The 1988 Goddard Space Flight Center Battery Workshop

T. Yi, Editor
NASA Goddard Space Flight Center
Greenbelt, Maryland

Proceedings of a workshop held at
NASA Goddard Space Flight Center
Greenbelt, Maryland
November 1-3, 1988
This document contains the proceedings of the 21st annual Battery Workshop held at Goddard Space Flight Center, Greenbelt, Maryland on November 1-3, 1988. The Workshop attendees included manufacturers, users, and government representatives interested in the latest developments in battery technology as they relate to high reliability operations and aerospace use. The subjects covered included battery testing methodologies and criteria, life testing of nickel-cadmium cells, testing and operation of nickel-hydrogen batteries in low earth orbit, and nickel-hydrogen technology issues and concerns.
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INTRODUCTION

Thomas Y. Yi
Goddard Space Flight Center

I would like to thank you for your continuing interest in the annual NASA Battery Workshop. We sincerely hope that the 1988 Workshop was as informative and enlightening as the past Workshops.

The first day was devoted to the presentations and discussion by the task groups that were formed this summer at the NASA sponsored Nickel-Cadmium Gates Cell Mini-Workshop at the Marshall Space Flight Center addressing recent test failures of the Gates Aerospace Batteries nickel-cadmium cells. Seven different task groups reported at the 1988 Workshop with the goal of improving the reliability of the aerospace nickel-cadmium cells. The task groups reported on 1) uniformity of the tests; 2) uniformity of the destructive physical analyses; 3) separator test and criteria; 4) plate issues; 5) future cell design; 6) evaluation of the on-ground life cycle data; and 7) quality oversight. I want to thank and congratulate the task group members for their effort and work in bringing their findings to the aerospace battery community.

The workshop continued with the NiCd session in the second morning with presentations on the nickel-cadmium cell/battery life testing. The 1988 Workshop was concluded with a full day's worth of presentation on the nickel-hydrogen cell/battery technology, covering simulated life cycle testing, component discussions, and current issues/concerns.

We would like to thank all the people that helped making the 1988 Workshop a success. We would like to thank the attendees, presenters, session chairmen and especially the task team members for the time and effort they have put in, for making the Workshop an active forum for discussion of aerospace cells and batteries.
GATES AEROSPACE BATTERIES PRESENTATION

M. Harrison, G. Klein, and L. Tinker
Gates Aerospace Batteries
Gainesville, FL
Aerospace Batteries
Taking Charge

- Gates Aerospace Batteries
- Quality Assurance
- Product/Separator
- Taking Charge
Aerospace Batteries
New Business

- Heritage and Autonomy
- Organization
- Mission
Gates Aerospace Batteries
Heritage and Autonomy

- Gates Corporation
  - Focus on Rubber and Batteries

- Gates Energy
  - World Leader in Rechargeable Batteries
  - Sealed Lead; Sealed Nickel Cadmium
  - Commercial Products - Household Names
  - GEP Denver: General Electric

- Autonomous Gates Aerospace Batteries
Gates Aerospace Batteries Organization

General Manager
Manufacturing

Quality Assurance

Test Unit
Engineering
Materiel
Finance
Sales

- Reports to President GEP
- Nickel Cadmium
- Nickel Hydrogen
- Cell Production
- Test
Gates Aerospace Batteries
Mission
To Be The Best . . . !
Aerospace Batteries
Taking Charge

- Autonomous
- Organized
- Under Control
- Directed and Managed to Serve Customers
- Future Is Predicated
  - Quality of Design
  - Quality of Production
  - Quality of Test
  - Quality of Quality

“To Be The Best. . .”
Gates Energy Products

Gates Aerospace Batteries

Product Assurance Improvements
Presented to NASA Goddard Annual Workshop

November 1, 2, 1988
Agenda

- 1986-1988 Quality Improvements
- Transition of Quality Control Engineering to Full Product Assurance Department
- Recent Growth of Quality Personnel
- Recent Quality Issues
- Corrective Actions
- Summary
November, 1986 - GE/BBD

Plant Manager

Manager, NiCd Operations (95% Commercial)

Q.C. Manager (Commercial)

Manager, Aerospace Operations

QC Engineer, Aerospace


Calib. Lab  Platemaking Quality  2 In-Proc. Q.C. Insp. Aerospace  1 Incoming Q.C. Insp. Aerospace
Autonomous Organization: Gates Aerospace Batteries
Aug. 15, 1988

President
GATES ENERGY PRODUCTS
R. H. Shiley

General Manager
GATES AEROSPACE BATTERIES
M. Harrison

- Sec. Open

Mgr. Manufacturing
R. Krientz

Mgr. Marketing
D. Schmidt

Product Assurance
G. Klein

Mgr. Engineering
L. Tinker

Controller
Open

QC Engr. (2)
QC Documents Spec.
Calibration Lab
Inspection Leader
- Inspectors
Source Inspector
Bottom Line

- Gates Aerospace Batteries is emerging from a manufacturing facility under GE/BBD to a full service, customer oriented aerospace facility under Gates Energy Products.
Quality Issues at Gates Energy Products

- No Centralized Quality Organization to Affect Clearly Defined Responsibility, Authority and Accountability
- GIDEP Alert (Electrodes & Separator)
- Acceptance Testing
Centralized Quality:
Autonomous Organization: Gates Aerospace Batteries

President
GATES ENERGY PRODUCTS
R. H. Shiley

General Manager
GATES AEROSPACE BATTERIES
M. Harrison

- Sec. Open

Mgr. Manufacturing
R. Kientz

Mgr. Marketing
D. Schmidt

Product Assurance
G. Klein

Mgr. Engineering
L. Tinker

Controller
Open

QC Engr. (2)
QC Documents Spec.
Calibration Lab
Inspection Leader
- Inspectors
Source Inspector
Centralized Quality: Gates Energy Products

November 1-3, 1988
GIDEP Alert:
Dr. Lawrence Tinker: Electrode & Separator

- Performance & Reliability - Not Traditional Quality Control

- Fall Out: (1) Method C - Specific Area 
  (2) General Platemaking Audit
Status: Method C:

- Immediate Action: Station Control 701-93, July 8, 1988

- Corrective Action: (1) Definition of Root Cause of the Deficiency
  (a) Communication
  (b) True Vendor Status of G.E.P. Platemaking to G.A.B.

  (2) Action Taken: “Charter Document: October 2, 1988

- Close Out: Entire Customer Base Must Approve “Charter Document:
Status: Platemaking Audit:

- Undefined Role of Commercial, Centralized Quality
- Customer Acceptance of “Charter Document”, October 31, 1988
- Immediate Actions: Centralized Quality Proposed
  Source Inspection Proposed
  Charter Document Definition
- Corrective Actions: (1) Charter Document Completed 10/2/88
  (2) Source Inspection by 12/31/88
Status: New Test Unit:
Randy Kientz:

- Technical Personnel on All Three Shifts
- Permanent Positions - Interviews Have Begun
- Will Define Responsibility, Authority and Accountability
Status: New Test Unit
Glenn Klein:

- Proposed Off Shift Inspection in Mid July
- Hired Two Inspectors Mid August
- Inspectors Now in Training for Placement by November 15, 1988

November 1-3, 1988
Conclusion:
Three Major Areas of Concern:

- Centralized Quality
- GIDEP Alert
  - Method C
  - Platemaking Audit
- Acceptance Testing
Conclusion
Major Changes

- Autonomous G.A.B. with Staff Level Product Assurance
- Commercial G.E.P. Has Established Centralized Quality Organization
- G.A.B. Has Completed Method C but Needs Customer Approval
- G.A.B. Is Resolving Platemaking Issues
- G.A.B. Will Institute Source Inspection
- New Test Unit Will Resolve Their Issues
Gates Aerospace Batteries is emerging from a classical manufacturing facility under General Electric to a more responsible and flexible aerospace facility and seek your continued guidance in establishing an alliance and partnership.
ENERGY PRODUCTS

Aerospace Batteries

Engineering Overview

Presented at

NASA/GSFC Battery Workshop

November 1-3, 1988
Topics

- Background
- Cells Investigated and Results
- Electrolyte Management and Separator
- Qualification Tests of 2536 Separator
- New Separator Program
Background

- Several Issues Concerning GAB Cells Have Surfaced During Past Year
  - Performance Anomalies and Failures in Separator Requalification Tests
  - Apparent Early Degradation of Freudenberg 2505 Separator
- Resulted in Issuance of Letter by GAB to Customers Regarding Cells with 2505 Separator
- Resulted in GIDEP Alert Issued by NASA/GSFC
- GAB Has Investigated These Issues Extensively During This Year
Summary of Cells Investigated

- 122 Cells Through DPA/CMA During Past Year
  - Does Not Include Cells After Pre-Charge

- 97 Cells with 2505 ML Separator
  25 Cells with 2536 Separator

- Cells Represented:
  55 Plate Lots
  27 Catalog Numbers
  12 Customers
  5 Separator Lots
  25 Separator Rolls
  72 Cells from Lot 30158
  46 Cells from Rolls 1-5LR037
Summary of Results from Tests

- 31 Cells with Overcharge Protection Factor $< 4.0$
  - 22 from Cells with 2505 (5 from Crane Test Cells)
  - 9 from Cells with 2536 (8 from Crane Test Cells)

- 26 Cells with Excessive Cadmium Migration
  - 9 from Cells with 2536 (8 from Crane Test Cells)
  - 7 Shorted Cells from This Group, 3 with 2505 and 3 with 2536 from Crane Test Cells

- 17 Cells with Some Amount of Separator Sticking

- 21 Cells with Poor Separator Strength (All 2505 Cells)
Summary of Results (Continued)

- Cells from Rolls 1-5LR037

<table>
<thead>
<tr>
<th>Roll</th>
<th># Cells</th>
<th>Excess Cadmium Migration</th>
<th>Poor Separator Strength</th>
<th>Overcharge Factor &lt; 4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>3 (Crane)</td>
<td>3 (Crane)</td>
<td>3 (Crane)</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>17</td>
<td>9</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>14</td>
<td>1</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>1 (Crane)</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

- Cells with 2505 from Outside of Five Suspect Rolls
  - 3 Cells with Excess Cadmium Migration
  - 5 Cells with Poor Separator Strength
  - 7 Cells with Overcharge Factor < 4.0
# Separator Comparison

<table>
<thead>
<tr>
<th>Property</th>
<th>100% Nylon 6</th>
<th>67% Nylon 66</th>
<th>33% Nylon 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nylon Type</td>
<td>2505 ml</td>
<td>2536</td>
<td></td>
</tr>
<tr>
<td>Weight, g/m²</td>
<td>60 ± 8</td>
<td>80 ± 5</td>
<td></td>
</tr>
<tr>
<td>Thickness, Mils (Compressed)</td>
<td>7 - 10</td>
<td>7 - 9</td>
<td></td>
</tr>
<tr>
<td>Electrolyte Absorption % of Dry Weight</td>
<td>400 Minimum (700-900 Typical)</td>
<td>300 Minimum (300-400 Typical)</td>
<td></td>
</tr>
<tr>
<td>Air Permeability CFM/ft²</td>
<td>200-300</td>
<td>100-200</td>
<td></td>
</tr>
<tr>
<td>Bonding Method</td>
<td>ZnCl₂</td>
<td>Hot Inert Gas</td>
<td></td>
</tr>
</tbody>
</table>
Electrolyte Management

- Both Positive and Negative Plate Characteristics Play Critical Role in Electrolyte Management
Positive Electrode

- Sinter Strength Important in Reducing Swelling

- Nickel Attack Needs to Be Controlled to Provide Strength and Maintain Porosity

- Loading Levels Need to Be Controlled to Reduce Swelling, Reduce Pore Blockage, Reduce Electrolyte Redistribution
Negative Electrode

- Loading Levels Should Be Controlled to Reduce Cadmium Migration
- Must Maintain Adequate -/+ Ratio, Precharge, and Overcharge Protection
- Critical in Maintaining Low Oxygen Pressure During Overcharge
Electrolyte Management

- Greater Electrolyte Levels Enhance Life Characteristics
  - Greater Reserve for Plate Swelling
  - Greater Thermal Conductivity - Reduces Heat Build-Up
Qualification Tests of 2536 Separator

- NASA Sponsored 50 Ah Cells
  - No Catastrophic Failures in Testing
  - Some Anomalous Voltage Behavior with Both Separators
  - Cells Remain on Test in LEO and GEO Cycles
  - Over 15,000 Cycles Completed in LEO Orbit with 2536 Separator
  - More Than 6 Seasons in GEO Completed (Real Time)
Qualification Tests of 2536 Separator

- PERFORMANCE IN MARTIN MARIETTA PROGRAM
  - 10 Ah Cells, 27% DOD, LEO, 20 °C
  - >10,000 Cycles to Date
  - No Distinguishable Differences Between 2505 and 2536 Cells

- PERFORMANCE IN GE-ASTRO SPACE PROGRAM
  - 26.5 Ah Cells, 25% DOD, LEO, 4 °C
  - Completed 9600 Cycles to Date
  - Evidence of Anomalous Behavior in Both Types of Cells
  - Shorts in Both Types of Separator Cells
  - Remaining Cells Performing Well
Qualification Tests of 2536 Separator

- Joint Air Force/Navy Program
  - Four Types of Cells from 26.5 to 50 Ah Cells
  - All Failures in LEO Test Cells
  - Failures Consistent with Accelerated Separator Dry Out Due to Overall Plate Issues
  - GEO Packs Still on Test with >10 Accelerated Seasons
Existing Cells Using 2536 Separator

- Plate Characteristics Should Be Reviewed for Porosity/Pore Volume and Loading Level

- Electrolyte Levels in Activated Cells Should Be Examined and Compared with Similar Cells Using 2505 mL.
Existing Cells Using 2536 Separator

- **Positive Plates Should Be Replaced if Porosity < 30%**
  - Porosities Below 30% Indicate Low Nickel Attack and/or High Loading Levels
  - These Characteristics Lead to Reduced Initial Electrolyte Levels and Accelerate Electrolyte Redistribution

- **Negative Plates Not as Critical but Porosity Should Be Maximized While Maintaining Adequate -/+ Ratio**
New Separator Program

- Separator Samples Received from Two Suppliers
  - Three Samples from Freudenberg
  - One Sample from Kendall

- Freudenberg to Provide One Additional Sample

- Sample Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Weight g/m²</th>
<th>Thickness mils</th>
<th>KOH Absorption % of Dry Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freudenberg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>64</td>
<td>10.9</td>
<td>570</td>
</tr>
<tr>
<td>B</td>
<td>69</td>
<td>16.4</td>
<td>1760</td>
</tr>
<tr>
<td>C</td>
<td>52</td>
<td>11.3</td>
<td>2650</td>
</tr>
<tr>
<td>Kendall</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>10.5</td>
<td>500</td>
</tr>
</tbody>
</table>
Separator Evaluation Program
Initial Tests

- Samples Are Being Processed Through Normal Incoming Inspection Tests
- Samples Are Being Tested in Oxidative Degradation Tests
- Most Promising Candidate(s) Will Be Selected for Complete Cell Tests
- Both Current 2536 and New Sample(s) Will Be Tested
Separator Evaluation Program

Design Parameters

- Cell Size to Be Used Is 27AB07 Type Cell
- Positive and Negative to Conform to GAB Design Parameters for Loading and Porosity
- Negative Will Be Teflon Treated
- C Rate Current Density Will Be 20 mA/cm²
- Cells Will See Pre-ATP and Limited ATP Testing
- Short Term Evaluation Test to Be Used
Separator Evaluation Program
Test Program

- Three Cells of Each Type Separator
- Leo Cycling, 30 Minute Discharge, 60 Minute Charge
- 50% DOD Based on Nameplate Capacity
- Initial C/O Ratio of 1.05
- Temperature: 20°C
- At 1000 Cycles Remove One Cell of Each and Do Complete DPA/CMA to Examine Separator and Plate Changes
Qualification Testing
Customer Involvement

- GAB Has Limited Life Test Capability
- Each Customer Has a Different Mission Profile
- Impractical for GAB to Test Many Different Cycle Regimes
- GAB Encourages Customers to Initiate Their Own Qualification and Life Test Programs to Support a Replacement Separator
- GAB Wants to Work with Customers to Satisfy Needs and Provide Reliable Products
MEMORANDUM

DATE: October 27, 1988
TO: Glenn Klein
FROM: Gregg Brandyberry
RE: Position Statement

In response to our discussion of October 24th, 1988, I thought it would be appropriate to provide Gates Aerospace Battery with a position statement detailing the philosophical and structural quality changes currently transpiring within Gates Energy Products, Inc.

POSITION STATEMENT

Gates Energy Products, Inc. is committed to supplying Gates Aerospace Battery with highly consistent plate product through cost efficient quality manufacturing. That is; providing our valued customer with:

The Right Quantity...
At The Right Time...
Of The Right Quality...
For The Right Cost...

This will be achieved by the development and implementation of a three fold process.

I. Restructuring of the Formal Quality Entity

All quality functions including a) purchased material control, b) process/product audit, c) process (PMQC) engineering, d) product test labs, and e) customer support services now report to the Manager of NiCd Quality; a staff position reporting directly to the Vice President of Manufacturing. This structure will elicit a broadbased, yet focused, quality system providing product/process maintenance, continuous improvement and cultural direction to insure that leading edge quality/manufacturing is inherent in the 1990's and beyond.
II. Full Implementation of Traditional Quality System

Policies and procedural documentation will be developed and implemented where substandard in the quality system elements of:

a. Purchased material control  
b. Supplier surveillance  
c. Specifications change and control  
d. Gauge calibration and gauge R&R evaluation  
e. Process/product instructions and inspection procedures  
f. Control of non-conforming product  
g. Problem identification and resolution  
h. Final test and audit  
i. Lot control/traceability

III. Implementation of "Preventative Manufacturing Quality Control" Philosophy (PMQC)

Preventative Manufacturing Quality Control is a philosophy/culture developed to support a manufacturing system which allows both quality and productivity to occur with balanced equivalence.

In theory, PMQC integrates both manufacturing and quality into one homogeneous system. PMQC is extremely production operator oriented and includes all "preventative" manufacturing techniques used to control and/or verify production processes. PMQC techniques include:

a. Advanced quality planning  
b. Failures mode effects analysis  
c. Statistical process control  
d. Design of experiments  
e. Cause/effect problem analysis  
f. Process syntactics

PMQC involves continually analyzing an entire manufacturing structure, identifying "pressure points" at which potential failures could occur, and implementing preventative process controls at these "pressure points" to prevent the occurrence of non-conformance.

PMQC is driven by the process engineering function. PMQC reduces the need for traditional "after the fact" inspection programs. True PMQC techniques meet the following criteria:

a. Does not hinder production  
b. Is based upon prevention  
c. Does not create inspection queues  
d. Is operator oriented (some exceptions)  
e. Identifies and resolves root causes of non-conformance

This summary, while not all inclusive, provides a brief outline of the future direction of the NiCd Division Quality Program.

November 1-3, 1988
I am convinced that adherence to this program will result in ongoing continuous improvement of process variability and ultimately product performance.

RGB/kdg4

cc: Paul Hinkson
    Mike Harrison
SESSION I

TASK GROUP PRESENTATION & DISCUSSION

Chairman: G. Halpert, JPL
INTRODUCTION OF TASK FORCE GROUPS

G. Halpert, JPL
N. Schulze, NASA/HQ
STRAWMAN DEFINITION OF AN AEROSPACE QUALITY CELL

OPERATIONAL

- COMPLETE 2 YEARS OF LOW-EARTH ORBIT CYCLING
  - 40% DEPTH-OF-DISCHARGE
  - TEMPERATURE AT 20°C
  - MAINTAIN END-OF-DISCHARGE VOLTAGE > 1.00V/CELL
  - END-OF-CHARGE VOLTAGE ± 8MV ON BATTERY BASIS
  - WITHOUT RECONDITIONING OR FAILURE

- SATISFACTORILY COMPLETE REQUIRED NASA ACCEPTANCE TESTS

CELL DESIGN

- MANUFACTURED TO NASA STANDARD SPECIFICATION
  - > 40% POSITIVE PLATE POROSITY
  - > 3CC/Ah OF ELECTROLYTE
  - 10mA/cm² OF POSITIVE PLATE AT THE C/2 RATE
PRESENT CELL DESIGNS INADEQUATE FOR

LONG TERM LEO MISSIONS

- PLATE LOADING HIGH
- PLATE AREA LIMITED --- 10mA/cm²
- ELECTROLYTE VOLUME LOW
  - PLATE POROSITY
  - SEPARATOR ABSORPTION
RELIABILITY IMPROVEMENTS

- UNIFORMITY OF TEST
- DESIGN CELLS FOR APPLICATION
- MATERIALS ADEQUATE
- QUALITY IMPOSED
- ANALYSIS/UNIFORM DPA
- TESTING/MODEL
- METHOD OF CHARGE CONTROL
  - RATE
  - TEMP
ATTACHMENT 4

TASK FORCE GROUPS

Uniform Core Tests and Acceptance Test Quality

Lead: T. Yi/GSFC
Members: G. Klein/GEP, S. Donley/Aerospace, K. Schwer/MDAC,
D. Webb/MMC, C. Koehler/Ford, P. Olbert/Ball,
G. Halpert/JPL

Uniform Destructive Physical Analysis (DPA)

Lead: W. Scott/TRW
Members: M. Earl/Comsat, L. Tinker/GEP, H. Lewis/NWSC,
S. DiStefano/JPL, A. Zimmerman/Aerospace,
D. Maurer/GE-EW

Separator Acceptance Test And Criteria

Lead: M. Manzo/LeRC
Members: L. Christensen/FN-USA, G. Klein/GEP, G. Methlie,
A. Zimmerman/Aerospace

Plate Issues

Lead: D. Maurer/AT&T,
Members: C. Lurie/TRW, R. Kientz/GEP, C. Koehler/Ford,
H. Thierfelder/GE-VF
TASK FORCE GROUPS (Cont.)

**Future NiCd Cell Design**

Lead: S. Gross/Boeing  
Members: L. Thaller/LeRC, L. Tinker/GEP, D. Maurer/AT&T,  
        D. Pickett/HAC, G. Methlie, G. Halpert/JPL

**Evaluation of NWSC Data - Recommend Near Term Cell Design Fixes**

Lead: B. Billerbeck/MRJ  
Members: G. Morrow/GSFC, C. Garner/NRL, S. Gaston/GE-EW,  
        D. Mains/NWSC, K. Clark/JPL, L. Tinker/GEP

**Quality Oversight Task Group**

Lead: C. Lurie/TRW  
Members: N. Schulze/NASA Hq., P. Olbert/Ball, T. Yi/GSFC  
        J. Dunlop/Consultant, B. Otzinger/Rockwell,  
        D. Sedgwick/JPL, W. Hwang/Aerospace
MESSAGE FOR PROJECTS

- CHEMICAL STORAGE DEVICE
- COMPLEX CHEMISTRY
- APPROPRIATE DESIGN
- CONSIDER APPLICATION
- REAL TIME TESTING
  - TIME CONSUMING
  - COSTLY
- RELIABILITY

November 1-3, 1988
UNIFORM CORE TESTS AND
ACCEPTANCE TEST QUALITY

THOMAS YI, NASA/GSFC
TASK GROUP PRESENTATION
1988 NASA/GSFC BATTERY WORKSHOP
NOVEMBER 1, 1988
UNIFORM CORE TESTS AND ACCEPTANCE TEST QUALITY

Members:  
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NASA/GSFC  
GAB  
Aerospace  
MDAC  
MM  
FAC  
Ball  
JPL
OBJECTIVES: Develop a common acceptance test procedure and associated quality instructions which can be agreeable to all cell users and manufacturer.

PROS: Since GAB needs to adhere to only 1 standard ATP requirements, its test reliability and quality assurance should improve.

The ATP data can form the basis of a "common data pool" that can be available to all users.

CONS: Loss of individual databases if a standard ATP is implemented.

Standard ATP may not be compatible with individual spec requirements.

Additional tests may be required for certain missions.
PLAN

1) Identify ATP's in place at GAB.  EASY
2) Identify common test steps.  EASY
3) Identify and recommend test steps that should form the uniform ATP.  EASY
4) Agree on the sequence of test steps.  HARD
5) Agree on the test description, and associated data parameters.  FAIRLY EASY
6) Identify additional tests: Short-term stress cycling, "common data pool" type tests.  HARD
ATP's CONSIDERED

- NASA Standard Design
- Air Force Common Data Pool recommendation
- 14 ATP's from various primes
<table>
<thead>
<tr>
<th>NASA Std</th>
<th>AF Common Data</th>
<th>ATP 149/156</th>
<th>ATP 213/215</th>
</tr>
</thead>
<tbody>
<tr>
<td>23°C Cap</td>
<td>25°C Cap</td>
<td>10°C Cap</td>
<td>Cap Stab.</td>
</tr>
<tr>
<td>30°C Cap</td>
<td>0°C Cap</td>
<td>0°C Overchg</td>
<td>23°C Overchg</td>
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<tr>
<td>0°C Overchg</td>
<td></td>
<td>Pulse Load</td>
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<td>Low Rate Eff.</td>
<td>0°C Overchg</td>
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<tr>
<td>23°C Cap</td>
<td>Chg Retention</td>
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<tr>
<td>Chg Retention</td>
<td>Impedance</td>
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<tr>
<td>Pulse Load</td>
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</tr>
<tr>
<td>ATP 433</td>
<td>22°C Cap</td>
<td>5°C Cap</td>
<td>5°C Overchg</td>
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</tr>
<tr>
<td>ATP 431</td>
<td>25°C Overchg</td>
<td>25°C Cap</td>
<td>10°C Cap</td>
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<tr>
<td>ATP 423</td>
<td>25°C Overchg</td>
<td>25°C Cap</td>
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<tr>
<td>ATP 313</td>
<td>0°C Overchg</td>
<td>25°C Cap</td>
<td>0°C Cap</td>
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*NASA/GSFC Battery Workshop*
<table>
<thead>
<tr>
<th>ATP 1105</th>
<th>ATP 1416</th>
<th>ATP 1611</th>
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<tbody>
<tr>
<td>22°C Cap</td>
<td>20°C Cap</td>
<td>22°C Cap</td>
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<tr>
<td>7°C Cap</td>
<td>10°C Cap</td>
<td>22°C Cap</td>
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<tr>
<td>5°C Overchg</td>
<td>0°C Cap</td>
<td>0°C Cap</td>
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<tr>
<td>35°C Cap</td>
<td>Chg Retention</td>
<td>0°C Cap</td>
</tr>
<tr>
<td>Pulse Load</td>
<td>Impedance</td>
<td>0°C Overchg</td>
</tr>
<tr>
<td>Impedance</td>
<td>Chg Retention</td>
<td>Chg Retention</td>
</tr>
</tbody>
</table>
PRESENT CRITERIA/TOLERANCES IN THE ATPs

Temp: \(\pm 3^\circ F \text{ to } \pm 6^\circ F\)
Max Pressure: \(60 \text{ psig to } 80 \text{ psig}\)
Room Temp: \(20^\circ C, 21^\circ C, 22^\circ C, 23^\circ C, 25^\circ C\)
High Temp: \(30^\circ C, 35^\circ C\)
Cold Temp: \(-1^\circ C, 0^\circ C, 5^\circ C, 7^\circ C\)
Pulse Load: up to 5C rate
Chg Ret Volt: \(1.15V, 1.16V\)
Impedance: \(3m\Omega \text{ to } 10m\Omega\)
**RECOMMENDATIONS:**

1) Implement common tolerances:
   - e.g., temp ±4°F, max pressure 60 psig, etc.

2) Core ATP (at minimum, include)
   - Room temp capacity - 20°C
   - High temp capacity - 30°C
   - Cold temp overchg - 0°C
   - Room temp capacity - 20°C
   - Pulse load/chg retention/impedance

   However, the order of these tests as well as the test description needs to be further studied.

3) Short-term test
   - e.g., common 500-cycle test

4) Air Force Common Data Pool type electrical test
   - conditioning cycle - 25°C
   - capacity checks - 25°C (repeat until last 2x agree)
   - overchg and capacity - 0°C
   - capacity - -10°C
   - charge retention

5) Depository of All Data
   - e.g., ATP data at GAB, Other data at Crane (?)
   - Data to be available for all; data not identified by program
ACCEPTANCE TEST QUALITY

- Automated testing is needed ASAP
  - GAB in process of automating the test area

- Fail-safes need to be implemented in the testing areas ASAP
  - Fail-safes currently planned and being installed at GAB

- Better Shop quality instructions needed
  - ASP-001 written and implemented at GAB
UNIFORM DPA COMMITTEE INTERIM REPORT

NASA GSFC BATTERY WORKSHOP

1 - 3 NOVEMBER 1988

W.R. SCOTT
CONTENTS

Proposed Definition of DPA

Proposed Near-Term Objectives

Proposed Longer-Term Objectives

Activity Status

DPA-Related Tests at Gates Energy Products

Rating Sheet for Existing Tests

Non-Conventional Test Methods

Interim Recommendations
Uniform DPA Committee - Report

PROPOSED DEFINITION OF "DPA" FOR BATTERY CELLS

The term "DPA" as applied to battery cells shall be defined as including:

1. Physical testing and chemical analysis of cell components and materials before they are put into cells, and after removal from cells;

2. Electrochemical analysis of electrodes before they are put into cells, and after removal from cells; and

3. Electrochemical analysis of electrodes as part of cells, where the analysis involves destroying the cell as a unit in the process.

Cell DPA shall not include electrical testing of end-item cells except as such testing may be a part of an overall destructive test procedure.
PROPOSED NEAR-TERM OBJECTIVES

1. **Determine the different purposes for which Nickel-Cadmium cell materials analysis and/or cell destructive analysis (a) has been used and (b) should be used.**

2. **Determine where in the normal cell manufacturing process at Gates Energy Products (GEP) they perform materials and/or cell destructive analysis, what they analyze, and what types of analyses they do at each point.**

3. **Determine which analysis GEP is now doing for different customers, and what other types of analyses GEP is equipped to do.**

4. **Determine the method GEP is using to record results of materials analysis in-house, what data is reported to customers, and in what form.**

5. **Recommend a "core" (minimum mandatory) set of analyses/tests (or more than one core set, if appropriate).**

6. **Recommend additional, optional analyses/tests to augment the core set(s).**

7. **Determine which of the tests GEP is willing to do.**
PROPOSED LONGER-TERM OBJECTIVES

1. **Determine the methods used by GEP to perform the various analyses they are doing. Identify those analyses for which the results may be method-sensitive or technician-sensitive.**

2. **Critique methods used for analyses. Provide improved methods where needed. Recommend research on methods where required.**

3. **Provide interpretation of results. Provide criteria/limits of acceptability for different applications.**

4. **Assess the effectiveness of analyses and tests currently used, to detect the results of manufacturing problems and to anticipate performance problems.**
COMMITTEE ACTIVITY STATUS

0 **Approximately 40% of the near-term objectives have been accomplished to date**

0 **Applications of DPA were examined**

0 **Analyses and tests performed by Gates Energy Products during cell manufacturing were reviewed**

0 **Committee members were polled on the relative merits of conventional types of analyses and tests**

0 **More sophisticated analytical methods are being considered**

0 **Some interim recommendations were formulated**
## SOME DPA-RELATED ANALYSES AND TESTS NOW DONE ROUTINELY BY GEP

<table>
<thead>
<tr>
<th>Where in the Process</th>
<th>What is Analyzed/Tested</th>
<th>Properties Determined</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Platemaking</strong></td>
<td>Sintered Strip (unimpregnated)</td>
<td>Thickness&lt;br&gt;Weight per unit area&lt;br&gt;Weight Ni per unit area</td>
</tr>
<tr>
<td></td>
<td>Impregnated Strip</td>
<td>Weight per unit area&lt;br&gt;Weight gain (by impregnation)&lt;br&gt;&quot;Hydrate&quot; weight per unit area</td>
</tr>
<tr>
<td><strong>Transition to Aerospace Cell Operations</strong></td>
<td>Positive and Negative Plate Material</td>
<td>Weight per unit area&lt;br&gt;Thickness&lt;br&gt;Active material per unit area&lt;br&gt;Weight Ni per unit area&lt;br&gt;APM level&lt;br&gt;Nickel attack (Positive only)&lt;br&gt;Porosity (by calculation)&lt;br&gt;Cadmium or Silver as applicable&lt;br&gt;Flooded capacity&lt;br&gt;Stress test resistance</td>
</tr>
</tbody>
</table>
### SOME DPA-RELATED ANALYSES AND TESTS NOW DONE ROUTINELY BY GEP (CONTINUED)

<table>
<thead>
<tr>
<th>WHERE IN THE PROCESS</th>
<th>WHAT IS ANALYZED/TESTED</th>
<th>PROPERTIES DETERMINED</th>
</tr>
</thead>
<tbody>
<tr>
<td>INCOMING</td>
<td>SEPARATOR Material</td>
<td>SEPARATOR ACCEPTANCE TESTS:</td>
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<tr>
<td></td>
<td></td>
<td>WEIGHT PER UNIT AREA</td>
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<td></td>
<td></td>
<td>THICKNESS</td>
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<td></td>
<td></td>
<td>ELECTROLYTE ABSORPTION</td>
</tr>
<tr>
<td>AFTER CARBONATE</td>
<td>POSITIVE AND</td>
<td>SELECTED CHEMICAL CONSTITUENTS</td>
</tr>
<tr>
<td>EXTRATION OF</td>
<td>NEGATIVE PLATES</td>
<td>VOID FRACTION</td>
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<tr>
<td>PLATES</td>
<td></td>
<td></td>
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<tr>
<td>AFTER CELL ASSEMBLY,</td>
<td>STARTS WITH A WHOLE CELL</td>
<td>TOTAL POSITIVE ELECTROCHEM. CAPACITY</td>
</tr>
<tr>
<td>ACTIVATION, AND</td>
<td></td>
<td>TOTAL POSITIVE CHEMICAL CAPACITY</td>
</tr>
<tr>
<td>SETTING OF PRECHARGE</td>
<td></td>
<td>TOTAL NEGATIVE CHEMICAL CAPACITY</td>
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<td></td>
<td></td>
<td>NEGATIVE CHARGED EXCESS CAPACITY</td>
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<td></td>
<td></td>
<td>(BY CALCULATION)</td>
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<td></td>
<td></td>
<td>INACTIVE NEGATIVE (BY CALCULATION)</td>
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<tr>
<td></td>
<td></td>
<td>CARBONATE CONTENT OF ELECTROLYTE</td>
</tr>
<tr>
<td>Material</td>
<td>Analysis/Test For</td>
<td>Initial</td>
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<tr>
<td>Nickel Powder</td>
<td>Bulk Density</td>
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<td></td>
<td>Particle Size</td>
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<tr>
<td>Sintered Plaque</td>
<td>Weight Nickel per Unit Area</td>
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<tr>
<td>(Unimpregnated)</td>
<td>Void Fraction (Porosity)</td>
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<td></td>
<td>Pore Size - Avg and Distributed</td>
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<td></td>
<td>Sinter Strength</td>
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<tr>
<td>Positive Plates</td>
<td>Thickness</td>
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<tr>
<td>(New and Used; Dry)</td>
<td>Weight per Unit Area</td>
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<tr>
<td></td>
<td>Residual Void Fraction (Porosity)</td>
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<td></td>
<td>Total Nickel Active Material</td>
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<td></td>
<td>Undischarged Nickel Active Material</td>
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<td></td>
<td>Metallic Nickel in Sinter</td>
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<td>Cobalt</td>
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<td></td>
<td>Cadmium</td>
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<tr>
<td>Material</td>
<td>Analysis/Test For</td>
<td>Initial</td>
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<tr>
<td>Positive Plates, dry (cont)</td>
<td>Water-Insoluble Carbonates</td>
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<td></td>
<td>Active Material Distribution (SEM, etc.)</td>
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<tr>
<td></td>
<td>Flooded Capacity</td>
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<tr>
<td>Positive Plates (from Activated Cells; Wet)</td>
<td>Electrolyte Content</td>
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<td></td>
<td>Flooded Capacity</td>
<td></td>
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<tr>
<td>Negative Plates (New and Used; Dry)</td>
<td>Thickness</td>
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<td>Weight per Unit Area</td>
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<td></td>
<td>Residual Void Fraction (Porosity)</td>
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<td></td>
<td>Total Cadmium Active Material</td>
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<td></td>
<td>Undischarged Cadmium Active Material</td>
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<td></td>
<td>Metallic Nickel in Sinter</td>
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<td>Silver</td>
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<td></td>
<td>Water-Insoluble Carbonates</td>
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<td>Active Material Distribution (SEM, etc.)</td>
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<td>Analysis/Test For</td>
<td>Initial</td>
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<tr>
<td>Negative Plates (from Activated Cells; Wet)</td>
<td>Electrolyte Content</td>
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<tr>
<td></td>
<td>Flooded Capacity</td>
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<td>Thickness</td>
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<td>Weight per Unit Area</td>
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<td>Tear Strength</td>
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<td></td>
<td>Compressibility</td>
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<td>Wettability by Electrolyte</td>
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<td>Electrolyte Absorption</td>
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<tr>
<td></td>
<td>Electrolyte Distribution between Separator and Plate Materials</td>
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<tr>
<td></td>
<td>Resistance to Hydrolysis in Electrolyte</td>
<td></td>
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<td></td>
<td>Effects of Standing in Electrolyte</td>
<td></td>
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<tr>
<td>Separator (Used, Wet)</td>
<td>Electrolyte Content</td>
<td></td>
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<tr>
<td></td>
<td>Cadmium Compounds Content</td>
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<tr>
<td>Material</td>
<td>Analysis/Test For</td>
<td>Initial</td>
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<tr>
<td>Electrolyte</td>
<td>KOH</td>
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<tr>
<td></td>
<td>Carbonate</td>
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<td></td>
<td>Lithium</td>
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<td></td>
<td>Copper</td>
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<td></td>
<td>Silica</td>
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<tr>
<td>Whole Cell, Activated</td>
<td>In-cell positive and negative capacities; excess negative capacities by the GEP &quot;Electrode Capacity Test&quot; and &quot;CMA&quot;.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electrolyte Distribution</td>
<td></td>
</tr>
</tbody>
</table>
NON-CONVENTIONAL TEST METHODS

SONIC AND ULTRA-SONIC SCANNING OF PLATE MATERIALS

X-RAY ANALYSIS OF PLATE MATERIALS

ELECTRONIC IMAGE ANALYSIS

PORE SIZE DISTRIBUTION ANALYSIS

OXIDATIVE TESTING OF SEPARATORS
INTERIUM RECOMMENDATIONS

1. At least four different applications of DPA have been identified, each of which may have different requirements for DPA:

1.1 For normal, quality assurance during the cell manufacturing process, prior to cell acceptance testing.

1.2 For end-item cell acceptance, in conjunction with or as a required part of cell acceptance testing.

1.3 For "extended quality verification", after some significant amount of additional cycling, e.g., during and/or after a 500-cycle test.

1.4 As part of a cell failure analysis.

2. The "core set" of analyses/tests should be the same for all applications. Options may be different for different applications.

3. Data should be obtained on each lot of components during cell manufacturing and these data used as the reference for any subsequent DPA on a given lot of cells. Samples should be taken and stored for possible future use.
4. **Measurement of Total Positive Capacity, Pre-Charged Negative Capacity, Excess Uncharged Negative Capacity, and Inactive Negative Capacity in Activated Sample Cells** should be performed as a part of an Initial DPA on each cell lot during manufacturing. GEP uses a proprietary integrated procedure, referred to as the "Electrode Capacity Test", and "Chemical Analysis" to make these measurements and to reduce the data. GEP normally performs this test immediately after setting precharge, at which point the results have their greatest validity. The test procedure, method of treating the data, and the interpretation of the data as done by GEP, should be understood by all cell users.

5. **Any DPA done on cells after significant cycling should be a sub-set of the initial DPA.** However, if anomalous behavior or electrical failure is observed, additional tests, tailored to reveal the problem determinant, should be used. The specifics of the latter type tests are considered to be beyond the scope of this committee.
NICKEL-Cadmium Separator
Acceptance Test and Criteria

1988 NASA/GSFC Battery Workshop
November 1-3, 1988
NICKEL-CADMIUM SEPARATOR ACCEPTANCE TEST AND CRITERIA

TASK GROUP MEMBERS

QUENTIN KAMPF  FREUDENBERG
GLEN KLEIN  GATES
MICHELLE MANZO  NASA LeRC
GEORGE METHLIE
ALBERT ZIMMERMAN  AEROSPACE
NICKEL-CADMIUM SEPARATOR ACCEPTANCE TEST AND CRITERIA

OBJECTIVE

DEFINE TESTS FOR EVALUATION OF SEPARATORS
ENSURE SEPARATOR QUALITY AND CONSISTENCY
RECOMMEND RANGE FOR SEPARATOR PROPERTIES
NICKEL-CADMIUM SEPARATOR ACCEPTANCE TEST AND CRITERIA APPROACH

REVIEW GATES TESTS AND PROCEDURES

MAKE RECOMMENDATIONS
  TYPE OF TESTS
  LEVEL OF TESTING
  SEPARATOR PROPERTIES
NICKEL-CADMIUM SEPARATOR ACCEPTANCE TEST AND CRITERIA

SEPARATOR ASSESSMENT

Ni-Cd CELLS HAVE BEEN EMPIRICALLY OPTIMIZED FOR PELLON 2505
PELLON 2536 IS NOT A DIRECT REPLACEMENT FOR PELLON 2505
REPLACEMENT SEPARATOR MUST HAVE PROPERTIES AS CLOSE TO THOSE OF PELLON 2505 AS POSSIBLE
EVALUATION AND ASSESSMENT OF NON-NYLON MATERIALS FOR LONG TERM REPLACEMENTS MUST BEGIN NOW
SPECIFICATIONS AND TESTING REQUIRE MORE DETAIL AND DEFINITION TO ENSURE TRACEABILITY:

IDENTIFY RELATIVE SAMPLE POSITION ON ROLL
PERFORM ALL TESTS AT SEPARATOR LOT LEVEL
IDENTIFY SUBSETS TO PERFORM AT THE ROLL LEVEL
MEASURE CRITICAL PARAMETERS AT CELL LOT LEVEL
GENERAL RECOMMENDATIONS

INITIATE EXTENSIVE TEST PROGRAM

ESTABLISH BASELINE FOR SEPARATOR PROPERTIES

PERIODICALLY EVALUATE AND REVIEW TEST PROGRAM TYPE OF TESTS LEVELS AT WHICH TESTS ARE PERFORMED REQUIRED SEPARATOR PROPERTIES

UPGRADE SEPARATOR TEST PROCEDURES

ADD TESTS AS REQUIRED ELIMINATE UNNECESSARY TESTS

MODIFY TEST PROCEDURES

NIKEL-Cadmium Separator Acceptance Test and Criteria

NASA/GSFC Battery Workshop
NICKEL-CADMIUM SEPARATOR ACCEPTANCE TEST AND CRITERIA

AEROSPACE SEPARATOR ACCEPTANCE TESTS

CHEMICAL ANALYSIS
EXTRACTABLE ORGANICS
INORGANICS

ELECTROLYTE RETENTION

SEM ANALYSIS

AIR PERMEABILITY

WEIGHT TEST
FOAM TEST

RESISTANCE TO ELECTROLYTE
WEIGHT LOSS AND SHRINKAGE
REDUCED STRENGTH

THICKNESS
THICKNESS VARIATION

CHEMICAL OXIDATION

TENSILE STRENGTH/ELONGATION
WITH MACHINE DIRECTION
ACROSS MACHINE DIRECTION

DISCOLORATION

FOREIGN PARTICLE COUNT
NICKEL-Cadmium Separator Acceptance Test and Criteria

Test: Extractable Organics

Purpose: Evaluate separator for presence of organics that might adversely effect cell performance or separator structural integrity

Criteria: Less than 2%

Recommendation:
Identify possible contaminants
Determine possible effects on cell performance
Set limits for individual components
NICKEL-CADMIUM SEPARATOR ACCEPTANCE TEST AND CRITERIA

TEST: SEM ANALYSIS

PURPOSE: VISUAL ANALYSIS OF SAMPLES FOR UNIFORMITY

CRITERIA:

RECOMMENDATION: SET UP A GO – NO-GO CRITERION FOR THIS TEST
NICKEL-Cadmium Separator Acceptance Test and Criteria

Test: Weight Test

Purpose: Determine level of leachables, volatiles, and weight loss

Criteria: Volatiles:
Water leachables: <1%
Total % weight loss:

Recommendation:
Identify what contaminants may be present and identify potential effects on cell
NICKEL-Cadmium Separator Acceptance Test and Criteria

TEST: THICKNESS, THICKNESS VARIATION

PURPOSE: DETERMINE SEPARATOR THICKNESS AND UNIFORMITY

CRITERIA: MATERIAL, CELL DEPENDANT

RECOMMENDATION:
STANDARDIZE PROCEDURES FOR MEASURING THICKNESS
EVALUATE THICKNESS VS APPLIED PRESSURE
NICKEL-CADMIUM SEPARATOR ACCEPTANCE TEST AND CRITERIA

TEST: TENSILE STRENGTH – WITH MACHINE DIRECTION ACROSS MACHINE DIRECTION.

PURPOSE: DETERMINE MATERIAL STRENGTH FOR MACHINE PROCESSING BASELINE TO COMPARE STRENGTH FOLLOWING EXPOSURE TO ELECTROLYTE (REDUCED STRENGTH TEST)

CRITERIA: MINIMUM PROCESSING REQUIREMENT

RECOMMENDATION:
- DETERMINE REQUIRED STRENGTH FOR INDIVIDUAL MATERIALS
- SPECIFY MINIMUM REQUIRED STRENGTH
NICKEL-Cadmium Separator Acceptance Test and Criteria

Test: Electrolyte Retention

Purpose: Evaluate separator electrolyte retention capabilities

Criteria: % based on weight, material specific

Recommendation:
Evaluate retention under compression
Express retention as (grams KOH)/area
NIKEL-CADMIUM SEPARATOR ACCEPTANCE TEST AND CRITERIA

TEST: AIR PERMEABILITY

PURPOSE: COMMERCIAL REQUIREMENT
EVALUATE GAS TRANSPORT
MEASURE OF UNIFORMITY

CRITERIA:

RECOMMENDATION:
EVALUATE BUBBLE PRESSURE AS A MORE REPRESENTATIVE MEASURE OF GAS TRANSPORT
NICHEL-CADMIUM SEPARATOR ACCEPTANCE TEST AND CRITERIA

TEST: OXIDIZABLE MATERIALS, AgO

PURPOSE: EVALUATE SEPARATOR FOR PRESENCE OF OXIDIZABLE MATERIAL TEST FOR TREATMENT OR CONTAMINATION

CRITERIA: DISCOLORATION INDICATES TREATMENT OR CONTAMINATION

RECOMMENDATION:
SPECIFY SOLUTION AND TEMPERATURE
NICKEL-Cadmium Separator Acceptance Test and Criteria

Test: Wettability

Purpose: Evaluate separator for presence of contaminants

Criteria: >5 minutes required for wetting
NICKEL-Cadmium Separator Acceptance Test and Criteria

Test:

Capillarity

Purpose: Measurement of Wicking as Test for Contamination

Criteria:
NICKEL-CADMIUM SEPARATOR ACCEPTANCE TEST AND CRITERIA

TEST: RESISTANCE TO ELECTROLYTE

PURPOSE: MEASUREMENT OF SUSCEPTIBILITY TO HYDROLYSIS

CRITERIA: DETERMINE NOMINAL ACCEPTABLE LEVELS

RECOMMENDATION:
EXPExURE TO 70 DEG KOH MUST BE DONE WITHOUT EXPOSURE TO AIR FOR REPRODUCIBILITY FOLLOWING EXPOSURE RINSE SAMPLE WITH FRESH WARM KOH TO LEACH REACTION PRODUCTS
NIKEL-CADMIUM SEPARATOR ACCEPTANCE TEST AND CRITERIA

TEST: REDUCED STRENGTH

PURPOSE: EVALUATE DETERIORATION FROM EXPOSURE TO KOH

CRITERIA: DIFFERENCES IN TENSILE STRENGTH FROM NEW MATERIAL

RECOMMENDATION:
EXPOSURE TO 70 DEG KOH MUST BE DONE WITHOUT
EXPOSURE TO AIR FOR REPRODUCIBILITY
FOLLOWING EXPOSURE RINSE SAMPLE WITH FRESH WARM
KOH TO LEACH REACTION PRODUCTS
NICKEL-CADMIUM SEPARATOR ACCEPTANCE TEST AND CRITERIA

TEST: CHEMICAL OXIDATION, KMnO4

PURPOSE: EVALUATE WEIGHT LOSS RESULTING FROM CHEMICAL OXIDATION

CRITERIA: DETERMINE ALLOWABLE MAXIMUM

RECOMMENDATION:
FREUDENBERG TEST
AEROSPACE IN CELL TEST MAY BE BETTER MEASURE
NICKEL-Cadmium Separator Acceptance Test and Criteria

TEST:
DISCOLORATION, FOREIGN PARTICLES

PURPOSE:
VISUAL OBSERVATIONS OF SEPARATOR QUALITY

CRITERIA:
DETERMINE GO - NO-GO CRITERION
NICKEL-Cadmium Separator Acceptance Test and Criteria

Additional Tests Recommended

Oxidation Resistance
In cell environment
Aerospace procedure

Resistivity in electrolyte
Compressed to predetermined level
Uncompressed

Porosity, pore size distribution
Bubble pressure
NICKEL-Cadmium Separator Acceptance Test and Criteria

Additional Tests Recommended

Oxidation Resistance
in Cell Environment
Aerospace Procedure

Resistivity in Electrolyte
Compressed to Predetermined Level
Uncompressed

Porosity, Pore Size Distribution

Bubble Pressure
# Nickel-Cadmium Separator Acceptance Test and Criteria

## Aerospace Separator Acceptance Tests

**Recommended Test Levels**

<table>
<thead>
<tr>
<th>Test</th>
<th>Separator Lot</th>
<th>Roll</th>
<th>Cell Lot</th>
</tr>
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<tbody>
<tr>
<td>Chemical Analysis</td>
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<td>Weight Test</td>
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<td>Foam Test</td>
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<td>Tensile Strength</td>
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<td>With Machine Direction</td>
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<td>Across Machine Direction</td>
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<td>Electrolyte Retention</td>
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<tr>
<td>Air Permeability</td>
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</table>
# Nickel-Cadmium Separator Acceptance Test and Criteria

## Aerospace Separator Acceptance Tests Recommended Test Levels

<table>
<thead>
<tr>
<th>TEST</th>
<th>SEPARATOR LOT</th>
<th>ROLL</th>
<th>CELL LOT</th>
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<tbody>
<tr>
<td>Oxidizable Materials, AgO</td>
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<tr>
<td>Wettability</td>
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<tr>
<td>Capillarity</td>
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<tr>
<td>Resistance to Electrolyte</td>
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<tr>
<td>Weight Loss and Shrinkage</td>
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<td>Reduced Strength</td>
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<tr>
<td>Chemical Oxidation</td>
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<td>Foreign Particle Count</td>
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<tr>
<td>Discoloration</td>
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<tr>
<td>Oxidation Resistance</td>
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<td>Electrical Resistance</td>
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<td>Porosity, Pore Size</td>
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<tr>
<td>Bubble Pressure</td>
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</tbody>
</table>

*Note: Details for certain tests are marked with 'BY REQUEST'.
NIckel-Cadmium separator acceptance test and criteria summary

Separator acceptance tests reviewed
Initiate evaluation process
Replacement materials require extensive study
Identify key properties and measurement requirements
TASK GROUP PRESENTATION:

4. PLATE ISSUES TASK TEAM

(NOT SUBMITTED)

DEAN MAURER, AT&T BELL LABS
NASA TASK FORCE -- FUTURE Ni-Cd CELL DESIGN

TEAM MEMBERS

S. Gross
L. Thaller
D. Pickett
L. Tinker
D. Maurer
G. Halpert
G. Methlie
OBJECTIVE

RECOMMEND PROMISING APPROACHES FOR DEVELOPMENT OF ADVANCED Ni-Cd CELL TECHNOLOGY.

LEO
10 YEARS, 30% DOD
7 YEARS, 35% DOD

GEO
20 YEARS, 60% DOD
15 YEARS, 75% DOD

CELL SIZE:
1) SAME AS STANDARD 50 AH CELL
2) NEW SIZE CELL
RECOMMENDATIONS

MANUFACTURING FACILITY

SEPARATOR

NICKEL POSITIVE ELECTRODES

CADMIUM NEGATIVE ELECTRODES
MANUFACTURING FACILITY

COMPLETE CONTROL, INCOMING MATERIALS TO FINISHED CELLS

- All steps
- All materials and processes
- Major improvements over present controls
SEPARATOR

NYLON DISALLOWED

USE SEPARATOR DEMONSTRATED TO BE EXCELLENT FOR Ni-Cd

- Wettability
- Electrolyte retention
- Handlability
- Suitable density
- Suitable porosity
- Additive-free

MAIN CANDIDATES

- ZIRCAR + PBI
- ZIRCAR + polysulfone
- Polypropylene-based + PBI
- Advanced polypropylene-based
NICKEL SINTER FOR NICKEL ELECTRODE

SLURRY OR DRY POWDER

- Mean pore size 12-13 microns
- < 5% greater than 50 microns
- < 5% less than 3 microns
- Sinter porosity 87-90%
- Substrate - open
- 3 point bend test, 550 +/- 50 psi
- No compression or sizing, coining only
- Aqueous impregnation:
  - Passivation required
  - Time and temperature controls required
  - Must pass corrosion test, 15 min at 325oF, Cd(NO3)2 bath, meet min and max requirements
NICKEL ELECTRODE

ELECTROCHEMICAL IMPREGNATION, AQUEOUS OR ALCOHOLIC METHOD

- **Loading Range**: $1.7 \pm 0.1$ g/cc void
- **Loading Control**: $+/- 0.05$ g/cc void
- **Co(OH)$_2$**: 7 to 10%, controlled to $+/- 1$
- **No Sizing**
- **Formation**
  - 60°C
  - 5C charge and discharge
  - 120% overcharge
- **Utilization**
  - Flooded capacity
  - 100% based on theoretical loading
  - C/5 charge, C/2 discharge
- **Stress Test**
  - 25°C
  - 10C rate charge/discharge
  - 100% overcharge, 100% overdischarge
  - 200 cycles
  - No more than 1% swelling
  - No more than 3.5% blemishes
  - No loss in capacity compared with first cycle with C/5 charge to 120%, C/2 discharge to 1.0 V, 25oC
NICKEL SINTER FOR CADMIUM ELECTRODE

SLURRY OR DRY POWDER

0 Thickness 30 mils max (28-30 mils typical)
0 Pore size distribution similar to Ni electrode
0 Max C rate current density: 5 mA/cm2 per interface
0 Substrate: open
0 No compression or sizing
0 Passivation required
   o Must pass corrosion test, same as for Ni
CADMIUM ELECTRODE

ELECTROCHEMICAL IMPREGNATION

- Load 1.8-1.9 grams Cd(OH)₂ per cc void, control to 0.08
- No compression, no sizing
- Formation: same as Ni electrode
- Utilization
  - 80% using C/5 charge and discharge
  - Discharge to 0.0 V vs Hg/HgO
- Stress test required (TBD)
MISCELLANEOUS

O Capacity -- 50 AH nominal
O Negative/Positive ratio -- 2.0 on theoretical basis
O Dimensions
  O Ni electrode thickness derived from above data
  O Interelectrode spacing -- 9 to 11 mils
  O Case wall -- 19 mils
O Electrolyte fill
  O Volume basis with pressure adjustment
  O 31% KOH
  O No Li(OH)
O Cell seal -- either ceramic, Zeigler, or Stadnick seal
O Core wrap
  O If polypropylene is use, bag Ni electrodes
  O If Zircar/PBI is used:
    O Must be in sheet form
    O Should have 5 mil polypropylene liner
    O Should extend to bottom of can
TASK GROUP 6 CHARTER

TASK 1: Scoping Tasks for Evaluation of NWSC Data

TASK 2: Recommendations on Near-Term Actions for Ni-Cd Cell Design

As I understand from Dr. Jerry Halpert's letter and subsequent discussions with and the other task force leaders, our present job assignment is to scope out the work we think needs to be done. We are not expected to actually do the work now!

We are to do the following:

A. Define the objectives.
B. Itemize specific operations to be done.
C. Identify specific steps or techniques to be used. Also point out steps or techniques that require additional study.
D. Prioritize the steps, and list the minimum required to achieve the task force objectives.
## TASK FORCE GROUP 6 - EVALUATION OF NWSC

Data, and Recommendation of Near-Term Design Fixes

### TASK LEADER

<table>
<thead>
<tr>
<th>Name</th>
<th>Phone #</th>
<th>Fax #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bill Billerbeck, MRJ</td>
<td>(703) 385-0742</td>
<td>(703) 385-4637</td>
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### MEMBERS

<table>
<thead>
<tr>
<th>Name</th>
<th>Phone #</th>
<th>Fax #</th>
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<tbody>
<tr>
<td>George Morrow/GSFC</td>
<td>(301) 286-6691</td>
<td>(301) 286-9214</td>
</tr>
<tr>
<td>Chris Garner/NRL</td>
<td>(202) 767-9075</td>
<td>(202) 767-1718</td>
</tr>
<tr>
<td>Steve Gaston/GE-EW</td>
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<td>(609) 426-3963</td>
</tr>
<tr>
<td>Don Mains/NWSC</td>
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<td>(812) 854-1212</td>
</tr>
<tr>
<td>Karla Clark/JPL</td>
<td>(818) 354-9033</td>
<td>(818) 393-6951</td>
</tr>
<tr>
<td>Lawrence Tinker/Gates</td>
<td>(904) 462-4715</td>
<td>(904) 462-6871</td>
</tr>
</tbody>
</table>

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**November 1-3, 1988**
Nickel-cadmium Battery Cell Life

Note: Low temperature point degraded
November 1-3, 1988

Nickel-cadmium Battery Cell Life

Note: Low temperature point reached
CELLS WITH LOWER AMOUNTS OF ELECTROLYTE OPERATED AT LOW TEMP.
CONCLUSIONS FROM CYCLE PLOTS

0 FIRST FAILURES DO NOT CORRELATE WELL WITH TYPE OF SEPARATOR OR TYPE OF POSITIVE PLATES

0 EARLIEST FAILURES WERE ON CELLS WITH LOW ELECTROLYTE FILL, THAT WERE CYCLED AT 0°C. CELLS TESTED AT HIGHER TEMPERATURE LASTED LONGER.

0 NI-Cd CELLS WITH NEW COMPONENTS ARE NOT PERFORMING AS WELL AS THE BEST "VINTAGE" NI-Cd CELLS (ABOUT 1/4 OR 1/2 THE NUMBER OF CYCLES)

0 ALL CELLS WITH SUFFICIENT ELECTROLYTE AND EITHER OLD OR NEW COMPONENTS PERFORMED EXCELLENTLY IN CYCLING TESTS!

0 ALL CELLS IN THE QUAL TESTS APPEAR TO EXCEED THE NI-Cd ESTIMATED LIFE CURVE BY A WIDE MARGIN!
## Electrolyte Quantity in NASA Qual Test Cells

<table>
<thead>
<tr>
<th>Pack and cell no.</th>
<th>sep type</th>
<th>Cap to 0v</th>
<th>ml of KOH</th>
<th>KOH/AH</th>
<th>Burns, Cd at top of cell</th>
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<tbody>
<tr>
<td>150A/50AB20/L13-5</td>
<td>2505</td>
<td>67.12</td>
<td>166</td>
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<td>150A/50AB20/L13-16</td>
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<td>150A/50AB20/L13-20</td>
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<td>72.67</td>
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<tr>
<td>REF/50AB20/L13-13</td>
<td>2505</td>
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<td>166</td>
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<tr>
<td>150B/50AB25/L1-6</td>
<td>2536</td>
<td>71.91</td>
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<td>150H/50AB25/L1-11</td>
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<td>72.65</td>
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<td>150C/50AB26/L1-7</td>
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<tr>
<td>REF/50AB26/L1-1</td>
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<td>150G/50AB27/L1-16</td>
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<td>69.08</td>
<td>155</td>
<td>2.24</td>
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2.30 ave.
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<th>Pack and cell no.</th>
<th>sep type</th>
<th>Cap to Ov</th>
<th>ml of KOH</th>
<th>KOH/AH</th>
<th>Burns,Cd at top of cell</th>
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<td>326A/30AB10/L16-109</td>
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<td>334D/34AB03/L1-27</td>
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<td>350D/50AB28/L1-23</td>
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<td>REF/50AB24/L8-19</td>
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<td>63.03</td>
<td>124.5</td>
<td>1.97</td>
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</table>

Average: 1.96
SUMMARY OF INFORMATION ON ELECTROLYTE QUANTITY

ABSTRACTED FROM DPA ANALYSES

0 NEW #2536 SEPARATOR ACCEPTS LESS KOH THAN OLD #2505 MATERIAL
   - EX. 84 VS 87ML IN RCA 26.5AH CELLS

0 NO SEPARATOR PINHOLE OR BURN SPOTS REPORTED IN DPA'S OF NASA CELLS,
   ALTHOUGH THERE HAD BEEN EVIDENCE OF SOFT SHORTS IN A FEW VOLTAGE
   PROFILES

0 PINHOLES, BURNS, AND Cd MIGRATION IN A BAND AT THE TOP OF THE PLATES
   OBSERVED IN DPA'S OF ALL CYCLED CELLS MADE FOR AEROSPACE CORP.

0 ALL NASA CELLS CONTAIN MORE ELECTROLYTE THAN CELLS MADE FOR AEROSPACE
   CORP - 2.30 VS 1.96 ML/AH

0 THIS SYSTEMATIC DIFFERENCE OF 15% MAY EXPLAIN THE EARLY DRYOUT AT THE
   TOP OF THE CELLS TESTED FOR AEROSPACE CORP.
ANALYSIS OF Ni-Cd TEST DATA

PRELIMINARY CONCLUSIONS

0 NO INFANT MORTALITY FAILURES IN QUAL DATA: ALTHOUGH SOME CELLS FAILED
ACCEPTANCE TESTS AND WERE REJECTED DUE TO HIGH VOLTAGE ON CHARGE.
0 FIRST FAILURES DO NOT CORRELATE WELL WITH TYPE OF SEPARATOR OR TYPE OF
POSITIVE PLATE
0 EARLIEST FAILURES OCCURRED ON CELLS WITH LOW ELECTROLYTE FILL, RUN AT LOW
TEMPERATURE (0ºC), WHILE CELLS TESTED AT HIGHER TEMP (20ºC) LASTED
LONGER.
0 OVERALL RATE OF CADMIUM BUILDUP IS ABOUT 50% LOWER IN NEW #2536 SEPARATOR
0 COMPLETE PACK FAILURES (80 TO 100% FAIL) OCCURRED ONLY WITH CELLS HAVING
NEW 2536 SEPARATOR IN COMBINATION WITH LOW ELECTROLYTE FILL. (1.8 TO 1.9
ML/AH)
0 ALL CYCLED CELLS WITH LOW ELECTROLYTE FILL THAT WERE ANALYZED BY DPA HAD
CD BAND AND PINHOLES OR BURNS AT TOP OF THE PLATES - PERFECT CORRELATION
0 CELLS WITH SUFFICIENT ELECTROLYTE AND EITHER OLD OR NEW TYPE COMPONENTS
PERFORMED EXCELLENTLY IN CYCLING TESTS!
0 SOME PACKS LOST ONE CELL, AND MOST PACKS IN THE TEST ARE CONTINUING TO
CYCLE
0 Ni-Cd CELLS WITH NEW COMPONENTS ARE NOT PERFORMING AS WELL AS THE BEST
"VINTAGE" Ni-Cd CELLS (ABOUT 1/3 OR 1/2 THE NUMBER OF CYCLES)
0 ALL CELLS IN QUAL TESTS APPEAR TO MEET OR EXCEED THE Ni-Cd ESTIMATED CYCLE
LIFE CURVE!
OUTLINE - TASKS FOR EVALUATION OF DATA FROM Ni-Cd SEPARATOR QUALIFICATION TESTS AT NWSC - 21 September 1988

Task A. Update and improve the data base.

1. Update the data summaries - Latest NWSC cycle data
   - Gates DPA data
   - Gates separator lot analysis, electrode lot analysis, and ATP data

2. Collect data on key design features of each of the cells - Ag or teflonated negative, positive loading, quantity of cobalt and cadmium in the positive, gas passivation, electrolyte quantity, lightweight or low profile can, etc.*

3. Enhance the data base - Clearly identify changes made in conditions during cycling period. Also obtain individual cell voltage plots just prior to failure, and/or just prior to pulling cell for DPA.

4. Publish the data base - compile the summaries of key characteristics, cyclic test results, and related DPA analyses in report form.

5. Flag any data that is questionable or invalid due to testing difficulties.

Task B. Analyze the data in more detail.

1. Plot up the updated cycle data obtained in this set of tests in a summary plot vs. DO0.

2. Compare the overall cyclic performance obtained in Crane tests of good Ni-Cd cells. Show averages and variability in the summary plot.

3. Pinpoint the cells in this test which became negative limited, by reference to voltage-time plots and DPA data.

*NOTE: Include plaque sintering time and temperature, type of powder, electrolyte quantity, etc.
Task B (con't).

4. Try to understand why these cells became negative limited. Check precharge. Examine the specific lot history of separator used. Did it degrade more rapidly than normal?

5. Pinpoint the cells that had soft or hard shorts, by reference to voltage-time plots and DPA data.

6. Try to understand why these cells went short. Evaluate electrolyte quantity. Examine their specific reconditioning history. Is more reconditioning recommended to avoid soft shorts? Were negatives teflonated? Cadmium migration patterns? Any other metal in the separator? Did they fail by separator dryout?

Task C. Summarize and publish the key results of the data analyses in report form.

1. If any "dry stored" old lot cells of the same P.N. are available, should they be filled, and added as control samples? Also, recommend specific new samples for inclusion in NWSC tests, if needed.

2. Consider whether there are any major holes in the data which could benefit from the addition of new test regimes or new test samples.

3. Include "lessons learned" and recommendations resulting from them regarding the planning and execution of future tests.
OUTLINE - TASK OF RECOMMENDING NEAR-TERM

ACTIONS FOR Ni-Cd CELLS

Task A. Map out logical courses of action based on a careful analysis of the NWSC cyclic performance data, as described in the data evaluation task.

Task B. Define alternatives. Some possibilities might include:

- One solution would be to "peel-back" as many of the design changes as possible made over the last 5 years. The intent is to go back to a design which all customers were very satisfied with in regard to its long term performance. Hopefully that leaves only one change - the separator material. Then either the use of acceptable stored Pellon 2505 or acceptable 2536, provided it can accommodate a minimum electrolyte quantity of 3 cc/rated A.H. in a finished cell (the old established rule), is suggested.

- Freeze the design for the short term until more research is done. NASA std. cell performance with 2536 Pellon separator appears acceptable for GEO and for some LEO applications.

- Continue production with 2536 separator; adding tests for separator oxidation, and ensuring that electrolyte quantity exceeds some specified value.

- Continue production; improve QA based on recommendations from QA task group, and adding tests for separator oxidation, ensuring that electrolyte quantity exceeds some specified value. Also perform extended DPA analysis on one cell from each lot, incorporating recommendations of DPA task group.

- Suggest more extensive cell design changes based on results of additional analysis of qual tests.

Task C. Recommend a short-term course of action for Ni-Cd cells from the above alternatives. Provide rationale demonstrating that this appears to be supported by analysis of all the existing NWSC and other pertinent data.
APPENDIX A

NASA AND USAF Ni-Cd

SEPARATOR QUALIFICATION

SUMMARIES OF CYCLE AND DPA DATA
### TABLE 1: SUMMARY OF NASA LEO TEST

<table>
<thead>
<tr>
<th>Type Cell</th>
<th># Cells</th>
<th>DOD</th>
<th>Temp</th>
<th>% Occurrence of Problem cells</th>
<th># Cycle</th>
<th># Cycle</th>
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#### Old Vintage

| 12 Ah, old sep & pos     | 4       | 40   | 20   | 2                            | 14517   | 17759   | 3E           |
| 12 Ah, old sep & pos     | 4       | 40   | 20   | 2                            | 14517   | 17759   | 3F           |
| 20 Ah, old sep & pos     | 4       | 40   | 0    | 2                            | 34369   | 40300   | 1H           |
| 20 Ah, old sep & pos     | 4       | 40   | 0    | 2                            | 34369   | 40300   | 1F           |
### Table 3: Summary of Air Force/Navy LEO Test

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### DPA SUMMARY - NASA CELLS

### CHAINE JOB 512-ANALYSIS RESULTS SUMMARY

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**NASA/GSFC Battery Workshop**

144
**DPA SUMMARY - USAF CELLS**

**4/14/88**

**CRANE JOB 513 - ANALYSIS RESULTS SUMMARY**

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</table>

| POS 0.5V | 29.82 33.18 40.26 40.09 35.45 41.71 44.30 43.57 57.11 54.18 N/A 56.27 |
| POS 0.5V | 22.06 34.66 25.17 24.82 23.45 28.12 30.71 30.06 41.87 39.04 0.00 0.00 |
| DELTA POS | 0.25 0.00 2.61 2.74 0.00 0.25 2.00 0.00 2.91 1.61 N/A 0.00 |
| CHG RESID | 3.90 4.87 2.11 2.73 2.38 4.48 4.4 2.34 5.52 7.39 4.53 2.20 |
| TOT PCG | 15.08 10.20 19.16 16.87 10.56 25.79 22.78 13.83 26.31 23.51 |
| DELTA TOTPCG | 4.88 0.00 7.60 6.31 0.00 11.96 8.95 0.00 12.98 10.12 0.00 0.00 |
| TOT CHG N9G | 53.79 48.66 63.53 62.37 53.32 74.95 73.69 62.74 92.25 88.15 0.00 76.36 |
| DELTA TCH | 5.13 0.00 10.21 9.05 0.00 12.21 10.95 0.00 15.89 11.77 0.00 0.00 |
| CHG N9G | 69.81 75.20 73.71 74.28 77.85 82.19 85.32 92.99 105.80 102.26 109.22 117.36 |
| IBER-CG2-CH | 0.249 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 |
| IBER-CG2-CHN | 0.057 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 |
| POS APH-AH | 5.46 3.42 6.58 6.72 3.66 8.28 9.06 3.85 5.63 4.64 5.42 1.13 |
| APH DELTA | 2.04 0.00 3.12 3.26 0.00 4.43 5.21 0.00 4.50 3.51 4.29 0.00 |
| TOT CMN | 71.96 75.20 77.33 78.30 77.96 89.48 92.63 93.08 112.71 108.08 115.81 117.37 |
| DELTA CMN | -3.24 0.00 -0.62 0.35 0.00 -3.60 -0.46 0.00 -4.66 -9.29 -1.55 0.00 |
| NA+AVN | 18.17 26.54 13.80 15.93 24.64 14.53 18.94 30.34 20.46 19.93 41.01 |
| DELTA NA+AVN | -8.37 0.00 -10.83 -8.70 0.00 -15.81 -11.41 0.00 -20.55 -21.08 0.00 0.00 |
| DELTA AVG AVAIL | -8.37 0.00 -10.83 -8.70 0.00 -15.81 -11.41 0.00 -20.55 -21.08 0.00 0.00 |
| POS TCH(NIL) | 29.4 29.2 29.7 29.7 29.6 30.4 28.6 29.8 32.2 32.0 31.3 29.1 |
| NOM SPEC | 27.2 27.2 27.2 27.2 27.2 27.2 27.2 27.2 27.2 27.2 27.2 27.2 |
| HEG TCH(NIL) | 33.5 31.4 31.1 32.2 30.1 32.7 31.8 31.9 31.0 31.4 31.4 31.0 |
| NOM SPEC | 31.5 31.5 31.1 32.1 32.1 31.5 31.5 31.5 29.9 29.9 29.9 |
| ION CTT (NL) | 81.0 81.0 85.0 82.0 85.0 100.0 100.0 102.0 120.0 120.0 120.0 |
| IZCS(5) | 6.60 6.07 7.05 7.51 5.15 5.50 5.50 3.76 6.76 5.04 N/A 3.89 |

**NOTE:** The data for baseline cells is from a dry pack just before insertion into the case. The DPA pos is on loaded plate, for DPA neg is on reloaded plate.

**November 1-3, 1988**

**ORIGINAL PAGE IS OF POOR QUALITY**

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TASK GROUP PRESENTATION:

7. QUALITY OVERSIGHT
TASK GROUP

(NOT SUBMITTED)

C. LAURIE, TRW
SESSION II

NICKEL-CADMIUM CELL TESTING

Chairman: T. Yi, NASA/GSFC
### 100 A.H. NiCd CELLS

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<td>17 NEG</td>
<td>17 NEG</td>
<td>18 NEG</td>
</tr>
<tr>
<td>PLATE CAPACITY</td>
<td>152.3 POS</td>
<td>113.6 POS</td>
<td>120.7 POS</td>
</tr>
<tr>
<td>A.H. BY ANALYSIS</td>
<td>246.3 NEG</td>
<td>235.3 NEG</td>
<td>249.1 NEG</td>
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<tr>
<td>CELL WEIGHT</td>
<td>3.30</td>
<td>3.22</td>
<td>3.18</td>
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<td>KILOGRAMS</td>
<td></td>
<td></td>
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<td>CONDITIONING</td>
<td>97.5 A.H.</td>
<td>89.2 A.H.</td>
<td>93.8 A.H.</td>
</tr>
<tr>
<td>CYCLE 20°C</td>
<td>36.3 WH/Kg</td>
<td>34.1 WH/Kg</td>
<td>36.3 WH/Kg</td>
</tr>
<tr>
<td>3RD CAPACITY</td>
<td>99.8 A.H.</td>
<td>92.3 A.H.</td>
<td>96.0 A.H.</td>
</tr>
<tr>
<td>@ 20°C</td>
<td>37.2 WH/Kg</td>
<td>35.3 WH/Kg</td>
<td>37.1 WH/Kg</td>
</tr>
<tr>
<td>POSITIVE</td>
<td>65.5%</td>
<td>81.2%</td>
<td>79.5%</td>
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<td>UTILIZATION</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>CC KOH</td>
<td>261</td>
<td>406.5</td>
<td>364</td>
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<tr>
<td>CC/AH</td>
<td>2.62</td>
<td>4.40</td>
<td>3.79</td>
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<td>A.H TO REACH</td>
<td>141 @ 20°C</td>
<td>111 @ 20°C</td>
<td>115 @ 20°C</td>
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<tr>
<td>MAX VOLTAGE</td>
<td>139 @ 15°C</td>
<td>109 @ 15°C</td>
<td>(118 @ 15°C)**</td>
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<tr>
<td>3RD CAPACITY</td>
<td>105 A.H.</td>
<td>93.7 AH</td>
<td>99.4 AH</td>
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<tr>
<td>@ 15°C</td>
<td>39.1 WH/Kg</td>
<td>35.8 WH/Kg</td>
<td>38.4 WH/Kg</td>
</tr>
</tbody>
</table>

**CHARGE INTERRUPTED**
E. D. POSITIVE PLATE

WHAT IS IT

- E. D. Means "Electro-Deposited"
  Impregnation As Opposed To
  Chemical Impregnation
  It Is Also Sometimes Called E. C. Or
  Electro-Chemically Deposited

ADVANTAGES

- Longer Life - Anticipate 10 To 15
  Years Of Orbital Life At 0 To 10°C Operation
- Virtually No Nickel Attack
- Virtually No Plate Swelling Resulting In
  Greater Mechanical Stability
- Improved Conductivity
- Used in NiH2 Cells
100 A.H. Ni Cd CELLS
CONDITIONING CYCLE #2 DISCHARGE
2/26/88

TEMPERATURE

- = EC09
- = EC08
- = AB07

CURRENT

- ALL CELLS IN SERIES

50

45

119 MIN.

40

VOLTAGE

- = EC09 NYLON
- = EC08 ZIRCAR
- = AB07 NYLON

EC09 NYLON 99.8 AH
EC08 ZIRCAR 99.2 AH
AB07 NYLON 97.5 AH

1.4

1.3

1.2

1.1

1.0

25 50 75 100 125 150

MINUTES

CELL VOLTS
100 A.H. Ni Cd CELLS
3RD CAPACITY TEST AT 20°C - DISCHARGE
3/31/88

CURRENT
- ALL CELLS IN SERIES
- 126 MINUTES

TEMPERATURE

VOLTAGE

- EC09 NYLON 96.0 AH
- EC08 ZIRCAR 92.3 AH
- AB07 NYLON 99.8 AH
3RD CAPACITY TEST AT 15°C - DISCHARGE

100 A.H. Ni Cd CELLS
4/20/88

CURRENT
ALL CELLS IN SERIES

TEMPERATURE
125 MINUTES

VOLTAGE

50 45 40 35 30 25 20 15 10 5

AMPERS

CELL VOLTS

50

25

75

100

125

150

MINUTES

NASA/GSFC Battery Workshop
100 A.H. NiCd CELLS
55 MINUTE DISCHARGE AT 54.3 A
655 MINUTE CHARGE AT 25.0 A PLUS V/T #2
20°C  50% DOD  8/24/88 TO 8/26/88

November 1-3, 1988
100 A.H. NiCd CELLS

SUMMARY

- ED PLATES HAVE HIGHER ACTIVE MATERIAL UTILIZATION
  - REQUIRE LIGHTER LOADING OF POSITIVE PLATES
  - HIGH POROSITY PERMITS HIGH ELECTROLYTE ADDITION
    >3.5 CC/AH

- SPECIFIC ENERGY OF CD AND ED CELLS ABOUT EQUAL
  - 37.1 WH/KG (16.9 WH/LB) AT 20°C

- ED CELLS CHARGE MORE EFFICIENTLY
  - SAVES TEST TIME
  - SAVES SOLAR ARRAY ENERGY

- CHARGE VOLTAGE OF CD AND ED CELLS NOT SIGNIFICANTLY DIFFERENT
  - TEMPERATURE COMPENSATED CHARGE CONTROL APPLICABLE TO BOTH
SAFT Ni-Cd LIFE TEST DATA UNDER GEO AND LEO CYCLING

J. VERNIOLLE, B. Hendel-Wormann & A. Sepers
European Space Agency / Estec

NASA/GSFC Battery Workshop
November 1988
LEO TESTING:
- ELAN PROGRAM
- X-80 TEST

GEO TESTING:
- ACC. HIGH DOD TEST
- OTS REAL SIMULATION
ELAN LOW EARTH ORBIT TESTING

Joint ESA/CNES program on Ni-Cd
12 cell battery assembly on cold plate
18 SAFT Bat.(13 V024S, 4 V040S3, 1 V0S20B)
1 G.E Bat.(22 Ah)
Cycling profile derived from SPOT
35mn discharge (last 10' at higher rate)
65 min charge (VL(T) tapering)
DOD : 10%, 20%, 30% & 40%
COLD PLATE TEMP.: -5, +5, +15, +25 Deg.C
<table>
<thead>
<tr>
<th>Battery</th>
<th>%DOD</th>
<th>Deg.C</th>
<th>Idc1(A)</th>
<th>Idc2(A)</th>
<th>Ich(A)</th>
<th>#cycl.</th>
<th>Veod (V)</th>
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<tbody>
<tr>
<td>VO24S</td>
<td>10</td>
<td>+5</td>
<td>3.45</td>
<td>5.77</td>
<td>8</td>
<td>17387</td>
<td>1.246*</td>
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<tr>
<td></td>
<td></td>
<td>+15</td>
<td>(0.14C)</td>
<td>(0.24C)</td>
<td>(0.33C)</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>+25</td>
<td></td>
<td></td>
<td></td>
<td>17387</td>
<td>1.213*</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>-5</td>
<td>3.45</td>
<td>20.0</td>
<td>8</td>
<td>15647</td>
<td>1.135*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+5</td>
<td>(0.14C)</td>
<td>(0.83C)</td>
<td>(0.33C)</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>+15</td>
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<td></td>
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<td>17395</td>
<td>1.083</td>
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<tr>
<td></td>
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<td>+15</td>
<td></td>
<td></td>
<td></td>
<td>17389</td>
<td>1.136*</td>
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<tr>
<td></td>
<td></td>
<td>+25</td>
<td></td>
<td></td>
<td></td>
<td>17379</td>
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<tr>
<td></td>
<td>30</td>
<td>-5</td>
<td>7.00</td>
<td>26.00</td>
<td>12</td>
<td>15621</td>
<td>1.069*</td>
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<tr>
<td></td>
<td></td>
<td>+5</td>
<td>(0.29C)</td>
<td>(1.08C)</td>
<td>(0.5C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>+15</td>
<td></td>
<td></td>
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<td>17412</td>
<td>1.037</td>
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<td></td>
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<td>15780</td>
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<td>40</td>
<td>+5</td>
<td>7.00</td>
<td>40.00</td>
<td>16</td>
<td>17389</td>
<td>0.995**</td>
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<tr>
<td></td>
<td></td>
<td>+25</td>
<td>(0.29C)</td>
<td>(1.67C)</td>
<td>(0.67C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.62C)</td>
<td>(0.83C)</td>
<td>(0.67C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>17361</td>
<td>1.007***</td>
</tr>
</tbody>
</table>

| VO40S3  | 10   | +5    | 6.8     | 6.8     | 10     | 7532   | 1.269*  |
|         |      |       | (0.17C) | (0.25C) |         |        |         |
|         | 20   | +5    | 13.7    | 13.7    | 10     | 7542   | 1.218*  |
|         |      |       | (0.34C) | (0.25C) |         |        |         |
|         | 30   | +15   | 20.0    | 25.00   | 20     | 10559  | 1.079   |
|         |      |       | (0.5C)  | (0.62C) | (0.5C) |        |         |
|         | 30   | +25   |         |         |        | 10536  | 1.087   |

| VOS20B  | 30   | +15   | 5.8     | 21.55   | 10     | 6831   | 1.062   |
|         |      |       | (0.29C) | (1.08C) | (0.5C) |        |         |
| G.E     | 20   | +15   | 3.28    | 18.28   | 7.38   | 12231  | 1.06    |
|         |      |       | (0.15C) | (0.83C) | (0.33C)|        |         |

* Reconditioning EVERY 6 MONTHS  
** After nominal DOD, DC with II down to 12V  
*** Reconditioned at cycle 15001  
**** Cycle condition changed at cycle 1350  
ELAN PROGRAM : TEST STATUS ON OCT. 24th 1988
ELAN Battery no. 14, bay no. 12
Nominal DOD 40%, Nominal temp 25 deg c
STARTING AT 04,10,88,23,01,27 (CYC 01 REP 17073)

Typical cycle of battery current
ELAN Battery no. 14, bay no. 12
Nominal Dod 40%, Nominal temp 25 deg. C
STARTING AT 04/10/88, 2017 (CYC 01 REP 17073)

Typical cycle of battery voltage

BATTERY VOLTAGE (00171)

DECIMAL HOURS

0 1 1.5 2
ELAN Battery no. 15, bay no. 27
Nominal DoD 30%, Nominal temp 15 deg c
STARTING AT 30.09.88.21.41.46 (CYC. 01 REP. 15433)

Typical cycle of top cell temperatures

Typical cycle of battery current

Typical cycle of battery voltage

November 1-3, 1988
SAFT Ni-Cd ELAN LEO TESTING: VO248 at 25°C (20% & 40% DOD)

AV. EOD CELL VOLTAGE (V)

- 40% DOD
- 20% DOD

CYCLES (*1000)

NASA/GSFC Battery Workshop
5AFT Ni-Cd ELAN LEO TESTING: VO24S at 40% DOD

- 25 Deg.C
  Disch.: 25mm at 15A, 10mm at 20A
- 5 Deg.C
  Disch.: 25mm at 7A, 10mm at 40A

AV. EOD CELL VOLTAGE (V)

25 Deg.C
Disch.: 25mm at 15A, 10mm at 20A

- K-factor
- Efficiency

69%
-72%
-75%
-78%

Cycles (x1000)
SAFT Ni-Cd ELAN LEO TESTING: INFLUENCE OF RECONDITIONING
80% 15°C & 20% DOD

AV. EOD CELL VOLTAGE (V)

1.50

1.40

1.30

1.20

1.10

1.00

78%

76%

72%

Veoc

k-factor

Veod

Efficiency

Reconditioning

No Reconditioning

Cycles (*1000)

NASA/GSFC Battery Workshop
SAFT Ni-Cd ELAN LEO TESTING: 15°C & 25°C (VO4OS3 & 30% DOD)

AV. EOD CELL VOLTAGE (V)

CYCLES (*1000)

1.50
1.40
1.30
1.20
1.10
1.00
0
5
10
15
20

Veoc

1.20
1.15
K-factor

76%
75%
72%

Efficiency

15 Deg.C
25 Deg.C

NASA/GSFC Battery Workshop
NI-Cd ELAN LEO TESTING: G.E & SAFT BATTERY (15°C & 20% DOD)

AV. EOD CELL VOLTAGE (V)

0 5 10 15 20

Cycles (*1000)

Veoc

K-factor

-1.20

-1.15

-1.10

Efficiency

78%

75%

72%

G.E 21 AH

SAFT V024S

Veod

November 1-3, 1988
ELAN LOW EARTH ORBIT TESTING

Very good battery performance
No failure observed
Cycling at 40% exceeds previsions
Effect of reconditioning is substantial
X-80 LEO LIFE TEST

Initiated for an X-ray astronomy mission
14 SAFT cell 23Ah battery
35mn discharge, DOD 22%
Const. I charge to a set volt. (61mn max)
Battery in chamber at 10 deg.C
Test started in Nov.1981, still running
32000 cycle achieved with no degradation

November 1-3, 1988
SAFT Ni-Cd X-80 LEO TEST: 22% DOD & 10°C

AV. EOD CELL VOLTAGE (V)

- Veoc 84%
- Efficiency 78%
- K-factor
- Veoq

CYCLES (x1000)
- NICd HIGH DOD ACCELERATED GEO TEST

3 ex-ECS1 28 SAFT cell 18AH Bat.
2 FM (V018S3), 1 EM (V018S)
Batteries on same cold plate
FM no.6 : 100% DOD max
FM no.5 : 90% DOD max
EM no.1 : 70% DOD max
**NiCd HIGH DOD ACC.GEO TEST CONDITIONS**

Eclipse season: 45 cycles
- 9 periods of 5 cycles of 24 hours
- Disch. rate for DOD max at 5th period
- C/10 charge to K=1.05 or back-up volt.
- Trickle charge at C/200 to C/100

Solstice shortened to 21 days
C/5 capacity check after solstice
Constant load (237.5 Ohms) reconditioning

Base plate temperature: 5 Deg.C
SAFT Ni-Cd HIGH DOD GEO TEST
14th eclipse season profile
SAFT Ni-Cd HIGH DOD GEO TEST: AVERAGE CELL VOLTAGE & K FACTOR EVOLUTION THROUGH SEASONS

1.60
1.50
1.40
1.30
1.20
1.10

1.60
1.50
1.40
1.30
1.20
1.10

1.60
1.50
1.40
1.30
1.20
1.10

VOLTS

VOLTS

VOLTS

SEASON No.

SEASON No.

SEASON No.

100% DOD

90% DOD

70% DOD

- Min. EOD
- Mean EOC
- Mean EOT
- Mean K factor

NASA/GSFC Battery Workshop
SAFT Ni-Cd HIGH DOD GEO TEST: BASE PLATE & CELL TEMPERATURE DURING ECLIPSE SEASONS

- Mean base plate
- Mean cell
- Mean EOC
- Mean EOT
- Mean EOD
- Max. EOD

ECLIPSE SEASON No.

November 1-3, 1988
- **NiCd HIGH DOD ACCELERATED GEO TEST**

14 seasons already simulated (7 years)
Very good battery performance achieved
No capacity degradation observed
Average cell voltage (V):
  - 1.095, 1.108, 1.165 for 100%, 90%, 70%DOD
No adverse effect from test acceleration

GEO NiCd at high DOD seems feasible
OTS-2 10y. REAL FLIGHT SIMULATION

Lab test to mirror OTS-2 bat. operation
Started 9/78, OTS-2 launched 5/78
OTS-2 operational for 6.5y, hib. since 5/85
28 V018S SAFT cell battery
2-14 cell halves in 2 chambers(-Y/+Y sim.
DOD max : 50% for operat., 60% for hib.
Charge C/10 to set K factor, Volt. back-up
Solstice trickle from 8h to 24h a day.
Av. Temperature through 10 years: 15 Deg.C
OTS-2
EVOLUTION OF THE DOD OVER 10 YEARS.
MAXIMUM VALUES

---

Fig: 5 DOD Maximum values

---

November 1-3, 1988
OTS-2
EVOLUTION OF THE VB AT EOD OVER 10 YEARS
MID ECLIPSE PERIOD

Fig. 8
OTS-2
USED K-FACTORS OVER 10 YEARS
MID-ECLIPSE PERIODS

Fig. 7

November 1-3, 1988
OTS-2

EVOLUTION OF THE VB AT EOC, OVER 10 YEARS MID ECLIPSE PERIOD

![Graph showing voltage over time with linear scale from 39.00 to 43.00 Volts]

Fig. 9
OTS-2 LAB
LOW RATE RECONDITIONING DATA
BATTERY CAPACITIES

Fig. 1 Reconditioning Capacities

November 1-3, 1988
<table>
<thead>
<tr>
<th>SAFT AEROSPACE DEPARTMENT</th>
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</thead>
</table>

**NOV. 1988**

**SAFT NICKEL-Cadmium Cells**

**Being Tested at the European Battery Test Center**

J. Guiralard

1988 NASA/GSFC Battery Workshop
SAFT NICKEL-Cadmium Cells
Being Tested at
The European Battery Test Center

Summary

1. Space Programs
   History Flight Experience
   Prismatic Cells Flight Experience
   Current Programs

2. Ground Test Experience
   - Geo Synchronous and Low Earth Orbit Simulation

3. Cell Design and Manufacturing

4. Cell Characteristics and Performances
   - Qualification Cells
   - ESA-BTC Test Geosynchronous Orbit
   - ESA-BTC Test Low Earth Orbit

5. Conclusion
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<th>YEAR OF LAUNCH</th>
<th>SPACE PROGRAM</th>
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<tr>
<td>1965 - 1969</td>
<td>DIAPASON - DIADEMES 1 - 2</td>
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<td>PEOLE - D2A - ESRO IV</td>
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<td>STARLETTE - CASTOR</td>
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<td>POLLUX - SIRET - COS B - D2B</td>
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<td>SIRIO 1 - METEOSAT 1 - OTS 2</td>
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<td>1980 - 1985</td>
<td>ROHINI 1 - 2 - 3</td>
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<td>METEOSAT 2 - APPLE</td>
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<td>ECS 2 - TELECOM 1A - 1B</td>
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<td>AMPTE - MARCE A B</td>
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<td>1986 - 1987</td>
<td>SPOT 1 - ECS 4</td>
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<td>1988</td>
<td>IRS 1 - TELECOM 1C ECS 5</td>
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<th>Ah RATING</th>
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<th>YEAR OF LAUNCH</th>
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<tr>
<td></td>
<td>3 - 5 Ah</td>
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<td>2</td>
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<td>40 Ah, 24 Ah, 18 Ah, 7 Ah</td>
<td>6</td>
<td>1988</td>
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</table>
IN FLIGHT EXPERIENCE
PRISMATIC CELLS

. CAPACITY : 7Ah to 40Ah

. 20 SATELLITES

.GEO SYNCHRONOUS ORBIT : 17 SATELLITES (13 OPERATING)

18Ah - OTS.2 - LAUNCHED MAY 1978
(OPERATING 20 ECLIPSES SEASONS 60% DOD)

. LOW EARTH ORBIT (3 SATELLITES)

24 Ah SPOT 1 LAUNCHED FEB 1986 (OPERATING)
40 Ah IRS 1 LAUNCHED MARCH 1988 (OPERATING)

. 18 MILLIONS/CELLS/HOURS OF OPERATION
GEOSTATIONARY ORBIT SIMULATION

- REAL TIME
  - 26Ah DOD 60%
  - 21Ah DOD 60%
  - 18Ah DOD 60%

- SIMULATION
  - CYCLE DURATION
    - 6h to 24 HOURS
  - ECLIPSE DURATION
    - REAL - STEPS - CONSTANT (MAX)
  - DEPTH OF DISCHARGE
    - 50 TO 100%
  - Ah RATING
    - 7AH TO 40Ah
  - TEMPERATURE
    - 0° TO 25° CENTIGRADE

- ~350 CELLS
- 13 MILLIONS/CELLS/HOURS OF OPERATION
GROUND TEST EXPERIENCE

. LOW EARTH ORBIT SIMULATION (100 MINUTES)

. Ah RATING 18Ah to 40Ah

. DOD 10 to 50%

. TEMPERATURE 0° to 30° CENTIGRADE

. 340 CELLS

7 MILLIONS/CELLS/HOURS OF OPERATION
<table>
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<td>DORNIER</td>
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<td>DORNIER (DG)</td>
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<td>24</td>
<td>SPOT-2-3</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>ROSAT</td>
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<tr>
<td>40</td>
<td>EURECA</td>
<td>A E G (ESA)</td>
</tr>
<tr>
<td>40</td>
<td>IRS 2</td>
<td>INDIAN RESEARCH ORGANISATION</td>
</tr>
<tr>
<td>40</td>
<td>SPOT 4/HELIOS</td>
<td>MATRA (CNES)</td>
</tr>
</tbody>
</table>
### NI-CD CELL DESIGN - VOS.A

**Nominal Capacity Range**: 10-26Ah

**Original Design**: 1970

**Qualified - ESA and CNES**: 1971 - 1972

#### Plates

<table>
<thead>
<tr>
<th></th>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>Sinter Porosity</td>
<td>80%</td>
<td>84.2%</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.76mm</td>
<td>0.89mm</td>
</tr>
<tr>
<td>Loading</td>
<td>13.2 g/dm²</td>
<td>17.5 g/dm²</td>
</tr>
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#### Capacity Ratio

- **Theoretical**: 1.80
- **Measured**: 1.55 - 1.80

- **Electrode Spacing**: 0.26mm
- **Separator**: NYLON
- **Electrolyte**: KOH - 31%
SAFT AEROSPACE DEPARTMENT

NICD CELL DESIGN VOS.A

NOMINAL CAPACITY RANGE
30-50Ah
40Ah (1984)

QUALIFIED BY ESA

PLATES

<table>
<thead>
<tr>
<th>NUMBER</th>
<th>SINTER POROSITY</th>
<th>THICKNESS</th>
<th>LOADING</th>
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<td>13</td>
<td>80%</td>
<td>0.79 mm</td>
<td>13.8 g/dm²</td>
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<table>
<thead>
<tr>
<th>NUMBER</th>
<th>SINTER POROSITY</th>
<th>THICKNESS</th>
<th>LOADING</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>84.2%</td>
<td>0.92 mm</td>
<td>18 g/dm²</td>
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<tr>
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<td></td>
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</tbody>
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CAPACITY RATIO

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<thead>
<tr>
<th>THEORETICAL</th>
<th>MEASURED</th>
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<tr>
<td>1.80</td>
<td>1.55 - 1.80</td>
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<tr>
<td></td>
<td>0.26 mm</td>
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</table>

ELECTRODE SPACING

SEPARATOR
NYLON

ELECTROLYTE
KOH - 31%
**SAFT AEROSPACE DEPARTMENT**

**NOV. 1988**

**NICKEL-CADMIUM CELL DESIGN VOS-B**
**NOMINAL CAPACITY RANGE 10-30 Ah**
**DESIGN 1985**

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<tr>
<td>NUMBER</td>
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<tr>
<td>12</td>
</tr>
<tr>
<td>SINTER POROSITY</td>
</tr>
<tr>
<td>80 %</td>
</tr>
<tr>
<td>THICKNESS</td>
</tr>
<tr>
<td>0.79 mm</td>
</tr>
<tr>
<td>LOADING</td>
</tr>
<tr>
<td>15 g dm²</td>
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<thead>
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<th>CAPACITY RATIO</th>
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<tr>
<td>THEORETICAL</td>
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<td>1.78</td>
</tr>
<tr>
<td>MEASURED</td>
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<td>1.55 TO 1.70</td>
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<th>ELECTRODE SPACING</th>
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<tr>
<td>0.23 mm</td>
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<td>13</td>
</tr>
<tr>
<td>84.2 %</td>
<td>84.2 %</td>
</tr>
<tr>
<td>0.92 mm</td>
<td>0.92 mm</td>
</tr>
<tr>
<td>19.4 g dm³</td>
<td>19.4 g dm³</td>
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MEDIUM AND HIGH CAPACITY

VO S B

1. COVER WITH TERMINALS
2. TERMINAL BOTTOM
3. LATERAL BLOCKING OF THE STACK
4. GROUPS OF ELECTRODE TABS TIG WELDED ON EACH SIDE OF THE TERMINAL BOTTOM
5. INSULATING SHEET
6. CASE
## Qualification - Evaluation

### Cell Characteristics

<table>
<thead>
<tr>
<th>Name Plate Capacity (Ah)</th>
<th>Agency Customer</th>
<th>Cell Manufacturing</th>
<th>Flooded Electrolyte Test (Ah)</th>
<th>Capacity Acceptance (Ah)</th>
<th>Capacity After Qualif Test (Ah)</th>
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</thead>
<tbody>
<tr>
<td>18</td>
<td>ESA (HSD)</td>
<td>06/1975</td>
<td>+22.7, -41.4</td>
<td>+22.3</td>
<td>+22.6</td>
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<tr>
<td>24</td>
<td>ESA</td>
<td>1971</td>
<td>+28.5, -54.7</td>
<td>+27.8</td>
<td>+28.6</td>
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<tr>
<td>40</td>
<td>ESA</td>
<td>06/1984</td>
<td>+48.3, -77.3</td>
<td>+49.2</td>
<td>+51.1</td>
</tr>
<tr>
<td>20B</td>
<td>CNES</td>
<td>09/1986</td>
<td>+24.8, -38.5</td>
<td>+24.5</td>
<td>+25.3</td>
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</table>
### Low Earth Orbit Test

**At ESA - BT Center**

**Cells Characteristics**

<table>
<thead>
<tr>
<th>Name Plate Capacity</th>
<th>Test</th>
<th>Cell Manufacture</th>
<th>Flooded Electrolyte Test (Ah)</th>
<th>Capacity Acceptance (Ah)</th>
<th>Capacity Burn In (Ah)</th>
<th>Test DOD</th>
<th>Cycles</th>
<th>Capacity (Ah)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>x80</td>
<td>11-1978</td>
<td>30.2</td>
<td>29.4</td>
<td>N.A</td>
<td>22%</td>
<td>29000</td>
<td>N.A</td>
</tr>
<tr>
<td>24</td>
<td>ELAN</td>
<td>11-1983</td>
<td>29.3</td>
<td>30.5</td>
<td>27.4</td>
<td>10 to 40%</td>
<td>15000</td>
<td>27.28</td>
</tr>
<tr>
<td>40</td>
<td>ELAN</td>
<td>07.1985</td>
<td>47.7</td>
<td>48.6</td>
<td>49.5</td>
<td>10 to 30%</td>
<td>17000</td>
<td>(C/7)</td>
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<tr>
<td>20B</td>
<td>ELAN</td>
<td>09.1986</td>
<td>24.8</td>
<td>24.5</td>
<td>N.A</td>
<td>30%</td>
<td>6000</td>
<td>N.A</td>
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<tr>
<td>NAME PLATE CAPACITY</td>
<td>TEST</td>
<td>CELL MANUFACTURING</td>
<td>FLOODED ELECTROLYTE TEST</td>
<td>CAPACITY ACCEPTANCE</td>
<td>CAPACITY BURN-IN</td>
<td>TEST</td>
<td>STATUS</td>
<td></td>
</tr>
<tr>
<td>---------------------</td>
<td>------</td>
<td>--------------------</td>
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<td>-----------------</td>
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<td>--------</td>
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<tr>
<td>18</td>
<td>OTE SIMULATION</td>
<td>04/1977</td>
<td>+ 23.3, - 40.9</td>
<td>23.1</td>
<td>NA</td>
<td>57 %</td>
<td>21</td>
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<tr>
<td>18</td>
<td>HIGH DOD GEO TEST (70%)</td>
<td>03/1978</td>
<td>+ 23.1, - 41.6</td>
<td>22.3</td>
<td>22</td>
<td>70 %</td>
<td>14</td>
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<tr>
<td>18</td>
<td>LCS (90%)</td>
<td>06/1981</td>
<td>+ 22.1, - 40.2</td>
<td>21.5</td>
<td>22.15</td>
<td>90 %</td>
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<tr>
<td>18</td>
<td>LCS (100%)</td>
<td>03/1983</td>
<td>+ 23.05, - 40.5</td>
<td>21.9</td>
<td>22.7</td>
<td>100 %</td>
<td>14</td>
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<tr>
<td>21</td>
<td>MARCS SIMULATION</td>
<td>07/1980</td>
<td>+ 27.5, - 51.4</td>
<td>25.9</td>
<td>NA</td>
<td>56 %</td>
<td>27</td>
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</table>

GEO SYNCHRONOUS ORBIT TEST
AT ESA BATTERY TEST CENTER
CELLS CHARACTERISTICS
EVALUATION TEST AT NASA - CRANE

CELLS CHARACTERISTICS

<table>
<thead>
<tr>
<th>NAME PLATE CAPACITY (Ah)</th>
<th>CELL MANUFACTURING</th>
<th>FLOODED ELECTROLYTE TEST (Ah)</th>
<th>CAPACITY ACCEPTANCE (Ah)</th>
<th>CAPACITY (Ah) RECONDITIONING JUNE 1988</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>06.1985</td>
<td>29.2</td>
<td>54.3</td>
<td>29.6</td>
</tr>
<tr>
<td></td>
<td>04.1986</td>
<td>30.4</td>
<td>54.7</td>
<td>29.9</td>
</tr>
<tr>
<td>40</td>
<td>12.1985</td>
<td>50.1</td>
<td>90.1</td>
<td>49.1</td>
</tr>
<tr>
<td>20(B)</td>
<td>09.1986</td>
<td>24.8</td>
<td>38.5</td>
<td>24.5</td>
</tr>
</tbody>
</table>
CONCLUSION

- CELL DESIGN-PERFORMANCES QUALIFIED BY THE AGENCIES IN THE EARLY 70's,
- PERMANENT EVALUATION TESTS MAINTAINED SINCE 1975,
- BASIC MANUFACTURING PROCESS AND COMPONENTS UNCHANGED:
  - SINTERED NICKEL
  - LOADING
  - SEPARATOR
  - ELECTROLYTE

IMPROVEMENTS INTRODUCED (OPTIONS)

- STACK TO COVER CONNECTION (RIGID/FLEXIBLE) 1978
  NO IMPACT ON CYCLE LIFE
- REDUCED ELECTRODE SPACING 1985 (B TECHNOLOGY) BEING EVALUATED
  NO DIFFERENCE AFTER 1/YEAR LEO 30% DOD
APL LIFE TEST PROGRAM ON
2505/2536 SEPARATOR

(NOT SUBMITTED)

L. GOLIASZEWSKI, APL
AIR FORCE/NAVY SEPARATOR QUALIFICATION PROGRAM FOR AEROSPACE CELLS

P. J. DALTON AND S. W. HALL
NAVAL WEAPONS SUPPORT CENTER
CRANE, INDIANA

W. C. HWANG AND P. A. MALACHESKY
THE AEROSPACE CORPORATION
EL SEGUNDO, CALIFORNIA

NASA GODDARD
2 NOV 1988
OUTLINE

- PURPOSE OF TEST PROGRAM
  - QUALIFY CELLS THAT USE PELLON 2536 SEPARATOR MATERIAL
  - CONDUCT BOTH REAL TIME LEO AND COMPRESSED TIME GEO LIFE TESTING

- BACKGROUND

- LEO TEST RESULTS
  - TEST CONDITIONS AND CELL FAILURE ANALYSIS
  - PERFORMANCE TRENDS AND FAILURE ANALYSIS

- GEO TEST RESULTS

- CONCLUSIONS
BACKGROUND

- MANUFACTURE OF AEROSPACE QUALIFIED PELLON 2505 ML DISCONTINUED IN 1976

- GATES ENERGY PRODUCTS (FORMALLY GENERAL ELECTRIC BATTERY BUSINESS DEPARTMENT) SELECTED PELLON 2536 AS REPLACEMENT

- CONDUCT JOINT AIR FORCE/NAVY SPONSORED PROGRAM
  - GENERAL QUALIFICATION OF CELLS MADE WITH 2536
  - QUALIFICATION BASED ON SIMILARITY WITH CELLS USING 2505
    - TEST CELLS IDENTICAL EXCEPT FOR SEPARATOR
    - IDENTICAL TEST PROFILE AND CONDITIONS FOR CELLS WITH PELLON 2505 AND 2536

- THREE DIFFERENT CELL TYPES
  - EXISTING MCD'S FROM 3 DIFFERENT PROGRAMS/CONTRACTORS
  - GATES STATE-OF-THE-ART IN 1984

- TEST PROGRAM STARTED IN 1985

- PREVIOUS REPORTS AT GSFC WORKSHOPS AND IECEC
## CELL BUILD INFORMATION

<table>
<thead>
<tr>
<th>Positive Plate</th>
<th>26.5 AH</th>
<th>34 AH</th>
<th>35 AH*</th>
<th>50 AH**</th>
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</thead>
<tbody>
<tr>
<td>Treatment</td>
<td>PQ</td>
<td>PQ</td>
<td>PQ</td>
<td>NO PQ</td>
</tr>
<tr>
<td>Sinter Date</td>
<td>1/84</td>
<td>1/83</td>
<td>4/84</td>
<td>10.11/84</td>
</tr>
<tr>
<td>Sinter wt (g/dm³)</td>
<td>10.90</td>
<td>10.03,9.81</td>
<td>9.77</td>
<td>10.87,10.35</td>
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<tr>
<td>Loading (g/dm³)</td>
<td>12.61</td>
<td>12.62,11.90</td>
<td>13.02</td>
<td>13.55,12.91</td>
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</table>

<table>
<thead>
<tr>
<th>Negative Plate</th>
<th>Teflon</th>
<th>Silver</th>
<th>Silver</th>
<th>Silver</th>
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<tbody>
<tr>
<td>Treatment</td>
<td>Teflon</td>
<td>Silver</td>
<td>Silver</td>
<td>Silver</td>
</tr>
<tr>
<td>Sinter Date</td>
<td>1/84</td>
<td>1/83</td>
<td>3/84</td>
<td>10.11/84</td>
</tr>
<tr>
<td>Sinter wt (g/dm³)</td>
<td>10.60</td>
<td>9.99,10.20</td>
<td>10.46</td>
<td>10.31,10.22,NA</td>
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<td>Loading (g/dm³)</td>
<td>15.79</td>
<td>15.53,15.70</td>
<td>15.58</td>
<td>15.53,15.98,15.21</td>
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<table>
<thead>
<tr>
<th>Electrolyte</th>
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<tr>
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<td>3/85</td>
<td>1/85</td>
<td>85</td>
<td>4/85</td>
</tr>
<tr>
<td>Fill 2505 (ml)</td>
<td>81.0</td>
<td>102.0</td>
<td>85.0</td>
<td>124.5</td>
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<tr>
<td>Fill 2536 (ml)</td>
<td>79.5</td>
<td>100.0</td>
<td>82.0</td>
<td>120.0</td>
</tr>
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</table>

*NOT ACCEPTED FOR TEST PROGRAM** LIGHTWEIGHT DESIGN
### TEST MATRIX

<table>
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<tr>
<th>SEPARATOR TYPE</th>
<th>2505 ML</th>
<th>2536</th>
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<tbody>
<tr>
<td></td>
<td>50AH</td>
<td>34AH</td>
</tr>
<tr>
<td>LEO</td>
<td>25</td>
<td>V/T TAP</td>
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<tr>
<td>LEO</td>
<td>40</td>
<td>V/T TAP</td>
</tr>
<tr>
<td>GEO</td>
<td>75</td>
<td>V/T TAP</td>
</tr>
<tr>
<td>GEO</td>
<td>75</td>
<td>V/T TAP</td>
</tr>
</tbody>
</table>

**NOTE:** 30 35 AH CELLS FAILED ACCEPTANCE TESTS
LEO TESTS

• ACCEPTANCE TESTS

• LIFE CYCLE TESTS (INITIAL)

• SIDE BY SIDE COMPARISON OF CELLS WITH PELLON 2505 AND 2536 SEPARATOR MATERIAL

• COMMON LIFE CYCLE TEST ANOMALY
  • VOLTAGE DISPERSION
  • MOST PREDOMINANT AT EOC
  • FIRST AND IN GREATER PERCENTAGE IN 2536 PACKS

• ATTEMPTS TO CORRECT PROBLEM ONLY SHORT TERM EFFECTS
  • RECONDITIONING
  • V/T CHARGE CONTROL VARIATIONS
  • CHARGE/DISCHARGE CURRENT RATE VARIATIONS
  • MANUFACTURER SUGGESTED PACK STABILIZATION SEQUENCE
RECERTIFICATION-LIFE CYCLING

Pack: 3348  Manuf: GE  34 AH  Cycle 1016
Orbit: LEO  Temp (C): 0  DOD (D): 25  Vt. Level: 6
Voltage Limit (v/c): 1.460  Time to Vt. Limit (Hrs):
Discharge (Amp/Hrs): 10.5/5.56  Charge (Amp/Hrs): 20.8/1.12
AH out: 10.568  AH in: 10.666  C/D RATIO: 1.029  EOC (m): 1.34
Cell Design: New Fellen

Key:
- - - - Volt: Cell 1
- - - - Volt: Cell 2
- - - - Volt: Cell 3
- - - - Volt: Cell 4
- - - - Volt: Cell 5

VOLTAGE

.00 .50 1.00 1.50
TIME IN HOURS

-25 -20 -15 -10 -5 0 5 10 15 20 25
CURRENT
RECERTIFICATION-LIFE CYCLING

Pack: 93/4B  Manuf: GE  34 AH  Cycle 1407
Orbit: LEO  Temp(C): 0  DOD(%): 25  Vt. Level: 6
Voltage Limit (v/c): 1.400  Time to Vt. Limit (hrs):
Discharge (Amp/Hrs): 18.5/.68  Charge (Amp/Hrs): 20.8/1.12
Cell Design: New Pelion

Key:

Current

Volt: Cell 2
Volt: Cell 3
Volt: Cell 4
Volt: Cell 5

V O L T A G E

.00  .50  1.00  1.50  2.00
TIME IN HOURS

25  20  15  10  5  0  -5  -10  -15  -20  -25
C U R R E N T
# RESULTS FROM LEO TESTS

<table>
<thead>
<tr>
<th>PACK ID</th>
<th>CAPACITY</th>
<th>PELLON TYPE</th>
<th># CELLS</th>
<th>DOD</th>
<th>TEMP</th>
<th>FAILED CELLS</th>
<th>CYCLES TO DATE</th>
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<tbody>
<tr>
<td>326A</td>
<td>26.5</td>
<td>2505</td>
<td>5</td>
<td>25</td>
<td>0</td>
<td>1</td>
<td>7978</td>
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<tr>
<td>326B</td>
<td>26.5</td>
<td>2536</td>
<td>5</td>
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<td>0</td>
<td>4</td>
<td>10151</td>
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<tr>
<td>326C</td>
<td>26.5</td>
<td>2505</td>
<td>9</td>
<td>40</td>
<td>20</td>
<td>3* 2</td>
<td>8231</td>
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<tr>
<td>326D</td>
<td>26.5</td>
<td>2536</td>
<td>9</td>
<td>40</td>
<td>20</td>
<td>7* 1</td>
<td>9885</td>
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<tr>
<td>334A</td>
<td>34</td>
<td>2505</td>
<td>5</td>
<td>25</td>
<td>0</td>
<td>1</td>
<td>6241</td>
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<tr>
<td>334B</td>
<td>34</td>
<td>2536</td>
<td>5</td>
<td>25</td>
<td>0</td>
<td>5</td>
<td>4012</td>
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<tr>
<td>334C</td>
<td>34</td>
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<td>0</td>
<td>-</td>
</tr>
<tr>
<td>334D</td>
<td>34</td>
<td>2536</td>
<td>10</td>
<td>40</td>
<td>20</td>
<td>10</td>
<td>6095</td>
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<tr>
<td>350C</td>
<td>LW 50</td>
<td>2536</td>
<td>5</td>
<td>25</td>
<td>0</td>
<td>5</td>
<td>4502</td>
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<tr>
<td>350D</td>
<td>LW 50</td>
<td>2536</td>
<td>10</td>
<td>40</td>
<td>0</td>
<td>10</td>
<td>3260</td>
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</tbody>
</table>

* CELLS CYCLING BELOW 1.00V CUT OFF
LEO TEST SUMMARY

• NEW SEPARATOR CELLS ARE PERFORMING POORER THAN OLD SEPARATOR CELLS

• EARLIER PROBLEMS AND FAILURES

• LARGER NUMBER OF FAILURES

• BASED ON SIDE-BY-SIDE COMPARISON
  • 28* OUT OF 29 CELLS WITH 2536 REACHED 1.00V CUT OFF OR ARE REMOVED FROM CYCLING
  • 17 OUT OF 29 CELLS WITH 2505 REACHED 1.00V CUT OFF OR ARE REMOVED FROM CYCLING

• CELLS REMOVED FROM CYCLING
  • 20 OUT OF 29 CELLS WITH 2536
  • 14 OUT OF 29 CELLS WITH 2505

* 2536 50 AH CELLS NOT INCLUDED
RESULTS OF DESTRUCTIVE PHYSICAL ANALYSIS (DPA)

• DPA OF 6 FAILED LEO-CYCLED CELLS (5 WITH 2536, 1 WITH 2505)
  • VISUAL OBSERVATIONS
    • LOCALIZED PROBLEMS - TOP, BETWEEN TABS
    • Cd MIGRATION
    • SEPARATOR DAMAGE FROM HEATING
  • NO EVIDENCE OF WEAKENED SEPARATOR
  • POSSIBLE FACTORS CONTRIBUTING TO FAILURE
    • ELECTROLYTE DISTRIBUTION
    • HEAT GENERATION

• DPA OF 35 AH WITH 2505- LOT 30158, ROLL RL326460
  • NO CYCLING- FAILED ACCEPTANCE TESTS
  • SYMPTOMS OF SEPARATOR OXIDATION
    • NO SEPARATOR STRENGTH
    • LOST 50% OF OVERCHARGE PROTECTION
RESULTS FROM GEO TESTS

- LIGHT WEIGHT 50 AH CELLS WITH PELLON 2536 AND 2505
  - 75% DOD (BASED ON ACTUAL CAPACITY)
  - PACKS AT 0° AND 20° C
  - USE V/T WITH TAPER CHARGE CONTROL
  - SIMULATE ECLIPSE SEASONS AND RECONDITIONING PERIODS

- NO FAILURES TO DATE FOR 30 CELLS IN COMPRESSED TIME TEST
  - CYCLING EQUAL TO 14 SIMULATED ECLIPSE SEASONS
  - 28 MONTHS OF ON LINE TESTING

- NO PROBLEMS FOR CELLS WITH PELLON 2505 OR 2536 AT 0° C

- PROBLEMS FOR 20° C CELLS (WITH PELLON 2505 AND 2536)
  - NO PQ TREATMENT OF POSITIVES CAN LEAD TO LOW CHARGE EFFICIENCY AT HIGHER TEMPERATURES
  - HIGH CHARGE/DISCHARGE RATIO NEEDED (>2.5) TO MAINTAIN CELLS ABOVE 1.1 VOLT AVERAGE
  - LOWER V/T LEVELS WOULD LEAD TO EOD VOLTAGES BELOW 1.0 VOLTS
START OF SHADOW: 5/17/88

RECERTIFICATION

Pack: 250A  Manuf: GE 50 AH

Shadow #12 - Cell Voltage vs Day

Cycle: 55i to 59i  Temp (C): 0  DOD(%): 75

Note: Discharge (34.6 Amps), Charge (5.5 Amps) With V/L Vt4 (1.440 V/C)

Cell Design: Old Pellon (Calculated 55 A/H)

CX Prior To Each Shadow Period

Key: Cell No

- Cell 1
- Cell 2
- Cell 3
- Cell 4
- Cell 5
Pack: 250B Manuf: GE 50 AH
Shadow #12 - Cell Voltage vs Day
Cycle: 551 to 591 Temp (C): 0 DOD(%): 75
Note: Discharge (34.6 Amps), Charge (5.5 Amps) With V/L Vt 4 (1.440 V/L)
Cell Design: New Pellon (Calculated 55 A/H)
CX Prior To Each Shadow Period

[Graph showing cell voltage over day]

Key: Cell No
--- ... Cell 1
--- ... Cell 2
--- ... Cell 3
--- ... Cell 4
--- ... Cell 5
Pack: 250C  Manuf: GE 50 AH
Shadow #12 - Cell Voltage vs Day
Cycle: 551 to 591  Temp (C): 20  DOD(%): 75
Note: Discharge (32.7 Amps). Charge (5.2 Amps) With V/L Vt 5 (1.414 V/C)
Cell Design: New Pellon (Calculated 52 A/H)
CX Prior To Each Shadow Period

Key: Cell No
--- --- Cell 1
--- --- Cell 2
--- --- Cell 3
--- --- Cell 4
--- --- Cell 5
Pack: 250D  Manuf: GE 50 AH
Shadow #12 - Cell Voltage vs Day
Cycle: 551 to 591  Temp (C): 20  DOD(%): 75
Note: Discharge (32.7 Amps), Charge (5.2 Amps) With V/L Vt 5 (1.414 V/C)
Cell Design: New Pellon (Calculated 52 A/H)
CX Prior To Each Shadow Period
ANALYSIS OF TEST RESULTS

- TEST DATA ANALYZED
  - DATA FROM THIS TEST
  - DATA FROM NASA QUALIFICATION TEST ON GE 50 AH NiCd
    CELLS WITH PELLON 2536 SEPARATOR AND PASSIVATED
    POSITIVE PLATES
- VARIABLES THAT HAVE BEEN CONSIDERED
  - CELL TYPE OR DESIGN
    - LIGHTWEIGHT VS STANDARD DESIGN
    - TREATMENT OF NEGATIVE ELECTRODE
    - PASSIVATION OF POSITIVE ELECTRODE
    - ADDITIVES TO POSITIVE ELECTRODE
    - SEPARATOR MATERIAL (PELLON 2505 & 2536)
  - AMOUNT OR LEVEL OF CELL COMPONENTS
    - POSITIVE AND NEGATIVE ELECTRODES
      - COATED WEIGHT (SINTERED MATERIAL)
      - IMPREGNATED WEIGHT
      - POROSITY/NICKEL ATTACK (POSITIVE ELECTRODE ONLY)
    - ELECTROCHEMICAL CAPACITY
    - THICKNESS
    - ELECTROLYTE LEVEL
CORRELATIONS OBSERVED

- BETTER CELL PERFORMANCE OBSERVED WITH FOLLOWING:
  - STANDARD RATHER THAN LIGHTWEIGHT DESIGN
  - TEFLOLATED RATHER THAN SILVERED NEGATIVES
  - PELLON 2505 RATHER THAN 2536
  - NORMAL RATHER THAN THICKER ELECTRODES
  - MORE ELECTROLYTE

- ABOVE CORRELATIONS BASED ON SMALL SAMPLING

- CORRELATION DOES NOT NECESSARILY
  IMPLY CAUSE AND EFFECT

- NUMBER AND TYPES OF CORRELATIONS IMPLY MORE
  THAN ONE PROBLEM OR CAUSE
NEW NiCd CELL
QUALIFICATION PROGRAM

- NEW PROGRAM FOR GENERIC QUALIFICATION OF AVAILABLE NiCd CELLS
- SPONSORED BY AIR FORCE AND NAVY
- CONTINUE EVALUATION OF GATES CELL FROM PREVIOUS TEST PROGRAM
- QUALIFICATION OF PRESENT AND NEW DESIGN CELLS
  - GATES
    PRESENT INTERIM DESIGN
    FUTURE BASELINE DESIGN
  - SAFT/FRANCE
    STANDARD DESIGN
    LIGHT-WEIGHT DESIGN
  - HUGHES ADVANCED DESIGN
CONCLUSIONS

- DO NOT HAVE GENERIC QUALIFICATION OF CELLS USING PELLON 2536
  - DATA TO DATE DOES NOT SUPPORT QUALIFICATION
- POOR ELECTROLYTE DISTRIBUTION AND LOCALIZED SEPARATOR HEATING APPEAR TO BE ASSOCIATED WITH POOR PERFORMANCE OF CELLS WITH 2536 MATERIAL
  - CAUSE OF PROBLEM HAS NOT BEEN VERIFIED
- MORE THAN ONE PROBLEM IS PROBABLY RESPONSIBLE FOR THE OBSERVED CELL PERFORMANCE
  WILL CONTINUE TO EVALUATE THESE GATE CELLS
- CONTINUE CYCLING OF GEO PACKS AND LEO PACKS WITH LIMITED FAILURES
- PERFORM ADDITIONAL DPA'S
- WILL INITIATE COMPREHENSIVE TEST PROGRAM TO CHARACTERIZE AND EVALUATE NICD CELLS THAT ARE/WILL-SOON-BE AVAILABLE
  - CELLS FROM DIFFERENT MANUFACTURERS
  - ADVANCED AS WELL AS STANDARD DESIGNS
SESSION III

NICKEL-HYDROGEN TECHNOLOGY

SESSION I - Current Programs

Chairman: P. Ritterman
NICKEL HYDROGEN
LOW EARTH ORBIT TESTING

- A Coordination of Efforts -

Presented at The NASA/GSFC Battery Workshop
November 1-3, 1988

Kenneth H. Fuhr
Martin Marietta Astronautics
Denver, Colorado

Thomas B. Miller & Theresa Romanofsky
NASA Lewis Research Center
Cleveland, Ohio

Samuel W. Donley & Carol A. Hill
The Aerospace Corporation
El Segundo, California

Penni Dalton & Steve Hall
Naval Weapons Support Center
Crane, Indiana
Air Force

Nickel-Hydrogen Test Program

Objective

- To demonstrate Nickel-Hydrogen performance in LEO applications and determine whether use in MAO will enable the achievement of performance levels superior to current Nickel-Cadmium capabilities.

- To demonstrate Nickel-Hydrogen cell performance in pulse applications.

- To demonstrate that the Manufacturing Technology Program (MANTECH) cells are capable of performing in high orbit as well as LEO.
Air Force Test Description

Approach


- Test enough cells from each manufacturer to provide a comparison and to establish a statistically significant data base at an adequate confidence level.

- Demonstrate the capability of achieving a minimum of 30,000 LEO cycles at 40% DOD, 20,000 LEO cycles at 60% DOD, and 5,000 cycles at 80% DOD in MAO or high orbit.

- LEO cells to be tested at -5°C and +10°C; MAO cells to be tested at +10°C.

- Test a small number of cells at 25% DOD to provide correlation with present Nickel-Cadmium testing and life data base.
Aerospace Corporation
Los Angeles, California

Objective

- Verify life capability of Nickel-Hydrogen cells in LEO orbit regime containing high rate (5C) pulses.

Approach

- Life test ten 3.5 inch and five 4.5 inch diameter cells.
- Acceptance and characterization testing to be done at NWSC and life testing to be performed at Aerospace.
- Life test to be at 10° C and an average of 60% DOD.
Objective

- To develop a data base for LEO use of Nickel-Hydrogen cells and batteries.

Approach

- Life cycle in a simulated 90 minute low earth orbit consisting of a 35 minute discharge period and a 55 minute charge period.

- Procure cells from domestic manufacturers of 50 and 100 ampere-hour capacities.

- Test cells of all designs including advanced designs.

- Cells tested at 10° C and 20° C, 40% and 60% depths of discharge.

- Oldest cells on test have accumulated over 13,500 cycles at 40% DOD.
Objective

- LEO life cycle test Nickel-Hydrogen cells to meet needs of the Hubble Space Telescope.

Approach

- Life cycle test 14 COMSAT design 30 ampere-hour cells.
- Life cycle test 12 Air Force design 33 ampere-hour cells.
- Place 12 Air Force design, HST specific, cells on test mid November, 1988.
- Place six - 23 cell HST flight configuration batteries on test January - February, 1989.
Test Parameters

- 90 minute simulated orbit, 35 minute discharge period, 55 minute charge period, 10° C, 10 - 12 % DOD.

- Oldest cells on test have accumulated over 11,000 cycles.
Objective

- Life test Nickel-Hydrogen cells specific to Space Station requirements.

Approach

- Testing to be a shared responsibility between LERC and Rocketdyne/Ford.

- Cells to be 65 and 81 ampere-hour capacities from three vendors...
  - 150 cells to be 65 ampere-hour standard Air Force design.
  - 60 cells to be 65 ampere-hour advanced design.
  - 105 cells to be 81 ampere-hour advanced design.

- Above cells to be tested at -5° C and +10° C, 35% and 60% DOD at the NWSC, Crane, Indiana

- Life test 40 cells at LERC at -5° C and +10° C, 35% DOD.
**Objective**
- Investigate Air Force design cells with NASA Lewis advanced modifications.

**Approach**
- Life cycle cells at 80% DOD and 10°C to ambient.
- Supply NASA Lewis (John Smithrick) with cells for in house testing.
Objective
Evaluate Nickel-Hydrogen for Low Earth Orbit applications.

Approach
- Life test 1981 version of Hughes 50 ampere-hour cells and 70 ampere-hour MANTECH design cells.
- Hughes cells being tested at 10° C, 40% and 60% DOD.
- MANTECH cells being tested at 10° C, 30% and 50% DOD.
- GE has launched 30, 35, 40, and 50 ampere-hour COMSAT design cells for GEO applications, and has demonstrated 30 GEO seasons without failure with up to 70% DOD on ground test.
Objective

- To obtain parametric and life test data for Nickel-Hydrogen specific to the AXAF program.

Approach

- Test 80 ampere-hour cells at 0 - 10° C and 20 - 30 % DOD.
- 30 - 50 cells on order from several manufacturers.
- Testing to start in March, 1989.
Whittaker-Yardney Power Systems

Pawcatuck, Connecticut

**Objective**

Life test MANTECH phase II and phase III cells.

**Approach**

- Two MANTECH phase II cells tested at 80% DOD and 20° C for 5000 cycles, then reduced to 60% DOD for an additional 3800 cycles, then further reduced to 35% DOD and 20° C for 4200 cycles.

- One phase III cell tested at 35% DOD and 20° C for 4200 cycles.

- During initial 2000 cycles on the phase II cells, a variety of recharge fractions was experimented with and certain test anomalies were encountered.
Eagle-Picher Industries, Inc.
Joplin, Missouri

Objective

- Life cycle test Eagle-Picher cells of the COMSAT design, Air Force design, and combinations of the two.

Approach

- All testing is at $5 \pm 3^\circ$ C.
- The charge and discharge rates are based on nameplate capacity and testing is either LEO or an accelerated cycle.
- Cells being tested at 15, 30, 35, and 50% DOD.
NIH2 LEO LIFE TEST AT
NWSC/CRAANE: UPDATE & STATUS

(NOT SUBMITTED)

S. DONLEY, C. HILL, A. MENICHIELLO, AEROSPACE CORP
P. DALTON, R. HAAG, S. HALL, NWSC
Ni-H$_2$ 12 CELL PACK

CUT-AWAY

$\frac{3}{4}$" STYROFOAM

AL. MOUNT

November 1-3, 1988
Ni-H₂ AVERAGE VOLTAGES VS. CHG. VOLTS

RNH 35-3, 12 CELL PACK

AVG. VOLTAGE (VOLTS)

MAX. Vchg (VOLTS)

□ 22 CELL, Ve  ▲  22 CELL, Vs
Ni–H₂ SOLAR ARRAY POWER VS. CHG. VOLTS

RHN 35–3, 12 CELL PACK

POWER (WATTS)
(Thousands)

MAX. Vchg (VOLTS)

□ 22 CELL
● 23 CELL

November 1-3, 1988
Ni−H2 BAT. DISSIPATION VS. CHG. VOLTS

RHN 35-3, 12 CELL PACK

Dissipation (Watts)

MAX. Vchg (VOLTS)

□ 22 CELL  □ 23 CELL
Ni-H2 RECHARGE FRACTION VS. CHG. VOLTS

RNH 35-3, 12 CELL PACK

RECHARGE FRACTION (AHi/AH0)

MAX. Vchg (VOLTS)

STEP-TAPER
Ni-H$_2$ Battery Cell Life Test Update

Lee Miller and Brad Burris
Eagle-Picher Industries, Inc.

Abstract

Eagle-Picher Industries has been conducting LEO type life cycle testing on Ni-H$_2$ battery cells for approximately six (6) years. Over 100 cells have been introduced into the cyclic regimes and some groups are now approaching 40,000 cycles. The depth-of-discharge (DOD) selected for evaluation has ranged from 15% to 50%.

This paper offers a test result summary update for the longer-term cell groups.

Introduction

Eagle-Picher Ni-H$_2$ battery cells have been successfully tested by both domestic and foreign spacecraft manufacturers and users in simulated GEO life cycle regimes. With this already established and growing mission type data base, Eagle-Picher elected to direct its resources toward LEO life cycle type testing.

To minimize equipment and operational, complexity and cost, the test regimes feature constant temperature (5° - 10°C), constant current charge and discharge and constant, manually selected C/D ratios. Both real-time 90 minute cycle and accelerated 45 minute cycle regimes are utilized. Cell performances at DOD's of 15%, 30% and 50% are being evaluated. (See Exhibit #1)

As of this date, the longest-term cell groups are now approaching 40,000 cycles with good performance characteristics. Additional details concerning this test activity were presented at the 23rd (1988) IECEC (1).
Discussion

Over the approximate six (6) year test period, various cells groups have been added to the test regimes and the total count now exceeds 100 cells.

In addition to numbers, various technologies were introduced for evaluation. These include 1) cell capacity size (30, 50 and 80 AH), 2) positive electrode mechanical strength variations, 3) separator types (asbestos and Zircar), 4) electrolyte quantities, 5) electrode stack geometries (pineapple and truncated electrodes), and 6) electrolyte additives (LiOH). (See Exhibit #2)

Results

Exhibits #3 - #5 present a data graph, end-of-charge/discharge voltages and measured capacity respectively for a group of 50 AH rated cells. These cells are tested in an accelerated, 45 minute, LEO cycle regime at a 15% DOD. Stable performance, good end-of-discharge voltages and no measurable capacity loss results continue to be recorded over 38,000 cycles.

Exhibits #6 - #8 present the same data for a group of 30 AH rated cells in a real-time, 90 minute cycle regime at a 30% DOD. These cells were accidentally subjected to a dead-short condition resulting in high heat generation (as a result, cells 003, 004 and 012 were lost due to terminal seal leakage). The remaining cells have now accumulated 5,000 more cycles for a total in excess of 26,000 cycles while maintaining the same good performance results as noted for the above group.

Exhibits #9 and #10 present data graphs for 80 AH rated cells in a real-time, 90 minute cycle regime at a 50% DOD. At this level of DOD, cell performance was demonstrated to be more sensitive to design technologies. As indicated in Exhibit #9, the combination of low positive electrode mechanical strength
and low electrolyte quantity did not perform well. However, when the combination included high electrolyte quantities (Exhibit #10), these cells have continued to perform well through 10,000 cycles.

Conclusion

A six (6) year life cycle test effort has demonstrated the Ni-H₂ battery system's capability to support long-term LEO type missions up to and including 30% DOD's. The data further suggest DOD's in excess of 30% may be equally viable; however, careful assessment and proper selection of design technologies will be important.

In support of this latter objective, Eagle-Picher plans to continue expansion of its LEO life cycle test effort. A few new technologies which are now being incorporated or considered are listed in Exhibit #11.

References

EXHIBIT #1

Typical LEO Test Regime Features

- Constant temperature (5° - 10°C)
- Constant current charge and discharge
- Constant, manually selected charge/discharge ratios
- Real-time 90 minute and Accelerated 45 minute cycle regimes
- Depths-of-Discharge (DOD) 15%, 30%, and 50%
EXHIBIT #2

Various NiH₂ Battery Cell Technologies Evaluated In LEO Life Cycle Testing

○ Cell capacity size

○ Positive electrode mechanical strength

○ Separator type

○ Electrolyte quantity

○ Electrode stack geometry

○ Electrolyte additive
### ACCELERATED LIFE TEST

**DATE:** 10/24/87  
**RNH-50-15**  
**CYCLE:** 38060

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*November 1-3, 1988*
Exhibit #5

RNH-50-15 LIFE TEST

CYCLE CAPACITY DATA SUMMARY

BATT TEMP: 5+-3 DEG C

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AVG  67.0
StD  0.63

DISCHG RATE: 25+-0.1 AMP
30-AH Battery Cells
30% DOD

Exhibit #6

High Mechanical Strength
Low Electrolyte Quantity

- MIN EODV
- MAX EODV
- MIN EOCV
- MAX EOCV

Voltage

0
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8

0
5000
10000
15000
20000
25000
30000

Cycles
## Exhibit #7

### RNH-30-1 LIFE TEST

**DATE** 10/27/88  
**CYCLE** 26200

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**RNH-30-1 LIFE TEST**

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**AVG** 35.6  33.1  34.8  38.4  37.7  39.0  36.5  
**StD** 0.87  1.69  1.56  1.30  0.97  0.90  0.75  

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**AVG** 36.6  39.1  39.0  36.9  37.1  35.9  
**StD** 0.64  0.76  2.87  1.04  0.92  1.37  

**NOTE:** ALL VALUES ARE AMPERE-HOURS TO 1.0V PRECEEDED BY A 0.1C CHARGE (17+-1 HOURS) 
**TEST TEMPERATURE = 5+-3 DEG.C** 
**DISCHARGE RATE = 15.00+-0.10 AMPERES**
80-AH Battery Cells
50% DOD

Low Mechanical Strength
Low Electrolyte Quantity
EXHIBIT #11
New NiH₂ Battery Cell Technologies
For Evaluation In LEO Life Cycle Testing

- Fiber positive electrode sinter structure
- Advanced separator materials
- Lower electrolyte concentrations
- Temperature gradient sensitivity
The Ni-H₂ Battery System:  
A Space Flight Application Summary

Lee Miller  
Eagle-Picher Industries, Inc. (EPI)

Abstract

It is generally accepted nickel-hydrogen will be the major rechargeable battery system selected for high-reliability, aerospace applications such as spacecraft through at least the remainder of this century. Therefore, it may be of benefit to potential aerospace users and others interested in system reliability aspects if an application summary were offered. For example, it may not be common knowledge there have been 16 satellite launches which have flown the Ni-H₂ battery system. Furthermore, these missions in total have surpassed 20,000,000 battery cell hours of space flight operation. Both of these data would be significantly greater but further launches were delayed as the results of the STS accident.

This paper will summarize the aerospace programs which have flown, are flying and will fly the Ni-H₂ battery system.

Background

The nickel-hydrogen battery design has been promoted as the most advanced, long life, rechargeable battery technology developed over the last 50 years. Per unit weight this system should offer more than twice the power available from the previously used battery system (nickel-cadmium). In the area of electrical cycle life capacity, a projected 30,000 cycle, 15 year capability (versus 10,000 - 15,000 cycles and 5-7 years for nickel-cadmium) renders a system ability to actually outlast the equipment in which it may be installed. In addition, the nickel-hydrogen battery offers a true hermetically sealed design which means it is totally maintenance free and the danger of electrolyte leakage is virtually eliminated.

This design also offers the advantage of not requiring acceptance of new electrochemical technology by the potential user. The Ni-H₂ battery cell simply combines the best features of the nickel-cadmium (Ni-Cd) system (positive electrode) and the hydrogen/oxygen (H₂/O₂) fuel cell system (H₂ electrode). A simple, common gas design evolves which features only established, and both chemically and structurally stable components (thus a high DOD and long cycle life capability), and which can operate over a wide temperature range (-20⁰ to 40⁰C has been demonstrated).

The electrochemical reactions involved are straightforward and are well known within the industry. For the first time a hermetically sealed, rechargeable battery system is available which can sustain high rate overcharge and even overdischarge without short term or long term system degradation. In addition, the reactions are "H₂O" balanced which is very important from an electrolyte management stand point.
By replacing one of the two opposing metal electrodes (conventional internal battery cell design) with hydrogen gas, significant system benefits are achieved. The weight of the replaced metal electrodes are of course eliminated plus overall system performance is enhanced. The potential for metal-to-metal shorting is minimized and the lack of a "wear-out" mechanism for a gas reaction greatly improves system cycle life capability. The nickel-hydrogen battery system has already demonstrated an abuse tolerance (both operational and environmental) far in excess of any competitive battery and this simply translates into superior system reliability.

Because of this inherent reliability, the nickel-hydrogen system has been initially designed and produced for "high rel" aerospace applications. To the extent this technology has been, is now and will be applied in this industry is the subject of this paper.

Space Flight Application Summary

The subject flight programs will be summarized under four (4) categories as follows.

I. Programs Which Have Flown
   These programs are now complete.

II. Programs Which Are Flying
    These programs have satellites now in operation and may have additional launches scheduled.

III. Programs Which Will Fly
     These programs are in the hardware production phase, but no launch has occurred as of this date.

IV. Programs Which Plan to Fly
    These programs are committed to or are seriously considering the application of the Ni-H2 battery system.

To facilitate a review of this information, the associated data will be presented in a tabular format under the above headings. The program will be identified and pertinent details listed.

Although EPI, in its role as a battery and a battery cell manufacturer, has some general program level knowledge, a few program detail errors may occur. We are obliged to apologize in advance if this is the case.
I. Programs Which Have Flown:

1. USAF "Flight Experiment"
   a) Prime Contractor - LMSC
   b) Mission - LEO
   c) Duration - approximately one (1) year
   d) Battery Capacity - 50 Ahr
   e) Battery Size - 21 cells
   f) Launch Date - 1976

2. US Navy "NTS-2 Satellite"
   a) Prime Contractor - TRW/Comsat
   b) Mission - High altitude polar, similar to accelerated GEO
   c) Duration - approximately eight (8) years
   d) Battery Capacity - 35 Ahr
   e) Battery Size - Two (2) 7 cell modules connected in series
   f) Launch Date - 1976

II. Programs Which Are Flying:

3. "Intelsat V"
   a) Prime Contractor - FACC
   b) Mission - GEO
   c) Duration - Longest, five (5) years now
   d) Battery Capacity - 30 Ahr
   e) Battery Size - 27 cells
   f) Launch Date - 1983 (2), 1984 (1), 1985 (3), 1986 (1)

4. "Spacenet"
   a) Prime Contractor - RCA
   b) Mission - GEO
   c) Duration - Longest, four (4) years now
   d) Battery Capacity - 40 Ahr
   e) Battery Size - Two (2) 11 cell modules connected in series
   f) Launch Date - 1984 (2)
5. "G-Star"
   a) Prime Contractor - RCA
   b) Mission - GEO
   c) Duration - Longest, three (3) years now
   d) Battery Capacity - 30 Ahr
   e) Battery Size - Two (2) 11 cell modules connected in series
   f) Launch Date - 1985 (1), 1986 (1)

6. "American Sat"
   a) Prime Contractor - RCA
   b) Mission - GEO
   c) Duration - Three (3) years now
   d) Battery Capacity - 35 Ahr
   e) Battery Size - Two (2) 11 cell modules connected in series
   f) Launch Date - 1985

7. "Sat Com K"
   a) Prime Contractor - RCA
   b) Mission - GEO
   c) Duration - Longest, three (3) years now
   d) Battery Capacity - 50 Ahr
   e) Battery Size - Two (2) 11 cell modules connected in series
   f) Launch Date - 1985 (1), 1986 (1)

III. Programs Which Will Fly:

8. "Olympus"
   a) Prime Contractor - BAe (UK)
   b) Mission - GEO
   c) Duration - 10 year requirement
   d) Battery Capacity - 35 Ahr
   e) Battery Size - 31 cells
   f) Launch Date - First projected 1989

9. "Intelsat VI"
   a) Prime Contractor - HAC
   b) Mission - GEO
   c) Duration - 10 year requirement
   d) Battery Capacity - 44 Ahr
   e) Battery Size - Two (2) 16 cell modules connected in series
   f) Launch Date - First projected 1989
10. "Military Satellite"
   Detailed information on these type applications is classified.

11. "Milstar"
   a) Prime Contractor - LMSC
   b) Mission - Multiple orbits
   c) Duration - 10 year requirement
   d) Battery Capacity - 76 Ahr
   e) Battery Size - 22 cells
   f) Launch Date - First projected 1990

12. "Italsat"
   a) Prime Contractor - FACC
   b) Mission - GEO
   c) Duration - 10 year requirement
   d) Battery Capacity - 30 Ahr
   e) Battery Size - 27 cells
   f) Launch Date - First projected 1989

13. "SCS-I"
   a) Prime Contractor - FACC
   b) Mission - GEO
   c) Duration - 15 year requirement
   d) Battery Capacity - 83 Ahr
   e) Battery Size - 27 cell
   f) Launch Date - First projected 1989

14. "Space Telescope (ST)"
   a) Prime Contractor - LMSC
   b) Mission - LEO
   c) Duration - Five (5) year requirement
   d) Battery Capacity - 90 Ahr
   e) Battery Size - 23 cells
   f) Launch Date - First projected 1990

15. "HBO Satellite"
   a) Prime Contractor - RCA
   b) Mission - GEO
   c) Duration - 10 year requirement
   d) Battery Capacity - 50 Ahr
   e) Battery Size - Two (2) 11 cell modules connected in series
   f) Launch Date - First projected 1989
16. "Anik-E Satellite"
   a) Prime Contractor - Spar/RCA
   b) Mission - GEO
   c) Duration - 12 year requirement
   d) Battery Capacity - 50 Ahr
   e) Battery Size - Two (2) 11 cell modules connected in series
   f) Launch Date - First projected 1989

17. "TV-Sat 2"
   a) Prime Contractor - MBB/AEG (Germany)
   b) Mission - GEO
   c) Duration - 10 year requirement
   d) Battery Capacity - 30 Ahr
   e) Battery Size - 27 cells
   f) Launch Date - First projected 1988

18. "Eutelsat II"
   a) Prime Contractor - ASCA (France)
   b) Mission - GEO
   c) Duration - 10 year requirement
   d) Battery Capacity - 65 Ahr
   e) Battery Size - 27 cells
   f) Launch Date - First Projected 1989

19. "Military Satellite"
    Detailed information on these type applications is classified.

20. "Telecom 2"
    a) Prime Contractor - Matra (France)
    b) Mission - GEO
    c) Duration - 10 year requirement
    d) Battery Capacity - 78 Ahr
    e) Battery Size - 27 cells
    f) Launch Date - First projected 1990

V. Programs Which Plan to Fly

21. "Space Station"
   a) Prime Contractor - FACC (Power Subsystem)
   b) Mission - LEO
   c) Duration - 6.5 year requirement
   d) Battery Capacity - 81 Ahr
   e) Battery Size - 30 cells
   f) Launch Date - Mid 1990's
22. "Columbus" (European Space Station)
   a) Prime Contractor - AEG (Germany)
   b) Mission - LEO
   c) Duration - N/A
   d) Battery Capacity - N/A
   e) Battery Size - N/A
   f) Launch Date - Mid 1990's

23. "SAX Satellite"
   a) Prime Contractor - FIAR (Italy)
   b) Mission - LEO
   c) Duration - Four (4) year requirement
   d) Battery Capacity - 30 Ahr
   e) Battery Size - 29 cells
   f) Launch Date - First projected 1990

NOTE: For the remaining applications under this category, we are not certain the prime contractor has been selected as of this date. The proposed detail program information which has been provided to EPI varies between prime contractors. It would not be appropriate to publish this information and only the program name and mission will be identified.

24. "Olympus" Follow On
   b) Mission - GEO

25. "Italsat" Follow On
   b) Mission - GEO

26. "UHF" Follow On
   b) Mission - LEO

27. "X-Ray Telescope"
   b) Mission - LEO

28. "Intelsat VII"
   b) Mission - GEO

29. "Aussat B"
   b) Mission - GEO

30. "GPS Block IIR"
   b) Mission - GEO
31. "Inmarsat II"
   b) Mission - LEO

32. "Super Program"
   b) Mission - Multiple orbits

33. "Military Satellites"
   At this time a total of six (6) programs are qualified for classification under this category.

Conclusion

This limited review has identified 38 programs which have, are or will likely constitute the application base for this battery technology. It is hoped this summary will provide a useful reference for potential users and others who may be interested in the extent of the application of the nickel-hydrogen battery system.
NICKEL HYDROGEN BATTERY DIODE BYPASS CIRCUIT TEST

Michael J. Mackowski

Presented by
Ken Schwer

November 1988
NASA GSFC Battery Workshop

McDonnell Douglas Astronautics Company – Missile and Defense Electronics Division
PURPOSE OF TEST

- To characterize the behavior of a NiH2 battery with a failed cell protected by a diode bypass circuit.

- To evaluate the hardware required to implement a diode bypass circuit for a low Earth orbit battery.
A bypass circuit was installed across one cell of a 19-cell (originally 21-cell) prototype battery.

Three diodes are required in series in the forward direction to prevent current flow during normal charge operation.

One diode is needed in the reverse path to prevent current flow during normal discharge operation.

NOTE: EACH DIODE RATED FOR 75 AMPS
TEST PROCEDURES

- The prototype battery had been stored for eleven months.
- A recharge and 79 cycles showed that it was in usable condition (38 Ah measured capacity).
- The fill tube of one cell was cut off and allowed to vent.
- After 90 cycles (10 Ah discharge each), the voltage across the test cell was sufficient to turn on the bypass diodes (both directions)
EFFECTS ON BATTERY OPERATION

- With a high internal resistance, the test cell had a disproportionate share of the battery voltage. This resulted in the other cells being undercharged.

- The V/T charge level was then increased two levels.

- To an outside observer (i.e., ground controller), this would be the only indication of a problem, unless individual cells or bypass circuits were monitored.
BYPASS CURRENT COMPARED TO TOTAL BATTERY CURRENT AND V/T CHARGE LEVEL

BEGINNING-OF-CHARGE CURRENT, Amperes

V/T Level
Battery BOC Current
Bypass BOC Current

CYCLE NUMBER
CELL DRY-OUT

- After about 300 cycles, no additional current was going through the bypass circuits.

- At the end of the test, bypass currents were:
  89% of the total discharge current
  78% of the total charge current

- Had a vacuum test been performed, these levels would have been reached much sooner, and probably exceeded.

- The test was terminated after 933 cycles.
BYPASS CURRENT COMPARED TO TOTAL BATTERY CURRENT

END-OF-DISCHARGE CURRENT, Amperes

CYCLE NUMBER

Battery Current
Bypass Current
CONCLUSIONS

- With individual cell bypass circuits installed, it will be difficult to discriminate a simple "sick" cell from a completely failed, open-circuited cell, using typical telemetry parameters.

- Bypass circuits, using 75-ampere-rated diodes, on low Earth orbit nickel hydrogen batteries, could add over one pound per cell. There are other significant impacts to the battery's thermal and mechanical design.

- Because of the above items and the lack of reported open-circuit cell failures, we do not recommend incorporating bypass circuits in LEO NiH2 batteries.
IMPEDANCE CHARACTERISTICS OF Ni ELECTRODES FROM DIFFERENT MANUFACTURERS

DR. MARGARET A. REID
NASA LEWIS RESEARCH CENTER

GODDARD BATTERY WORKSHOP
NOVEMBER 2, 1988
GOAL OF IMPEDANCE STUDIES

TO UNDERSTAND WHAT IS HAPPENING AS THE ELECTRODE IS CYCLED AND WHEN THE ELECTRODE UNDERGOES OVERCHARGE, OVERDISCHARGE, AND STORAGE

TO DEVELOP AN ACCEPTANCE TEST THAT WILL PREDICT AT THE TIME OF CELL ACTIVATION WHETHER THE GOALS OF LIFE AND PERFORMANCE WILL BE MET BY A GIVEN CELL

TEST ITEMS UNDER STUDY

FLIGHTWEIGHT CELLS
BOILER PLATE CELLS
HALF-CELLS WITH LIGHTWEIGHT ELECTRODES
BIPOLAR CELLS
ELECTRODES FOR STUDYING CAPACITY LOSS ON STORAGE
IF THE CELL CAN BE CONSIDERED TO BE AN ASSEMBLY OF RESISTORS, CAPACITORS, AND INDUCTORS, THE VALUES OF THESE COMPONENTS CAN BE DETERMINED, ALTHOUGH NOT UNIQUELY, BY MEASURING THE IMPEDANCE OF THE CIRCUIT OVER A WIDE RANGE OF FREQUENCIES, USUALLY AT LEAST FIVE TO SIX DECADES.

MODERN, SOPHISTICATED, COMPUTER CONTROLLED EQUIPMENT CAN MEASURE IMPEDANCES ACCURATELY OVER A WIDE RANGE OF FREQUENCIES AND SIGNAL MAGNITUDES. THE TECHNIQUE IS NON-DESTRUCTIVE AND CAN BE USED FOR ELECTRODES OF SIZES RANGING FROM SUB-MILLIMETER DIMENSIONS TO FULL SCALE BATTERIES UP TO OVER 100 A-H CAPACITY,
ELECTRICAL COMPONENTS OF IMPEDANCE SETUP

INPUT Voltage of working electrode vs reference

OUTPUT Magnitude of current and phase angle with respect to AC input voltage

TIME

PRINTER- PLOTTER

COMPUTER AND DISK DRIVES

TRANSFER FUNCTION ANALYZER

FAST RISE TIME POTENTIOSTAT

CELL Reference Working Counter

V

I
VECTOR REPRESENTATION OF IMPEDANCE AND DETERMINATION OF $Z_{\text{real}}$ AND $Z_{\text{imaginary}}$

INDUCTANCE

IN-PHASE COMPONENT = $Z_{\text{real}}$

ANGLE = PHASE SHIFT

OUT-OF-PHASE COMPONENT = $Z_{\text{imaginary}}$

LENGTH OF VECTOR = MAGNITUDE OF IMPEDANCE ($V_{\text{max}}/I_{\text{max}}$)

CAPACITANCE
Simple Impedance Networks

Resistor

Capacitor

Series

Parallel

Relationship between current and voltage dependent on frequency

Bode Plots

Complex Plane Plots

Other ways to express impedance—Randles, Complex capacitance, Admittance, etc.
SIMPLE CIRCUIT FOR A SINGLE ELECTRODE INCLUDING DIFFUSION IMPEDANCE $Z_W$ (WARBURG IMPEDANCE)

COMPLEX PLANE PLOT FOR ABOVE CIRCUIT

WARBURG PLOTS FOR ABOVE CIRCUIT

OTHER METHODS OF PLOTTING DATA CAN BE USED, FOR EXAMPLE, CAPACITANCE PLOTS
ALTERNATIVE CIRCUITS FOR A SINGLE ELECTRODE

SIMPLE CIRCUIT FOR A COMPLETE CELL
IMPEDEANCE MEASUREMENTS ON ELECTRODES FOR STORAGE EXPERIMENT

ELECTRODES:
3–1/2" PINEAPPLE SLICE, 42.9 SQUARE CM, TRIPlicate SAMPLES

TEST REGIME:
FORMATION CYCLES – 5 CYCLES AT C/10 CHARGE FOR
16 HRS, C/5 DISCHARGE TO 1.0 V VS AMALGAMATED ZN
CAPACITY CYCLES – 5 CYCLES AT C/2 CHARGE FOR 1 HR
PLUS 10% OVERCHARGE, DISCHARGE AT C/4 TO
1.0 V VS AMALGAMATED ZN

IMPEDEANCE TESTS:
EQUILIBRATE FOR 1 HR AT 0.2 V VS Hg/HgO, MEASURE
CHARGE 20%, HOLD AT 0.4 V FOR 1 HR, MEASURE
STORE 28 DAYS UNDER VARIOUS CONDITIONS
MEASURE AT THE OCV AFTER STORAGE
DETERMINE POST STORAGE CAPACITY
EQUILIBRATE FOR A HR AT 0.2 VS Hg/HgO, MEASURE

IMPEDEANCE PARAMETERS:
1 MV SIGNAL, 5.65 HZ TO 0.0007 HZ
Impedances of Ni electrodes vary enormously with voltage. On the basis of measurements on a chemically impregnated electrode, it was decided to make measurements at 0.4 V and 0.2 V vs Hg/HgO.

Warburg coefficient of chemically impregnated electrode
THE DATA PRESENTED HERE ARE
PRELIMINARY AND SHOULD NOT BE
USED TO JUDGE THE MERITS OR FAULTS
OF ANY PARTICULAR MANUFACTURING
PROCESS OR ELECTROLYTE CONCENTRATION
Impedance of typical electrochemically impregnated electrode at 0.400 V vs Hg/HgO.

Impedance of typical electrochemically impregnated electrode at 0.200 V vs Hg/HgO.

Impedance of typical electrochemically impregnated electrode at 0.050 V vs Hg/HgO.
IMPEDANCE PLOTS OF FOUR TYPES OF ELECTRODES
0.200V vs Hg/HgO , 31% KOH
A CHARACTERISTIC CURVE IS OBTAINED FOR EACH MANUFACTURER.

IMPREGNATION I

IMPREGNATION II

IMPREGNATION III

IMPREGNATION IV

IMPEDANCES OF ELECTRODES AT 0.4 V WERE SIMILAR AND COULD NOT BE DIFFERENTIATED WITH THE EQUIPMENT USED. NEW EQUIPMENT RECENTLY RECEIVED SHOULD ALLOW DIFFERENCES TO BE MEASURED.
IMPEDANCES AND VOLTAGES VS Hg/HgO AFTER REMOVAL FROM STORAGE
HIGH PRESSURE, ROOM TEMPERATURE, 31% KOH

IMPREGNATION I
+171 MV

IMPREGNATION II
−766 MV

IMPREGNATION III
+168 MV

IMPREGNATION IV
+53 MV

REDUCTION BY HYDROGEN PRODUCED LOWER VOLTAGES AND HIGHER IMPEDANCES.
VALUES TABULATED ARE THE PARALLEL RESISTANCES OBTAINED BY DRAWING THE "BEST" SEMICIRCLE ON THE NYQUIST (COMPLEX PLANE) PLOTS

STORAGE CONDITIONS ARE INDICATED AS FOLLOWS:

HPRT31 = 500 PSI HYDROGEN, ROOM TEMP, 31% KOH
MPRT31 = 50 PSI HYDROGEN, ROOM TEMP, 31% KOH
LPRT31 = 1 ATM HYDROGEN, ROOM TEMP, 31% KOH
HPLT31 = 500 PSI HYDROGEN, −20 C, 31% KOH
HPRT26 = 500 PSI HYDROGEN, ROOM TEMP, 26% KOH

IMPEDANCES OF ALL ELECTRODES WERE GREATER AFTER STORAGE. THE HIGHER THE PRESSURE, THE LOWER THE VOLTAGE AFTER STORAGE. STORAGE AT LOW TEMPERATURES REDUCED THE AMOUNT OF VOLTAGE LOSS AND IMPEDANCE INCREASE.

THE VOLTAGE DROP AND INCREASE IN IMPEDANCE COULD BE CORRELATED QUALITATIVELY, BUT NOT QUANTITATIVELY, WITH THE MAGNITUDE OF CAPACITY LOSS ON STORAGE.
**IMPEDANCE AND VOLTAGE CHANGES UPON STORAGE**

<table>
<thead>
<tr>
<th>HUGHES</th>
<th>PRE-STORAGE R</th>
<th>POST-STORAGE R</th>
<th>VOLTAGE AFTER STORAGE VS Hg/HgO</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPRT31</td>
<td>1.3</td>
<td>20.0</td>
<td>-0.765</td>
</tr>
<tr>
<td>MPRT31</td>
<td>0.9</td>
<td>1.0</td>
<td>0.186</td>
</tr>
<tr>
<td>APRT31</td>
<td>0.9</td>
<td>1.7</td>
<td>0.212</td>
</tr>
<tr>
<td>HPLT31</td>
<td>0.6</td>
<td>1.3</td>
<td>0.199</td>
</tr>
<tr>
<td>HPRT26</td>
<td>0.1</td>
<td>100.0</td>
<td>-0.365</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>YARDNEY</th>
<th>PRE-STORAGE R</th>
<th>POST-STORAGE R</th>
<th>VOLTAGE AFTER STORAGE VS Hg/HgO</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPRT31</td>
<td>0.7</td>
<td>77.0</td>
<td>0.032</td>
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<tr>
<td>MPRT31</td>
<td>1.8</td>
<td>10.2</td>
<td>0.191</td>
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<tr>
<td>APRT31</td>
<td>3.7</td>
<td>4.4</td>
<td>0.216</td>
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<td>HPLT31</td>
<td>2.1</td>
<td>3.7</td>
<td>0.221</td>
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<tr>
<td>HPRT26</td>
<td>3.9</td>
<td>79.0</td>
<td>0.073</td>
</tr>
<tr>
<td>GATES</td>
<td>E-P</td>
<td>PRE-STORAGE R POST-STORAGE R VOLTAGE AFTER STORAGE VS Hg/Hg₀</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-----</td>
<td>-----------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>HPRT31</td>
<td>2.0</td>
<td>14.0</td>
<td></td>
</tr>
<tr>
<td>MPR31</td>
<td>2.1</td>
<td>0.173</td>
<td></td>
</tr>
<tr>
<td>APRT31</td>
<td>2.2</td>
<td>0.198</td>
<td></td>
</tr>
<tr>
<td>HPLT31</td>
<td>2.1</td>
<td>0.240</td>
<td></td>
</tr>
<tr>
<td>HPR26</td>
<td>1.2</td>
<td>0.230</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GATES</th>
<th>E-P</th>
<th>PRE-STORAGE R POST-STORAGE R VOLTAGE AFTER STORAGE VS Hg/Hg₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPRT31</td>
<td>1.7</td>
<td>2.2</td>
</tr>
<tr>
<td>MPR31</td>
<td>1.6</td>
<td>3.3</td>
</tr>
<tr>
<td>APRT31</td>
<td>0.8</td>
<td>3.3</td>
</tr>
<tr>
<td>HPLT31</td>
<td>0.6</td>
<td>2.2</td>
</tr>
<tr>
<td>HPR26</td>
<td>0.7</td>
<td>4.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GATES</th>
<th>PRE-STORAGE R POST-STORAGE R VOLTAGE AFTER STORAGE VS Hg/Hg₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPRT31</td>
<td>1.0</td>
</tr>
<tr>
<td>MPR31</td>
<td>3.2</td>
</tr>
<tr>
<td>APRT31</td>
<td>2.2</td>
</tr>
<tr>
<td>HPLT31</td>
<td>1.7</td>
</tr>
<tr>
<td>HPR26</td>
<td>3.3</td>
</tr>
</tbody>
</table>

NASA/GSFC Battery Workshop
MORE COMPLETE CHARACTERIZATION OF THESE ELECTRODES IS NOW UNDER WAY WITH NEW EQUIPMENT.

EXAMPLES OF COMPLEX IMPEDANCE, WARBURG, AND COMPLEX CAPACITANCE PLOTS ARE SHOWN FOR A GATES ELECTRODE.

RESISTANCES, WARBURG SLOPES, AND CAPACITANCES VARY BY SEVERAL ORDERS OF MAGNITUDE AS VOLTAGE IS CHANGED. THE ELECTRODES FROM OTHER MANUFACTURERS HAVE SOMewhat DIFFERENT CHARACTERISTICS.
TYPICAL COMPLEX CAPACITANCE PLOT FOR GATES ELECTRODE SHOWING LARGE CHANGES IN CAPACITANCE WITH VOLTAGE

COMPLEX CAPACITANCE

0.410V TO 0.290V

CAPACITANCE real

0 100 200 300 400 500 600

CAPACITANCE imaginary

0 0.10V 0.370V 0.330V 0.290V
LOG PARALLEL RESISTANCE

NORMALIZED

LOG RESISTANCE, OHM CM-2

VOLTAGE VS Hg/HgO, MV

ELECTRODE 1
FUTURE PLANS

FULLY CHARACTERIZE ELECTRODES FROM OTHER IMPREGNATION PROCESSES
CYCLE CHARACTERIZED ELECTRODES AND DETERMINE CHANGES OF PARAMETERS WITH CYCLING
MEASURE IMPEDANCES OF FULL-SIZE CELLS AS CELLS ARE CYCLED AND TRY TO CORRELATE CHANGES WITH CYCLE LIFE AND PERFORMANCE.
ABSTRACT

A general survey of the last French development in NiH2 technology for GEO applications is given: main results are discussed, and perspective toward future evolution presented.

INTRODUCTION

Geostationary applications require mainly reliable and well evaluated Nickel Hydrogen technology. In Europe, that kind of power device remains of great interest, particularly in France.

Since 1985, a new development activity started under CNES control, taken place within a general search a technology plan.

NiH2 DEVELOPMENT

This development was done at SAFT, under major founding from CNES and SAFT, with the contribution of ESA. Substantial development program was defined to respond a requirement level approved by CNES and ESA.

The purpose was to build up and evaluate a cell's definition fitted to the range 30-50 Ah in capacity, to provide power for a ten years mission.

Cell's technology developed was of the IPV type, operating at high pressure. Essential details related to this definition were presented in 1986 (ref. 1).

Conception was based on the maximum value in the range (ie 50 Ah) and basic technological components issued from SAFT background.

The choice of an individual pressure vessel, mounted into a single piece sleeve, was done assuming the fact it should permit to reach a high safety factor while offering good thermal features.

All along the program, accurate evaluation at components and cell level was done.

End of development was marked in May 1988 by a critical definition review where VHS 50 BL definition (namely 50 Ah cell) was presented and evaluation tests results largely discussed.
Validation test program was performed on 50 Ah cells or same sized vessels, following a schedule presented hereafter in figure 1.

Each cell or vessel tested was compliant with the same definition file and of the same manufacture and control lot.

Figure 1 - Validation test plan
GENERAL CHARACTERISTICS

Based on a 22 cells lot experience. Main features for the VHS 50 BL NiH$_2$ cell are given hereafter in Table 1.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean capacity at 1 V 20°C C/2</td>
<td>51.5 Ah</td>
</tr>
<tr>
<td>Mean energy density (at cell level)</td>
<td>48 Wh/kg</td>
</tr>
<tr>
<td>Mean volumic energy (at cell level)</td>
<td>70 Wh/l</td>
</tr>
</tbody>
</table>

Table 1 - VHS 50 BL characteristics

On the referenced lot, mass and capacity dispersion values were smaller than expected, which is a proof of the good manufacture control level got.

MECHANICAL TESTS

Fatigue tests

The goal of this test was to check out resistance limit of Inconel vessel design to cyclic loading, in order to simulate charge-discharge pressure variation of the structure in absence of the effect of Hydrogen.

- Conditions
  
  . Pressure fluid was special oil used as neutral agent for the cycling.
  
  . Frequency was chosen to accelerate the test and perform a large number of cycles, his value was close to 5 cycles/min.
  
  . Amplitude was 25-75 bars pressure range corresponding to a 100 % DOD level (75 bars being the DMOP : Design Maximum Operating Pressure).

Three vessels (each mounted into integral sleeve) were proof tested at first at 1.5 time the DMOP and then cycled under the previous conditions, and they reached more than 150,000 cycles without any damage.

Modifying the maximum pressure value up to the proof test pressure value, complementary cycling permit to get respectively for each vessel 10,000, 23,000 and 31,000 cycles more. Leakage was observed at these points. Using SEM, we have confirmed pure fatigue micro faciès and typical crack trip growth leading to leakage.

These results were in good agreement with predictive datas got previously from a mechanical rupture analysis (ESA crack computing mode).
Burst tests

Six naked vessels were bursted to verify the limit of the design.

- Conditions

Pressure fluids used were oil or gaseous helium and pressurization rate chosen in the application range.

Requirement level was 2,5 time the DMOP value, and for each cell this limit largely overshooted.

Such results confirmed the right vessel's design with margins good enough to take into account statistical dispersion.

Safety tests

This activity was aiming at characterize more closely safety area for this device. As a preliminary task, SAFT performed an FMECA analysis (failure mode and critical effects analysis) to define completely, cell's behaviour under functional aspects, hazardous events and main consequences.

Fault tree method was also employed, and this study permit to start safety tests while fixing specific conditions.

- Conditions

An overall amount of 8 cells (into sleeve) was submitted to hazardous events ; specific conditions are summarized hereafter in table 2.

<table>
<thead>
<tr>
<th>Type of test</th>
<th>Test N°</th>
<th>Test conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>current</td>
</tr>
<tr>
<td>Overcharge</td>
<td>1</td>
<td>C/S</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>C/10</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>C/2</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>C</td>
</tr>
<tr>
<td>Over-discharge</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Shock</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 - Safety test conditions

November 1-3, 1988
The one cell shocked, presented of course, trails of the test (de visu, at sleeve level and inside by X-ray observation, at stack level). Nevertheless, it hasn’t affected electrical properties as demonstrated by a follow on control.

Short circuit led to an instantaneous current higher than 8C regim. As shown in figure 2, after a transient during the first minutes there were a pseudo plateau in current at approximately 240 A with a voltage stabilization, then a sharp decrease for both electrical parameters. But after a ten minutes discharge time, current and voltage decreased slightly.

Cell’s temperature measured on sleeve wall increased up to 77°C as a maximum value while pressure decreased in two steps.

Cells tested under overdischarge conditions presented a peak temperature never exceeding 40°C for a time below 1 hour, and pressure temperature and voltage reached a steady state value after 2 hours evolution as presented in figure 3.

Figure 4 compare for two cells tested under overcharge conditions respectively, at 20°C and 0°C, at a same C regime, their characteristics. Temperature effect at this kinetic of charge is not so detectable, though we can deduce from pressure behaviour the better efficiency at 20°C for the recombining reaction between O₂ and H₂. As well as it appears at lower temperature how exothermic are the phenomena involved during overcharge.

Main datas got from overcharge tests figured in table 3.

<table>
<thead>
<tr>
<th>Test N°</th>
<th>Pmax (bars)</th>
<th>Tmax (°C)</th>
<th>Voltage max (V)</th>
<th>Capacity at 1.0 V and C/5 (Ah)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C/5 20°C</td>
<td>72,2</td>
<td>30,7</td>
<td>1,54</td>
</tr>
<tr>
<td>2</td>
<td>C/10 0°C</td>
<td>78,2</td>
<td>5,5</td>
<td>1,65</td>
</tr>
<tr>
<td>3</td>
<td>C 20°C</td>
<td>89,5</td>
<td>56,4</td>
<td>1,57</td>
</tr>
<tr>
<td>4</td>
<td>C 0°C</td>
<td>90,1</td>
<td>61,6</td>
<td>1,7</td>
</tr>
</tbody>
</table>

Table 3 - Overcharge test results

It is clear that the lower is the charge regime the best is the recombination of H₂ and O₂ because of the small amount of O₂ produced.

Others features to analyse are capacities restituted after overcharge, at lower temperature, which are higher than those in normal conditions (ie. C/2 20°C) by 10 to 25 %.

From these tests results, we can deduce that under abnormal conditions, this NiH₂ technology never presented very dangerous behaviour; though if we should classified risky events we’d find in growing order, overdischarge, overcharge and short circuit.
Figure 2 - NiH$_2$ cell short circuit characteristics
Thermal tests

These tests conducted under ESA contract at Aerospatiale Cannes (AS.CA), were aimed to evaluate thermal behaviour of NiH₂ 50 Ah SAFT cells. In parallel, was developed by AS.CA a thermal 59 node computer model of the cell-sleeve assembly (using a SINDA program).

Two thermal prototypes instrumented as indicated in figure 5 were built. The test was realized in thermal vacuum chamber and standard cycling conditions were C/2 discharge, C/10 charge, C/100 trickle with a DOD of 70% and a recharge factor of 1.2. Typical curve temperature comparing two follow on cycles at node level is presented in figure 6. This original test permit to measure instantaneous temperature and to promote a thermal cartography of the cell sleeve design to correlate the model.

Main results, in perfect agreement with predictions, are for BOL conditions (end of discharge step)
- Maximum inner temperature at stack level : 20°C
- Maximum inner gradient between stack and vessel : 6.8°C
- Mean conduction gradient along the sleeve : < 2°C

Calculation results with the model gave peaks power, dissipated during a cycle, not exceeding 6.5 W on discharge, 5 W on charge and 0.5 W on trickle.

Vibration tests

Six cells were tested to check whether the definition was compliant with usual launching loading. Vibrations requirements indicated in table 4 were jointly accepted by ESA and CNES. Previous and later electrical characteristics were determined and no important effects observed.

Two cells were removed of the test and opened to perform a DPA but everything was found to be conform to the initial state. Finally these results demonstrate the ability of SAFT design to withstand reference loading level without showing any mechanical or electrochemical damages.

<table>
<thead>
<tr>
<th>1) Sine vibrations</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 - 22 Hz : 22 mm C-C</td>
</tr>
<tr>
<td>22 - 100 Hz : + 20 g</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2) Random vibrations (along the 3 axis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 - 150 Hz : 0.25 g²/Hz</td>
</tr>
<tr>
<td>150 - 212 Hz : + 12 db/oct</td>
</tr>
<tr>
<td>212 - 480 Hz : 1 g²/Hz</td>
</tr>
<tr>
<td>480 - 1000 Hz : -12 db/gct</td>
</tr>
<tr>
<td>1000 - 2000 Hz : 0.053 g²/Hz</td>
</tr>
</tbody>
</table>

Table 4 - Vibrations spectra for qualification tests

Life tests

Three cells coming from the vibration test and six more unvibrated cells, or a total amount of nine, started a life test.

Cycling discharge profile is shown in figure 7 and related to a 45 cycles eclipse season, with a maximum discharge time of 72 minutes (this represent the typical case for Eutelsat 2 spacecraft application).
Figure 5 - Thermocouples instrumentation on thermal prototypes

- outer
- inner
Figure 6 - Node's curve temperature

Figure 7 - Discharge time profile
used for life test
Cycling conditions are presented herebelow in table 5. The test remains very realistic because it is a low accelerated test (i.e. 2 cycles a day).

<table>
<thead>
<tr>
<th>Regime</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge</td>
<td>C/1.7</td>
</tr>
<tr>
<td>Charge</td>
<td>C/13.5</td>
</tr>
<tr>
<td>Trickle</td>
<td>C/200</td>
</tr>
<tr>
<td>Maximum DOD</td>
<td>70 %</td>
</tr>
<tr>
<td>Recharge ratio K</td>
<td>1.15</td>
</tr>
<tr>
<td>Mean test temperature</td>
<td>10 + 5°C</td>
</tr>
</tbody>
</table>

Table 5 - Life test conditions

On figure 8 we establish the very low evolution on first three eclipse seasons on discharge step. Cells tested never exceeded 25°C outer temperature, and on maximum depth of discharge cycle, end of discharge voltage remained very stable at values close to 1.2 V.

This test is going on, one season more having been done, and normally it should only be stopped after completing 900 cycles or 20 eclipse seasons, corresponding to the ten years mission to be demonstrated.

Another encouraging result must be added. Apart of the validation test, a first prototype, cycling the same way, but at constant maximum DOD of 70 %, has reached satisfactorily more than 700 cycles.

Electrical evolution is shown in figure 9 and it is notably interesting to see how good is the stability for mid and end of discharge voltage. In addition, we should mentioned capacity evolution, checked regularly, hasn't decreased at all.

Considering thoroughly that kind of results, prequalification label was given to SAFT 50 Ah cell by CNES Quality Insurance Authority: which significate for the device the possibility to be mounted onto next term projects.
Figure 8 - Discharge characteristics evolution

Figure 9 - Discharge voltage evolution with time

November 1-3, 1988
Future activities

ESA and CNES, with the high level of confidence got from the last development experience, decided jointly to initiate a new GEO development, while intending to improve performances at components level.

Main trends for the new GEO development can be summarized as follow :

- Wider range capacity : 40 - 90 Ah
- Longer life requirement : 12 years
- Light weight concept : 55 - 60 Wh/kg

Results will be available by the end of 1990.

At the same time, and because of interesting results (ref. 2) CNES and ESA have procured approximately 20 cells to be tested under LEO conditions.

CNES tests conditions will be typically 100 minutes cycle at 10°C and 40 % DOD with a goal of 30 000 cycles.

Next steps for french NiH₂ technology are driven by opportunities to be aboard, on SAT2 project (a technological GEO spacecraft belonging to ESA PSDE program) and on Columbus program (European contribution to the international space station).

CONCLUSIONS

Large effort has been made in France to promote a NiH₂ cell development to an advanced status. Important results deduced from a comprehensive program permit right now to ascertain our knowledge concerning this promising technology.

Specially, SAFT design was found to be correctly sized on vibration, thermal, mechanical, electrical and safety aspects, as proved by the prequalification status got.

Life time is still under evaluation with good chances to reach the objective of a ten years GEO mission.

Ambitious improvements are planned for the next short term development with as key words, "high capacity and high energy density".

ACKNOWLEDGMENTS

Our acknowledgments are particularly addressed to all people who have worked hard and therefore contributed to the success of this activity.

REFERENCES

1. J. VERNIOLLE - Battery development and testing at ESA - NASA Battery Workshop 1986 - Washington

SESSION IV

NICKEL-HYDROGEN TECHNOLOGY

SESSION II - Current Issues & Concerns

Chairman: J. Smithrick, NASA/LeRC
Storage Considerations for Ni-H₂ Battery Cells

1988 NASA/GSFC Battery Workshop, 3 Nov. 1988
Goddard Space Flight Center, Greenbelt, Maryland 20771

R.V. Whiteley, Chemistry Department, Pacific University, Forest Grove, OR, and
A. Gibney, O/62-12, Lockheed Missiles and Space Co., Sunnyvale, CA

Introduction
The principal concern with the long term storage of nickel-hydrogen battery cells is the development of a low voltage plateau in the discharge profile of the cell (Figure 1). While the total capacity of a cell might remain essentially unchanged despite long periods of storage, the formation of this secondary plateau constitutes a decrease in the discharge voltage of some of the cells' capacity. When this lower voltage is below the voltage requirements of a particular power system, that portion of the capacity is no longer considered useful capacity, and therefore, there is a loss in useful capacity.

In order to understand this loss in useful capacity, the problem was characterized as fully as possible: the nature of the secondary plateau, the storage conditions which affect the development of the secondary plateau, the cell designs which make cells less likely to show losses in useful capacity after storage, and charging/discharging regimes which lead to recovery of some useful capacity losses were all delineated (Table I). The strategy was, then, to formulate a mechanism for the capacity loss which would be consistent with all of these characteristics. Only with the correct mechanism in hand would it be possible to propose measures (storage, design, cycling) which would mitigate the loss of useful capacity after long term cell storage.

Discussion
The nature of this secondary plateau and its causes and effects (Tables 1 and 2) are consistent with the formation of a higher resistance barrier between the current-carrying sinter and the active material of the positive electrode. The nickel sinter intrinsically develops a thin barrier of NiO which inhibits electron transfer, and it is this barrier which protects the sinter from spontaneous oxidation by the Ni(III) and Ni(IV) hydroxides which are generated on cell charging. Without this barrier, the sinter would eventually become bivalent nickel hydroxide by way of:

\[
\begin{align*}
\text{Ni}^0 + 2 \text{NiOOH} + 2 \text{H}_2\text{O} & \rightarrow 3 \text{Ni(OH)}_2 \\
\text{Ni}^0 + \text{NiO}_2 + 2 \text{H}_2\text{O} & \rightarrow 2 \text{Ni(OH)}_2
\end{align*}
\]
The barriers of restive material can be thought of as energy barriers as illustrated in Figure 2. Although the electrons in metallic nickel are at a considerably higher energy than those in the NiOOH and NiO₂, there is minimal electron transfer, and therefore minimal oxidation of the sinter, because the electrons in the metallic nickel are unable to overcome the small energy barrier of the intrinsic oxide film. On the other hand, electrons in the platinum, negative electrode are at a sufficiently high energy to surmount this barrier when the platinum is exposed to H₂ gas; that is, when the cell contains any pressure of hydrogen.

It should be noted at this point that some of the other proposed mechanisms for the development of a secondary plateau after long term cell storage are not entirely consistent with the characteristics delineated in Table 1. For example, a recent explanation suggests that CoOOH (or Co(OH)₃) is reduced by the hydrogen gas in a Ni-H₂ cell and that this leads to differential solubilities of the nickel and cobalt hydroxides. It is proposed that there is a migration of Co from the active material matrix. Certainly, such a mechanism would profoundly affect the charge and discharge profile of a cell stored for long periods. But the secondary plateau is found in Ni-Cd cells despite the absence of hydrogen, and it is found in Ni-H₂ cells with a positive precharge. Such cells have a residual oxidizing environment, and reduction of Co(III) in the active material would be highly unlikely. Even Ni-H₂ cells with a modest hydrogen precharge show residual Ni(III) in their positive electrodes after several years of storage in the shorted condition. In the presence of Ni(III), the reduction of Co(III) to bivalent Co is unlikely.

The NiO film on the nickel sinter is not the only energy barrier between the metallic nickel and the active material: the active material itself can provide considerable electrical resistance (a high energy barrier). The height of this barrier is indeterminate because the electrical resistance of the active material barrier is largely a function of its thickness, its structure, and the oxidation state of the Ni within its structure. The fully discharged positive electrode contains mostly bivalent nickel hydroxide. There is the brucite form, usually referred to as β-Ni(OH)₂, and there is the loosely hydrated form, α-Ni(OH)₂ which can contain 0.5 to 0.7 molecules of H₂O per Ni atom. This alpha form is a much more open structure as its intercalated water molecules hold the Ni-O planes 0.8 nm apart. This is also a much more electrically conductive material than the β-Ni(OH)₂ which contains as little as one H₂O molecule per twenty Ni atoms and has an interlaminar spacing of only 0.46 nm.

So, although a higher energy barrier might be expected of the β-Ni(OH)₂ than of the α-Ni(OH)₂ active material, other considerations determine the exact barrier heights. It is evident that the β-Ni(OH)₂ barrier can become insurmountable to even those electrons from the charged negative electrode. This conclusion is drawn from the destructive physical analyses of cells which have been short-circuited for years: the apparent oxidation state of the nickel in the active material is always found to exceed +2, indicating the presence of at least some trivalent nickel. The analyses typically show
about 5% NiOOH in the active material and it has been observed that the discharged active material is $\beta$-Ni(OH)$_2$. For the most part, however, the active material is accessible for discharge, and this is largely at about the same energy or voltage. Highly resistive regions do not compromise all of the capacity because the positive electrodes behave much like a network of innumerable parallel resistors (Figure 3). The high resistance paths are simply bypassed until all of the active material in low resistance regions is discharged. Only then is the more isolated material discharged.

The highly resistive nature of the $\beta$-Ni(OH)$_2$ is due, only in part, to the lack of water in its interlaminar regions. As this bivalent hydroxide ripens, its structure becomes more and more regular (ordered), and it is the highly ordered form of $\beta$-Ni(OH)$_2$ which shows such poor electrical conductivity. Water is not the only defect in the structure which can enhance the electrical conductivity of the material: even traces of higher oxidation state material like NiOOH can have a profound effect. And so, while it might seem desirable to achieve total reduction of the higher oxidation state nickel when discharging a cell, it is preferable to leave traces of the Ni(III) and Ni(IV) within the active material matrix to act as defects as the $\beta$-Ni(OH)$_2$ ripens over time. Fortunately, leaving some undischarged material is unavoidable as discussed earlier.

Charged positive electrodes have been found to contain $\alpha$-NiOOH, $\beta$-NiOOH, $\gamma$-NiOOH, and some form of tetravalent Ni which, for simplicity, will be described here as NiO$_2$. The $\beta$-NiOOH and $\gamma$-NiOOH are the important charging products. It is generally accepted that the beta structure is more conductive than the gamma structure, but the key issue is the structures themselves. On charging of the cell $\beta$-Ni(OH)$_2$ is smoothly oxidized to $\beta$-NiOOH with only minor changes in the crystal structure. The interlaminar distance opens slightly, from 0.46nm to 0.48nm. $\gamma$-NiOOH on the other hand is a product of charging $\alpha$-Ni(OH)$_2$ or of prolonged overcharging of $\beta$-NiOOH, and this, as with the $\alpha$-Ni(OH)$_2$, is a much more open structure. Cell dimensions indicating an interlaminar spacing of 2.1nm have been reported. The separation of the Ni-O planes in this structure is attributed to the incorporation of K$^+$ ions which are drawn into the structure during charging and expelled during discharging.

Because the $\gamma$-NiOOH is a poorer conductor than the $\beta$-NiOOH, the $\gamma$-NiOOH material discharges at a lower voltage and is therefore a less desirable product of cell charging. However, it is the precursor to $\alpha$-Ni(OH)$_2$, and in that respect it is more desirable to form $\gamma$-NiOOH on cell charging. By forming $\gamma$-NiOOH through extended overcharging, $\alpha$-Ni(OH)$_2$ will be formed on subsequent discharge, and this more conductive form of discharged material will provide a lower energy barrier between the active material and the nickel sinter. This is why some capacity lost to the low voltage discharge can be recovered through severe overcharging of the cell: any active material which has not been isolated by highly resistive $\beta$-Ni(OH)$_2$ is charged, first to $\beta$-
NiOOH and then on to $\gamma$-NiOOH. This opens the structure of the active material allowing $\text{H}_2\text{O}$ and $\text{K}^+$ between the layers of Ni and O atoms. On discharge, a significant amount of $\alpha$-Ni(OH)$_2$ is formed in the pores of the sinter. Repeated cycling (over-charging and discharging) slowly works $\text{H}_2\text{O}$ into the structure of the active material. This is not likely to be an efficient process, and so, total recovery of capacity is not expected. When the $\beta$-Ni(OH)$_2$ becomes highly ordered (dehydrated) after prolonged storage, it is not easily re-hydrated and therefore it remains highly resistive.

The hypothesis that the loss of useful capacity is a dehydration process is consistent with most of the factors delineated in Table 1. Dehydration of either form of Ni(OH)$_2$ is thermodynamically favorable, and so, the discharged, active material has a natural tendency to lose water and become less conductive. But dehydration is a slow process and can be virtually eliminated at very low temperatures (cf. Table 2). Dehydration could readily occur in cells with no $\text{H}_2$ precharge as is the case in Ni-Cd and negative-limited Ni-$\text{H}_2$ cells, and some low voltage discharge plateau has been observed in both of these cell designs (Table 2). Recovery of capacity by overcharge and trickle charge is not surprising when these reactions at the positive electrode are examined (Table 3). The trickle charge reaction is the same as the overcharge reaction: both consume hydroxide ions, but more important, both generate $\text{H}_2\text{O}$ within the active material and this is the source for the "re-hydration" process. The final factor described in Table 1 is not obviously connected to dehydration of active material.

The sensitivity of capacity loss to the rigidity of the plaque is due to the significant changes in the volume of active material as a function of state-of-charge. Zimmerman and Effa have clearly demonstrated that the intrinsic volume of discharged material ($\beta$-Ni(OH)$_2$) is considerably larger in a fully discharged cell than in a partly charged cell (Figure 4). This implies that when a cell is fully discharged, the active material swells inside the pores of the nickel sinter creating stresses within the positive electrode. These stress can be relieved by expansion of the pores or by squeezing water from the Ni(OH)$_2$ structure to reduce its volume. Expansion of the pores is a function of the rigidity of the plaque, and for plaque with a high bend strength, this is less likely. This leaves only the dehydration option. Given that dehydration of Ni(II) hydroxides is already thermodynamically favorable, the stresses created by rigid plaque can only accelerate the process. And given that the highly conductive $\alpha$-Ni(OH)$_2$ occupies much more volume than the less conductive $\beta$-Ni(OH)$_2$, more rigid plaque should favor formation of $\beta$-Ni(OH)$_2$.

Closely related to the issue of rigid plaque is loading levels: electrodes which are heavily loaded, like rigid plaque, are less able to expand to accommodate $\alpha$-Ni(OH)$_2$ as the cell is discharged. And so, such electrodes are more likely to enhance the formation of the highly resistive, dehydrated $\beta$-Ni(OH)$_2$ which leads to the secondary voltage plateau. It has been pointed out that plaque contains large void volumes even after being heavily loaded, but it should also be pointed out that access to these
voids is the issue. It is unlikely that any form of nickel hydroxide has any ductility to speak of, and therefore, as it expands, it is unlikely that it would flow into any available voids. Instead, it will create stresses within the electrode pores and spontaneously dehydrate.

The hypothesis that the loss of useful capacity is a dehydration process is not consistent with all of the factors delineated in Table 1. These inconsistencies are explained when a more general description of the process is used. It is the highly ordered form of $\beta$-Ni(OH)$_2$ which is a poor conductor, and the presence of crystal defects, like H$_2$O, enhance its conductivity. Other defects, however, are possible and are vital to maintaining good conductivity within the active material. Either form of NiOOH serves this purpose well. Besides providing Ni$^{3+}$ defects within the $\beta$-Ni(OH)$_2$ structure, neither form of NiOOH has as much tendency to dehydrate as the two forms of Ni(OH)$_2$ and the $\gamma$-NiOOH brings with it K$^+$ ions which further disrupt the highly regular structure of the $\beta$-Ni(OH)$_2$. The need for NiOOH within the discharged active material explains the observations that cells with a hydrogen precharge and cells stored in the shorted condition are more likely to develop a secondary plateau (Tables 1 and 2).

The NiOOH defects can be removed from the active material matrix by any or all of the reactions listed in Table 3 for self discharge at the nickel electrode. The first reaction listed does not require hydrogen; it is the mechanism for self discharge of Ni-Cd cells. If it occurs in a Ni-H$_2$ cell, it is evidently coupled to the self discharge reaction under "At the Platinum Electrode or on Any Ni$^0$ Surface" (Table 3), because O$_2$ does not accumulate during Ni-H$_2$ cell self discharge. Nevertheless, in a discharged cell, the higher oxidation state nickel ions are spontaneously removed from the matrix by the electrolyte and by any hydrogen precharge, the greater the H$_2$ precharge, the more thoroughly the NiOOH can be removed from the matrix. Inasmuch as residual NiOOH is always found in Ni-H$_2$ cells, even those stored for long periods with a hydrogen precharge, it can be said that this reduction process is not absolutely complete.

The intrinsic nature of each electrode in a fully discharged cell is very much a function of the precharge on the cell (Tables 4A and 4B). With either cell design, the open circuit voltage of the positive electrode should lie at least 100 mV positive of the negative electrode (Table 5). This means that in either design the positive electrode is inherently electron-deficient with respect to the negative electrode. When, however, the electrodes are shorted together after full discharge, the potential of each electrode is driven to exactly the same value and this causes the positive electrode to become artificially electron-rich (and the negative, artificially electron-poor). This electron-rich environment will enhance the reduction NiOOH defects in the active material. This is why cells stored shorted consistently show a greater proclivity for the secondary plateau (Table 2). On the other hand, when a cell is stored at open circuit after discharge, each electrode remains at its intrinsic rest potential and an artificially electron-rich (reducing) environment is not created within the positive electrode.
Purely in terms of mitigating the secondary voltage plateau, it is apparent that the negative limited cell (that with a positive precharge) is preferable. With its positive precharge, a higher concentration of NiOOH defects remain in the active material matrix after fully discharging the cell. But other storage issues should be considered. Because NiOOH can be reduced by H₂O to produce O₂, as described earlier, it should not be expected that a negative limited cell will retain its precharge as NiOOH. Rather, on prolonged storage, the positive precharge is probably inventoried as O₂ gas. The disadvantage of this is that the precharge is then no longer confined to the positive electrode; it is free to move throughout the cell. As the cell is recharged, H₂ will be generated at the negative electrode, and the H₂ + O₂ recombination to form H₂O will quickly follow. But prior to recharge, the liberated oxygen gas can be problematic. In an alkaline solution, as in the Ni-H₂ cell, oxygen can readily dissolve platinum metal from the negative electrode by:

\[ 2 \text{Pt}^0 + \text{O}_2 + 4 \text{OH}^- + 2 \text{H}_2\text{O} \rightarrow 2 \text{Pt(OH)}_4^{2-} \]

Other platinum oxidation processes can be written, and all of them show that the platinum becomes a soluble material which can diffuse throughout the cell. Only the oxidized platinum which remains in contact with the negative electrode would be reduced back to Pt metal on charging the cell. When the negative limited cell is stored shorted, the oxidation of Pt from the negative can proceed without the need for the O₂ shuttle. In this case the electron deficiency created at the negative is enough to drive the oxidation reaction.

**Conclusions**

The loss of some capacity after prolonged storage of Ni-H₂ batteries and battery cells is unavoidable; it is simply a consequence of confining several elements, each existing in two or more oxidation states, to a single container for extended periods. Thermodynamically, the oxidation-reduction reactions are highly spontaneous as are the deleterious dehydration reactions which cause the active material to lose its conductivity. But the rates of these reactions, particularly below room temperature become sufficiently slow to make capacity losses acceptably small. Other measures, besides low temperature storage can further decrease the rate of capacity-draining reactions. The discharge prior to cell storage should be somewhat modest, i.e. it should not be so thorough as to drive both electrodes to the same voltage (a zero volt open circuit condition). The use of minimal hydrogen precharge, and open circuit storage of the cells also slow the reduction of NiOOH in the active material. With such relatively simple precautions, it should be possible to store Ni-H₂ batteries and battery cells for prolonged periods with virtually no capacity loss to a low voltage plateau.
Figure 1  Two discharge profiles: one with a small secondary plateau and another with a significant secondary plateau.
Figure 2. Relative energies of electrons in the various materials in the Nickel-Hydrogen cell electrodes. For a single electron the ordinate is expressed in electron volts; for one Coulomb, this axis would be in expressed Joules.
Figure 3. A parallel resistor model illustrating the many different resistive barriers between the nickel sinter and the active material. The boxes represent regions of active material, and the arrows within those boxes are in the direction of the charging reaction. The length of a particular resistor is an indication of its relative resistance.
Figure 4  The volume of active material as a function of state of charge for a nickel electrode containing 10% cobalt hydroxide in the active material.
Table 1

CHARACTERISTICS of the SECONDARY VOLTAGE PLATEAU PROBLEM

It diminishes *useful* capacity (up to 30% loss).
   The total capacity is essentially retained, but a significant portion is shifted to a discharge voltage of less than 0.9 V

It develops *relatively* slowly, even at room temperature.

The rate of development is clearly affected by temperature.
   It is almost non-existent at 0°C and below.

The severity of the problem depends upon cell precharge.
   It is sensitive to the presence of H₂ pressure.

The plateau is more prominent in cells stored shorted.

It diminishes charge efficiency.
   Cells with this plateau show premature oxygen evolution.

Capacity loss can be recovered with severe overcharging.

The problem is *somewhat* mitigated with trickle charge.

It *seems* to be sensitive to physical properties (rigidity) of the plaque.
Table 2

REFERENCE DATA

From: H. Vaidyanathan, Long-Term Storage of Nickel-Hydrogen Cells, COMSAT Laboratories, Clarksburg, MD 20871-9475

Five cells were fully discharged and stored open-circuit at room temperature. After 30 days, all five cells had retained at least 71% of initial capacity.

Fully discharged cells stored open circuit at 0°C retained more than 90% of initial capacity after 253 days in storage, and cells stored at -20°C showed 103% of initial capacity after similar storage period.

With -20°C, 0°C, and room temperature storage of fully discharged, open circuited cells, those with a negative precharge (residual H2 pressure after discharge) always lost the greater fraction of initial capacity.


Loss in Capacity for Ni-Cd Cells

<table>
<thead>
<tr>
<th>STORAGE CONDITION</th>
<th>STORAGE TEMPERATURE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Room Temp.</td>
</tr>
<tr>
<td>Shorted</td>
<td>5</td>
</tr>
<tr>
<td>Open Circuit</td>
<td>2</td>
</tr>
</tbody>
</table>

NASA/GSFC Battery Workshop
Table 3

Reactions of Interest

**Charge**
At the Nickel Electrode
\[
\text{Ni(OH)}_2 + \text{OH}^- \rightarrow \text{NiOOH} + \text{H}_2\text{O} + \text{e}^-
\]
\[
\text{NiOOH} + \text{OH}^- \rightarrow \text{NiO}_2 + \text{H}_2\text{O} + \text{e}^-
\]
At the Platinum Electrode
\[
2 \text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2 + 2\text{OH}^-
\]

**Overcharge**
At the Nickel Electrode
\[
4 \text{OH}^- \rightarrow 2 \text{H}_2\text{O} + \text{O}_2 + 4\text{e}^-
\]
At the Platinum Electrode
\[
2 \text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2 + 2\text{OH}^-
\]

**Self Discharge**
At the Nickel Electrode
\[
4 \text{NiOOH} + 2 \text{H}_2\text{O} \rightarrow 4 \text{Ni(OH)}_2 + \text{O}_2
\]
\[
2 \text{NiOOH} + \text{H}_2 \rightarrow 2 \text{Ni(OH)}_2
\]
\[
\text{NiO}_2 + \text{H}_2 \rightarrow \text{Ni(OH)}_2
\]
At the Platinum Electrode or on Any Ni⁰ Surface
\[
2 \text{H}_2 + \text{O}_2 \rightarrow 2 \text{H}_2\text{O}
\]
Table 4B

THE NEGATIVE LIMITED CELL

-Will contain no residual hydrogen, not even adsorbed to the negative electrode.

-Will contain electrochemically available NiOOH in the positive electrodes.

-All remaining NiOOH will continue to be reduced, but by H_2O only.

-Oxygen gas could accumulate in the discharged cell.

**Shorted for Storage**

-Both electrodes will be driven to the same potential.

-The positive electrode will enhance oxidation at the negative electrode, and with no adsorbed H_2 to be oxidized:

\[
2 \text{Pt} + \text{O}_2 + 2 \text{H}_2\text{O} + 4 \text{OH}^- \rightarrow 2 \text{Pt(OH)}_4^{2-}
\]

-The negative electrode will drive electrons into the positive electrode thereby accelerating the reduction of electrochemically available NiOOH.

**Open Circuit for Storage**

-Each electrode is allowed to achieve its rest potential.

-Neither electrode drives the other.
Table 4A

THE POSITIVE LIMITED CELL

- Will contain a residual pressure of hydrogen gas after full discharge. The negative electrode will, therefore, contain adsorbed hydrogen.

- Will contain no electrochemically available NiOOH in the active material (positive electrode) after full discharge.

- Non-electrochemically available NiOOH will continue to be reduced, either by H₂O or by H₂. The extent and rate of this reduction will depend largely on the amount of H₂ precharge.

Shorted for Storage

- Both electrodes will be driven to the same potential.

- This will enhance oxidation of the adsorbed layer of H₂ at the Pt (negative) electrode.

- Reduction of Ni(OH)₂ and Co(OH)₂ in the positive electrode will be enhanced.

- The artificially induced reducing environment in the nickel (positive) electrode will drive the reduction of NiOOH.

Open Circuit for Storage

- Each electrode is allowed to achieve its rest potential.

- Neither electrode drives the other.
Table 5

ESTIMATES of ELECTRODE REST POTENTIALS
For Two Cell Designs

**The positive limited cell:**

The negative electrode is $\text{Pt/ H}_2, \text{OH}^- \quad E = -0.85 \text{ V vs N.H.E.}$

The positive electrode is $\text{Ni/ Ni(OH)}_2, \text{OH}^- \quad E = -0.73 \text{ V vs N.H.E.}$

**The negative limited cell:**

The negative electrode is $\text{Pt/ Pt(OH)}_2, \text{OH}^- \quad E = +0.15 \text{ V vs N.H.E.}$

The positive electrode is $\text{Ni/ Ni(OH)}_2, \text{NiOOH} \quad E = +0.47 \text{ V vs N.H.E.}$
SUMMARY

The active material in a fully discharged cell is a mixture of $\alpha$-Ni(OH)$_2$, $\beta$-Ni(OH)$_2$, and higher oxidation state hydroxides of Ni, principally $\beta$-NiOOH.

This material is an excellent electrical conductor and therefore is easily charged.

The excellent conductivity is due to:

- The presence of $\alpha$-Ni(OH)$_2$ because of its open lattice which holds H$_2$O molecules between Ni-O planes.
- The presence of Ni(III) and Ni(IV) hydroxides and oxides. These create defects in the $\beta$-Ni(OH)$_2$ lattice as it forms. Also, these hydroxides do not readily dehydrate.

Over extended storage:

- The bivalent hydroxides dehydrate, and the oxyhydroxides are reduced.
- A highly ordered form of beta-Ni(OH)$_2$ slowly forms. This material is a poor electrical conductor.

Dehydration is thermodynamically favorable and is accelerated by:

- Elevated temperature
- Compression of the active material by rigid plaque.

Reduction of the oxyhydroxides is also thermodynamically favorable and is accelerated by:

- High pressure hydrogen (hydrogen precharge)
- Shorting the positive electrode to the negative electrode during storage.
Table 7

RECOMMENDATIONS

- Use minimal negative precharge after cell activation.

- Store cells at low temperature (ca. 0°C).

- Store cells in open circuit condition after full discharge.
Table 8

ADDITIONAL REFERENCES


Electrolyte Concentration Effects on Ni-H$_2$ Battery Cells

A. Gibney
Lockheed Missiles and Space Co.

R. Whiteley
Pacific University

R. Baker
Eagle-Picher Industries
CELL SUMMARY

Application: Hubble Space Telescope

Nameplate: 93 Ahr

Normal DOD: 8 - 10%

Cell Design Features:
- Eagle-Picher Manufactured
- Back-to-back, Air Force Electrodes
- Zircar Separators
- Rabbit Ear Terminals with Ziegler Seals

Engineering Cell Electrolyte:
- Cell populations activated with either 25 w/o (eg cell 12) or 31 w/o (eg cell 31) KOH
- Additional cells (eg cell 5) subjected to special activation procedure with 31 w/o KOH
- Actual post-conditioning electrolyte concentration shown by DPA
DPA Results of Engineering Cells
<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>25% KOH (Cell #12)</th>
<th>31% KOH (Cell #13)</th>
<th>Double Activation (Cell #5)</th>
<th>85.02</th>
<th>48.43</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolyte Takeup, g</td>
<td>282.0</td>
<td>304.4</td>
<td>288.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(avg. of 5 cells)</td>
<td></td>
<td>(avg. of 5 cells)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avg. Plate Thickness (mils)</td>
<td>37.0</td>
<td>39.7</td>
<td>44.9</td>
<td>35.1</td>
<td>39.0</td>
</tr>
<tr>
<td>Avg., Pre-activation</td>
<td>25.5</td>
<td>36.0</td>
<td>35.1</td>
<td>9.8</td>
<td></td>
</tr>
<tr>
<td>Avg. from DPA</td>
<td>1.5</td>
<td>3.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrolyte Conc. %</td>
<td>30.7</td>
<td>38.8</td>
<td>38.9</td>
<td>35.9</td>
<td>39.7</td>
</tr>
<tr>
<td>in positive electrodes</td>
<td>34.3</td>
<td>37.8</td>
<td>39.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>in separators</td>
<td>26.7</td>
<td>34.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weighted average</td>
<td>28.6</td>
<td>36.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk Porosity, %</td>
<td>85.50</td>
<td>86.67</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active material in positive electrodes, %</td>
<td>48.02</td>
<td>47.79</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Figure 1** *Electrolyte wt. in DPA cell components*  
(corrected for carbonate)

**Figure 2** *Electrolyte conc. in DPA cell components*  
(corrected for carbonate)
Figure 3  Plate thickness in DPA cells

Plate thickness (mils)

Plate pair

+  CELL 5  (39.0%)
•  CELL 12  (28.6%)
■  CELL 13  (36.7%)
Acceptance Performance
of
Engineering and Test Module Cells
### Table 2  ACCEPTANCE DATA, 28.6% vs 36.7%

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>28.6% KOH (Avg. of 5 Cells)</th>
<th>36.7% KOH (Avg. of 5 Cells)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity at 0°C</td>
<td>102.07 Ah</td>
<td>110.47 Ah</td>
</tr>
<tr>
<td>Capacity at 10°C</td>
<td>94.05 Ah</td>
<td>104.39 Ah</td>
</tr>
<tr>
<td>Capacity at 20°C</td>
<td>83.85 Ah</td>
<td>95.15 Ah</td>
</tr>
<tr>
<td>Charge Retention 72h, 20°C</td>
<td>78.83/98.73 --&gt;79.8%</td>
<td>91.38/107.68--&gt;84.9%</td>
</tr>
</tbody>
</table>
Figure 4  RNH-90-3 EM-2 ACCEPTANCE TEST
0C Capacity Test
SECOND CYCLE CHARGE, May 5, 1988

Cell Voltage (volts)

Time (mins)

- - - 25% (cell 18)
- - - 31% (cell 19)
Figure 5  RNH-90-3 EM-2 ACCEPTANCE TEST
OC Capacity Test
SECOND CYCLE DISCHARGE and SHORT DOWN
May 5, 1988

Cell Voltage (volts)

Time (mins)
Figure 6  RNH–90–3 EM–2 ACCEPTANCE TEST
10C Capacity Test
SECOND CYCLE CHARGE, May 5, 1988

![Graph showing cell voltage over time for two different cells.](image-url)
Figure 7  RNH-90-3 EM-2 ACCEPTANCE TEST
10C Capacity Test
SECOND CYCLE DISCHARGE and SHORT DOWN
May 5, 1988

![Graph of cell voltage over time showing two curves for 25% (cell 18) and 31% (cell 19).](image)
Figure 8  RNH-90-3 EM-2 ACCEPTANCE TEST
20C Capacity Test
SECOND CYCLE CHARGE, May 5, 1988

Cell Voltage (volts)

Time (mins)
Figure 9  RNH-90-3 EM-2 ACCEPTANCE TEST
20C Capacity Test
SECOND CYCLE DISCHARGE and SHORT DOWN
May 5, 1988
Figure 10  End-of-Charge Pressures during Acceptance

16-h charge, 2nd capacity cycle

- ▲ 28.6% (3 cells)
- ■ 36.7% (3 cells)
- ● 31.5% (projected)
- ○ TM-1 (actual)

End-of-charge P, psig

Temperature, deg F

NASA/GSFC Battery Workshop
### Table 3  HST NIH2 ATP TEST DATA SUMMARY

<table>
<thead>
<tr>
<th>TEST ARTICLES</th>
<th>2ND CAP AT 32°F</th>
<th>2ND CAP AT 50°F</th>
<th>2ND CAP AT 68°F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MIN AVG MAX</td>
<td>MIN AVG MAX</td>
<td>MIN AVG MAX</td>
</tr>
<tr>
<td>86 TM-1 (31%)</td>
<td>100.7 104.1 106.9</td>
<td>93.0 96.2 98.9</td>
<td>82.9 85.9 88.0</td>
</tr>
<tr>
<td>82 TM-2 (31%)</td>
<td>99.2 104.2 106.5</td>
<td>90.7 93.7 96.7</td>
<td>81.5 84.8 87.5</td>
</tr>
<tr>
<td>3 EM-2 (29%)</td>
<td>101.7 102.1 102.5</td>
<td>93.4 94.0 94.3</td>
<td>82.5 83.2 84.0</td>
</tr>
</tbody>
</table>
Figure 11 RNH-90-3 TM1

ACCEPTANCE TEST PROCEDURE

S/N 107 - Discharge at Temperature

- 68°F - Cycle #3
- 50°F - Cycle #3
- 32°F - Cycle #2

Voltage

Elapsed Time (Hours)
Self-Discharge
Figure 12  EM-1 Self-Discharge at 24 deg C
after short-down and chg. @ 0 deg C

Capacity, Ah

Open Circuit Time, h

KOH concentration 39.0%

□ cell 1
◆ cell 8
Figure 11 EM-2 Self-Discharge at 24 deg C

- KOH concentration 36.7%
- After short-down and charge @ 0 deg C

Capacity, Ah

Open Circuit Time, h

120
100
80
60
40
20
0

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Figure 15  Self-Discharge Rate Constant
as a function of KOH concentration

KOH conc., wt. %

K exp3, 0 degC
Table 4  CHARGE RETURN DURING TRICKLE CHARGE 0°C, FOLLOWING CHARGE AT 9.3A TO 1.52V

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Cell No.</th>
<th>16</th>
<th>18</th>
<th>20</th>
<th>17</th>
<th>19</th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Baseline cap.</td>
<td>68.0</td>
<td>68.5</td>
<td>68.0</td>
<td>68.16</td>
<td>66.5</td>
<td>66.9</td>
</tr>
<tr>
<td>2.</td>
<td>.5h, .5A in (.25Ah in)</td>
<td>68.1</td>
<td>68.6</td>
<td>68.2</td>
<td>67.6</td>
<td>65.9</td>
<td>66.4</td>
</tr>
<tr>
<td></td>
<td>△ to baseline</td>
<td>+.1</td>
<td>+.1</td>
<td>+.2</td>
<td>-.56</td>
<td>-.6</td>
<td>-.5</td>
</tr>
<tr>
<td></td>
<td>Tr. ch. efficiency</td>
<td>40%</td>
<td>40%</td>
<td>80%</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>3.</td>
<td>1.0h, .5A in (.5Ah in)</td>
<td>68.2</td>
<td>68.8</td>
<td>68.3</td>
<td>67.9</td>
<td>66.2</td>
<td>66.5</td>
</tr>
<tr>
<td></td>
<td>△ to baseline</td>
<td>+.2</td>
<td>+.3</td>
<td>+.3</td>
<td>-.26</td>
<td>-.3</td>
<td>-.4</td>
</tr>
<tr>
<td></td>
<td>Tr. ch. efficiency</td>
<td>40%</td>
<td>60%</td>
<td>60%</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>4.</td>
<td>5.0h, .5A in (2.5Ah in)</td>
<td>69.4</td>
<td>69.7</td>
<td>69.1</td>
<td>68.7</td>
<td>67.2</td>
<td>67.5</td>
</tr>
<tr>
<td></td>
<td>△ to baseline</td>
<td>+1.4</td>
<td>+1.2</td>
<td>+1.1</td>
<td>+.54</td>
<td>+.7</td>
<td>+.6</td>
</tr>
<tr>
<td></td>
<td>Tr. ch. efficiency</td>
<td>56%</td>
<td>48%</td>
<td>44%</td>
<td>22%</td>
<td>28%</td>
<td>24%</td>
</tr>
<tr>
<td>5.</td>
<td>.2h, 3.0A (.6Ah)</td>
<td>68.8</td>
<td>69.5</td>
<td>69.1</td>
<td>68.0</td>
<td>66.3</td>
<td>66.7</td>
</tr>
<tr>
<td></td>
<td>△ to baseline</td>
<td>+.8</td>
<td>+1.0</td>
<td>+1.1</td>
<td>-.16</td>
<td>-.2</td>
<td>-.2</td>
</tr>
<tr>
<td></td>
<td>Tr. ch. efficiency</td>
<td>125%</td>
<td>166%</td>
<td>183%</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>6.</td>
<td>.5h, 3.0A (1.5Ah)</td>
<td>69.7</td>
<td>70.3</td>
<td>69.9</td>
<td>69.0</td>
<td>67.4</td>
<td>67.7</td>
</tr>
<tr>
<td></td>
<td>△ to baseline</td>
<td>+1.7</td>
<td>+1.8</td>
<td>+1.9</td>
<td>+.74</td>
<td>+.9</td>
<td>+.8</td>
</tr>
<tr>
<td></td>
<td>Tr. ch. efficiency</td>
<td>113%</td>
<td>120%</td>
<td>127%</td>
<td>49%</td>
<td>60%</td>
<td>53%</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Run No.</th>
<th>Cell No.</th>
<th>16</th>
<th>18</th>
<th>20</th>
<th>17</th>
<th>19</th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Baseline cap.</td>
<td>82.4</td>
<td>82.0</td>
<td>81.6</td>
<td>91.3</td>
<td>90.9</td>
<td>91.5</td>
</tr>
<tr>
<td>2.</td>
<td>24h, .5A (12 Ah in)</td>
<td>79.8</td>
<td>78.6</td>
<td>76.3</td>
<td>91.8</td>
<td>91.0</td>
<td>91.8</td>
</tr>
<tr>
<td></td>
<td>Δ to baseline</td>
<td>-2.6</td>
<td>-3.4</td>
<td>-5.3</td>
<td>+.5</td>
<td>+.1</td>
<td>+.3</td>
</tr>
<tr>
<td></td>
<td>Tr. ch. efficiency</td>
<td>&lt;0%</td>
<td>&lt;0%</td>
<td>&lt;0%</td>
<td>-0%</td>
<td>-0%</td>
<td>-0%</td>
</tr>
<tr>
<td>3.</td>
<td>96h, .5A (48 Ah in)</td>
<td>80.0</td>
<td>78.7</td>
<td>78.3</td>
<td>90.1</td>
<td>89.4</td>
<td>89.6</td>
</tr>
<tr>
<td></td>
<td>Δ to baseline</td>
<td>-2.4</td>
<td>-3.3</td>
<td>-4.1</td>
<td>-1.2</td>
<td>-1.5</td>
<td>-1.9</td>
</tr>
<tr>
<td></td>
<td>Tr. ch. efficiency</td>
<td>&lt;0%</td>
<td>&lt;0%</td>
<td>&lt;0%</td>
<td>&lt;0%</td>
<td>&lt;0%</td>
<td>&lt;0%</td>
</tr>
<tr>
<td>4.</td>
<td>24h, .25A (6 Ah in)</td>
<td>76.5</td>
<td>75.1</td>
<td>72.4</td>
<td>85.6</td>
<td>85.3</td>
<td>86.0</td>
</tr>
<tr>
<td></td>
<td>Δ to baseline</td>
<td>-5.9</td>
<td>-6.9</td>
<td>-9.2</td>
<td>-5.7</td>
<td>-5.6</td>
<td>-5.5</td>
</tr>
<tr>
<td></td>
<td>Tr. ch. efficiency</td>
<td>&lt;0%</td>
<td>&lt;0%</td>
<td>&lt;0%</td>
<td>&lt;0%</td>
<td>&lt;0%</td>
<td>&lt;0%</td>
</tr>
</tbody>
</table>
Figure 16: EM-1 Orbital Cycling Performance

Recharge Ratio (\%) vs. Capacity (Ah)

- EM-1 Cap. w/r.ch.
- RR w/r.ch.
- RR w/o r.ch.

Step-to-Trickle Voltage (V)

96-min. cycling, 0 deg C
Figure 17  EM-2 Orbital Cycling Performance

KOH Concentration 28.6%

- 96-min. cycling, 0 deg C

- Capacity (Ah)

- Step-to-Trickle Voltage (V)

- Recharge Ratio (%)

- 26% Cap.
- RR w/tr.ch.
- RR w/o tr.ch.
Figure 10  EM-2 Orbital Cycling Performance

- KOH Concentration 36.7%
- 96-min. cycling, 0 deg. C

Recharge Ratio (%)

Step-to-Trickle Voltage (V)

Capacit (Ah)

November 1-3, 1988
NASA BATTERY WORKSHOP

NASA GODDARD SPACE FLIGHT CENTER

ISSUES REGARDING STRUCTURAL ASPECTS OF THE NiH₂ CELL

NOVEMBER 3, 1988

JOHN A. ANDRASIK
QUALITY, MATERIALS & PROCESSES OFFICE
NASA LEWIS RESEARCH CENTER
BACKGROUND

- A PRESSURE VESSEL IS A CONTAINER THAT STORES PRESSURIZED FLUIDS AND:
  - CONTAINS STORED ENERGY OF 14,240 FT./LBS. (19,307 J) OR GREATER BASED ON ADIABATIC EXPANSION OF A PERFECT GAS; OR
  - CONTAINS A GAS OR LIQUID WHICH WILL CREATE A HAZARD IF RELEASED; OR
  - WILL EXPERIENCE A DESIGN LIMIT PRESSURE GREATER THAN 100 PSI

- THE NH\textsubscript{2} CELL IS ESSENTIALLY A PRESSURE VESSEL
  - INTERNAL MAXIMUM CELL PRESSURE WILL APPROXIMATELY BE 1000 PSI FOR THE SPACE STATION LEO APPLICATION
BACKGROUND, CONT'D.

- PRESSURE VESSELS DESIGNED FOR (MANNED) AEROSPACE APPLICATIONS MUST MEET SPECIFIC REQUIREMENTS
  - STANDARD GENERAL REQUIREMENTS FOR DESIGN AND OPERATION
  - PAYLOAD SAFETY
  - FRACTURE CONTROL

- CURRENT NIH₂ PRESSURE VESSEL ISSUES RESULT FROM THE INABILITY TO MEET THESE REQUIREMENTS IN SPECIFIC AREAS:
  - MATERIAL PROPERTIES
  - NONDESTRUCTIVE EVALUATION (NDE)
  - FAILURE MODE DETERMINATION
  - FABRICATION-INDUCED RESIDUAL STRESSES
  - ANALYTICAL ASSESSMENT TECHNIQUE (FRACTURE MECHANICS ANALYSIS)
MATERIAL PROPERTIES

- PRESSURE VESSEL MATERIAL IS INCONEL 718
- NORMAL CELL OPERATION INCLUDES THE CYCLIC EVOLUTION/RECOMBINATION OF GASEOUS HYDROGEN AT HIGH PressURES
  - INTERNAL NIH₂ CELL ENVIRONMENT CONSISTS OF MORE THAN GASEOUS HYDROGEN
- NI-BASE SUPERALLOYS ARE CATAGORIZED AS BEING "EXTREMELY SUSCEPTIBLE" TO HYDROGEN ENVIRONMENT EMBRITTLEMENT (H/E)
- ISSUES
  - LACK OF INCONEL 718 MATERIAL PROPERTY TEST DATA RELATIVE TO NIH₂ OPERATING PARAMETERS
  - CELL PressURES
  - CELL ENVIRONMENT
NDE

- GENERIC SPACE STATION NIH₂ CELL PRESSURE VESSEL DESIGN INCLUDES A CLOSURE WELD

- UNIQUE ASPECTS OF THIS GENERIC DESIGN PRECLUDES NORMAL NDE OF THE CLOSURE WELD
  - ELECTRODE STACK
  - WELD RING

- BOSS WELDS HISTORICALLY HAVE NOT BEEN COMPLETELY INSPECTED

- ISSUE
  - WELDS IN THE NIH₂ CELL PRESSURE VESSEL ARE NOT COMPLETELY INSPECTED
FAILURE MODE DETERMINATION

- The manner in which an initial flaw will grow through the wall of a pressure vessel must be assessed:
  - Lead-before-burst (nonhazardous); or
  - Lead-before-burst (hazardous); or
  - Brittle failure

- The failure mode can be analytically modeled (e.g., Flagro computer algorithm)
  - Valid material property and flaw size inputs are required
  - A valid analytical model is required

- The failure mode can be physically demonstrated
  - Pressure vessel(s) with flaws of known size and aspect ratios is (are) required
  - Demonstration will be valid relative only to those pressure vessels tested
FAILURE MODE DETERMINATION, CONT'D.

- THE FAILURE MODE CAN BE DETERMINED VIA DUCTILE SCREENING(?)

- ISSUES
  - DIFFICULTIES EXIST WITH SUPPLYING REQUIRED INPUTS TO EITHER THE ANALYTICAL MODEL OR PHYSICAL DEMONSTRATION
  - UNKNOWN MATERIAL PROPERTIES
  - INCOMPLETE NDE

- CONSIDERABLE DEBATE STILL RAGES REGARDING THE ACCEPTABILITY OF DUCTILE SCREENING WITHIN THE NASA FRACTURE MECHANICS COMMUNITY
RESIDUAL STRESS

- A stress that exists in a structure as manufactured which is due to processing, fabrication, and/or prior loading
  - Effects may be additive to operating stresses

- Techniques exist to assess structural residual stresses
  - Destructive
  - Nondestructive

- Residual stresses are present in NiH₂ pressure vessel
  - Magnitude and directionality are unknown

- ISSUE
  - Safe-life verification is questionable if residual stresses are not considered

- Historically have not been assessed
ANALYTICAL ASSESSMENT TECHNIQUE

- NASA SPACEFLIGHT COMMUNITY GENERICALLY APPLIES LINEAR ELASTIC FRACTURE MECHANICS ANALYSIS IN FRACTURE CONTROL APPLICATIONS
  - FLAGRO FAMILY OF COMPUTER CODES

- THIN-WALL PRESSURE VESSEL FABRICATED FROM "TOUGH" METALLIC MATERIALS (E.G., INCONEL 718) TYPICALLY FAIL (FRACTURE) IN AN ELASTIC-PLASTIC MANNER
  - ELASTIC-PLASTIC FRACTURE MECHANICS IS IN ITS INFANCY

- ISSUE
  - DEBATE EXISTS REGARDING THE CONSERVATISM OF LINEAR ELASTIC FRACTURE MECHANICS ANALYSIS (FLAGRO) WHEN APPLIED TO THIN-WALL PRESSURE VESSELS
NASA/LEWIS CURRENT ACTIVITIES SUMMARY

1. MATERIAL TEST PROGRAM
   - POSSIBLE FUNDING THROUGH WP-04 SPACE STATION PROGRAM OFFICE ($80K)

2. NDE OF CLOSURE WELD
   - SAMPLES SIMULATING NIH₂ CLOSURE WELD FABRICATED AT LERC AND
     FORWARDED TO NASA NDE PERSONNEL FOR EVALUATION (APPROXIMATELY $1K IN MANHOURS)
   - SCOPE OF ACTIVITIES IS TO IDENTIFY MOST PROMISING NDE
     TECHNIQUE(S) FOR FURTHER DEVELOPMENT

3. RESIDUAL STRESS ANALYSIS
   - PRESSURE VESSEL PURCHASED FROM NIH₂ CELL MANUFACTURER ($1.75K)
   - SOURCE FOR NEUTRON DIFFRACTION IDENTIFIED - PR RELEASED ($8.5K)
   - SAMPLES ASSESSED VIA X-RAY DIFFRACTION
RECOMMENDATIONS

- INCREASE IN SCOPE OF ACTIVITIES

- CURRENT ACTIVITIES UNDERTAKEN AT NASA/LEWIS WILL NOT SOLVE ALL OF
  THE ISSUES

- NH2 USERS SHOULD ORGANIZE EFFORTS

- ADDRESS THE ISSUES IDENTIFIED DIRECTLY

- BEWARE OF MANNED SPACECRAFT REQUIREMENTS
EFFECT OF PRECHARGE ON Ni/H₂ CELL STORAGE CAPACITY

H. S. Lim and S. J. Stadnick

Hughes Aircraft Company
TYPES OF PRECHARGE OF Ni/H₂ CELLS

H₂ PRECHARGE:
EXCESS OF H₂ IN CELL

NICKEL PRECHARGE:
DEFICIT OF H₂ IN CELL
PRECHARGE AND REVERSAL ELECTRODE REACTIONS

H₂ PRECHARGE CELL:

(+) \[ \text{H}_2\text{O} + e = \frac{1}{2} \text{H}_2 + \text{OH}^- \]

(-) \[ \frac{1}{2} \text{H}_2 + \text{OH}^- = \text{H}_2\text{O} + e \]

NICKEL PRECHARGE CELL:

(+) \[ \text{NiOOH} + \text{H}_2\text{O} + e = \text{Ni(OH)}_2 + \text{OH}^- \]
or \[ \text{H}_2\text{O} + 1/2 \text{O}_2 + 2e = 2\text{OH}^- \]

(-) \[ 2\text{OH}^- = \text{H}_2\text{O} + 1/2 \text{O}_2 + 2e \]
CAPACITY FADING OF Ni/H₂ CELL ON OPEN CIRCUIT STORAGE
RECOVERY OF FADED CAPACITY OF A Ni/H₂ CELL

AVERAGE BATTERY CAPACITY, A/h

TEST PERIOD, days

LEO CYCLING

ACCEPTANCE TEST

WEEKLY TOP-OFF CHARGE STAND
DISCHARGE VOLTAGE OF HEALTHY AND CAPACITY FADED CELLS

A: CELL WITHOUT CAPACITY LOSS
B: CELL WITH CAPACITY LOSS

Diagram: Graph showing discharge voltage over time. The graph compares a healthy cell (A) and a cell with capacity loss (B). The x-axis represents discharge time in minutes, ranging from 0 to 150, while the y-axis represents voltage, ranging from 0.8 to 1.6. The graph shows a decline in voltage over time for both cells, with B showing a more rapid decline and a lower final voltage compared to A.
### CELL PRESSURE OF HEALTHY AND CAPACITY FADED CELL

<table>
<thead>
<tr>
<th>Pack No.</th>
<th>Capacity, Ah</th>
<th>EOCP, psig</th>
<th>EODP, psig</th>
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<tbody>
<tr>
<td>Q3</td>
<td>50.62</td>
<td>766-742</td>
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<td>52.42</td>
<td>742-736</td>
<td>190-202</td>
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<td>Q4</td>
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<td>273-301</td>
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<td>749-771</td>
<td>280-303</td>
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<td></td>
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<td>746-780</td>
<td>267-308</td>
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<td></td>
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<td>714-760</td>
<td>237-299</td>
</tr>
</tbody>
</table>

*November 1-3, 1988*
EFFECT OF PRECHARGE ON CAPACITY FADING

CAPACITY, Ah

STORAGE TIME, days

6.6% H1 precharge
2.8% H2 precharge
12.3% H2 precharge

NASA/GSFC Battery Workshop
EFFECT OF PRECHARGE ON CAPACITY FADING

CAPACITY, Ah

STORAGE TIME, days

6.6% Ni PRECHARGE

2.8% H2 PRECHARGE

12.8% H2 PRECHARGE
PRECHARGE EFFECT ON CAPACITY FADING OF 1-6 FLIGHT BATTERIES
Ni/H₂ CELL VOLTAGES DURING REVERSAL

VOLTAGE

TIME
Voltage at End of Discharge, Eclipse Day 23
Ni vs H$_2$ Precharge
POSSIBLE MECHANISM OF CAPACITY FADEING

ASSUMPTION: ACTIVE Co IS NEEDED FOR HIGH ACTIVE MATERIAL UTILIZATION

ACTIVE Co IS CoOOH OR Co(OH)_3

CHEMICAL REACTIONS DURING STORAGE:

\[
\begin{align*}
\text{CoOOH} + \frac{1}{2} \text{H}_2 &= \text{Co(OH)}_2 & \text{(Slow)} \\
\text{Co(OH)}_2 + 2 \text{CoOOH} &= \text{Co}_3\text{O}_4 + 2 \text{H}_2\text{O} & \text{(Fast)}
\end{align*}
\]

\[
3 \text{CoOOH} + \frac{1}{2} \text{H}_2 = \text{Co}_3\text{O}_4 + 2 \text{H}_2\text{O}
\]

OR

\[
3 \text{Co(OH)}_3 + \frac{1}{2} \text{H}_2 = \text{Co}_3\text{O}_4 + 5 \text{H}_2\text{O}
\]
EFFECT OF COBALT ON NICKEL ELECTRODE CAPACITY

S. Januszkiewicz, 1959
X-RAY DIFFRACTION PATTERNS

Co₃O₄ AND BROWN RESIDUE FROM Ni ELECTRODE

November 1-3, 1988
CONCLUDING REMARKS

- Capacity of Ni/H₂ cells (31% KOH) did not fade if sufficient amount of Ni precharge is used.
- A short term reversal of Ni precharge cell did not damage the cell.
- No long term problem of Ni precharge cell has been identified.
- Ni precharge cell has advantage of low operation pressure.
- Reaction of cobalt with H₂ might cause capacity fading.
NIH2 BATTERIES AND THEIR APPARENT VARYING H2 PRECHARGE

(NOT SUBMITTED)

PAUL RITTERMAN, COMSAT
EVALUATION

OF

DEVELOPING Ni-H₂ CELL COMPONENTS

S. KUWAJIMA*, K. YAMAWAKI*

and

M. KANDA**

*National Space Development Agency of Japan
**Toshiba R&D Center, Toshiba Corporation
### Cell Feature

<table>
<thead>
<tr>
<th>CELL No</th>
<th>POS. ELEC</th>
<th>NEG. ELEC</th>
<th>SEPARATOR</th>
<th>CELL CASE</th>
<th>STACK</th>
<th>NOTE</th>
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<tbody>
<tr>
<td>BP1</td>
<td></td>
<td></td>
<td></td>
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</tr>
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<td>BP2</td>
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<td>PV1</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>PV2</td>
<td></td>
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<td>PV3</td>
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<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>RM1</td>
<td>N-STD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RM2</td>
<td></td>
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<tr>
<td>RM3</td>
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</tr>
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<td>RM4</td>
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<td>RM5</td>
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<td>RM6</td>
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</tr>
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<td>RM7</td>
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</tr>
<tr>
<td>RM8</td>
<td></td>
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</tr>
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<td>RM9</td>
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</tr>
<tr>
<td>RM10</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>RM11</td>
<td>N-CD3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RM12</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

- BP1: BOILOR PLATE
- PV1: PRESS. VESSEL
- RM1: BOILOR PLATE
- RM5: BOILOR PLATE
- RM11: BOILOR PLATE

- 1/1 STACK
- 1/3 STACK

**Note:** KOH ELECTROLYTE WITH Li ADDITIVE
## ELECTRODE FEATURE

<table>
<thead>
<tr>
<th>Positive Electrode</th>
<th>N-STD</th>
<th>EI Ni(OH)$_2$ WITH Co</th>
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<tbody>
<tr>
<td></td>
<td>N-CD3</td>
<td>EI Ni(OH)$_2$ WITH Co AND Cd</td>
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<tr>
<td>Negative Electrode</td>
<td>H-STD</td>
<td>Pt CARBON CATALYST LAYER OF SINGLE PORE SIZE</td>
</tr>
<tr>
<td></td>
<td>H-DP</td>
<td>Pt CARBON CATALYST LAYER OF DUAL PORE SIZE</td>
</tr>
<tr>
<td>Separator</td>
<td>S-ZA1</td>
<td>ZIRCONIA-ASBESTOS MONO-LAYER (BUTYL BINDER)</td>
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<tr>
<td></td>
<td>S-ZA2</td>
<td>ZIRCONIA-ASBESTOS DUAL-LAYER (BUTYL BINDER)</td>
</tr>
<tr>
<td></td>
<td>S-TF</td>
<td>ZIRCONIA MONO-LAYER (PTFE BINDER)</td>
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SIMULATION TEST CONDITION

LEO SIMULATION TEST

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<tr>
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<tbody>
<tr>
<td>CHG</td>
<td>0.96 C</td>
<td>55 MIN</td>
</tr>
<tr>
<td>DISCHG</td>
<td>1.37 C</td>
<td>35 MIN</td>
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<tr>
<td>DOD</td>
<td>80 %</td>
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<tr>
<td>CD RATIO</td>
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</tr>
<tr>
<td>TEMP</td>
<td>25 °C</td>
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GEO SIMULATION TEST

<p>| | | |</p>
<table>
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<tr>
<th></th>
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<tbody>
<tr>
<td>CHG</td>
<td>0.10 C</td>
<td>22.8 HRS</td>
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<tr>
<td>DISCHG</td>
<td>0.67 C</td>
<td>1.2 HRS</td>
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<tr>
<td>DOD</td>
<td>80 %</td>
<td></td>
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<tr>
<td>TEMP</td>
<td>25 °C</td>
<td></td>
</tr>
</tbody>
</table>
CELLS UNDER TEST
LEO SIMULATION TEST

DOD 88%
C/D=1.10

Voltage (Volts)

Pressure (Kg/Cm² G)

Time (minutes)
LEO SIMULATION TEST

November 1-3, 1988
LEO SIMULATION TEST

![Graph showing voltage and pressure over time for different cycles.]

- RH4 1200th CYCLE
- RH6 1200th CYCLE
- RH12 1200th CYCLE

Voltage (Volts)

Pressure (Kg/Cm² G)

Time (minutes)
CAPACITY TEST

(INITIAL)

Voltage (Volts)

Pressure (Kg/Cmsq)

Time (minutes)

RNG
CIIG 0.1C 16HRS
DISCHG 0.5C

November 1-3, 1988
(AFTER 1000 CYCLES)

RH6
CHG 0.1C 16HRS
DISCH 0.5C
MAIN ISSUES IN Ni-H₂ CELL ELECTROCHEMICAL DESIGN

* To minimize pressure increase and residual hydrogen pressure
* To minimize Ni electrode expansion during LEO cycling
* To minimize capacity dependence on charge rate
* Eliminate hot spots resulting from rapid oxygen recombination
*
Last year, we presented the halfway status of Ni-H2 cell development in Japan, and mainly showed the results of R&D focused on each component such as electrodes, pressure vessel and terminal. The mechanical features of Ni-H2 cell had been specified, and now we are validating the fabrication process of mechanical components and cell. On the other hand, cell system studies focused on the electrical performance had been initiated at the beginning of this year, succeeding R&D of electrochemical components. I'm going to present some results of the cycle tests that we are conducting now to specify the electrochemical features of Ni-H2 cell stack.

Fig. 1

Here are requirements of Ni-H2 cell and cell configuration. The requirements explicitly provide only for GEO mission because cell development involved Ni-H2 battery space experiment on GEO. However, life of 30,000 cycles at 40% DOD is also expected for LEO applications in the development. Maximum operating pressure of 70 kg/sq.cm is specified for vessel design. The cell stack consists of 34 pairs of electrodes with a back-to-back configuration. To examine the several different kinds of electrodes and separator advanced in preceding R&D, and the effect of some additives, we are evaluating the cells whose electrochemical features are summarized in next figure.

Fig. 2

On the positive electrode, substrate is made of dry sintered nickel porous plaque on nickel screen mesh. Nickel hydroxide is impregnated on substrate by electrochemical method. N-STD is a electrode with cobalt hydroxide as a additive. N-CD3 is a electrode containing cadmium hydroxide as well as cobalt additive.
On the negative electrode, catalyst layer of H-STD is made from mixture with Pt black catalyst and PTFE binder, and is thermally treated after pressed over nickel mesh grid.

H-DP is a electrode containing two different sized pores, large pores of which are formed through thermal decomposition of some agent added to the catalyst layer.

This electrode H-DP showed lower polarization than H-STD as presented later, and become a promising electrode at present.

On the separator, S-ZAI is a paper made of Buthyl latex binder and fiber mixture which consists of zirconium-oxide and asbestos. S-ZA2 is a modified paper with dual layer structure. S-TF uses PTFE instead of Buthyl latex.

The stack of BP1, BP2, RM1 and so on are put into boiler-plate case, which has the same inner diameter as the cell pressure vessel.

PV1, PV2 and PV3 are flight type cells, using developed pressure vessels.

On the other hand, the stack of RM1 and so on consist of 12 pairs of electrode, so approximately one third scale model for those of BP1 and BP2. Additionally, the potassium hydroxide electrolyte of RM5 and RM6 contains lithium hydroxide as a additive.

Another design parameters such as preload on the stack and hydrogen pre-pressure were set up at the same level in cell assembly process.

Fig. 3

This table briefly summarizes design features of each electrodes and separator.
On the cell evaluations, we are conducting two kinds of cycle test. One means severe cycle regimes, accelerating the conditions of LEO applications. The other simulates the cycle regimes of GEO applications.

Fig. 4

Here are cycle regimes, and we simply call them as LEO and GEO simulation test.

Fig. 5
Concerning temperature control, heat from boiler-plate cells is rejected by circulating coolant around the case wall.

Fig. 6
Flight type cells are put into the test box in which coolant is circulating around the cells. Pressure is measured by transducer connecting fill tube.

Now, I'm going to present some results of cycle tests, especially of LEO cycle. Up to now, GEO cycle tests did not show any distinct results from LEO. This may be due to lower stress for the cell stacks.

Fig. 7

This is a comparison of the initial charge and discharge characteristics of BPI and PV1, which have the same stack with put into different case. The difference in voltage is mainly due to Ohmic resistances of terminal and so on.

Fig. 8

This is data of BPI and PV1 at 500 cycles. The pressure increase during the cycle test is about 2 kg/sq.cm on PV1 and about 6 kg/sq.cm on BPI. We consider it is very important issue to limit the pressure increase in Ni-H2 cell.

Fig. 9

This is data of RM2 and RM4 at 2nd cycle. RM4 used H-DP as negative electrodes, and shows better voltage characteristics than RM2 using H-STD. So, we consider H-DP with two different sized pores is a promising negative electrode.
This is data of RM4, RM6 and RM12 at 1200 cycles. RM6 contains lithium hydroxide in electrolyte. RM12 uses N-CD3 positive electrode containing cadmium hydroxide besides cobalt hydroxide. We are concerned about Cd migration to negative electrodes in RM12, but there are not any signs of Cd migration from an electrical view point. The voltage rise of RM6 at the latter part of charge is very clear, and will be convenient to charge control systems.

Fig. 11

This shows charge characteristics of RM6 in initial capacity measurement.

Fig. 12
This is similar data of RM6 after 1000 cycles. The voltage rise at the latter part of charge occurs about 60 minutes earlier. And, there is EOC pressure increase of about 1 kg/sq.cm from initial measurement.

Fig. 13
This shows discharge characteristics of RM6 in initial capacity measurement.

Fig. 14
This is similar data of RM6 after 1000 cycles. Discharge time until cell voltage reached 1.0 volt is about 10 minutes shorter, but there are not found any degradations in voltage.

Now we are fabricating the 16 flight type cells for EM space experiment battery. These cells have the same electrochemical features as RM6, which has indicated good performance up to now. However, we have about one year until specifying the design features of a space experiment cell. So, we will continue system studies including DPA of cells now under testing and the cell evaluations with newly advanced features, in order to improve the Ni-H2 cell performance.

Fig. 15
At the end, this summarizes main issues we have to take measures with the cell evaluations.
THE EVALUATION OF NEW NICKEL-HYDROGEN BATTERY SEPARATORS IN BOILERPLATE CELLS

BY
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1988 NASA/GSFC BATTERY WORKSHOP
NOVEMBER 1-3, 1988
BACKGROUND

- REPLACEMENT SEPARATOR FOR ASBESTOS IS DESIRABLE
- HIGH BUBBLE PRESSURE, LOW RESISTIVITY, GOOD ELECTROLYTE RETENTION REQUIRED
- POTASSIUM TITANATE-POLYETHYLENE BLEND DEVELOPED
- RADIATION-GRAFTED POLYETHYLENE FILM AVAILABLE
- SCREENING TESTS VERIFIED NECESSARY CHARACTERISTICS
- BOILERPLATE CELLS ASSEMBLED AND TESTED IN-HOUSE
OBJECTIVES

- COMPARE PERFORMANCES OF CELLS BUILT WITH BLENDED POTASSIUM TITANATE-POLYETHYLENE SEPARATORS AND WITH ZIRCAR CLOTH/RADIATION-GRAFTED POLYETHYLENE FILM SEPARATORS TO CELLS BUILT WITH ASBESTOS SEPARATORS.

- EVALUATE SEPARATOR INTEGRITY FOLLOWING CYCLING.
APPROACH

- BUILD THREE, THREE AMPERE HOUR CELLS FROM EACH OF THE THREE SEPARATOR MATERIALS
- CHARACTERIZATION CYCLE UP TO THE 2 C RATE
- LEO CYCLE FOR 2,000 CYCLES
- DISASSEMBLE CELLS AND EVALUATE THE SEPARATORS AND OTHER COMPONENTS
POWER TECHNOLOGY DIVISION

NICKEL-HYDROGEN BOILERPLATE CELL STUDIES

HARDWARE

PURPOSE
DESIGN VERIFICATION
COMPONENT EVALUATION
SIMULATE CYCLING MODES

FEATURES
IN-HOUSE CAPABILITY
EASE OF ASSEMBLY
REUSABLE HARDWARE
COST EFFECTIVE
# MID-DISCHARGE VOLTAGES AFTER 2000 LEO CYCLES

80% DOD, C/D = 1.10, 1.37 C DISCHARGE

<table>
<thead>
<tr>
<th>CELL</th>
<th>SEPARATOR</th>
<th>VOLTAGE, VOLTS</th>
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<tr>
<td>1</td>
<td>ASBESTOS</td>
<td>1.193</td>
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<tr>
<td>2</td>
<td>&quot;</td>
<td>1.229</td>
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<td>3</td>
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<td>1.229</td>
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<td>4</td>
<td>POTASSIUM TITANATE-POLYETHYLENE</td>
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<td>7</td>
<td>ZIRCAR CLOTH AND POLYETHYLENE FILM</td>
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<td>1.225</td>
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# POSTTEST CELL OBSERVATIONS

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<tr>
<th>CELL</th>
<th>SEPARATOR TYPE</th>
<th>SEPARATOR APPEARANCE</th>
<th>CELL CORE</th>
<th>H₂ ELECTRODE</th>
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<td>ASBESTOS</td>
<td>NORMAL</td>
<td>LOOSE</td>
<td>GOOD CONDITION</td>
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<tr>
<td>2</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>INTACT, BUT NOT TIGHT</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>PKT-PE</td>
<td>INTACT, SOME ADHESION TO H₂ AND Ni ELECTRODES</td>
<td>LOOSE FINE WHITE RESIDUE</td>
<td>SOME FLOODING APPARENT</td>
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<tr>
<td>5</td>
<td></td>
<td></td>
<td>INTACT, BUT NOT TIGHT FINE WHITE RESIDUE</td>
<td>BURNED AREAS ON TWO ELECTRODES</td>
</tr>
<tr>
<td>6</td>
<td></td>
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<td>LOOSE, FINE WHITE RESIDUE</td>
<td>BURNED AREAS ON ONE ELECTRODE</td>
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<tr>
<td>7</td>
<td>ZIRCAR/PE</td>
<td>ZIRCAR - VERY MOIST PE - UNCHANGED</td>
<td>INTACT, BUT NOT TIGHT</td>
<td>GOOD CONDITION</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td>LOOSE Ni RESIDUE</td>
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</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td>LOOSE Ni RESIDUE</td>
<td></td>
</tr>
</tbody>
</table>
POSTTEST SEPARATOR WEIGHT ANALYSIS
ELECTROLYTE RETENTION AFTER 2000 CYCLES

ELECTROLYTE, % OF DRY WEIGHT

ASBESTOS

PKT-PE

ZIRCAR/PE

CELL NUMBER

1  2  3  4  5  6  7  8  9
SUMMARY AND CONCLUSIONS

- TWO NEW SEPARATOR CONCEPTS WERE TESTED IN BOILERPLATE CELLS BY CHARACTERIZATION CYCLING TO 2 C AND LEO CYCLING FOR 2000 CYCLES

- PERFORMANCES OF POTASSIUM TITANATE-POLYETHYLENE CELLS AND ZIRCAR/POLYETHYLENE FILM CELLS WERE COMPARABLE TO ASBESTOS CELLS

- SEVERAL POTASSIUM TITANATE-POLYETHYLENE SEPARATORS APPEARED TO ALLOW OXYGEN PASSAGE

- ZIRCAR CLOTH/POLYETHYLENE FILM SEPARATOR WARRANTS FURTHER EVALUATION IN FLIGHT WEIGHT CELLS
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