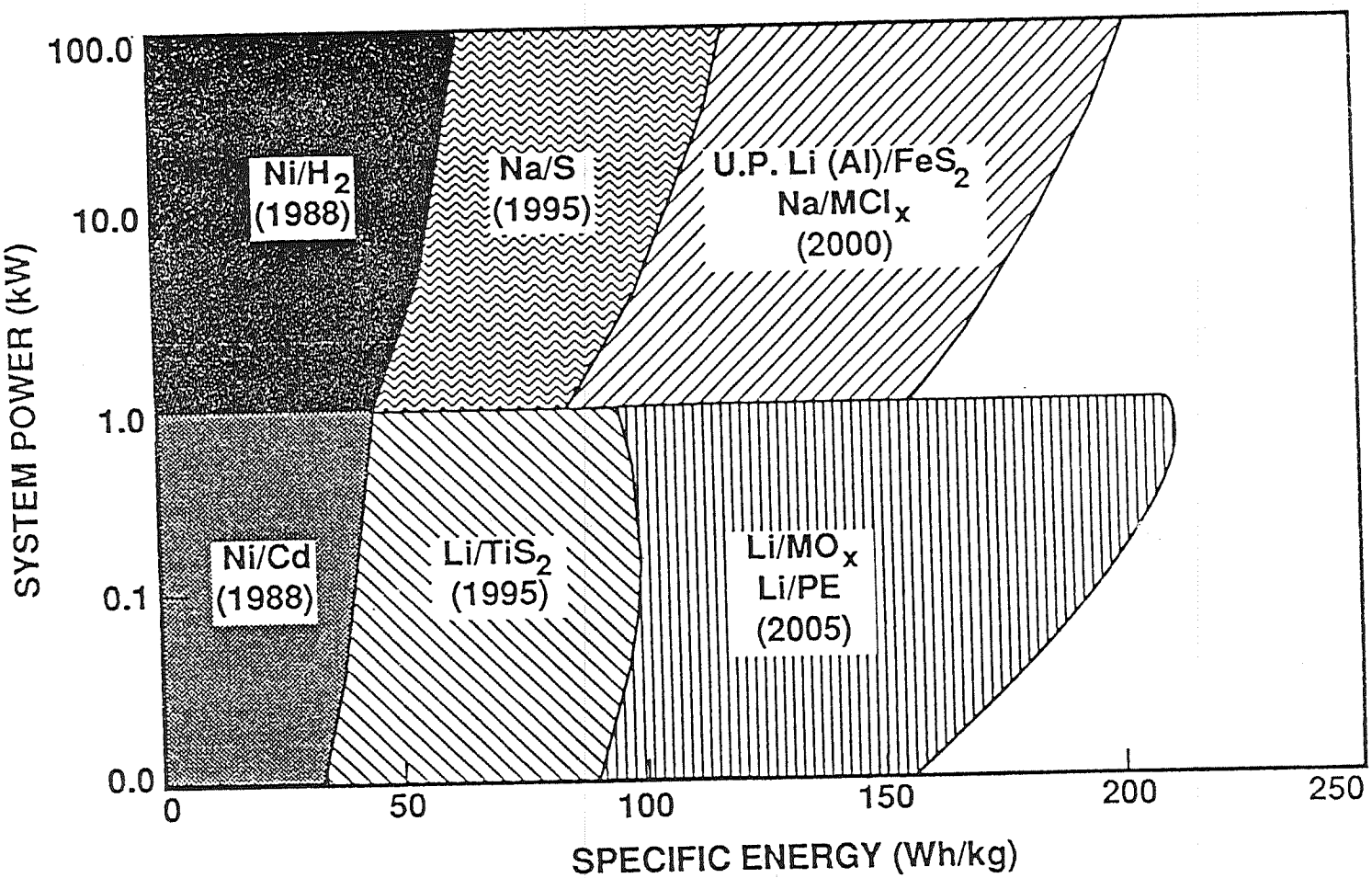
JPL

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

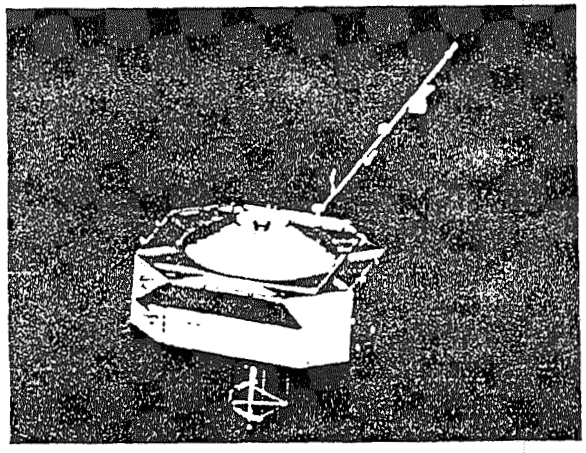
ADVANCED RECHARGEABLE BATTERY PERFORMANCE ENVELOPE



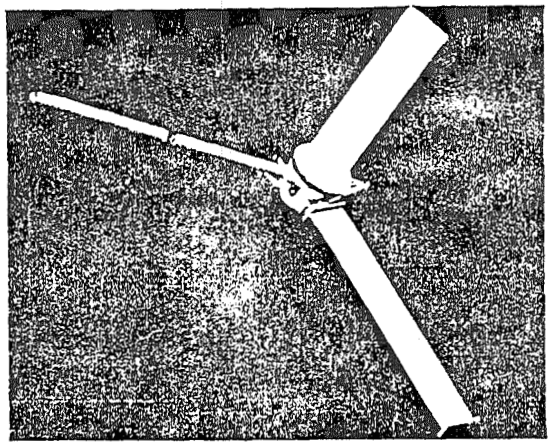
JPL

RECHARGEABLE LITHIUM CELL PROGRAM
PROJECTED APPLICATIONS

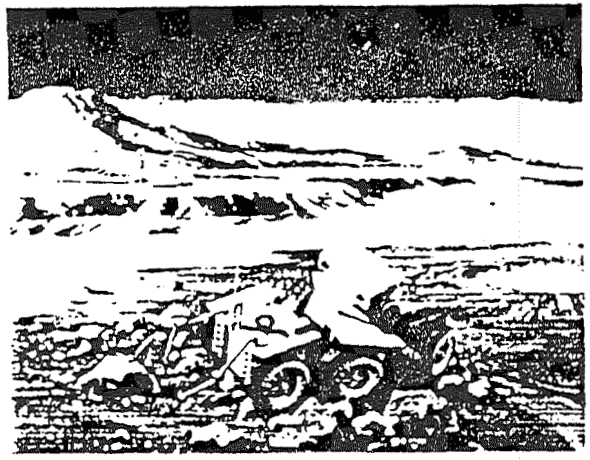
PLANETARY ORBITERS (MERCURY ORBITER)



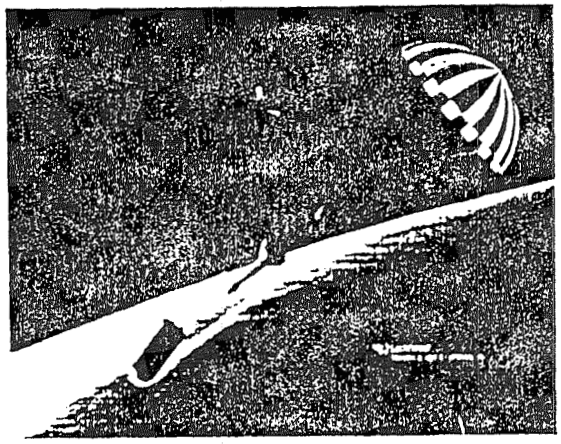
MISSIONS TO COMETS (COMET NUCLEUS SAMPLE RETURN TAIL PROBE)



MARS ROVER



PENETRATORS (GLOBAL NETWORK MISSION)



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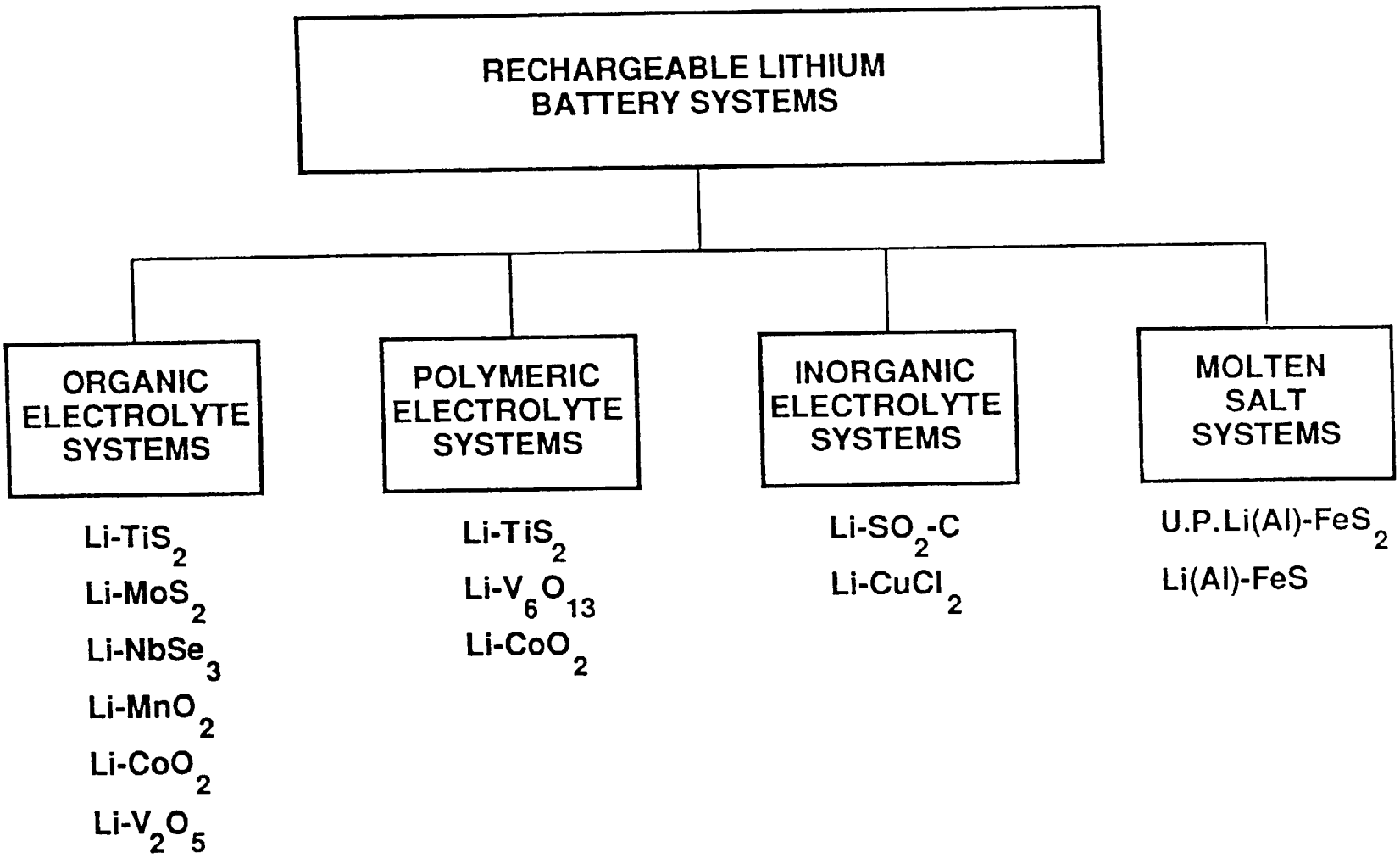
CLASSIFICATION OF SECONDARY LITHIUM CELLS



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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
JPL STUDIES (EXPERIMENTAL CELLS)					
Li-TiS_2	2.1	0.9	473	417	300+
MoS_2	1.9	2.0	717	421	50+
$NbSe_3$	1.8	2.8	412	384	150+
V_6O_{13}	2.2	4.0	636	361	50+
FROM LITERATURE (PROTOTYPE CELLS)					
Li-TS_2	2.1	0.8	473	378	200+
$NbSe_3$	1.8	2.5	412	330	200+
MoS_2	1.7	0.8	272	214	200+
MnO_2	3.0	0.5	855	364	200+
CoO_2	4.0	0.5	1094	465	50+
$CuCl_2$	3.2	2.0	1125	665	140+
SO_2	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

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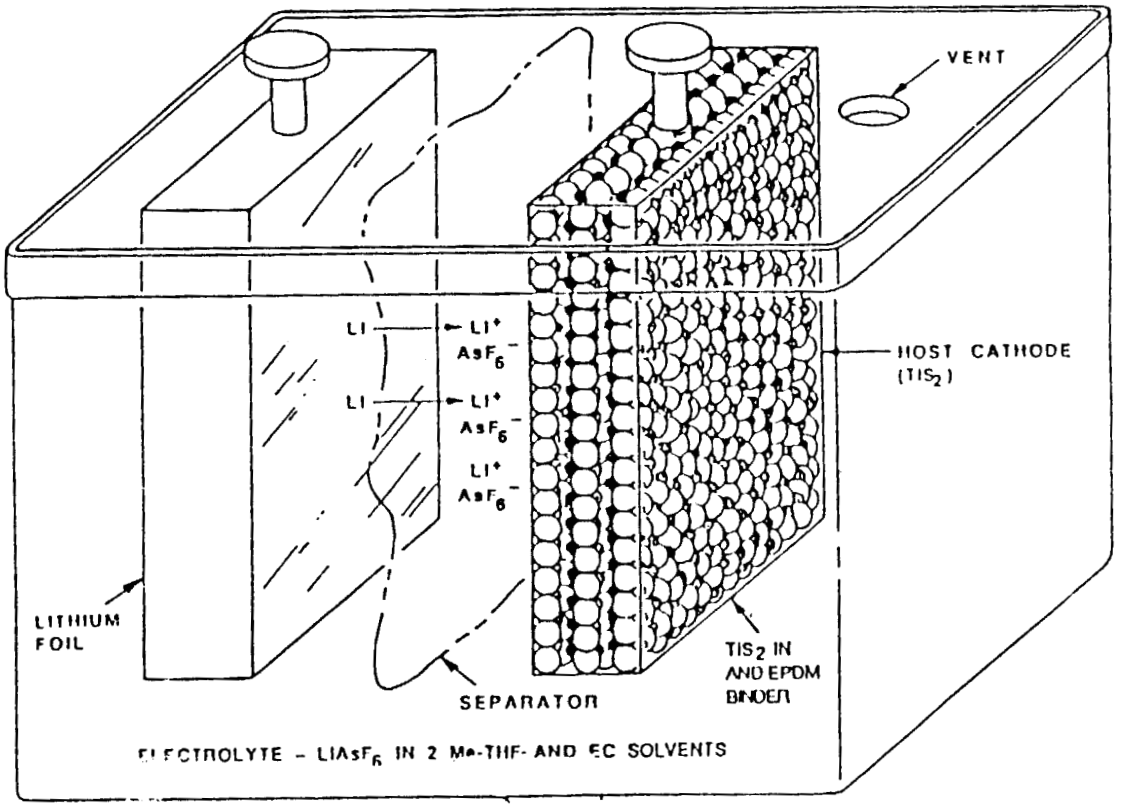
SCHEMATIC DIAGRAM OF A Li-TiS_2 CELL



CELL REACTIONS

DISCHARGE . . LI INTERCALATION (INSERTION)

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

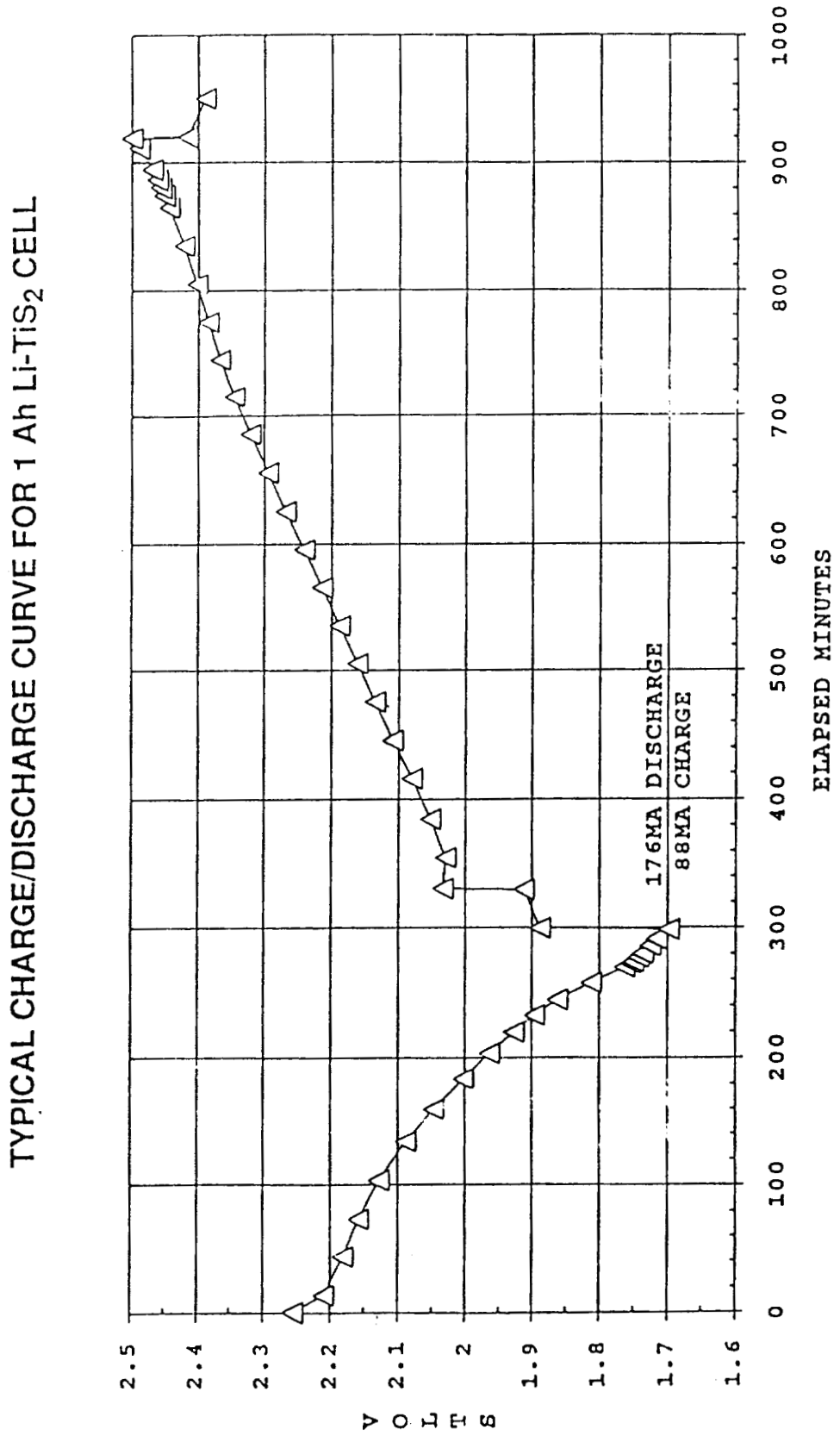
$$LI + TiS_2 \underset{C}{\overset{D}{\rightleftharpoons}} LI\text{-}TiS_2$$

ELECTROLYTE

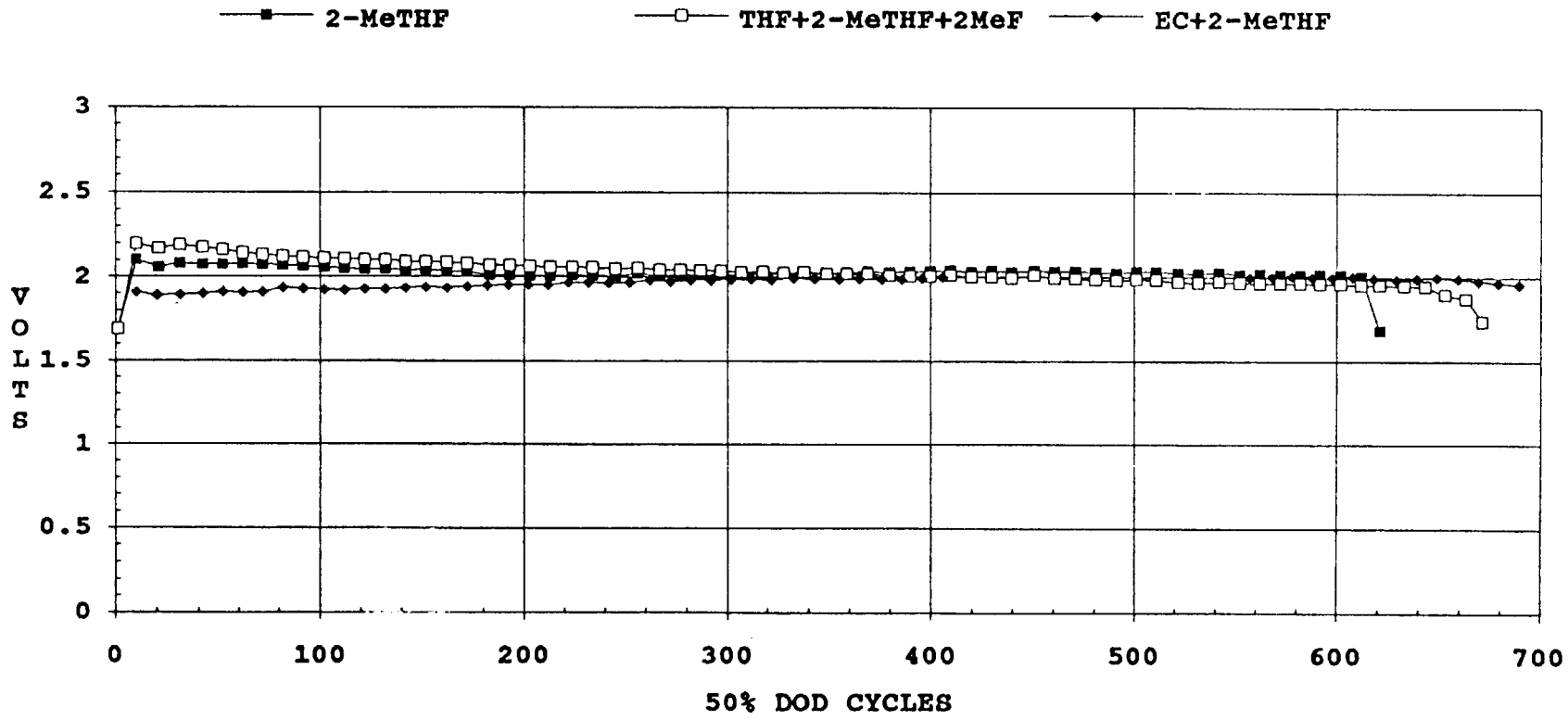
LITHIUM ARSENIC HEXAFLUORIDE ($LiAsF_6$) – SALT

2-METHYL TETRA HYDROFURAN (2-MeTHF) WITH

ETHYLENE CARBONATE (EC) – MIXED SOLVENT


TYPICAL CHARGE/DISCHARGE CURVE FOR 1 Ah Li-TiS2 CELL
VOLTS
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
0
100
200
300
400
500
600
700
800
900
1000
ELAPSED MINUTES
176MA DISCHARGE
88MA CHARGE

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



ETC-22.XLC

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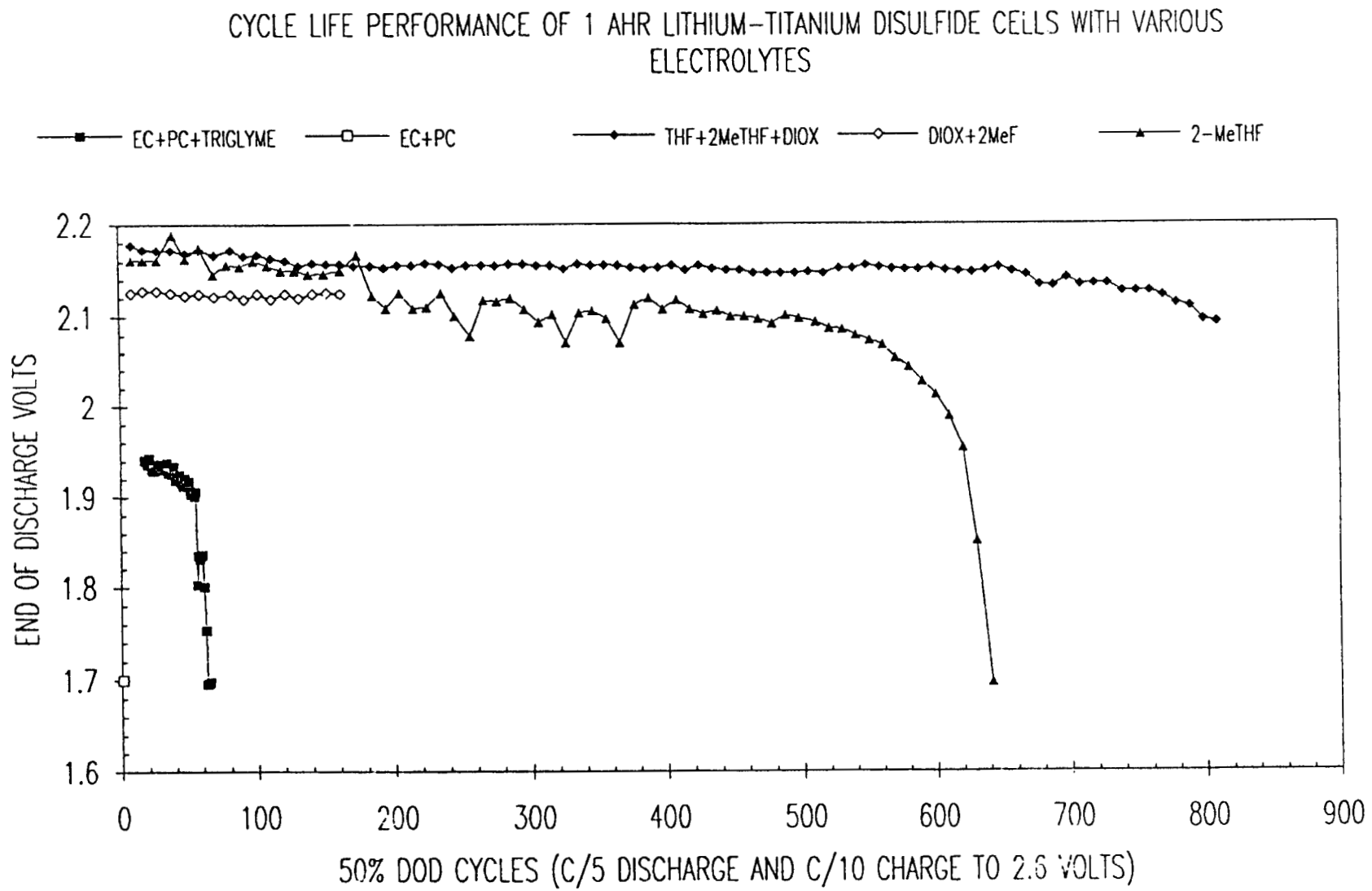

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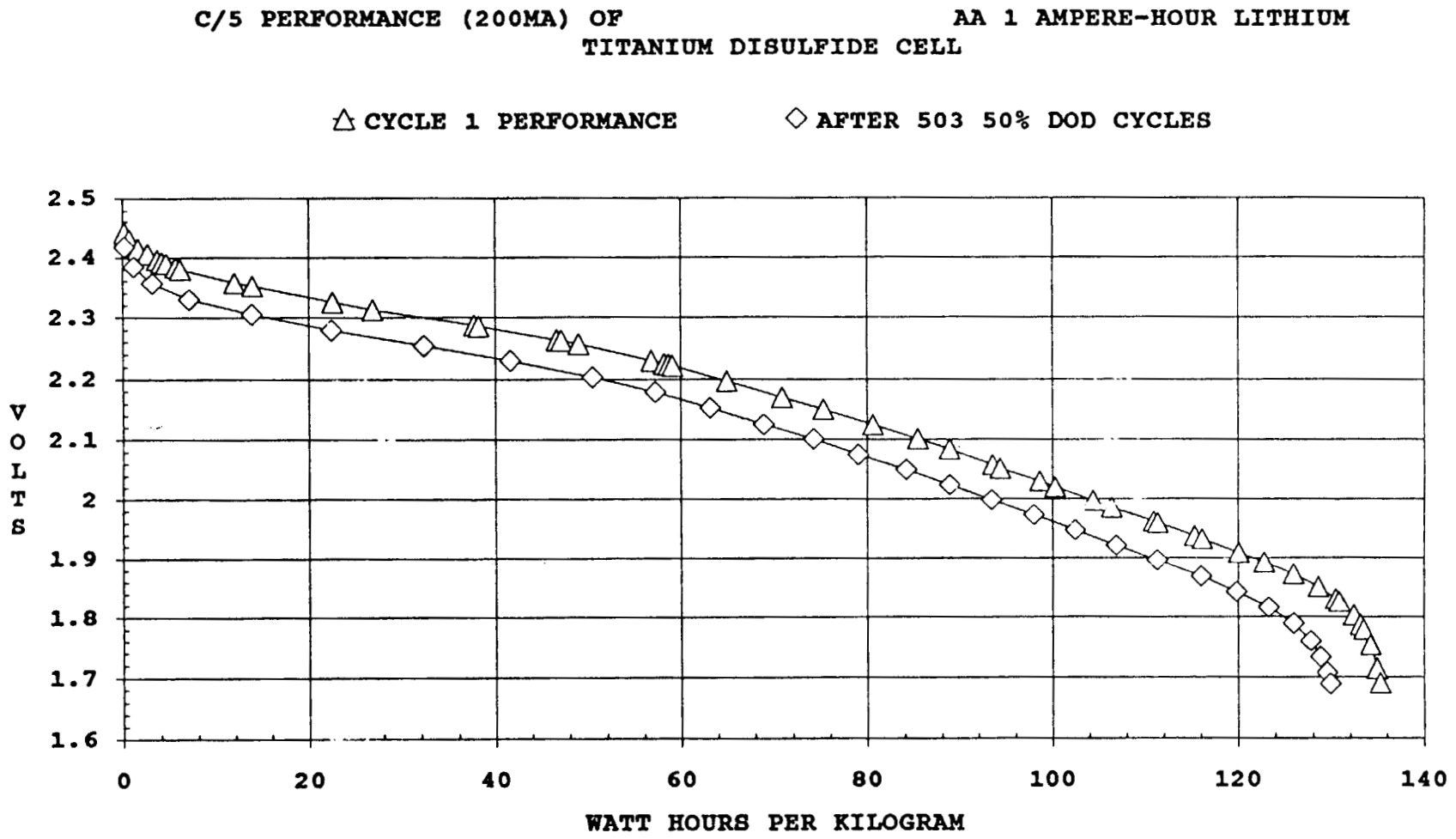
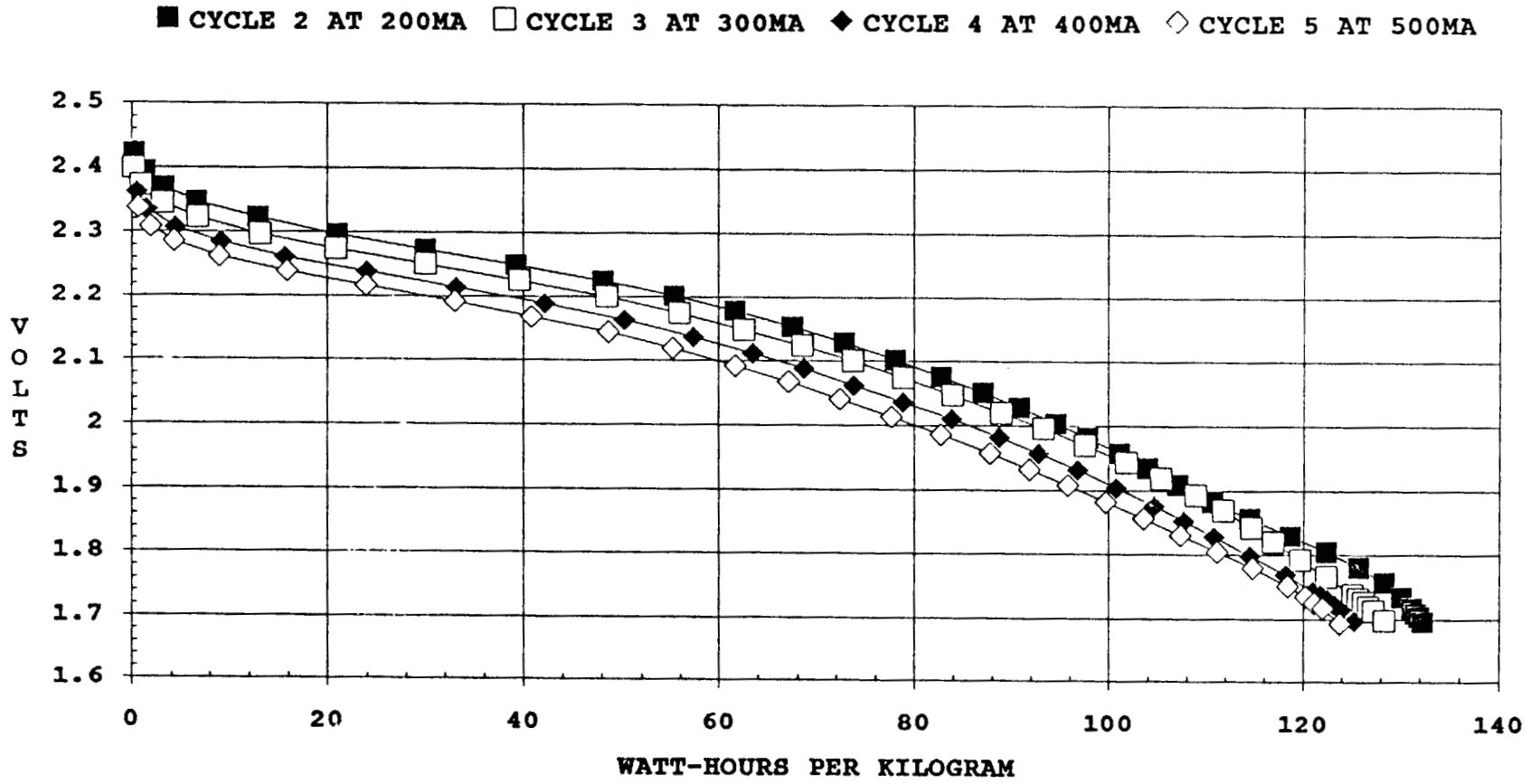

C/5 PERFORMANCE (200MA) OF AA 1 AMPERE-HOUR LITHIUM
TITANIUM DISULFIDE CELL
△ CYCLE 1 PERFORMANCE
◇ AFTER 503 50% DOD CYCLES
VOLTS
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
0
20
40
60
80
100
120
140
WATT HOURS PER KILOGRAM

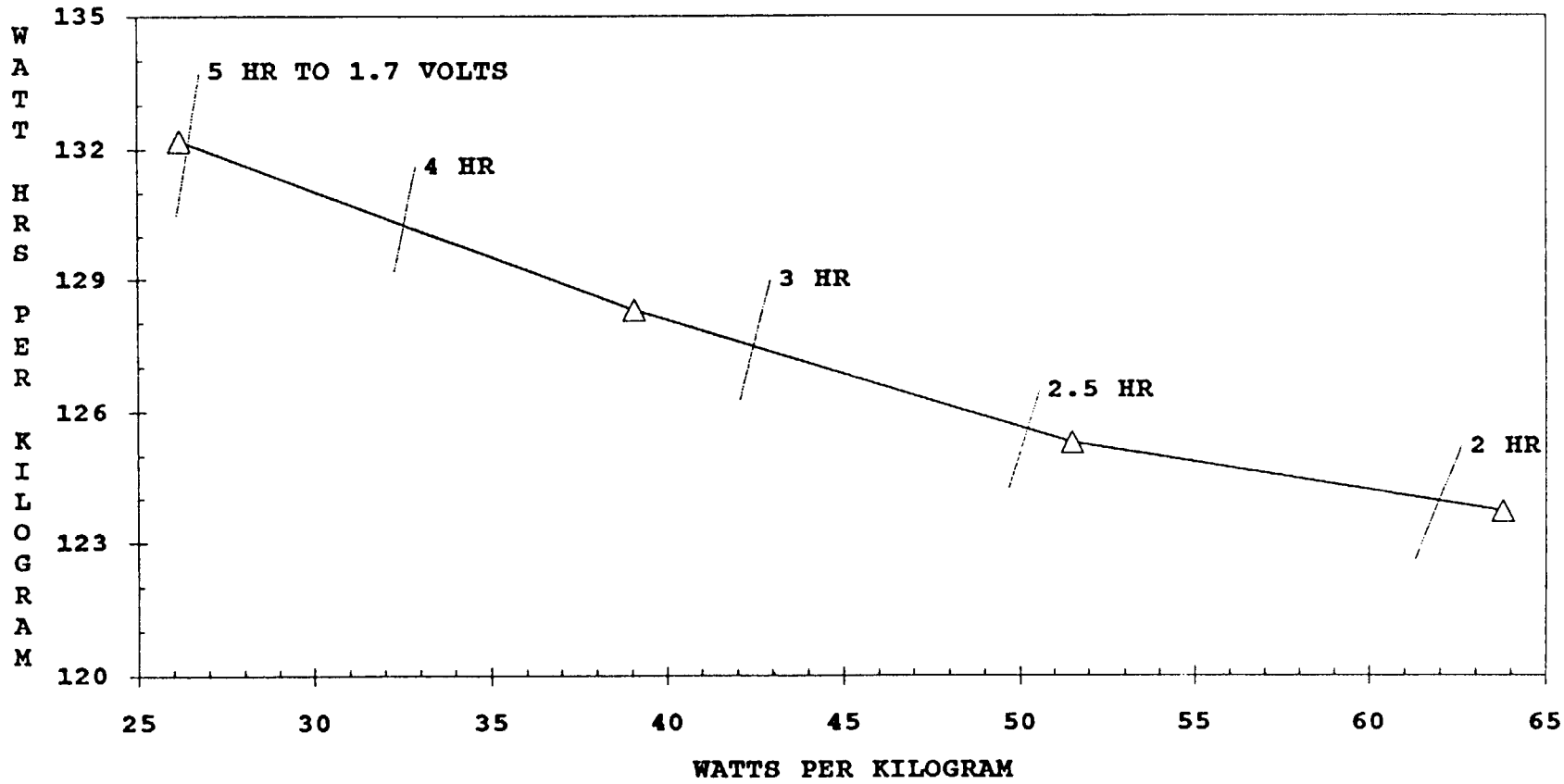
TYPICAL PERFORMANCE OF MANUFACTURED AA 1 AMPERE-HOUR LITHIUM TITANIUM DISULFIDE CELL



ETC-8.XLC

DEP 9/9/91 3:20 PM

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



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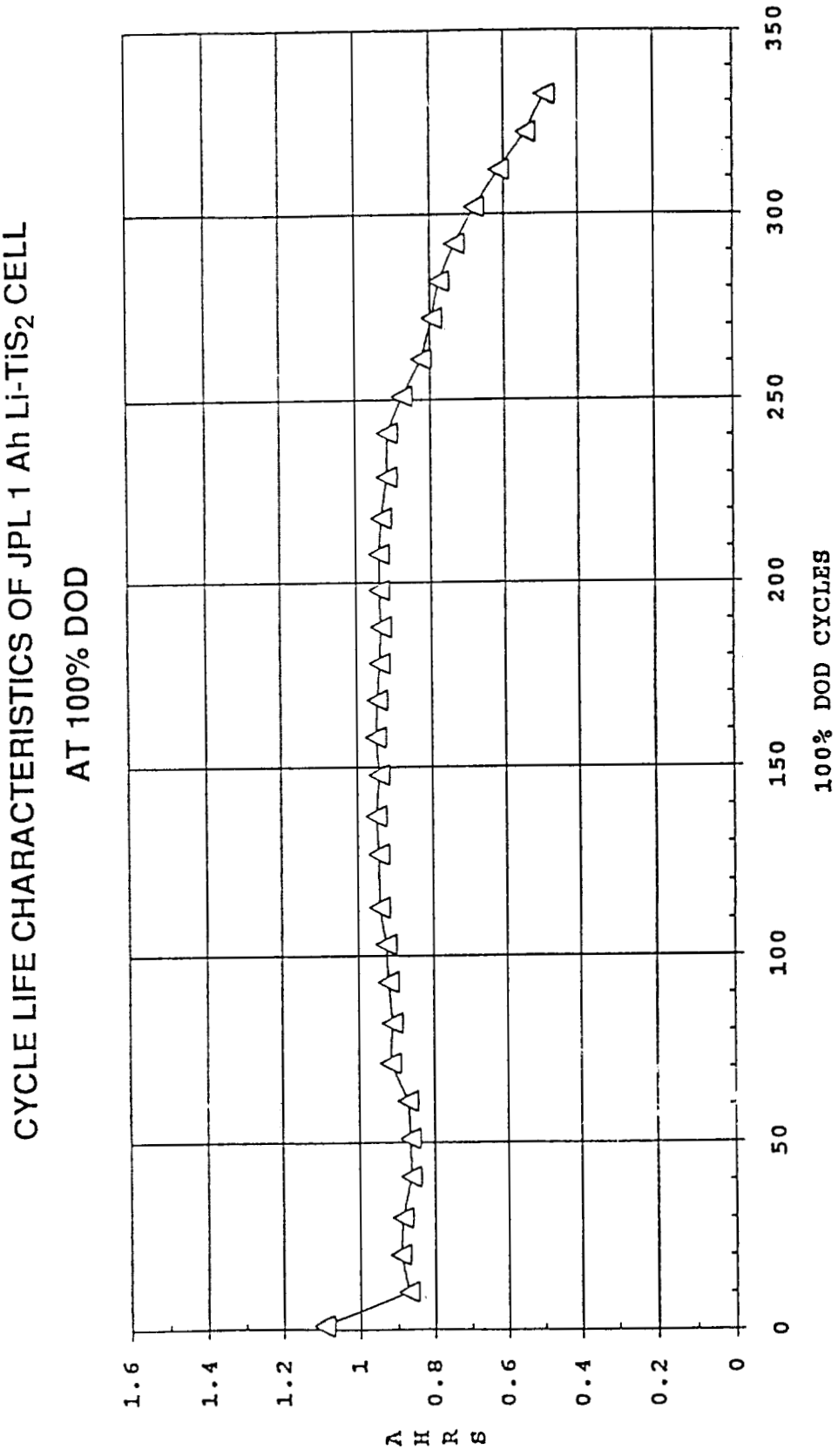

CYCLE LIFE CHARACTERISTICS OF JPL 1 Ah Li-TiS2 CELL
AT 100% DOD
AHRS
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
100% DOD CYCLES

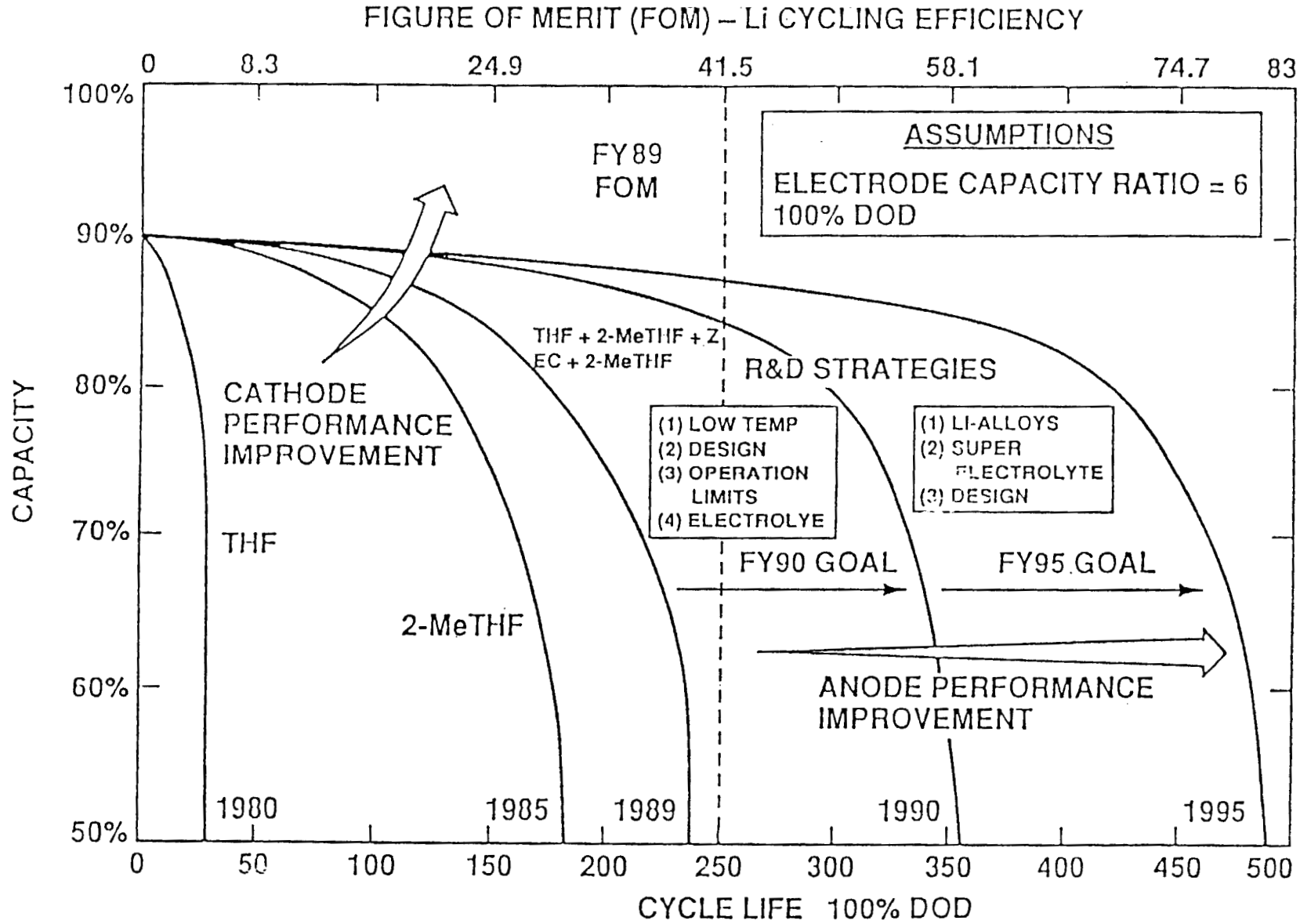
JPL

REQUIRED TECHNOLOGY IMPROVEMENTS

IPARAMETER	PRESENT STATUS	NASA REQUIREMENT
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_2 CELL TECHNOLOGY



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ALTERNATE Li ANODE MATERIAL STUDIES

EXPERIMENTAL EVALUATION OF SELECTED Li ALLOYS

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

* Microcalorimetric and OCV measurements.

** Galvanostatic cycling studies.

*** Calculated based on TiS2 cathode.

SUMMARY OF FINDINGS:

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

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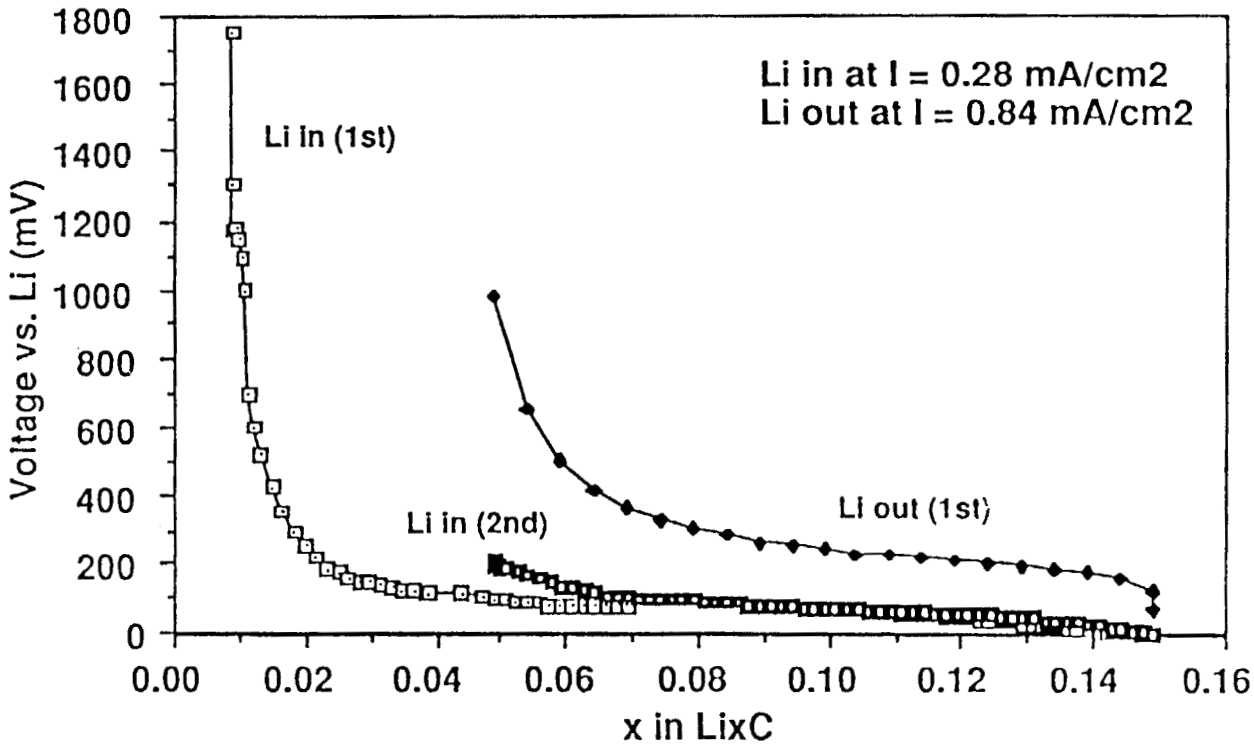
ELECTROCHEMICAL INTERCALATION & DE-INTERCALATION OF Li IN Li_xC



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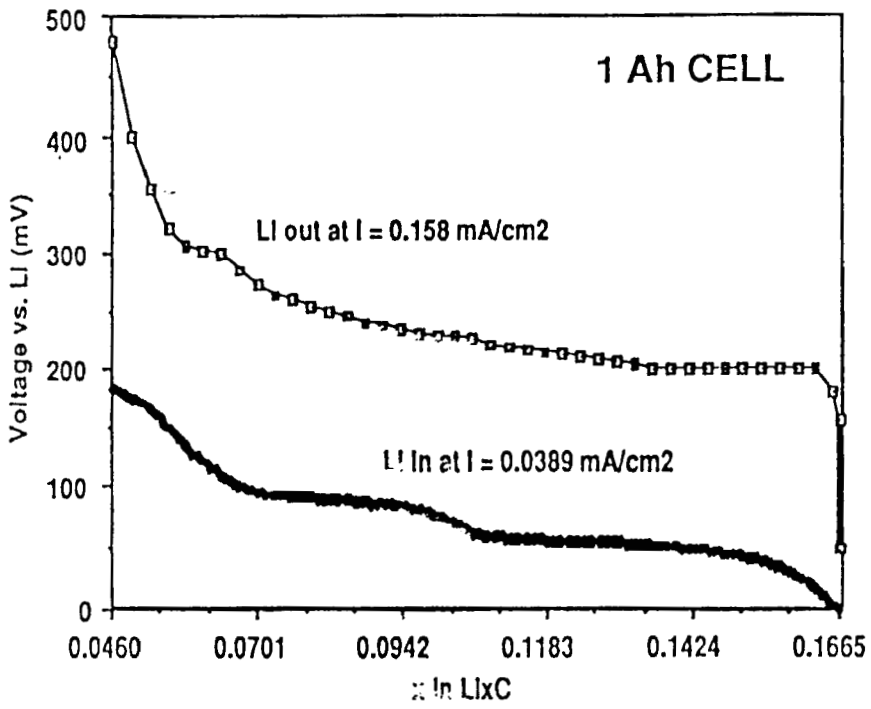
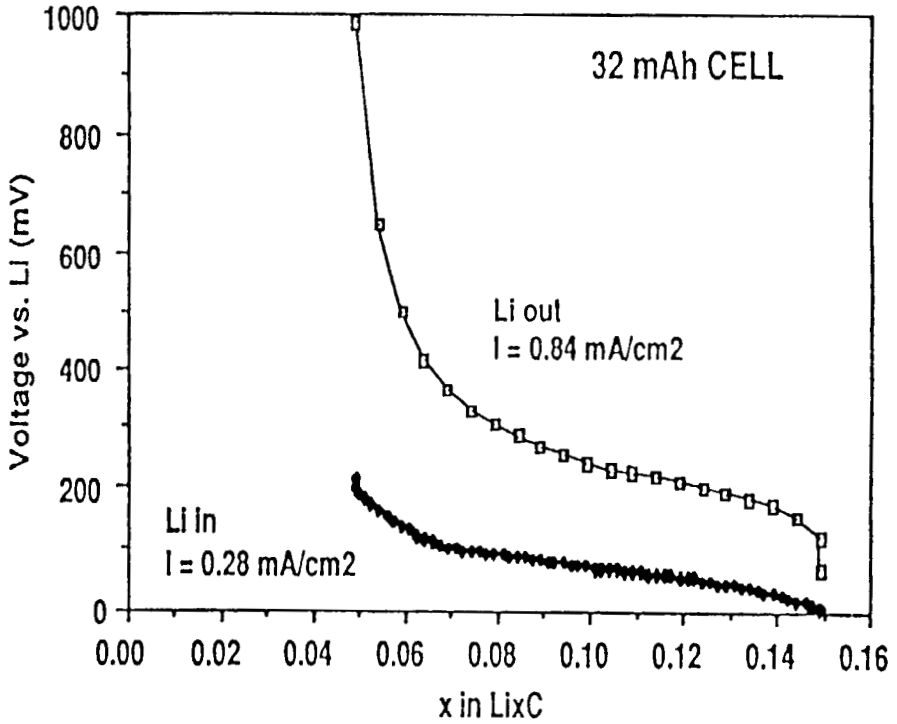
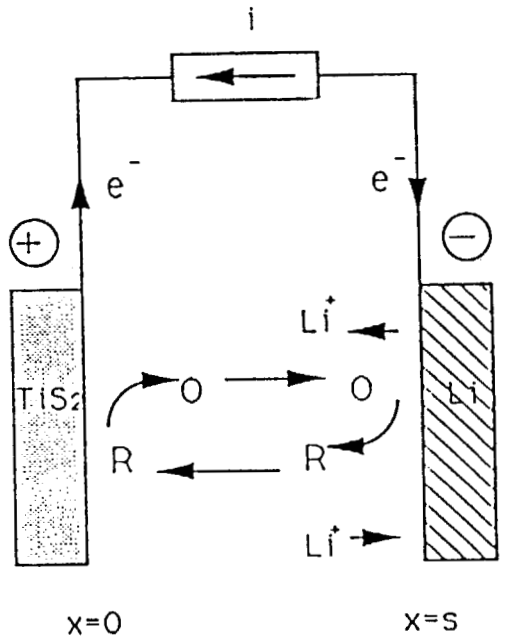
COMPARISON OF CHARGE & DISCHARGE CHARACTERISTICS OF 1 Ah & 32 mAh CELLS





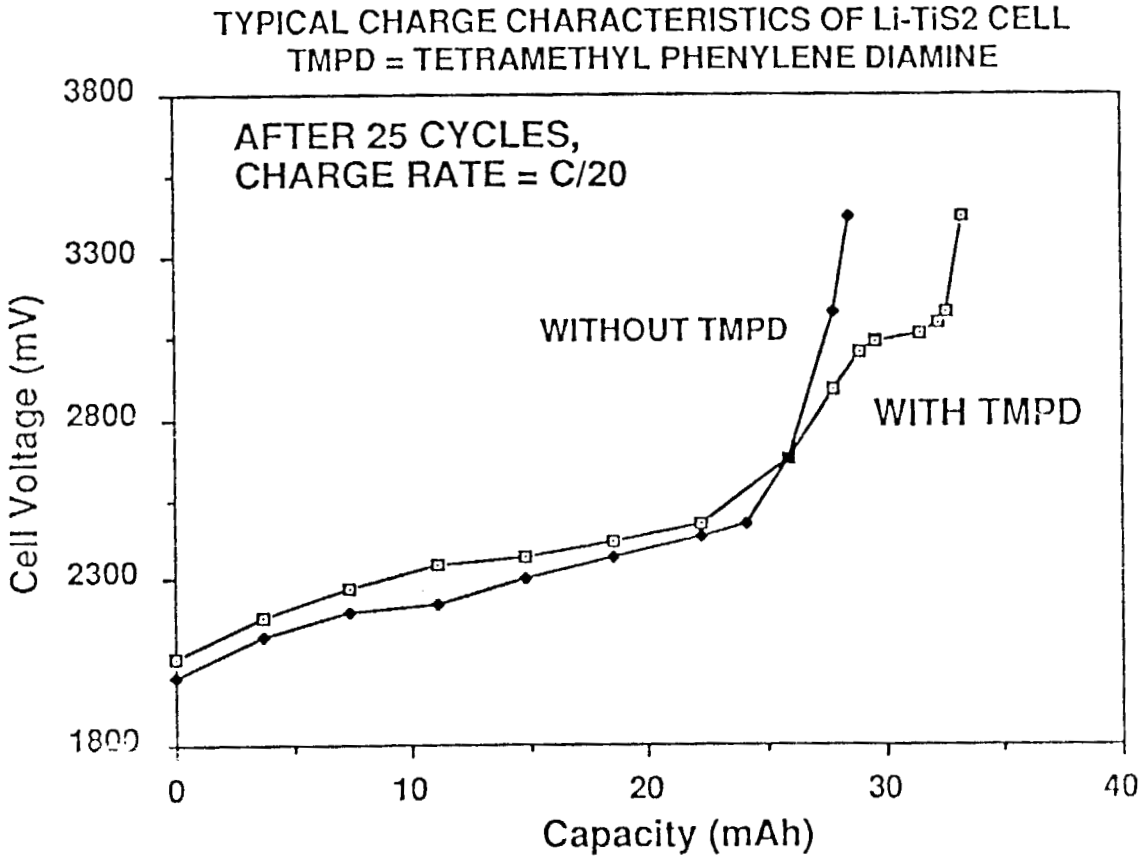
REDOX SHUTTLE APPROACH TO OVERCHARGE PROTECTION



CHEMICAL ENERGY CONVERSION (BATTERY) TECHNOLOGY

JPL RECHARGEABLE LITHIUM CELL PROGRAM

STUDIES ON OVERCHARGE PROTECTION



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..CONDARY 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

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SECONDARY LITHIUM CELLS/BATTERIES
ACKNOWLEDGEMENTS

THIS WORK DESCRIBED HERE WAS CARRIED OUT AT THE JET PROPULSION LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY, THROUGH AN AGREEMENT WITH THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION. (Code RP)

THE DEVELOPMENT OF NICKEL-METAL HYDRIDE TECHNOLOGY FOR USE IN AEROSPACE APPLICATIONS

Guy Rampel, Herschel Johnson

Dan Dell, Tony Wu, and Vince Puglisi

GATES ENERGY PRODUCTS, INC.

GATES AEROSPACE BATTERIES

October 30, 1991

BACKGROUND

The nickel metal hydride technology for battery application is relatively immature even though this technology was made widely known by Philips' Scientists as long ago as 1970. In particular Willem's 1984 dissertation in the Philips Journal of Research, Volume 39 Supplement No. 1, summarized for the reader the implications of metal hydrides for battery applications. However, recently, because of the international environmental regulatory pressures being placed on cadmium in the workplace and in disposal practices, battery companies worldwide have initiated extensive development programs to make this technology a viable commercial option. These hydrides do not pose a toxilogical threat as does cadmium. In addition, they provide higher energy density and specific energy when compared to the other nickel based battery technologies as will be shown. For these reasons, the nickel metal hydride electrochemistry is being evaluated as the next power source for varied applications such as laptop computers, cellular telephones, electric vehicles and satellites.

The NIMH system uses a positive electrode that is similar to both NiCd and NiH2 systems. The negative electrode is a metal alloy that absorbs hydrogen generated on charge and desorbs hydrogen during discharge. This leads to a cell that operates at a much lower pressure than a NiH2 cell, 50 psig versus 950 psig. The technology would be a direct replacement for NiCd technology in most applications, along with a significant improvement in both specific energy and energy density. Since the technology is low pressure and has similar electrical performance to a NiCd cell,it can be used in prismatic designs that are similar to current aerospace NiCd cell designs. In addition, since the cells would be prismatic in design, the battery design would be very similar to current NiCd battery designs.

GAB's parent company, Gates Energy Products (GEP), has a substantial ongoing effort to develop commercial NiMH wound cell technology. GEP's investigations and development started in mid 1987 in search of the best technology. A license agreement, established with Ovonic Battery Company in October 1990, initiated an intense product development.

GAB has a parallel development effort with GEP to look at aerospace applications for NIMH cells. This effort is focused on life testing of small wound cells of the commercial type to validate design options and development of prismatic design cells for aerospace applications. The manufacturing techniques for NiMH cells will be similar to current NiCd manufacturing techniques; however, some development of technology for flat plate metal hydride electrodes is required.

Although the promise is beckoning, one cannot lose sight of the shortfalls. These must be identified, studied, overcome or circumvented. The list includes end-of-life failure mechanisms; identification of optimum charge rates and charge termination methods; and stability of end-of-charge pressure. This will require intensive dedicated effort in the years ahead.

DESCRIPTION OF TABLES AND FIGURES

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 & NiH2 product designs with the prototype 22AH NiMH cells assembled with flight qualified hardware. As can be seen, the specific energy and energy density of the NiMH cell are significantly better than that of the NiCd and NiH2 cells. The advantage which the NiMH cell exhibits relative to the NiCd cell is derived from the higher energy density of the metal hydride electrode, expressed as AH/in^3, versus the sintered cadmium electrode. On the other hand, the disadvantage the NiH2 exhibits relative to the NiMH cell stems primarily from the pressure vessel weight and volume, which is a particularly large percentage of the total cell weight and volume for capacities less than about 30AH.

TABLE II: A comparison of nickel metal hydride, nickel cadmium and nickel hydrogen 22AH cell dimensions.

TABLE III: A comparison of 6 and 22AH nickel metal hydride cell designs.

It should be noted that for the 6AH cell design nylon separator is employed as the baseline and is therefore listed. However, some of these cells have been assembled with polypropylene separator which is di-

mensionally a direct substitute for the nylon. The significance for examining polypropylene is its stability in the alkaline environment of the cell. This is to be contrasted to the slow degradation experienced by nylon, even though nylon is the primary separator utilized in most qualified Aerospace nickel cadmium cell applications.

FIGURE 1: Prototype Aerospace Prismatic 6AH cells on cycle life test.

FIGURE 2: Prototype Aerospace Prismatic 6AH cell discharge rate capability.

To examine the dependence of capacity as a function of discharge rate, cells were discharged at either the C/2, C or 3C rate following a C/10 charge. These tests were conducted at room temperature. As can be seen, the dependence on discharge rate over the range tested is minimal.

FIGURE 3: Cylindrical cell capacity vs temperature @ C rate.

FIGURE 4: Prototype Aerospace Prismatic 6AH cell EOCV and EODV trends as a function of number of 50% DOD LEO cycles.

The data shown illustrates the end-of-charge voltage (EOCV) and end-of-discharge voltage (EODV) trend over the cycle life accumulated to date. The discharge/charge regime is currently set at 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

	Nickel Cell Electrochemistry		
	NiCd	NiH_2	NiMH
Performance Attribute	(Note 1)	(Note 1)	(Note 2)
Midpoint Discharge Voltage (v)	1.20	1.24	1.24
Typical Capacity @ C/2 (AH)	22	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^3)	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

	Nickel Cell Electrochemistry		
Cell Dimensions	**NiCd**	**NiH_2**	**NiMH**
(Inches)	(Note 1)	(Note 1)	(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)	
Item	**6AH**	**22AH**
Positive Electrodes		
Number	14	15
Thickness (in)	0.028	0.028
Capacity (AH) theoretical	7.5	27.6
Negative Electrodes		
Number	15	16
Thickness (in)	0.0125	0.0125
Capacity (AH)	11.5	42.2
Separator	Nylon-2538	Nylon-2538
Negative to Positive Capacity Ratio	**1.5**	**1.5**
Electrolyte		
Type	KOH	KOH
Concentration (%)	31	31
Cell Dimensions (in)		
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

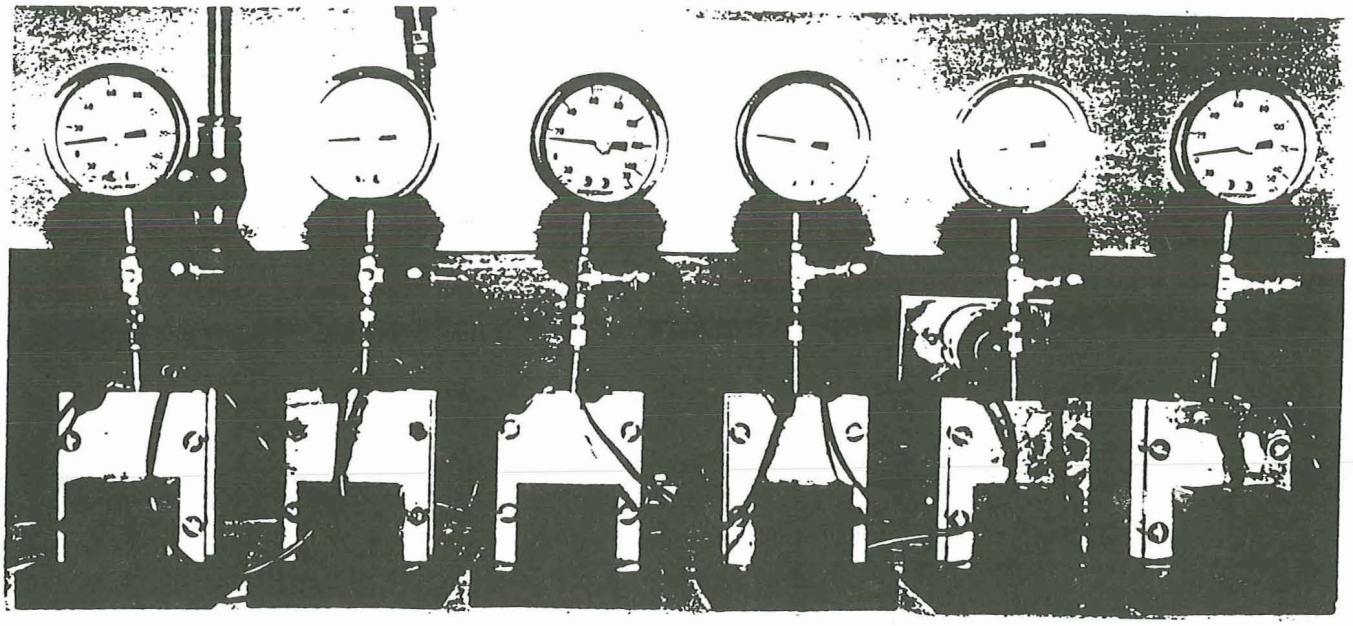


Figure 1 *Prototype Aerospace Prismatic 6AH cells on cycle life test*

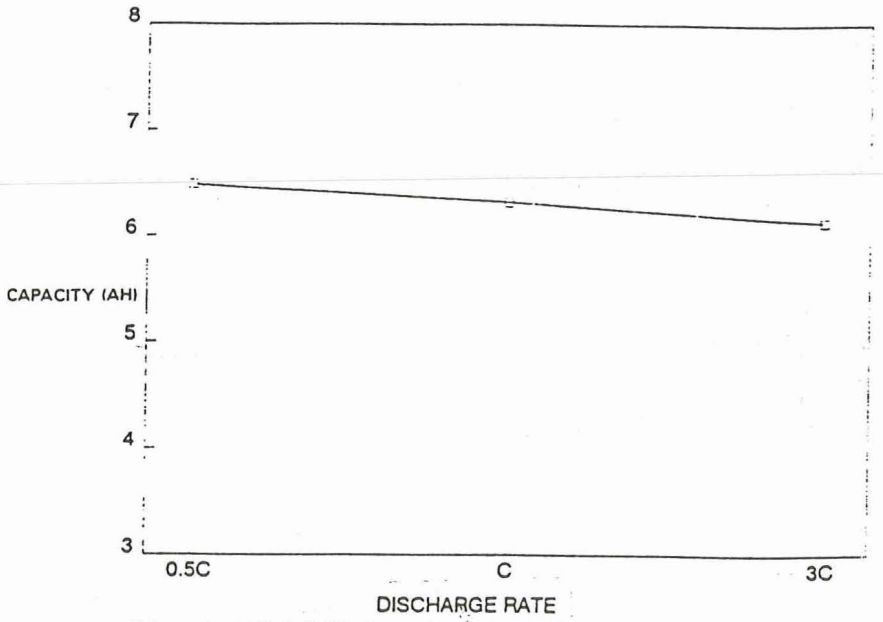


Figure 2 *Prototype Aerospace Prismatic 6AH Cell Discharge Rate Capability*

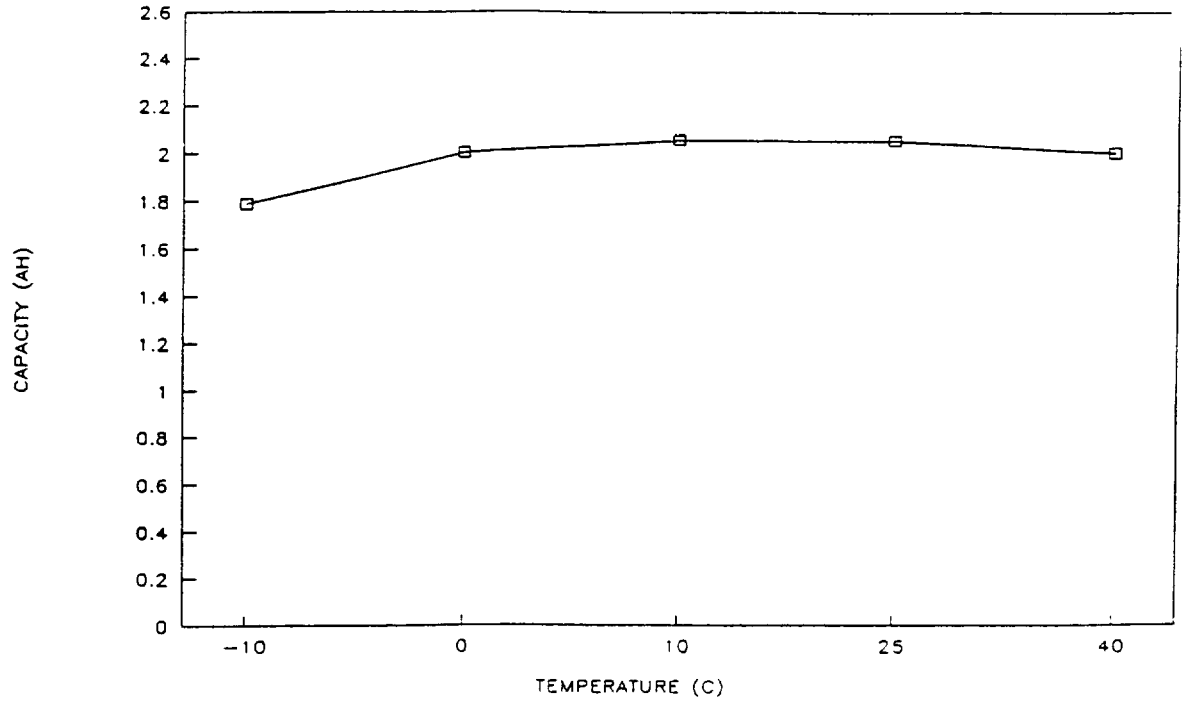


Figure 3 Cylindrical Cell Capacity vs. Temperature @ C Rate

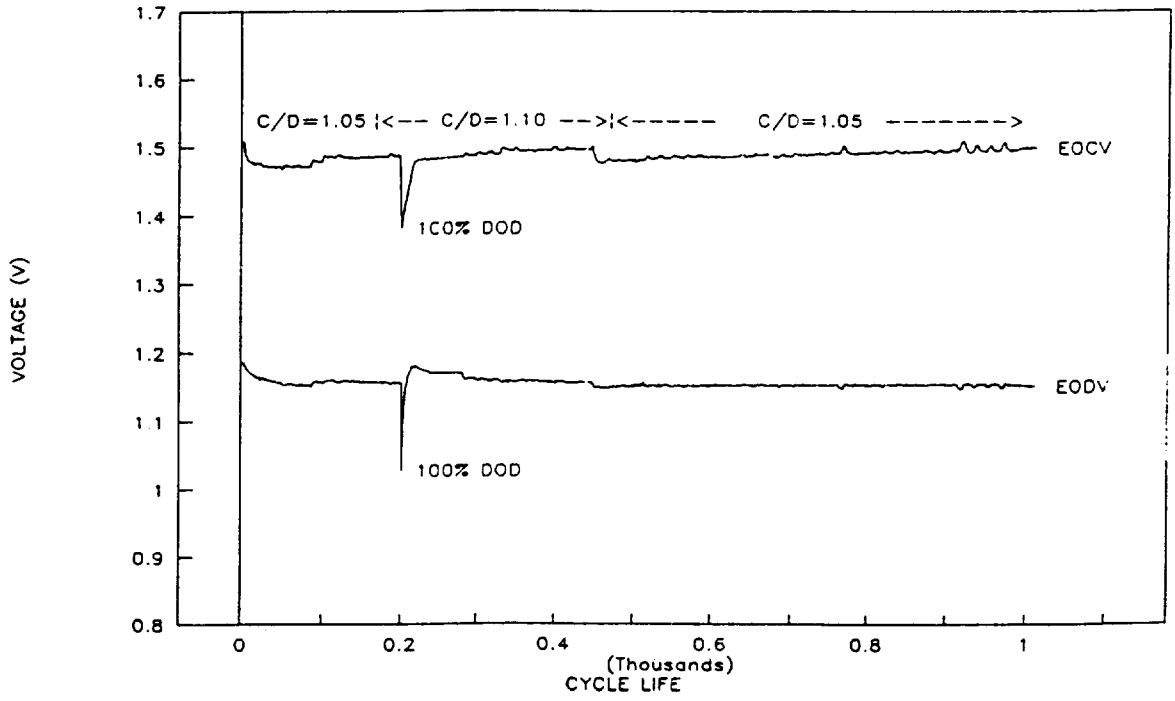


Figure 4 Prototype Aerospace Prismatic 6AH Cell EOCV and EODV Trends as a Function of Number of 50% DoD LEO Cycles

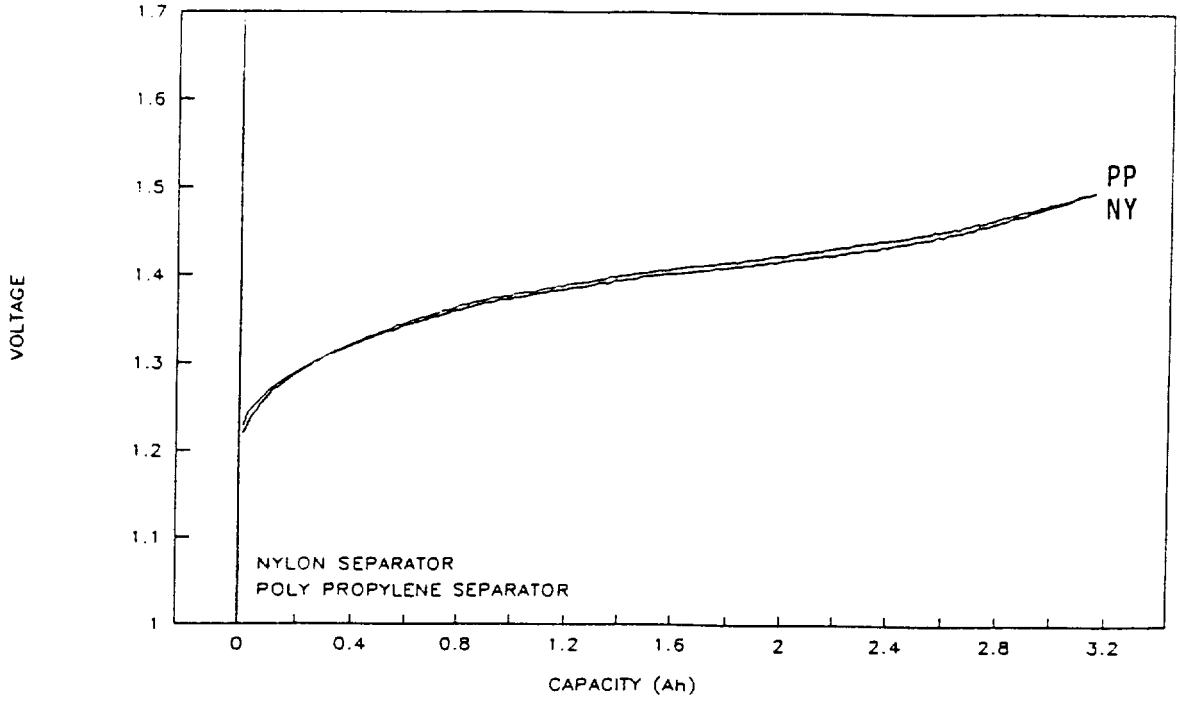


***Figure 5** Prototype Aerospace Prismatic 6AH Cell Charge Voltage Curve While undergoing 50% DoD LEO Cycle: Recharge Ratio = 1.05, Cycle 1010*

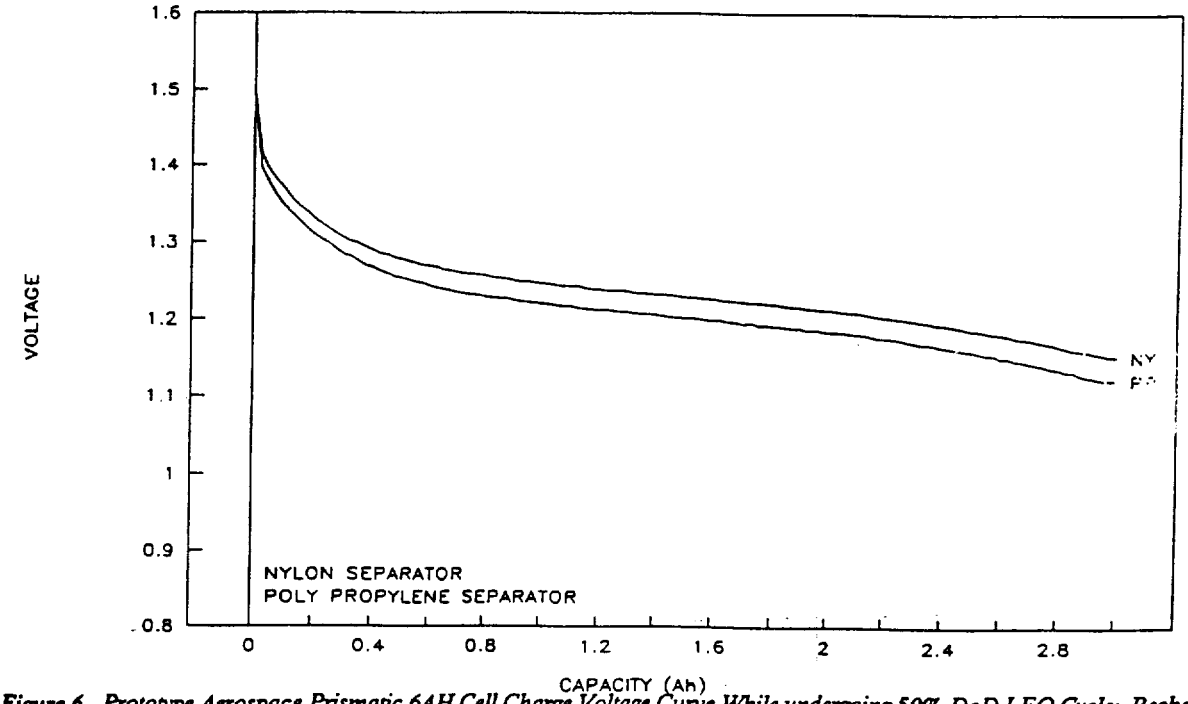


***Figure 6** Prototype Aerospace Prismatic 6AH Cell Charge Voltage Curve While undergoing 50% DoD LEO Cycle: Recharge Ratio = 1.05, Cycle 1010*

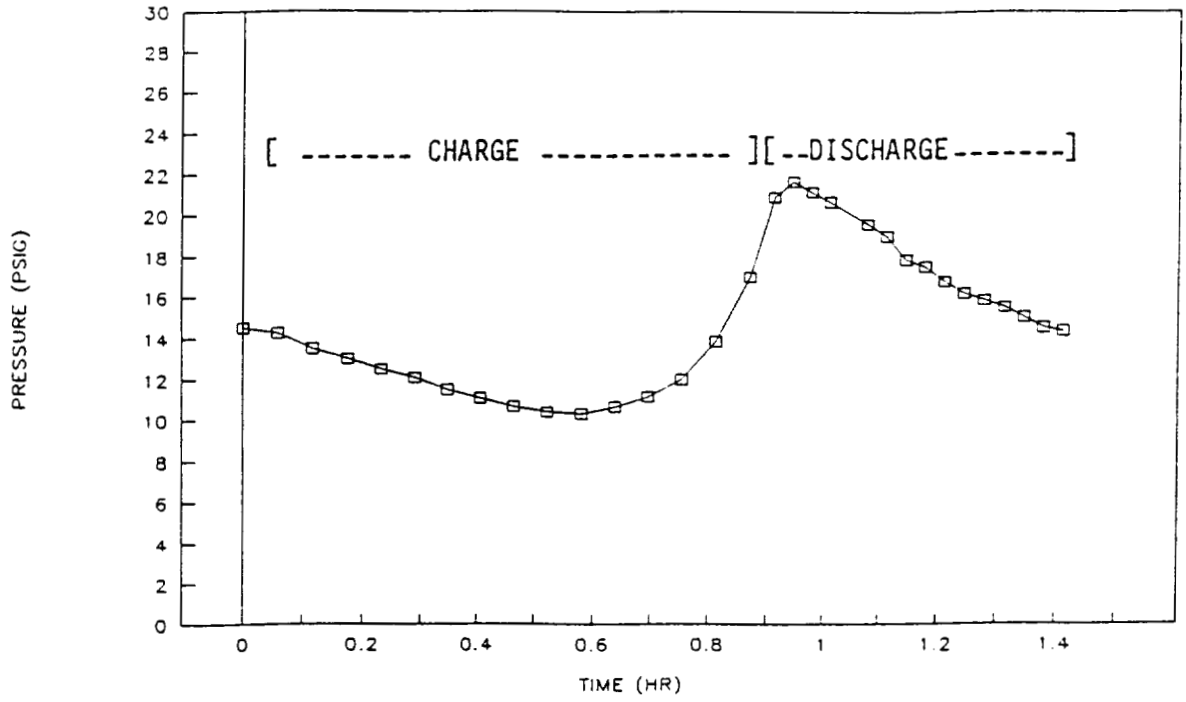


Figure 7 Prototype Aerospace Prismatic 6AH Cell Pressure Curve While undergoing 50% DoD LEO Cycle: Recharge Ratio = 1.05, Cycle 788

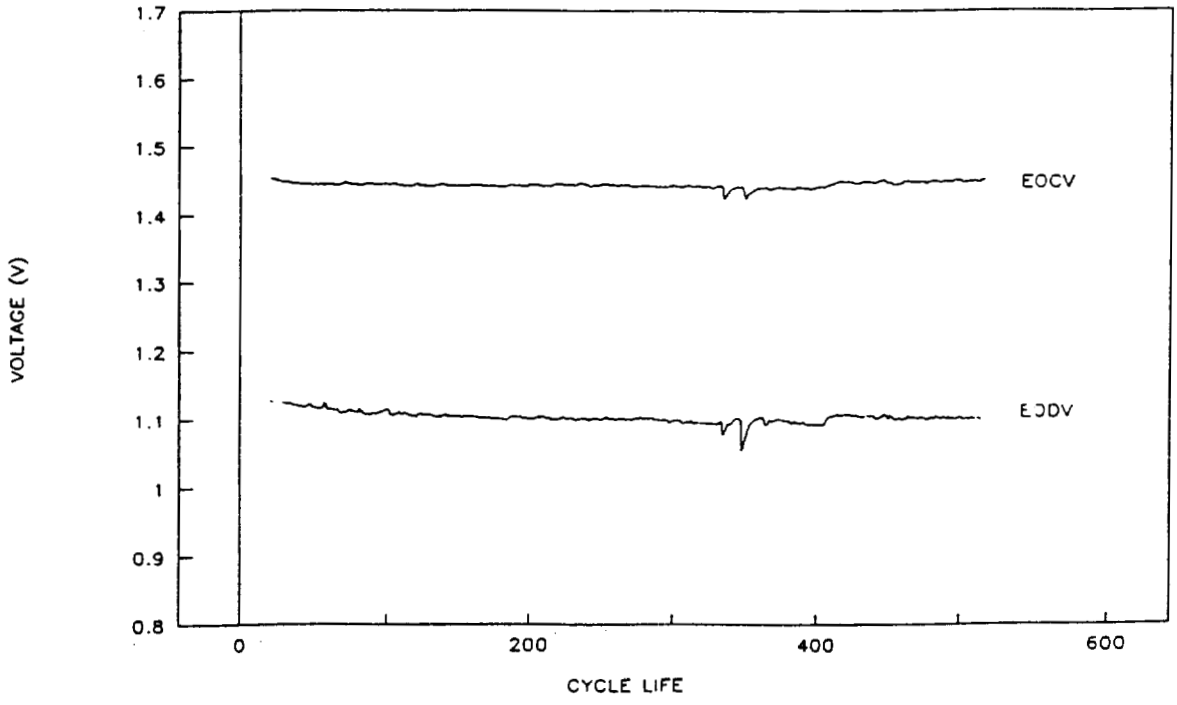


Figure 8 Prototype Aerospace Prismatic 22AH Cell EOCV and EODV Trends as a Function of Number of 50% DoD LEO Cycles

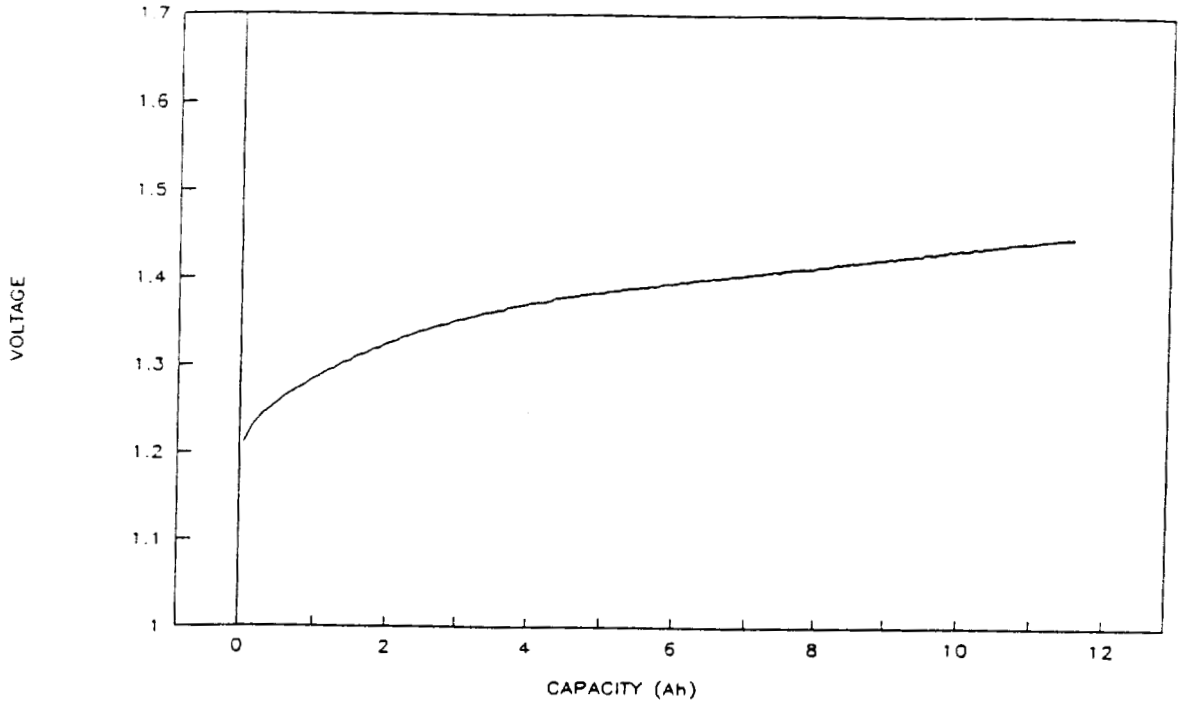


Figure 9 Prototype Aerospace Prismatic 22AH Cell Charge Voltage Curve While Undergoing 50 % DoD LEO Cycle: . charge Ratio = 1.05, Cycle 512

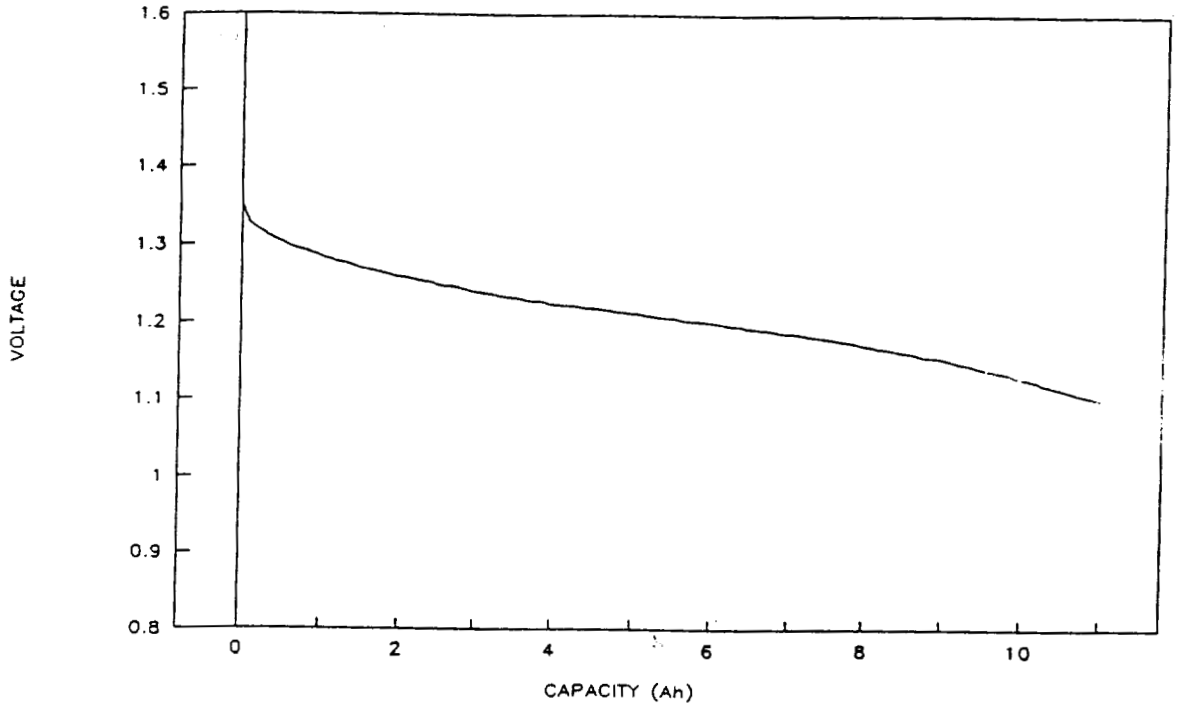


Figure 10 Prototype Aerospace Prismatic 22AH Cell Discharge Voltage Curve While Undergoing 50% DoD LEO Cycle: R : charge Ratio = 1.05, Cycle 512

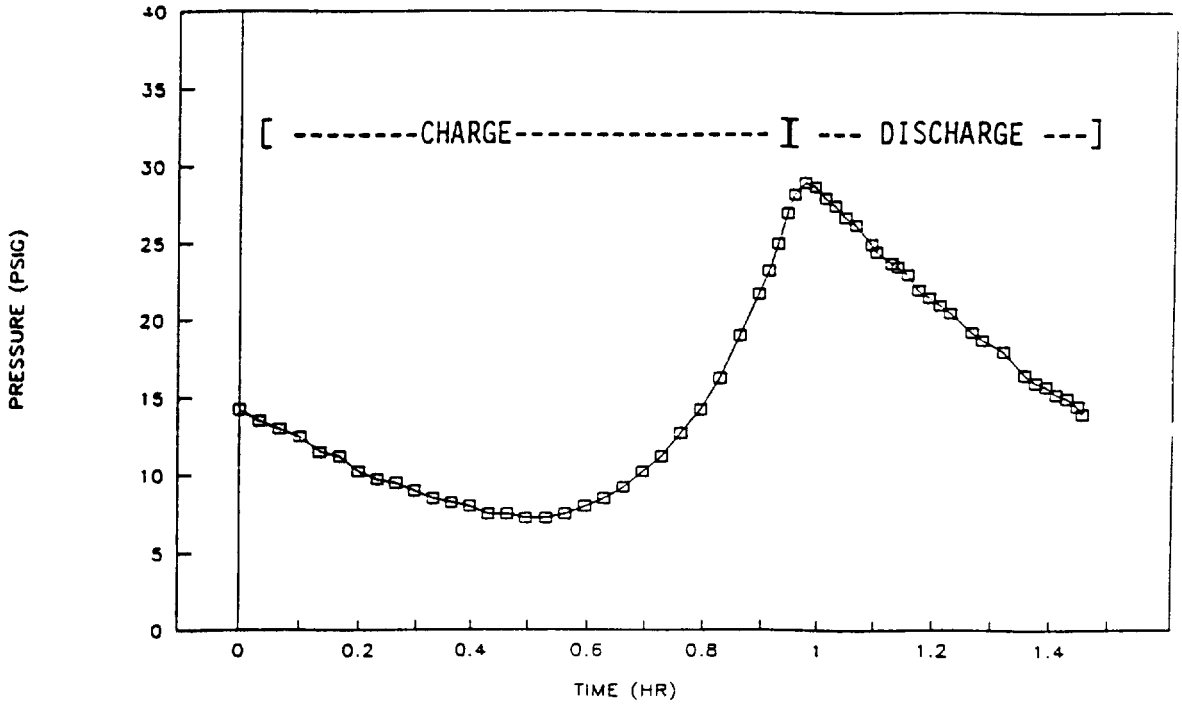


Figure 11 *Prototype Aerospace Prismatic 22AH Cell Pressure Curve While Undergoing 50% DoD LEO Cycle: Recharge Ratio = 1.05, Cycle 401*

Figure 12

Conclusions

Acceptable Pressures < 50 PSIG

ide Operating Temperature Range, -10 to + 40 C

Insensitive to High Rate Regime - 3C

Promising Cycle Life - 1000 LEO cycles and counting

Energy Density > NiH_2 and NiCd

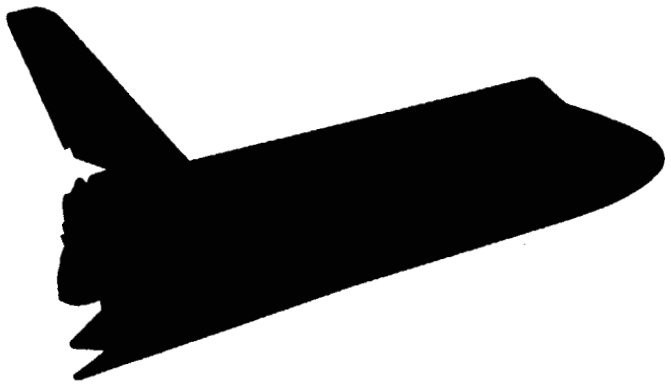
Specific Energy > NiCd and NiH_2

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

HERMERICALLY SEALED

OPERATE AT LOW PRESSURE

PRISMATIC GEOMETRY

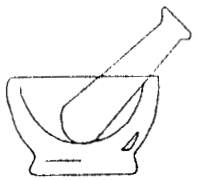
EXCELLENT OVERCHARGE

EXCELLENT OVERDISCHARGE

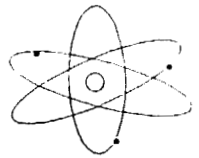
EXCELLENT THERMAL

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
Treibacher-Austria
Rhone-Poulenc
Nissho-Iwai America
Sumitomo
Ergenics
HCI-Denver
Aesar/Johnson Matthey
Baotou Research

Tricoastal Lanthanides
Crucible
Goldschmidt AG
Indian Rare Earths
Molycorp/Unocal
REMACOR
Santoku Metal
Chori-Osaka
Japan Metals

There are currently a large number of companies interested in the metal hydride battery business. Nearly all of the commercial battery companies have either announced products or are in the development stage of a product. There are a lot of potential sources for hydride electrode materials. This table shows only the sources that I am aware of and is not necessarily complete. Materials from several of these sources are currently on test and other materials are either in-house or in-transit. A comprehensive development effort is currently underway at Eagle-Picher to evaluate as many prospective materials as possible.

METAL-HYDRIDE ENERGY DENSITY
DISCHARGE VOLTAGE
CAPACITY (mAH/g)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0
50
100
150
200
250
300
RATE: 50mA
TEMP: 23 DEG.C
○ TREIBACHER
△ OVONICS
□ RHONE-POULENC

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.

EAGLE PICHER
Electronics Division
Joplin, MO

Sealed Metal-Hydride Batteries for Aerospace Applications

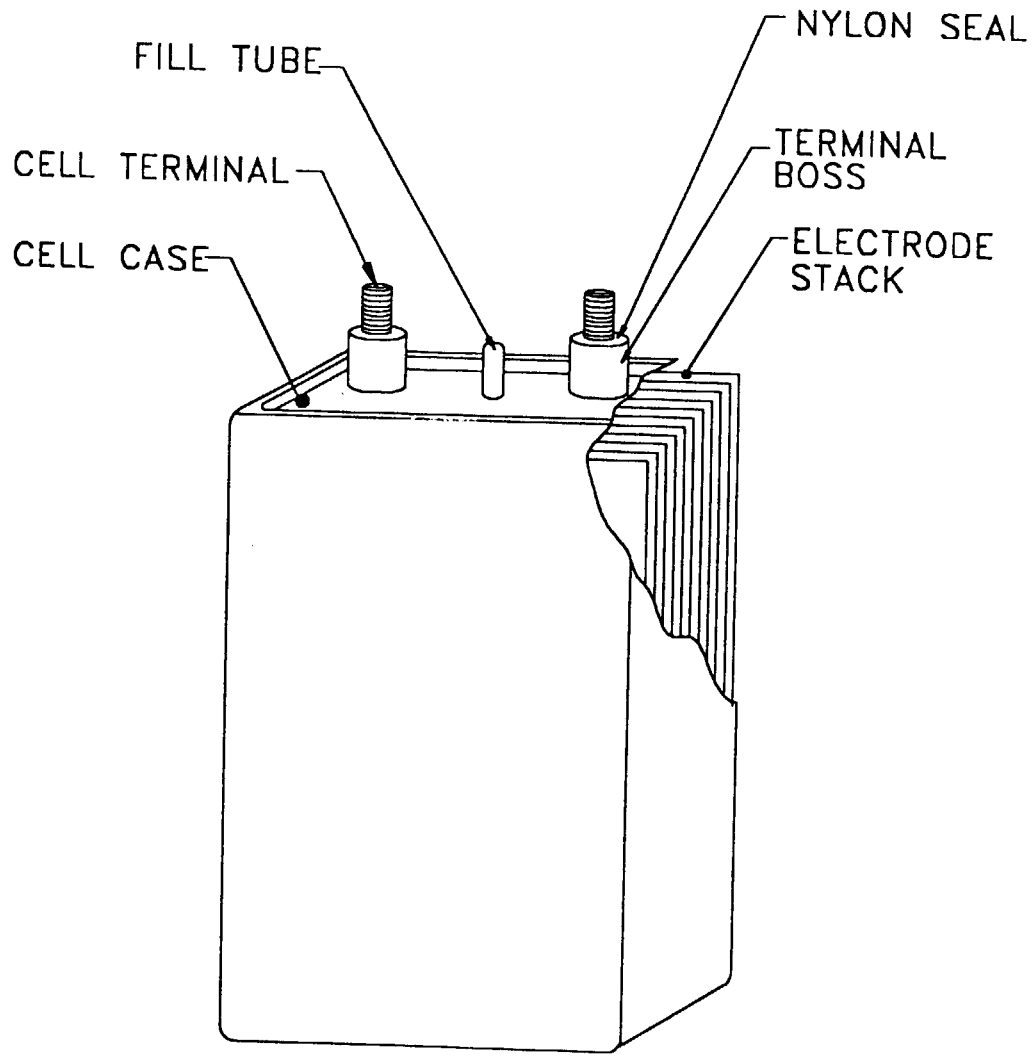


Figure 2
Prismatic Aerospace Nickel-Metal Hydride Cell

EAGLE PICHER Quality First!

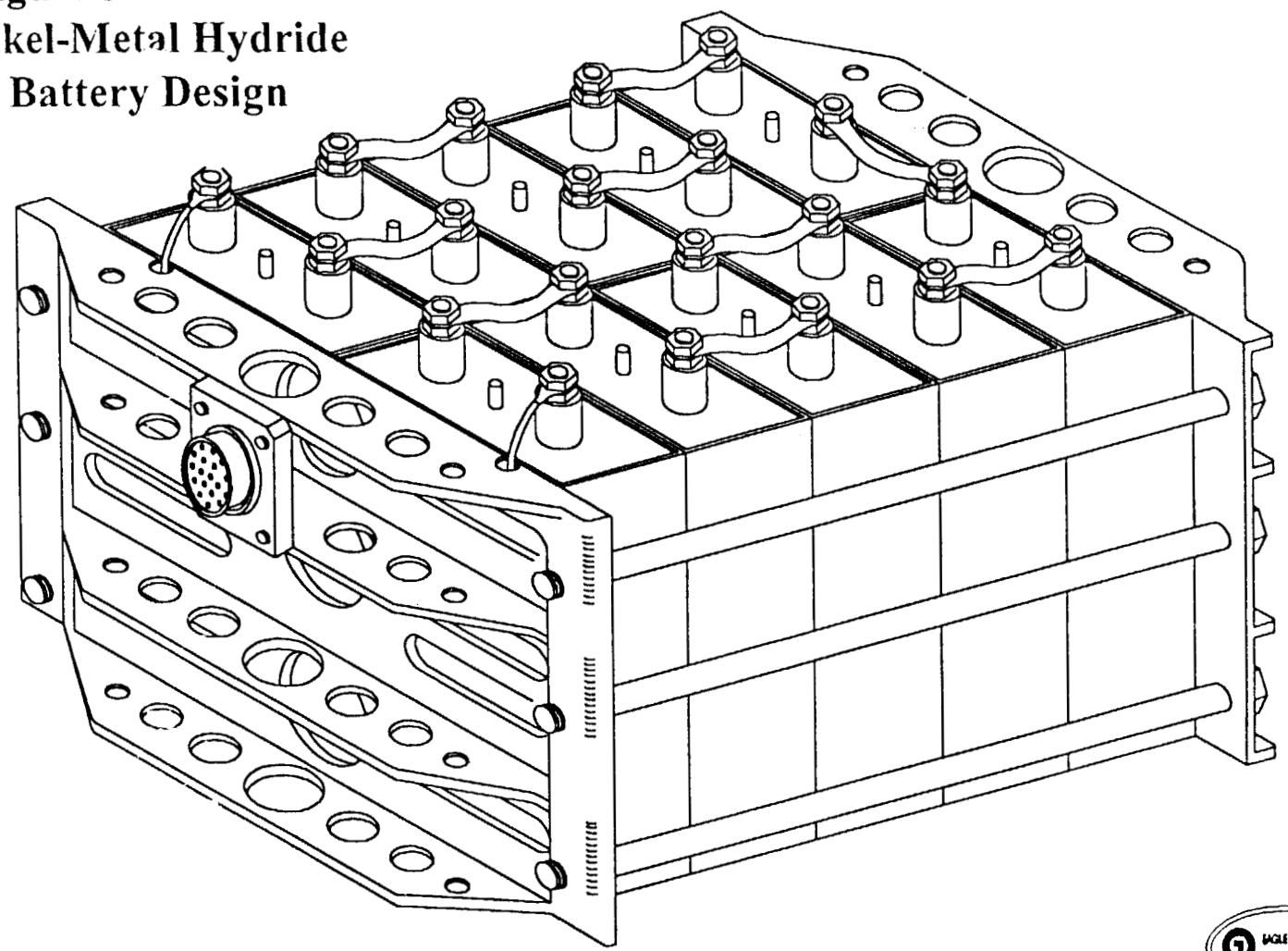
The advantage of the metal hydride cell over nickel-hydrogen is that the hydrogen is stored as a solid metallic hydride rather than as a gas. Therefore the cell operates at low pressure and a rectangular geometry can be used for the cell container. The volumetric energy density of the cell is much higher 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.

EAGLE PICHER

Electronics Division
Joplin, MO

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.

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Sealed Metal-Hydride Batteries for Aerospace Applications

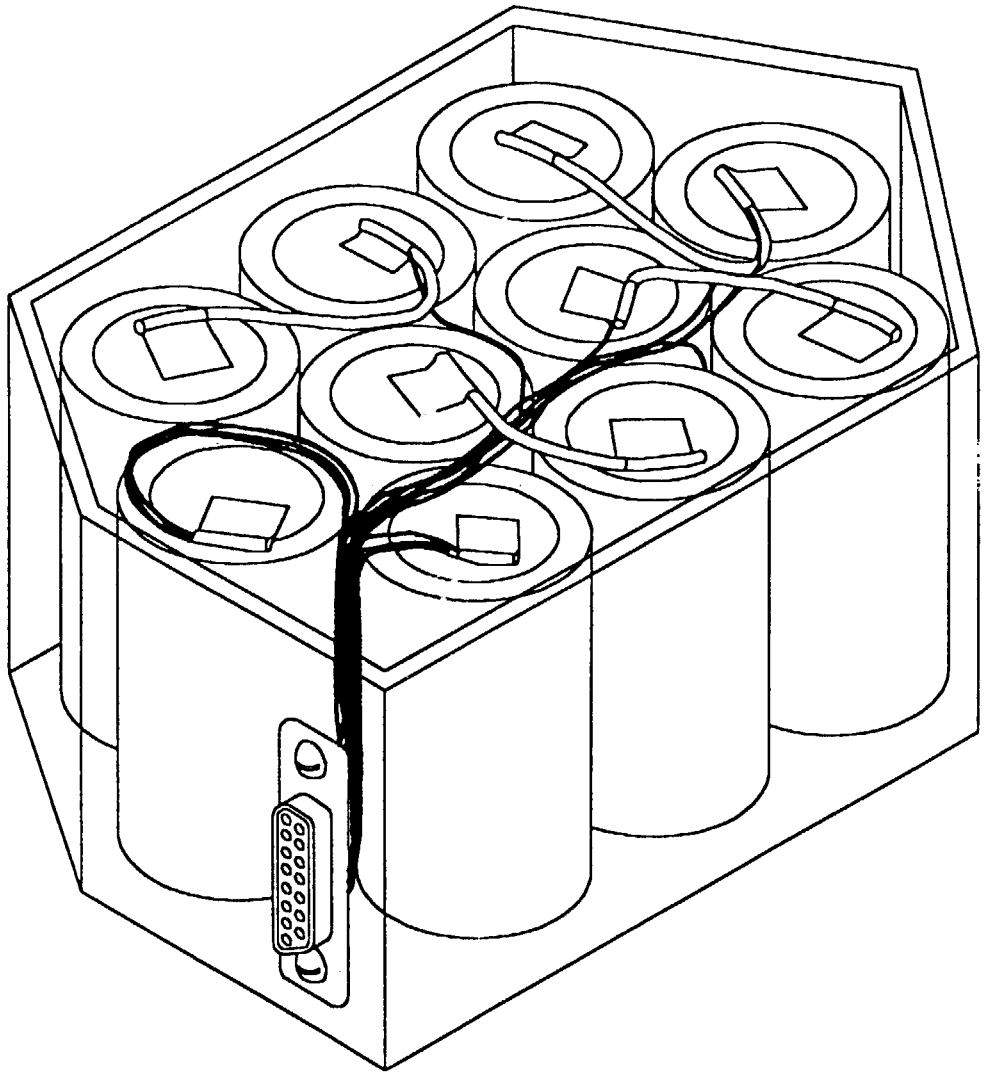

Figure 4
Nickel-Metal Hydride
Alternative Battery Design

EAGLE PICHER Quality First!

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.

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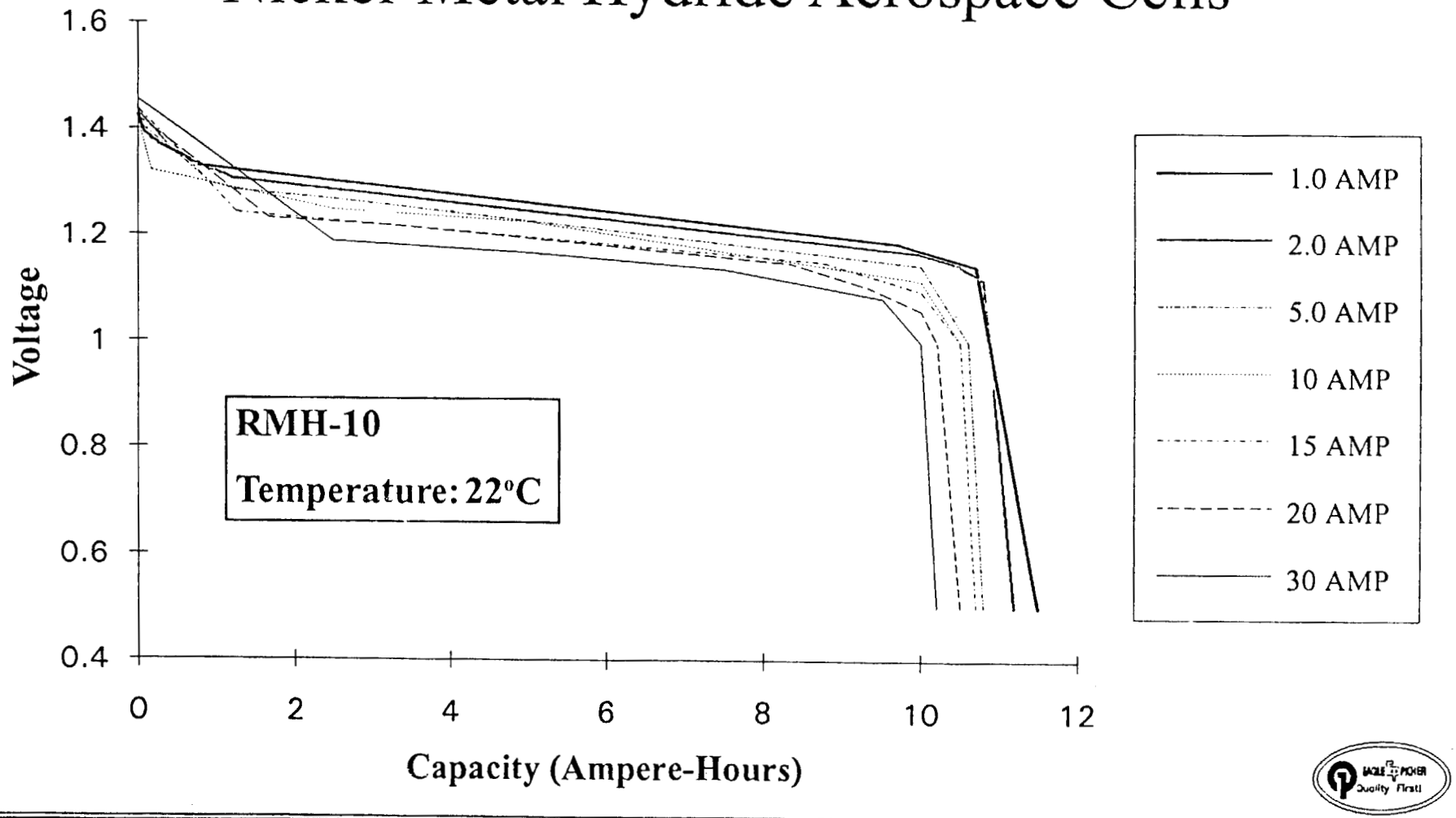
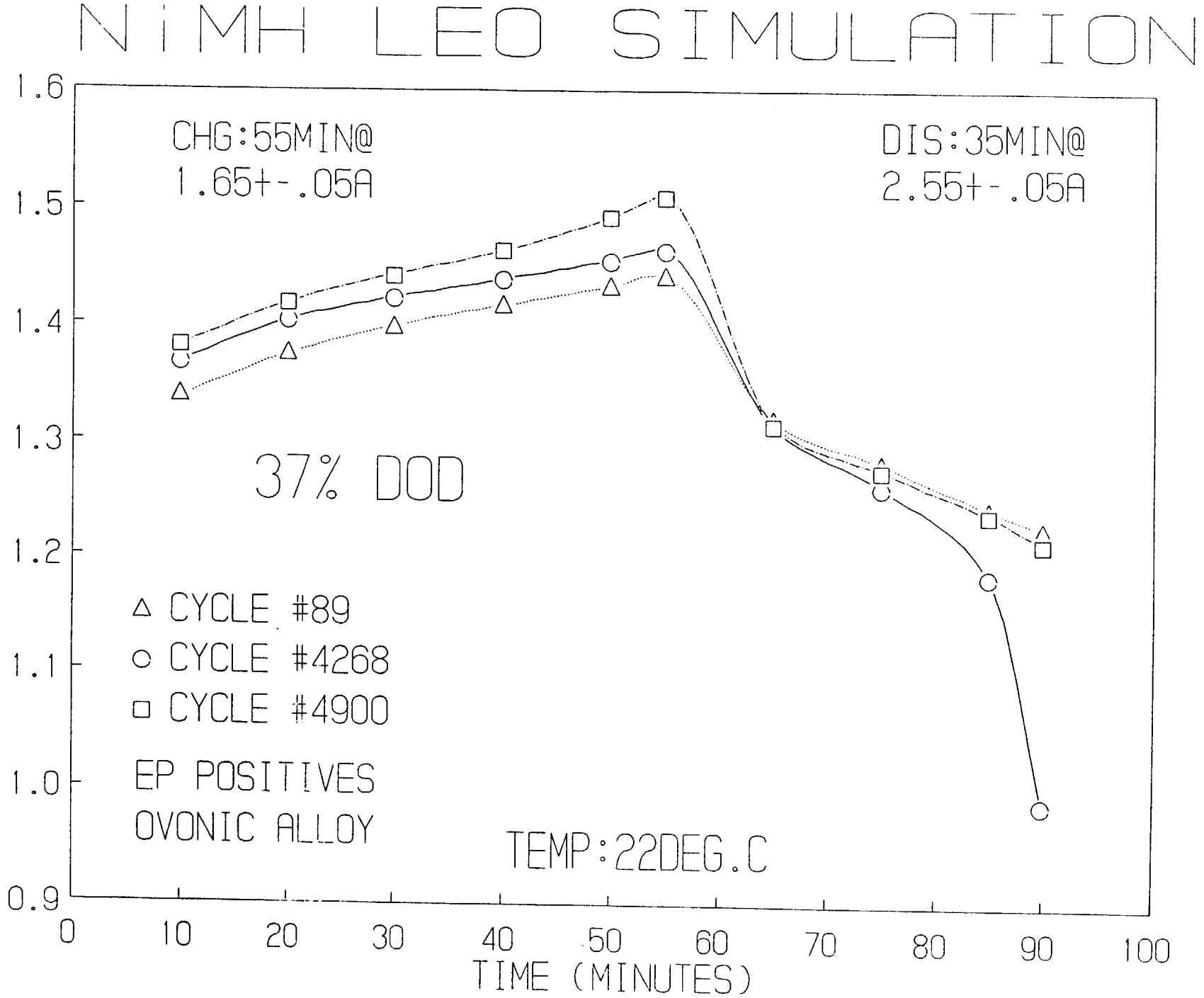
Sealed Metal-Hydride Batteries for Aerospace Applications

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
CHG:55MIN@
1.65+-.05A
DIS:35MIN@
2.55+-.05A
37% DOD
△ CYCLE #89
○ CYCLE #4268
□ CYCLE #4900
EP POSITIVES
OVONIC ALLOY
TEMP:22DEG.C
CELL VOLTAGE
TIME (MINUTES)
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0
10
20
30
40
50
60
70
80
90
100

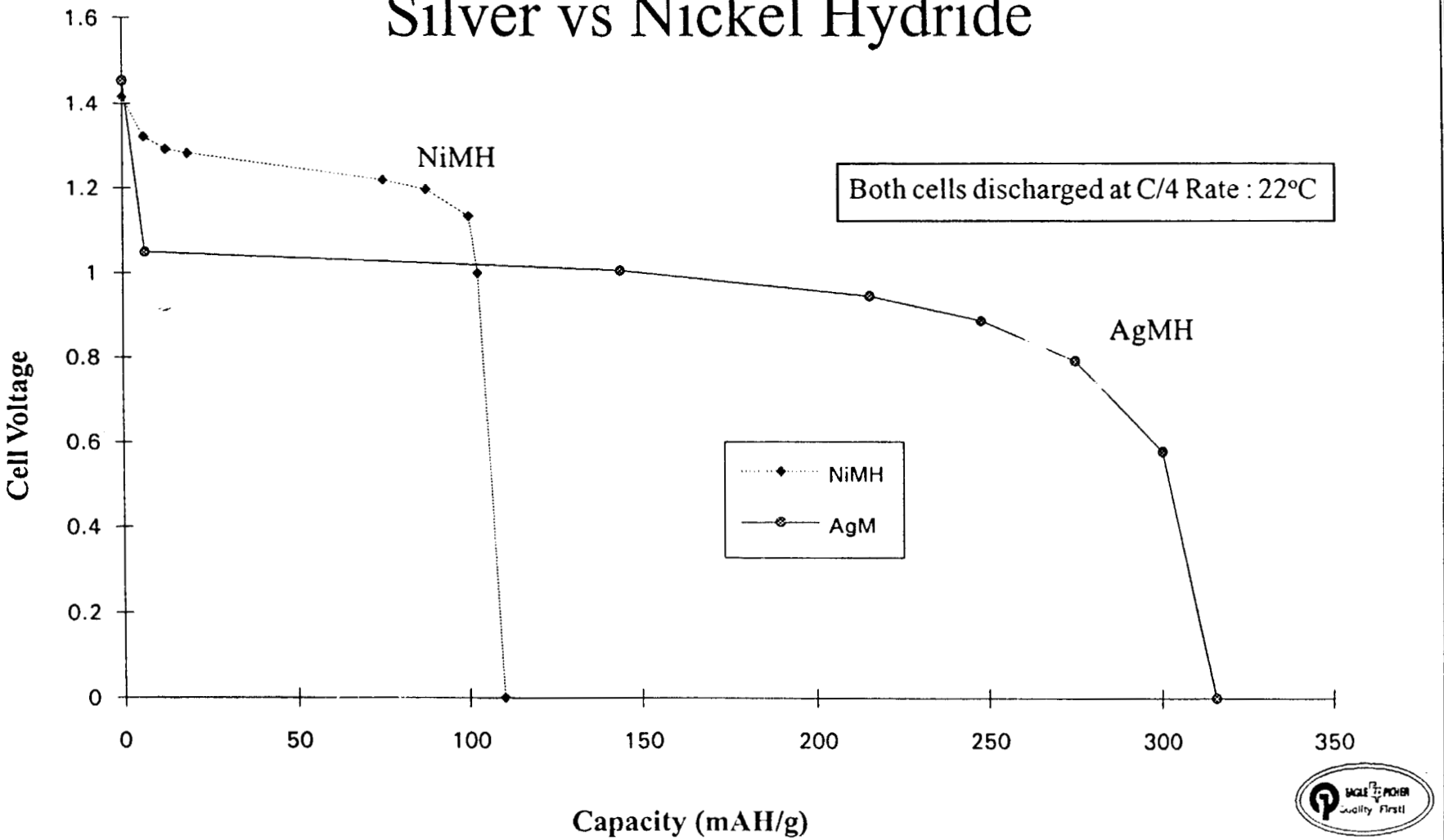
Several metal hydride cells are currently on cycle life test. The cells are operating under a low-earth-orbit regime at 37 per cent depth-of-discharge. The cells are on charge for 55 minutes and then discharge 35 minutes. The charge return ratio is about 1.02. The cells are being cycled at room temperature 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.

EAGLE PICHER
Electronics Division
Joplin, MO

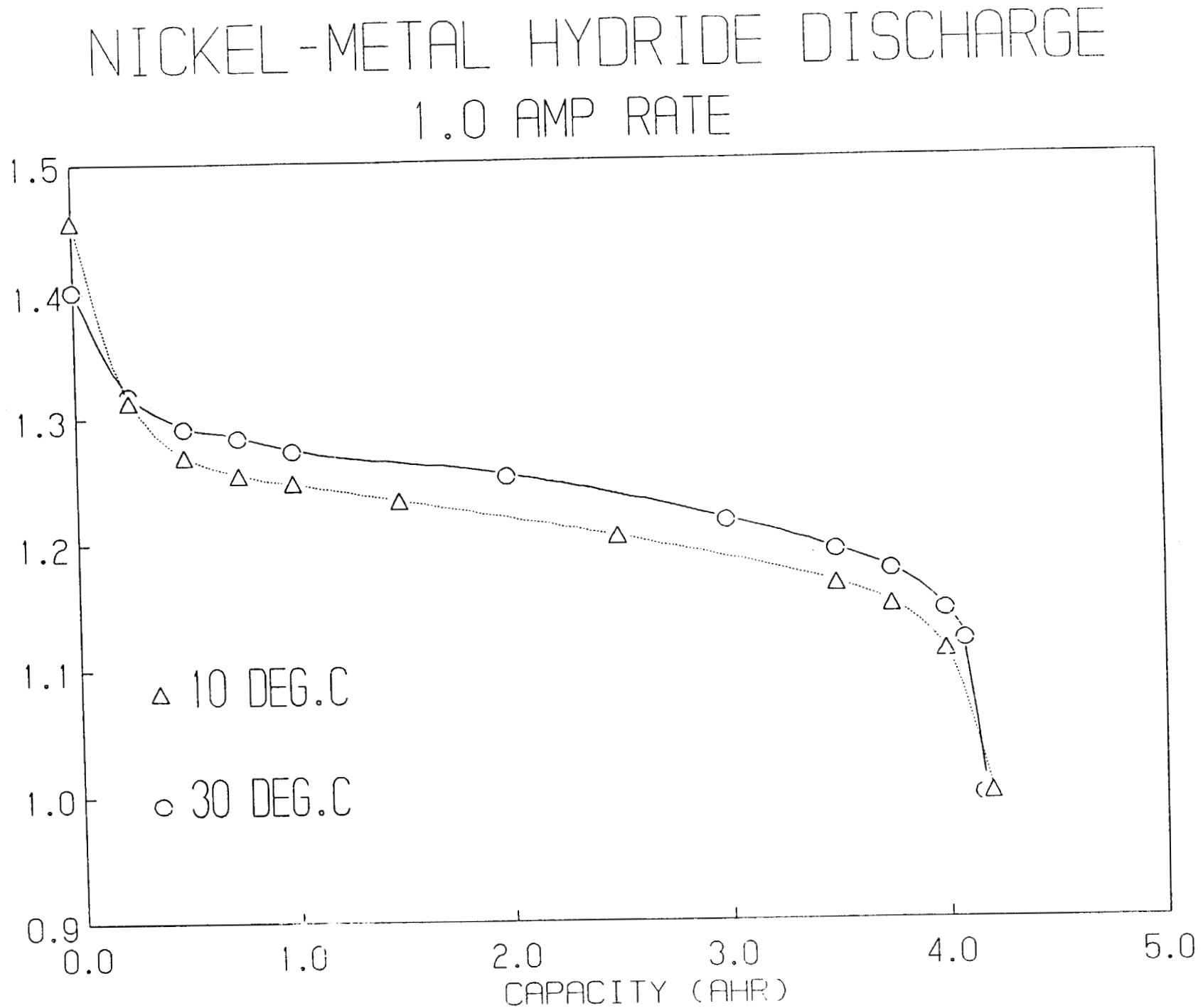
Sealed Metal-Hydride Batteries for Aerospace Applications

Figure 9

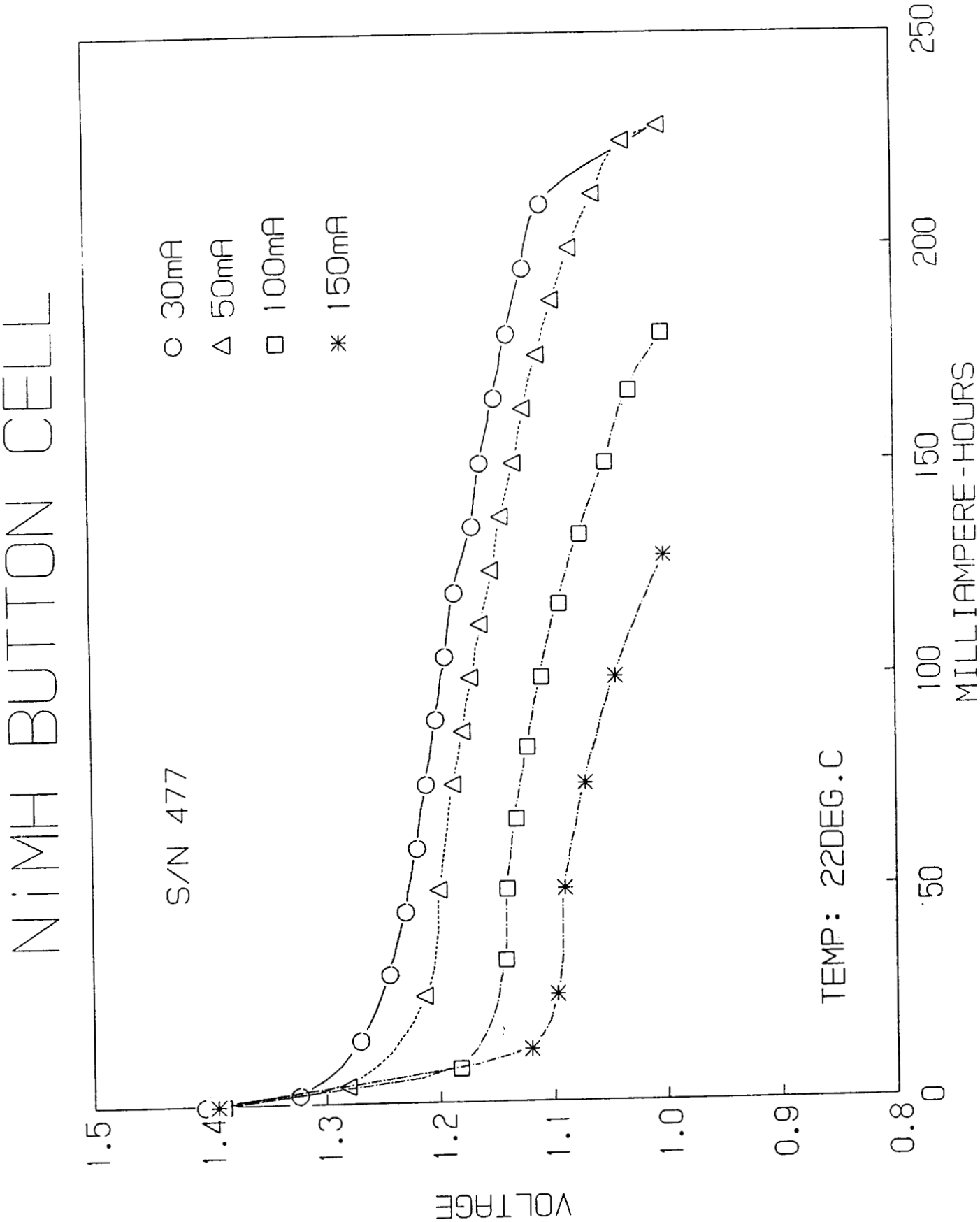
Silver vs Nickel Hydride



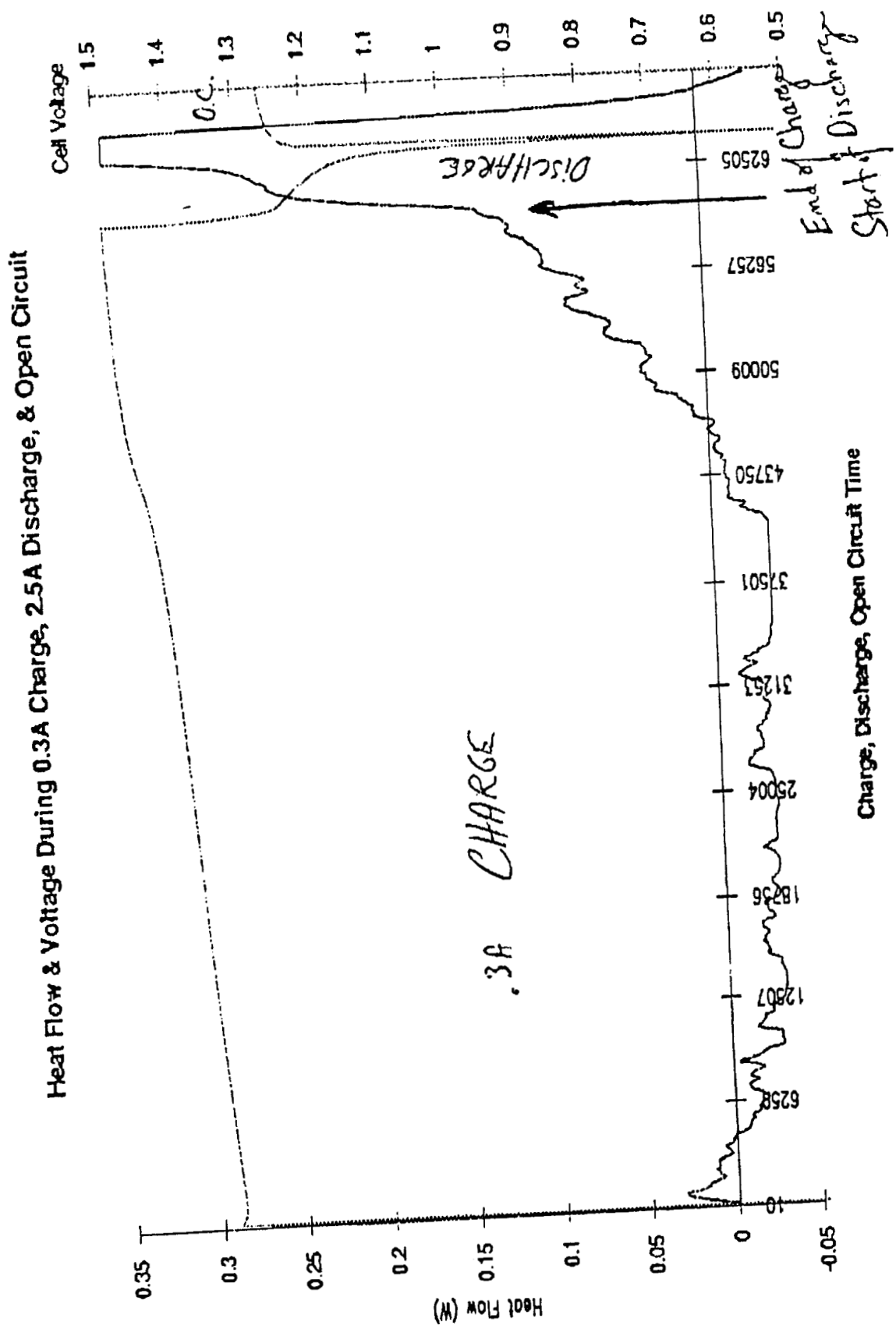
This graph directly compares the nickel-metal hydride system with the silver-metal hydride system. The silver electrode has a much high energy density than the nickel electrode. The silver-metal hydride system delivers about three times the electrical capacity of the nickel-metal hydride system, although 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
VOLTAGE
1.5
1.4
1.3
1.2
1.1
1.0
0.9
△ 10 DEG.C
○ 30 DEG.C
0.0
1.0
2.0
3.0
4.0
5.0
CAPACITY (AHR)

This graph shows the temperature dependence of the nickel-metal hydride system. Two discharges were done at the same rate, one at 10 degrees C and the other at 30 degrees C. The cell yields the same capacity at either temperature, however, there is a depression of the discharge plateau voltage at the colder temperature. Warm temperature performance is slightly better than NiCd and much better than NiH2.

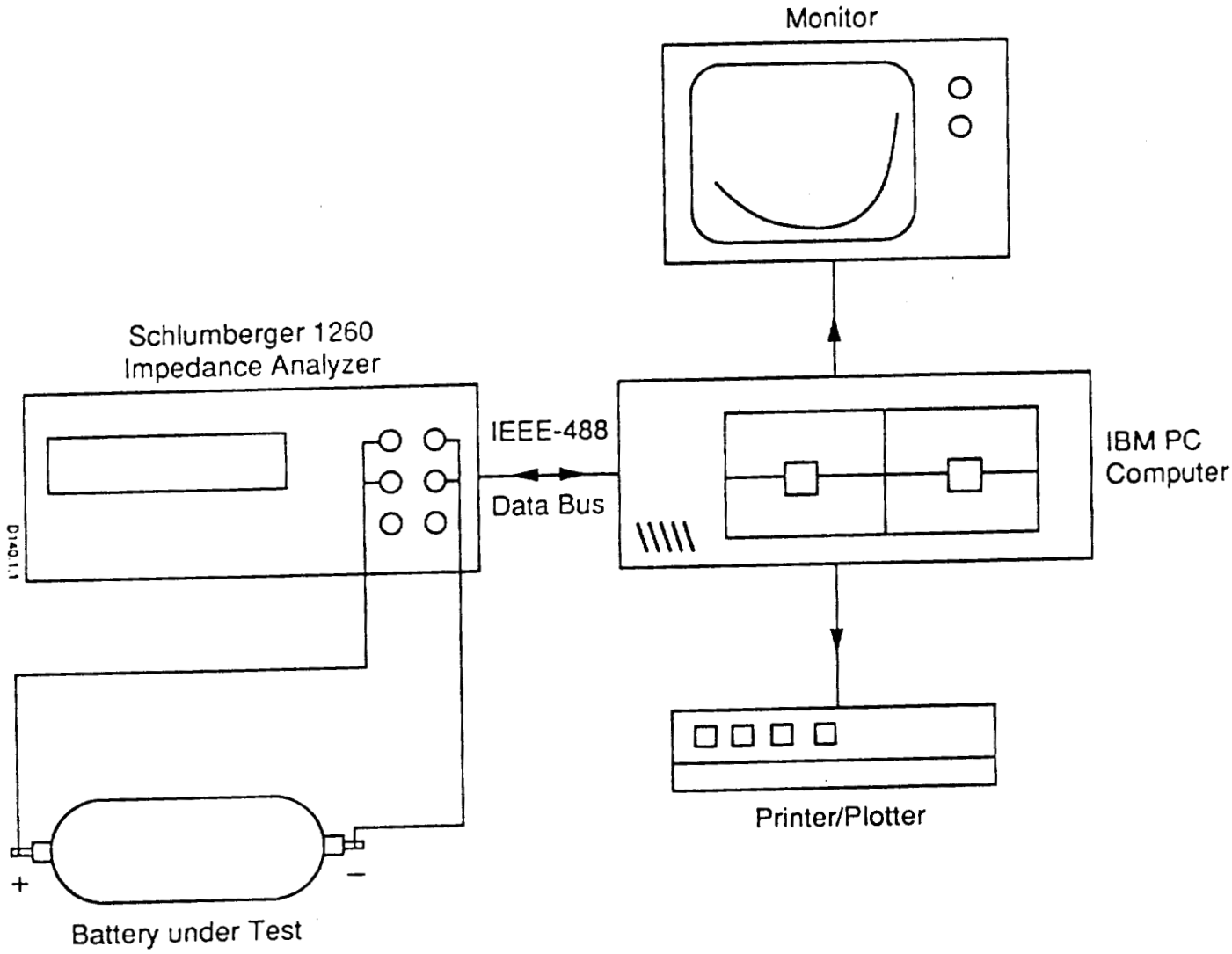

NiMH BUTTON CELL
S/N 477
○ 30mA
△ 50mA
□ 100mA
✳ 150mA
TEMP: 22DEG.C
VOLTAGE
MILLIAMPERE-HOURS
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0
50
100
150
200
250

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
Cell Voltage
Heat Flow (W)
Charge, Discharge, Open Circuit Time
O.C.
DISCHARGE
.3A CHARGE
End of Charge
Start of Discharge
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
62505
56257
50009
43750
37501
31253
25004
18756
12507
6258
10

NMH2-CD.XLC

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.

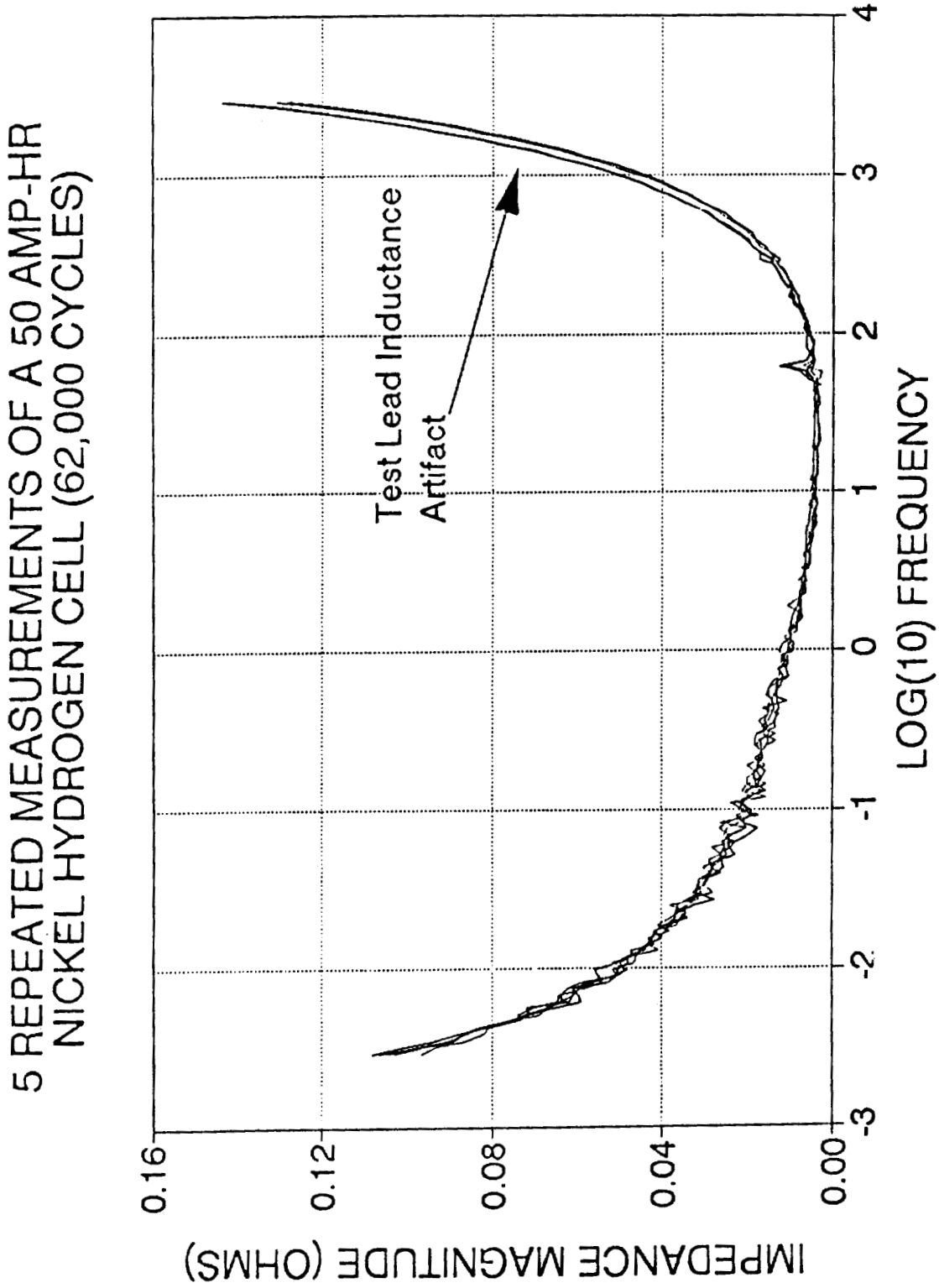
Summary of the Significant Groups of Cells for which AC Impedance Data Were Collected

Cell Type	Capacity (Amp-Hrs)	No. of Cells Measured	Storage Time (Years)	No. of Aging Cycles	Type of Life Test	
NiH_2	30	1	7	10,800	Real-Time LEO	
"	30	1	0	10,800	"	Best Aging Comparisons
"	30	2	0	3,800	"	
"	30	9	0	38,000		
"	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	
NiMH	4	8	0	3,801	Real-Time LEO	
"	4	2	0.33	0	"	
"	8	2	0	3,801	"	
"	C-cell	3	0	2,001	"	
"	C-cell	1	1	0	"	

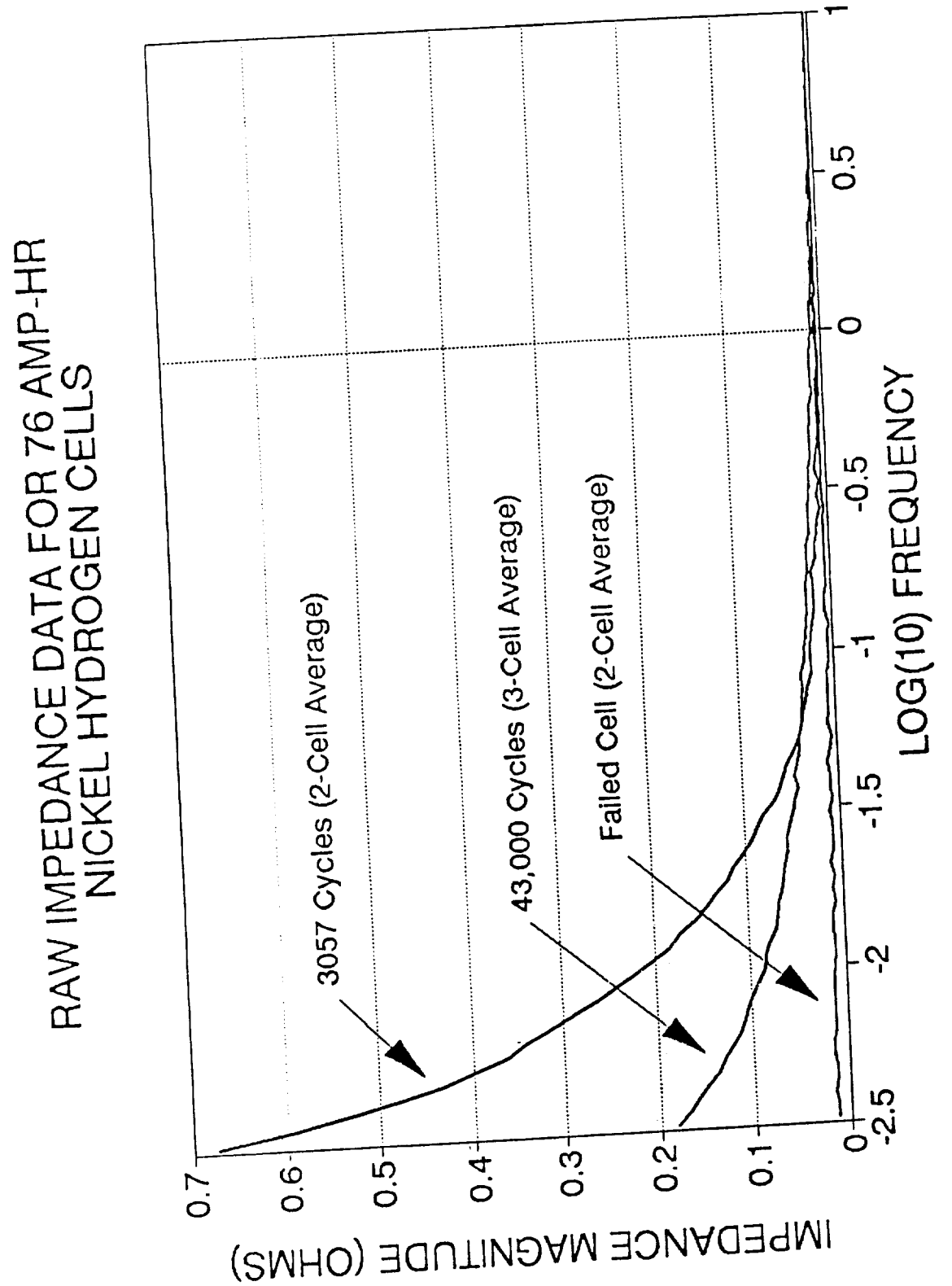
D140.22

* A number of fabrication variations

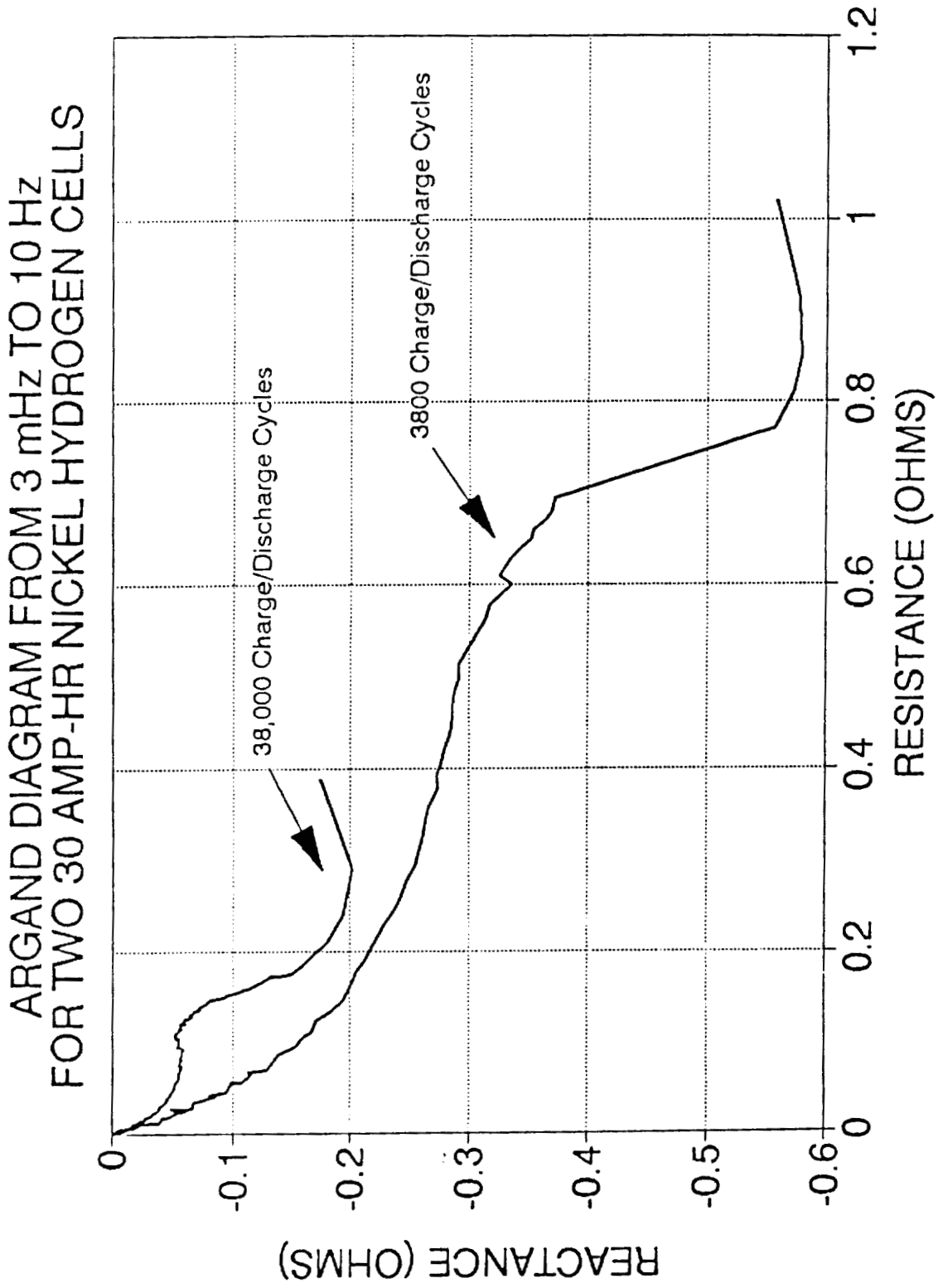
Data was acquired on a large number of life test cells including aerospace nickel-metal hydride cells, commercial nickel-metal hydride cells and space nickel-hydrogen cells. The cells are being tested under several regimes including a real-time low-earth-orbit (LEO) regime, an accelerated LE regime and a real-time geostationary-earth-orbit (GEO) regime. A number of cell designs are represented in size ranging from 3.5 amp-hours to 76 amp-hours.


5 REPEATED MEASUREMENTS OF A 50 AMP-HR
NICKEL HYDROGEN CELL (62,000 CYCLES)
Test Lead Inductance
Artifact
IMPEDANCE MAGNITUDE (OHMS)
0.16
0.12
0.08
0.04
0.00
LOG(10) FREQUENCY
-3
-2
-1
0
1
2
3
4

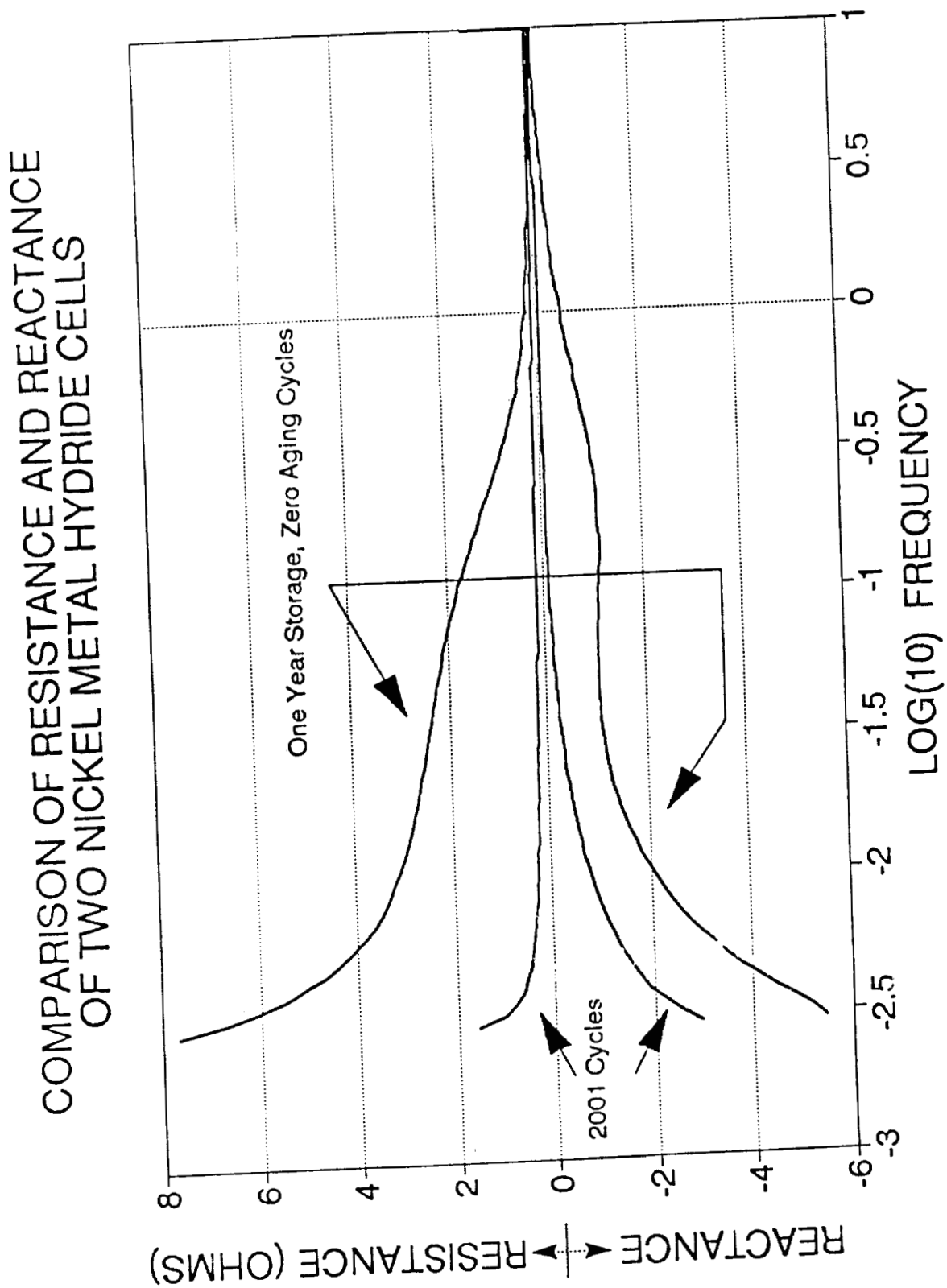
A typical scan ranges from 3 milliHertz to 30 kiloHertz. Multiple runs were frequently made on the same cell at random intervals to evaluate the reproducibility of the method. This data represents five runs on the same cell made at various times during a two week period. The data shows excellent reproducibility.


RAW IMPEDANCE DATA FOR 76 AMP-HR
NICKEL HYDROGEN CELLS
3057 Cycles (2-Cell Average)
43,000 Cycles (3-Cell Average)
Failed Cell (2-Cell Average)
IMPEDANCE MAGNITUDE (OHMS)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
LOG(10) FREQUENCY

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
38,000 Charge/Discharge Cycles
3800 Charge/Discharge Cycles
REACTANCE (OHMS)
RESISTANCE (OHMS)
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
0.2
0.4
0.6
0.8
1
1.2

The Argand diagram for two 30 amp-hour Intelsat V type cells also shows a definite trend. Two cells are compared, one with 3800 cycles and the other with 38,000 cycles. The capacitive to Warburg transition is significantly frequency shifted for the aged cell.


COMPARISON OF RESISTANCE AND REACTANCE
OF TWO NICKEL METAL HYDRIDE CELLS
One Year Storage, Zero Aging Cycles
2001 Cycles
RESISTANCE (OHMS)
REACTANCE
LOG(10) FREQUENCY
8
6
4
2
0
-2
-4
-6
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3

Comparisons of resistance and reactance also show some trends with cell aging. The gap between the two decreases as the cell is cycled. The uncycled cell shows a much larger delta between resistance and reactance than the cell with 2001 cycles. This relationship also hold true for nickel-hydrogen cells.

THE FUTURE

BASIC ELECTRODE MATERIALS

FABRICATION TECHNIQUES

CYCLE LIFE TESTING

IMPROVEMENTS:

ENERGY DENSITY

PERFORMANCE

CYCLE LIFE

The idea for a metal hydride battery has been around for a long time. However, practical batteries have only come about recently. So recently that they are still not generally available. The development of the metal hydride chemistry is still in the early stages particularly for aerospace applications. Future efforts will be aimed at the further refinement of the nickel and silver metal hydride battery chemistry. Work is being continued on developing and improving hydride electrode materials and fabrication techniques. Life cycle testing will be continued. The system will be optimized to yield improved energy density, improved performance and longer cycle life.

SODIUM SULFUR BATTERIES FOR SPACE APPLICATIONS

James A. DeGruson

Eagle-Picher Industries, Inc.
C&Porter Streets
Joplin, MO

30 October 1991

1991 NASA AEROSPACE BATTERY WORKSHOP

PRESENTATION ABSTRACT

Name James A. DeGruson

Company Eagle-Picher Industries, Inc.

Address P.O. Box 47, Joplin, MO 64802

Telephone 417-623-8000, ex. 491

Preliminary Title Sodium Sulfur Batteries for Space Applications

Brief Abstract In 1986, Eagle-Picher Industries was selected by the Air Force to develop sodium sulfur cells for satellite applications. Specifically, the development program was geared toward low earth orbit goals requiring high charge/discharge rates. A number of improvements have been made on the cell level and a transition to a complete space battery has been initiated at Eagle Picher.

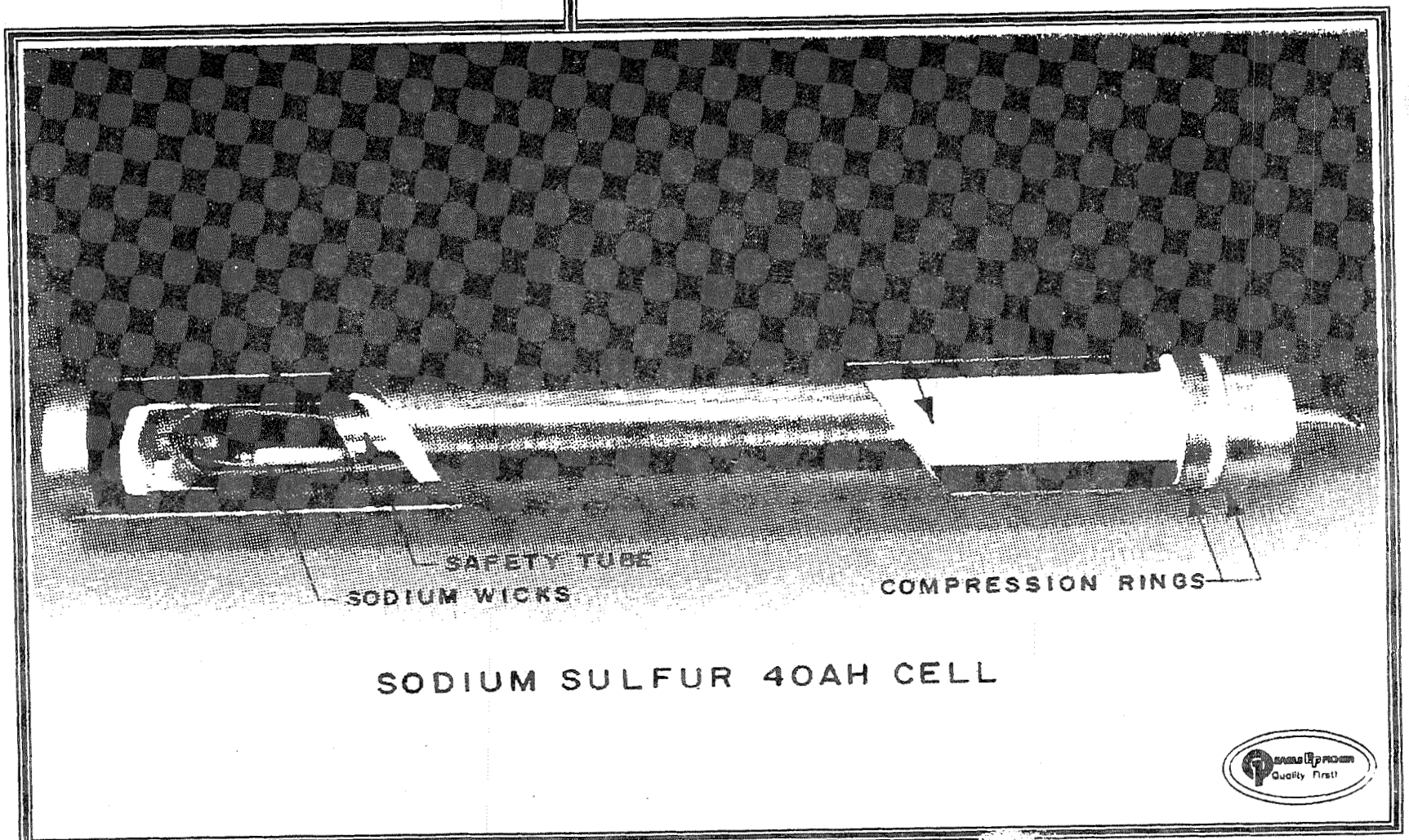
The results of six months of testing a 250 watt-hour sodium sulfur space battery look very promising. With over 1,000 LEO cycles conducted on this first battery, the next generation battery is being designed. This next design will focus on achieving greater energy densities associated with the sodium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

EAGLE PICHER

ELECTRONICS DIVISION
JOPLIN, MO

THERMAL-ORDNANCE OPERATION

Na-S BATTERIES



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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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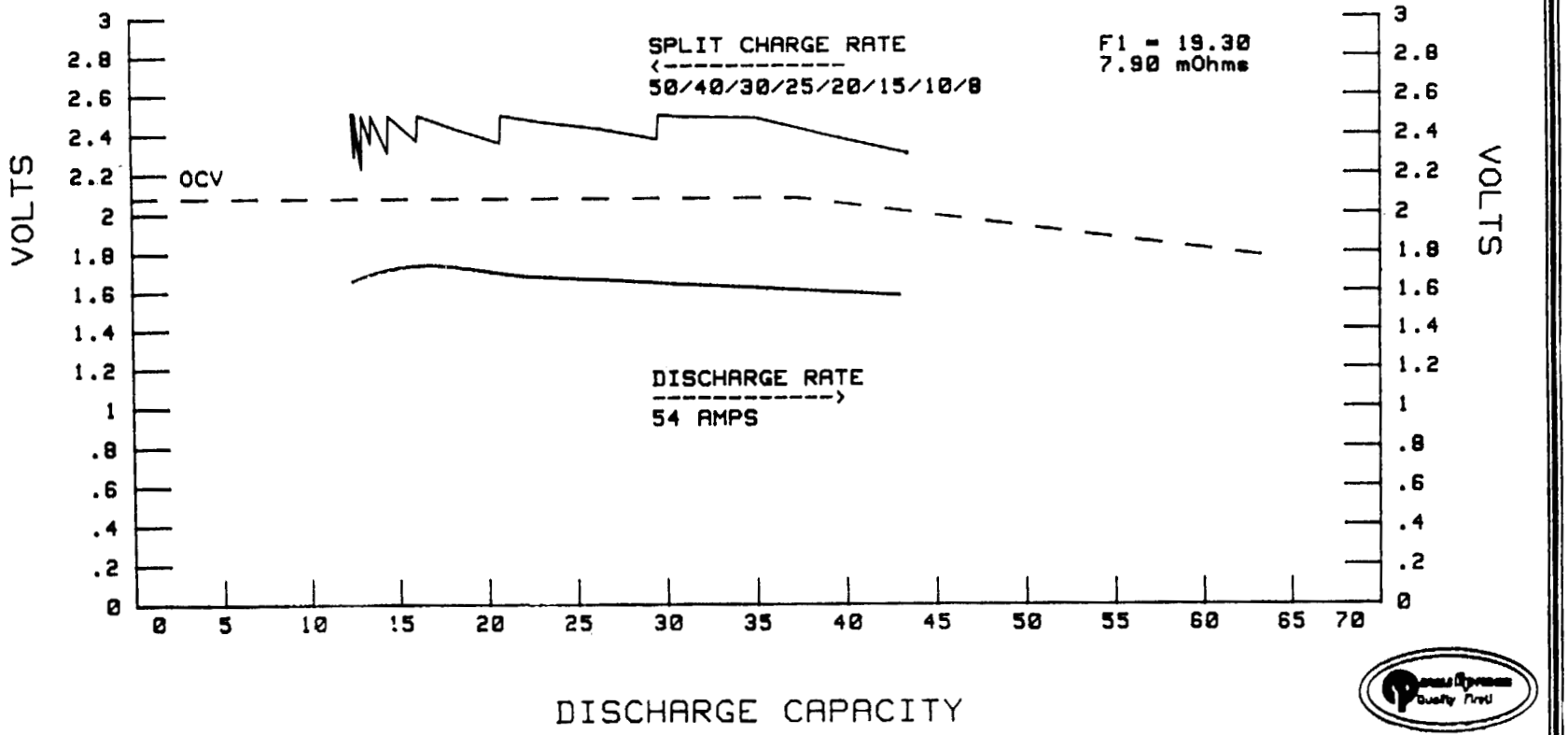
Na-S BATTERIES



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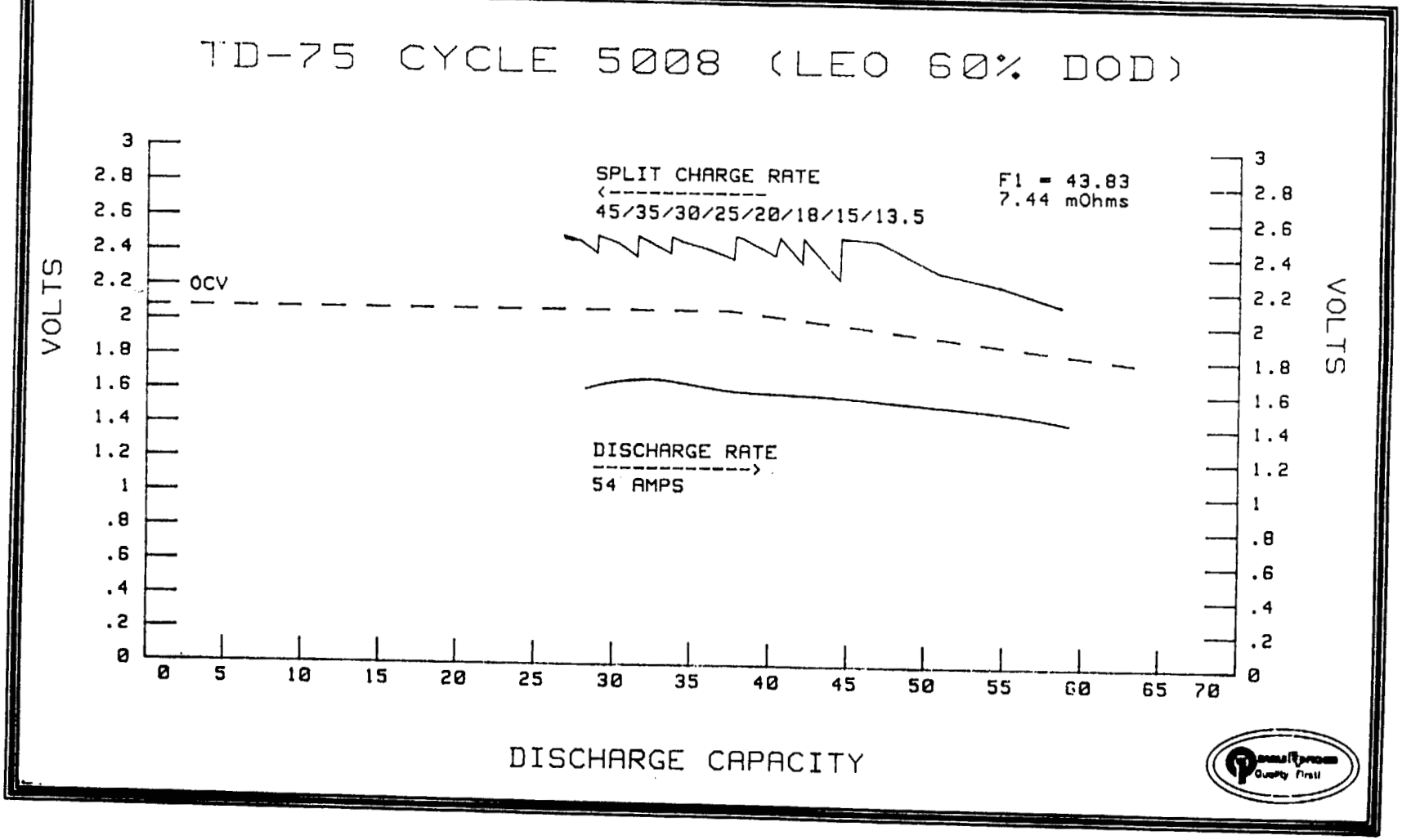
Na-S BATTERIES



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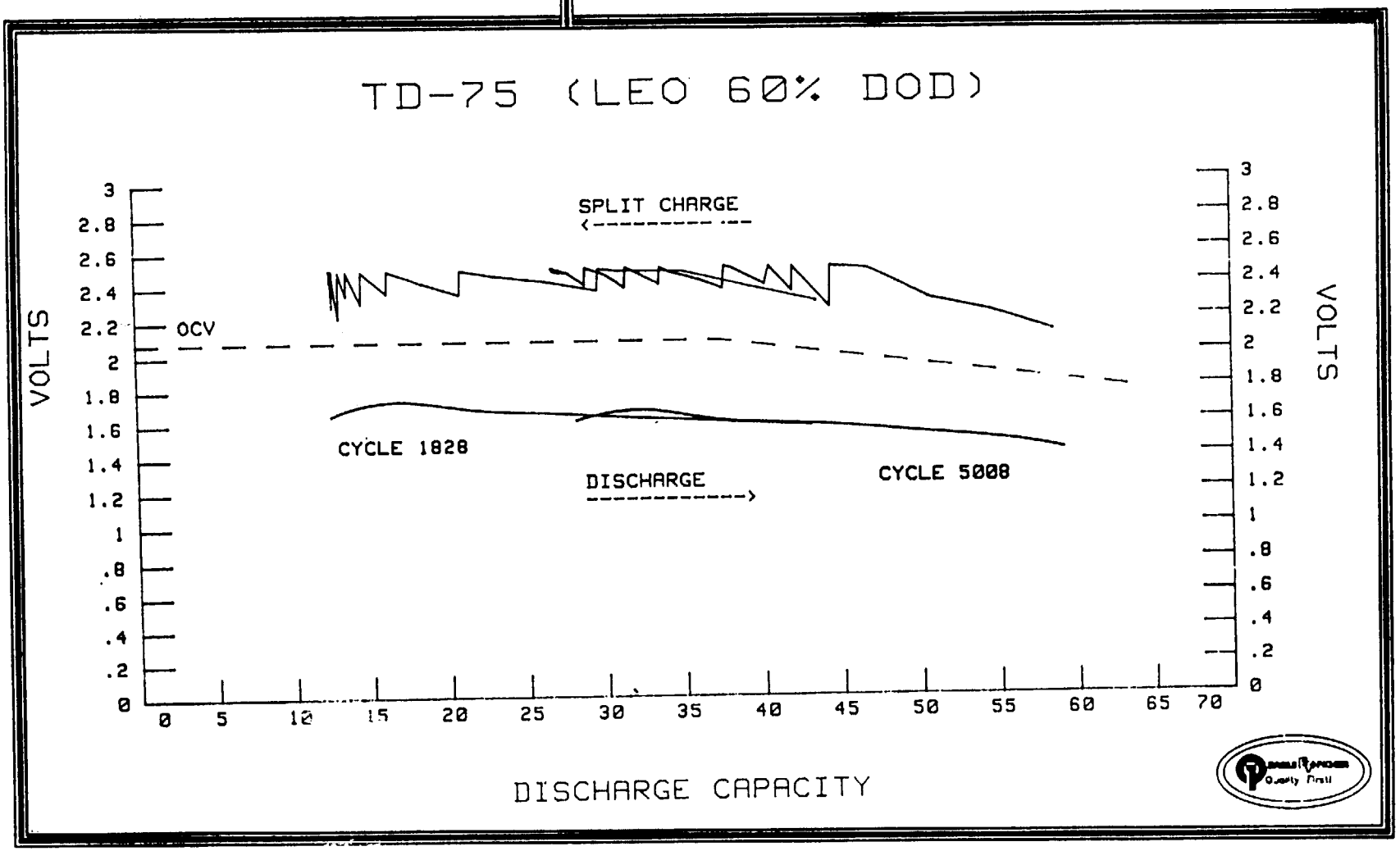
Na-S BATTERIES



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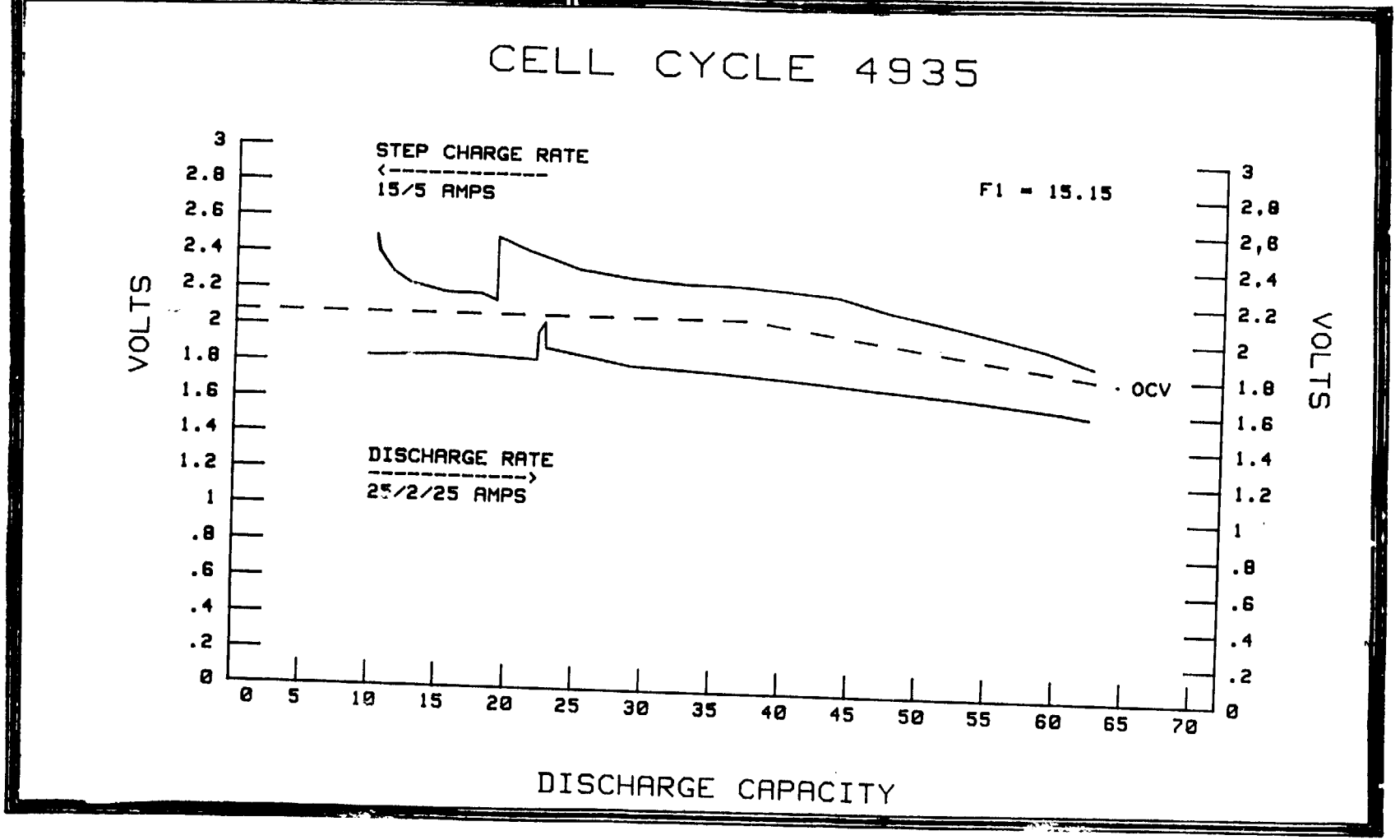
Na-S BATTERIES



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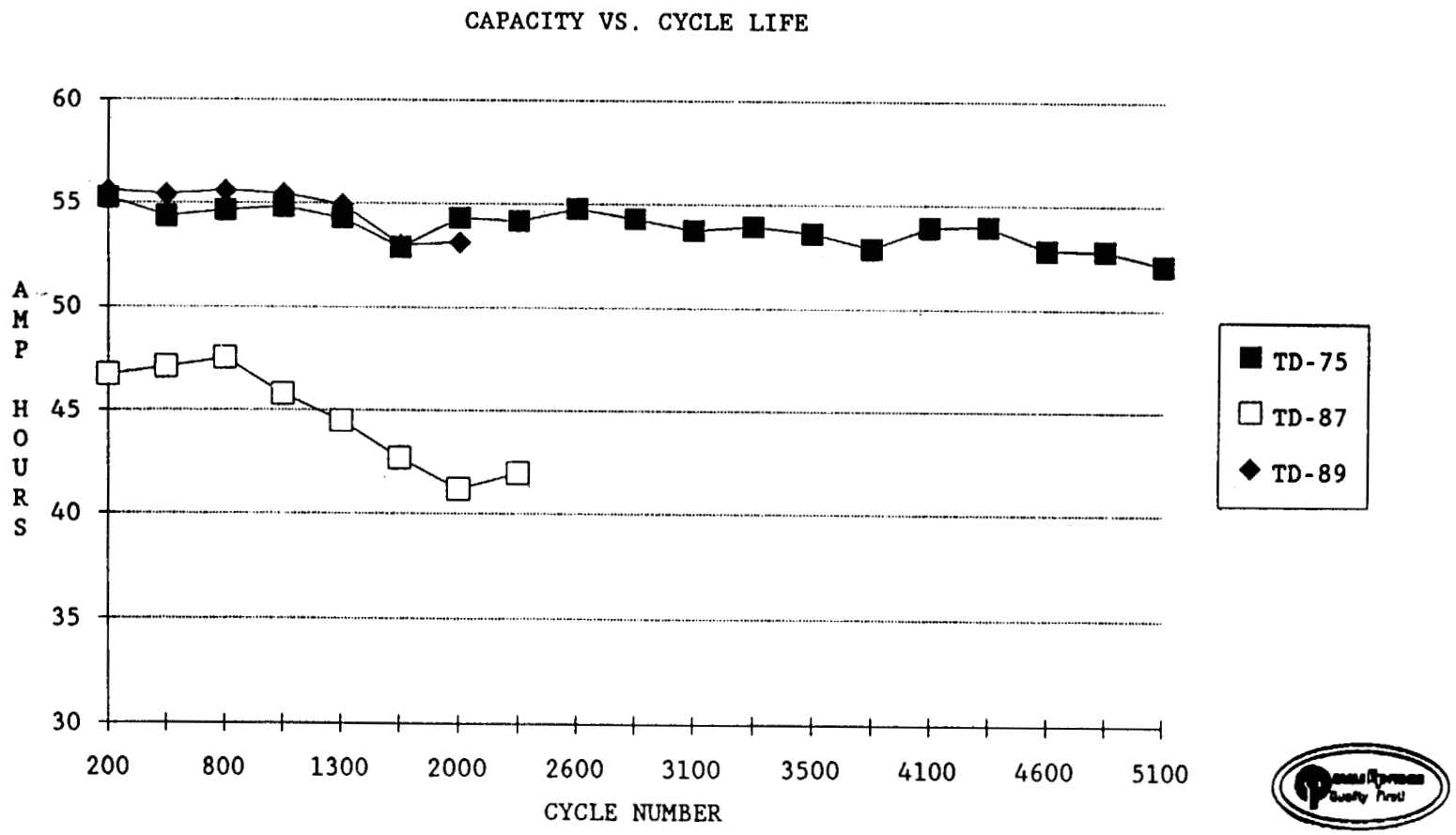
Na-S BATTERIES



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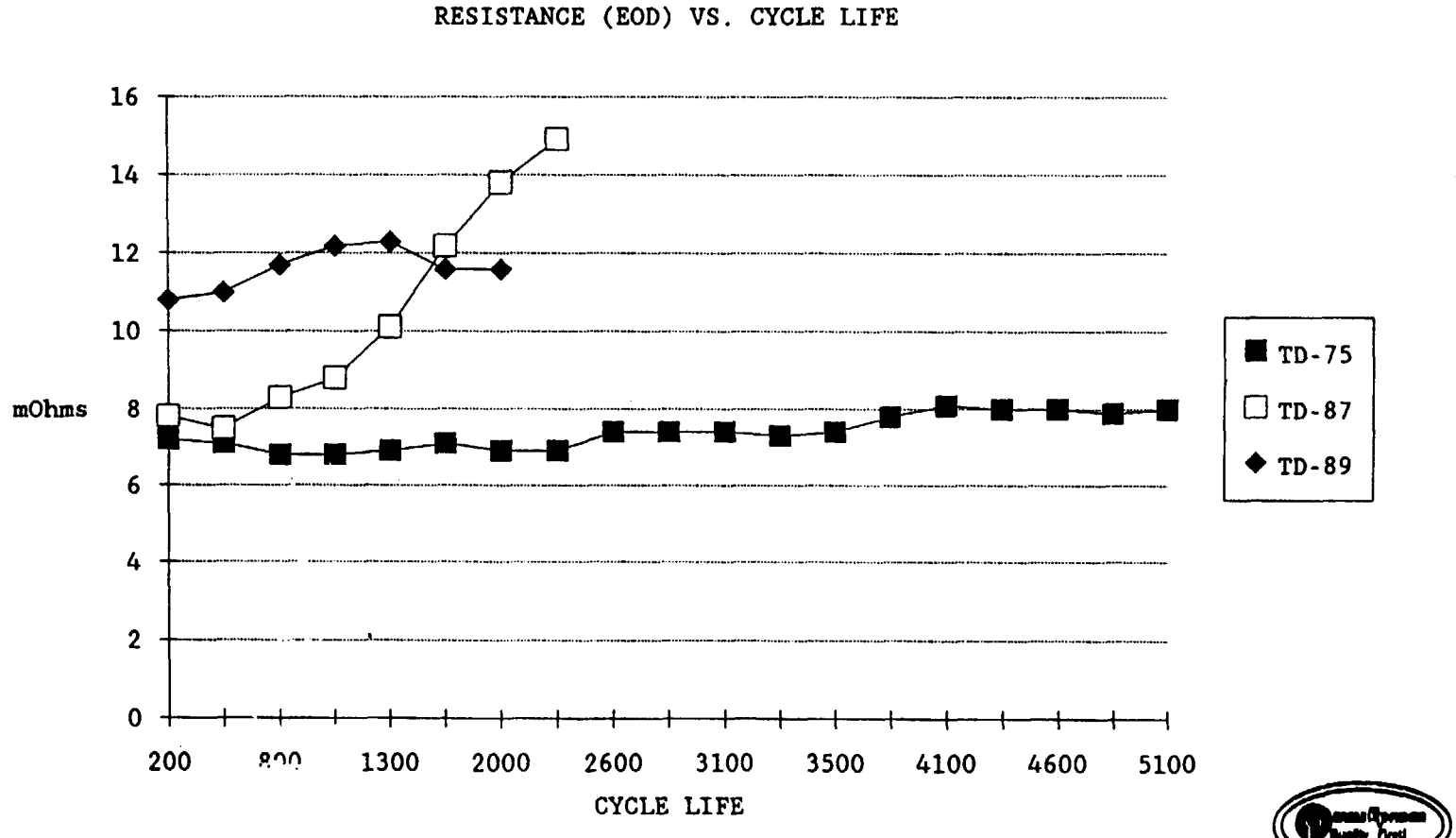
Na-S BATTERIES



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THERMAL-ORDNANCE OPERATION

Na-S BATTERIES

LIFE CYCLE TESTS

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

CYCLES ACCOMPLISHED TO DATE: 7,200

AVERAGE VOLTS WHILE DISCHARGING: 1.50

AVERAGE VOLTS DURING CHARGE: 2.40

SPECIFIC ENERGY: 63.3 WH / KG

ENERGY DENSITY: 145 WH / l

E.O.D. RESISTANCE: .0088 ohms

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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 / I

E.O.D. RESISTANCE: .0075 ohms

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THERMAL-ORDNANCE OPERATION

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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THERMAL-ORDNANCE OPERATION

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

Quality First

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THERMAL-ORDNANCE OPERATION

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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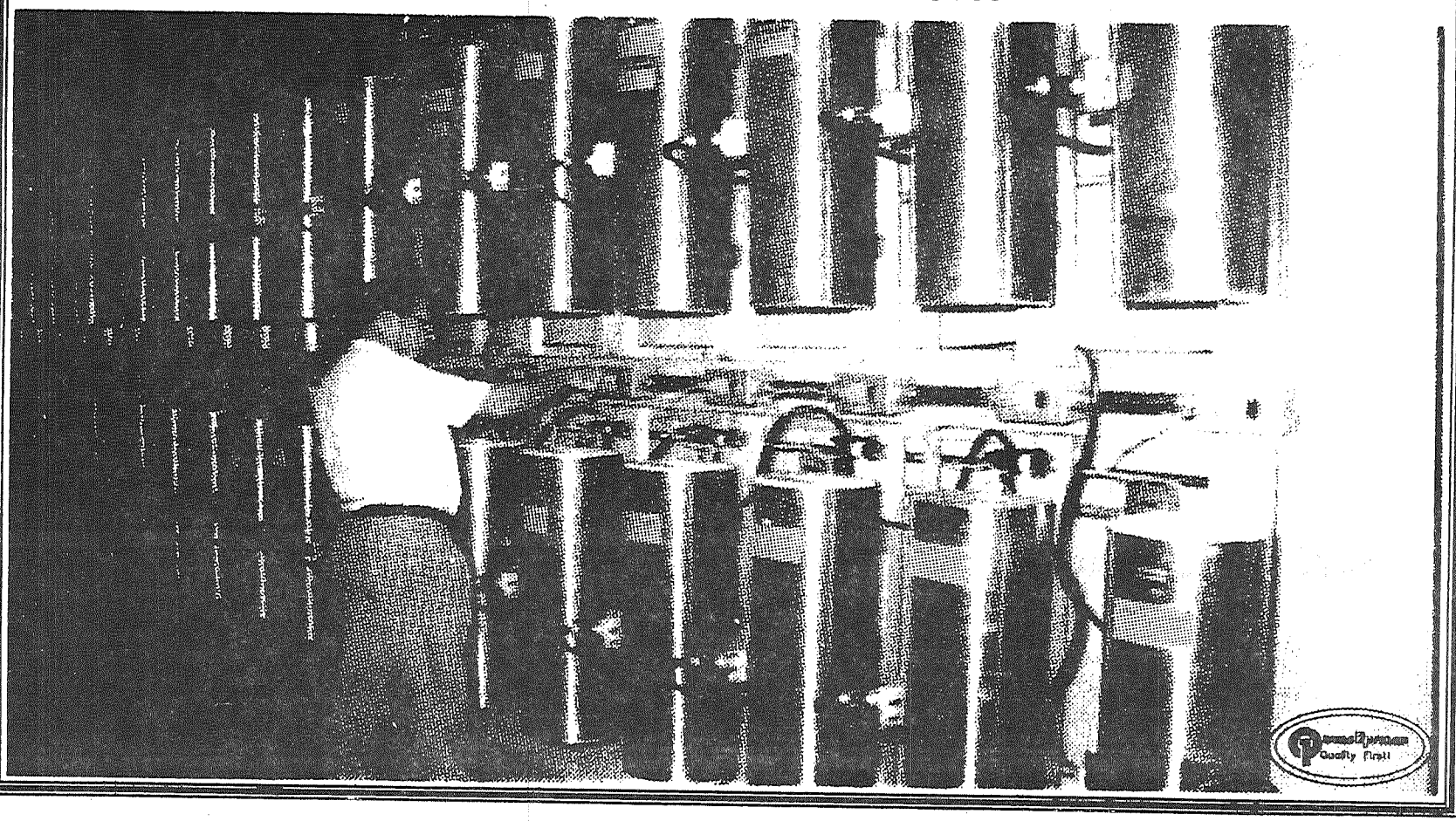
Na-S BATTERIES

CELL TEST LABORATORY



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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.

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THERMAL-ORDNANCE OPERATION

Na-S BATTERIES

BATTERY STATUS

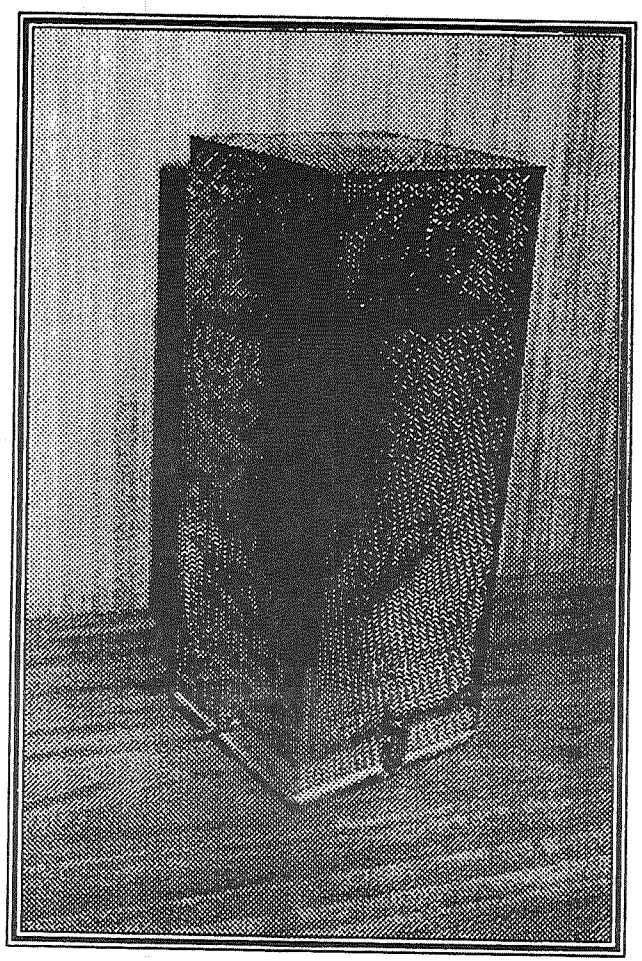
ENTRY LEVEL BATTERY EFFORTS FUNDED INTERNALLY

UNIT APPROACHING 1000 CYCLES
CONSTANT CURRENT CHARGE / DISCHARGE
NOMINAL 60% DOD (= 30 A.H.)

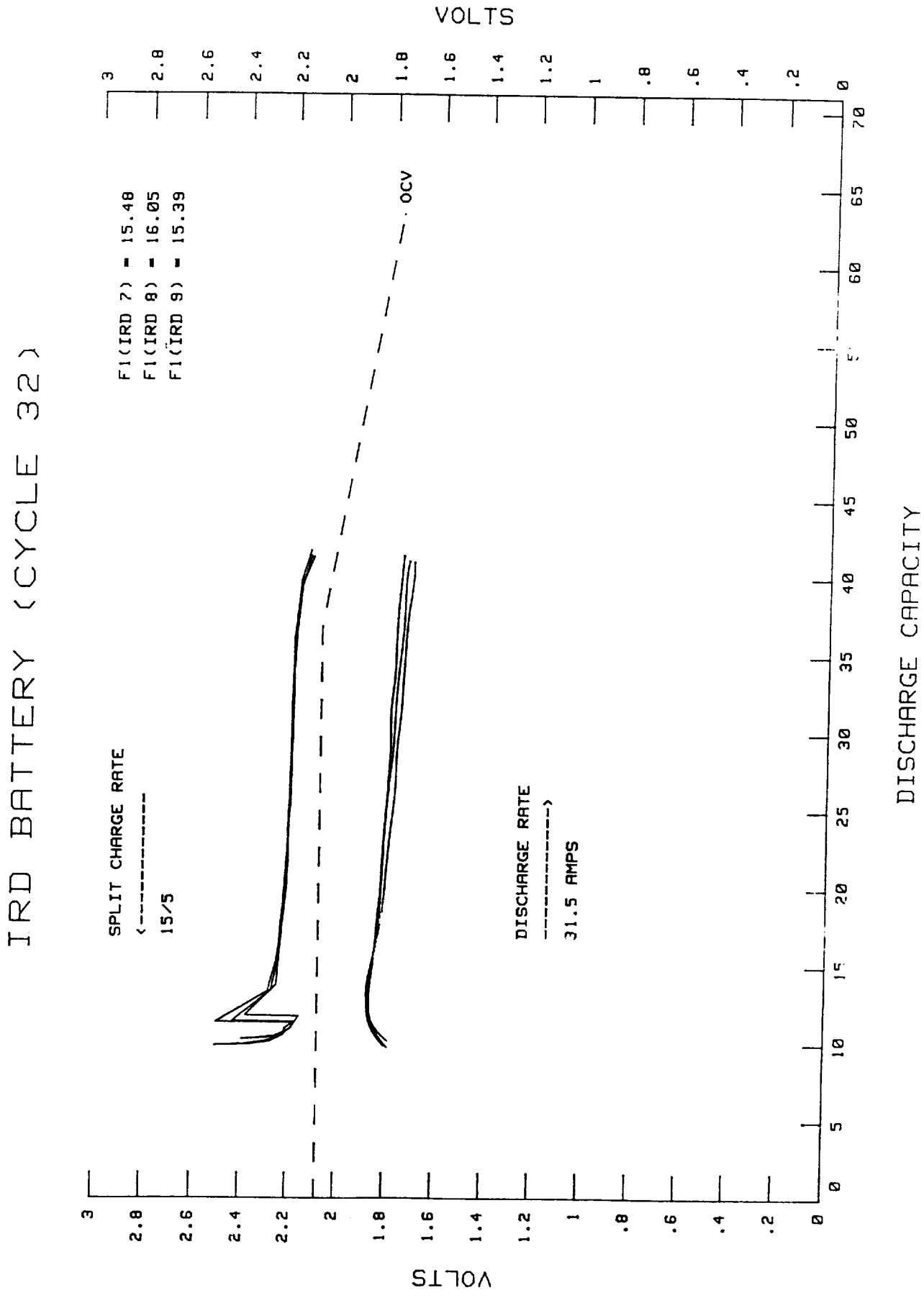
CYCLE CONTROLLED BY FIRST CELL TO ACHIEVE PRE-SET VALUES
(OTHERWISE BY CYCLE DEFINITION ONLY)

CALENDAR LIFE NOW FIVE MONTHS

Sodium Sulfur Battery



Battery Test Set-up


IRD BATTERY (CYCLE 32)
VOLTS
DISCHARGE CAPACITY
F1(IRD 7) = 15.48
F1(IRD 8) = 16.05
F1(IRD 9) = 15.39
OCV
SPLIT CHARGE RATE
<----------
15/5
DISCHARGE RATE
---------->
31.5 AMPS

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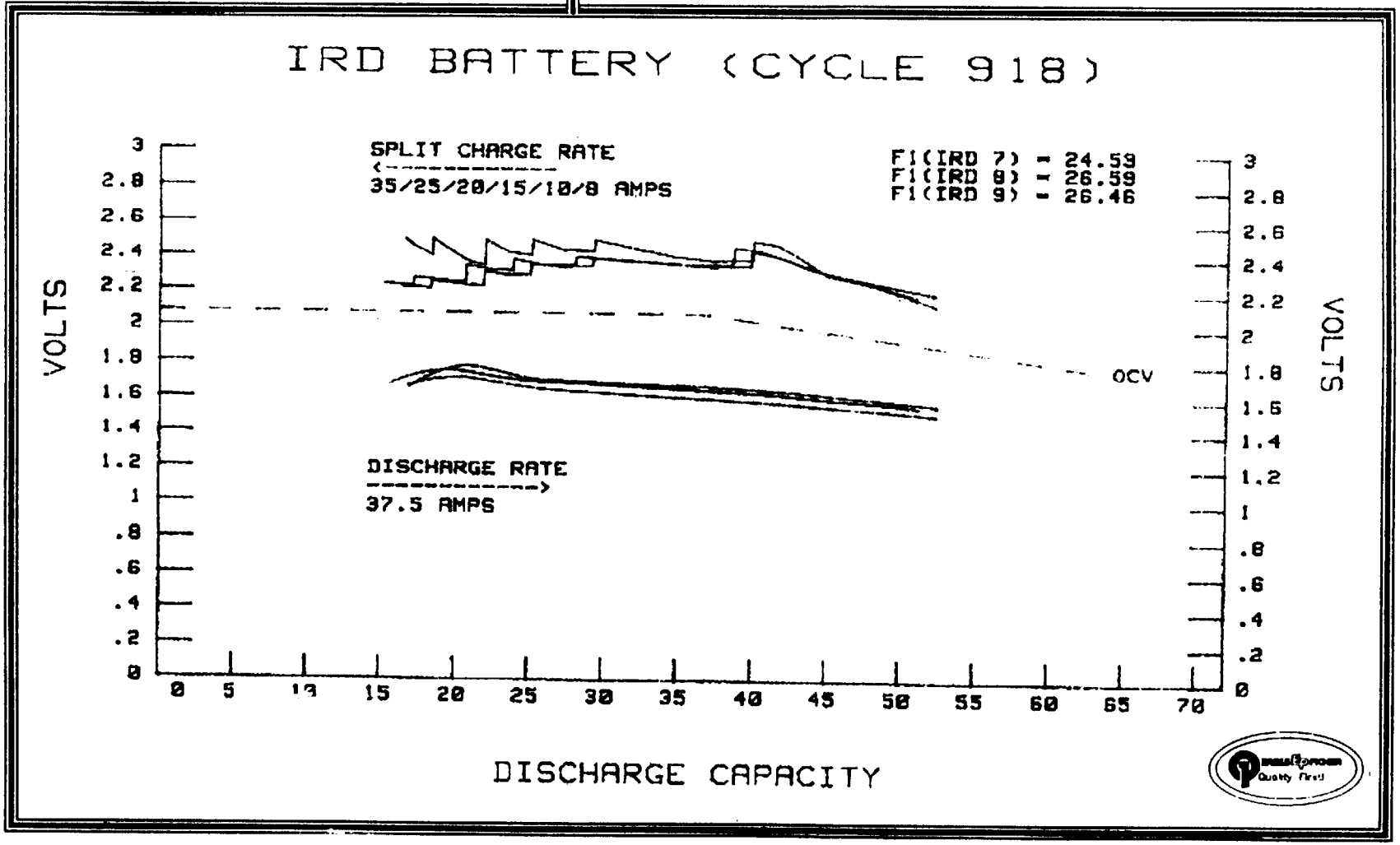
THERMAL-ORDNANCE OPERATION

Na-S BATTERIES



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THERMAL-ORDNANCE OPERATION

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)

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SODIUM - METAL CHLORIDE BATTERIES

JPL

B. V. RATNAKUMAR, A. I. ATTIA, G. HALPERT

OCTOBER 30, 1991
THE 1991 NASA AEROSPACE BATTERY WORKSHOP

OUTLINE

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

JPL

SODIUM - METAL CHLORIDE BATTERIES

- CONFIGURATION

$$Na\ (m)\ //\ Beta''\ ALUMINA\ //\ NaAlCl_4\ (m)\ //\ MCl_2\ (s)$$

Anode	Solid Electrolyte Separator	Basic or Neutral	Transition Metal Chloride

- CELL REACTION

$$2\,Na + MCl_2 \underset{ch}{\overset{disch}{\rightleftharpoons}} M + 2\,NaCl$$

- METAL CHLORIDES

FERROUS CHLORIDE
NICKEL CHLORIDE

- OPERATING TEMPERATURES : $\geq$ 250°C

COMPARISON WITH Na - S

ADVANTAGES

- LOWER OPERATING TEMPERATURES (≥ 250°C)
- WIDER RANGE OF OPERATING TEMPERATURES (180 - 425°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 DISCHARGED 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^2)

- 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

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CAPABILITIES OF THE SYSTEMS

PERFORMANCE OF MCl_2 CELLS AND BATTERIES

PARAMETER → / TYPE ↓		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, 22nd IECEC; 1078 (1987)

JPL

ENVIRONMENTAL TESTS ON Na/MCl_2 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)

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Na / $NiCl_2$ 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

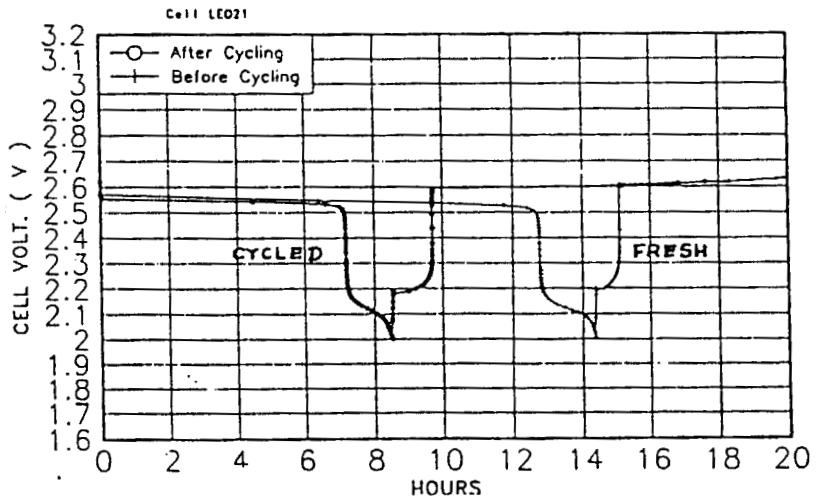


Fig. 8 CELL CAPACITY AT 1 A RATE BEFORE & AFTER 2810 CYCLES

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 $FeCl_2$ AND $NiCl_2$
  - 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 $FeCl_2$ REDUCTION

- EVIDENCE FOR TWO - STEP REACTION MECHANISM FROM CYCLIC VOLTAMMETRY
  Na_6FeCl_8 INTERMEDIATE

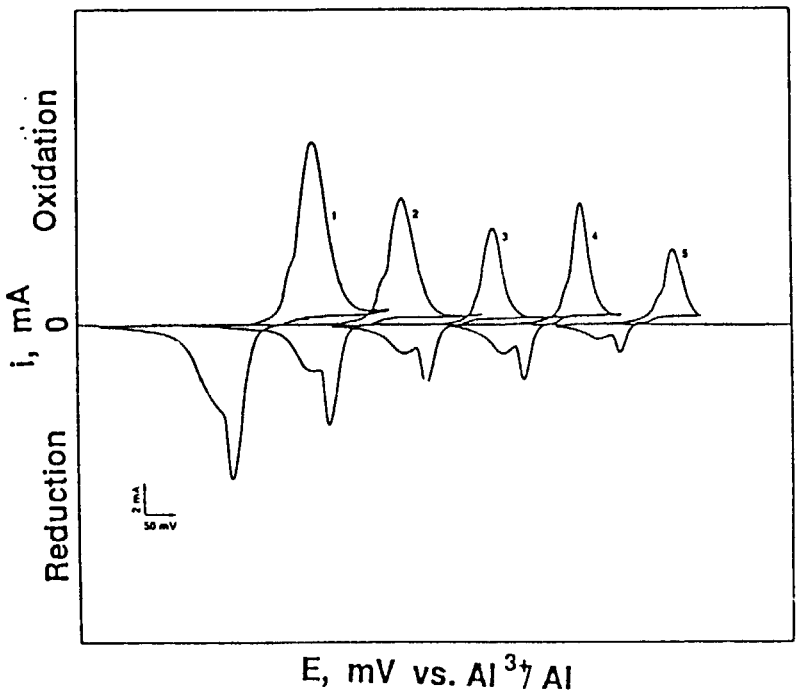
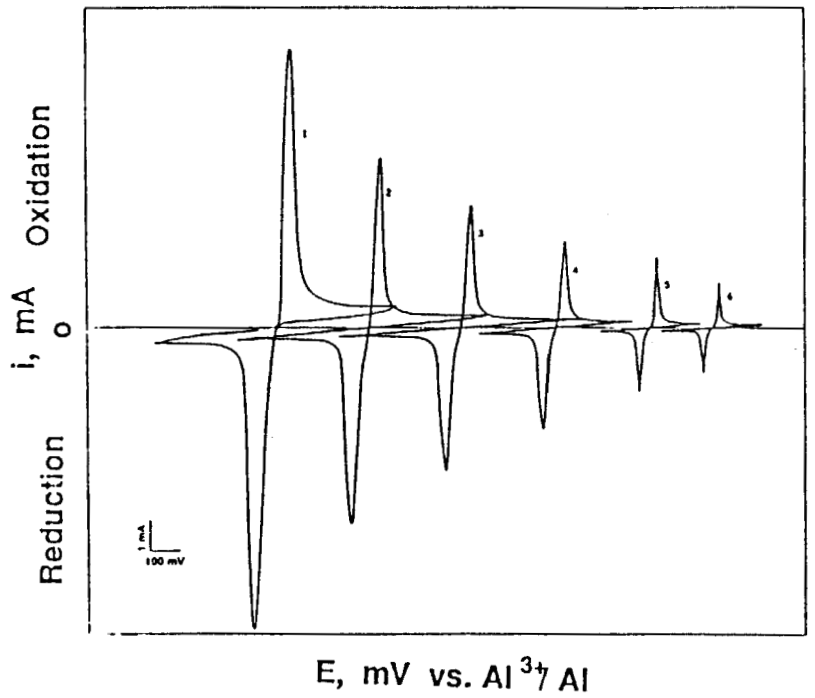


Fig. 3. Cyclic voltammograms of Fe electrode (area: 0.05 cm^2) in $NaAlCl_4$ at 220°C at scan rates of 1.) 20, 2.) 10, 3.) 5, 4.) 2, and 5.) 1 mV/s. Scale on the y axis is 1 mA/cm (reduced to half) for curves 4 and 5.

- Ni ADDITIONS FOR OVERCHARGE PROTECTION OF $FeCl_2$

MECHANISM OF $NiCl_2$ REDUCTION

- SINGLE - STEP REACTION SCHEME CONFIRMED BY CYCLIC VOLTAMMETRY



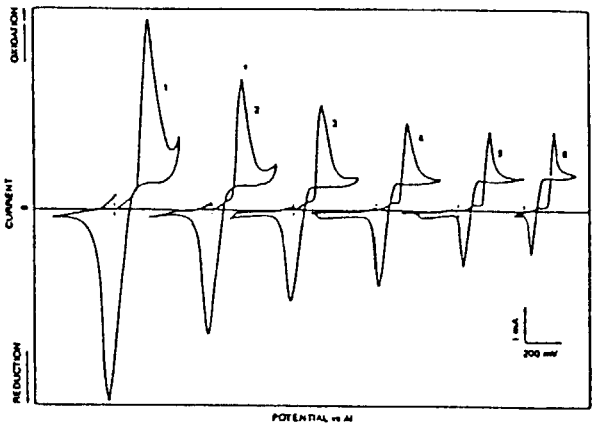
Cyclic voltammetric curves of Ni electrode in $NaAlCl_4$ at 220°C at different scan rates of 1) 50, 2) 20, 3) 10, 4) 5, 5) 2 and 6) 1 mV/s.

- GOOD REVERSIBILITY

OTHER METAL CHLORIDES

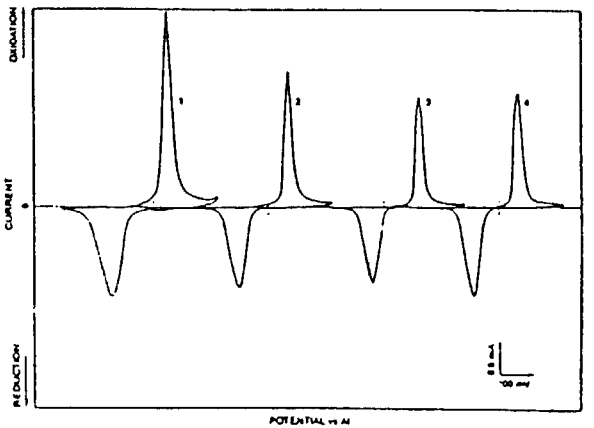
- REQUIRED CRITERIA FROM CYCLIC VOLTAMMETRY
  - ..Low oxidation currents subsequent to peak indicate low solubility for the chloride
  - .. Reversible peaks and single step
- Ti, V, Mn, Cr, Al and Ag UNLIKELY.
  - .. High oxidation currents.
- COPPER EXHIBITS TWO - STEP OXIDATION (SECOND STEP FORMS SOLUBLE CHLORIDE)
  - .. Unlikely.
- COBALT AND MOLYBDENUM ARE LIKELY CATHODE MATERIALS
  - .. Low oxidation currents.
- MOLYBDENUM IS A STABLE CURRENT COLLECTOR FOR $NiCl_2$.

Co



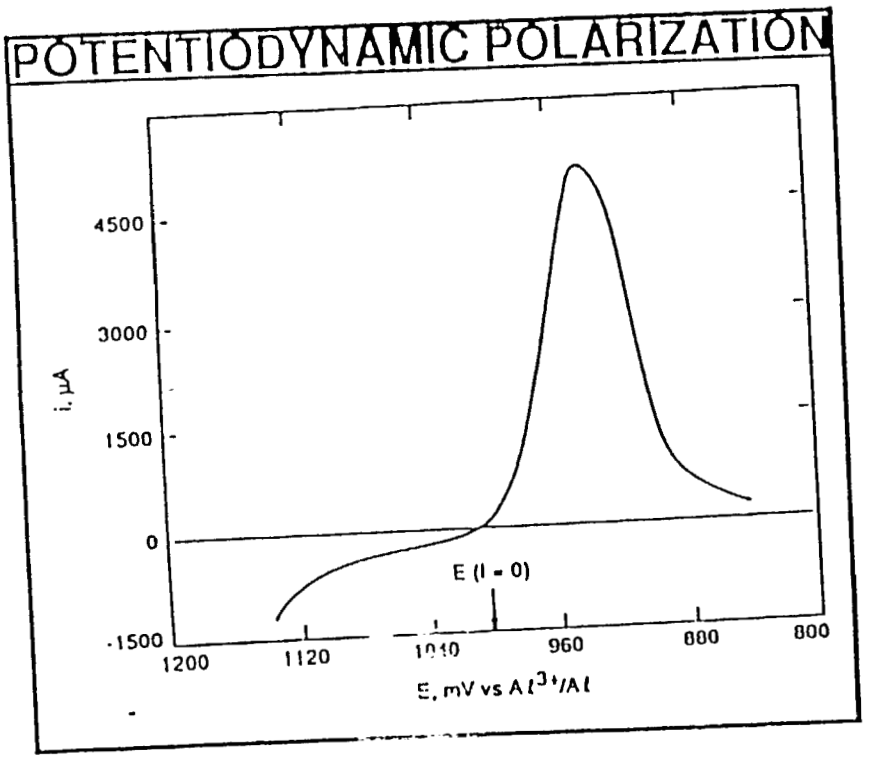
Voltammograms of Co (E_o:870 mV) at 1) 50, 2) 20, 3) 10, 4) 5, 5) 2 and 6) 1 mV/s.

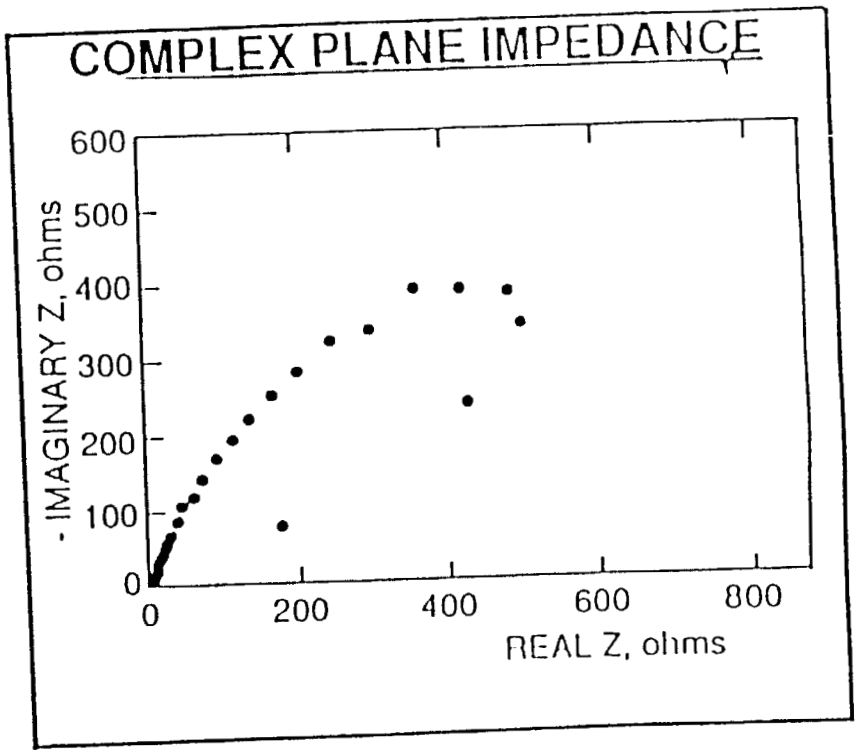
Mo



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

PASSIVATION OF $NiCl_2$





- PASSIVATION DURING REDUCTION BY NaCl PRECIPITATION
- PASSIVATION MORE PROMINENT THAN IN $FeCl_2$

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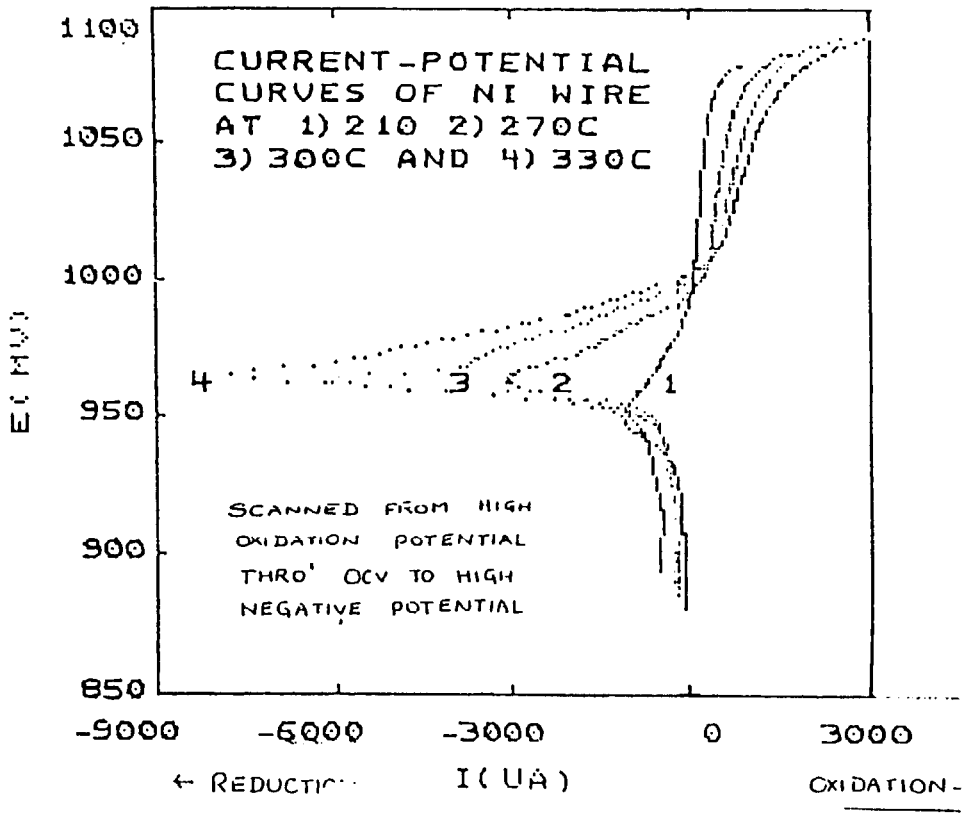
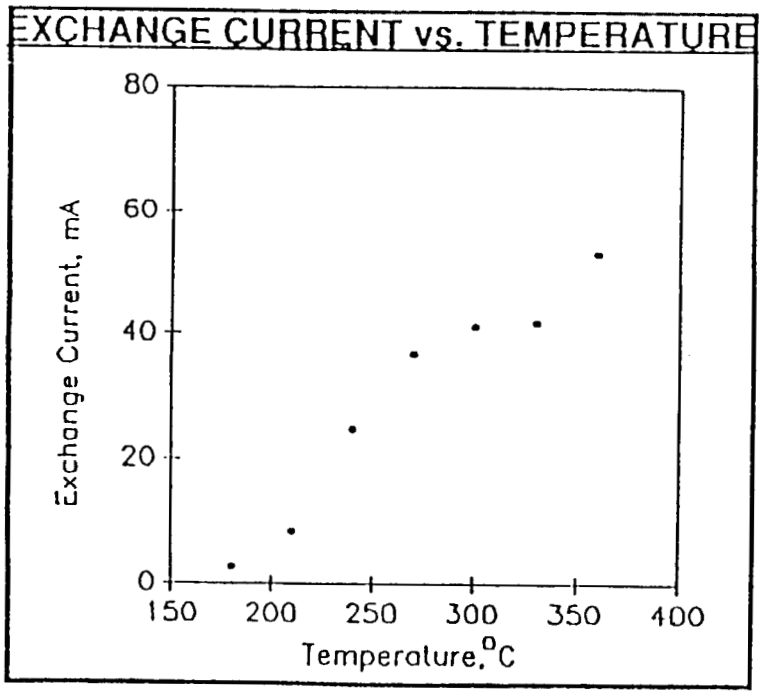
PASSIVATION OF $NiCl_2$

- PASSIVATION INCREASES AT LOWER STATES OF CHARGE AND LOWER ELECTRODE POTENTIALS.
- PASSIVATION IS ALLEVIATED BY INCREASING THE PORE SIZE OF THE ELECTRODE
- PASSIVATION CAN BE REDUCED BY OPERATING AT HIGHER TEMPERATURES



KINETICS OF MCl_2 REDUCTION

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



ADDITIVE REQUIRED FOR $NiCl_2$

- DECLINE IN CAPACITY PREMATURELY

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

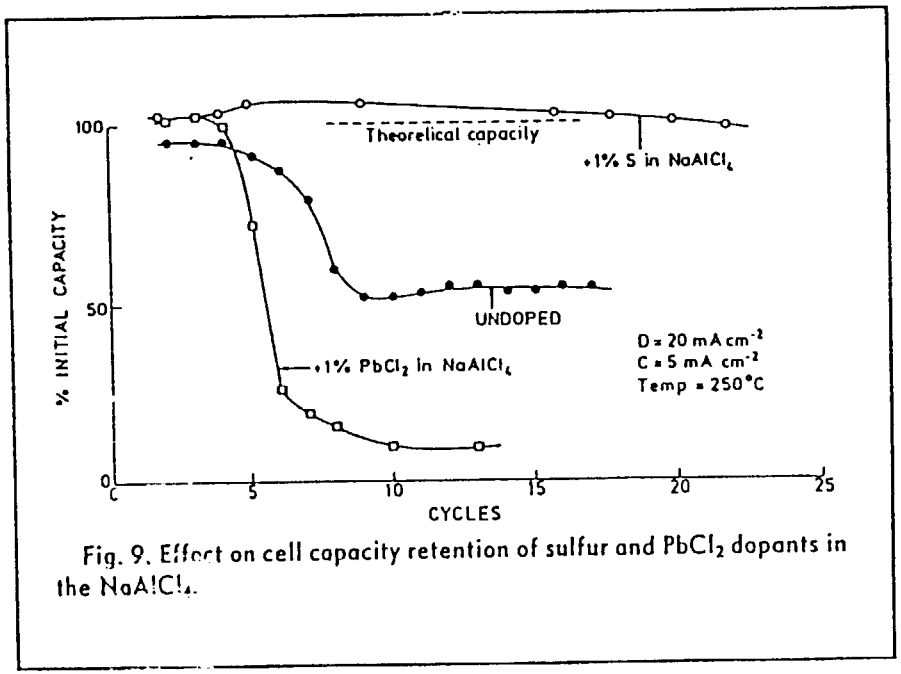


Fig. 9. Effect on cell capacity retention of sulfur and $PbCl_2$ dopants in the $NaAlCl_4$.

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

- SULFUR REDUCES MORPHOLOGICAL CHANGE

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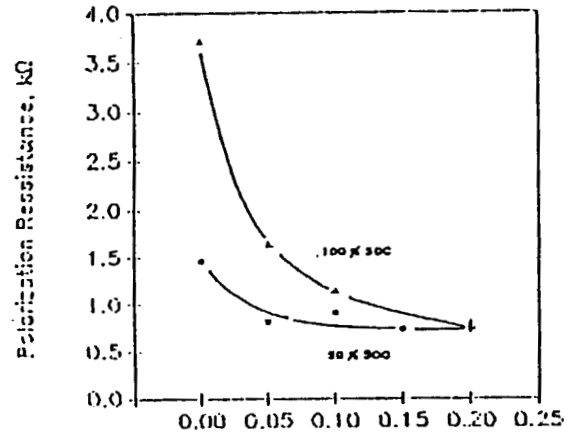
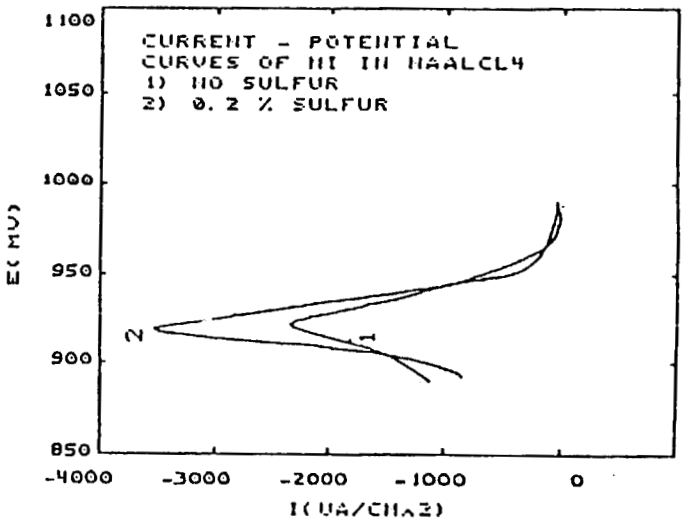
EFFECT OF SULFUR ON $NiCl_2$ KINETICS

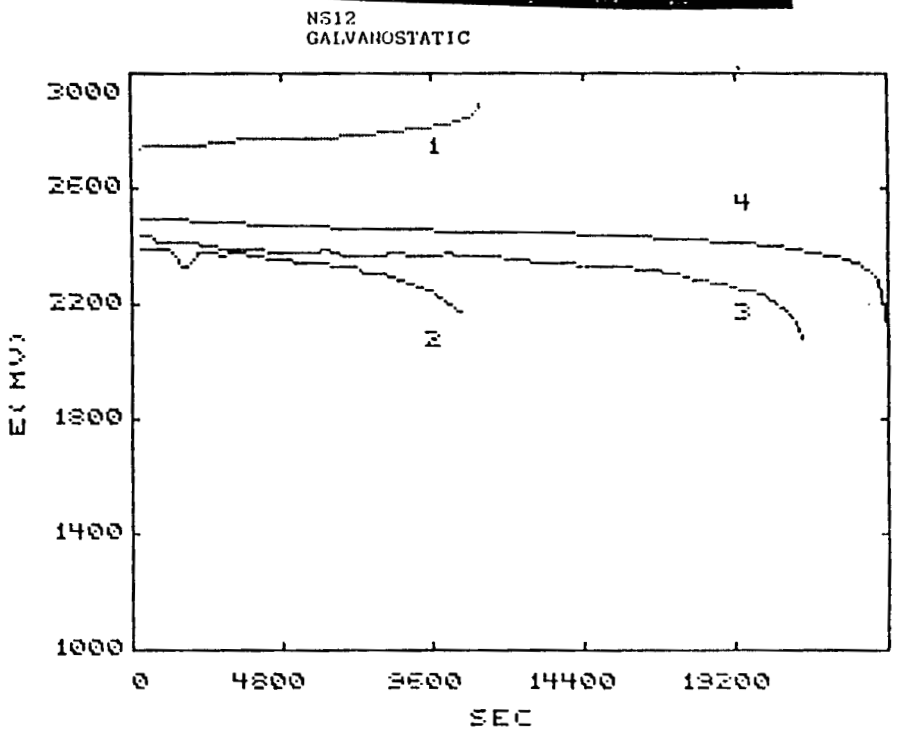
- HIGHER PEAK CURRENTS IN CYCLIC VOLTAMMETRIC CURVES
- IMPROVEMENT IN RECHARGEABILITY
- ENHANCED KINETICS OF $NiCl_2$ REDUCTION
- REDUCED PASSIVATION
- MAXIMUM SULFUR CONTENT ~0.2 w% IN THE ELECTROLYTE





PRELIMINARY PERFORMANCE DATA OF 1 Ah CELL

- HIGH ROUND TRIP EFFICIENCY (~ 95%)
- 50 % CONVERSION OF NaCl
- HIGH DISCHARGE YIELDS OF ABOVE 80 % AT THE 4 - 5 h RATES
- FORMATION APPEARS TO BE INCOMPLETE AND REQUIRES OPTIMIZATION



DISCHARGE CURVES OF 1 Ah Na /$NiCl_2$ CELL AT 75 mA (7.5 mA/cm^2) AND AT 250°C

1) FIFTH CHARGE AT 75 mA
2) FIFTH DISCHARGE
3) SIXTH DISCH. AFTER CHARGE AT 30 mA
4) SEVENTH DISCH. AFTER CHARGE AT 20 mA

FABRICATION PARAMETERS VS. ENERGY DENSITY

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

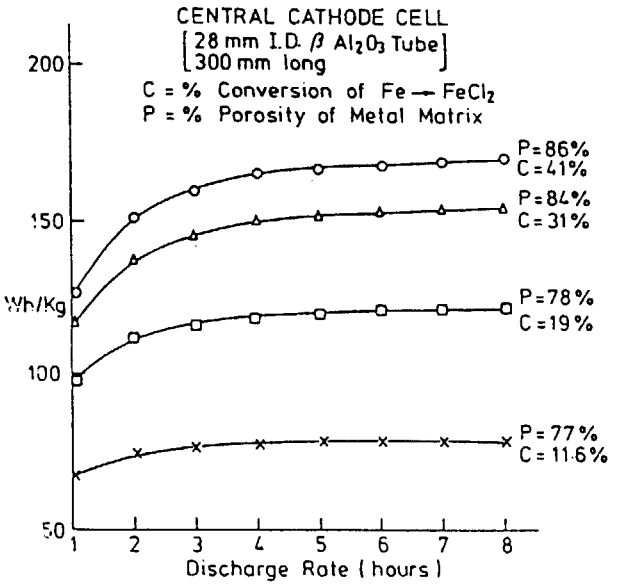


Fig. 5. Cell energy density at various discharge rates (each at optimum cathode thickness).

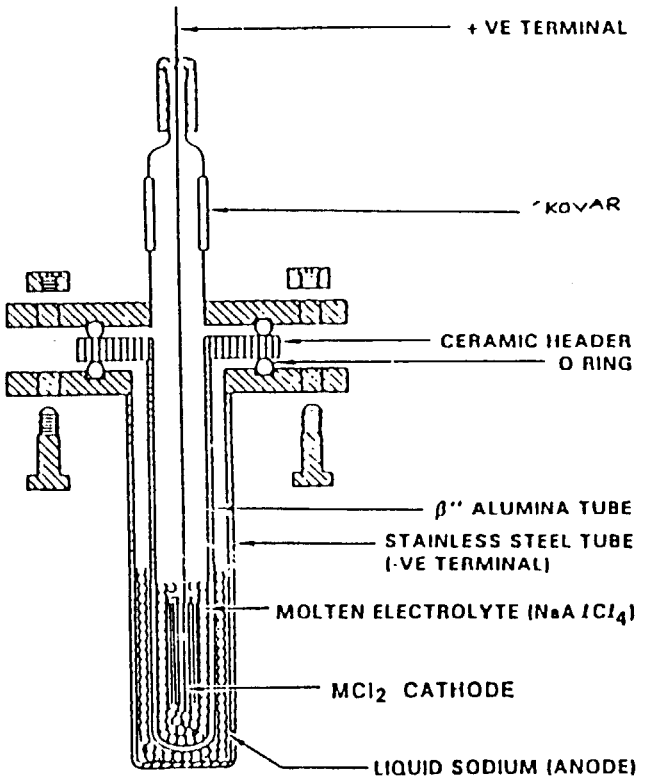
R. J. Bones, J. Coetzer, R. C. Galloway and D. A. Teagle, J. Electrochem., Soc., 134, 2379 (1987).

- 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

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SODIUM- METAL HALIDE CELL PROGRAM

ACTIVITY	88 89 90 91 92 93 94 95 96 97 98 99 2000	
SCREENING STUDIES	Evaluate organic and inorganic cathodes Down select to Na/MCl2	IDENTIFY SYSTEM CAPABLE OF PROVIDING > 1000 CYCLES AND 150 Wh/Kg
ELECTROCHEMICAL CHARACTERIZATION OF MCl2	Short term studies performance and reversibility Identify suitable materials Identify and overcome rate limiting processes Down select to Na/NiCl2	ESTABLISH MECHANISMS DETERMINE REACTION KINETICS AND IDENTIFY RATE LIMITING PROCESSES
COMPONENT DEVELOPMENT	Develop 5 Ah TEST CELL Study of performing enhancing additives Develop cathode fabication process Identify cell failure mechanism Charge methods Optimize and improve design	DEFINE DESIGN REQUIREMENTS FOR 20-25 Ah CELLS
PERFORMANCE AND SAFETY EVALUATION	Develop performance data base Evaluate safety and environmental effects Identify failure modes	DEMONSTRATE CYCLE LIFE AND PERFORMANCE IN OPTIMIZED 20-25 Ah CELL
PROTO TYPE	Develop eng model cell Demo 1000 cycles and 150 Wh/Kg	FINAL DEMONSTRATION

PUBLICATIONS FROM JPL ACTIVITIES

1. "AEROSPACE APPLICATIONS OF SODIUM BATTERIES USING NOVEL CATHODE MATERIALS", PROC. OF 24th IECEC, WASINGTON 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. 26th IECEC, BOSTON, MA, AUG. 1991.

CONCLUSIONS

- RAPID DEVELOPMENT IN THE TECHNOLOGY OF Na / 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 ~ 100 Wh/Kg HAVE BEEN DEMONSTRATED IN BOTH Na / $FeCl_2$ AND Na / $NiCl_2$ CELLS.

- OPTIMIZATION OF POROUS CATHODE AND SOLID ELECTROLYTE GEOMETRIES ARE ESSENTIAL FOR FURTHER ENHANCING THE PERFORMANCE.

- FUNDAMENTAL STUDIES CONFIRM THE CAPABILITIES OF THESE SYSTEMS. $NiCl_2$ EMERGES AS THE CANDIDATE CATHODE MATERIAL FOR HIGH POWER DENSITY APPLICATIONS SUCH AS ELECTRIC VEHICLE AND SPACE.

PRESENTATION TO

1991 NASA AEROSPACE BATTERY WORKSHOP

OCTOBER 29-31, 1991
U.S. SPACE & ROCKET CENTER
HUNTSVILLE, AL

PULSED POWER MOLTEN SALT BATTERY

CONTRACT NO. F33615-88-C-2911

AERO PROPULSION LABORATORY
WRIGHT LABORATORY, WL/POOS-2
WRIGHT PATTERSON AIR FORCE BASE, OH 45433

S.D. ARGADE

TECHNOCHEM COMPANY
203-A CREEK RIDGE RD.
GREENSBORO, NC 27406

INTRODUCTION

CHLORINE CATHODES

UNIT CELL DEVELOPMENT

CELL STACK DEVELOPMENT

SUMMARY

INTRODUCTION

CHLORINE CATHODES

UNIT CELL DEVELOPMENT

CELL STACK DEVELOPMENT

SUMMARY

INTRODUCTION

PHASE II PROGRAM GOALS

- **Develop and demonstrate a Li/Al/chlorine molten salt battery design**
  - Develop improved chlorine cathodes
  - Develop unit cell design
  - Demonstrate a stack/battery design

INTRODUCTION

CHLORINE CATHODES

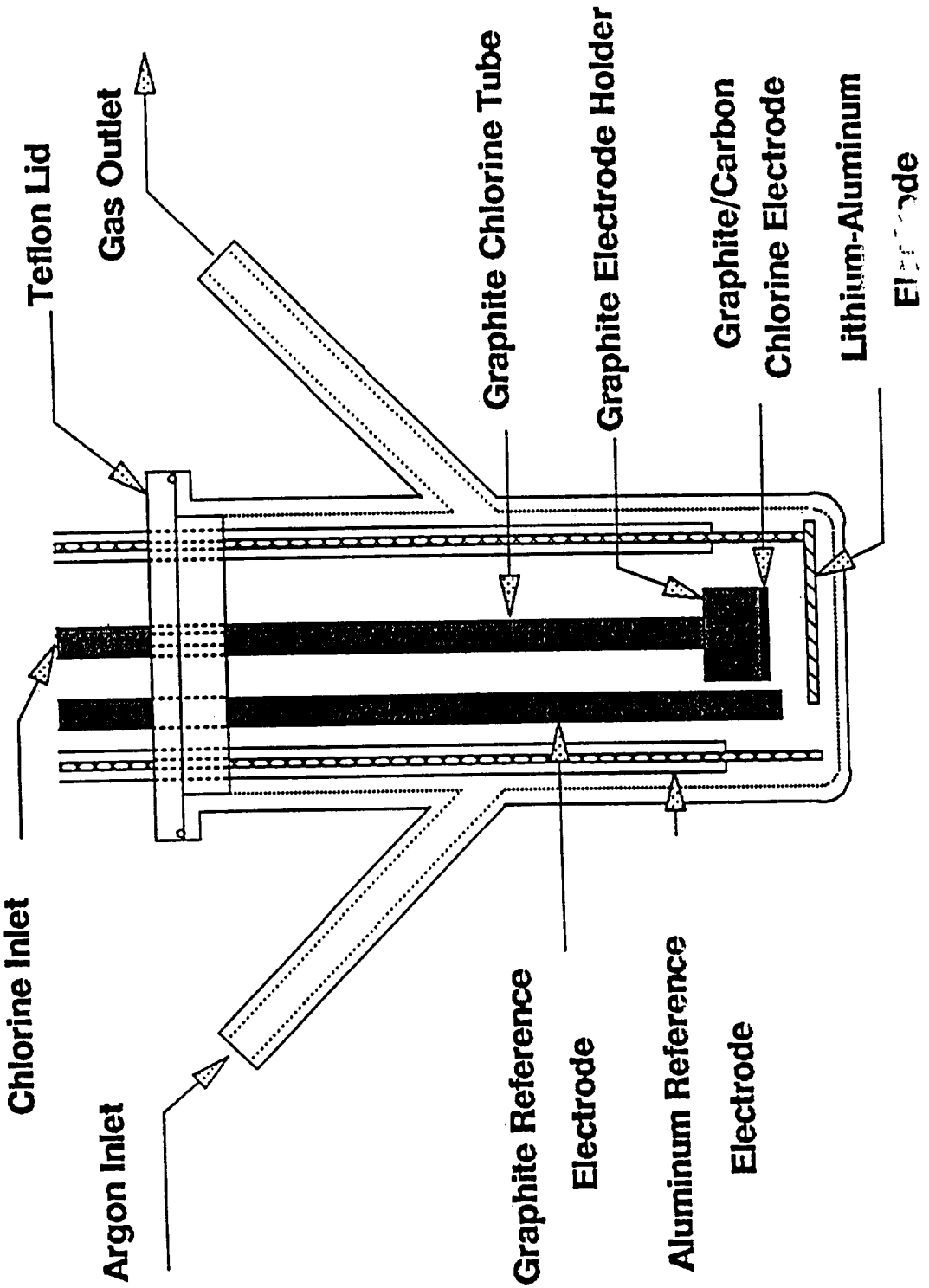
UNIT CELL DEVELOPMENT

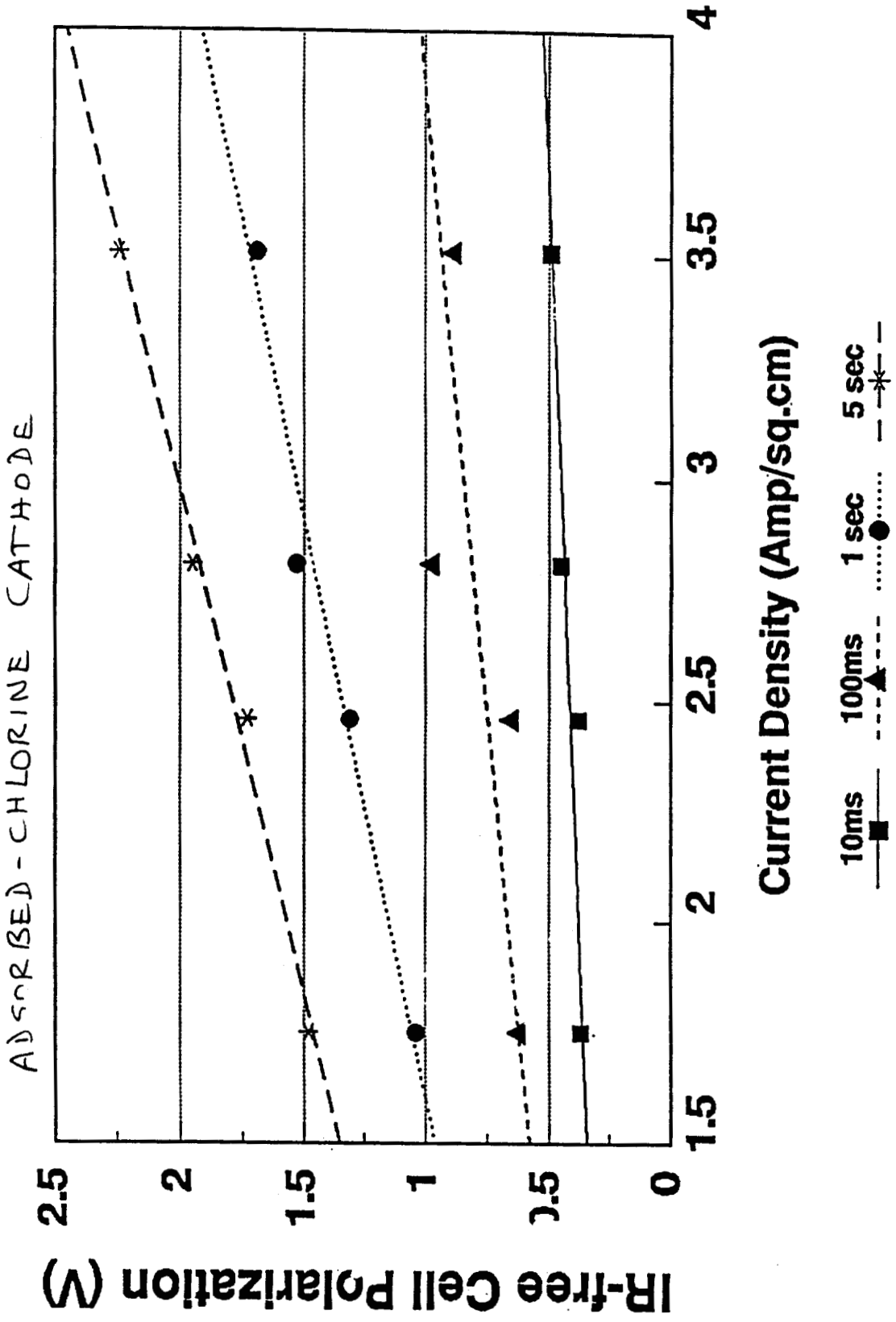
CELL STACK DEVELOPMENT

SUMMARY

CHLORINE CATHODES

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


Teflon Lid
Gas Outlet
Graphite Chlorine Tube
Graphite Electrode Holder
Graphite/Carbon
Chlorine Electrode
Lithium-Aluminum
Chlorine Inlet
Argon Inlet
Graphite Reference
Electrode
Aluminum Reference
Electrode


ADSORBED-CHLORINE CATHODE
IR-free Cell Polarization (V)
2.5
2
1.5
1
0.5
0
1.5
2
2.5
3
3.5
4
Current Density (Amp/sq.cm)
10ms
100ms
1 sec
5 sec

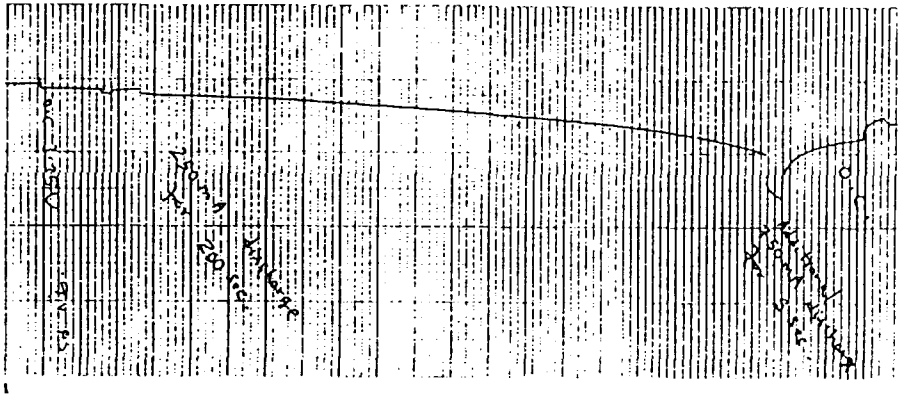
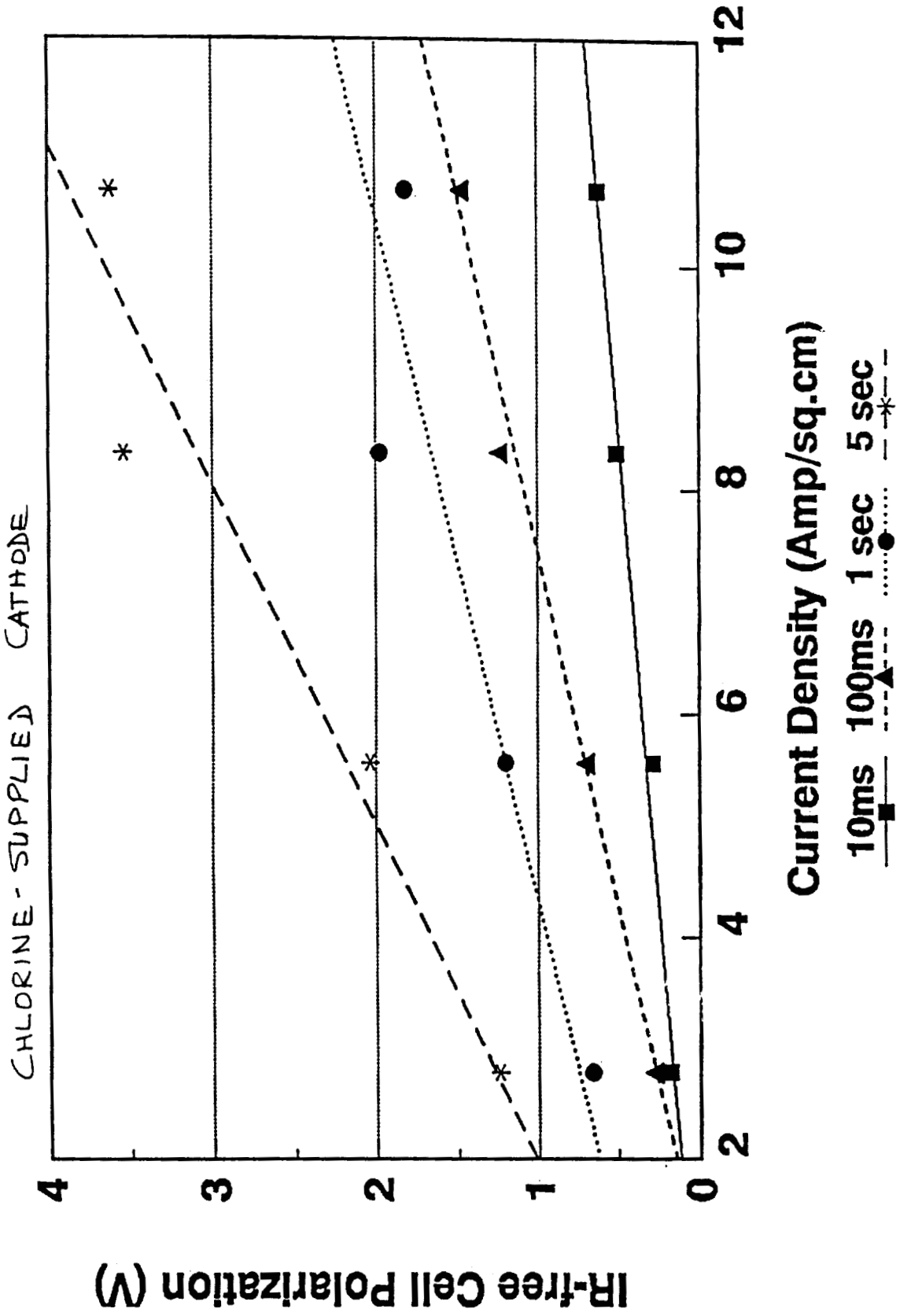
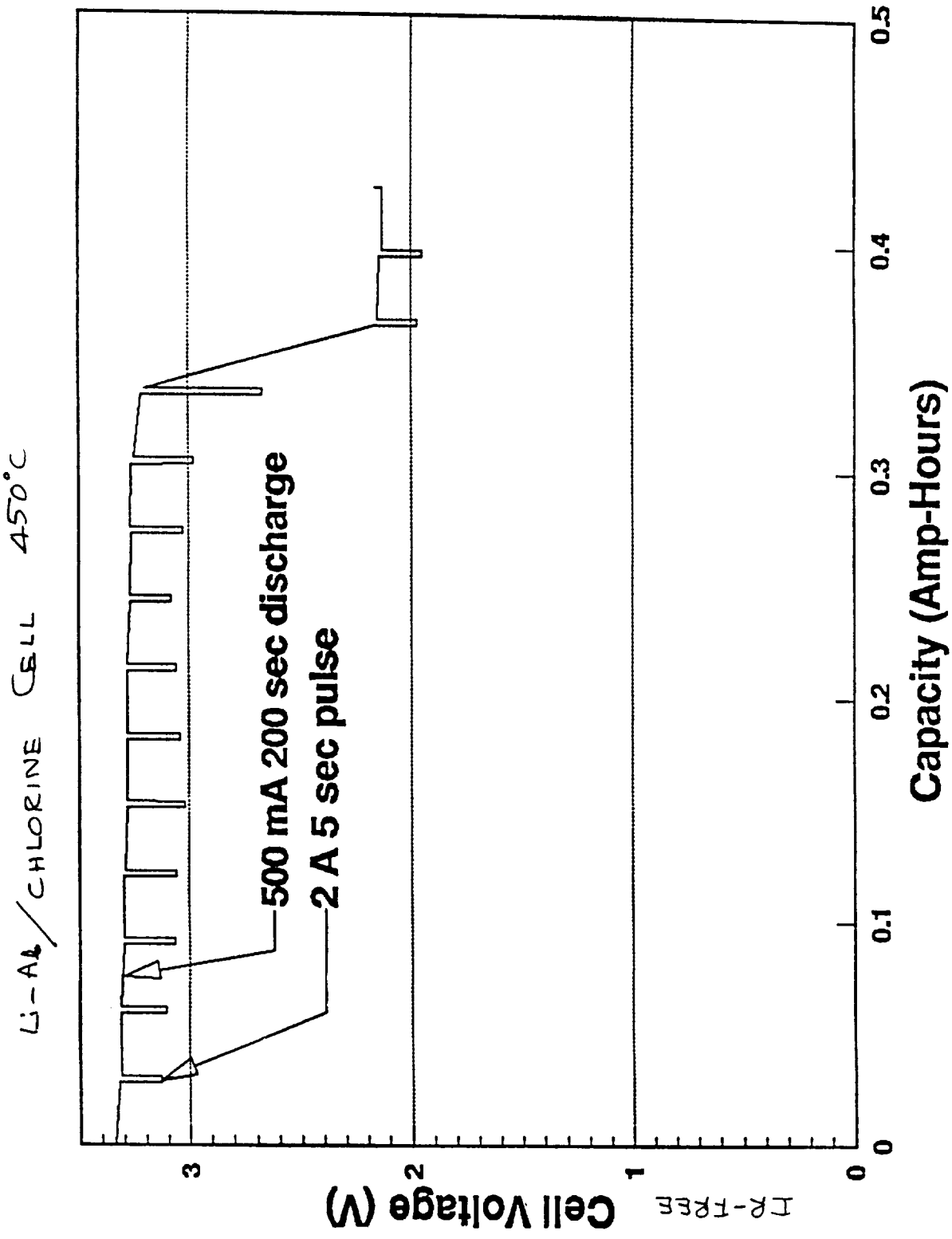
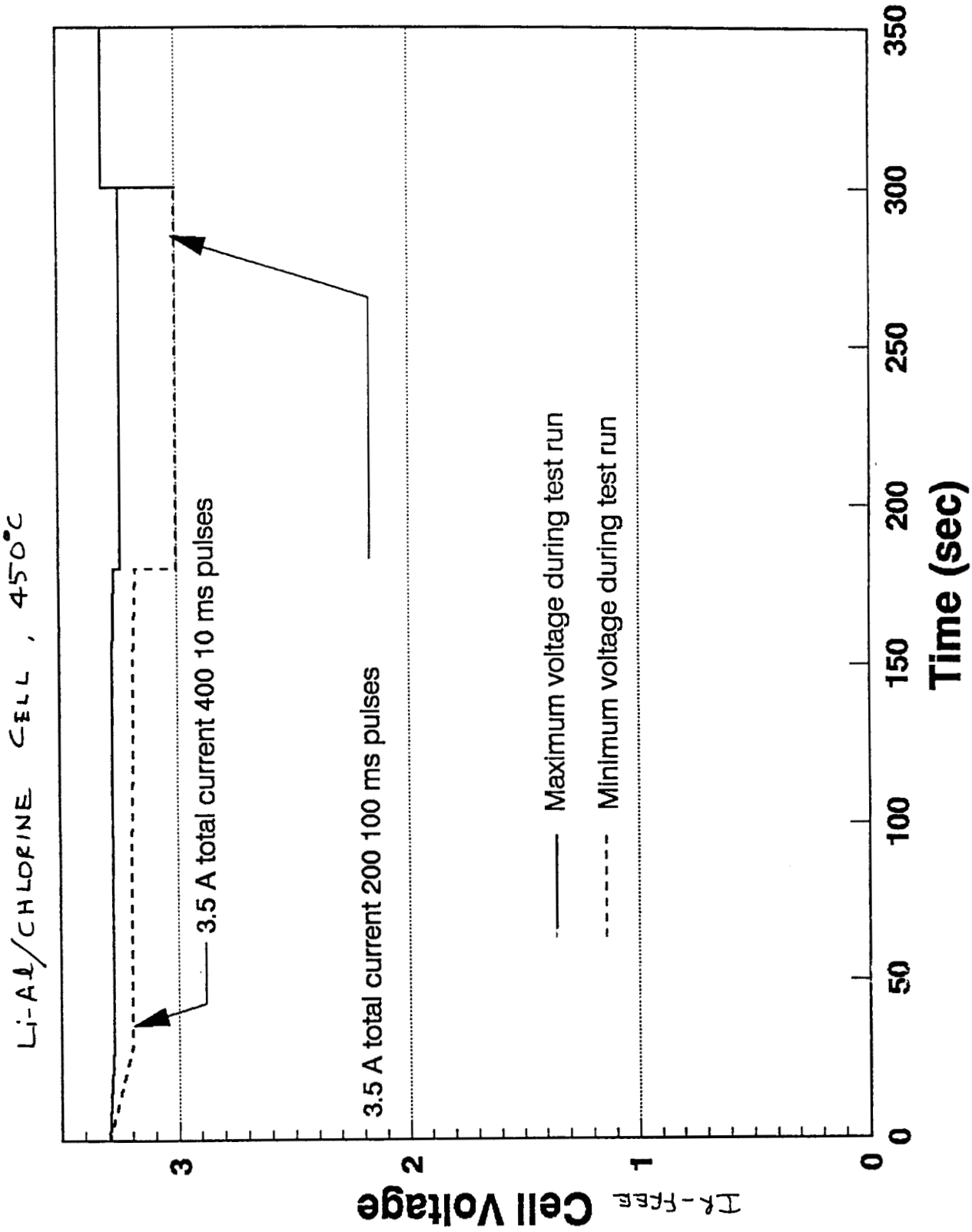


Fig. 5 Discharge characteristics for a Li-Al/carbon 8-9-2 absorbed chlorine cell under test cycle 1 regime, 250 mA for 200 sec followed by 1 A current


CHLORINE - SUPPLIED CATHODE
IR-free Cell Polarization (V)
0
1
2
3
4
2
4
6
8
10
12
Current Density (Amp/sq.cm)
10ms
100ms
1 sec
5 sec


Li-Al/CHLORINE CELL 450°C
500 mA 200 sec discharge
2 A 5 sec pulse
IR-FREE
Cell Voltage (V)
Capacity (Amp-Hours)
0
1
2
3
0
0.1
0.2
0.3
0.4
0.5


Li-Al/CHLORINE CELL, 450°C
3.5 A total current 400 10 ms pulses
3.5 A total current 200 100 ms pulses
Maximum voltage during test run
Minimum voltage during test run
Cell Voltage
Time (sec)
0
1
2
3
0
50
100
150
200
250
300
350

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

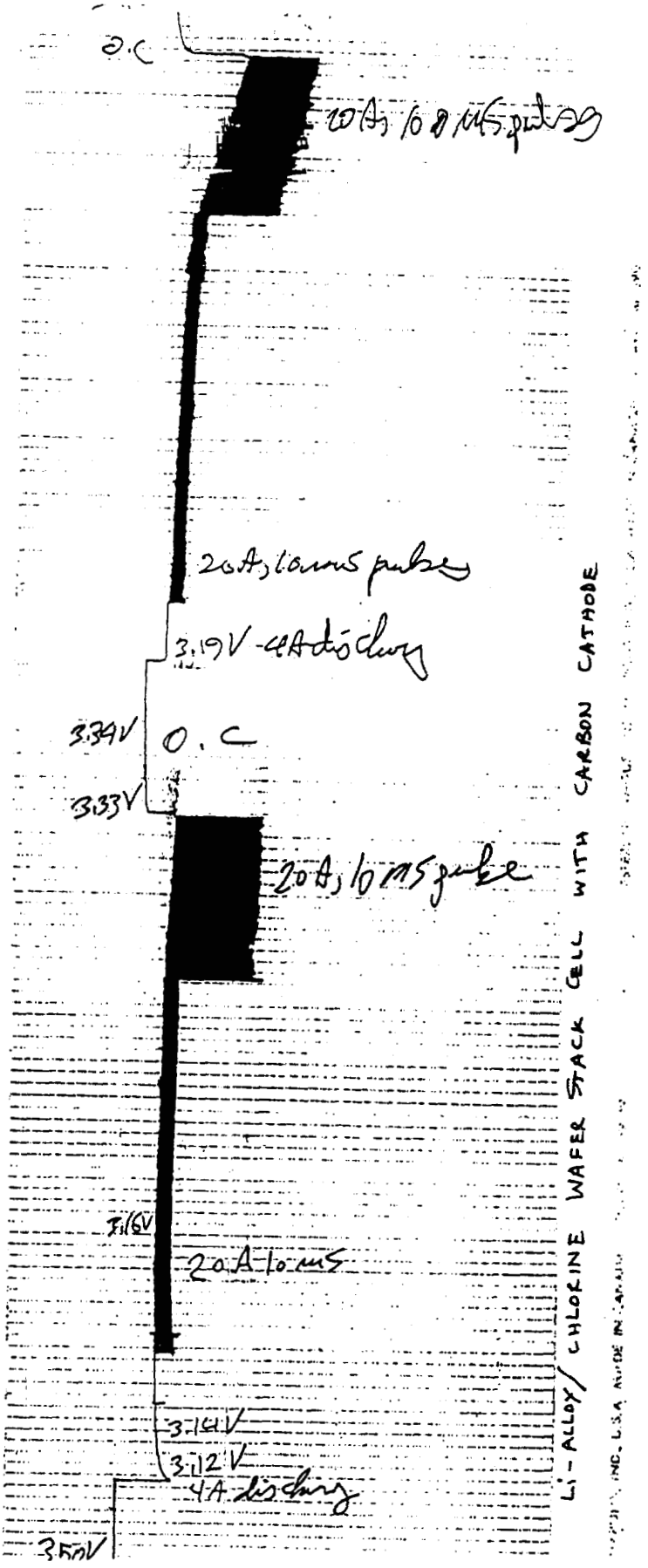
UNIT CELL DEVELOPMENT

CELL STACK DEVELOPMENT

SUMMARY

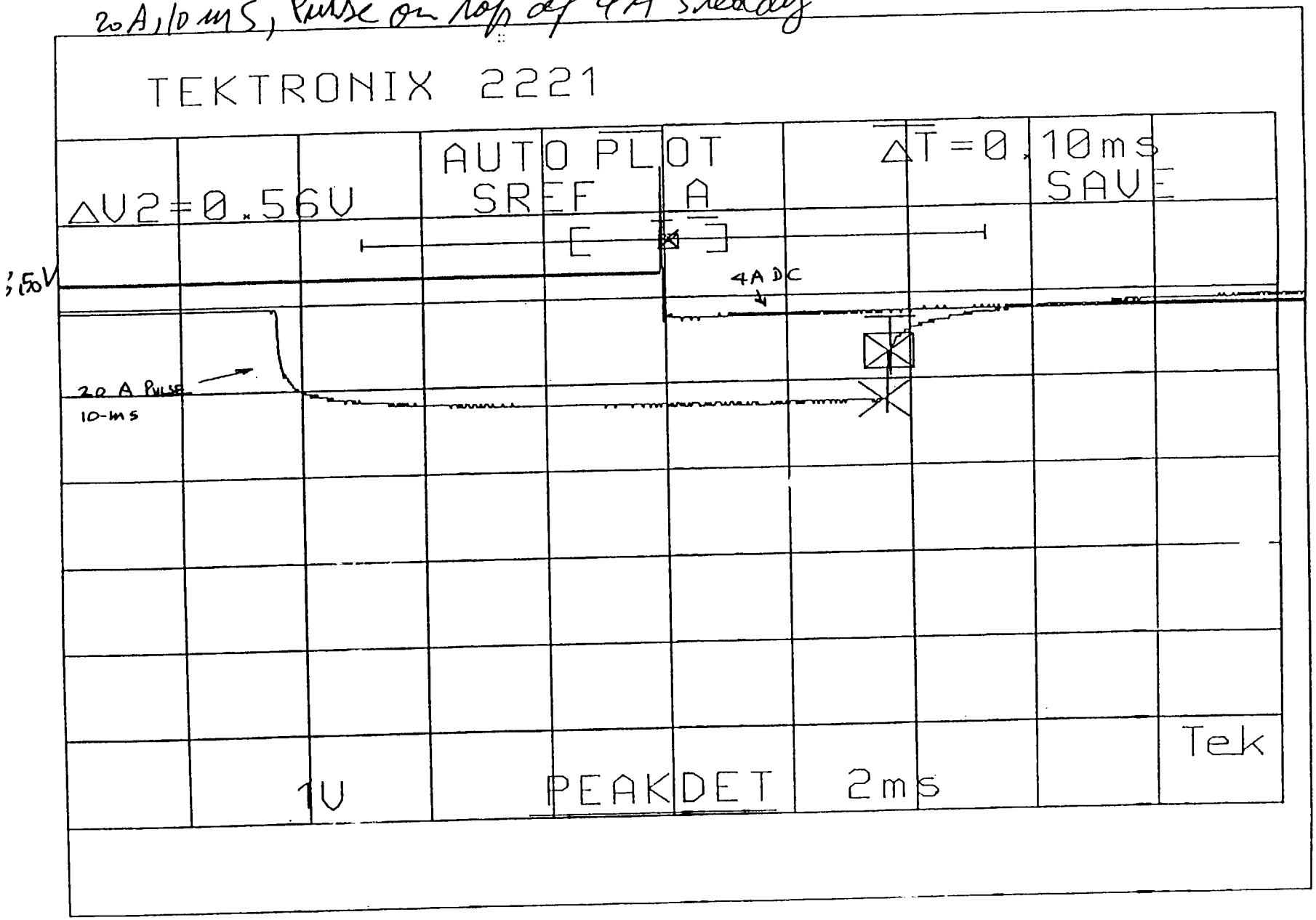
Cell Development

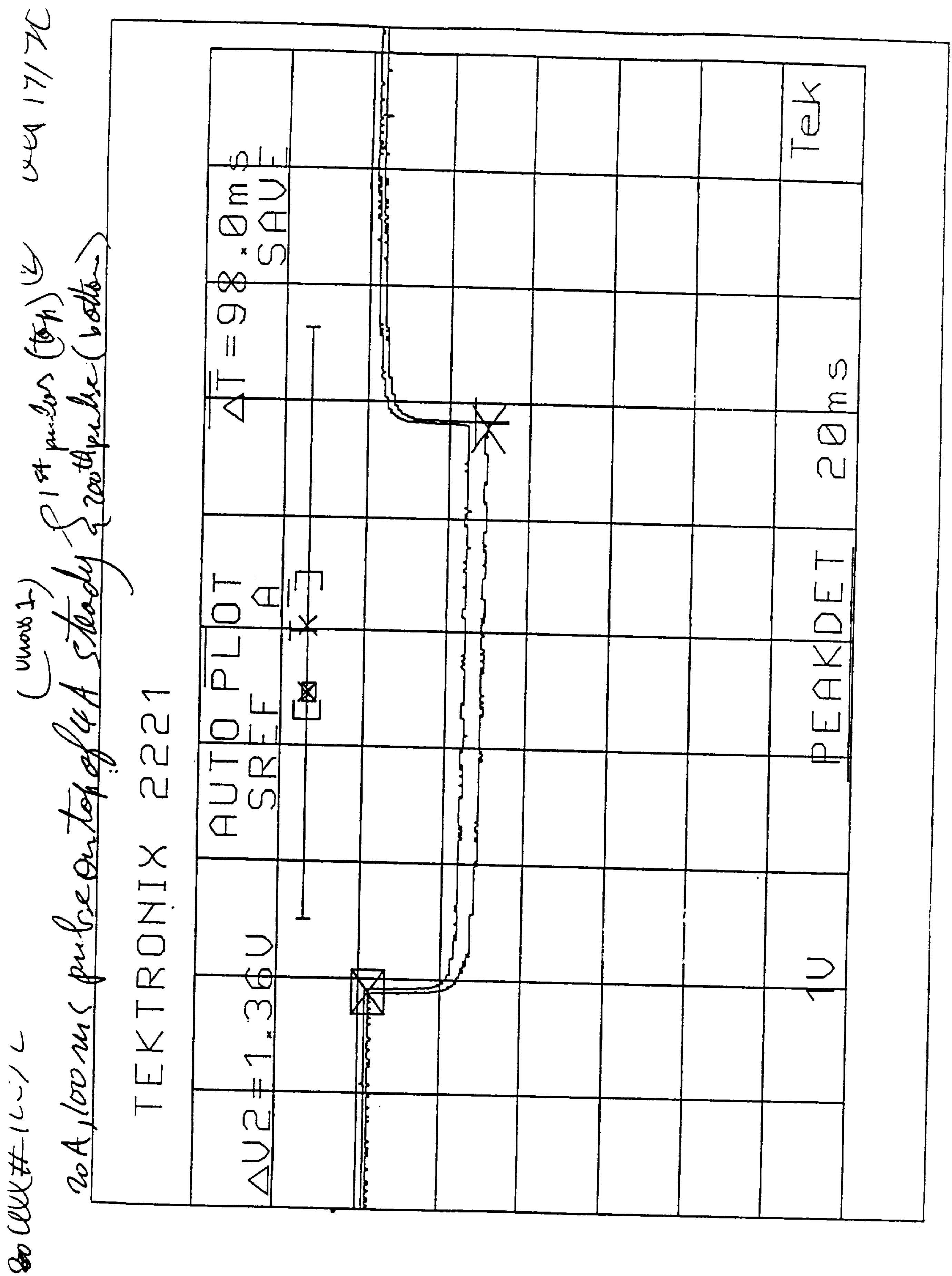
- **Test Hardware**
  - Glass Enclosure Cell
  - Anode Wafer in Stainless Steel or Ni Cup, Nickel leads
  - Cathode rests on EB salt wafer backed by graphite current collector
  - Chlorine fed to the wafer-ambient pressure
- **Test Regime**
  - Steady discharge load + 400 10 ms pulses + 200 100 ms pulses


O.C
20A, 10 ms pulse
20A, 10ms pulse
3.19V - 4A discharge
3.34V
O.C
3.33V
20A, 10 ms pulse
3.16V
20A 10ms
3.14V
3.12V
4A discharge
3.50V
Li - ALLOY / CHLORINE WAFER STACK CELL WITH CARBON CATHODE

cell # 12-92 (Unit 1) (1) oct 19/90

20A, 10 mS, Pulse on top of 4A steady




TEKTRONIX 2221
ΔV2=1.36V
AUTO PLOT
SREF
ΔT=98.0ms
SAVE
1V
PEAKDET
20ms
Tek

INTRODUCTION

CHLORINE CATHODES

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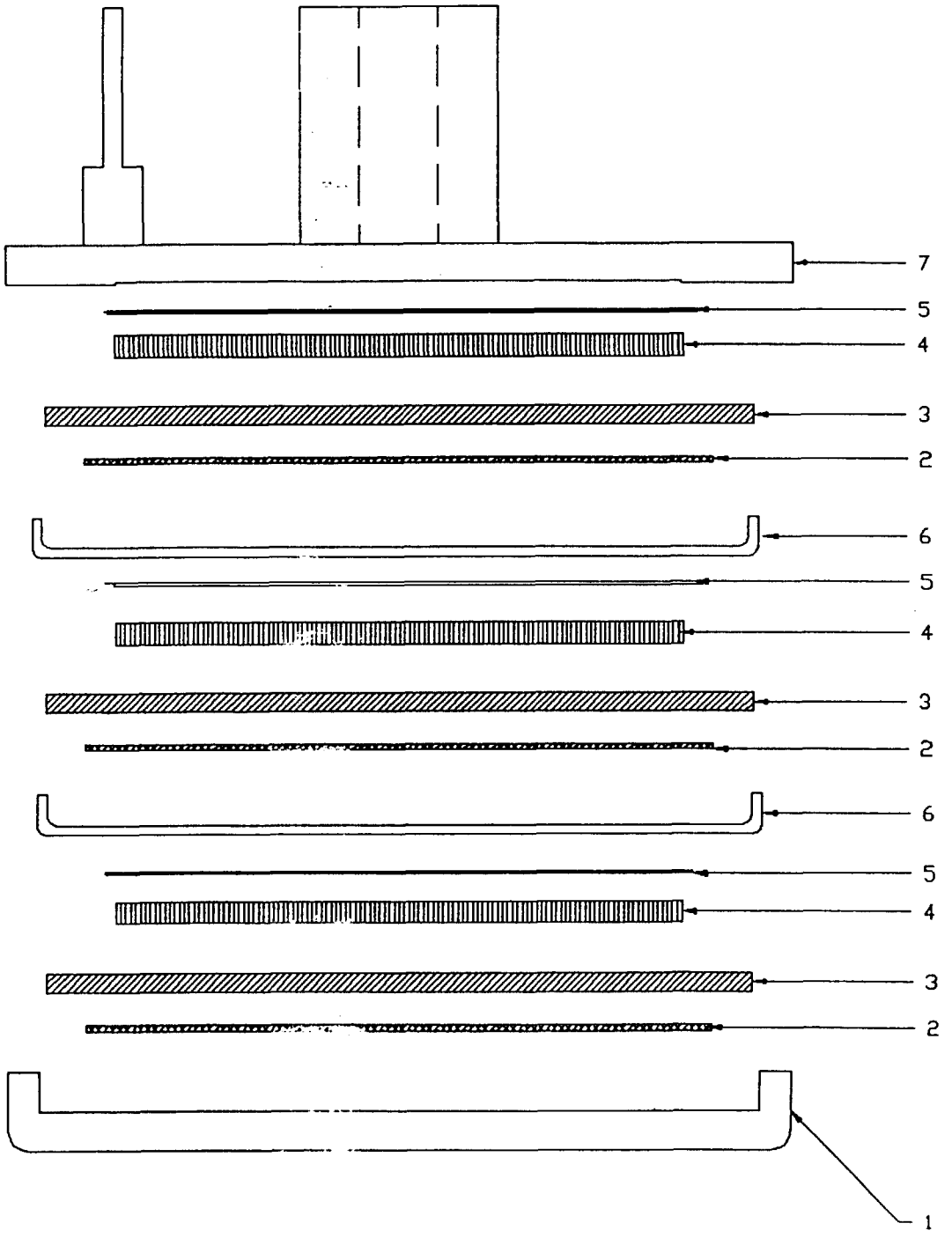
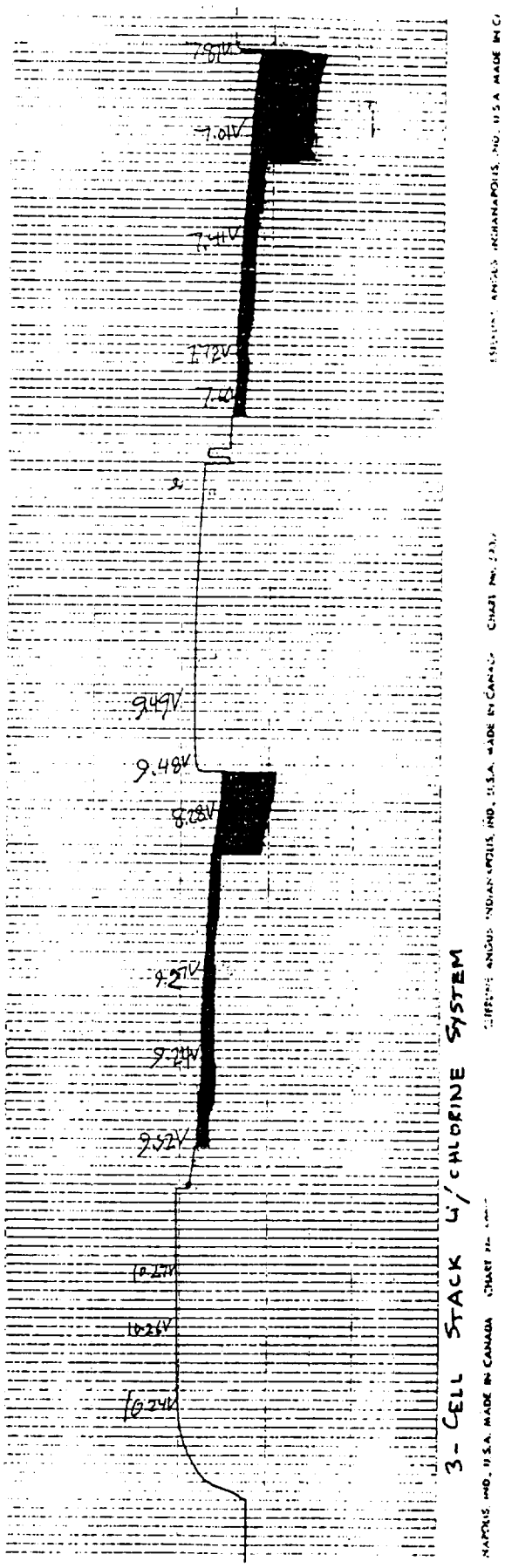
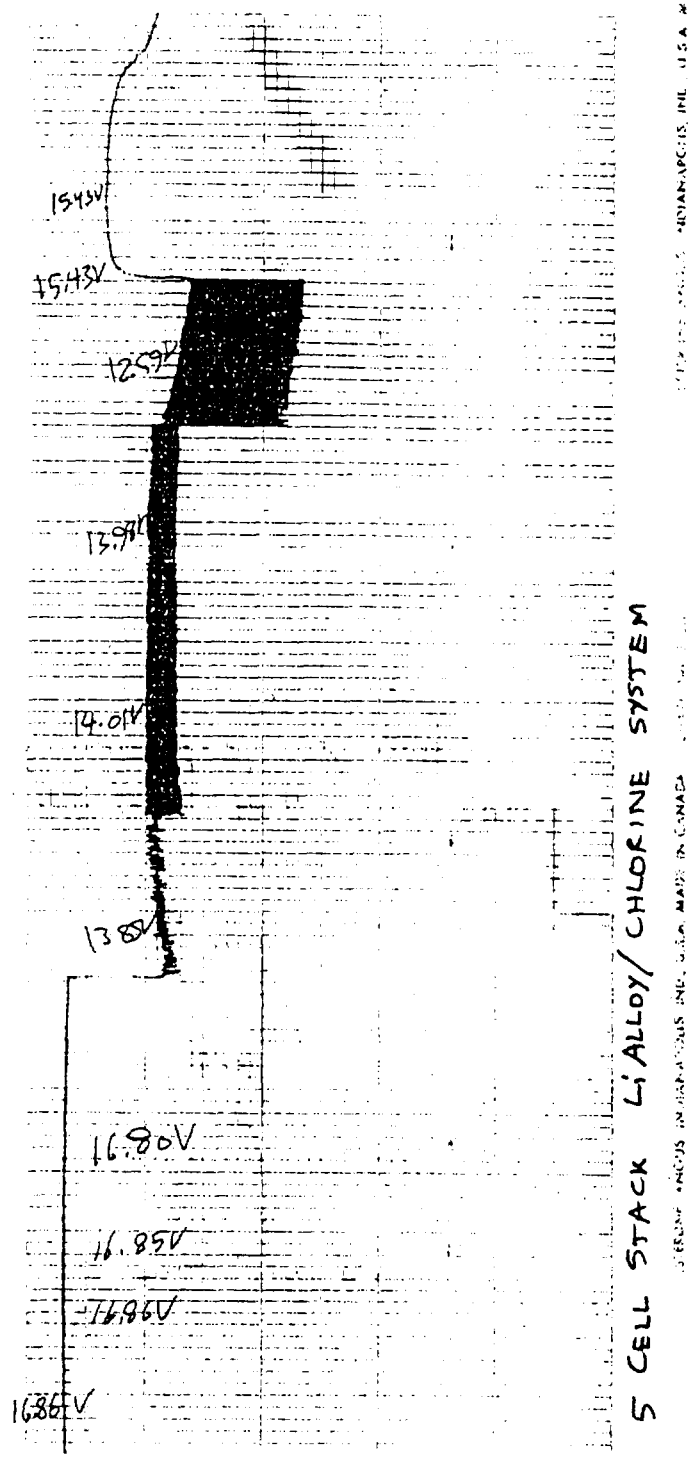
SUMMARY



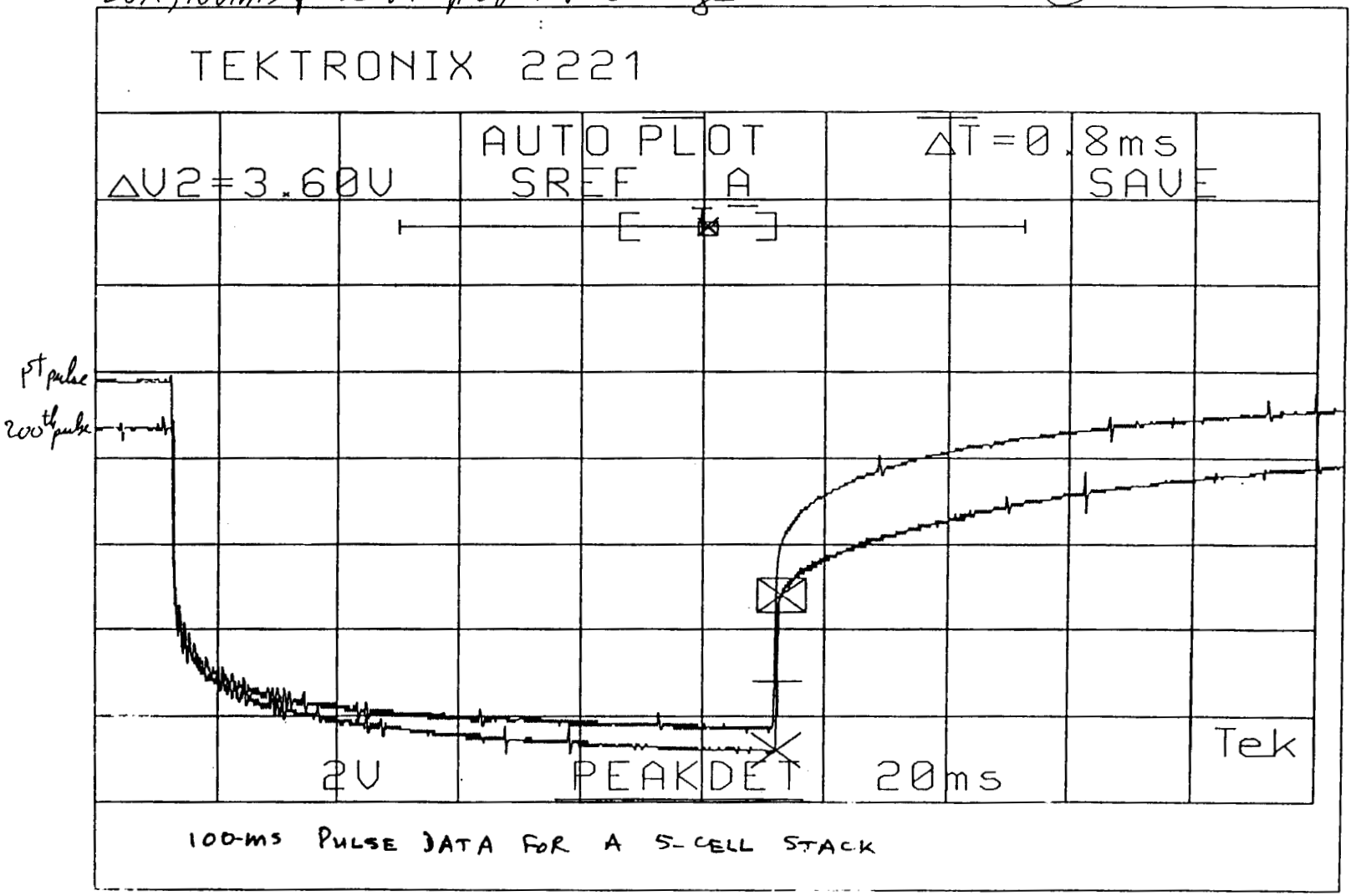
1. Anode Current Collector
2. Li-Al Anode
3. Salt Wafer
4. Carbon Cathode
5. Grafoil
6. Nickel Cup
7. Cathode Current Collector with Chlorine Feed Tube


3- CELL STACK 4/CHLORINE SYSTEM
9.49V
9.48V
9.25V
9.24V
9.52V
10.24V

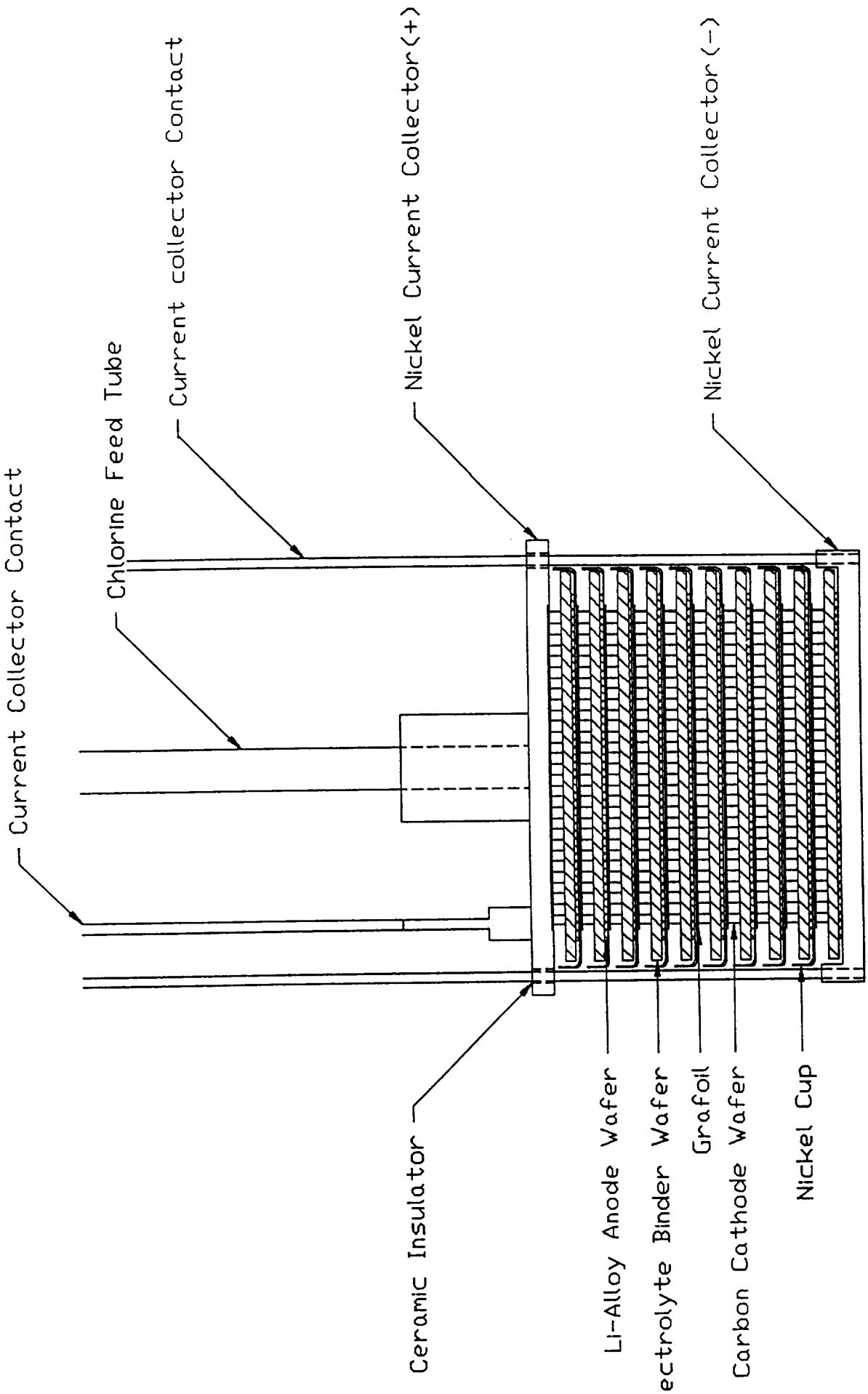

5 CELL STACK Li ALLOY/ CHLORINE SYSTEM
15.43V
15.43V
12.59V
13.91V
14.01V
13.8V
16.80V
16.85V
16.86V
16.86V

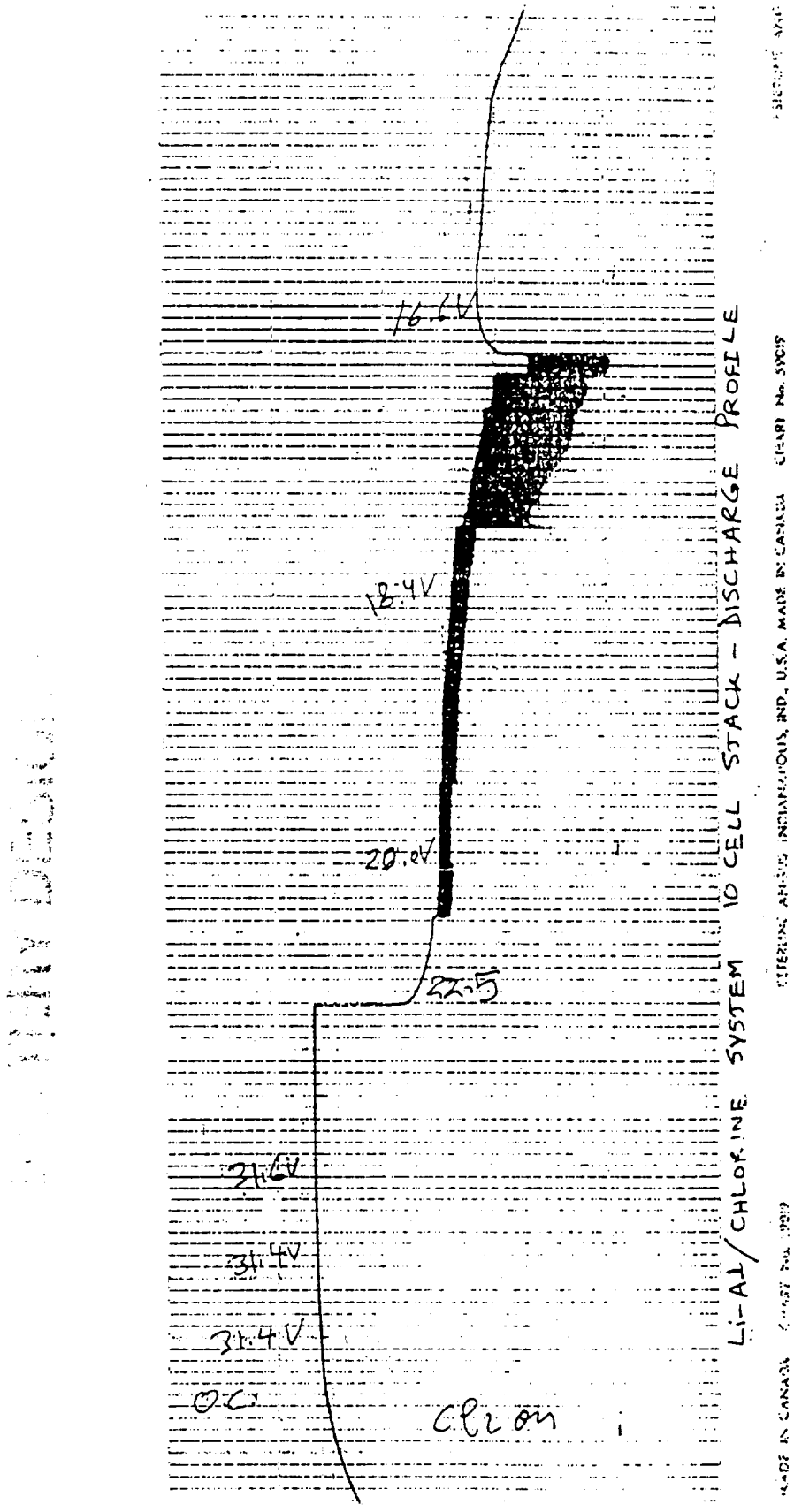
all#12-146 (trial 1) 11/17/9

20A, 100ms pulses on top of 4A discharge (2)



100-ms PULSE DATA FOR A 5-CELL STACK


Current Collector Contact
Chlorine Feed Tube
Current collector Contact
Nickel Current Collector(+)
Nickel Current Collector(-)
Ceramic Insulator
Li-Alloy Anode Wafer
Electrolyte Binder Wafer
Grafoil
Carbon Cathode Wafer
Nickel Cup


Li-Al/CHLORINE SYSTEM 10 CELL STACK - DISCHARGE PROFILE
16.6V
18.4V
20.0V
22.5
31.6V
31.4V
31.4V
OC
Cl2 on

BATTERY DESIGN PARAMETERS

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

POWER DENSITY

4A DC, 24A PULSE REGIME

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

ENERGY DENSITY

4A DC, 24 A PULSE REGIME

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

INTRODUCTION

CHLORINE CATHODES

UNIT CELL DEVELOPMENT

CELL STACK DEVELOPMENT

SUMMARY

SUMMARY

- Carbon Cathodes with chlorine work well
- Li-Alloy/chlorine at 450 deg. C, 1atm
  - 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

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 retangular 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 amphours 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_2 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 Olumpus Space Craft, P. Leggett and A. Sepers, 20th IECEC, August 1985 (Page 1.331).

FIGURE 1: 26-CELL CPV BATTERY AND IPV EQUIVALENT

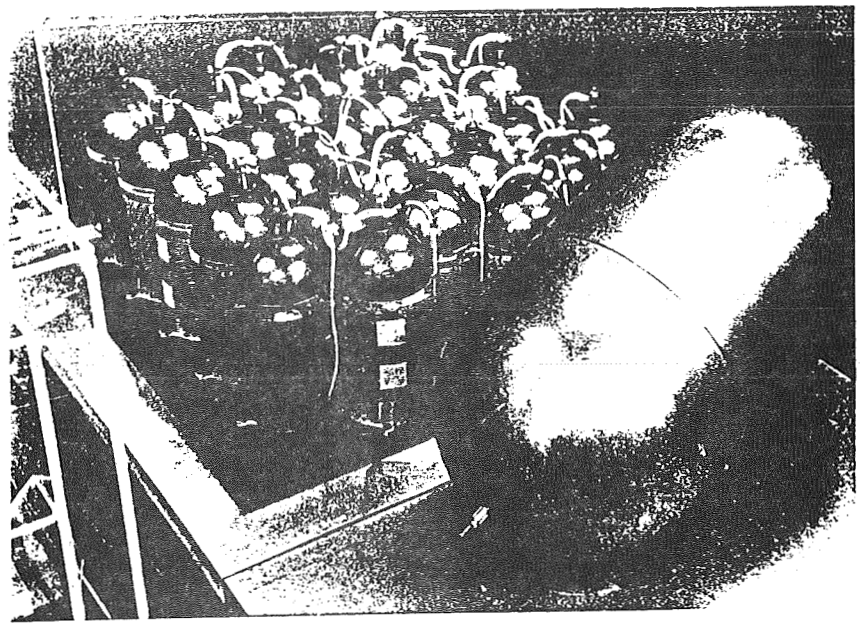


FIGURE 2: VARIETY OF CPV BATTERIES CURRENTLY IN PRODUCTION

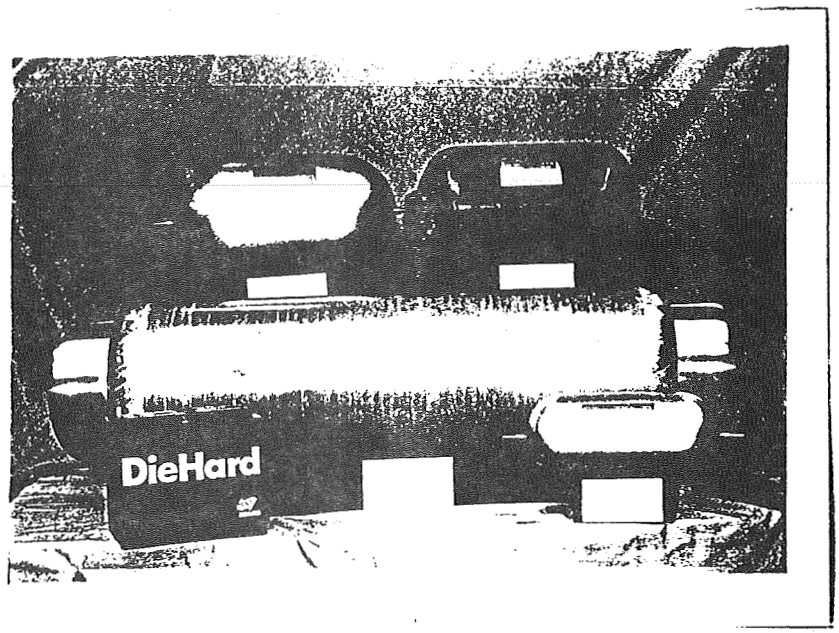


FIGURE 3: 5" CIRCULAR CPV CELL

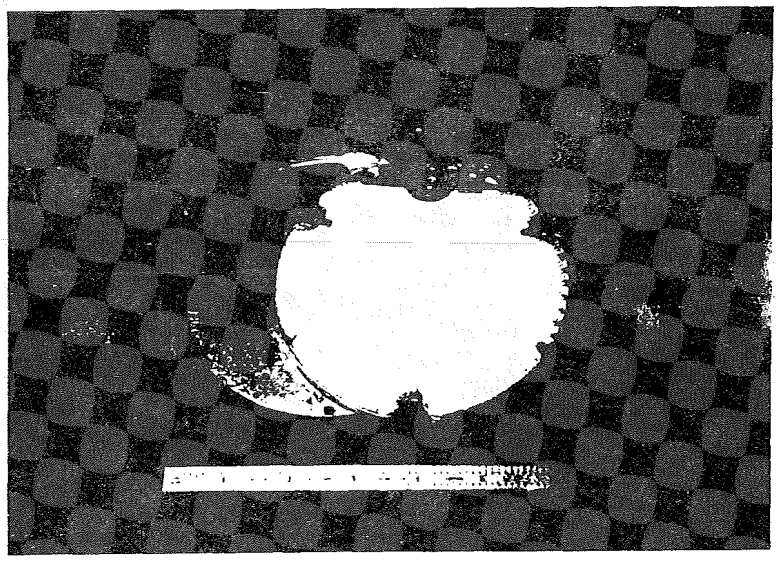


FIGURE 4: 10" SEMI-CIRCULAR CPV CELL

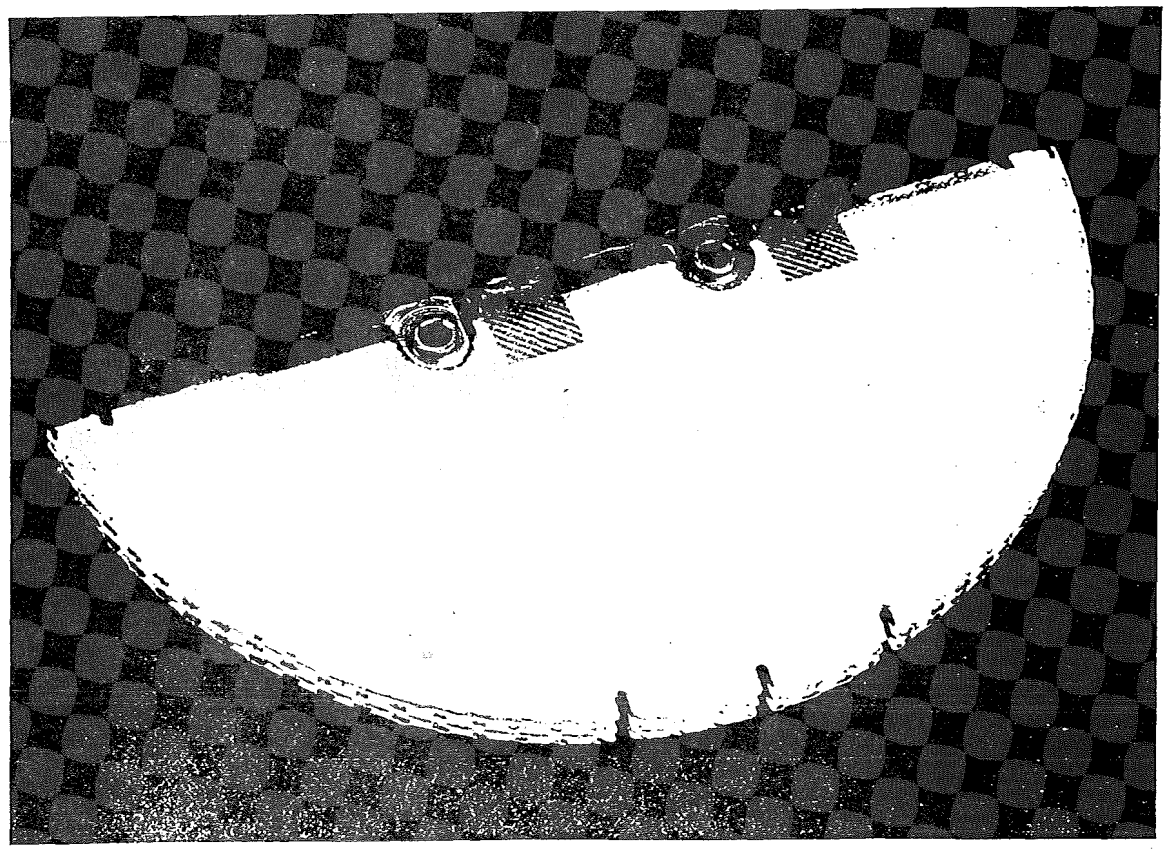


FIGURE 5: RECTANGULAR CPV CELL MODULE AND COMPONENTS

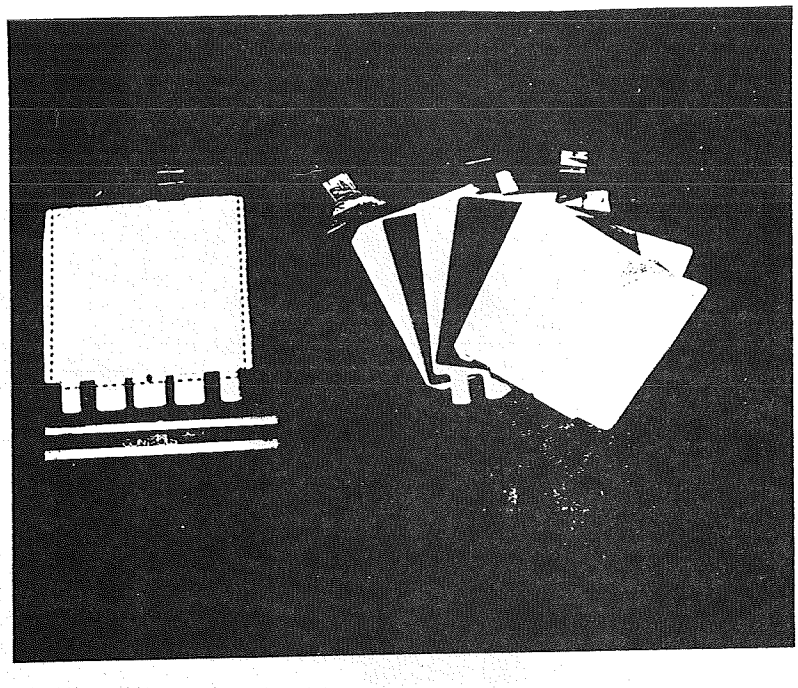


FIGURE 6:

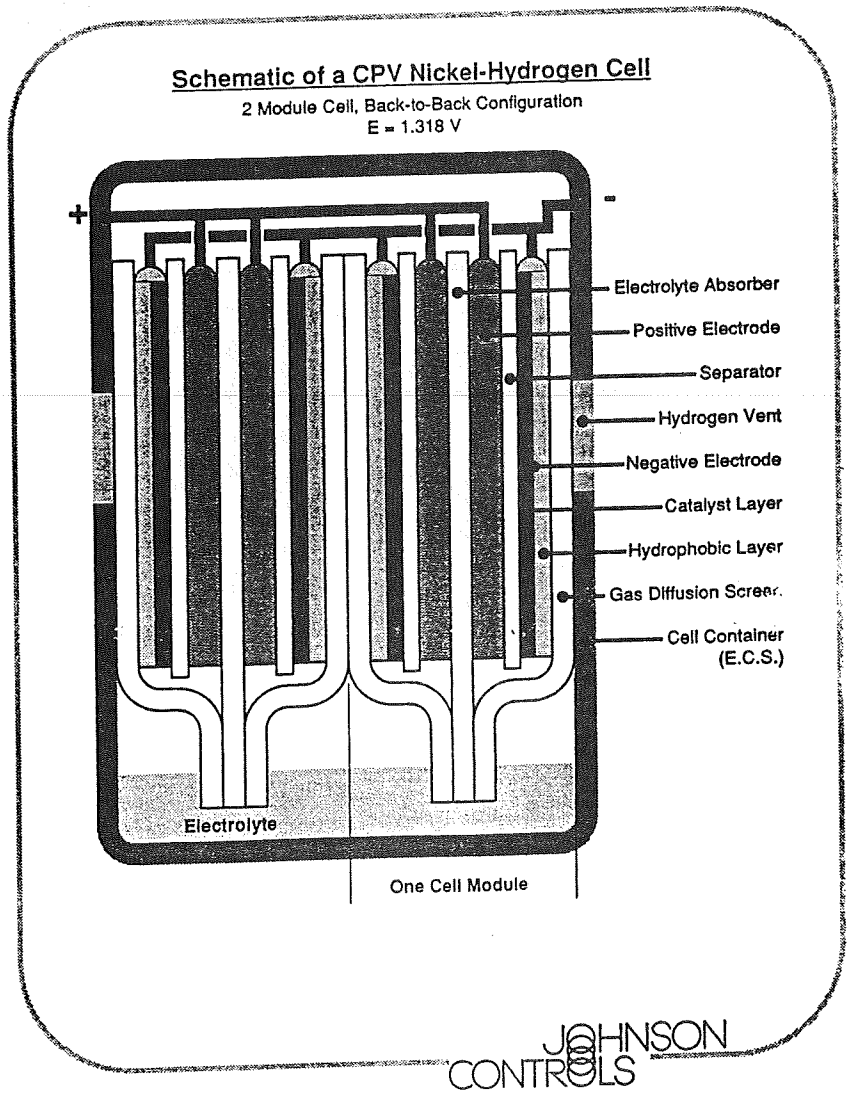
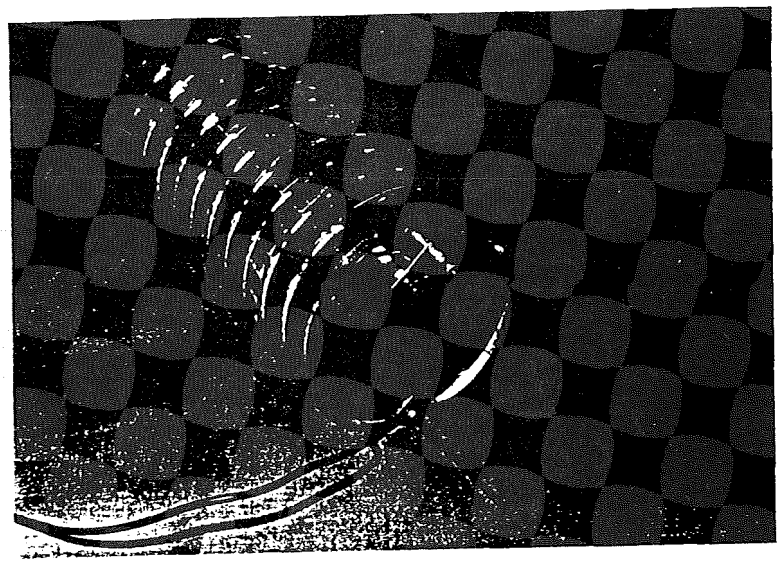


FIGURE 7: 22 CELL CPV LEO BATTERY STACK



1991 NASA Aerospace Battery Workshop

A NICKEL- HYDROGEN COMMON PRESSURE VESSEL SPACEFLIGHT EXPERIMENT

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SPACE SYSTEMS DEVELOPMENT DEPARTMENT
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S.W. WASHINGTON D.C. 20375

INTRODUCTION

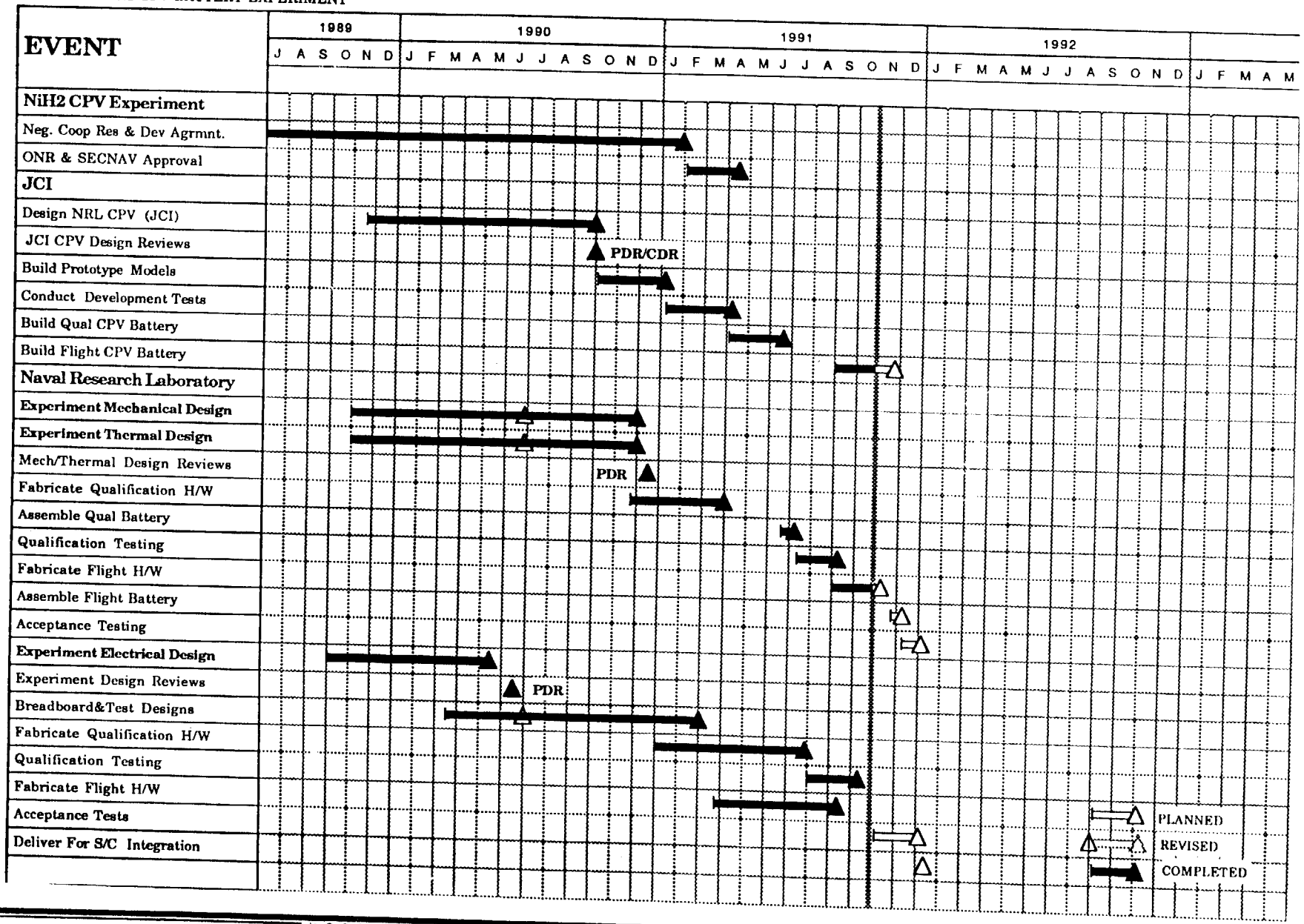
- DATA FROM NRL'S 1977 NTS-2 NiH2 BATTERY ENABLED RISK FREE INTRODUCTION TO COMMERCIAL AND DOD GEO MISSIONS
- GOOD WORKING RELATIONSHIP BETWEEN NRL AND COMSAT
- OCTOBER 1988 COMSAT/JOHNSON CONTROLS APPROACH NRL WITH COMMON PRESSURE VESSEL (CPV) BATTERY DESIGN
- JOHNSON CONTROLS (JCI) AND NRL AGREE TO A SPACEFLIGHT EXPERIMENT OF A JCI NiH2 CPV BATTERY

COOPERATIVE RESEARCH AND DEVELOPMENT AGREEMENT

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

SCHEDULE

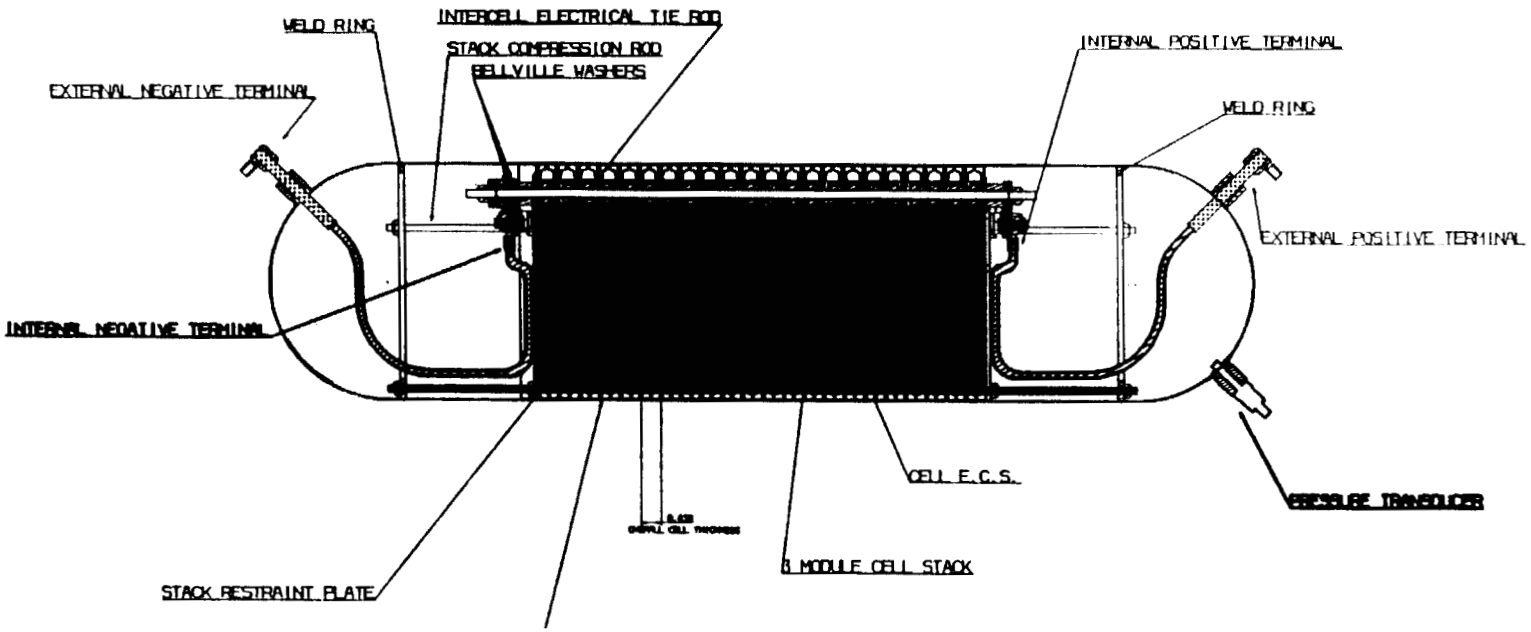
NRL/ JCI NIH2 CPV BATTERY EXPERIMENT



EXPERIMENT DETAILS

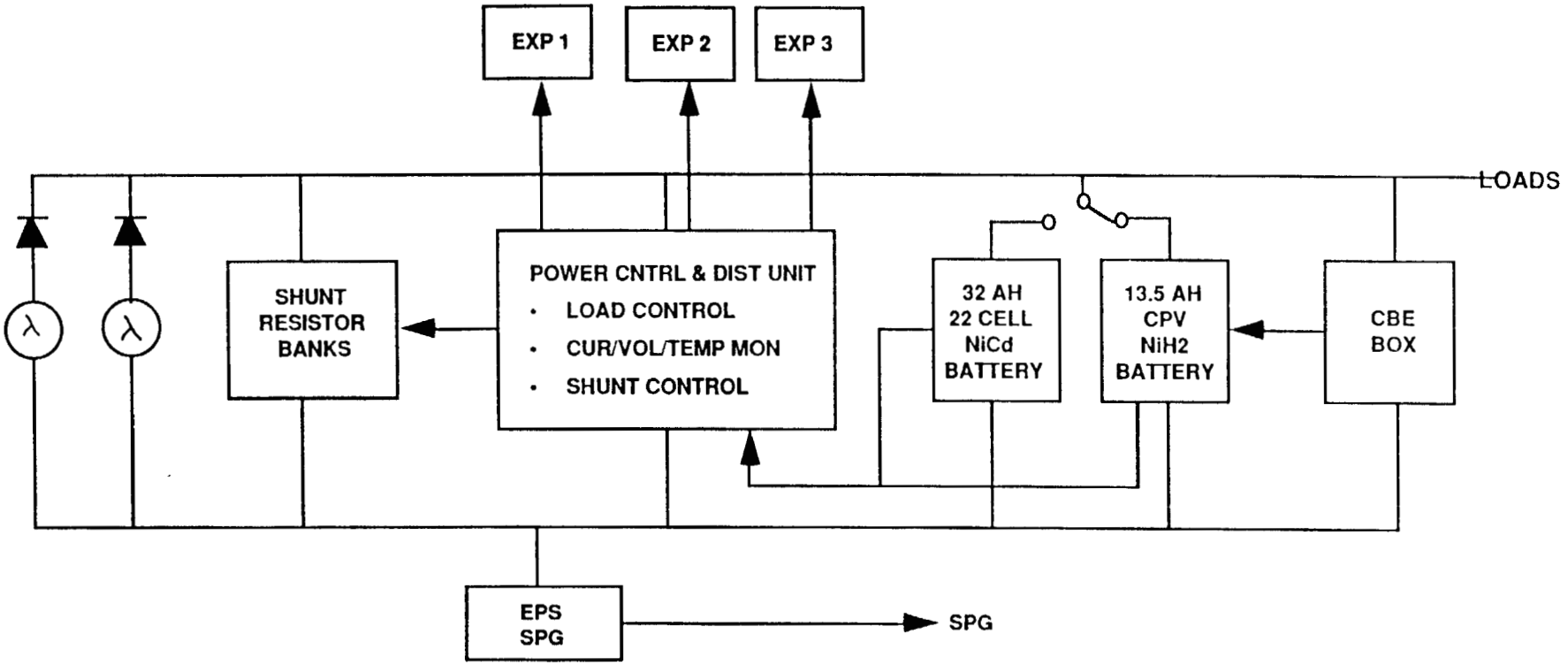
- LAUNCH CY 92
- 240 MINUTE ORBIT
- MAXIMUM ECLIPSE PERIOD 45 MINUTES
- BATTERY SIZED TO SUPPORT A 50% DEPTH OF DISCHARGE
- EXPERIMENT DURATION 3+ YEARS
- DATA WILL INCLUDE:
  - BATTERY VOLTAGE
  - CHARGE/DISCHARGE CURRENT
  - BATTERY TEMPERATURE
  - PRESSURE BY TWO METHODS
  - (PRESSURE TRANSDUCER &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

JOHNSON CONTROLS INC 5" DIA NIH2 CPV BATTERY FEATURES

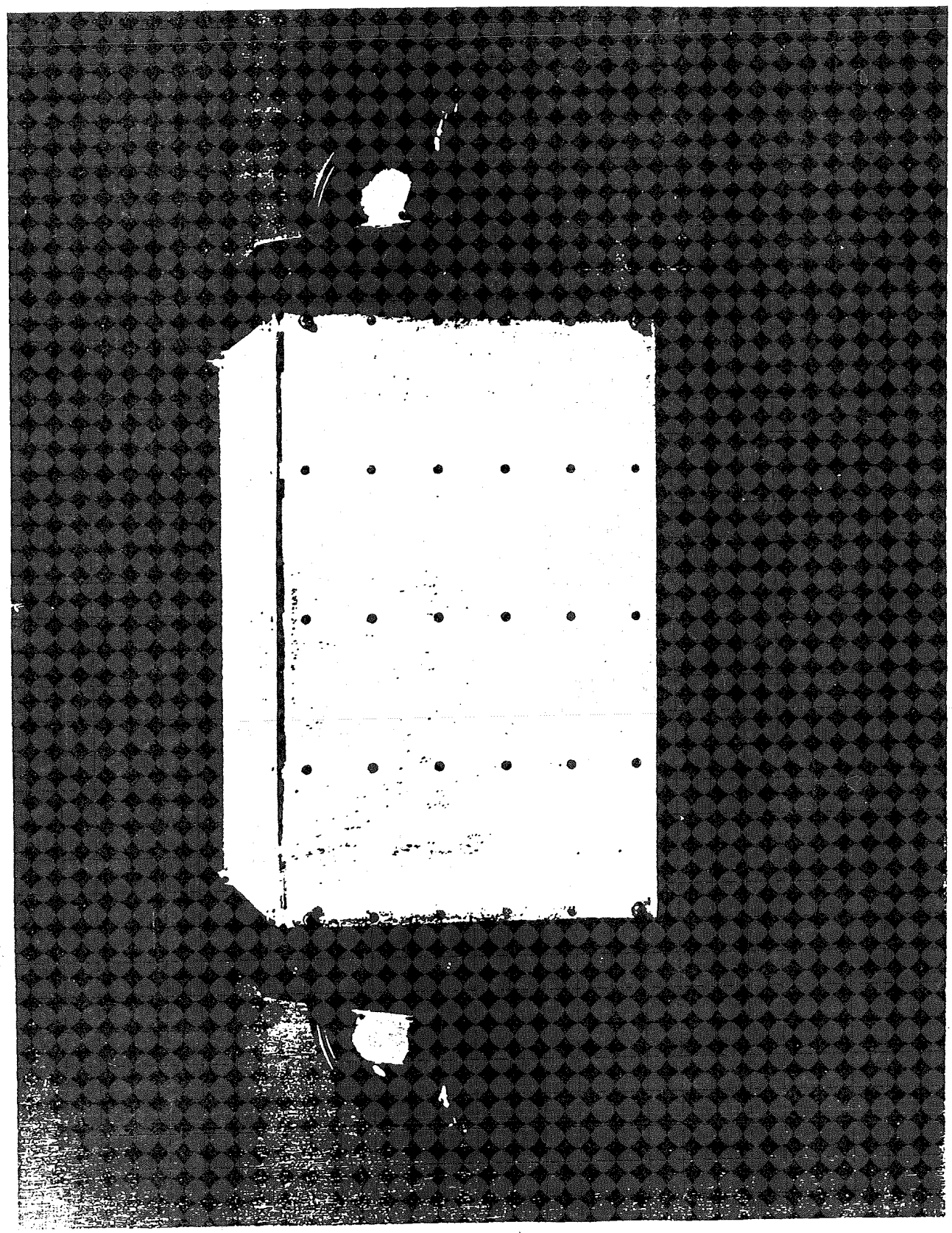


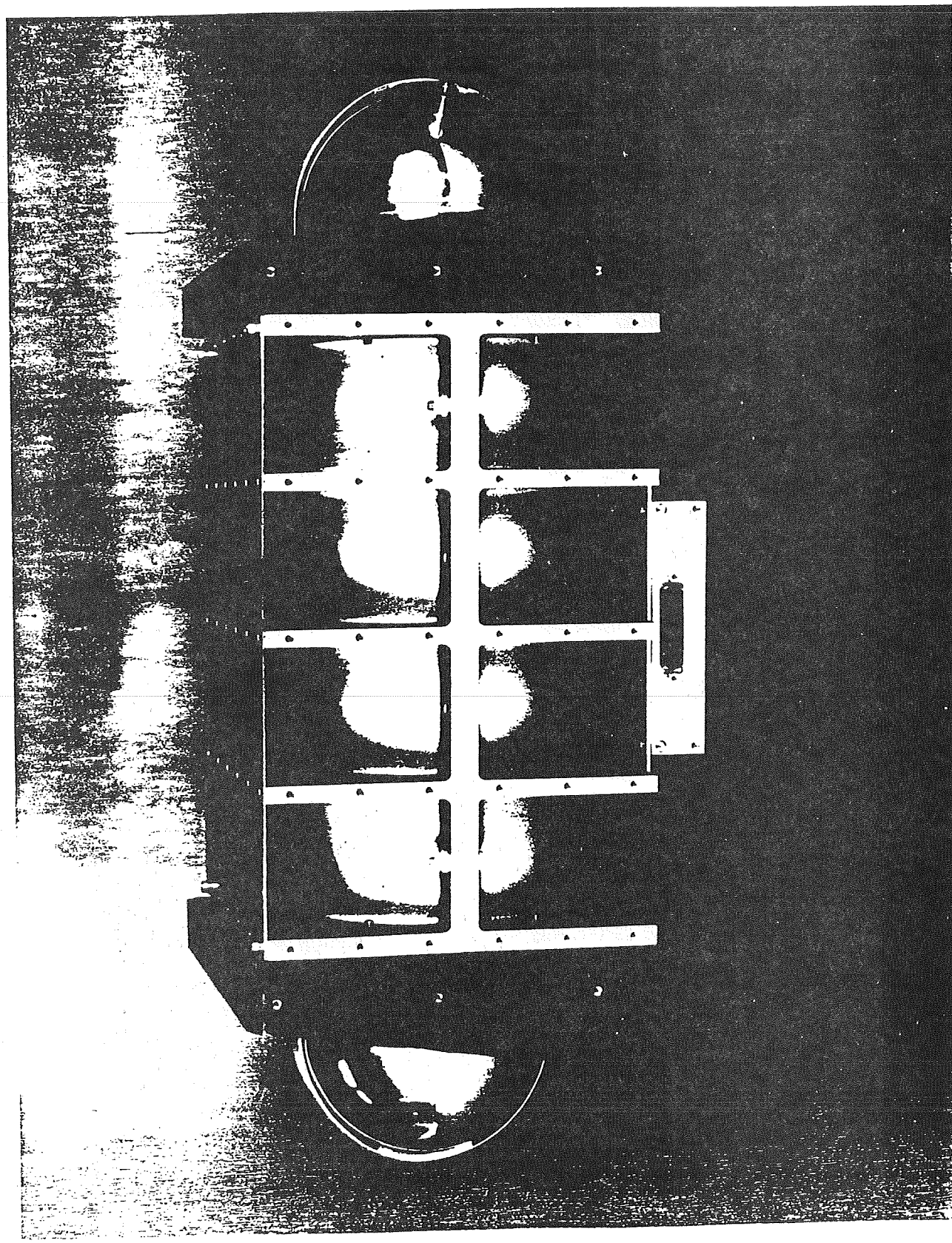
- **NOMINAL CAPACITY:** 10.7 Ah
- **THEORETICAL CAPACITY:** 13. 4 Ah
- **NUMBER OF CELLS:** 22
- **WEIGHT:** 6.80 kg (15.0 lbs)
- **NO. MODULES/CELL** 3
- **PRESSURE VESSEL** INCONEL 718
  LENGTH - 20.7"
  DIAMETER - 5.0"

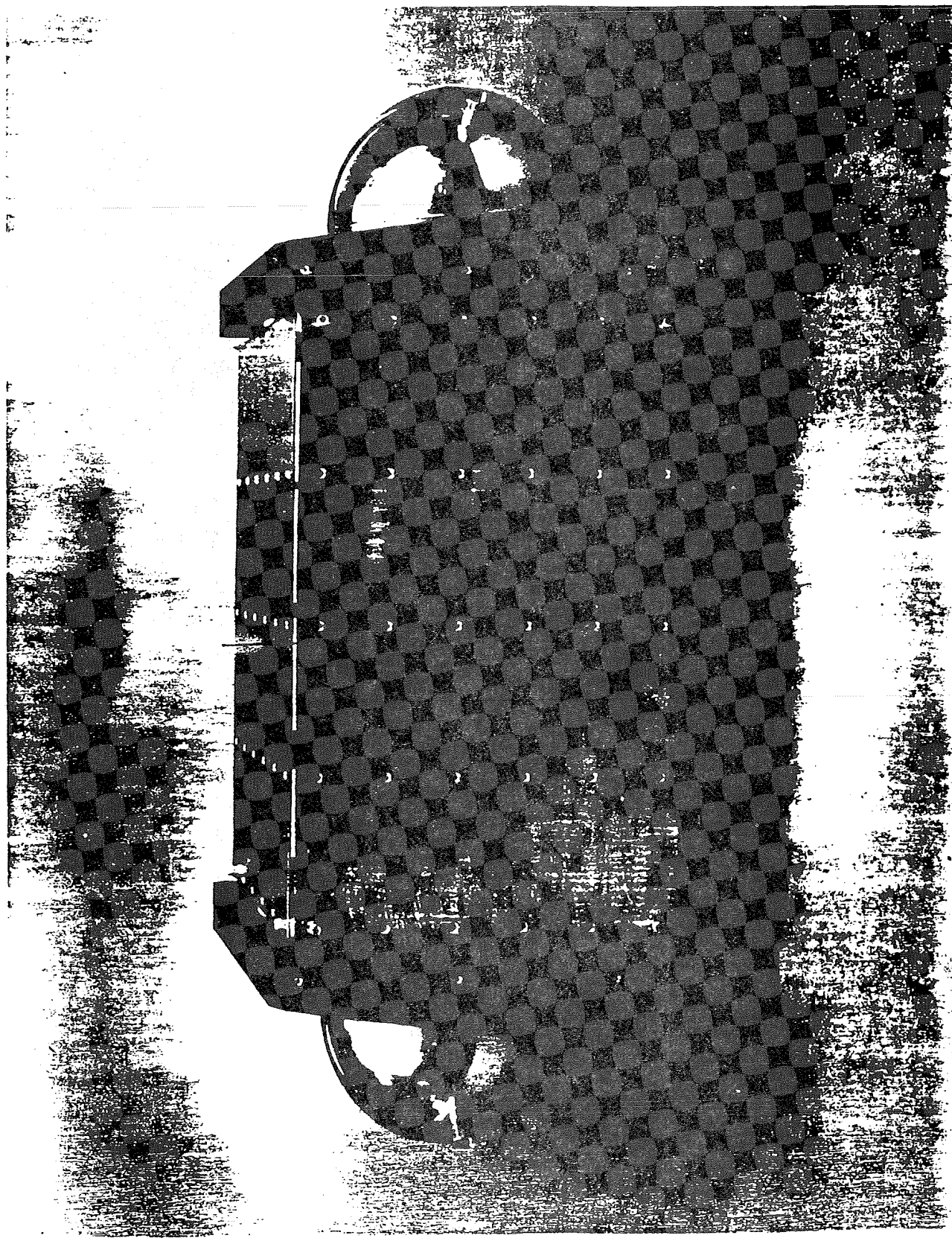
NiH2 CPV BATTERY WITH S/C ELECTRICAL POWER SUBSYSTEM



- 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







EAGLE PICHER
ELECTRONICS DIVISION
Joplin, MO

ADVANCED SYSTEMS OPERATION

CPV Designs Developed and Tested

Technology Update

Nickel-Hydrogen Common Pressure Vessel (CPV) 2.5V Twin Stack Cell Designs

Tim Harvey and Lee Miller
EAGLE-PICHER INDUSTRIES, INC.
Joplin, Missouri

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

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

	Rate C/2	Ah	Energy
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 (2.5 V) vs. IPV: "Same Energy" Analysis (Battery Level)

1. Example: 28 cell/80 Ah (IPV) vs. 28 cell/40 Ah (CPV)
2. Wiring Configuration:

   IPV = **One** 28 cell series string = 80 Ah and 2.9 kWh
   CPV = **Two** 14 cell series strings connected in parallel = 80 Ah and 2.9 kWh
3. Assume a two (2) battery spacecraft in which an open string failure occurs:

   IPV = 50% Capacity Loss
   CPV = 25% Capacity Loss

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

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

	Mass		Energy Density (gravimetric)
IPV	66.3	kg (w/diodes) per batt.	43.7 Wh/kg
CPV	60.6	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**

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ELECTRONICS DIVISION
Joplin, MO

ADVANCED SYSTEMS OPERATION

CPV Designs Developed and Tested

CPV Design Comparison

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

CPV Designs Developed and Tested

CPV Design Comparison (cont.)

	RNHC-6-1	RNHC-12-1	RNHC-35-9	RNHC-40-3 (Proto.)
Separator:	Zircar	Asbestos	Zircar	Asbestos
Negative Elect.:	------Platinum/Teflon Catalyst Over Patented Nickel Grid ------ w/Reduced Pt			
Electrolyte Management:	Non-Recirc. No Weld Ring	Non-Recirc.	Recirc.	Non-Recirc.
		------Open Spoke Weld Ring------		
Design MEOP:	500 psig	480 psig	950 psig	950 psig

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ELECTRONICS DIVISION
Joplin, MO

ADVANCED SYSTEMS OPERATION

CPV Designs Developed and Tested

CPV Design Comparison (cont.)

	RNHC-6-1	RNHC-12-1	RNHC-35-9	RNHC-40-3 (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

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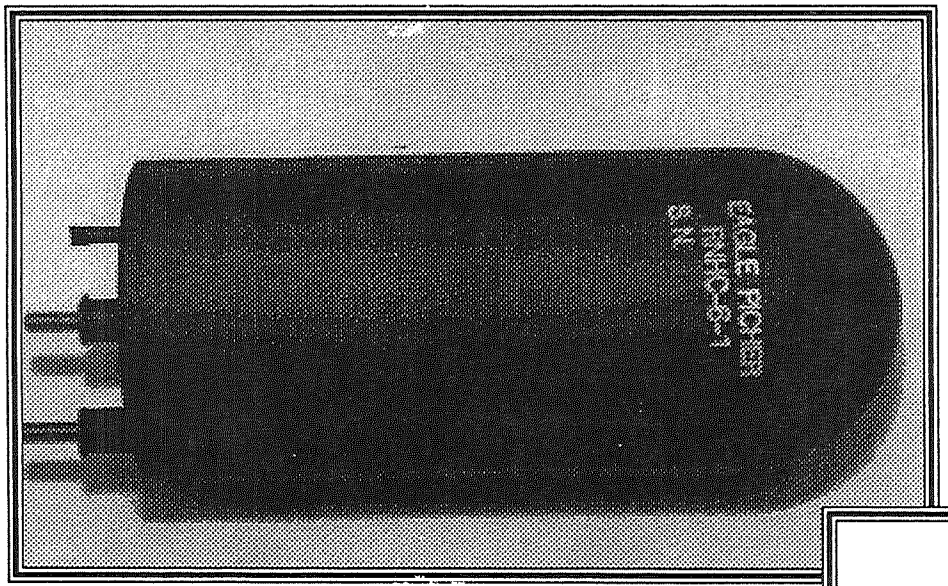
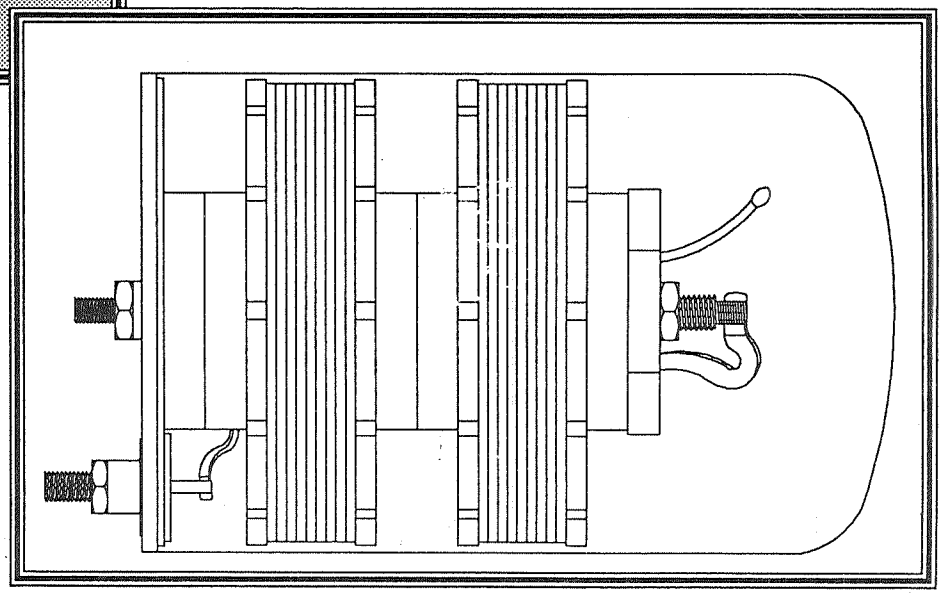
ADVANCED SYSTEMS OPERATION

CPV Designs Developed and Tested



RNHC-6-1
&
RNHC-10-1



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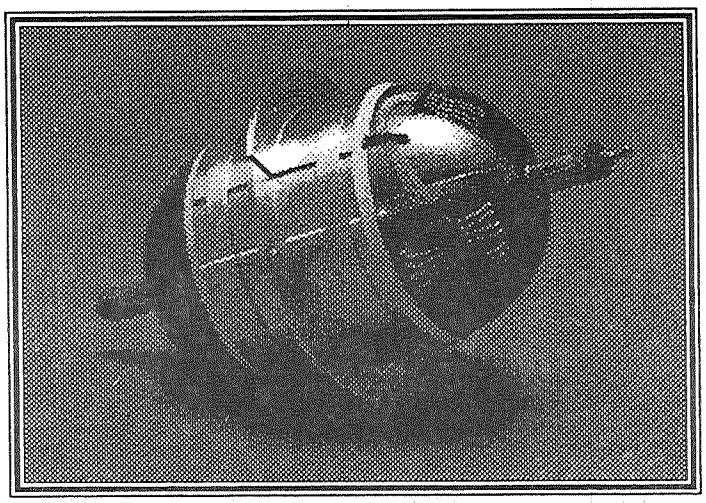
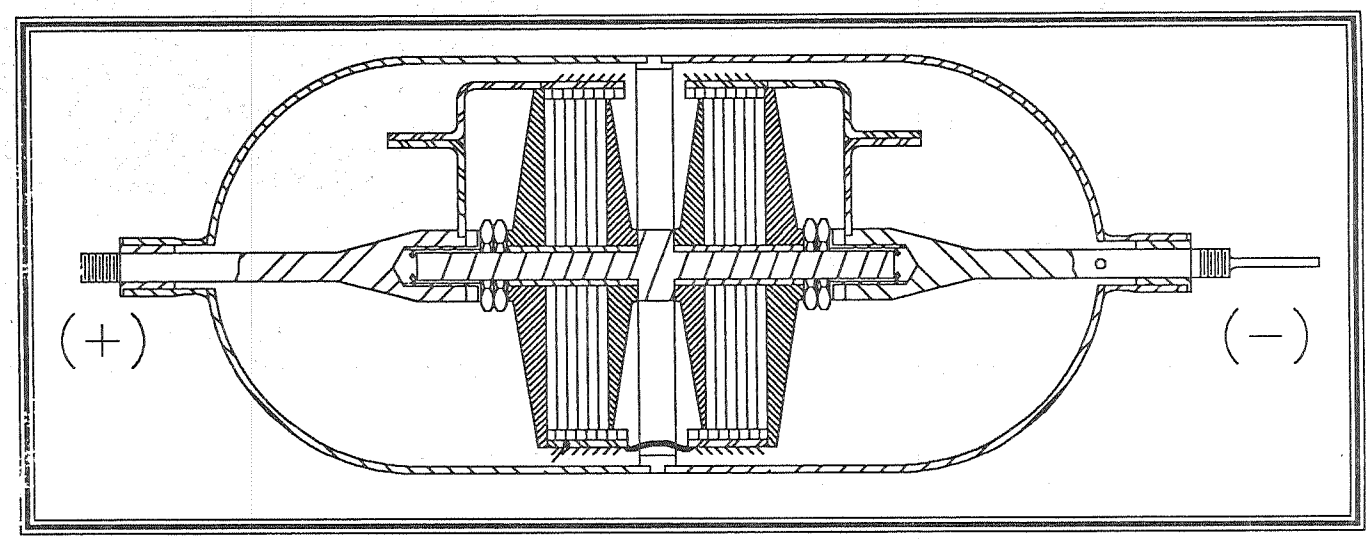
ADVANCED SYSTEMS OPERATION

CPV Designs Developed and Tested



RNHC-12-1



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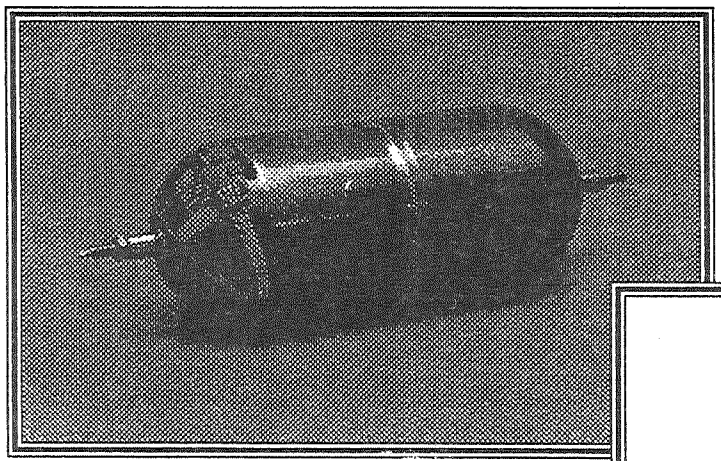
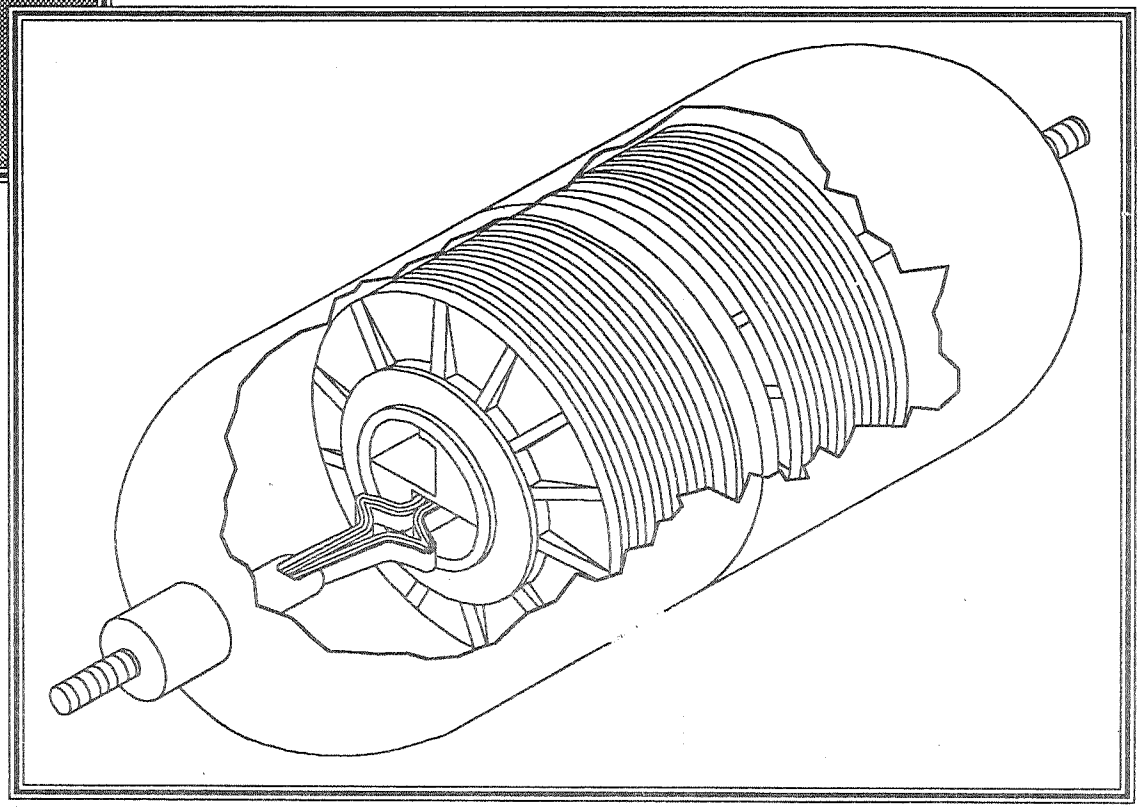
ADVANCED SYSTEMS OPERATION

CPV Designs Developed and Tested





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

*See Design Details

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ADVANCED SYSTEMS OPERATION

CPV Designs Developed and Tested

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

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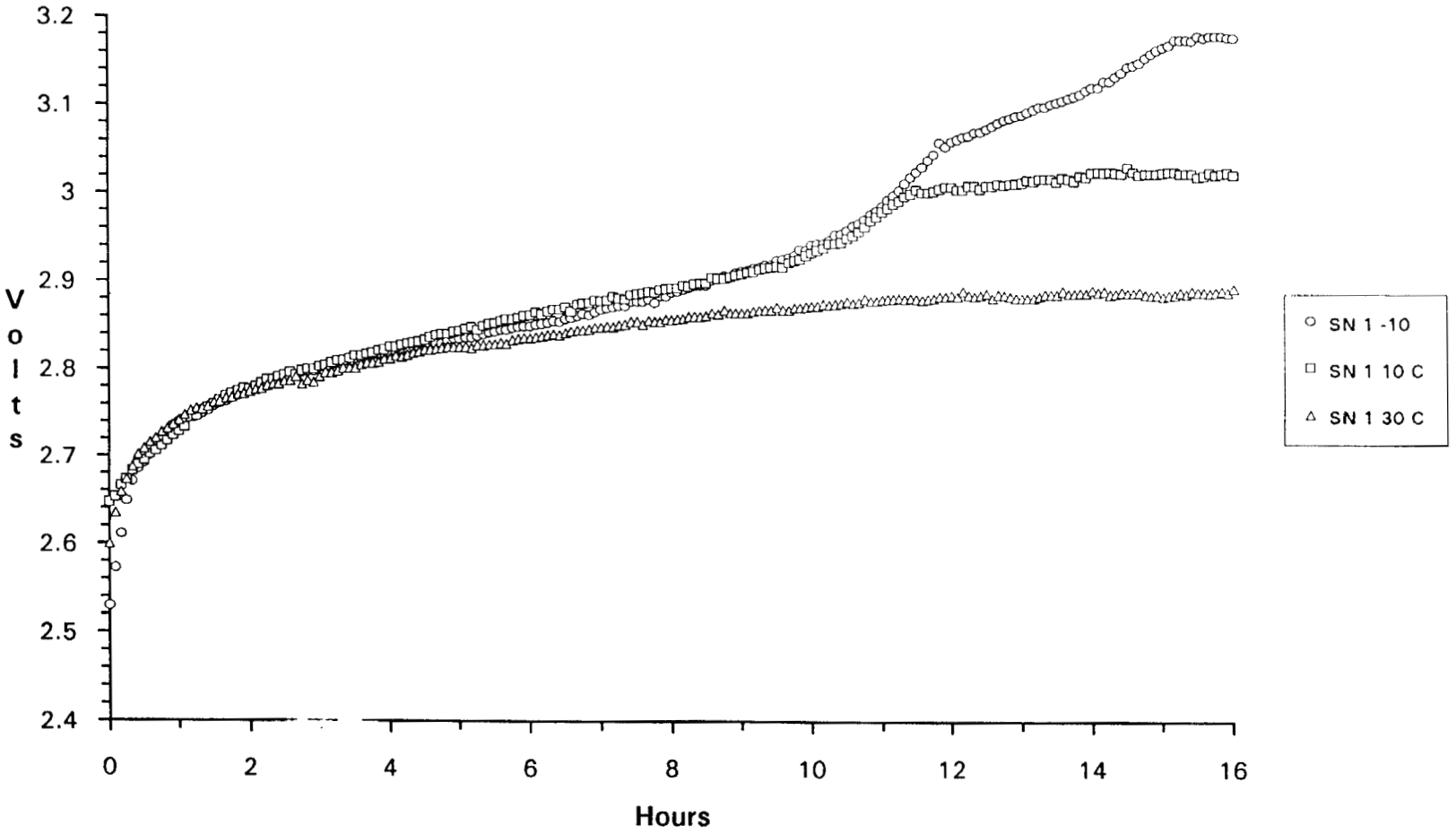
ADVANCED SYSTEMS OPERATION

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



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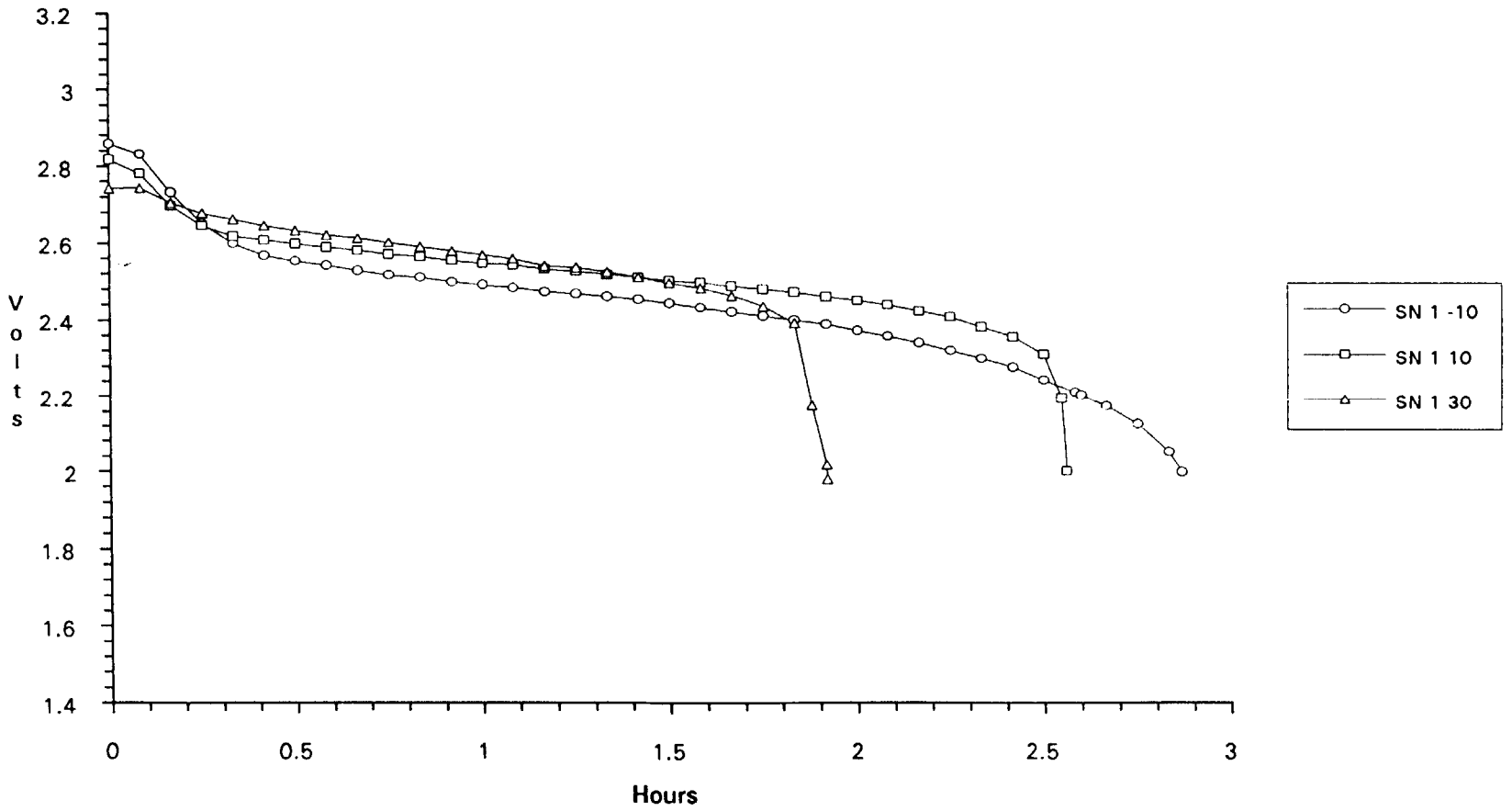
ADVANCED SYSTEMS OPERATION

CPV Designs Developed and Tested

RNHC-6-1 (CPV) Characterization Tests: Comparison of Discharge Voltage: -10°, 10° & 30°C: Discharge 3.0 Amps to 2.0 Volts



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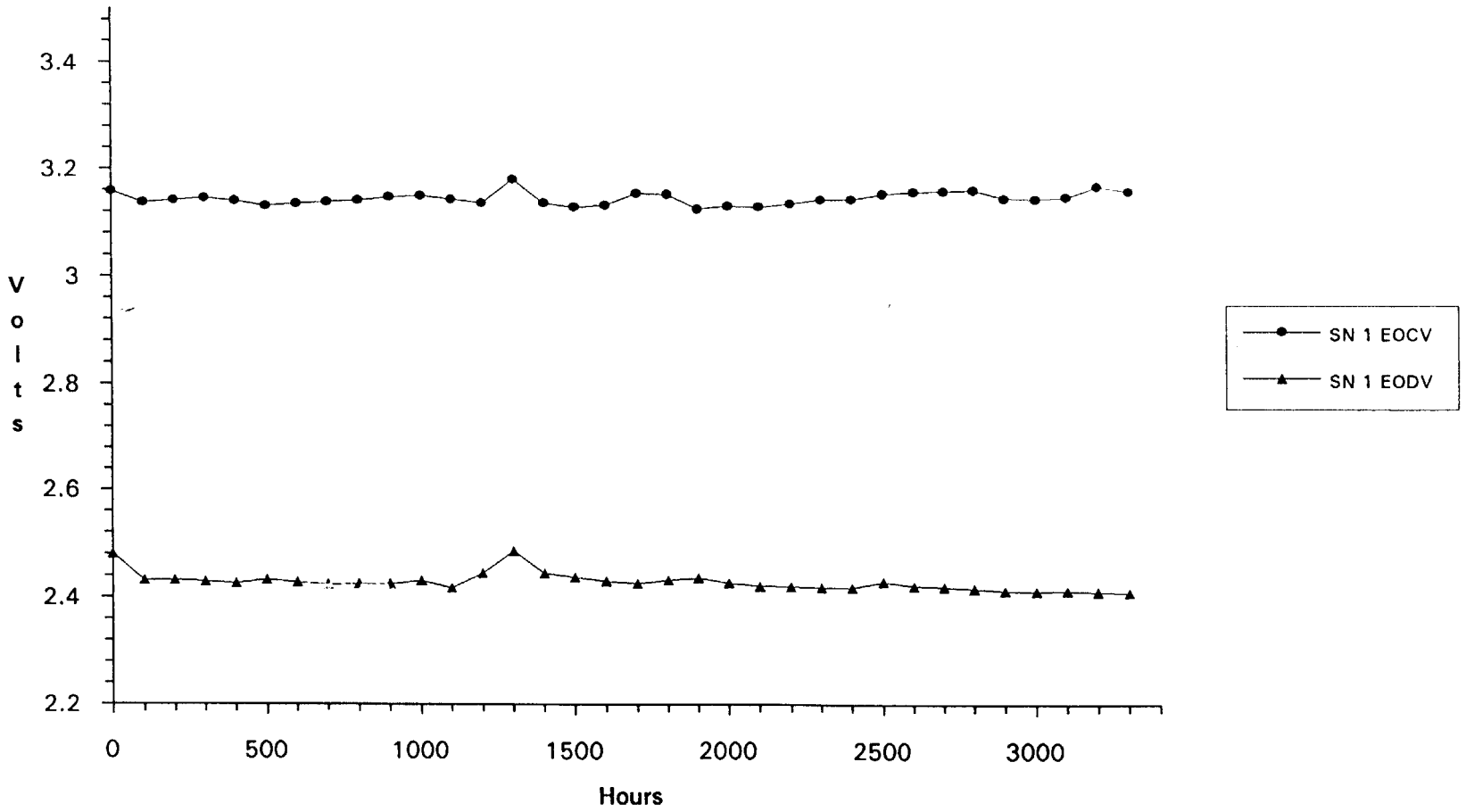
ADVANCED SYSTEMS OPERATION

CPV Designs Developed and Tested

RNHC-10-1 (CPV) Life Test: 10°C: 40% DOD: 3300 Cycles As of 11-1-91



CPV Designs Developed and Tested

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.

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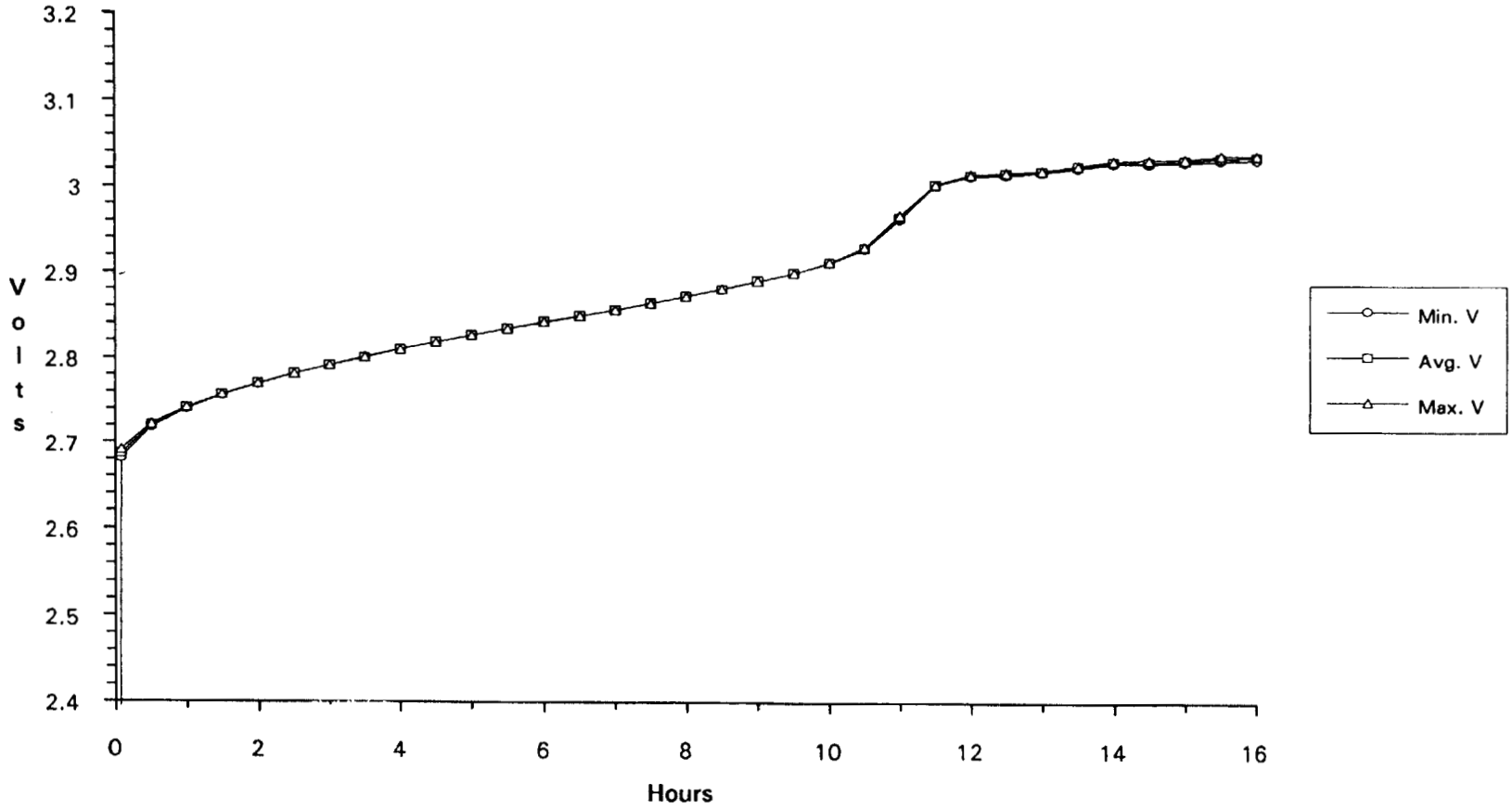
ADVANCED SYSTEMS OPERATION

CPV Designs Developed and Tested

RNH-12-1 (CPV) Characterization Tests: Test Sequence "B": 10°C Charge: 1.2 Amps for 16 Hrs.



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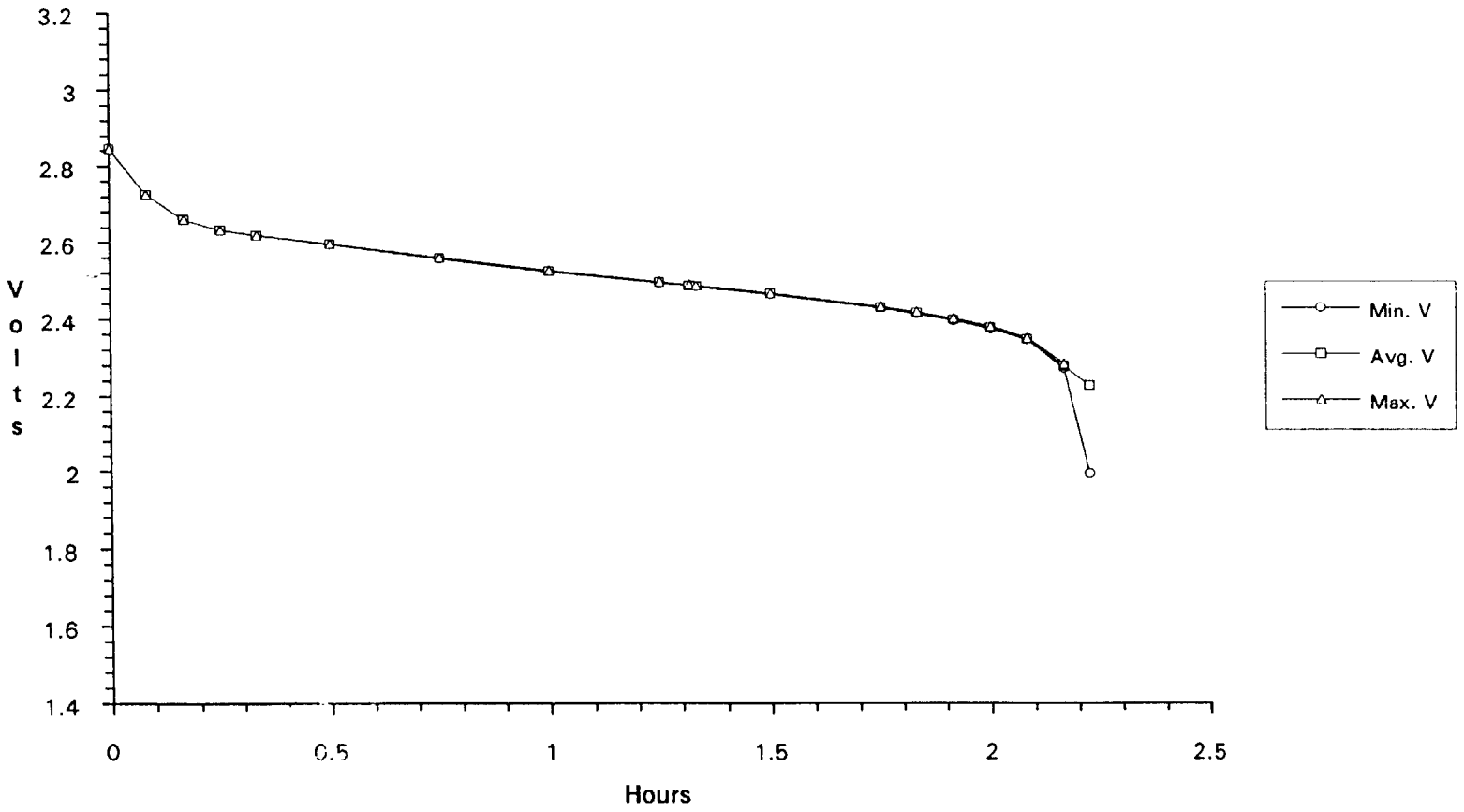
ADVANCED SYSTEMS OPERATION

CPV Designs Developed and Tested

RNH-12-1 (CPV) Characterization Tests: Test Sequence "B": 10°C Disharge: 6.0 Amps to 2.0 Volts



CPV Designs Developed and Tested

RNHC-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

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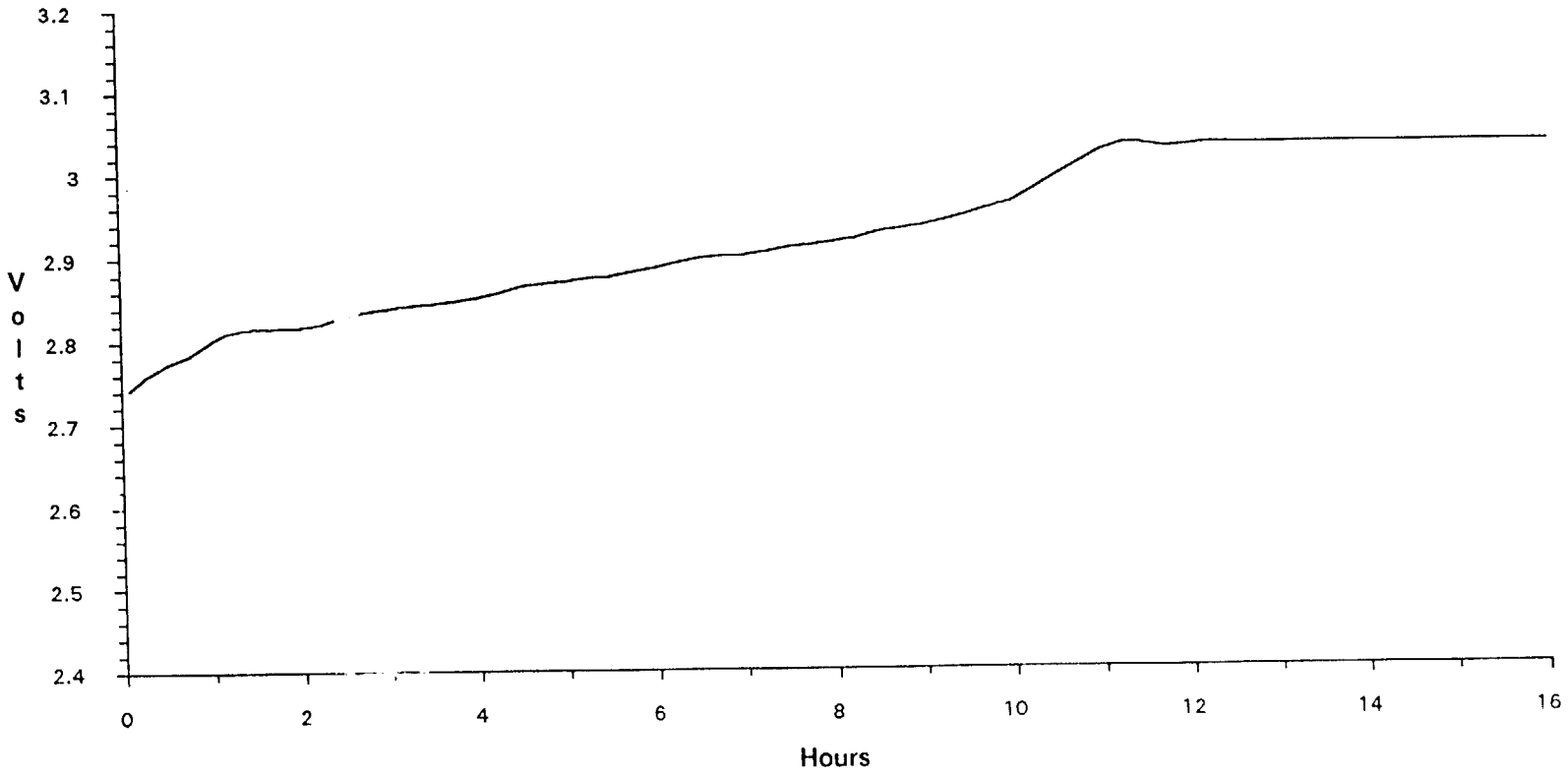
ADVANCED SYSTEMS OPERATION

CPV Designs Developed and Tested

RNHC-35-9 (CPV) Characterization Test: 10°C Charge: 3.5 Amps for 16 Hours



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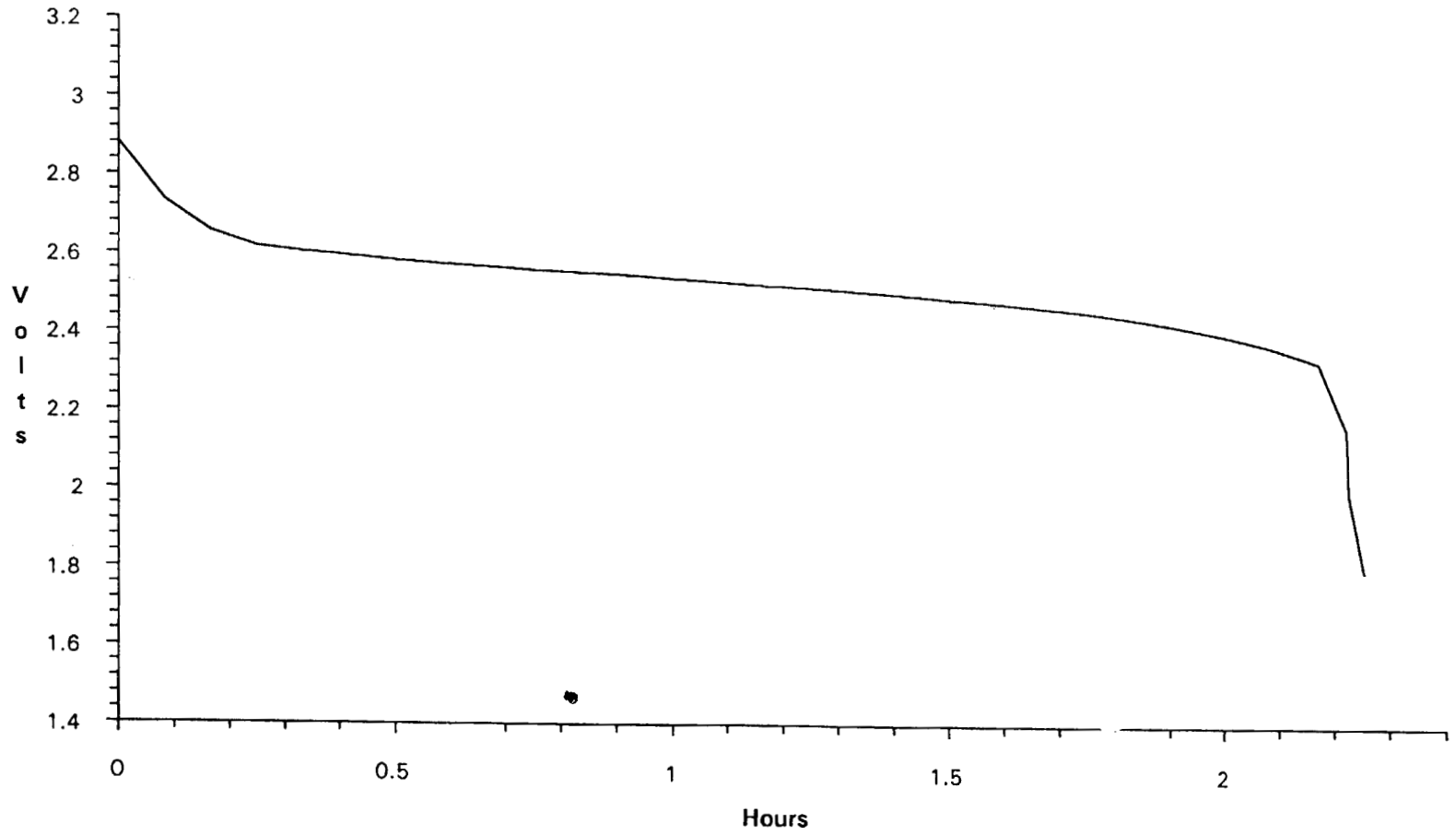
ADVANCED SYSTEMS OPERATION

CPV Designs Developed and Tested

RNHC-35-9 (CPV) Characterization Test: 10°C Discharge: 17.5 Amps to 1.8 Volts



CPV Designs Developed and Tested

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%**

CPV Designs Developed and Tested

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

4. 20°C Std. Cap. Test
   Charge 4.0 Amps for 16 hrs.
   Discharge 20.0 Amps to 2.0 V: ..... **41.7 Ah**

5. 10°C Overcharge Test
   Charge 2.0 Amps for 72 hrs.
   Discharge 20.0 Amps to 2.0 V: ..... **53.8 Ah**

CPV Designs Developed and Tested

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

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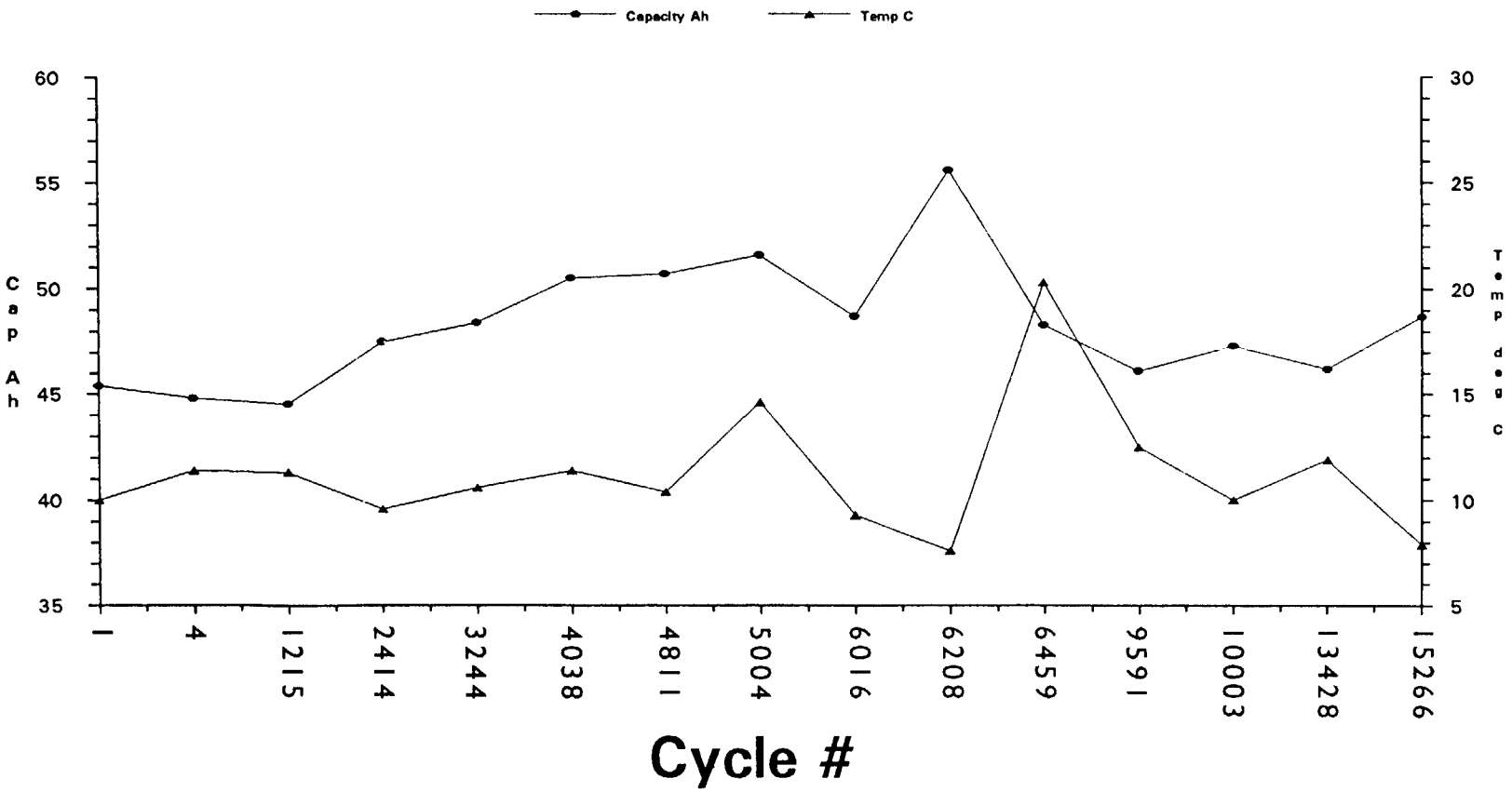
ADVANCED SYSTEMS OPERATION

CPV Designs Developed and Tested

RNHC-40-3 (Proto.) (CPV) Life Test Data: Approx. 10°C Charge 4.0 Amps for 16 Hours: Discharge 20.0 Amps to 2.0 Volts



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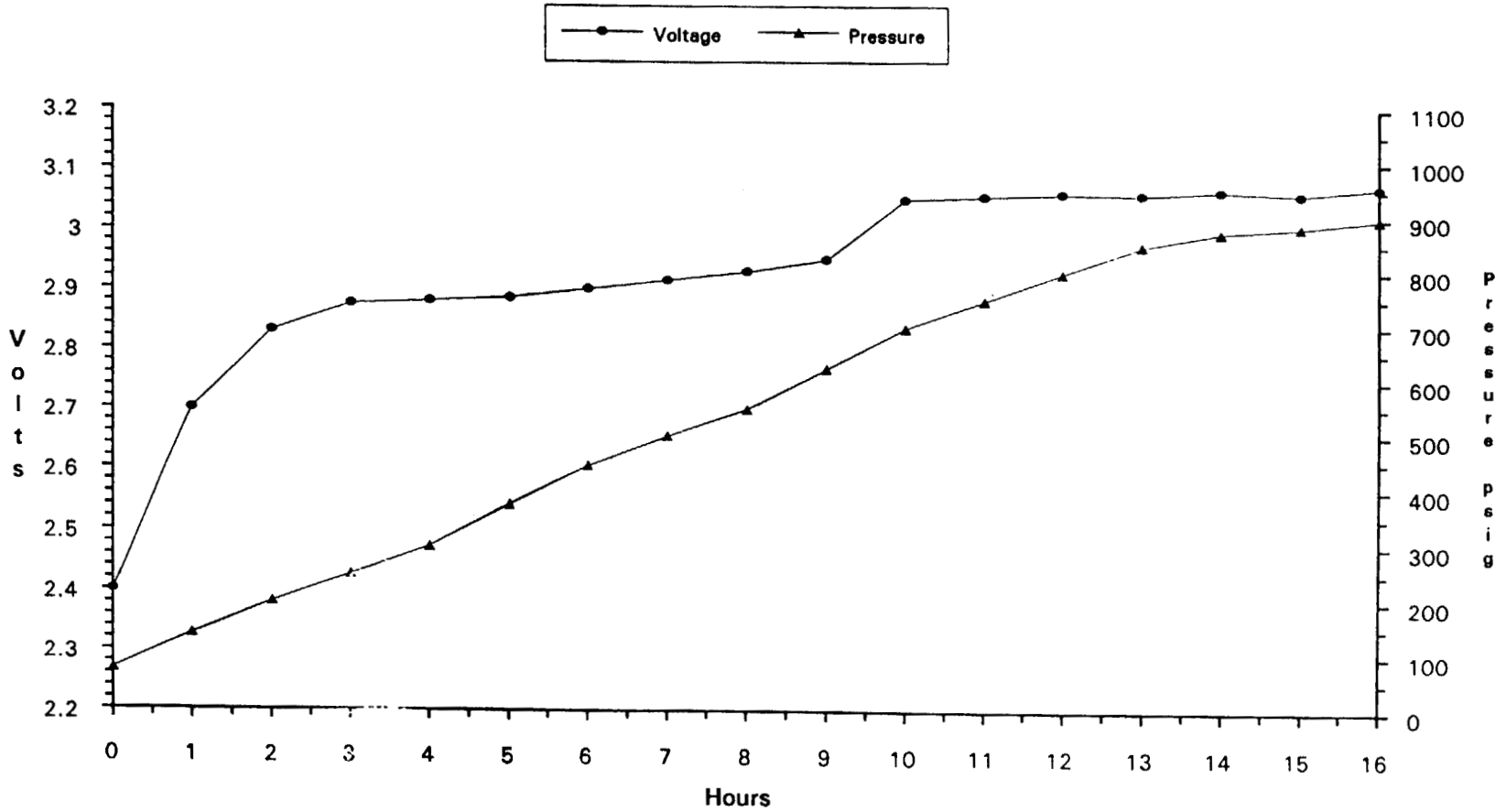
ADVANCED SYSTEMS OPERATION

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



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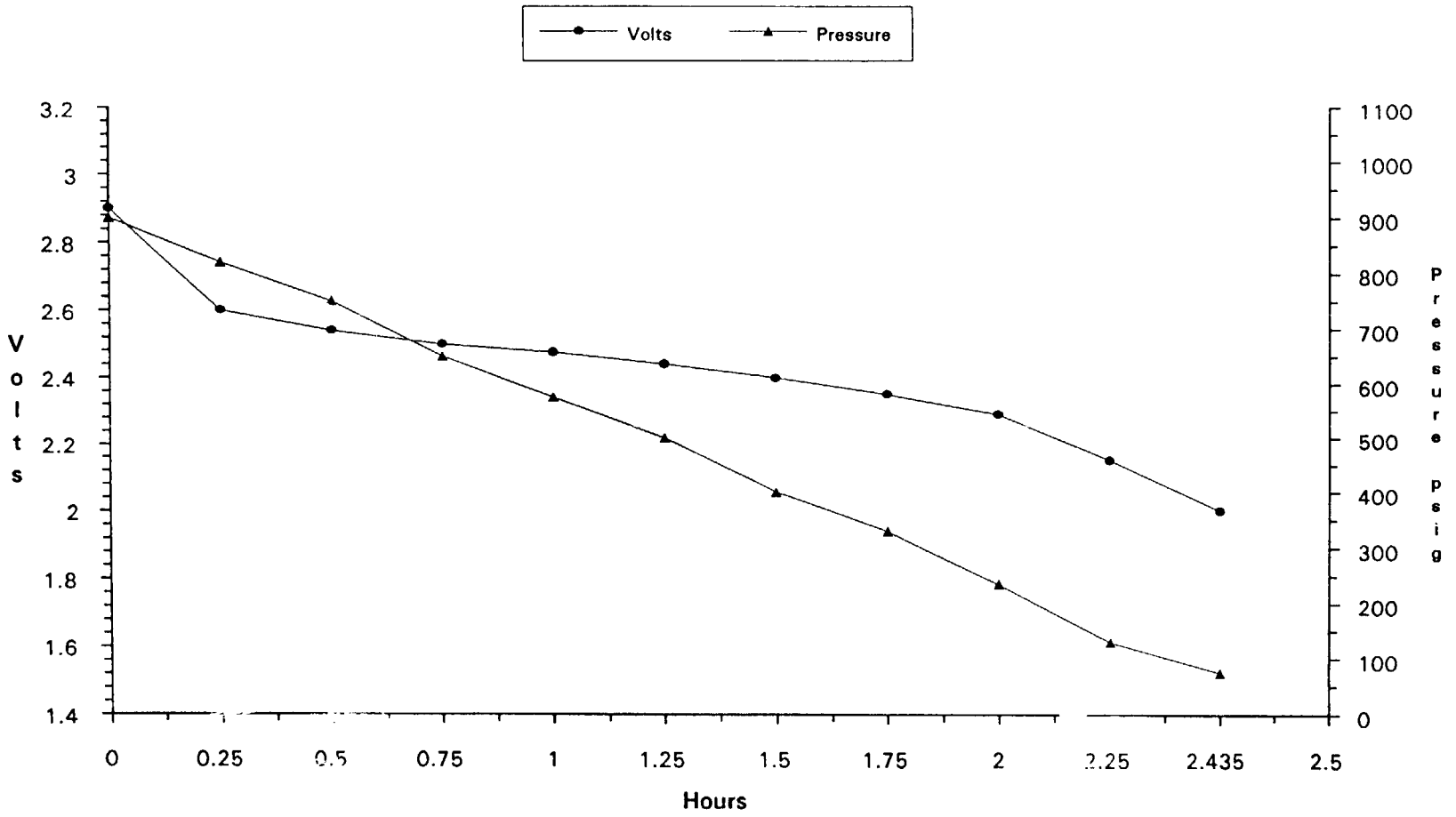
ADVANCED SYSTEMS OPERATION

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_2 CELLS

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

COMSAT LABORATORIES
CLARKSBURG, MD. 20871-9475

Abstract

Heat Generation During Overcharge of Ni/H_2 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_2 cell was measured using a radiative-type calorimeter. A flight configuration-type Ni/H_2 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.

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- EXPERIMENTS USING FLIGHT MODEL NI/H_2 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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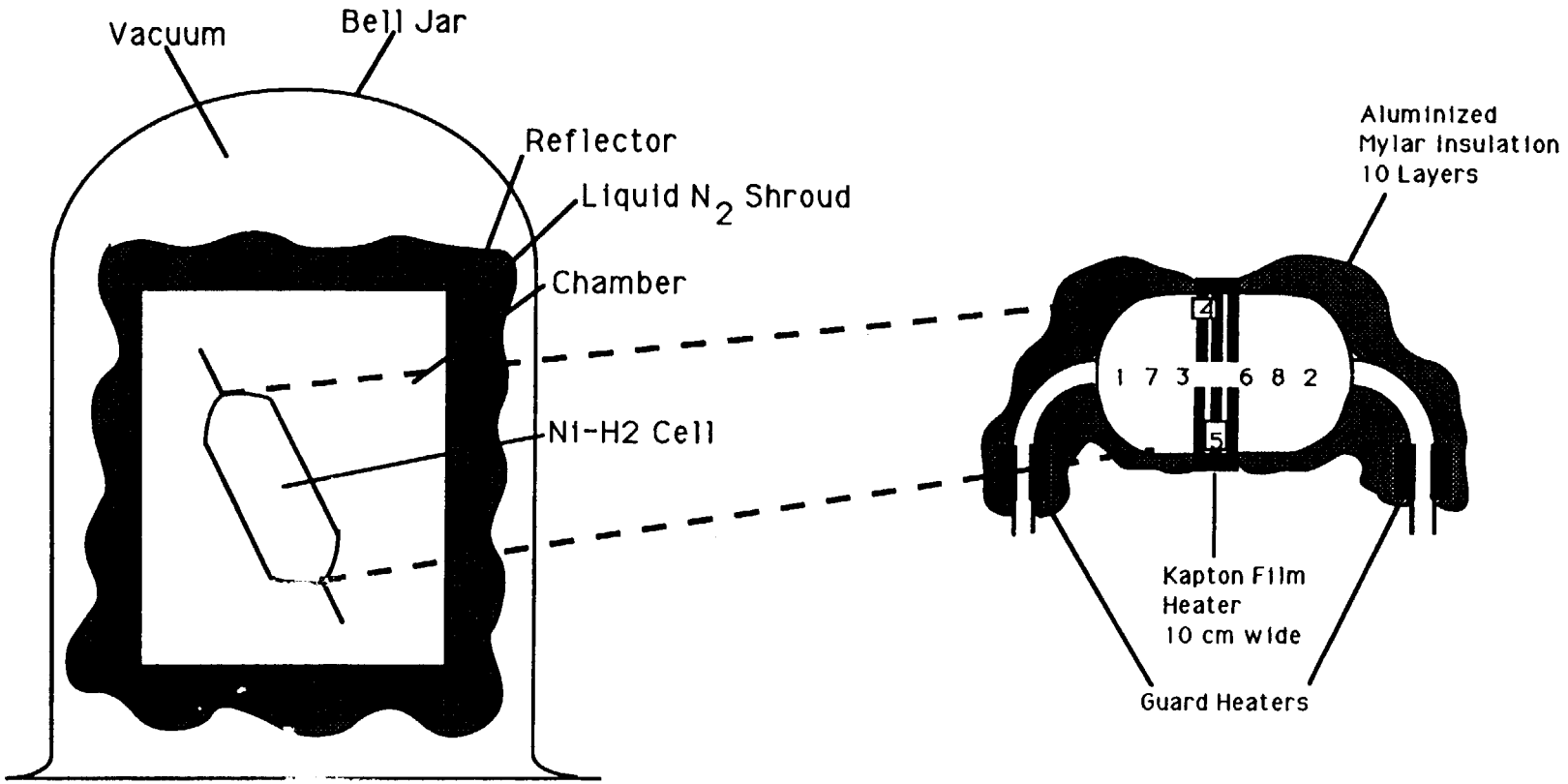
LITERATURE DATA

C. J. JOHNSON ELECTROCHEMICAL SOCIETY, FALL, 1989	NI/H_2 CELL, CONDUCTION TYPE, SILICON OIL BATH, ISOTHERMAL CONDITIONS
H. KAWAMOTO AND ET. AL. JECS 136,1355, 1989	NA/S CELL, FURNACE, HEAT TRANSFER BY CONVECTION AND RADIATION
R. COHEN AND ET. AL. JECS 137,2649, 1990	Ca/SO CL_2 CELL, CONDUCTION TYPE, WATER BATH. CARBON CLOTH AS CONDUCTOR. FACTOR = 1W/^oC
ERIC DARCY 1990 NASA BATTERY WORKSHOP	Li/BCX AND Li/SO CL_2 CONDUCTION TYPE, DROP CALORIMETRY WATER BATH. Al AS CONDUCTOR

CALORIMETER

- HEAT TRANSFER BY RADIATION
- LIQUID N_2 COOLED CHAMBER OF 0.5 M^3 (TEMP = -184°C)
- CHAMBER ENCLOSED IN A VACUUM JAR (10^{-6} 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

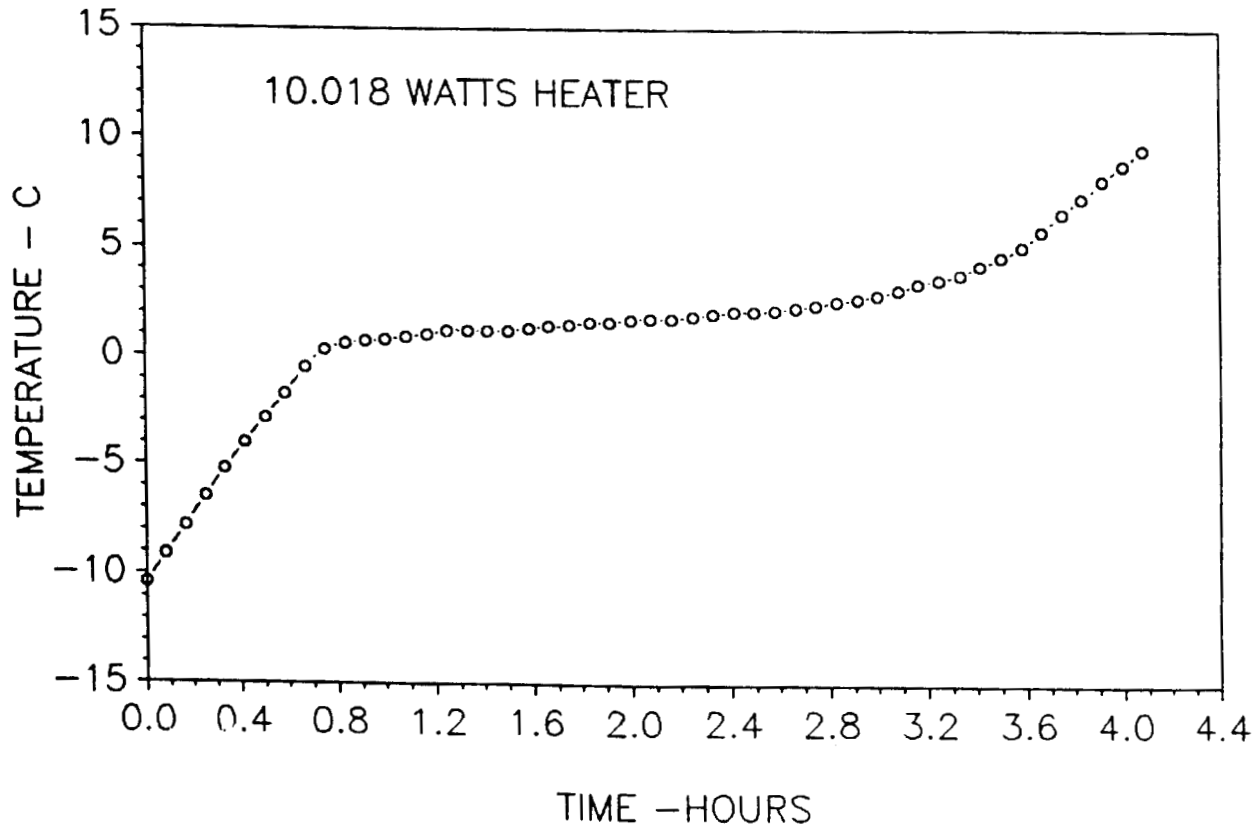
CALORIMETER



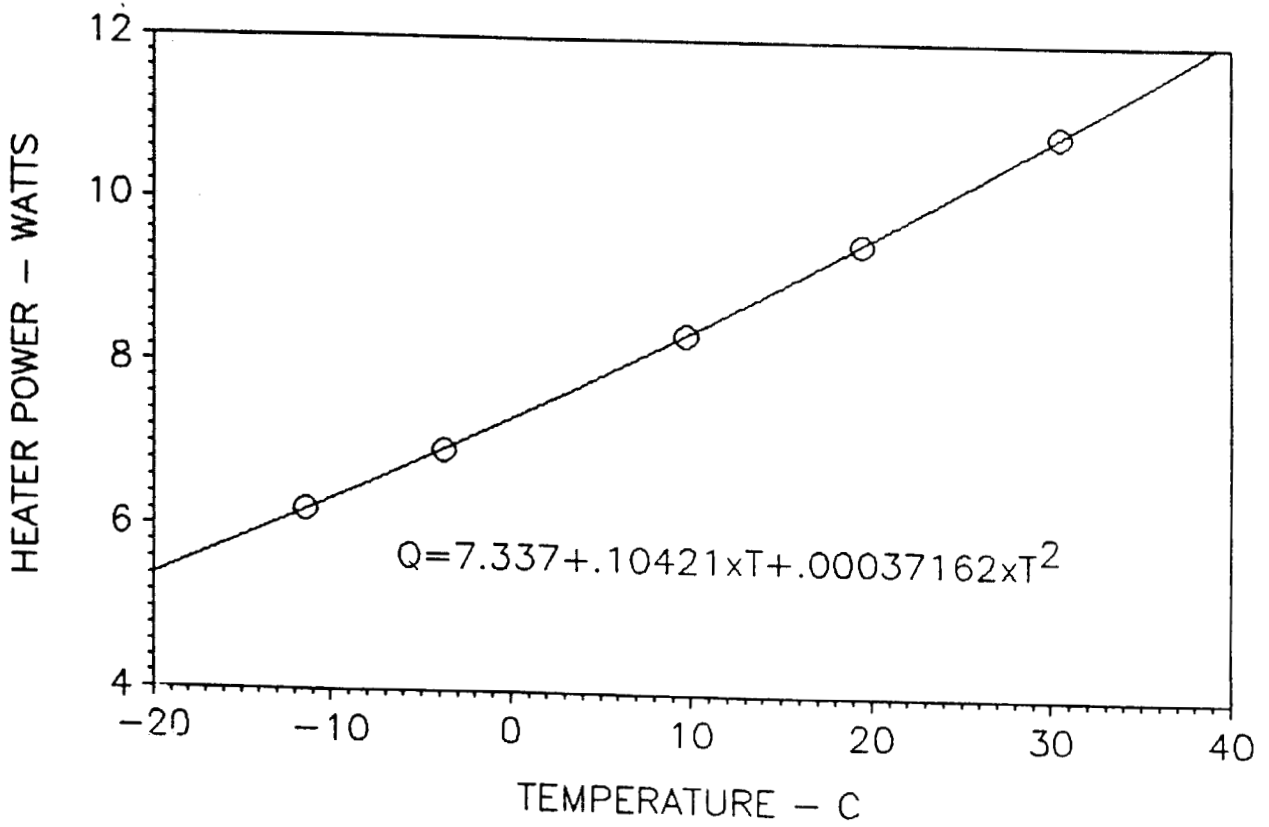
CALIBRATION AND MEASUREMENT

- 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_2O



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



THERMAL ANALYSIS

- HEAT DISSIPATION CALCULATED USING ENTHALPY VOLTAGE

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

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

- FACTOR ANALYSIS TECHNIQUE (STATISTICAL APPROACH)

$$Q = C_1 + C_2 Y_1 + C_3 Y_1^2 \ldots . C_n Y^5 m$$

Y_n = independent variable, C_n = dimensional constant

GOVERNING EQUATIONS

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

cp = thermal capacity of the cell

m = mass of the cell

Q_{in} = cell heater power = current x voltage

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

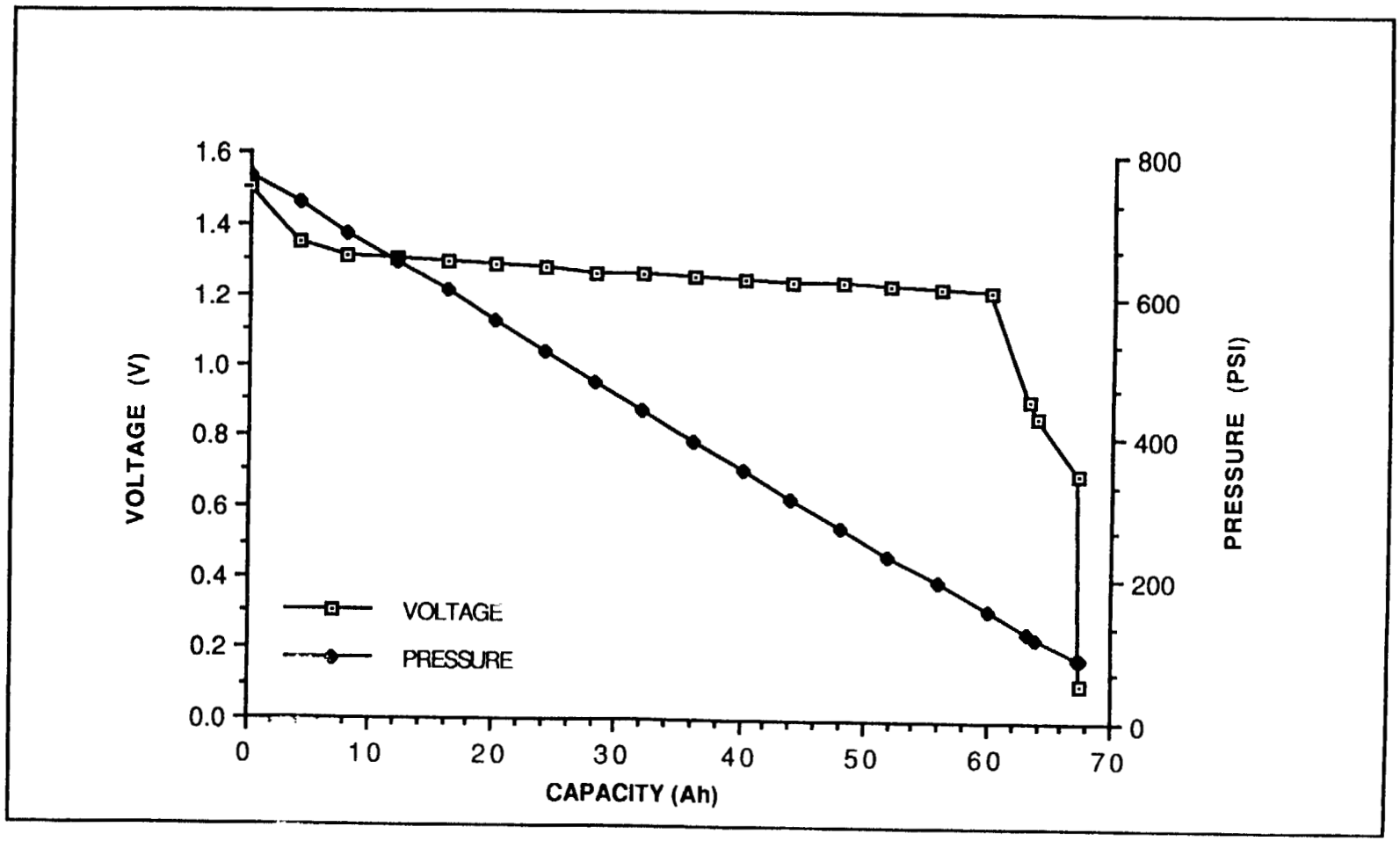
$$= 7.337 + 1.0421T + 0.00037162\ T^2$$

Q_{diss} = heat dissipation

CALCULATION OF THERMAL CAPACITY

MATERIAL	SPECIFIC HEAT J/gM °C	M X Cp JOULE/°C
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
TOTAL		1732.6128

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



TEMPERATURE DISTRIBUTION

STATE OF CHARGE		CELL DOMES 1 °C	CELL DOMES 2 °C	STACK AVERAGE OF 4 °C	ΔT DOME TO STACK °C
4.8A Charge	Mid-Charge	-3.75	-3.78	-2.6	1.165
	EOC	15.5	15.87	17.25	1.74
12A Charge	Mid-Charge	-5.47	-5.57	-4.64	0.88
	EOC	2.89	3.41	4.61	1.48
24A Charge	Mid-Charge	-3.02	-4.19	-3.73	0.13
	EOC	6.66	7.35	10.62	3.62
24A Discharge	Mid-Discharge	-8.98	-7.16	- 7	1.07
	EOD	3.61	5.24	6.81	2.39

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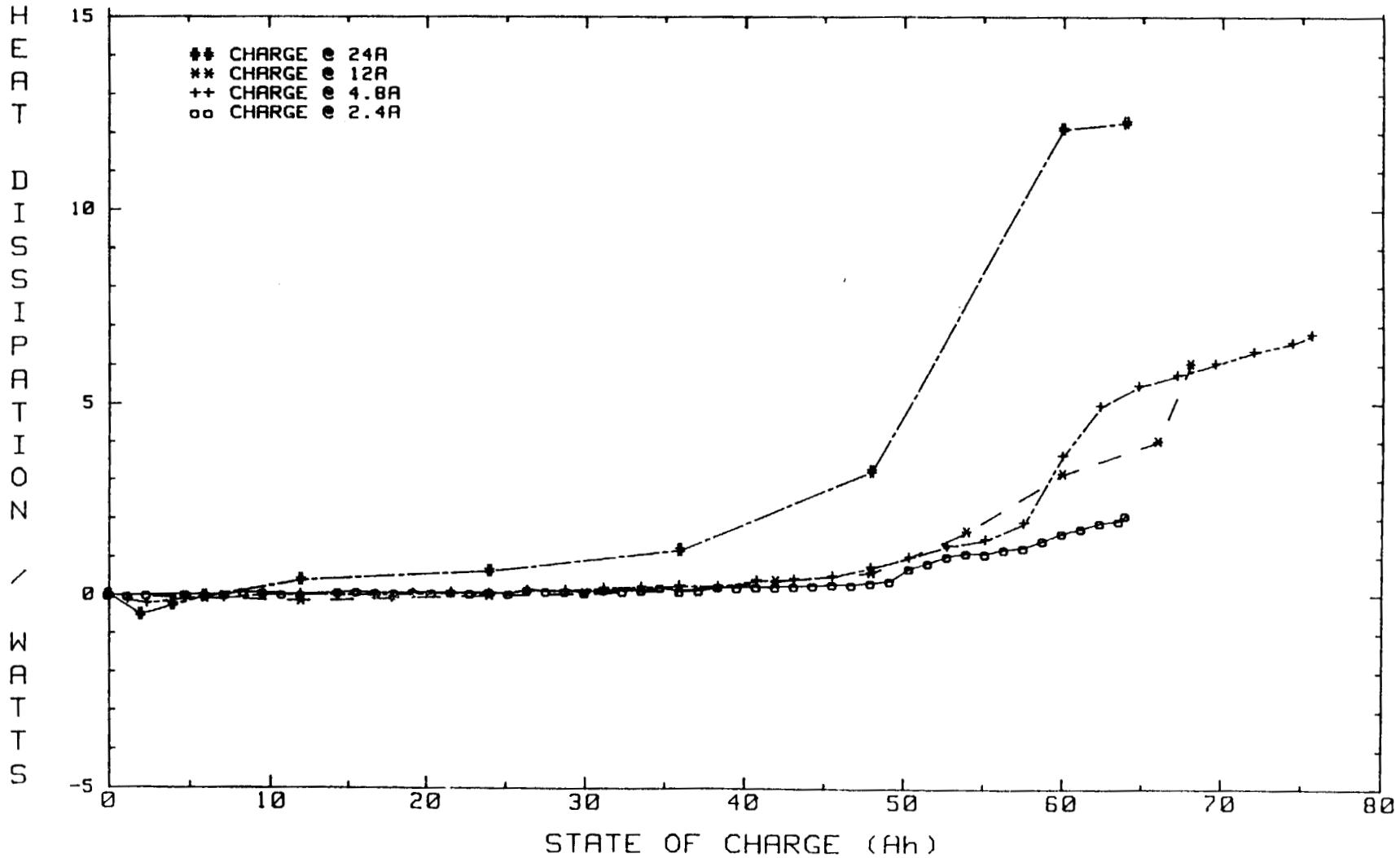
HEAT DISSIPATION AT VARIOUS RATES OF CHARGE



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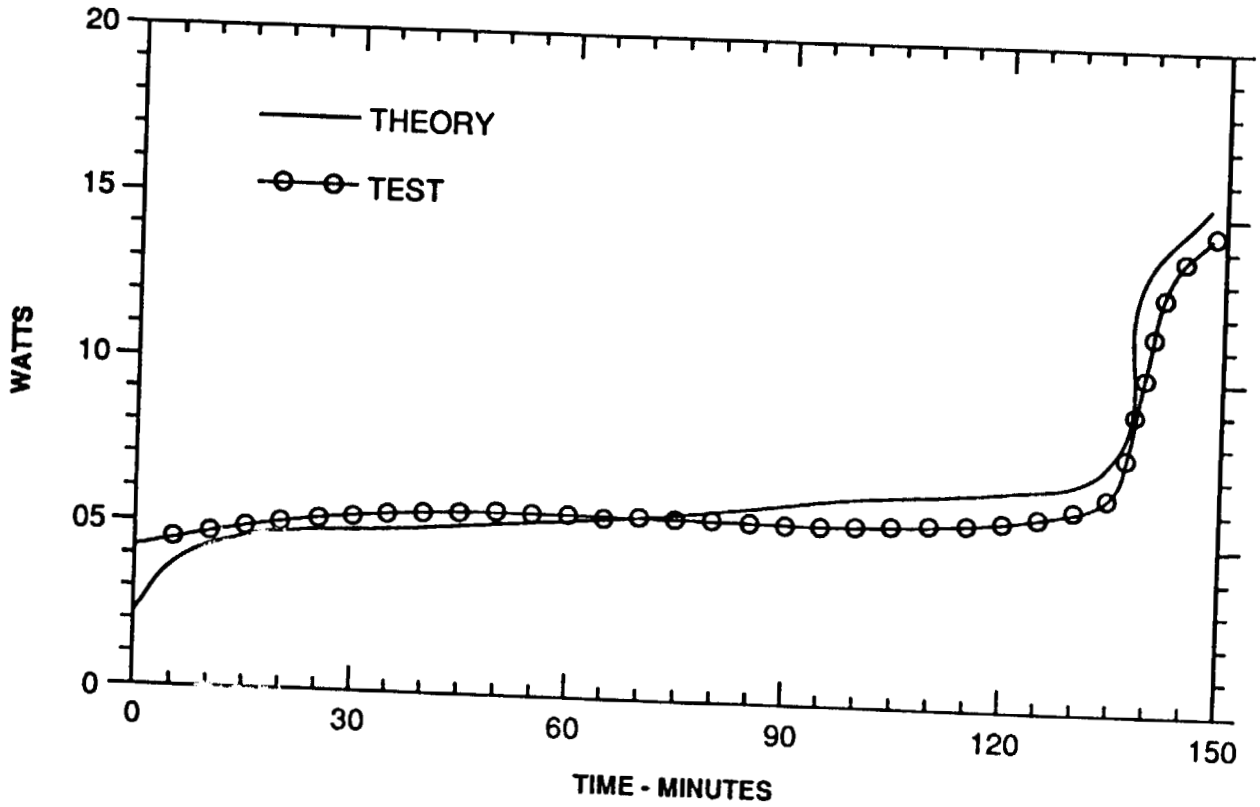
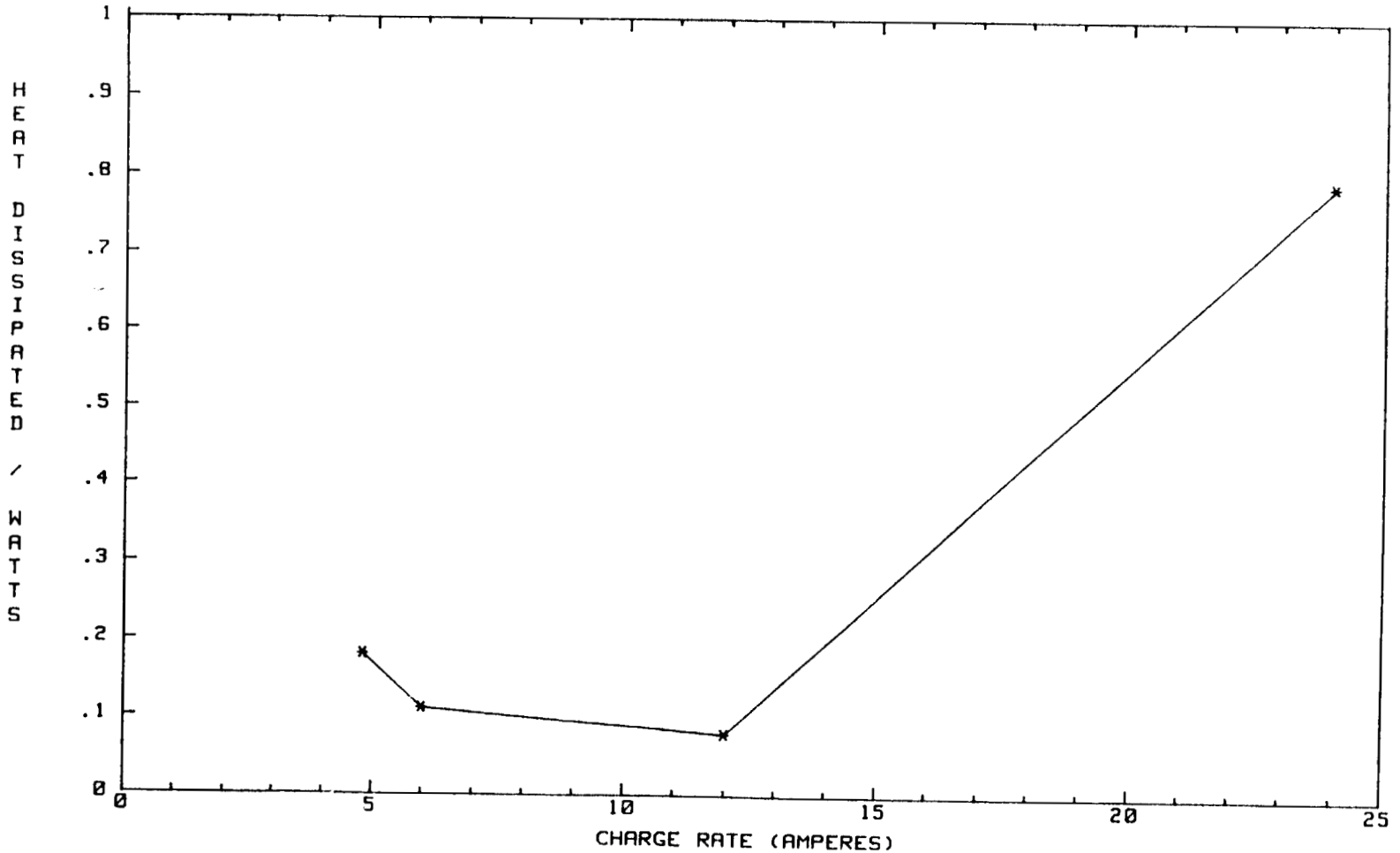
HEAT DISSIPATION DURING DISCHARGE AT C/2



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

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) **ΔH 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) **Δ 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

TEMPERATURE °C	MEASURED HEAT WATTS	CALCULATED HEAT 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

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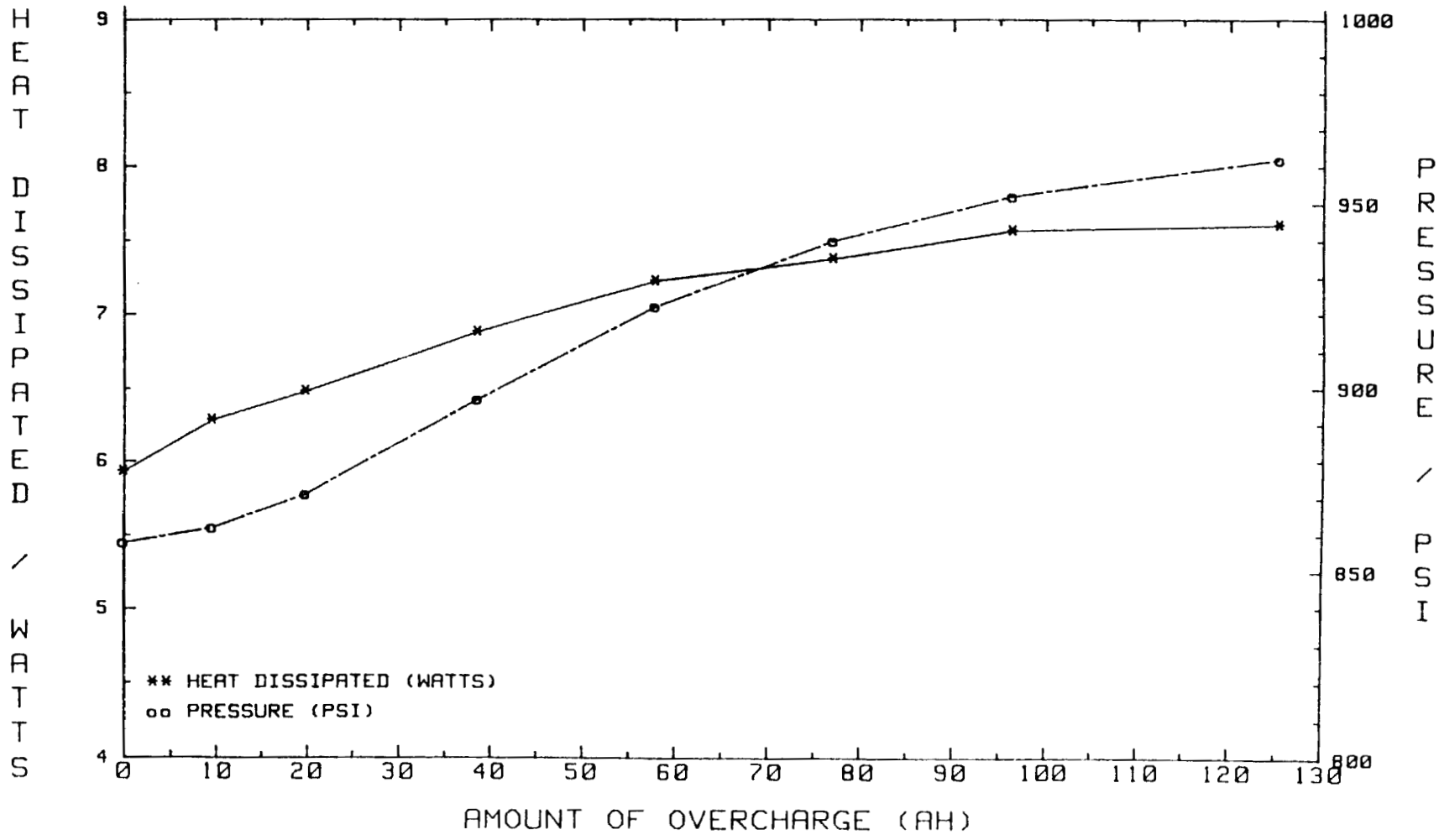
RELATIONSHIP BETWEEN HEAT GENERATION AND PRESSURE INCREASE DURING C/10 OVERCHARGE AT -3 +/- 3° C

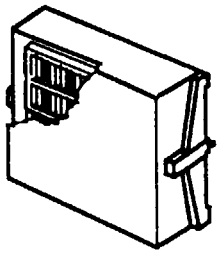


HEAT DISSIPATION DURING OPEN CIRCUIT STAND

CHARGE RATE PROCEEDING THE OPEN CIRCUIT STAND	TEMPERATURE (°C)	CELL PRESSURE (PSI)	HEAT DISSIPATED (WATTS)
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 INACCURATE VALUES FOR E_H AND CHARGE EFFICIENCY



TRANSPORTER
ENERGY STORAGE
SUBSYSTEM

MDESC - L&ES

NICKEL-HYDROGEN BATTERY DESIGN

FOR THE

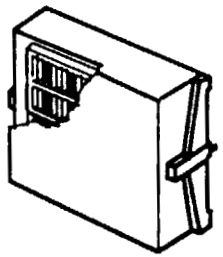
TRANSPORTER ENERGY STORAGE SUBSYSTEM (TESS)

BY

JOHN R. LAPINSKI
MDESC-L&ES

&

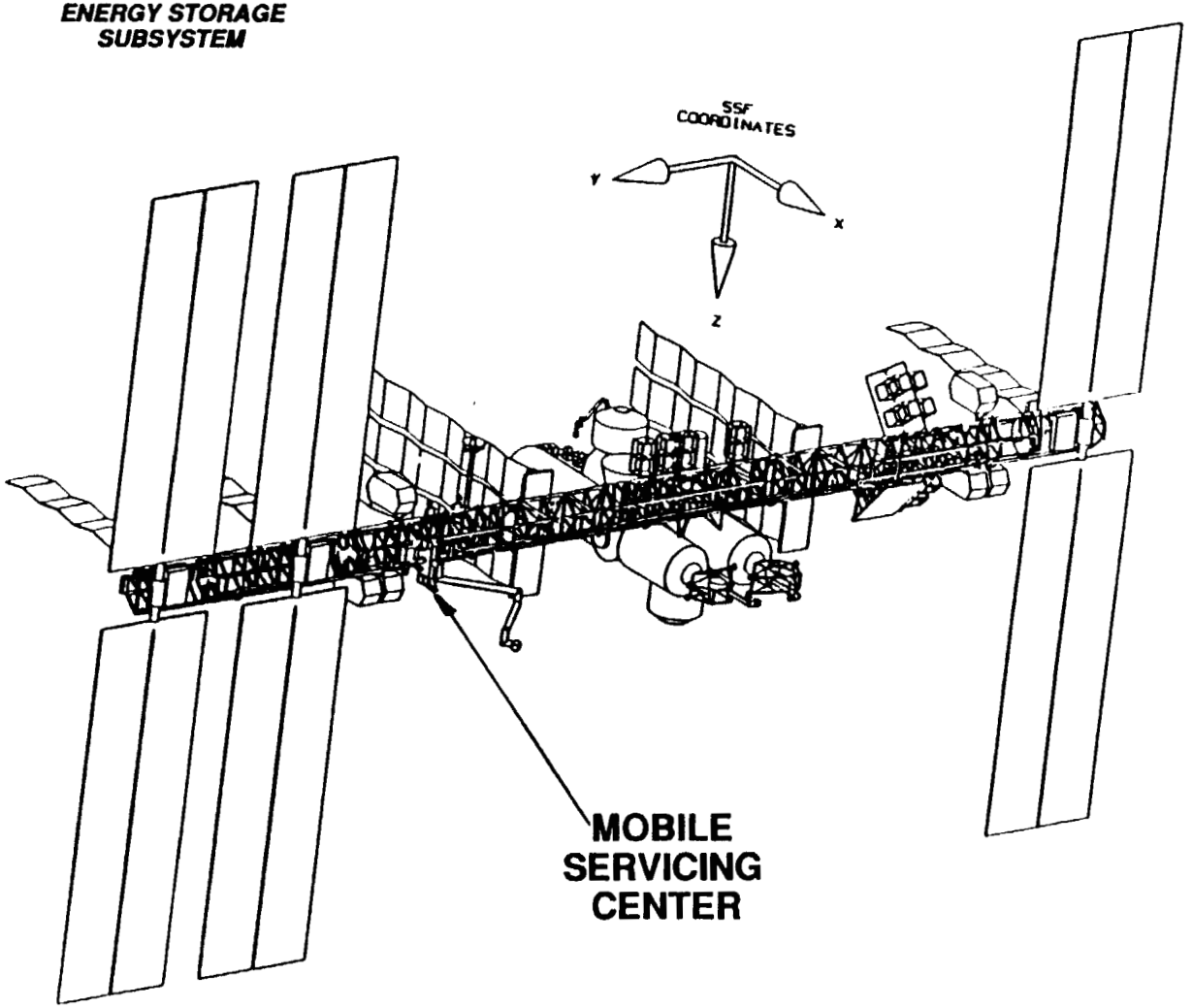
DEBORAH S. BOURLAND
NASA-JSC



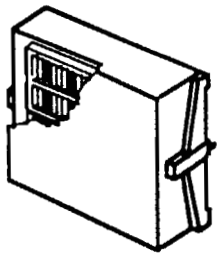
TRANSPORTER ENERGY STORAGE SUBSYSTEM

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.

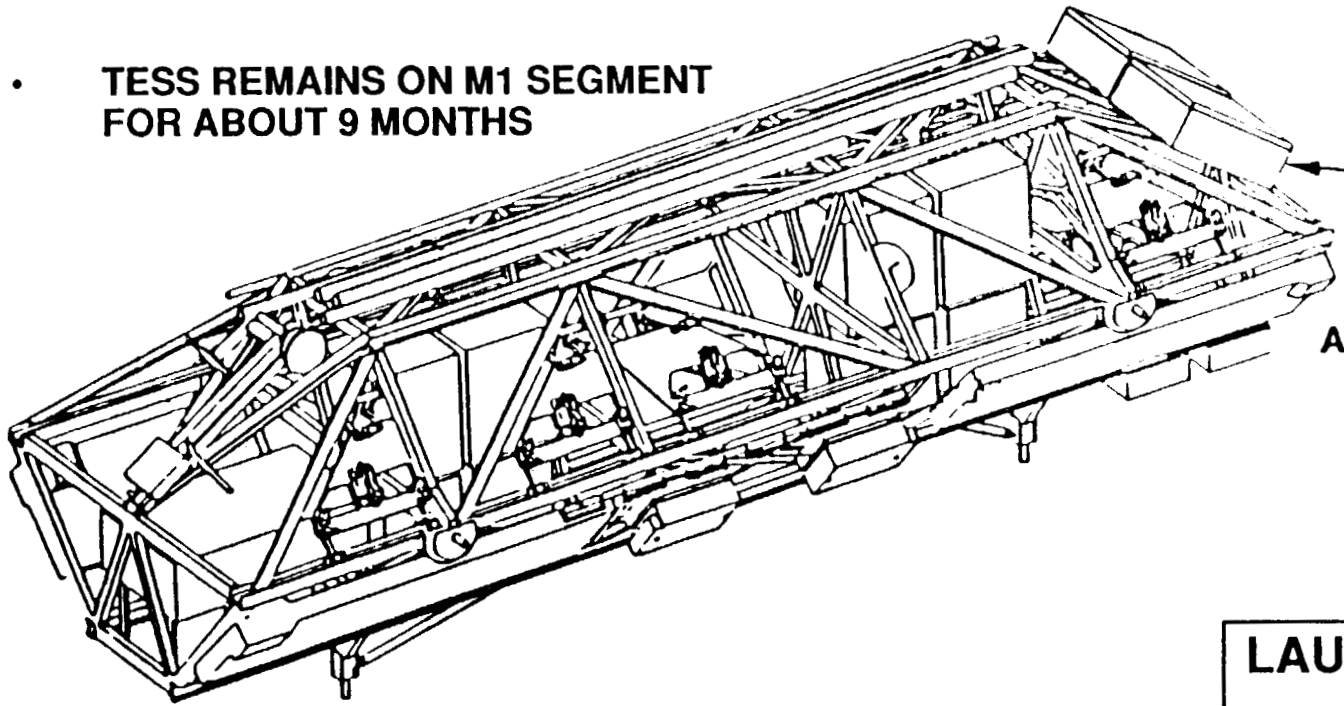


TRANSPORTER ENERGY STORAGE SUBSYSTEM

TESS IN LAUNCH CONFIGURATION

MDESC - L&ES

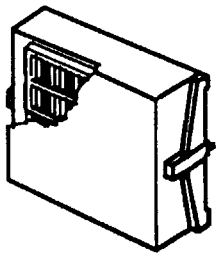
- TESS BATTERY LAUNCHED DISCHARGED AND OPEN CIRCUIT
- TESS REMAINS ON M1 SEGMENT FOR ABOUT 9 MONTHS



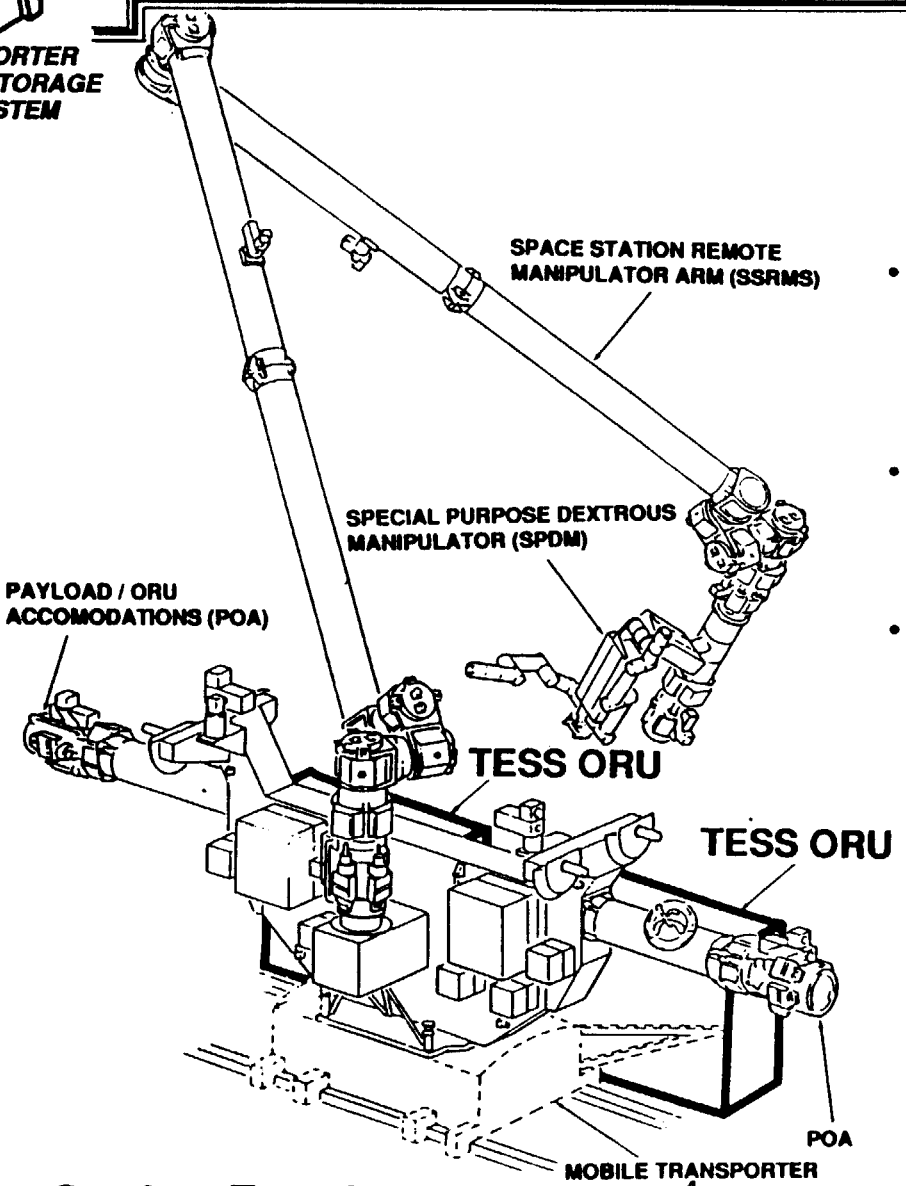
LAUNCH	MB-4
SEGMENT	M1

TESS INSTALLED ON MOBILE SERVICING CENTER

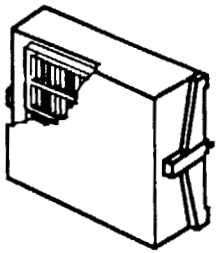
MDESC - L&ES



TRANSPORTER ENERGY STORAGE SUBSYSTEM



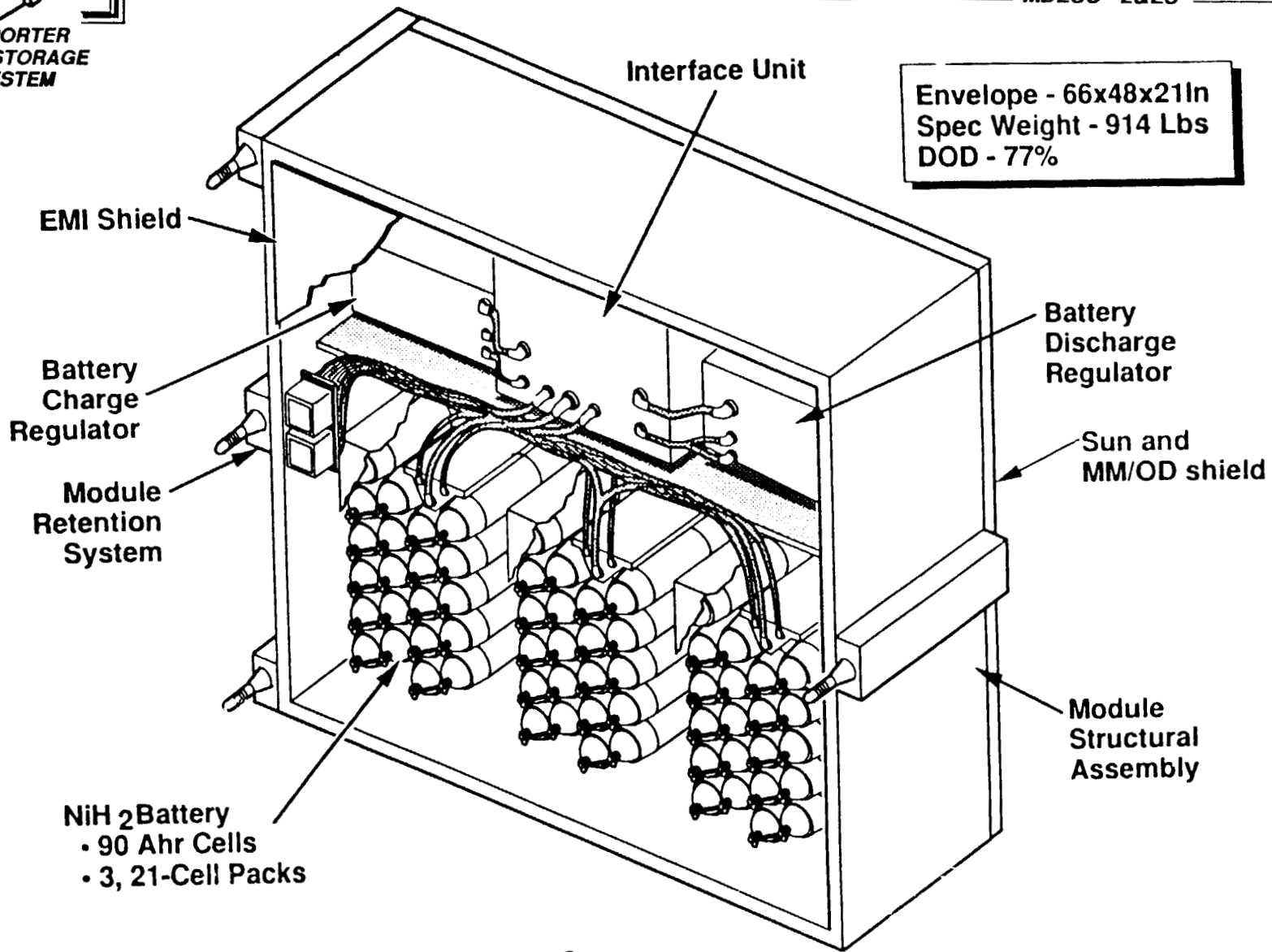
- TESS INSTALLED ON MOBILE TRANSPORTER DURING MB-7 EVA OPERATIONS.
- TESS PROVIDES ABOUT 3.3 HOURS OF MSC TRANSLATION
- TESS PROVIDES REGULATED 120 VOLTS:
  - 10 KW-HR OF ENERGY
  - 3000 WATTS AVERAGE POWER
  - 6000 WATTS PEAK POWER

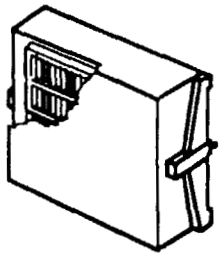


TRANSPORTER ENERGY STORAGE SUBSYSTEM

TESS ORU LAYOUT

MDESC - L&ES





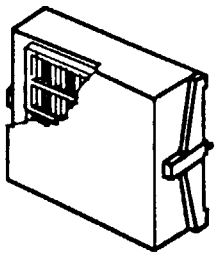
TRANSPORTER ENERGY STORAGE SUBSYSTEM

BATTERY DESIGN REQUIREMENTS

- SUPPORT TESS/MT INTERFACE POWER & ENERGY REQUIREMENTS
  - 3000 WATTS OF AVERAGE OUTPUT POWER AT 120 VOLTS
  - 6000 WATTS OF PEAK OUTPUT POWER AT 120 VOLTS
  - 12,000 WATTS OF FAULT CLEARING POWER
  - 10 KILOWATT-HOURS OF MAXIMUM OUTPUT ENERGY AT 120 VOLTS
  - 7 KILOWATT-HOURS OF NOMINAL OUTPUT ENERGY AT 120 VOLTS

- OPERATIONAL LIFE OF 10 YEARS, THUS 2 REPLACEMENTS OVER SPACE STATION MISSION LIFE OF 30 YEARS.
  - 150 MOBILE SERVICING CENTER MISSIONS PER YEAR
  - 65 % AT NOMINAL ENERGY LEVEL (7 KW-HR), 35 % AT MAXIMUM

- SYSTEM RE[illegible]DANCY, FAIL DEGRADE, FAIL SAFE



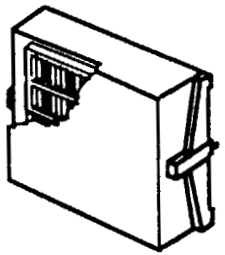
TRANSPORTER
ENERGY STORAGE
SUBSYSTEM

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



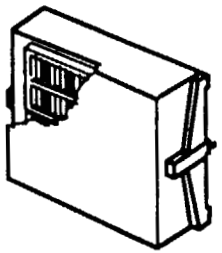
TRANSPORTER ENERGY STORAGE SUBSYSTEM

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

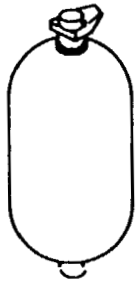
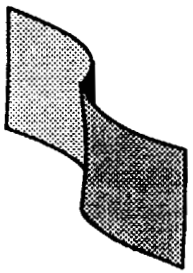
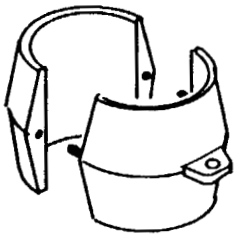
- 21-CELL SUBASSEMBLY
  - WEIGHT: 149 LBS INCLUDING MM/OD COVERS
  - SIZE: 14.9 W x 23.7 L x 13.0 H (INCHES)
  - 3 ELECTRICAL CONECTORS: POWER, INSTRUMENTATION, AND TEST MONITOR
  - CELL ISOLATION: FIBERGLASS WRAP POTTED BETWEEN CELL AND COLLAR
  - BATTERY HOUSING, CELL COLLARS, AND BATTERY COVERS MADE OF ALUMINUM



TESS NICKEL-HYDROGEN BATTERY SUBASSEMBLY DESIGN

MDESC - L&ES

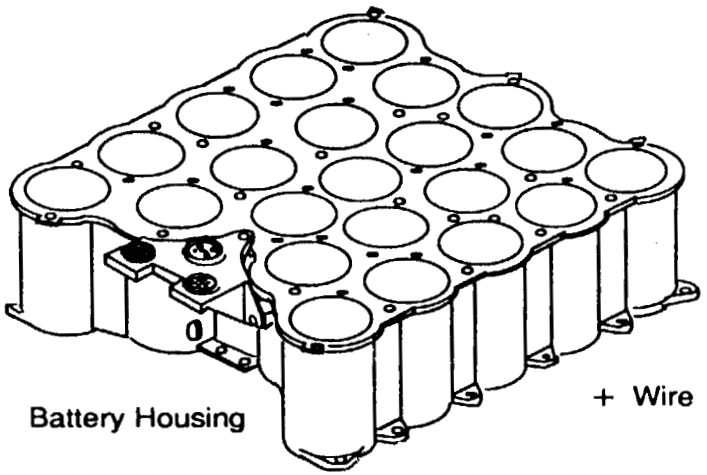
TRANSPORTER ENERGY STORAGE SUBSYSTEM

[ +  + CV-2942 RTV + ] X 21 + CV-2942 RTV +

Cell Supplier = TBD

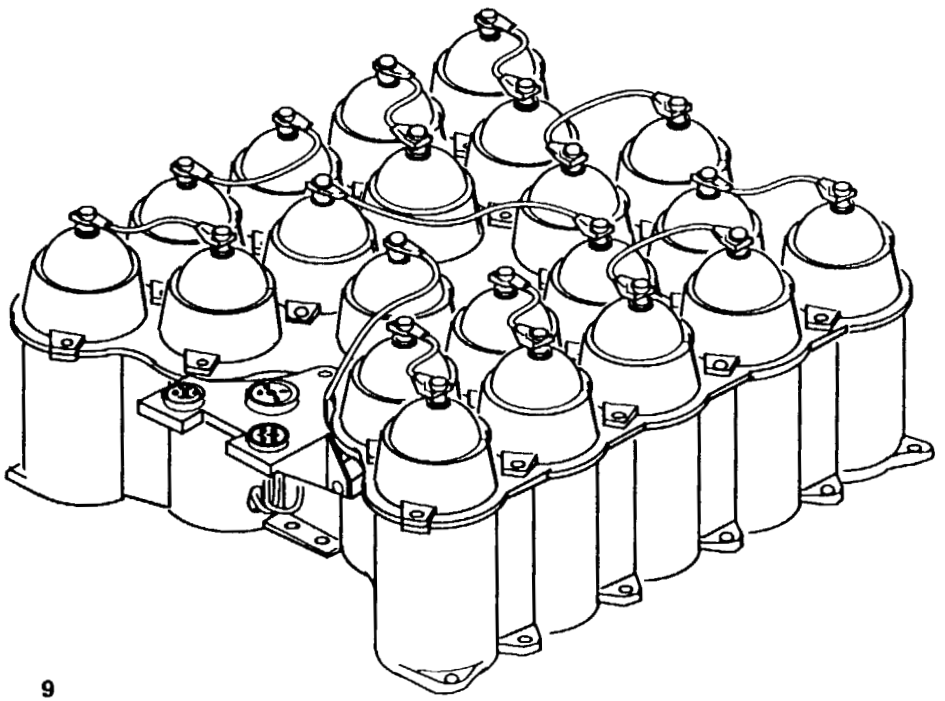
Fiberglass Wrap

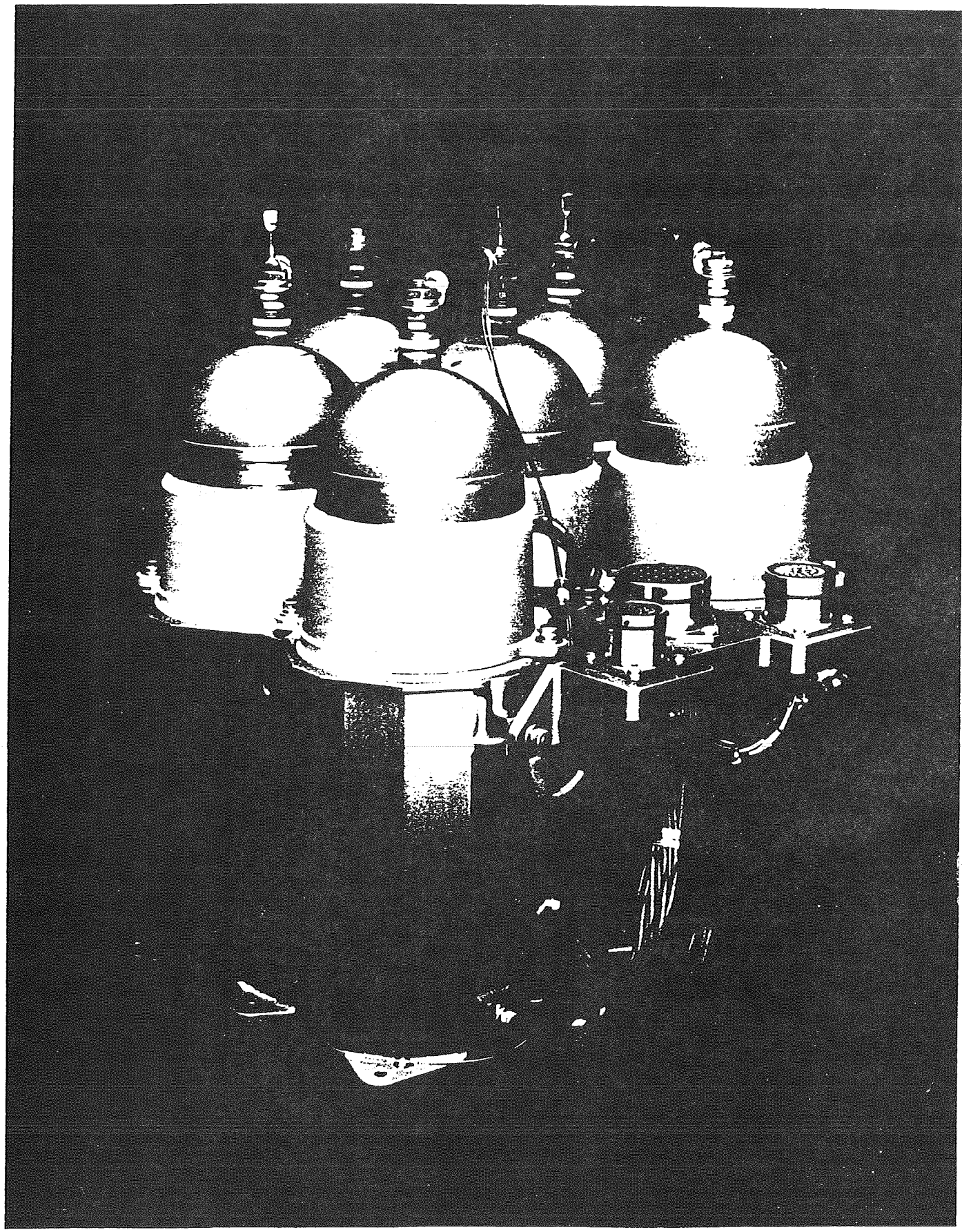
Cell Collars

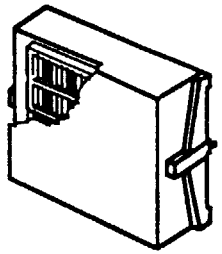


Battery Housing

+ Wire =





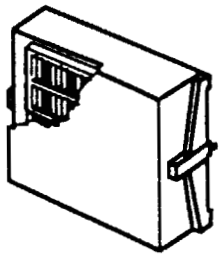


TRANSPORTER ENERGY STORAGE SUBSYSTEM

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.

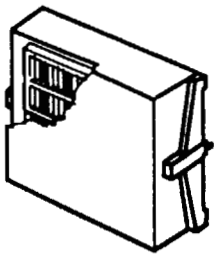


TRANSPORTER
ENERGY STORAGE
SUBSYSTEM

POSSIBLE DOWNSIZING OF TESS

TO SUPPORT

MOBILE REMOTE SERVICER BASE SYSTEM (MBS) REDESIGN



TRANSPORTER ENERGY STORAGE SUBSYSTEM

GROUNDRULES FOR DOWNSIZING TESS

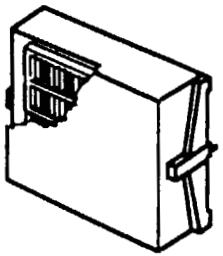
- DESIRED RESULT IS LOWER WEIGHT AND VOLUME OF TESS.
  - SINGLE ORU IS A DESIGN GOAL.

- OPERATIONAL SCENARIOS STILL UNDEFINED.
  - REDUCE OPERATIONAL CONSTRAINTS DURING EVA/EVR MISSIONS

- REDUCTION OF TESS POWER AND ENERGY IS REASONABLE.

	WAS	NOW
- 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

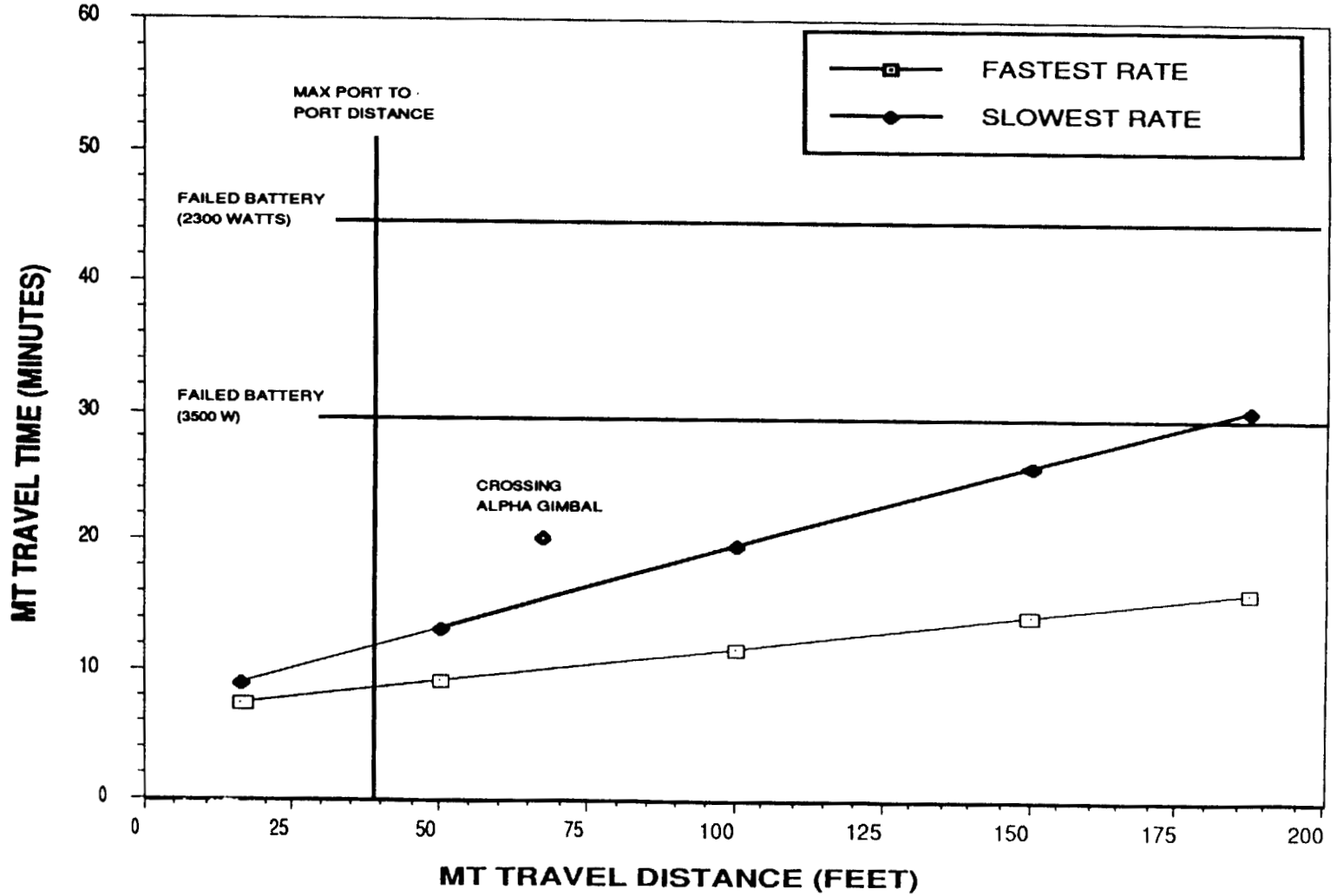


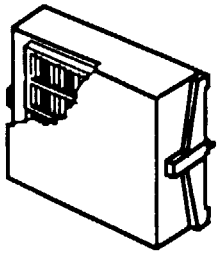
TRANSPORTER ENERGY STORAGE SUBSYSTEM

TRAVEL DISTANCE FOR MT BASED ON TESS SIZE

MDESC - L&ES

BASED ON FAILED BATTERY CONDITION FOR AVERAGE & PEAK LOADS





TRANSPORTER ENERGY STORAGE SUBSYSTEM

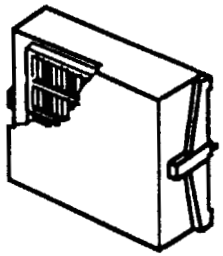
TESS TRANSLATION OUTPUT CAPABILITY

MDESC - L&ES

ASSUMING ONE EVA/EVR MISSION PER DAY.

TIMELINE - HOURS 0	6, 8, OR 12	24
EVA/EVR MISSION	COOLDOWN/RECHARGE/ PREP FOR NEXT EVA/EVR	
TESS • SUPPLIES 1.5 HRS OF MT TRANSLATION. • SMALL AMOUNT OF COOLDOWN OR CHARGING DURING MBS OPERATIONS. • POSSIBLE INCREASE OF MT TRANSLATION TIME TO 2 HRS.	**TESS** • COOLS AND RECHARGES AS NECESSARY TO BE AVAILABLE FOR NEXT DAY'S ACTIVITIES.	

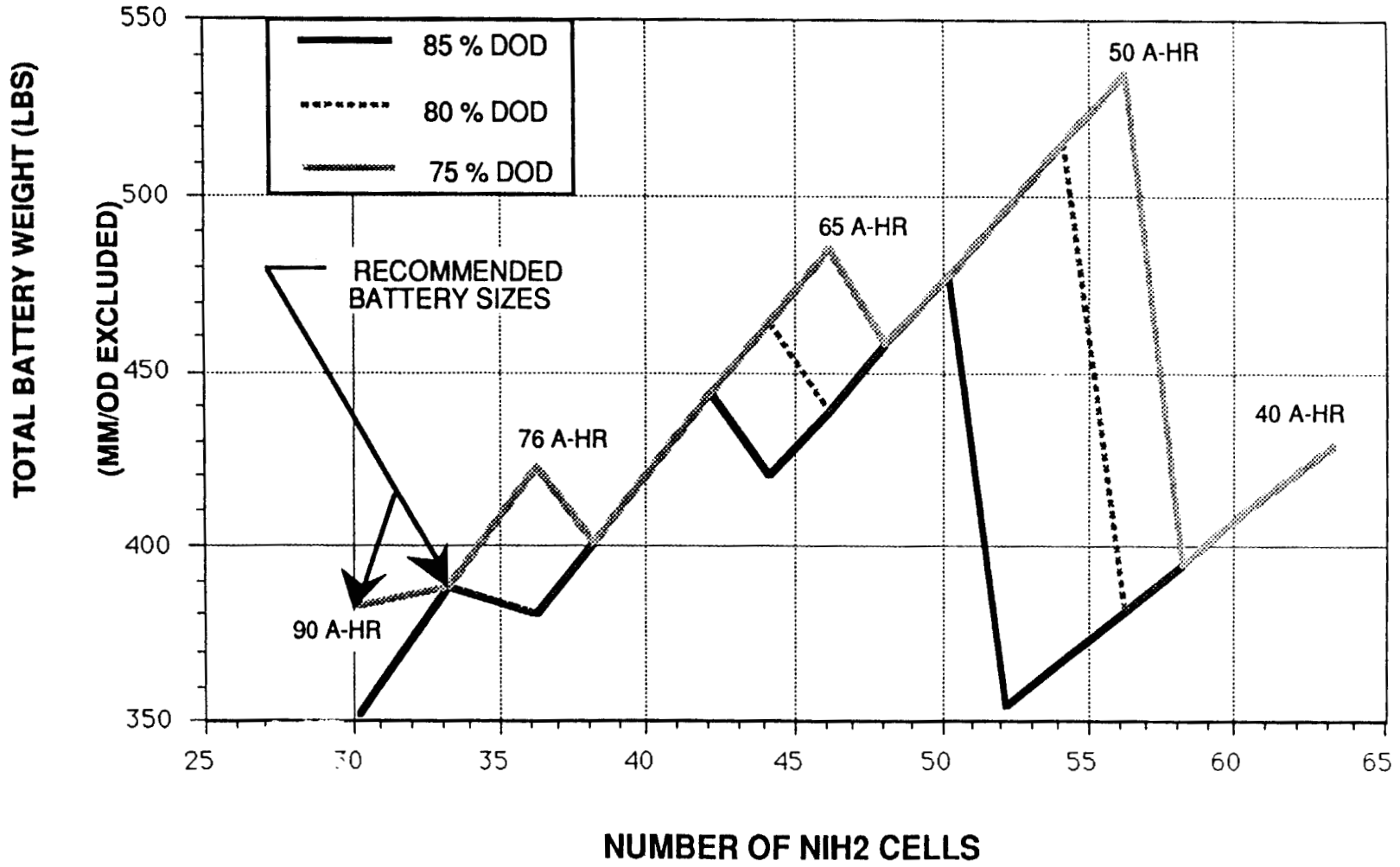
NOTE: TRANSLATION TIMES WILL BE CUT IN HALF FOR FAILED BATTERY CONDITION

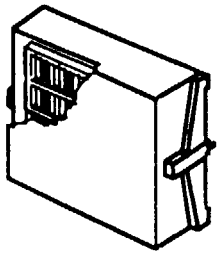


TRANSPORTER ENERGY STORAGE SUBSYSTEM

BATTERY SIZING BASED ON MAXIMUM DOD

MDESC - L&ES





TRANSPORTER ENERGY STORAGE SUBSYSTEM

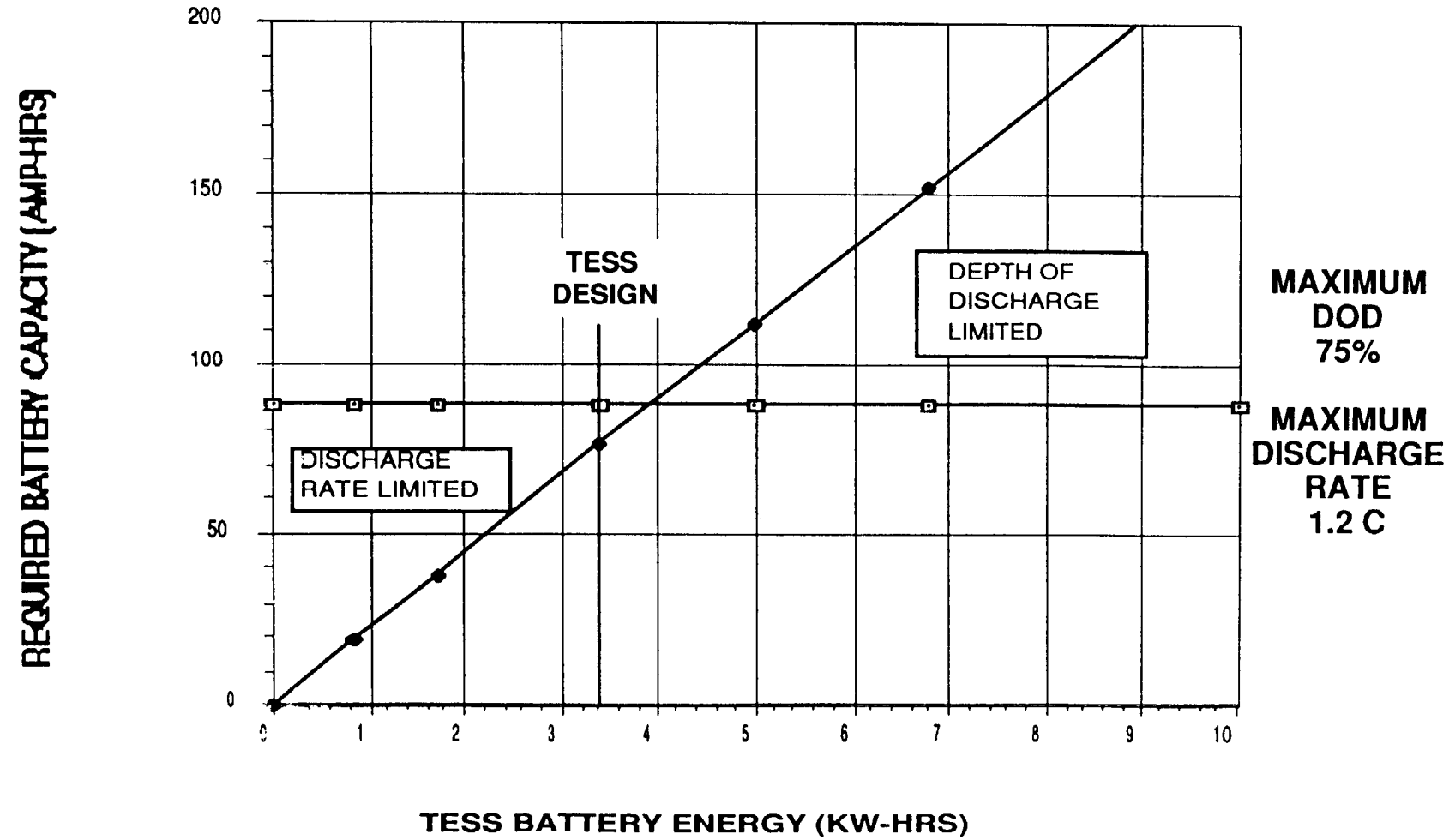
TESS BATTERY WILL BE DISCHARGE RATE LIMITED

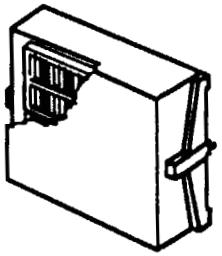
MDESC - L&ES

AVERAGE POWER 2300 W

PEAK POWER 3500 W

33 NIH2 CELL BATTERY



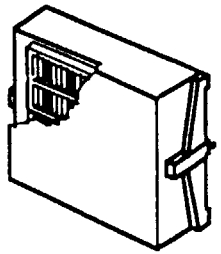


TRANSPORTER ENERGY STORAGE SUBSYSTEM

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

- 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

NICKEL HYDROGEN CELL DESIGN

A DESIGNER'S ASPECT

Raymond Rehm

Nickel Hydrogen Battery Cells

October 30, 1991

Gates Energy Products

Gates Aerospace Batteries

1. Scope

The following paper is designed to give added insight into the methodology of Nickel Hydrogen cell design and aid in deciphering the battery cell reference guide which has been distributed to many of GAB's current and potential customers. Due to certain information's proprietary nature, and sensitivity to international 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 compression in the welded condition. This method of compression alleviates concerns of deep drawing Nickel Alloy 718 to meet the lengths required by long electrode stacks for higher capacity cells.

The cell sealing method is performed via the GAB patented ceramic seal. This seal has demonstrated 164,000 hydraulic pressure cycles, from 0 to 1000 PSIG, without affecting the cells' hermeticity requirements.

Gates currently utilizes TIG welding for cell closure. This method has been proven reliable to the same cycling regime listed for the ceramic seal.

The component materials utilized in the manufacture of the nickel hydrogen cells have been chosen based on their individual capabilities to withstand the caustic environment of the cell for a design life in excess of 15 years without degradation. The components have also demonstrated capabilities to cycle beyond 10,000, 70 % DoD and 27,000 40 % DoD charge/discharge cycles in low earth orbit regimes at pressures up to 1000 psig of hydrogen.

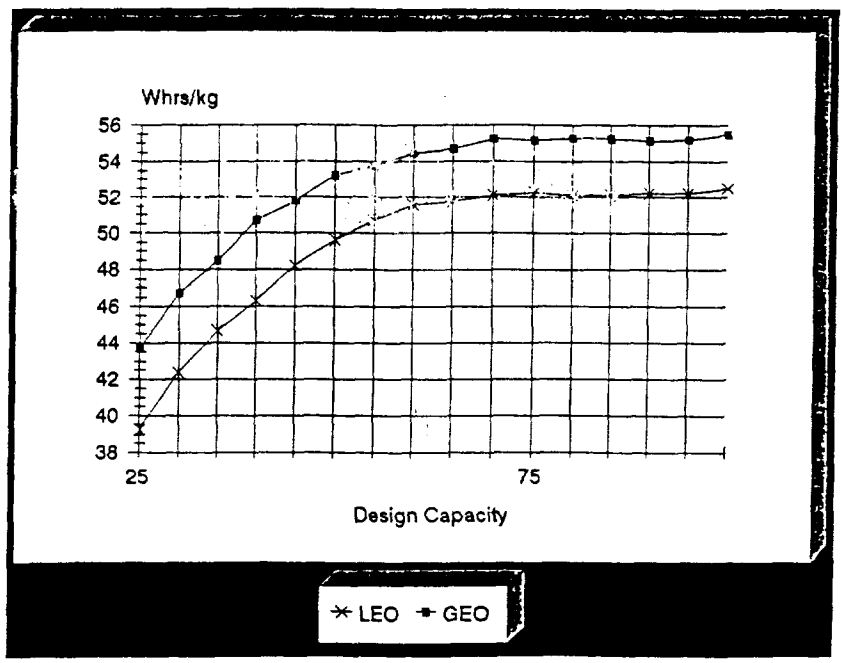


Figure 1. Specific Energy for Gates 3.5" Cells

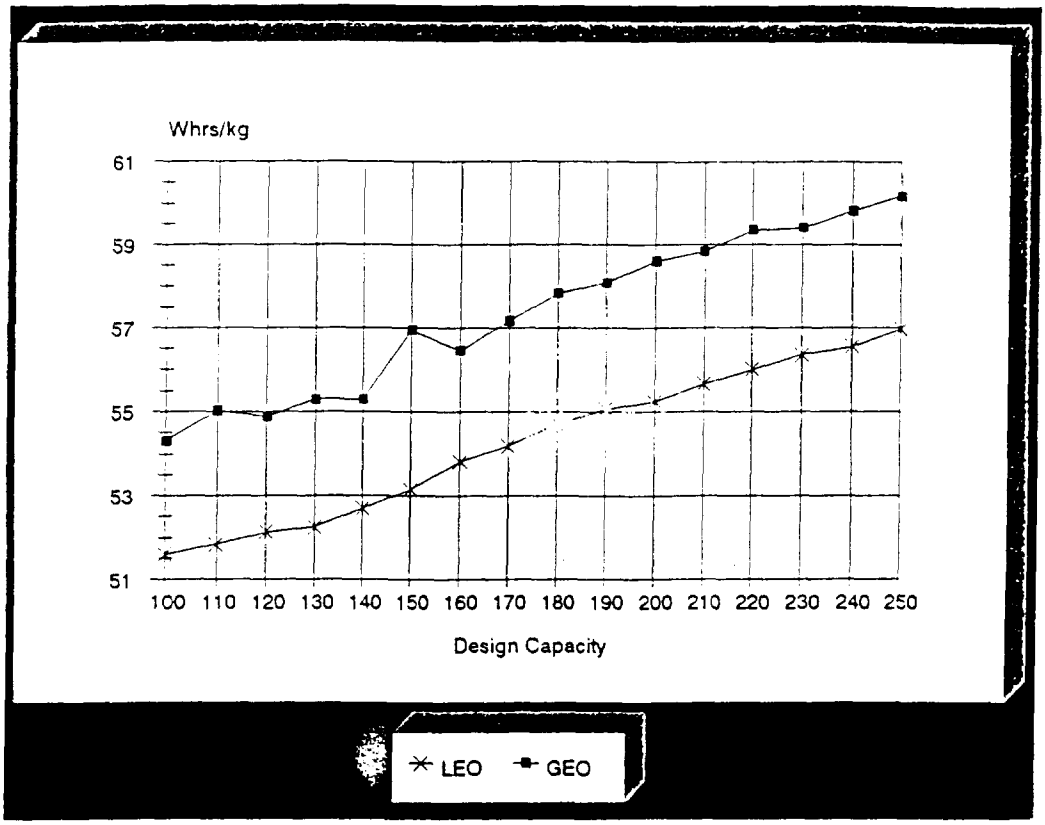


Figure 2. Specific Energy for Gates 4.5" Cells

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 between the two, as it pertains to the cell design, is the rapidity and rate of charge/discharge and the amount of oxygen generated as a result of the stack design at the higher recharge rate required by the LEO regime. Oxygen generation and recombination is not problematic for a GEO regime from the aspect of lower recharge rates and the number of cycles required for design life.

For the reasons outlined above a stack design which is sufficient for one orbit would not necessarily be recommended for the other. Gates currently employs two designs which can be broken down to a LEO (recirculating) and a GEO (back-to-back) cell stack design. The GEO cell design also incorporates a positive electrode which is nominally thicker than the LEO cell electrode design. This makes it possible to reduce the number of electrode pairs needed to meet the capacity required for the application. The difference in the Volumetric and Mass Energies between the two cell configurations can be seen in Figures I through IV.

4. Capacity

Another major point of confusion is the question of cell capacity. There are as many ways of determining "Nameplate" as there are customers who buy NiH_2 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.

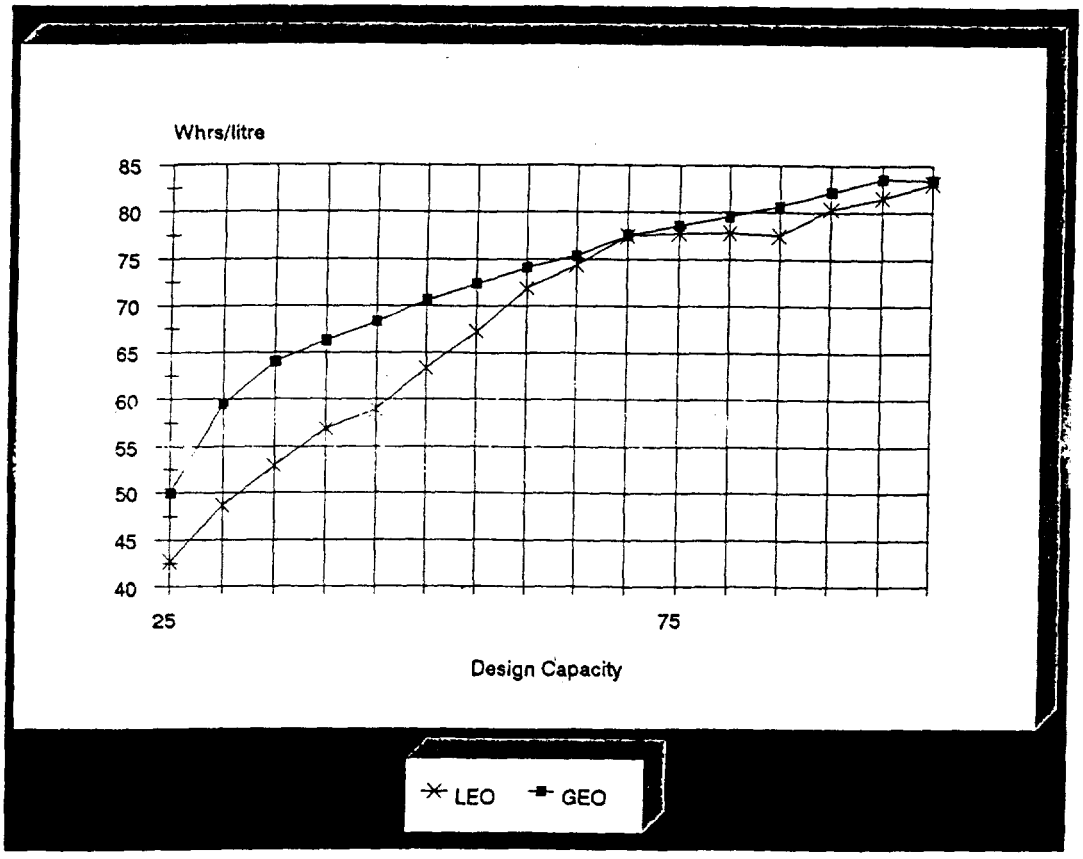


Figure 3. Energy Density of Gates 3.5" Cells

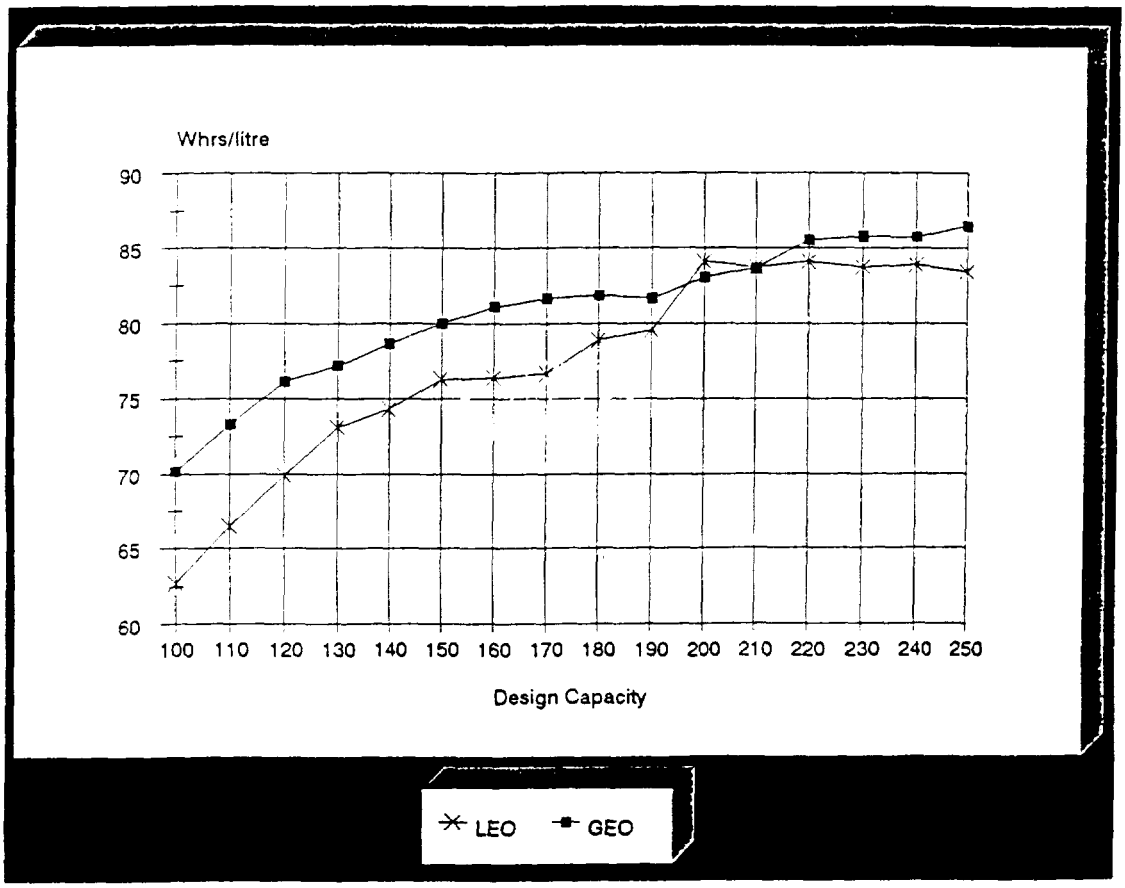


Figure 4. Energy Density of Gates 4.5" Cells

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

EOS OVERALL PROGRAM

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 TRANDUCERS
- 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	20
C/2		1	1	
C	1		3	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
C	1		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, OC, 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)

FAULT TREE ANALYSIS

NiH_2 AEROSPACE CELLS

FOR LEO MISSION

Glenn C. Klein
Gates Aerospace Batteries

Donald E. Rash, Jr.
Reliability Analysis Center

FAULT TREE ANALYSIS, NiH_2 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.

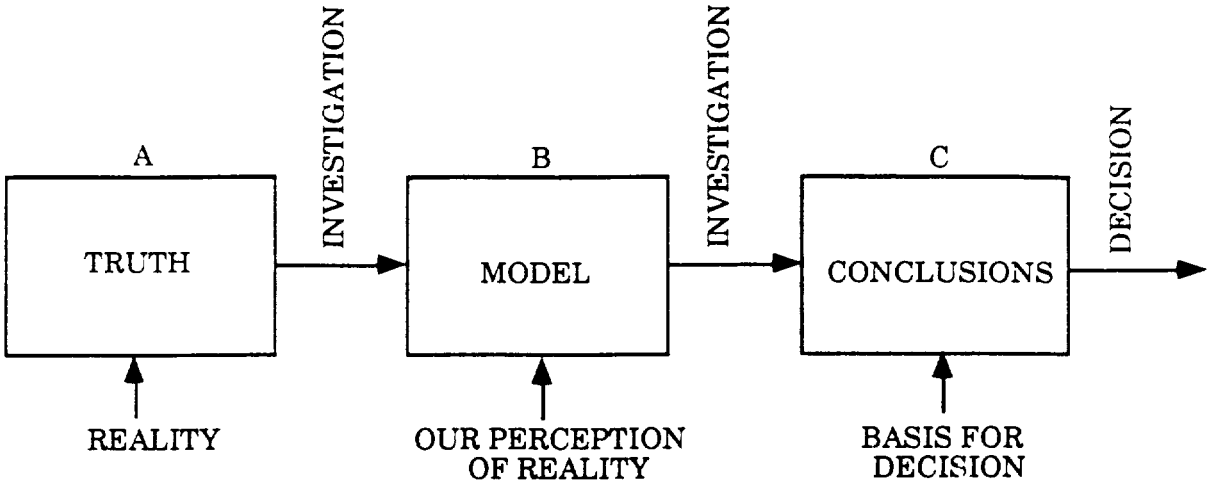


FIGURE 1: RELATIONSHIP BETWEEN REALITY, SYSTEM MODEL, AND DECISION PROCESS

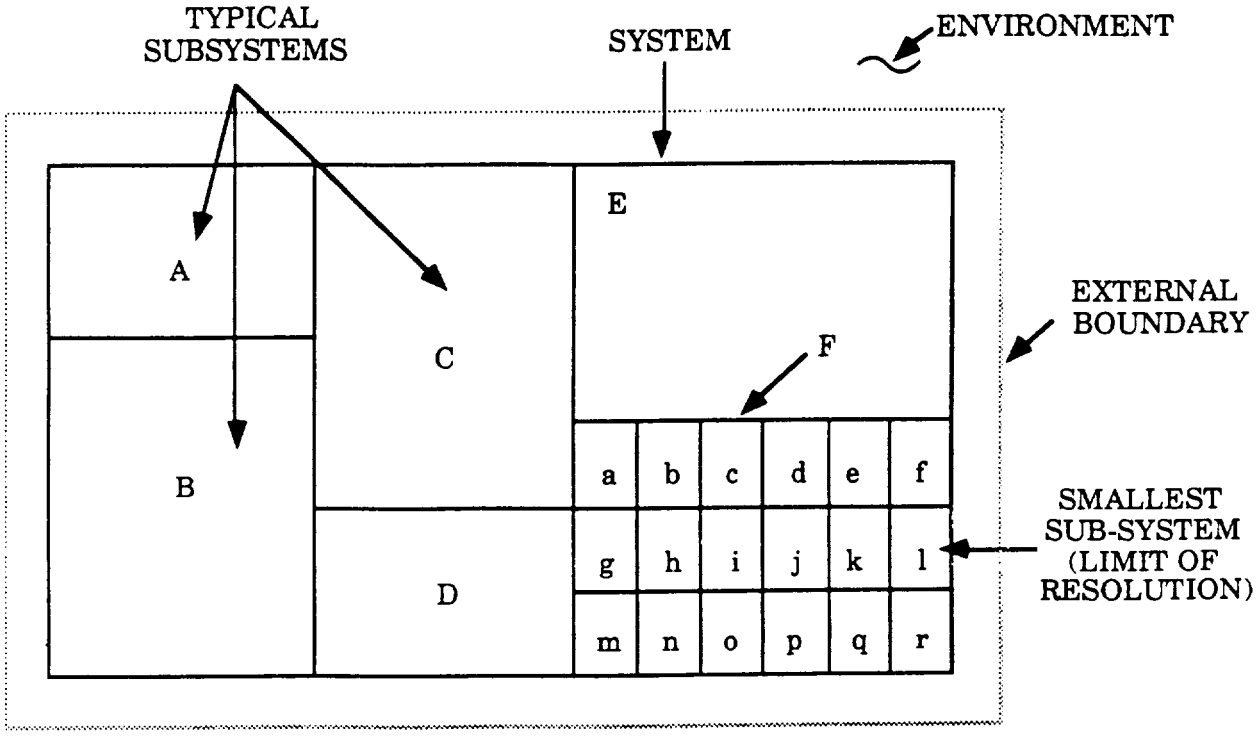


FIGURE 2: SYSTEM DEFINITION: EXTERNAL AND INTERNAL BOUNDARIES

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_2 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_2 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

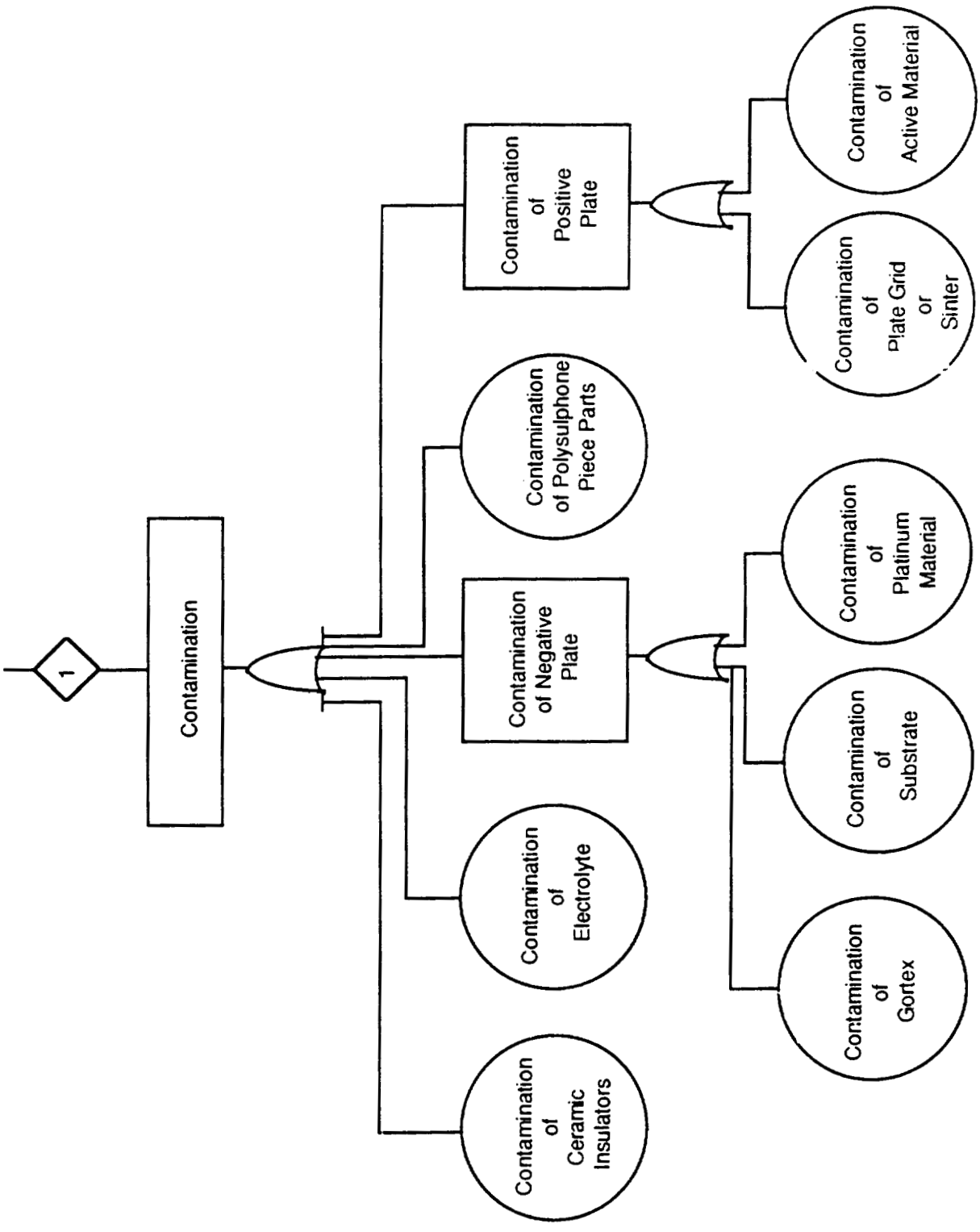


FIGURE 3: FAULT TREE SYMBOLOGY

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_2 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_2 pressure vessels and presents a generic path of construction criticality. By placing probabilities in each of the

lower fault events a manufacturer will be able to construct a detailed quantitative fault tree.

High Charge Voltage

This fault is divided into three generic failure modes of which two are identical to Loss of Capacity. These generic failure modes are further divided into specific failure modes which can be identified or traced back to respective FMEA failure modes. Some of these failure modes have been traced to their failure causes. These expanded fault trees may have no failure modes associated with them because either they are failure causes or are under review for inclusion into the growing Operational FMEA database.

High Pressure

Only two generic failure modes cause high pressure and one is unique to this fault. The flooding of the negative membrane is an operational fault that is a result of various contamination failures. We do not have FMEA worksheets filled out for contamination as it usually is identified in various FMEA worksheets as a failure cause.

Loss of Capacity

This fault tree is the least extensive of the operational critical faults. This is because it is associated with wearout mechanisms of the NiH_2 battery cell that are not modeled and has duplicity in other failure modes. The purpose of this fault tree is to show unique failure mechanisms associated with just Loss of Capacity. The loss of capacity has been divided into two larger groups of generic failure modes. These in turn have been broken down into other root causes and easily identifiable failure modes.

Suppressed Discharge Voltage

This fault tree is broken down into three specific failure modes identified by the operational FMEA worksheet numbers and one failure mode associated with NiH_2 wearout. A particularly interesting feature of this fault tree is that both hard and soft shorts can be caused by conductive particles. The conductive particle fault tree shows how these particles can be inherent to a fault process or introduced as foreign particles from material handling.

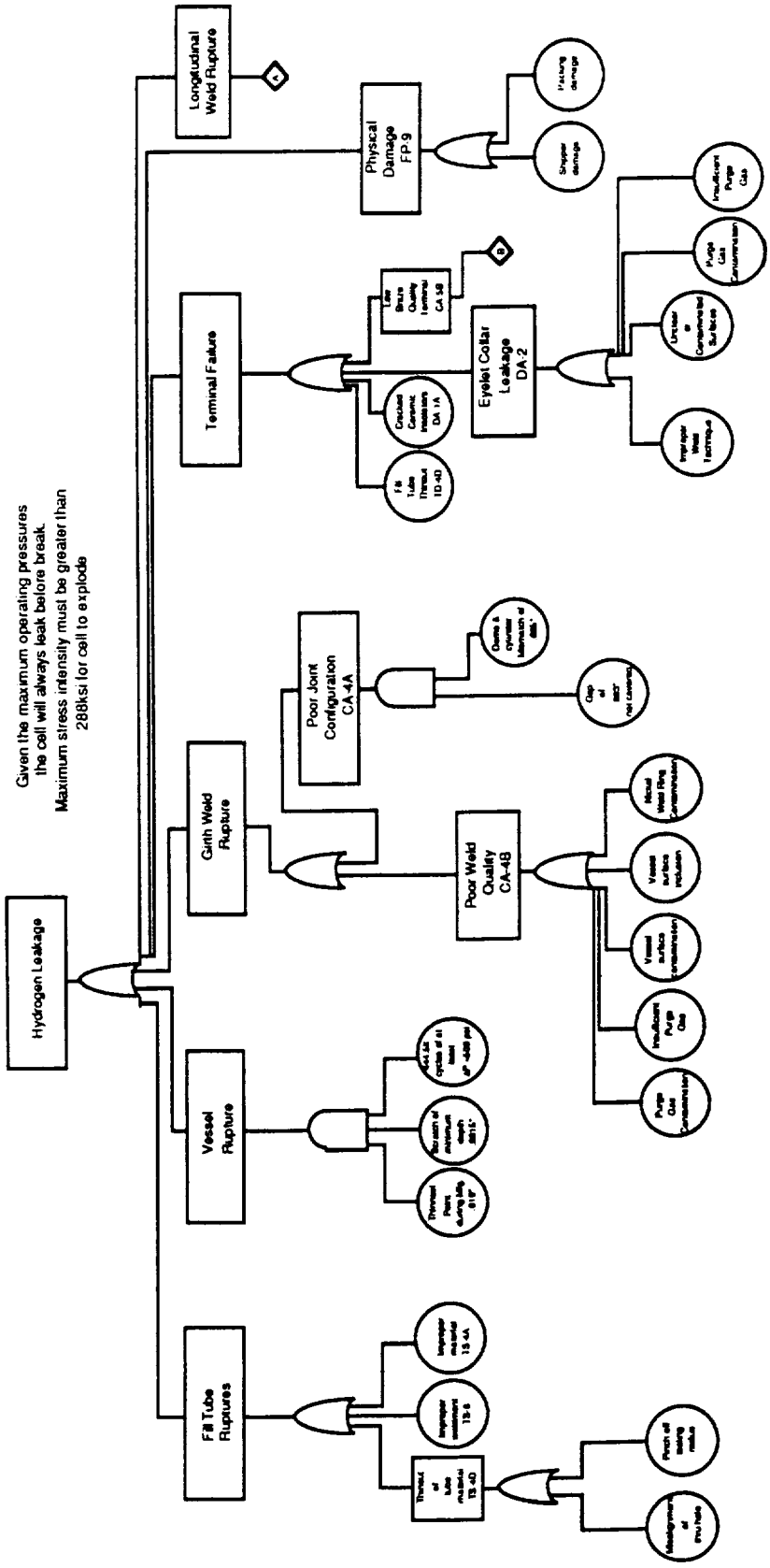

Given the maximum operating pressures
the cell will always leak before break.
Maximum stress intensity must be greater than
288ksi for cell to explode
Hydrogen Leakage
Longitudinal Weld Rupture
Physical Damage FP-9
Terminal Failure
Eyelet Collar Leakage DA-2
Girth Weld Rupture
Poor Joint Configuration CA-4A
Poor Weld Quality CA-4B
Vessel Rupture
Fill Tube Ruptures

FIGURE 4

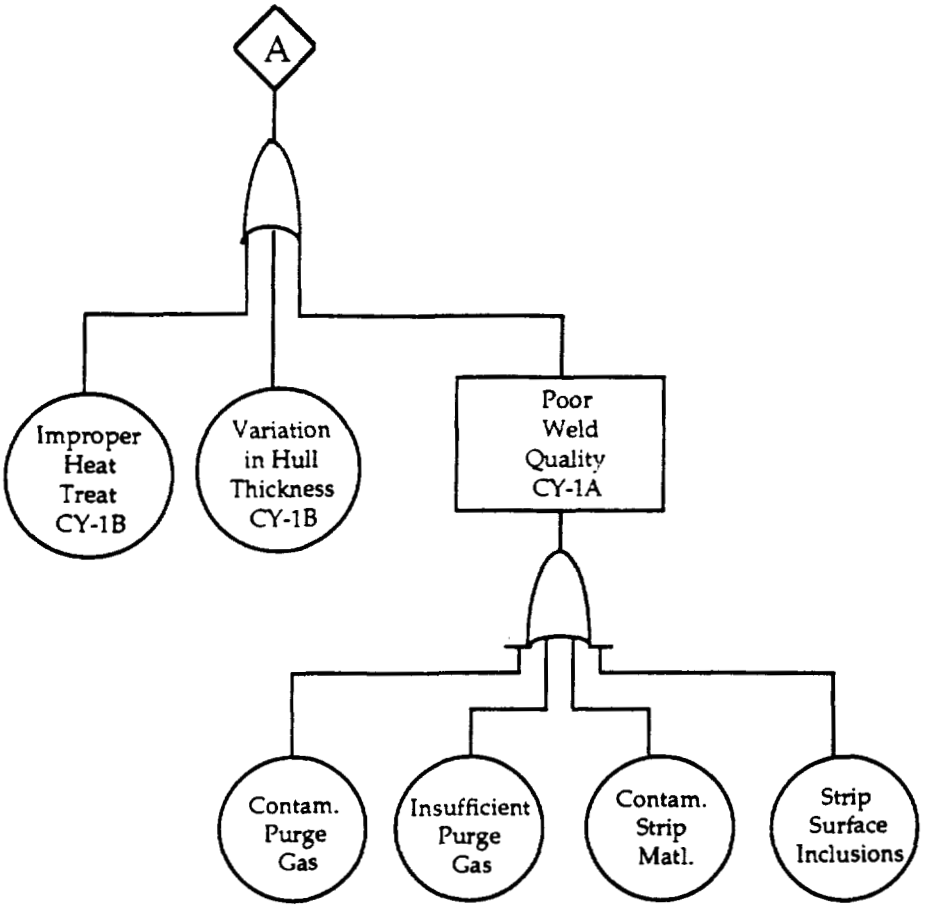

A
Improper Heat Treat CY-1B
Variation in Hull Thickness CY-1B
Poor Weld Quality CY-1A
Contam. Purge Gas
Insufficient Purge Gas
Contam. Strip Matl.
Strip Surface Inclusions

FIGURE 5

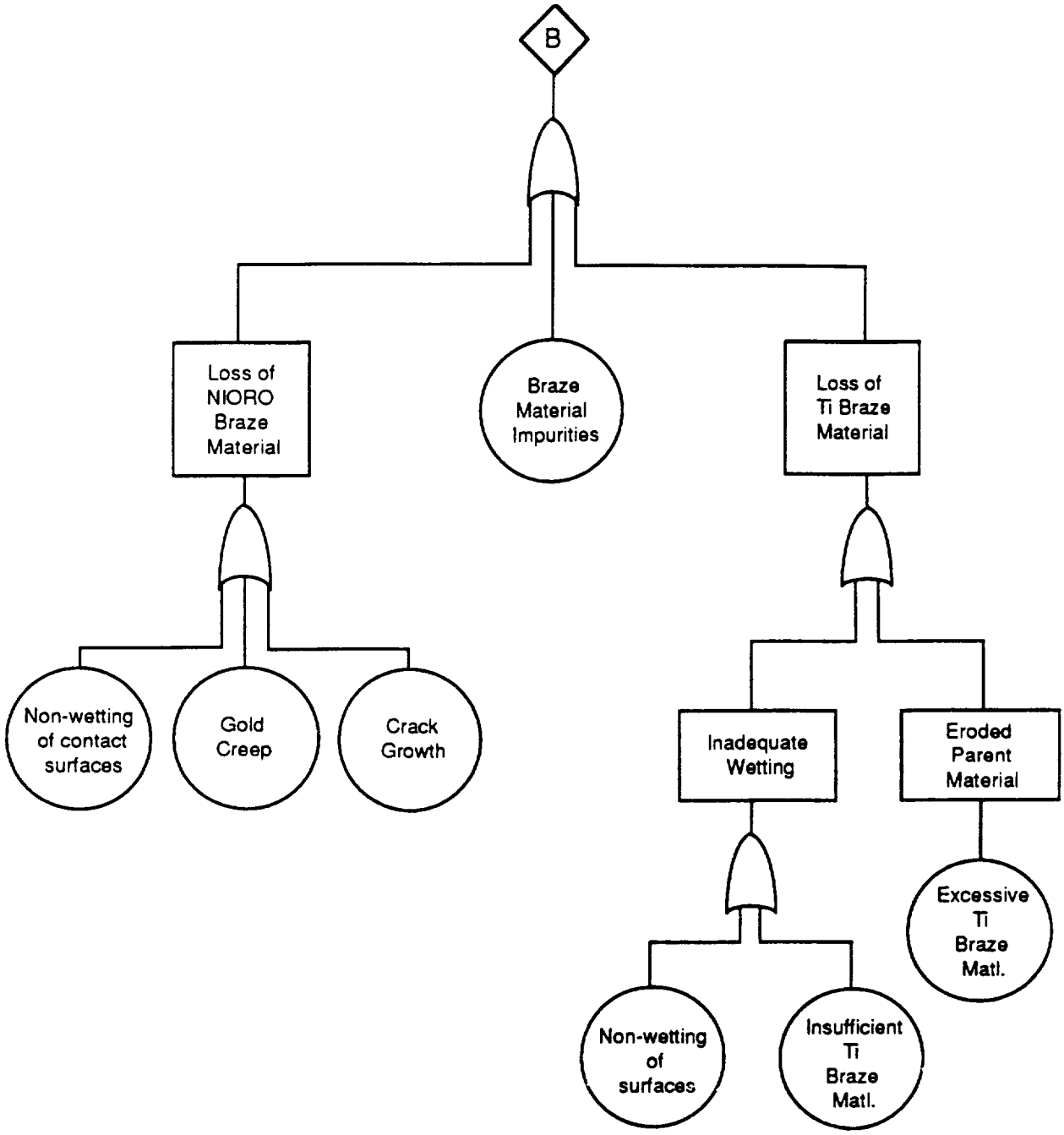

B
Loss of NIORO Braze Material
Braze Material Impurities
Loss of Ti Braze Material
Non-wetting of contact surfaces
Gold Creep
Crack Growth
Inadequate Wetting
Eroded Parent Material
Excessive Ti Braze Matl.
Non-wetting of surfaces
Insufficient Ti Braze Matl.

FIGURE 6

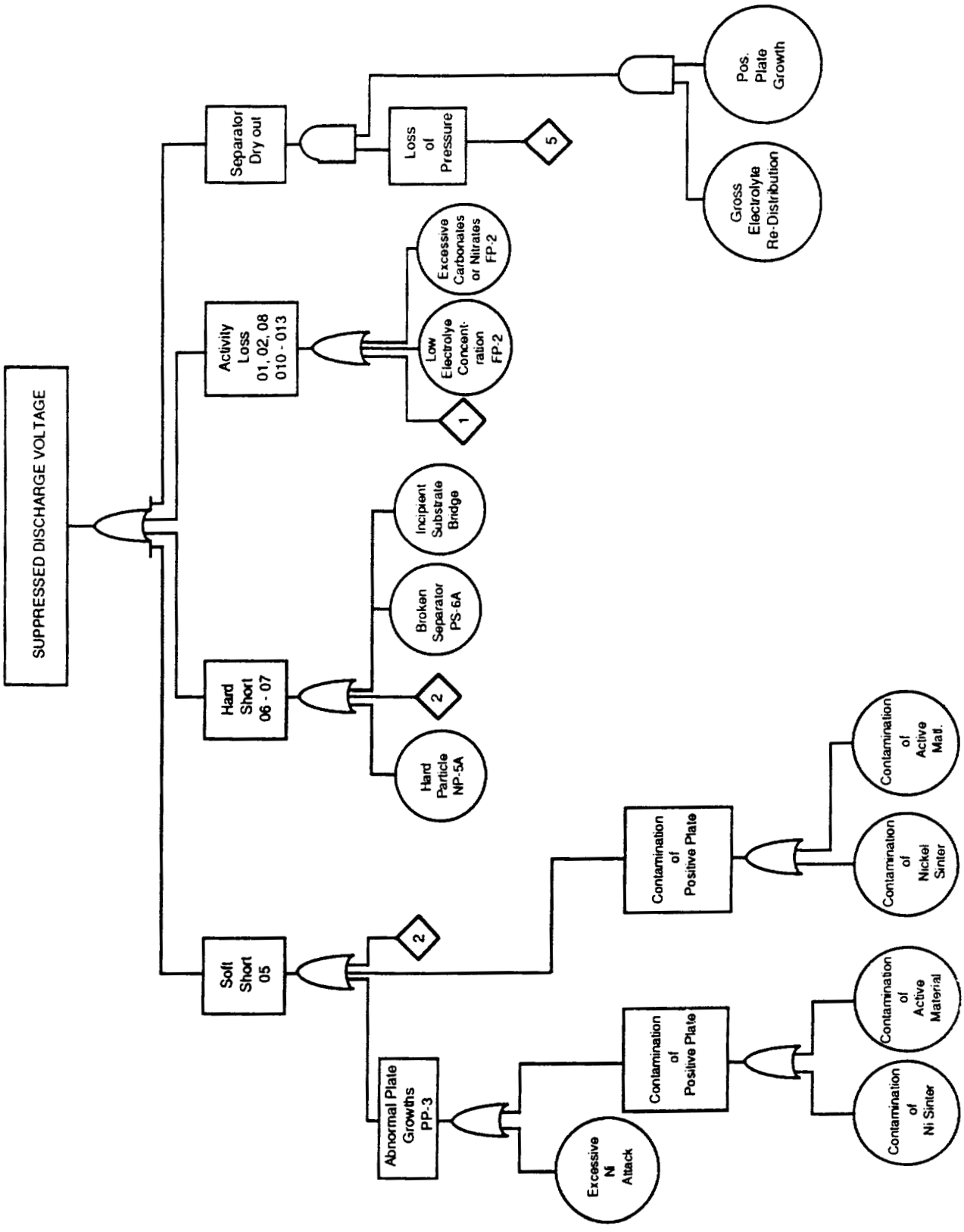

SUPPRESSED DISCHARGE VOLTAGE
Separator Dry out
Loss of Pressure
5
Pos. Plate Growth
Gross Electrolyte Re-Distribution
Activity Loss 01, 02, 08 010 - 013
Excessive Carbonates or Nitrates FP-2
Low Electrolyte Concentration FP-2
1
Hard Short 06 - 07
Incipient Substrate Bridge
Broken Separator PS-6A
2
Hard Particle NP-5A
Soft Short 05
2
Contamination of Positive Plate
Contamination of Active Mat.
Contamination of Nickel Sinter
Abnormal Plate Growths PP-3
Contamination of Positive Plate
Contamination of Active Material
Contamination of Ni Sinter
Excessive N Attack

FIGURE 7

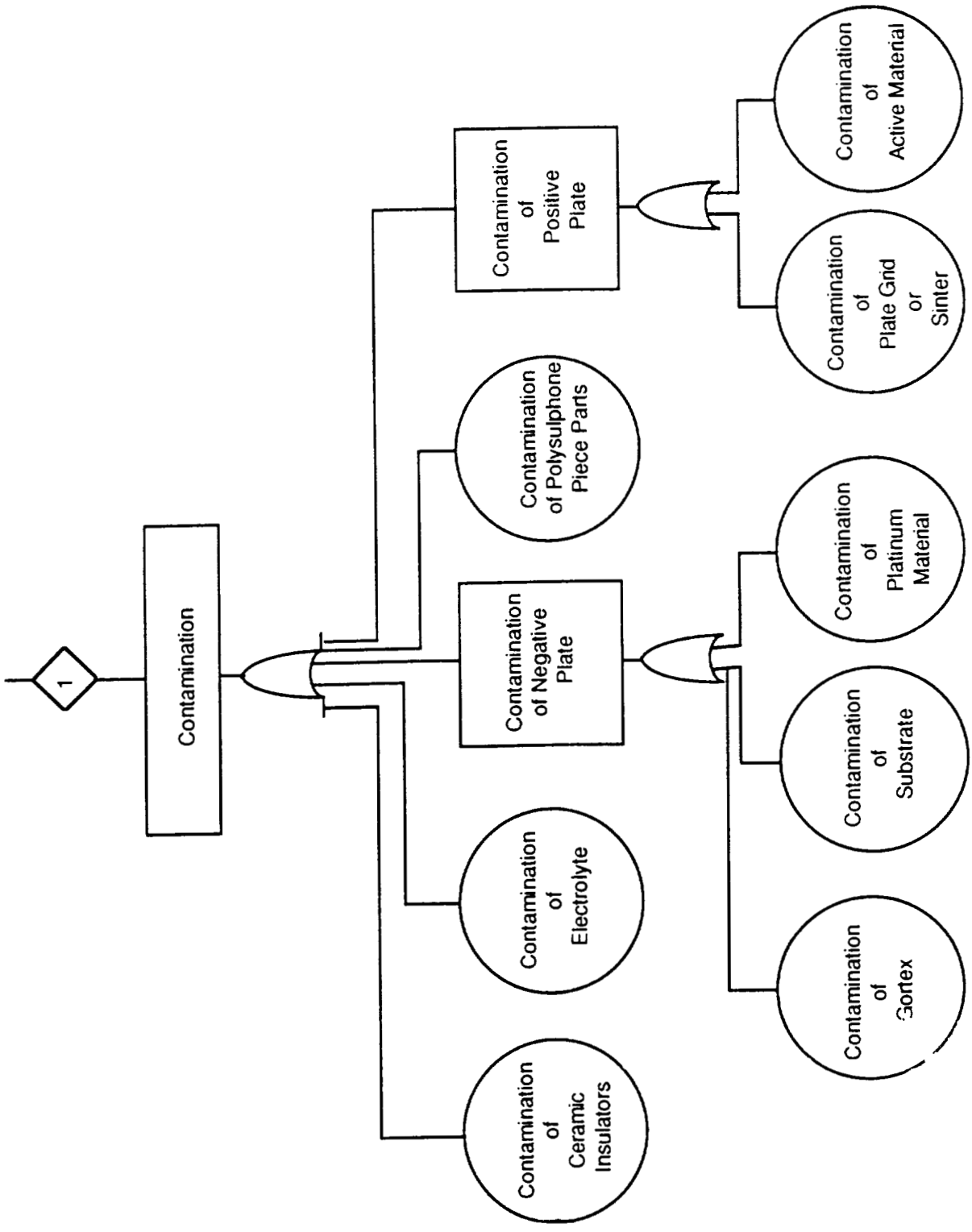

1
Contamination
Contamination of Positive Plate
Contamination of Active Material
Contamination of Plate Grid or Sinter
Contamination of Polysulphone Piece Parts
Contamination of Negative Plate
Contamination of Platinum Material
Contamination of Substrate
Contamination of Electrolyte
Contamination of Cortex
Contamination of Ceramic Insulators

FIGURE 8

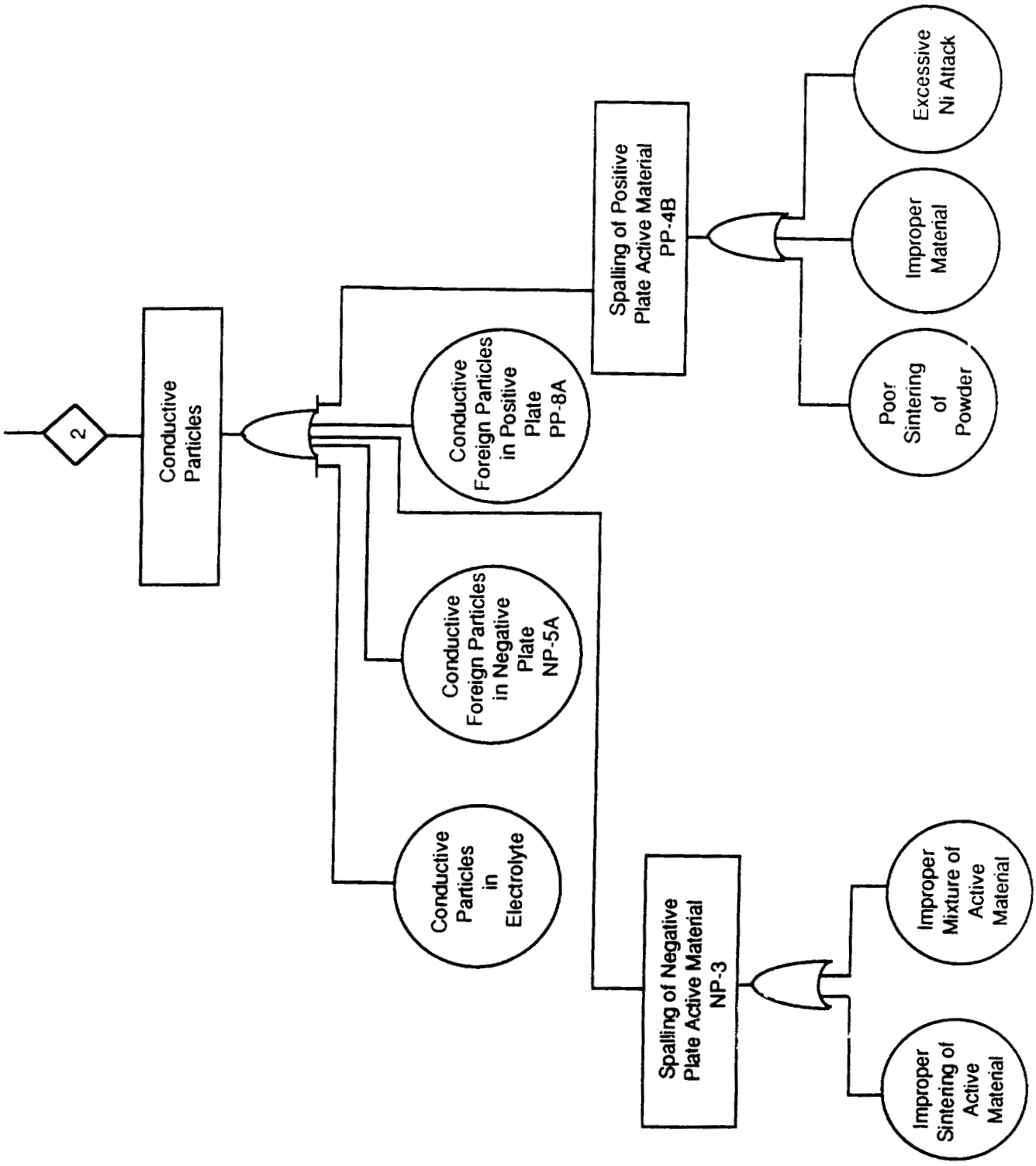

2
Conductive Particles
Conductive Particles in Electrolyte
Conductive Foreign Particles in Negative Plate NP-5A
Conductive Foreign Particles in Positive Plate PP-8A
Spalling of Negative Plate Active Material NP-3
Improper Sintering of Active Material
Improper Mixture of Active Material
Spalling of Positive Plate Active Material PP-4B
Poor Sintering of Powder
Improper Material
Excessive Ni Attack

FIGURE 9

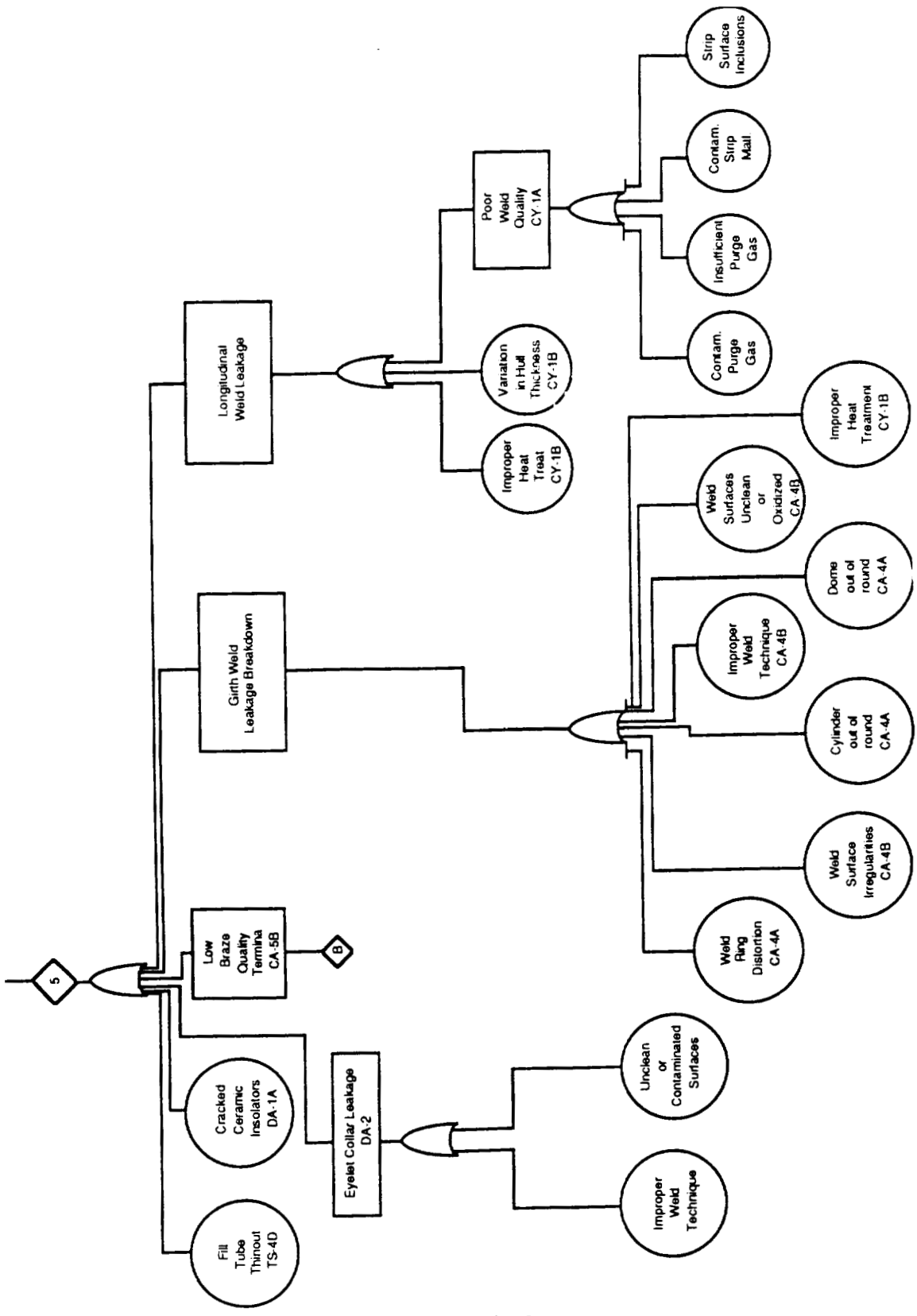

5
Low Braze Quality Termina CA-5B
B
Fill Tube Thinout TS-4D
Cracked Ceramic Insolators DA-1A
Eyelet Collar Leakage DA-2
Unclean or Contaminated Surfaces
Improper Weld Technique
Girth Weld Leakage Breakdown
Weld Ring Distortion CA-4A
Weld Surface Irregularities CA-4B
Cylinder out of round CA-4A
Improper Weld Technique CA-4B
Dome out of round CA-4A
Weld Surfaces Unclean or Oxidized CA-4B
Improper Heat Treatment CY-1B
Longitudinal Weld Leakage
Improper Heat Treat CY-1B
Variation in Hull Thickness CY-1B
Poor Weld Quality CY-1A
Contam. Purge Gas
Insufficient Purge Gas
Contam. Strip Mail
Strip Surface Inclusions

FIGURE 10

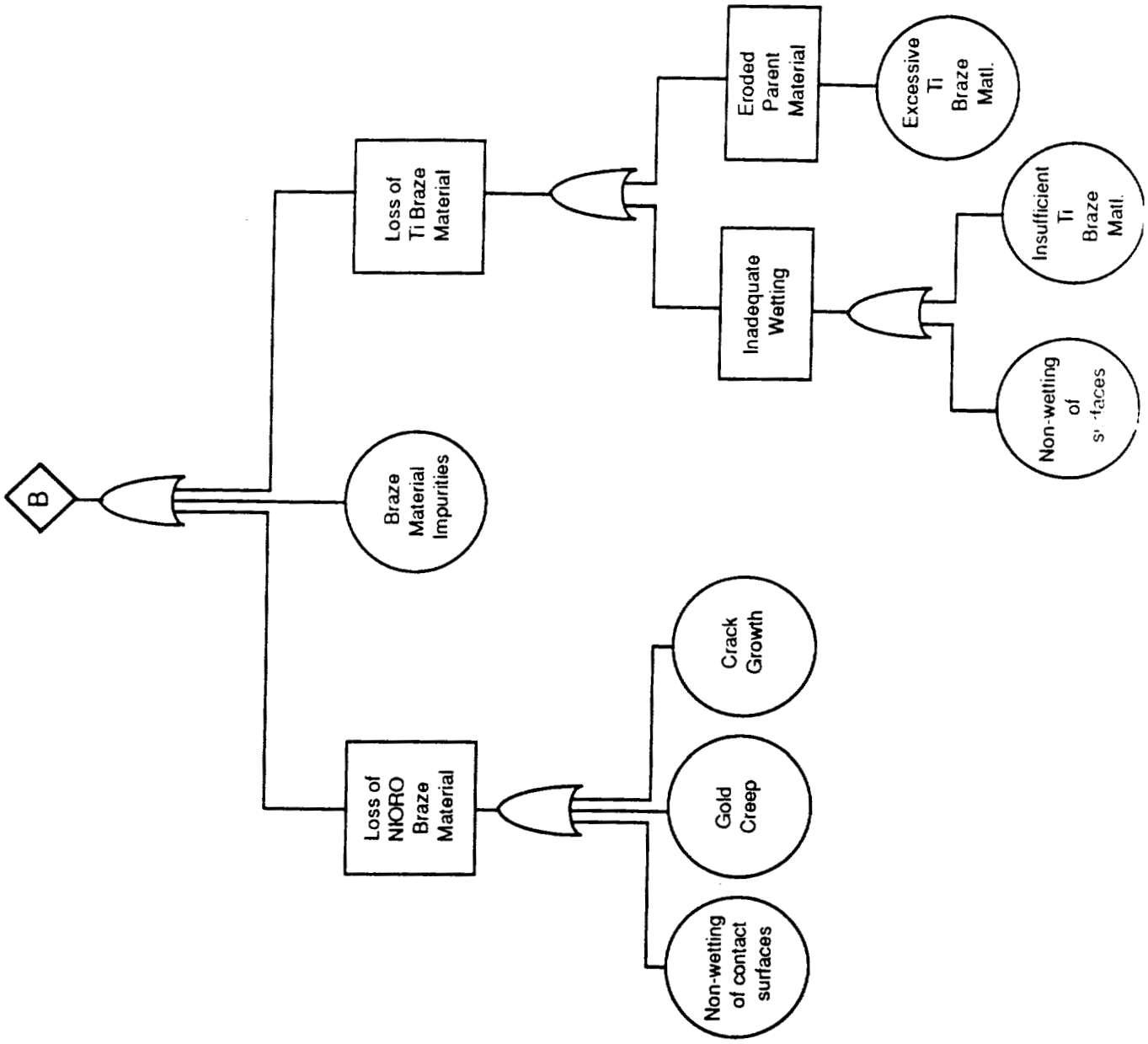

B
Braze Material Impurities
Loss of Ti Braze Material
Eroded Parent Material
Excessive Ti Braze Matl.
Inadequate Wetting
Insufficient Ti Braze Matl.
Non-wetting of s·faces
Loss of NiORO Braze Material
Crack Growth
Gold Creep
Non-wetting of contact surfaces

FIGURE 11

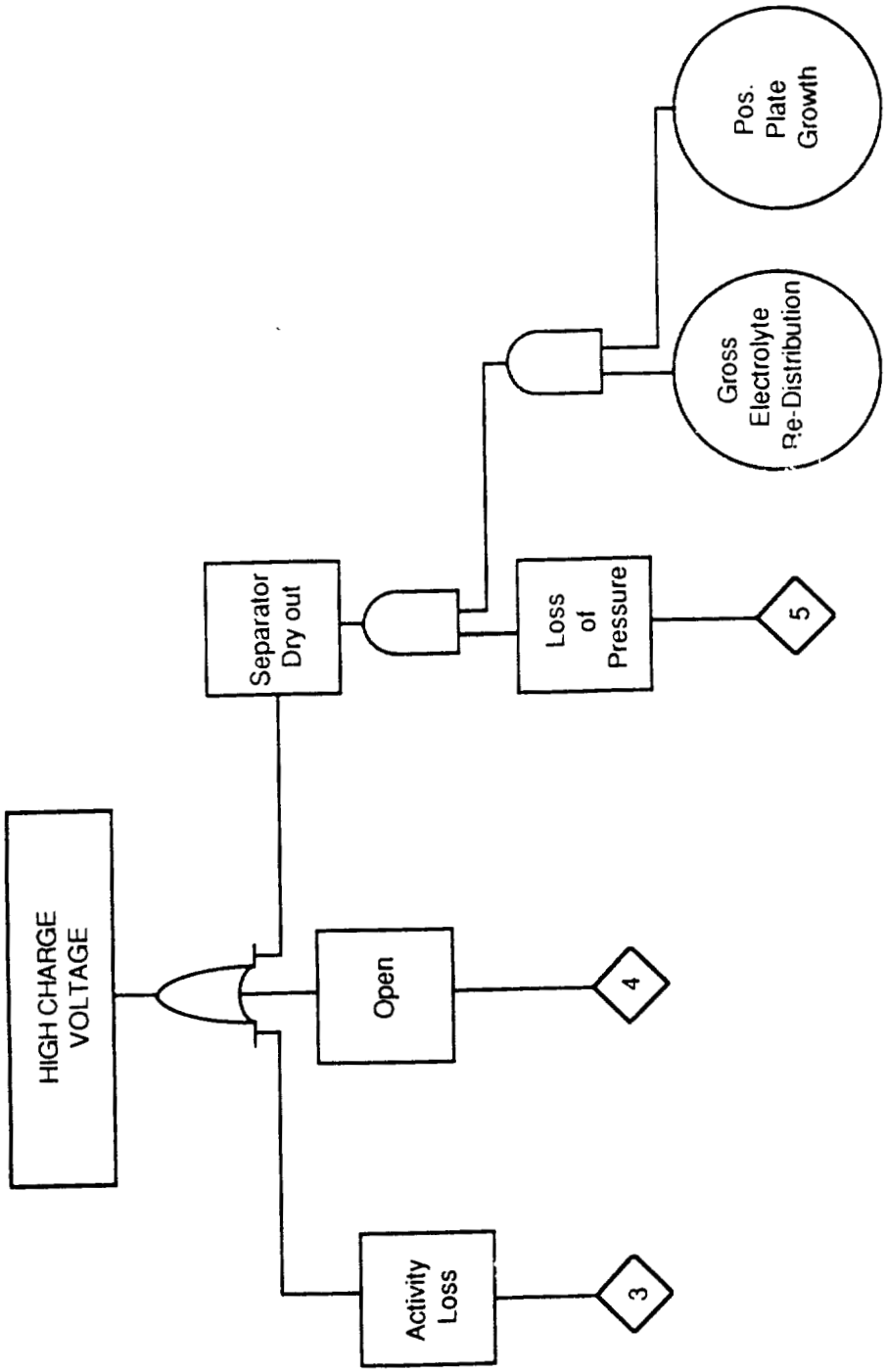

HIGH CHARGE VOLTAGE
Separator Dry out
Loss of Pressure
5
Gross Electrolyte Re-Distribution
Pos. Plate Growth
Open
4
Activity Loss
3

FIGURE 12

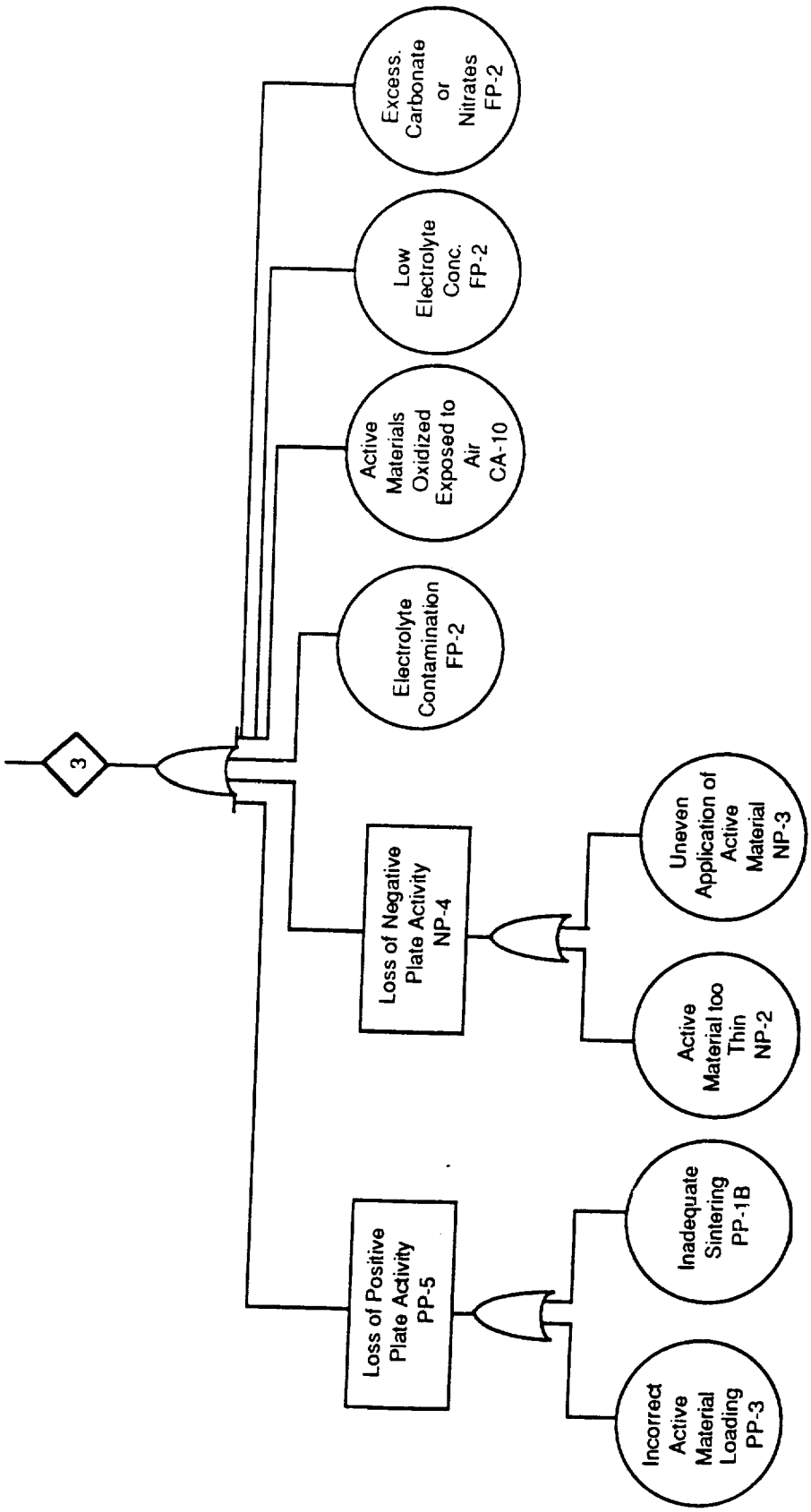

3
Excess. Carbonate or Nitrates FP-2
Low Electrolyte Conc. FP-2
Active Materials Oxidized Exposed to Air CA-10
Electrolyte Contamination FP-2
Loss of Negative Plate Activity NP-4
Uneven Application of Active Material NP-3
Active Material too Thin NP-2
Loss of Positive Plate Activity PP-5
Inadequate Sintering PP-1B
Incorrect Active Material Loading PP-3

FIGURE 13

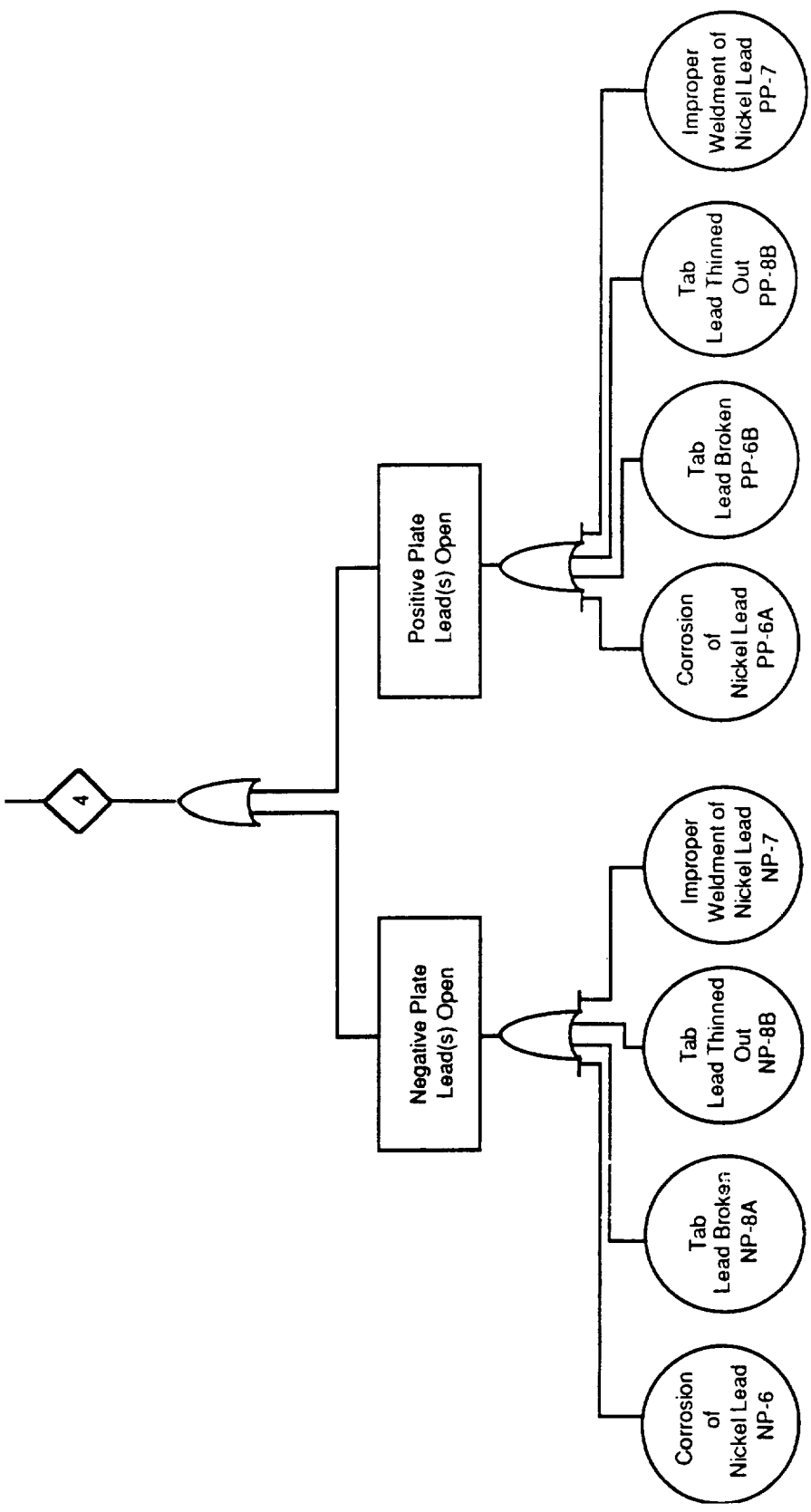

4
Positive Plate Lead(s) Open
Negative Plate Lead(s) Open
Corrosion of Nickel Lead PP-6A
Tab Lead Broken PP-6B
Tab Lead Thinned Out PP-8B
Improper Weldment of Nickel Lead PP-7
Corrosion of Nickel Lead NP-6
Tab Lead Broken NP-8A
Tab Lead Thinned Out NP-8B
Improper Weldment of Nickel Lead NP-7

FIGURE 14

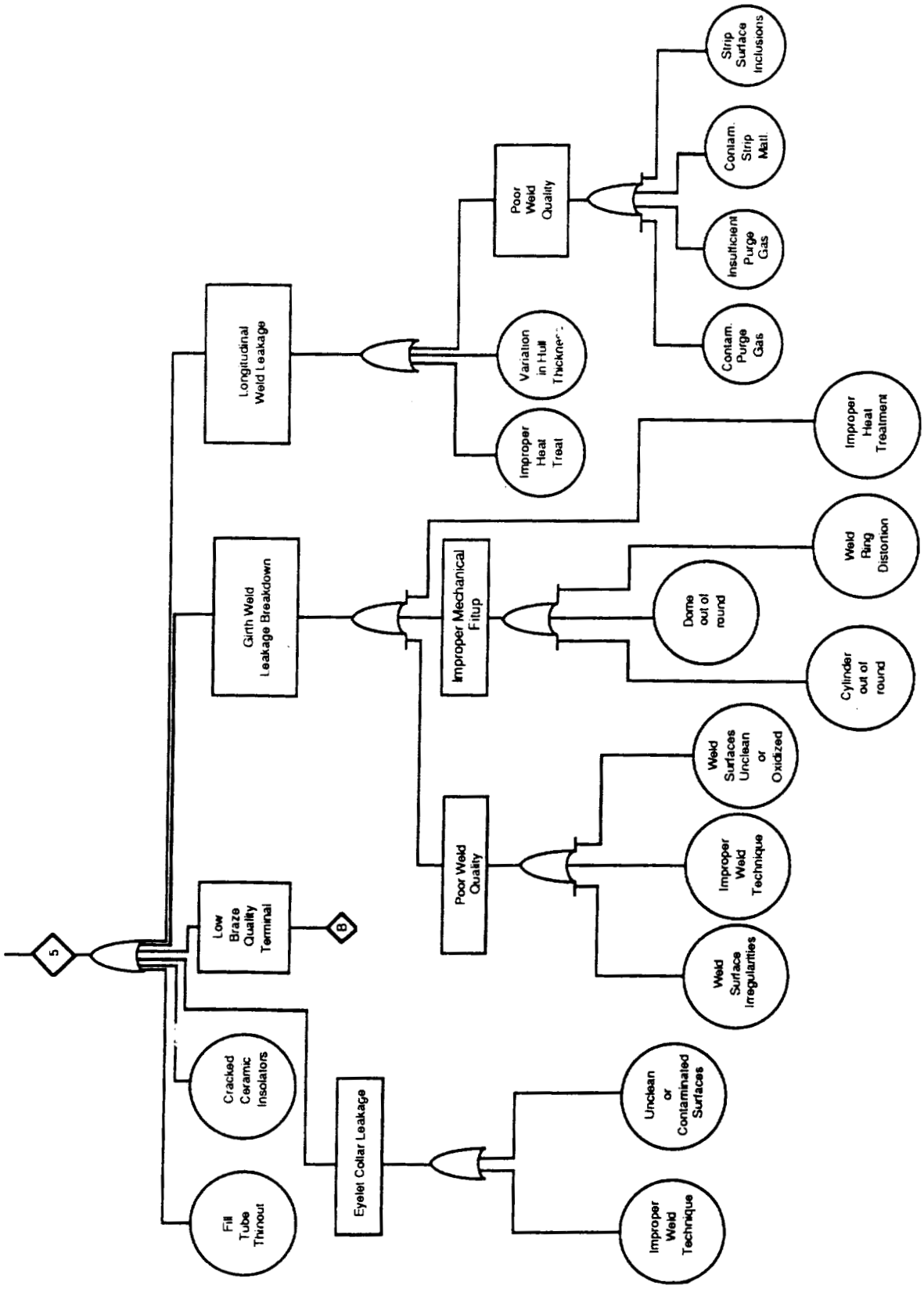

5
Fill Tube Thinout
Cracked Ceramic Insolators
Eyelet Collar Leakage
Unclean or Contaminated Surfaces
Improper Weld Technique
Low Braze Quality Terminal
B
Girth Weld Leakage Breakdown
Improper Mechanical Fitup
Poor Weld Quality
Weld Surface Irregularities
Improper Weld Technique
Weld Surfaces Unclean or Oxidized
Dome out of round
Cylinder out of round
Weld Ring Distortion
Improper Heat Treatment
Longitudinal Weld Leakage
Improper Heat Treat
Variation in Hull Thickness
Poor Weld Quality
Contam. Purge Gas
Insufficient Purge Gas
Contam. Strip Mill
Strip Surface Inclusions

FIGURE 15

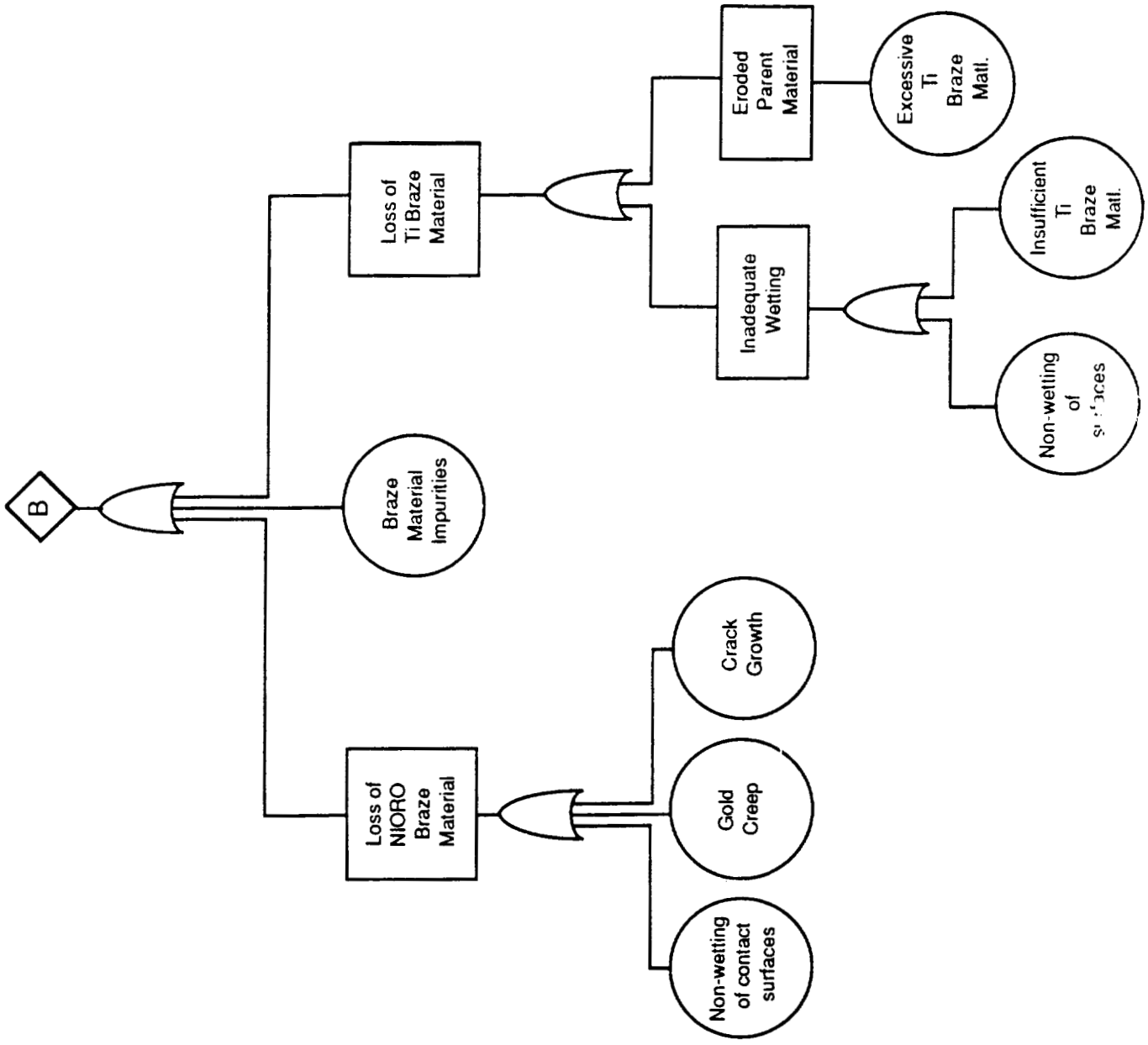

B
Loss of Ti Braze Material
Braze Material Impurities
Loss of NiORO Braze Material
Eroded Parent Material
Inadequate Wetting
Excessive Ti Braze Matl.
Insufficient Ti Braze Matl.
Non-wetting of surfaces
Crack Growth
Gold Creep
Non-wetting of contact surfaces

FIGURE 16

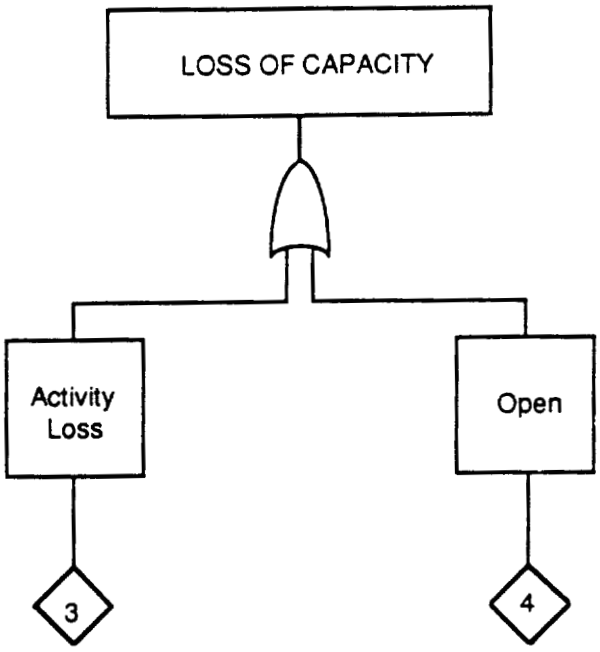


FIGURE 17

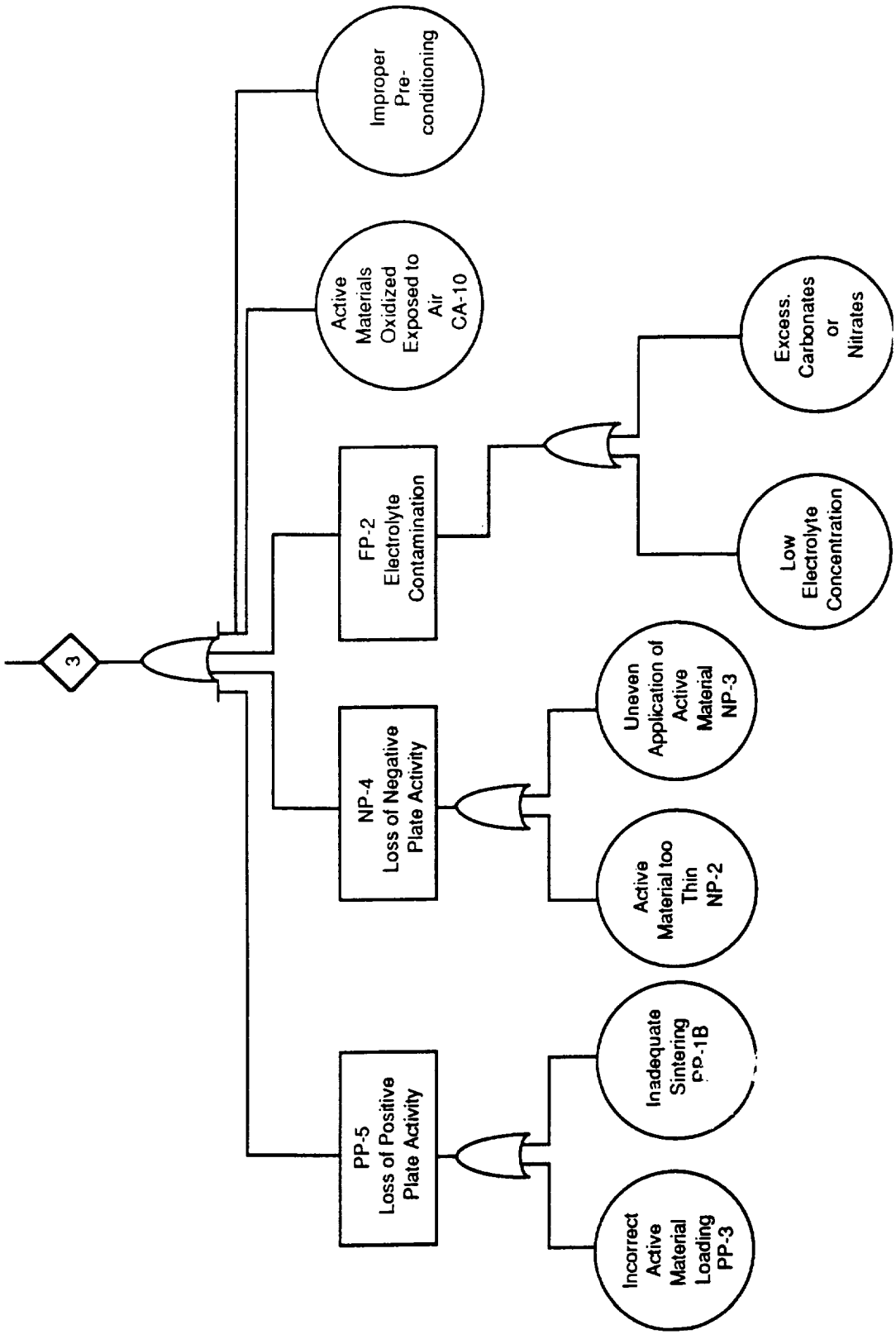

3
Improper Pre-conditioning
Active Materials Oxidized Exposed to Air CA-10
FP-2 Electrolyte Contamination
Excess. Carbonates or Nitrates
Low Electrolyte Concentration
NP-4 Loss of Negative Plate Activity
Uneven Application of Active Material NP-3
Active Material too Thin NP-2
PP-5 Loss of Positive Plate Activity
Inadequate Sintering PP-1B
Incorrect Active Material Loading PP-3

FIGURE 18

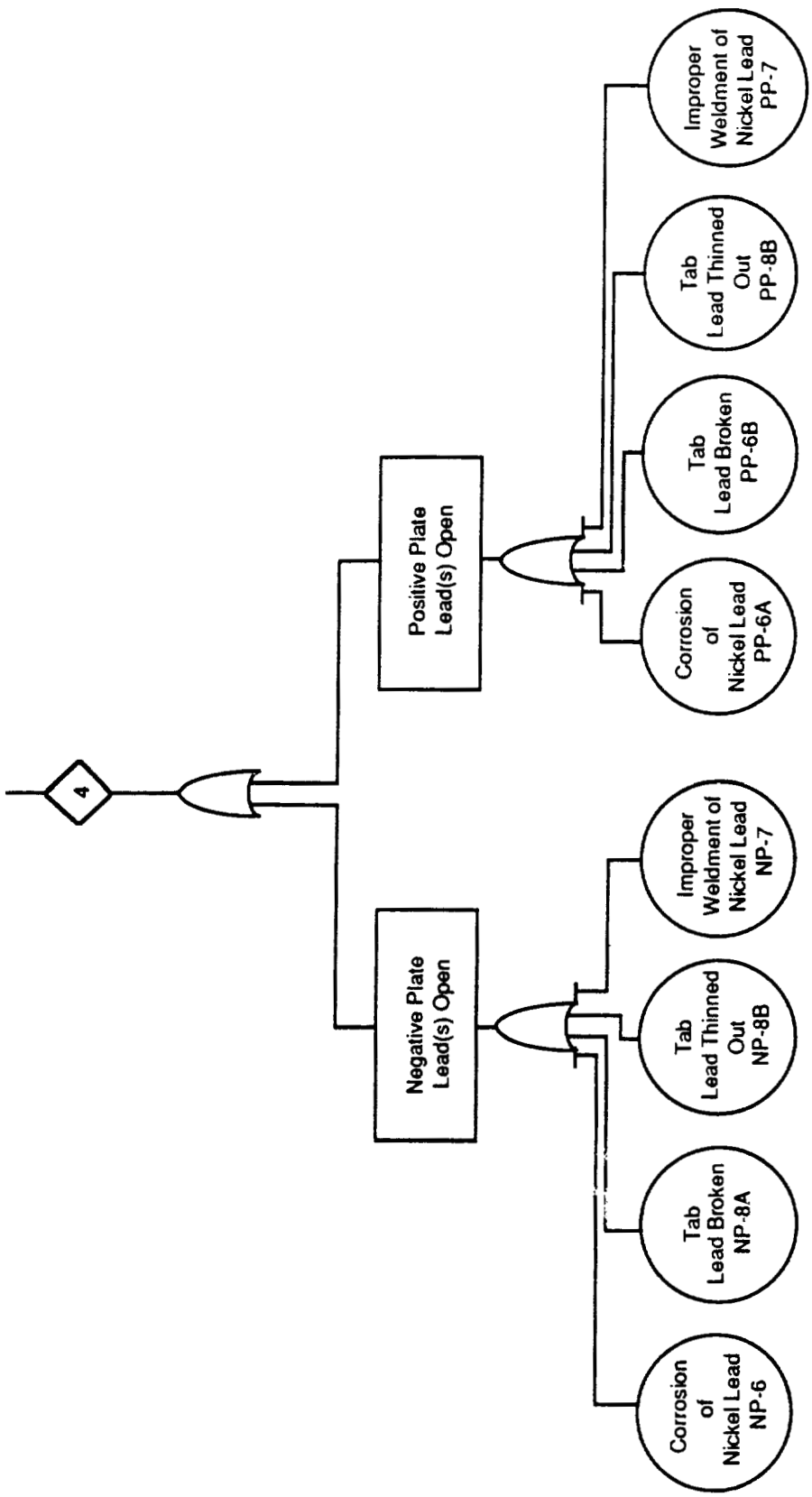

4
Positive Plate Lead(s) Open
Negative Plate Lead(s) Open
Corrosion of Nickel Lead PP-6A
Tab Lead Broken PP-6B
Tab Lead Thinned Out PP-8B
Improper Weldment of Nickel Lead PP-7
Corrosion of Nickel Lead NP-6
Tab Lead Broken NP-8A
Tab Lead Thinned Out NP-8B
Improper Weldment of Nickel Lead NP-7

FIGURE 19

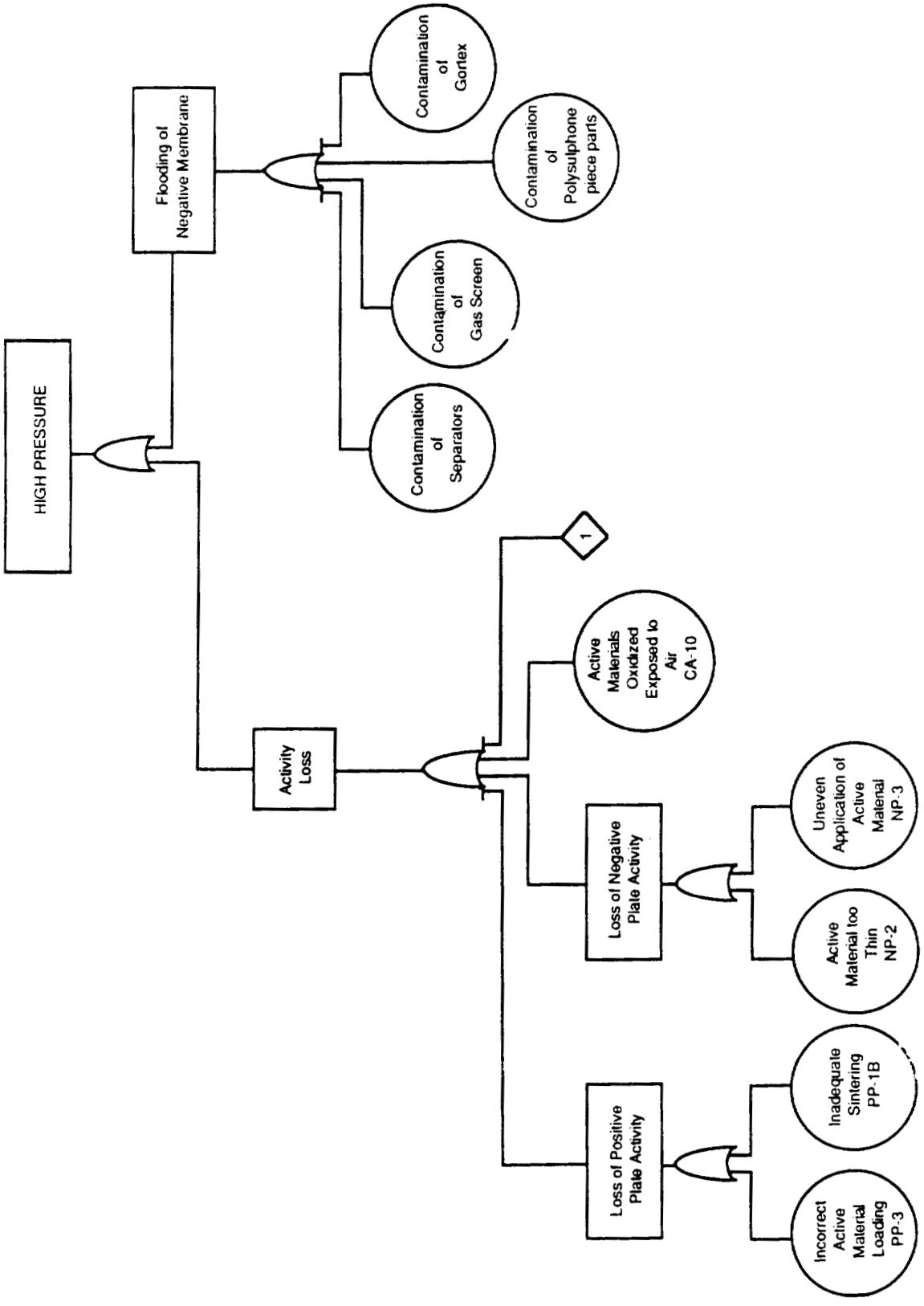

HIGH PRESSURE
Flooding of Negative Membrane
Contamination of Gortex
Contamination of Polysulphone piece parts
Contamination of Gas Screen
Contamination of Separators
Activity Loss
1
Active Materials Oxidized Exposed to Air CA-10
Loss of Negative Plate Activity
Uneven Application of Active Material NP-3
Active Material too Thin NP-2
Loss of Positive Plate Activity
Inadequate Sintering PP-1B
Incorrect Active Material Loading PP-3

FIGURE 20

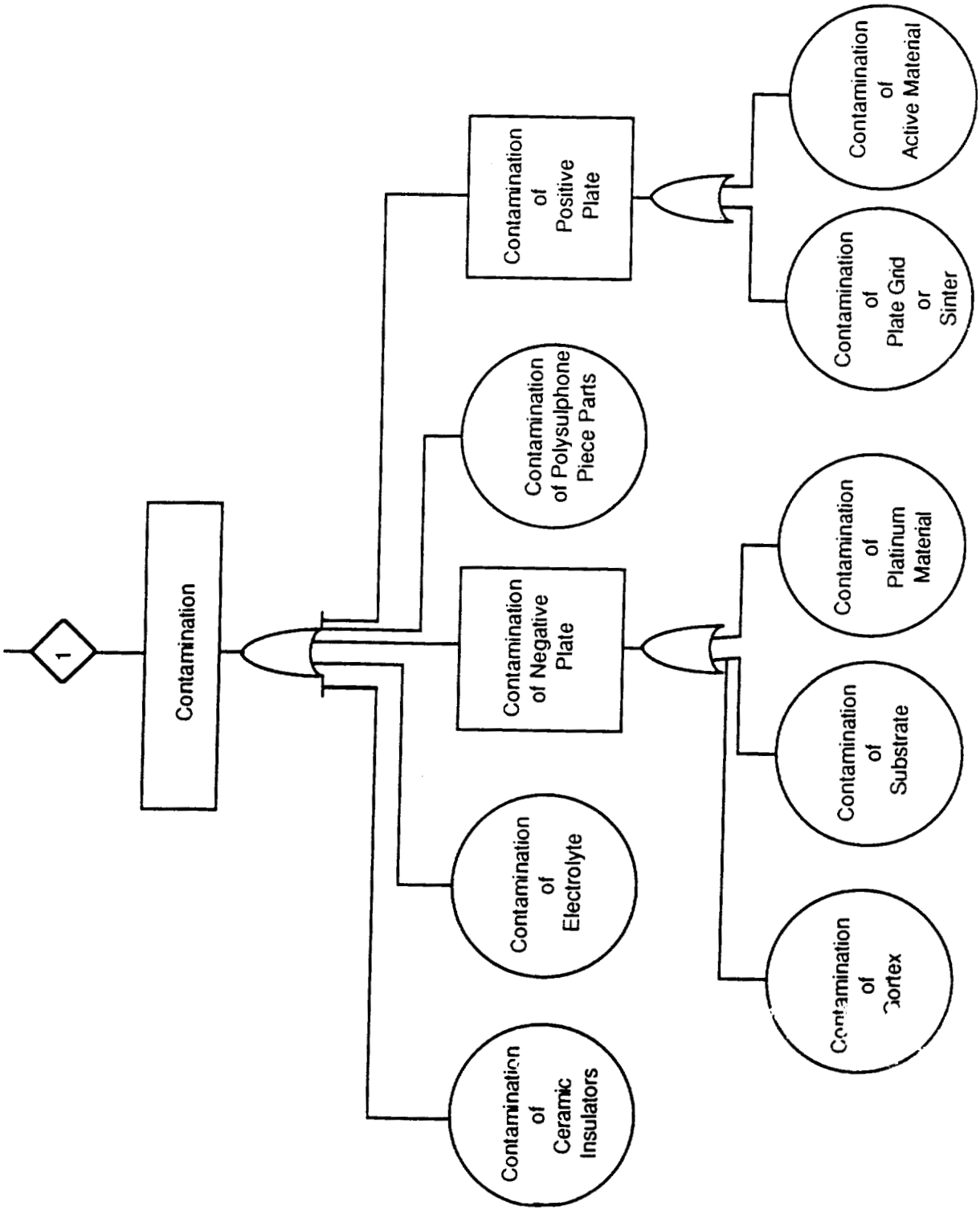

1
Contamination
Contamination of Ceramic Insulators
Contamination of Electrolyte
Contamination of Negative Plate
Contamination of Polysulphone Piece Parts
Contamination of Positive Plate
Contamination of Cortex
Contamination of Substrate
Contamination of Platinum Material
Contamination of Plate Grid or Sinter
Contamination of Active Material

FIGURE 21

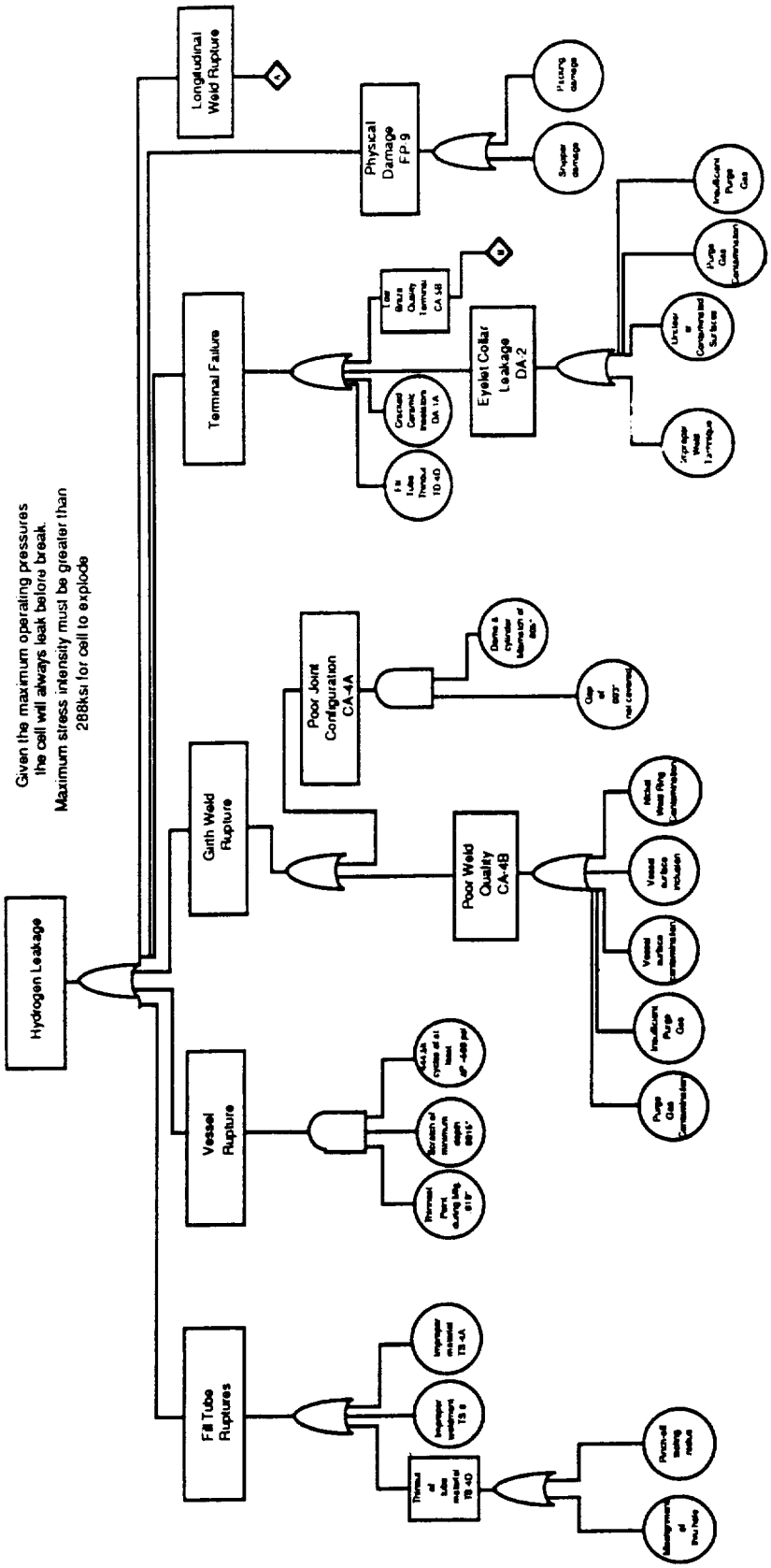

Given the maximum operating pressures
the cell will always leak before break.
Maximum stress intensity must be greater than
288ksi for cell to explode
Hydrogen Leakage
Longitudinal Weld Rupture
Physical Damage FP 9
Terminal Failure
Eyelet Collar Leakage DA-2
Girth Weld Rupture
Poor Joint Configuration CA-4A
Poor Weld Quality CA-4B
Vessel Rupture
Fill Tube Ruptures

FIGURE 22

Failure Modes and Effects Analysis on Gates NiH_2 Battery for LEO Mission

FMEA NO. CA-4B
Critical Item (Yes/No) Yes
Item Name: Girth weld
Part Number: 149C1930AJ1
Quantity: 1
Hardware Location: (Internal)
System: NiH2 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 NiH2 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: D. Rash	Approved By: _____
Approved By: G. Ebel	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: (Note: Rational for Acceptability is applicable to CIL Items only)
(A) Design Safety factor of 3 for burst/operationg pressure & safety factor of 4 for burst/operating cycles
(B) Test Hydrogen leak, chemical leak, cycle, burst and proof tests
(C) Inspection First article and first piece _____
(D) Failure History _____
(E) Operations _____
(F) Maintainability N/A _____

Remarks/Hazards: HAZARD POTENTIAL - Leakage of Hydrogen

FIGURE 23

Establishing Parity with the FMECA

An example of a completed failure mode effects analysis worksheet (Figure 23) is provided to demonstrate how the failure causes are attributed to fault events, in this case Girth Weld Breakdown. The numbering system has been assigned to manufacturing flow steps and the example is FMEA number CA-4B. The failure mode corresponds directly to an event that has three distinct events associated to the upper level event.

Conclusion

The decision process for either qualitative or quantitative analyses is tempered by our view of reality and some model of our system under anlaysis; and, further constrained by our expectations of the external boundaries and robustness of the design. The Fault Tree Analysis is not a stand alone technique due to the top down approach which presupposes the determination of all Top-level or Major fault events; however, the Fault Tree when in a graphic, visual format is an excellent tool for technical reviews. Fault Tree Analyses can be quantified in areas such as System Assessment, Confidence Analysis, and Sensitivity Analysis. The Qualitative Fault Tree Analysis for NiH_2 cells in LEO Mission identifies and analyzes five specific Top-Level failure events; quantification of this Fault Tree has already begun.

References

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).

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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

- DEVELOPPMENT OF A MEDIUM CAPACITY RANGE (30 - 50 Ah) IPV SAFT Ni H_2 CELL (1985 - 1988)

- SHORT TERM QUALIFICATION TESTING REALISED BY MID 1988

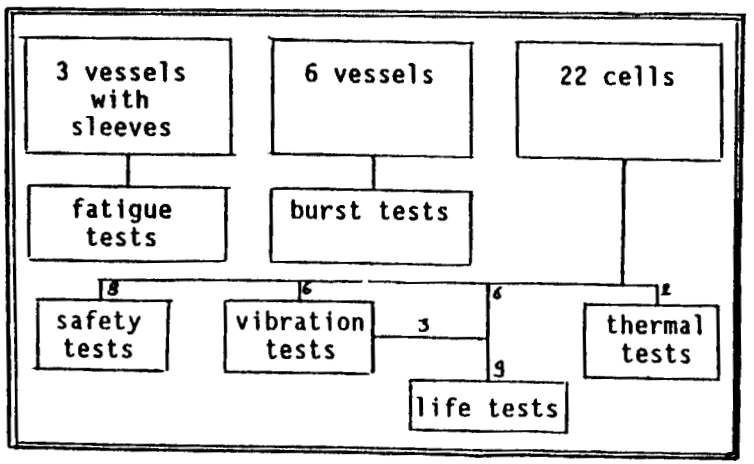


Table 1 : Qualification Test Programm

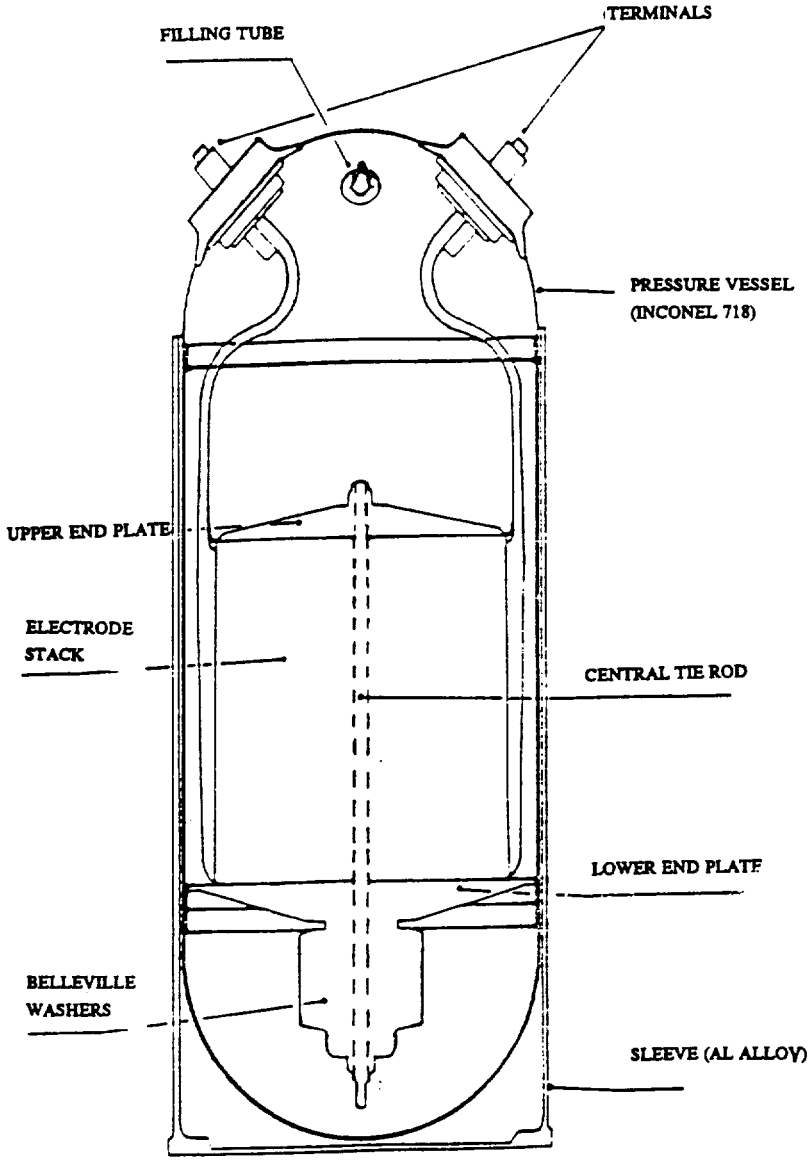
SAFT 50 Ah CELL DESIGN (VHS BL SERIE)

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 (| 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

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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.

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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 ALLOY.

GAP INTERFILLER

- POLYMERIC RESIN.

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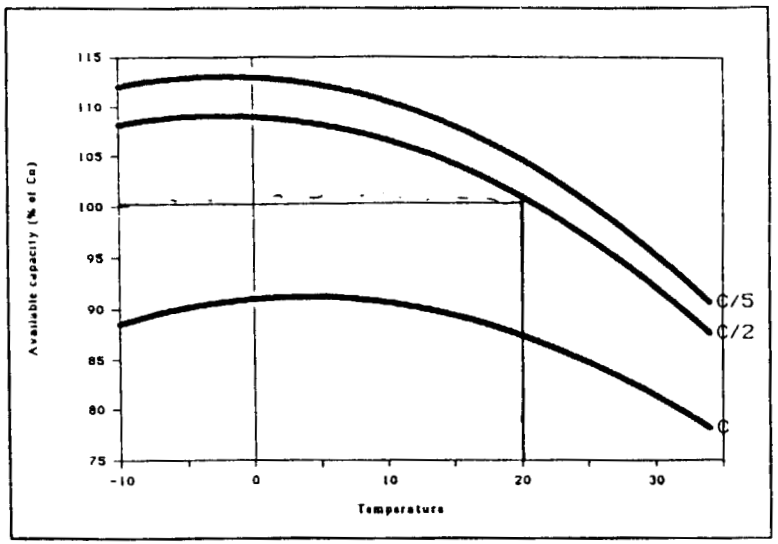
SAFT 50 Ah CELL DESIGN (VHS BL SERIE)

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

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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

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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.

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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

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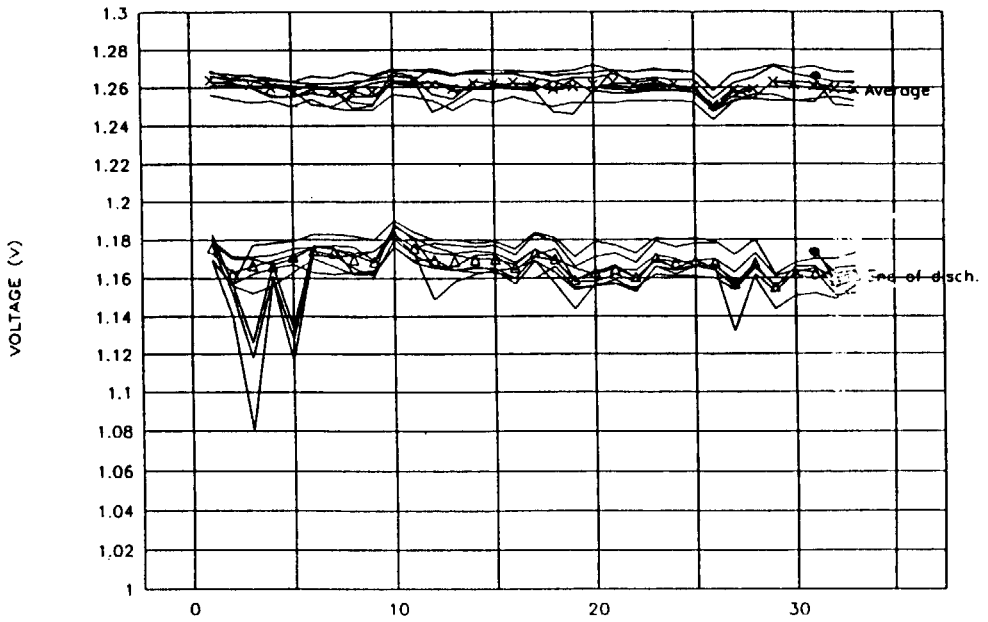
SAFT 50 Ah CELL LIFE TEST

RESULTS

DISCHARGE VOLTAGE EVOLUTION

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



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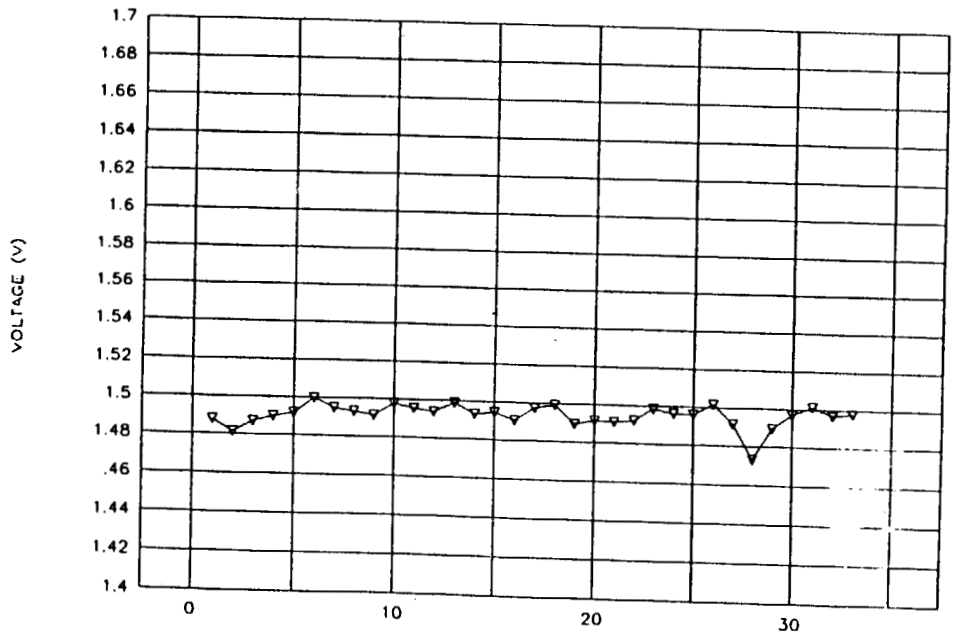
SAFT 50 Ah CELL LIFE TEST RESULTS

END OF CHARGE VOLTAGE EVOLUTION

- NO APPARENT DEGRADATION (1,5 V)



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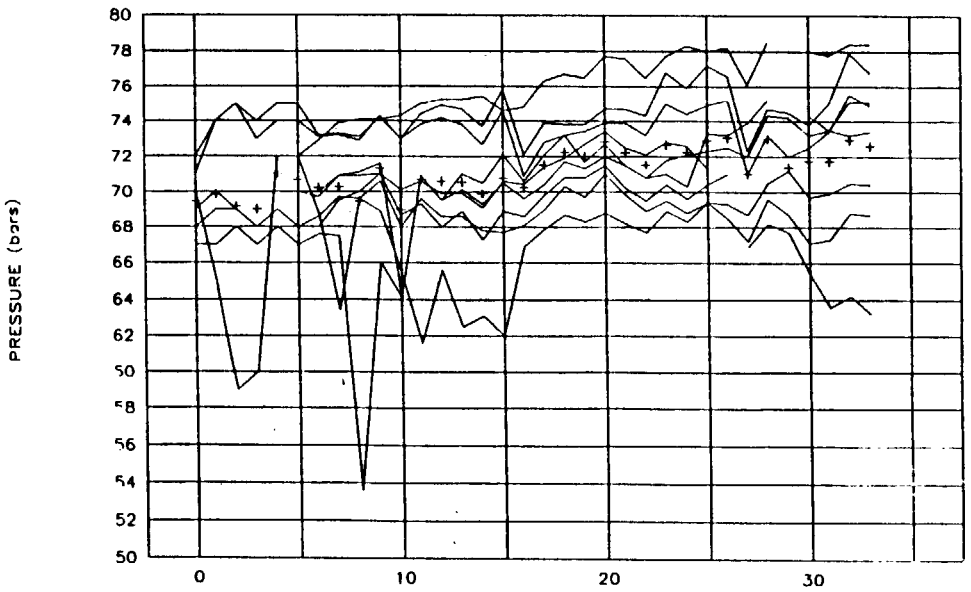
SAFT 50 Ah CELL LIFE TEST RESULTS

END OF CHARGE PRESSURE EVOLUTION REFERENCE CYCLE

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



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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.

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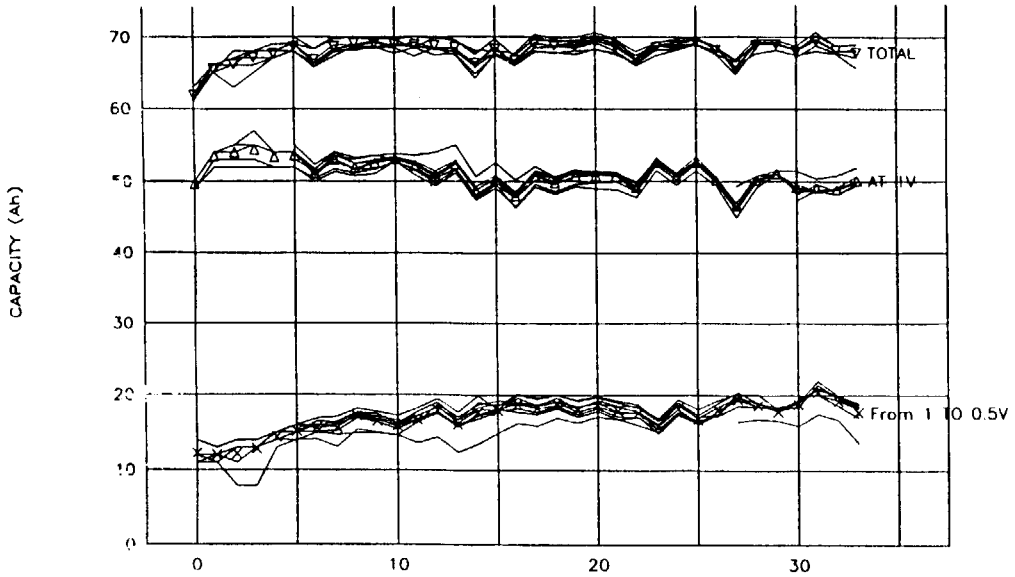
SAFT 50 Ah CELL LIFE TEST RESULTS

STANDARD CAPACITY MEASUREMENT

- OVERALL CAPACITY REMAINS VERY STABLE.
- SLIGHT STANDARD CAPACITY FADING (54 ---> 49 Ah)

  WITH CORRESPONDING RESIDUAL INCREASE.



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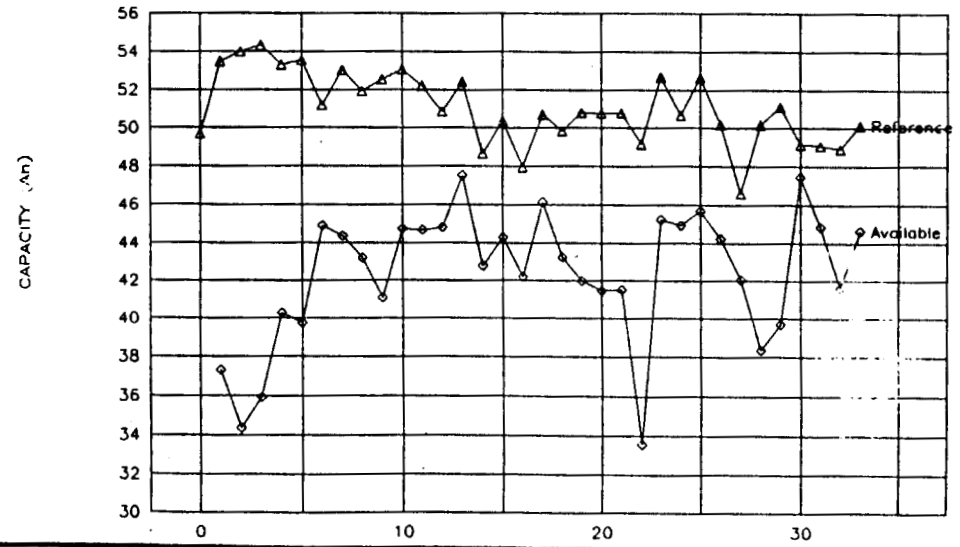
SAFT 50 Ah CELL LIFE TEST RESULTS

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).



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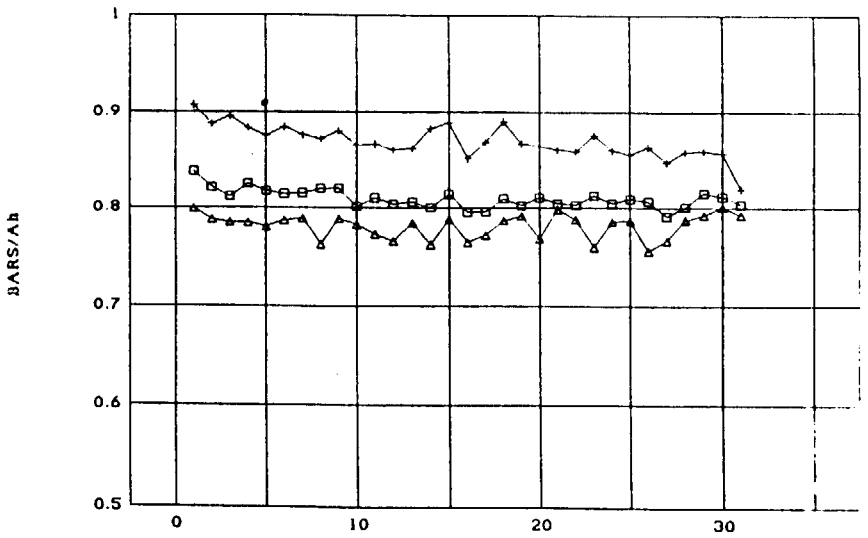
SAFT 50 Ah CELL LIFE TEST RESULTS

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.

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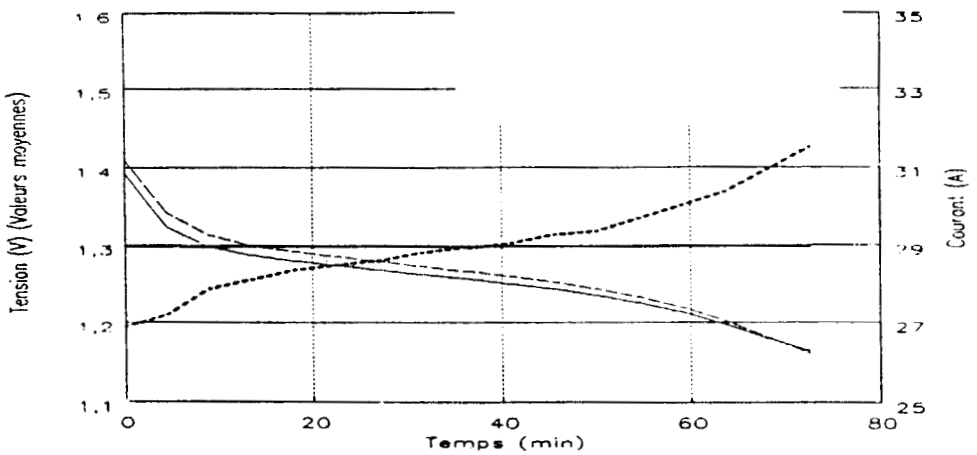
SAFT 50 Ah CELL LIFE TEST RESULTS

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.



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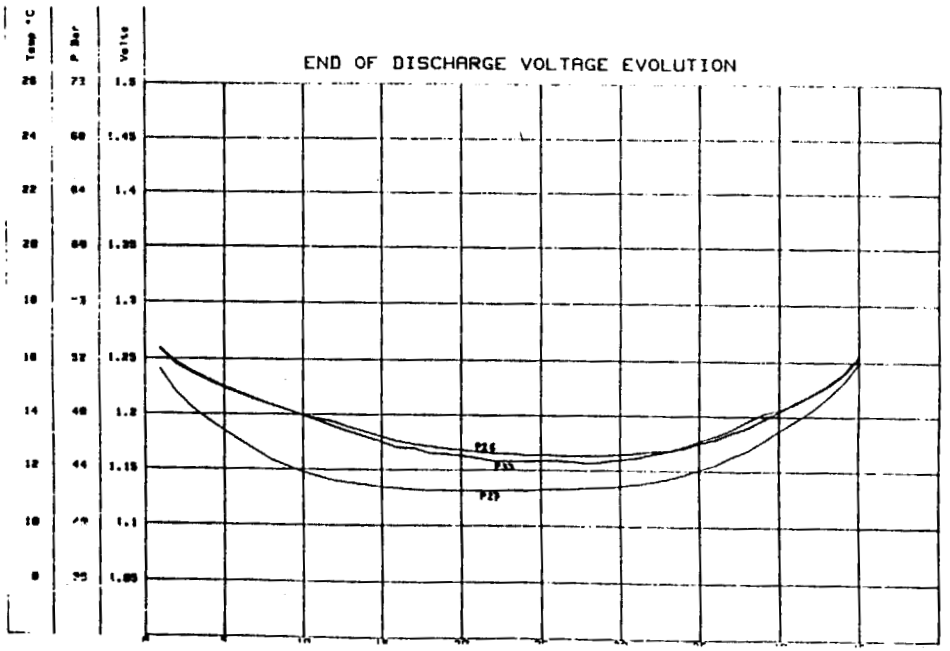
SAFT 50 Ah CELL LIFE TEST RESULTS

RECONDITIONNING EFFECT

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



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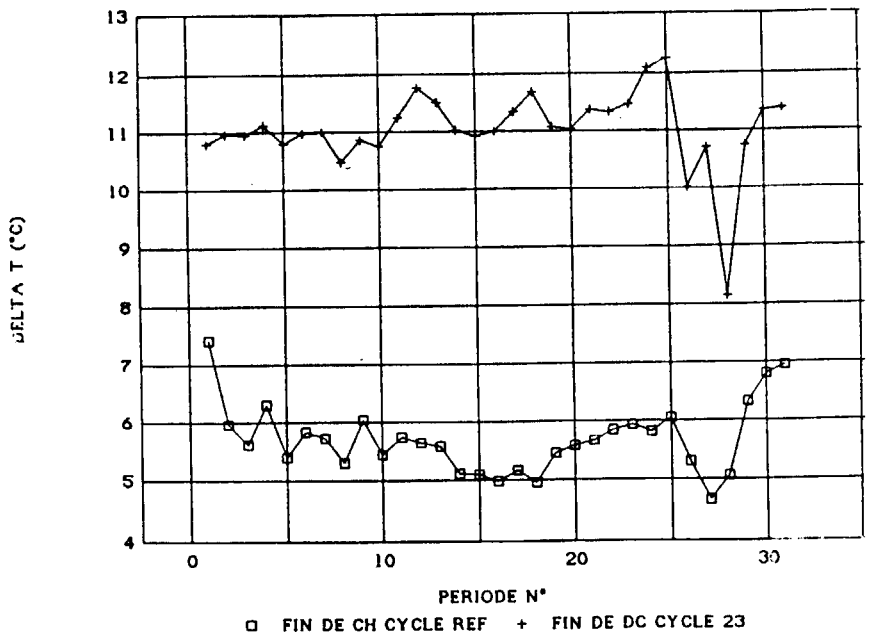
SAFT 50 Ah CELL LIFE TEST RESULTS

TEMPERATURE EVOLUTION

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



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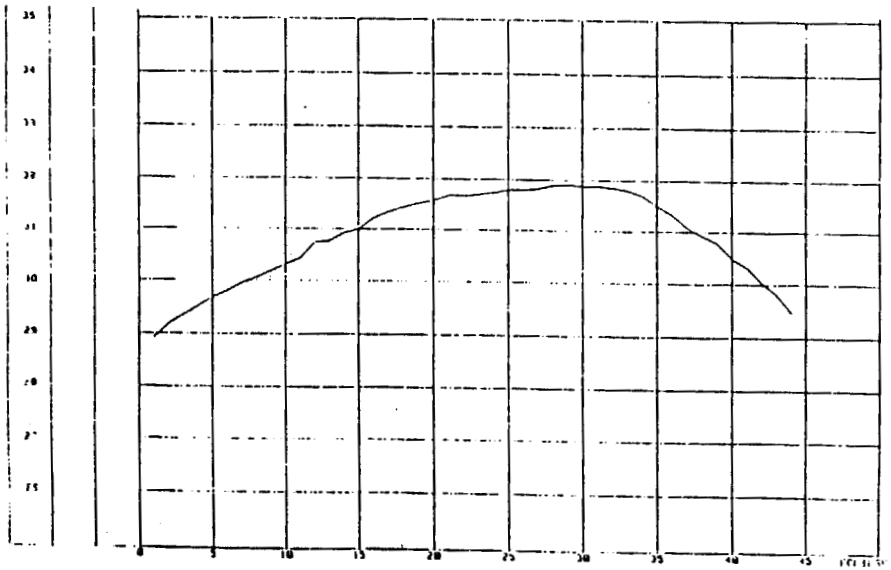
SAFT 50 Ah CELL LIFE TEST RESULTS

EOD CURRENT PROFILE (POWER ct) SEASON 29

- ASSYMETRIC CURVE WITH MAXIMUM AT CYCLE 30.



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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.

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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.

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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.

EAGLE PICHER
Electronics Division
Joplin, MO

ADVANCED SYSTEMS OPERATION

1991 NASA AEROSPACE BATTERY WORKSHOP

Use of Semi-Automated Test Systems for Nickel-Hydrogen Cells and Batteries

Steve Girard
Eagle-Picher Industries, Inc.
Joplin, Missouri

EAGLE PICHER
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

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1991 NASA AEROSPACE BATTERY WORKSHOP

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

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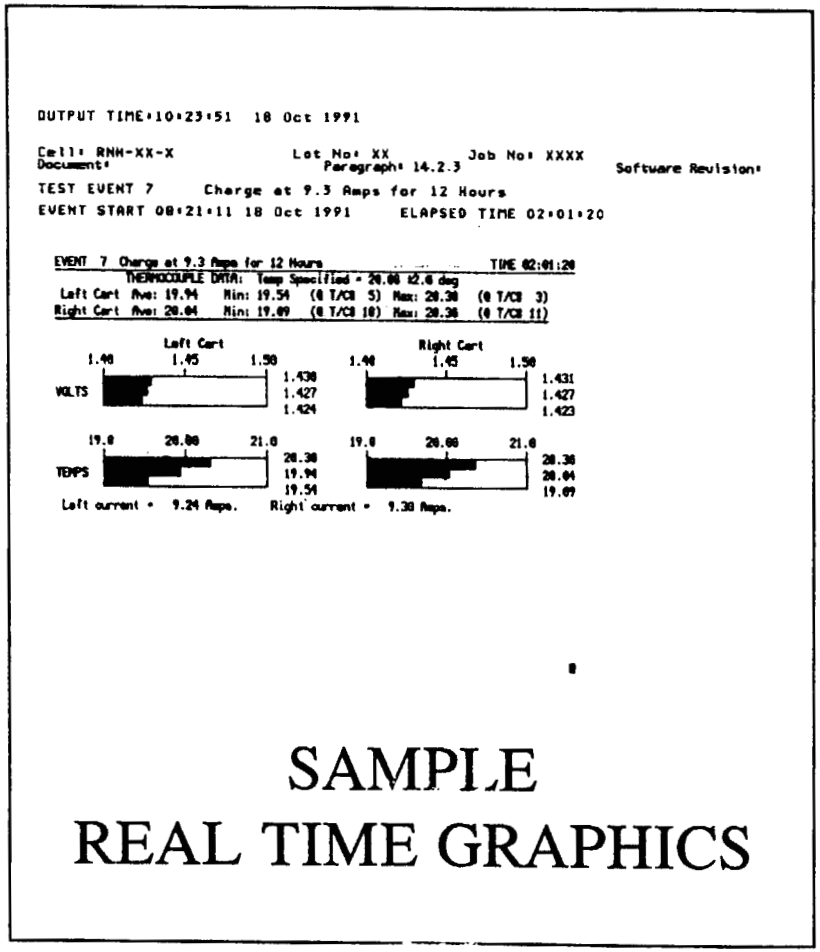
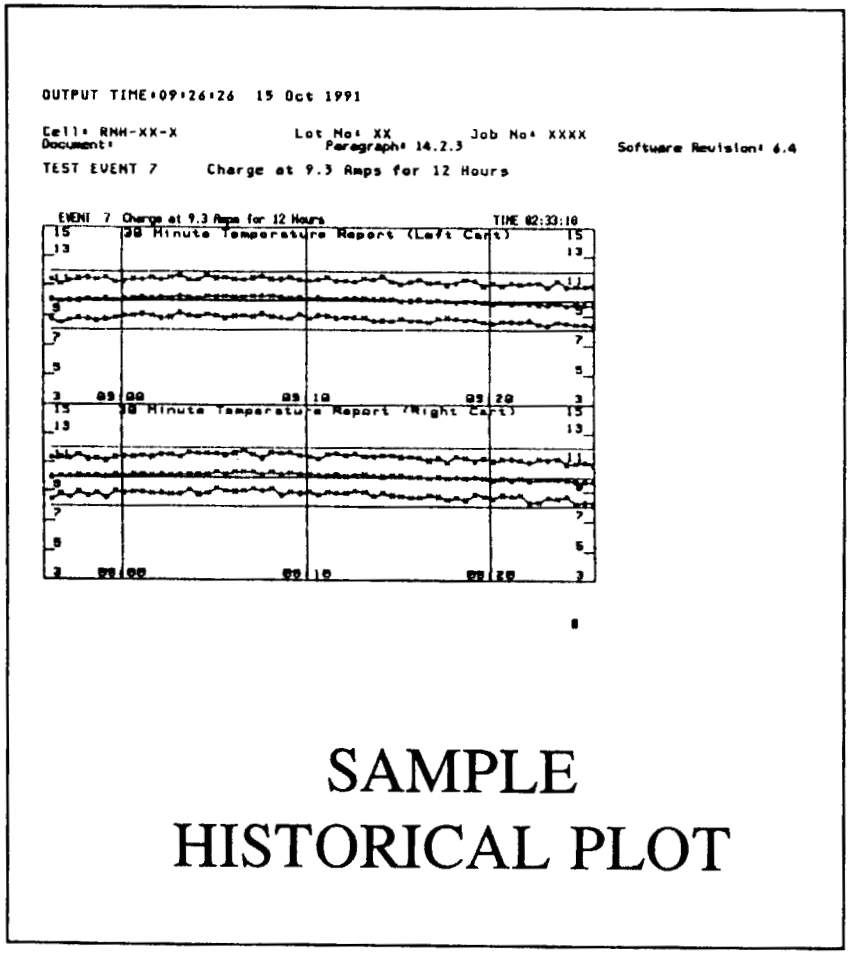
1991 NASA AEROSPACE BATTERY WORKSHOP



SAMPLE
REAL TIME GRAPHICS



SAMPLE
HISTORICAL PLOT

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Joplin, MO

ADVANCED SYSTEMS OPERATION

1991 NASA AEROSPACE BATTERY WORKSHOP

```
OUTPUT TIME:18:40:19  14 Oct 1991

Cell: RNH-XX-X              Lot No: XX          Job No: XXXX
Document:                   Paragraph: 14.2.3              Software Revision: 6.4

TEST EVENT 7      Charge at 9.3 Amps for 12 Hours
EVENT START 16:40:16 14 Oct 1991      ELAPSED TIME 02:00:00

------------------------------------------ CELL VOLTAGES ------------------------------------------
 1) 1.424   2) 1.426   3) 1.425   4) 1.425   5) 1.428   6)         7) 1.429   8) 1.424   9) 1.428  10) 1.428
11) 1.428  12) 1.430  13) 1.427  14)        15) 1.427  16) 1.426  17) 1.429  18) 1.429  19) 1.425  20) 1.428
21) 1.425  22) 1.429  23) 1.427  24) 1.426  25) 1.429  26) 1.427  27) 1.426  28) 1.429  29) 1.426  30)
31) 1.426  32) 1.427  33)        34) 1.427  35) 1.426  36) 1.429  37) 1.427  38) 1.424  39) 1.425  40) 1.426
41) 1.427  42) 1.427  43) 1.425  44) 1.429  45) 1.429  46) 1.425  47) 1.429  48) 1.429  49) 1.425  50) 1.427
51) 1.427  52) 1.425  53) 1.429  54) 1.428  55) 1.429  56) 1.427  57)        58)        59)        60) 1.428
61) 1.431  62) 1.431  63) 1.424  64) 1.427  65) 1.425  66) 1.427  67) 1.424  68) 1.429  69) 1.429  70) 1.428
71)        72) 1.426  73) 1.425  74) 1.429  75) 1.430  76)        77) 1.425  78) 1.429  79) 1.429  80) 1.424
81) 1.429  82) 1.429  83) 1.423  84) 1.430  85) 1.426  86) 1.427  87) 1.429  88) 1.429  89) 1.427  90) 1.431
91) 1.423  92) 1.431  93) 1.426  94) 1.424  95) 1.424  96) 1.425  97) 1.425  98) 1.425  99)        100) 1.424

           Minimum      Average      Maximum
Voltages:  1.4231 ( 83)   1.4269   1.4308 ( 62)
 Left current =  9.24 Amps (  18.49 AH)   Right current =  9.30 Amps (  18.60 AH)
---------------------------------------- THERMOCOUPLE DATA ----------------------------------------
 1) 19.00   2) 20.36   3) 20.37   4) 19.51   5) 19.92   6) 20.44   7) 19.62   8) 20.32   9) 20.29  10) 19.80  Ave: 20.00
11) 19.55  12) 19.71  13) 19.93  14) 20.41  15) 19.75  16) 20.28  17) 20.23  18) 20.03  19) 20.23  20) 19.84  Ave: 19.99


STRAIN GAGES:
   1  0.0030352   2  0.0030625   3  0.0030797   4  0.0030344   5  0.0030040   6  0.0030194   7  0.0030402   8  0.0030234
   9  0.0030530  10  0.0030703  11  0.0030859  12  0.0030821  13  0.0030429  14  0.0030698  15  0.0030600

TRANSDUCERS:
   1   2.23004   2   2.23442   3   2.23417   4   2.23019

EXCITATION VOLTAGE:  15.9560000
```

SAMPLE
CELL LEVEL
PRINTOUT

```
Post-Thermal Vac Testing

Battery: SAR-XXXXX          Job No: XXXX
Document: ATP-XXX Rev X     Paragraph: 4.16.3.5            Software Revision: 6.14

TEST EVENT 5      Nameplate - Initial Charge - Step 2
EVENT START 08:47:04 26 Jul 1991      ELAPSED TIME 11:00:00

------------------------------------ BATTERY#1 (SN12) ------------------------------------
CELL CHANNELS
 1  1.514   2  1.511   3  1.514   4  1.513   5  1.513   6  1.520   7  1.511   8  1.512
 9  1.512  10  1.511  11  1.510  12  1.511  13  1.512  14  1.514  15  1.513  16  1.514
17  1.525  18  1.511  19  1.512  20  1.511  21  1.511  22  1.512
BATTERY VOLTS  33.284                                                  CURRENT    3.97

T/C DATA (DEG C)
 1) 10.38   2)         3) 9.11    4) 8.40    5) 10.42   6) 9.97
 7)  .78    8)  .16    9) -.85   10) -.17   11) -.51   12) -.89
13) n/a    14) n/a    15) n/a    16) n/a    17) n/a    18) n/a
19) n/a    20) n/a    21) n/a    22) n/a    23) n/a    24) n/a
AVE) 9.65

STRAIN GAGES:    1 3.30406 (  793.0)    2 3.57333 (  857.6)    3 3.52104 (  845.0)
                 4 3.66844 (  880.5)
THERMISTORS :    1  3409.4 ( 11.81)    2  3373.5 ( 12.07)    3  3566.0 ( 10.74)
                 4  3325.4 ( 12.41)    5  3485.7 ( 11.29)    6  3391.7 ( 11.94)
EXCIT. VOLTS:      30.065

------------------------------------ BATTERY#2 (SN13) ------------------------------------
CELL CHANNELS
 1  1.515   2  1.514   3  1.516   4  1.515   5  1.514   6  1.523   7  1.512   8  1.513
 9  1.513  10  1.515  11  1.513  12  1.515  13  1.514  14  1.514  15  1.513  16  1.515
17  1.522  18  1.515  19  1.514  20  1.515  21  1.514  22  1.513
BATTERY VOLTS  33.317                                                  CURRENT    4.01

T/C DATA (DEG C)
25)  9.45   26)  8.90   27) 10.14   28) 10.58   29)  9.38   30)  9.74
31) -1.21   32)  -.62   33)  -.04   34)  -.31   35) -1.15   36) -1.17
37)  n/a    38)  n/a    39)  n/a    40)  n/a    41)  n/a    42)  n/a
43)  n/a    44)  n/a    45)  n/a    46)  n/a    47)  n/a    48)  n/a
AVE)  9.70

STRAIN GAGES:    1 3.44639 (  875.1)    2 3.50263 (  840.6)    3 3.56037 (  854.5)
                 4 3.77540 (  904.1)
THERMISTORS :    1  3504.0 ( 11.16)    2  3522.1 ( 11.04)    3  3527.5 ( 11.00)
                 4  3457.1 ( 11.48)    5  3494.0 ( 11.23)    6  3500.5 ( 11.19)
EXCIT. VOLTS:      30.060
```

SAMPLE
BATTERY LEVEL
PRINTOUT

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Electronics Division
Joplin, MO

ADVANCED SYSTEMS OPERATION

1991 NASA AEROSPACE BATTERY WORKSHOP

Activation and Conditioning / Cell Selection

Cell: RNH-XX-X Lot No: 14
Document: EP-MP-XXX Rev X Paragraph: 5.2.2 Software Revision: 6.4

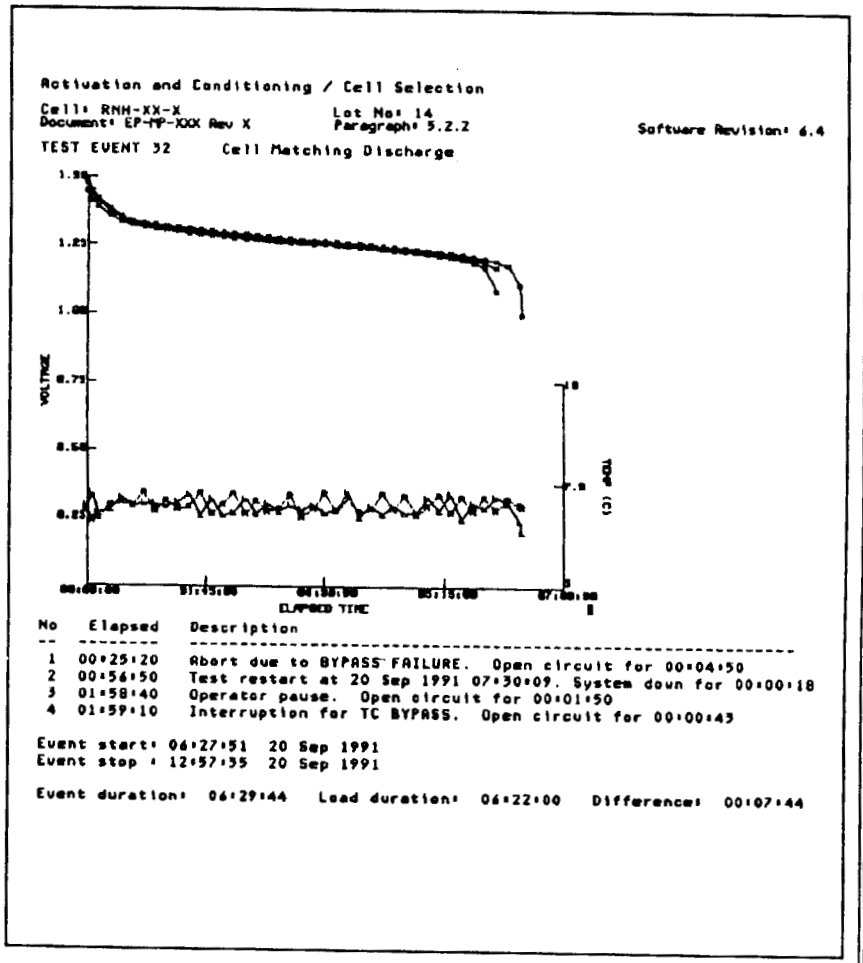
TEST EVENT 32 Cell Matching Discharge

Time to bypass at 1.000 volt

Cell	MM:SS	AH	WH	Volts	Cell	MM:SS	AH	WH	Volts	Cell	MM:SS	AH	WH	Volts
1	376:10	94.8	120.8	0.988	2	374:10	94.8	120.7	0.991	3	379:00	95.5	121.5	0.992
4	379:30	95.4	121.8	0.995	5	382:00	96.3	122.6	0.997	6	377:10	95.1	120.9	0.994
7	375:10	94.6	120.5	0.997	8	376:40	94.9	120.8	0.998	9	379:10	95.6	121.6	0.999
10	381:40	96.2	122.5	0.995	11	380:20	95.8	122.0	0.996	12	375:50	94.7	120.7	0.997
13	376:20	94.8	120.8	0.997	14	378:30	95.4	121.5	0.998	15	380:20	95.8	122.0	0.998
16	377:00	95.0	120.9	0.996	17	374:10	94.3	119.9	0.995	18	371:20	93.6	119.0	0.999
19	378:50	95.5	121.2	0.998	20	375:50	94.7	120.2	0.989	21	373:30	94.1	119.6	0.999
22	373:50	94.2	119.7	0.997	23	374:00	94.5	119.6	1.000	24	377:00	95.0	120.7	0.993
25	373:40	94.2	119.7	0.999	26	374:50	94.5	120.1	0.989	27	373:00	94.0	119.6	0.998
28	374:00	94.3	119.8	0.995	29	374:50	94.5	120.0	0.990	30	376:30	94.9	120.5	0.992
31	374:40	94.4	119.8	0.994	32	375:10	94.6	120.2	0.981	33	376:30	94.9	120.4	0.996
34	370:50	93.5	118.7	0.998	35	373:10	94.1	119.4	0.992	36	375:10	94.1	119.4	1.000
37	375:50	94.6	120.1	0.994	38	373:00	94.0	119.5	0.999	39	375:00	94.0	119.4	0.994
40	375:30	94.6	120.1	0.992	41	375:10	94.6	120.2	0.995	42	371:50	93.7	119.0	0.999
43	370:10	93.3	118.6	0.979	44	371:00	93.5	118.8	0.995	45	372:20	93.8	119.2	0.992
46	370:50	93.5	118.7	0.989	47	372:40	93.9	119.4	0.999	48	373:10	94.1	119.2	0.990
49	370:40	93.4	118.4	1.000	50	373:30	94.1	119.4	1.000	51	n/a	n/a	n/a	n/a
52	n/a	n/a	n/a	n/a	53	n/a	n/a	n/a	n/a	54	n/a	n/a	n/a	n/a
55	n/a	n/a	n/a	n/a	56	n/a	n/a	n/a	n/a	57	n/a	n/a	n/a	n/a
58	n/a	n/a	n/a	n/a	59	n/a	n/a	n/a	n/a	60	n/a	n/a	n/a	n/a
61	370:10	93.4	118.5	0.980	62	371:50	93.8	119.1	0.996	63	375:10	94.6	120.0	0.994
64	368:20	92.9	118.0	0.999	65	361:50	91.3	115.5	0.996	66	372:40	94.0	119.3	0.996
67	372:40	94.0	119.2	0.993	68	374:10	94.4	119.9	0.990	69	371:00	93.6	118.8	0.995
70	373:40	94.3	119.5	0.993	71	375:10	94.6	120.1	0.984	72	371:20	93.7	118.9	0.998
73	373:10	94.1	119.6	0.992	74	371:30	93.7	119.2	0.998	75	375:10	94.6	120.1	0.981
76	370:10	93.4	118.5	0.999	77	373:10	94.1	119.4	0.998	78	371:50	93.8	119.2	1.000
79	370:30	93.5	118.7	0.997	80	374:10	94.4	119.7	0.998	81	370:40	93.5	118.6	0.998
82	371:50	93.8	119.0	0.990	83	371:20	93.7	118.7	0.992	84	368:10	92.9	117.8	1.000
85	363:40	91.8	116.0	0.994	86	368:10	92.9	117.7	0.996	87	369:40	93.3	118.2	0.995
88	370:00	93.4	118.4	0.989	89	372:20	93.9	119.1	0.992	90	365:50	92.3	116.6	0.989
91	369:40	93.3	118.2	0.998	92	374:20	94.4	119.7	0.993	93	373:20	94.2	119.4	0.991
94	372:10	93.9	119.0	0.994	95	366:50	92.6	117.1	0.998	96	366:10	92.4	116.9	1.000
97	363:00	91.6	115.9	0.991	98	363:40	91.8	116.1	0.995	99	371:10	93.6	118.4	0.993
100	366:40	92.5	116.9	0.999	101	375:30	94.7	120.0	0.994	102	362:50	91.5	115.8	0.989
103	370:40	93.5	118.4	1.000	104	364:50	92.1	116.3	0.999	105	367:50	92.8	117.7	0.995
106	363:10	91.6	115.9	0.992	107	366:40	92.5	116.9	0.990	108	366:50	92.6	117.0	0.992
109	367:30	92.7	117.2	1.000	110	366:20	92.4	116.6	0.997	111	379:20	95.7	121.3	0.998

	Amp.Hr.	Cell	Watt Hr.	Cell
Minimum	91.29	65	115.44	65
Maximum	94.26	5	122.64	5
Average	93.94		119.20	
Sigma	1.06		1.56	

Group Range (AH)			#	
91.200	-	91.838	6	******
91.838	-	92.475	4	****
92.475	-	93.112	9	*********
93.112	-	93.750	20	********************
93.750	-	94.388	26	**************************
94.388	-	95.025	25	*************************
95.025	-	95.662	6	******
95.662	-	94.300	5	*****



No	Elapsed	Description
1	00:25:20	Abort due to BYPASS FAILURE. Open circuit for 00:04:50
2	00:56:50	Test restart at 20 Sep 1991 07:30:09. System down for 00:00:18
3	01:58:40	Operator pause. Open circuit for 00:01:50
4	01:59:10	Interruption for TC BYPASS. Open circuit for 00:00:43

Event start: 06:27:51 20 Sep 1991
Event stop : 12:57:35 20 Sep 1991

Event duration: 06:29:44 Lead duration: 06:22:00 Difference: 00:07:44

SAMPLE SUMMARY SHEETS

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

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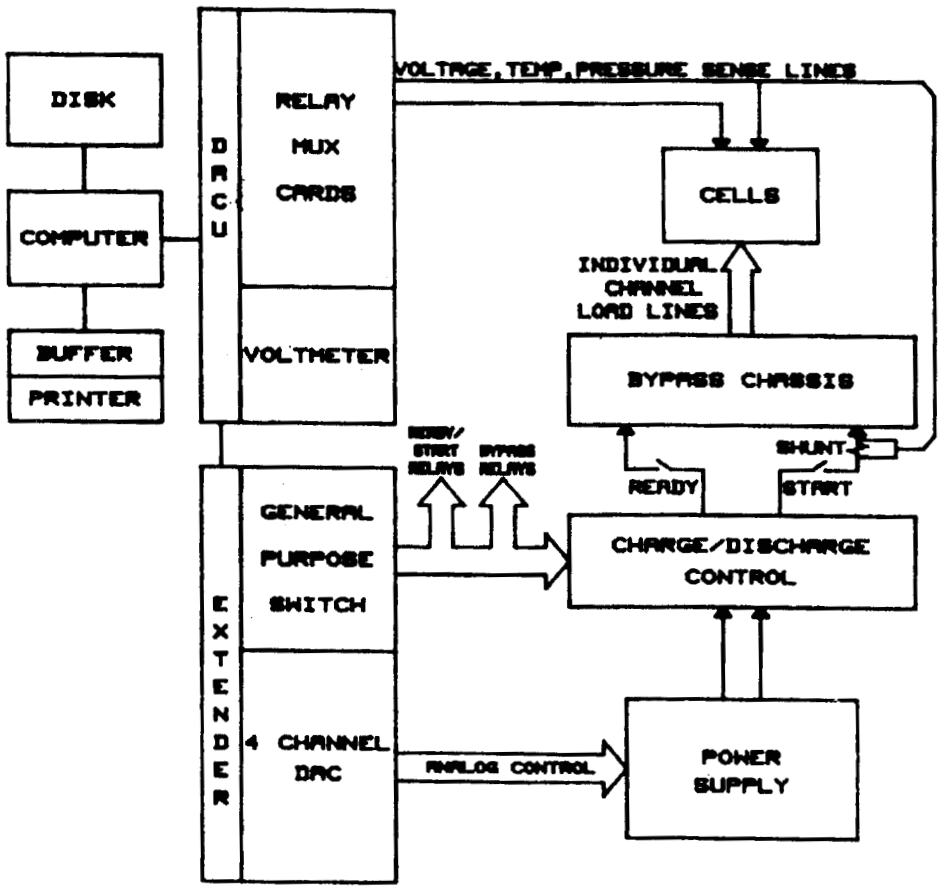
STANDARD CELL LEVEL TEST SYSTEM



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ADVANCED SYSTEMS OPERATION

1991 NASA AEROSPACE BATTERY WORKSHOP

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

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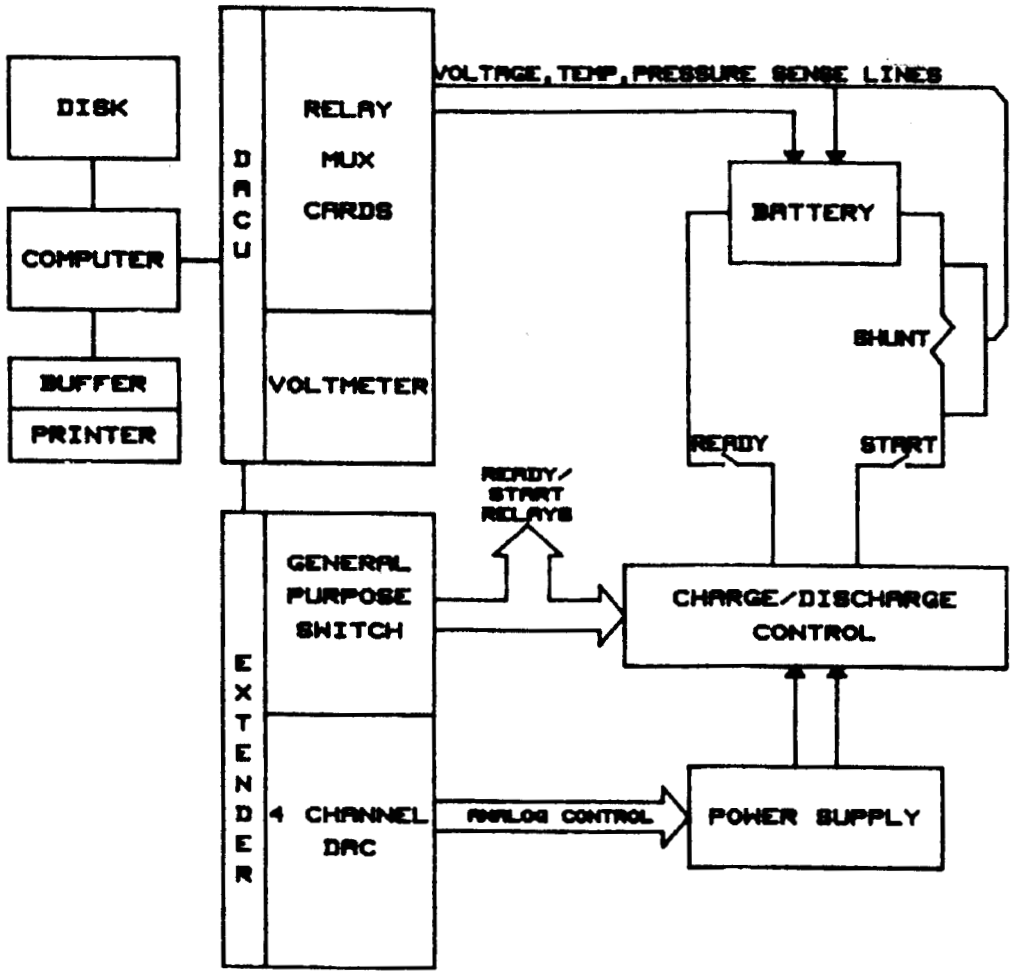
ADVANCED SYSTEMS OPERATION

1991 NASA AEROSPACE BATTERY WORKSHOP

STANDARD BATTERY LEVEL TEST SYSTEM



EAGLE PICHER
Electronics Division
Joplin, MO

ADVANCED SYSTEMS OPERATION

1991 NASA AEROSPACE BATTERY WORKSHOP

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

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Joplin, MO

ADVANCED SYSTEMS OPERATION

1991 NASA AEROSPACE BATTERY WORKSHOP

Sample Procedure File

Program: ATPXXX

Document: ATP-XXX Rev X

Record	Event	Description
1	1	Stabilization at 10C
2		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	Abort	Warn 1	Warn 2	
Temperature:	10.0	±10.0	± 2.0	± 3.0	(Degrees C)

	Time	Volts
Termination:	12:00:00	n/a

Warning : Voltage > 1.520

	Nominal	Abort	Warn
Current :	9.30	±04.65	±0.0?0

Print-outs : 5 Minute mark
Intervals of 00:30:00
Operator command
Maximum voltage and time of same

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	Abort	Warn 1	Warn 2	
Temperature:	10.0	±10.0	± 2.0	± 3.0	(Degrees C)

	Time	Volts
Termination:	n/a	.500

	Nominal	Abort	Warn
Current :	36.00	±18.00	±0.100
@ 01:30:10 :	85.00	±42.50	±0.100
@ 01:30:40 :	36.00	±18.00	±0.100

Print-outs : 00:05:00 00:10:00 00:15:00
30 Minute intervals til .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 .900 volts
Time to 1.000 volts
Time to 1.200 volts

SAMPLE TEST DEFINITION SHEETS

EAGLE PICHER Quality First!

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Electronics Division
Joplin, MO

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

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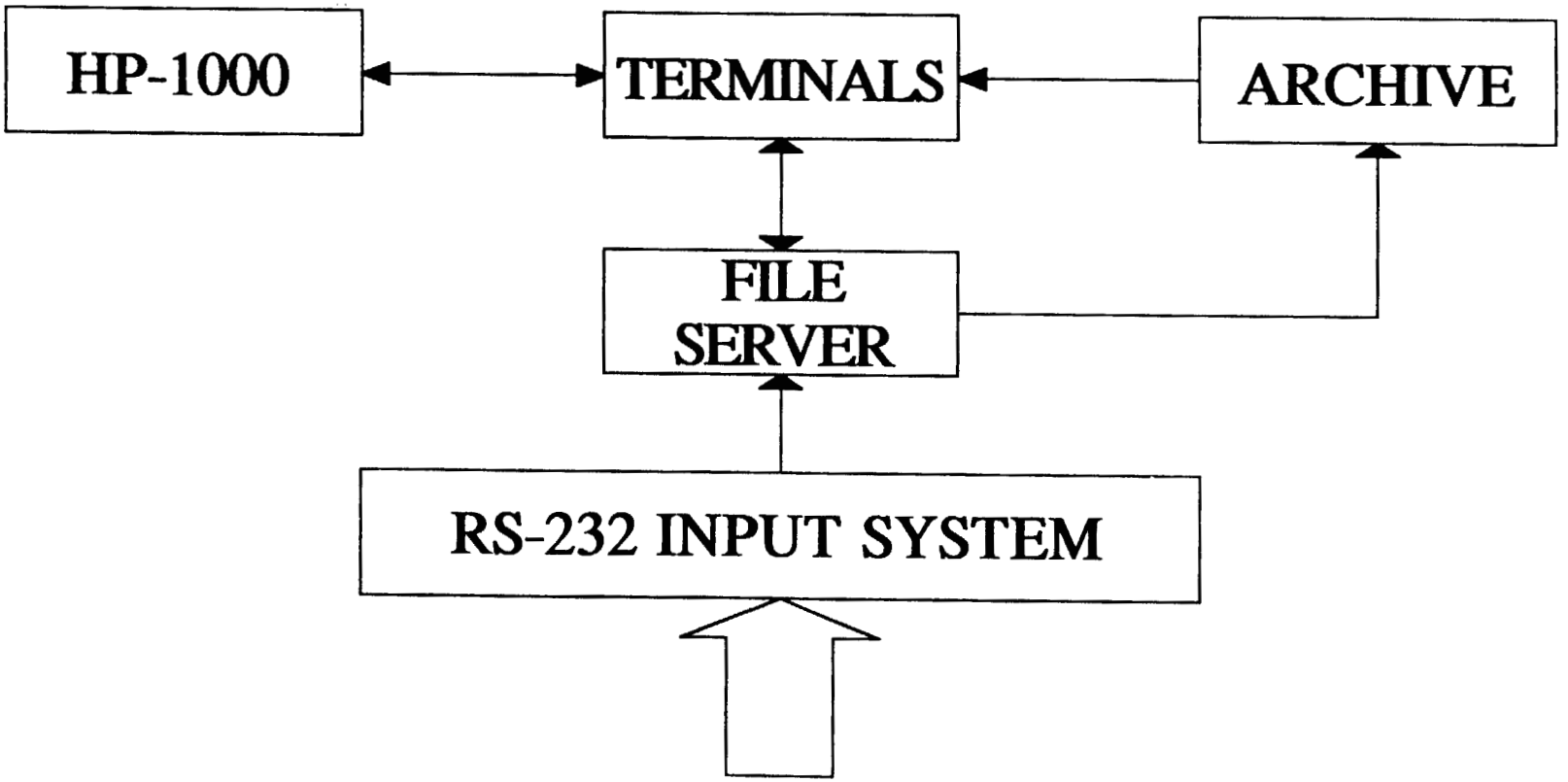
Electronics Division
Joplin, MO

ADVANCED SYSTEMS OPERATION

1991 NASA AEROSPACE BATTERY WORKSHOP

FUTURE DATA NETWORK



Quality First!

N92-22730

Capacity Loss on Storage and Possible Capacity Recovery for HST Nickel-Hydrogen Cells

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Nickel-Hydrogen Capacity Loss During Storage

- Observed in cells with Negative (Hydrogen) Precharge.
- Capacity Loss measured in cells stored for one month.
- Amount of recoverable capacity decreases with an increase in length of storage period.
- Plausible explanation is migration of Cobalt in Nickel Plate under Hydrogen pressure.
- At low potentials CoHO2 is formed from Nickel active material.
- CoHO2 will redistribute upon cycling as differences in electrode potentials are increased and held.
- Orignal 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, $CoHO_2$ 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.

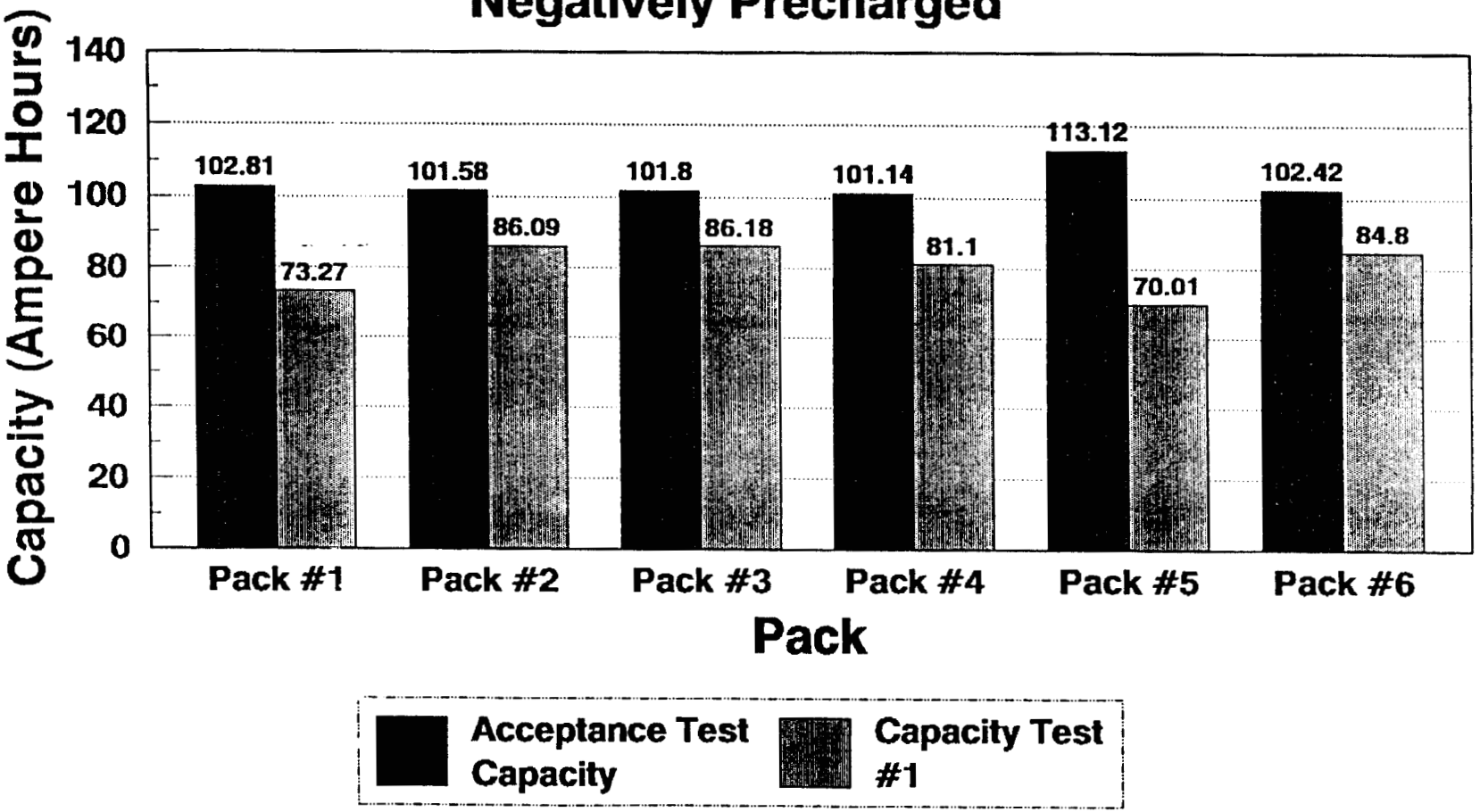
A capacity fade on storage has been observed in the negatively precharged Nickel-Hydrogen cells built during the Hubble Space Telescope program. This capacity fade was noted when residual HST cells were brought out of storage for use in other Nickel-Hydrogen test activities. Twenty four cells were removed 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

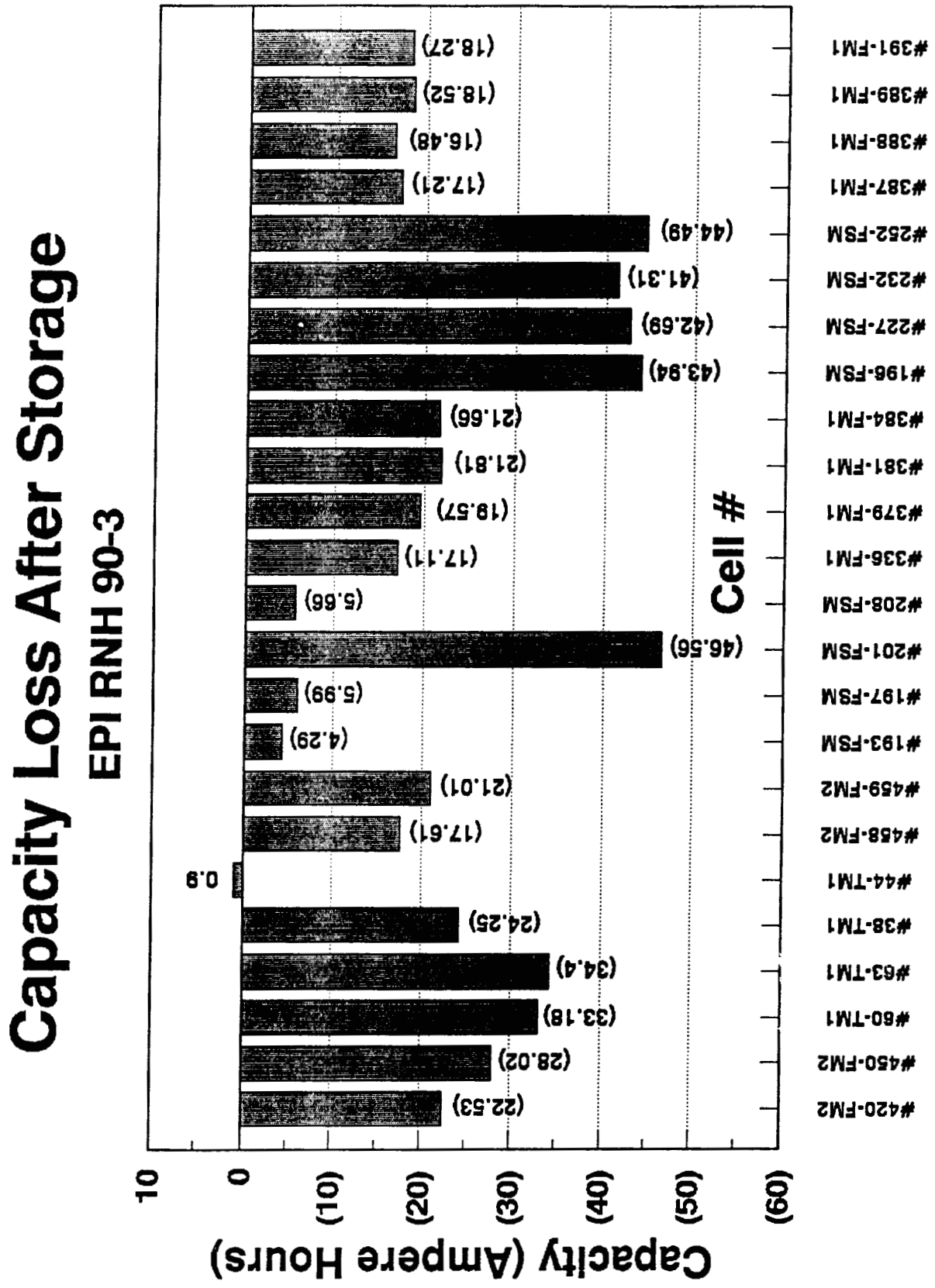
Negatively Precharged



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
Capacity (Ampere Hours)
10
0
(10)
(20)
(30)
(40)
(50)
(60)
Cell #
#420-FM2
#450-FM2
#60-TM1
#63-TM1
#38-TM1
#44-TM1
#458-FM2
#459-FM2
#193-FSM
#197-FSM
#201-FSM
#208-FSM
#336-FM1
#379-FM1
#381-FM1
#384-FM1
#196-FSM
#227-FSM
#232-FSM
#252-FSM
#387-FM1
#388-FM1
#389-FM1
#391-FM1
(22.53)
(28.02)
(33.18)
(34.4)
(24.25)
0.9
(17.61)
(21.01)
(4.29)
(5.99)
(46.56)
(5.66)
(17.11)
(18.57)
(21.81)
(21.66)
(43.94)
(42.69)
(41.31)
(44.49)
(17.21)
(16.48)
(18.52)
(18.27)

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.

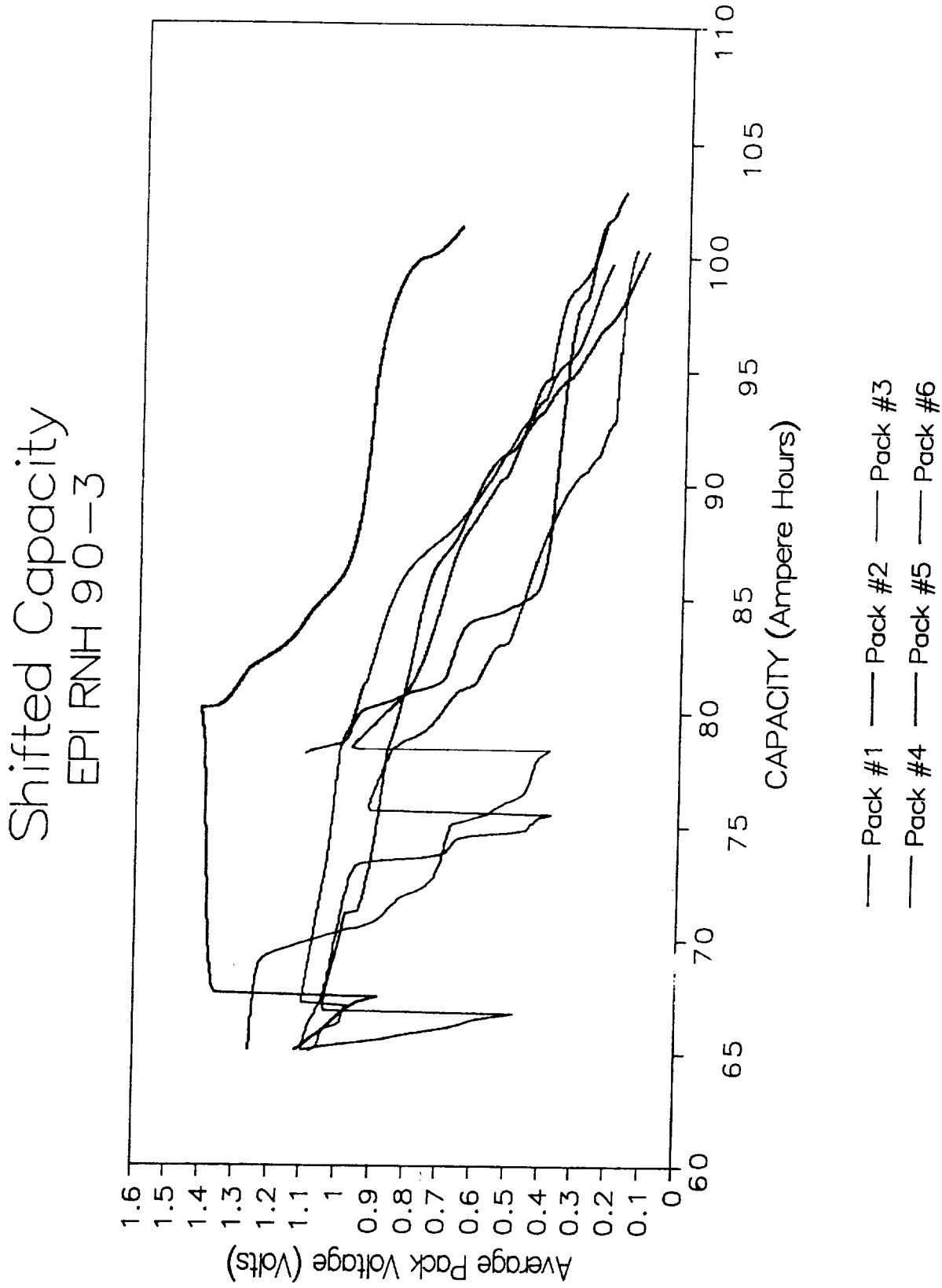
One cell in the group did not show a capacity loss; it delivered the same capacity as measured before storage. This cell belonged to the test module lot of cells and probably had a neutral or positive precharge.

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

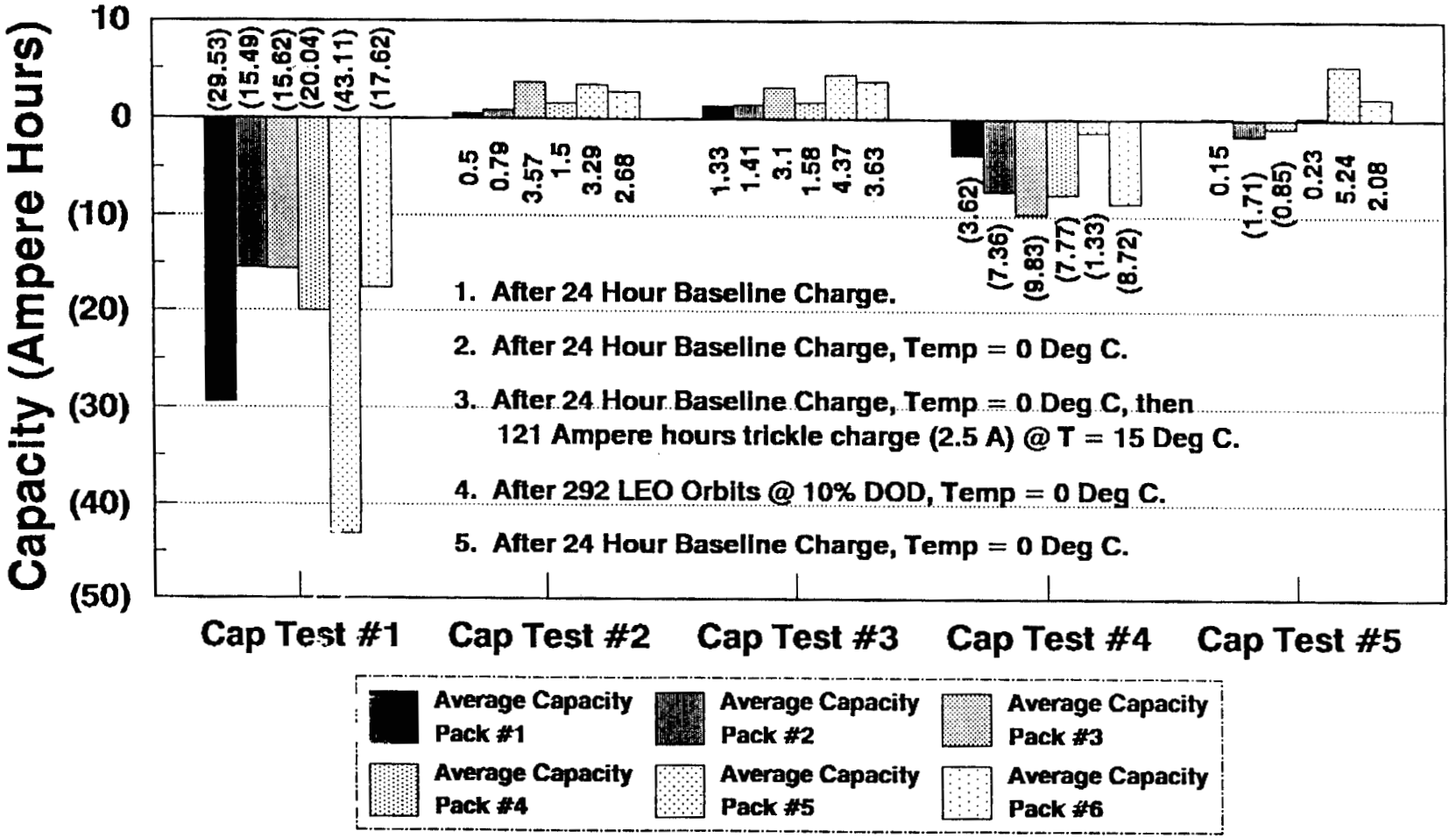
During activation an attempt was made to achieve a neutral or slightly negative precharge. The activation procedure and the variance allowed on the test module cells could have produced a cell with positive precharge. End of discharge pressures for test module 1 cells indicate that this may have happened. 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
Average Pack Voltage (Volts)
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
60
65
70
75
80
85
90
95
100
105
110
CAPACITY (Ampere Hours)
Pack #1
Pack #2
Pack #3
Pack #4
Pack #5
Pack #6

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 Tests, – 1.0 Volts.

After the first capacity test a second baseline charge and capacity test were performed to check the validity of the first test. The results of the second test verified the first test. At this point, it was recognized that the HST spare battery module (FM1), stored similarly, probably had the same kind of loss in useable capacity. Several procedures followed in an effort to demonstrate the ability of the cells to recover enough capacity to meet the requirements of the HST specification.

The third capacity test occurred after a baseline charge and extensive overcharge. At 0' C the cells received a 24 hour baseline charge and 121 ampere hours trickle charge at 2.5 amperes rate; the temperature was raised to 15' C during the period of trickle charge. It was hoped that by increasing the electrode potential difference to more than 1.2 volts and maintaining the difference at an elevated temperature, the Cobalt would redistribute. The results were not encouraging. It seems that the gas recombination during overcharge precluded the movement.

LEO cycling is thought by many people to be an effective way of recovering faded capacity; subsequently, 292 LEO orbits at 10% DOD were run. The forth capacity test was ran after the LEO cycles and the fifth test after a baseline charge. Capacity recovered was still not at an acceptable level. The beneficial effects of LEO cycling are magnified as the DOD increases; the 292 orbits at 10% DOD had no appreciable effect. Cycling at a deeper DOD was not immediately attempted. A relatively quick method for regaining lost capacity was desired.

EPI

Capacity Recovery Procedure

Cool Cells to 0 Deg C.

Perform Baseline Charge:

160% Overcharge in a 24 hour Period.
Charge 10 Hours at 9.3 Amperes.
Charge 14 Hours at 4 Amperes.

Raise Temp to 25 Deg C.

Allow Cells to stand open circuit for 10 - 14 days.

Lower Cell Temp to Deg C.

Discharge cell at C/6 to 1.0 V/Cell.

Discharge at 15 Amperes.

Recondition Cell to > .1 V with resistor.

Perform Baseline Charge.

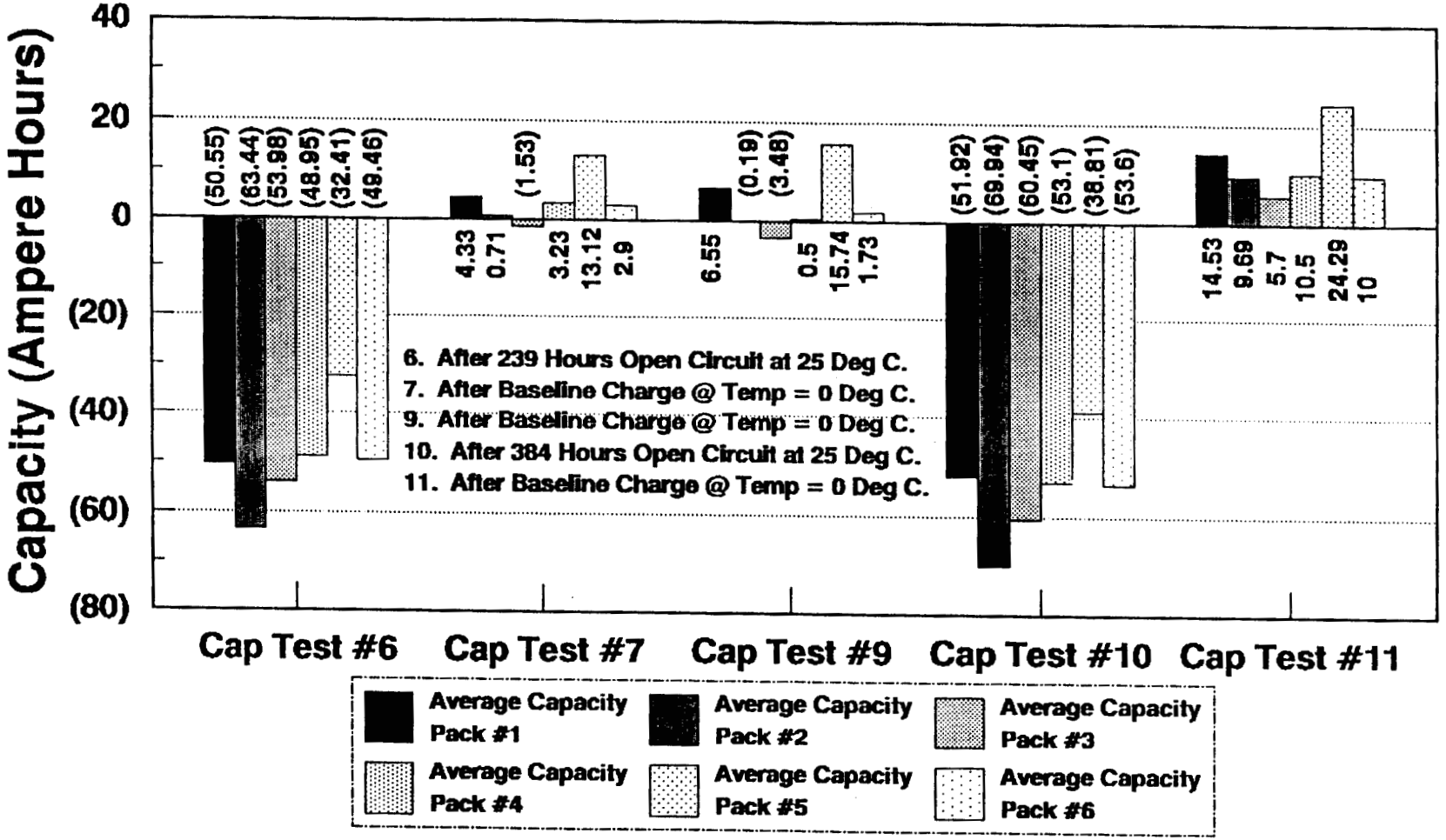
Allow Cells to Stand Open Circuit for 1 Hour.

Discharge cell at C/6 to 1.0 V/Cell.

The cell manufacturer recommended a capacity recovery procedure that elevated the electrode difference of the cell to a high level and allowed the cell to self discharge at room temperature for 10 to 14 days. The manufacturer's suggested procedure was then employed. A capacity test and reconditioning were run after the period of self discharge. A baseline charge and capacity test were then run to measure the effectiveness of the capacity recovery technique.

Attempts to Recover Capacity

EPI RNH 90-3



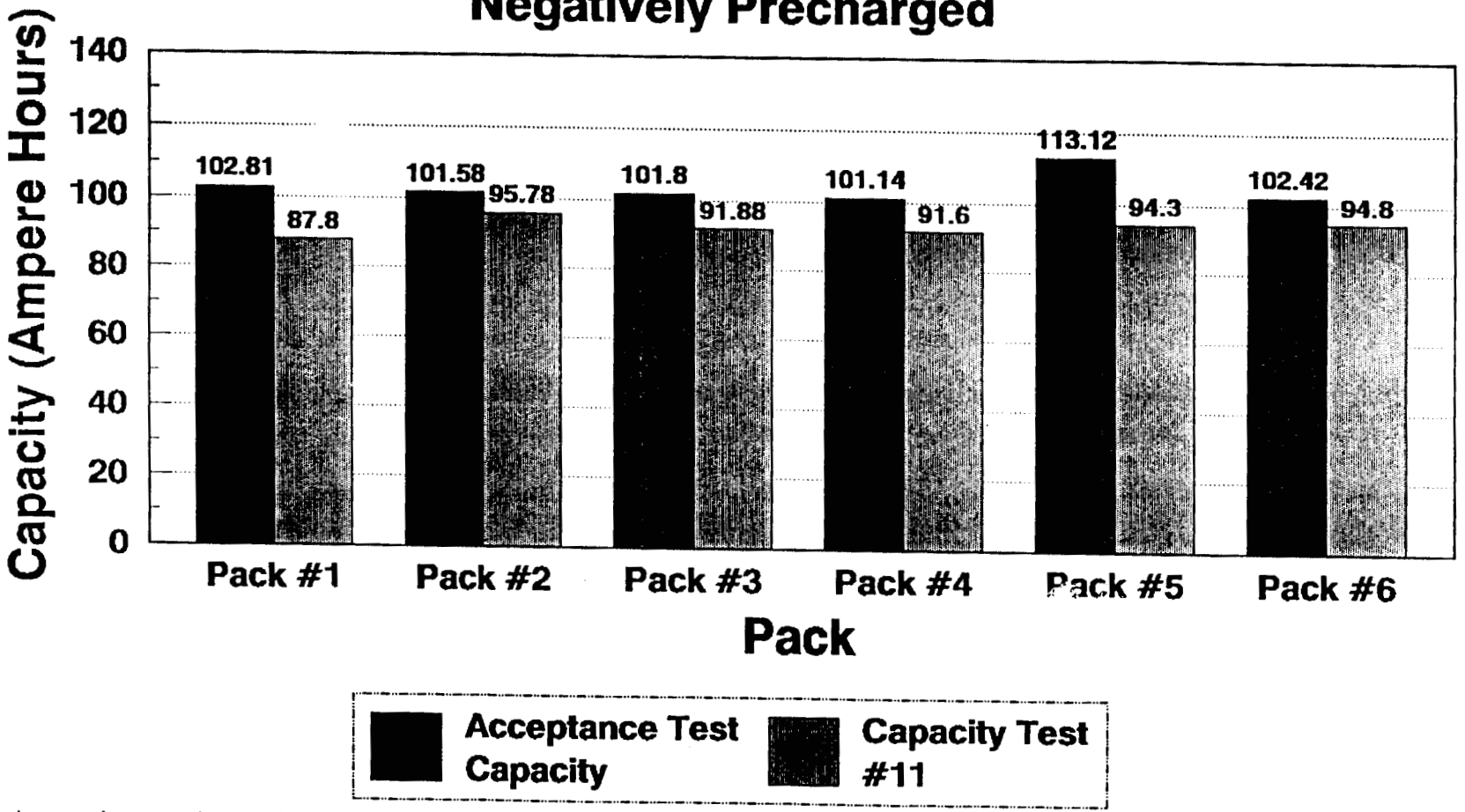
Acceptance Test Capacity, June 1989 – 1.2 Volts.
Other Capacity Tests, – 1.0 Volts.

Capacity test #6 was after the 239 hour open circuit stand. Capacity test #7 measured the capacity gain related to the charged open circuit stand at room temperature. The measured capacities showed a definite improvement when compared to capacity test #5. After capacity test #7 the packs were LEO cycled at moderate DOD's for two hundred orbits. Packs #1, #2, #3 and #4 cycled at 22% DOD while packs #5 and #6 cycled at 33% DOD. Capacity test #8 was interrupted by a power outage and data was lost. Capacity test #9 measured the effect of the LEO orbits; the LEO orbits did not significantly increase the measured capacity. The manufacturer's recovery procedure was run again with the open circuit stand time increased to 384 hours. Capacity test #11 showed the most dramatic increase in recovered capacity. Sufficient capacity had been regained to meet the requirements of the HST specification.

Useable Capacity Fading

EPI RNH 90-3

Negatively Precharged



Acceptance Test Capacity, June 1989 – 1.2 Volts.
Eleventh Capacity Test, Sept 1991 – 1.0 Volts.

After the 11th capacity test, the cells were still 8 to 10 percent degraded in capacity. The capacity will continue to increase slightly with LEO cycling at the moderate DOD's. The effect of the higher concentration of electrolyte (pack #5, 31%) after storage is negligible; the pack with 27% KOH lost much less capacity during storage and showed only slightly less capacity than the pack with 31% KOH. Pack #4 and #6, from the same lot of cells showed capacity recoveries of 10.5 and 10 ampere hours respectively.

Summary

Capacity Fading Of Negatively Precharged Nickel-Hydrogen Cells can be reversed.

Capacity can be recovered through cycling.

Recovery can be accelerated by elevating temp and keeping electrode potential difference high.

Original capacity is lost; the lattice structure of the plate is altered.

If possible, Use Positively Precharged Cells.

In summary, negatively precharged Nickel-Hydrogen cells will experience a useable capacity loss during extended open circuit storage periods. Some of the lost capacity can be recovered through cycling. Capacity recovery through cycling can be enhanced by cycling at high DOD's. The most timely procedure for recovering the faded capacity is to charge the cell fully and allow the cell to sit open circuit at room temperature. This procedure seems to be effective in part because of the enlarged structure of the active material. The compounds that formed during storage at the low electrode potentials can more easily dissolve and redistribute. All of the original capacity cannot be recovered because the lattice structure of the active material is irreversibly altered during storage. The recommendation is to use positively precharged cells activated with 26% KOH if possible. In aerospace applications the benefits of negative precharge are offset by the possibility of delays and storage periods.

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