NASA Conference Publication 3192

The 1992 NASA Aerospace Battery Workshop

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The 1992 NASA Aerospace Battery Workshop

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

Proceedings of a workshop sponsored by
the NASA Aerospace Flight Battery Systems
Program, hosted by the George C. Marshall
Space Flight Center, and held at the
U.S. Space and Rocket Center
Huntsville, Alabama
November 15–19, 1992

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Preface

This document contains the proceedings of the 23rd annual NASA Aerospace Battery Workshop, hosted by the Marshall Space Flight Center on November 17-19, 1992. The workshop was attended by scientists and engineers from various agencies of the U.S. Government, aerospace contractors, and battery manufacturers, as well as international participation in like kind from a number of countries around the world.

The subjects covered included nickel-cadmium, nickel-hydrogen, nickel-metal hydride, and lithium based technologies, as well as advanced technologies including sodium-sulfur and various bipolar designs.

Introduction

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

The 1992 Workshop was held on three consecutive days and was divided into five sessions. The first day consisted of a General Topic Session and a Special Topic (nickel-hydrogen storage and capacity fade issues) Session. The second day began with the Nickel-Cadmium Technologies Session and concluded with the Nickel-Hydrogen Technologies Session. The third and final day was devoted to the Advanced Technologies Session.

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

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

Sal Di Stefano, Jet Propulsion Laboratory; **Joe Stockel**, Office of Research & Development; and **Michelle Manzo**, NASA Lewis Research Center, for serving as Session Organizers, which involved soliciting presentations, organizing the session agenda, and orchestrating the session during the workshop;

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

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

Marshall Space Flight Center employees, for their help in stuffing envelopes, registering attendees, handling the audience microphones, and flipping transparancies during the workshop.

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

Jeff Brewer
NASA Marshall Space Flight Center

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General Topic Session

NASA CENTER UPDATE
GODDARD SPACE FLIGHT CENTER

Presented to
1992 NASA AEROSPACE BATTERY WORKSHOP

Presented By
Gopalakrishna M. Rao
Space Power Applications Branch
Electrical Engineering Division
Engineering Directorate
NASA Goddard Space Flight Center

November 17, 1992

NASA GODDARD SPACE FLIGHT CENTER UPDATE

- SPACECRAFT OPERATIONS
- LIFE CYCLE TESTING AT NAVAL SURFACE WARFARE CENTER (NSWC), CRANE, INDIANA
- DESTRUCTIVE PHYSICAL ANALYSIS (DPA) AT COMSAT LABORATORIES, CLARKSBURG, MARYLAND
  - Ms. Kathleen Robbins from COMSAT is presenting the DPA data later in the morning at this Workshop

SPACECRAFT OPERATIONS

- Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX)
- Extreme Ultraviolet Explorer (EUVE)
- Upper Atmosphere Research Satellite (UARS)
- Compton Gamma Ray Observatory (GRO)
- Earth Radiation Budget Satellite (ERBS)
- Hubble Space Telescope (HST)

SAMPEX

- Single 9 Ah Super NiCd battery
- 22 series cells per battery
- Plate fabrication in 10/90
- Cell activation in 5/91
- Launched on 7/3/92
- Completed 1545 eclipse orbits and 525 full sun orbits
- Nominal performance
  - VT 5, recharge ratio 1.04, temperature 2 - 11 °C, and average DoD 12% (maximum 17.2%)

EUVE

- Three 50 Ah conventional NiCd batteries in parallel configuration (Modular Power Subsystem (MPS))
- 22 series cells per battery
- Plate fabrication
  - positive in 5/85
  - negative in 1 - 2/85
- Cell activation in 3/88
- Launched on 6/7/92
- Completed 2470 eclipse orbits
- Nominal performance
  - VT 4; recharge ratio 1.07 - 1.08; temperature : changed from -1°C to 2°C on 9/8/92, to 4.5°C on 9/15/92, and to 7.5°C on 10/23/92 ; and average DoD 9% (maximum 10%)

UARS

- Three 50 Ah conventional NiCd batteries in parallel configuration (MPS)
- 22 series cells per battery
- Plate fabrication
  - positive in 8 - 11/88
  - negative in 11/88 - 1/89
- Cell activation in 10/30/89
- Launched on 9/12/91
- Completed 1730 eclipse orbits and 139 full sun orbits during the first four months with nominal performance
  - VT 6/5, recharge ratio 1.09 - 1.15, temperature 2 - 4°C and average DoD 6 - 18% (maximum 20%)
- After high beta angle, about 40 mV half-battery differential voltage on 1/92

UARS - continued

- VT levels 5 and 6, and successive high beta angle increased the half-battery differential voltage up to 500 mV
- Monitored and managed battery performance since 5/92 by adjusting solar ray offset or power demand control battery charge/discharge ratio or disable/enable VT control
  - completed 6219 eclipse orbits and 139 full sun orbits
    - VT 4, recharge ratio 1.02 - 1.07, temperature 3 - 9^{0}C and average DoD 6-18 % (maximum 22%)

GRO

- Two sets of three 50 Ah conventional NiCd batteries in parallel configuration
  - MPS 1
  - MPS 2
- 22 series cells per battery
- Launched on 4/5/91

GRO MPS 1

- Plate fabrication
  - positive in 9 - 10/88
  - negative in 6 - 11/88
- Cell activation in 7/89
- Nominal performance up to 3174 eclipse orbits
  - VT 5, recharge ratio 1.1 (uncorrected), temperature 1°C, and average DoD 10% (maximum 12%)
- About 80 mV half-battery differential voltage on 12/91
- Lowered VT level to 4 on 2/92
  - half-battery differential voltage increased to 450 mV in the next 4 months

GRO MPS 1 - continued

- Lowered VT level to 3 on 5/92
  - battery #2 half-battery differential voltage reached 699 mV and half-battery differential voltage reached 200 - 400 mV for Batteries #1 and #3 on 7/2/92
- Performance of battery#2 degraded even after load shedding, and VT switching or VT control inhibition
  - half-battery differential voltage reached again 699 mV and temperature reached greater than 28°C on 7/16/92
  - cell short, battery #2 disabled
- Monitored and managed battery performance since 9/15/92 by charging at 0.8 A constant current for the first 15 minutes of the day, and then usual VT control at level 3 with taper
  - completed 9150 eclipse orbits
    - VT 3, recharge ratio 1.2 - 1.3 (uncorrected), temperature 1°C, average DoD 4% (maximum 6%) and half-battery differential voltage up to 200 mV

GRO MPS 2

- Plate fabrication
  - positive in 7/85
  - negative in 1 - 3/85
- Cell activation in 11/88
- Completed 9166 eclipse orbits
- Nominal performance
  - VT 6, recharge ratio 1.1 (uncorrected), temperature 2 - 4^{0}C, and average DoD 14% (maximum 16%)

ERBS

- Two 50 Ah conventional NiCd batteries in parallel configuration (MPS)
- 22 series cells per battery
- Plate fabrication
  - positive in 6 - 9/83
  - negative in 6 - 9/83
- Cell activation in 11/83
- Launched on 10/4/84
- Completed 19500 eclipse orbits and 2500 full sun orbits during the first four years with nominal performance
  - VT 6, recharge ratio 1.08, temperature 10°C and average DoD 9% (maximum 50%)

ERBS - continued

- Half-battery differential voltage up to 200 mV for battery #1 and up to 1 V for battery #2 during the last three quarters of 90, 91, and the first six months of 92
- Cell short in battery #1 on 8/7/92
  - lowered VT level from 4 to 3
- Second cell short in battery #1 on 9/4/92
  - battery #1 disabled
  - raised VT level first to 4 and then to 5
- Completed 39200 eclipse orbits and 5000 full sun orbits with nominal performance
  - VT 5, recharge ratio 1.08, temperature 7°C and average DoD 12% (maximum 18%)

HST

- Six 88 Ah Ni-H2 batteries in two three-battery modules (Flight Spare Module(FSM) and Flight Module 1(FM2))
- Common bus for all batteries to operate at a common voltage
- 22 series cells per battery
- Positive plate fabrication
  - FSM in 2 - 6/88
  - FM2 in 6 - 11/88
- Cell activation
  - FSM in 1/89
  - FM2 in 3/89
- Launched on 4/24/90

HST - continued

- Reconditioned batteries #1 and #4 through 5.1 ohm load to about 19 V on 12/90
  - capacity dropped to about 65 Ah
  - capacity recovered to 75 Ah in two weeks and recovered to 89 Ah in 20 months
- Reconditioned batteries #5, #2, #6 and #3 through 5.1 ohm load to about 13 V on 8-9/92
  - capacity dropped to about 63 Ah
  - capacity recovered to about 68 Ah in two weeks
  - current system capacity recovery rate 0.4 Ah per day
- Completed 13987 eclipse orbits
- Nominal performance
  - VT levels K1L3 and K2L3, trickle charge current 12 A and period 42 minutes, recharge ratio 1.06 - 1.13 (time based), temperature -3 - 3^{0}C, average DoD 5 - 8% (maximum 8.5%), and system capacity 480 Ah

LIFE CYCLE TESTING AT NSWC, CRANE

- Advanced NiCd cells from Hughes Aircraft Company/Eagle Picher Industries, Inc., Colorado Springs
- Conventional NiCd cells from Gates Aerospace Batteries (GAB)
- Conventional NiCd cells from General Electric
- NiCd cells from SAFT
- NiH2 cells from Eagle Picher Industries, Inc., Joplin
- Data as of 10/26/92

ADVANCED NICD CELL LIFE CYCLE TEST

- Pack # 6000A - 21 Ah, Polypropylene, PBI
- Pack # 6001A - 21 Ah, Zircar/Polysulfone
- Pack # 6002A - 21 Ah, Zircar/PBI
- Pack # 6003A - 21 Ah, Zircar/Polysulfone
- Pack # 6004A - 21 Ah, Zircar/Polysulfone
- Pack # 6005A - 21 Ah, Zircar/Polysulfone
- Pack # 6006A - 21 Ah, Zircar/PBI w/ additive
- Pack # 6053A - 21 Ah, Zircar/PBI w/ additive
- Pack # 0090A - 9 Ah, Zircar/PBI w/ additive
- Pack # 0090B - 9 Ah, Zircar/PBI w/ additive

ADVANCED NICD CELL LIFE CYCLE TEST- continued

Pack #	SIZE Ah	ORBIT	DoD %	TEMP °C	C/D	VT	EOD V	CYCLE #
6000A	21	LEO	40	20	1.03	6	1.064	15278
6001A	21	LEO	40	20	1.03	6	1.026	15190
6002A	21	LEO	40	20	1.01	6	1.073	15110
6003A	21	LEO	40	20	1.04	6	1.038	13872
6004A	21	LEO	25	30	1.03	6	0.999	13819
6005A	21	LEO	40	30	1.04	7	0.972	13744
6006A	21	LEO	40	20	1.02	6.5	1.077	13212
6053A	50	LEO	40	20	1.04	6	1.095	6551
0090A	9	LEO	40	30	1.16	7	1.134	2652
0090B	9	LEO	0-18	5	1.07	4	1.235	782

GAB NICD CELL LIFE CYCLE TEST

Pack #	SIZE Ah	ORBIT	DoD %	TEMP °C	C/D	VT	EOD V	CYCLE #
6051D (EUVE)	50	LEO	40	20	1.01	7	0.975	18030
6051F	50	LEO	40	20	1.01	6	0.952	14471
6051G (GRO-MPS2)	50	LEO	40	20	1.01	6	0.974	14376
6051I (EUVE AND GRO-MPS2)	50	LEO	15	15	1.06	6	1.217	12433 (MINIMUM 24000)
6051H (GRO-MPS1)	50	LEO	40	20	1.01	6	1.101	11941
6052A (UARS)	50	LEO	18	0	1.03	4	1.218	6222
			(UP TO 5380 CYCLES: DoD - 40% AND 20°C)					
6052B (UARS)	50	LEO	18	0	1.03	2	1.115	5687
			(UP TO 4356 CYCLES: DoD - 21.5% AND 15°C)					

GAB NICD CELL LIFE CYCLE TEST - CONTINUED

Pack #6051H (GRO-MPS1)

- Started testing on 6/90 with 40% DoD at 20°C
- Cell voltage divergence first seen around 6600 cycles
- Maximum cell voltage divergence around 7500 cycles
  - EOC about 36 mV
  - EOD about 123 mV
- Gradual recovery with cycling
  - Cell voltage divergence around 9200 cycles
    - EOC about 12 mV
    - EOD about 10 mV
- Stopped testing after 11941 cycles
- No second voltage plateau during the capacity check

GAB NICD CELL LIFE CYCLE TEST - CONTINUED

Pack #6052A (UARS)

- **Started testing on 5/91 with 40% DoD at 20°C and VT6**
  - **Cell voltage divergence first seen around 1500 cycles and increased with cycling**
  - **Cell voltage divergence around 5300 cycle**
    - EOC about 31 mV
    - EOD about 52 mV
- **Moved to 0°C at 5380th cycle**
  - **Cell voltage divergence around 5477 cycle**
    - EOC about 40 mV
    - EOD about 60 mV
- **One cell (S/N2-7) removed for DPA at 5508th cycle**
- **Continued testing with 4 cells under UARS profile at 5510th cycle**
  - **34.5 A charge current followed by a linear decrease in current for the first 16.5 minutes and then at 18.3 A constant current with VT taper**
  - **18% DoD**

GAB NICD CELL LIFE CYCLE TEST - CONTINUED

Pack #6052A (UARS) - continued

- Cell voltage divergence around 5585 cycle
  - EOC about 10 mV
  - EOD about 10 mV
- Changed VT level to 4 at 5591th cycle
  - Cell voltage divergence around 5844 cycle
    - EOC about 53 mV
    - EOD about 26 mV
- Another cell (S/N2-21) removed for DPA at 5846th cycle
- Stopped testing after 6222 cycles
  - Cell voltage divergence
    - EOC about 34 mV
    - EOD about 0 mV
- Second voltage plateau around 1 V during the capacity check

GAB NICD CELL LIFE CYCLE TEST - CONTINUED

Pack #6052B (UARS)

- **Started testing on 5/91 with 21.5% DoD at 15°C, 18.3 A constant current charge rate, and VT6**
  - **Cell voltage divergence first seen around 2000 cycles and increased with cycling**
  - **EOD voltage decline began around 2000 cycles and continued with cycling**
  - **Cell voltage divergence around 2530 cycle**
    - EOC about 40 mV
    - EOD about 30 mV
- **Moved to 0°C at 5380th cycle**
  - **Cell voltage divergence around 5477 cycle**
    - EOC about 40 mV
    - EOD about 60 mV
- **Started testing under UARS profile at 4357th cycle**
  - **34.5 A charge current followed by a linear decrease in current for the first 16.5 minutes and then at 18.3 A constant current with VT taper**
  - **18% DoD and 0°C**

GAB NICD CELL LIFE CYCLE TEST - CONTINUED

Pack #6052B (UARS) - continued

- Rapid increase in cell voltage divergence during the 4393th charge cycle and the high values during the subsequent charge/discharge cycles
  - EOC about 105 mV
  - EOD about 142 mV
- No improvement after trickle charging at 0°C and 20°C
- Continued cycling at 20°C
  - Cell voltage divergence around 4946 cycle
    - EOC about 55 mV
    - EOD about 120 mV
- One cell (S/N2-73) removed for DPA at 4947th cycle

GAB NICD CELL LIFE CYCLE TEST - CONTINUED

Pack #6052B (UARS) - continued

- Moved to 0°C at 5101th cycle
  - Cell voltage divergence around 5132 cycle
    - EOC about 187 mV
    - EOD about 39 mV
- Changed charge rate to 25 A constant current with VT 2 taper at 5298th cycle
  - Cell voltage divergence around 5370 cycle
    - EOC about 100 mV
    - EOD about 70 mV
- Stopped testing after 5687 cycles
  - Cell voltage divergence
    - EOC about 23 mV
    - EOD about 113 mV
- Second voltage plateau around 1 V during the capacity check

GAB NICD CELL LIFE CYCLE TEST - CONTINUED

Pack # #	SIZE	ORBIT Ah	DoD	TEMP %	C/D °C	VT	EOD	CYCLE V
6051C	50	LEO	40	20	1.01	6	0.937	17169
6051E	50	LEO	40	20	1.01	6	0.958	15505
6053B	50	LEO	40	20	1.04	6	1.032	6455
6085A	20	LEO	20	15	1.06	6	1.221	11945
6085B	20	LEO	28	15	1.08	6	1.067	10420
6085C	20	LEO	40	20	1.01	6	1.075	14699

GAB NICD CELL LIFE CYCLE TEST - CONTINUED

Pack #	SIZE Ah	ORBIT	DoD %	TEMP °C	EOD V	SHADOW#
0231A	6	GEO(IUE)	80	10	1.157	30
0232A	40	GE0(TDRSS)	50	0	1.187	27
0232B	40	GE0(TDRSS)	50	15	1.188	24
0232C	40	GE0(TDRSS)	75	0	1.162	21
0232D	40	GE0(TDRSS)	75	0	1.183	1
6232A	40	GE0(TDRSS)	50	0	1.190	21
6232B	40	GE0(TDRSS)	50	0	1.200	1
6232C	40	GE0(TDRSS)	50	10	1.185	45
6232D	40	GE0(TDRSS)	50	15	1.196	40
6227B	12	GE0(GOES)	60	10	1.173	7
6227C	12	GE0(GOES)	60	10	1.138	7

GENERAL ELECTRIC NICD CELL LIFE CYCLE TEST

Pack #	SIZE Ah	ORBIT	DoD %	TEMP °C	C/D	VT	EOD V	CYCLE #
0004H	4	HEO?	40	15	3.54	6	1.184	4136
0026G	26.5	LEO	20	10	1.01	3.5	1.063	68480
0028I	26.5	LEO	18.5	10	1.02	4	1.231	43000
0026J	26.5	LEO	25	10	1.04	4	1.121	29328

SAFT NICD CELL LIFE CYCLE TEST

Pack #	SIZE Ah	ORBIT	DoD %	TEMP °C	C/D	VT	EOD V	CYCLE #
6024S	24	LEO	40	0	1.03	6.5	1.115	19761
6124S	24	LEO	40	20	1.02	7	0.972	19501
6120S	20	LEO	40	20	1.05	7	1.024	19359

NiH2 CELL LIFE CYCLE TEST

Pack #	SIZE Ah	ORBIT	DoD %	TEMP °C	C/D	VT V	EOD	CYCLE #
3600H FM1	93	LEO	9	-3.5	1.02	1.52	1.311	2149
3600H FM2	93	LEO	9	-3.5	1.02	1.52	1.312	2160

NASA CENTER UPDATE
JET PROPULSION LABORATORY

PRESENTED BY
Sal Di Stefano

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1992 NASA AEROSPACE BATTERY WORKSHOP
November 17-19, 1992
U. S. Space and Rocket Center
Huntsville, Al

AGENDA

- FLIGHT PROJECT SUPPORT ACTIVITIES
  - TOPEX
  - MARS OBSERVER
- RESEARCH / DEVELOPMENT AND ENGINEERING ACTIVITIES
  - NiCd MODEL DEVELOPMENT
  - SECONDARY LITHIUM BATTERY DEVELOPMENT
  - SODIUM - $NiCl_2$ MODERATE TEMPERATURE BATTERY
  - Li-$SOCl_2$ BATTERIES FOR CENTAUR LAUNCH VEHICLE
  - DIRECT HYDROCARBON / METHANOL FUEL CELLS

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TOPEX MISSION / BATTERY DEFINITION

- PRIME CONTRACTOR - FAIRCHILD / McDONNELL DOUGLAS MPS (BATT)

- BATTERY DESIGN
  - MODULAR POWER SUBSYSTEM (3 x 22 CELL 50 Amp-Hr BATT)
  - CELL DESIGN
    - GATES AEROSPACE - NASA STANDARD
    - 16 POS / 17 NEG
    - PELLON 2505 SEPARATOR
    - NONPASSIVATED POS / TEFLONATED NEG

- BATTERY CYCLE REGIME
  - MEDIUM ALTITUDE ORBIT - VARIABLE OCCULTATIONS AND SOME ÍFULL SUN PERIODS

BATTERY SYSTEMS GROUP

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TOPEX STATUS

- LAUNCH AUGUST 10, 1992
- BATTERY OPERATIONAL STRATEGY
  - LIMIT PEAK CHARGE CURRENTS TO 20 AMPS (OFFSET ARRAY)
  - LIMIT OVERCHARGE BY MAINTAINING RECHARGE RATIO (C/D) TO 103% @ 0°C (OPERATE AT LOWER V/T LEVELS)
  - AVOID HIGH CHARGE CURRENTS DURING FULL SUN PERIODS (OPERATE AT LOWER V/T LEVELS)
- CURRENT STATUS - NOMINAL OPERATION

BATTERY SYSTEMS GROUP

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MARS OBSERVER MISSION / BATTERY DEFINITION

- PRIME CONTRACTOR - GE ASTROSPACE

- BATTERY DESIGN
  - TWO 17 CELL / 42 Amp-Hr BATTERIES
  - CELL DESIGN
    - GATES AEROSPACE
    - 13 POS / 14 NEG
    - PELLON 2505 ML
    - NONPASSIVATED POS / TEFLONATED NEG
- BATTERY CYCLE REGIME
  - 11 MONTH CRUISE
  - ~ 120 Min ORBIT 41 Min ECLIPSE (max)
  - REQUIRE 9000 CYCLES

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MARS OBSERVER STATUS

- LAUNCH - SEPTEMBER 25, 1992
- BATTERY OPERATIONAL STRATEGY
  - DEVELOP METHOD FOR MINIMIZING EFFECT OF 850 mA TRICKLE CHARGE DURING CRUISE
  - MINIMIZE TRICKLE CHARGE BY BATTERY SWITCHING - SWITCH ONE BATTERY OFF LIE FOR 12 HOURS AND THEN REVERSE
- CURRENT STATUS - NOMINAL PERFORMANCE

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NiCd MODEL DEVELOPMENT

OBJECTIVE: TO DEVELOP A NiCd BATTERY PERFORMANCE MODEL BASED ON FUNDAMENTAL ELECTROCHEMICAL PRINCIPLES AND CAPABLE OF PREDICTING BATTERY VOLTAGE UNDER SPACECRAFT OPERATING CONDITIONS OVER MISSION LIFE

STATUS: BEGINNING OF LIFE BATTERY LEVEL PREDICTION MODEL IS OPERATIONAL - CELL DESIGN ENGINEERING DATABASE DEVELOPED ALLOWING FOR COMPREHENSIVE CELL SPECIFICATION

PLANS: INCORPORATION AND VERIFICATION OF DEGRADATION FEATURES - FINALIZE DOCUMENTATION - SUBMIT FOR FIELD EVALUATION

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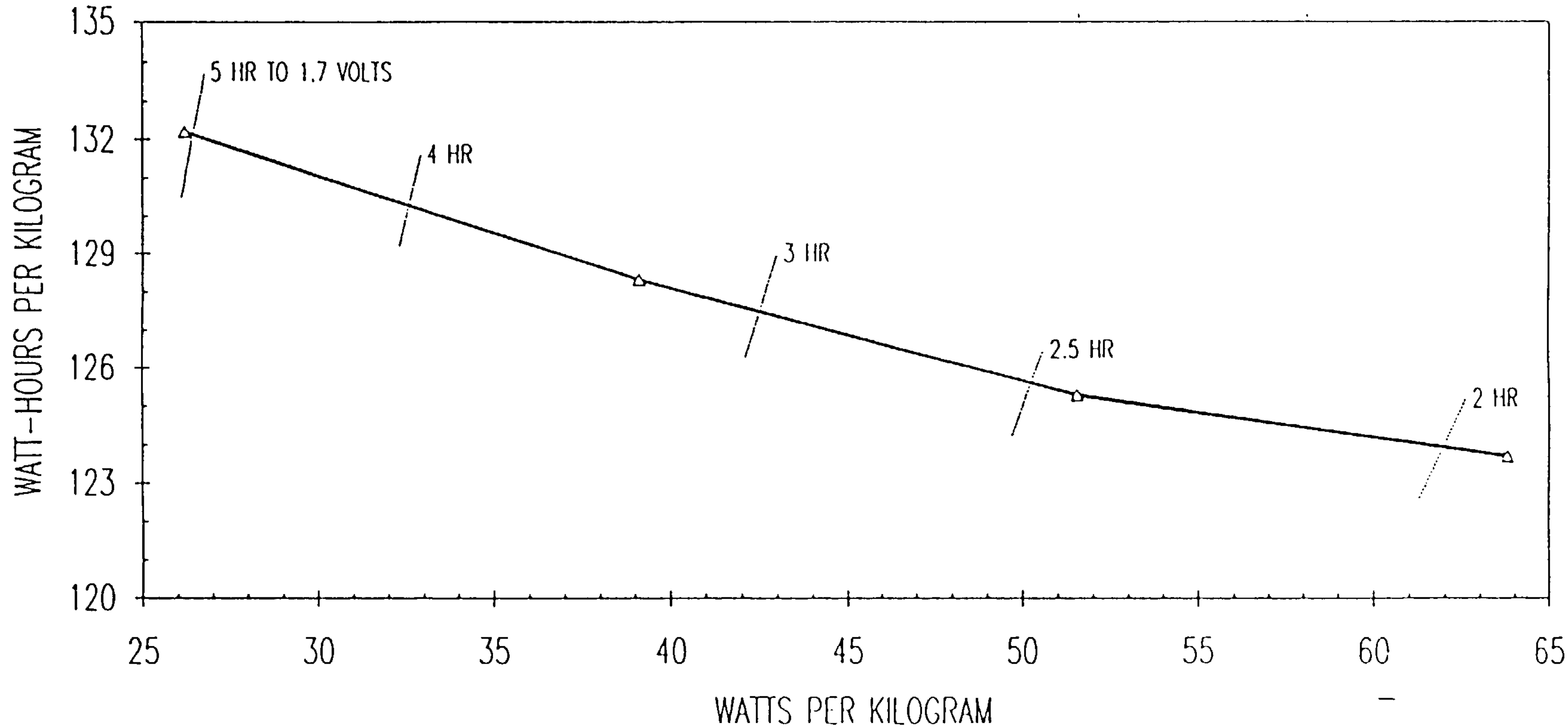
SECONDARY LITHIUM CELLS

OBJECTIVE: TO DEVELOP AND DEMONSTRATE A 100 WH/Kg $LiTiS_2$ RECHARGEABLE CELL CAPABLE OF 1000 CYCLES AT 50 % DEPTH OF DISCHARGE AND A 5 YEAR STORAGE LIFE

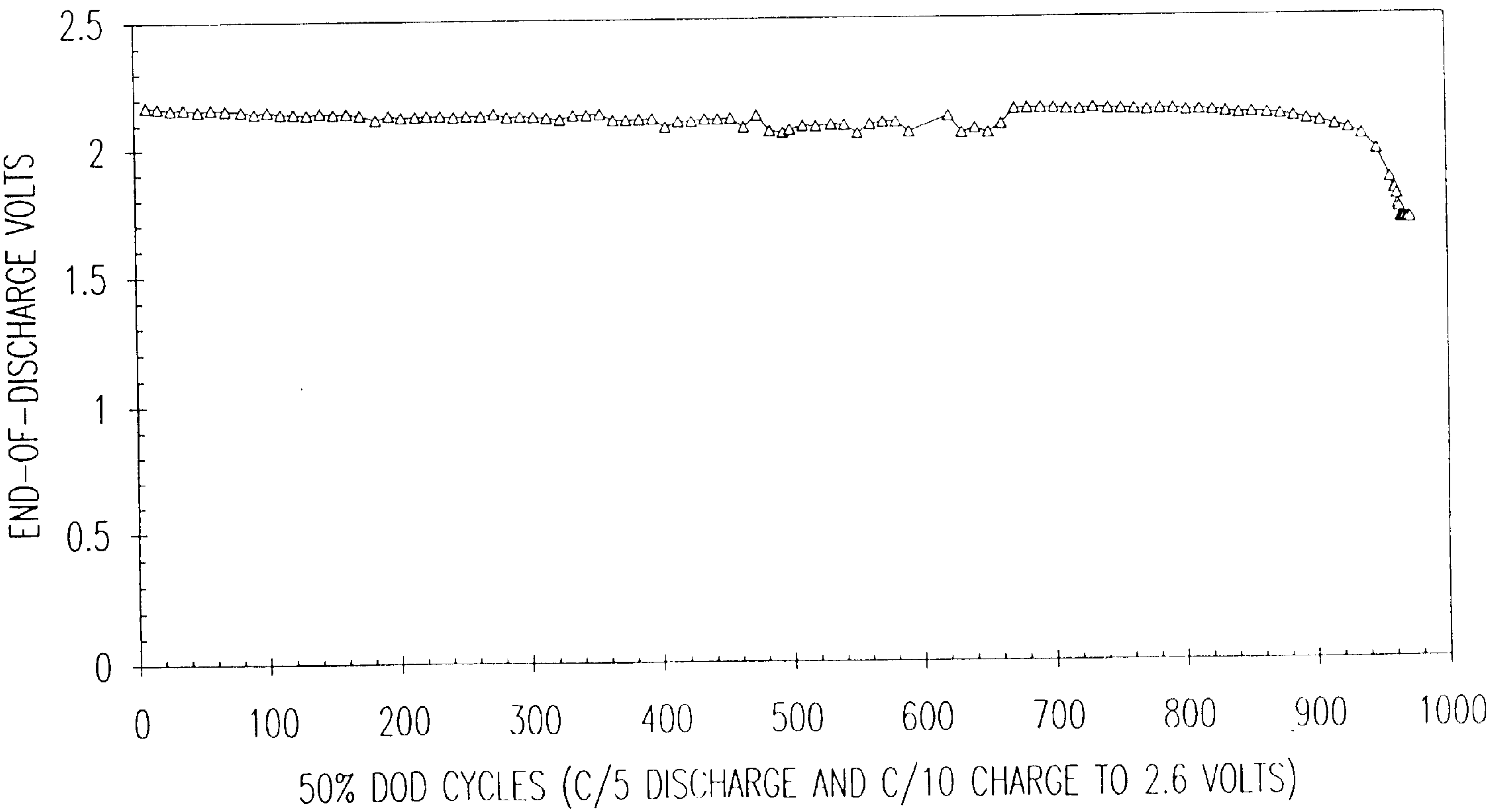
STATUS: 965 CYCLES AT 50 % DEPTH OF DISCHARGE IN 1 AH 'AA' SIZE $LiTiS_2$ CELLS AT 50% DOD - DEMONSTRATED 125 WH/Kg

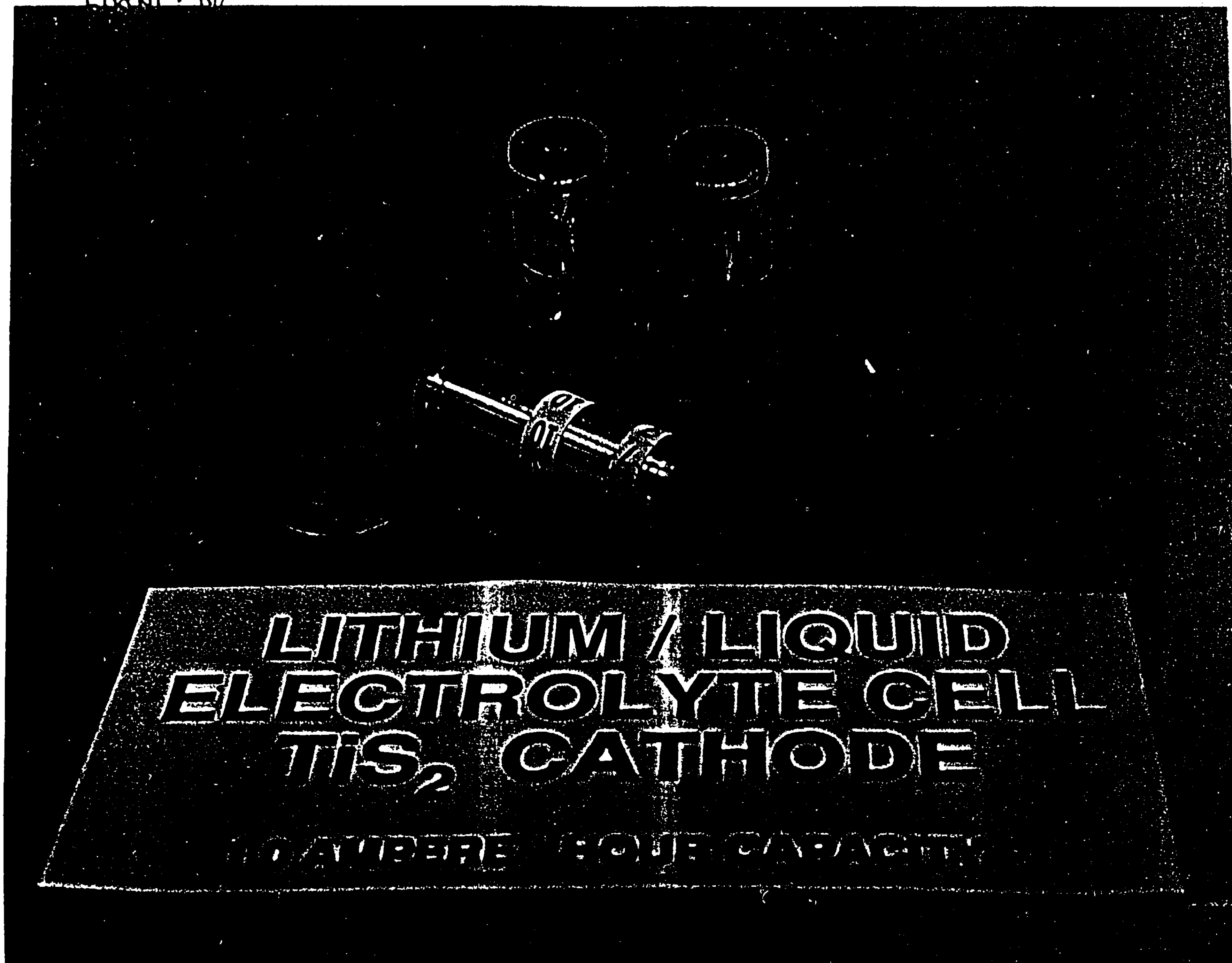
PLAN: DEMONSTRATE 1000 CYCLES IN 5 AH PRISMATIC CELLS - VERIFY OVERCHARGE MECHANISM - COMPLETE SAFETY TESTING - DETERMINE OPERATING LIMITS

PERFORMANCE OF A TYPICAL 1 AHR (AA) LITHIUM TITANIUM DISULFIDE CELL



CYCLE LIFE PERFORMANCE OF A 1 AMPERE-HOUR AA LITHIUM-TITANIUM DISULFIDE CELL




LITHIUM / LIQUID
ELECTROLYTE CELL
TiS_2 CATHODE

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SODIUM METAL HALIDE CELLS

OBJECTIVE: TO DEVELOP A HIGH SPECIFIC ENERGY (>150 WH/Kg) BATTERY FOR FUTURE NASA SPACE MISSIONS

STATUS: $NiCl_2$ SELECTED FROM SEVERAL METAL CHLORIDES - EXPERIMENTAL CELL TESTS REVEAL OPTIMAL OPERATION AT 275°C - LONG CYCLE LIFE IN LEO CYCLING INDEPENDENTLY VERIFIED AT IN ESA SPONSORED TESTS

PLANS: FABRICATE LABORATORY CELLS AND INVESTIGATE LIFE LIMITING MODES

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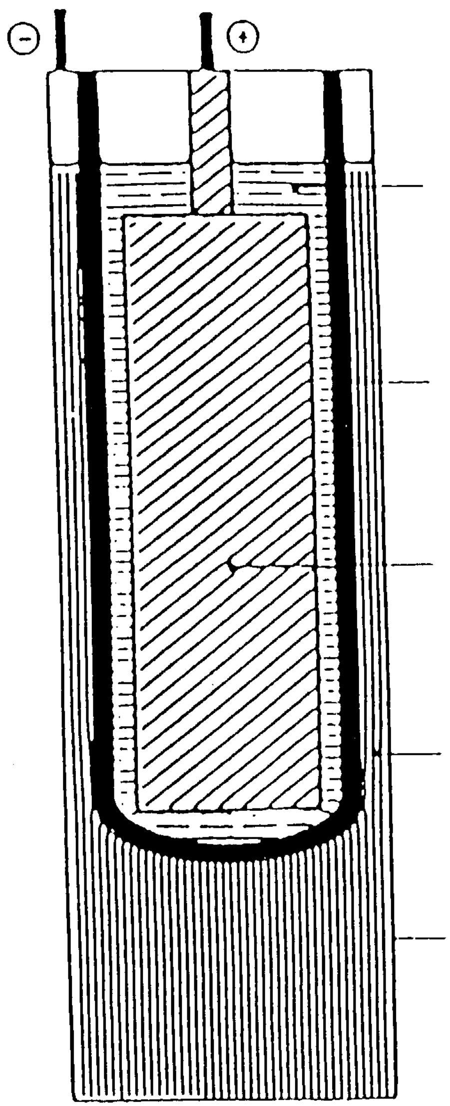
ADVANCED BATTERY CONCEPTS
SODIUM-METAL HALIDE CELLS



CONFIGURATION

Na (l) / BETA ALUMINA (s) / $NaAlCl_4$ (l) / MCl_2 (s)

CELL REACTION

$Na = Na^+ + e^-$ (ANODE)

$MCl_n + n\,e^- = M + n\,Cl^-$ (CATHODE)

$MCl_n + n\,Na = M + n\,NaCl$ (OVERALL)

WHY Na-MCl_2 BATTERIES?

- HIGH ENERGY AND POWER DENSITIES COMPARABLE TO Na - S BATTERIES
- SEVERAL POTENTIAL ADVANTAGES OVER Na-S
- LONG CYCLE AND ACTIVE LIFE
- SEVERAL IMPROVED CATHODE MATERIALS POSSIBLE

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SODIUM- METAL HALIDE CELL PROGRAM

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

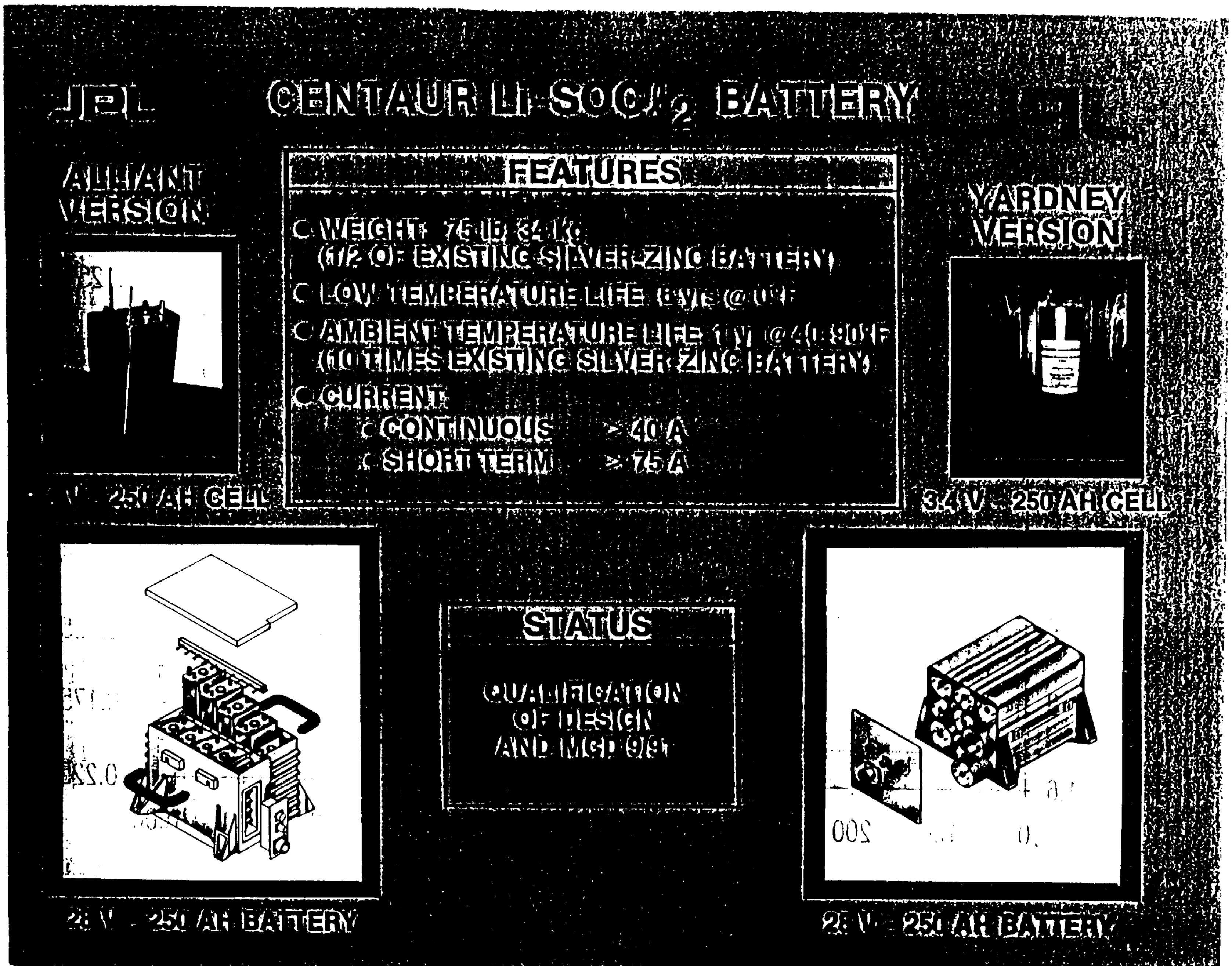
JPL

250 AH Li - $SOCl_2$ BATTERY FOR THE CENTAUR LAUNCH VEHICLE

OBJECTIVE: TRANSFER JPL DEVELOPED Li-$SOCl_2$ BATTERY TECHNOLOGY TO 2 CONTRACTORS, FABRICATE CELLS AND BATTERIES AND DEMONSTRATE CAPABILITY FOR MEETING CENTAUR QUALIFICATION REQUIREMENTS

STATUS: DOWN SELECTED TO YARDNEY TECHNICAL PRODUCTS - 5 BATTERIES READY FOR QUALIFICATION - 48 CELLS SUBJECTED TO CHARACTERIZATION TESTS (TEMP, RATE) AND PERFORMED WELL - PDR's. CDR's, AND MRR's COMPLETED

PLANS: COMPLETE CELL / BATTERY TESTS PER CENTAUR REQUIREMENTS - COMPLETE DOCUMENTATION AND DELIVER MCD TO AIR FORCE



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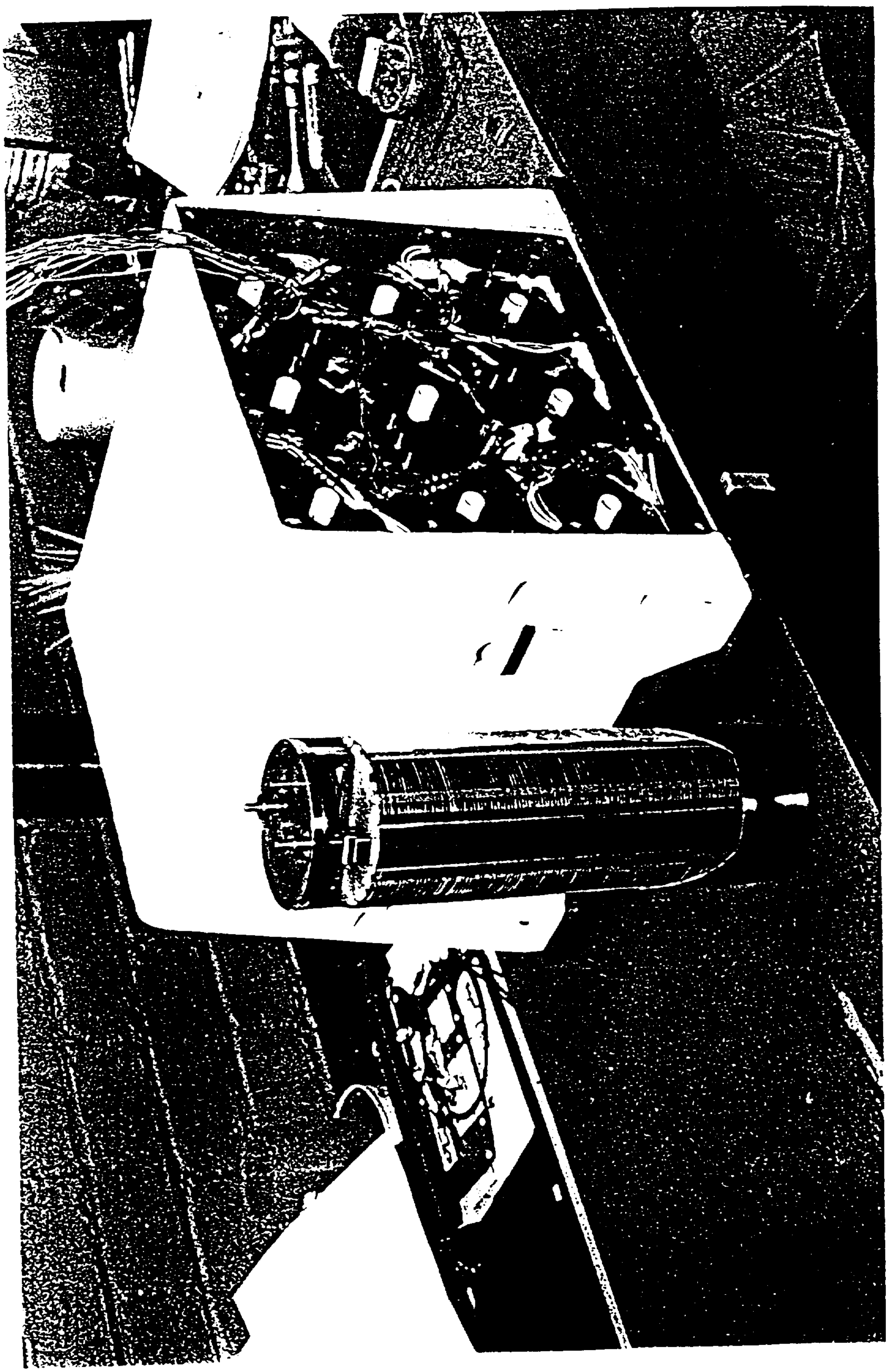


JPL

DIRECT HYDROCARBON / METHANOL FUEL CELLS

OBJECTIVE: TO DEVELOP A FUEL CELL SYSTEM CAPABLE OF THE DIRECT OXIDATION OF METHANOL, METHANE OR OTHER HYDROCARBON

STATUS: NEW CONCEPT IN FUEL CELLS (LIQUID FEED FUEL CELL) HAS BEEN DEMONSTRATED AND ACHIEVED 80 mA/cm^2 AT 0.5 VOLTS

PLANS: CONTINUE THE DEVELOPMENT AND EVALUATION OF LIQUID FEED FUEL CELL - EVALUATE NEW CATALYSTS - FAB DEMONSTRATION UNIT

HIGHLIGHTS OF THE

JPL DARPA DIRECT METHANOL FUEL CELL TASK

OBJECTIVE

DEVELOP DIRECT METHANOL FUEL CELL TECHNOLOGY (DMFC) AT THE CELL LEVEL WITH TARGET PERFORMANCE LEVELS BY 1994

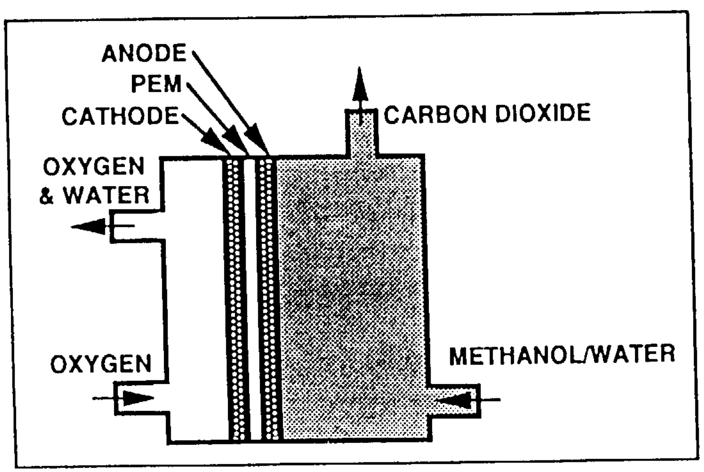
TARGETS (CELL LEVEL)

CURRENT DENSITY	> 150 mA/cm^2
CELL VOLTAGES	> 0.6 VOLTS
LIFE	> 1000 HOURS
TEMPERATURE	< 200°C

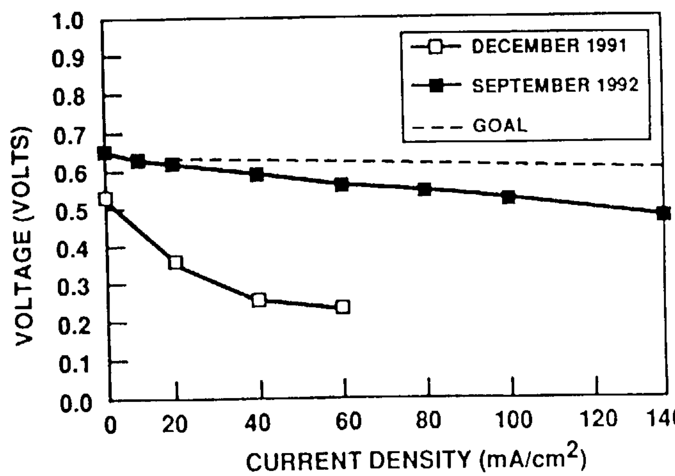
ACCOMPLISHMENTS

- SELECTED CATALYSTS AND ELECTROLYTES WITH INPUTS FROM UNIVERSITIES FOR THE INTERIM METHANOL/O2 SYSTEM DEMONSTRATION
  - -PT/RU
  - -NAFION MEMBRANE
  - -C8 ACID
- IDENTIFIED LIQUID FEED DESIGN AS ATTRACTIVE FOR LOW TO MEDIUM POWER APPLICATIONS
- DEMONSTRATED FEASIBILITY OF LIQUID FEED DESIGN WITH SUPPORT FROM GINER 0.54V AT 100 mA/cm^2
- EVALUATION OF ALTERNATIVE FUELS IN PROGRESS
  - -TRIMETHOXYMETHANE
  - -DIMETHOXYMETHANE

SCHEMATIC OF LIQUID FEED CELL



ADVANCES IN DIRECT METHANOL FUEL CELLS



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POWER TECHNOLOGY DIVISION

NASA
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1992 NASA AEROSPACE BATTERY WORKSHOP

LEWIS RESEARCH CENTER BATTERY OVERVIEW

BY

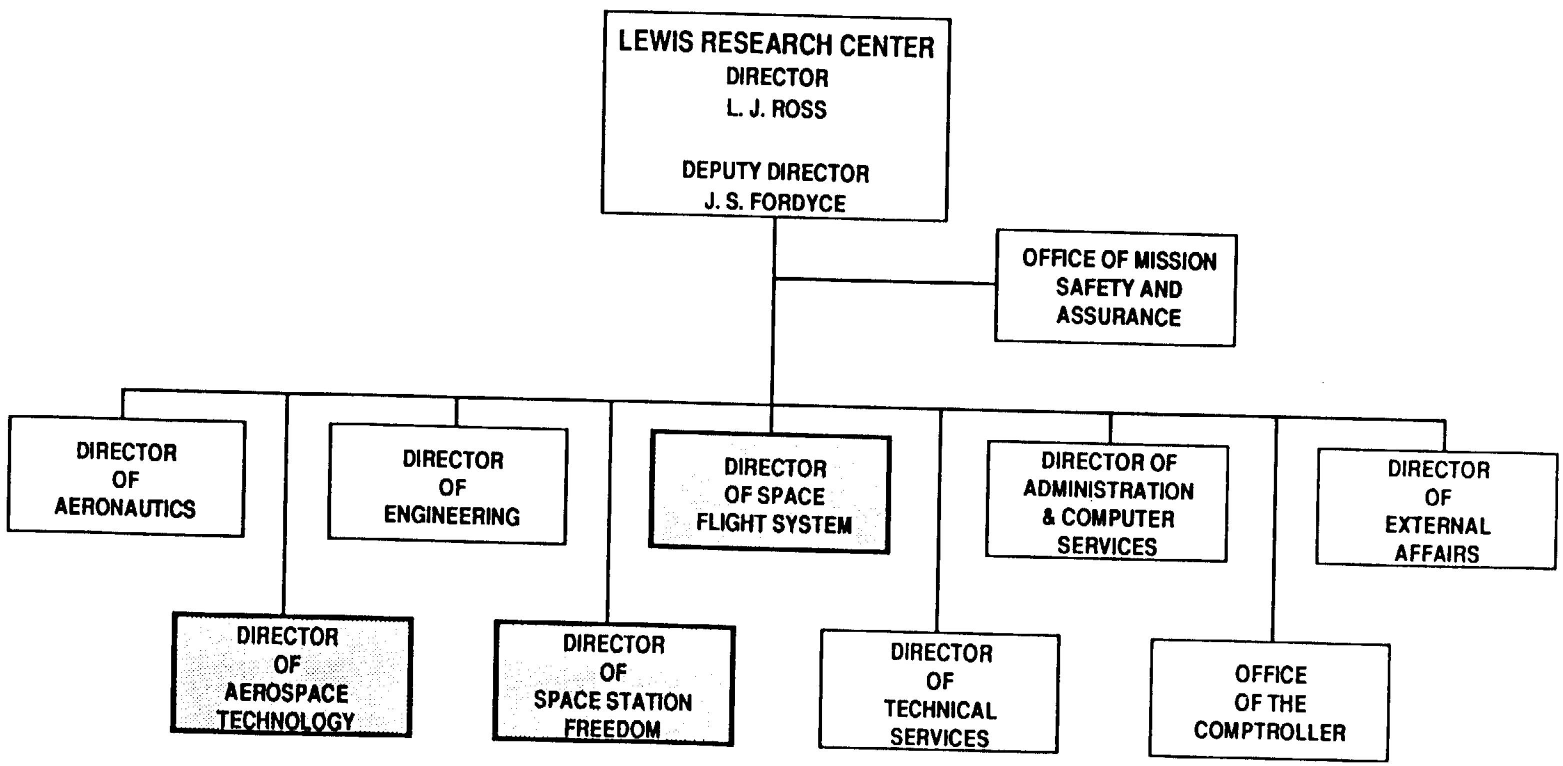
DR. PATRICIA O'DONNELL
D. CHIEF, ELECTROCHEMICAL TECHNOLOGY BRANCH

U.S. SPACE AND ROCKET CENTER
HUNTSVILLE, ALABAMA

NOVEMBER 17-19, 1992

N93-20493

NASA LEWIS RESEARCH CENTER



☐ BATTERY POWER SYSTEM PROGRAMS

ADVANCED COMMUNICATIONS TECHNOLOGY SATELLITE

PROJECT:	ACTS
LAUNCH DATE:	6/93
POWER SYSTEM:	GE-ASTRO SPACE
RESOLUTION:	GEO ORBIT MISSION OF APPROXIMATELY 4 YEARS USING 2 GATES 19 Ah Ni-Cd AT 50% DOD WITH RECONDITIONING AND INDIVIDUAL CELL VOLTAGE MONITORING AVAILABLE
# CYCLES REQUIRED:	400

National Aeronautics and
Space Administration

Lewis Research Center

SPACE STATION FREEDOM

Photovoltaic Power Module Division

FREEDOM

Ni/H_2 BATTERY and CELL DESIGN

National Aeronautics and Space Administration

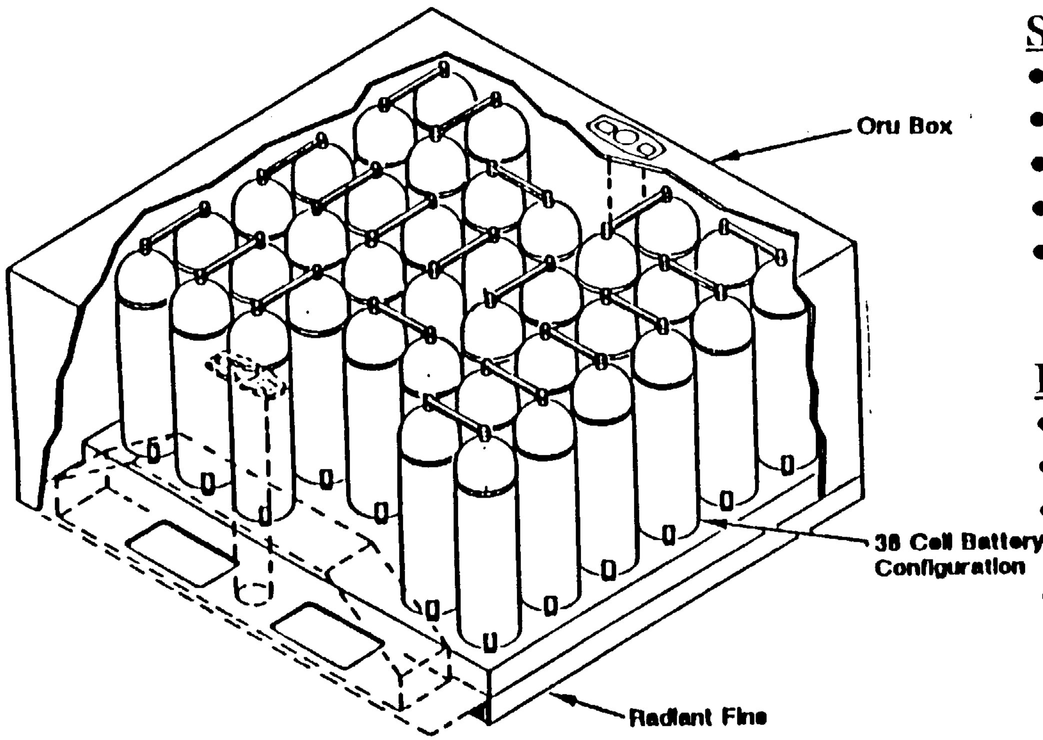
Lewis Research Center

SPACE STATION FREEDOM

Photovoltaic Power Module Division

FREEDOM

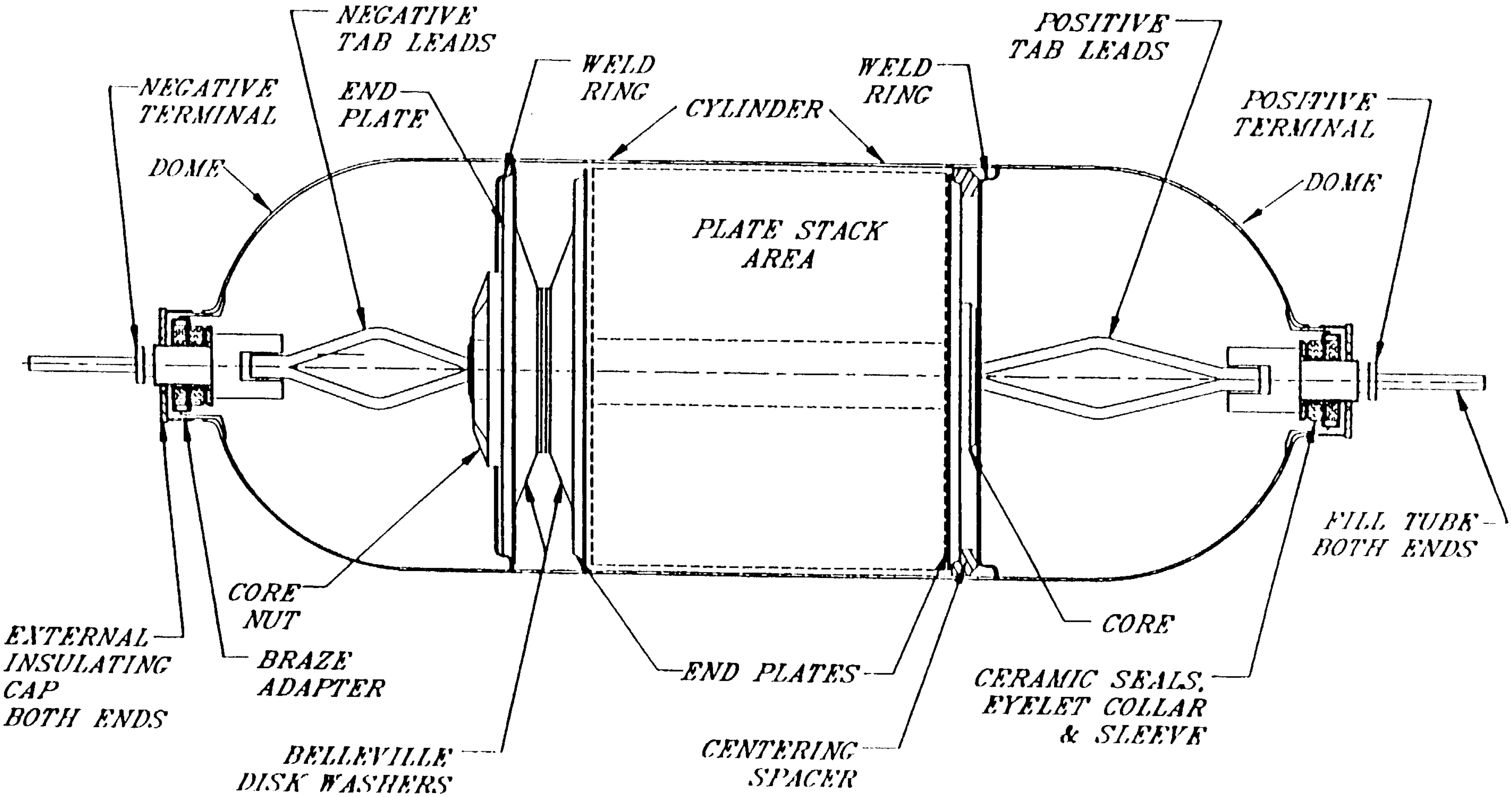
ENERGY STORAGE SUBSYSTEM
Ni/H_2 BATTERY ORU



STATION
- 38 Cells per ORU
- Two ORUs per battery
- Nominal 95V
- Six Batteries per PV Module
- 24 Batteries total at Assembly Complete

REQUIREMENT
- ORU Interface Envelope 36"x40"x18.5"
- Battery ORU Assembly Mass 351 lb
- Nominal/Minimum Battery Cell Capacity 81/77 Ah
- Mean Time between Replacement 5.0 yr
- Design Life 6.5 yr
- Design Cycle Life 36,000 cycles
- Storage Life 4 yr
- Nominal Depth of Discharge 35%

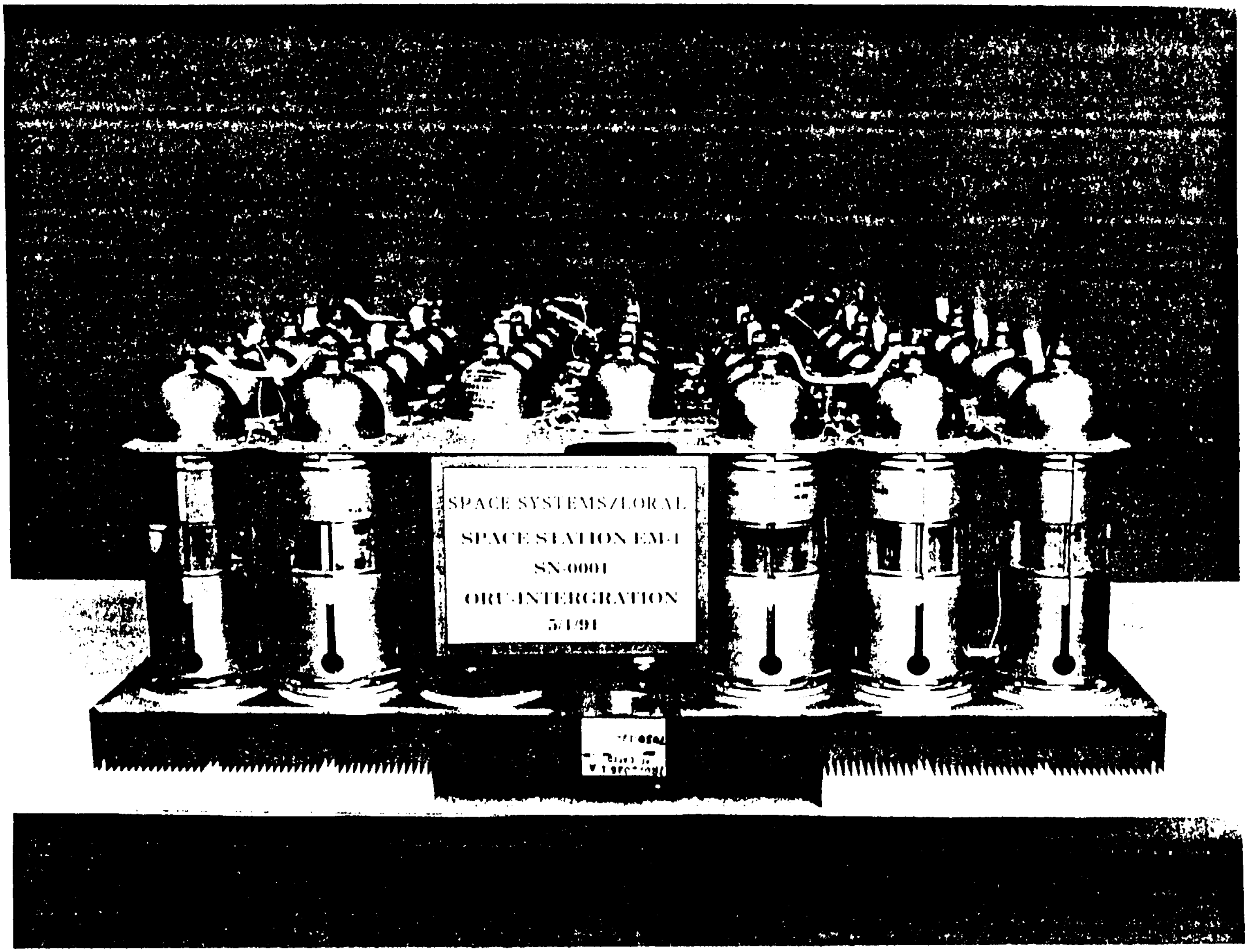
- Battery ORU provides station power during solar eclipse periods



GATES NICKEL HYDROGEN AEROSPACE CELL

SPACE STATION FREEDOM

US PATENTS 4,904,551, 4,950,564, & 5,002,842


SPACE SYSTEMS/LORAL
SPACE STATION EM-1
SN-0001
ORU-INTERGRATION
5/1/91

SPACE STATION FREEDOM

PHOTOVOLTAIC POWER MODULE DIVISION

FREEDOM

SPACE STATION FREEDOM GOALS AND PROGRAMS

- In March of 1986, Nickel–Hydrogen (Ni/H2) cells were chosen as the energy storage system for Space Station Freedom
- Goals
  - Obtain Experience in handling and testing Ni/H2 cells
  - Learn the effects on performance due to design differences
  - Prove 5–year life capability in a 90–minute Low–Earth–Orbit
  - Improve process control and optimize cell manufacturing parameters at cell vendor level
- Programs to Accomplish Goals
  - Non–Prime
    - LeRC in–house Ni/H2 Test Facility in Bldg 309
    - Ni/H2 cell testing at the Naval Weapons Support Center (NWSC) at Crane, IN
  - Prime
    - Cell development program with vendors
    - Engineering model life test at NASA LeRC/PSF
    - Two battery/BCDU integrated life tests at PSF

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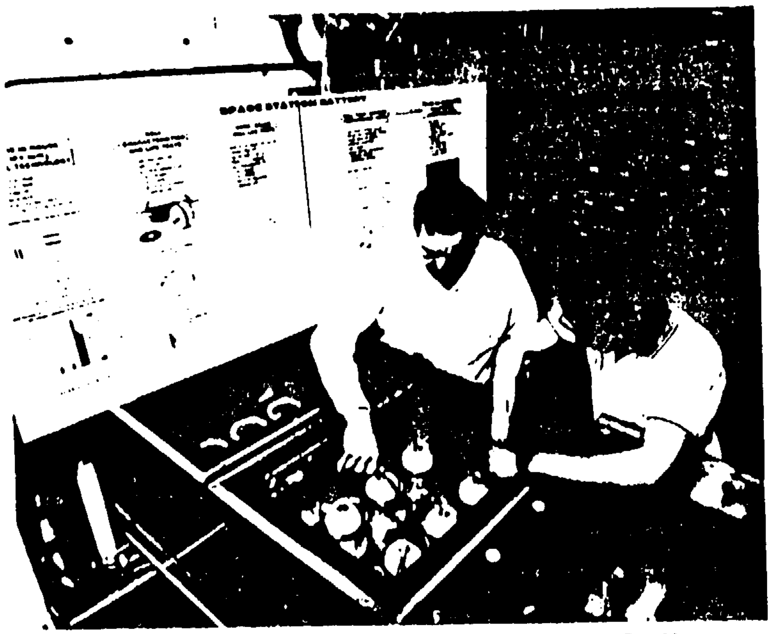
IPV NICKEL HYDROGEN CELL TESTING SPACE STATION FREEDOM SUPPORT



Space Station Freedom Ni-H_2 Cells

- LEO life tests
- 39 Flightweight cells on test
- 50 Ah and 65 Ah capacity
- 3 Commercial vendors
- 10 °C and -5 °C temperatures
- 35% Depth-of-discharge
- 26% and 31% KOH comparison
- Cell design variations

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ELECTROCHEMICAL TECHNOLOGY BRANCH

ROLES

RESEARCH & TECHNOLOGY DEVELOPMENT	DEVELOPING ELECTROCHEMICAL GENERATION AND STORAGE TECHNOLOGY TO A LEVEL OF READINESS SUFFICIENT TO ENABLE OR ENHANCE FUTURE MISSIONS
PROGRAM MANAGEMENT	DEVELOPING AND MANAGING THE FOCUSED R&T AND MISSION ORIENTED PROGRAMS WHICH WILL BRING THE ELECTROCHEMICAL TECHNOLOGY ADVANCEMENTS TO FRUITION

LeRC ELECTROCHEMICAL TECHNOLOGY BRANCH

RESEARCH & TECHNOLOGY DEVELOPMENT

I BATTERIES
- IPV $Ni-H_2$
- BIPOLAR $Ni-H_2$
- NICKEL ELECTRODE, SEPARATORS
- Na/S SPACE SYSTEM - FLIGHT EXPT.
- MODELLING AND ANALYSIS

II FUEL CELL SYSTEMS
- ADVANCED CATALYSTS & SUPPORT (AFC)
- BIFUNCTIONAL CATALYST (AFC & PEM FC)
- MODELLING
- SYSTEM ANALYSIS
- CELL/STACK F.C. & ELECTROLYZER EXPTS.

III ADVANCED CONCEPTS
- LITHIUM/CO_2 ELECTROCHEMICAL SYSTEM

PROGRAM MANAGEMENT

- NASA AEROSPACE FLIGHT BATTERY SYSTEMS PROGRAM
- SPACE EXPLORATION (LUNAR/MARS) REGEN. FUEL CELL PROGRAM
- SUBMARINE FUEL CELL AUX. POWER SYSTEM PROGRAM
- UNMANNED UNDERSEA VEHICLE ELECTROCHEMICAL POWER PROGRAM

MISSION SUPPORTING

- SPACE STATION $Ni-H_2$ BATTERY PROGRAM
- HST, EOS, & ADVANCED TDRSS BATTERIES
- DOE/GM FUEL CELL AUTO ENGINE PROJECT

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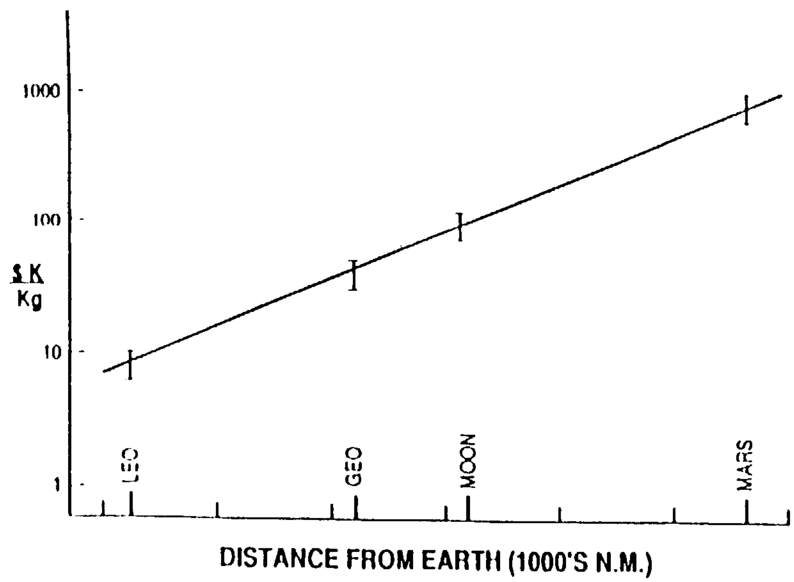
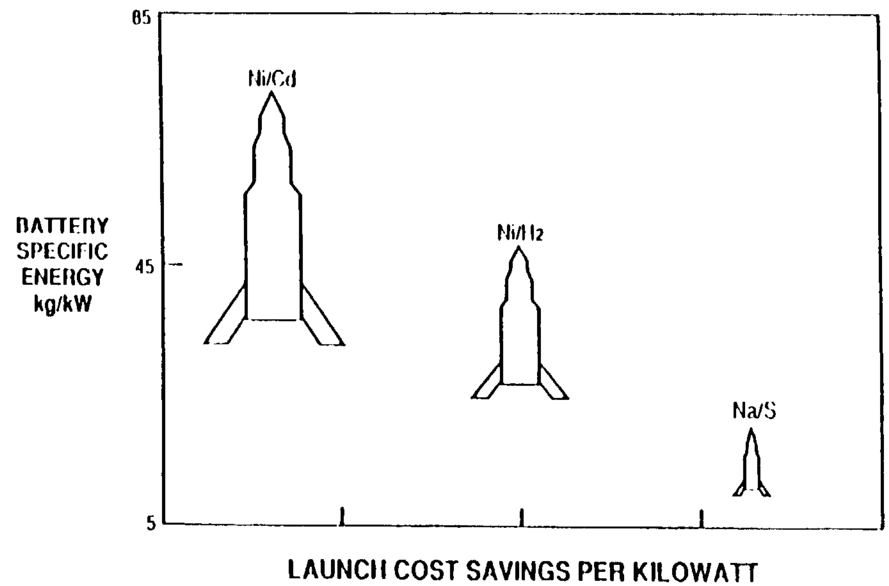
MASS COST ADVANTAGE





IMPROVED DESIGN IPV NICKEL HYDROGEN CELLS

MAJOR PROGRAM OBJECTIVES/GOALS

- DEVELOP TECHNOLOGY BASIS FOR ADVANCED POWER SYSTEMS FOR LEO, GEO, AND ADVANCED PLANETARY MISSIONS FOR TRANSITION TO FOCUSED PROGRAMS
  - GEO NICKEL HYDROGEN (NiH_2) BATTERIES WITH INCREASED SPECIFIC ENERGY (2X SOA) AND RELIABILITY
  - ESTABLISH HIGH SPECIFIC ENERGY SODIUM SULFUR (NaS) BATTERY AS A VIABLE FLIGHT SYSTEM
  - ESTABLISH REGENERATIVE FUEL CELL (RFC) TEST BED
  - ADVANCED FUEL CELL AND ELECTROLYZER COMPONENT DEVELOPMENT
  - DEMONSTRATE FEASIBILITY OF NOVEL ELECTROCHEMICAL SYSTEMS SUCH AS THE LITHIUM CARBON DIOXIDE SYSTEM

ADVANCED TECHNOLOGY FOR IPV NICKEL-HYDROGEN FLIGHT CELLS

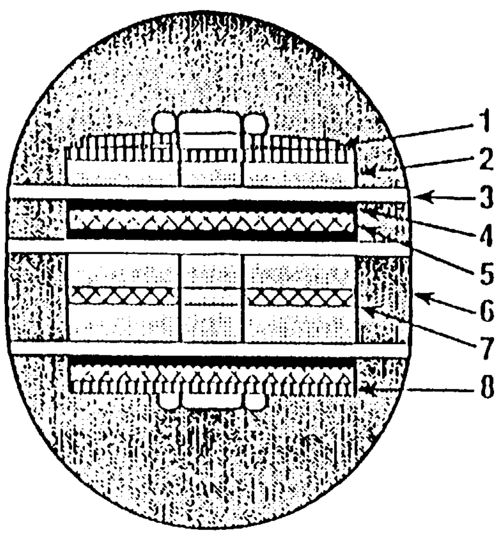
GOAL

IMPROVE CYCLE LIFE AND PERFORMANCE OF NICKEL-HYDROGEN BATTERY

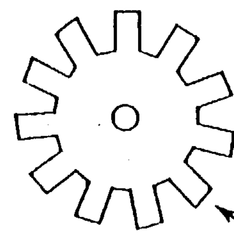
OBJECTIVES

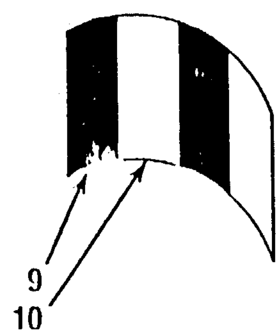
- VALIDATE SUPERIOR LEO CYCLE LIFE OF CELLS USING 26% KOH
- VALIDATE NASA LEWIS 125 Ah ADVANCED DESIGN IPV NICKEL-HYDROGEN CELL

NASA ADVANCED DESIGN IPV NICKEL-HYDROGEN



1. BELLEVILLE SPRING
2. NICKEL ELECTRODE
3. SEPARATOR
4. HYDROGEN ELECTRODE
5. GAS SCREEN
6. WALL WICK
7. OXYGEN SEAL
8. END PLATE
9. CATALYZED STRIP
10. ZIRCONIUM OXIDE STRIP





CELL FEATURES

- USE OF 26% KOH - IMPROVES CYCLE LIFE 10 X SOA
- SERRATED EDGE SEPARATOR - FACILITATES GAS MOVEMENT
- FLOATING STACK - ACCOMMODATES NICKEL ELECTRODE EXPANSION
- CATALYZED WALL WICK IMPROVES THERMAL AND OXYGEN MANAGEMENT
- ELECTROLYTE VOLUME TOLERANCE - MAINTAINS PROPER STACK ELECTROLYTE
- BACK-TO-BACK ELECTRODES - DIRECT OXYGEN TO CATALYZED WALL WICK
- COMPATIBLE WITH SOA AIR FORCE/HUGHES DESIGN - MINIMIZES DEVELOPMENT COST AND TIME

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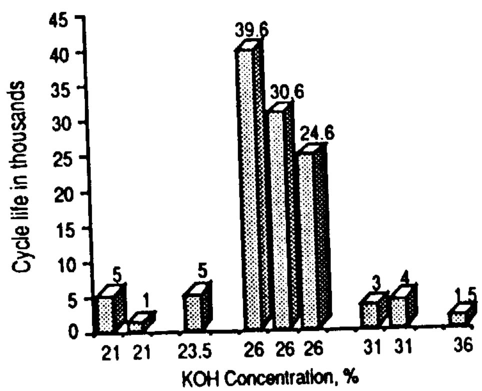
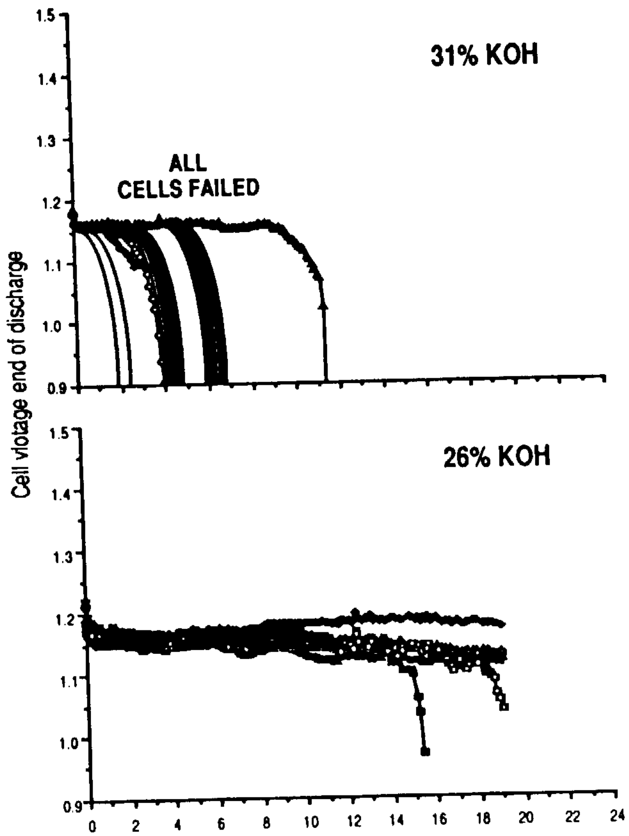
BREAKTHROUGH IN NiH_2 LEO CYCLE LIFE - EMERGING FROM KOH ELECTROLYTE CONCENTRATION EXPERIMENTS

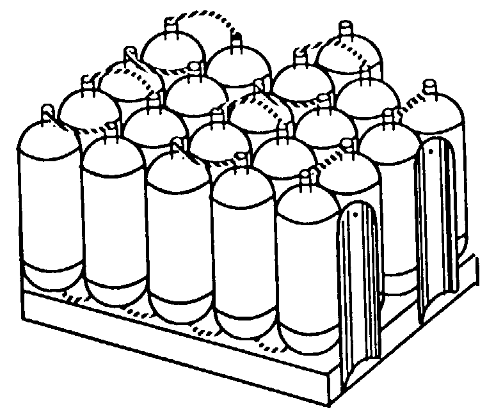
SCREEN COMPLETED ⟶ VALIDATION IN PROGRESS ⟶ IMPROVED NiH_2 BATTERY



- Boiler plate cells
- Accelerated cycles



- Flight cells
- Real cycle times



- Will enhance NASA missions (e.g., SSF, HST, EOS, etc.)

LIGHTWEIGHT NICKEL-HYDROGEN CELL

- APPROACH:
  - ELECTRODE FABRICATION AND CHARACTERIZATION
  - HALF-CELL ELECTRODE TESTING
  - BOILERPLATE CELL TESTING
  - FLIGHTWEIGHT CELL TESTING
  - TECHNOLOGY TRANSFER
- FACILITIES:
  - ELECTRODE PREPARATION, SCREENING, AND CHARACTERIZATION LABORATORY
  - 12 TEST STANDS WITH AUTOMATED DATA ACQUISITION

LIGHTWEIGHT NICKEL-HYDROGEN CELL

- OBJECTIVE:
  - DEVELOP AND DEMONSTRATE A NICKEL ELECTRODE FOR A NICKEL-HYDROGEN CELL WITH IMPROVED SPECIFIC ENERGY AND LIFE
- GOAL:
  - 100 W-hr/kg (2X SOA), 10 YEAR LIFE IN GEO
- SCOPE:
  - LIGHTWEIGHT, LONG-LIVED GEO
    - DEVELOPMENTAL DESIGN EFFORTS
  - MOVE INTO FOCUSSED PROGRAM IN '94
    - PLATFORM POWER AND THERMAL MANAGEMENT

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BIPOLAR NICKEL-HYDROGEN BATTERY DEVELOPMENT

OBJECTIVE: DESIGN, BUILD, AND TEST BIPOLAR NICKEL-HYDROGEN BATTERY SYSTEM WITH HIGH SPECIFIC ENERGY AND ENERGY DENSITY. BATTERY DESIGN ADDRESSES OXYGEN, ELECTROLYTE, AND THERMAL MANAGEMENT CONCERNS.

APPROACH: PARALLEL IN-HOUSE AND CONTRACT EFFORTS

COMPONENT DEVELOPMENT AND OPTIMIZATION

INVESTIGATE ACTIVE COOLING AND PASSIVE COOLING APPROACHES

DEVELOP HIGH VOLTAGE DESIGN

DESIGN FLIGHT WEIGHT BATTERY

DEMONSTRATE PERFORMANCE OF FLIGHT BATTERY

STATUS: TESTING AND ANALYSIS OF PRELIMINARY VERSIONS OF BATTERIES ARE COMPLETE

BATTERIES REDESIGNED BASED ON DESTRUCTIVE PHYSICAL ANALYSIS RESULTS

IMPROVED BATTERIES BUILT AND ON TEST

RESULTS: IN-HOUSE 40 Ah, 10 CELL, BATTERY HAS ACCUMULATED >10,000 40% DOD LEO CYCLES

SPACE SYSTEMS/LORAL 75 Ah, 10 CELL, BATTERY HAS ACCUMULATED >10,500 , 40% DOD LEO CYCLES

NASA
C-90-10555

ATD
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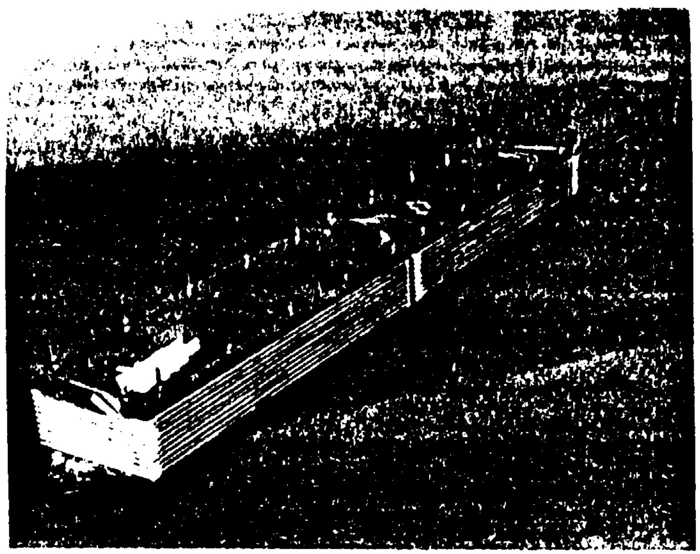
BIPOLAR NICKEL HYDROGEN BATTERY TECHNOLOGY OFFERS ADVANCES OVER IPV SYSTEM



Ford Aerospace 75 Ah Bipolar Ni-H_2 battery

- Managed at the system level
- Higher energy density
- Reduced internal resistance yields higher efficiency
- High voltage and high current give higher DC and pulse power capability
- Improved specific volume

NASA
C-90-10338

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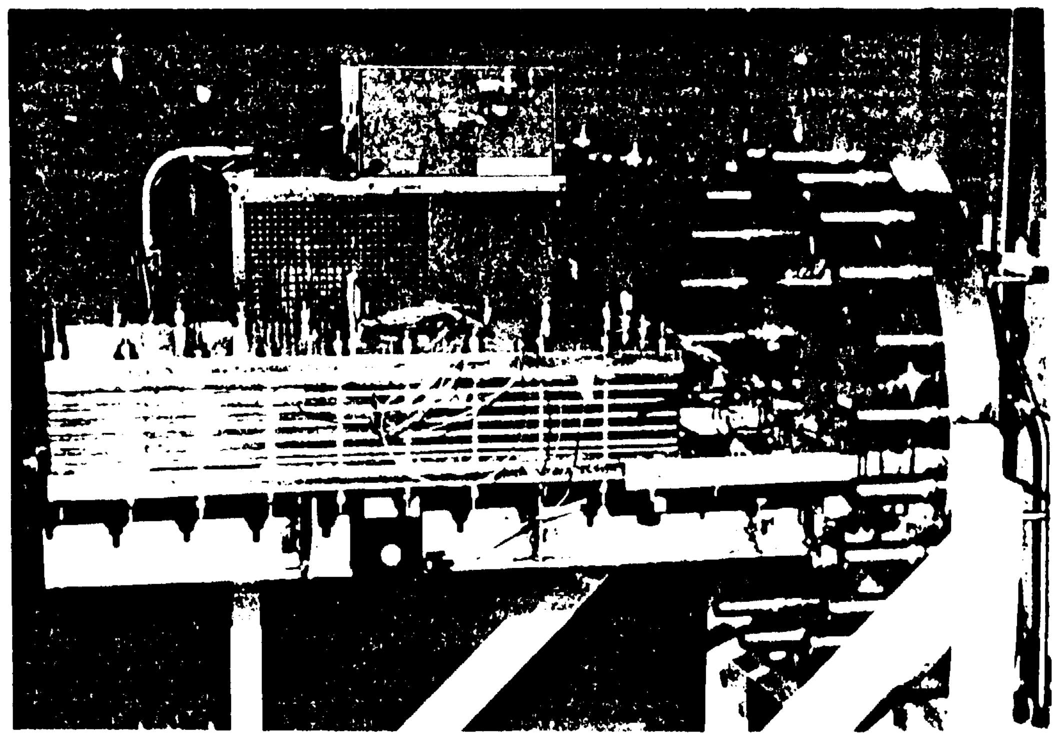
BIPOLAR NICKEL HYDROGEN BATTERY TECHNOLOGY

LeRC BIPOLAR Ni-H_2 BATTERY



40 Ampere hour, 12 volts, active cooling

AEROSPACE NICKEL-METAL HYDRIDE CELLS

GOAL

- EVALUATE SOA NICKEL-METAL HYDRIDE CELL TECHNOLOGY

OBJECTIVE

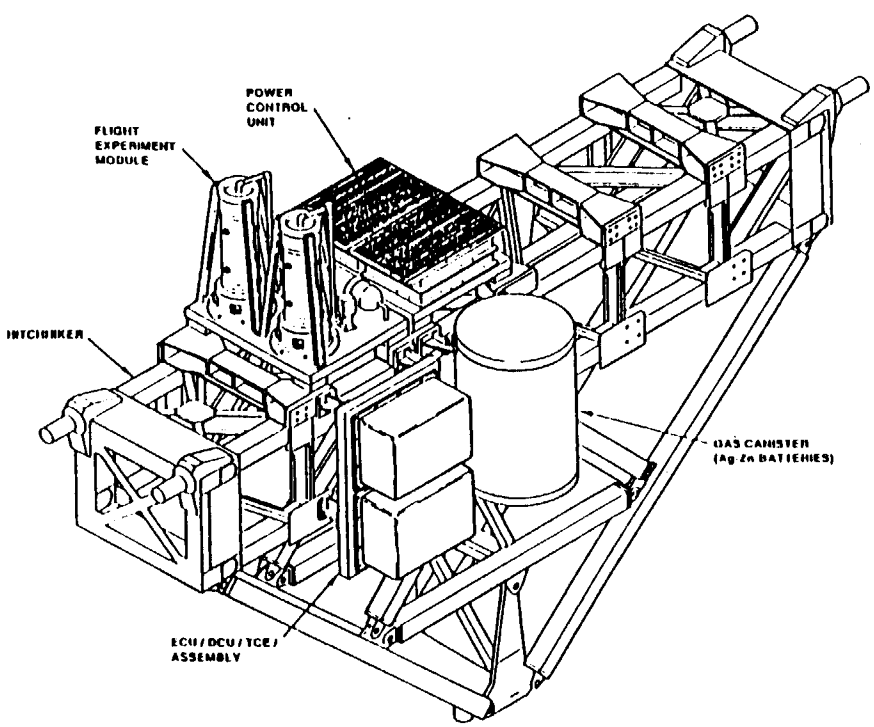
- CONDUCT CHARACTERIZATION AND CYCLE LIFE TEST ON SOA AEROSPACE NICKEL-METAL HYDRIDE CELLS

APPROACH

- PURCHASE PRISMATIC AEROSPACE CELLS
  - EAGLE-PICHER
  - GATES AEROSPACE BATTERIES
- TEST AT NWSC-CRANE, INDIANA
  - CHARACTERIZATION AND CYCLE LIFE TEST
- CONDUCT DPA-AT CELL MANUFACTURER DUE TO PROPRIETARY RESTRICTION
- MAINTAIN COGNIZANCE OF METAL HYDRIDE TECHNOLOGY ADVANCES

NASA SODIUM-SULFUR CELL TECHNOLOGY FLIGHT EXPERIMENT

OBJECTIVE: INVESTIGATE THE CRITICAL ISSUES OF SODIUM-SULFUR CELL OPERATION IN THE MICROGRAVITY ENVIRONMENT AND VALIDATE DESIGN METHODOLOGIES FOR SPACECRAFT SYSTEM CONTROLS AND SAFETY



LEAD CENTER: NASA LeRC

PRIME CONTRACTOR:
SPACE SYSTEMS/LORAL

ADVANTAGE OF Na-S SYSTEM FOR SPACE USE

HIGH ENERGY DENSITY	LESS MASS AND VOLUME NEEDED
HIGH EFFICIENCY ROUND TRIP (82%) FARADAY (100%)	LESS WASTE HEAT AND LIGHTER SOLAR CELL ARRAY
NO SELF DISCHARGE	INFINITE STORAGE LIFE BOTH HOT & COLD
MODERATE TEMPERATURE (350°C)	LIGHTER RADIATOR REQUIRED
PASSIVE OPERATING SYSTEM	HIGHER RELIABILITY

NASA SODIUM-SULFUR CELL TECHNOLOGY FLIGHT EXPERIMENT

TECHNICAL APPROACH:

- ESTABLISH EFFECTS OF uG ON CELL PERFORMANCE
- DEVELOP A PERFORMANCE DATABASE
- DETERMINE REACTANT SPATIAL DISTRIBUTIONS
- DETERMINE CELL CURRENT AND TEMPERATURE DISTRIBUTIONS
- DOCUMENT PERFORMANCE OF SUB-SYSTEMS TO RELATE TO BATTERY OPERATIONS

ACCOMPLISHMENTS/STATUS:

- CONCEPTUAL DESIGN REVIEW COMPLETED 6/92
  - NO MAJOR TECHNICAL OR DEVELOPMENT ISSUES IDENTIFIED
- READY TO PROCEED TO PHASE C/D
  - REVIEW FOR APPROVAL TO PROCEED PLANNED FOR 11/92

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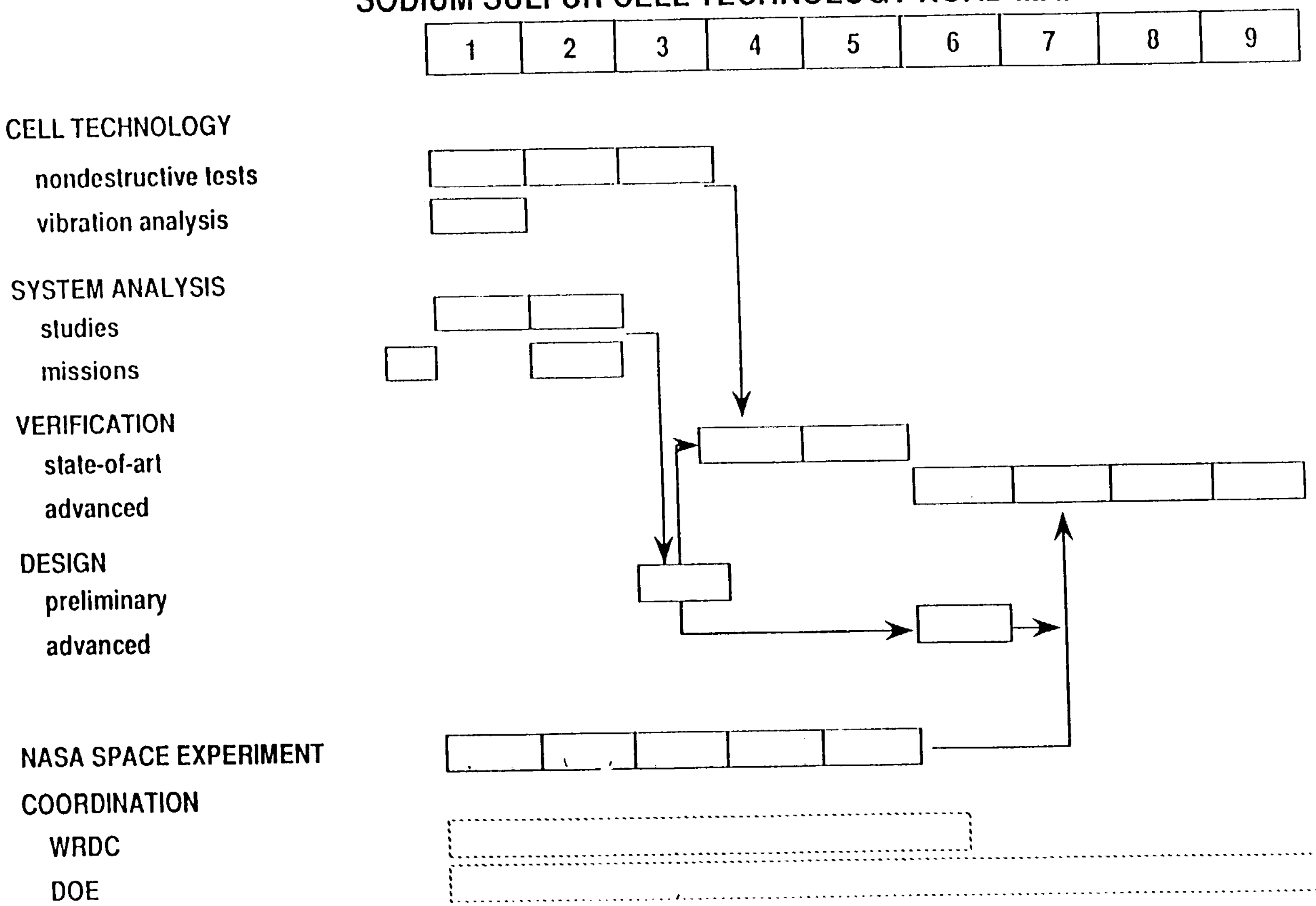
SODIUM SULFUR CELL TECHNOLOGY ROAD MAP



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LITHIUM–CARBON DIOXIDE BATTERY

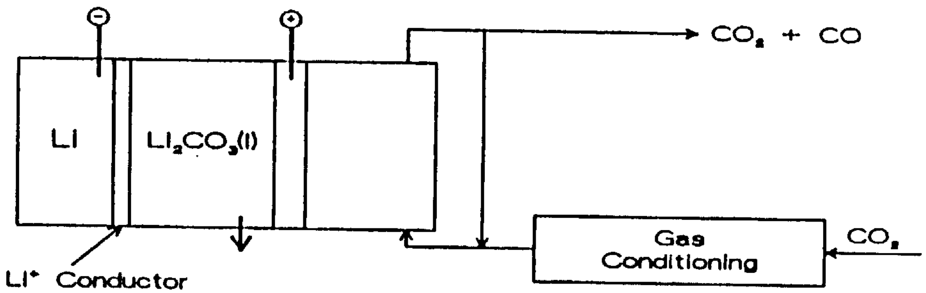
Thermodynamic Model

Discharge

$$2Li = 2Li^+ + 2e$$

$$2CO_2 + 2e = CO + CO_3^=$$

$$2Li + 2CO_2 = Li_2CO_3 + CO$$



Charge

Chemically

- Replenish Li Supply
  - 6400 wh/kg

Electrochemically

- Regenerate Li Supply
- Central Station

$$2Li^+ + 2e = 2Li$$

$$CO_3^= = CO_2 + 1/2O_2 + 2e$$

$$Li_2CO_3 = 2Li + CO_2 + 1/2O_2$$

BENEFITS OF TECHNOLOGY DEVELOPMENT

- QUANTIFIABLE -

- MISSION COST SAVINGS
  - \$100 - 400 M SAVINGS FOR SSF USING ADVANCED NiH_2 TECHNOLOGY
- INCREASED MISSION LIFE
  - 10 X LEO CYCLE LIFE USING ADVANCED NiH_2 TECHNOLOGY
- RFC STORAGE SYSTEM IS ENABLING TECHNOLOGY FOR EXPLORATION SOLAR SURFACE POWER SYSTEM
  - 20,000 hr LIFE RFC SYSTEM
  - 800 - 1000 Wh/kg FOR LUNAR MISSION
- IN-SITU UTILIZATION FOR MARS AND VENUS USING THE LITHIUM CARBON DIOXIDE SYSTEM
  - CO_2 CONVERSION
  - 850°C OPERATION

NASA AEROSPACE FLIGHT BATTERY SYSTEMS PROGRAM

OBJECTIVE: PROVIDE NASA WITH THE POLICY AND POSTURE TO INCREASE AND INSURE THE SAFETY, PERFORMANCE AND RELIABILITY OF BATTERIES FOR SPACE POWER SYSTEMS

PROGRAM STRUCTURE

- BATTERY SYSTEMS TECHNOLOGY
- SECONDARY BATTERY TECHNOLOGY
- PRIMARY BATTERY TECHNOLOGY

NASA AEROSPACE FLIGHT BATTERY SYSTEMS PROGRAM

NASA HEADQUARTERS
S&MQ OFFICE
CODE QE
S. HABIB

BATTERY STEERING COMMITTEE

NASA LeRC
PROGRAM MANAGER
PATRICIA O'DONNELL
DEPUTY - MICHELLE MANZO

NASA KSC
- TRAINING

NASA GSFC
- *BATTERY SYSTEMS* GUIDELINES & TRAINING
- EVALUATION & RESOLUTION OF Ni-Cd PROBLEMS
- VERIFICATION OF QUALITY & RELIABILITY OF *SECONDARY CELLS*

NASA JSC
- *PRIMARY BATTERIES* GUIDELINES & QUALIFICATIONS
- BATTERY SAFETY & HANDLING
- $Zn\text{-}O_2$ DEVELOPMENT
- LI CELL DEVELOPMENT

JPL
- Ni-Cd MODEL
- CRANE DATA EVALUATION

NASA LeRC
- PROGRAM SUPPORT
- $Ni\text{-}H_2$ TECHNOLOGY
- Ni-Cd TECHNOLOGY
- SEPARATOR DEV.
- IMPEDANCE
- DATA BASE

NASA MSFC
- BATTERY WORKSHOP
- DPA PROCEDURE/ FACILITY

NASA LaRC
- ADVANCED NDE FOR $Ni\text{-}H_2$

APPROACH

- PROVIDE FOR IMPROVED CELL/BATTERY MANUFACTURING CONTROL PROCESSES
- ESTABLISH SPECIFICATIONS, DESIGN AND OPERATIONAL GUIDELINES FOR CELLS & BATTERIES
- COORDINATE BATTERY TECHNOLOGY ACTIVITIES BETWEEN CODE R PROGRAM AND CODE Q NEEDS
- OPEN COMMUNICATION LINES WITHIN NASA AND THE AEROSPACE COMMUNITY
- INCREASE THE FUNDAMENTAL UNDERSTANDING OF PRIMARY AND SECONDARY CELLS

Marshall Space Flight Center Battery Activity

Eric Lowery
Electrical Division
Marshall Space Flight Center

NASA Battery Workshop
Alabama Space and Rocket Center
Huntsville, AL
November 17, 1992

Outline:

-- Flight Program History

-- In-House Activities:

Hubble Space Telescope Testing

Other Testing

MSFC Flight Program History

Program Name	Launch Date	Time of Operation	Regime	Battery Type	Capacity	Cell Manuf.	Battery Manuf.	Remarks
Explorer								Explorer 1 -- First free-world satellite, solar array, and Ni-Cd battery power system
1	2/58	4 mos.	LEO	Ni-Cd		Sonotone		
3	3/58	3 mos.	LEO	Ni-Cd		Sonotone		
4	7/58	4 mos.	LEO	Ni-Cd		Sonotone		
Pegasus								Three satellites with multi-battery SA/Ni-Cd system for large micro-meteroid satellite
1	2/65	3+ yrs.	LEO	Ni-Cd		Gulton ?		
2	5/65	3+ yrs.	LEO	Ni-Cd		Gulton ?		
3	7/65	3+ yrs.	LEO	Ni-Cd		Gulton ?		
Skylab								First manned space station; two SA/Ni-Cd power systems (ATM & OWS) with total capability of >8 kW; operated in parallel; EPS reactivated after more than 4 years in "orbital storage"
ATM	5/73	6 yrs. incl.	LEO	Ni-Cd	20 Ah	GE	MSFC	
OWS	5/73	4 yrs. storage	LEO	Ni-Cd	33 Ah	EPI-J	MDAC-E	
HEAO								Three satellites with multi-battery SA/Ni-Cd power system built by TRW for MSFC; no battery failures
1	8/77	19 mos.	LEO	Ni-Cd		SAFT-Amer.	TRW	
2	11/78	30 mos.	LEO	Ni-Cd		SAFT-Amer.	TRW	
3	9/79	27 mos.	LEO	Ni-Cd		SAFT-Amer.	TRW	

MSFC Flight Program History

Program Name	Launch Date	Time of Operation	Regime	Battery Type	Capacity	Cell Manuf.	Battery Manuf.	Remarks
HST	4/90	30 mos. (active)	LEO	$Ni\text{-}H_2$	88 Ah	EPI-J	EPI-J	First reported, non-experimental use of $Ni\text{-}H_2$ batteries in LEO; multi-battery SA/$Ni\text{-}H_2$ 2.4 kW power system built by LMSC for MSFC; first flight-qualified BPRC (MSFC patent) developed for Ni-Cd batteries before change to $Ni\text{-}H_2$
CRRES	7/90	B1-5 mos. B2-15 mos.	MEO	Ni-Cd	15 Ah	GAB	Ford Aerospace	Battery 1 failed after 5 months of operation; battery 2 failed after 15 months of operation; excessive on-orbit overcharge likely major contributor to failures
AXAF-I *	~1999		Elliptical	TBD	30 Ah	TBD	TBD	TRW is the prime contractor for this effort
AXAF-S *	~1999		Polar	TBD	TBD	TBD	TBD	This is an MSFC in-house project

** – Planned flights*

MSFC Secondary Battery / Cell Testing Summary

Hubble Space Telescope Support:

Test Name	Cell Manufacturer	Cell Type	Capacity	Completed Cycles	Regime	%DOD	# of Cells
Type 40 Battery 1 *1	EPI-J	Ni-Cd RSN55	55 Ah	23211	LEO	13 - 16	22
Type 40 Battery 2 *2	EPI-J	Ni-Cd RSN55	55 Ah	6641	LEO	13 - 16	22
Type 41 *4	EPI-J	Ni-Cd RSN55	55 Ah	25891	LEO	13 - 16	22
GE Battery *3	GE	Ni-Cd	50 Ah	23872	LEO	13 - 16	22
Six Battery System *5	EPI-J	Ni-Cd RSN55-15	55 Ah	21856	LEO	13 - 16	132
Six Four-Cell Packs 6	EPI-J	Ni-Cd RSN55-15	55 Ah	30803	LEO	13 - 16	24
Fourteen-Cell Pack	EPI-J	Ni-H_2 RNH30-1	30 Ah	31860	LEO	6 - 9	14
Three Four-Cell Packs	EPI-J	Ni-H_2 RNH90-3	90 Ah	20992	LEO	6 - 9	12
Six Battery System	EPI-J	Ni-H_2 RNH90-3	90 Ah	19012	LEO	6 - 9	132
Flight Spare Battery	EPI-J	Ni-H_2 RNH90-3	90 Ah	18581	LEO	6 - 9	22

* – *Test has been terminated*
1 – *First cell failure at 14 months*
2 – *First cell failure at 14 months; DPA showed excessive cadmium migration*
3 – *Cell divergence at >14,000 orbits; >100 mV at 19,000 orbits; capacity as low as 30 Ah*
4 – *Cell divergence at >10,000 orbits; capacity as low as 20 Ah*
5 – *Built with reject positive plates; met system reqt. of 36 Ah/battery thru 4 yrs.; had cell short in B3 at 18,300 orbits*
6 – *Cells from flight battery lots; continues to meet system reqt. after 5½ yrs.*

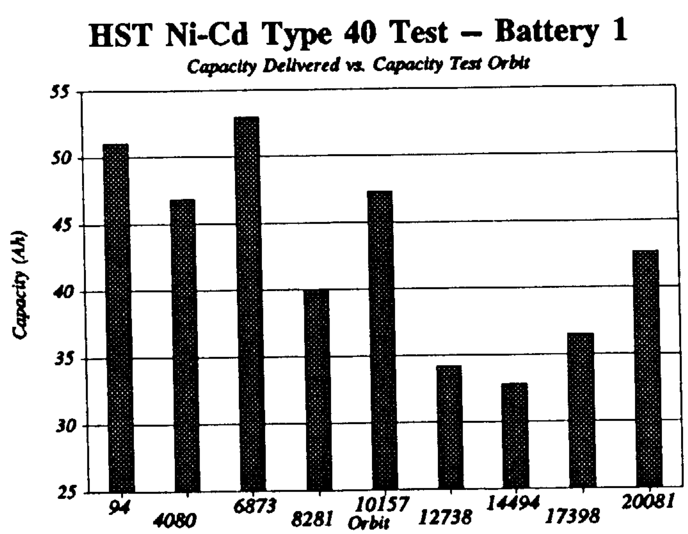
MSFC Secondary Battery / Cell Testing Summary

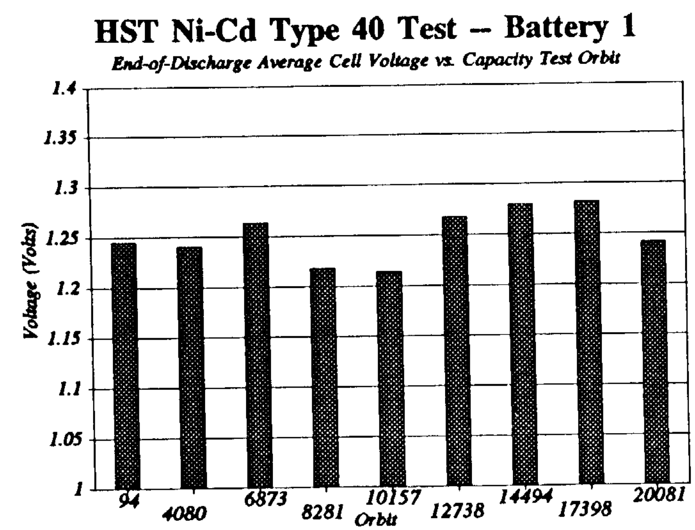
Other Testing:

Test Name	Cell Manufacturer	Cell Type	Capacity	Completed Cycles	Regime	%DOD	# of Cells
Twelve-Cell Pack	EPI-J	$Ni\text{-}H_2$ RNH35-3	33 Ah	22080	LEO	22	12
Four Four-Cell Packs	EPI-J	$Ni\text{-}H_2$ RNH90-3	90 Ah	71	Elliptical	30	16
Reconditioning	EPI-J	$Ni\text{-}H_2$ RNH90-3	90 Ah	6265	LEO	30	8
Parametric Tests	EPI-J	Ni-MH RMH10-1	10 Ah				24
AXAF-S Ni-MH	EPI-J	Ni-MH RMH10-1	10 Ah		LEO		8
SEDS / UAH	EPI-J	Ni-MH RMH10-1	10 Ah		LEO		22
SEDS Satellite	EPI-J	Ni-MH RMH10-1	10 Ah		LEO		22

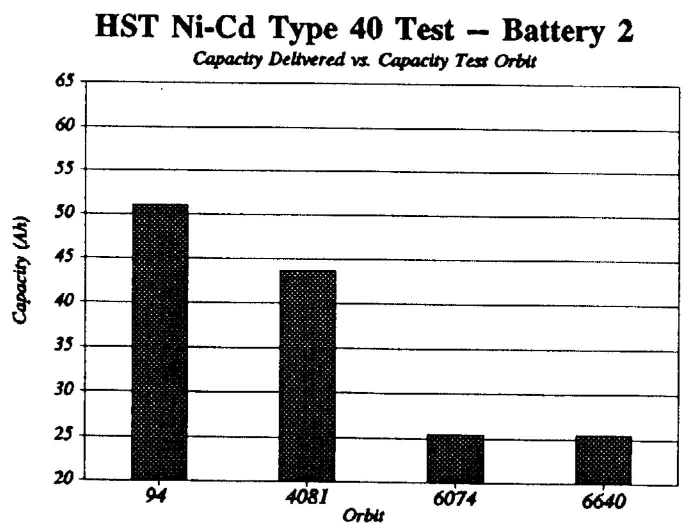
Hubble Space Telescope Test Data Update -- Type 40 Battery 1

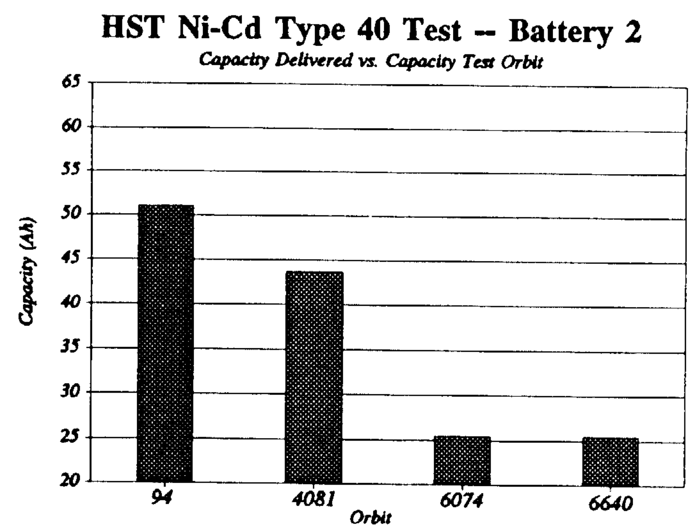
Two 22-cell Ni-Cd type 40 baseline HST batteries were placed on test in April, 1983. These batteries along with the type 41 battery were used to evaluate the longevity and applicability of these early designs to HST mission requirements.





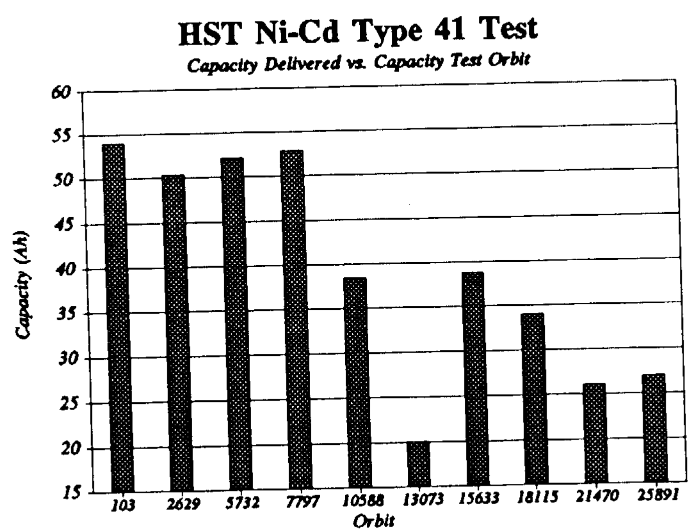
Hubble Space Telescope Test Data Update -- Type 40 Battery 2

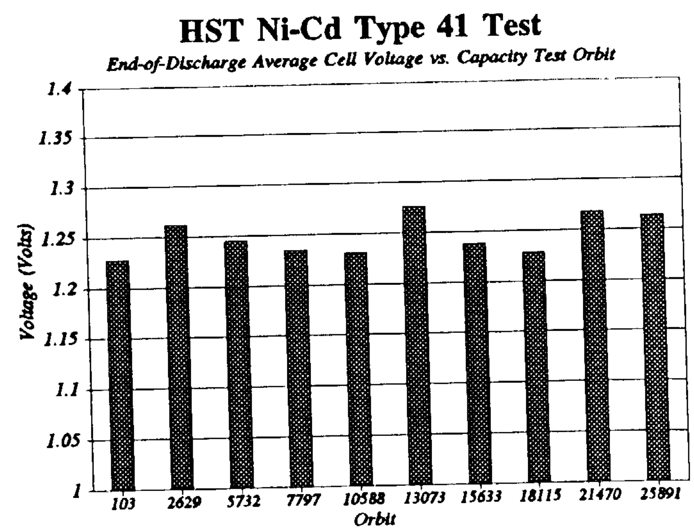




Hubble Space Telescope Test Data Update -- Type 41 Battery

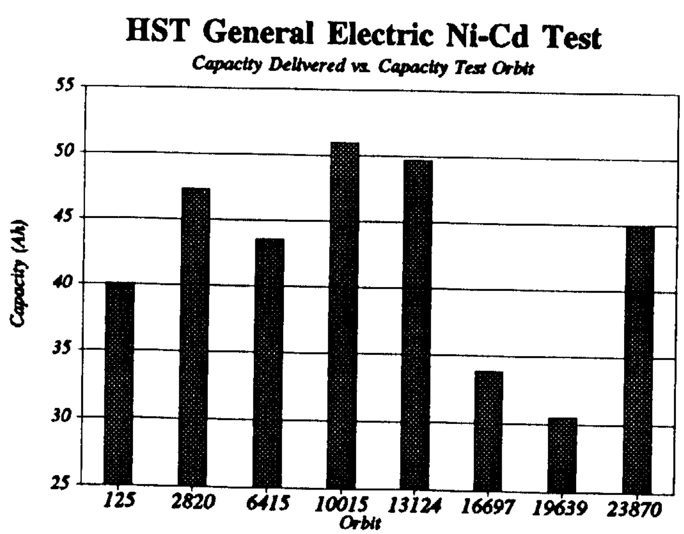
A 22-cell Ni-Cd type 41 battery incorporating improvements on the type 40 design were placed on test in February, 1984. This battery was one of three early-design batteries that were tested in support of the HST.

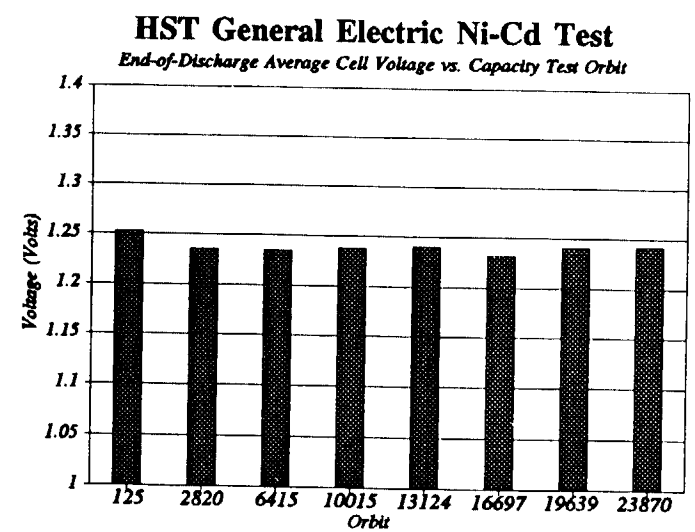




Hubble Space Telescope Test Data Update -- General Electric Battery

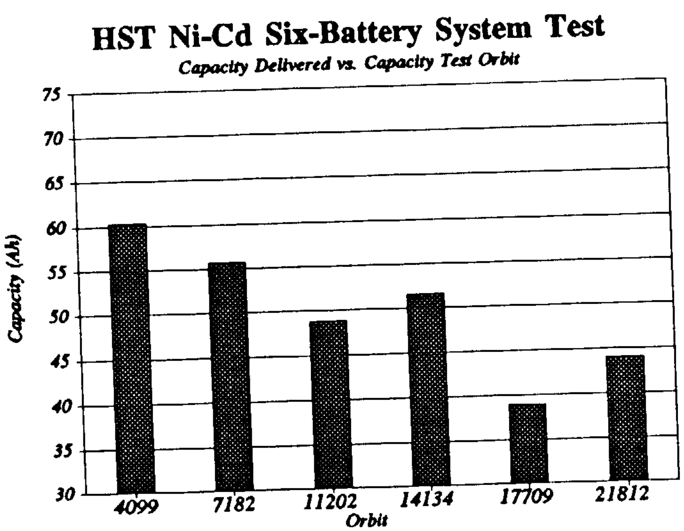
A 22-cell Ni-Cd battery made up of 50 Ah General Electric cells were placed on test in May, 1986. This battery was used to evaluate the longevity and applicability of this design to HST mission requirements.

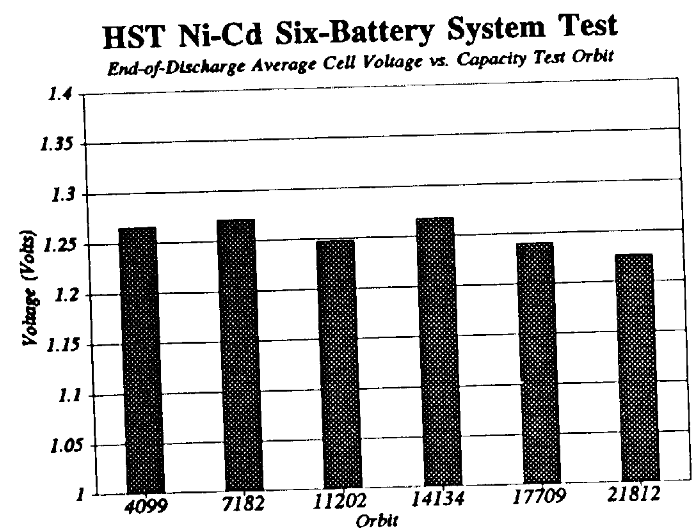




Hubble Space Telescope Test Data Update – Ni-Cd Six-Battery System

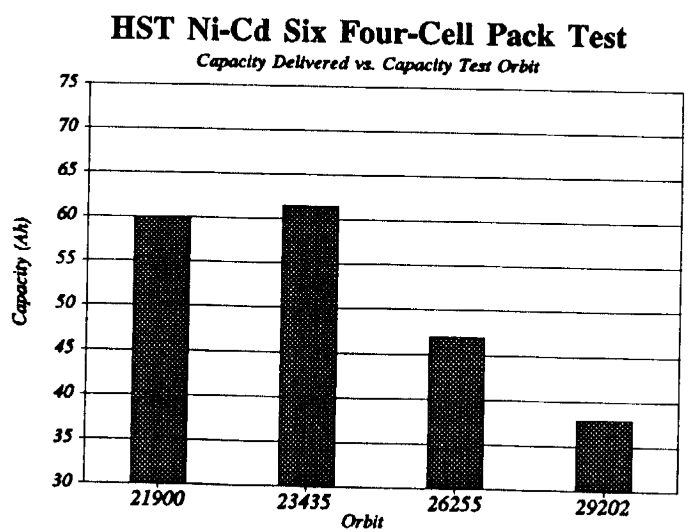
A Ni-Cd six-battery electrical power system simulation began in April, 1986, utilizing six 22-cell type 44 batteries configured for flight including being equipped with a battery protection and reconditioning circuit. These batteries cycled for 21855 cycles demonstrating fully the capability of this Ni-Cd cell to meet HST mission requirements. The test terminated when the batteries failed to meet the capacity requirement.

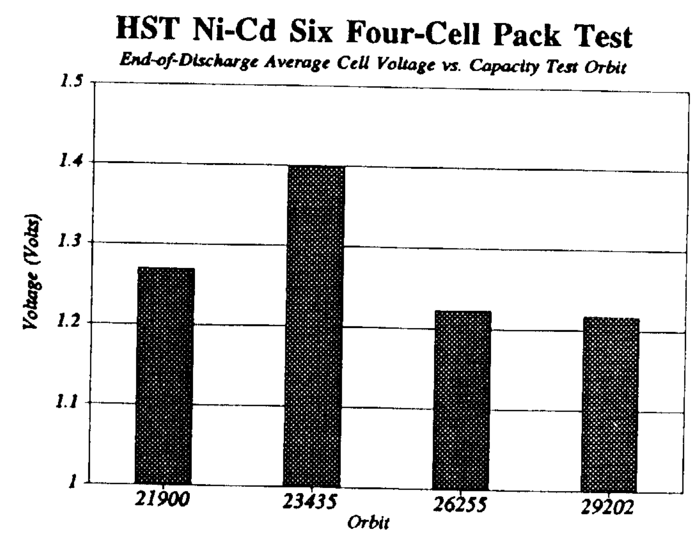




Hubble Space Telescope Test Data Update -- Six Four-Cell Packs

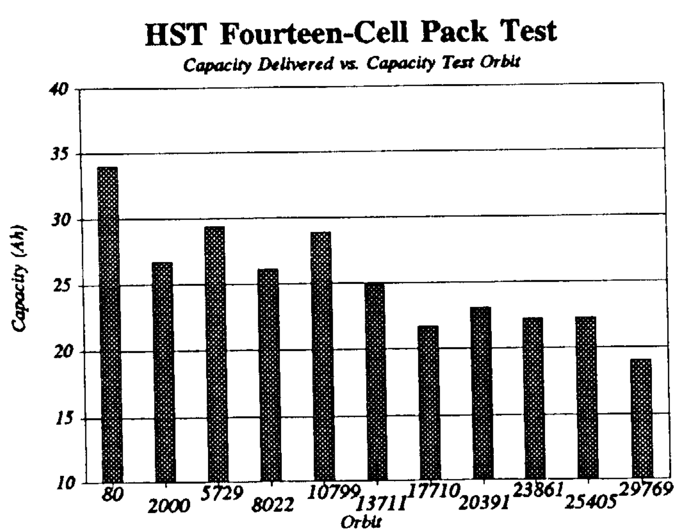
Six, 4-cell packs of type 44 cells were placed on test at MSFC in October, 1990. These cells had been cycling at Lockheed in a parallel test to the Ni-Cd six-battery system test being run at MSFC. When the contract that provided funding to operate this test terminated, the cells were moved to MSFC where they have continued cycling to a point that far exceeds their original program requirements. They have currently completed 30803 cycles.

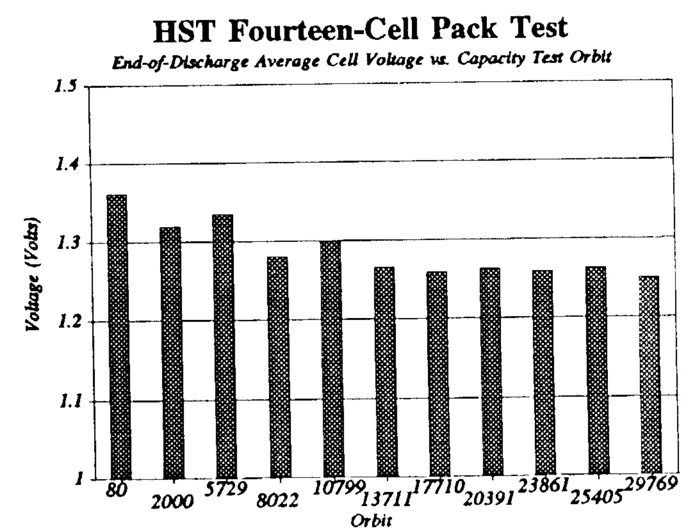




Hubble Space Telescope Test Data Update -- Fourteen-Cell Pack

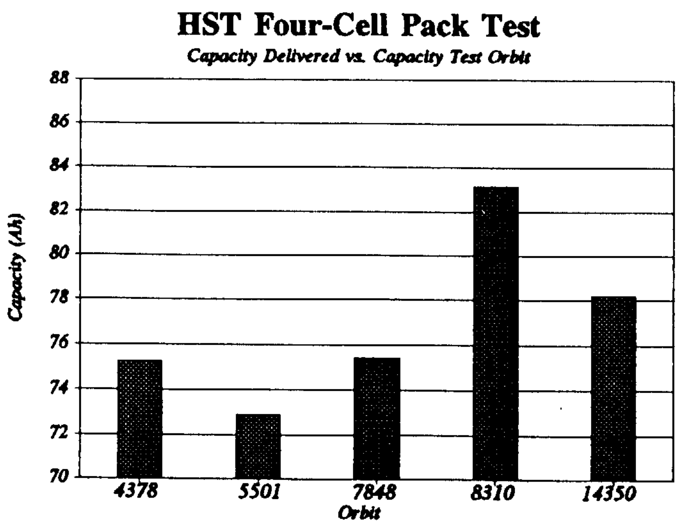
Fourteen 30 Ah Ni-H_2 cells of COMSAT design were placed on test in 1986 in the first Ni-H_2 test bed established for the HST program at MSFC. These cells were used to gather preliminary data on the operation of Ni-H_2 cells in a LEO profile in anticipation of a decision to fly Ni-H_2 cells on the HST. The cells will continue to cycle indefinitely according to current test parameters to enhance the database for Ni-H_2 LEO operation at shallow depths of discharge. They have currently completed 31860 cycles.

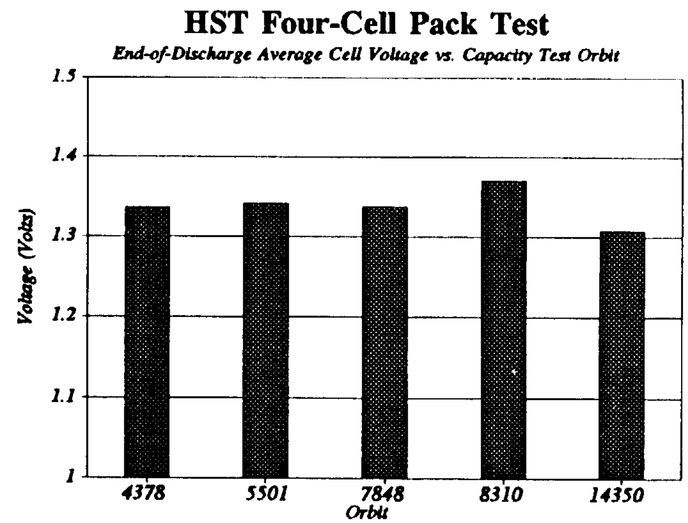




Hubble Space Telescope Test Data Update – Three Four-Cell Packs

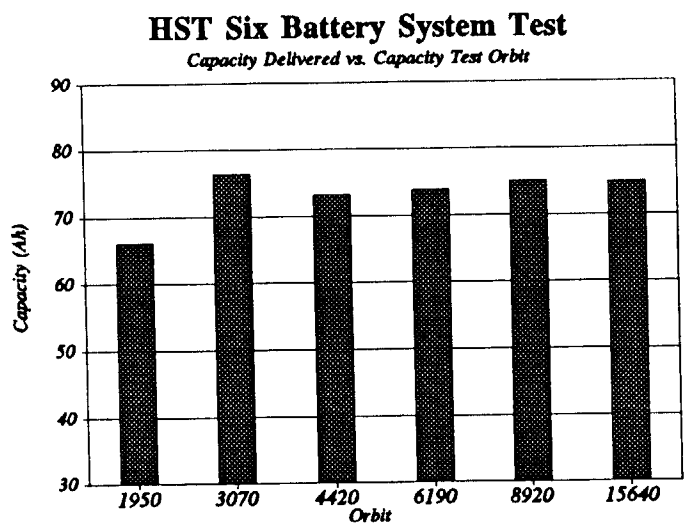
Three four-cell packs comprised of FSM, TM1, and TM2 cells were placed on test in March 1989, November 1988, and February 1989, respectively, and are operating on a simulated HST LEO profile. The packs provided early data on the performance of HST $Ni\text{-}H_2$ cells being charged on the VT curve already in place for use on the HST. These cells have been used extensively in parametric and investigative testing and will continue to be used primarily for that purpose. They have currently completed 20992 cycles.

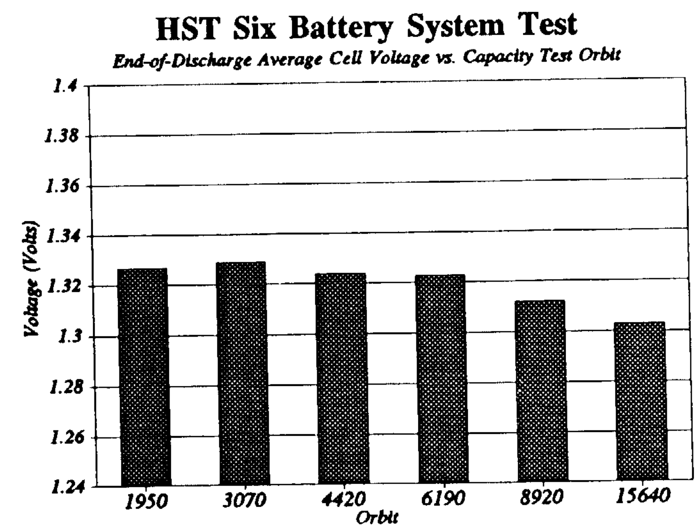




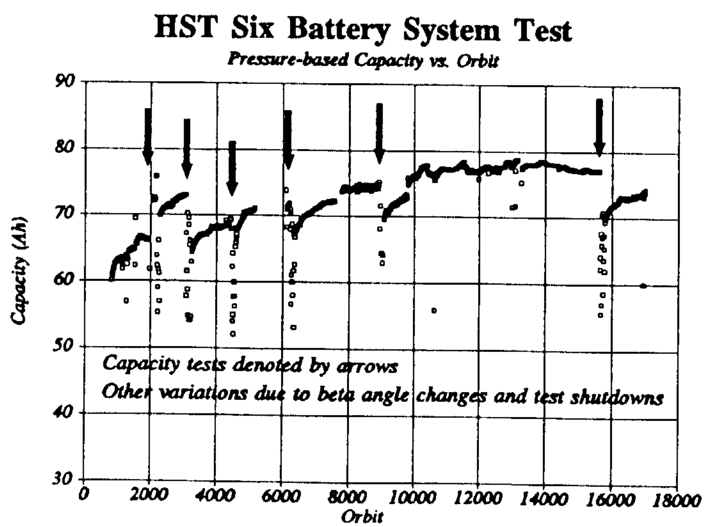
Hubble Space Telescope Test Data Update -- $Ni\text{-}H_2$ Six-Battery System

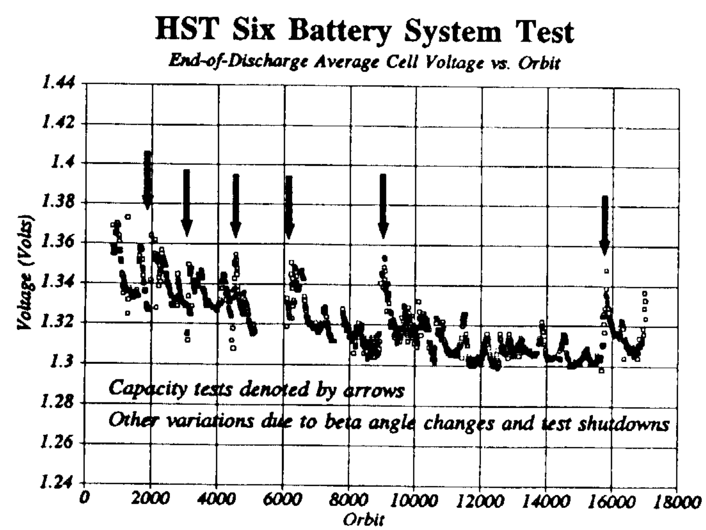
A $Ni\text{-}H_2$ six-battery electrical power system (EPS) simulation began in May, 1989, utilizing TM1 and TM2 modules configured for flight. Solar panel assemblies were simulated with power supplies, the electrical loads with load banks, and the flight computer with a system control computer. This test is to provide information on the operation of the HST EPS by simulating the expected mission profile of the HST and will continue to operate for an indefinite period of time in support of the HST. They have currently completed 19012 cycles.





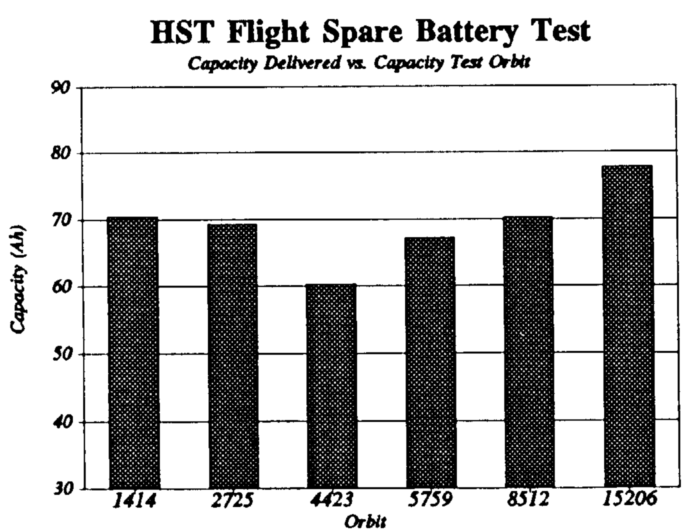
Hubble Space Telescope Test Data Update -- Ni-H_2 Six-Battery System

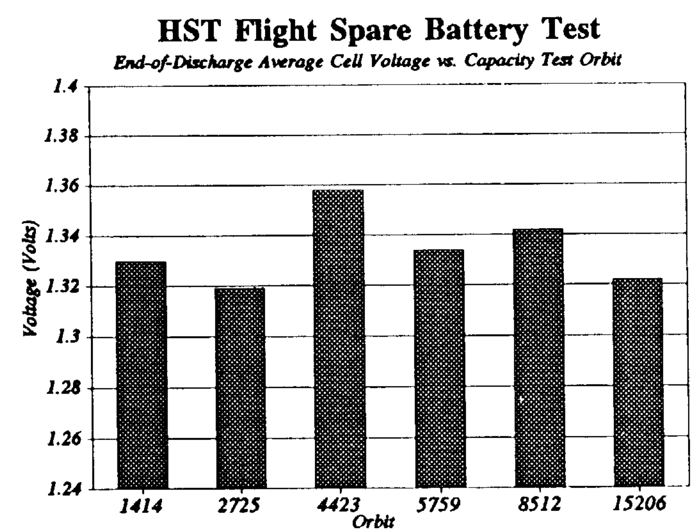




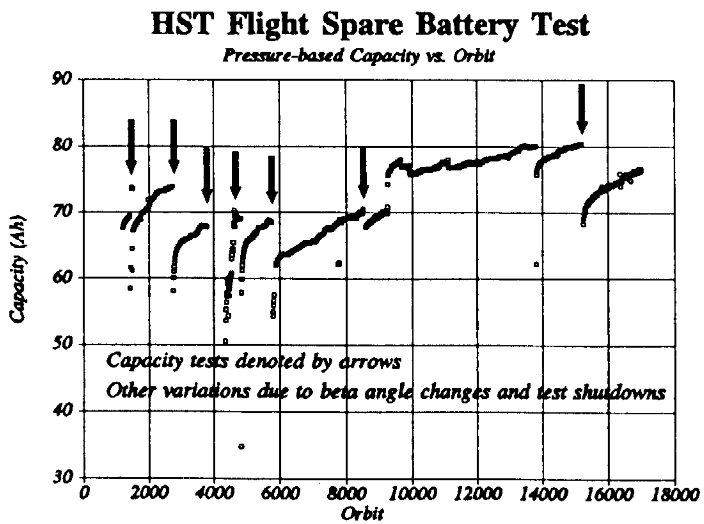
Hubble Space Telescope Test Data Update – Flight Spare Battery

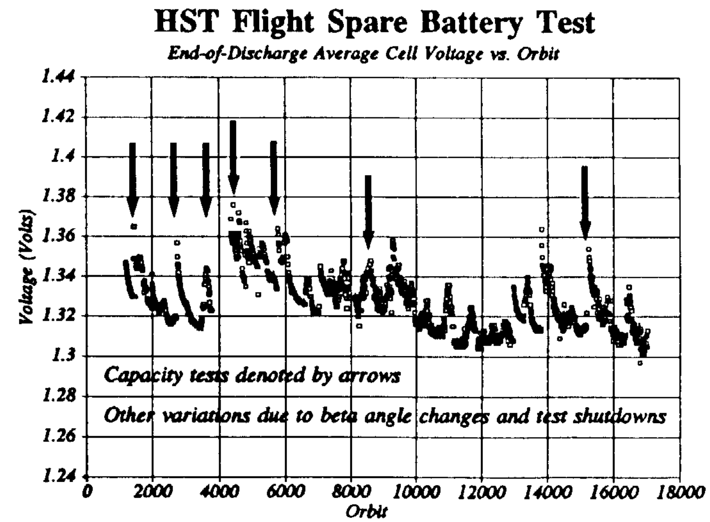
One 22-cell Ni-H_2 battery comprised of flight spare module cells was placed on test in June, 1989, to serve as a life test article for the HST flight cells. Operation of this battery test is similar to that of the six-battery system test in that an accurate mission simulation is desired. Plans for this test are to continue to operate for an indefinite period of time in support of the HST. It has currently completed 18581 cycles.





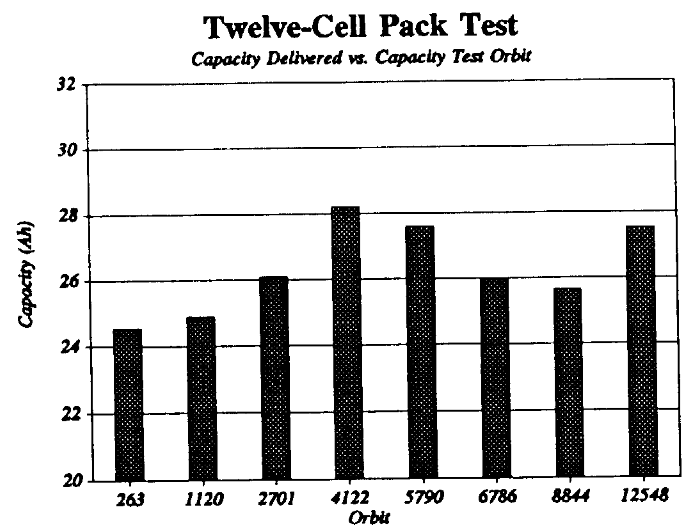
Hubble Space Telescope Test Data Update -- Flight Spare Battery

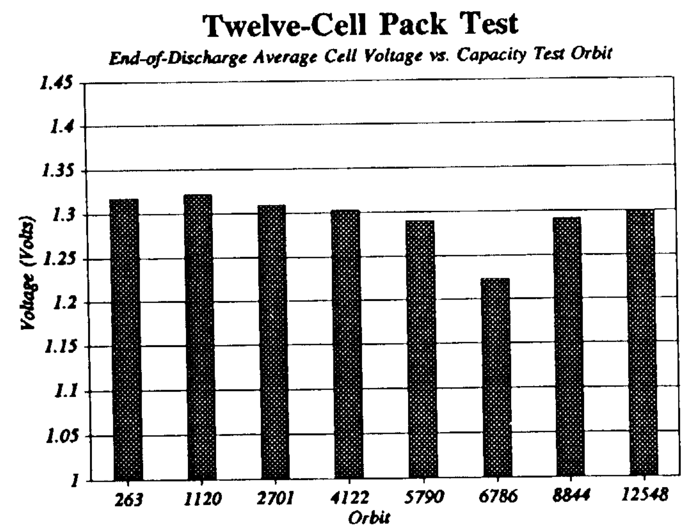




General Test Data Update -- Twelve-Cell Pack

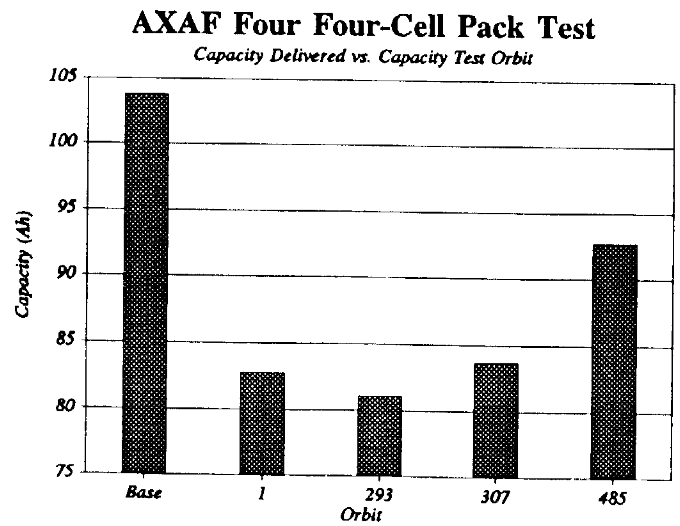
Twelve 33 Ah Ni-H_2 cells of Air Force design were placed on test in May, 1988. These cells are currently cycling to a 22% DOD based on their 33 Ah nameplate capacity and charging with a taper charge at constant voltage. These cells cycled initially for over 2 years using an HST LEO profile. Since the profile change, the cells have cycled nearly an additional 2 years.





General Test Data Update -- Four Four-Cell Packs

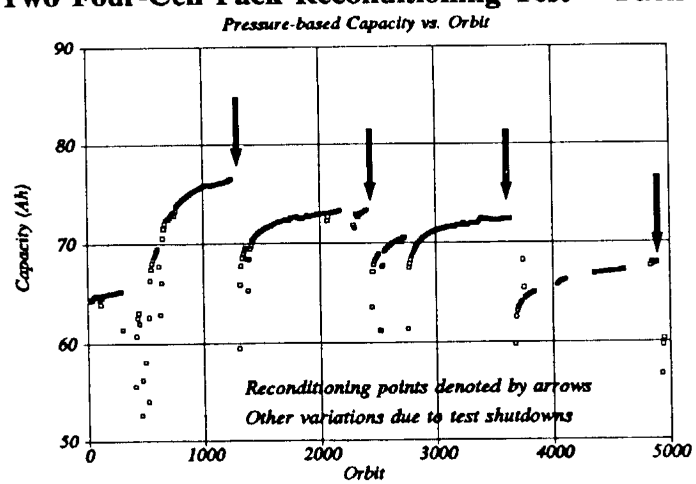
Four four-cell Ni-H_2 packs comprised of HST FM1 and FSM cells were placed on test in June, 1991, and are following as closely as possible to the AXAF-I cycle profile (elliptical orbit). This testing will provide early information about the behavior of Ni-H_2 cells during long periods of trickle charge. These cells were previously LEO cycled for one year following the original AXAF cycle profile. The data below reflects capacity tests run during that period of LEO cycling.



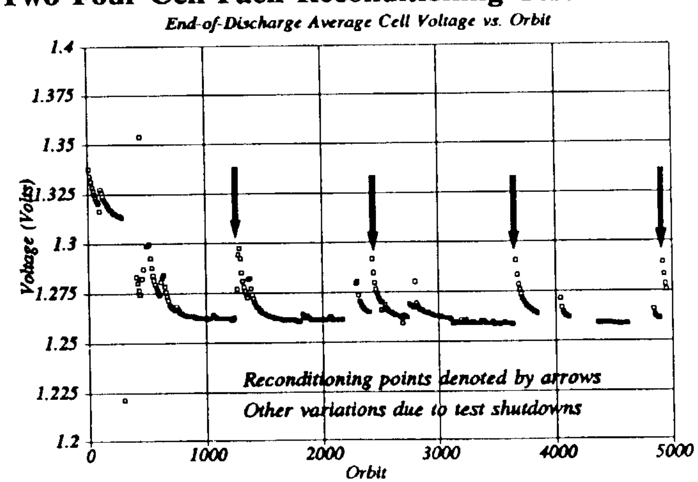
General Test Data Update -- Reconditioning Test

Two four-cell Ni-H_2 packs comprised of HST TM1 and FM2 cells were placed on test in June, 1991, and are studying the effects of reconditioning on Ni-H_2 cells. Another objective is to enhance the capabilities to perform Destructive Physical Analyses (DPA) at MSFC. One pack will cycle with no reconditioning while the other will cycle identically but with quarterly reconditionings. A control cell will be DPA'd uncycled with cycled cells being reconditioned after 12,000 and 20,000 cycles.

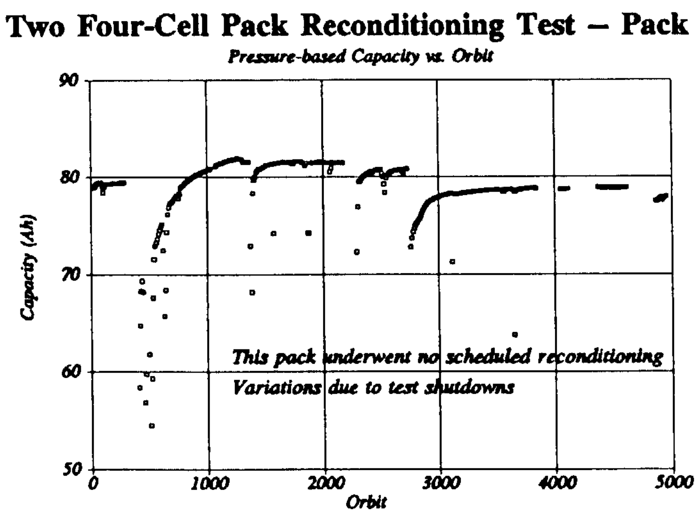
Two Four-Cell Pack Reconditioning Test -- Pack 1

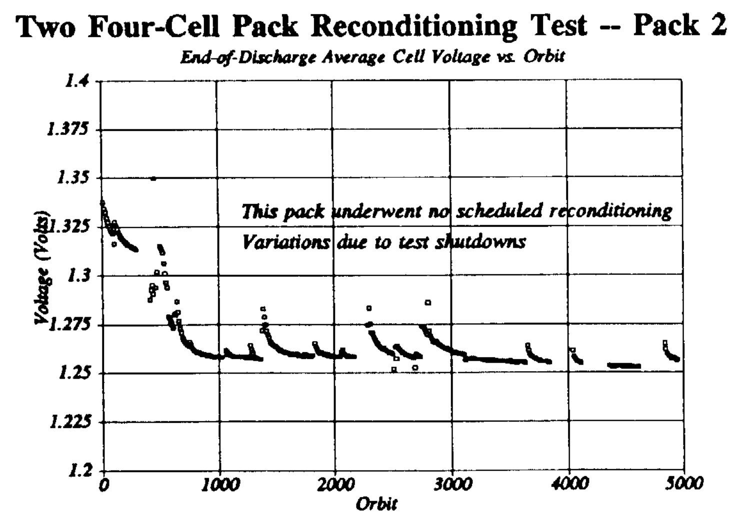


Two Four-Cell Pack Reconditioning Test -- Pack 1



General Test Data Update – Reconditioning Test





General Test Data Update -- Planned Ni-MH Testing

-- Parametric tests using 10 Ah EPI RMH10-1 cells shall be conducted to characterize the behavior of Ni-MH cells.

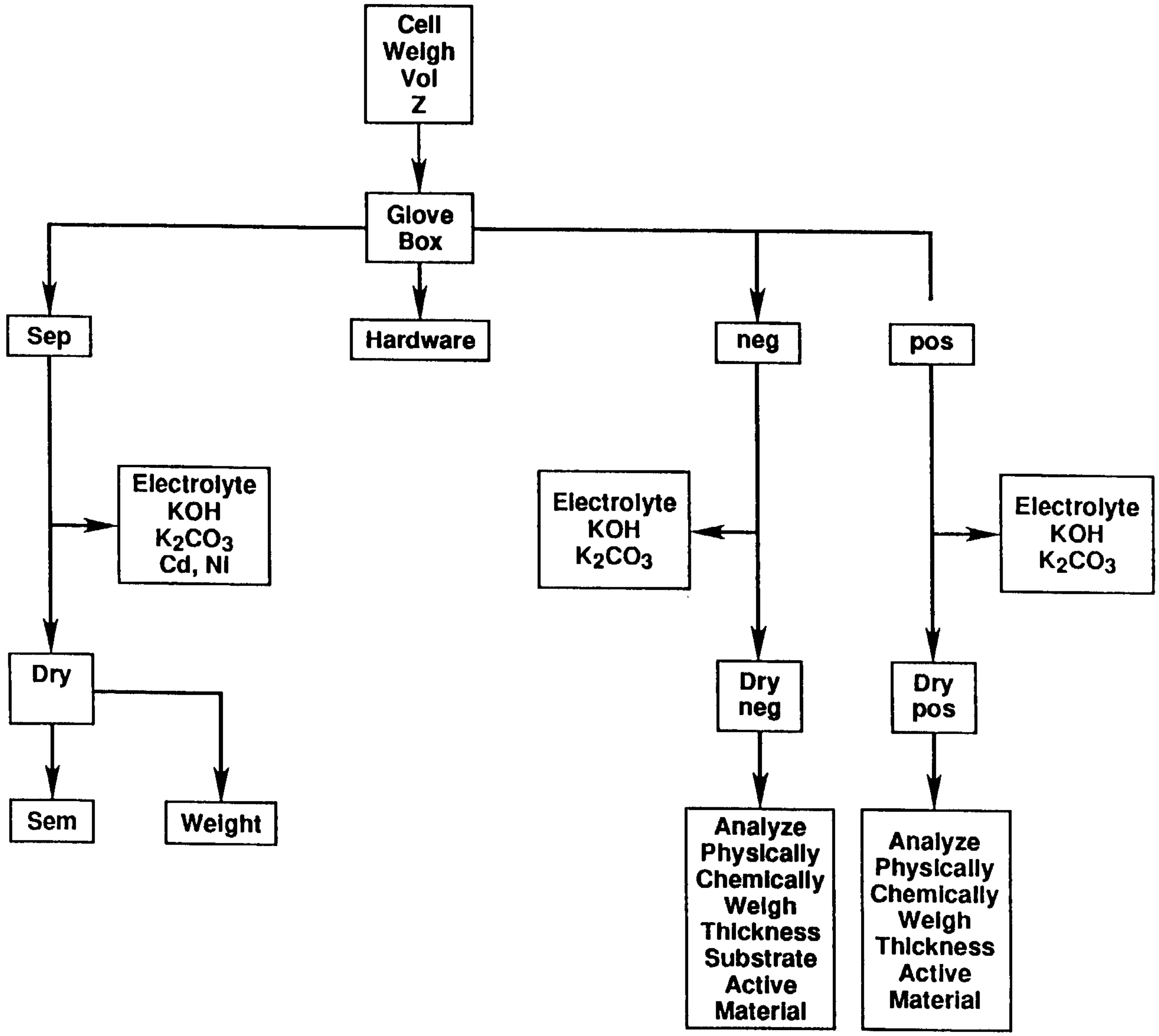
-- Eight 10 Ah EPI RMH10-1 cells shall be tested to investigate the applicability of Ni-MH cells to the AXAF-S mission.

-- A 22-cell 10 Ah EPI RMH10-1 battery is to be used as a test article in an EPS simulation for a small satellite.

-- A 22-cell 10 Ah EPI RMH10-1 battery is to be placed on a LEO satellite in a microgravity testing environment. This could be the first reported use of Ni-MH in a LEO satellite. Launch date is set for March, 1994.

An Update on the Marshall Space Flight Center DPA Facility

November 17, 1992



Cell
Weigh
Vol
Z
Glove
Box
Sep
Hardware
neg
pos
Electrolyte
KOH
K_2CO_3
Cd, Ni
Electrolyte
KOH
K_2CO_3
Electrolyte
KOH
K_2CO_3
Dry
Dry
neg
Dry
pos
Sem
Weight
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Thickness
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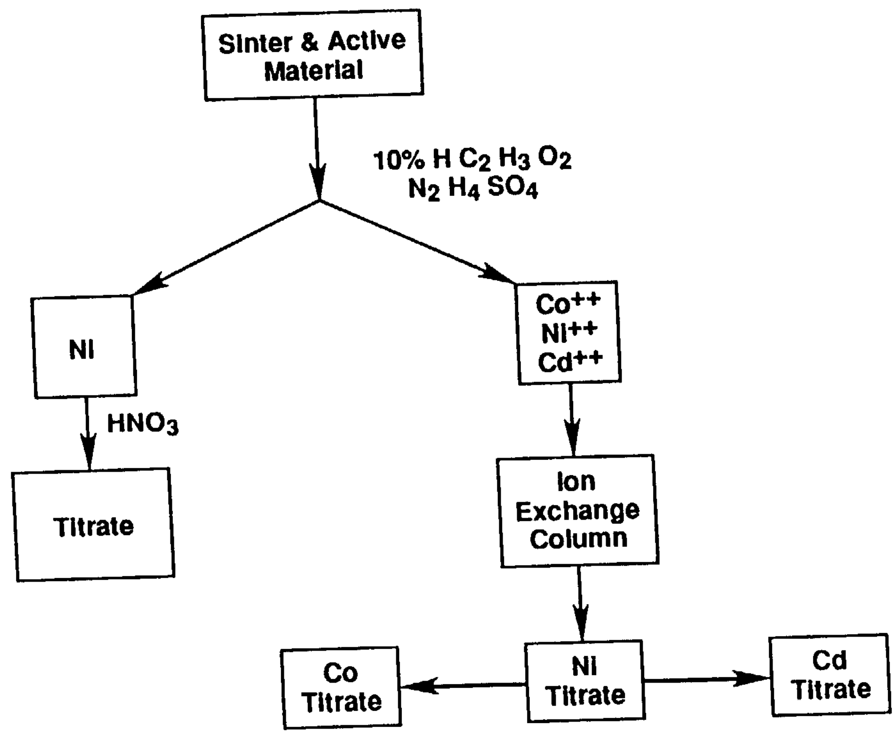
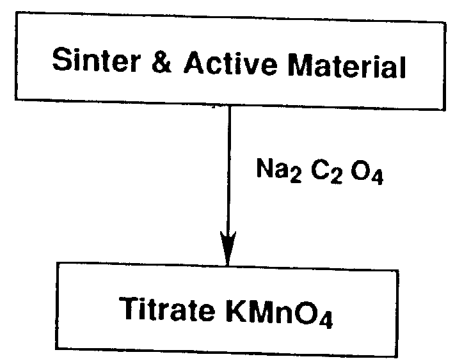
Material

Nickel


Sinter & Active Material
10% $H C_2 H_3 O_2$
$N_2 H_4 SO_4$
Ni
HNO$_3$
Titrate
Co^{++}
Ni^{++}
Cd^{++}
Ion Exchange Column
Co Titrate
Ni Titrate
Cd Titrate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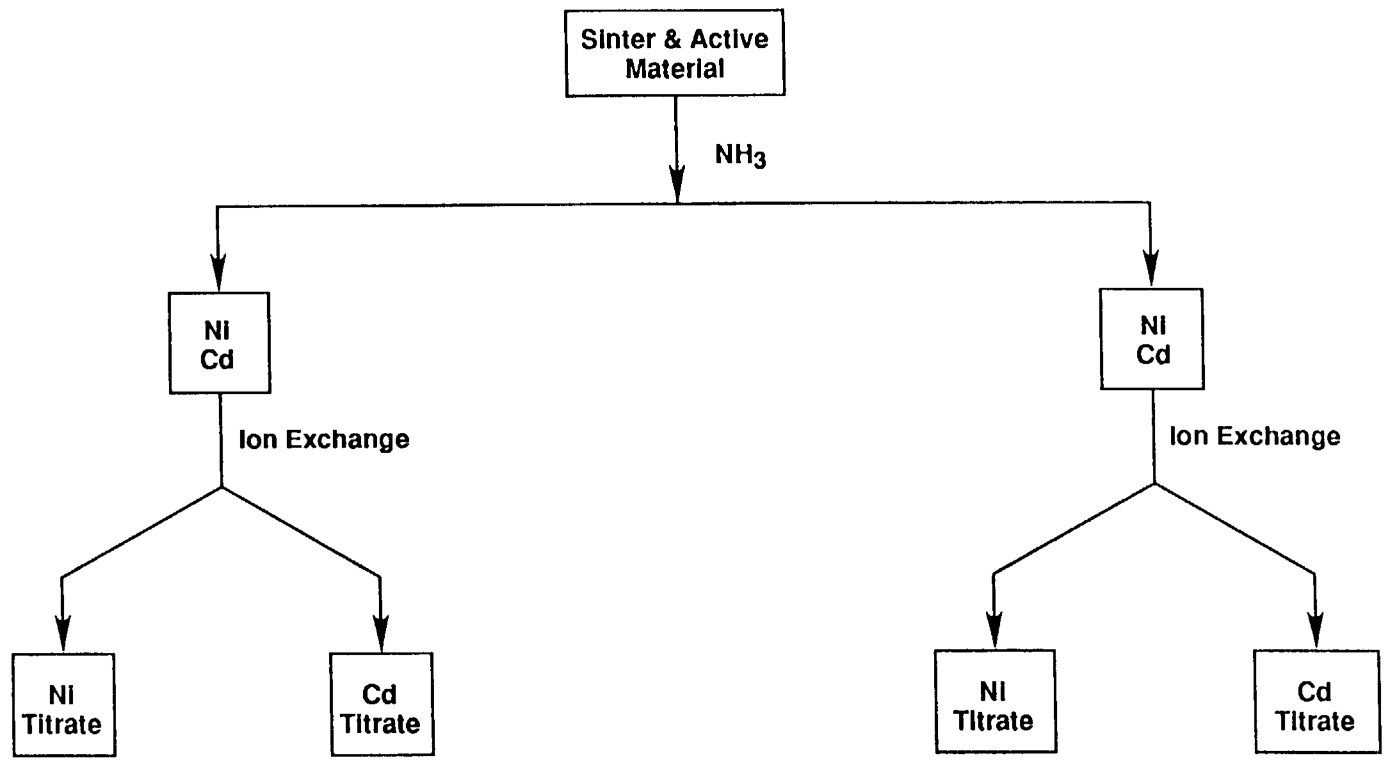
Titrate $KMnO_4$

Cadmiun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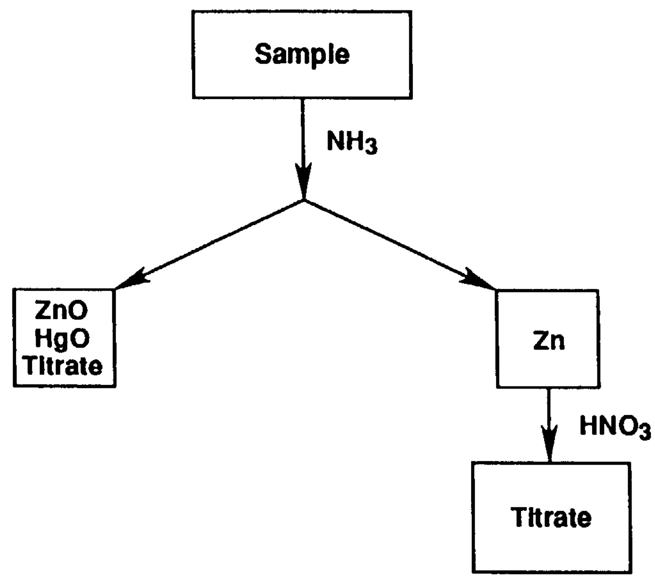
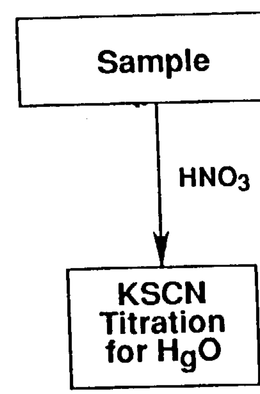
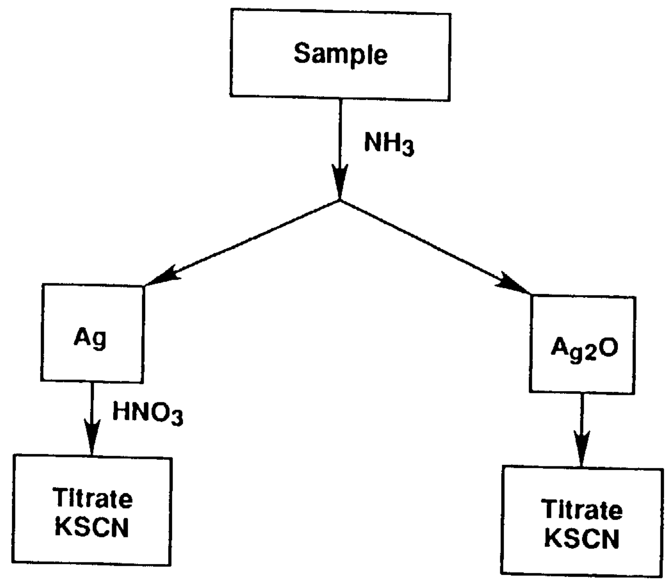
NH_3
Ni Cd
Ion Exchange
Ni Titrate
Cd Titrate
Ni Cd
Ion Exchange
Ni Titrate
Cd Titrate

Zinc




Sample
HNO3
KSCN
Titration
for HgO

Silver



Bottle	Sample Size (mg)	% HgO
024	452.9	1.13
038	402.9	1.01
090	408.4	.49
007	436.6	1.80

Ag-Zn	Ni-H2	Ni-Cd
9	1	25

NiCd DPA Summary

Type	Serial No.	Negative Charged Capacity	Prechg Ahrs	Ovrchg Protect Ahrs	History
RSN 55−15 (44)	189	20.50	20.50	19.40	100 acceptance cycles followed by storage
RSN 55−15 (44)	399	18.50	18.50	10.70	4 years activated storage followed by 444 LEO cycles
RSN 55−15 (44)	417	16.13	16.13	16.50	100 acceptance cycles followed by storage
RSN 55−15 (44)	438	21.60	21.60	19.70	4 yrs activated storage
RSN 55−15 (44)	440	20.02	20.02	22.50	4 yrs activated storage +128 LEO cycles
RSN 55−3 (41)	3	17.30	17.30	11.20	66 months activated storage
RSN 55−3 (41)	12	23.40	23.40	28.10	63 months activated storage
RSN 55−3 (41)	81	21.20	21.20	11.10	cycled 5 years
RSN 55−3 (41)	119	19.25	19.25		54 months activated storage
RSN 55−3 (41)	176	15.90	15.90	11.90	66 months activated storage
RSN 55−3 (41)	197	23.50	23.50		54 months activated storage
RSN 55−3 (41)	198	21.20	21.20	11.10	cycled 5 years
(40)	1399	15.80	15.80	1.97	cycled until the cells were badly deteriorated
(40)	1400	15.80	15.80	1.97	cycled until the cells were badly deteriorated
(40)	1406	15.80	15.80	1.97	cycled until the cells were badly deteriorated

NiCd DPA Summary

Type	Serial No.	Pos Plt. %Ni(OH)2 avg	Pos Plt. %Co(OI avg	Pos Plt. %NiOOH avg	Pos Plt. thickness avg (in.)	mg Cd Separ avg	mg Ni Separ avg	Positive Dischd Capacity	Positive Charged Capacity	Negative Dischd Capacity
RSN 55−15 (44)	189	48.62	3.37	5.40	0.0318	99.35	15.95	69.10	7.20	88.50
RSN 55−15 (44)	399	45.25	2.25	12.70	0.0300	152.60	8.95	70.60	14.98	81.30
RSN 55−15 (44)	417	49.57	3.27	5.47	0.0306	81.28	13.15	71.00	7.40	87.50
RSN 55−15 (44)	438	51.80	4.30	6.65	0.0297	63.90	3.95	64.20		83.90
RSN 55−15 (44)	440	46.60	3.90	11.35	0.0295	90.15	7.10	64.20	15.70	86.70
RSN 55−3 (41)	3	49.00	4.00	5.60	0.0286	136.00	8.73	76.30	5.62	87.50
RSN 55−3 (41)	12	49.00	2.20	5.40	0.0283	158.00		70.40	7.80	98.50
RSN 55−3 (41)	81	44.10	3.65	9.80	0.0302	117.24	9.70	71.30	14.70	82.40
RSN 55−3 (41)	119				0.0290					75.91
RSN 55−3 (41)	176	48.60	3.20	4.80	0.0282	145.70	20.30	73.80	6.80	85.70
RSN 55−3 (41)	197				0.0284					95.40
RSN 55−3 (41)	198	45.10	3.60	10.10	0.0301	129.40	8.80	71.30	14.70	82.40
(40)	1399	49.10	1.10	6.16	0.0311			70.93	9.62	72.90
(40)	1400	44.10	4.14	5.90	0.0314			70.93	9.62	72.90
(40)	1406	46.83	2.80	6.92	0.0310			70.93	9.62	72.90

N93-20495

COMSAT'S DESTRUCTIVE PHYSICAL ANALYSIS OF AEROSPACE NICKEL-CADMIUM CELLS FOR NASA/GODDARD SPACE FLIGHT CENTER

Kathleen M. B. Robbins
COMSAT Laboratories
Clarksburg, Maryland 20871

and

Gopalakrishna M. Rao and Thomas Y. Yi
Goddard Space Flight Center
Greenbelt, Maryland 20771

Over the past 5 years, COMSAT has performed numerous destructive physical analyses (DPAs) on NASA-Goddard-supplied nickel-cadmium (Ni/Cd) cells. The samples included activated but uncycled cells, wet stored cells, cycled cells, and anomalous cells. The DPAs provided visual, morphological, and chemical analyses of the cell components. The DPA data for the analyzed cells are presented herein. For the cells investigated, the leading cause of poor performance, as determined by DPA, has been poor negative electrode utilization, which resulted in negative-electrode-limiting operation.

INTRODUCTION

Traditionally, NASA/Goddard has requested destructive physical analyses (DPAs) on Ni/Cd cells with anomalous performance. This technique has been used to understand poor performance and failure mechanisms in the cells. COMSAT recommends DPAs of cell components and cells at the beginning of life to establish a database, which can then be used in determining causes of cell anomalies and for predicting cell life.

Over the past 5 years, COMSAT has performed approximately 20 DPAs (Table 1) on NASA-Goddard-supplied NASA Standard Ni/Cd cells. The majority of these cells have been of the NASA Standard 50-Ah design built since the mid 1980s. These samples have included wet stored cells, activated cycled and uncycled cells, and anomalous cells. The characteristics of anomalous cells have included accelerated separator degradation, cell shorting, and loss of overcharge protection. Although various reasons exist for poor cell performance, one characteristic that has become evident from DPA data is a negative-electrode-limited condition, where cell capacity is limited by the negative electrode on discharge. DPA provided evidence of this condition, which is caused by poor utilization in the negative plate.

RESULTS AND DISCUSSION

Electrical Cycling Performance

When cells are received for DPA, various electrical tests are performed to evaluate and characterize the cell. One area of poor performance in some of the NASA cells has been a continual drop in capacity with successive measurements (Table 2). This behavior indicates a negative-limited cell. The effect is also observed in the charge profile, where voltage rollover occurs at an earlier time with each successive cycle for a negative-limited cell (Figures 1 - 4). Voltage rollover is associated with the point where the cell goes into overcharge. Earlier voltage rollover indicates that charge input, and therefore capacity, is reduced in successive cycles. The negative-limited condition of the cell on discharge inhibits the positive electrode from being completely discharged. Consequently, the positive electrode, which is already in a partially charged state, will reach overcharge at an earlier point during the next charge period. In a positive-limited cell, the capacity of the rollover point remains fairly constant for a given charge rate.

At a C/10 charge rate at 10°C, rollover occurs where charge input approximately equals cell capacity. One positive-limited cell (UARS Lot 2 S/N 7), exhibited voltage rollover occurring much later than the point where charge input equaled cell capacity (Figure 5). This late rollover is atypical for a positive-limited cell.

The second evidence for a negative-limited cell can be found in the resistive discharge profile generated after a power discharge (Figure 6). The resistive discharge profile for a positive-limited cell exhibits a gradual drop in voltage to a plateau around 0.6 V. A sudden drop in voltage and a voltage plateau around 0.2 V indicate a negative-limited cell.

The third evidence from electrical testing for the negative-limited condition can be found in the voltage recovery stand, where the cell is discharged, shorted, and then open-circuited while the voltage is monitored (Figure 7). Negative-limited cells exhibit higher voltages throughout the 24-hr open circuit period. This higher voltage is likely a result of the higher state of charge of the positive electrode due to the negative-limited condition. Negative limited cells also exhibit fast voltage rise during the first hour of the voltage recovery stand. Positive-limited cells typically show more gradual initial voltage rise.

DPA Work

On completion of the electrical characterization, the cell is opened and visually examined. Comments are made on the physical condition of the cell components, electrolyte distribution, and overall cleanliness.

Chemical, electrical, and microscopic analyses are then performed on the cell components. The electrolyte is analyzed for potassium hydroxide (KOH) and potassium carbonate (K_2CO_3) concentrations. The separator is analyzed for cadmium content and tested for tensile strength. Positive and negative plates are chemically analyzed and electrically cycled in a flooded condition. Microscopic analysis is conducted on sample plates. Precharge and overcharge protection are then calculated for the cell.

The following text presents the results from DPA which confirm the negative limited condition. The source of this condition was determined to be poor performance of the negative electrode. The test results for the cell components (i. e., electrolyte, separator, and positive electrode) suggest that variations in results within these components have been due to natural degradation processes or are the result of the negative-limited condition of the cell.

Electrolyte

The K_2CO_3 and KOH concentrations were determined for the electrolyte (Table 3). As expected, carbonate concentrations increased with increased cycling due to separator degradation. In response to these changes, KOH concentrations also change. However, differences in hydroxide concentration could not be explained by the formation of carbonate alone. Some cells were found to contain excess water in the electrolyte. This excess was evidenced in lower KOH concentrations and increased electrolyte volume relative to quantities added during cell activation. As water is consumed at the positive electrode during discharge, excess water in the electrolyte can be explained by the fact that the positive electrode is not fully discharged. This condition is consistent with cells that are negative-limited in discharge.

The calculated electrolyte quantity per Ampere-hour of theoretical positive capacity was obtained by converting the total potassium weight to 30-weight percent KOH and dividing this by the theoretical cell capacity, which is based on positive plate active material loading. This value has typically been around 2 cm^3/Ah for the NASA 50-Ah Standard Cells. Differences in these values have been caused by variations in positive plate loading. The exceptions within the data reported here-in have been the IUE cells that were manufactured with more electrolyte.

Separators

The separators were characterized for their cadmium content (Table 4). Pellon 2505 was used in the cells analyzed. Cadmium migration into the separators was measured both by the amount per cell and the amount in the heaviest migrated area. As expected, increased cycling leads to increased migration. However, negative-limited cells have shown lower-than-expected cadmium migration levels, due to inactive cadmium in the negative electrode.

Positive Electrode

The positive plates were chemically and electrochemically analyzed. Positive electrode weight differences between cells have been due to loading differences between cell lots. Active nickel loading has typically been greater than 1.9 g/cm^3 of void volume (Table 5). Cobalt levels have been consistent among lots and account for approximately 5 weight percent of the total active material. The total cadmium in the plate comes from two sources: the cadmium added during manufacturing as an "antipolar mass," and that which has migrated from the negative to the positive electrode. Analysis of the cadmium in the positive plates has shown not only decreased cadmium migration in the negative-limited cells relative to the positive-limited cells, but also migration patterns within a plate where positive-limited cells contain more cadmium in the bottom of the positive plates (Figure 8).

Theoretical plate capacity was calculated assuming a one-electron transfer of the active $Ni(OH)_2$ during discharge. Cell utilization based on the theoretical positive cell capacity is typically around 85 to 90 percent for the positive electrode in a new cell. Because of the negative-limited condition and capacity fading in negative-limited cells, cell utilization has been as low as 70 percent. When in a flooded state, all positive plate performed well, with utilization of 85 percent or greater.

Negative Electrode

Chemically, there are only slight variations in active material loading between cell lots (Table 6). Loading also changes with cycle life due to cadmium migration. The major differences in negative plate characteristics between the subject cells are in the electrochemical performance of the negative plate. Negative electrodes from negative-limited cells have shown approximately 60 percent negative plate utilization, whereas negative electrodes from positive-limited cells have achieved 75 percent negative plate utilization.

Electron microscopic examination has been performed on the cross section of the plate (Figures 9 and 10) to qualitatively judge the pore and active material distributions in the negative plates. Backscattered electrons were used to generate the images shown, and X-ray maps were made to distinguish particle composition on plate cross sections. In the cross-sectional images, the brighter areas were determined to be cadmium rich, while the gray areas are sinter. Due to a lack of gray level contrast, charged and discharged cadmium could not be separated. Voids in the plate appear black. Plates from negative-limited cells were found to have cadmium agglomerating in the center of the plates. This condition would cause charged cadmium in the center of an agglomeration to become isolated and thus electrochemically unusable. This is believed to be responsible for the measured low utilization in these electrodes.

Surface cadmium crystals were also examined by scanning electron microscopy (Figures 11 and 12). The crystal sizes on the negative plates from positive- and negative-limited cells were different. The majority of crystals in a positive-limited cell were 1 μm in size, and occasionally a crystal as large as 20 μm was found. Conversely, negative-limited cells contain many larger crystals.

Precharge and Overcharge Protection

From the data on both the chemical and electrochemical analyses, precharge and overcharge protection (OCP) values were calculated for each cell (Table 7). The values for these parameters have varied from cell to cell and lot to lot. Generally, with increased cycling, there has been increased precharge capacity and loss of OCP due to separator degradation and loss in negative electrode utilization. Cells that were diagnosed as being negative-limited have shown a slight increase in precharge levels.

CONCLUSION

The electrical characterization and subsequent DPA data on NASA Standard Aerospace Ni/Cd cells have been collected. For the cells investigated, the leading cause of poor performance was poor negative plate utilization, which resulted in a negative-limited condition. This condition has been found in several cells manufactured since the mid 1980s.

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COMSAT'S DESTRUCTIVE PHYSICAL ANALYSIS OF AEROSPACE NICKEL-CADMIUM CELLS FOR NASA/GODDARD SPACE FLIGHT CENTER

Kathleen M. B. Robbins
COMSAT Laboratories
Clarksburg, MD 20871

Gopalakrishna M. Rao and Thomas Y. Yi
Goddard Space Flight Center
Greenbelt, MD 20771

November 17, 1992

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TABLE 1: LIST OF NASA/GSFC CELLS ANALYZED

CELL	HISTORY	TEST TYPE	Nameplate Capacity (Ah)	Plate Manufacturing Date	Cell Activation Date	Negative Limited Condition
IUE 3-010	ATP	RT storage	12	mid 1974	early 1975	
IUE 3-011	ATP	RT storage	12	mid 1974	early 1975	
TDRSS 15-78	ATP	cold storage	40	late 1981	mid 1983	
EUVE 16-053	ATP	cold storage	50	early 1985	early 1988	
EUVE 4-005 back-up	ATP	cold storage	50	early 1990	late 1990	bordeline
EUVE 4-068 back-up	Battery ATP		50	early 1990	late 1990	yes
GOES 5-110	I AND T		12	late 1986	late 1988	
TDRSS L8-69	60 cycles	test battery	40	mid 1980	early 1982	
GRO 17-073	576 cycles	40 % DOD	50	early 1985	late 1988	
EUVE 16-030	2480 cycles	40 % DOD	50	early 1985	early 1988	yes
EUVE 16-079	3900 cycles	15 % DOD	50	early 1985	early 1986	
UARS 2-073	5010 cycles	15 % DOD	50	late 1988/1989	late 1989	yes
EUVE 16-014	5360 cycles	40 % DOD	50	early 1985	early 1988	yes
UARS 2-007	5500 cycles	40 % DOD	50	late 1988/1989	late 1989	
UARS 2-021	5700 cycles	40 % DOD	50	late 1988/1989	late 1989	borderline
COBE 15-005	6000 cycles	40 % DOD	50	mid 1985	late 1985	
EUVE 16-003	10600 cycles	15 % DOD	50	early 1985	early 1986	
GRO 17-063	11800 cycles	15 % DOD	50	early 1985	late 1988	yes

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Ni-Cd CELL DPA

ELECTRICAL CHARACTERIZATION
- C/2 Rate of Discharge
- Charge Retention
- Charge Efficiency
- Voltage Recovery

ELECTROLYTE
- Composition
- Distribution

SEPARATOR
- Absorbency
- Wicking
- Resistivity
- Mechanical Strength
- Cadmium Migration

POSITIVE PLATES
- Weight and Thickness
- Tensile Strength
- Corrosion of Plaque
- Active Material
  - Loading
  - Distribution
- Cadmium Distribution
- Flooded Capacity
- High Rate Cycling

NEGATIVE PLATES
- Weight and Thickness
- Tensile Strength
- Active Material Loading
- Flooded Capacity
- High Rate Cycling

PRECHARGE CAPACITY

OVERCHARGE PROTECTION

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TABLE 2: TESTING REGIMEN AND CAPACITIES FOR 50 Ah CELLS

					LOT 16-053 ATP POS LIM Capacity (Ah)			LOT 4-068 Battery ATP NEG LIM Capacity (Ah)			LOT 16-003 10600 LIFE POS LIM Capacity (Ah)			LOT 17-063 11800 LIFE NEG LIM Capacity (Ah)			LOT 2-007 5500 STRESS LOSS OCP Capacity (Ah)		
CYCLE	TEMP (°C)	CH HR	CH I(A)	DCH I(A)	EOCV	1.0 V	0.1 V	EOCV	1.0 V	0.1 V	EOCV	1.0 V	0.1 V	EOCV	1.0 V	0.1 V	EOCV	1.0 V	0.1 V
recond	10	48	2.5	25	1.490	66.3	66.9	1.487	64.5	65.2	1.501	63.4	63.7	1.484	58.4	59.4	1.533	62.1	63.7
1	10	16	5	25	1.503	66.1	66.9	1.495	61.6	62.4	1.519	62.2	63.0	1.493	55.2	56.3	1.570	61.5	63.0
2	10	16	5	25	1.494	65.0	66.3	1.487	58.4	59.4	1.518	62.1	62.6	1.489	51.8	52.8	1.569	61.3	62.6
3 *	10	16	5	25	1.492	58.6	59.9				1.518	56.7	59.1	1.486	43.1	44.0			
			% return				90.3						92.7			83.4			
4 **	10	16	5	25	1.492	64.0	-	1.484	57.2	-		62.9	-		48.7	-	1.571	61.1	-
				1Ω		-	75.7		-	64.0		-	76.2		-	56.2		-	73.3

* charge retention test - 72 hour open circuit stand after complete charge
percent of capacity remaining

** voltage recovery test - discharged with 1Ω after power discharge to 1.0 V
then shorted for 16 hours

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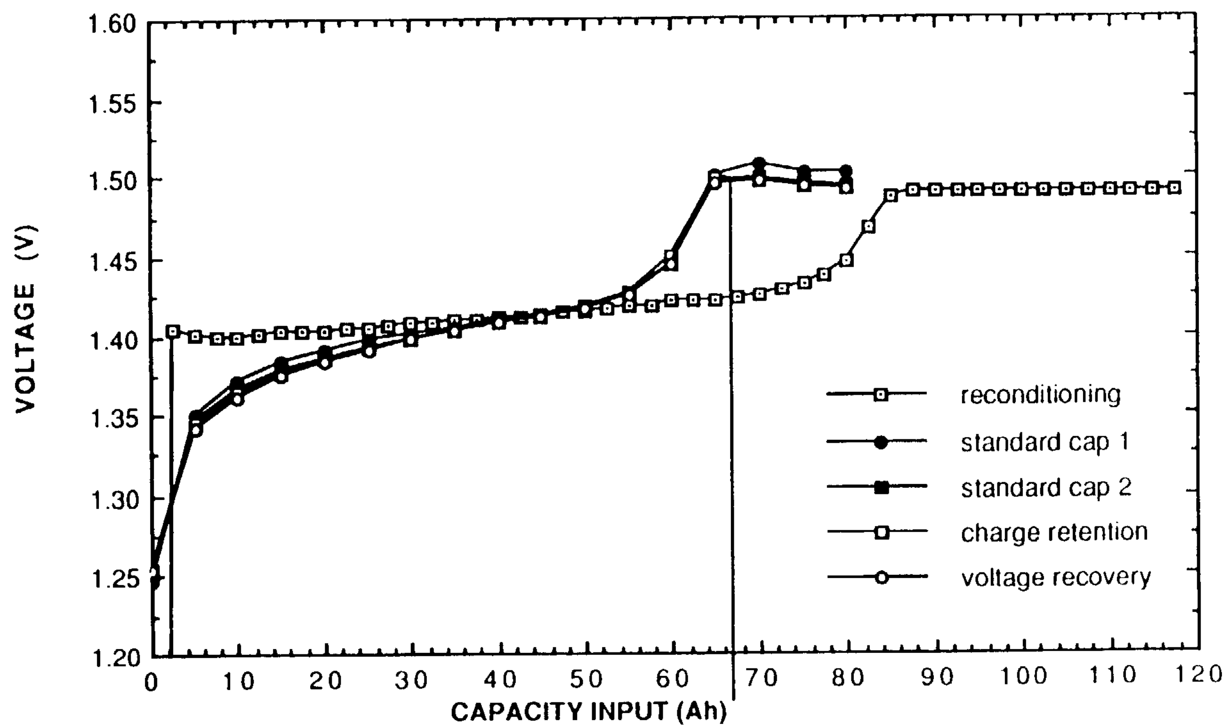
FIGURE 1: CHARGE PROFILES NASA-EUVE S/N 16-53 POSITIVE LIMITED



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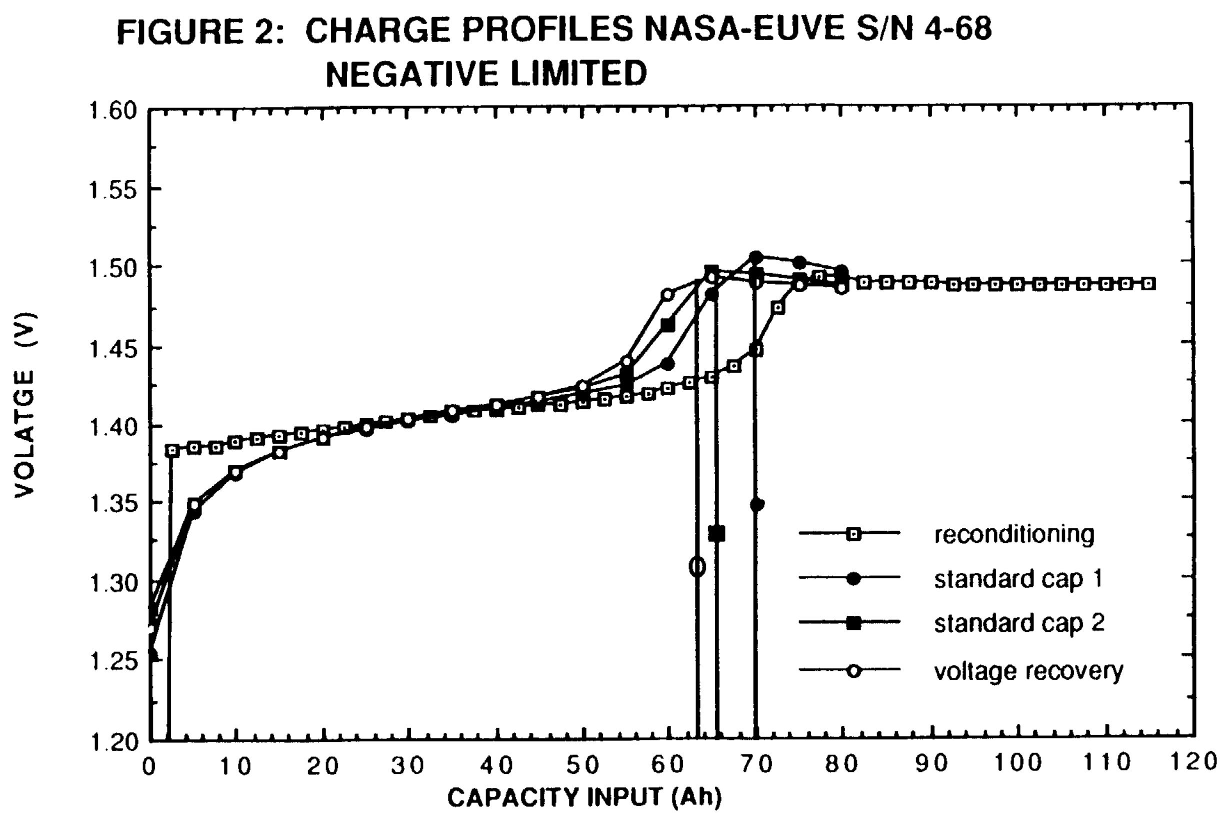

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FIGURE 3: CHARGE PROFILES- EUVE S/N 16-003 POSITIVE LIMITED

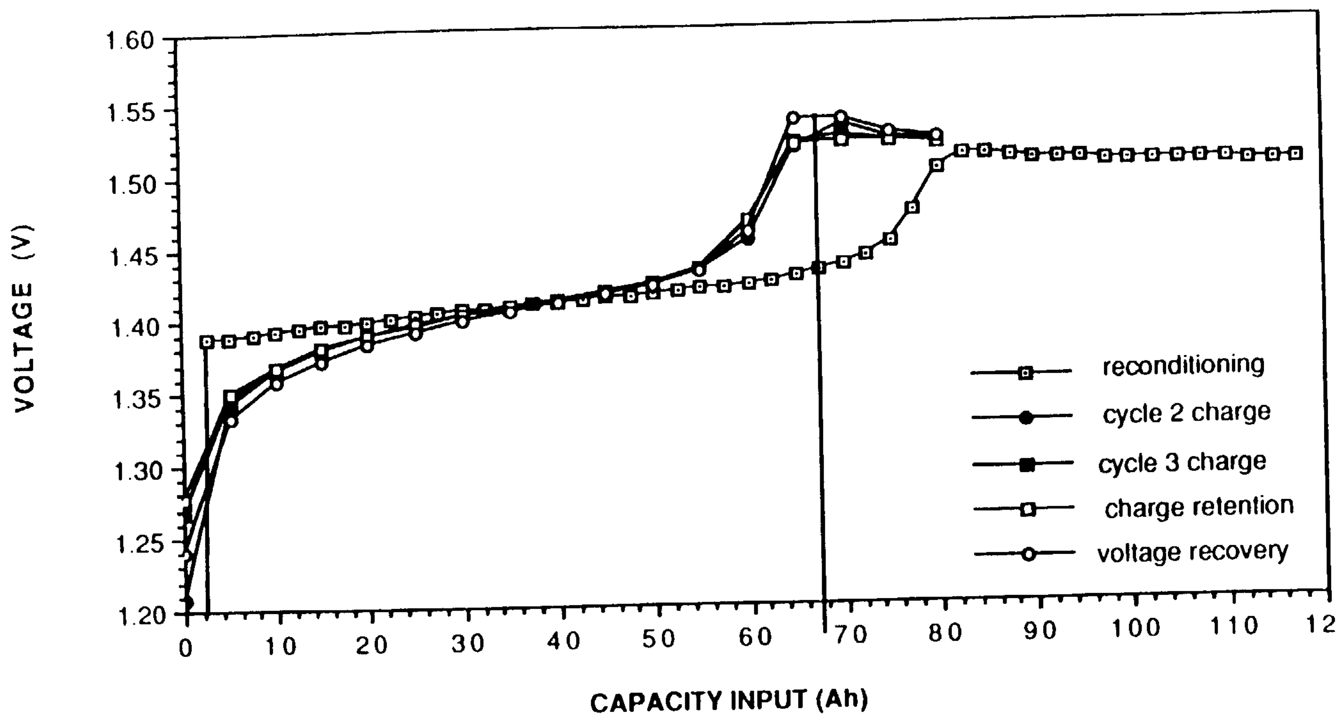

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FIGURE 4: CHARGE PROFILES - GRO S/N 17-063
NEGATIVE LIMITED

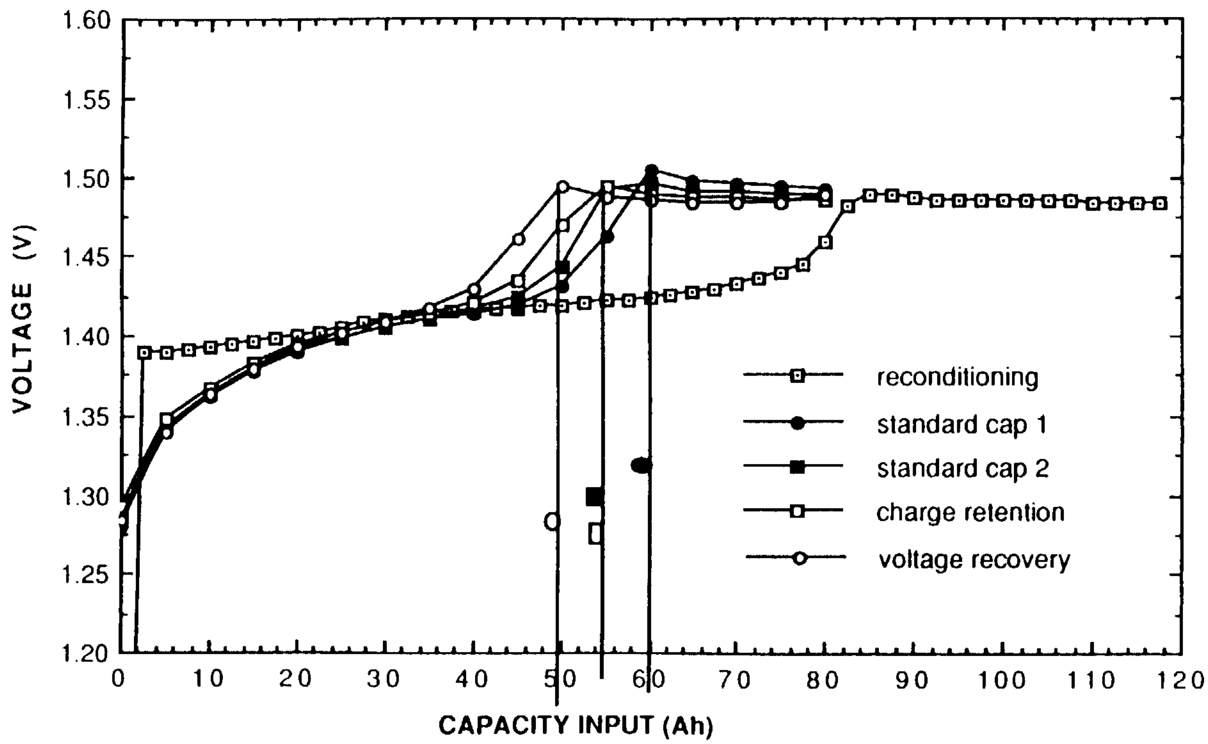

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FIGURE 5: CHARGE VOLTAGE PROFILES LOT 2 S/N 7 POSITIVE LIMITED

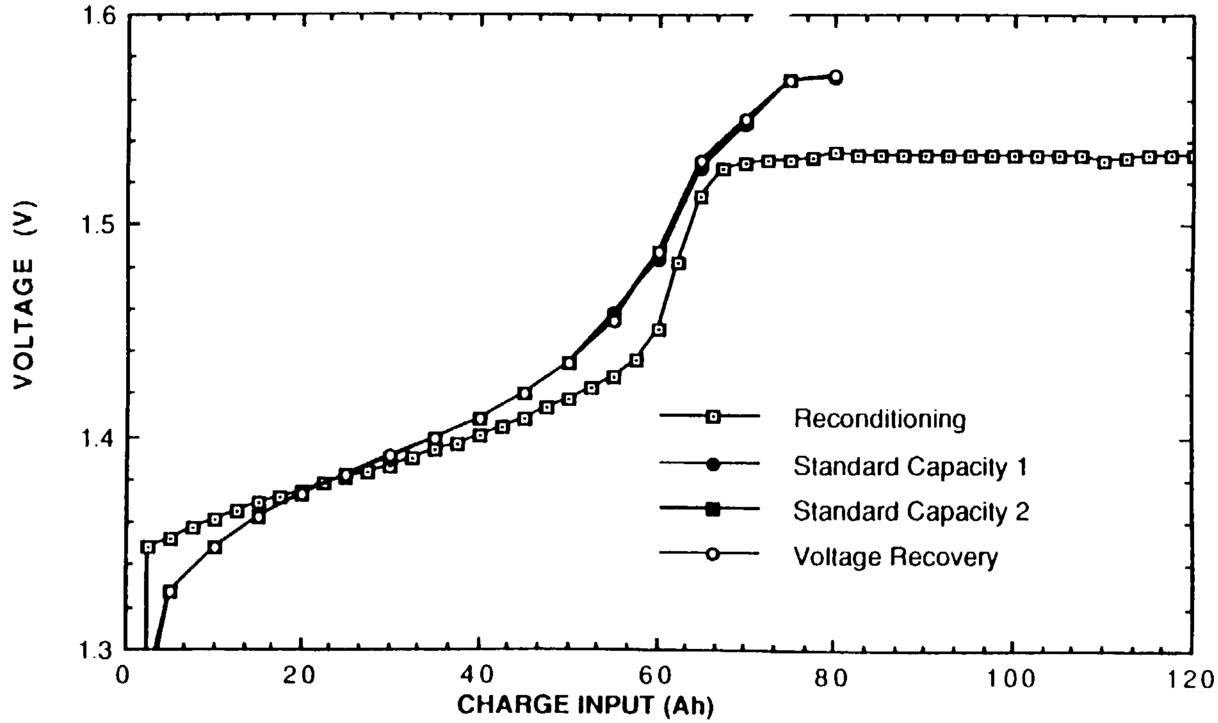

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FIGURE 6: RESISTIVE DISCHARGE PROFILES

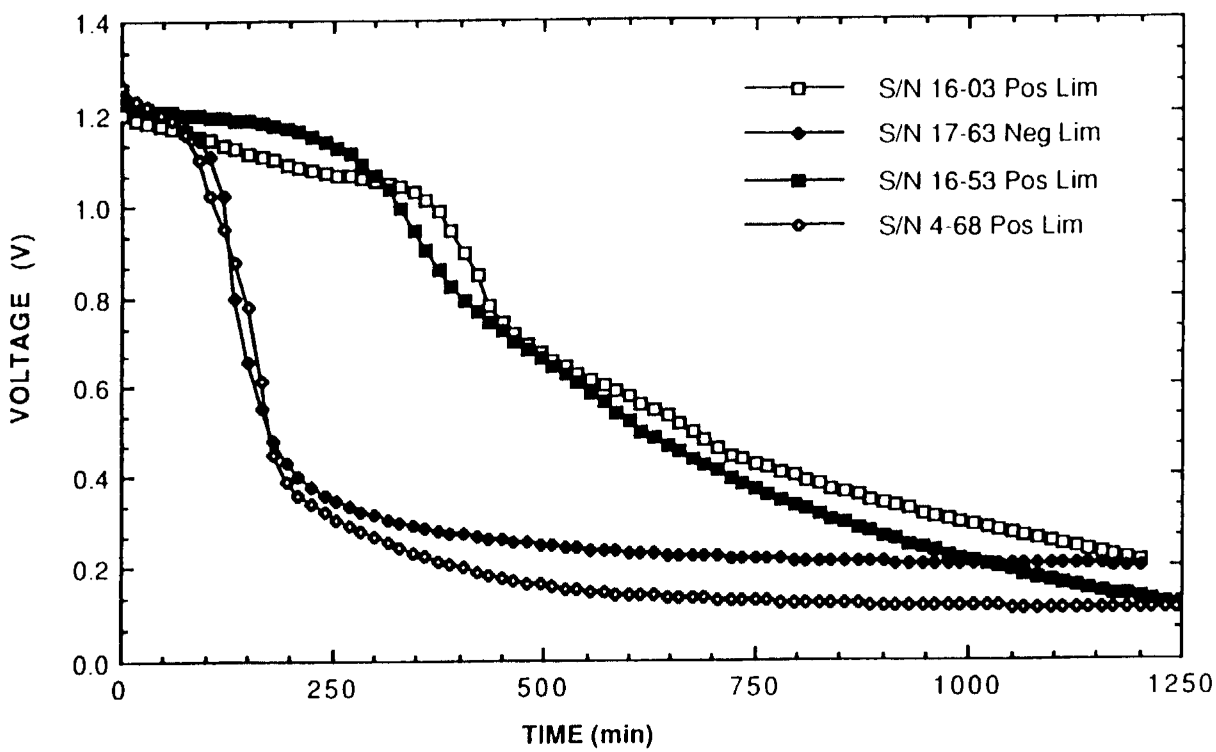

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FIGURE 7: 24 HOUR VOLTAGE RECOVERY STAND

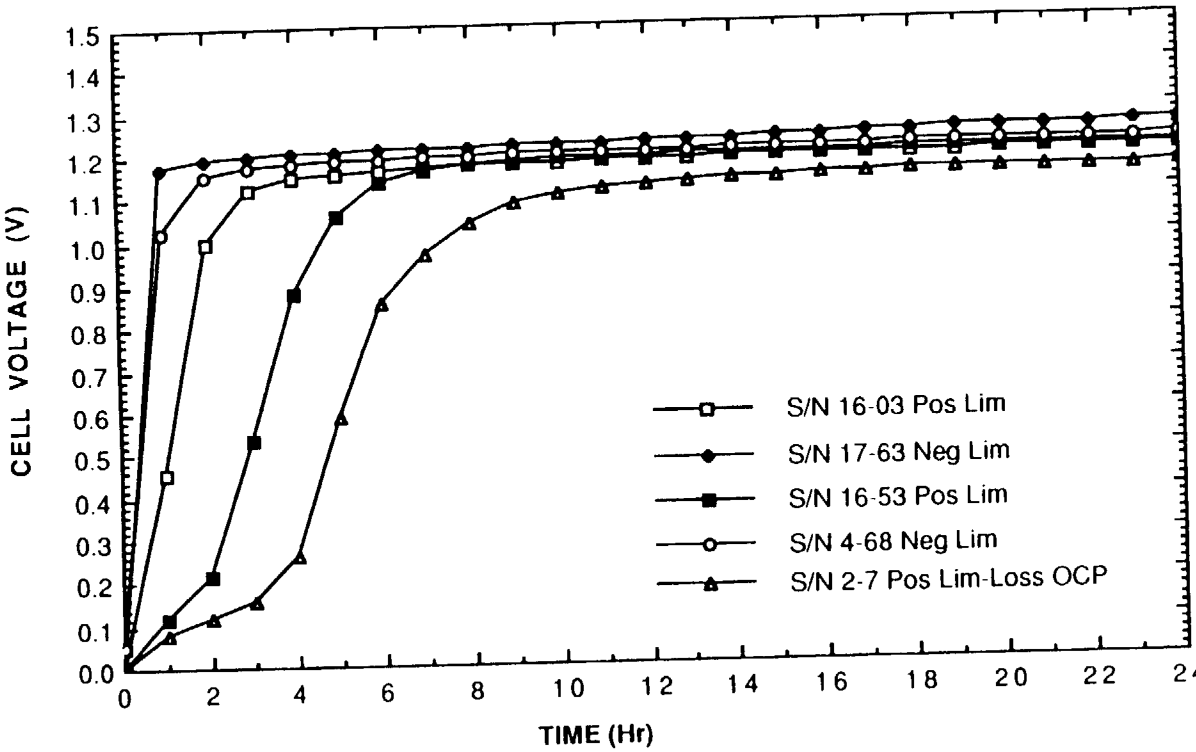

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TABLE 3: ELECTROLYTE COMPARISONS

CELL	HISTORY	Negative Limited	Nameplate Capacity (Ah)	Reported Fill Volume of 31 % (mL)	Volume (Theor KOH) (mL)	KOH Concentration (w/o)	K2CO3 Concentration (w/o)	Theoretical KOH (w/o)	cc/Ah
IUE 3-010	ATP		12	46	46.5	24.0	7.1	29.8	2.44
IUE 3-011	ATP		12	46	47.3	20.9	10.3	29.2	ND
TDRSS 15-78	ATP		40	120	123.9	27.3	3.5	30.1	2.06
EUVE 16-053	ATP		50	150	147.6	28.5	4.3	32.0	2.22
EUVE 4-005 backup	ATP	borderline	50	162	165.4	26.1	3.9	29.3	2.10
EUVE 4-068 backup	Battery ATP	yes	50	162	171.3	24.5	5.1	28.7	2.10
GOES 5-110	I AND T		12	30.5	35.1	18.9	11.0	27.8	2.03
TDRSS 8-69	60 cycles		40	120	129.2	21.5	7.4	27.6	2.05
GRO 17-073	576 cycles		50	163	161.8	26.5	5.1	30.7	2.14
EUVE 16-030	2480 cycles	yes	50	153	169.6	23.9	5.2	28.2	1.99
EUVE 16-079	3900 cycles		50	150	153.4	25.1	5.7	29.7	1.99
UARS 2-073	5010 cycles	yes	50	155	160.4	26.0	5.4	30.4	2.26
EUVE 16-014	5360 cycles	yes	50	153	160.7	20.6	5.8	25.6	1.73
UARS 2-007	5500 cycles		50	155	154.8	26.6	7.0	32.2	2.29
UARS 2-021	5700 cycles	borderline	50	163.8	174.9	24.2	6.7	29.7	2.35
COBE 15-005	6000 cycles		50	166	172.8	24.1	6.3	29.2	2.25
EUVE 16-003	10600 cycles		50	150	151.3	24.6	7.2	30.4	2.09
GRO 17-063	11800 cycles	yes	50	160	162.1	23.7	7.1	29.4	1.95

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TABLE 4: CADMIUM MIGRATION INTO THE SEPARATORS

CELL	HISTORY		TOTAL IN ALL SEPARATORS (g/cell)	(mg/sep. area)	HEAVIEST AREA OF MIGRATION (mg/cm^2)
TDRSS 15-78	ATP		0.40	0.16	0.7
EUVE 16-53	ATP		0.51	0.11	2.6
EUVE 4-05 backup	ATP	NL	0.40	0.09	0.3
EUVE 04-068 backup	Battery ATP	NL	0.61	0.13	1.6
GOES 05-110	I and T		0.10	0.05	0.4
TDRSS 8-69	60 cycles	L	0.76	0.31	0.6
GRO 17-073	576 cycles	S	0.49	0.11	0.9
EUVE 16-30	2480 cycles	S NL	0.51	0.11	0.7
EUVE 16-79*	3900 cycles	L	1.82	0.40	9.6
UARS 2-073	5010 cycles	L NL	1.28	0.28	5.9
EUVE 16-014	5360 cycles	S NL	0.68	0.15	1.1
UARS 2-007	5500 cycles	S	12.10	2.65	7.6
UARS 2-021	5700 cycles	S NL	1.37	0.30	1.5
COBE 15-5	6000 cycles	S	1.00	0.22	8.3
EUVE 16-003*	10600 cycles	L	2.86	0.63	9.9
GRO 17-063 *	11800 cycles	L NL	1.14	0.25	11.7

* = separator sticking may effect results for Cd in all separators.
NL = capacity limited by the negative electrode
S = stress cycling, 40 % DOD
L = life cycling, 15 % DOD

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TABLE 5: POSITIVE PLATE ANALYSIS COMPARISON

Identification	History	Ni(OH)2 (%)	Co(OH)2 (%)	Cd(OH)2 (%)	Sinter (%)	Substrate (%)	Porosity Sinter (%)	Porosity Plaque (%)	Loading Ni (g/cc)	Loading Total (g/cc)	Utilization Plate (%)	Utilization Cell (%)	
IUE 3-10	ATP	44.5	2.7	3.1	28.3	19.8	87.8	80.2	1.93	2.25	76.8	74.0	
TDRSS 15-78	ATP	41.3	2.6	5.6	30.6	19.8	86.8	79.2	1.82	2.18	92.9	94.4	
EUVE 16-53	ATP	41.4	2.1	4.4	28.4	20.0	87.6	79.7	1.84	2.29	89.7	87.3	
EUVE 4-05 backup	ATP	44.7	2.6	3.6	28.2	17.7	87.9	81.0	1.94	2.34	83.2	75.0	NL
EUVE 4-68 backup	BATT	44.9	2.6	3.6	28.7	17.3	87.8	81.0	1.94	2.34	84.1	75.1	NL
GOES 5-110	I and T	42.4	2.8	3.4	33.1	16.4	85.9	79.6	1.87	2.23	83.0	83.0	
TDRSS 8-69	60 Life	43.2	2.9	4.3	32.1	17.4	85.3	78.3	2.06	2.40	72.9	75.8	
GRO 17-73	576 Stress	43.9	1.9	5.0	28.9	18.5	87.4	80.0	1.95	2.34	84.1	77.3	
EUVE 16-30	2480 Stress	43.7	1.6	5.9	28.3	18.8	87.2	79.6	2.01	2.43	78.7	63.0	NL
GRO 16-79	3900 Life	43.5	2.4	4.7	28.4	19.1	87.5	79.9	1.94	2.35	86.4	83.4	
UARS 2-73	5010 Life	41.9	2.2	4.5	30.6	19.1	87.1	79.8	1.81	2.17	83.1	71.4	NL
EUVE 16-14	5360 Stress	42.5	2.1	7.3	28.7	18.3	87.06	79.6	2.0	2.44	78.2	63.3	NL
UARS 2-07	5500 Stress	41.6	2.2	5.5	29.8	19.4	87.7	80.4	1.74	2.13	84.6	84.4	
UARS 2-21	5700 Stress	42.6	2.4	5.5	28.4	18.4	88.2	81.1	1.79	2.24	84.2	78.6	NL
COBE 15-5	6000 Stress	42.0	2.2	5.7	29.3	20.3	87.7	79.9	1.80	2.15	85.0	78.3	
EUVE 16-03	10600 Life	41.7	2.1	6.7	29.4	18.1	87.0	79.8	1.88	2.37	85.4	84.4	
GRO 17-63	11800 Life	46.3	2.1	5.0	27.4	19.1	88.2	80.7	2.01	2.32	81.0	59.7	NL

NL = negative limited

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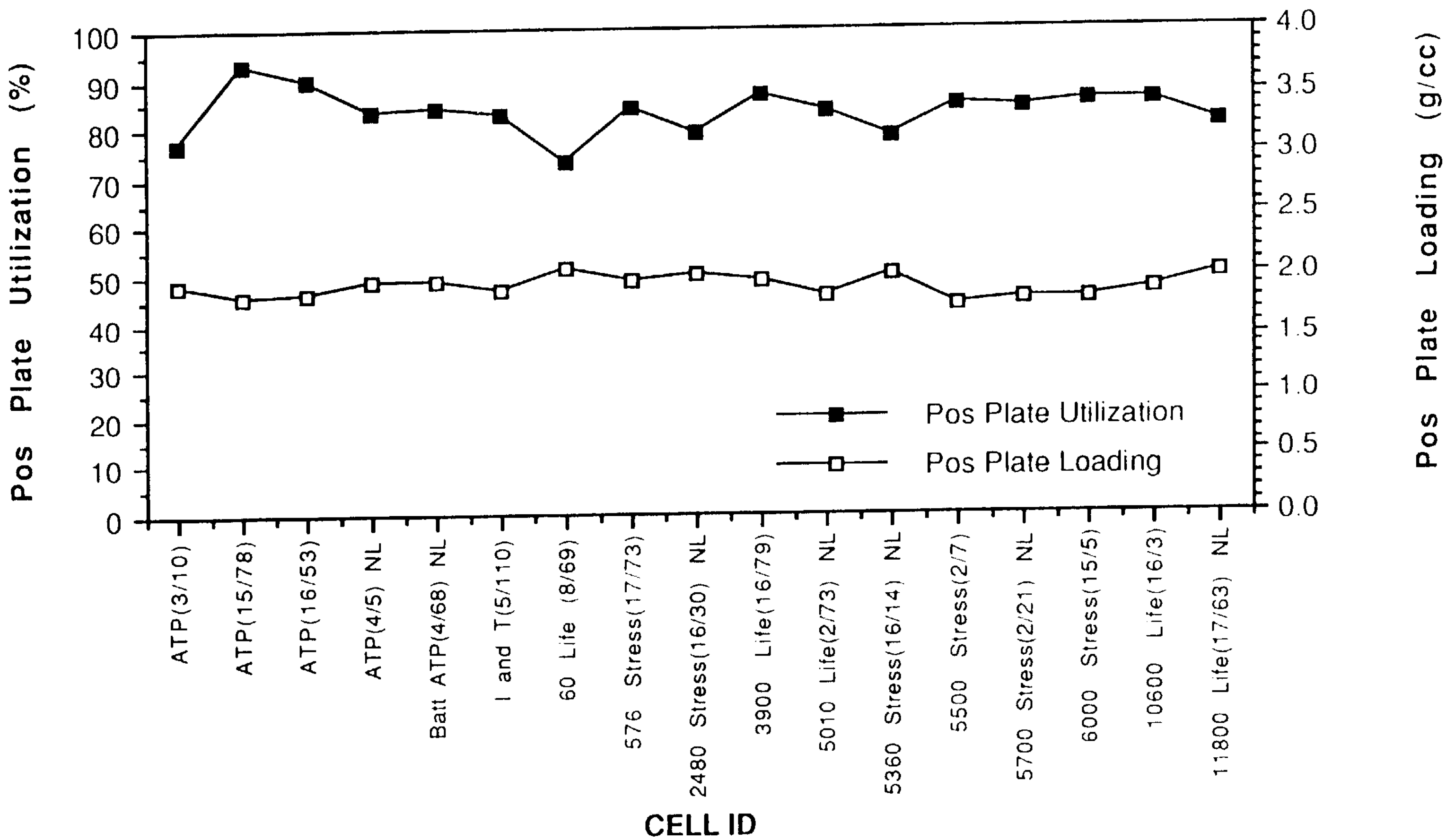
POSITIVE PLATE CHARACTERISTICS



COMSAT Laboratories

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FIGURE 8: CADMIUM CONCENTRATION IN THE POSITIVE PLATES

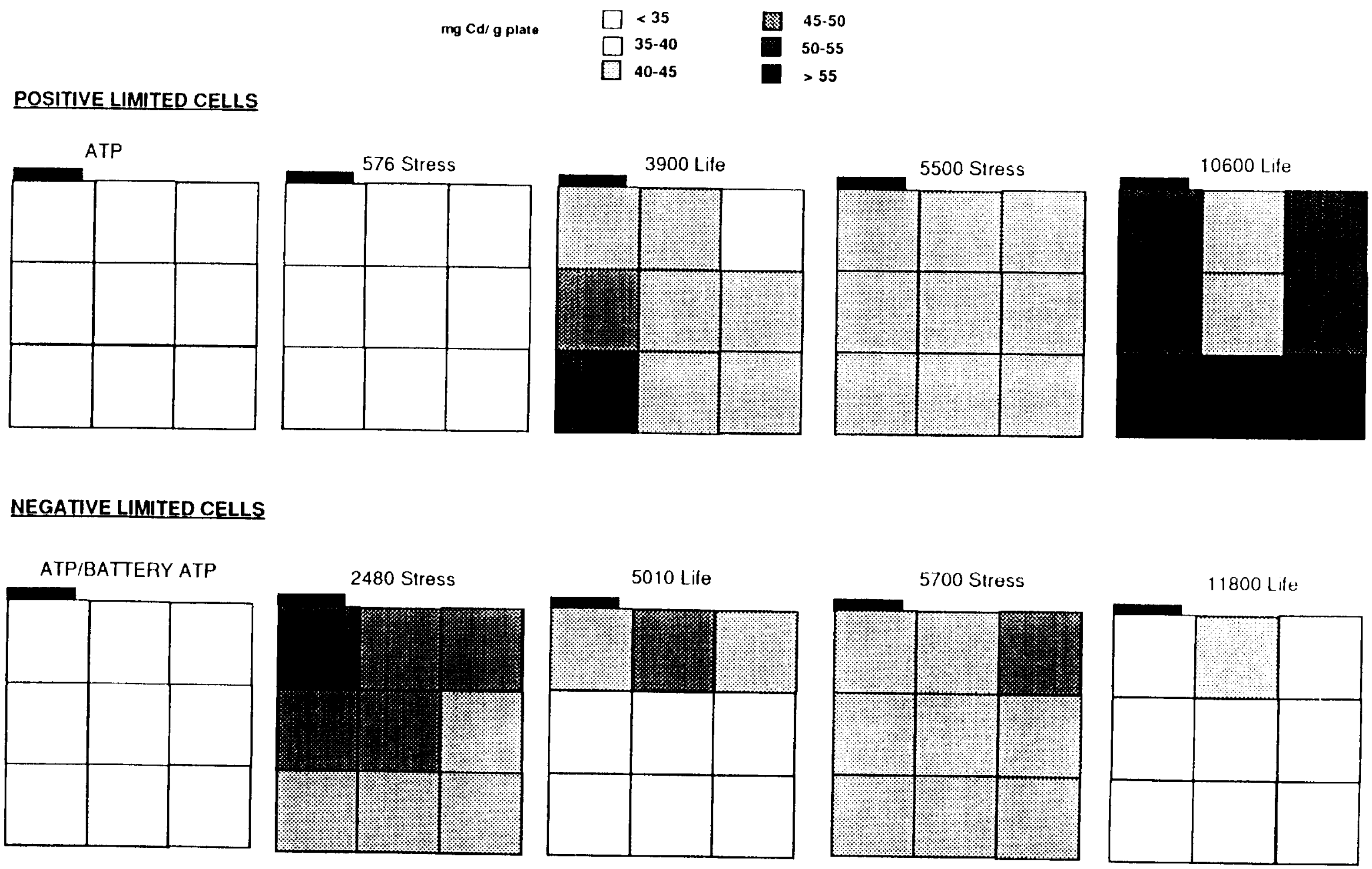

TABLE 6: NEGATIVE PLATE ANALYSIS SUMMARY

Identification	History	Cd(OH)2 (%)	Cd (%)	Ni (%)	Ni(OH)2 (%)	Fe (%)	Loading (g Cd/g plate) Cd(OH)2	Cd	Total	Normalized Loading (g Cd/g)	Flooded Capacity (Ah)	Plate Utilization (%)	
IUE L3-10	ATP	44.4	2.4	35.3	3.7	14.1	0.341	0.024	0.365	0.407	1.87	64.4	
TDRSS L15-78	ATP	43.1	4.3	34.5	2.8	15.0	0.331	0.043	0.373	0.416	4.10	76.0	
EUVE L16-53	ATP	46.3	2.0	31.1	3.6	14.0	0.356	0.020	0.375	0.422	5.96	76.0	
EUVE L4-5 backup	ATP	41.8	5.7	33.2	3.8	14.4	0.321	0.058	0.378	0.420	5.10	63.4	**NL**
EUVE L4-68 backup	BATT ATP	36.0	9.1	34.3	4.1	13.8	0.276	0.092	0.367	0.402	4.60	59.9	**NL**
GOES L5-110	I AND T	38.5	7.0	33.9	1.6	15.6	0.296	0.070	0.366	0.402	1.60	72.0	
TDRSS L8-69	60 LEO	44.1	3.9	33.7	3.9	13.7	0.339	0.039	0.378	0.421	3.60	60.6	
GRO L17-73	576 Stress	42.1	5.6	35.9	3.4	12.8	0.323	0.056	0.379	0.420	4.79	60.5	
EUVE L16-30	2480 Stress	37.0	10.1	34.1	3.8	13.7	0.284	0.101	0.386	0.421	4.08	51.6	**NL**
EUVE L16-79	3900 Life	43.6	3.4	32.1	3.7	14.7	0.335	0.034	0.368	0.411	5.66	74.7	
UARS L2-73	5010 Life	36.1	7.8	35.2	4.5	13.3	0.277	0.078	0.355	0.388	4.48	61.1	**NL**
EUVE L16-14	5360 Stress	36.8	8.2	36.4	4.4	14.2	0.283	0.083	0.365	0.400	4.07	55.4	**NL**
UARS L2-7	5500 Stress	37.1	6.7	36.5	3.7	14.3	0.285	0.067	0.352	0.385	5.15	73.7	
UARS L2-21	5700 Stress	32.7	10.8	36.3	4.4	13.5	0.251	0.108	0.359	0.389	4.55	62.0	**NL**
COBE L15-5	6000 Stress	35.0	11.1	33.1	4.7	14.7	0.269	0.111	0.380	0.414	4.32	57.0	
EUVE L16-3	10600 Life	39.7	7.3	34.4	3.6	14.6	0.305	0.074	0.378	0.418	4.83	63.7	
GRO L17-63	11800 Life	37.9	9.6	35.2	4.2	12.4	0.291	0.096	0.387	0.424	4.24	54.4	**NL**

NL = negative limited

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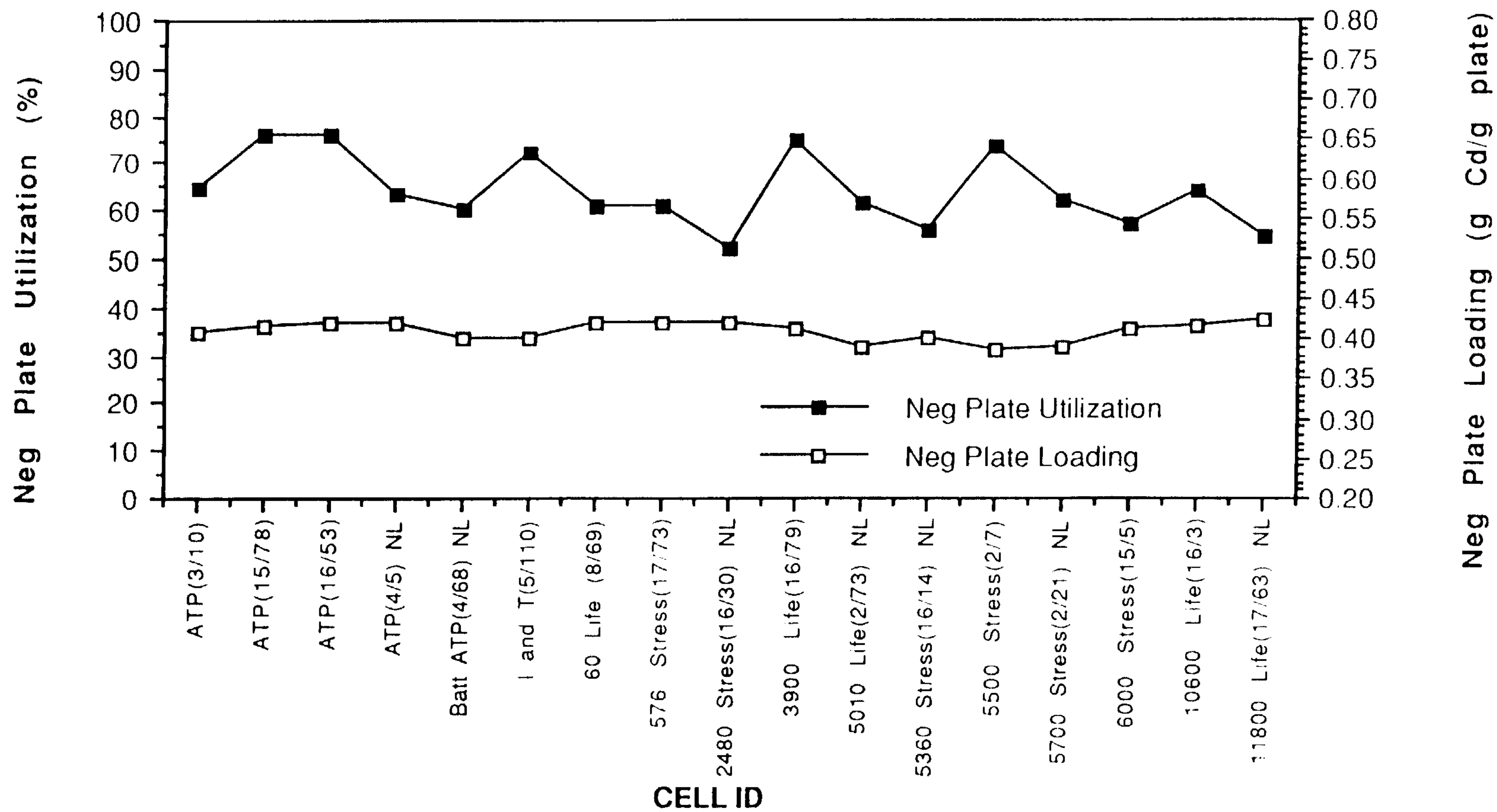
NEGATIVE PLATE CHARACTERISTICS



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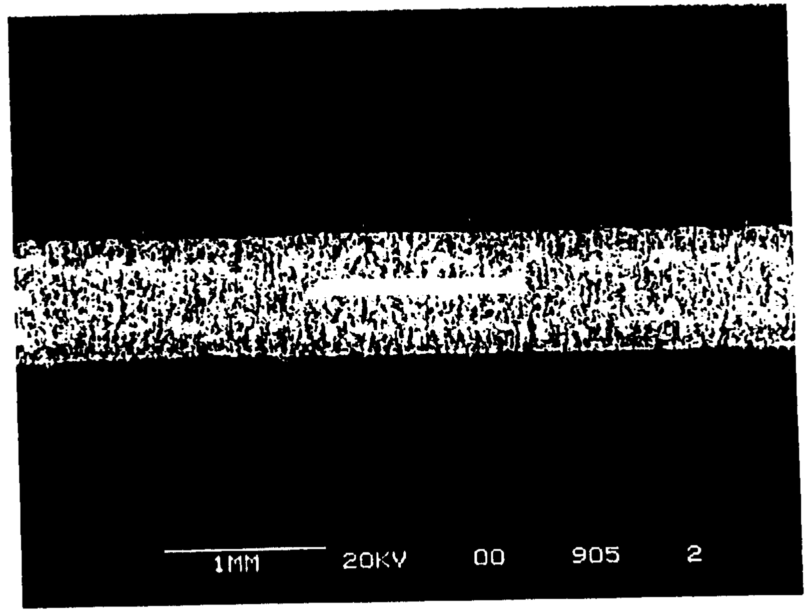
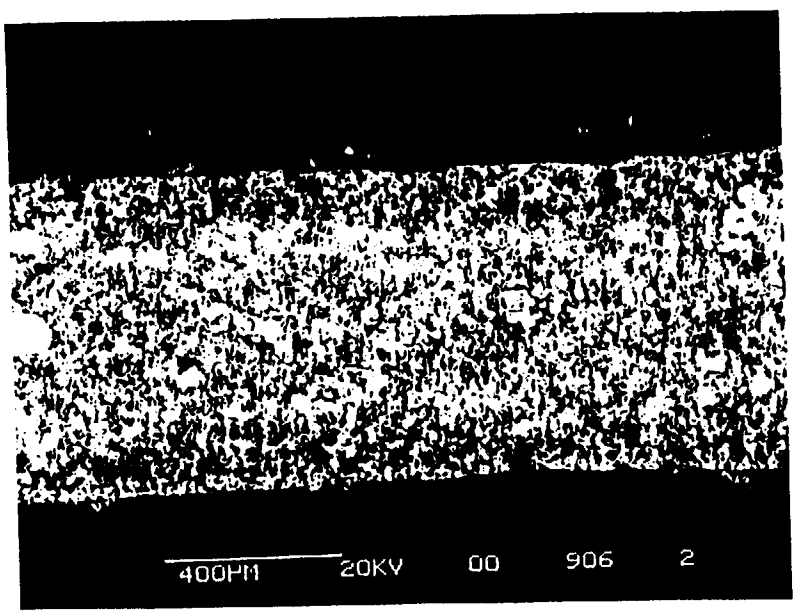
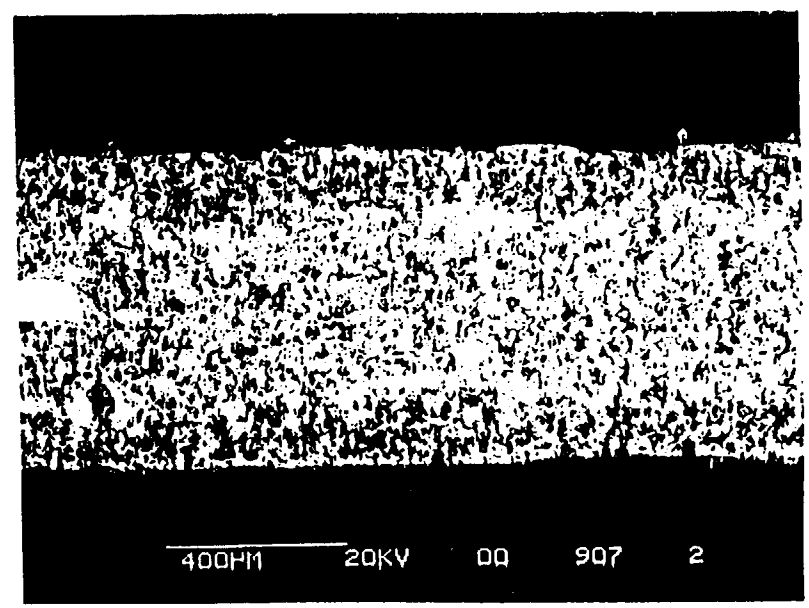


FIGURE 9:

POSITIVE LIMITED CELL

BSE Analysis of Cross Section
of Negative Plate #15
UARS 1 of 2 S/N 7





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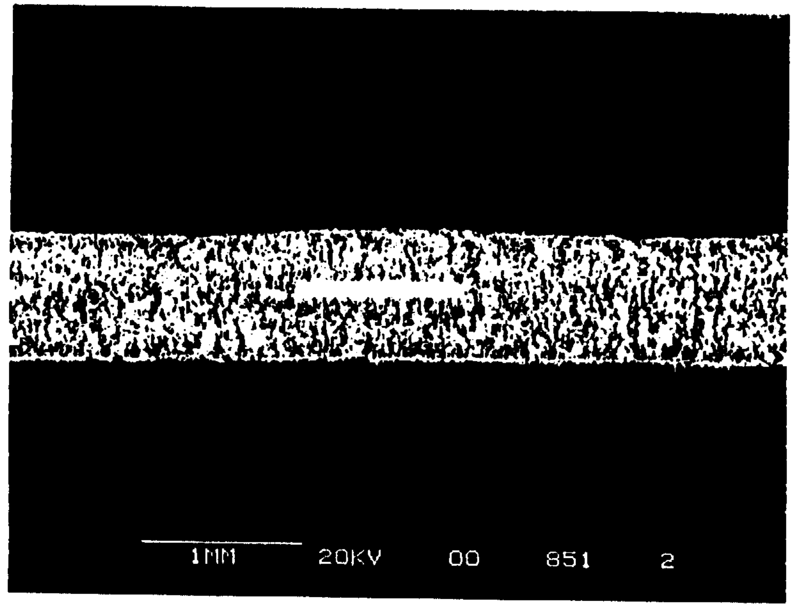
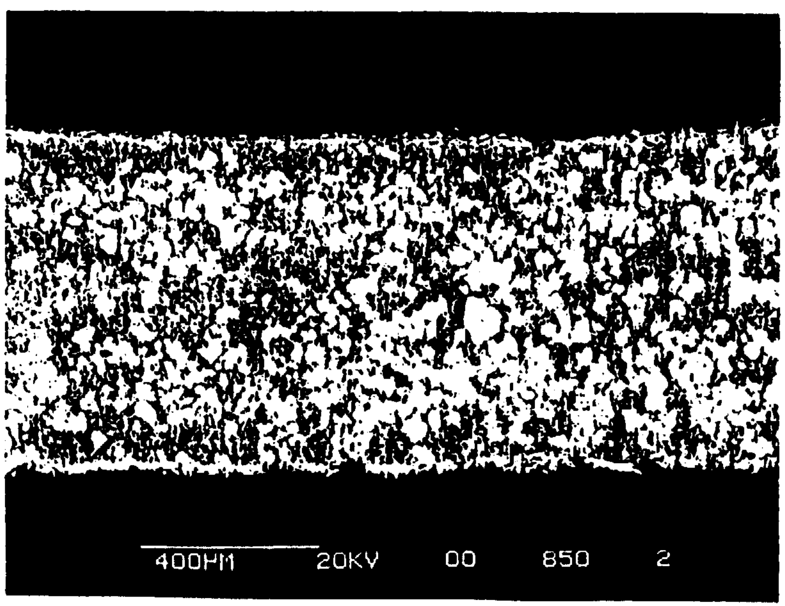
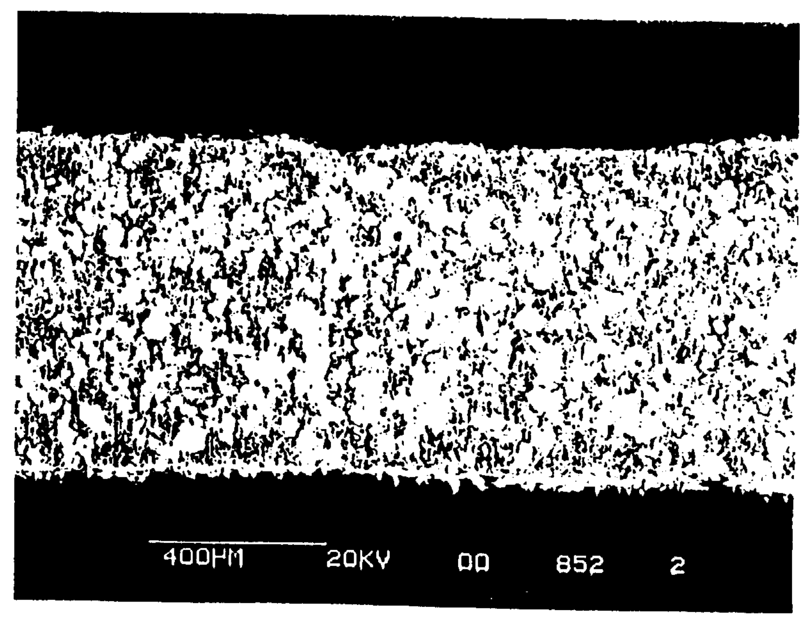


FIGURE 10:

NEGATIVE LIMITED CELL

BSE Analysis of Cross Section of Negative Plate #17
UARS Lot ? S/N 73





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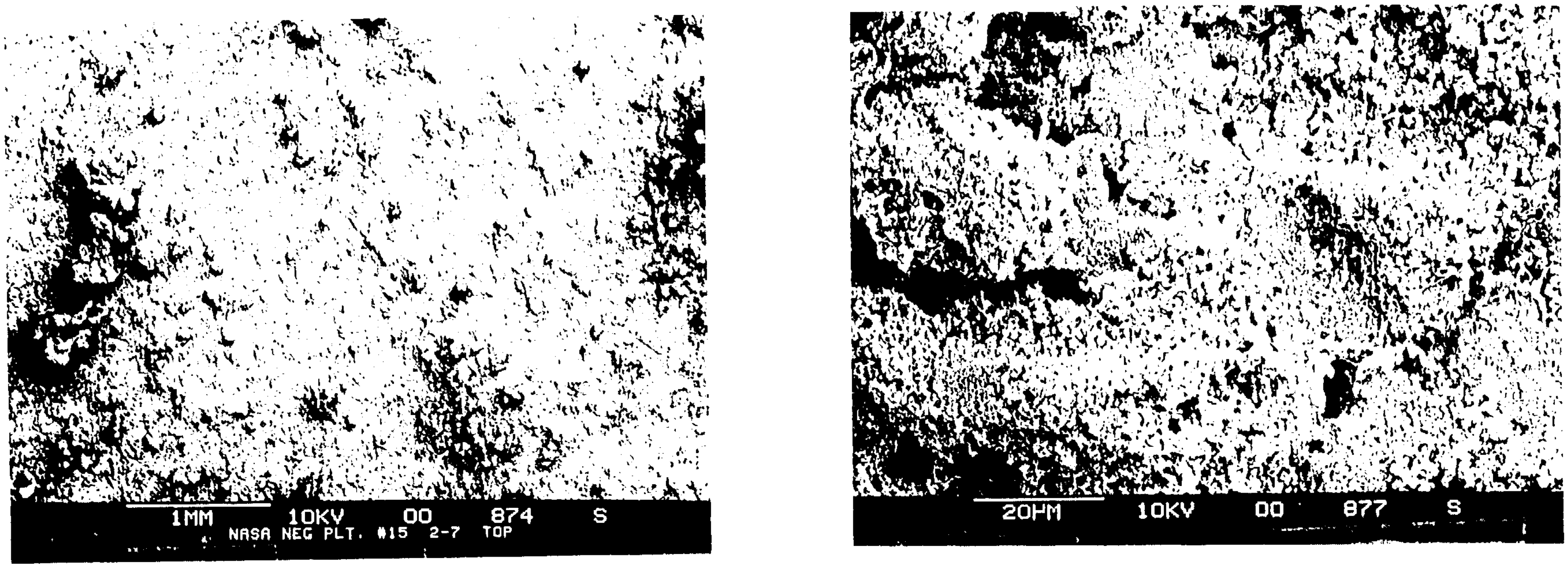
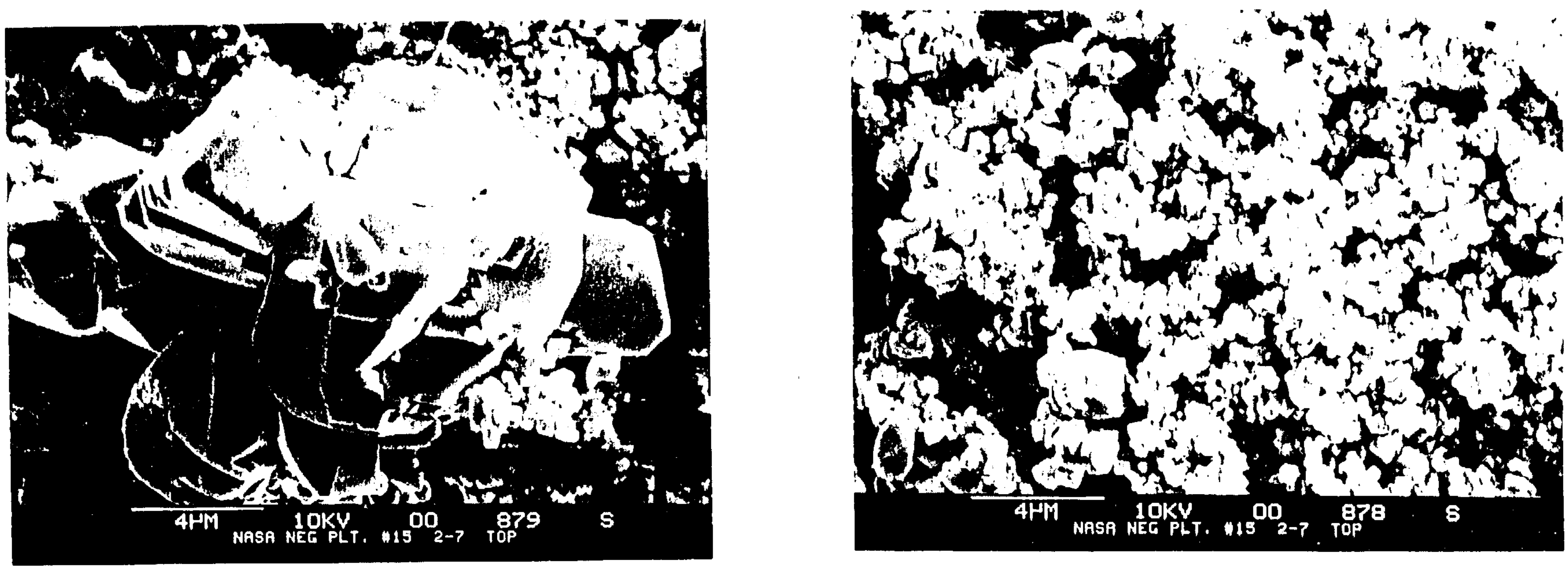


FIGURE 11: SEM Analysis of Top of Negative Plate #15 - UARS Lot 2 S/N 7 POSITIVE LIMITED



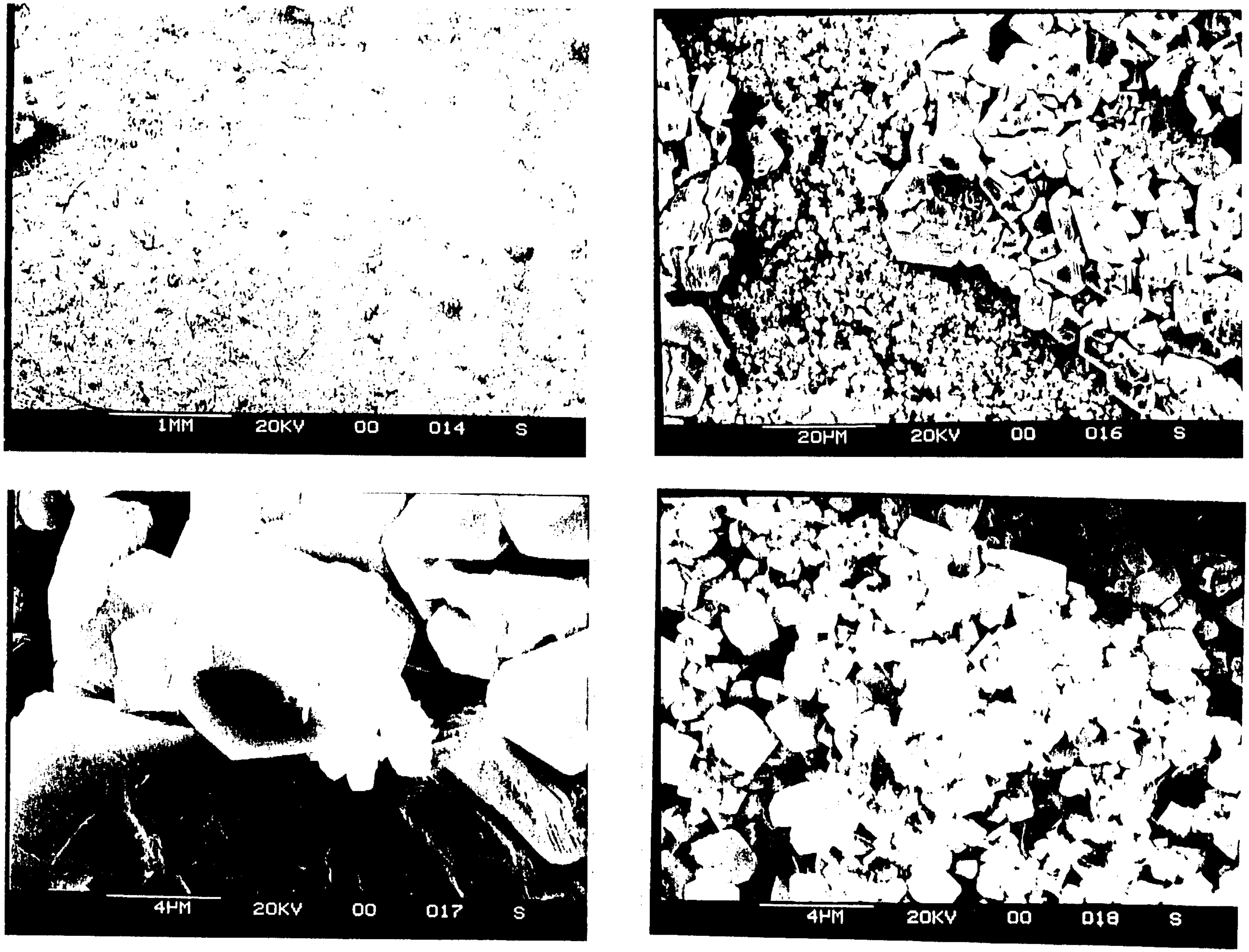


FIGURE 12: SEM Analysis of Bottom of Negative Plate #15 - UARS Lot 2, S/N 21

NEGATIVE LIMITED

TABLE 7: PRECHARGE AND OVERCHARGE PROTECTION

Identification	History	Chemical Negative Capacity (Ah)	Cell Capacity (Ah)	Negative Flooded Capacity (Ah)		Precharge Total (Ah)	Overcharge Protection (Ah)	Unavailable Discharged Cd (Ah)
IUE 3-10	ATP	34.8	13.96 40.1%	22.42 64.4%		4.27 12.3%	10.05 28.9%	6.52 18.7%
EUVE 16-053	ATP	129.11	62.81 48.6%	100.81 78.1%		21.10 16.3%	26.95 20.9%	18.28 14.2%
EUVE 4-005 backup	ATP	138.84	57.78 41.6%	86.7 62.4%	NL	32.68 23.5%	23.36 16.8%	24.82 17.9%
EUVE 4-068 backup	Battery ATP	133.39	57.21 42.9%	78.12 58.6%	NL	39.85 29.9%	20.99 15.7%	14.56 10.9%
TDRSS 15-78	ATP	106.98	47.86 44.7%	61.81 57.8%		11.16 10.4%	13.29 12.4%	34.67 32.4%
GOES 5-110	I and T	27.09	12.63 46.6%	19.16 70.7%		8.27 30.5%	3.36 12.4%	5.93 21.9%
TDRSS 8-69	60 Life	103.08	55.46 53.8%	72.75 70.6%		11.85 11.5%	8.34 8.1%	27.43 26.6%
GRO 17-073	576 Stress	134.35	59.8 44.5%	81.43 60.6%		32.06 23.9%	21.5 16.0%	20.99 15.6%
GRO 16-030	2480 Stress	130.79	50.42 38.6%	68.1 52.1%	NL	45.55 34.8%	5.29 4.0%	29.53 22.6%
GRO 16-079	3900 Life	125.81	65.13 51.8%	96.28 76.5%		15.91 12.6%	22.25 17.7%	22.52 17.9%
UARS 2-073	5010 Life	123.82	51.39 41.5%	76.17 61.5%	NL	39.64 32.0%	17.03 13.8%	15.76 12.7%
GRO 16-014	5360 Life	126.18	47.07 37.3%	68.88 54.6%	NL	43.7 34.6%	7.71 6.1%	25.41 20.1%
UARS 2-007	5500 Stress	118.60	61.09 51.5%	87.55 73.8%		34.85 29.4%	3.16 2.7%	19.50 16.4%
UARS 2-021	5700 Stress	124.57	55.35 44.4%	77.35 62.1%	NL	53.69 43.1%	9.97 8.0%	5.56 4.5%
COBE 15-05	6000 Stress	129.46	59.56 46.0%	70.91 54.8%		37.90 29.3%	1.78 1.4%	30.22 23.3%
GRO 16-003	10600 Life	128.34	62.93 49.0%	82.28 64.1%		42.36 33.0%	12.93 10.1%	10.12 7.9%
GRO 17-063	11800 Life	135.67	48.67 35.9%	72.07 53.1%	NL	38.38 28.3%	12.58 9.3%	33.17 24.4%

Percentages based on overall negative capacity
NL = negative limited on discharge

Nickel-Hydrogen Storage / Capacity Fade Session

Organizer: Joe Stockel
Office of Research & Development

Mechanisms for Capacity Fading in the NIH_2 Cell
and its Effects on Cycle Life

N93-20496

Albert H. Zimmerman
Electronics Technology Center
The Aerospace Corporation
El Segundo, California 90245

During recent years there have been a number of instances where the capacity of nickel hydrogen battery cells has proven to be unstable during storage. The capacity losses seen after periods of cell or battery storage have typically varied from only a small amount of fading, up to about 30% of the total cell capacity. Detailed studies into the root causes for such fading have been carried out in a number of instances. This report provides an overview of the different mechanisms that have been found to be responsible for such capacity fading in nickel hydrogen cells, and summarizes the presently available data on how each responsible mechanism affects ultimate cell cycle life.

A clear result from the observations of capacity fading and the analyses that have been done for each case, is that there are a number of factors that can either cause or accelerate fading. In general, the origins of capacity fading may be linked to the presence of the highly catalytic platinum material in the hydrogen electrode. This high catalytic activity enables the other components in the nickel hydrogen cell, primarily the nickel electrode, to undergo chemical changes into thermodynamically more stable materials via. pathways not otherwise readily available. Unfortunately, in general the chemical modifications that result from such processes tend to degrade rather than enhance cell performance. During the past 10 years, nickel hydrogen cell fading has been observed to result from chemical or physical changes in the electrodes, separator, and electrolyte during storage.

The discussion of capacity fading in nickel hydrogen cells is divided here into two general sections. The first section describes mechanisms for capacity fading in hydrogen precharged cells. This mechanism is relatively well understood through a number of studies published over recent years (Refs. 1-3). Fading in hydrogen precharged cells is controlled by chemical changes that take place in the nickel electrode. The second section discusses capacity fading mechanisms in nickel precharged cells. Such fading is clearly slower than that in hydrogen precharged cells, and can be caused by either temporary or permanent loss of the nickel precharge, or by leaking of hydrogen. The loss of nickel precharge can be induced by chemical changes in the nickel hydrogen cell, or by changes in the electrochemical activity of the nickel electrode.

Fading in Hydrogen Precharged Cells

The balance between the capacity in the nickel electrode and that in the hydrogen electrode in a hydrogen precharged nickel hydrogen cell is graphically illustrated in Fig. 1. The cell is built with sufficient hydrogen gas to leave some hydrogen remaining in the fully discharged cell. In this case the cell capacity is always limited by the active capacity of the nickel electrode, assuming that no significant leaks exist in the cell pressure vessel. Typically the nickel electrode delivers approximately 70-80% of its total capacity at useful discharge rates. The remaining capacity is divided into residual capacity, i.e. capacity that can be discharged at reduced rates and voltages, and unavailable capacity, which simply cannot be electrochemically discharged. The relative proportions of residual and unavailable capacity can vary depending on the construction details of the nickel electrode and how it is charged and discharged. However, the residual capacity is often about 20% of the cell capacity and the unavailable capacity is about 5% of the total.

Thus, during the storage of a nickel hydrogen cell with hydrogen precharge in a fully discharged state, the presence of remaining hydrogen gas forces the nickel electrode to the highly reducing potential of the hydrogen electrode. Indeed, under these conditions the nickel electrode becomes a hydrogen electrode having an appreciable reducing capability. This occurs as the compact oxide layers on the nickel sinter are reduced, thus de-passivating the catalytic nickel metal surfaces. Since both the nickel and the platinum electrodes act as hydrogen electrodes, the potential of the cell during storage is clamped very close to zero volts -- irrespective of whether the cell is left open circuited or is shorted.

The reducing environment at the nickel metal surfaces during storage initiates reduction of the nickel and cobalt hydroxides (cobalt hydroxides are generally added to the nickel electrode active material at levels of 5-10% to improve performance and life) if the cell potential is below 0.1 volts, which is guaranteed by the presence of excess hydrogen. These reduction reactions produce finely divided nickel and cobalt metal in the layers that are in electrical contact with the nickel current collecting surfaces within the sinter of the electrode. This solid state reduction process propagates slowly into the active material deposit during lengthy storage periods. Subsequent recharge of the cell will oxidize these metallic particles to the respective nickel and cobalt hydroxides. As described in Ref. 1, cobalt hydroxide thus formed is soluble to some extent in alkaline electrolyte, forming the dicobaltite ion, $HCoO_2^-$. Movement of this ion results in migration of cobalt away from the nickel surfaces. The cobalt is redeposited in any of a number of inactive cobalt containing phases, including CoOOH, $CoHO_2$, and Co_3O_4 during subsequent cell operation. Capacity fading can result from layers of these poorly conducting materials preventing discharge of some active material, or probably more likely, preferential discharge of the cobalt-depleted layer surrounding all the current collecting surfaces. Such preferential discharge will occur because cobalt depleted nickel hydroxide has an elevated discharge voltage. The depleted layer thus formed during discharge can isolate charged material that is not close to the current collector, since the discharged material has relatively poor electronic conductivity. Fig. 2 illustrates this condition.

The situation that develops in the nickel electrode that is stored in hydrogen is thus a chemical modification of the active material. This same process is possible in nickel electrodes from nickel cadmium cells, however the incorporation of cadmium hydroxide into the nickel electrode in these cells is likely to offer some protection, since the cadmium should be preferentially reduced during low voltage storage. Likewise, the addition of some cadmium to the nickel electrode in the nickel hydrogen cell could offer some degree of protection from the degrading effects of a hydrogen precharge.

The net consequence of the degradation illustrated in Fig. 2 is a non-uniform discharge of the nickel electrode, leaving behind an appreciable amount of isolated charged active material. Such a non-uniform discharge can also result from non-uniform loading, sinter that contains large voids, or anomalous phase distributions in the active material. We have developed an empirical test that allows the degree of discharge uniformity to be quantified using a simple procedure. This test is indicated in Fig. 3, where a flooded (31.29% KOH) nickel electrode is discharged at 10 ma/cm^2 following a 32 hr charge at 2 ma/cm^2 (prior to this cycle a standard conditioning cycle is used to stabilize the electrode). A uniformity parameter F is defined as

$$F = Gamma/(Gamma + Beta)$$

where gamma and beta are the relative quantities of the γ-NiOOH and β-NiOOH discharged at the 10 ma/cm^2 rate. It has been empirically found that non-uniform discharge results in isolation of the lower potential gamma phase, as well as a reduced tendency to readily form this phase during the standard recharge employed in this test.

Figure 4 indicates the correlation typically found between active material utilization at the 10 ma/cm^2 discharge rate and the uniformity parameter F. Normal nickel electrodes typically fall between 90 and 110% utilization, with variables such as cobalt level, sinter porosity and uniformity, loading level, and local loading uniformity giving a significant range of utilization across different electrode lots and types. Very uniformly and lightly loaded electrodes with high cobalt levels can easily give utilizations as high as 130% or more, as indicated in Fig. 4. However, nickel electrodes from cells that have experienced fading exhibit a significant reduction in both utilization and the uniformity parameter F. The three points in Fig. 4 having lowest utilization are all from cells that exhibited differing, but significant degrees of capacity fading. Thus, an empirical test such as that indicated in Figs. 3 and 4 can provide a good indication of the origin of degradation in any given nickel electrode. Particularly when the measurements are combined with chemical analyses for $CoHO_2$, the level of which also has been found to correlate with capacity fading (Ref. 2), an excellent diagnostic capability for the root cause of capacity fading emerges.

The capacity fading and redistribution of cobalt that occurs when nickel electrodes are exposed to hydrogen is not neatly recoverable by any obvious method, unless the cobalt depleted layers are quite thin. Empirically, it has been found that repeated high depth-of-discharge cycles or significant long-term overcharge at low rates can recover faded capacity. Since the chemically modified materials remain present in the nickel electrode through such recovery procedures, it is concluded that recovery is successful whenever the layered structures evident in Fig. 2 can be somewhat dissipated. The most obvious approach to such a recovery method is to utilize the physical movement of active material during deep cycles or from oxygen evolution to dissipate such layers through a mixing of the active material layers. Because capacity recovery procedures do not restore the initial phase composition of nickel and cobalt compounds in the active material, a concern exists that the chemical changes in the nickel electrode will have a deleterious effect on long-term cycle life, i.e. capacity will fade again during cycling much more quickly than otherwise expected.

To evaluate this concern a hydrogen precharged nickel hydrogen cell that had experienced approximately a 30% capacity fade during several years of storage, followed by capacity recovery by means of about 250 80% depth-of-discharge LEO cycles, was placed on an accelerated cycle life test. The results of this life test are indicated in Fig. 5 along with the cycle life behavior of a new cell (no fading) of the same design in the identical life test cycling regime. The conclusion drawn from the test in Fig. 5 is that in spite of the recovery seen in cell capacity, the chemical changes that had taken place in the nickel electrode during storage resulted in loss of about 85% of the cycle life capability of this cell for these test conditions. In view of these results, it clearly is very desirable to avoid the chemical changes responsible for capacity fading.

Capacity Fading Mechanisms in Nickel Precharged Cells

A nickel precharged nickel hydrogen cell is built with more capacity in the nickel electrode than there is hydrogen gas available for the negative electrode. Thus in the fully discharged state typically utilized for cell storage, the cell contains no hydrogen gas, but does contain some remaining charge in the nickel electrode active material. Because the charged nickel electrode active material is generally unstable relative to oxygen, it will evolve some level of oxygen gas in the stored cell. Thus, this cell will contain an oxidizing atmosphere of gas during storage, which will make the platinum catalyst electrode become an oxygen electrode. The relative electrode capacities typically desired in this cell design are indicated in Fig. 6. So that the usable capacity of the cell is not reduced by the nickel precharge, the cell is normally built so that the hydrogen is fully consumed only by discharge after the active capacity of the nickel electrode is depleted, i.e. during discharge of the residual capacity. With typical nickel electrodes this approach places an upper limit of about 10-20% nickel precharge on the cell, with a concomitant decrease in the operating pressure of the cell. Although higher precharge levels may be used, they can reduce the capacity of the cell below that which could otherwise be attained.

The positioning of the relative nickel and hydrogen electrode capacities indicated in Fig. 6 has some potential problems. First, if the nickel electrode has an extremely high utilization, the band of residual charge will be quite narrow, resulting in a very narrow window of acceptable precharge. In this situation it is probably more desirable to increase the nickel precharge into the active capacity region, instead of risking cell degradation if the nickel precharge is insufficient. It should be noted here that any oxidation of sinter or other materials in the cell during operation will tend to increase the amount of hydrogen in the cell. Thus, some excess nickel precharge is highly desirable to get the cell through early life cycling and storage without developing a hydrogen precharge.

The second point to note in Fig. 6 is that any significant shifts in the amounts of either residual capacity or unavailable capacity during cell operation can convert a nickel precharged cell into a cell that is effectively hydrogen precharged. There are several operational conditions commonly encountered during cell testing that can shift the amounts of residual and unavailable capacity significantly, and thus are to be avoided just prior to storage periods except under carefully controlled test conditions. The first of these conditions is indicated in Fig. 7, and involves allowing the charged cell to stand open circuit prior to discharge. Such open circuit stand, which is commonly used for charge retention tests, causes most of the residual capacity to become unavailable through charge redistribution processes described in Ref. 3. This can easily convert a nickel precharged cell into a cell that contains undischargeable hydrogen, although this hydrogen may eventually be depleted by self-discharge processes. Storage of this cell at a low voltage, however, will clearly initiate the processes responsible for capacity fading in the hydrogen precharged nickel hydrogen cell. Thus, a common test to which nickel hydrogen cells are exposed is capable of temporarily generating conditions known to degrade cell performance.

Another relatively common test condition that can have a similar effect is indicated in Fig. 8. Here the cell is simply discharged at low temperature, which significantly increases the amounts of both residual and unavailable capacities. This is primarily due to the reduced conductivity of the active material at lower temperatures. Here again, the unavailable capacity in the discharged cell can rise to exceed the level of hydrogen in the cell, thus leaving a temporary hydrogen precharge condition. The scenarios presented in Figs. 7 and 8 clearly show that a nickel precharged cell should be carefully prepared for a storage period, employing a standard preparation cycle which is guaranteed to leave the desired state of precharge.

A number of other conditions in the nickel hydrogen cell have been found to cause increases in the residual and unavailable capacities in the nickel electrodes. One of these conditions occurs when silicate contaminants build up to levels much above 1000 ppm in the KOH electrolyte, particularly when the cell is operated at low temperatures. The typical sources for silicate contaminants are dirt or dust particles, or the presence of silicate based minerals such as asbestos in the separator. These silicate containing materials generally lose silicate by replacement with hydroxide from the electrolyte over time, thus allowing silicate levels to build up in the electrolyte during extended storage. The rate of this buildup can vary significantly, as the rate at which different silicate minerals are attacked by KOH varies tremendously. For very slow processes of this kind, low temperature storage is clearly beneficial. However, the best solution to this problem is simply to insure, through attention to cleanliness and appropriate design, that negligible amounts of silicate minerals are present in the cell.

The mechanism by which silicate affects the nickel electrode is not fully understood (Ref. 4). Empirical evidence indicates that silicates are incorporated into the nickel electrode active material during overcharge, as evidenced by anomalous increases in overcharge voltage. Whether this results from silicate crystallization, dehydration of the active material by the silicate, or some other mechanism is not fully certain. This incorporation is accompanied by a significant increase in the resistance of the nickel electrode. The added resistance component has a large temperature coefficient, thus affecting cell charge and discharge voltage markedly at low temperatures. Typically, as the cell is discharged the silicate will come out of the nickel electrode and the resistance will drop. The result can be a significantly depressed discharge plateau voltage as indicated in Fig. 9, which in extreme cases can exhibit a pronounced minimum part way through the discharge. The results of Fig. 9 are for small laboratory cells operated at 600 psia of hydrogen, and with calcium silicate added to the interface between the nickel electrode and the zircar separator. The behavior of Fig. 9 developed gradually over approximately 40 100% depth-of-discharge cycles at 25 deg C, performed over a period of 44 days.

Clearly, silicate contaminants can decrease cycle life, although the extreme case represented in Fig. 9 may not be representative of the silicate levels from spot contamination. However, cells containing silicate based separators such as asbestos have exhibited anomalous discharge voltage profiles much like those of Fig. 9, ranging in severity from causing failure within the first 100 cycles, to causing failure after 12,000 LEO cycles at 40% depth-of-discharge.

Another contaminating material that has been found to change the relative amounts of residual and unavailable capacity is sulfate ions in the electrolyte (Ref. 4). More than 300-500 ppm of sulfate in the electrolyte can result in significant increases in the amount of capacity discharged on the second plateau, particularly when combined with low temperature operation and charged open circuit stand. This behavior is indicated in Fig. 10, again for small nickel hydrogen cells operated at about 600 psia with calcium sulfate added between the zircar separator and the nickel electrode. In actual nickel hydrogen cells, the sources for such sulfate materials have been found to be spot contamination by mineral particles (gypsum, $CaSO_4$, most commonly), and separators. Sulfates have been found in both zircar and asbestos separator materials.

One effect that sulfate ions can have on the nickel electrode is also a real concern for a number of other anionic contaminants, i.e. accelerated corrosion of the sinter structure. Clearly this process is capable of converting a nickel precharged cell into a hydrogen precharged one either during storage or during early cycling prior to storage. In a flooded life test consisting of 6500-7000 100% depth-of-discharge cycles, the rate of corrosion in the presence of sulfate ions was found to be 2 to 5 times greater than that in the absence of sulfate.

The mechanism by which sulfate ions alter the performance of the nickel electrode is again not fully understood. It seems most likely that the sulfate ions react with cobalt sites in the active material, decreasing active capacity by forming traps for the normally mobile protons in the active material. The complex that sulfate forms with cobalt appears to be somewhat soluble in KOH. After 6500 cycles in sulfate containing electrolyte a nickel electrode was observed to have lost about 50% of its total cobalt additive, with the lost cobalt being deposited onto the counterelectrode in the flooded cell.

Figure 11 indicates capacity performance over 6500-7000 accelerated cycles for flooded nickel electrodes in 31% KOH with 0.5 g/100 cc of calcium sulfate added. This test was to 100% depth-of-discharge, with 100% depth defined as 0.0 volts vs. Hg/HgO at 100 ma/cm^2. Charge return was 100% of the beginning of life capacity of each electrode as measured at the 10 ma/cm^2 discharge rate. After 6500 cycles, the electrode cycled with added sulfate exhibited a discharge voltage plateau depressed to near the 0.0 volt level, thus its capacity appeared to suddenly drop. Actually the discharge voltage of this electrode had degraded continuously during the cycling after about cycle 1000. The electrode cycled with no sulfate had experienced only about a 20 mv drop in the discharge plateau after nearly 7000 cycles, and essentially no capacity loss. After almost 7000 cycles this test was stopped based on the observation that the electrode cycled with sulfate had failed while the electrode cycled with no sulfate remained far from failure.

In Fig. 11 the electrode cycled with no sulfate exhibited a normal capacity profile over cycle life. A capacity rise during the initial 2000-3000 cycles was followed by a level then a gradually dropping capacity. With sulfate present, however, a very different behavior was seen. The initial rapid drop, then rise in capacity over the first 800 cycles appears to be associated with the slow incorporation of sulfate species into the cobalt sites within the active material. Thereafter, while capacity appears to be relatively stable, the cobalt in the active material is slowly undergoing solubilization causing the active material to lose cobalt, as well as experiencing accelerated corrosion. About 10% of the sinter had corroded after 6500 cycles. It is likely that the combination of these changes played a significant role in the earlier failure of the electrode exposed to sulfate.

A final chemical reaction of potential concern during the storage of a nickel precharged cell involves the platinum electrode. As was previously discussed, in a discharged nickel precharged cell the platinum catalyst electrode adopts the potential of an oxygen electrode, which is near that of the nickel electrode, depending on the pressure of oxygen in the cell. At this potential the platinum catalyst will undergo oxidation, forming a layer of $Pt(OH)_2$ on its surface. In KOH electrolyte this compound has some solubility, thus the platinum does not fully passivate. The result is an equilibrium level of $Pt(OH)_4^=$ in the electrolyte after an extended storage period. These platinate ions can migrate to the nickel electrode, where they can participate in various chemical reactions.

Platinate ions appear to catalytically interact with the precharge in the nickel electrode. These ions appear to slowly associate with adjacent cobalt and nickel sites to form a CoNiPt oxyhydroxide complex. The platinum in this complex is in equilibrium with platinate ions in the electrolyte. Cell recharge will plate the platinum from the platinate species back onto the catalyst electrode, thus causing the platinum to leave the complex formed in the nickel electrode by the resulting shift in the equilibrium. However, this process leaves behind in the nickel electrode a relatively stable NiCo oxyhydroxide compound. This reaction is capable of consuming much of the precharge in the nickel electrode. This reaction provides a rationale for using a level of precharge significantly greater than the amount of cobalt in the nickel electrode.

The NiCo oxyhydroxide compound formed in a nickel precharged cell provides an unambiguous signature indicating whether the precharge has indeed remained intact over the life of the cell. Figure 12 shows the voltage signature for this compound. While not having a high electrochemical activity, in a slow scan voltammetric measurement (Fig. 12 uses less than a 2 μV/sec sweep rate) reduction of a well defined phase is seen at about 0.15 volts vs. Hg/HgO. This is a potential region where a normal nickel electrode has a clean minimum in its electrochemically active constituents. Complete reduction of this compound causes it to dissociate within a 24 hr period. Subsequent oxidation of the nickel electrode shows no trace of being able to regenerate this structure, unless done very quickly, whereupon very limited reversibility is seen. Thus, the observation of the 0.15 volt peak of Fig. 12 in a nickel electrode from a stored cell is good evidence that the cell has not experienced temporary conversion to a hydrogen precharged condition at any time in its past history. Conversely, the complete absence of this structure in nickel electrodes from a stored cell with nickel precharge suggests that at some time the precharge has been compromised. We have in fact used this method in several instances to detect conditions that can temporarily compromise the nickel precharge in a cell.

The long term effects of forming NiCo oxyhydroxides in nickel electrodes is uncertain. After extensive cell cycling there will clearly be sufficient hydrogen generated (from corrosion) to reduce these materials if a cell is fully discharged, such as would happen during reconditioning. The products of this reduction process are not presently known. It is clearly possible that these products could initiate cobalt segregation processes. In view of these uncertainties, and considering the long-term storage and test times required to address these issues, it seems best to avoid the formation of these NiCo oxyhydroxide compounds by not allowing the platinum electrode to rise to the oxygen potential.

Summary of Processes Affecting Stored Cells

Figure 13 attempts to summarize the principal processes that can occur in stored nickel hydrogen cells. At the bottom of Fig. 13, the situation in a hydrogen precharged cell is shaded in. The depleted nickel electrode is reduced to a potential near that of the hydrogen electrode, giving an open circuit cell potential near zero. At these potentials the nickel and cobalt hydroxides in the active material can undergo reduction, and if the potential is subsequently increased, the dicobaltite ion can form from cobalt hydroxide. Above about 0.3 volts vs. hydrogen the nickel sinter begins to oxidize and develops a passivation layer, becoming fully passivated above about 0.5 volts.

The shaded region at the top of Fig. 13 indicates the reactions that can take place during storage of a nickel precharged cell. The platinum electrode is driven above the potential at which it can oxidize to the potential dictated by the oxygen in the cell, again giving a cell voltage of 0 to +0.3, depending on the exact oxygen pressure in the cell. Formation of platinate ions and their reaction with the nickel electrode can eventually reduce the potential of the nickel electrode, thus driving the open circuit cell potential negative. When the CoOOH couple is also included, it is possible to have the open circuit potential of the stored cell go negative by up to -0.3 volts. Thus the open circuit potential of a stored nickel precharged cell can drift between about 0.3 and -0.3 volts, depending on the oxygen pressure and the chemical state of the nickel precharge.

The most interesting aspect of Fig. 13 is that there is a region in the middle where none of the reactions considered here are possible except nickel corrosion. However, at cell potentials above 0.5 volts and below 1.0 volt, nickel metal is passivated, and actually more stable than in ambient atmosphere, assuming that no anionic species are present that can accelerate corrosion by breaking down the passivation layer. Whether a cell has a hydrogen precharge or a nickel precharge, it can be maintained in this window of stability simply by maintaining a cell potential of 0.5 to 1.0 volts. This appears to be an ideal storage condition for a nickel hydrogen cell, one which eliminates concern over the precise details of precharge, its level, and its stability.

Summary of Causes for Capacity Fading

In general, capacity fading has been found to result from having hydrogen in contact with the nickel electrode when its potential is below 0.5 volts. Clearly, hydrogen precharged cells meet this condition. It is also possible however, to generate a temporary hydrogen precharged condition by the cycling environment and the cycling method for the cell. Finally, chemical modification of the nickel electrode by reaction with platinum, silicates, sulfates, or perhaps other species as well, can impact the availability of nickel precharge to protect the stored cell from fading.

Recommendations to Avoid Fading

1. Use nickel precharge. It avoids reducing potentials at the nickel electrode, which have been shown to be capable of rapidly degrading cell capacity. It also reduces operating pressure.

2. Maintain a controlled potential of 0.5 to 1.0 volts on each cell during storage periods. This prevents platinum oxidation in nickel precharged cells, and prevents degradation from hydrogen precharge, should it ever develop in the life of a cell.

3. Store cold (about 32 deg F). This will slow all degradation processes, including those that we have not yet seen.

4. Always go into storage using a well defined procedure designed to maximize the availability of active precharge in the nickel electrode. A recommended procedure is to simply precede storage with one 20 deg C capacity cycle:
   - Charge fully at 20 deg C, with no open circuit stand time allowed.
   - Discharge at C/2 to 0.7 volts for each cell.
   - Resistive letdown to 10 mv, or for 16 hr maximum.

Storage at voltages above 1 volt or on trickle charge or top-charge will also keep the degradation processes discussed above in abeyance. However, concern exists regarding sinter corrosion at these more oxidizing potentials. It is this concern that suggests the recommended 1.0 volt upper limit for a storage potential.

References

1. A. H. Zimmerman and R. Seaver, J. Electrochem. Soc. 137, 2662 (1990).

2. A. H. Zimmerman, Proceedings of the Mini-Workshop on Capacity Fading, J. Stockel ed., US Govt. Dept. of Research and Dev., 1991.

3. A. H. Zimmerman, in Nickel Hydroxide Electrodes, Proc. Vol. 90-4, The Electrochemical Soc. Inc., Pennington, N. J., 1990, p. 311.

4. A. H. Zimmerman, in Hydrogen Storage Materials, Batteries, and Electrochemistry, Proc. Vol. 91-6, The Electrochemical Soc. Inc., Pennington, N. J., 1991.

5. A. H. Zimmerman,J. Power Sources 36, 253(1991).

Normal Hydrogen Precharged Nickel Hydrogen Cell

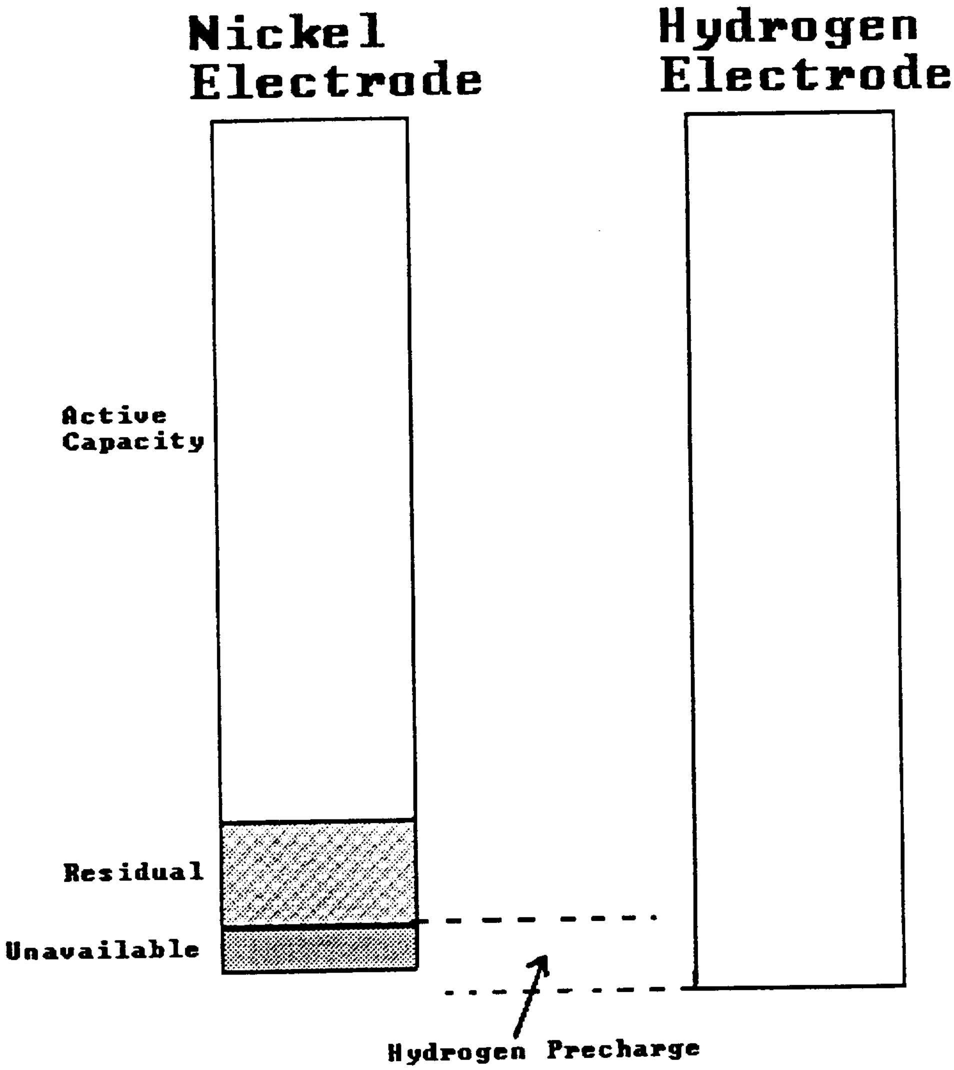


FIGURE 1.

FIGURE 2.

Movement of Cobalt in Active Material of Nickel Electrode

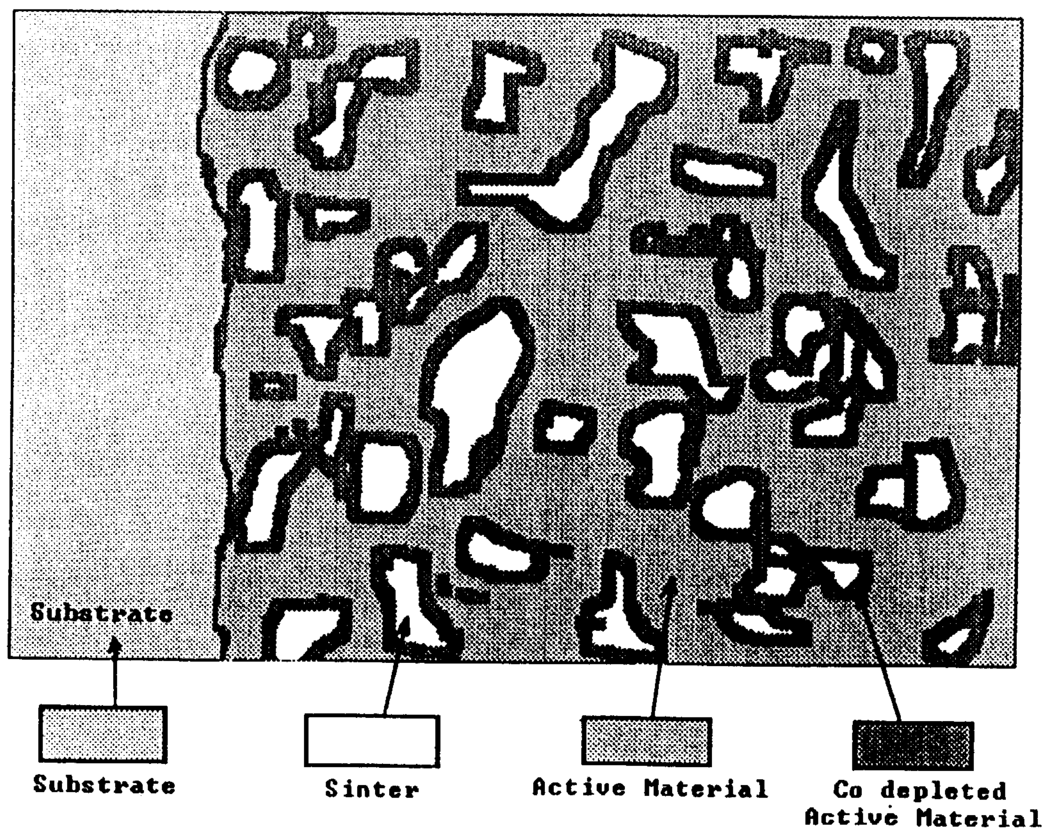


FIGURE 3.

Definition of Uniformity Parameter, F
31% KOH, 10 ma/cm2 disch after 32 hr ch

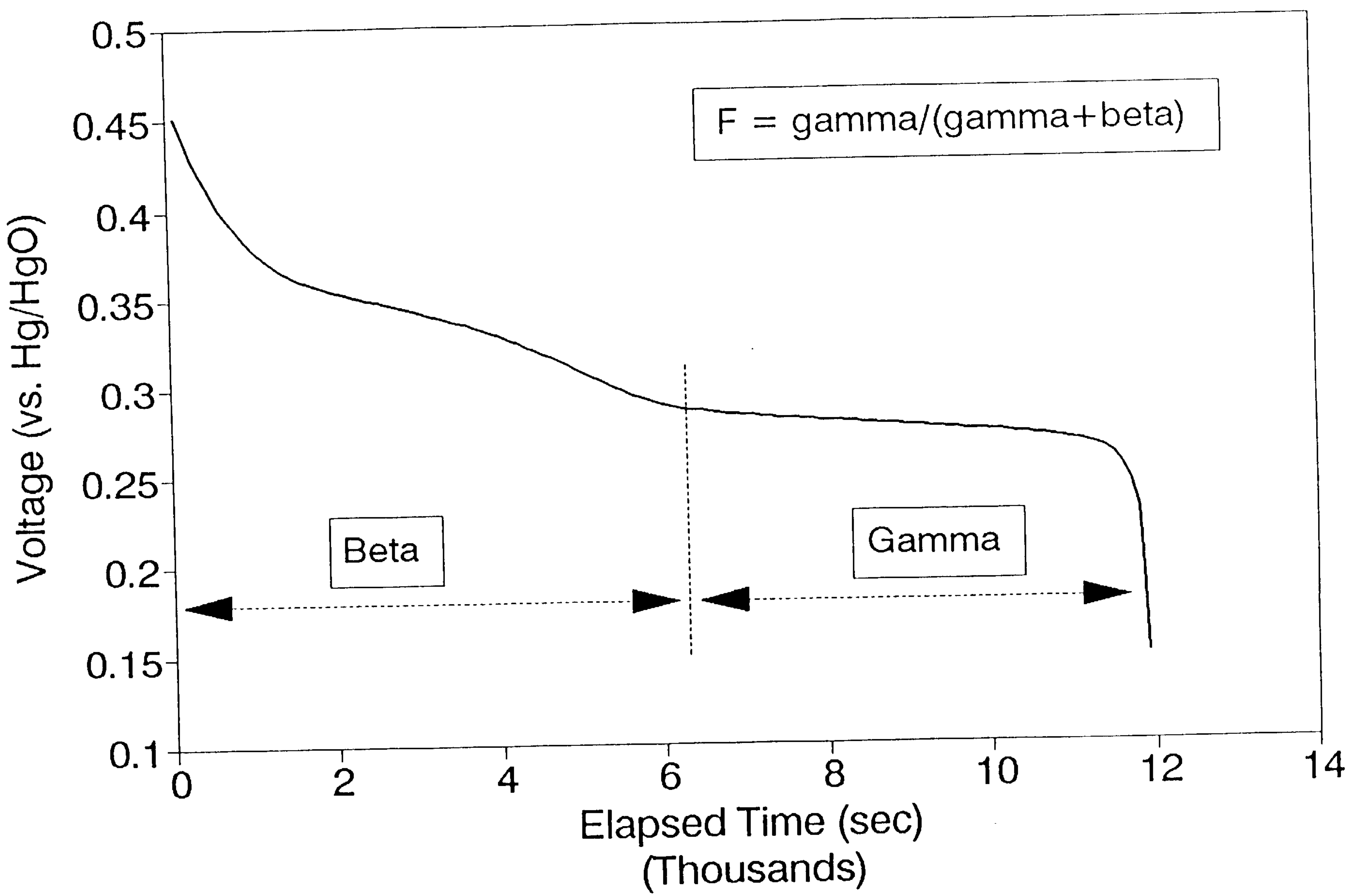
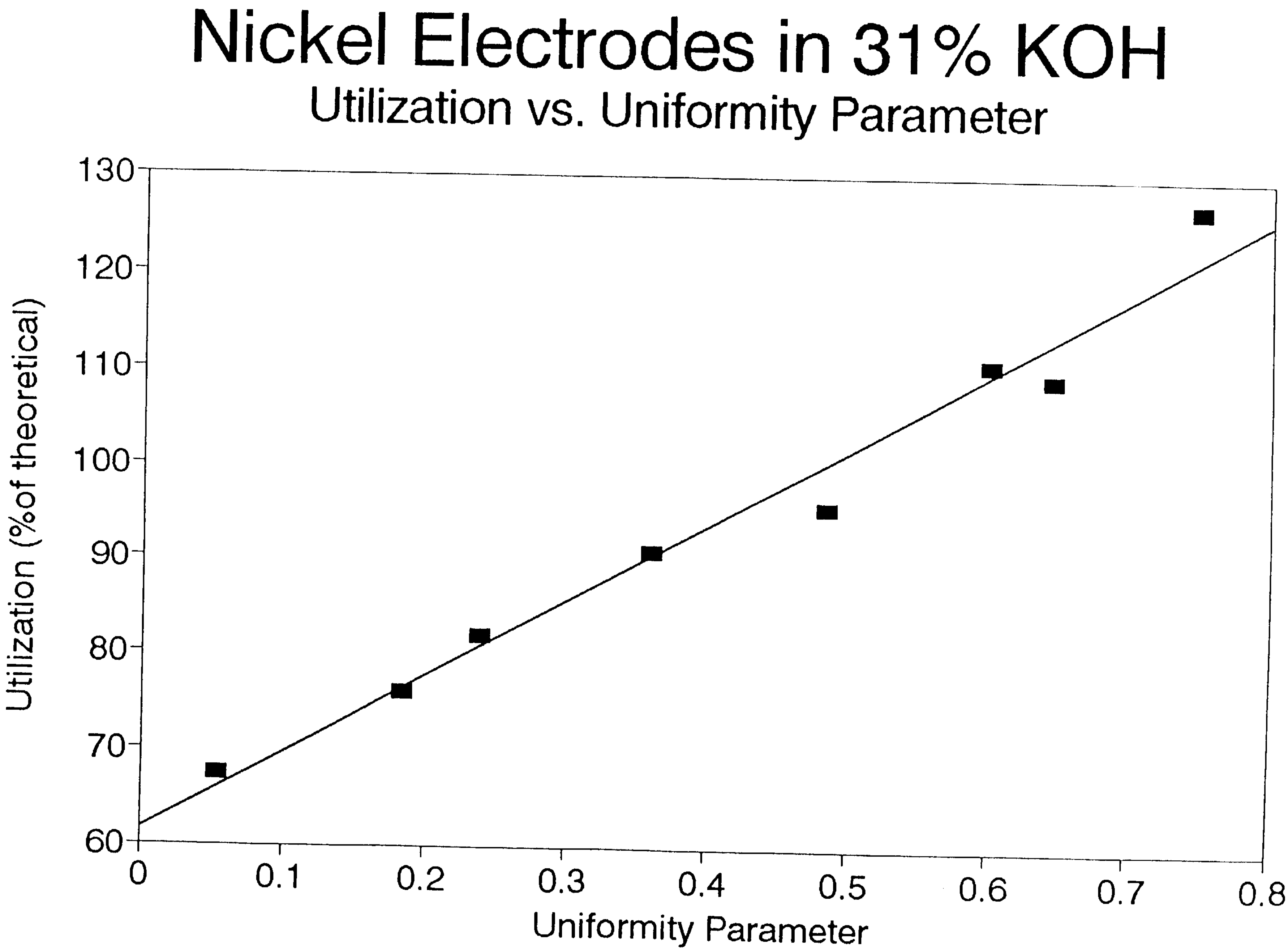


FIGURE 4.

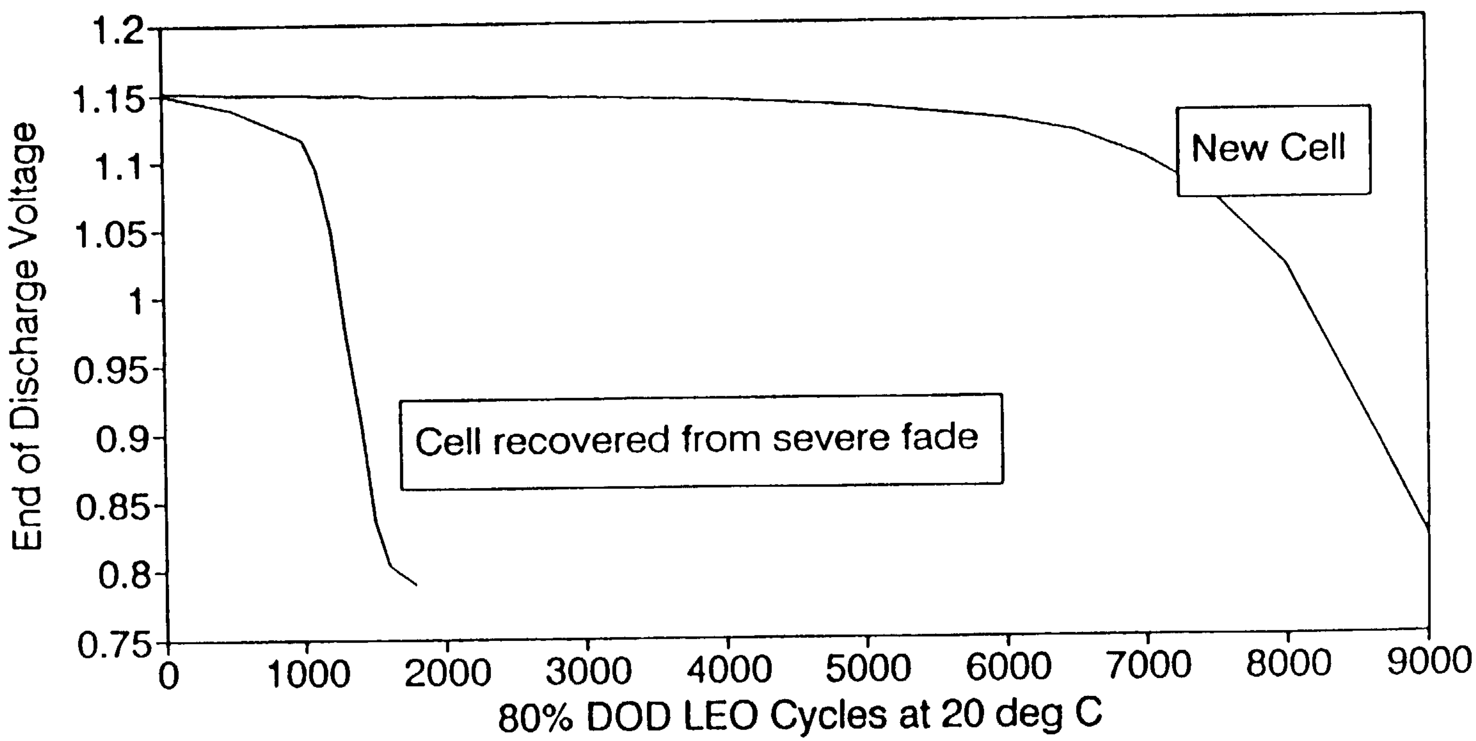


Nickel Electrodes in 31% KOH
Utilization vs. Uniformity Parameter
Utilization (%of theoretical)
130
120
110
100
90
80
70
60
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Uniformity Parameter

FIGURE 5.

PERFORMANCE OF FADED CELL AFTER CAPACITY RECOVERY BY EXTENSIVE CYCLING

- RAN LIFE TEST: 80% DOD, LEO CYCLE, 20 DEG C, 1.05 RETURN RATIO
- CONCLUSION: FADING DEGRADES CYCLE LIFE SIGNIFICANTLY, EVEN WITH APPARENT CAPACITY RECOVERY



Normal Nickel Precharged Cell

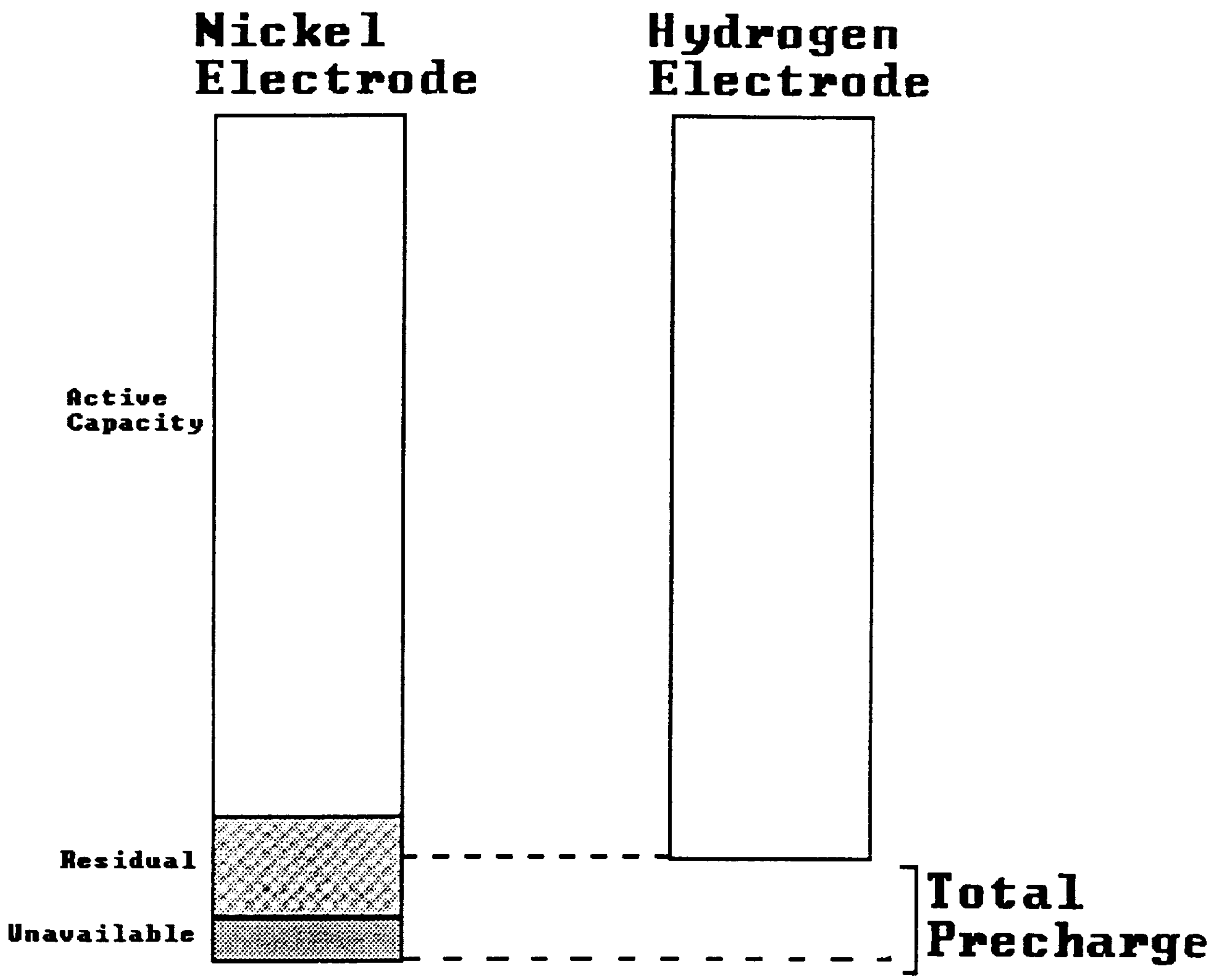


FIGURE 6.

Nickel Precharged Cell After Stand in Partly Charged or Open-Circuit Charged State

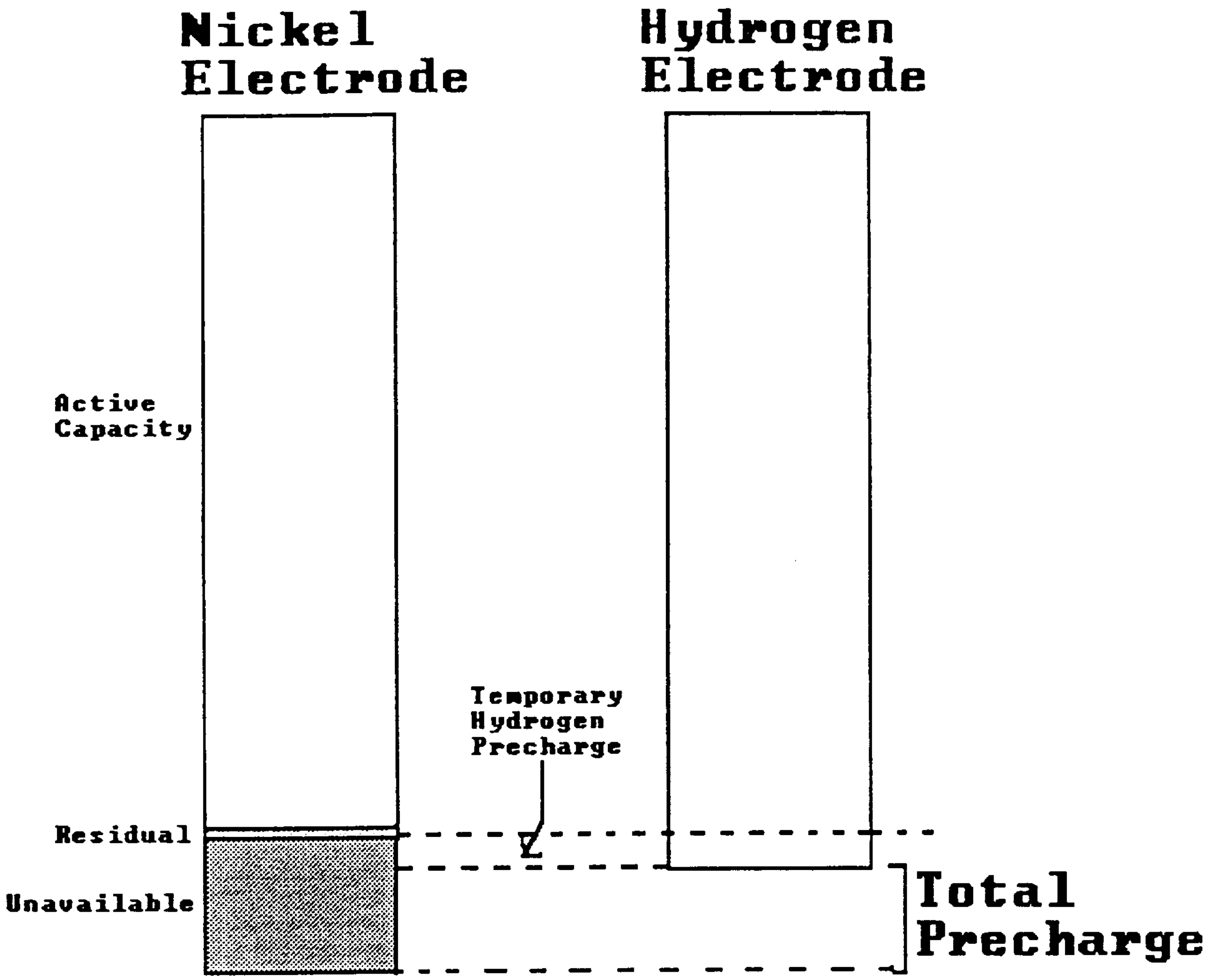


FIGURE 7.

Nickel Hydrogen Cell After a Low-Temperature Discharge

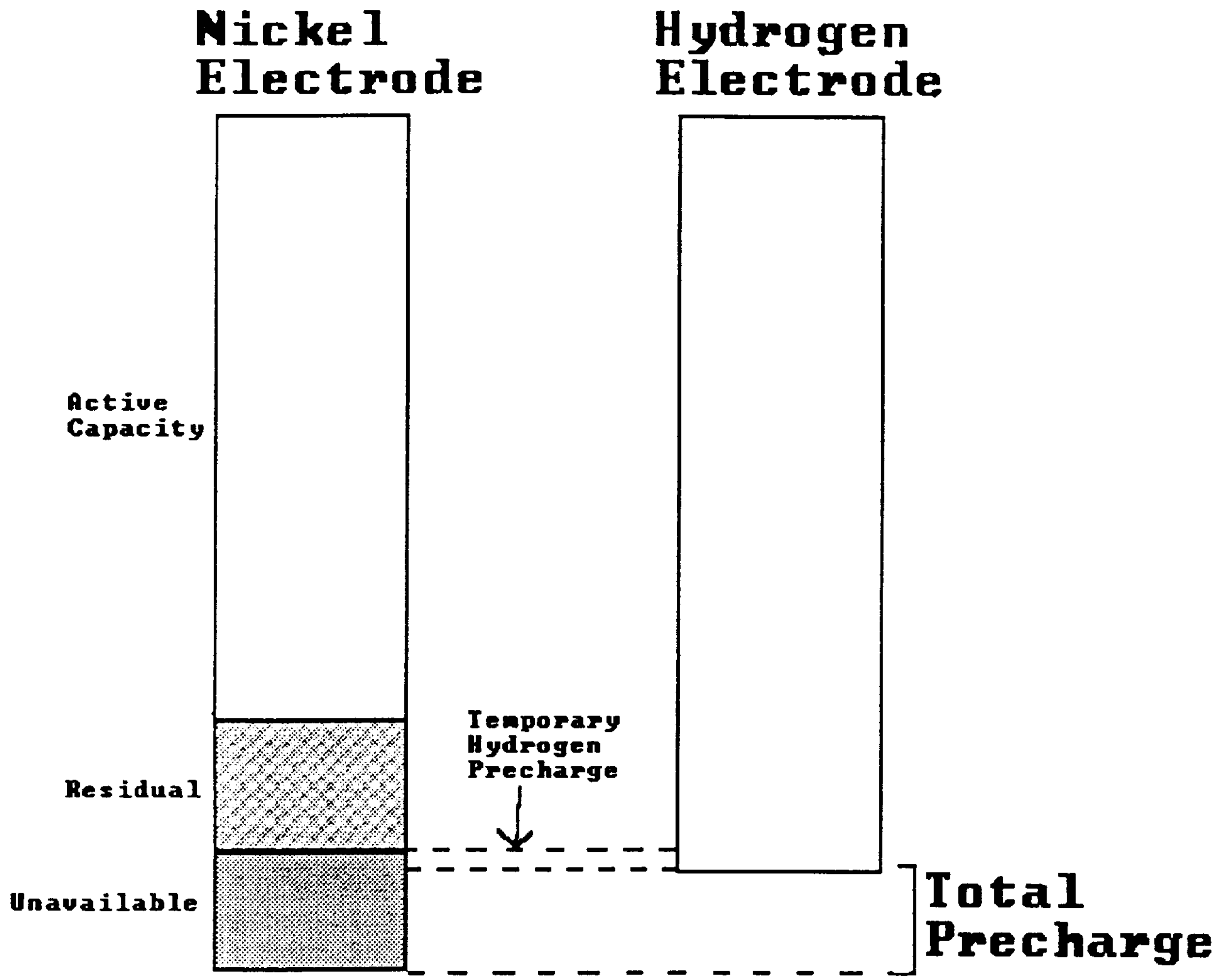


FIGURE 8.

FIGURE 9.

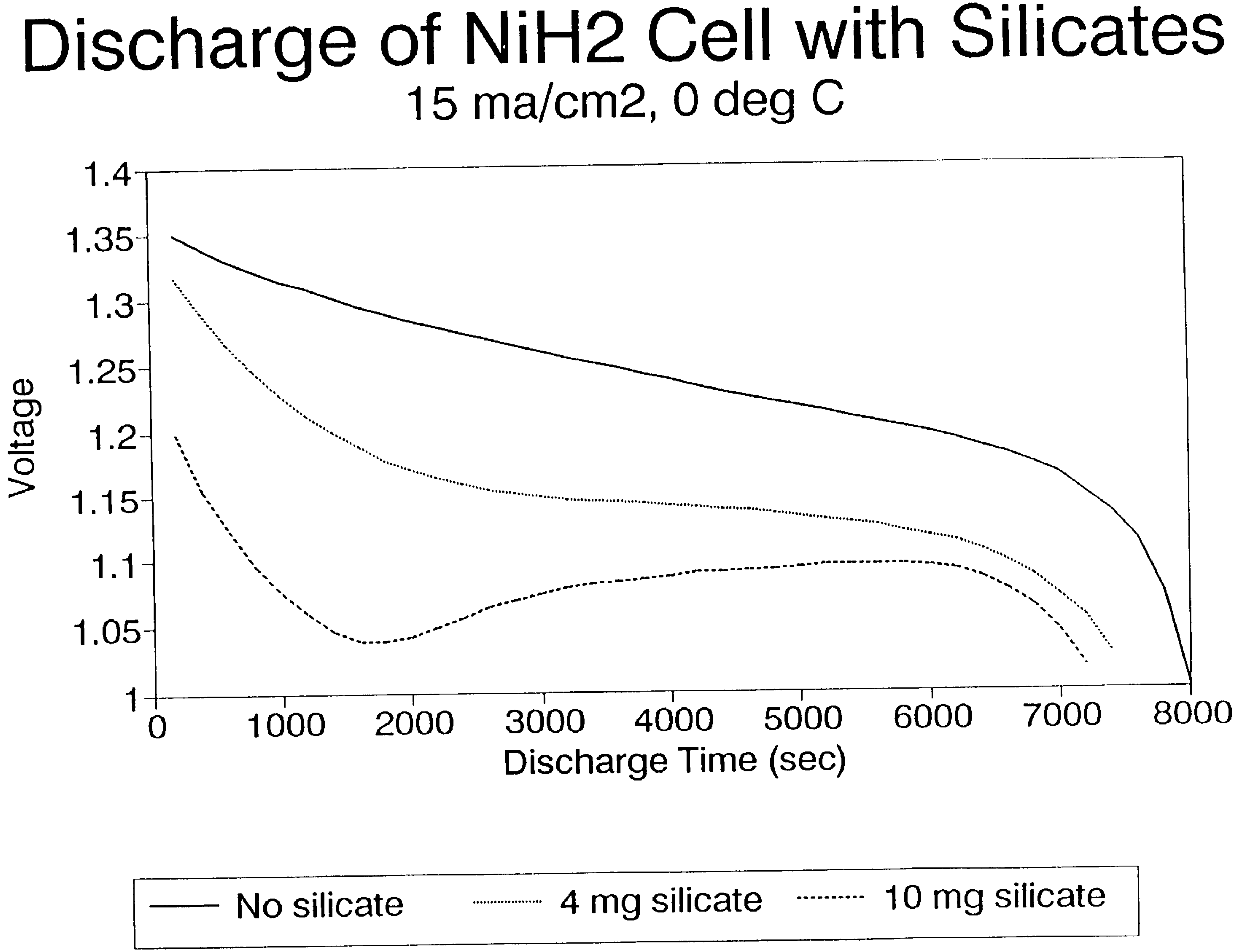

Discharge of NiH2 Cell with Silicates
15 ma/cm2, 0 deg C
Voltage
1.4
1.35
1.3
1.25
1.2
1.15
1.1
1.05
1
0
1000
2000
3000
4000
5000
6000
7000
8000
Discharge Time (sec)
No silicate
4 mg silicate
10 mg silicate

FIGURE 10.

Discharge of NiH2 Cell with Sulfate

15 ma/cm2, 20 deg C

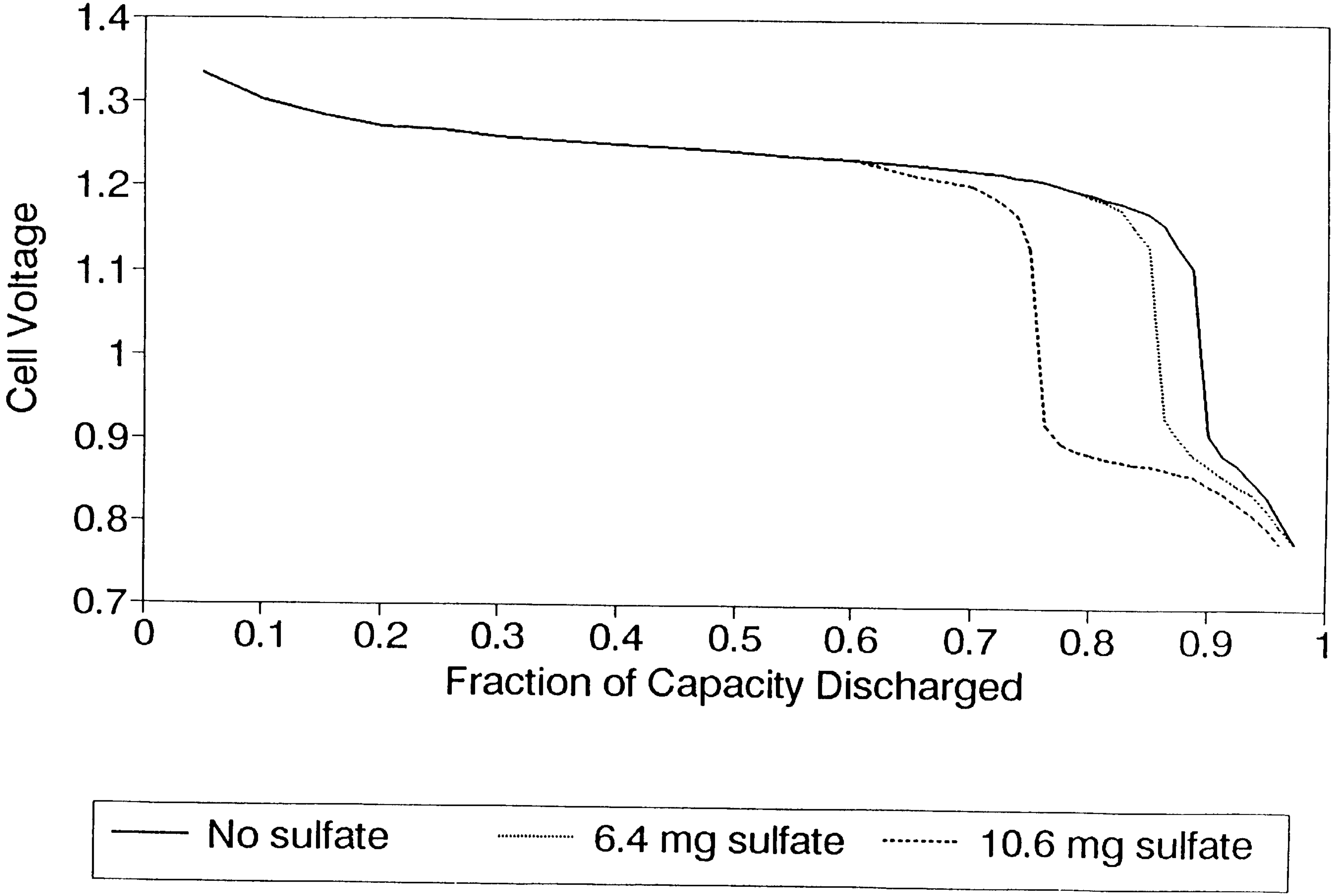


FIGURE 11.

Cycling of Ni Electrode with Sulfate

100 ma/cm2, 23 deg C

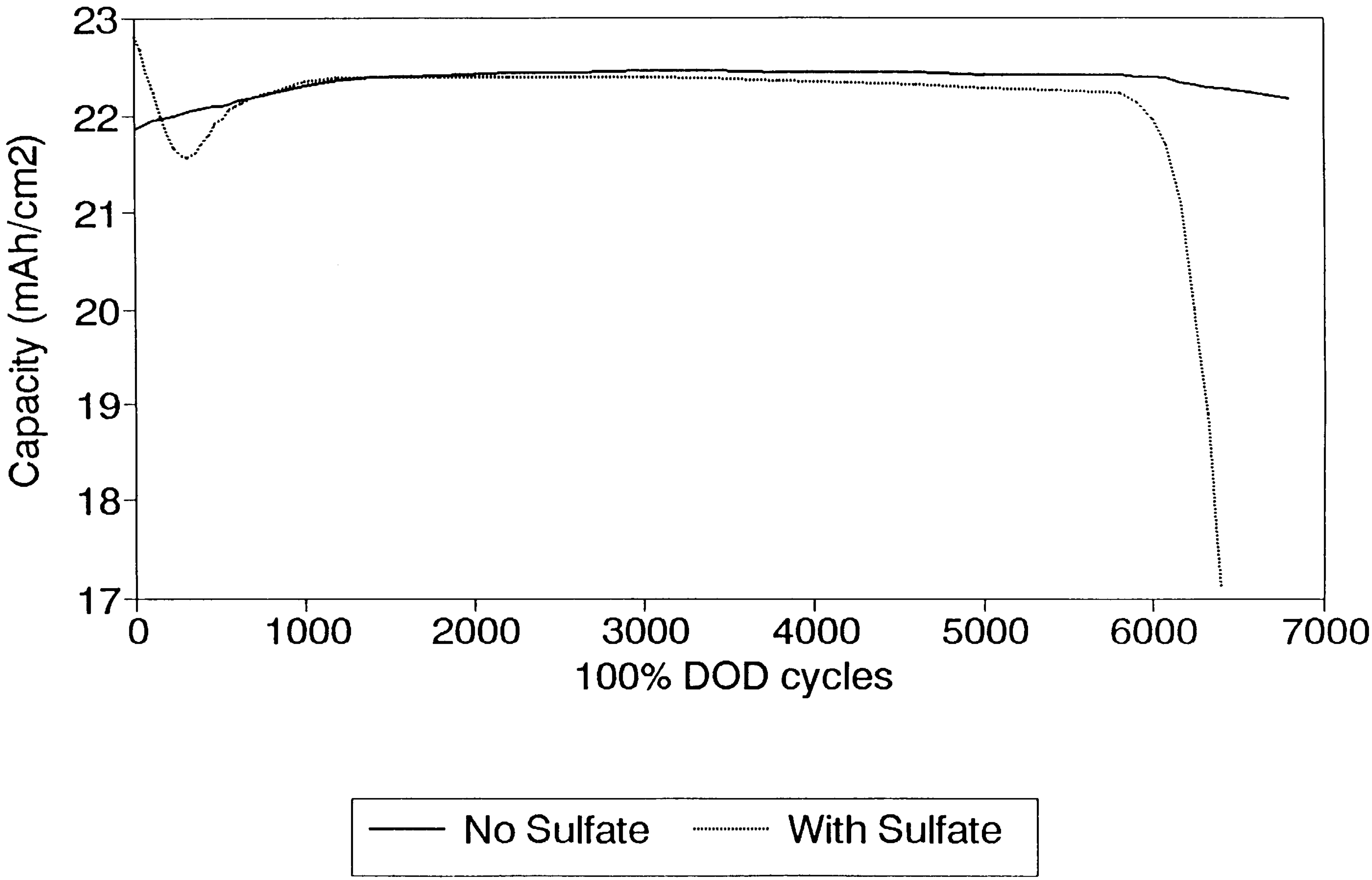


FIGURE 12.

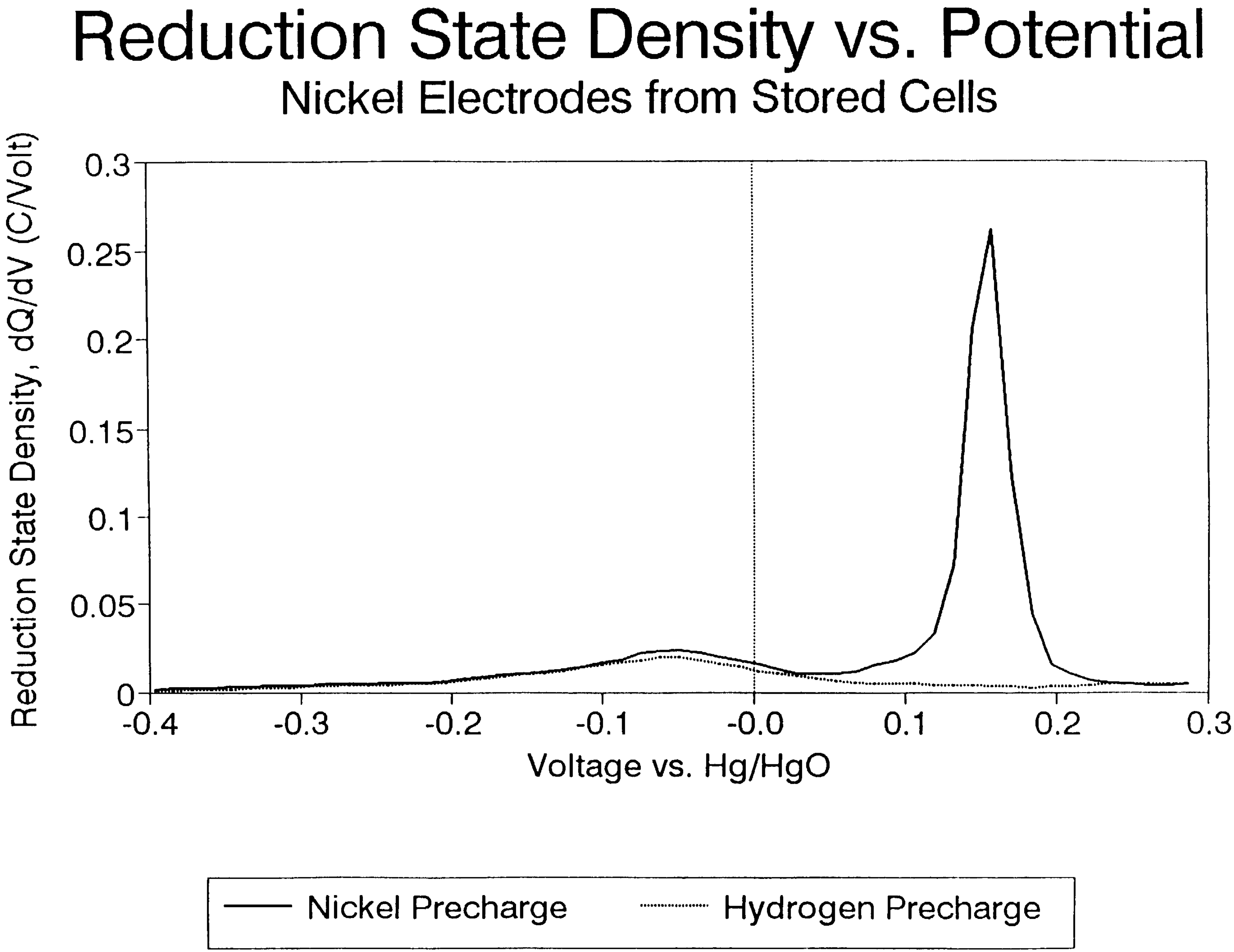
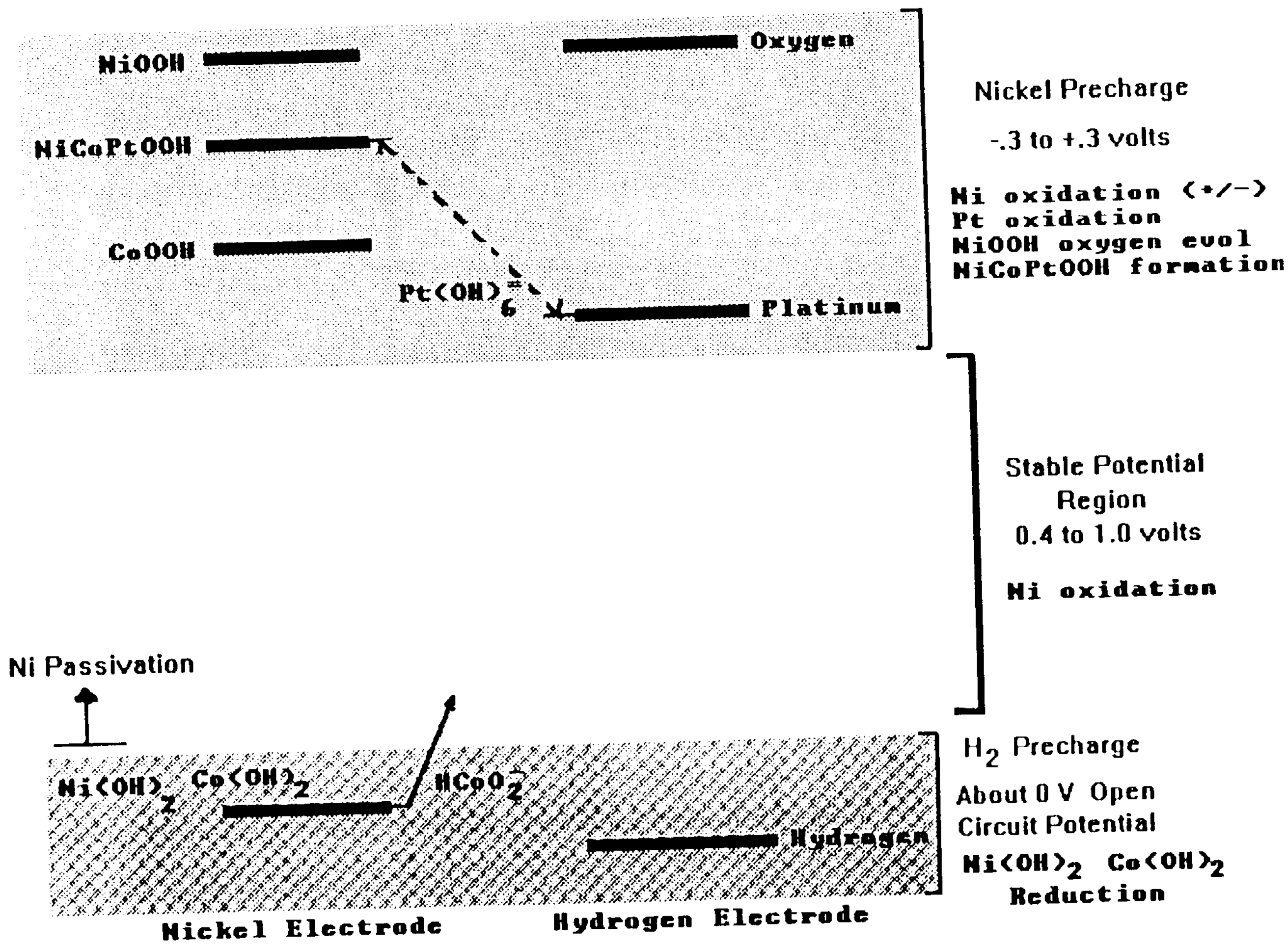

Reduction State Density vs. Potential
Nickel Electrodes from Stored Cells
Reduction State Density, dQ/dV (C/Volt)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.4
-0.3
-0.2
-0.1
-0.0
0.1
0.2
0.3
Voltage vs. Hg/HgO
Nickel Precharge
Hydrogen Precharge

FIGURE 13.

Nickel Hydrogen Cell Reactions and Regions of Stability



Migration of Co in Nickel Oxide/Hydroxide of a Nickel Electrode in a Ni/H2 Cell

Hong S. Lim and Robert E. Doty
Hughes Aircraft Company

OBJECTIVE OF STUDY

HUGHES

BACKGROUND: COBALT REDISTRIBUTION IN NICKEL ACTIVE MATERIAL HAS BEEN REPORTED. THIS REDISTRIBUTION WAS SUSPECTED TO BE RELATED TO CAPACITY FADING.

- Zimmerman and Seaver in 1990
- Lim and Verzwyvelt in 1990

OBJECTIVE: TO ESTABLISH RELATIONSHIP BETWEEN COBALT REDISTRIBUTION AND CAPACITY FADING.

TECHNIQUES USED

HUGHES

MICROSCOPIC COBALT DISTRIBUTION IN NICKEL ACTIVE MATERIAL STUDIED USING THREE EDX TECHNIQUES:

- LINE SCAN
- POINT-BY-POINT ANALYSIS
- DOT MAPS

Storage Test History of Nickel Electrodes in a Ni/H2 Cell.

Electrode ID	Storage history, days				Initial Cell Cap.*, Ah	Final Cell Cap.*	
	Trickle	Ni-prech	Vac.	H2-prech.		Ah	% of init.
Co-10	New containing 10% Co						
Co-7	New containing 7% Co						
Co-4	New containing 4% Co						
W/Al	New containing 10% Co						
BP1(10Co;26%;H2)	0	0	0	565	5.08	4.78	94.1
BP3 (7Co;26%;H2)	0	0	0	565	5.47	4.91	89.8
BP5 (4Co;26%;H2)	0	0	0	565	5.80	5.29	91.2
BP2 (10Co;26%;Ni)	0	146	142	277	4.95	5.74	116.0
BP4 (7Co;26%;Ni)	0	146	142	277	5.48	5.59	102.0
BP6 (4Co;26%;Ni)	0	146	142	277	5.89	5.35	90.8
BP8 (D/Al;31%;H2)	0	0	0	*229	4.85	2.64	54.4
BP9 (D/Al;31%;0)	229	0	*134	0	4.93	3.82	77.5
BP3b(W/Al;26%;H2)	0	0	0	*268	3.41	1.76	51.6
BP4b (D/Al;26%;0)	0	0	*268	0	4.96	3.77	76.0
BP4c(D/Al;26%;H2)	0	0	0	*268	4.90	1.98	40.4

* Second measurement capacity by C/10 rate charge for 18 h followed by discharge at C/2 rate to 1.0 V.

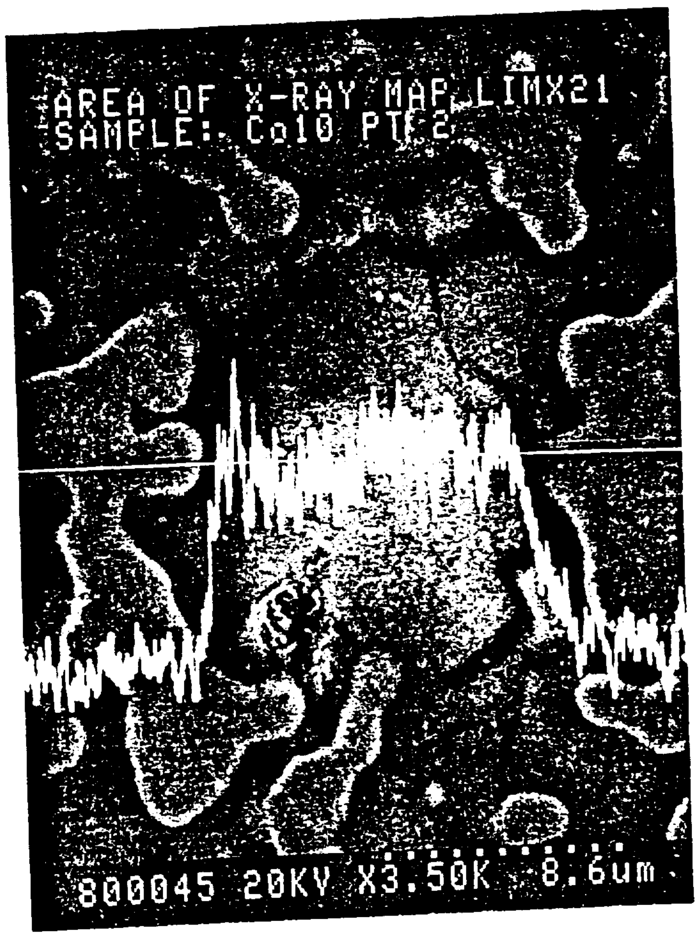


Fig. 1 SEM picture and EDX cobalt line scan result of metallographic sample of a new nickel electrode containing nominal 10% cobalt. Light colored islands in the picture are nickel metal particles and remaining grey area represent active material.

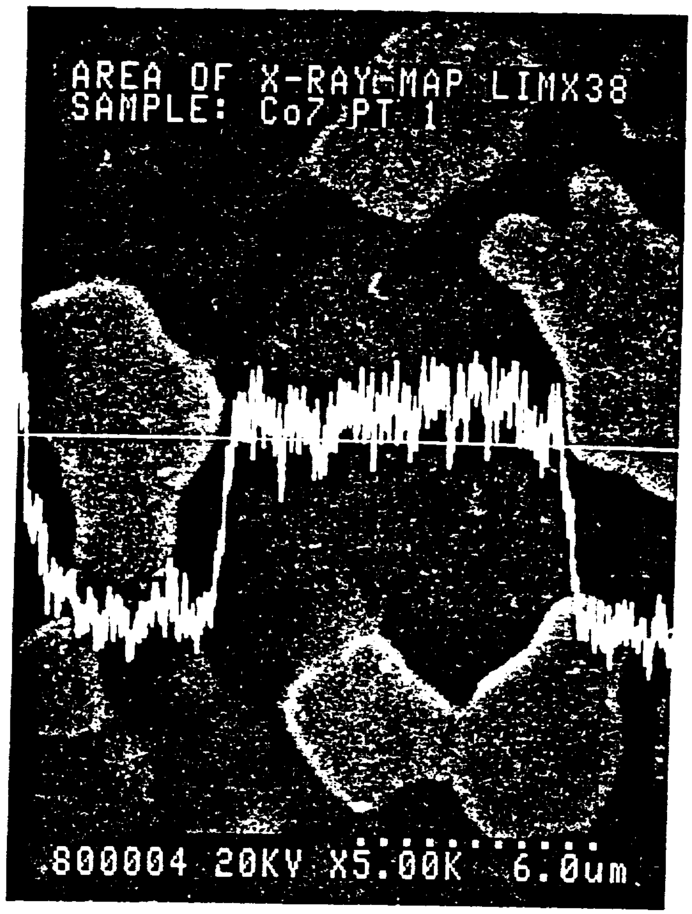


Fig. 2 SEM picture and EDX cobalt line scan result of metallographic sample of a new nickel electrode containing nominal 7% cobalt. Light colored islands in the picture are nickel metal particles and remaining grey area represent active material.

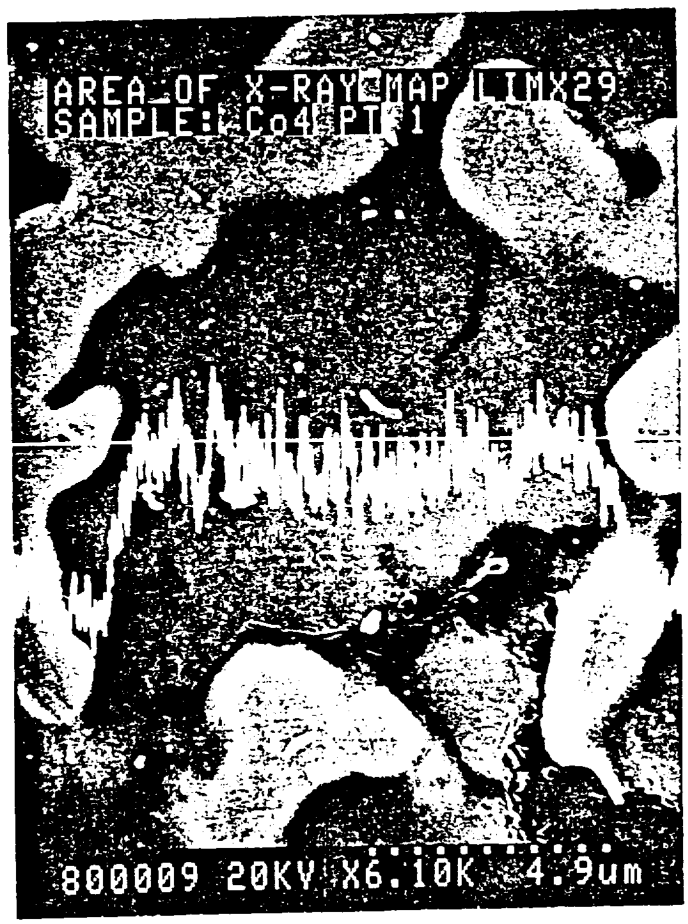


Fig. 3 SEM picture and EDX cobalt line scan result of metallographic sample of a new nickel electrode containing nominal 4% cobalt. Light colored islands in the picture are nickel metal particles and remaining grey area represent active material.

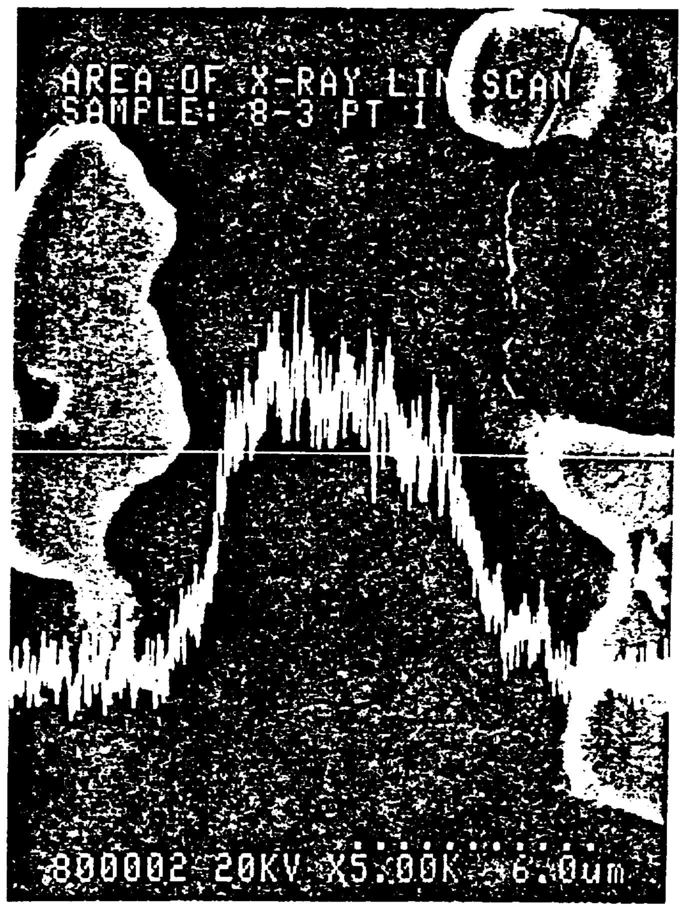


Fig. 4 SEM picture and EDX cobalt line scan result of metallographic sample of a nickel electrode from BP 8. Light colored islands in the picture are nickel metal particles and remaining grey area represent active material.

Fig. 5 SEM picture and EDX cobalt line scan result of metallographic sample of a nickel electrode from BP2. Light colored islands in the picture are nickel metal particles and remaining grey area represent active material.

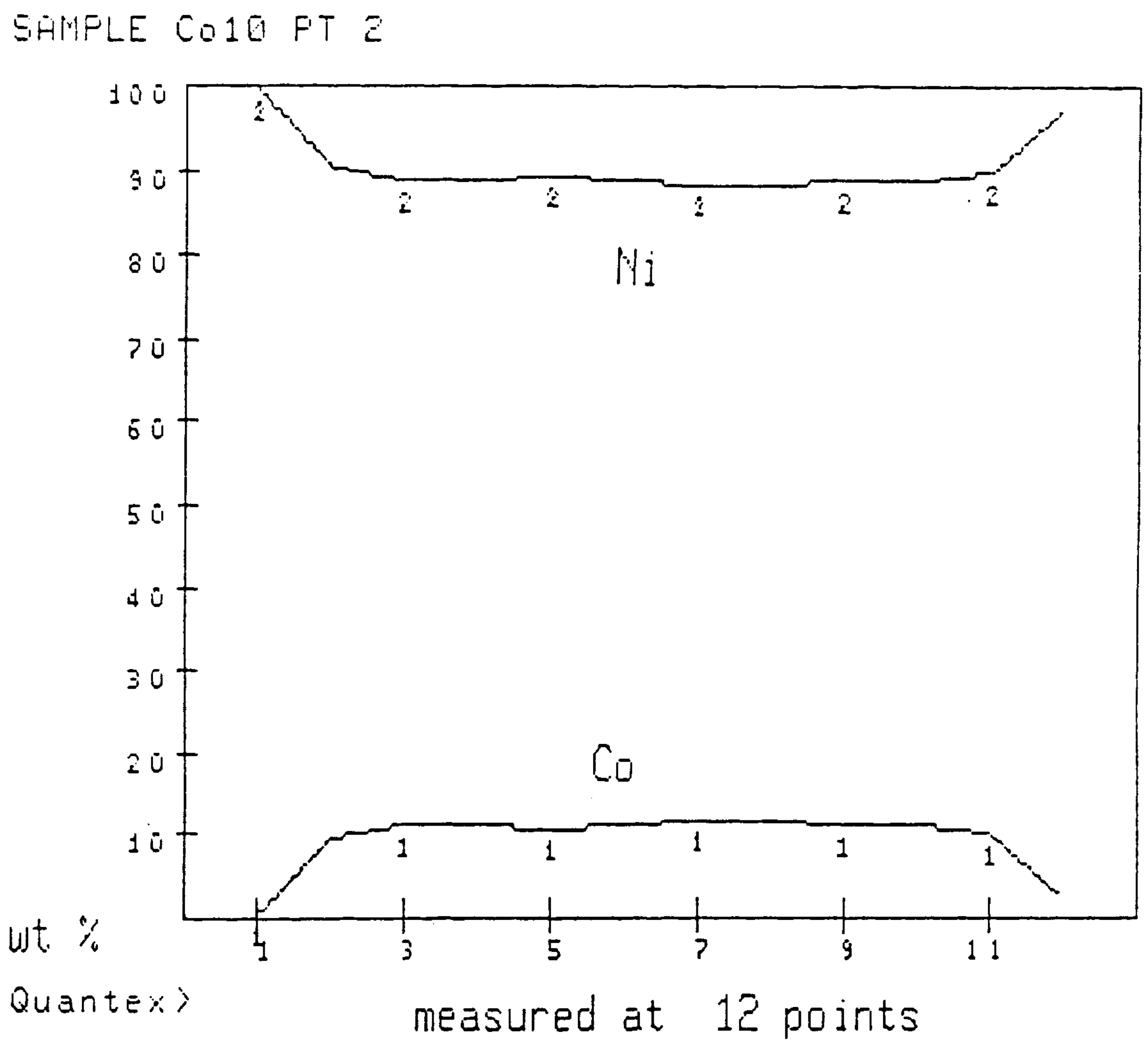


Fig. 6 Point-by-point analysis results of cobalt and nickel in the same sample and in the similar region as the EDX line scan in Fig. 1.

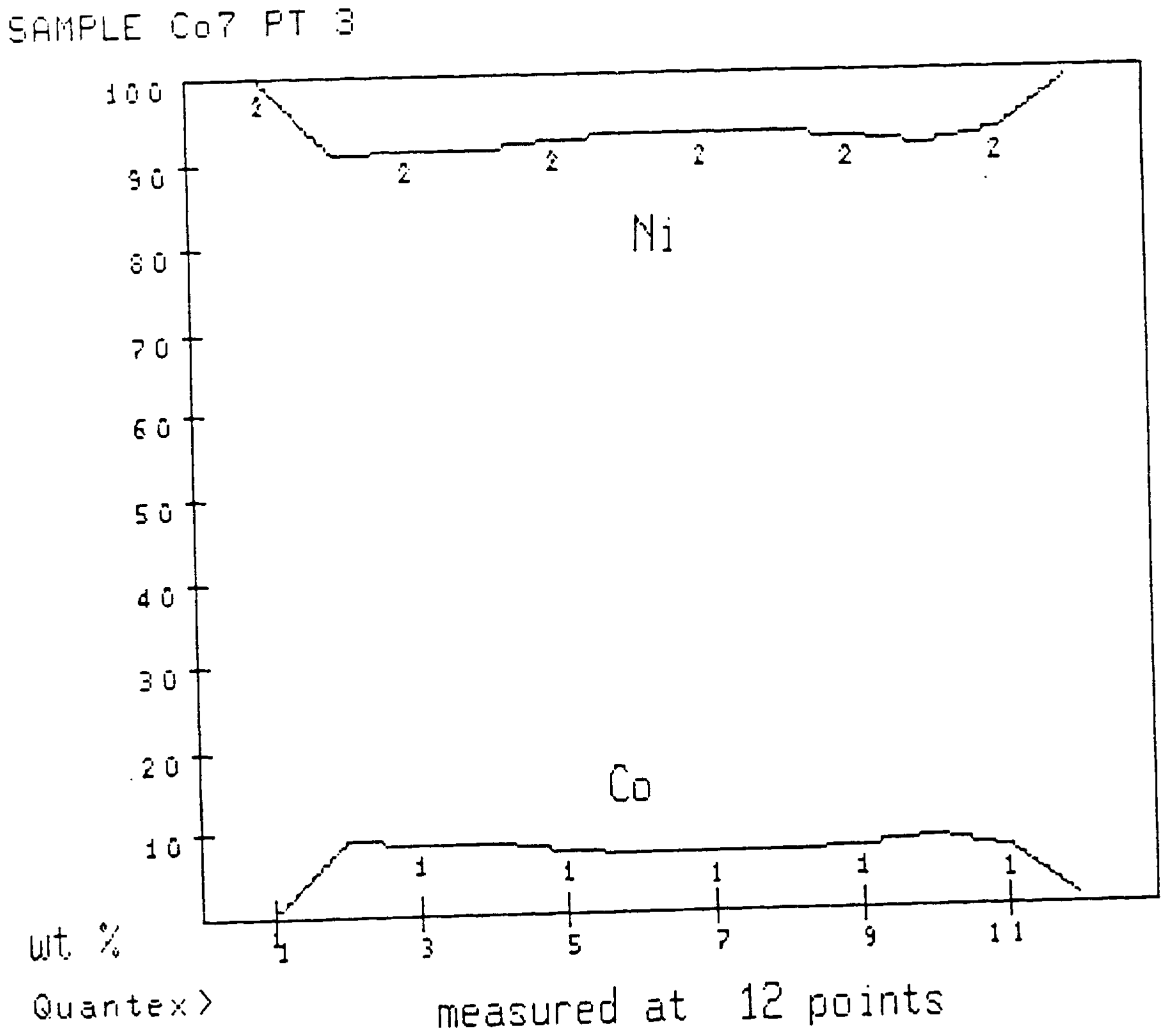


Fig. 4.7 Point-by-point analysis results of cobalt and nickel in the same sample and in the similar region as the EDX line scan in Fig. 2.

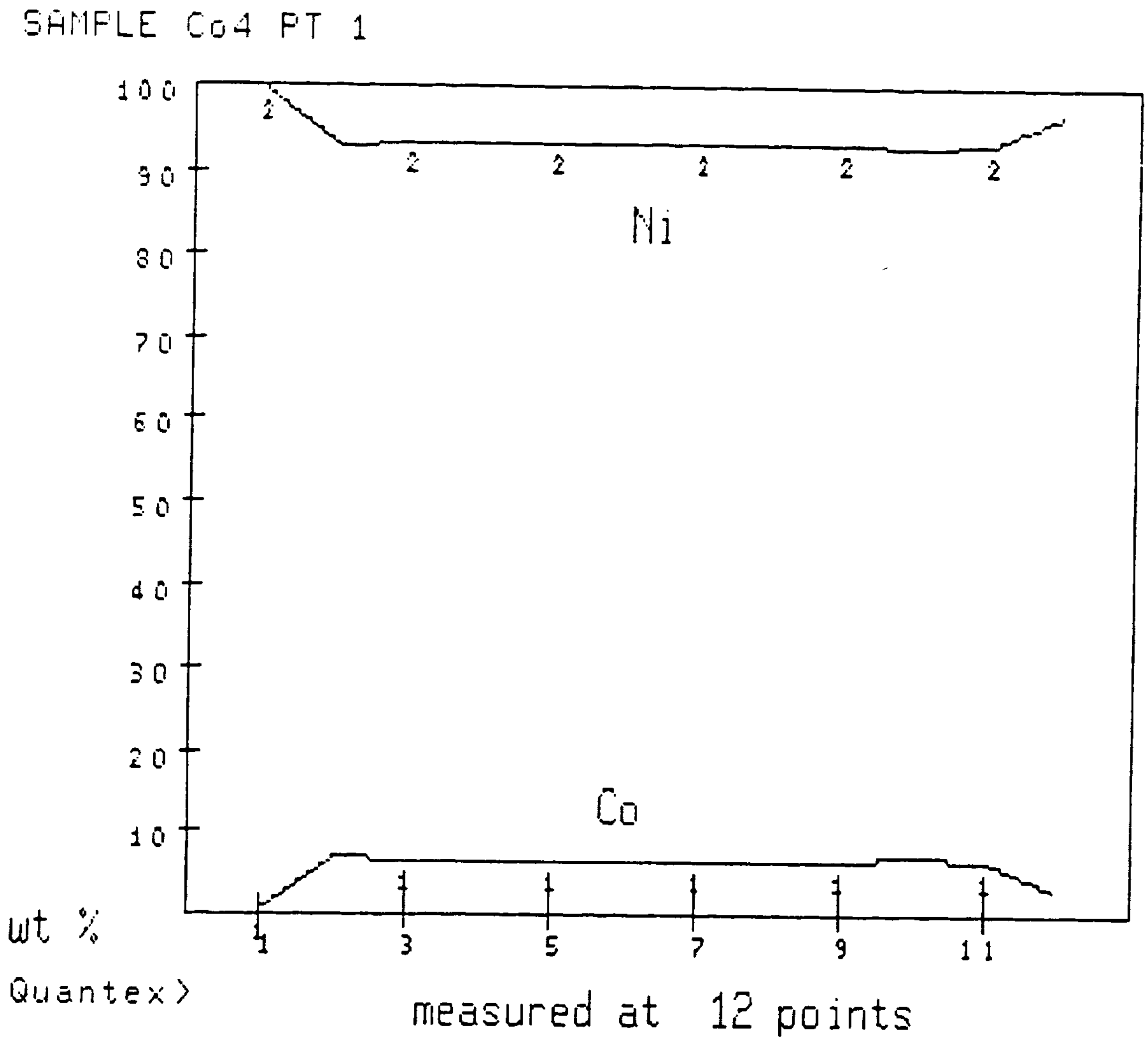


Fig. 4.8 Point-by-point analysis results of cobalt and nickel in the same sample and in the similar region as the EDX line scan in Fig. 3.

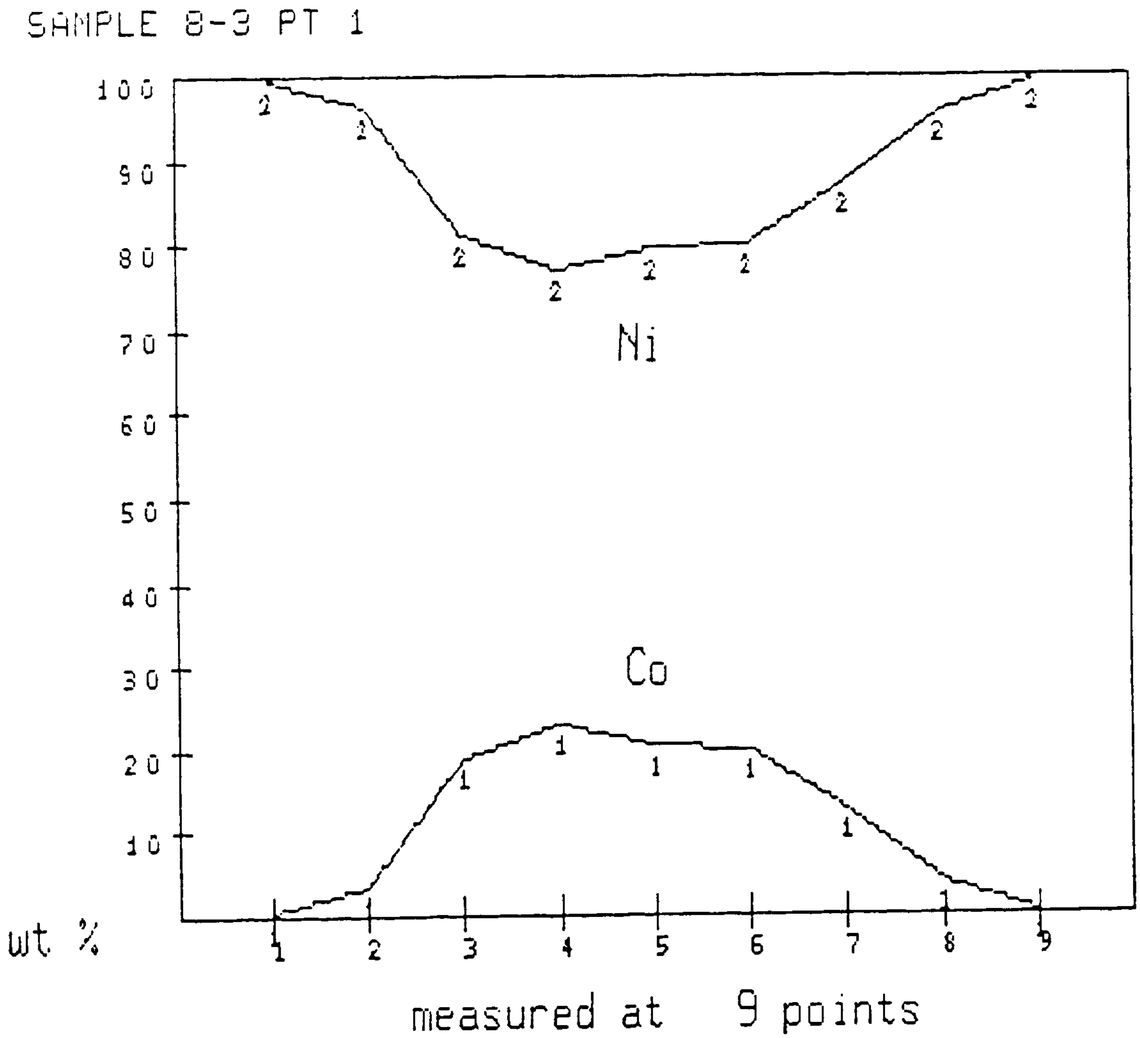


Fig. 9 Point-by-point analysis results of cobalt and nickel in the same sample and in the similar region as the EDX line scan in Fig. 4.

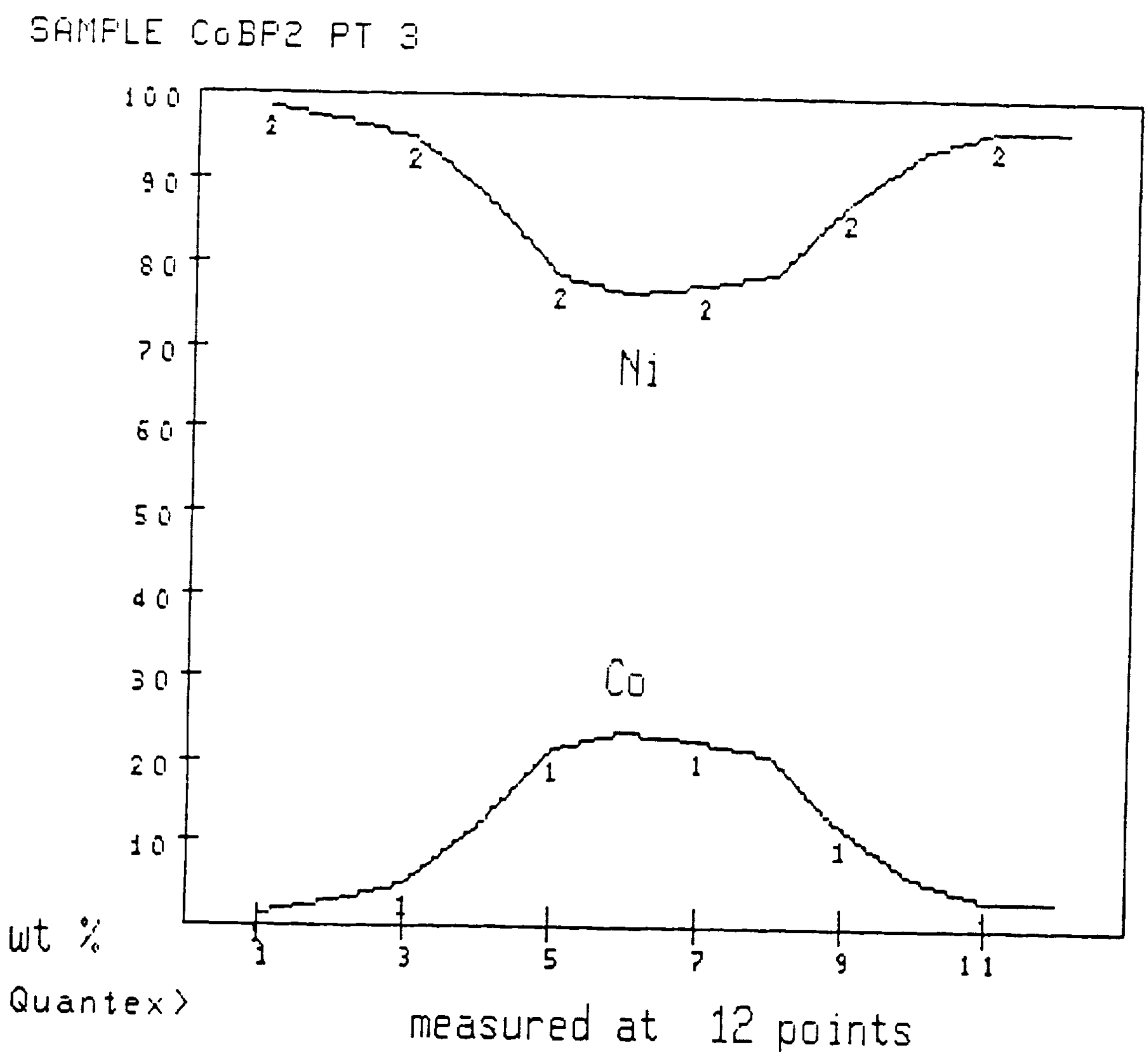


Fig. 10 Point-by-point analysis results of cobalt and nickel in the same sample and in the similar region as the EDX line scan in Fig. 5.

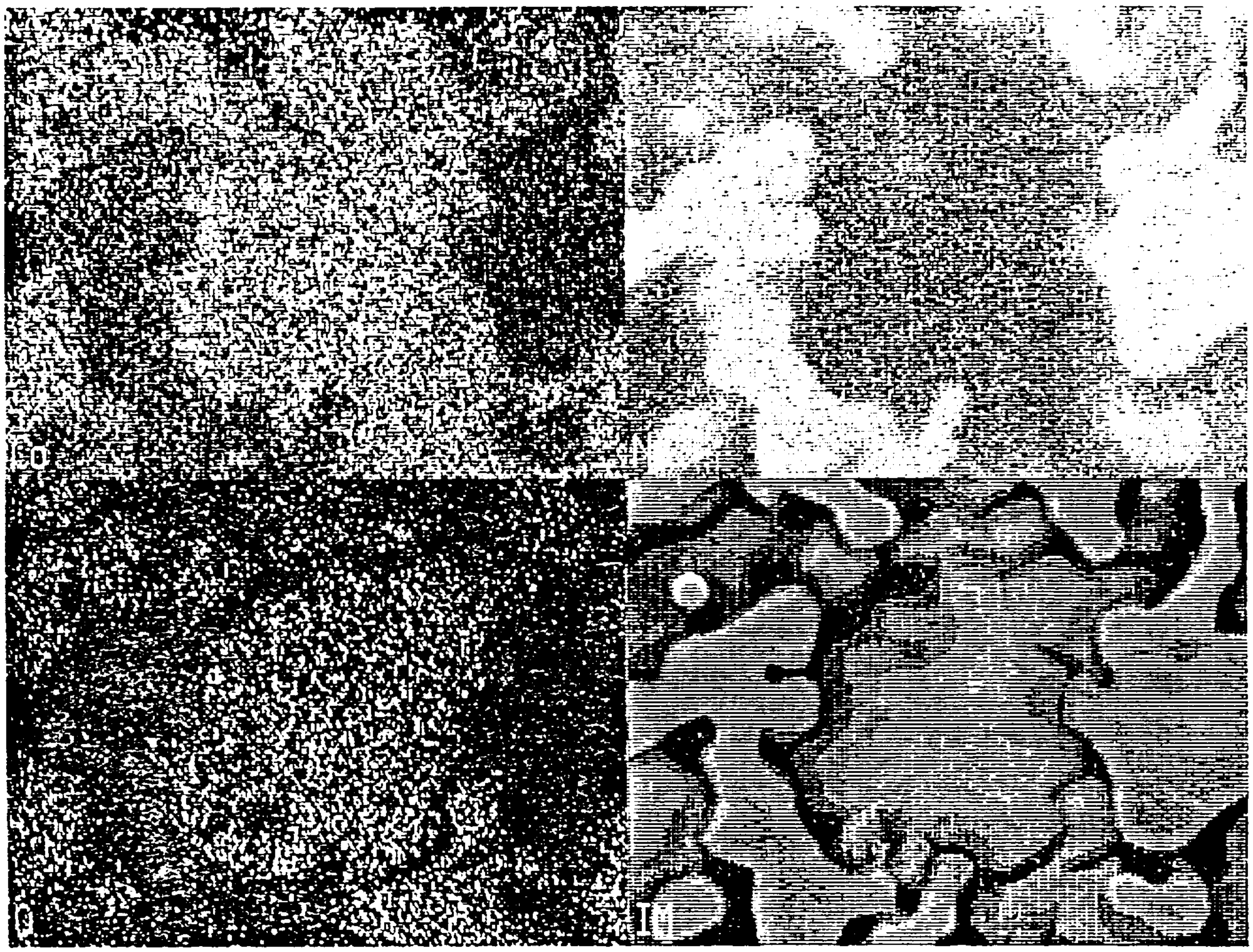


Fig. 11 EDX maps of Ni, Co and O in the same sample and in the similar region as in Fig. 1. Brightness of area represent the concentration of the corresponding elements.

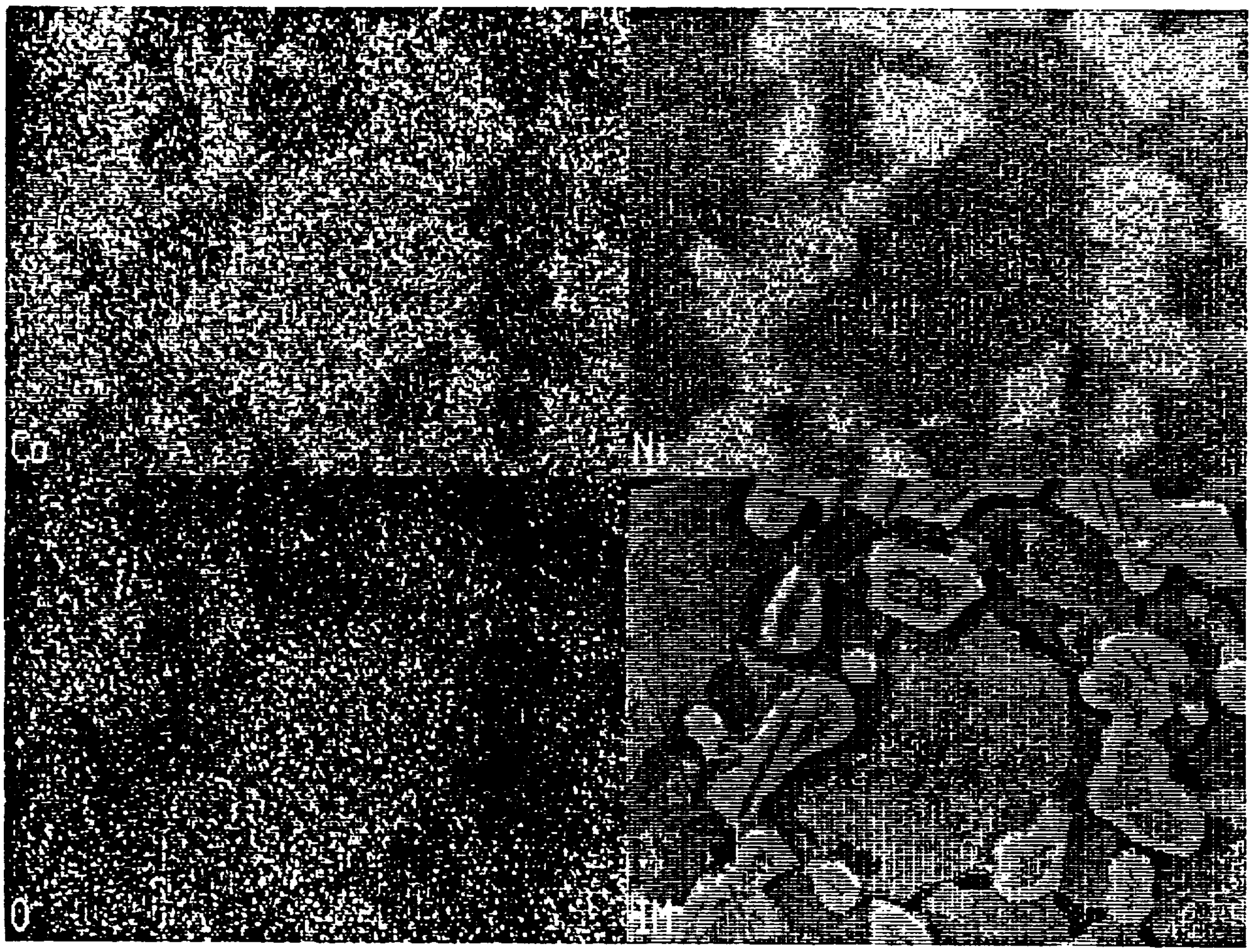


Fig. 12 EDX maps of Ni, Co and O in the same sample and in the similar region as in Fig. 4.2. Brightness of area represent the concentration of the corresponding elements.

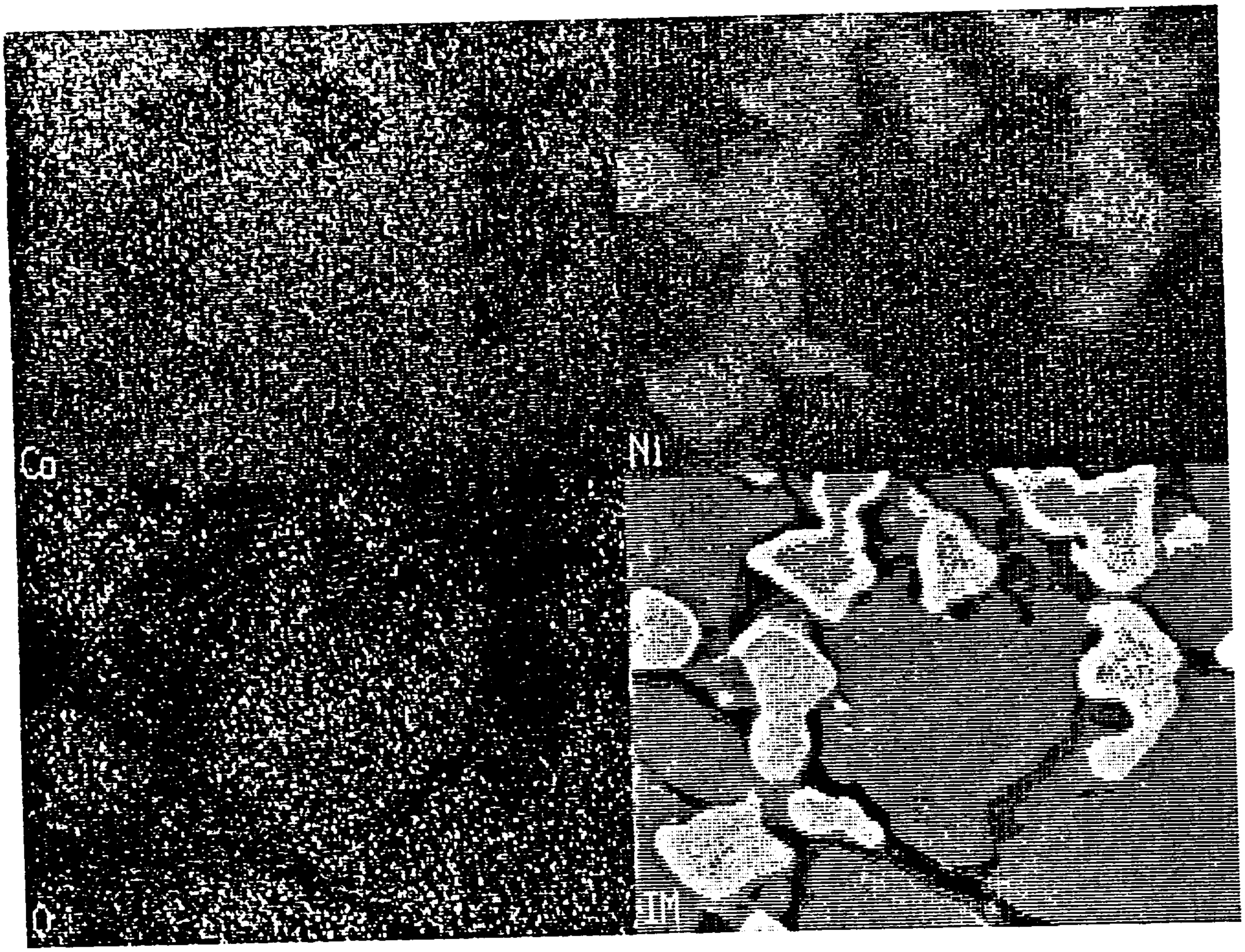


Fig. 13 EDX maps of Ni, Co and O in the same sample and in the similar region as in Fig. 4.3. Brightness of area represent the concentration of the corresponding elements.

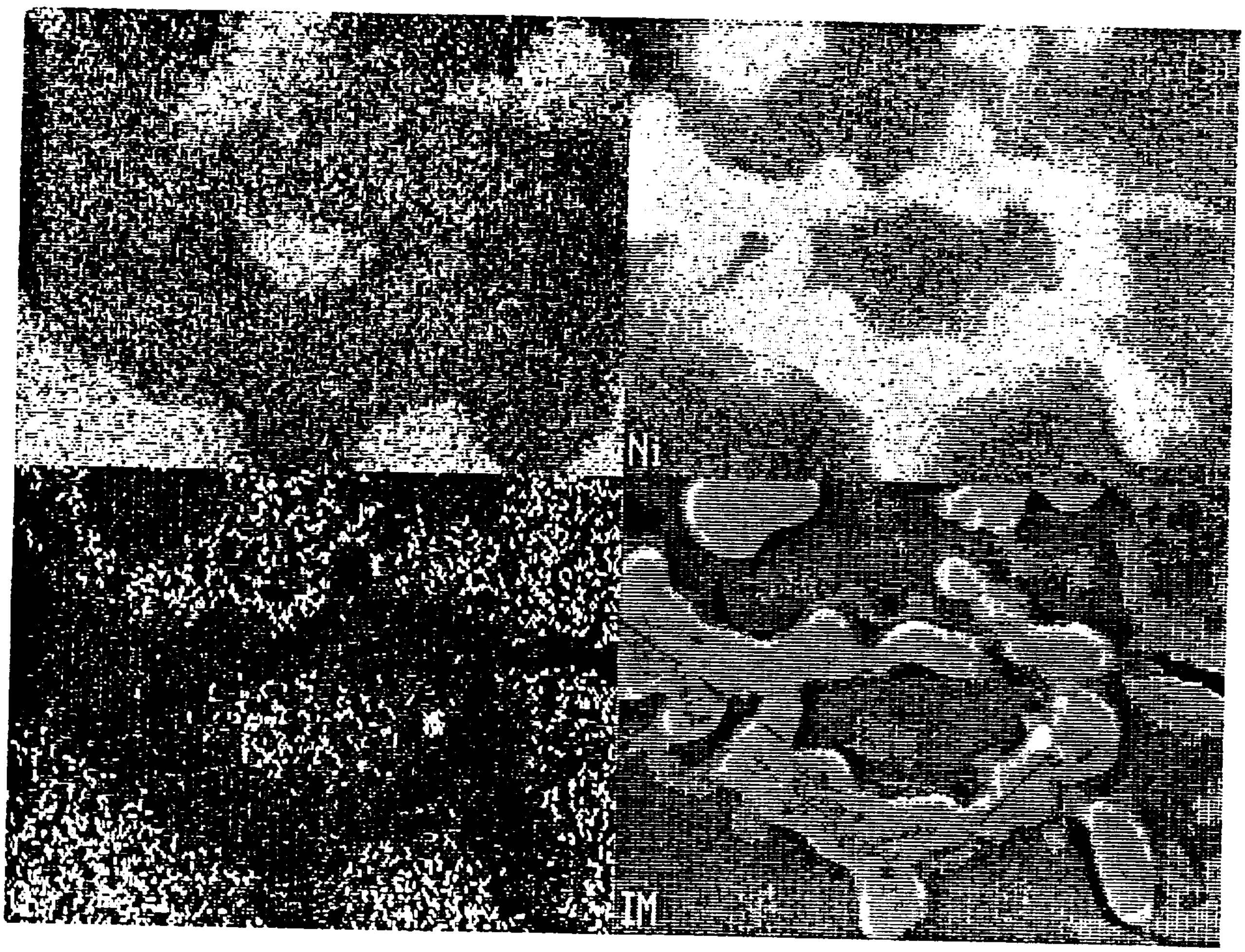


Fig. 14 EDX maps of Ni, Co and O in the same sample and in the similar region as in Fig. 4.4. Brightness of area represent the concentration of the corresponding elements.

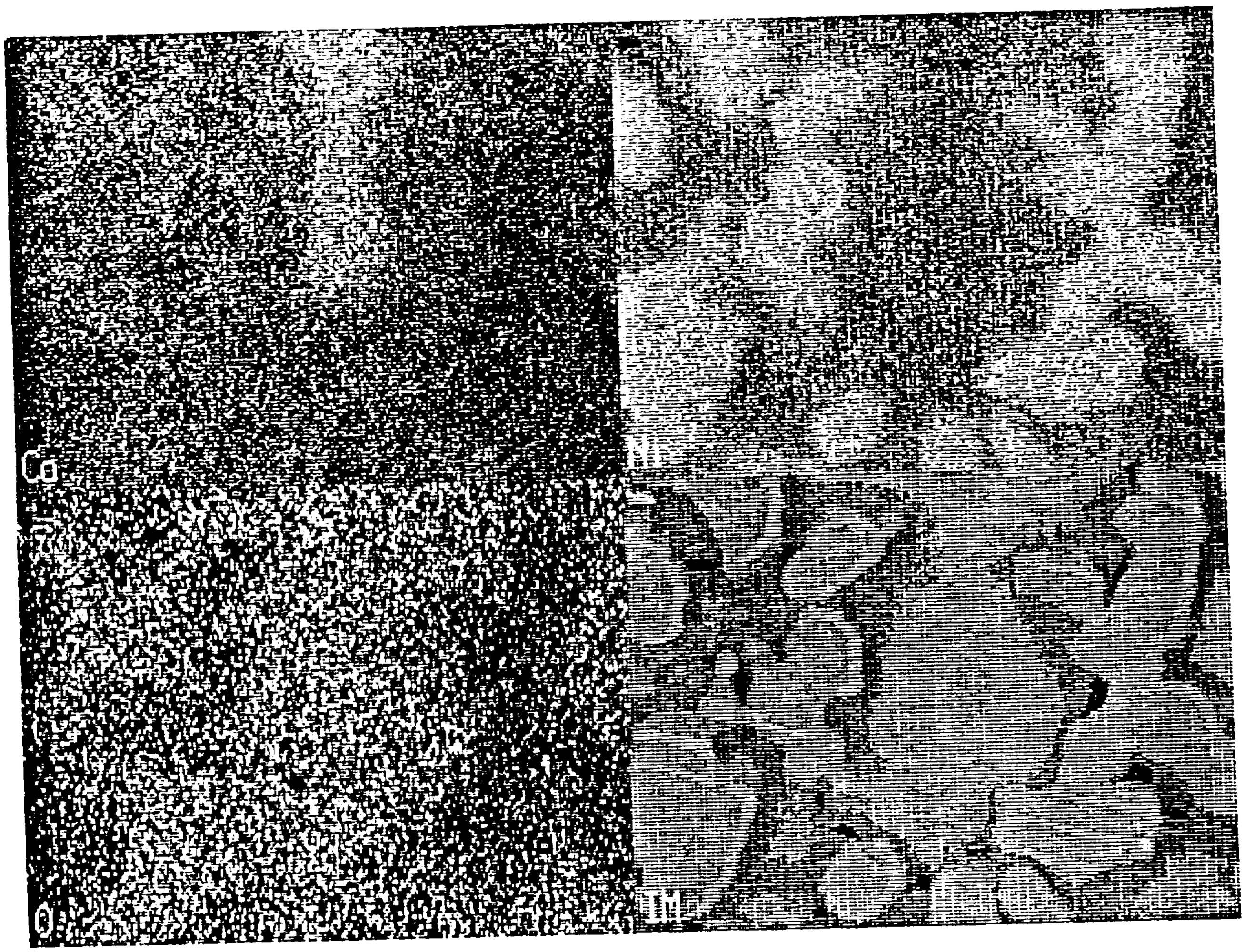


Fig. 15 EDX maps of Ni, Co and O in the same sample and in the similar region as in Fig. 4.5. Brightness of area represent the concentration of the corresponding elements.

SEM and EDX Observation Summary

Electrode ID	Dot-by-dot results: Peak %Co	Dot-by-dot results: Distribution	Line Scan Results	Dot mapping Results
Co-10	11~14	Flat	Flat	Match SEM
Co-7	7~11	Flat	Flat	Match SEM
Co-4	5~8	Flat	Flat	Match SEM
W/Al	10~14	Flat	Flat	Match SEM
BP1(10Co;26%;H2)	14~16	Flat	Flat	Co $\leq$ Ni ~ O
BP3 (7Co;26%;H2)	14~17	Sl. parabolic	Flat	Co $\leq$ Ni ~ O
BP5 (4Co;26%;H2)	8~14	Flat	Flat	Co $\leq$ Ni ~ O
BP2 (10Co;26%;Ni)	23~26	Parabolic	Parabolic	Co $<$ Ni ~ O
BP4 (7Co;26%;Ni)	14~20	Sl. parabolic	Sl. parabolic	Co $<$ Ni ~ O
BP6 (4Co;26%;Ni)	6~13	Sl. parabolic	Sl. parabolic	Co $<$ Ni ~ O
BP8 (D/Al;31%;H2)	22~24	Parabolic	Parabolic	Co $<$ Ni ~ O
BP9 (D/Al;31%;0)	14~19	Flat	Flat	Co $<$ Ni ~ O
BP3b(W/Al;26%;H2)	22~26	Sl. parabolic	Sl. parabolic	Co $<$ Ni ~ O
BP4b (D/Al;26%;0)	14~15	Flat	Flat	Co $\leq$ Ni ~ O
BP4c(D/Al;26%;H2)	20~21	Parabolic	Parabolic	Co $<$ Ni ~ O

Comparison of Co Redistributions and Cell Storage History

Electrode ID	Capacity Fade % of init.	Peak Co, %	Severity of Co redistribution, 0~10*
BP1(10Co;26%;H2)	94.1	14~16	2
BP3 (7Co;26%;H2)	89.8	14~17	2
BP5 (4Co;26%;H2)	91.2	8~14	2
BP2 (10Co;26%;Ni)	116.0	23~26	10
BP4 (7Co;26%;Ni)	102.0	14~20	9
BP6 (4Co;26%;Ni)	90.8	6~13	8
BP8 (D/Al;31%;H2)	54.4	22~24	6
BP9 (D/Al;31%;0)	77.5	14~19	4
BP3b(W/Al;26%;H2)	51.6	22~26	4
BP4b (D/Al;26%;0)	76.0	14~15	2
BP4c(D/Al;26%;H2)	40.4	20~21	4

* Visual determination by the shrinkage of Co area from the dot maps.

CONCLUDING REMARKS

HUGHES

- MIGRATION OF Co IN THE Ni ELECTRODE CONFIRMED

- THE DIRECTION OF MIGRATION IS FROM THE INTERFACE BETWEEN THE ACTIVE MATERIAL AND NICKEL METAL PARTICLES OF SINTERED PLAQUE INTO THE BULK OF ACTIVE MATERIAL.

- THERE WAS NO DIRECT CORRELATION BETWEEN CAPACITY FADING AND REDISTRIBUTION OF COBALT.

- PRACTICAL IMPLICATION: IT MIGHT BE A LITTLE EASIER TO DEVELOP A METHOD FOR CAPACITY RECOVERY THAN RECOVERING THE ORIGINAL DISTRIBUTION OF Co.

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DIVISION ESPACE · SPACE DEPARTMENT

ROMAINVILLE FRANCE

1992 - NASA AEROSPACE BATTERY WORKSHOP

NICKEL HYDROGEN CAPACITY LOSS

J. GOUALARD - D. PAUGAM - Y. BORTHOMIEU

US SPACE AND ROCKET CENTER

HUNSTSVILLE - AL

17 - 19 NOVEMBER 1992

1.

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CONTENT

. CELL DESIGN

. DEFINITIONS

. EXPERIENCE

. PRELIMINARY CONCLUSIONS

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CELL DESIGN

. GENERAL : "COMSAT" DESIGN

. POSITIVE ELECTRODE

  . SINTERED NICKEL - SLURRY PROCESS - PERFORATED STEEL GRID
  . AQUEOUS ELECTROCHEMICAL IMPREGNATION
  . LOADING 1.7 g/cm^3 OF VOIDS - COBALT 5%

. NEGATIVE ELECTRODE

  . ACTIVE CHARCOAL 5% PLATINUM CATALYST ON NICKEL GRID
  . TEFLON HYDROPHOBIC LAYER

. ELECTRODES STACK

  . BACK TO BACK STACKING
  . SEPARATOR : NON WOVEN POLYAMID FELT
  . GAS SCREEN : WOVEN POLYAMID
  . CENTRAL TIE ROD

. CELL

  . HYDROGEN (NEGATIVE) PRECHARGE   3 BARS (40 PSI)
  . KOH 31% (STANDARD)
  . MAXIMUM OPERATING PRESSURE   75 BARS (1040 PSI)

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DEFINITIONS

REFERENCE CAPACITY AT 21 ± 3° C

A) . 5 Ω RESISTORS FOR 16 HOURS
B) CHARGE 7.7 H AT C/5

---> C) DISCHARGE C/2 TO 1 VOLT
D) C/5 TO .5V

TOTAL CAPACITY : CAPACITY TO 1V + CAPACITY 1V - .05V

AVERAGE VALUES : CAPACITY 1V TO.5V (D) 15% - 20% OF TOTAL

2ND PLATEAU OR CAPACITY LOSS

IF CAPACITY 1V TO .5V (D) > 20 - 25% OF TOTAL

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ROMAINVILLE FRANCE

1992 - NASA AEROSPACE BATTERY WORKSHOP

EXPERIENCE : 1 - BOILER PLATES 8 AH

	MM V 1 COBALT 5%	MM V 2 COBALT 10%
FLOODED ELECTROLYTE CAPACITY	10.8 AH	13.2 AH
A) PRECHARGE H_2 3 BARS (40 PSI)		
REFERENCE CAPACITY (AH)	7.7	8
2ND PLATEAU AH (%)	2.3 (23%)	2.2 (23%)
B) PRECHARGE 30 BARS (400 PSI)		
INITIAL : REFERENCE CAPACITY	7.6	8.1
2ND PLATEAU	2.8 (26.9%)	2.4 (22.8%)
STORAGE 3 WEEKS		
REFERENCE CAPACITY	6.4	7.2
2ND PLATEAU	3.4	2.9 (28.7%)
C) PRECHARGE 3 BARS		
REFERENCE CAPACITY	6.2	7
2ND PLATEAU	3.7 (37.4%)	3.3 (32%)
FLOODED ELECTROLYTE CAPACITY	9.2 AH	11.2

---> STORAGE UNDER H_2 PRESSURE INCREASES CAPACITY LOSS
---> EFFECT OF H_2 PRESSURE SEEMS REDUCED IN HIGH COBALT CONTENT CELL

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EXPERIENCE : 2 - VHS 50 BL - L1

A) ACCEPTANCE	
REFERENCE CAPACITY	49.6 AH
2^{ND} P.	16 (24,4%)
B) STORAGE 3 MONTHS	
REFERENCE CAPACITY	52.5 AH
2^{ND} P.	7.3 AH (12%)
C) GEO CYCLING 70% DOD - 10°C CAPACITY MEASUREMENT AFTER EACH SHADOW PERIOD	
SHADOW 4	54.5 7.5 (12.1%)
SHADOW 13	50.8 12.2 (19%)

---> INITIAL CAPACITY LOSS RECOVERED AFTER STORAGE 3 MONTHS.
---> NORMAL BEHAVIOR IN CYCLING.

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EXPERIENCE : 3 - VHS 90 CM - L1

	QUALIFICATION TESTS	QUALIFICATION TESTS + REVERSAL
A) ACCEPTANCE		
REFERENCE CAPACITY (AH)	100 AH	100 AH
2ND P.	19.5 (16%)	19.5 (16%)
B) QUALI. TESTS STORAGE 3 DAYS - CHARGED CELL	1 VOLT 72.3 AH 2 ND P. 5.7 (7%)	
REFERENCE CAPACITY	98.8	91.5
2ND P.	26 (21 %)	36 (28%)
C) STORAGE 2 MONTHS	98	90
D) CYCLING GEO 80 % DOD 10°C		ON PROGRESS NORMAL BEHAVIOR

---> EFFECT OF REVERSAL TO BE CONFIRMED

---> NO CAPACITY LOSS DURING STORAGE

8.

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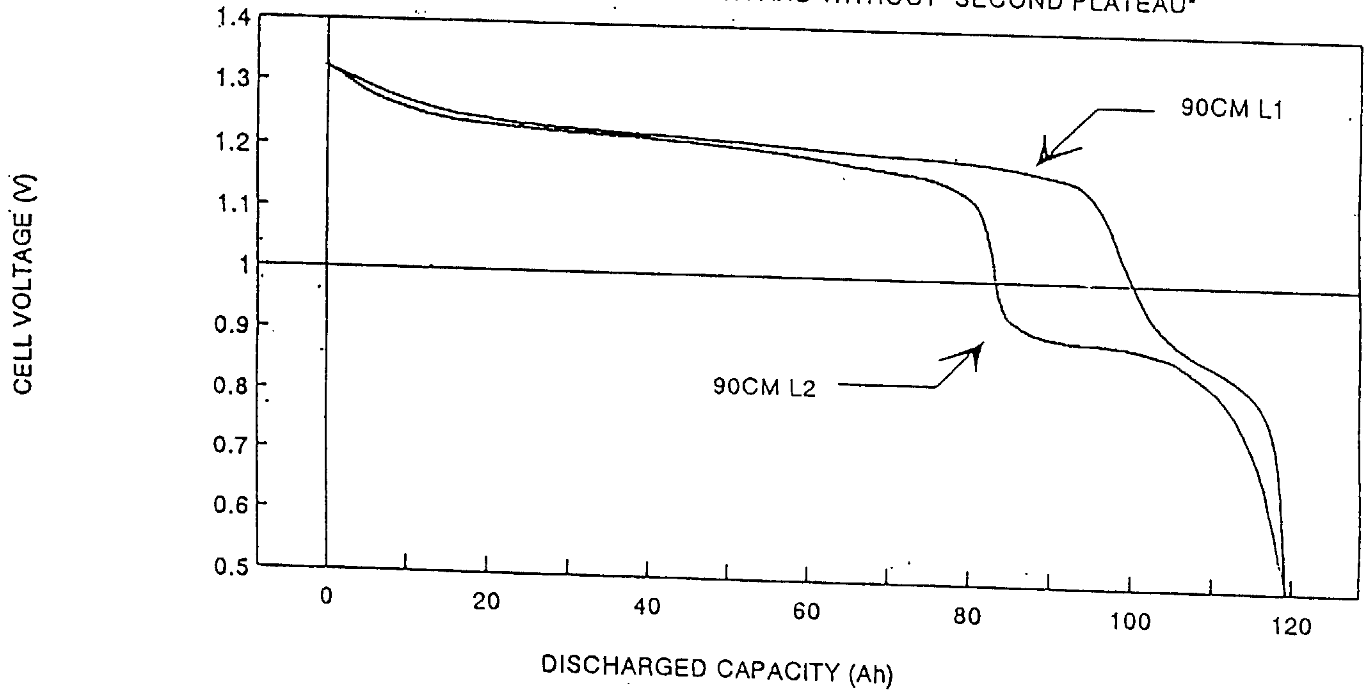
TYPICAL DISCHARGE CURVE WITH AND WITHOUT "SECOND PLATEAU"



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EXPERIENCE : 4 - VHS, 90 CM - L2

A) ACCEPTANCE		
REFERENCE CAPACITY (AH)	97.8 AH	
2^{ND} PLATEAU	21.6 AH	(18%)
B) BURN -IN CYCLES (50 CYCLES)		
REFERENCE CAPACITY	88 AH	
2^{ND} PLATEAU	34.5 AH	(28%)
C) TENTATIVE RECOVERY PROCEDURE		
LOW RATE CHARGE C/10 + C/20		
STORAGE 15 DAYS OPEN CIRCUIT 23°C		
REFERENCE CAPACITY	86	
2^{ND} P	34	(28.3%)
D) STORAGE 2 MONTHS		
DISCHARGED OPEN CIRCUIT 23°C		
REFERENCE CAPACITY	91	
2^{ND} P	27	23%

---> EFFECT OF RECOVERY PROCEDURE NOT PROVEN
---> NO CAPACITY LOSS DURING LONG STORAGE

9.

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1992 - NASA AEROSPACE BATTERY WORKSHOP

EXPERIENCE : 5 - VHS 100 CM - PR

A) ACCEPTANCE		
REFERENCE CAPACITY (AH)	108 AH	
2^{ND} P.	21	(16%,3)
B) STORAGE 5 DAYS CHARGED CELL OPEN CIRCUIT		
DISCHARGE 1 VOLT	58 AH	
2^{ND} P	2.2 AH	(3.7%)
C) 2 MONTHS TESTING VIBRATIONS - OVERCHARGE 3 GEO CYCLES		
REFERENCE CAPACITY	100	
2^{ND} P	29	(22.5%)
D) 10 MONTHS STORAGE 0°C - 23° C		
REFERENCE CAPACITY	99	
2^{ND} P	25	(20%)

---> 2^{ND} PLATEAU DOES NOT EXISTS AFTER CHARGE RETENTION

---> NO CAPACITY LOSS DURING LONG STORAGE

PRELIMINARY CONCLUSIONS

CAPACITY LOSS - 2ND PLATEAU PHENOMENA

- NOT OBSERVED DURING LONG STORAGE (> 1 MONTH)
- OBSERVED DURING ELECTRICAL FORMATION
- FAVOURED BY HIGH HYDROGEN PRESSURE AND LOW VOLTAGE
- CAPACITY LOSS SEEMS REDUCED IN CELLS WITH HIGH COBALT CONTENT
- WHEN OBSERVED, ALL SHORT TIME TENTATIVE RECOVERY ACTIONS HAD MORE DETRIMENTAL THAN BENEFICIAL EFFECT.
- DOES NOT AFFECT THE CELL BEHAVIOR IN CYCLING GEO 80% DOD AND LEO 40% DOD.

N93-20499

CAPACITY FADE IN IN NICKEL CADMIUM AND NICKEL HYDROGEN CELLS

CO-AUTHORS: TIM EDGAR AND JEFF HAYDEN; EAGLE PICHER IND. INC.
DR D. F. PICKETT HUGHES ELECTRON DYNAMICS DIV.

CONTRIBUTORS:
BRUCE ABRAMS-BLAKEMORE, EAGLE PICHER IND. INC.
ED LIPTAK, EAGLE PICHER IND. INC.

CAPACITY FADE
A DEFINITION

√ TYPICALLY UP TO 20% LOSS IN PREVIOUSLY DEMONSTRATED CAPACITY

√ NORMALLY SEEN AFTER A PERIOD OF CELL STRORAGE

√ SEEN IN NiH_2 & NiCd CELLS WITH ELECTROCHEMICALLY DEPOSITED POSITIVE PLATES

SCOPE OF PRESENTATION

1 THEORETICAL CAUSES OF CAPACITY FADE
- ROLE OF CELL STORAGE
- ROLE OF POSITIVE ELECTRODE
- ROLE OF COBALT ADDITIVE

2 EXAMPLES OF OBSERVED CAPACITY FADE
- INTELSAT V (30 AH NiH_2)
- INTELSAT VI (48 AH NiH_2)
- EXPLORER PLATFORM (50 AH NiCd)

3 PREVENTION AND RECOVERY METHODS
- OPEN CIRCUIT STORAGE
- STORAGE UNDER TRICKEL CHARGE
- STORAGE FULLY CHARGED

4 CURRENT EAGLE PICHER/HUGHES RESEARCH STATUS

CAPACITY FADE
THEORY OF PHENOMENON

1. ATTRIBUTED TO ACTIVE MATERIAL CHANGES IN THE POSITIVE PLATE AT LOW STATES OF CHARGE

2. APPEARS TO BE SPECIFIC TO ELECTROCHEMICALLY DEPOSITED PLATES IN BOTH NiH_2 AND NiCD CELLS

3. OCCURS AFTER A PERIOD OF STORAGE OPEN CIRCUIT DISCHARGED SHORTED CONDITION

4. CAPACITY FADE HAS BEEN LINKED TO THE COBALT ADDITIVE AND ITS SEVERITY MAY BE ASSOCIATED WITH COBALT CONCENTRATION

5. CHARGED ACTIVE MATERIAL IS UNABLE TO BE COMPLETELY DISCHARGED AT HIGHER RATES

6. OVERALL CELL PERFORMANCE IS NOT AFFECTED AND CAPACITY IS RECOVERED THROUGH CYCLING AND USE

CAPACITY FADE
ROLE OF THE POSITIVE ELECTRODE

1. ELECTROCHEMICALLY DEPOSITED POSITIVE ELECTRODES HAVE DISPLAYED CAPACITY FADE IN BOTH NICKEL CADMIUM AND NICKEL HYDROGEN CELLS

2. MANY RESEARCHERS BELIEVE THAT THE PHENOMENON IS LOCALIZED TO THE POSITIVE

3. CAPACITY FADE HAS NOT BEEN OBSERVED IN CHEMICALLY DEPOSITED POSITIVE ELECTRODES

4. SOME RESEARCHERS BELIEVE THAT CAPACITY FADE CAN BE ATTRIBUTED TO THE DEPTH OF DISCHARGE OF THE POSITIVE ELECTRODE.

    - THIS THEORY IS SUPPORTED BY THE ABSENCE OF FADING DURING CYCLING
    - THE FACT THAT FADING HAS BEEN GENERALLY SEEN AFTER STORAGE IN THE DISCHARGED CONDITION IS ALSO SUPPORTIVE OF THE THEORY.

CAPACITY FADE

ROLE OF STORAGE

1. CELL VOLTAGE AT START OF STORAGE IS A CRITICAL FACTOR
   - CAPACITY FADE HAS NOT BEEN OBSERVED IN CELLS STORED AT POTENTIALS BETWEEN 0.5 AND 1.0 VOLTS

2. HIGHER STORAGE TEMPERATURES APPEAR TO ACCELERATE CAPACITY FADING
   - OPTIMUM TEMPERATURES ARE BELOW 23° C

3. SHORTING CELLS FOR EXTENDED PERIODS DURING STORAGE HAS BEEN DEMONSTRATED TO INCREASE THE DEGREE OF CAPACITY FADE

4. THE LONGER THE STORAGE TIME THE MORE IMPORTANT THE FACTORS LISTED ABOVE BECOME.

CAPACITY FADE
ROLE OF COBALT ADDITIVE

1. RESEARCH INDICATES A POSSIBLE CHEMICAL COMBINATION OF COBALT AND NICKEL

   √ THIS REACTION IS BELIEVED TO OCCUR AT LOW STATES OF CHARGE IN THE ACTIVE MATERIAL

   √ THE PRESENCE OF NICKEL IN THE CHARGED FORM (NIOOH) APPEARS TO INHIBIT THE REACTION

   √ THE RESULTANT HYBRID COMPOUND DRAMATICALLY CHANGES THE DISCHARGE CHARACTERISTICS OF THE ACTIVE MATERIAL

2. SEVERITY OF CAPACITY FADE MAY BE LINKED TO COBALT CONCENTRATION

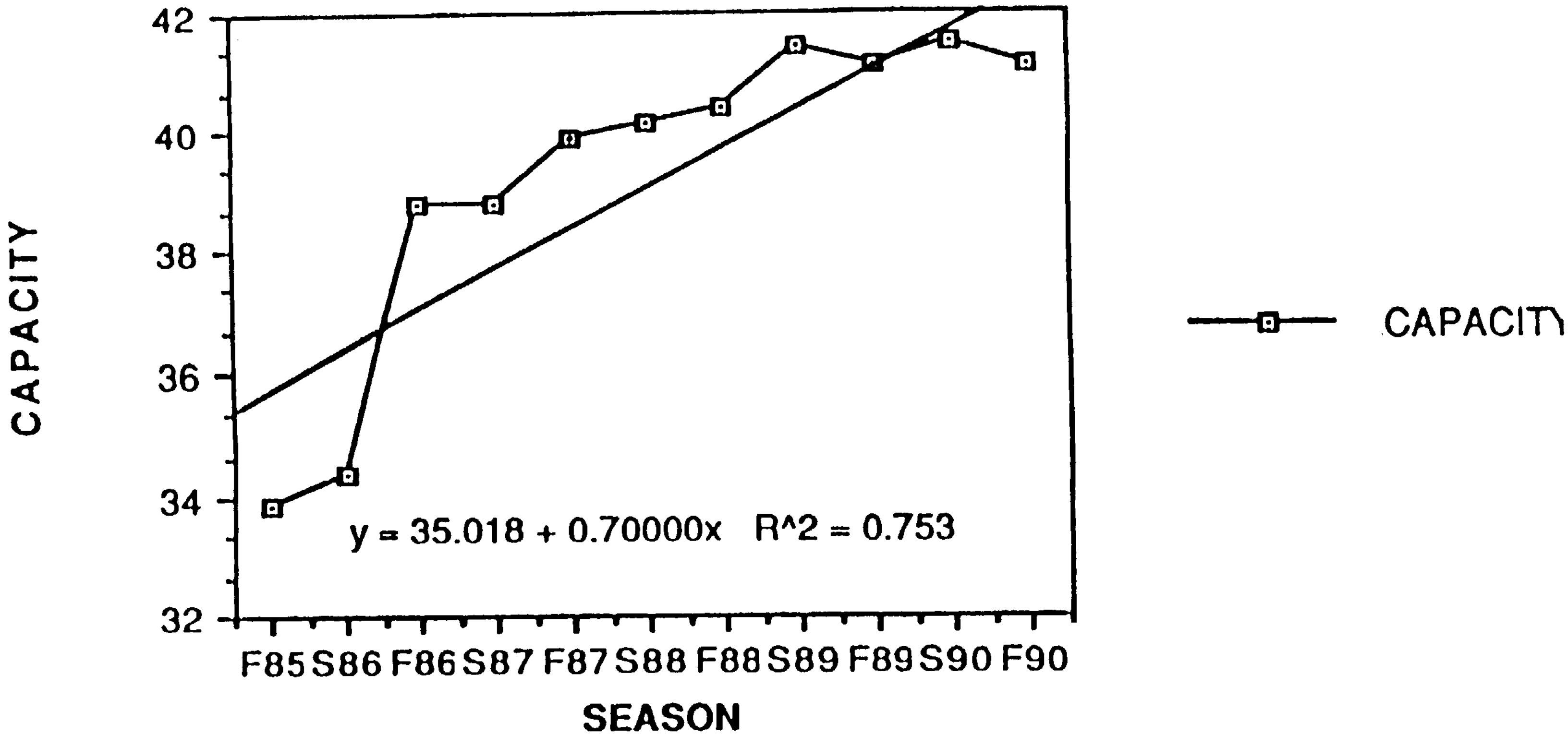
   √ HIGHER COBALT CONCENTRATION APPEARS TO LEAD TO MORE PRONOUNCED FADING

CAPACITY FADE
OCCURANCE OF

1. CELLS WHICH EXHIBIT CAPACITY FADE HAVE:
   a. NORMALLY BEEN THROUGH A PERIOD OF STORAGE
   b. HAVE BEEN STORED IN A DISCHARGED CONDITION
   c. HAVE BEEN STORED AT HIGHER THAN NORMAL TEMPERATURES ($\geq$ 23° C)
   d. HAVE IN MANY CASES BEEN SHORTED FOR ALL OR PART OF THE STORAGE TIME

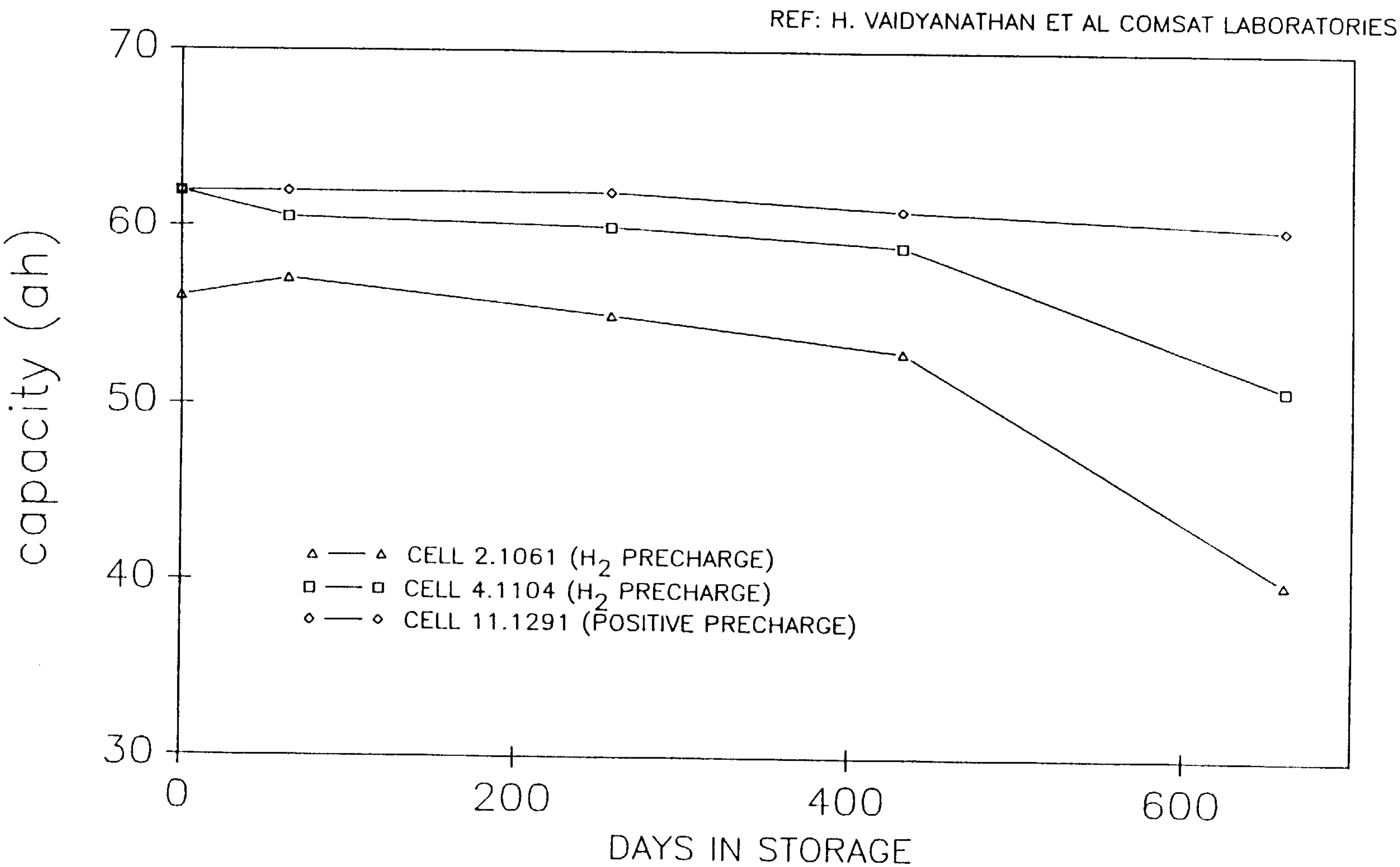
2. TO BE CLASSIFIED AS CELLS WHICH EXHIBIT CAPACITY FADE THE CELLS SHOULD:
   a. EXHIBIT A DECREASED CAPACITY THAT IS NOT RECOVERED THROUGH ROUTINE CYCLING
   b. GENERALLY OCCURS EARLY IN CELL CYCLE LIFE
   c. DEMONSTRATE NO OTHER ANOMALY WHICH WOULD CONTRIBUTE TO CAPACITY LOSS
   d. PERFORM NORMALLY IN ALL OTHER RESPECTS

Capacity vs Eclipse Season
Intelsat 5 F-10 Battery 2



Ref.: J. Dunlap
COMSAT

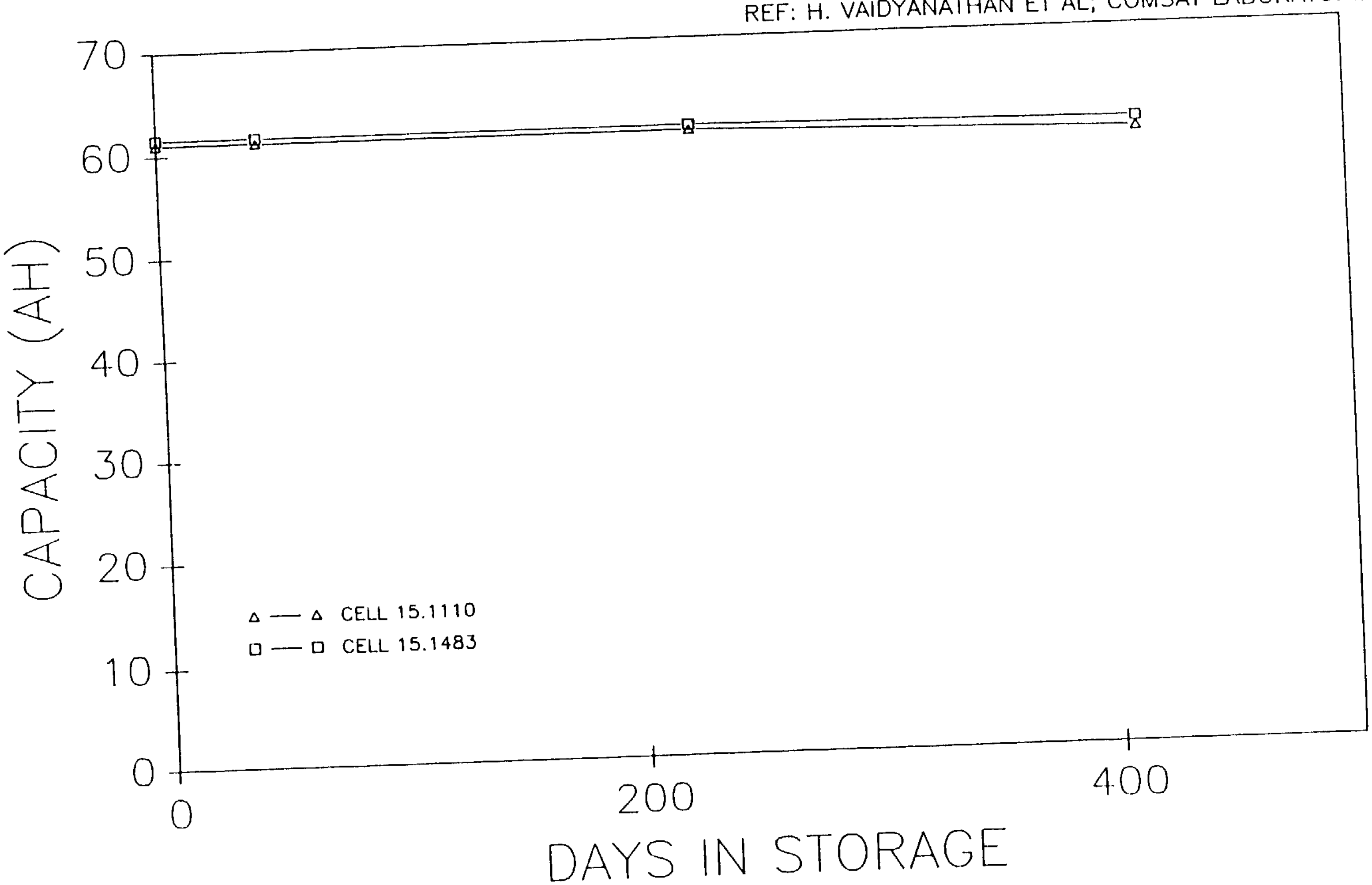
INTELSAT VI STORAGE STUDY



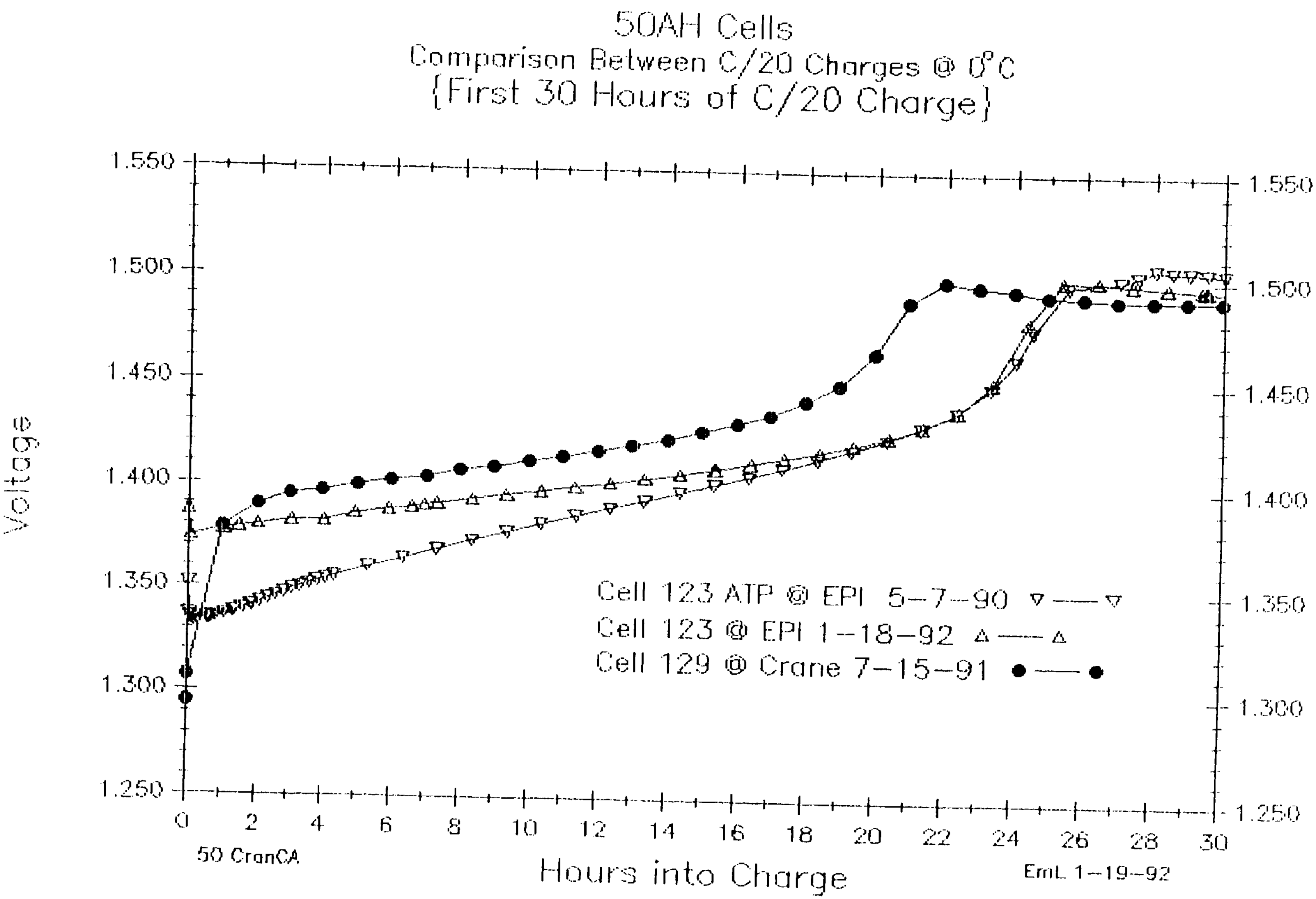
CAPACITY TO 1V FOR CELLS
STORED AT 0° C

INTELSAT VI CAPACITY
BEHAVIOR WHEN STORED
ON TRICKLE–CHARGE

REF: H. VAIDYANATHAN ET AL; COMSAT LABORATORIES

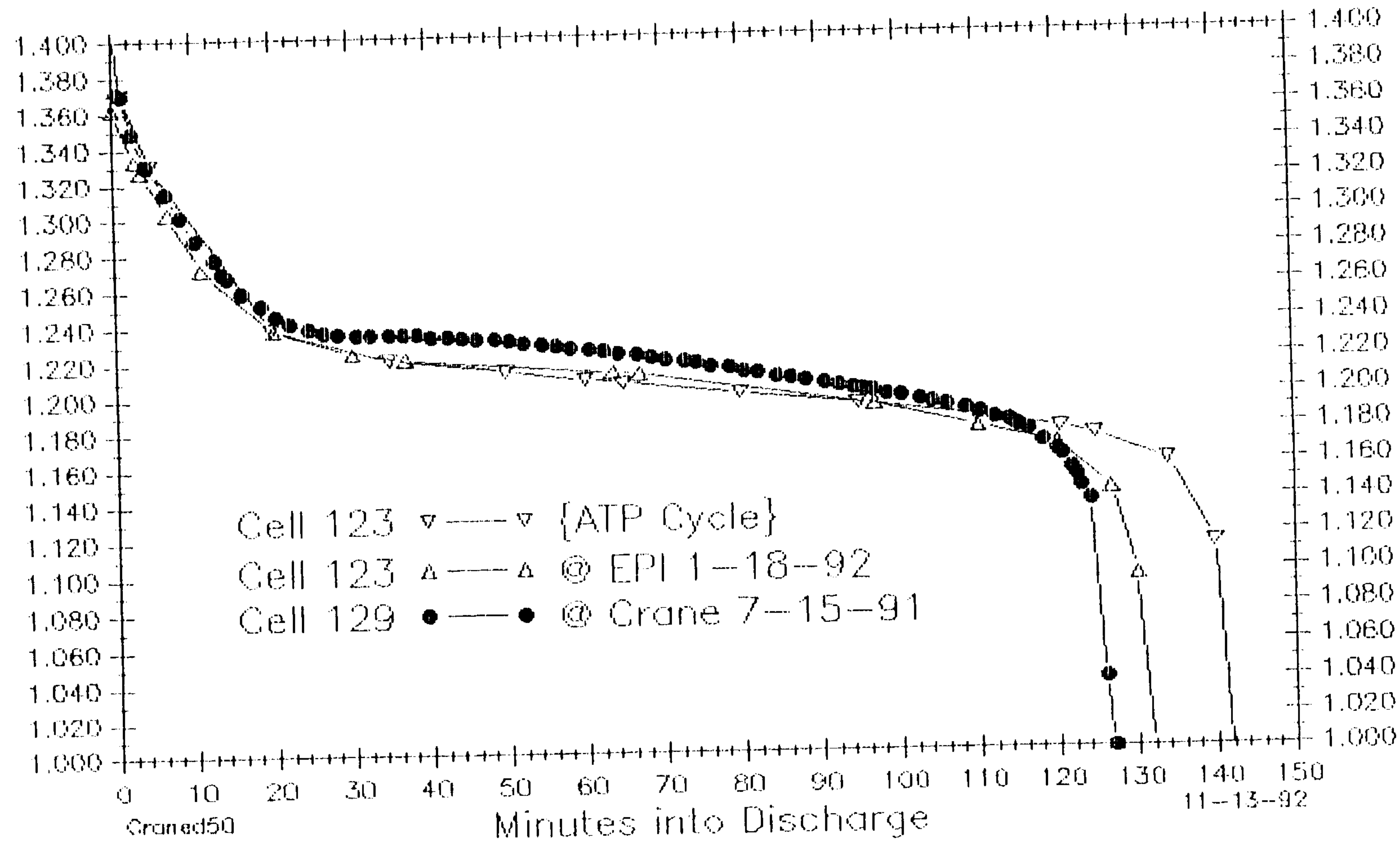


TEMPERATURE = 23° C


50AH Cells
Comparison Between C/20 Charges @ 0°C
{First 30 Hours of C/20 Charge}
Voltage
Hours into Charge
1.550
1.500
1.450
1.400
1.350
1.300
1.250
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Cell 123 ATP @ EPI 5-7-90
Cell 123 @ EPI 1-18-92
Cell 129 @ Crane 7-15-91
50 CranCA
EmL 1-19-92

50 AH Cells

Comparison Between C/2 Discharges after 72 Hr C/20 Charge @ 0°C



CAPACITY FADE
METHODS OF PREVENTION

1. USE OF THE NICKEL PRECHARGE IN NICKEL HYDROGEN CELLS

2. STORAGE OPEN CIRCUIT IN A DISCHARGED CONDITION

3. STORAGE IN A CHARGED CONDITION

4. STORAGE WITH TRICKLE CHARGE

CAPACITY FADE
STORAGE UNDER TRICKLE CHARGE

CELL IS FULLY CHARGED

CELL IS STORED UNDER A LOW CURRENT CHARGE

- C/80 IS USUAL TRICKLE CURRENT
- TEMPERATURE IS MAINTAINED AT $6 \pm 3°$ C
- VOLTAGE AND CELL TEMPERATURE ARE MONITORED TO PREVENT DAMAGE TO CELLS

TRICKLE STORAGE METHOD IS SUITABLE FOR LAUNCH PAD STORAGE

TRICKLE STORAGE METHOD IS ACCEPTABLE FOR UNSUPERVISED STORAGE

IT IS THE STORAGE METHOD OF CHOICE

CAPACITY FADE
STORAGE CHARGED

CELL SHOULD BE FULLY CHARGED

- 100% CHARGE FOLLOWED BY EXTENDED TRICKLE CHARGE TYPICAL PRE-STORAGE REGIME

MAINTAIN LOW STORAGE TEMPERATURE

- LOWEST TESTING TEMPERATURE (NORMALLY 0° C) IS THE NORM

CELL RECEIVES A PERIODIC "TOP-OFF" CHARGE

- TRICKLE RATE IS RECOMMENDED CURRENT (C/80)
- FREQUENCY OF CHARGE DETERMINED BY SELF-DISCHARGE RATE

ACCEPTABLE METHOD FOR LAUNCH PAD STORAGE

ACCEPTABLE FOR UNSUPERVISED STORAGE

RECOMMENDED BY EAGLE PICHER AND HUGHES AIRCRAFT

BEST WHEN CONSTANT CELL MONITORING IS NOT FEASIBLE

CAPACITY FADE
OPEN CIRCUIT STORAGE

OPEN CIRCUIT STORAGE IS NOT HIGHLY RECOMMENDED

STORAGE TEMPERATURE MUST BE CONTROL

- STORAGE AT LOWEST TESTING TEMPERATURE (USUALLY 0° C) IS A GOOD RULE OF THUMB

IT IS ESSENTIAL TO AVOID SHORTING DURING STORAGE

MAXIMUM 80% DEPTH OF DISCHARGE PRIOR TO STORAGE

EAGLE PICHER BELIEVES THAT THIS IS A RISKY METHOD OF STORAGE

- THIS METHOD SHOULD BE USED AS LAST RESORT
- NOT AN ACCEPTABLE METHOD FOR LAUNCH PAD STORAGE
- NOT AN ACCEPTABLE METHOD FOR UNSUPERVISED STORAGE

CAPACITY FADE
RECOVERY OF CAPACITY

1. ALL CAPACITY FADE EXAMPLES HAVE DEMONSTRATED SOME DEGREE OF RECOVERY WITH CONTINUED CYCLING

   - INTELSAT V IS CURRENTLY ON ORBIT WITHOUT A FAILURE
   - INTELSAT VI HAS RECOVERED CAPACITY WITH CYCLING
   - EXPLORER 50 AH IS PRESENTLY ON LEO STRESS TEST AT CRANE NWSC AND IS PERFORMING WELL.

2. EAGLE PICHER IS NOW TESTING CELLS TO IDENTIFY THE MOST APPROPRIATE RECOVERY REGIME

   - THE OBJECTIVE OF THE STUDY IS TO SPEED RECOVERY
   - A SECOND OBJECTIVE IS TO BETTER UNDERSTAND CAPACITY FADING.

     SPECIFICALLY:

     - HOW FADING IS AFFECTED BY TEMPERATURE
     - HOW FADING IS AFFECTED BY RESTING VOLTAGE

HUGHES EXPERIENCE WITH CAPACITY FADING ON STORAGE

I. Early Experiences

A. Lot 700 Plates Made at EPI, Colorado Springs for Flight Program

1. Recovered almost completely by LEO cycling at 80% DOD.

2. Maintained capacity in storage by methods:

a. Trickle charge storage

b. Periodic C/10 top-off charge

c. never hard shorting cells for more than a few hours!

B. Plates made from aqueous process for technology program.

1. Partially recovered capacity by LEO cycling at 80% DOD.

2. Plates analyzed by customer.

a. Capacity loss correlated with deficiency in residual charged material.

b. Loading levels on low side (1.4 - 1.5 g/cc void).

HUGHES EXPERIENCE WITH CAPACITY FADING ON STORAGE (Contd.)

II. INTELSAT VI Program

A. Numerous tests conducted by both Hughes and COMSAT Laboratories aimed at prevention.

1. Cold Storage

a. Without trickle charge (COMSAT) - Results reported at IECEC in 1986.

b. With trickle charge - used for some flight packs.

2. Periodic Top-off.

a. Every two weeks at C/10, initially.

b. Every few weeks at C/10, eventually.

3. Elimination of Hydrogen Precharge - Results Published by Stadnick & Lim.

a. Effect of 50 psi hydrogen - Capacity loss in about 4 days.

b. Effect of 14.7 psi hydrogen - Capacity loss in week or two.

c. Effect of nickel electrode precharge - No capacity loss after six months storage.

d. Life test conducted for 30 real time seasons.

(1) Cells with both Ni and H_2 precharge.

(2) Capacity measured at end of test - no loss for cells with either precharge.

(3) H_2 precharge cells had undergone capacity recovery
- 100 80% DOD LEO cycles.

B. Cells have performed per specification in orbit.

HUGHES EXPERIENCE WITH CAPACITY FADING ON STORAGE (Contd.)

II. INTELSAT VI Program (Cont'd)

C. Cells furnished to USAF for tests at Crane

- Nickel Precharge - prior to test.
- ~20,000 cycles at 60% DOD.

D. Cells of similar designed furnished to NASA LeRC for Test

- Both 26% and 31% KOH
- Results reported on testing by John Smithrick and Steve Hall

III. Other Nickel Hydrogen Program

- INTELSAT VI Experienced Used - No capacity loss on storage.

IV. Nickel Cadmium Programs

- Capacity fading on early cells purchased from G.E. which had E.D. positive plates.
- Capacity loss on flight lot of G.E./Gates cells when shorted during manufacturing.
  - First Super NiCd flight.
- Capacity loss on commercial Super NiCd programs recovered (EPI, Colorado Springs Cells).
  - Low temperature overcharge at C/20 rate for 72 hours (repeated).
  - Extended (3-6 months) trickle charge at low temperature.
  - Handling procedures devised which appear to eliminate problem.
  - IR&D program in place to correct problem - initial results promising.

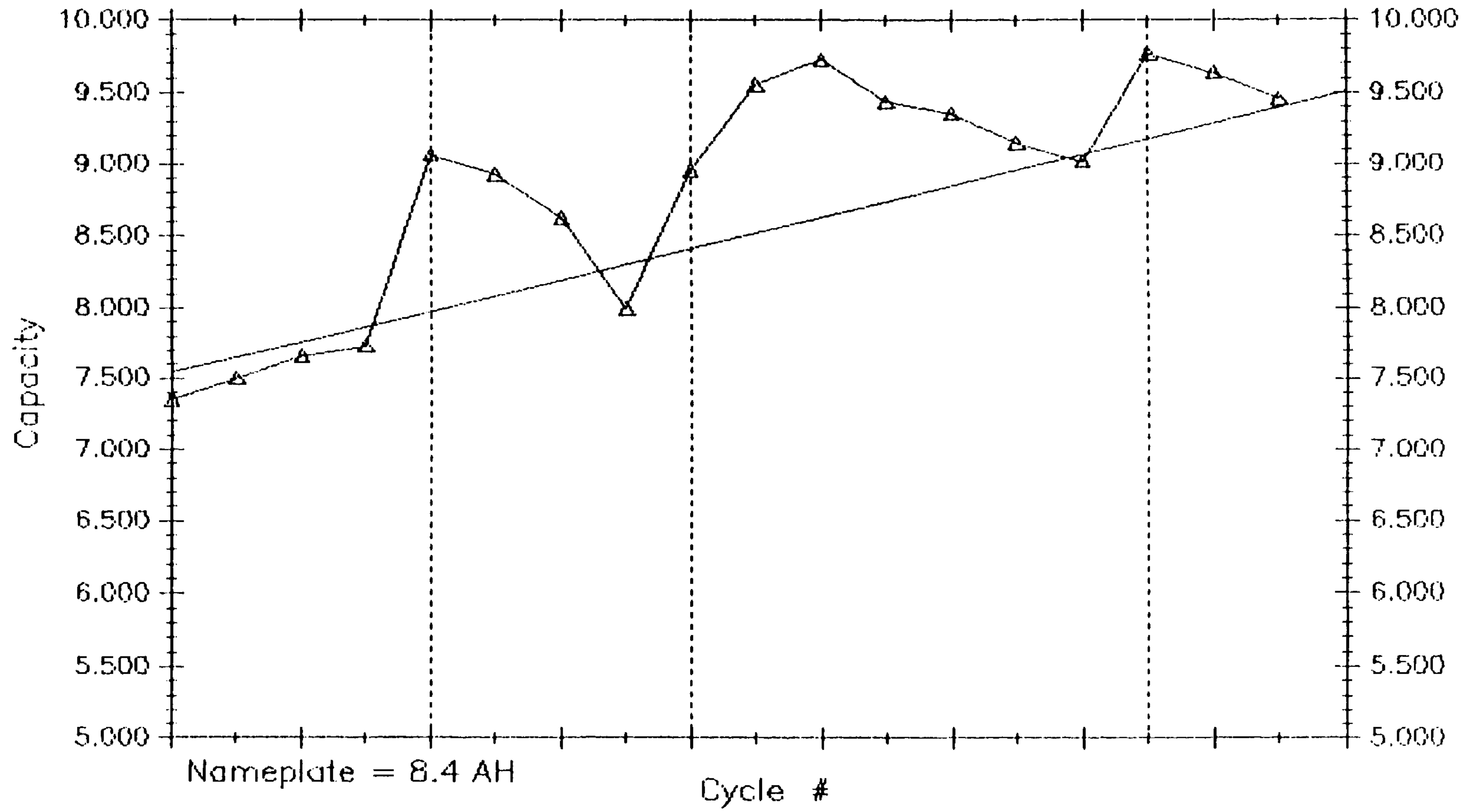
CAPACITY FADE

POTENTIAL CELL IMPROVEMENTS

- EAGLE PICHER HAS LOWERED THE COBALT ADDITIVE CONCENTRATION
- EAGLE PICHER IS CURRENTLY DEVELOPING A MORE "ROBUST" CELL DESIGN
  - THE CELL HAS A RESERVOIR OF UNAVAILABLE ACTIVE MATERIAL
  - THIS RESERVOIR HELPS TO PREVENT THE NICKEL - COBALT REACTION THAT IS SEEN IN CAPACITY FADE.

Boiler Plate Testing 6-26-92 thru 10-23-92

Advanced Dry Sinter Ni Cd Design



Dashed line indicates 33°C 48 Hr Short

N93-20500

NiH_2 CAPACITY FADE DURING EARLY CYCLING

JOHNSON CONTROLS BATTERY GROUP, INC.
NICKEL HYDROGEN BATTERY DIVISION

JEFFREY P. ZAGRODNIK

GENERAL CAPACITY LOSS OBSERVATIONS

Terrestrial batteries:
- stored in warehouse for over 18 months
- no capacity loss
- electrodes contain cadmium additive
- electrodes contain no cobalt additive
- discharged to 1.0 volt/cell at C/2 rate prior to storage
- open circuit storage at room temperature

Initial aerospace batteries:
- stored in warehouse for over 18 months
- no capacity loss
- electrodes contain cobalt/cadmium additive
- discharged to 1.0 volt/cell at C/2 rate prior to storage
- voltage above 1.0 volt/cell at end of stand
- open circuit storage at room temperature

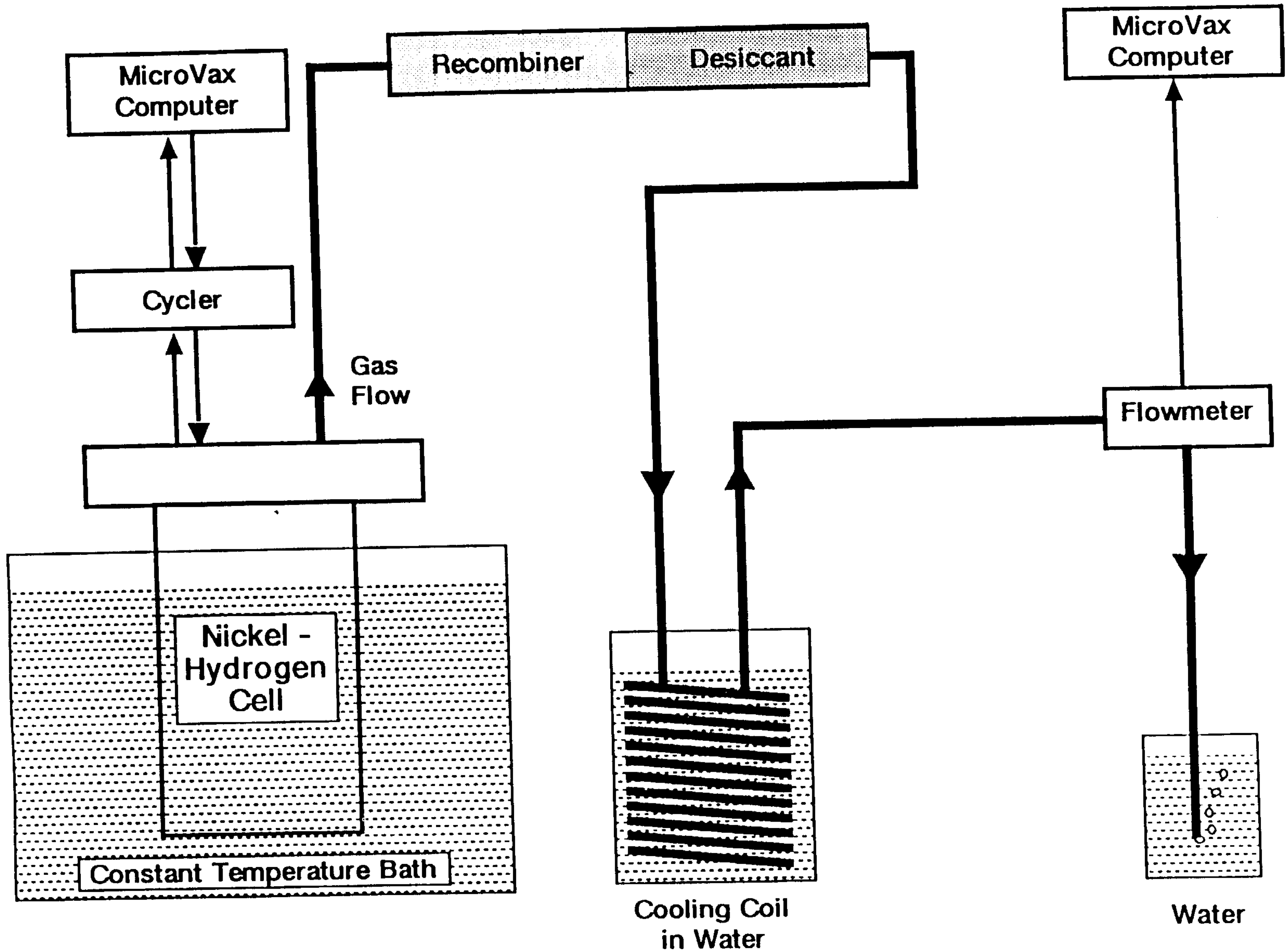
Recent aerospace batteries:
- capacity loss of over 25% seen in 3-8 week storage periods
- electrodes contain all cobalt additive
- shorted to 0 volts prior to storage
- charged stand methods not effective for recovery
- standard LEO or stepped LEO cycling was effective for recovery
- LEO cycling allowed recovery in 30-40 cycles

CHARGE EFFICIENCY TEST PROGRAM

Experiments were designed to measure the charge efficiency of the nickel electrode as a function of rate and temperature. The test matrix was varied to incorporate both cobalt, cadmium and combinations of the two nickel electrode additives. Electrolyte concentration was eliminated as a variable and was held constant at 31% KOH. Three groups of four (4) cells were tested sequentially. Lithium hydroxide was added to the electrolyte in the second set of test cells.

CELL ADDITIVE COMPOSITIONS

Cell #	Bath Additive Composition	Electrode Additive Composition[1]
X004	0% Co/10% Cd	0.1% Co/5.6% Cd
X007	10% Co/0% Cd	10.6% Co/0.1% Cd
X010	3.3% Co/6.7% Cd	4.1% Co/3.3% Cd
X013	6.7% Co/3.3%Cd	7.1% Co/1.8% Cd



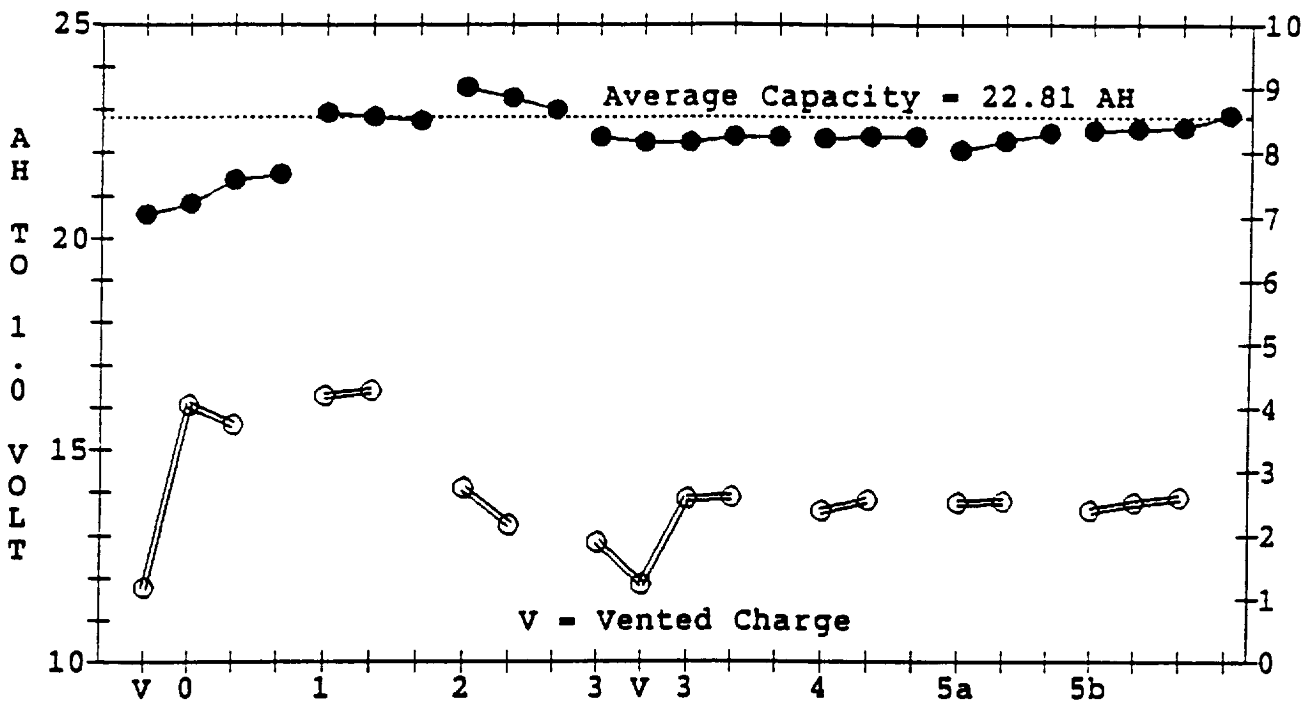
Experimental Set-Up to Measure Charging Efficiency

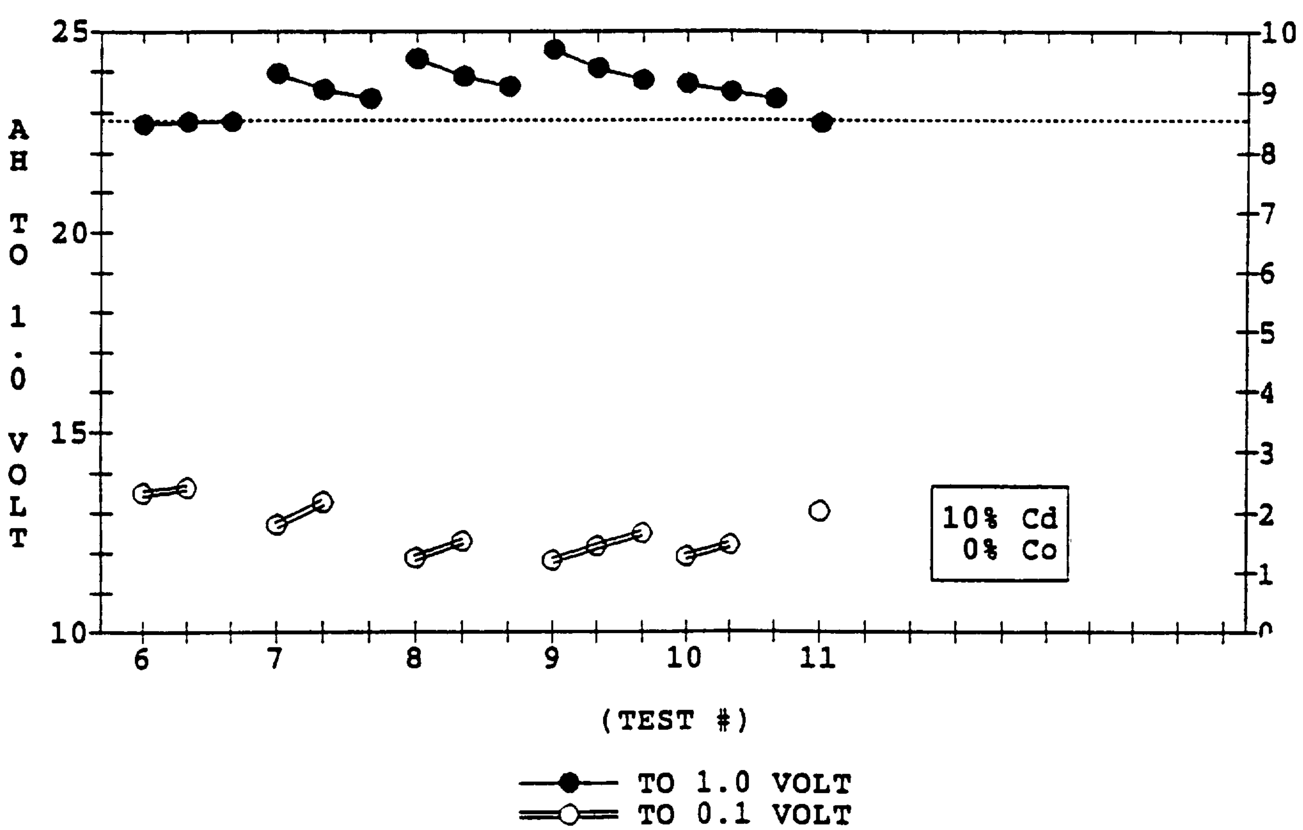
TESTING SEQUENCE

After assembly, each cell completed a routine condition/ activation cycle regime followed by a two (2) week LEO cycle period designed to stabilize performance.

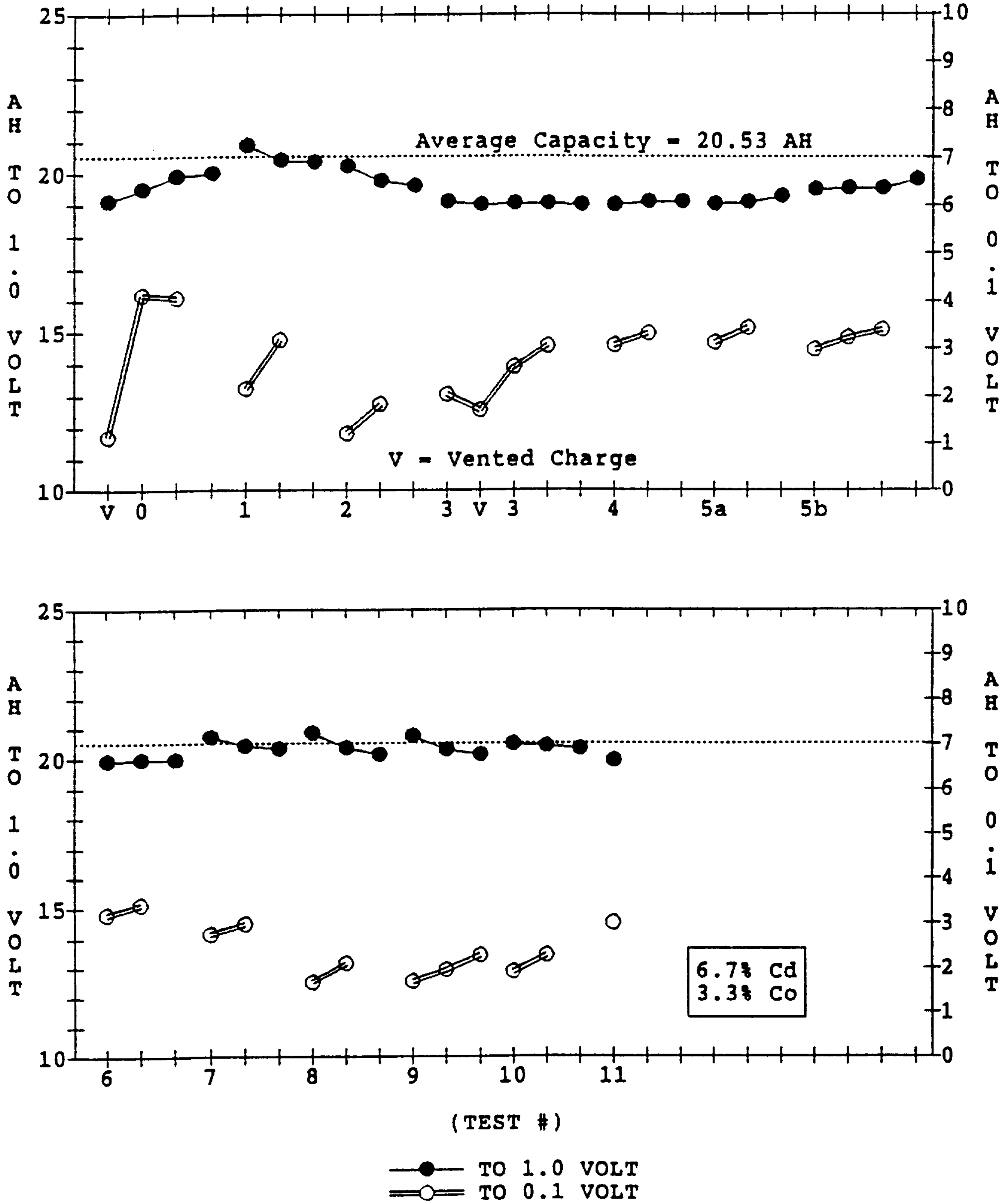
Prior to testing and after each efficiency test the cells were characterized by three charge/discharge cycles at 10° C to determine how the prior test had affected capacity and also to bring the cells to a reproducible state of charge before the next efficiency test. The first two cycles consisted of a C/10 charge for 16 hours followed by a 10A (~C/2) discharge to 1.0 volt and a 4.78 A discharge to 0.1 volt. On the third discharge the cells were only discharged to 1.0 volt and allowed to remain on open circuit.

DISCHARGE CAPACITY OF TEST CELL X004 DURING CHARACTERIZATION. T = 10 DEGREES C.

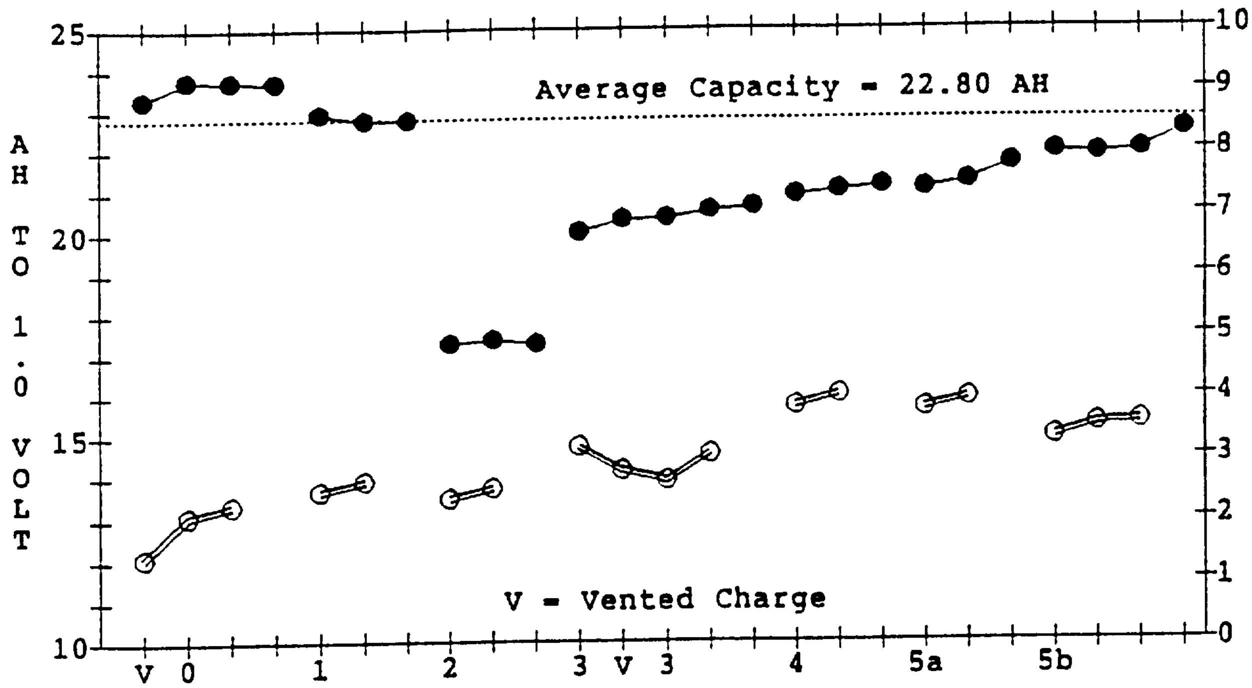


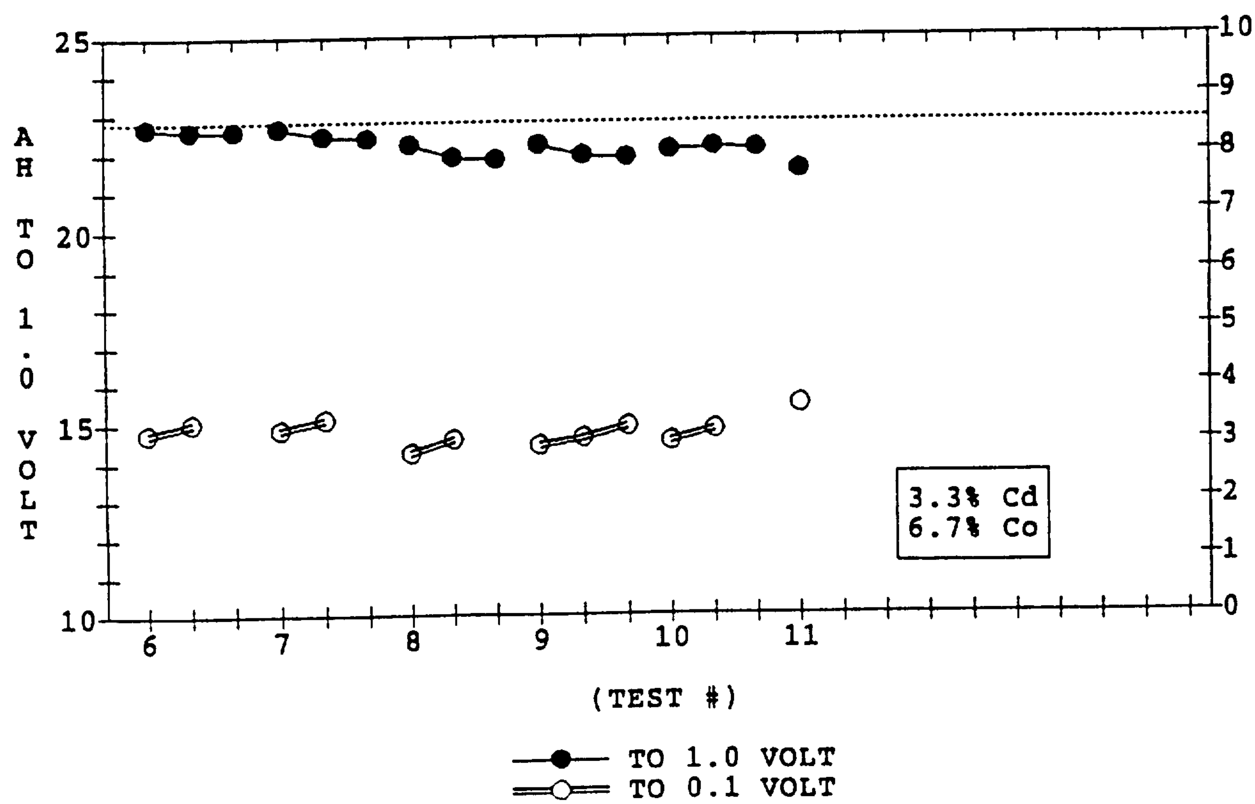


DISCHARGE CAPACITY OF TEST CELL X013 DURING CHARACTERIZATION. T = 10 DEGREES C.

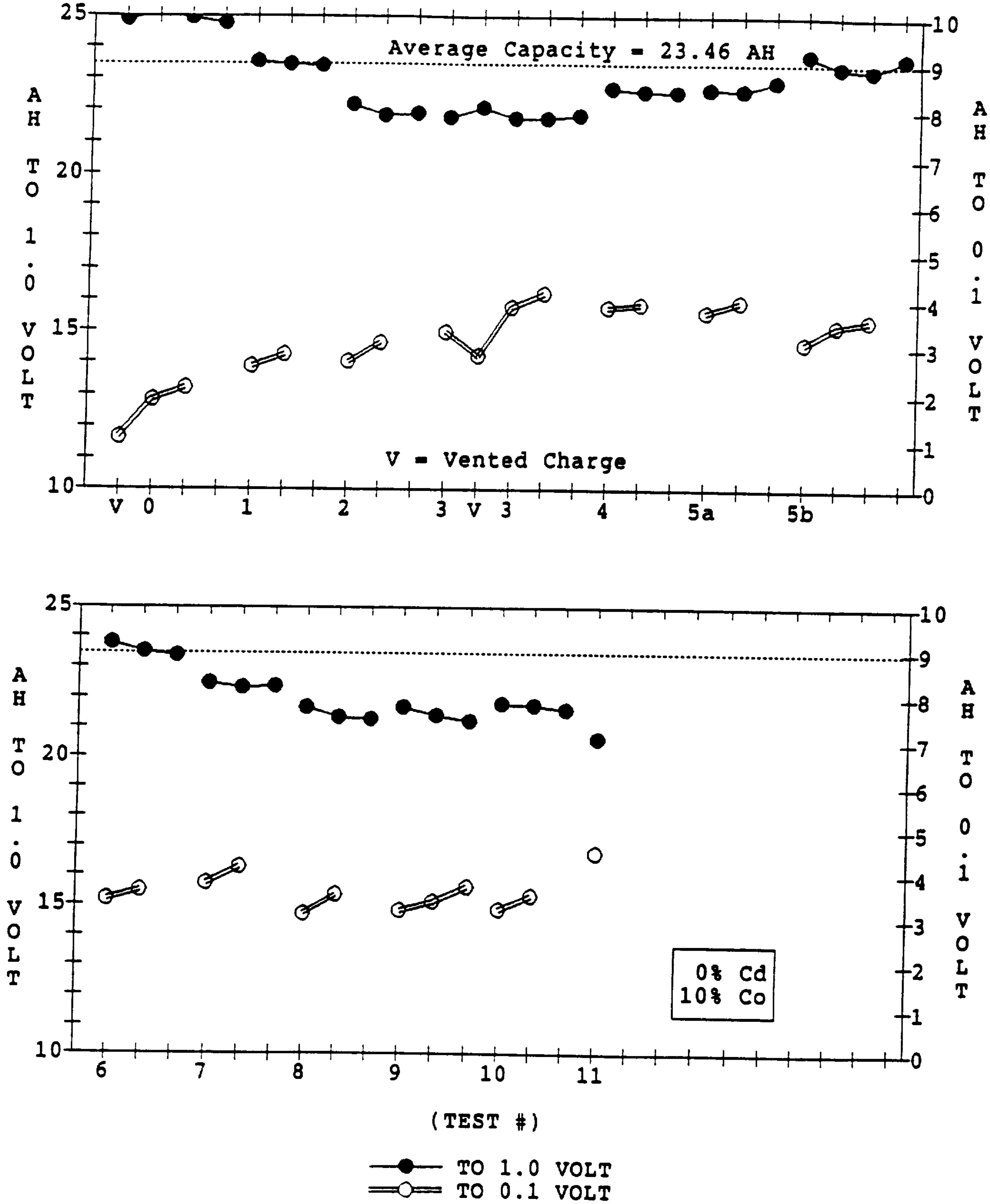


DISCHARGE CAPACITY OF TEST CELL X010 DURING CHARACTERIZATION. T = 10 DEGREES C.





DISCHARGE CAPACITY OF TEST CELL X007 DURING CHARACTERIZATION. T = 10 DEGREES C.



DEFINITION OF CAPACITY FADE TEST

Three capacity check cycles run at 10°C and 23°C before initiating test.

Stand at room temperature, open-circuit, 50 psig hydrogen.

Prior to the first stand cells were discharged at C/2 rate to 1.0 volt/cell

First stand was 48 days duration (open circuit voltages were steady in the 1.2-1.3 volt range for all cells except X004 throughout the stand).

Cell X004 started stand at 1.3 volts but dropped suddenly to 0 volts after 27 days. Cell behaved normally in capacity cycling following the stand.

Prior to the second stand cells were discharged at C/2 rate to 0.5 volt/cell then shorted across a 1-ohm resistor for 16 hours.

Second stand was 40 days duration (all cell voltages were steady at 0 volts throughout).

Cell X007 did not recover from the second stand. Voltage behavior on subsequent charge attempts suggests that cell is shorted.

CAPACITY FADE TEST RESULTS

	0% Co/10% Cd		10% Co/0% Cd		3.3% Co/6.7% Cd		6.7% Co/3.3%Cd	
Cell:	X004		X007		X010		X013	
	10°C	23°C	10°C	23°C	10°C	23°C	10°C	23°C
Theoretical Ah Capacity[1]:	23.9		23.8		24.0		23.9	
Initial Test								
Ah capacity to 0.5 volt:	24.0	23.4	23.9	20.7	24.3	21.8	21.9	19.7
Utilization:	100%	98%	100%	87%	101%	91%	91%	82%
Following First Stand[2]								
Ah capacity to 0.5 volt:	25.5	25.4	26.4	22.1	27.4	23.0	25.7	22.4
Utilization:	107%	106%	111%	93%	114%	96%	108%	94%
% change from previous test:	+6%	+9%	+10%	+7%	+13%	+6%	+17%	+14%
Following Second Stand[3]								
Ah to 0.5 volt:	25.8	24.6	---	---	25.5	21.3	24.5	21.1
Utilization:	108%	103%	---	---	106%	89%	103%	88%
% change from previous test:	+1%	-3%	---	---	-7%	-7%	-5%	-6%
% change from initial test:	+4%	+5%	---	---	+5%	-2%	+12%	+7%

[1] Based on weight gain from total active material.
[2] 48-day stand following C/2 discharge to 1.0 volt cut-off.
[3] 40-day stand following shorting cells to 0 volts.

STD/92-118

N93-20501

CHARACTERISTICS OF STORAGE RELATED CAPACITY LOSS IN NI/H_2 CELLS

H. Vaidyanathan
COMSAT Laboratories
Clarksburg, MD 20871

The changes in the capacity, voltage and pressure profile of flight configuration Ni/H_2 cells when they are stored for extended periods is examined in this manuscript. The Ni/H_2 cells exhibit capacity fade phenomenon regardless of their design when they are stored at room temperature. Capacity loss also occurs if old cells (5 years old) are stored in a very low rate trickle charge (C/200 rate) condition. Periodic recharge technique leads to pressure rise in the cells. Conventional trickle charge (C/100 rate) helps in minimizing or eliminating the second plateau which is one of the characteristics of the capacity fade phenomenon.

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1992 NASA AEROSPACE BATTERY WORKSHOP

HUNTSVILLE, ALABAMA

CHARACTERISTICS OF STORAGE RELATED CAPACITY LOSS IN NI/H_2 CELLS

HARI VAIDYANATHAN

COMSAT LABORATORIES
CLARKSBURG, MD. 20871

CAPACITY FADE AND RECOVERY IN VARIOUS CELL DESIGNS

CELL CAPACITY	DESIGN	ACTIVE MATERIAL LOADING g/cc	COEFFICIENT OF UTILIZATION OF POSITIVE IN FLOODED KOH (%)	COEFFICIENT OF UTILIZATION IN CELL (%)	KOH CONTENT gKOH/Ah	CAPACITY FADE AND RECOVERY
44 Ah	Alcohol/ Ni precharge	1.58	135	123	4.50	Fades extensively Recoverable with trickle charge In orbit battery recovered capacity
44 Ah	Alcohol/ Ni precharge	1.45	151	132	4.66	No fade in 3 months
30 Ah	Aqueous/ H2 Precharge	1.60	124	120	3.03	Flight battery Trickle charged to maintain capacity, showed excellent in orbit data
65 Ah	Aqueous/ H2 Precharge	1.57	112	102	2.74	Fades extensively
83 Ah	Aqueous/ H2 Precharge	1.66	118	107	2.85	Simple reconditioning recovers capacity
83 Ah	Aqueous/ Ni Precharge	1.56	130	123	4.40	No fade for 3 months

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CAPACITY MAINTENANCE AT VARIOUS STORAGE CONDITIONS

STORAGE CONDITIONS	LENGTH OF STORAGE	CAPACITY BEHAVIOR
Open circuit Room temperature	12 months	Ni precharged cell showed one-third of the loss suffered by H2 precharge cells. Second plateau appears.
Open circuit 0°C	9 months	Capacity is maintained for 6 months.
Trickle charge at C/100 at 10°C	9 months	Not only maintains but also recovery capacity.
Recharge every 7 days	6 months	Maintains and recovery capacity. However there is a pressure rise.
Recharge every 14 days	6 months	Maintains capacity. Pressure rises.
Very low rate trickle charge C/290 at 0°C	6 months	Capacity declined for 5 year old batteries.

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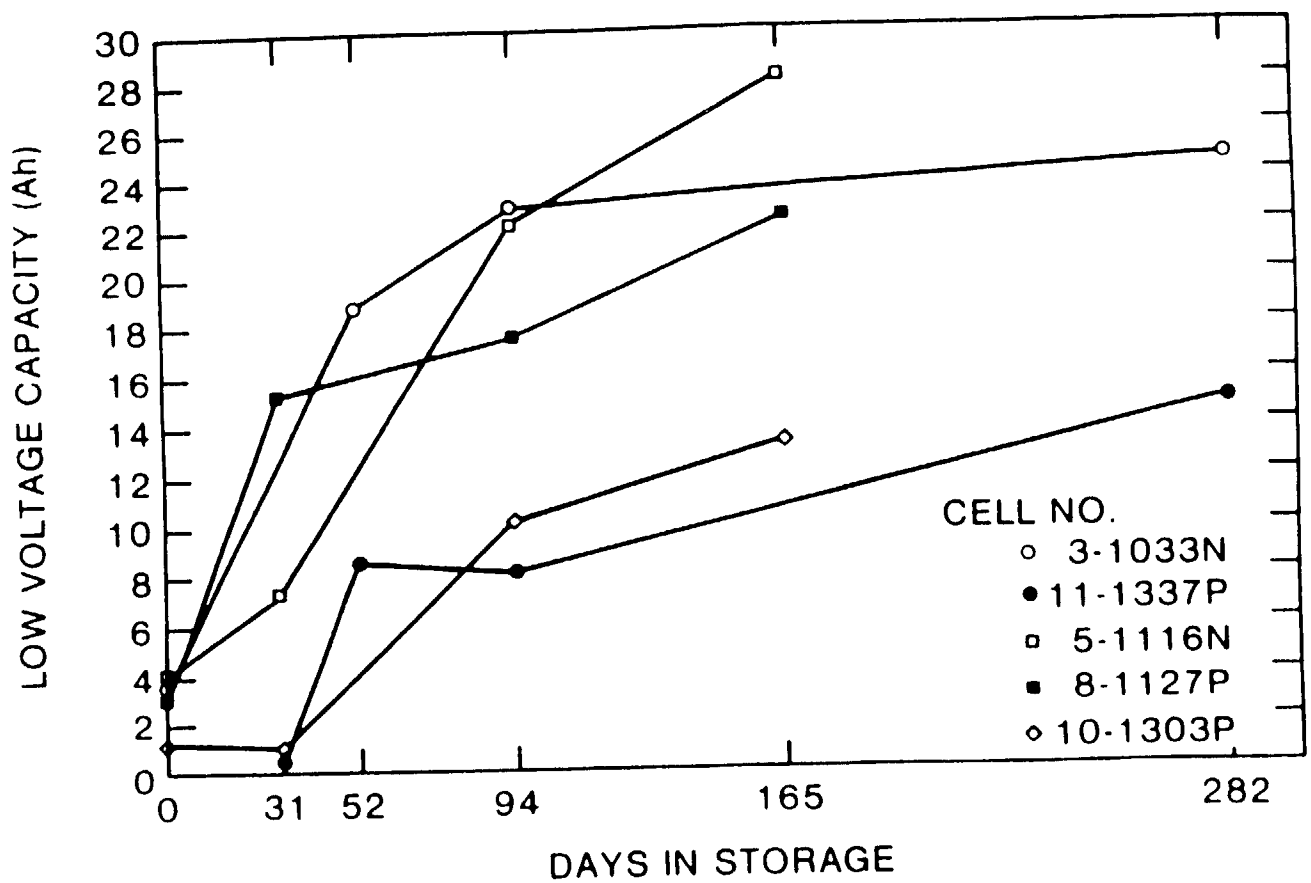
VARIATION OF ADDITIONAL CAPACITY AT LOW VOLTAGES WITH STORAGE TIME AT ROOM TEMPERATURE



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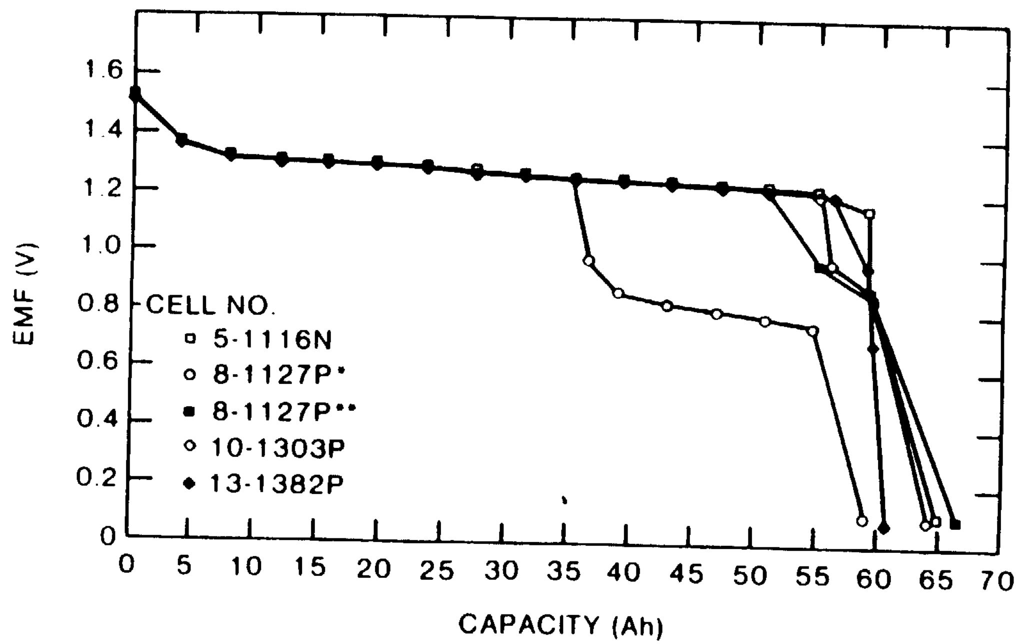
EMF PROFILE OF CELLS AT 23.5A DISCHARGE RATE AFTER TWO 6-WEEK PERIODS OF TOP-OFF CHARGE



* BEFORE TOP CHARGE

** AFTER TOP CHARGE

CAPACITY VARIATION AT -20°C

Cell No.	Precharge	Initial Capacity (to 1 V) (Ah)	Storage Period (days)	Final Capacity (to 1 V) (Ah)
4-1104N	H_2	63.6	270	66.0
5-1116N	H_2	60.7	270	67.2
13-1382P	None	66.7	112	66.3
1-1081N	H_2	59.9	112	60.3

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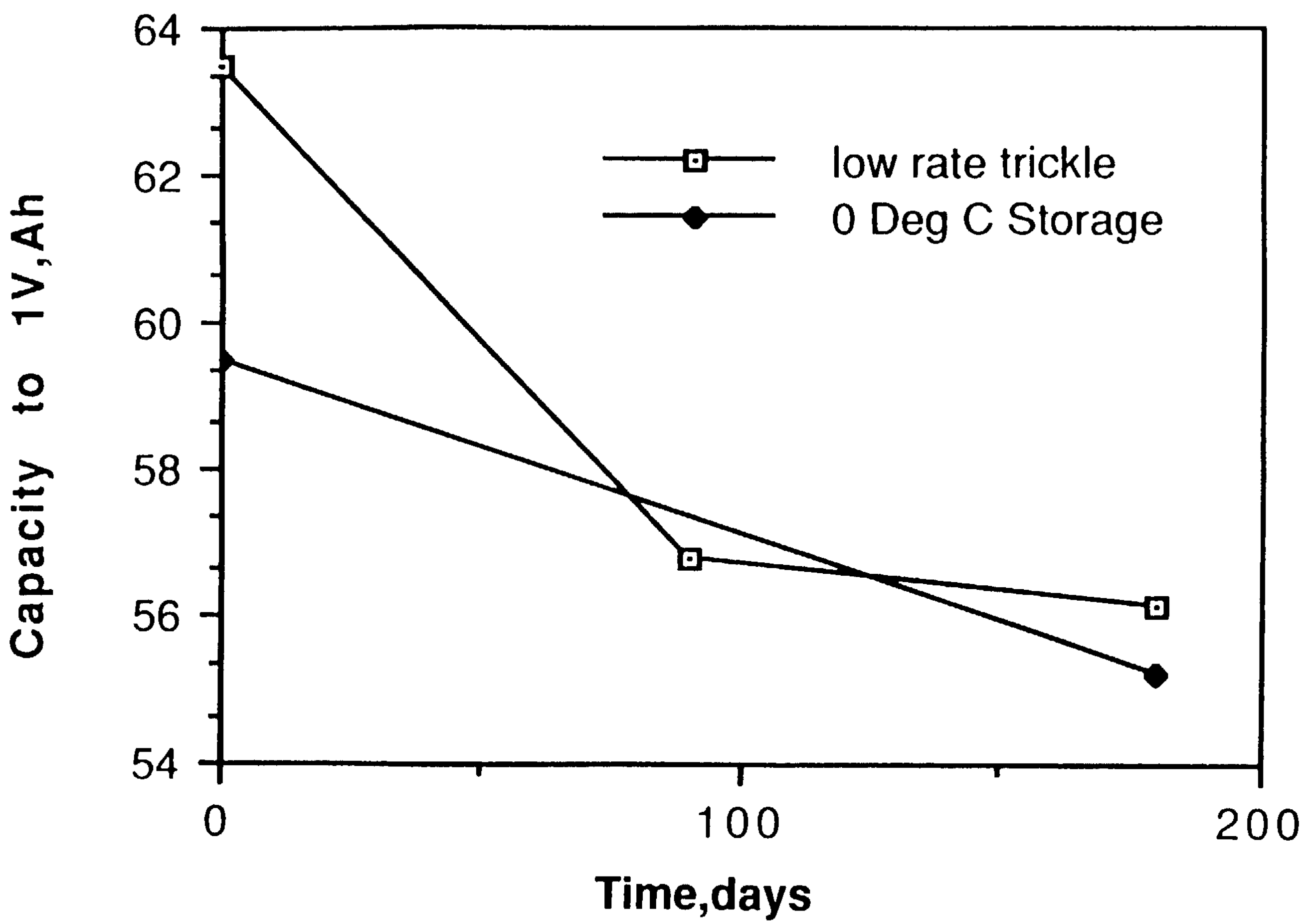
CAPACITY VARIATION WITH STORAGE



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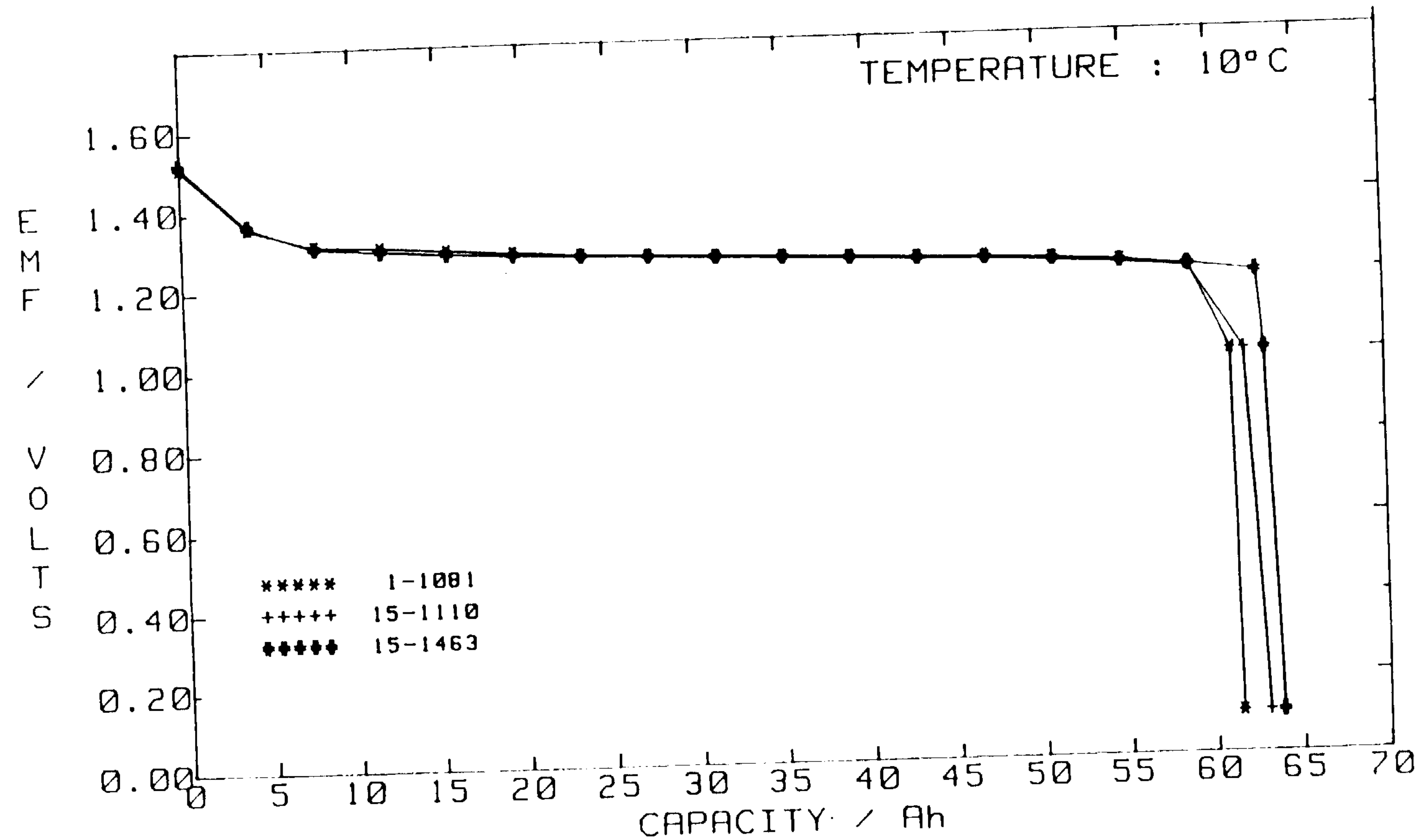
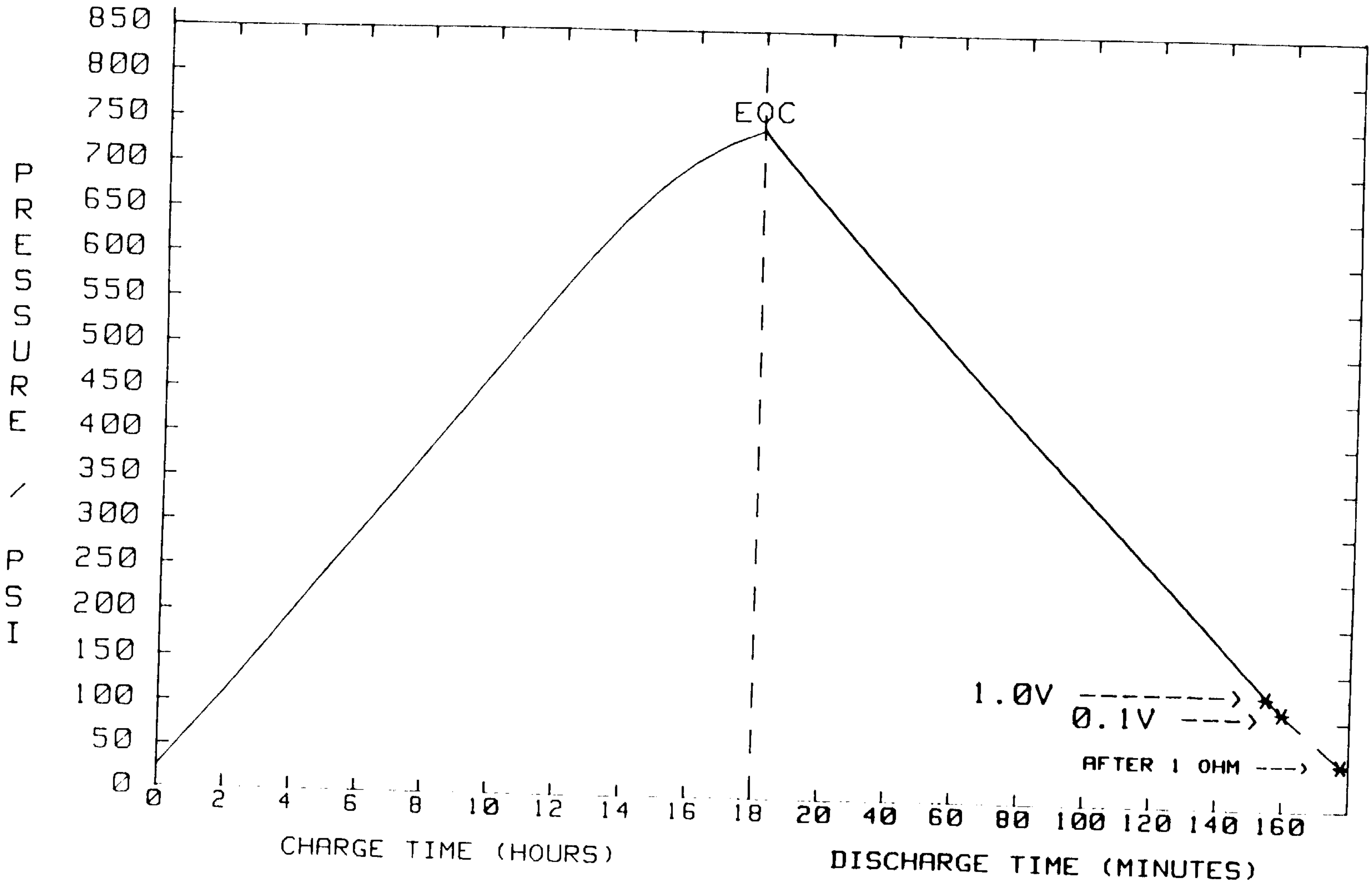
CAPACITY OF RTTC STORED CELLS



CHARGE/DISCHARGE DATA FOR S/N 15-1110 PRESSURE FROM RTTC STORED CELL



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HYDRATION OF ACTIVE MATERIAL

- Literature data for molar ratio of Ni to H_2O in $Ni(OH)_2$ is between 1.1 to 2.36

- Three possible types of hydroxyl groups - interstitial water, water of crystallization and hydroxyl groups bonded to Ni atoms

- Exchange of water from the active material with the electrolyte is believed to be important in the redox reaction

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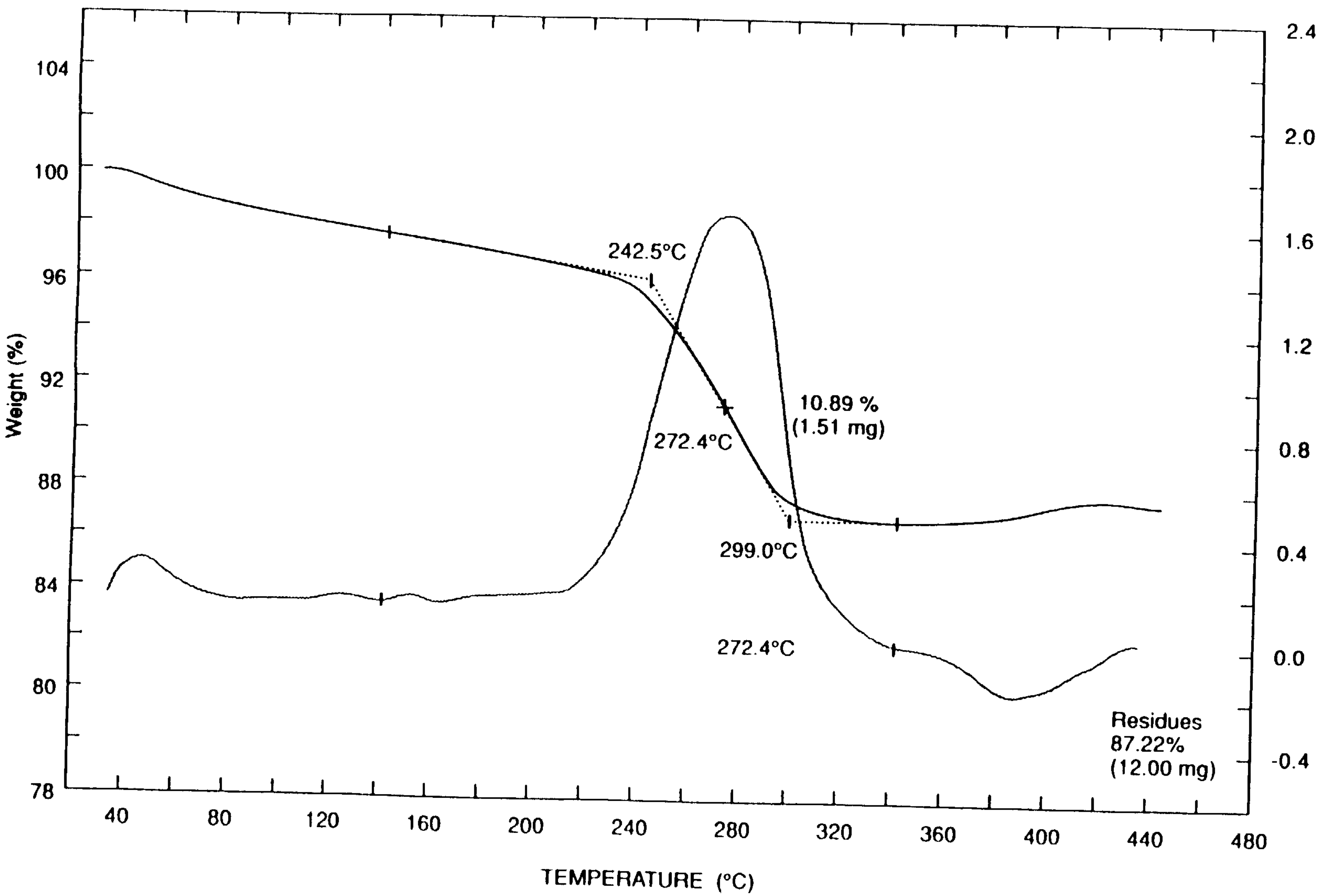
TGA INTEGRAL AND DERIVATIVE PLOTS FOR ACTIVE MATERIAL FROM HAC/I-VI CELL S/N 074



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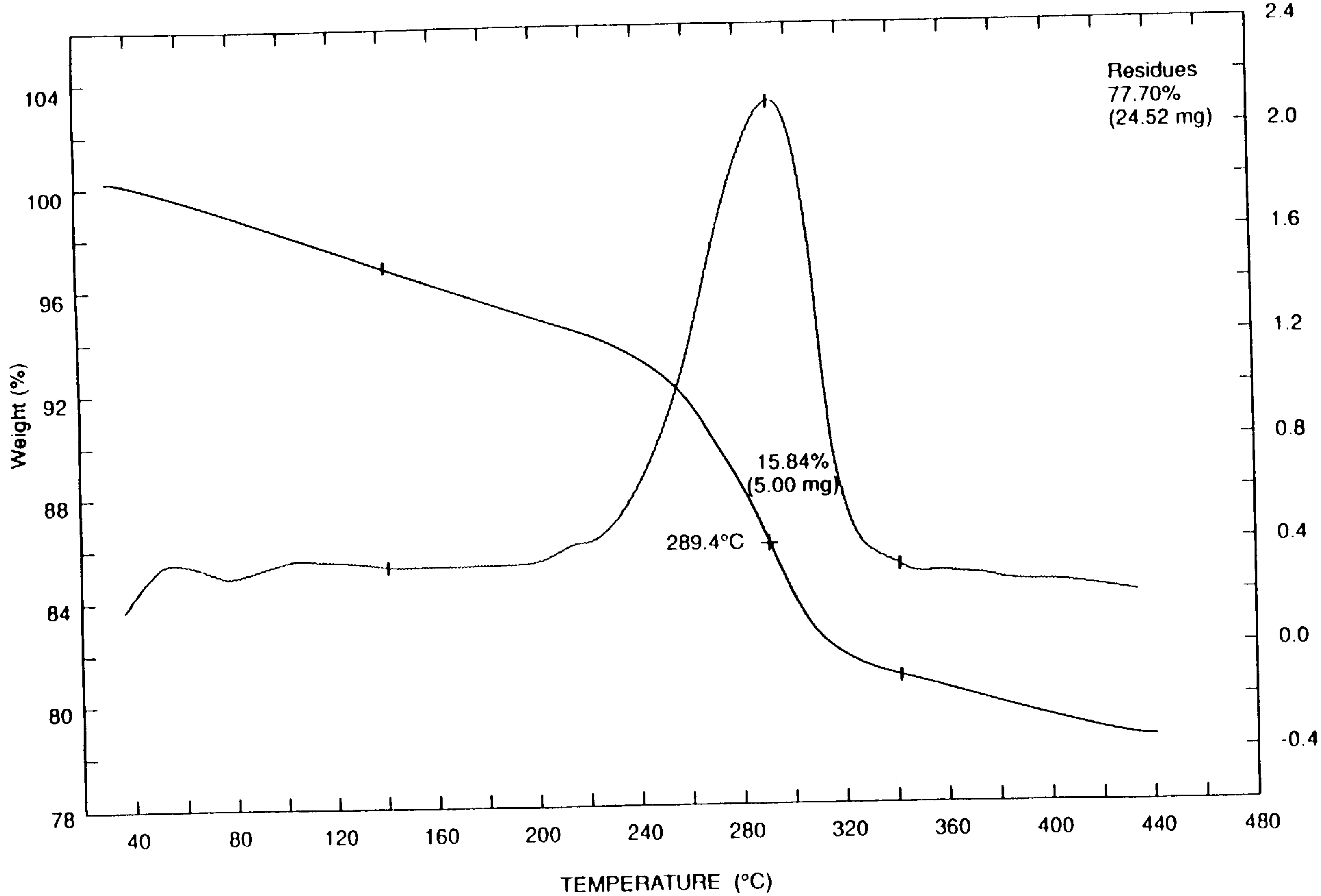
TGA INTEGRAL AND DERIVATIVE PLOTS FOR POSITIVE ACTIVE MATERIAL EP/I-V CELL S/N 06085



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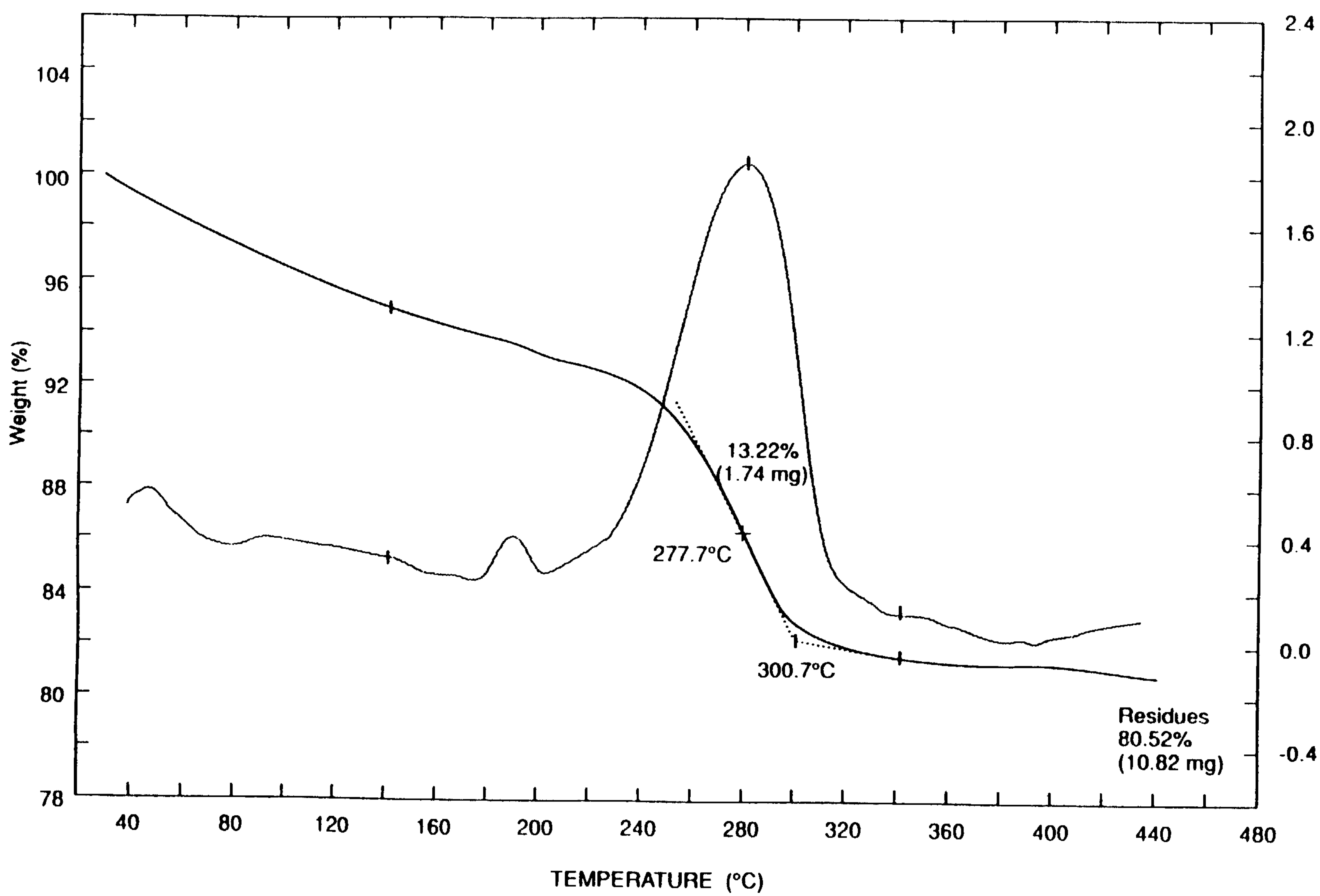
TGA INTEGRAL AND DERIVATIVE PLOTS FOR ACTIVE MATERIAL FROM HAC/I-VI CELL S/N 161



WATER CONTENT FROM TGA

POSITIVE PLATE I.D.	WATER LOSS FROM 140-340°C OR WATER CONTENT (%)	PEAK TEMPERATURE (%)	COMMENTS
EP/INTELSAT V Cell S/N 06-085	15.84	289.4	Plate produced by aqueous electrochemical procedure. Did not exhibit capacity fading.
HAC/INTELSAT VI Virgin Plate 2087	13.71	253.9	Uncycled plate stored under N2 for 8 months.
HAC/INTELSAT VI	13.22	277.7	Exhibited capacity fading, but regained capacity upon conditioning.
HAC/INTELSAT VI S/N 074	10.89	272.4	Exhibited capacity fading. Did not regain capacity upon conditioning.

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HYDRATION OF ACTIVE MATERIAL

$$(Ni(OH)_2 \cdot x\,H_2O) \cdot y\,H_2O$$

- x and y cannot be determined since it is impossible to know the quantity of intercalated water removed before 150°C

- W. Dennstedt and W. Loser 1971

  S. Lebihan and M. Figlarz 1973

STRUCTURAL FORMULAE PROPOSED FOR THE ACTIVE MATERIAL *

CHARGED	DISCHARGED
$NiO(OH) \cdot 0.2\ H_2O$	$Ni(OH)_2$
$NiO(OH) \cdot H_2O$	$2Ni(OH)_2 \cdot 2H_2O$
$Ni_2O_3 \cdot 2H_2O$	$Ni(OH)_2 \cdot 0.34\ H_2O$
$Ni_2O_3 \cdot 3.21\ H_2O$	$2Ni(OH)_2 \cdot 1.28\ H_2O$
$Ni_3O_4 \cdot 2H_2O$	
$NiO(OH) \cdot 0.14\ KOH$	
$3NiO(OH) \cdot 7/2\ H_2O \cdot 3/4\ KOH$	
$kNiO_3O_6 \cdot 2H_2O$	

* Literature Data

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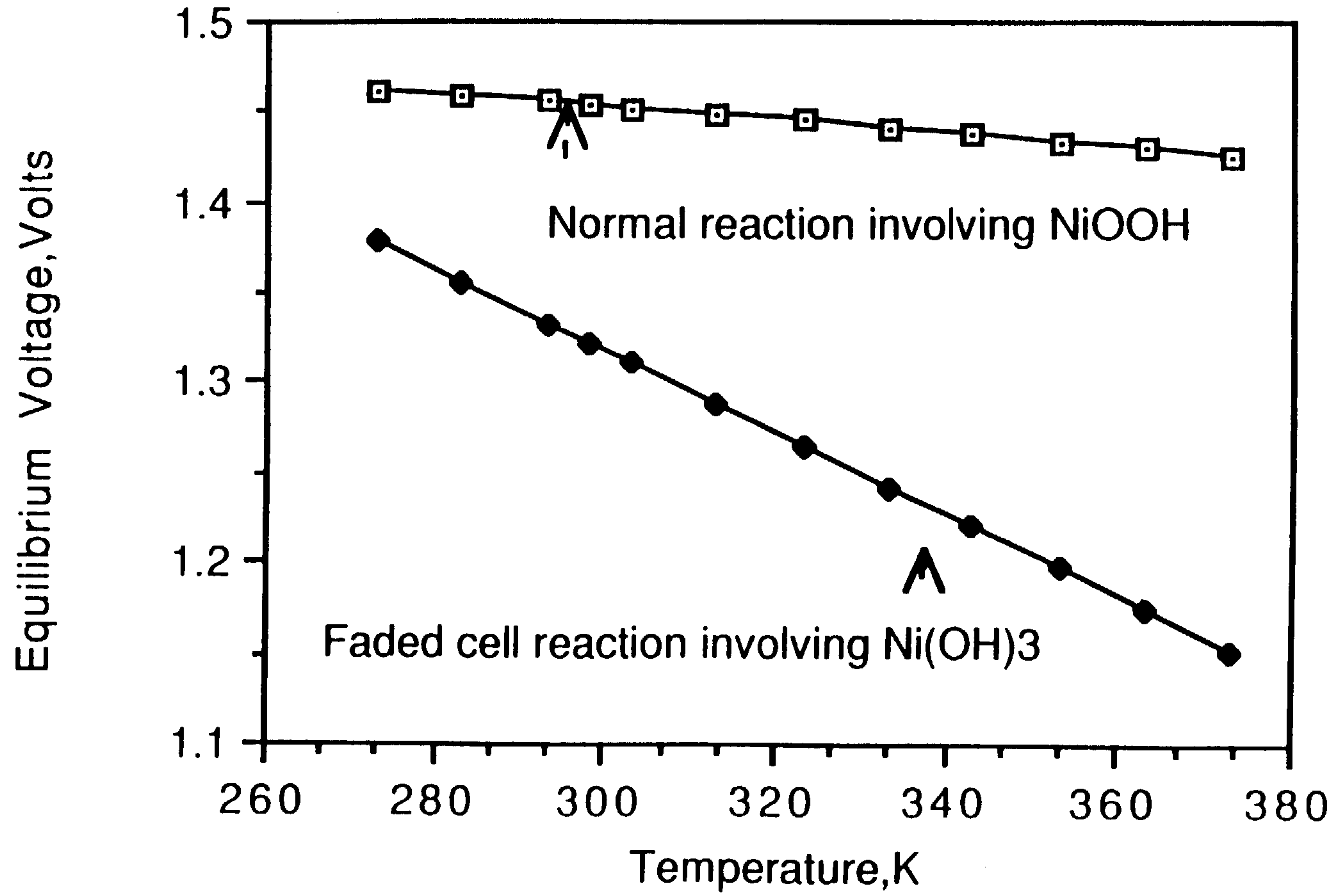
TEMPERATURE DEPENDENCY OF CALCULATED EMF *



* Data published by D. D. Macdonald and Mark L. Challingsworth in "Thermadynamics of Nickel-Cadmium and Nickel-Hydrogen Batteries"

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MECHANISM FOR CAPACITY FADE

EXPERIMENTAL EVIDENCE

- The process is reversible since 95% of the capacity can be recovered
- Extremely low temperature maintains the capacity and sometimes helps in capacity recovery
- Techniques involving overcharging aid in capacity recovery
- Analysis of positive plates from faded cells indicated lower active material utilization
- Thermogravimetric analysis of plates from faded cells showed decreased water content
- The second plateau which appears is particularly prominent at high temperatures
- Low temperature cell capacity is lower in the cycle which immediately follows a 20-25°C capacity cycle

PROPOSED MECHANISM

The capacity fade is due to the predominence of $Ni(OH)_3$ (alternately represented as $NiOOH\ H_2O$) in the positive active material. The reaction of the species produces an equilibrium potential which is not only lower but also very sensitive to increase in temperature. The interstitial water in this form of active material is less than that in the normal NiOOH structure.

Nickel Hydrogen Battery Cell Storage Matrix Test

Authors: James R. Wheeler
Gary W. Dodson

Eagle-Picher Industries, Inc.

FILE: STORE005.XLS

N93-20502

Objective

Evaluate post storage performance of Nickel-Hydrogen cells with various design variables, the most significant being nickel-precharge versus hydrogen-precharge.

FILE: STORE006.XLS

STORAGE MATRIX --- BATTERY CELL CONFIGURATION

GROUP Nº	POSITIVE LOT	SEPARATOR TYPE*	WALL WICK (Yes/No)	CATALYZED WICK (Yes/No)	PRECHARGE TYPE (Ni/H2)	FINAL ELECTROLYTE (%)	DESIGN PRESSURE** (PSIG)
1	X	ZZ	Yes	No	Ni	31	700***
2	X	AZ	Yes	Yes	Ni	31	700***
3	Y	A	No	-	H2	36	600
4	Y	A	No	-	Ni	36	500***

NOTES:

* Z = Zircar, A = Fuel Cell Grade Asbestos

** Maximum pressure AFTER Nickel Precharge.

FILE: STORE001.XLS

STORAGE MATRIX --- BATTERY CELL TEST HISTORY		
GROUP N°	DURATION (Months)	EVENT DESCRIPTION
1.2	0.75	Activation and Conditioning
1,2	0.75	Acceptance Testing (2 standard cycles + 16 high-rate cycles)
1,2	1	Stored, room temperature, discharged, open-circuit
1,2	5	Stored, 5°C ± 3°C, discharged, open-circuit
1,2	0.25	Wake-up cycles (2 standard cycles)
1,2	0.75	Demonstration testing (8 high-rate cycles)
3,4	0.75	Activation and Conditioning
3	0.75	Acceptance Testing (11 cycles)
1,2,3,4	1	Baseline Testing (9 cycles)
1,2,3,4	9	Stored, room temperature, discharged, open-circuit
1,2,3,4	1	Post-storage Testing (9 cycles)

FILE: STORE002.XLS

Common Design Features

- 65 AH rated capacity
- 48 ea, .030" slurry nickel electrodes, 80% porosity, aqueous electrochemical impregnation
- "Mantech" configuration (internal electrode leads)
- Axial Terminals

FILE: STORE007.XLS

STORAGE MATRIX --- PHASE 1 STORAGE TEST

GROUP N°	ATP* Capacity (AH)	Wake-up** Capacity (AH)	Capacity Increase (AH)
1	78.9	81.6	2.7
2	79.8	81.0	1.2

* ATP cycle prior to before storage:	08/23/90
** Wake-up cycle performed:	03/07/91

FILE: STORE003.XLS

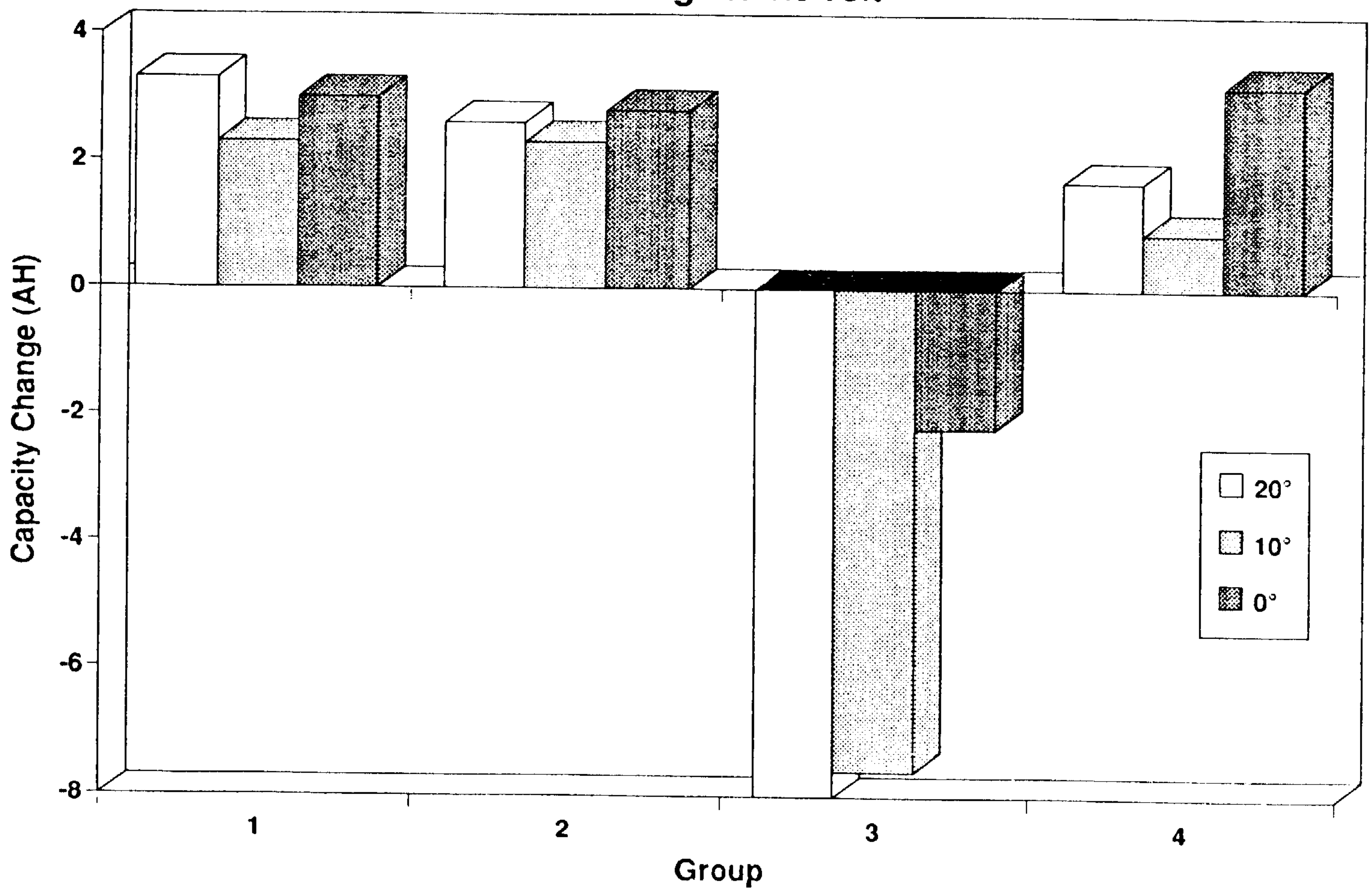
STORAGE MATRIX --- PHASE 2 STORAGE TEST

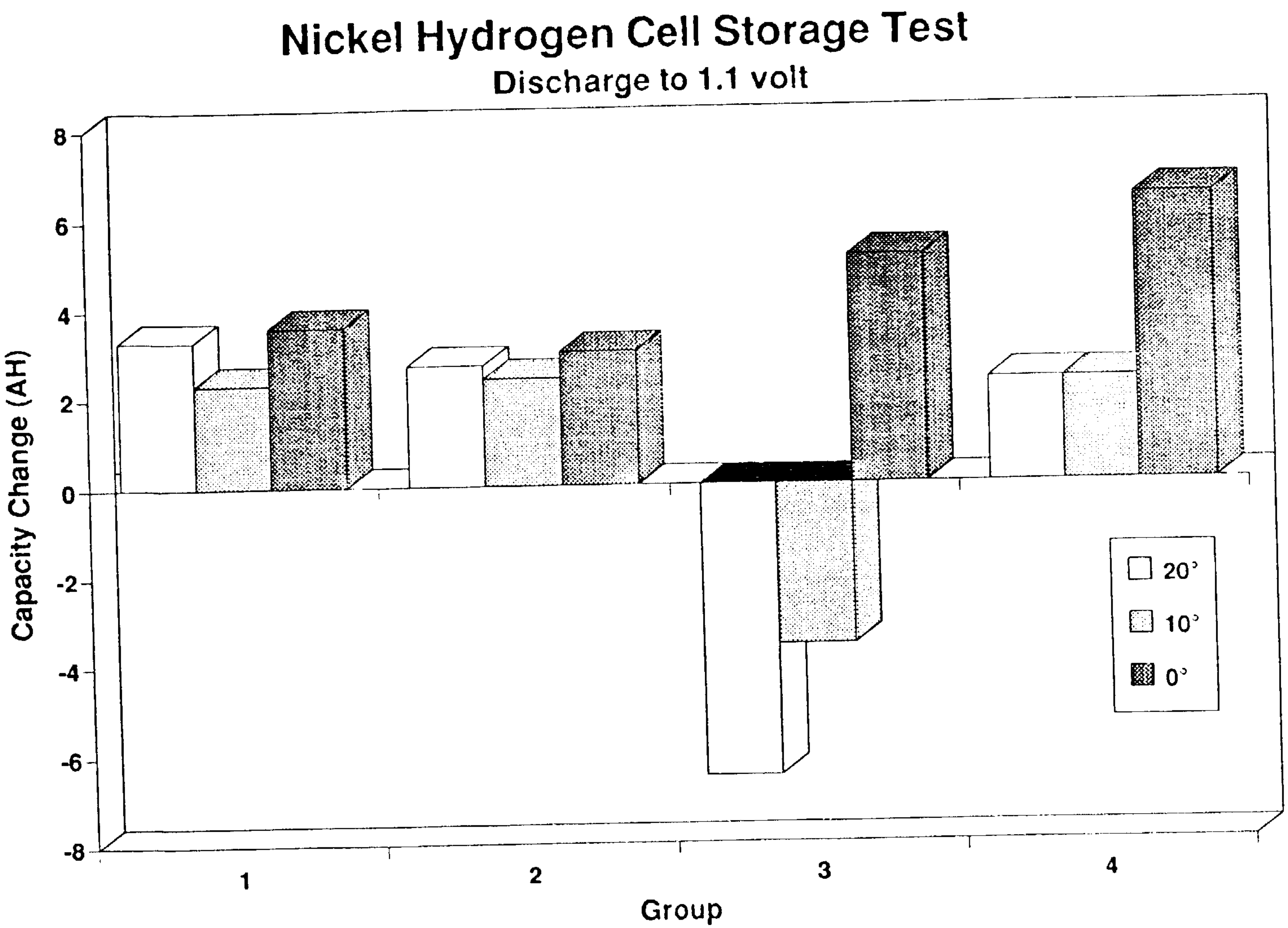
GROUP N°	20°C Increase (AH)	10°C Increase (AH)	0°C Increase (AH)
Discharge to 1.0 volt			
1	+3.3	+2.3	+3.0
2	+2.6	+2.3	+2.8
3	-8.0	-7.6	-2.2
4	+1.7	+0.9	+3.2
Discharge to 1.1 volt			
1	+3.3	+2.3	+3.6
2	+2.7	+2.4	+3.0
3	-6.5	-3.6	+5.1
4	+2.3	+2.3	+6.4

FILE: STORE004.XLS

Nickel Hydrogen Cell Storage Test

Discharge to 1.0 volt




Nickel Hydrogen Cell Storage Test
Discharge to 1.1 volt
Capacity Change (AH)
8
6
4
2
0
-2
-4
-6
-8
1
2
3
4
Group
20°
10°
0°

Conclusions

- Hydrogen precharged cells are more susceptible to post storage loss of performance than nickel precharged cells.

- Room temperature storage is more degrading than low temperature storage.

FILE: STORE008.XLS

CAPACITY RECOVERY AFTER STORAGE

Negatively Precharged Nickel Hydrogen Cells

John E. Lowery

NASA, Marshall Space Flight Center

Recovery of Capacity Lost During Open Circuit Storage of Negatively Precharged Nickel Hydrogen Battery Cells

- During Storage, NiH2 Cells Experience Loss in Useable Capacity.
- Cells from all Manufacturers exhibit losses.
- Loss Due to Cobalt Migration?
- Extent of Migration and the Ability to recover are function of the Length of Storage Period.
- Attempt to quantify amount of useable capacity that may be recovered and propose a timely procedure for the recovery.

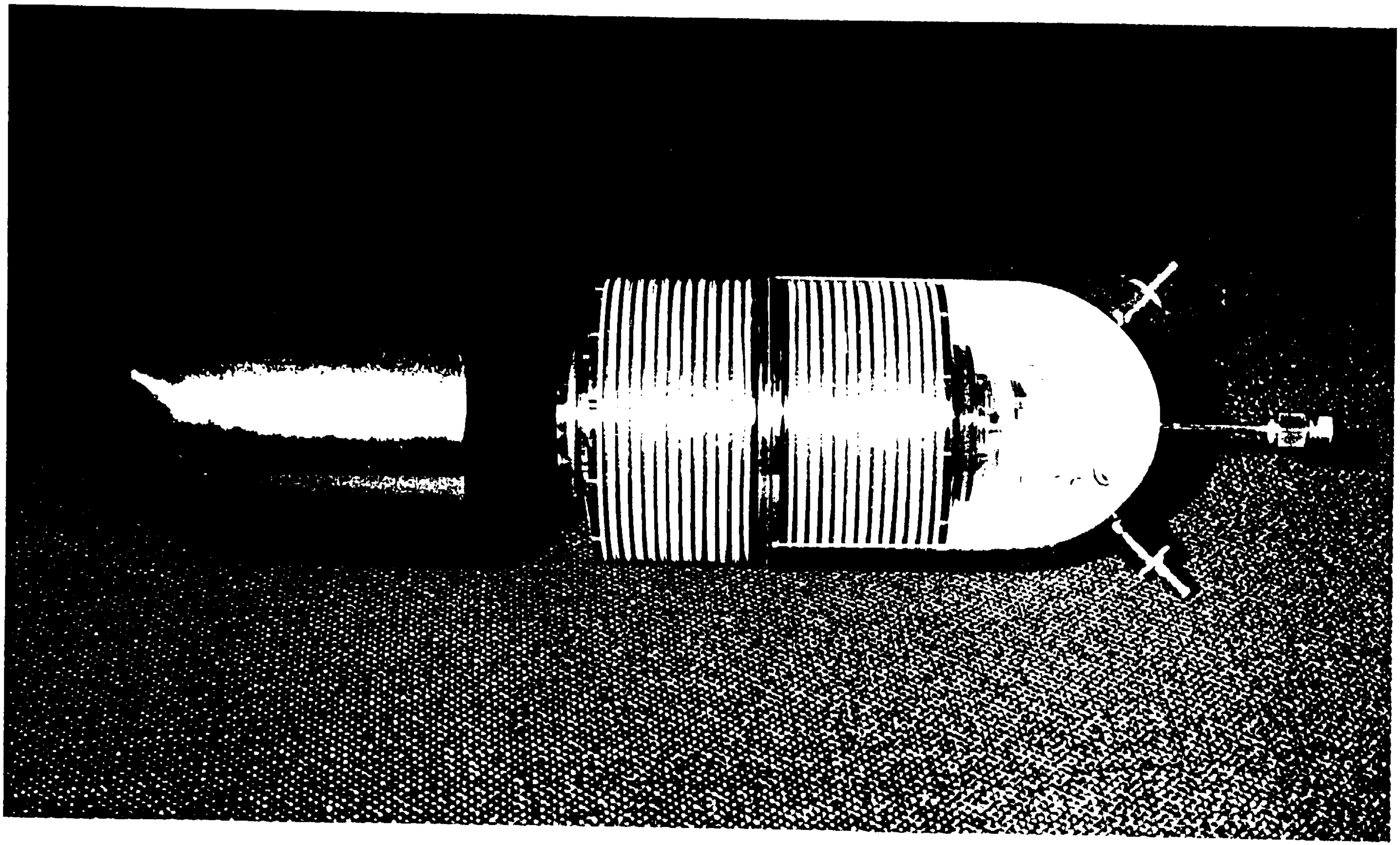
Test Cells

- Four EPI RNH 90-3, TM2 Lot.
- Air Force Design, Pineapple Slice, Neg Precharge.
- Acceptance Test Procedure after build.
- 41 Months Open Circuit Storage at 0 deg C.

C-4

Eagle Picher RNH-90-3

Developed for the Hubble Space Telescope

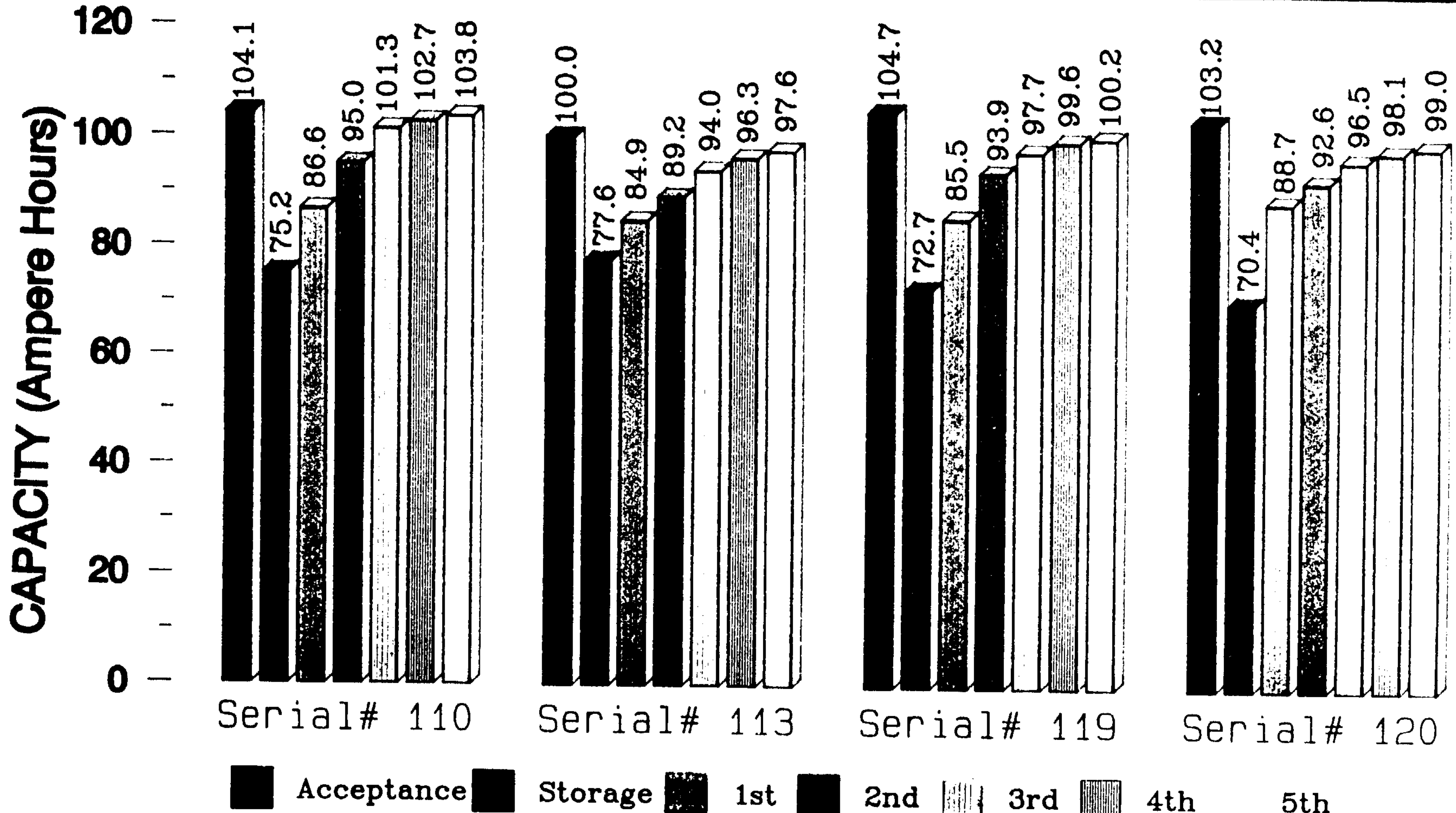


RECOVERY PROCEDURE

- Cells Initially discharged (OCV < .2 V).
- Temp stabilized at) deg C.
- Baseline Charge, 160% of C rating in 24 hours:
  - C/10 (9.3 A) for 10 hours.
  - C/22.5 (4 A) for 14 hours.
- Raise Temp to room level.
- Allow to sit open circuit for 14 - 16 days.
- Lower Temp to 0 deg C.
- Discharge cells at C/6 (15 A) to 1.0 V/cell.
- Recondition cells 12 - 16 hours (V < .2).
- Baseline charge cells and allow to stabilize 1 hour.
- Discharge cells at C/6 (15 A) to 1.0 V/cell.
- Capacity is measured at 1.0 V/cell.

Capacity Gain from Open Circuit Stand

EPI RNH 90-3

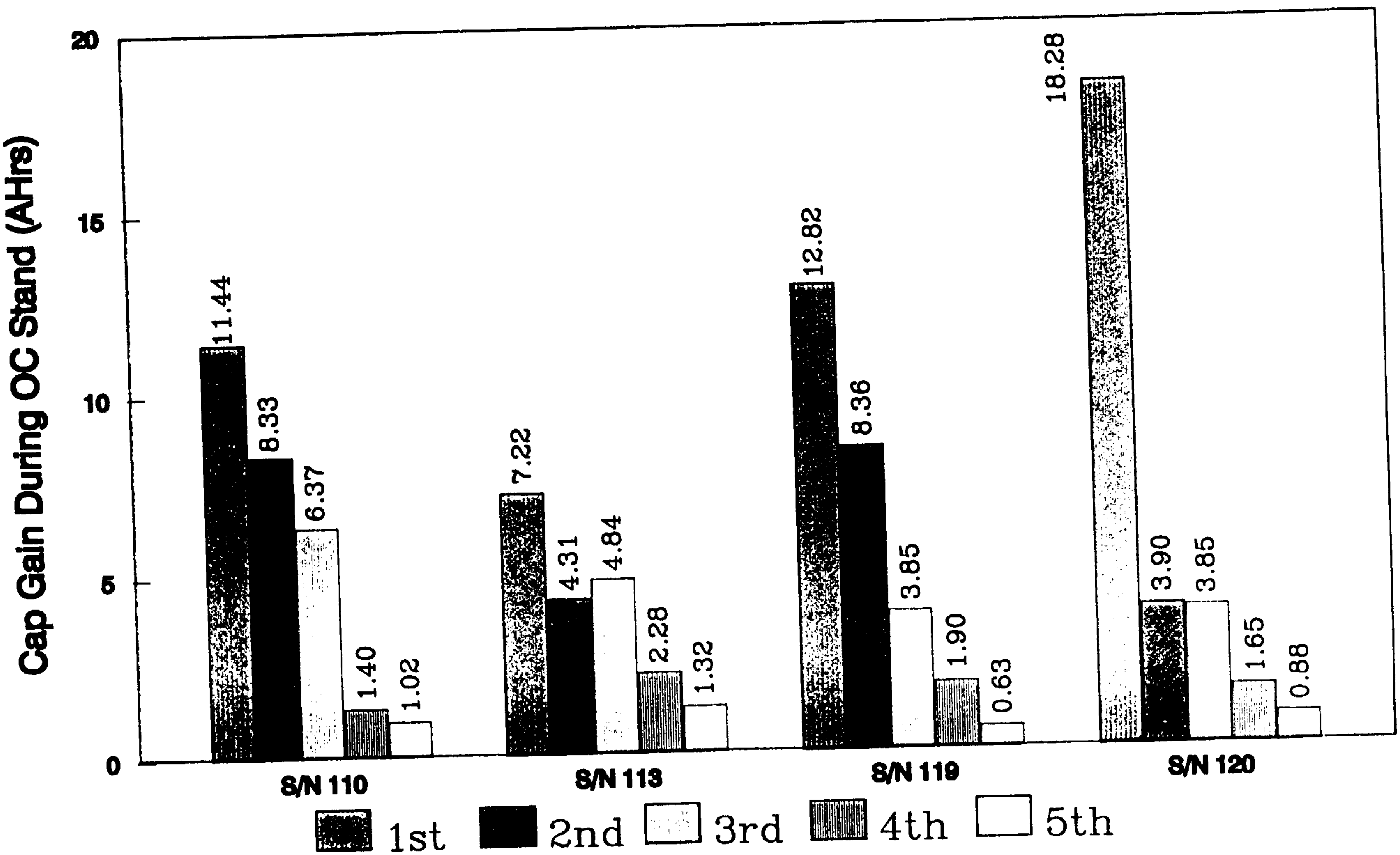


41 Months Storage

Fig. 1.

Capacity Gain from OC Stand

EPI RNH 90-3

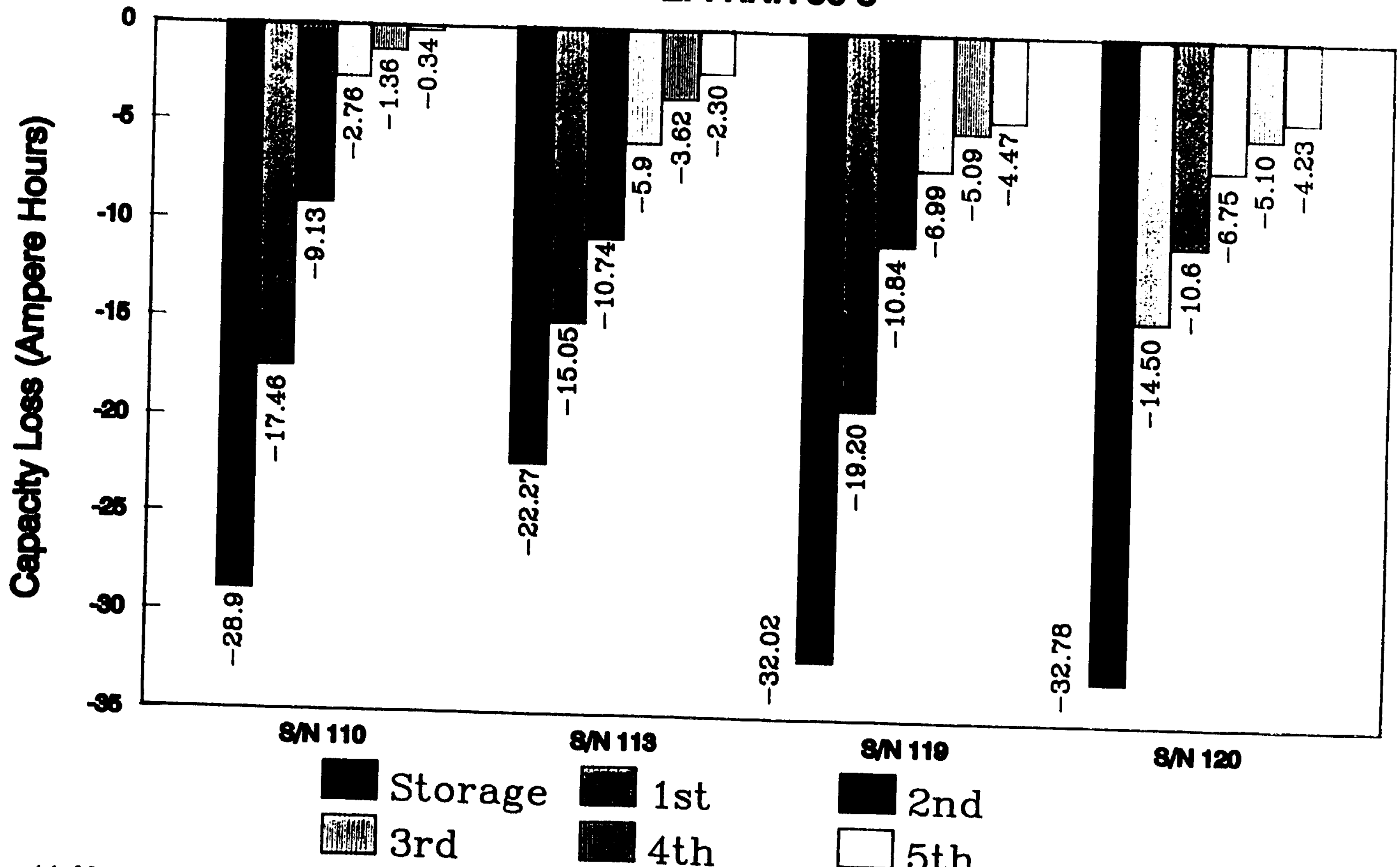


41 Months Storage

Fig. 2.

Capacity Loss from Acceptance Test Value

EPI RNH 90-3



41 Months Storage

Fig. 3.

Present Capacity as % of Acceptance Test Value

EPI RNH 90-3

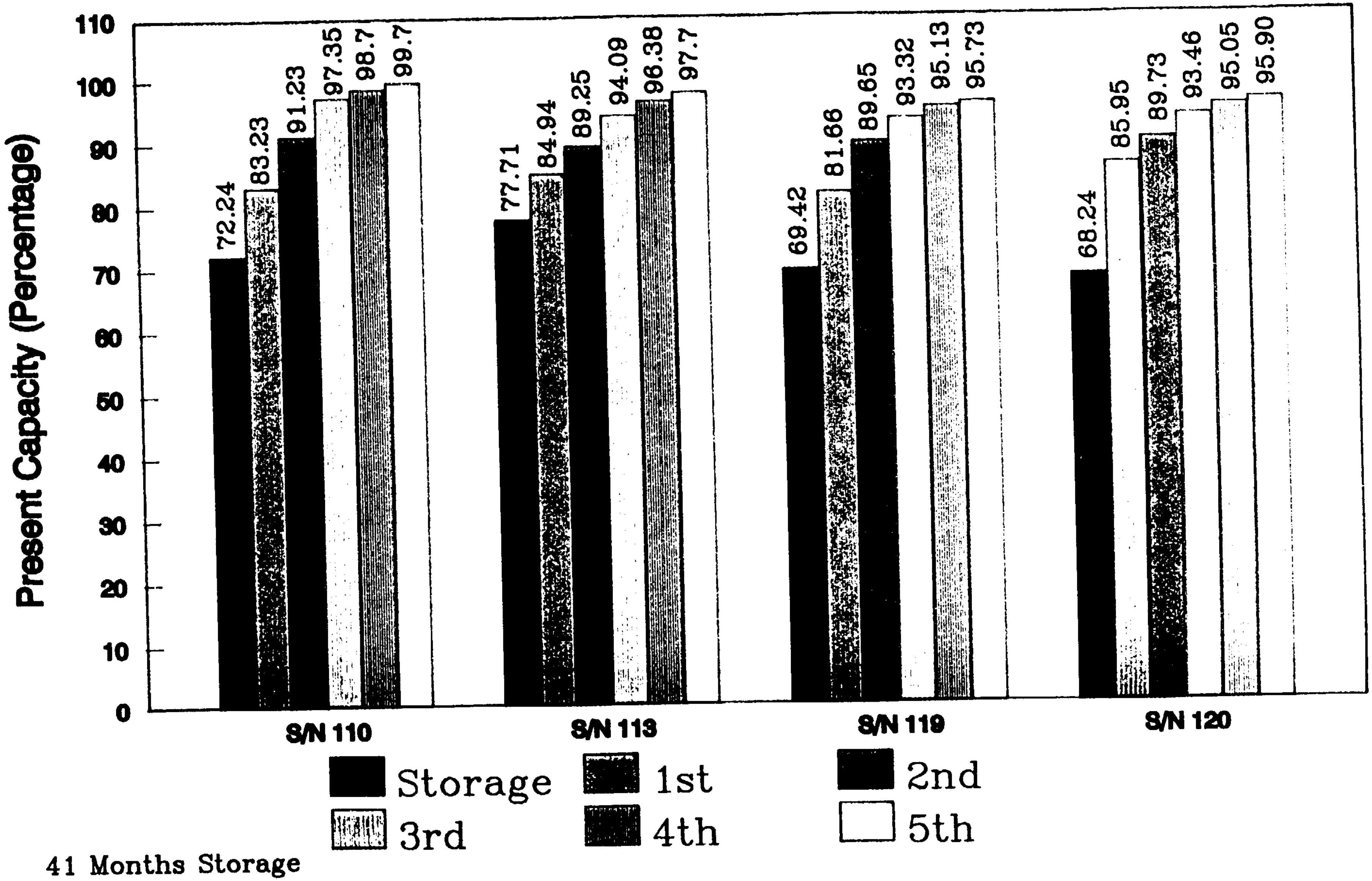


Fig. 4.

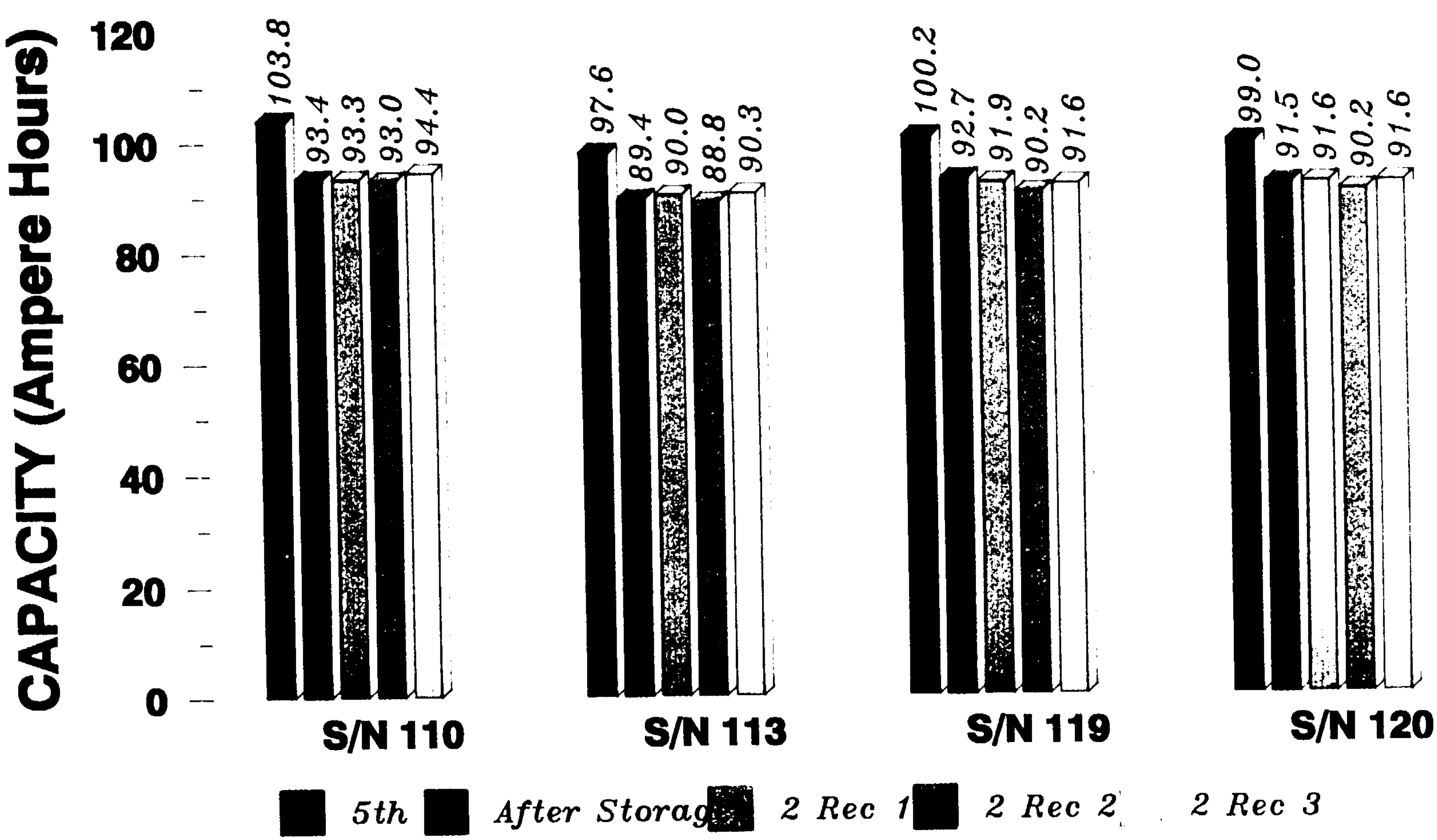
STORAGE

Open Circuit vs. 3/4 Volt at 0 deg?

- 2 Cells OC:
  - S/N 119, 120.
- 2 Cells in series at 1.5 V:
  - S/N 110 - 1.32 V, S/N 113 - .18 V.
    - 1 month in series
- Divide equally at 1.1 V/cell.
- 2 Cells paralleled at .75 V:
  - S/N 110 - .75 V, S/N 113 - .75 V.
    - 1.5 months paralleled.
- Question??? Do cells retain their recovered capacity upon cycling?

Capacity Behavior After Initial Recovery

EPI RNH 90-3



2 1/2 Months Later.

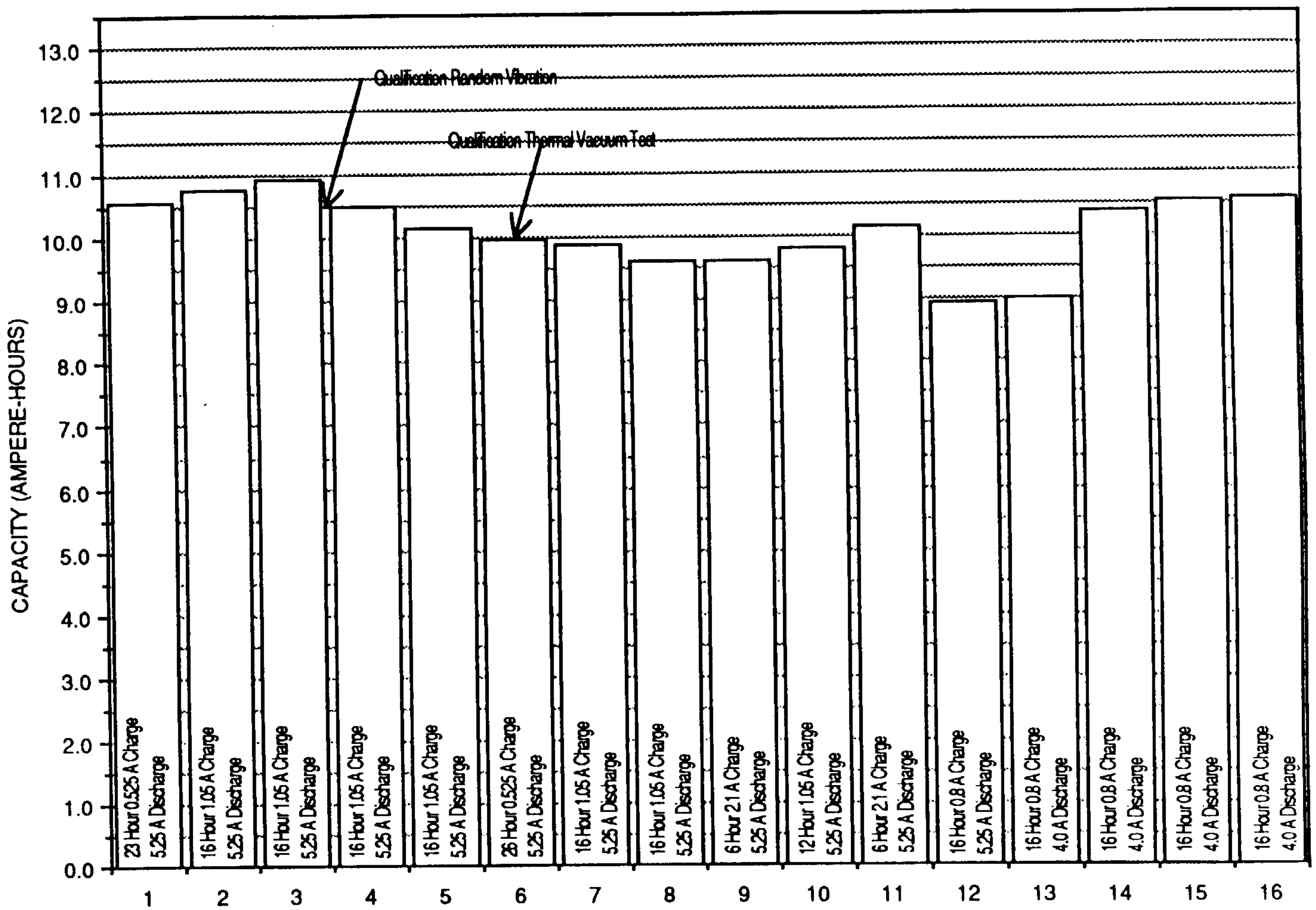
Fig. 5.

CONCLUSIONS

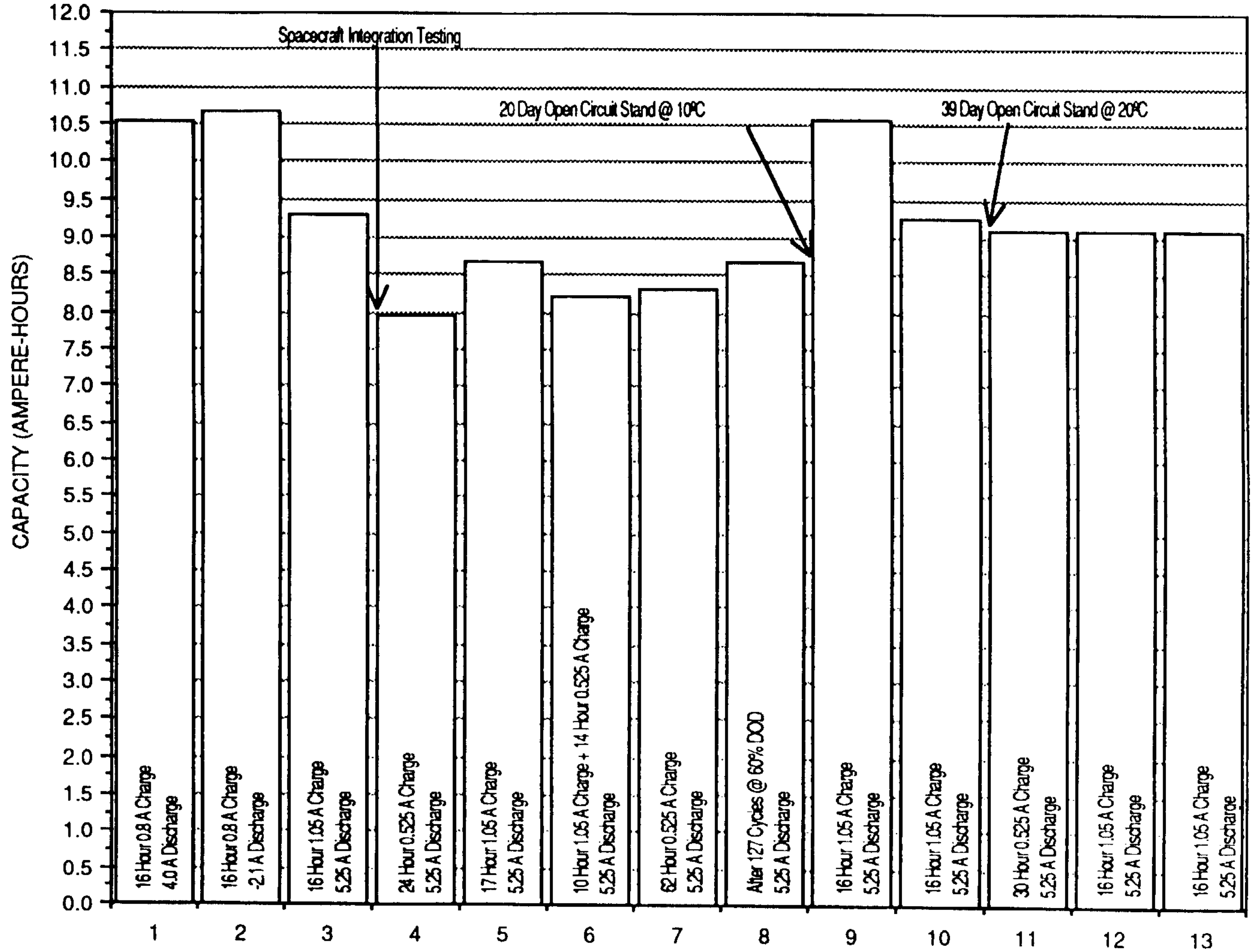
- Capacity lost during storage can be regained as useable capacity.
- Storage conditions did not appear to effect ability to retain capacity.
- Useable capacity lost cannot be regained a second time.
- Future Plan is to LEO cycle cells to investigate capacity retention during cycling.

NASA BATTERY WORKSHOP NiH2 CAPACITY FADE WORKSHOP 17 NOVEMBER 1992

QUALIFICATION NiH2 CPV BATTERY

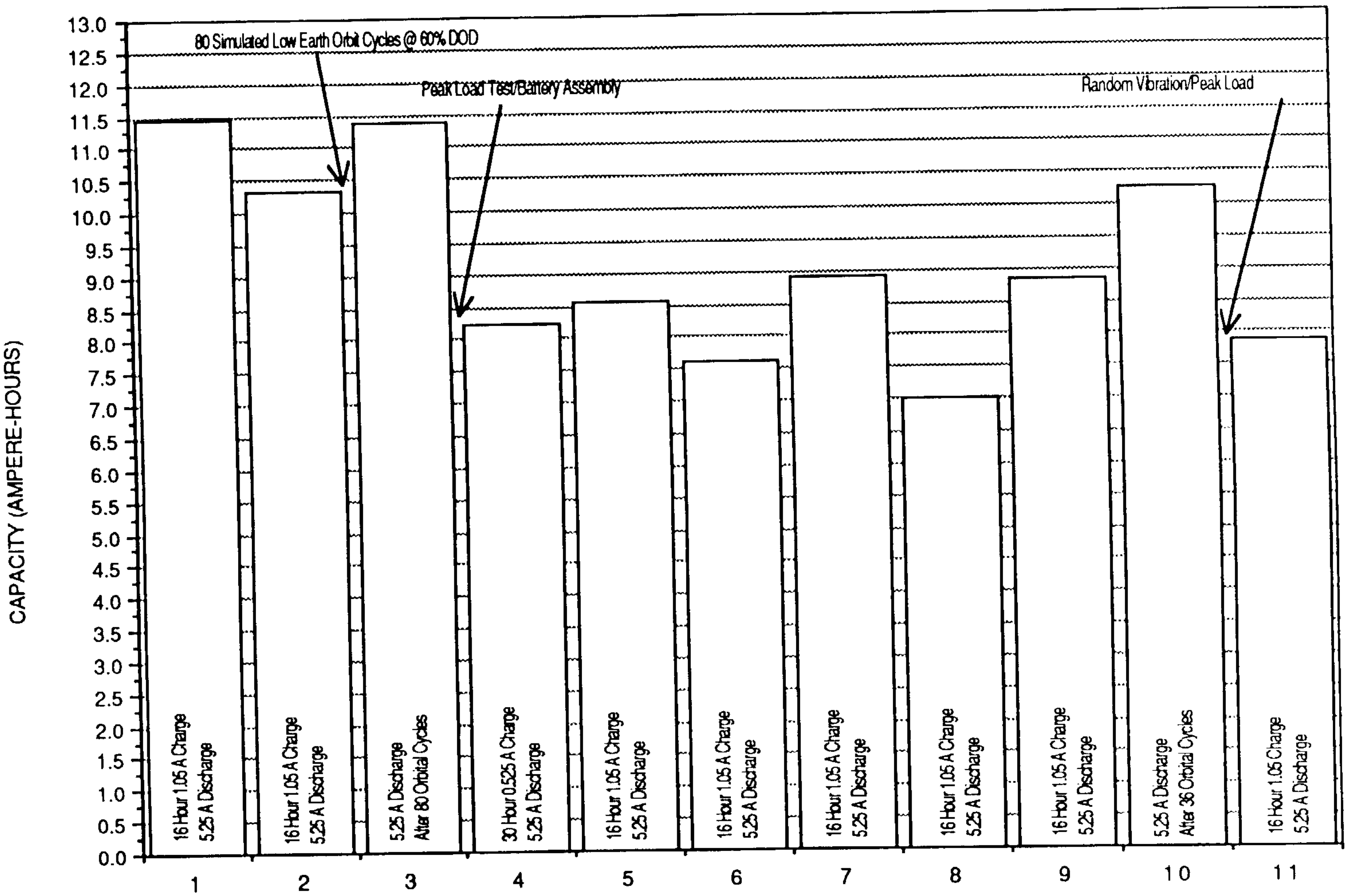


QUALIFICATION NiH2 CPV BATTERY



NASA BATTERY WORKSHOP NIH2 CAPACITY FADE WORKSHOP 17 NOVEMBER 1992

FLIGHT NiH2 CPV BATTERY



N93-20504

CHARGE RETENTION TEST EXPERIENCES ON HUBBLE SPACE TELESCOPE NICKEL-HYDROGEN BATTERY CELLS

D. E. Nawrocki, J. R. Driscoll, J. D. Armantrout,
Lockheed Missiles & Space Co.

R. C. Baker, Eagle-Picher Ind.

H. Wajsgras, Goddard Space Flight Center

DEN 1/22/92
CHART 1

The Hubble Space Telescope (HST) Nickel-Hydrogen Battery Module was designed by Lockheed Missile & Space Co (LMSC) and manufactured by Eagle-Picher Ind. (EPI) for the Marshall Space Flight Center (MSFC) as an Orbital Replacement Unit (ORU) for the Nickel-Cadmium batteries originally selected for this Low Earth Orbit Mission. The Hubble Space Telescope was successfully launched on 24 Apr 90 and is presently being operated in orbit by the Goddard Space Flight Center (GSFC) in Greenbelt, MD with the science mission being managed by the Space Telescope Science Institute in Baltimore, MD.

Nickel-Hydrogen Battery Cell Chemistry

- Provides a lighter design with longer life potential than Nickel-Cadmium
- Has a higher rate of self discharge during open circuit stand than that of Nickel-Cadmium

Provisions were not provided for this higher rate of self-discharge because Nickel-Cadmium batteries were originally slated for the HST launch and deployment mission.

Concern: Nickel-Hydrogen Charge Retention limitations could have caused capacity disparities if all contingencies had been used during launch and deployment of the HST.

DEN 1/22/92
CHART 2

The Nickel Hydrogen Battery cell provides a higher specific energy (w-hr/lb.) over the Nickel-Cadmium cell design. The negative electrode utilizes the relatively stable performance characteristics of the Hydrogen electrode of the Oxygen-Hydrogen fuel cell instead of the less stable characteristics of the Cadmium electrode. The Cadmium electrode tends to shed active material during life which causes a slow deterioration and loss of capacity due to shorting from dendrite growth. This makes the Nickel-Hydrogen cell a more robust design for space missions.

One major drawback to the Nickel-Hydrogen cell design is its inherent self discharge characteristics. As much as 10% of the capacity can be lost in a 24 hour period if the cell is allowed to to stand open circuit at room temperature.

Since Nickel-Cadmium batteries were originally slated for the HST launch and deployment mission, provisions were not provided for the higher Nickel-Hydrogen self-discharge characteristics by way of an improved of trickle charging interface. Nickel-Hydrogen trickle-charging charge inefficiencies generate more heat, and a heat rejection system could not be developed to accommodate this characteristic in time for the HST launch.

There was a concern that insufficient capacity would remain in the Nickel-Hydrogen battery system at 77°F while the HST/shuttle remained on the launch pad through several launch scrubs. Also, there was always the possibility of a delay in deployment once the shuttle was in orbit. The battery system is required to supply the electrical power to the HST following umbilical disconnect from the shuttle until the solar array system can be deployed.

With the increased amount of capacity that the HST Nickel-Hydrogen battery system had and reviewing other test results from charge retention tests, it appeared that adequate capacity would be available for deployment with all contingencies included.

Given that capacity was such a critical matter, testing for a very accurate prediction of the charge retention performance characteristics was needed.

During this testing, the sensitivity to capacity fade due to open circuit/ fully discharged stands at room temperature was revealed.

The purpose of this presentation is to summarize capacity fade characterization of this cell design and to show the methods used to regain this capacity.

DEN 1/22/92
CHART 3

The HST battery system utilizes six batteries (sized primarily for autonomous safe modes) with 65 to 95 amp-hr capacity per battery, depending on how the system is charged. Most of the published charge retention data for Nickel-Hydrogen cells exists for up to 72 hours and extrapolation of this data provides a well behaved decay curve. It was determined that about 42 Amp-hr per battery (including 15% contingency) was needed after 168 hours of open circuit stand.

This being a critical parameter for successful deployment, a high fidelity test data base was required for this particular cell design.

The Extended Charge Retention Test (ECRT) was contrived and conducted from August 89 through March 90. More details of this test will be given later.

During the ECRT, sensitivity to capacity fade was discovered during room temperature, open circuit, fully discharged stand periods.

An overview of this phenomena and the methods used to recover this capacity is the intent of this presentation.

Lockheed HST Ni-H2 Cell Design

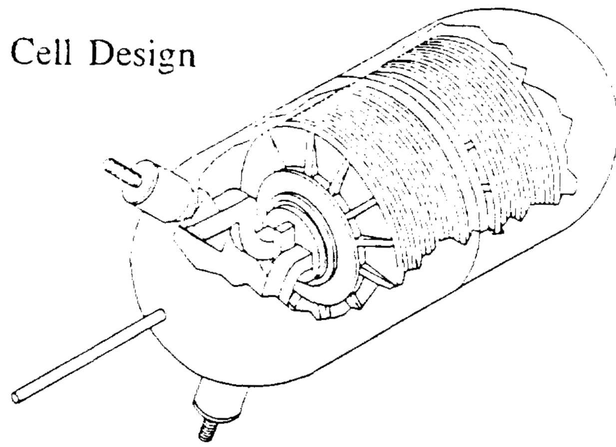
Air Force "Pineapple Slice" Cell Design with the following:

- 48 Dry Sintered Nickel Positive Electrodes
  - Aqueous Impregnation
- 48 Platinum Negative Electrodes
- Zirconium oxide Cloth Separators and Gas Screens
- Activated with 27% KOH electrolyte
- Wall wick (Zirconium oxide)
- Hydrogen Precharge (15 psia)

DEN 1/22/92
CHART 4

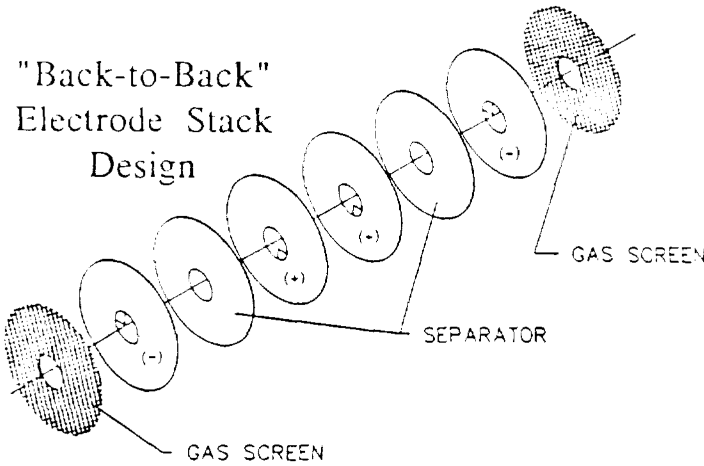
The HST cell design features related to this discussion are as follows:

The AF pineapple slice electrode shape is used and a plastic core is employed with all the electrode leads running through the plastic core. The positives are dry sintered nickel impregnated by an aqueous process. The negatives are fuel cell grade platinum Hydrogen gas electrodes. The separator material between the positive and negative electrodes is Zirconium oxide cloth. Gas screens are provided between the negative electrodes while the positives are positioned in a "back to back" configuration. Activation of the cell is performed using 27% KOH electrolyte. Inventory of electrolyte is maintained in the cell stack by way of a wall wick on the inside of the pressure vessel. Cells are sealed with one atmosphere (zero gage) of Hydrogen, thus giving a slight negative precharge or a positive limited cell.



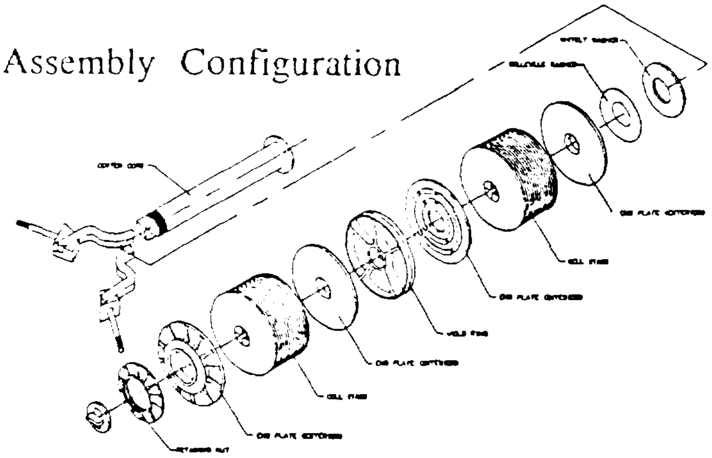
DEN 1/22/92
CHART 5

The HST Ni-H2 cell is designated by Eagle-Picher as the "RNH-90-3" cell design. This design features terminals exiting one end of the pressure vessel for ease in battery wiring which also allows for a low battery profile. The terminals are insulated from the pressure vessel by nylon seals. The pressure vessel is made from 0.040" Inconel 718 parent material which provides the high burst pressure margin required for astronaut handling in space.



The exploded view of the electrode stack shows how the electrodes are separated relative to each other. "Back to Back" means that every two positives are adjacent to each other. It can be seen here why this electrode is described as a "pineapple slice". The pointed tabs protruding inward from the electrode bodies are used for attaching corresponding electrode leads.

Assembly Configuration



DEN 1/22/92
CHART 7

This is an exploded view of all the cell internal components. Two cell electrode stacks are separated by a weld ring which provides a backing plate for the pressure vessel girth weld where the two halves of the vessel are fused.

Extended Charge Retention Test (ECRT)

- 48 residual cells, 24 from each Flight lot, were placed into cell testing fixtures.
- All cells were cycled six times to the 50°F acceptance capacity test sequence
- One additional capacity test conducted at 50°F served as a baseline
- All cells were then charged up and left open circuit
- The temperature was raised to 68°F in the testing fixture
- Two cells (one from each lot) were discharged following 4, 12 and 24 hour stand periods, and then every day, up to 21 days

OEH 1/22/92
CHART 8

The Extended Charge Retention Test (ECRT) was conducted on 48 cells from the two flight cell lots. These cells had passed acceptance testing and were residual from battery cell matching. The cells were placed in the testing fixture and kept isothermal in aluminum blocks during the entire test period.

All cells were conditioned by performing 50°F acceptance test capacity cycles until sufficiently conditioned. A capacity cycles is madeup of 24 hours of charge consisting of 9.3 amps for 10 hours followed by 4.0 amps for 14 hours (160 %), one hour open circuit followed by 15 amp discharge to 0.9 Vdc per cell. Cells were shorted down with 0.2Ω resistor to 0.1 Vdc/cell.

The cells were then charged at 50°F, open circuited for four hours while the temperature stabilized at 68°F, and then discharged at 15 amps for a "baseline capacity" measurement.

Again, the cells were charged at 50°F, and open circuited at 68°F for varying lengths of time. The first pair (one from each lot) was discharged (15 amps) after 4 hours of open circuit, the second pair was discharged following 12 hours, the third following 24 hours, then the remaining pairs were discharged every day up to 21 days (504 hours).

The capacities obtained following the open circuit stands were divided by the respective "baseline" capacities to obtain a high fidelity percent capacity retained versus open circuit time plot.

Extended Charge Retention Test (ECRT)

The previous sequence of tests was repeated twice at the following temperatures:

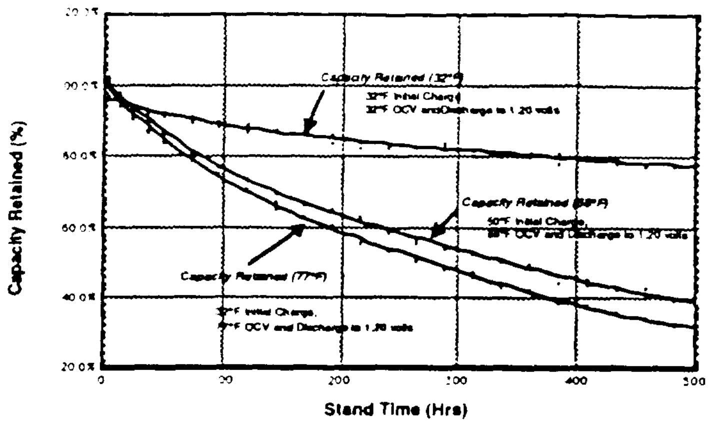
Second series of charge open circuit stands:
Charge temperature: 32°F
Open circuit temp. 77°F

Third series of charge open circuit stands:
Charge temperature: 32°F
Open circuit temp. 32°F

DEN 1/22/92
CHART 9

The original testing sequence was repeated for two more temperature conditions. The second condition had the charge up performed at 32°F with the open circuit temperature held at 77°F. The third condition also had the charge up performed at 32°F, but this time the open circuit temperature was held at 32°F.

These three open circuit conditions were all considered potential scenarios which could occur in the shuttle payload bay while awaiting launch, and each proved invaluable for on pad processing scenario trades.



DEH 1/22/92
CHART 10

The final results of the Extended Charge Retention Tests (ECRT) performed to support the launch of the HST showed good correlation with temperature and open circuit stand time.

The data can be used for predicting capacity retained for a launch scenario where trickle charge is not provided on the pad (assuming battery installation can be made on the pad).

Lockheed PREDICTION MODEL

LMSC developed a capacity prediction model with the following assumptions:

- First order kinetics with respect to hydrogen gas density
- Arrhenius model behavior

$$C(t) = C(t_o) \exp[-k(t-t_o)]$$

The following rate constant (k) relationship with respect to temperature was obtained by analysis of self-discharge characteristics of similar Nickel-Hydrogen cell designs:

$$k = 354.9 \exp(-3510 / T)$$

where:

k is in units of reciprocal hours

T is the temperature in degree Kelvin

DCN 1/22/92
CHART 11

In the early planning stages for the Nickel-Hydrogen batteries for the HST, a self discharge capacity math model was developed which would generated capacity as a function of temperature and time.

Assumptions were:

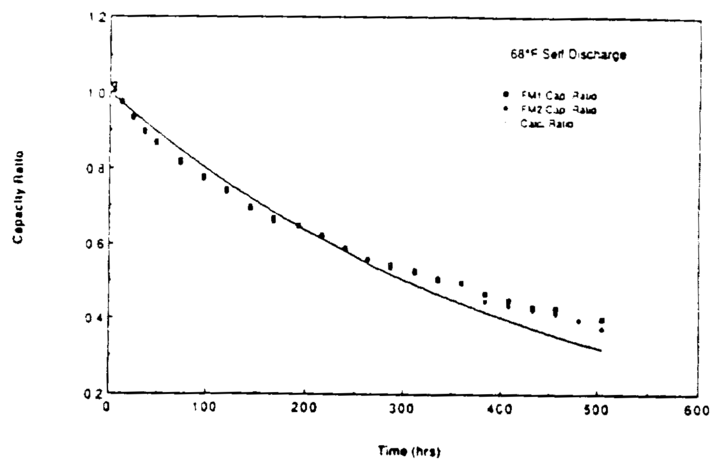
First order kinetics with respect to hydrogen gas density

Arrhenius equation behavior

Fitting open circuit capacity data from similar Nickel-Hydrogen cell designs, this relationship of the first order rate constant was arrived at.

Lockheed

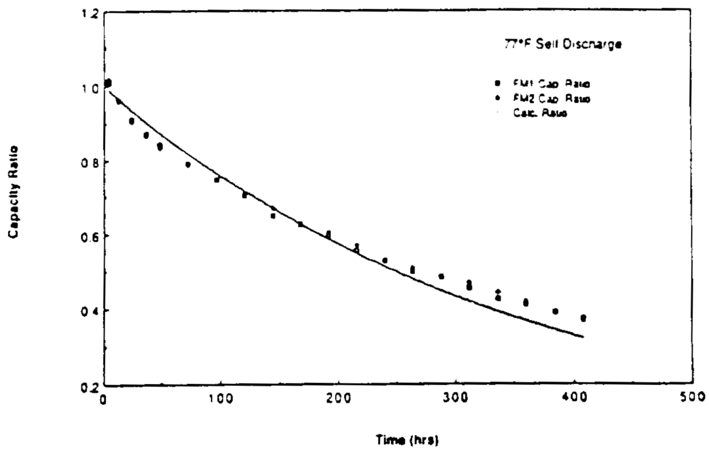
PREDICTION AT 68°F



DEN 1/22/92
CHART 12

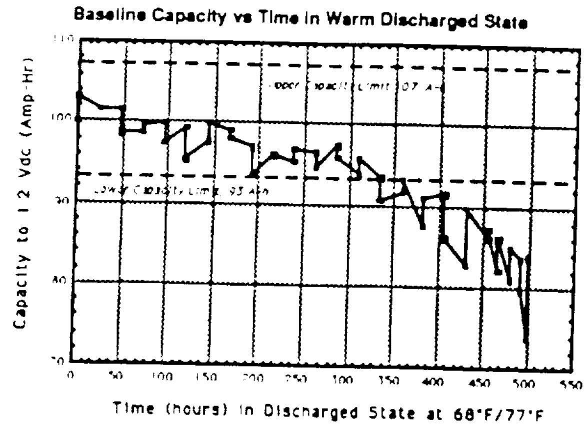
This is the actual capacity of the two lots of flight cells along with the Arrhenius prediction curve at 68°F.

PREDICTION AT 77°F



OEN 1/22/92
CHART 13

This is the actual capacity of the two lots of flight cells along with the Arrhenius prediction curve at 77°F.



DEN 1/22/92
CHART 14

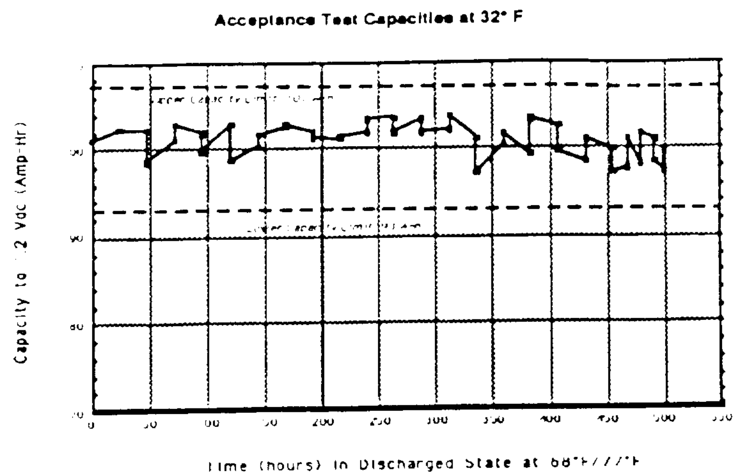
The baseline capacity of the cells remaining in the discharged open circuit condition experienced a larger fade in capacity than cells stored in the charged open circuit condition.

This graph depicts this capacity fade phenomena with discharged open circuit storage time.

Before presenting the next graph, let me explain the construction and the data used in this graph first.

This is a plot of the baseline capacity of the cells just prior to the last (32°F/32°F) condition of the Extended Charge Retention Tests. The abscissa is the time a particular pair of cells spent in the discharged open circuit condition. All cells were discharged in the same sequence of charged open circuit time. Cells discharged first (4 hours after charge up) spent 500 hours discharged open circuit at 68°F and then at 77°F. These cells showed the most pronounced capacity fade. Cells left charged open circuit for longer times showed proportionally less capacity fade.

A very distinct fade in capacities can seen here as discharged open circuit time increases.



DEN 1/22/92
CHART 15

This plot has the same abscissa as the previous plot representing relative lengths of time that a particular cell pair spent <u>discharged</u> open circuit condition. The ordinate represents the acceptance test capacities of particular cell pair. As stated before, all cells were acceptance tested and considered nominal performing cells. Note the low (93 A-h) and high (107 A-h) acceptance test capacity limits shown on this and the previous graph for relative capacity performance criteria.

Cell capacity performance can be correlated with time in the <u>discharged</u> open circuit state.

Following are efforts made to recover this faded capacity.

Following the 32°F charge / 32° open circuit ECRT sequence, cycling was performed to attempt capacity recovery of the deficient cells.

- A full 32°F capacity test cycle with 24 hr charge; 10 hrs at 9.3 amps followed by 4.0 amps for 14 hrs (160%), one hour open circuit, 15 amp discharge to 0.9 Vdc/cell, short down with 0.2 Ω to 0.1 Vdc/cell
- A 32°F, 24 hr charge; 10 hrs at 9.3 amps followed by 4.0 amps for 14 hrs (160%)
- 20 cycles
  - 15 amp discharge for 2 hours
  - 9.3 amp charge for 4 hours (124% charge return)

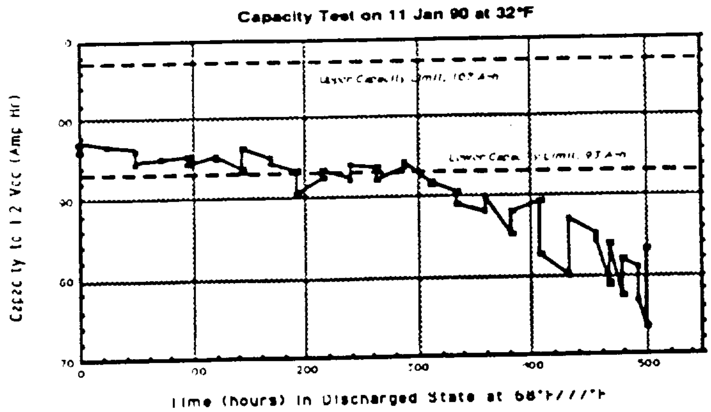
A 32°F capacity test with the following results (next graph)

DEN 1/22/92
CHART 16

Another 32°F capacity cycle was performed and then the cells were recharged to full state of charge at 32°F and placed on 6 hour, 30% DoD cycles with a 1.24 recharge ratio.

It was hypothesized that cycling to lower depths of discharge than the cell was used in service with a high recharge ratio would restore capacity performance.

A subsequent 32°F capacity test showed that this did not occur (next graph)



DEN 1/22/92
CHART 17

The overall capacities were less after cycling at lower depths of discharge followed by 1.24 recharge ratio.

Following the 11 Jan 90 Capacity Test, the following sequence of conditioning was performed:

Two low rate overcharge cycles:

- A 32°F charge up (9.3 amp for 10 hrs)
- 32°F low rate overcharge (4.0 amp for 72 hrs) (410%)
- 15 amp discharge to 0.9 Vdc / cell, 0.2 Ω short down to 0.010 Vdc / cell

One warm charged open circuit stand:

- A 32°F charge up (9.3 amp for 10 hrs)
- 32°F low rate overcharge (4.0 amp for 14 hrs) (160%)
- 77°F charged open circuit stand for 168 hrs
- 15 amp discharge to 0.9 Vdc / cell, 0.2 Ω short down to 0.010 Vdc / cell

A 32°F capacity test with the following results (next graph)

DEN 1/22/92
CHART 18

Subjecting the cells to extended low rate (C/23 or 4.0 amp) overcharge for extended periods did not improve capacity performance.

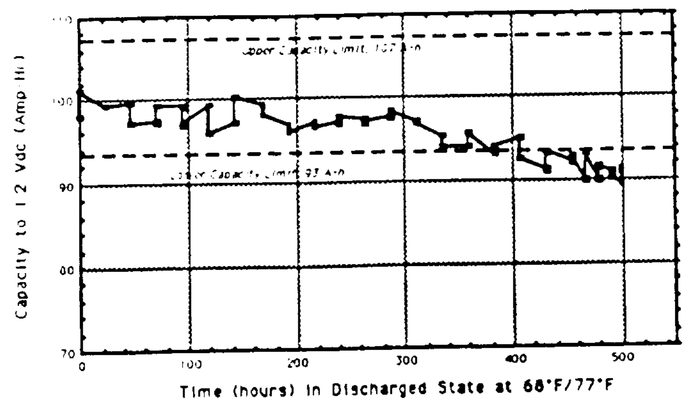
The cells were then charged up to full state of charge (32°F is a very efficient charge temperature) and allowed to stand open circuit, in the <u>charged</u> state at 77°F.

A 32°F capacity test with the following results was performed (next graph)

Lockheed

32°F CAPACITY TEST (2-05-90)

Capacity Test on 5 Feb 90 at 32°F



DEN 1/22/92
CHART 19

An improvement in capacity of cells which had previously spent more time in the discharged open circuit condition was observed.

Following the 5 Feb 90 Capacity Test, the following sequence of conditioning was performed:

One warm charged open circuit stand:

- **A 32°F charge up (9.3 amp for 10 hrs)**
- **32°F low rate overcharge (4.0 amp for 14 hrs) (160%)**
- **77°F charged open circuit stand for 118 hrs**
- **15 amp discharge to 0.9 Vdc / cell, 0.2 Ω short down to 0.10 Vdc / cell**

A 32°F capacity test

A 32°F resistor drain

- **A 32°F charge up (9.3 amp for 10 hrs)**
- **32°F low rate overcharge (4.0 amp for 14 hrs) (160%)**
- **After one hour open circuit, 1.0 Ω short down to 1.0 Vdc / cell**
- **0.2 Ω short down to 0.10 Vdc / cell**

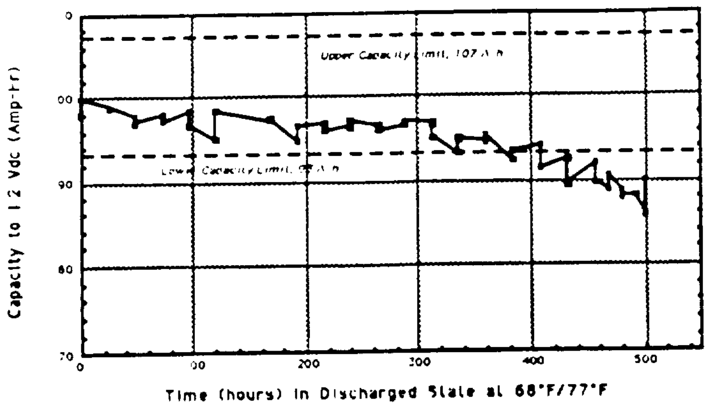
A 32°F capacity test with the following results (next graph)

DEN 1/22/92
CHART 29

Again, the cells were charged up and allowed to stand charged open circuited, this time for 118 hours instead of 168 hours.

Since there was a desire to accelerated this self discharge, allowing for recovery to come quicker, the self discharge was "coaxed along" by adding a low rate, constant resistance discharge. The one ohm resister gives approximately a 1.25 amp discharge, which was thought to be a "half way medium" between the standard 15 amp discharge and the slow, charged open circuited self discharge rate.

A 32°F capacity test with the following results was performed (next graph)



DEN 1/22/92
CHART 21

A comparison to this cell capacity profile compared to the profile of 5 Feb 90, it appears that the results are going in the wrong direction.

Apparently the <u>charged</u> open circuited shelf discharging stands is what is needed to allow capacity recovery.

Following the 24 Feb 90 Capacity Test, the following sequence of conditioning was performed:

One warm charged open circuit stand:

- A 32°F charge up (9.3 amp for 10 hrs)
- 32°F low rate overcharge (4.0 amp for 14 hrs) (160%)
- 77°F charged open circuit stand for 21 days
- 15 amp discharge to 0.9 Vdc / cell
- 0.2 Ω short down to 0.10 Vdc / cell

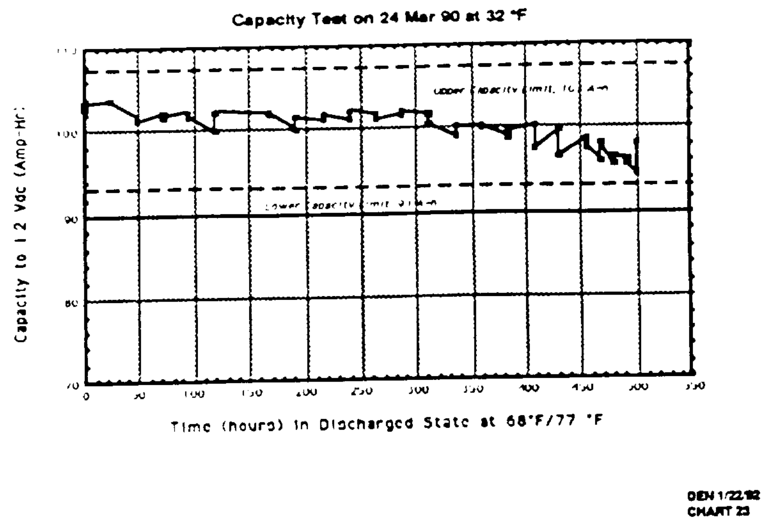
A 32°F capacity test

A 32°F capacity test with the following results (next graph)

DEN 1/22/92
CHART 22

Again, the cell set was fully charged , but this time allowed to stand at room temperature in a charged open circuit state for a full 21 days.

Two 32°F capacity tests were run, the second gave more favorable results as appear on the following graph.



All cells are now within the specified capacity requirement band for the 32°F ATP capacity test.

Cells which spent the most time in the discharged open circuited condition at room temperature continue to show some disparity compared to their acceptance test 32°F capacity performance.

Based on these results, it was concluded that charged open circuit storage at warm temperatures is the preferred storage mode for periods up to 21 days.

The 32°F capacity performance of all cells was restored to within the specification requirements

A slight disparity in capacity in the cells exists which were stored in the discharged open circuit condition for longer periods.

Charged open circuit stand at warm temperature appears to restore capacity lost due to warm, discharged open circuit stands for nickel-hydrogen cells having sight hydrogen precharge.

DEN 1/22/92
CHART 34

The 32°F capacity performance of all cells was restored to within the specification requirements, but there still existed a slight disparity in capacity for the cells which were in a discharged open circuit condition for the longer time spans.

It is a well known fact that battery cell performance is a strong function of prior test/storage history, and it is difficult to say exactly which conditioning effort made the strongest contribution to the capacity recovery however, charged open circuit stand appears to restore capacity lost due to warm, discharged open circuit stands of nickel-hydrogen cells having sight hydrogen precharge.

One explanation of this recovery response is that warm charged open circuit stand allows the nickel electrode to discharge at its own rate (self-discharge) facilitating re-incorporation of active material during subsequent low temperature recharge.

This information is presented to the technical community to further understand the operations of battery cell chemistry under specific operating conditions.

Nickel-Cadmium Technologies Session

AF Ni-Cd CELL
QUALIFICATION PROGRAM UPDATE

S. Hall and H. Brown NWSC Crane
G. Collins, W. Hwang Aerospace Corporation
Lt. Q. Bui USAF

N93-20505

AIR FORCE NI-CD PROGRAM REVIEW
OVERVIEW OF TEST PROGRAM

BACKGROUND

1976 - QUALIFIED 2505ML SEPARATOR MANUFACTURE DISCONTINUED

1984 - SURPLUS SUPPLY OF 2505ML DEPLETED

1985 - AIR FORCE/NAVY SPONSORED CRANE DIVISION TEST SEPARATOR QUALIFICATION PROGRAM

1986-1988 - NO GENERIC QUALIFICATION OF REPLACEMENT PELLON 2536 SEPARATOR

1989 - AIR FORCE SPONSOR CRANE DIVISION TEST NICKEL-CADMIUM CELL QUALIFICATION PROGRAM

1990 - SAFT/FRANCE VOS A (up to 30 Ah) DESIGN CELLS RECOMMENDED FOR GENERIC QUALIFICATION FOR USAF PROGRAMS.

AIR FORCE NI-CD PROGRAM REVIEW
OVERVIEW OF TEST PROGRAM

PURPOSE

GENERIC QUALIFICATION OF AEROSPACE NICKEL-CADMIUM CELLS

- ALL AVAILABLE MANUFACTURERS
- ALL AVAILABLE DESIGNS
- INCLUDES CELLS FROM PREVIOUS PROGRAM
- HIGH AND LOW ORBIT LIFE CYCLING

CHARACTERIZE BEGINNING OF LIFE PERFORMANCE

AIR FORCE NI-CD PROGRAM REVIEW
OVERVIEW OF TEST PROGRAM

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CHARACTERIZE BEGINNING OF LIFE PERFORMANCE

AIR FORCE NI-CD PROGRAM REVIEW
OVERVIEW OF TEST PROGRAM

OUTLINE

ACCEPTANCE TEST - BASED ON MANUFACTURER TEST

CHARACTERIZATION TEST

CHARGE RATE	TEMPERATURE °C			
	-10	0	10	25
C/2		X	X	X
C/4		X	X	
C/10	X	X	X	X
C/20	X	X		X
C/80		X	X	

NOTE: DISCHARGES AT C/2

STRESS TEST
PACK : 0342H

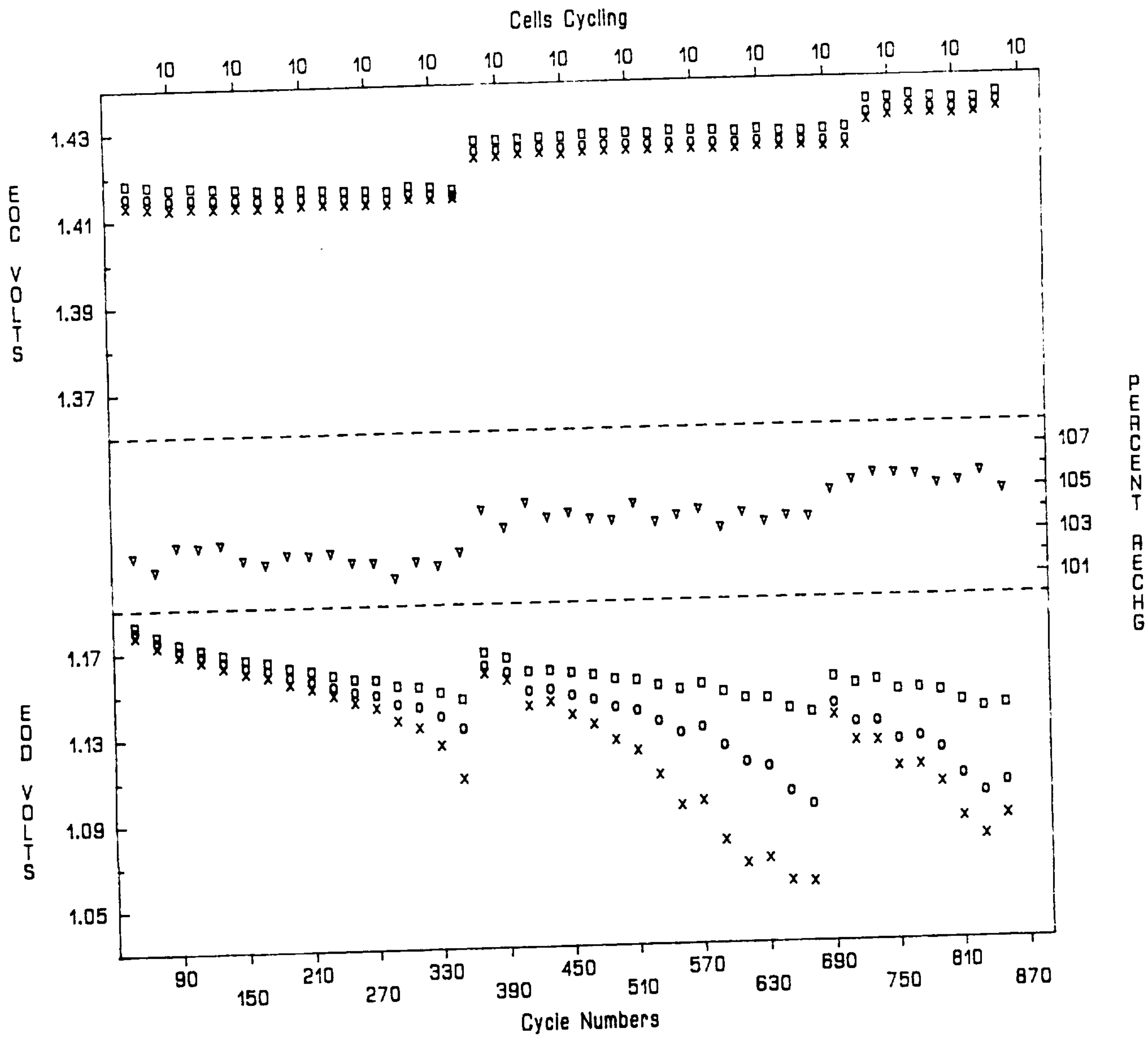
TYPE	42 A/H SUPER NI-CD , HUGHES
TEMPERATURE	20 DEGREES CENTIGRADE
ORBIT	100 MINUTES
DISCHARGE	30.0 AMPS FOR 34 MINUTES, 40%DOD
CHARGE	21.0 AMPS WITH V/T TAPER AT V/T 5.5 (1.424) V/C

TRENDPLOT

Pack: 0342H Manf: HUGHES 42.0 AH
Orbit: LEO Temp (C): 20 DOD(%): 40.0
Discharge(Amp/Hrs): 30.0/0.56 Charge(Amp/Hrs): 21.0/1.12

TEST DATA AS OF JUNE 30, 1992

Plot area #1 -- keys:
Left-side: □ -- High Cell, o -- Average, x -- Low Cell; Right-side: OFF
Plot area #2 -- keys:
Left-side: OFF; Right-side: ▽ -- PERCENT
Plot area #3 -- keys:
Left-side: □ -- High Cell, o -- Average, x -- Low Cell; Right-side: OFF



1. CYCLE #310, INCREASED FROM VT 5 (1.414 V/C) TO VT 5.5 (1.424 V/C).
2. CYCLE #680, INCREASED FROM VT 5.5 (1.424 V/C) TO VT 6 (1.434 V/C).
3. CYCLE #722, DUE TO SOFTWARE PROBLEM, THE LAST STEP OF CHARGE WAS ONLY TO 1.424 V/C.
4. CYCLE #870, EQUIPMENT MALFUNCTION CAUSED PACK TO BE DISCHARGED FOR 1.5 HOURS. THE PACK WAS DISCONTINUED DUE TO SWELLING OF CELLS.

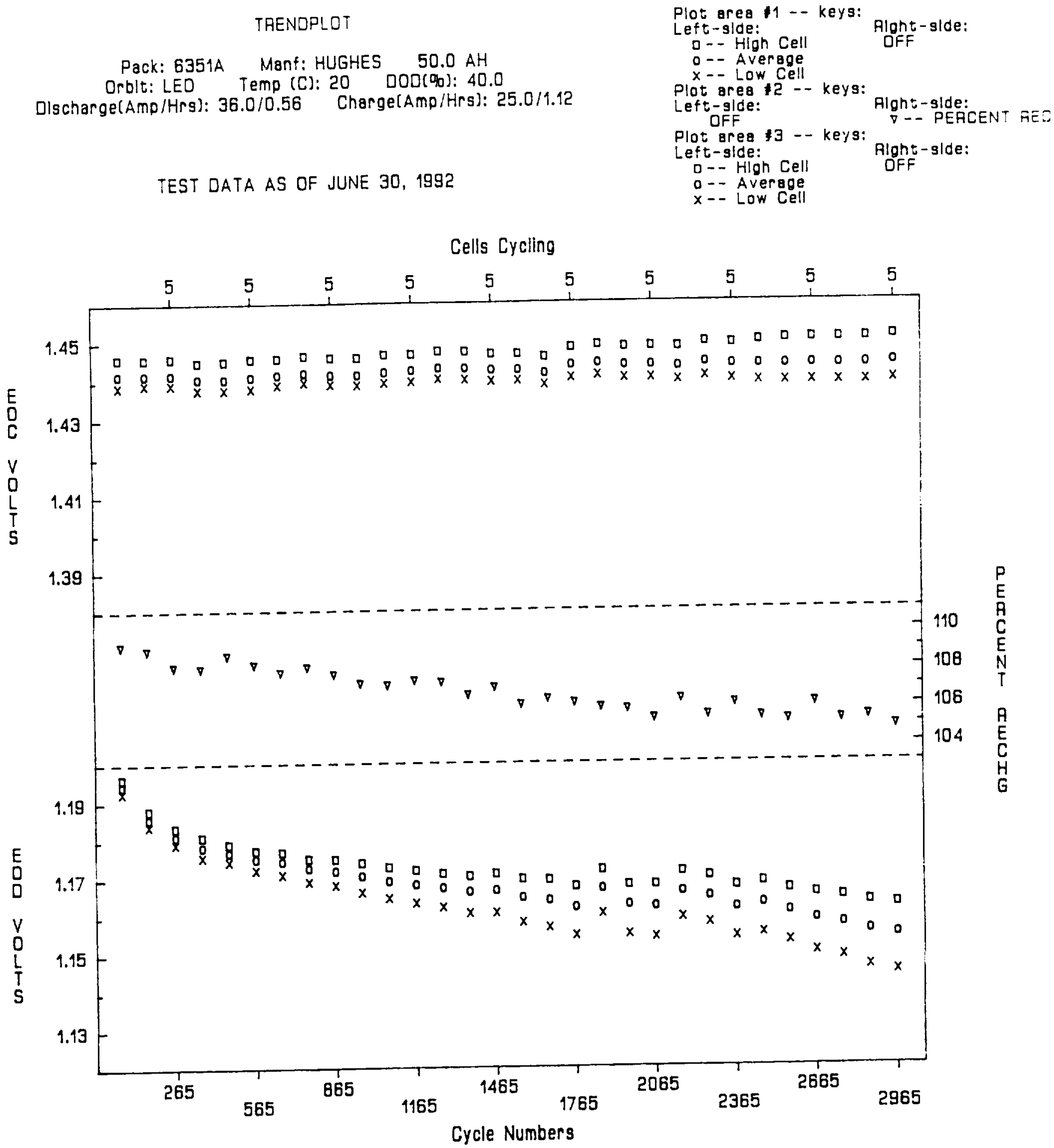
STRESS TEST
PACK : 6351A

TYPE	50 A/H SUPER NI-CD , HUGHES
TEMPERATURE	20 DEGREES CENTIGRADE
ORBIT	90 MINUTES
DISCHARGE	36 AMPS FOR 34 MINUTES, 40%DOD
CHARGE	25 AMPS WITH V/T TAPER AT 6.5 (1.444 V/C)

TRENDPLOT

Pack: 6351A Manf: HUGHES 50.0 AH
Orbit: LEO Temp (C): 20 DOD(%): 40.0
Discharge(Amp/Hrs): 36.0/0.56 Charge(Amp/Hrs): 25.0/1.12

TEST DATA AS OF JUNE 30, 1992



1. CYCLE #18, DECREASED FROM VT 7 (1.454 V/C) TO VT 6.5 (1.444 V/C) DUE TO HIGH PERCENT RECHARGE.

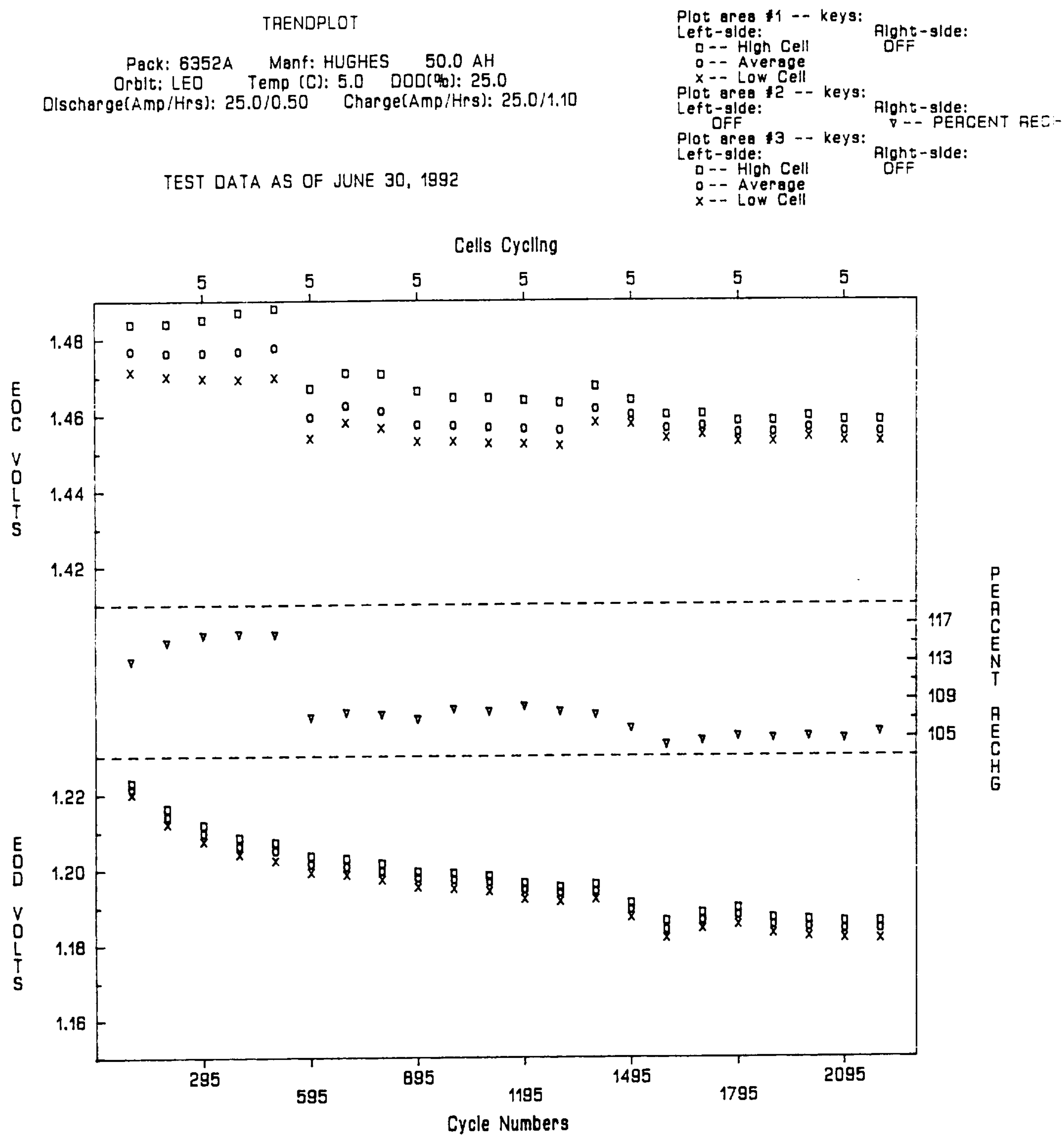
PACK : 6352A

TYPE	**50 A/H SUPER NI-CD , HUGHES**
TEMPERATURE	**5 DEGREES CENTIGRADE**
ORBIT	**96 MINUTES**
DISCHARGE	**25 AMPS FOR 30 MINUTES, 25%DOD**
CHARGE	**25 AMPS WITH V/T TAPER AT 5.5 (1.458 V/C)**

TRENDPLOT

Pack: 6352A Manf: HUGHES 50.0 AH
Orbit: LEO Temp (C): 5.0 DOD(%): 25.0
Discharge(Amp/Hrs): 25.0/0.50 Charge(Amp/Hrs): 25.0/1.10

TEST DATA AS OF JUNE 30, 1992



1. CYCLE #47, LOWERED FROM VT 7 (1.488 V/C) TO VT 6.5 (1.478 V/C) DUE TO HIGH PERCENT RECHARGE.
2. CYCLE #529, LOWERED FROM VT 6.5 (1.478 V/C) TO VT 6 (1.468 V/C) DUE TO HIGH PERCENT RECHARGE.
3. CYCLE # 569, LOWERED FROM VT 6 (1.468 V/C) TO VT 5.5(1.458 V/C) DUE TO HIGH PERCENT RECHARGE (111%).

RESULTS OF "SUPER NICD" CELLS LEO TEST

* CAPACITY LOSS DUE TO STORAGE/HANDLING PROCEDURES
  - o 50-Ah CELL, 40% DOD & 20 C: EODV > 1.14 AFTER 2900 CYCLES
  - o 50-Ah CELL, 25% DOD & 5 C: EODV > 1.18 AFTER 2100 CYCLES
  - o 42-Ah CELL, 40% DOD & 20 C: EODV > 1.05 FIRST 800 CYCLES WHILE OPTIMIZING V/T LEVEL

SUMMARY OF RESULTS OF "SUPER NICD" CELLS

* THERE IS A STORAGE/HANDLING ISSUE

* NO PROBLEMS ON LIFE TEST
  o STILL IN EARLY PART OF TEST

STRESS TEST
PACK : 6340S

TYPE	40 A/H NI-CD , SAFT
TEMPERATURE	20 DEGREES CENTIGRADE
ORBIT	100 MINUTES
DISCHARGE	28.6 AMPS FOR 34 MINUTES, 40%DOD
CHARGE	20.0 AMPS WITH V/T TAPER AT V/T 9 (1.494 V/C)

POST CYCLING C/2, CAPACITY CHECK

1.00 VOLT	C-1 25.0, C-2 31.0, C-3 29.6, C-4 ,31.6
0.75 VOLT	C-1 46.5, C-2 51.0, C-3 49.2, C-4 ,51.6

TRENDPLOT

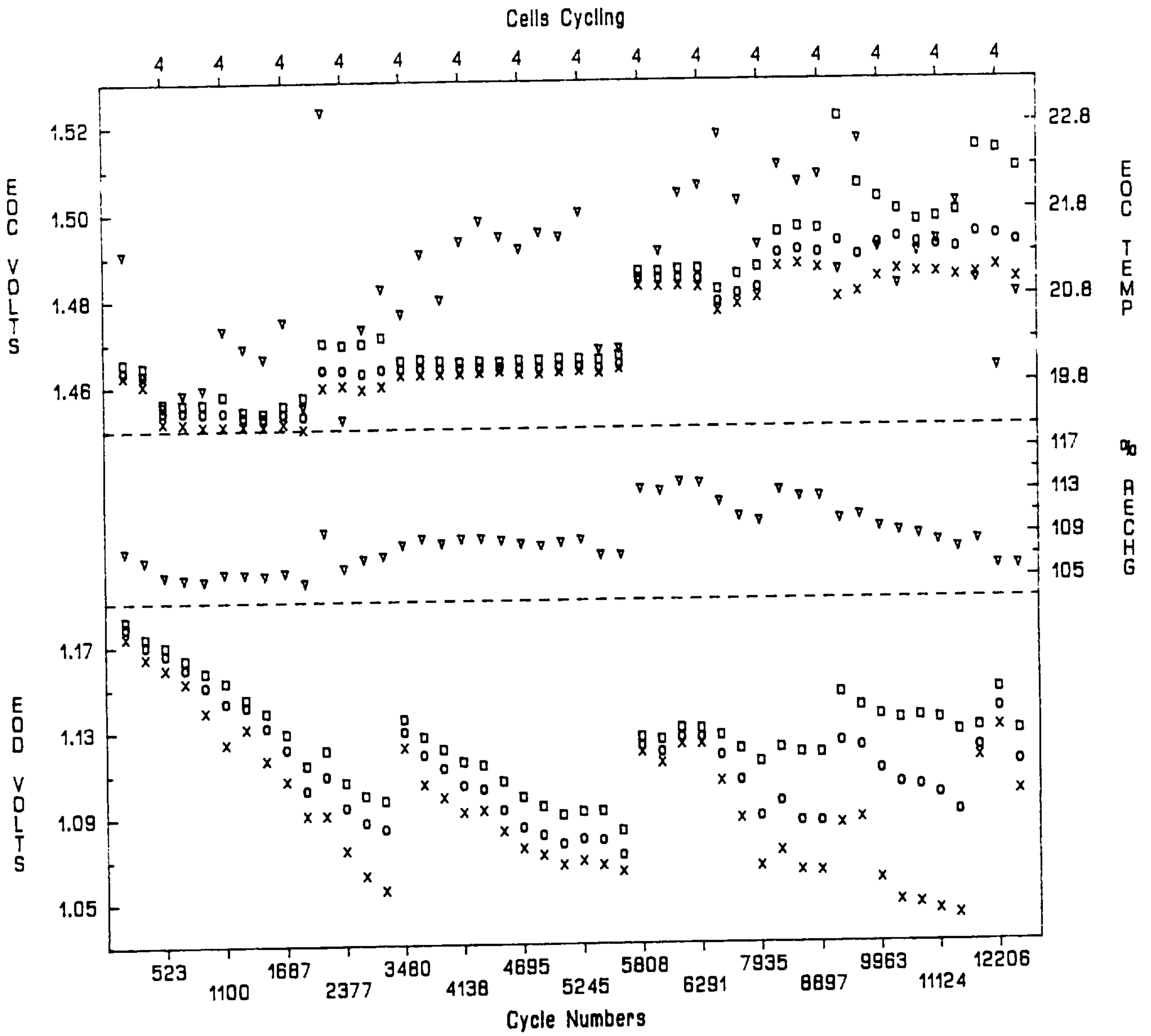
Pack: 6340S Manf: SAFT 40.0 AH AIR FORCE
Orbit: LEO Temp (C): 20 DOD(%): 40.0
Discharge(Amp/Hrs): 28.6/ .56 Charge(Amp/Hrs): 20.0/1.12

TEST DATA AS OF JUNE 30, 1992

Plot area #1 -- keys:
Left-side: □ -- High Cell; o -- Average; x -- Low Cell
Right-side: ▽ -- EOC TEMP

Plot area #2 -- keys:
Left-side: OFF
Right-side: ▽ -- % RECHG

Plot area #3 -- keys:
Left-side: □ -- High Cell; o -- Average; x -- Low Cell
Right-side: OFF



1. Cycle # 467, lowered VT to 7.5 (1.454 V/C) due to slight temperature rise of 1 degree C.
2. Cycle # 2080, raised VT to 8.0 (1.464 V/C).
3. Cycles # 2793 thru 3200, Special Testing performed.
4. Cycle # 5752, raised VT to 9.0 (1.484 V/C) due to low EOD's.
5. Cycle # 8091, raised VT to 9.5 (1.494 V/C).
6. Cycle #7257, Voltage clamp changed to temperature controlled voltage limit.
7. Cycle #12416, pack discontinued per Aerospace Instructions.

STRESS TEST
PACK : 6324S

TYPE	24 A/H NI-CD , SAFT
TEMPERATURE	20 DEGREES CENTIGRADE
ORBIT	100 MINUTES
DISCHARGE	17.2 AMPS FOR 34 MINUTES, 40%DOD
CHARGE	12.0 AMPS WITH V/T TAPER AT V/T 8.5 (1.484 V/C)
POST CYCLING	C-1 29.7, C-2 25.1, C-3 24.0

C/2, CAPACITY CHECK

AFREV 30 June 92

TRENDPLOT

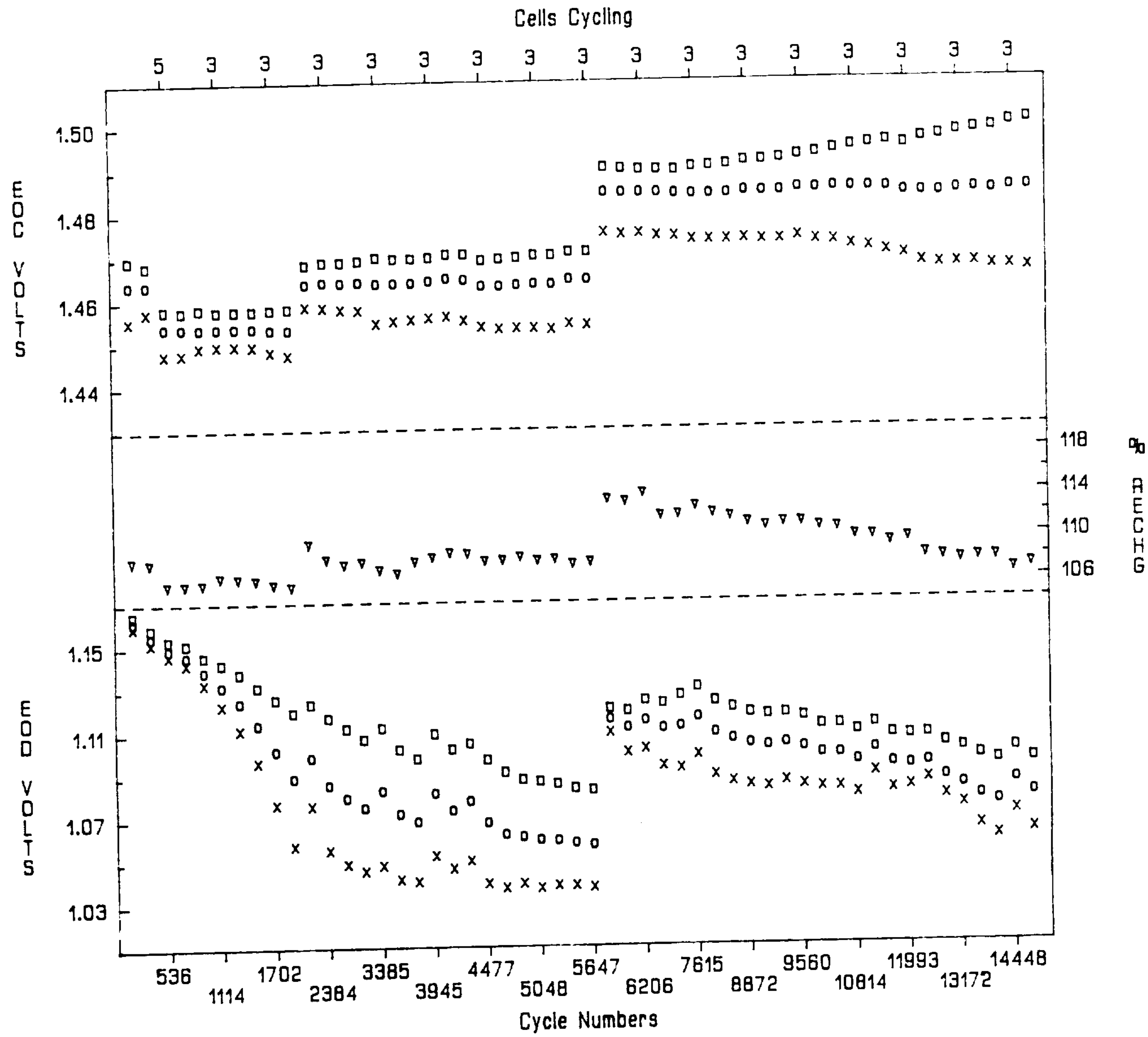
Pack: 6324S Manf: SAFT 24.0 AH AIR FORCE
Orbit: LEO Temp (C): 20 DOD(%): 40.0
Discharge(Amp/Hrs): 17.2/ .56 Charge(Amp/Hrs): 19.2/1.12

TEST DATA AS OF JUNE 30, 1992

Plot area #1 -- keys:
Left-side: □ -- High Cell, o -- Average, x -- Low Cell
Right-side: OFF

Plot area #2 -- keys:
Left-side: OFF
Right-side: ∇ -- % RECHG

Plot area #3 -- keys:
Left-side: □ -- High Cell, o -- Average, x -- Low Cell
Right-side: OFF



1. Cycle # 481, lowered VT to 7.5 (1.454 V/C) due to slight temperature rise.
2. Cycle # 740, cells # 4 & 5 were removed for vibration cycle.
3. Cycle # 2100, VT raised to 8.0 (1.464 V/C).
4. Cycles # 2803 thru 3215, Special Testing performed.
5. Cycle # 5764, VT raised to 9.0 (1.484 V/C) due to low EOD's.
6. Cycle # 14,821, pack was discontinued.

COMPRESSED TIME GEO
PACK : 6240S

TYPE	**40 A/H NI-CD , SAFT**
TEMPERATURE	**20 DEGREES CENTIGRADE**
ORBIT	**24 HOURS**
DISCHARGE	**26.7 AMPS FOR MAXIMUM OF 80%DOD**
CHARGE	**4.0 AMPS WITH V/T TAPER AT V/T 5 (1.414 V/C)**

GEOAIR FORCE
TREND OF MID SHADOW
Pack: 6240S Manf: SAFT 40.0 AH
Orbit: GEO Temp (C): 20 DOD(%): 80.0

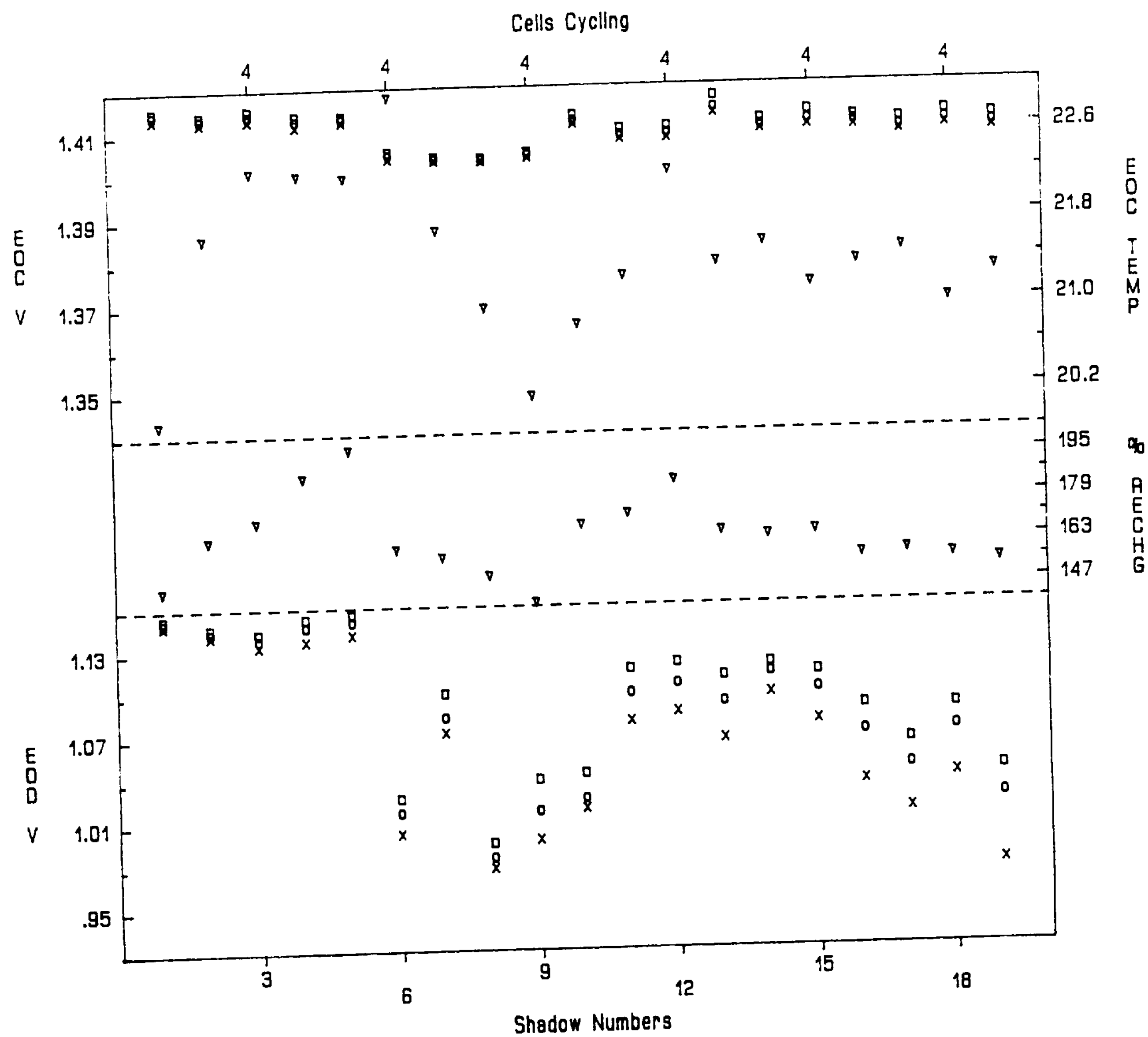
DISCHARGE (26.7 AMPS)
CHARGE (4.0 AMPS)

SHADOWS 1 THRU 19

Plot area #1 -- keys:
Left-side: □ -- High Cell; o -- Average; x -- Low Cell
Right-side: ▿ -- EOC TEMP

Plot area #2 -- keys:
Left-side: OFF
Right-side: ▿ -- % RECHG

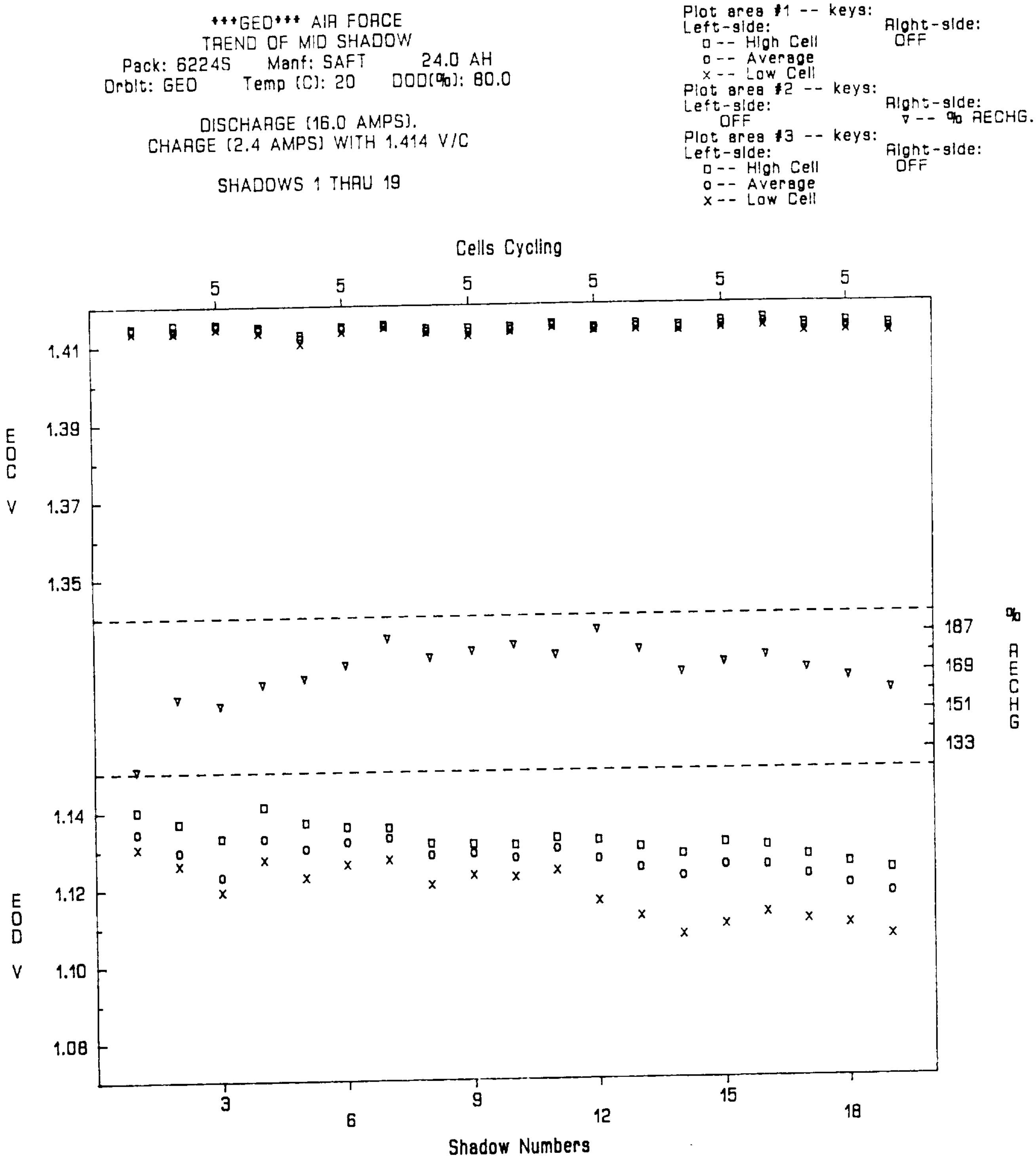
Plot area #3 -- keys:
Left-side: □ -- High Cell; o -- Average; x -- Low Cell
Right-side: OFF



1. Shadow # 1, VT 5 (1.414 V/C).
2. Shadow # 4, DOD changed from 86 to 80 per cent recharge.
3. Shadow # 6, VT 4.5 (1.404 V/C) due to cells warming during charge.
4. During Shadow # 9, the pack was using a 2 step V/T. The first ten days and the last nine days of the shadow period were at VT 4.0 (1.394 V/C). During days 11 thru 33 (mid-shadow) the pack ran at VT 4.5 (1.404 V/C).
5. Shadow # 10, voltage clamp changed to voltage/temperature controlled voltage limit at VT 5 (1.414 V/C).

COMPRESSED TIME GEO
PACK : 6224S

TYPE	24 A/H NI-CD , SAFT
TEMPERATURE	20 DEGREES CENTIGRADE
ORBIT	24 HOURS
DISCHARGE	16.0 AMPS FOR MAXIMUM OF 80%DOD
CHARGE	2.4 AMPS WITH V/T TAPER AT V/T 5 (1.414 V/C)



1. Shadow # 4, DOD changed from 86 to 80 per cent recharge.

RESULTS FOR SAFT CELLS

* COMPRESSED TIME GEO: 80% DOD, 20 C
- o EODV > 1.00 AFTER 18 ECLIPSE SEASONS
- o TERMINAL & THERMAL TEST PROBLEMS FOR 40-Ah CELLS
- o C/D AS HIGH AS 185 % TO MAINTAIN

* LEO: 40% DOD, 20 C
- o EODV> 1.03 AFTER 14800 CYCLES FOR 24-Ah CELLS
- o EODV> 1.03 AFTER 12400 CYCLES FOR 40-Ah CELLS
- o TEST DISCONTINUED

SUMMARY OF RESULTS OF SAFT
24-Ah & 40-Ah CELLS

*C/D HIGHER THAN THAT OF PRE-1986 GATES CELLS
* LEO RESULTS VERIFY GENERIC QUALIFICATION OF VOS A CELLS

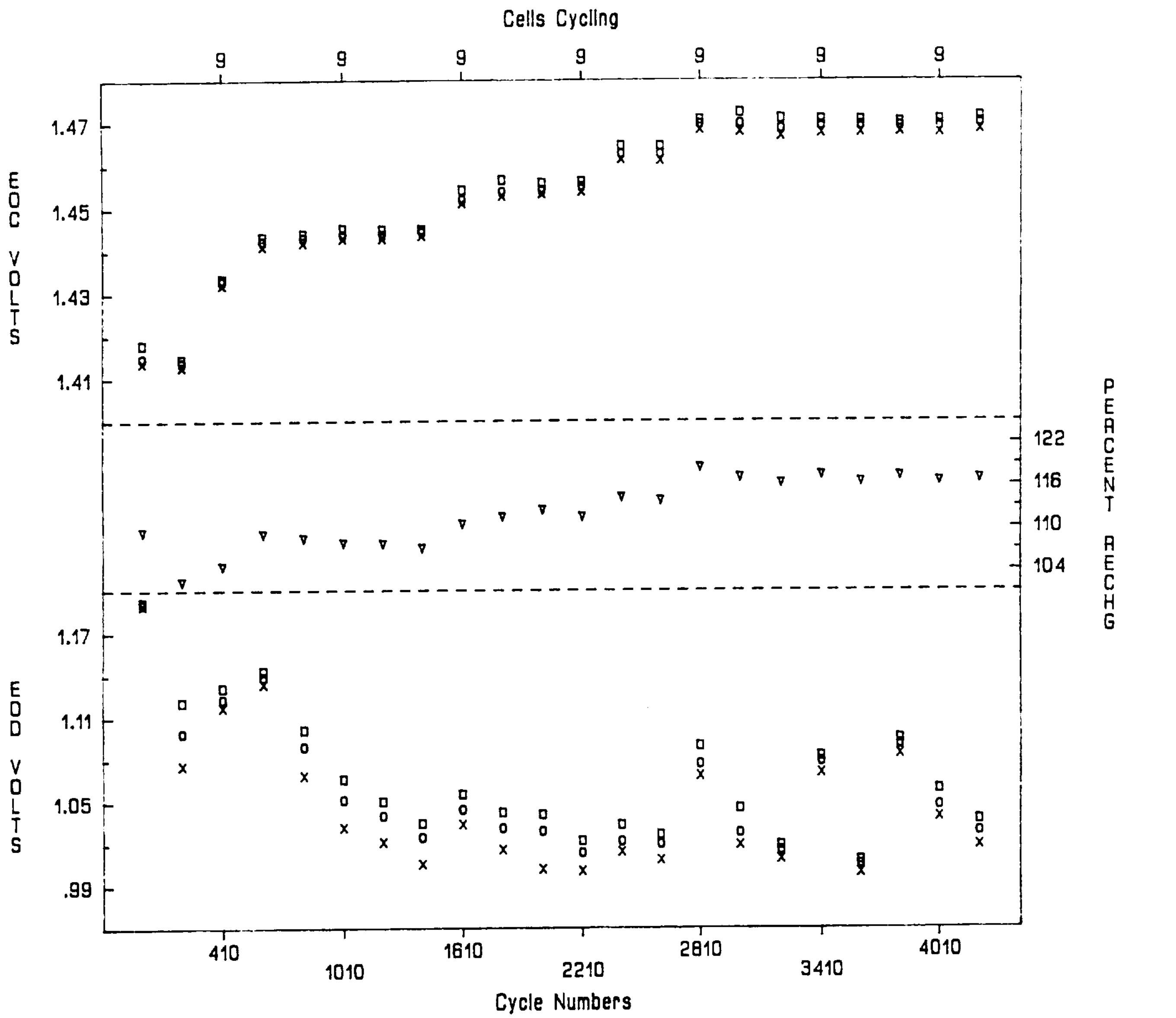
GPS STRESS TEST
PACK : 6335A

TYPE	35 A/H NI-CD , GATES
TEMPERATURE	20 DEGREES CENTIGRADE
ORBIT	100 MINUTES
DISCHARGE	25 AMPS FOR 34 MINUTES, 40%DOD
CHARGE	17.5 AMPS WITH V/T TAPER AT V/T 8 (1.474 V/C)

TRENDPLOT

Pack: 6335A   Manf: GPS   35.0 AH
Orbit: LEO   Temp (C): 20   DOD(%): 40.0
Discharge(Amp/Hrs): 25.0/0.56   Charge(Amp/Hrs): 17.5/1.12

TEST DATA AS OF JUNE 30, 1992



1. CYCLE #8, VT INCREASED TO VT5 (1.414 V/C) DUE TO LOW EOD.
2. CYCLE #223, VT INCREASED TO VT6 (1.434 V/C) DUE TO LOW % RECHG.
3. CYCLE #607, VT INCREASED TO VT6.5 (1.444 V/C).
4. CYCLE #1424, VT INCREASED TO VT7 (1.454 V/C) PER AEROSPACE INSTRUCTIONS
5. CYCLE #2235, VT INCREASED TO VT7.5 (1.464 V/C) PER AEROSPACE INSTRUCTIONS.
6. CYCLE #2627, VT INCREASED TO VT8 (1.474 V/C) DUE TO LOW EOD.
7. A PERCENT OF RECHARGE INCREASE WAS NOTICED AFTER EXTENDED OPEN CIRCUIT TIMES DURING CHAMBER PROBLEMS.
8. CYCLE #3840, PACK HALTED BECAUSE ALL CELL CASES FOUND SWOLLEN DUE TO HIGH PERCENT OF RECHARGE (117%).
9. ON JUNE 30, 1992, PACK RETURNED TO AUTOMATIC CYCLING PER AEROSPACE INSTRUCTIONS.

GPS SIMULATED ORBIT TEST
PACK : 6335B

TYPE	**35 A/H NI-CD , GATES**
TEMPERATURE	**20 DEGREES CENTIGRADE**
ORBIT	**10 HOURS ,26 MINUTES**
DISCHARGE	**15.8 AMPS FOR 56 MINUTES, 42%DOD**
CHARGE	**3.5 AMPS WITH V/T TAPER AT V/T 6 (1.444 V/C)**

TRENDPLOT

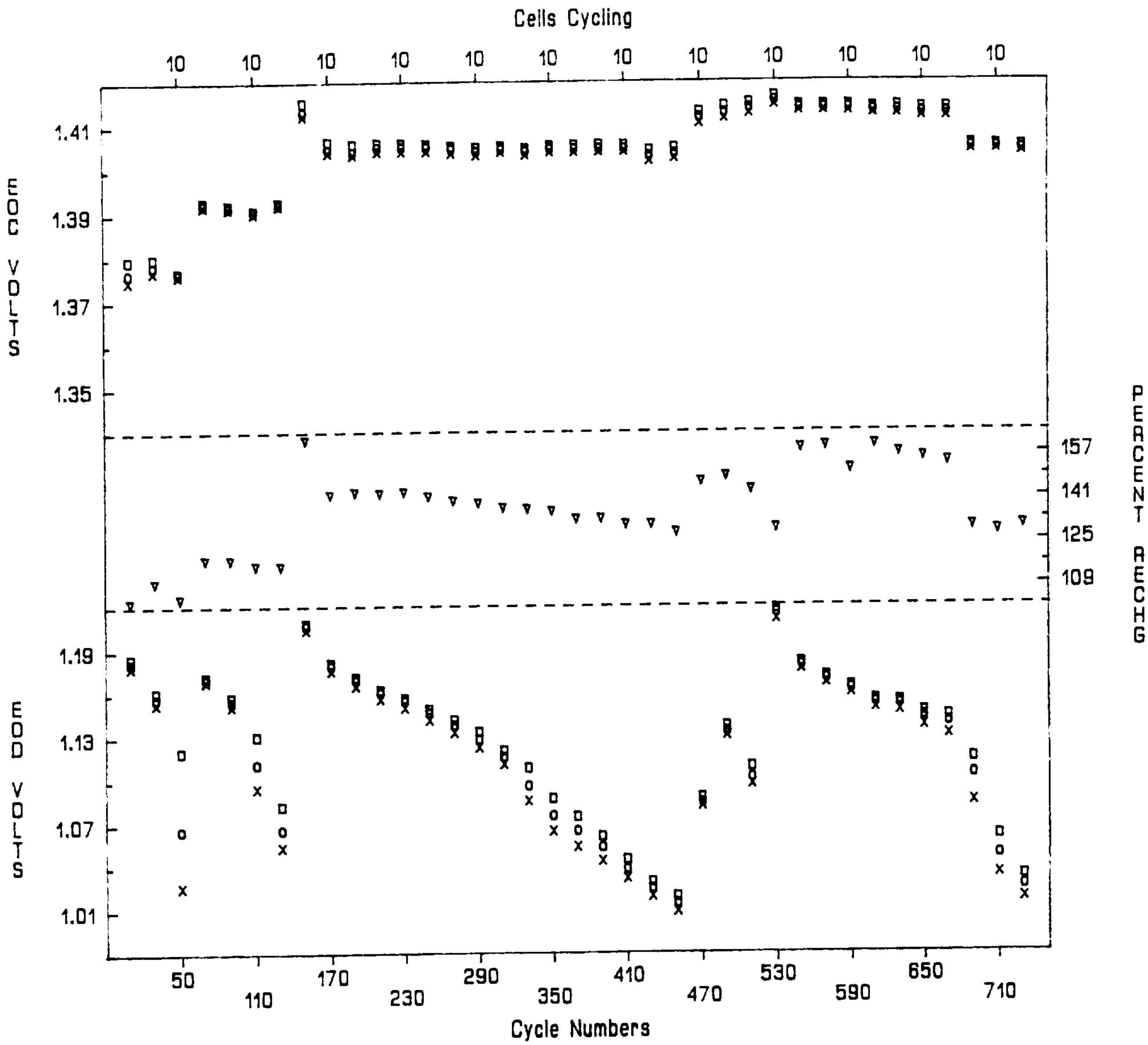
Pack: 6335B Manf: GPS 35.0 AH
Orbit: LEO Temp (C): 20 DOD(%): 41.4
Discharge(Amp/Hrs): 15.8/0.92 Charge(Amp/Hrs): 03.5/9.50

TEST DATA AS OF JUNE 30, 1992

Plot area #1 -- keys:
Left-side: □ -- High Cell, o -- Average, x -- Low Cell
Right-side: OFF

Plot area #2 -- keys:
Left-side: OFF
Right-side: ▿ -- PERCENT REC-

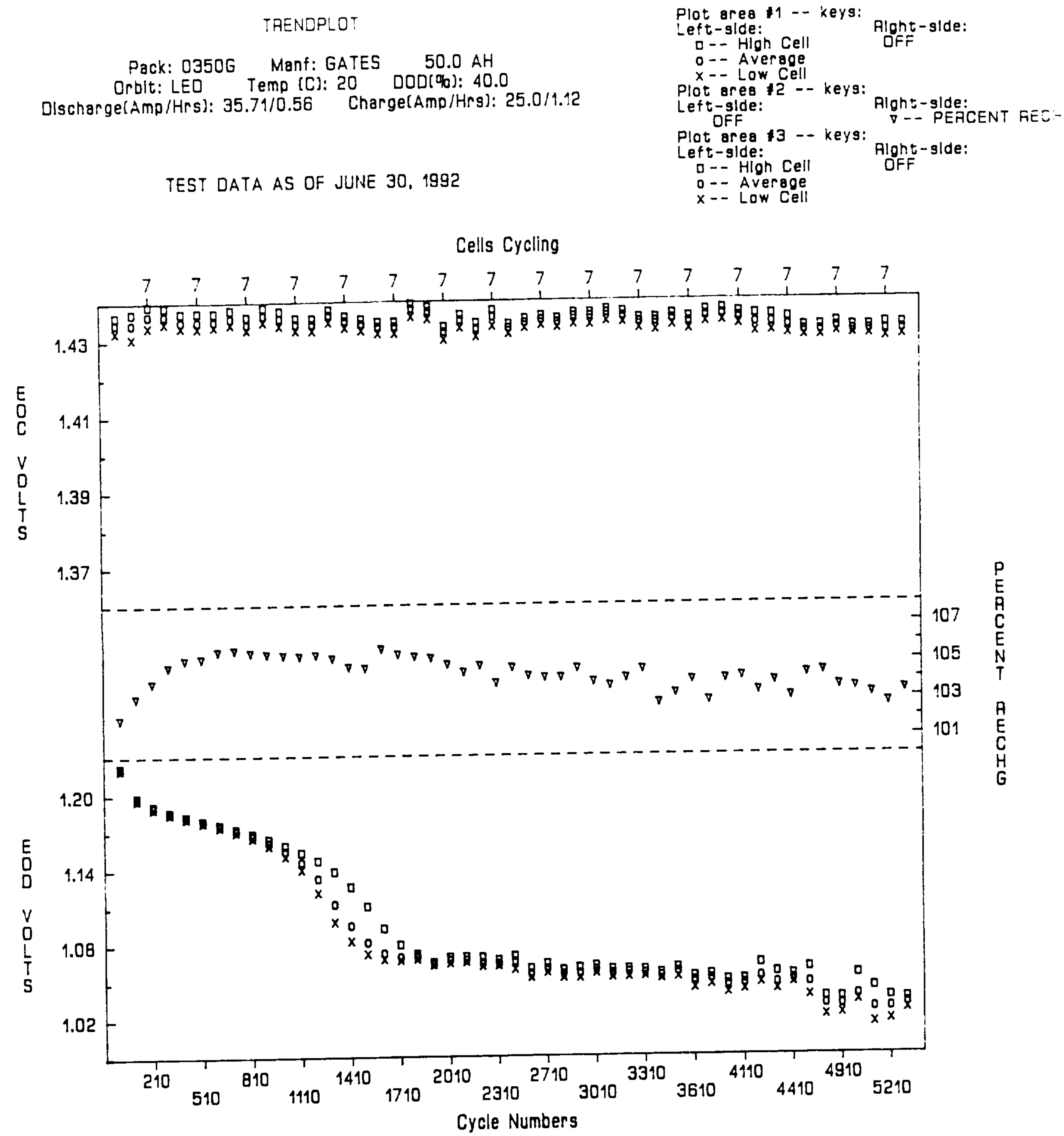
Plot area #3 -- keys:
Left-side: □ -- High Cell, o -- Average, x -- Low Cell
Right-side: OFF



1. CYCLE #52, INCREASED TO V/T 4.5(1.390 V/C) DUE TO LOW EOD VOLTS.
2. CYCLE #137, INCREASED TO V/T 5(1.414 V/C) DUE TO LOW EOD VOLTS.
3. CYCLE #160, DECREASED TO V/T 4.5(1.404 V/C) DUE TO HIGH % RECHARGE.
4. CYCLE #467, INCREASED TO V/T 5.0(1.414 V/C) DUE TO LOW EOD.
5. CYCLE #528, PACK WAS RECONDITIONED WITH A/HO 20.12.
6. CYCLE #694, DECREASED TO V/T 4.5(1.404 V/C) DUE TO HIGH EOC TEMP.

STRESS TEST
PACK : 0350G

TYPE	50 A/H NI-CD , GATES, WITH 2505ML SEPARATOR
TEMPERATURE	20 DEGREES CENTIGRADE
ORBIT	100 MINUTES
DISCHARGE	35.7 AMPS FOR 34 MINUTES, 40%DOD
CHARGE	25.0 AMPS WITH V/T TAPER AT V/T 6 (1.434 V/C)


TRENDPLOT
Pack: 0350G Manf: GATES 50.0 AH
Orbit: LEO Temp (C): 20 DOD(%): 40.0
Discharge(Amp/Hrs): 35.71/0.56 Charge(Amp/Hrs): 25.0/1.12
TEST DATA AS OF JUNE 30, 1992
Plot area #1 -- keys:
Left-side: □-- High Cell o-- Average x-- Low Cell
Right-side: OFF
Plot area #2 -- keys:
Left-side: OFF
Right-side: ▽-- PERCENT REC-
Plot area #3 -- keys:
Left-side: □-- High Cell o-- Average x-- Low Cell
Right-side: OFF
Cells Cycling
EOC VOLTS
1.43
1.41
1.39
1.37
PERCENT RECHG
107
105
103
101
EOD VOLTS
1.20
1.14
1.08
1.02
210
510
810
1110
1410
1710
2010
2310
2710
3010
3310
3610
4110
4410
4910
5210
Cycle Numbers

STRESS TEST
PACK : 0351G

TYPE	50 A/H NI-CD , GATES, WITH 2536 SEPARATOR
TEMPERATURE	20 DEGREES CENTIGRADE
ORBIT	100 MINUTES
DISCHARGE	35.7 AMPS FOR 34 MINUTES, 40%DOD
CHARGE	25.0 AMPS WITH V/T TAPER AT V/T 6 (1.434 V/C)

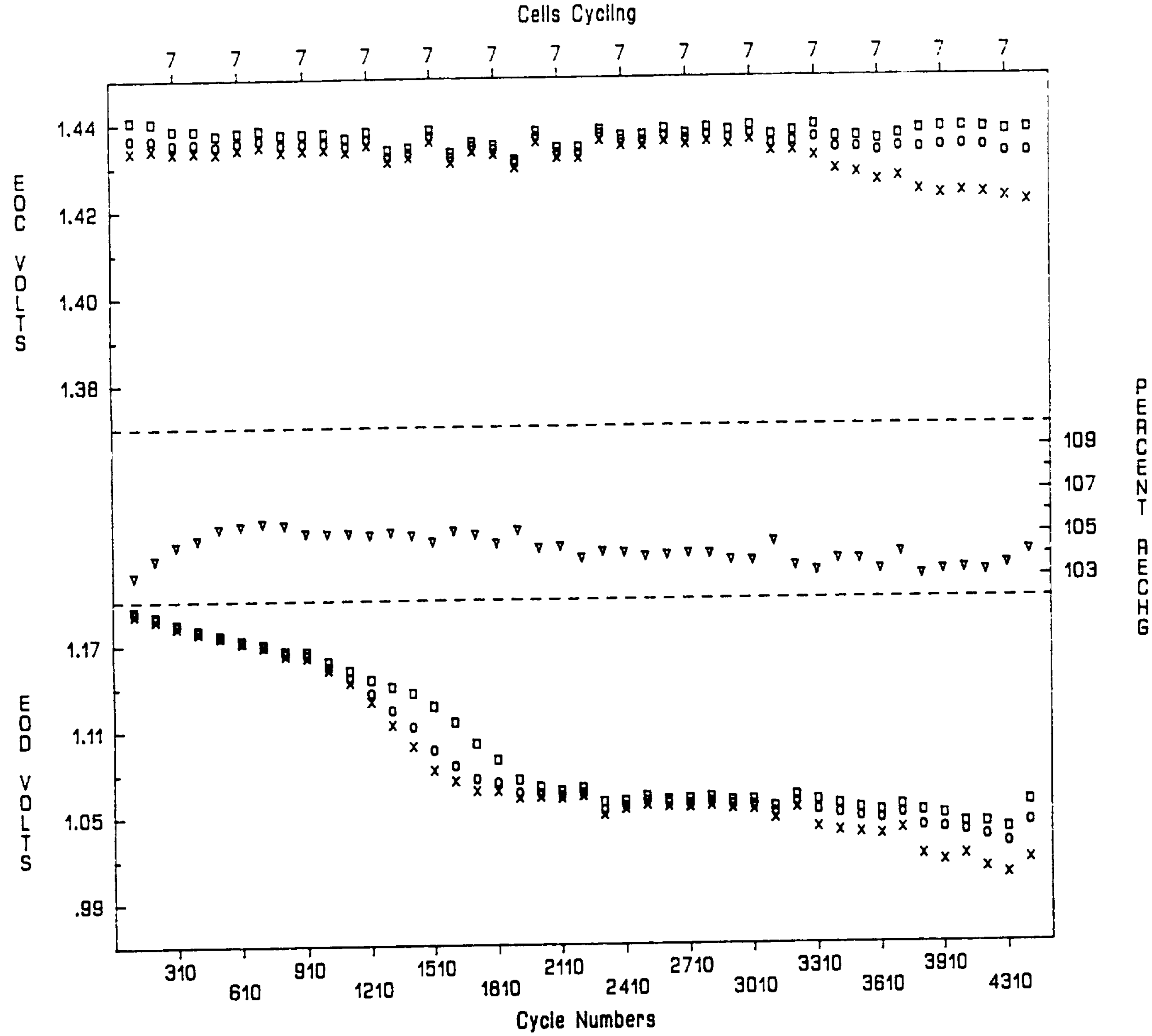
TRENDPLOT

Pack: 0351G Manf: GATES 50.0 AH
Orbit: LEO Temp (C): 20 DOD(%): 40.0
Discharge(Amp/Hrs): 35.71/0.56 Charge(Amp/Hrs): 25.0/1.12

PELLON 2536 SEPARATOR

TEST DATA AS OF JUNE 30, 1992

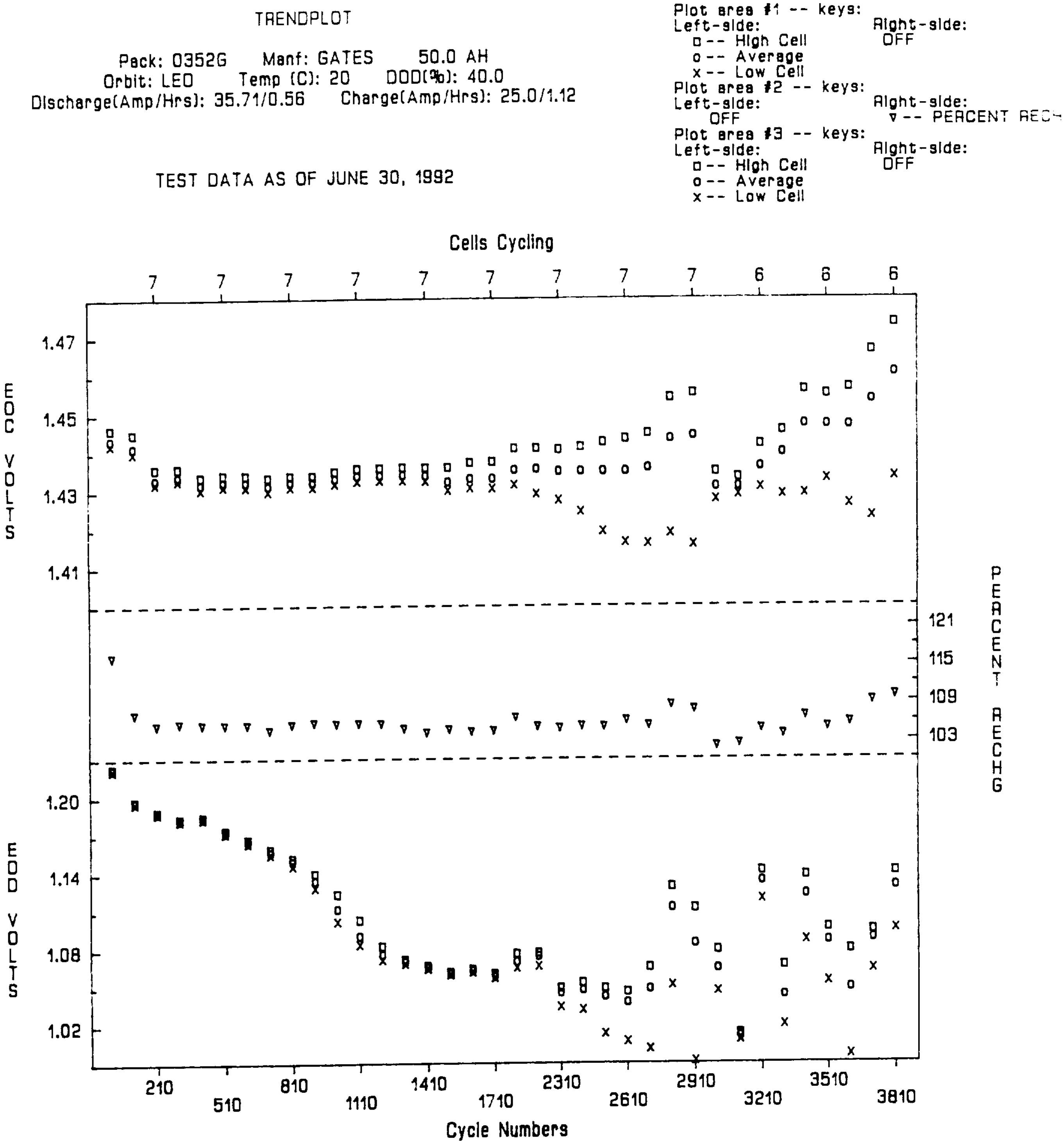
Plot area #1 -- keys:
Left-side: □ -- High Cell, o -- Average, x -- Low Cell; Right-side: OFF
Plot area #2 -- keys:
Left-side: OFF; Right-side: ▿ -- PERCENT RECH
Plot area #3 -- keys:
Left-side: □ -- High Cell, o -- Average, x -- Low Cell; Right-side: OFF



1. CYCLE #4424, DUE TO EQUIPMENT MALFUNCTION, PACK WAS DISCHARGED FOR 2.0 HOURS, CAUSING SWELLING OF CELLS. PACK WAS DISCONTINUED.

STRESS TEST
PACK : 0352G

TYPE	50 A/H NI-CD , GATES, WITH 2538 SEPARATOR
TEMPERATURE	20 DEGREES CENTIGRADE
ORBIT	100 MINUTES
DISCHARGE	35.7 AMPS FOR 34 MINUTES, 40%DOD
CHARGE	25.0 AMPS WITH V/T TAPER AT V/T 6 (1.434 V/C)



1. CYCLE #2789, INCREASED VT 6.0 (1.434 V/C) TO VT 6.5 (1.444 V/C) DUE TO LOW EOD.
2. CYCLE #3004, REMOVED CELL #2 DUE TO LOW END OF CHARGE AND END OF DISCHARGE. LOWERED VT 6.5 (1.444 V/C) TO VT 6.0 (1.434 V/C).
3. CYCLE #3190, INCREASED VT 6.0 (1.434 V/C) TO VT 6.5 (1.444 V/C) DUE TO LOW END OF DISCHARGE.
4. CYCLE #3389, INCREASED VT 6.5 (1.444 V/C) TO T 7 (1.454 V/C) DUE TO LOW END OF DISCHARGE VOLTAGES.
5. CYCLE #3701, INCREASED VT 7 (1.454 V/C) TO VT 7.5(1.464 V/C) PER AEROSPACE INSTRUCTIONS.
6. CYCLE #3838, EQUIPMENT MALFUNCTION CAUSED PACK TO BE DISCHARGE FOR 2.0 HOURS. THE PACK WAS DISCONTINUED DUE TO SWELLING OF CELLS.

RESULTS FOR GATES 50-Ah CELLS

LEO TEST: 40% DOD , 20 C

* 2538 SEPARATOR CELLS: CELL #2
- o SOFT SHORT CHARACTERISTICS (LOW EOCV & EODV) AFTER 2500 CYCLES
- o BELOW 1.0 V (FAILED) AFTER 3000 CYCLES

* 2536 SEPARATOR CELLS: CELLS #1 & #3
- o SOFT SHORT CHARACTERISTICS AFTER 3300 CYCLES

* 2505 SEPARATOR CELLS
- o AS LOW AS 1.02 V AFTER 5000 CYCLES

SUMMARY OF RESULTS OF GATES CELLS COMPARISON WITH PRE-1986 (GE/BBD)

* EARLY FAILURE OF PRESENT 2538 50-Ah CELL

* EARLIER SIGN OF SOFT SHORTS FOR PRESENT 50-Ah CELLS

* NOT ABLE TO GENERICALLY QUALIFY CELL WITH 2538 MATERIAL

STATUS OF PACKS AS OF 11/9/92

PACK ID	MFG	REGIME	SIZE (AH)	QTY	D.O.D (%)	TEMP (C)	START DATE	CYCLE NUMBER
0350S	SAFT	LEO	50	10	40	20	12/15/92	
0250S	SAFT	GEO	50	10	80	20	12/15/92	
6240S	SAFT	GEO	40	4	80	20	7/ 5/89	892
6224S	SAFT	GEO	24	5	80	20	7/ 5/89	977
6335A	GEP	LEO	35	9	40	20	7/25/91	5143
6335B	GEP	GPS (GEO)	35	10	41.4	20	7/25/91	859
0350G	GEP	LEO	50ST	7	40	20	7/17/91	6478
6351A	HUGHES	LEO	50	5	40	20	12/27/91	4253
6352A	HUGHES	LEO	50	5	25	5	12/27/91	3439
6321H	HUGHES	LEO	21	10	40	20	12/15/92	

ELECTRICAL CHARACTERIZATION OF THE MAGELLAN BATTERIES AFTER STORAGE

F. Deligiannis, D. Perrone,
S. Di Stefano and P. Timmerman

JPL

N93-20506

1992 NASA AEROSPACE BATTERY WORKSHOP
November 17-19, 1992
U. S. Space and Rocket Center
Huntsville, Al

JPL

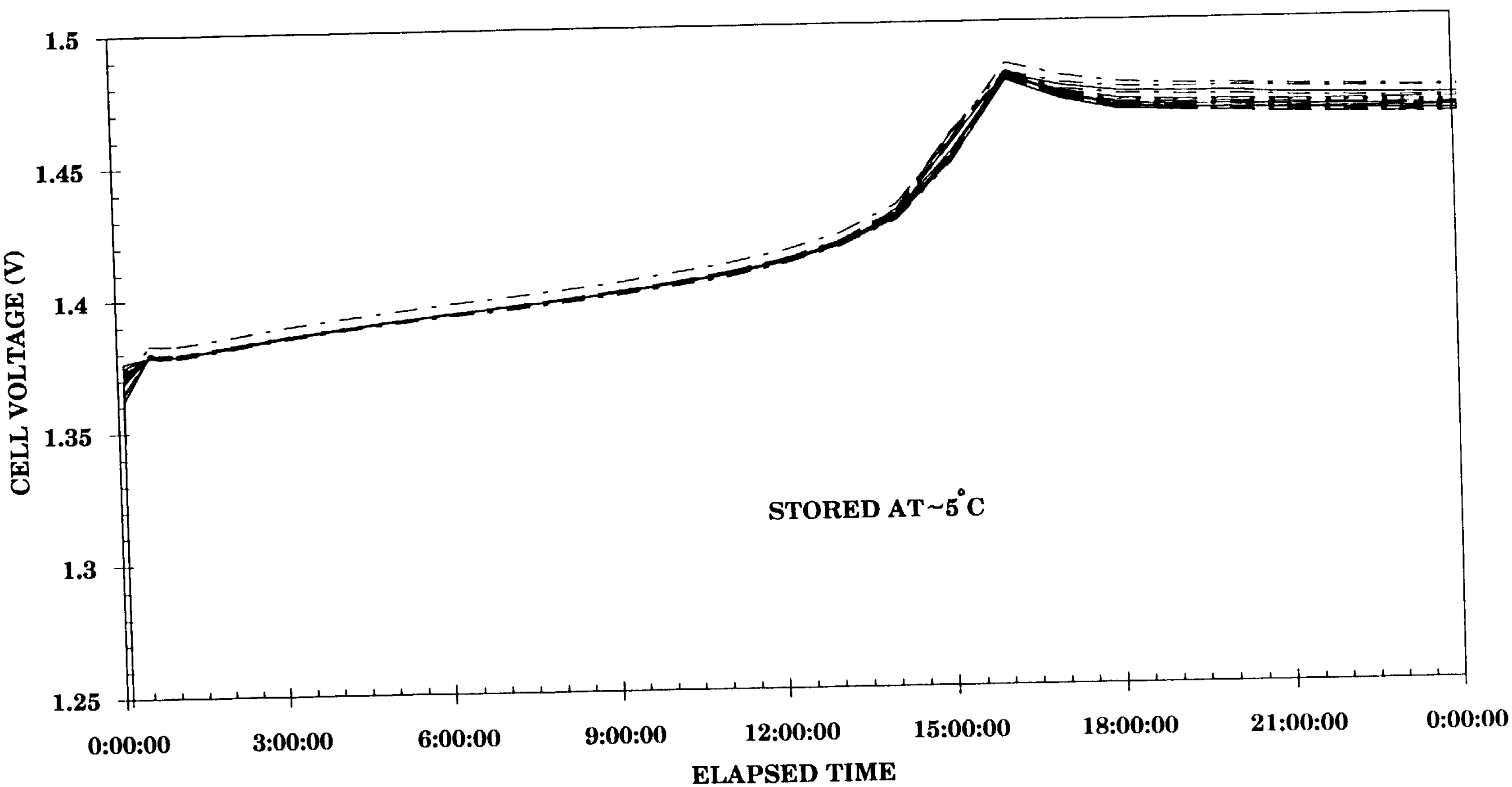
MAGELLAN / MSTI BATTERY SUMMARY

- PRIME CONTRACTOR - MARTIN MARIETTA

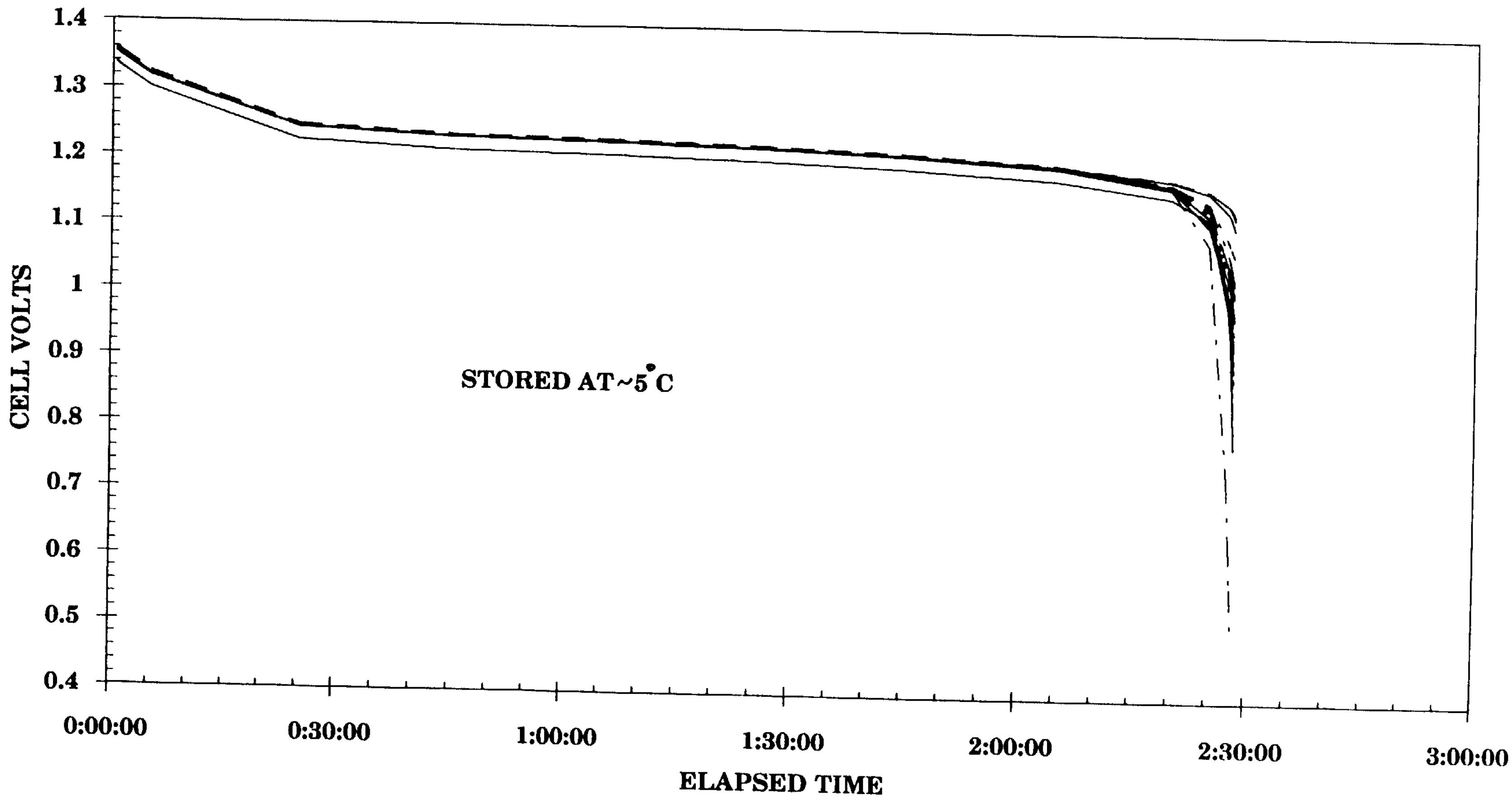
- BATTERY DESIGN
  - TWO 22 CELL / 26.5 Amp-Hr BATTERIES
  - CELL DESIGN
    - GATES AEROSPACE 42B030AB15
    - 11 POS / 12 NEG
    - PELLON 2536 SEPARATOR
    - PASSIVATED POS / TEFLONATED NEG

- BATTERY CYCLE REGIME
  - 15 MONTH CRUISE PERIOD
  - HIGHLY ELLIPTICAL VENUSIAN POLAR ORBIT (3.25 Hr)
  - 6.5 Amp 200 ms pulse @ 1.1 Hz DURING MAPPING CYCLE (37 min)

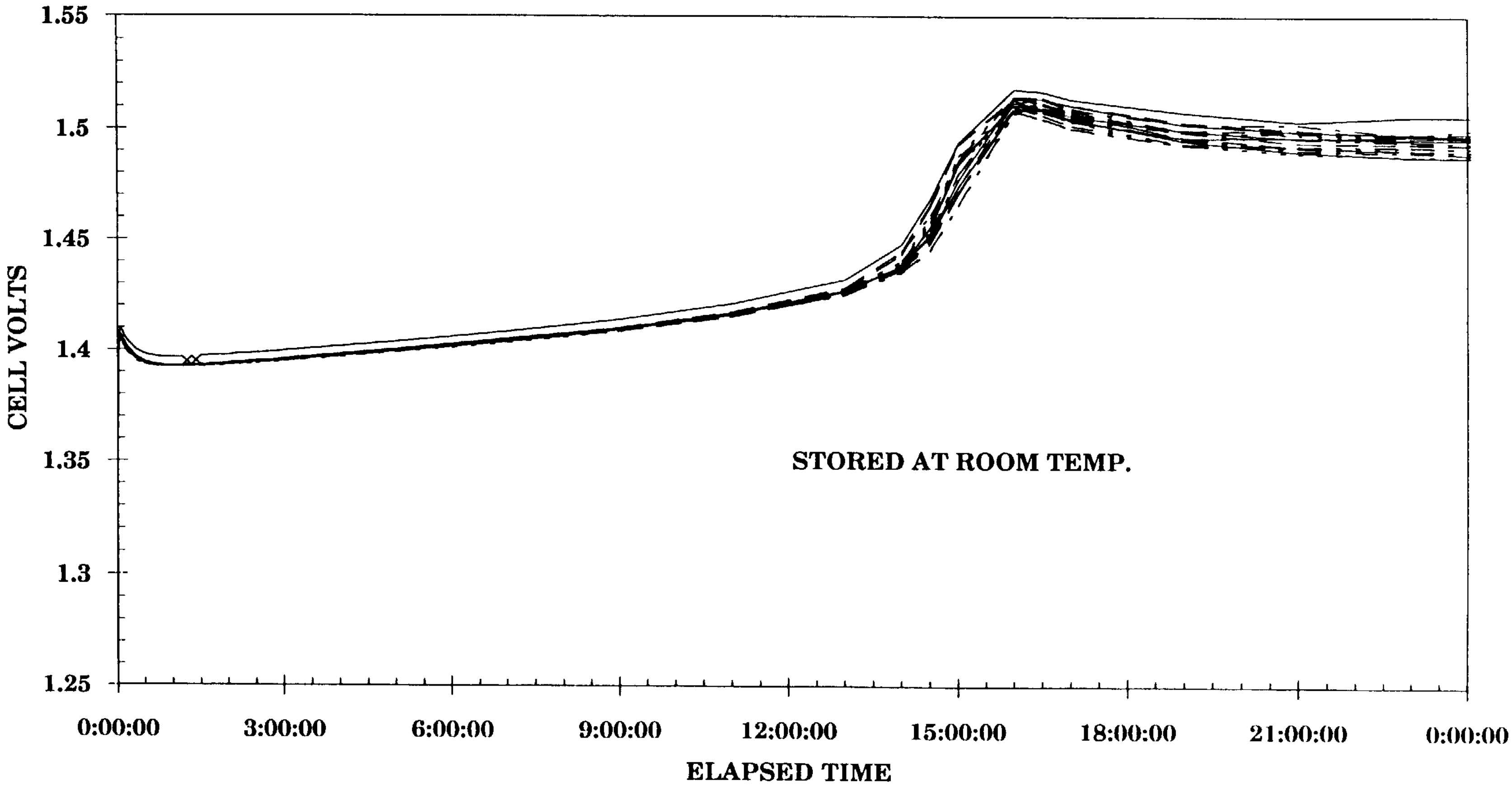
MSTI FLIGHT BATTERY
CYCLE #1 - C/10 CHARGE (2.65 A)



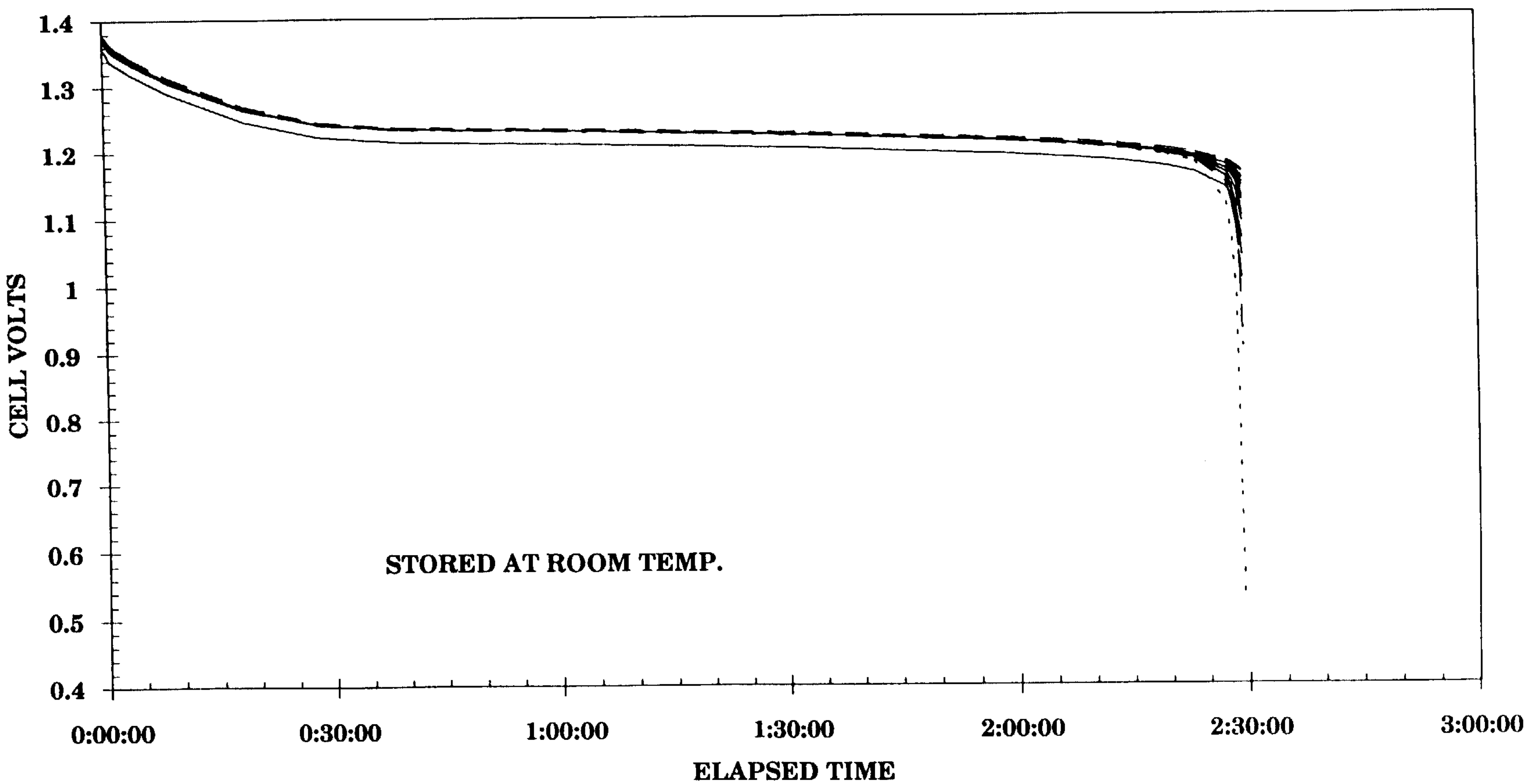
MSTI FLIGHT BATTERY
CYCLE #1 - C/2 DISCHARGE (13.25 A)



MSTI TEST BATTERY
CYCLE #1- C/10 CHARGE (2.65 A)



MSTI TEST BATTERY
CYCLE #1 - C/2 DISCHARGE (13.25 A)



FLIGHT BATTERY CAPACITY

	BEFORE STORAGE	AFTER STORAGE
C/20 CH. & C/2 DISCH.	33.87	30.91
C/10 CH. & C/2 DISCH.	31.79	32.02

STORED AT ~5°C

TEST BATTERY CAPACITY

	BEFORE STORAGE	AFTER STORAGE
C/20 CH. & C/2 DISCH.	33.06	32.57
C/10 CH. & C/2 DISCH.	32.77	32.91

STORED AT ROOM TEMP.

SUMMARY

- NO NOTICEABLE CAPACITY LOSS AFTER STORAGE PERIOD AT BOTH TEMPERATURES.
- TEST BATTERY EXHIBITED LARGER NON-UNIFORMITY OF CELL VOLTAGES DURING CONSTANT CURRENT CHARGE.

TOPEX / POSEIDON BATTERY PERFORMANCE

F. Deligiannis, S. Di Stefano, and G. Halpert

JPL

1992 NASA AEROSPACE BATTERY WORKSHOP
November 17-19, 1992
U. S. Space and Rocket Center
Huntsville, Al

OPERATIONAL RECOMMENDATIONS PRIOR TO LAUNCH

- LIMIT PEAK CHARGE CURRENT TO 20 A MAX.
  Offset the solar array.
- LIMIT OVERCHARGE BY CONTROLLING THE RECHARGE FRACTION (C/D) TO 1.03 $\pm$ 3% AT 0 C.
  Operate at lower V/T levels.
- MINIMIZE CHARGE CURRENTS DURING THE FULL SUN PERIODS.
  Operate at lower V/T levels.
- SWITCH TO THE LOWER CURRENT SENSOR FOR AMP-HOUR INTEGRATION TO IMPROVE C/D RATIO ACCURACY.

KEY BATTERY PARAMETER TRENDING

- **ΔV - DIFFERENTIAL HALF BATTERY VOLTAGE**
  This parameter historically trended to evaluate battery state of health. [V(cell 1-11) - V(cell 12-22)]=ΔV

- **PEAK CHARGE CURRENT**
  Charge current during peak power mode / initial part of day.

- **C/D - CHARGE/DISCHARGE RATIO**
  Monitors energy balance and overcharge.

- **EONV - END-OF-NIGHT-VOLTAGE**
  Indicator of battery wearout/efficiency.

- **NET OVERCHARGE**
  Monitors total excess energy input into batteries.

- **OTHER PARAMETERS INCLUDE: CURRENT, VOLTAGE, TEMPERATURE AND TIME.**

TOPEX/POSEIDON BATTERY EVENT HIGHLIGHTS

DOY	DATE	EVENT
223	8/10/92	LAUNCH - V/T 3 - DISCHARGE APPR. 15%
223	8/10/92	FULL SUN FOR NEXT 18 DAYS
225	8/12/92	COMMANDED V/T 2 AFTER REACHING 100% SOC
240	8/27/92	COMMANDED V/T 3
241	8/28/92	OFF-POINTED SOLAR ARRAY TO 55 DEGREES
242	8/29/92	FIRST OCCULTATION
247	9/3/92	ADJUSTED SOLAR ARRAY TO 57.5 DEGREES
248	9/4/92	COMMANDED V/T 4
275	10/1/92	COMMANDED V/T 3
281	10/7/92	FINAL OCCULTATION PRIOR TO 20 DAYS FULL SUN
282	10/8/92	COMMANDED V/T 2 FOR THE DURATION OF FULL SUN

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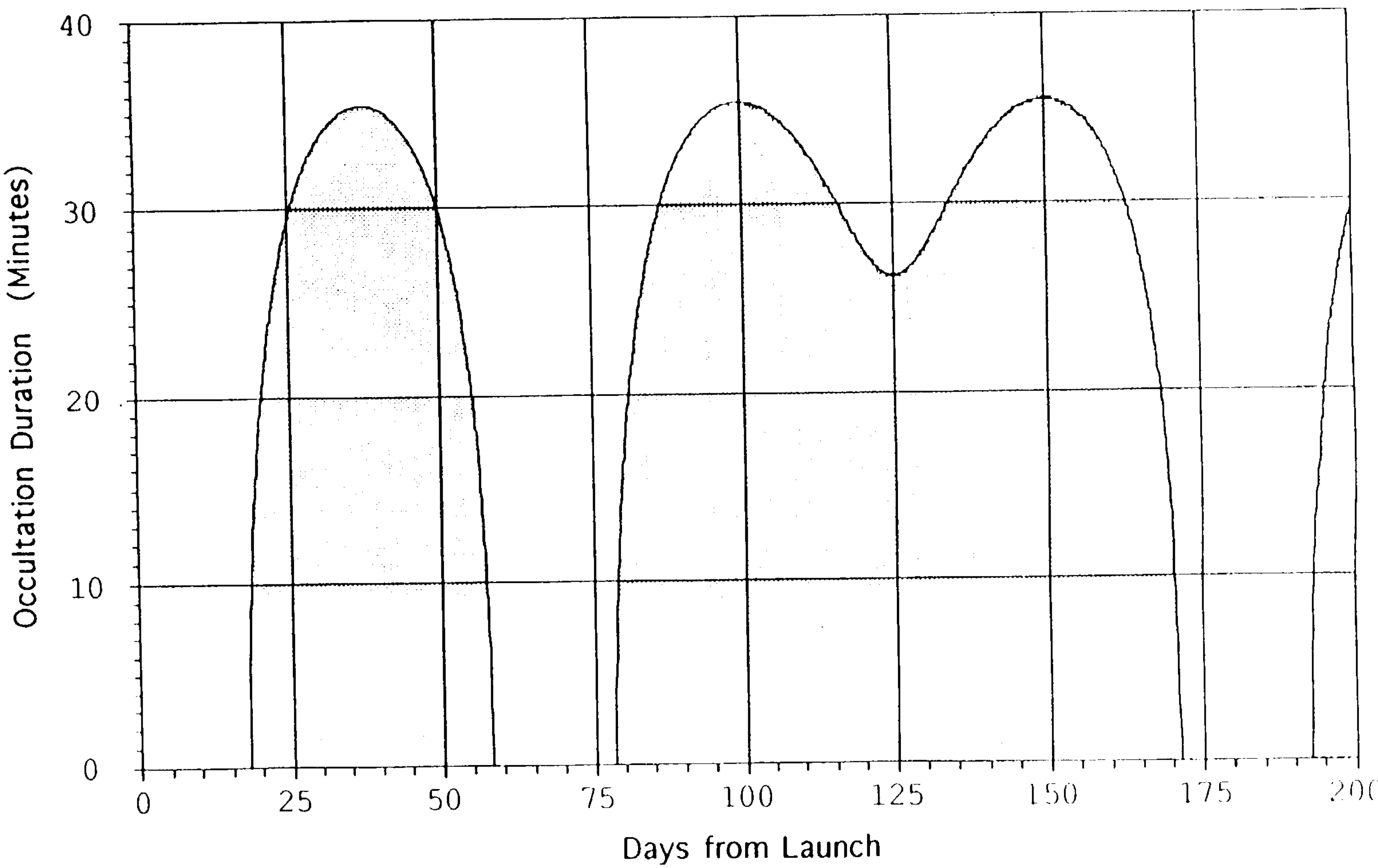
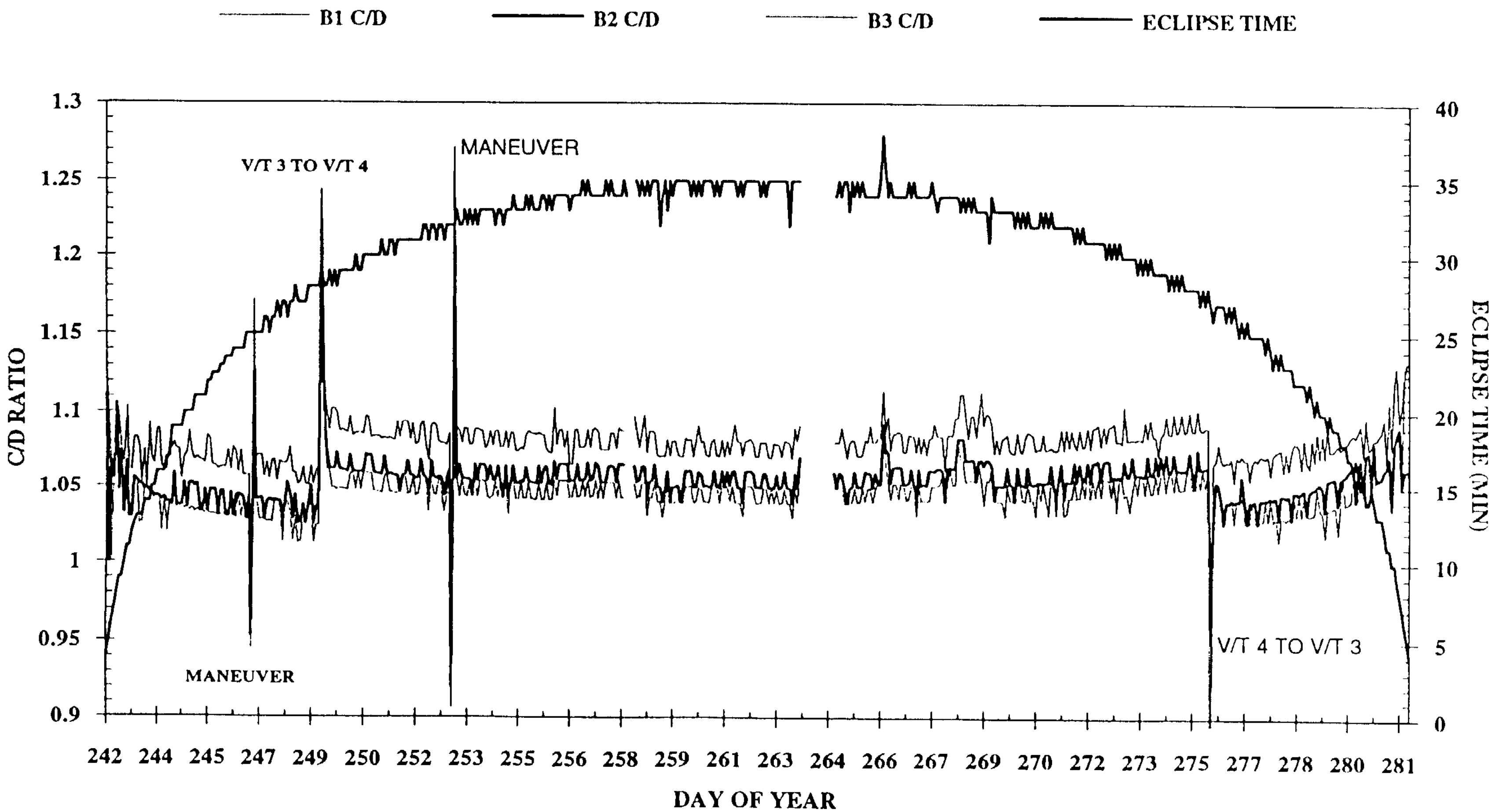
TOPEX/POSEIDON PROJECT
PRESENTATION TO DR. FISK

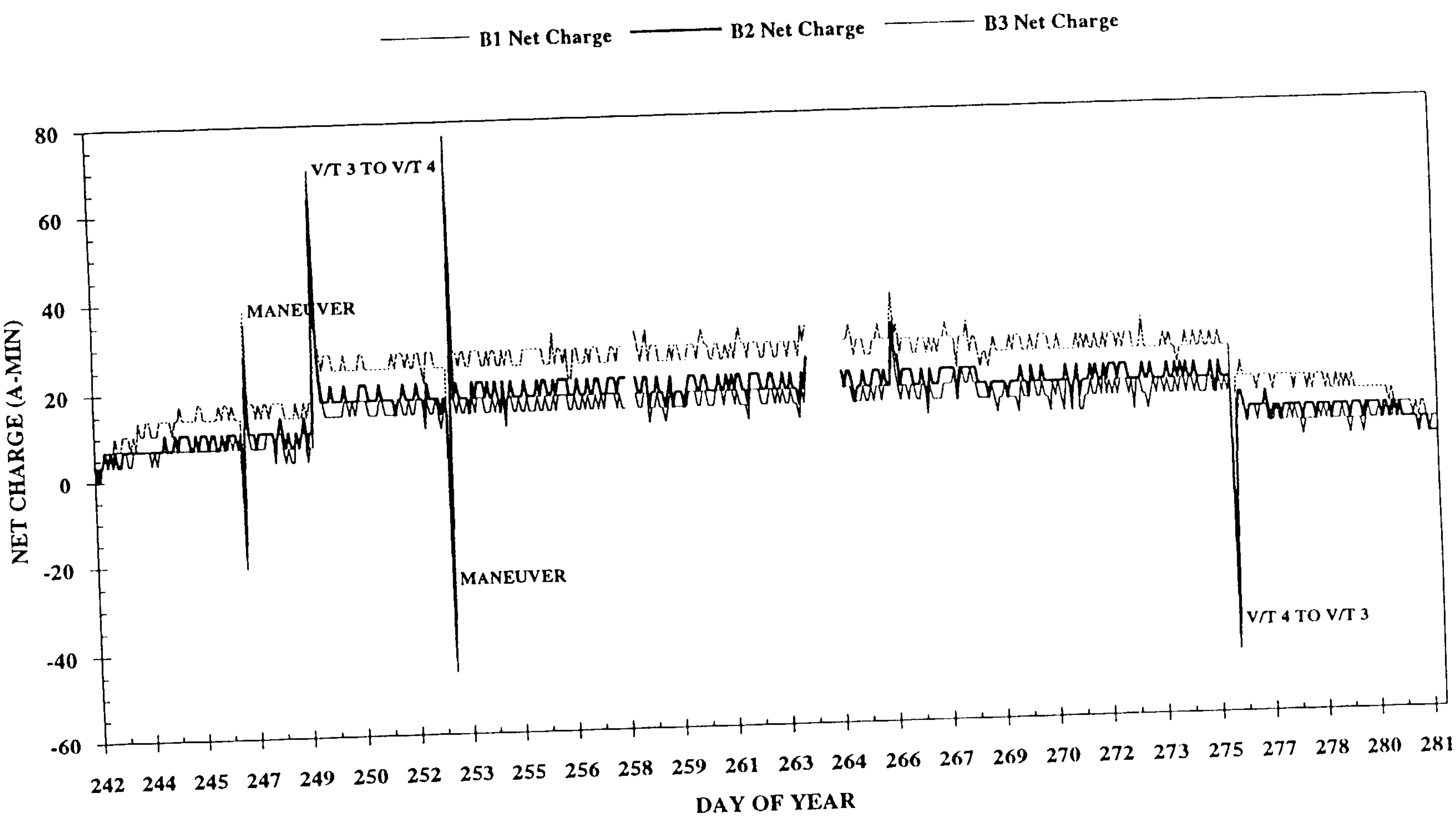
BATTERY MANAGEMENT PLAN
OCCULTATIONS – FIRST 200 DAYS



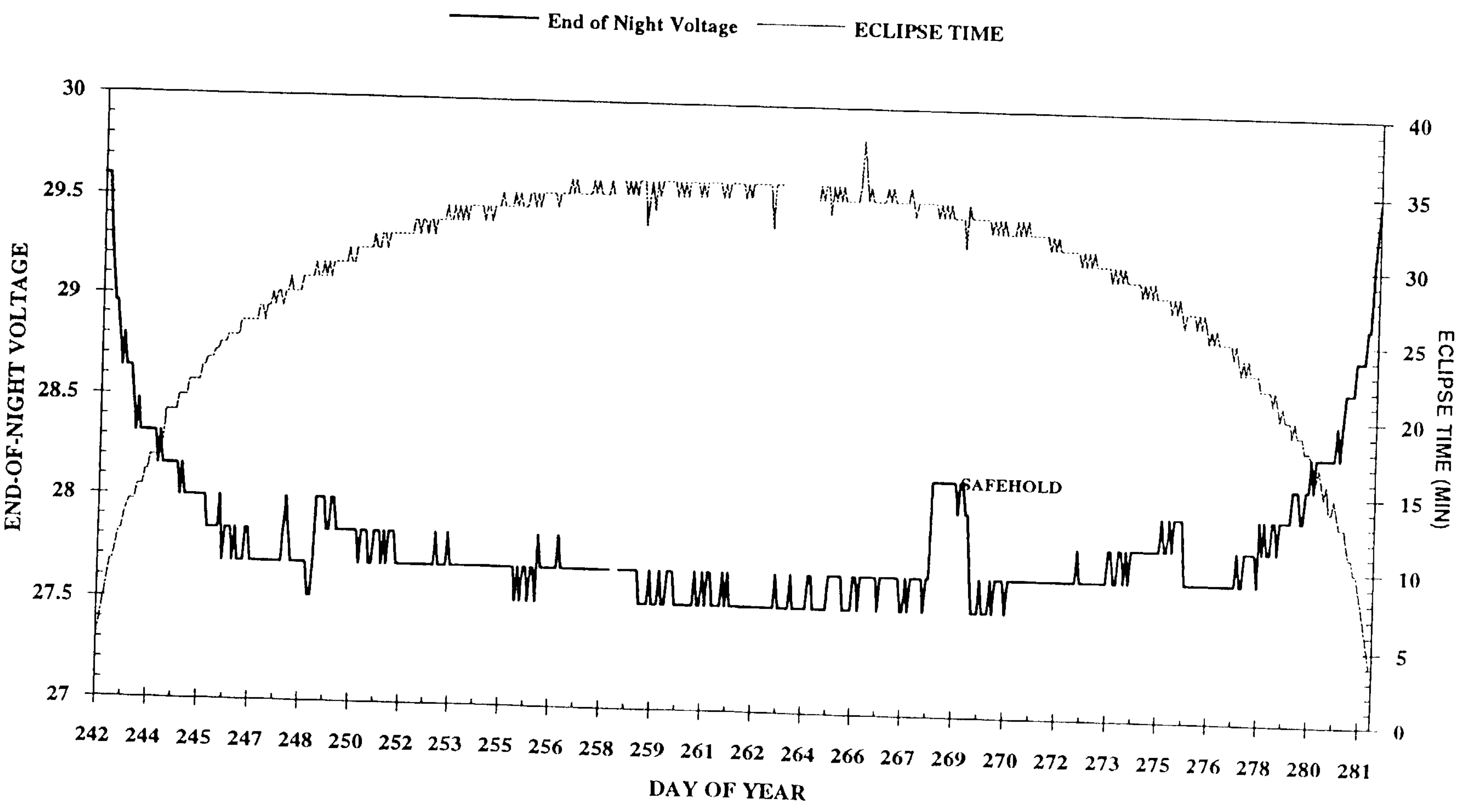
TOPEX/POSEIDON
BATTERY CHARGE/DISCHARGE RATIO



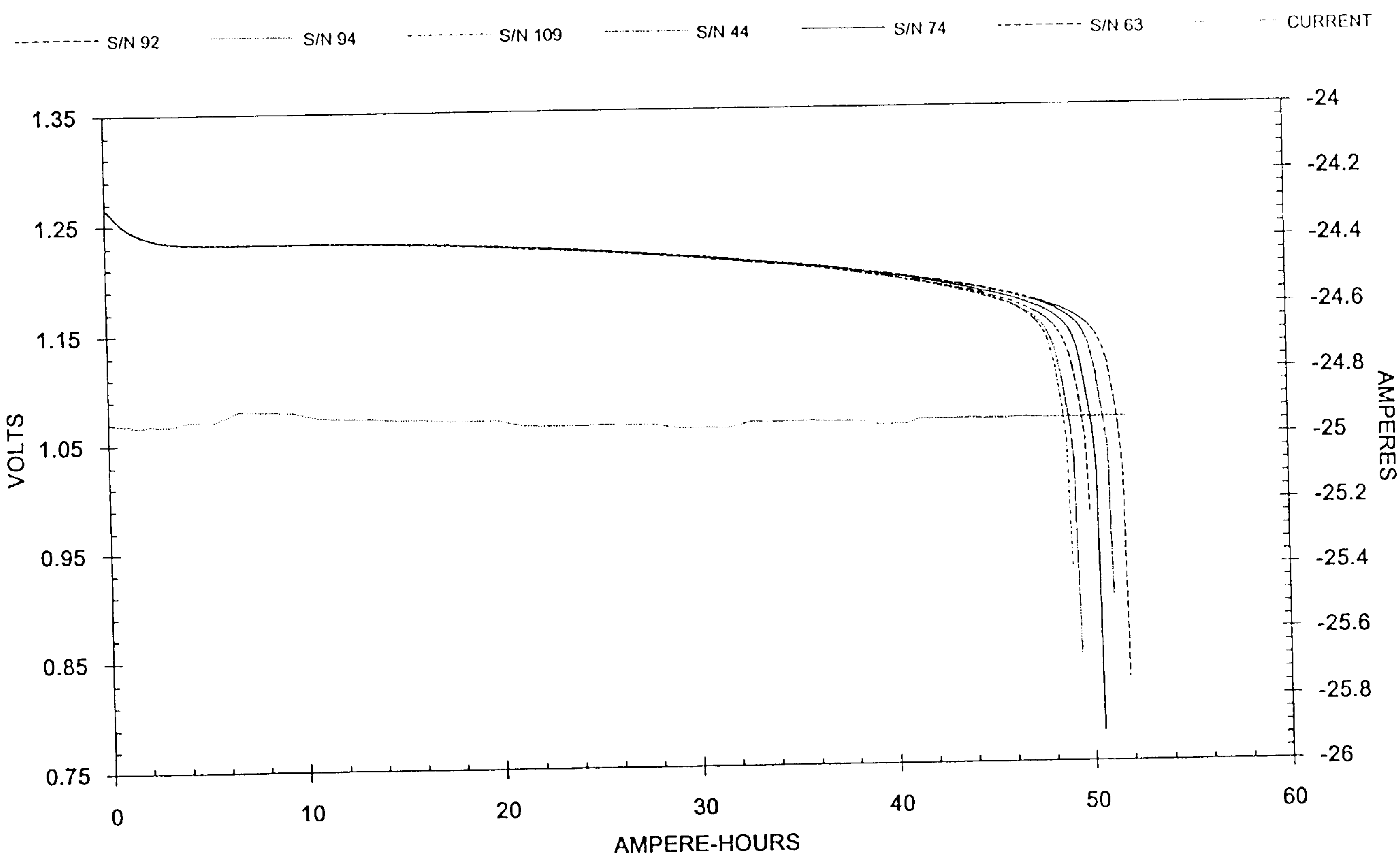
TOPEX/POSEIDON BATTERY NET CHARGE



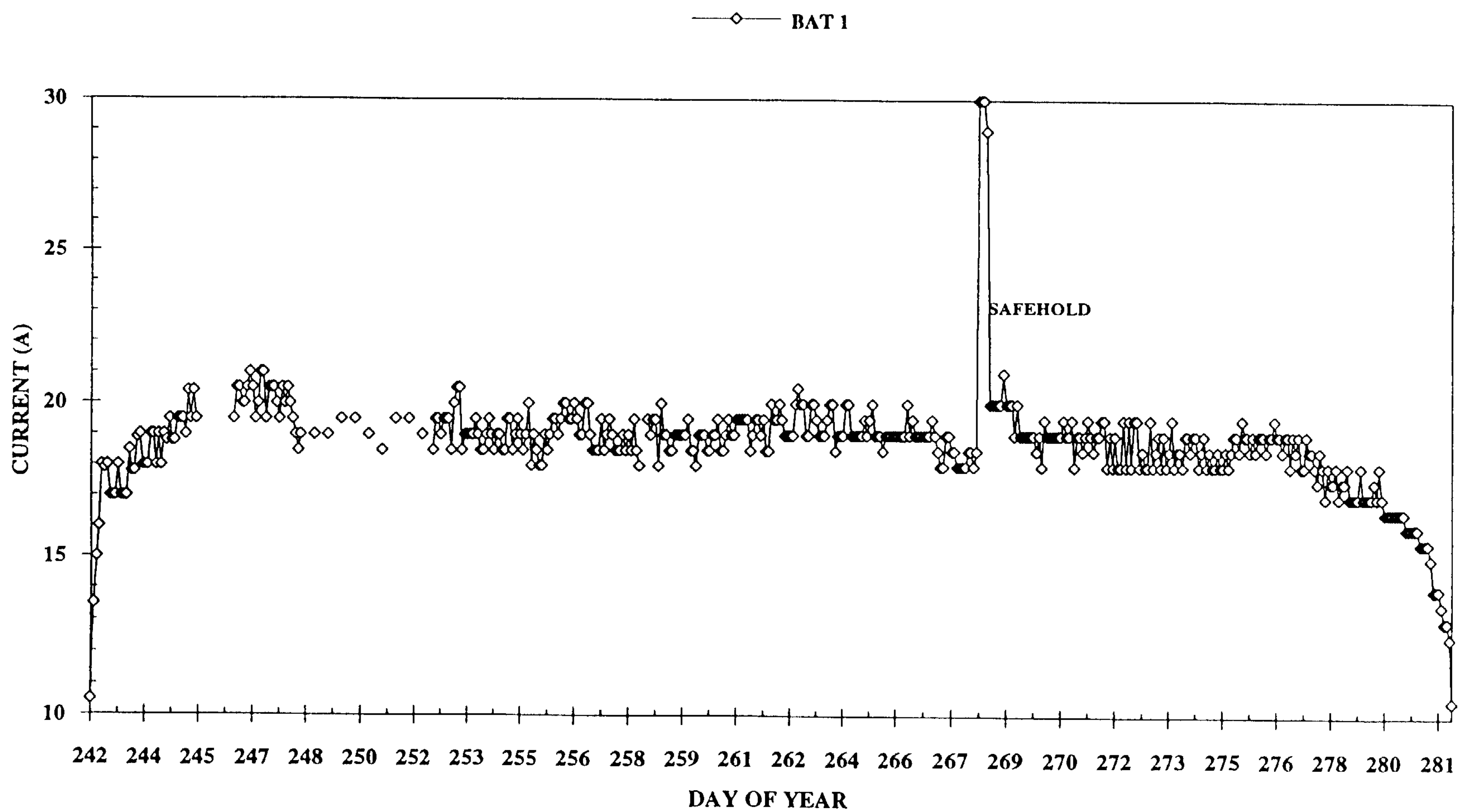
TOPEX/POSEIDON
BATTERY END-OF-NIGHT VOLTAGE



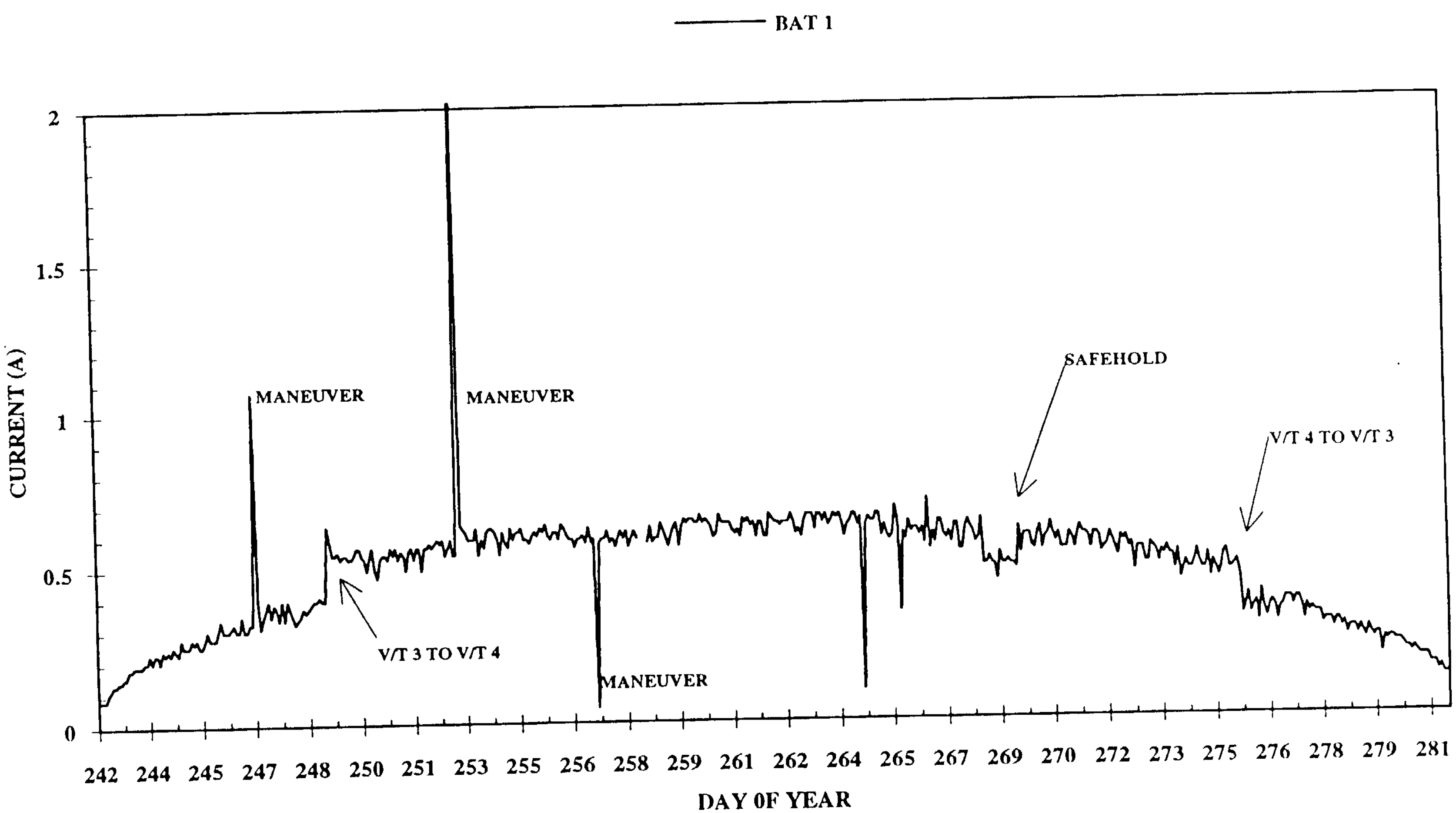
INITIAL EVALUATION "CHARGE RETENTION TEST" C/2 DISCHARGE #4



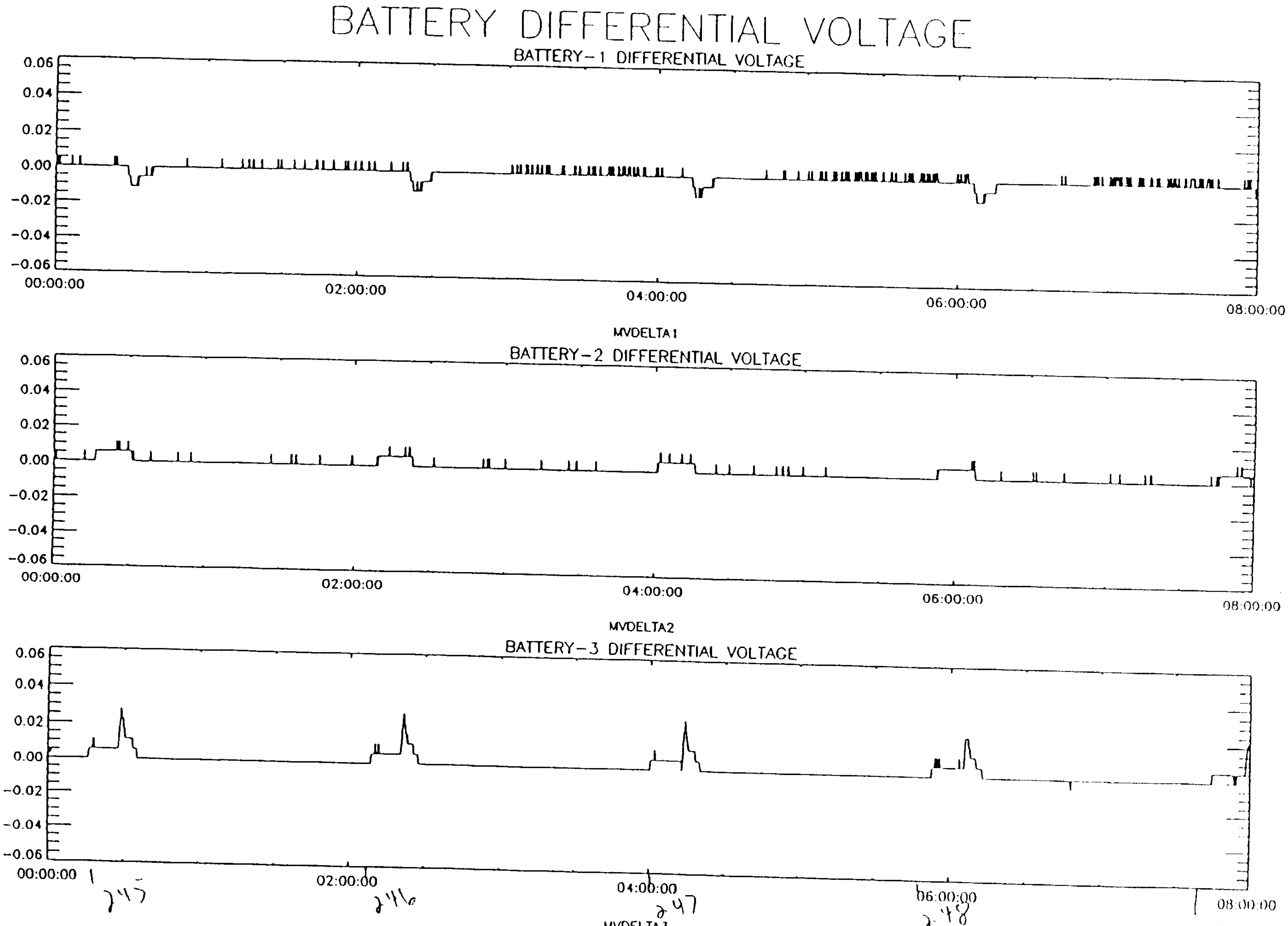
TOPEX/POSEIDON
BATTERY PEAK CHARGE CURRENT



TOPEX/POSEIDON
BATTERY END-OF-DAY (TAPER) CURRENT



C-5



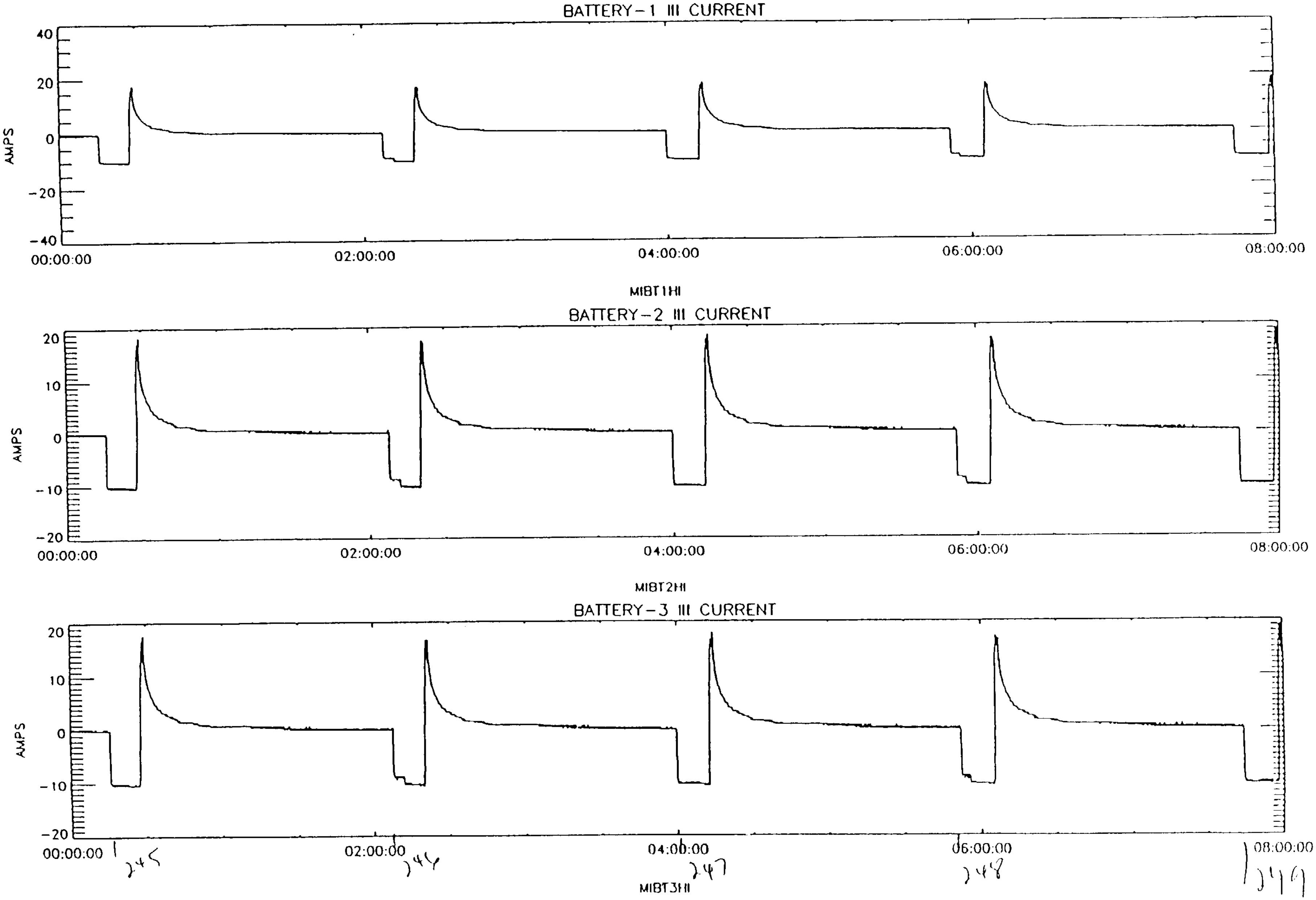
Source: SPA$DISK:[OPS.PWR.STR]TCC_PWR1_1992242T080000.BIN;1 Data: LIVE

PV-WAVE Def File: PLOT_MVDELTA.PV:

Data Time: 1992-243

Plot Time: Sun Au

HI CURRENT STATUS



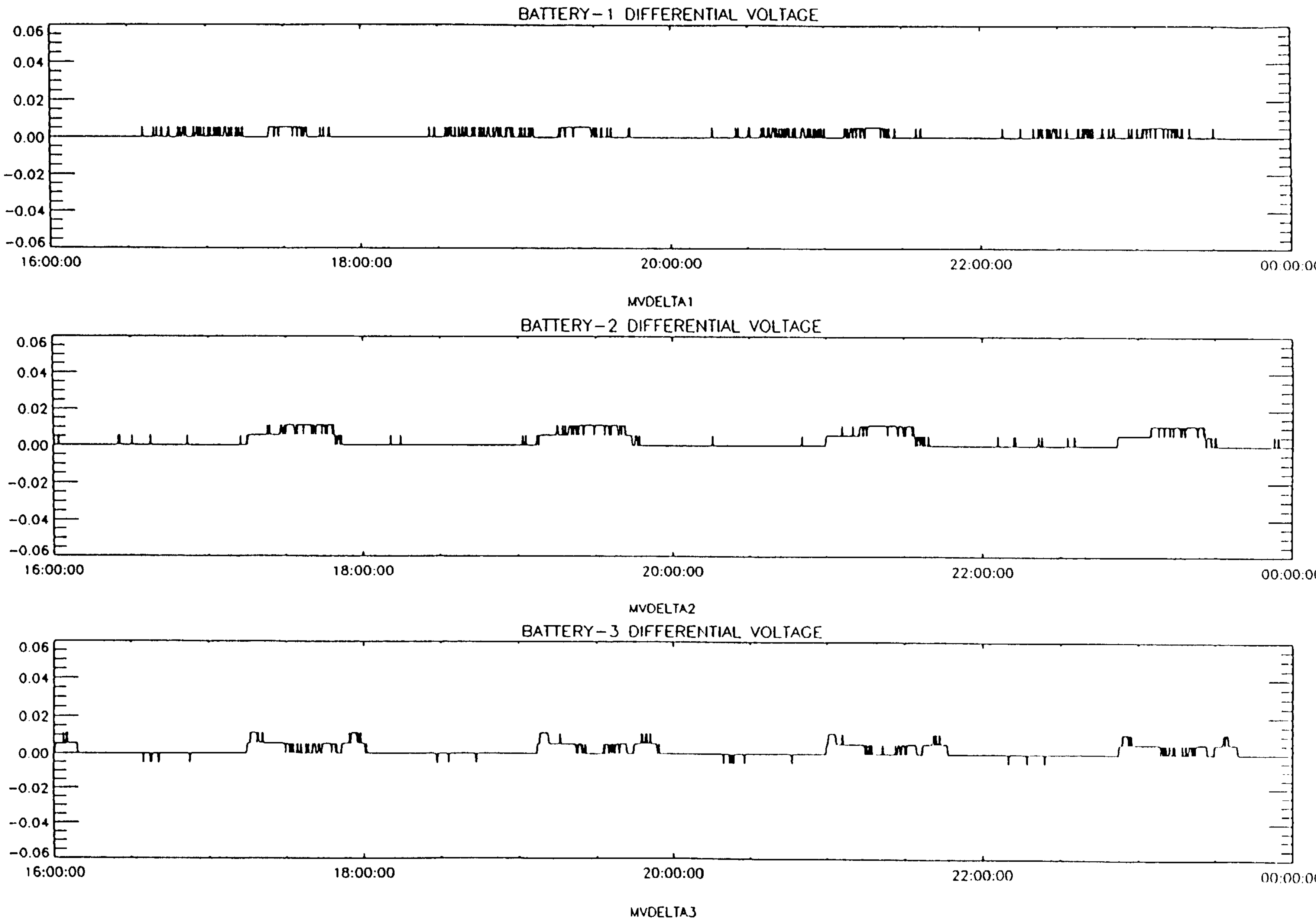
Source: SPA$DISK:[OPS.PWR.STR]TCC_PWR1_1992242T080000.BIN;1 Data: LIVE

Data Time: 1992-243

PV-WAVE Def File: PLOT_MIBT.PV:

Plot Time: Sun Aug 30 14:51:07 1992

BATTERY DIFFERENTIAL VOLTAGE



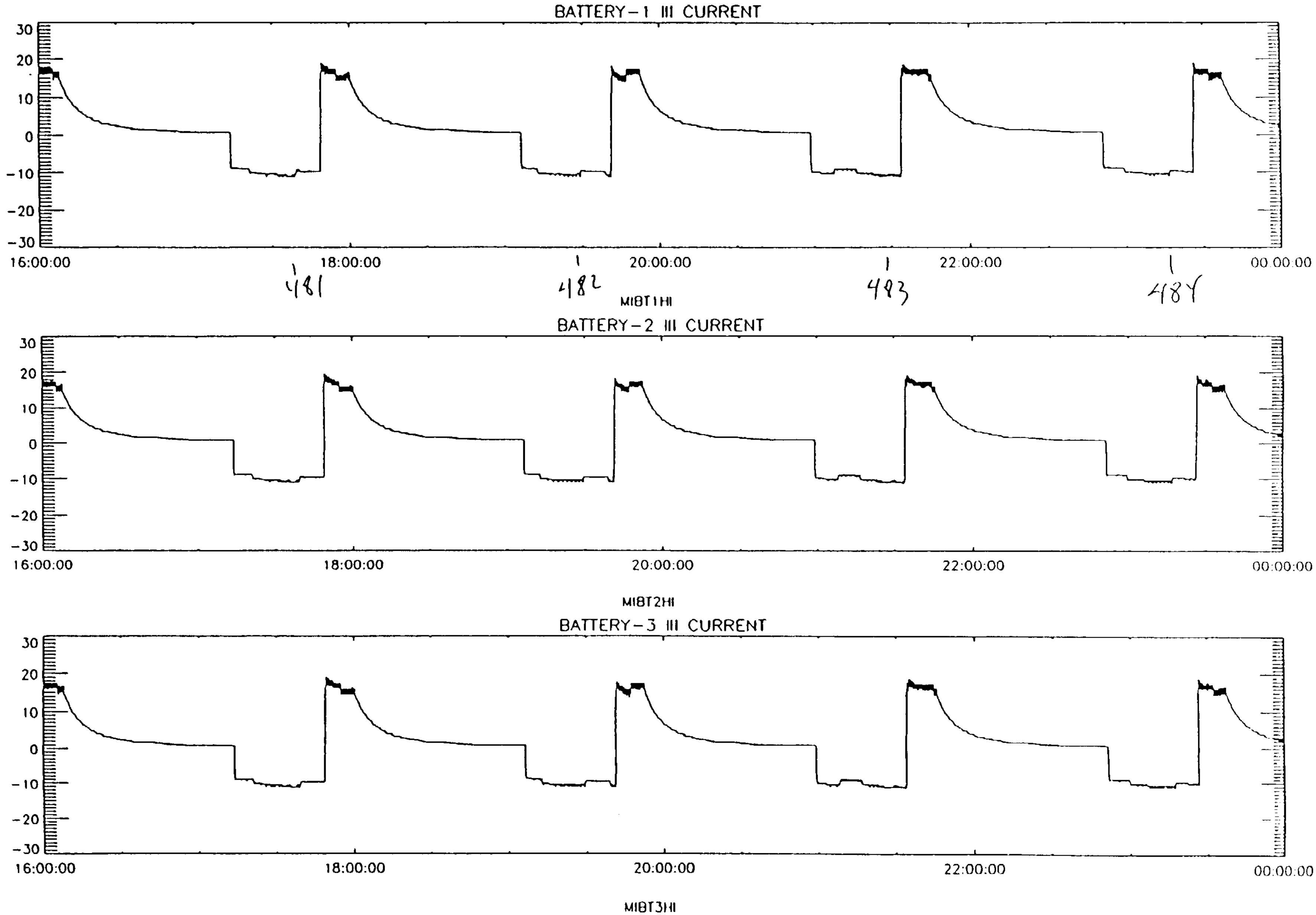
Source: SPA$DISK:[OPS.PWR.STR]TCC_PWR1_1992260T080000.BIN;1 Data: LIVE

Data Time: 1992-260

PV-WAVE Def File: PLOT_MVDELTA.PV:

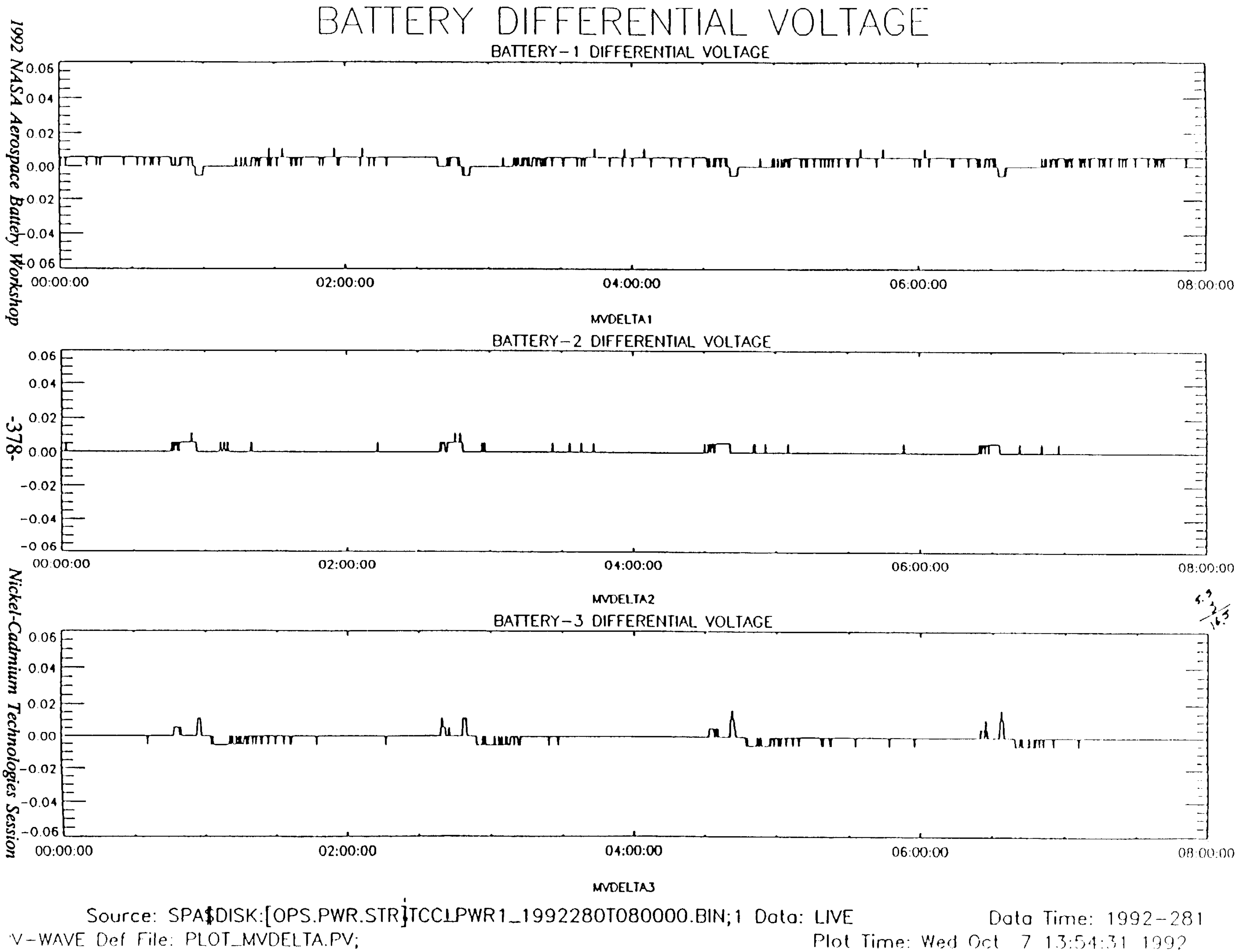
Plot Time: Thu Sep 17 12:28:34 1992

HI CURRENT STATUS



Source: SPA$DISK:[OPS.PWR.STR]TCC_PWR1_1992260T080000.BIN;1 Data: LIVE   Data Time: 1992-260

'V-WAVE Def File: PLOT_MIBT.PV: Plot Time: Thu Sep 17 12:00:26 1992


BATTERY DIFFERENTIAL VOLTAGE
BATTERY-1 DIFFERENTIAL VOLTAGE
0.06
0.04
0.02
0.00
0.02
-0.04
-0.06
00:00:00
02:00:00
04:00:00
06:00:00
08:00:00
MVDELTA1
BATTERY-2 DIFFERENTIAL VOLTAGE
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
00:00:00
02:00:00
04:00:00
06:00:00
08:00:00
MVDELTA2
BATTERY-3 DIFFERENTIAL VOLTAGE
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
00:00:00
02:00:00
04:00:00
06:00:00
08:00:00
MVDELTA3
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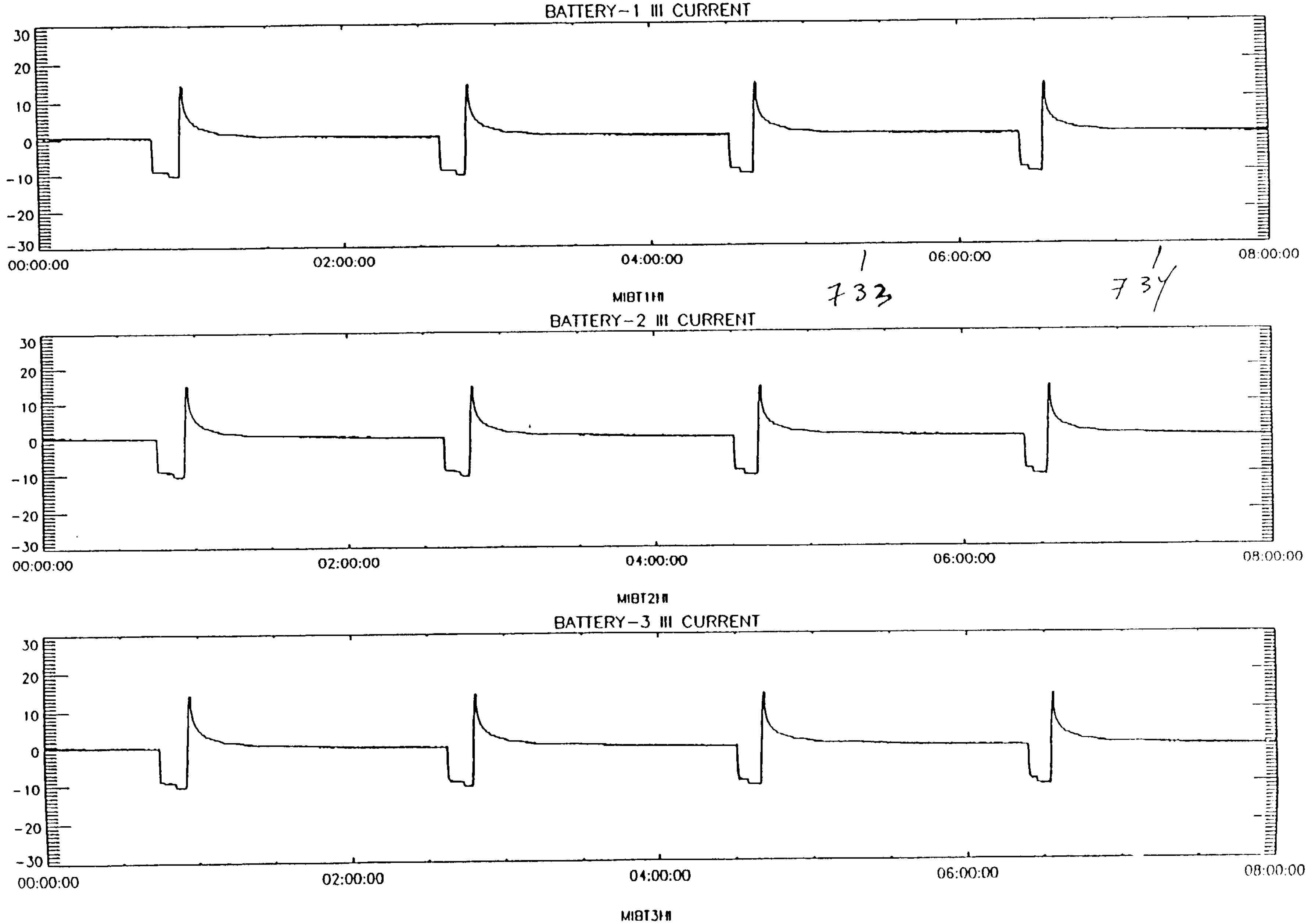
HI CURRENT STATUS



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OBSERVATIONS MADE DURING THE FIRST OCCULTATION PERIOD

- C/D RATIOS TEND TO BE HIGHER DURING THE INITIAL AND FINAL SEGMENT OF THE OCCULTATION PERIOD.
- NET OVERCHARGE PARAMETER USEFUL IN ASSESSING C/D's.
- SMALL PEAK POWER CUSPS DURING THE INITIAL AND FINAL SEGMENT OF THE OCCULTATION PERIOD. NO CUSPS DURING THE REMAINING PERIOD.
- SMALL DIFFERENTIAL VOLTAGES. (< 12 mV)
- PEAK CHARGE CURRENT WITHIN THE RECOMMENDED LIMITS.

SUMMARY

- BATTERIES ARE OPERATING WITHIN RECOMMENDED LIMITS.
- EXCELLENT BATTERY PERFORMANCE.

PRELIMINARY RESULTS: ROOT CAUSE INVESTIGATION OF ORBITAL ANOMALIES AND FAILURES IN NASA STANDARD 50 AMPERE-HOUR NICKEL-CADMIUM BATTERIES

PRESENTED: 1992 NASA AEROSPACE BATTERY WORKSHOP
17 - 19 NOVEMBER 1992

BY: MARK R. TOFT
BATTERY ENGINEER
SPACE ELECTRONICS
(314)-925-7692

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PROBLEM STATEMENT

TWO LOTS OF NASA STANDARD 50 A.H. NICD BATTERY CELLS, MANUFACTURED BY GATES AEROSPACE BATTERIES AND BUILT INTO BATTERIES BY McDONNELL DOUGLAS, HAVE EXPERIENCED SIGNIFICANT PERFORMANCE PROBLEMS:

- COMPTON GAMMA RAY OBSERVATORY - MODULAR POWER SUBSYSTEM (MPS) #1: 3 BATTERIES (GRO-1)*
- UPPER ATMOSPHERE RESEARCH SATELLITE: 3 BATTERIES (UARS)

BOTH ARE LEO SATELLITES CONTAINING BATTERIES ON A PARALLEL BUS CHARGED TO NASA STANDARD V/T CURVES USING A NASA STANDARD POWER REGULATOR.

* A SECOND MPS (GRO-2), WHICH IS ELECTRICALLY INDEPENDENT OF THE FIRST MPS (GRO-1), ALSO CONTAINS 3 BATTERIES THAT HAVE EXPERIENCED NO PERFORMANCE PROBLEMS TO DATE.

NOTE: DEVELOPMENT OF BATTERIES FOR THE GRO AND UARS MISSIONS WAS PERFORMED UNDER CONTRACTS NAS5-28066 AND NAS5-30227 WITH THE GODDARD SPACE FLIGHT CENTER, GREENBELT, MARYLAND.

ANOMALY DESCRIPTION

GRO-1 BATTERIES

- SPACECRAFT LAUNCHED 5 APRIL 1991.
- BATTERIES DEVELOPED HALF-BATTERY DIFFERENTIAL VOLTAGES EXCEEDING 100 mV APPROXIMATELY 7 MONTHS AFTER LAUNCH.

  NOTE: THE HALF-BATTERY DIFFERENTIAL MONITORS THE VOLTAGE DIFFERENCE BETWEEN THE "TOP" 11 CELLS IN THE 22-CELL SERIES STRING AND THE "BOTTOM" 11 CELLS.
- BATTERIES LATER DEVELOPED EVEN GREATER DIFFERENTIAL VOLTAGES, LOAD-SHARING IMBALANCE, AND TEMPERATURE DIVERGENCE.
- ONE BATTERY APPARENTLY DEVELOPED A HARD SHORT AFTER ONLY 15 MONTHS ON ORBIT, AND HAD TO BE REMOVED FROM THE CHARGE BUS.
- THE REMAINING TWO BATTERIES ARE BEING EXTENSIVELY "MANAGED" TO MINIMIZE OVERCHARGE

NOTE: THE GRO-2 BATTERIES, FROM A DIFFERENT CELL LOT, ON A SEPARATE CHARGE BUS, CONTINUE TO OPERATE SATISFACTORILY.

ANOMALY DESCRIPTION (continued)

UARS BATTERIES

- LAUNCHED 12 SEPTEMBER 1991.
- BEGAN DEVELOPING HALF-BATTERY DIFFERENTIAL VOLTAGES JUST 4 MONTHS AFTER LAUNCH, EVENTUALLY EXCEEDING 400 mV IN ONE BATTERY.
- SIGNIFICANT LOAD-SHARING IMBALANCES AND TEMPERATURE ANOMALIES HAVE ALSO BEEN OBSERVED.
- THESE BATTERIES ARE ALSO BEING EXTENSIVELY "MANAGED" TO MINIMIZE OVERCHARGE.

OTHER RELATED ANOMALIES

CELL PACKS ON LIFE-TEST AT NWSC

- PACK 6051H (GRO-1 FLIGHT LOT; LEO REGIME, 20°C, 40% DOD) BEGAN DEVELOPING VOLTAGE DIVERGENCE AT END OF CHARGE AND END OF DISCHARGE AFTER ~6600 CYCLES.

- PACK 6052A (UARS FLIGHT LOT; LEO REGIME, 20°C, 40% DOD) BEGAN DEVELOPING VOLTAGE DIVERGENCE DUE TO HIGH VOLTAGE AT END OF CHARGE AND END OF DISCHARGE AFTER ~1700 CYCLES. (NOTE: EXCEPT FOR ONE, THESE CELLS HAVE 2 - 4% LESS ELECTROLYTE THAN THE LOT AVERAGE.)

- PACK 6052B (UARS FLIGHT LOT; LEO REGIME, 15°C, 21.4% DOD) BEGAN DEVELOPING VOLTAGE DIVERGENCE DUE TO LOW VOLTAGE IN ONE CELL AT END OF CHARGE AFTER ~2000 CYCLES.

  THE TEST REGIME WAS CHANGED AFTER ~4300 CYCLES TO REFLECT THE TRUE MISSION CONDITIONS (0°C, HIGHER CHARGE RATE, LOWER V/T LEVEL, SAME DOD) . THE ORIGINAL DIVERGENT CELL WAS UNAFFECTED BY THE CHANGE, BUT A 2ND CELL DEVELOPED A SEVERELY DEGRADED CHARGE AND DISCHARGE VOLTAGE AFTER JUST <u>39</u> CYCLES

OTHER RELATED ANOMALIES (continued)

CELL PACKS ON LIFE-TEST AT NWSC (continued)

- PACK 0351G (UARS PLATE AND 2536 NYLON SEPARATOR; LEO REGIME, 20°C, 40% DOD) BEGAN DEVELOPING VOLTAGE DIVERGENCE DUE TO LOW CHARGE VOLTAGE AND LOW DISCHARGE VOLTAGE IN ONE CELL AFTER ~3200 CYCLES. (NOTE: EXCEPT FOR TWO, THESE CELLS HAVE 2% LESS ELECTROLYTE THAN THE FLIGHT LOT AVERAGE.)

- PACK 0352G (UARS PLATE AND 2538 NYLON SEPARATOR; LEO REGIME, 20°C, 40% DOD) BEGAN DEVELOPING VOLTAGE DIVERGENCE DUE TO LOW DISCHARGE VOLTAGE IN ONE CELL AFTER ~2800 CYCLES. (NOTE: THESE CELLS HAVE APPROXIMATELY THE SAME AMOUNT OF ELECTOLYTE AS THE FLIGHT CELLS)

- PACK 0350G (UARS PLATE AND SEPARATOR; LEO REGIME, 20°C, 40% DOD) HAS NOT SHOWN ANY SIGNIFICANT DIVERGENCE IN OVER 6000 CYCLES. (NOTE: EXCEPT FOR ONE, THESE CELLS HAVE 2.5% MORE ELECTROLYTE THAN THE FLIGHT LOT AVERAGE.)

OTHER RELATED ANOMALIES (continued)

ERBS BATTERIES

- LAUNCHED 5 OCTOBER 1984.
- BEGAN DEVELOPING HALF-BATTERY DIFFERENTIAL VOLTAGES APPROXIMATELY 4 YEARS AFTER LAUNCH, WITH SOME SUBSEQUENT LOAD-SHARING IMBALANCES AND TEMPERATURE ANOMALIES.
- APPROXIMATELY 8 YEARS AFTER LAUNCH, ONE BATTERY DEVELOPED A HARD SHORT IN ONE OF ITS CELLS. THE BATTERY WAS KEPT ON THE CHARGE BUS, HOWEVER, FOR EVALUATION AND EXPERIMENTATION.
- APPROXIMATELY 4 WEEKS AFTER THE FIRST HARD SHORT, A SECOND CELL DEVELOPED A HARD SHORT AND THE BATTERY HAD TO BE TAKEN OFF OF THE CHARGE BUS.
- PERFORMANCE OF THE ERBS BATTERIES WAS SUCCESSFUL AND ACCEPTABLE SINCE THE MISSION OBJECTIVES WERE MET LONG AGO.

SPACECRAFT BATTERY USAGE PROFILES

(BEGINNING OF LIFE VALUES)

SPACECRAFT	LAUNCH DATE	DEPTH OF DISCHARGE	BATTERY TEMPERATURE	COMMENTS
LANDSAT 4	JULY 1982	10 - 14%	0 - 5°C	SOLAR ARRAY NOW PARTIALLY DISABLED
LANDSAT 5	MARCH 1984	10 - 14%	0 - 5°C	
ERBS	OCTOBER 1984	0 - 12%	9°C	FIXED SOLAR ARRAY (COSINE POWER CURVE)
GRO-1 / GRO-2	APRIL 1991	12%	2 - 4°C	
UARS	SEPTEMBER 1991	0 - 20%	3 - 8°C	BATTERY TEMPS ORIGINALLY 0°C TO 4°C
EUVE	MAY 1992	8 - 10 %	7 - 8°C	BATTERY TEMPS ORIGINALLY -2°C TO 0°C
TOPEX	AUGUST 1992	0 - 14%	5 - 7°C	

DATABASE FOR INVESTIGATION

MORE THAN 20 PLATE AND CELL LOTS HAVE BEEN PRODUCED UNDER THE NASA STANDARD 50 A.H. DESIGN. FOURTEEN CELL LOTS WERE SINGLED OUT FOR DETAILED INVESTIGATION FOR VARIOUS REASONS:

- FLIGHT BATTERY EXPERIENCE
- EXPOSURE OF RESIDUAL CELLS TO LONG-TERM LEO CYCLING UNDER A NOMINAL OR ANTICIPATED MISSION ENVIRONMENT
- EXPOSURE OF RESIDUAL CELLS TO LONG-TERM LEO CYCLING UNDER AN ACCELERATED OR STRESSFUL MISSION ENVIRONMENT
- LONG-TERM SUCCESSFUL USAGE AS BATTERIES FOR SPACECRAFT INTEGRATION AND TEST
- BATTERIES WERE POTENTIAL OR IMMINENT CANDIDATES FOR LAUNCH

IT SHOULD BE NOTED THAT ALL OF THE FLIGHT BATTERIES, WITHOUT EXCEPTION, SUCCESSFULLY MET STRINGENT NASA-CONTROLLED ACCEPTANCE TEST CRITERIA.

DATABASE FOR INVESTIGATION (continued)

SUMMARY OF BATTERY/CELL LOT USAGE AND EXPOSURE

CELL LOT	PROGRAM	FLIGHT	LONG I & T BATTERY USE	CELL LIFE TEST	CELL STRESS TEST	BATTERY ANOMALIES	BATTERY FAILURES	COMMENTS
50AB20 LOT 1	LANDSAT		X			0 of 1	0 of 1	QUAL BATTERY
LOT 2	LANDSAT		X	X	X	0 of 4	0 of 4	
LOT 3	LANDSAT	X				0 of 3	0 of 3	
LOT 4	LANDSAT	X				0 of 2	0 of 2	
LOT 5	LANDSAT	X				0 of 2	0 of 2	
LOT 7	LANDSAT	X				0 of 2	0 of 2	
LOT 12	ERBS	X	X (3rd battery)			1 of 3	1 of 3	
LOT 14	GRO		X		X	0 of 3	0 of 3	
LOT 16	GRO/EUVE	X		X	X	0 of 3	0 of 3	
LOT 17	GRO	X		X	X	0 of 3	0 of 3	
50AB35 LOT 1	GRO	X			X	2 of 3	1 of 3	
LOT 2	UARS	X		X	X	3 of 3	0 of 3	
LOT 4	EUVE				limited	0 of 3	0 of 3	RECENT FLIGHT CANDIDATE
LOT 6	TOPEX	X		limited	limited	0 of 3	0 of 3	

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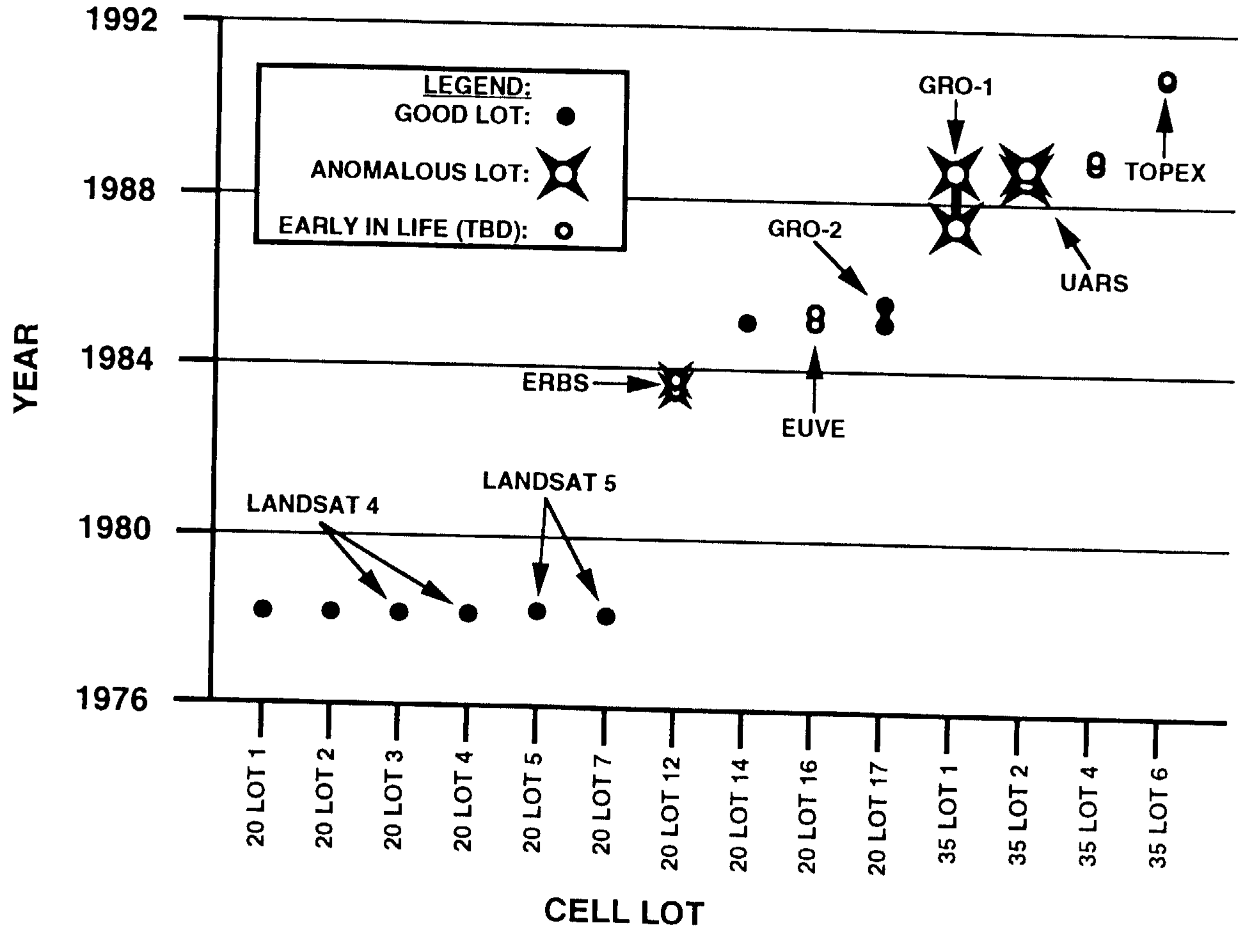
DATABASE FOR INVESTIGATION (continued)

- OVER 60 PARAMETERS OR PARAMETRIC RELATIONSHIPS WERE CALCULATED AND TABULATED IN SUPPORT OF THIS INVESTIGATION, ~ 40 WERE PLOTTED.
- 21 OF THESE PLOTS ARE REPRODUCED HERE BECAUSE OF THE OVERALL TRENDS THAT THEY IDENTIFIED (MANY OF WHICH MAY BE COUNTER-PRODUCTIVE TO LONG CYCLE-LIFE) OR BECAUSE OF THEIR APPARENT UTILITY IN DISTINGUISHING BETWEEN GOOD AND ANOMALOUS CELL LOTS.
- THESE PLOTS, WITH THEIR ACCOMPANYING ANALYSES, ARE A SUMMARY OF THE SIGNIFICANT FINDINGS TO-DATE IN MDC'S ONGOING INVESTIGATION INTO THE AFOREMENTIONED PERFORMANCE ANOMALIES IN THE NASA STANDARD 50 A.H. NICD BATTERIES.

NASA STANDARD 50 A.H. BATTERY CELL

SINTERING DATE CHRONOLOGY



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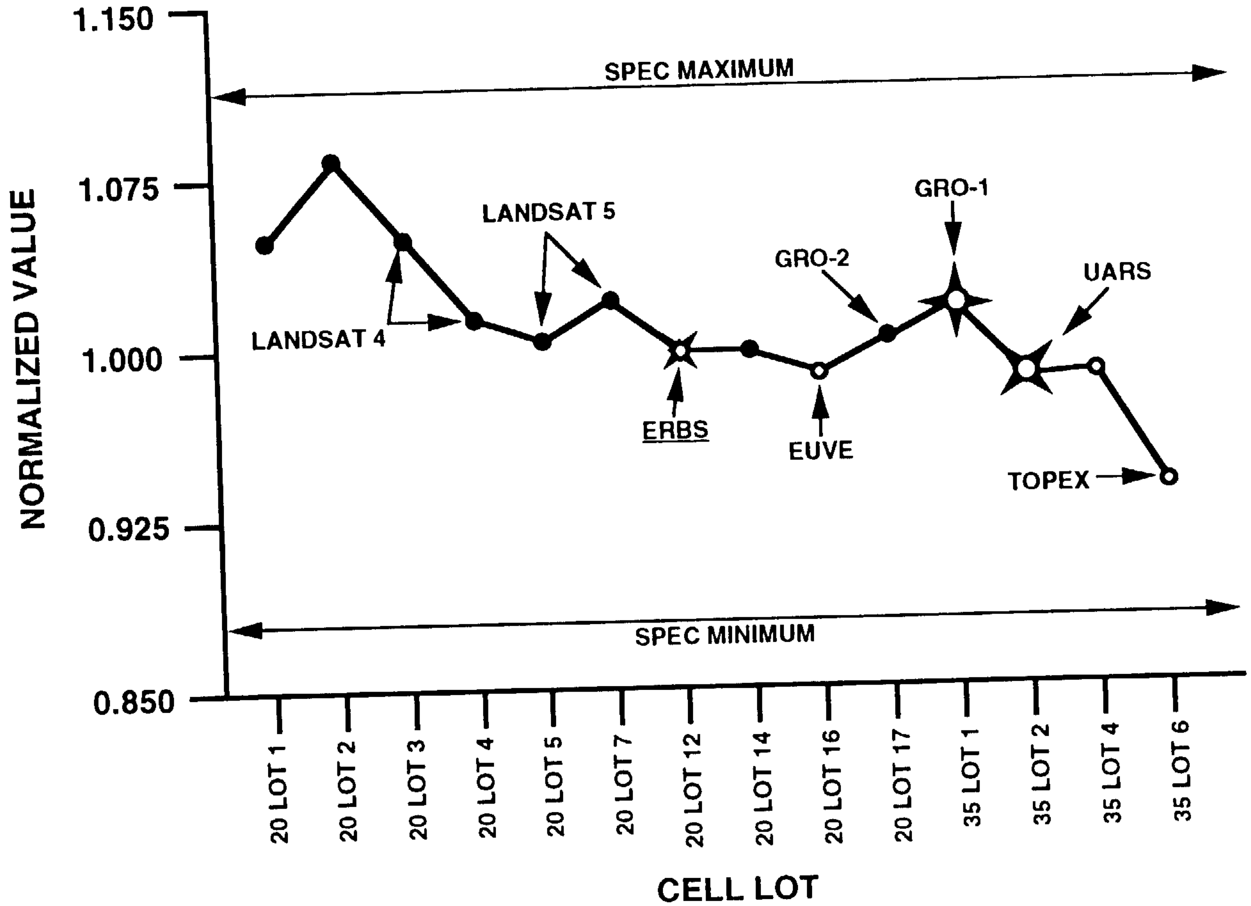
NASA STANDARD 50 A.H. BATTERY CELL HISTORICAL TREND

INTER-ELECTRODE SPACING (I.E.S.)



- ALL VALUES ARE LOT AVERAGES AND ARE NORMALIZED TO THE SPEC NOMINAL.
- VALUES ARE DERIVED FROM NOMINAL DIMENSIONS OF CELL CASE AND CELL PACK WRAPPER, AND ACTUAL CELL PACK THICKNESS MEASUREMENTS (UNDER COMPRESSION).
- I.E.S. HAS DECREASED ~11% FROM THE FIRST LOT.
- THERE IS NO KNOWN CORRELATION BETWEEN DIMINISHED I.E.S. AND ANY PAST OR PRESENT ANOMALOUS NASA STANDARD 50 A.H. CELL LOTS.

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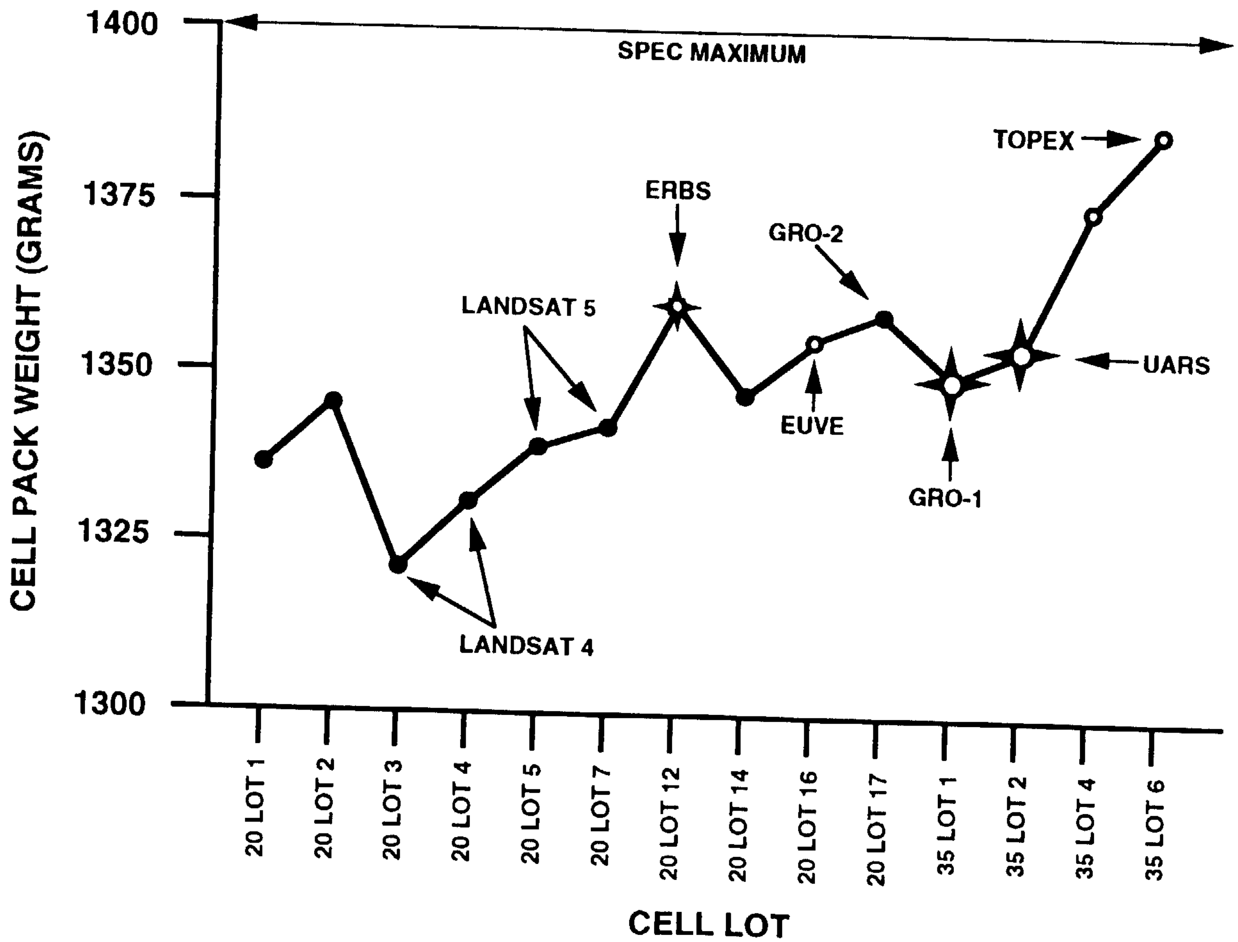
NASA STANDARD 50 A.H. BATTERY CELL HISTORICAL TREND

CELL PACK WEIGHT



- ALL VALUES ARE LOT AVERAGES AND WERE OBTAINED FOR EACH CELL PACK IN CONCERT WITH CELL PACK THICKNESS MEASUREMENTS.
- NO SPEC MINIMUM.
- RECENT LOT-AVERAGE CELL PACK WEIGHTS ARE ALMOST 5% GREATER THAN EARLIER CELL LOTS.
- TREND IS CONSISTENT WITH DECREASED I.E.S.
- THERE IS NO KNOWN CORRELATION BETWEEN INCREASED CELL PACK WEIGHT AND ANY PAST OR PRESENT ANOMALOUS NASA STANDARD 50 A.H. CELL LOTS.

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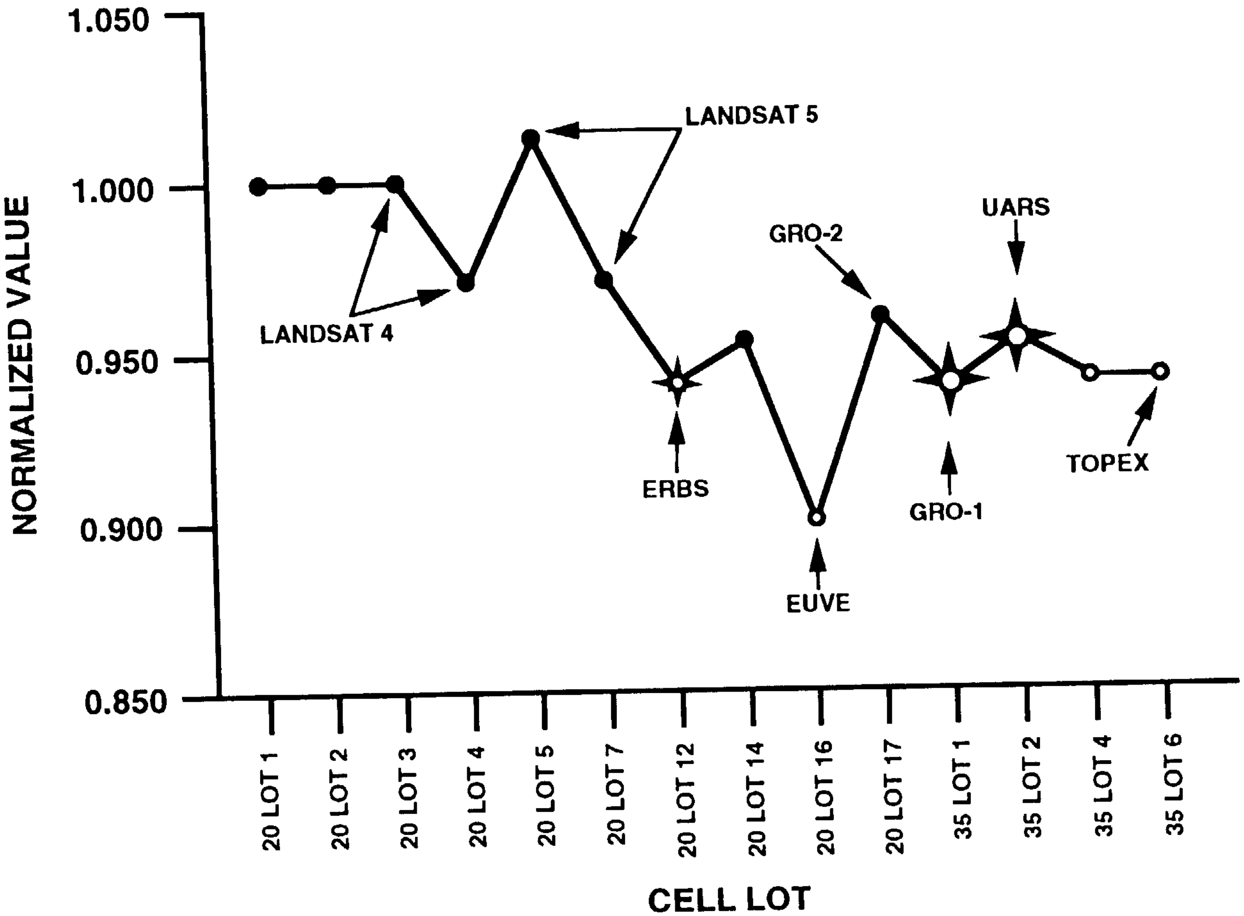
NASA STANDARD 50 A.H. BATTERY CELL HISTORICAL TREND

FINAL ELECTROLYTE AMOUNT



- ALL VALUES ARE LOT AVERAGES AND ARE NORMALIZED TO 50AB20 LOT 1.
- NO SPEC MINIMUM OR MAXIMUM.
- RECENT CELL LOTS CONTAIN ~6% LESS ELECTROLYTE THAN EARLIER LOTS.
- THIS TREND IS CONSISTENT WITH THICKER AND HEAVIER PLATE (LESS FREE VOLUME).
- THERE IS NO KNOWN CORRELATION BETWEEN DECREASED ELECTROLYTE AND ANY PAST OR PRESENT ANOMALOUS NASA STANDARD 50 A.H. CELL LOTS.

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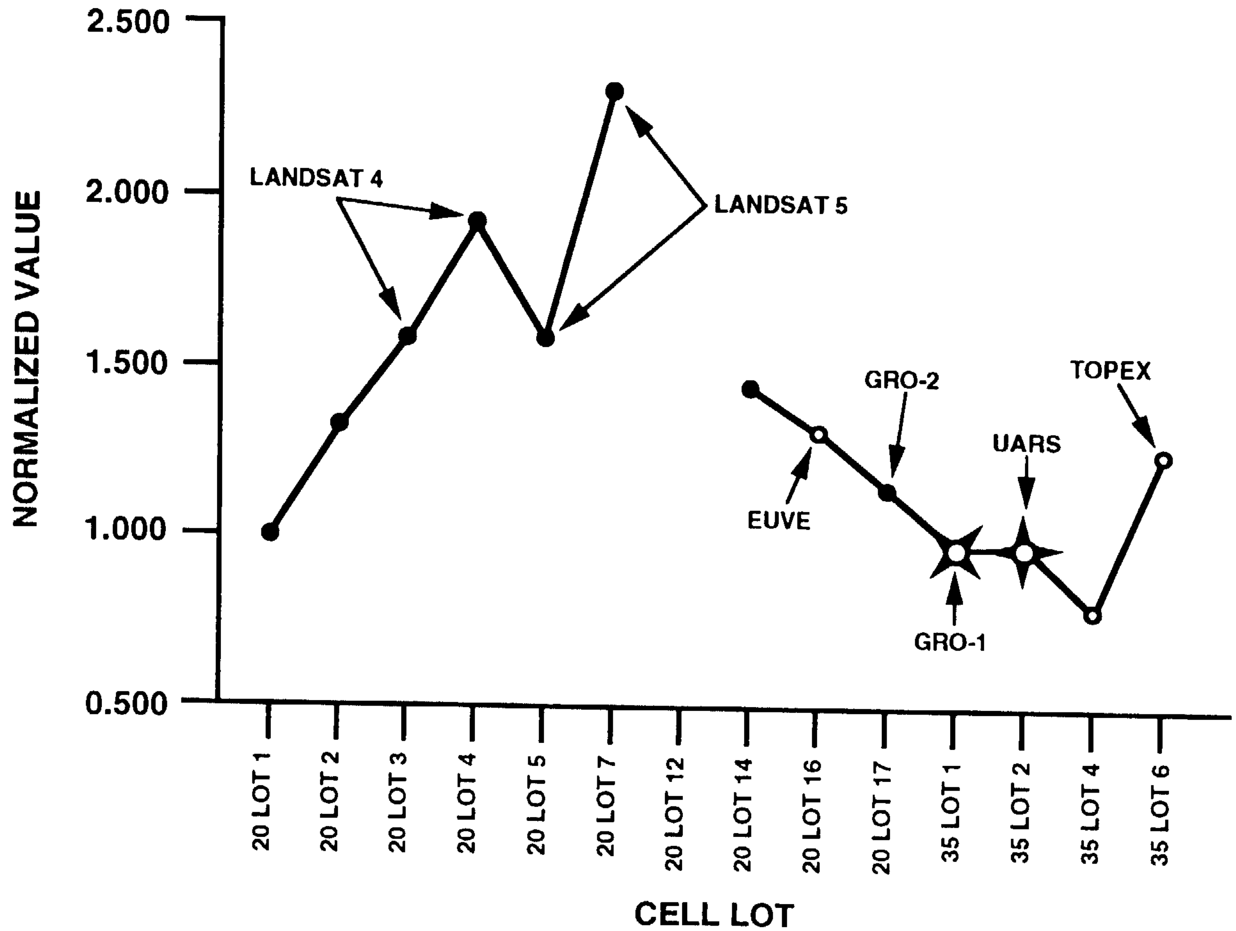
NASA STANDARD 50 A.H. BATTERY CELL HISTORICAL TREND

NEGATIVE PLATE TEFLON LOADING



- ALL VALUES ARE LOT AVERAGES AND ARE NORMALIZED TO 50AB20 LOT 1.
- NO SPEC MINIMUM OR MAXIMUM.
- NO TEFLON LOADING DATA AVAILABLE FOR ERBS (50AB20 LOT 12).
- EARLIER LOTS HAD 1.5 TO 3 TIMES THE AMOUNT OF TEFLON LOADING OF RECENT LOTS.
- NO KNOWN CHANGES OR DEVIATIONS HAVE BEEN INTRODUCED INTO THE TEFLON LOADING PROCESS.
- LIGHTER TEFLON LOADING MAY MAKE TREATMENT/ COATING LESS UNIFORM AND MAY ALSO BE PARTLY RESPONSIBLE FOR DECREASED ELECTROLYTE.
- THERE MAY BE SOME CORRELATION BETWEEN REDUCED TEFLON AND THE ANOMALOUS NASA STANDARD 50 A.H. CELL LOTS.

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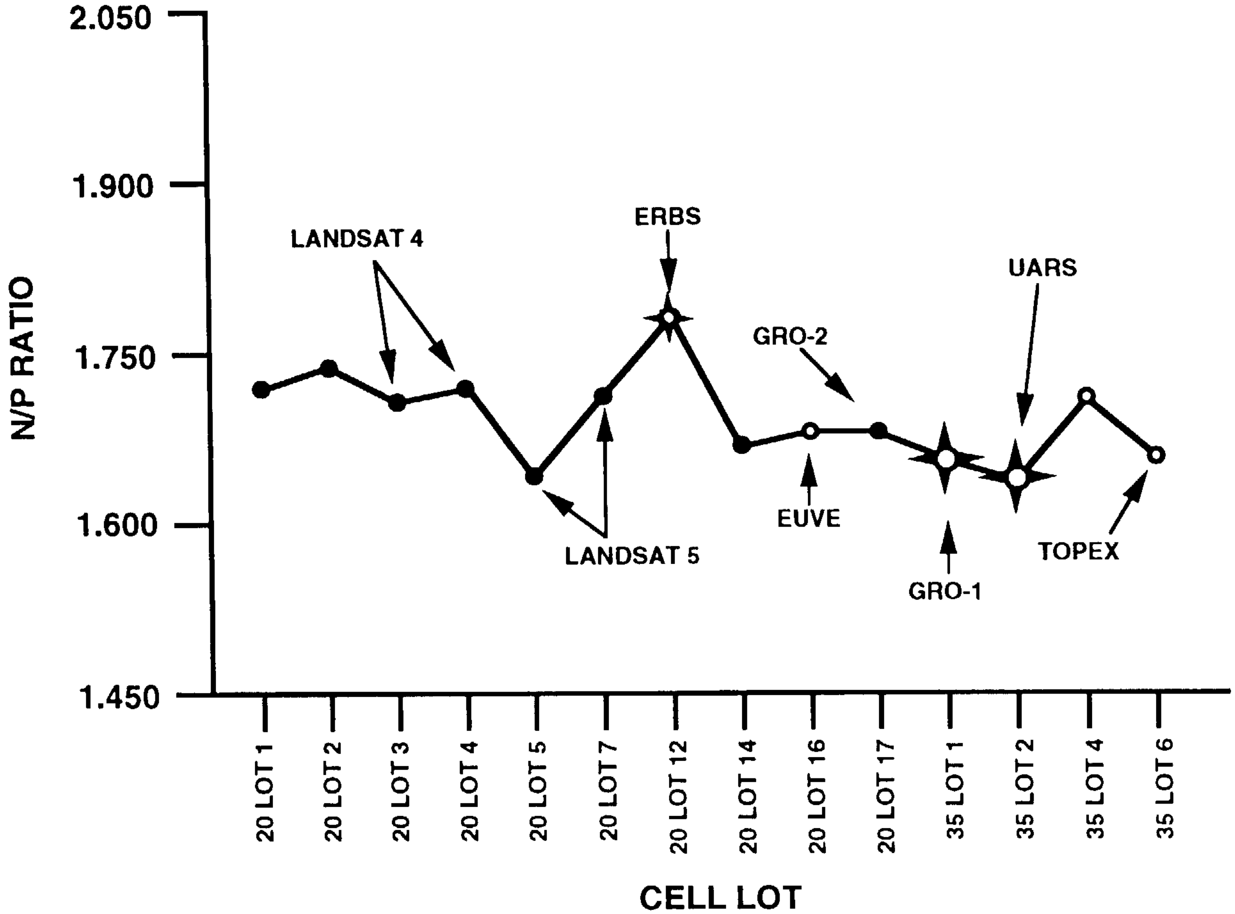
NASA STANDARD 50 A.H. BATTERY CELL HISTORICAL TREND:

THEORETICAL NEGATIVE TO POSITIVE (N/P) RATIO



- NO SPEC MINIMUM OR MAXIMUM.
- VALUES WERE DERIVED USING THE MAXIMUM THEORETICAL NEGATIVE AND MAXIMUM THEORETICAL POSITIVE CAPACITY. THESE ARE BASED ON PLATE LOADING, PLATE AREA, # OF PLATES, AND ELECTROCHEMICAL CONSTANTS.
- TREND APPEARS TO BE VERY CONSTANT AND STABLE, WITH A SLIGHT DECREASE OVER TIME..
- THERE IS NO KNOWN CORRELATION BETWEEN THEORETICAL N/P RATIO AND ANY PAST OR PRESENT ANOMALOUS NASA STANDARD 50 A.H. CELL LOTS.

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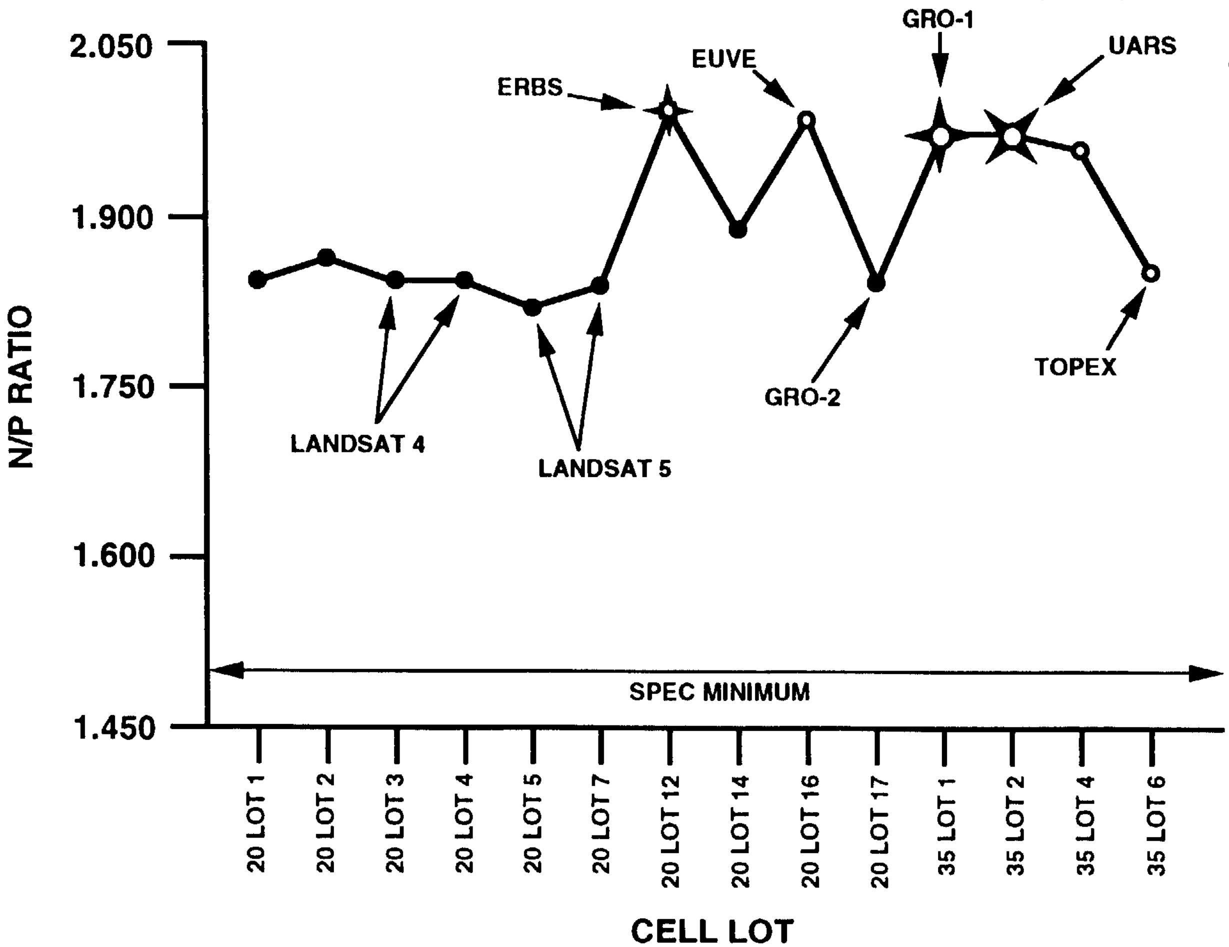
NASA STANDARD 50 A.H. BATTERY CELL HISTORICAL TREND

ACTUAL NEGATIVE TO POSITIVE (N/P) RATIO



- DATA IS FROM 100% FLOODED-CELL TESTING AND IS THE RATIO OF THE NEGATIVE PLATE CAPACITY (DISCHARGED TO SOME NEGATIVE VOLTAGE) TO THE POSITIVE PLATE CAPACITY (DISCHARGED TO SOME POSITIVE VOLTAGE < 1.0 VOLT).
- TEMPORARY FLOODED-CELLS CONTAIN THE SAME NUMBER OF PLATES AS THE SEALED CELL.
- ALL VALUES ARE LOT AVERAGES.
- NO SPEC MAXIMUM.
- THE TREND IS NOT AS STABLE AS THE THEORETICAL N/P RATIO.
- THE TREND APPEARS TO MAKE AN EXCELLENT DISTINCTION BETWEEN GOOD AND ANOMALOUS LOTS, WITH SOME LOTS STILL TBD AND PROVIDED THE FIRST REAL CLUE ABOUT WHICH WAY TO TAKE THE INVESTIGATION.
- QUESTION: WHICH IS THE DYNAMIC ELEMENT: N OR P?

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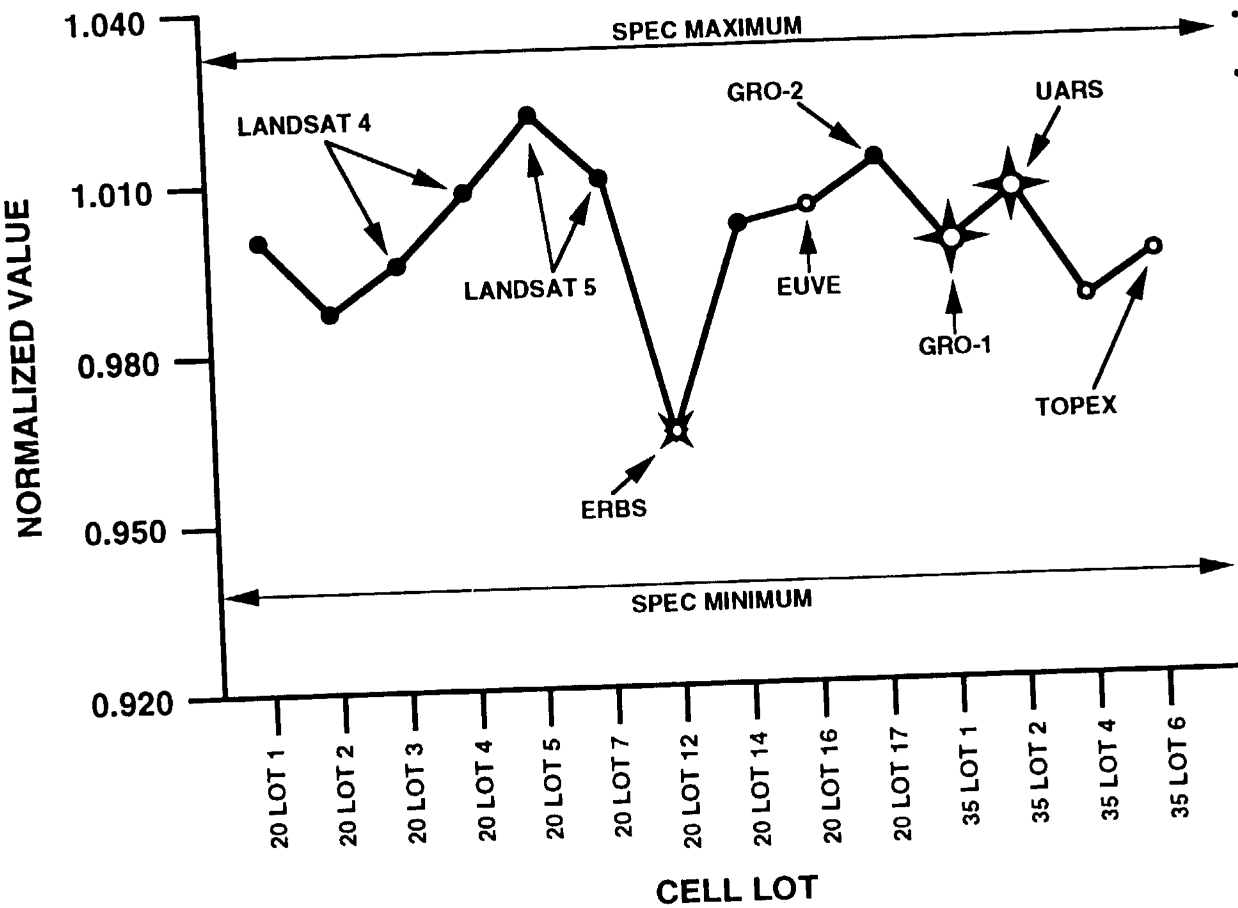
NASA STANDARD 50 A.H. BATTERY CELL HISTORICAL TREND

POSITIVE PLATE LOADING



- NORMALIZED TO 50AB20 LOT 1.
- POSITIVE LOADING HAS REMAINED WITHIN SPEC AND IS, FOR THE MOST PART, VERY TIGHTLY CONTROLLED.
- THE LEVEL OF LOADING IS MOST OFTEN HIGHER THAN NOMINAL.
- THE LOADING SPEC HAS NOT CHANGED SINCE 50AB20 LOT 1.
- NOTE: THIS IS NON-PASSIVATED PLAQUE . (I.E. THE SINTER IS CORRODED BY THE IMPREGNATION PROCESS, A.K.A. NICKEL ATTACK.)
- THERE IS NO KNOWN CORRELATION BETWEEN THE LEVEL OF POSITIVE PLATE LOADING AND ANY PAST OR PRESENT ANOMALOUS NASA STANDARD 50 A.H. CELL LOTS.

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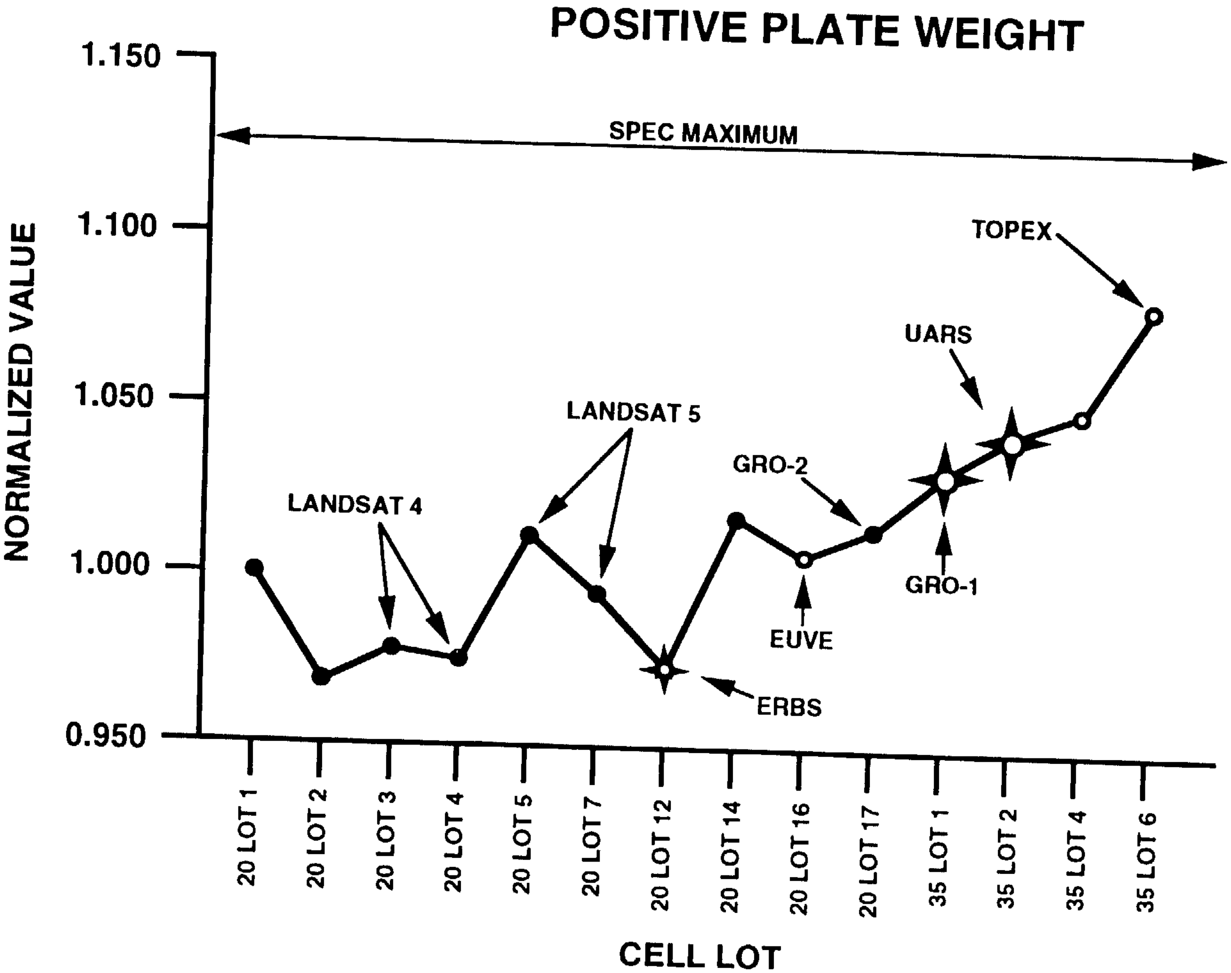
NASA STANDARD 50 A.H. BATTERY CELL HISTORICAL TREND



- NORMALIZED TO 50AB20 LOT 1.
- NO SPEC MINIMUM.
- NOTE: THIS IS NON-PASSIVATED PLAQUE. (I.E. THE SINTER IS CORRODED BY THE IMPREGNATION PROCESS, A.K.A. NICKEL ATTACK.)
- POSITIVE PLATE WEIGHT HAS INCREASED 8 - 11 % SINCE EARLY LOTS AND IS THE OVERWHELMING FACTOR IN THE INCREASE OF PLATE PACK WEIGHT.
- PROBABLE CAUSE OF THE INCREASE (FROM OTHER DATA NOT PRESENTED HERE): LESS NICKEL ATTACK.
- THERE IS NO KNOWN CORRELATION BETWEEN INCREASED POSITIVE PLATE WEIGHT AND ANY PAST OR PRESENT ANOMALOUS NASA STANDARD 50 A.H. CELL LOTS.

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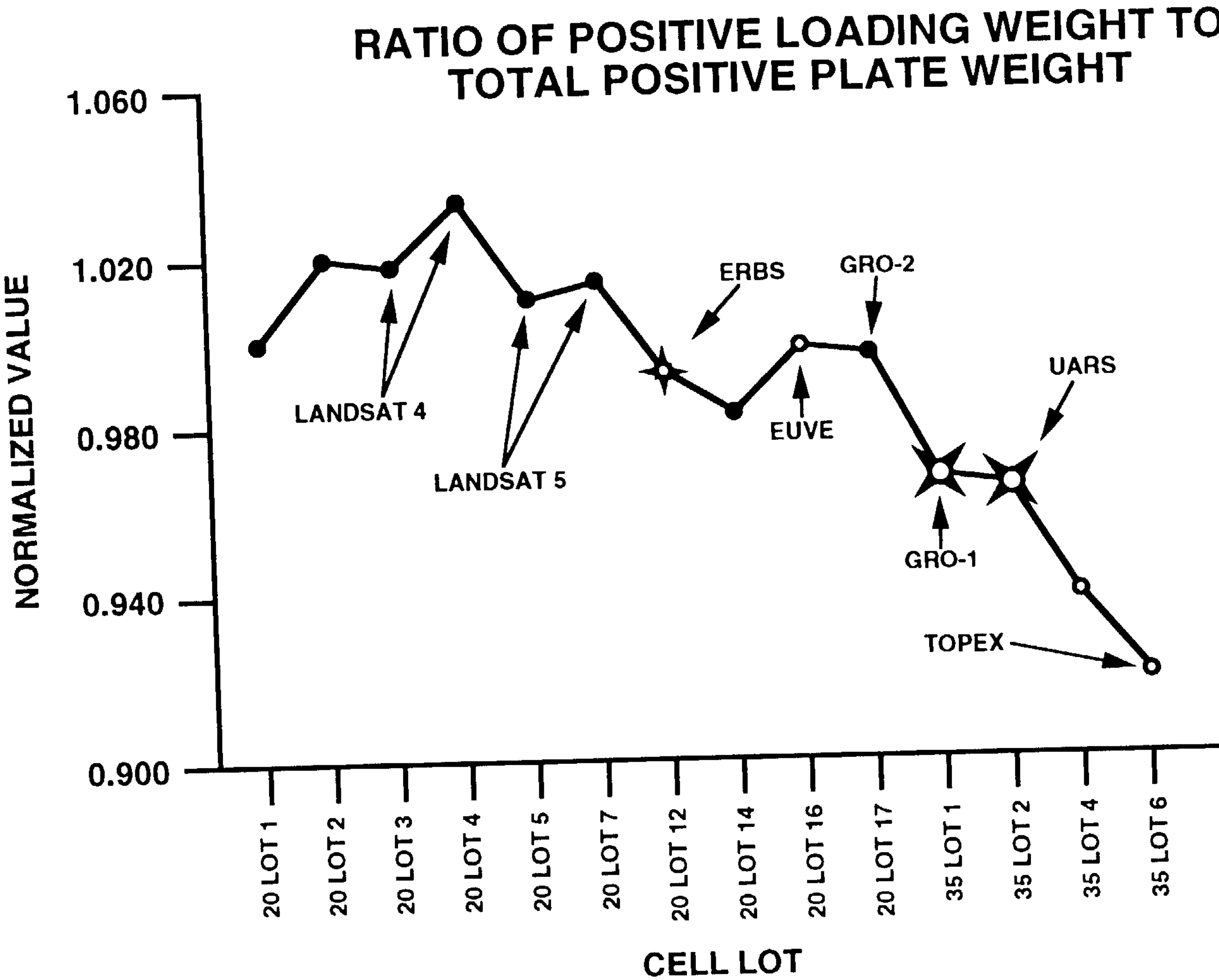
NASA STANDARD 50 A.H. BATTERY CELL HISTORICAL TREND



- NORMALIZED TO 50AB20 LOT 1.
- NO SPEC MINIMUM OR MAXIMUM.
- THE RATIO FOR MORE RECENT LOTS IS 8 - 10 % LESS THAN OLDER LOTS.
- THERE IS SOME CORRELATION BETWEEN A LOWER RATIO OF POSITIVE LOADING WEIGHT TO TOTAL POSITIVE PLATE WEIGHT AND THE ANOMALOUS NASA STANDARD 50 A.H. CELL LOTS, WITH SOME LOTS STILL TBD.

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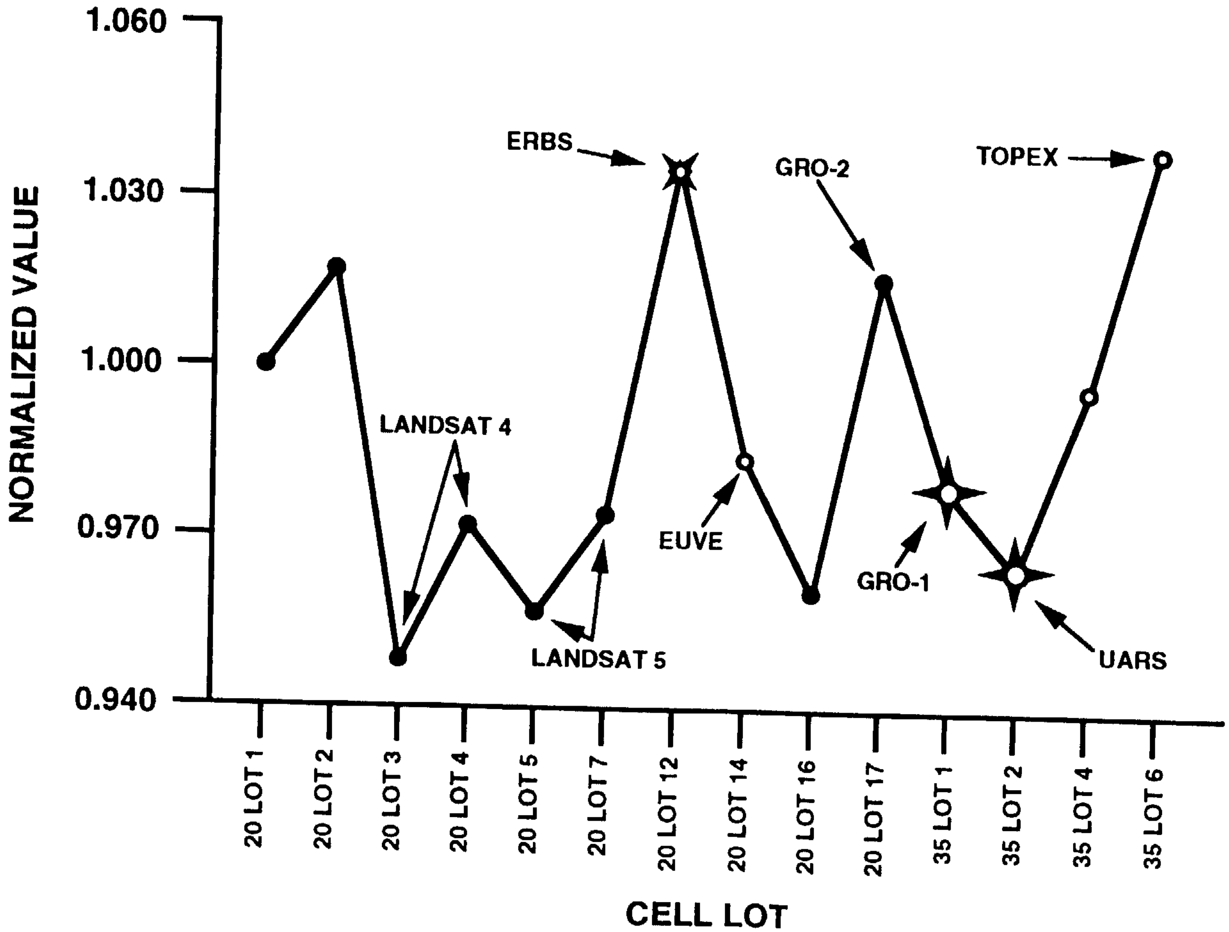
NASA STANDARD 50 A.H. BATTERY CELL HISTORICAL TREND

POSITIVE PLATE UTILIZATION



- ALL VALUES ARE LOT AVERAGES AND ARE OBTAINED BY DIVIDING THE LOT-AVERAGE FLOODED-CELL POSITIVE PLATE CAPACITY BY THE MAXIMUM THEORETICAL POSITIVE PLATE CAPACITY (AS DESCRIBED EARLIER).
- NO SPEC MINIMUM OR MAXIMUM.
- UTILIZATION HAS VARIED CONSIDERABLY OVER TIME .
- THERE IS NO KNOWN CORRELATION BETWEEN POSITIVE PLATE UTILIZATION AND ANY PAST OR PRESENT ANOMALOUS NASA STANDARD 50 A.H. CELL LOTS.

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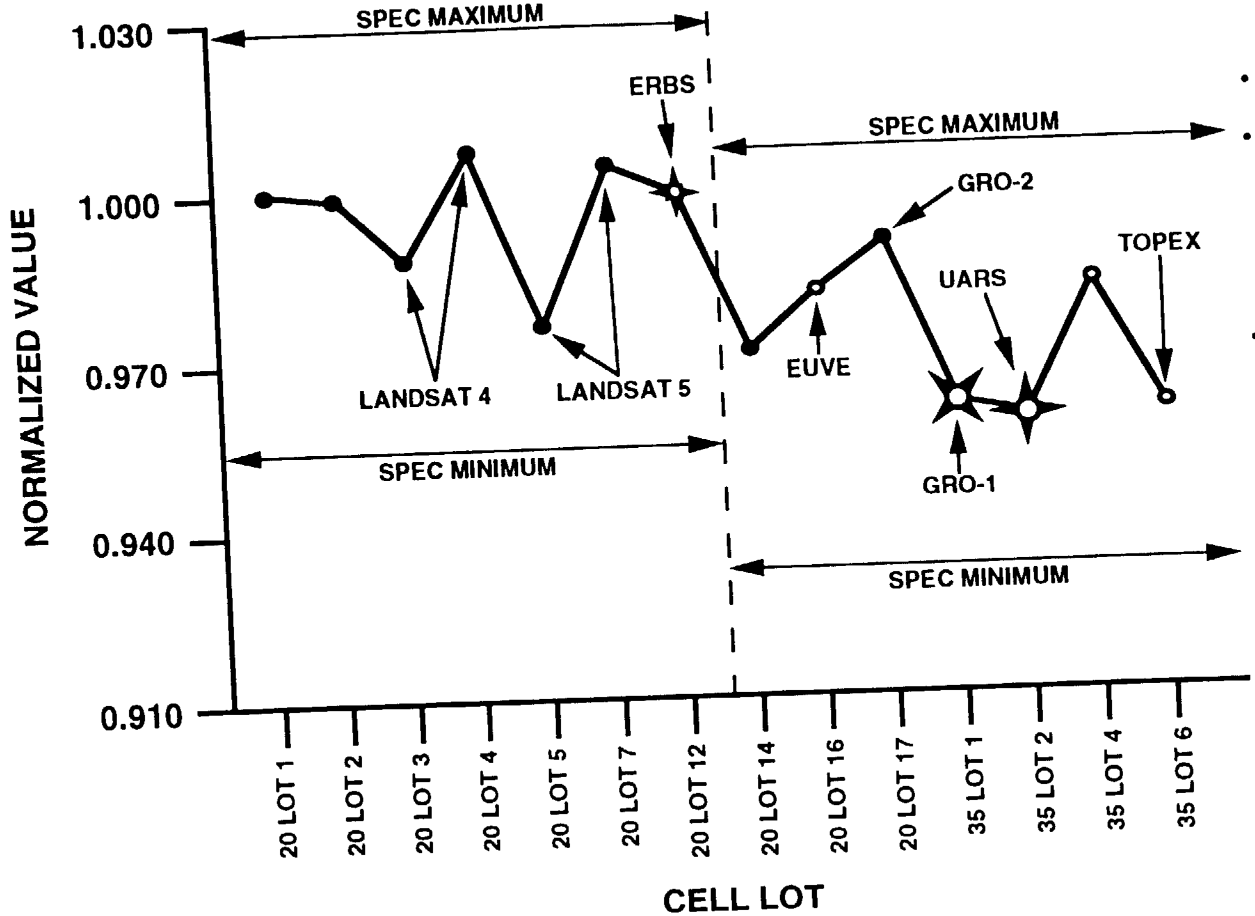
NASA STANDARD 50 A.H. BATTERY CELL HISTORICAL TREND

NEGATIVE PLATE LOADING



- NORMALIZED TO 50AB20 LOT 1.
- THE LOADING SPECIFICATION WAS CHANGED AFTER 50AB20 LOT 12 WITH THE RESULT THAT LOADING IS 2 - 4 % LOWER IN THE MOST RECENT LOTS VERSUS EARLIER LOTS.
- THERE IS NO KNOWN CORRELATION BETWEEN THE LEVEL OF NEGATIVE PLATE LOADING AND ANY PAST OR PRESENT ANOMALOUS NASA STANDARD 50 A.H. CELL LOTS.

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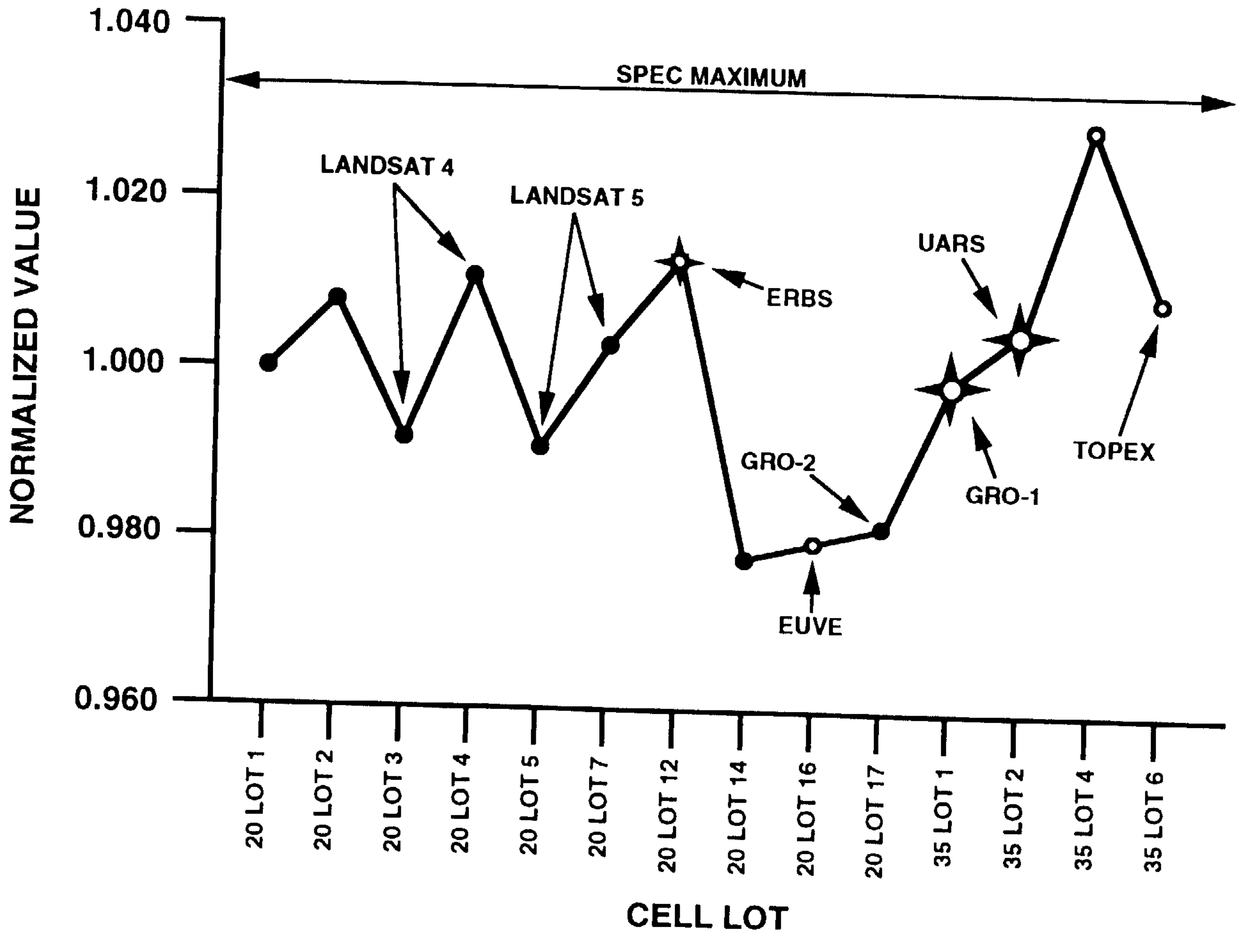
NASA STANDARD 50 A.H. BATTERY CELL HISTORICAL TREND

NEGATIVE PLATE WEIGHT



- NORMALIZED TO 50AB20 LOT 1.
- NO SPEC MINIMUM.
- NEGATIVE PLATE WEIGHT HAS NOT VARIED SIGNIFICANTLY OVER THE LIFE OF THE DESIGN.
- NEGATIVE PLATE WEIGHT INITIALLY DECREASED WITH THE REDUCTION IN LOADING THAT STARTED WITH 50AB20 LOT 14, BUT IT HAS MIGRATED BACK TO THE OLD PLATE WEIGHT DESPITE THE LOWER LOADING.
- THERE IS NO KNOWN CORRELATION BETWEEN NEGATIVE PLATE WEIGHT AND ANY PAST OR PRESENT ANOMALOUS NASA STANDARD 50 A.H. CELL LOTS.

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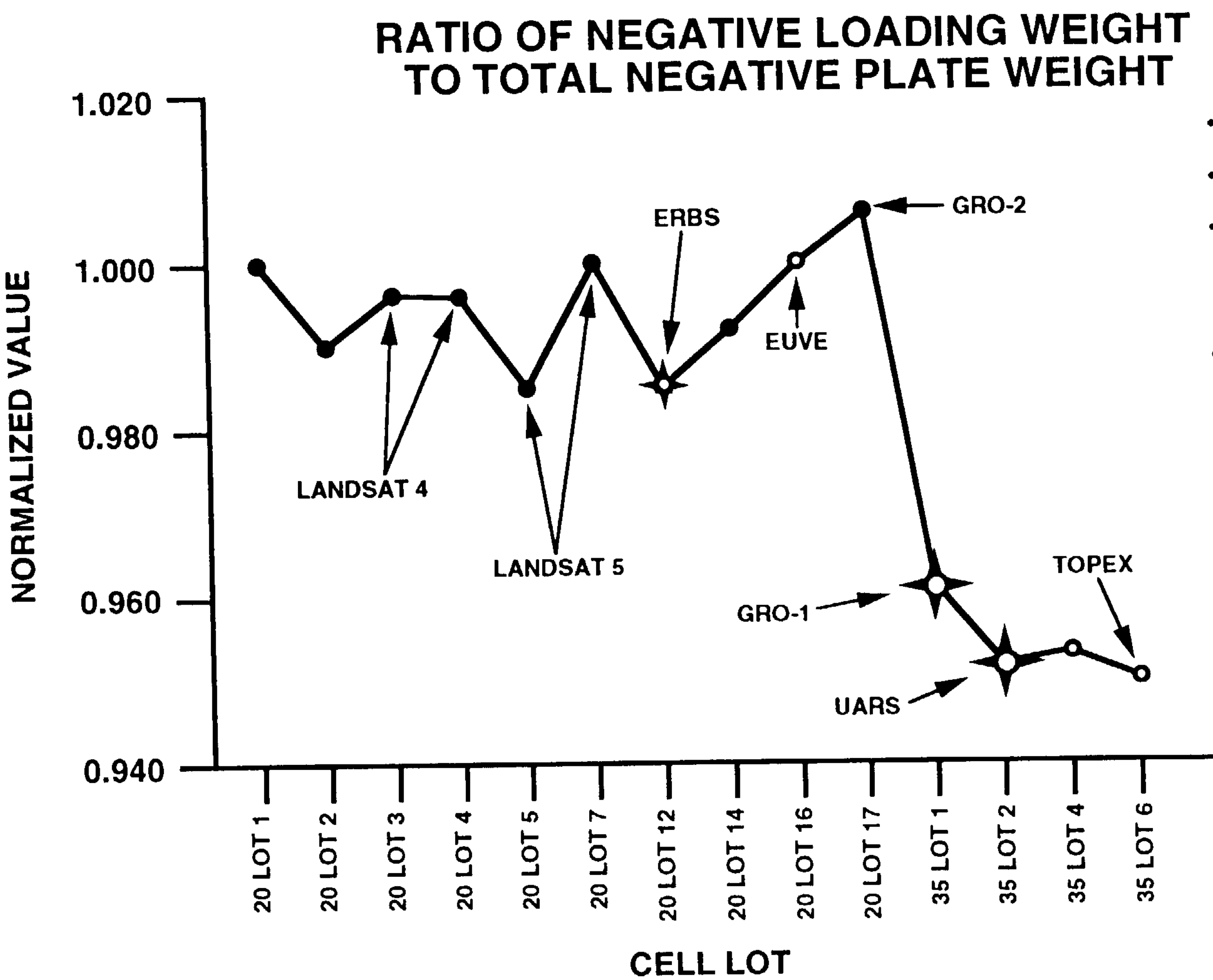
NASA STANDARD 50 A.H. BATTERY CELL HISTORICAL TREND



- NORMALIZED TO 50AB20 LOT 1.
- NO SPEC MINIMUM OR MAXIMUM.
- THIS RATIO CHANGED DRAMATICALLY BETWEEN 50AB20 LOT 17 AND 50AB35 LOT 1 (MID-1985 TO MID-1987).
- RATIO HAS BEEN REDUCING PARTLY AS A RESULT OF THE DECREASED LOADING (YET PLATE WEIGHT HAS INCREASED).
- DIMENSIONS OF THE STEEL SUBSTRATE HAVE NOT CHANGED.
- PROBABLE CAUSE OF TREND: HEAVIER SINTERED PLAQUE.
- THERE IS SOME CORRELATION BETWEEN A LOWER RATIO OF NEGATIVE LOADING TO TOTAL NEGATIVE WEIGHT AND THE ANOMALOUS NASA STANDARD 50 A.H. CELL LOTS, WITH SOME LOTS STILL TBD.

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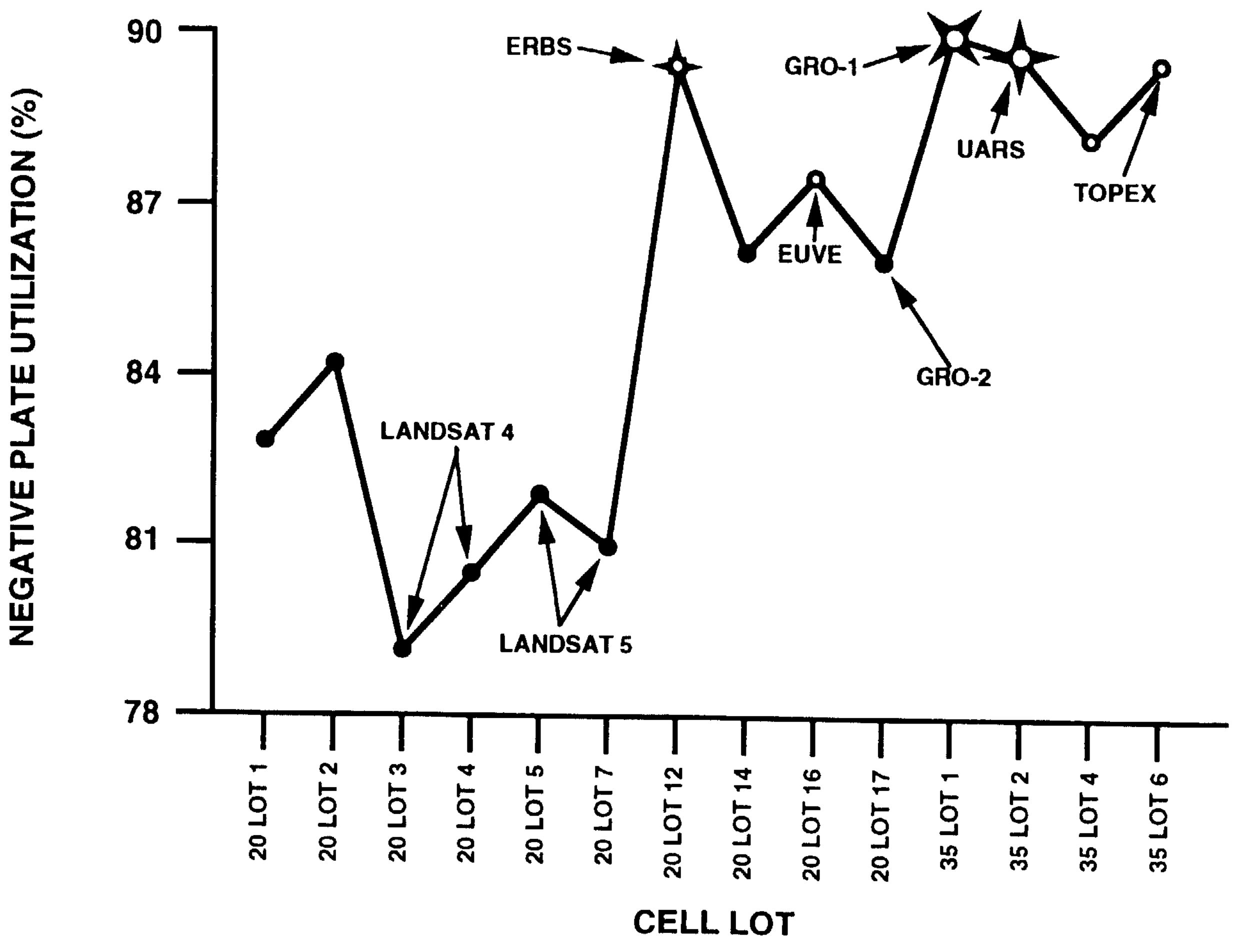
NASA STANDARD 50 A.H. BATTERY CELL HISTORICAL TREND

NEGATIVE PLATE UTILIZATION



- ALL VALUES ARE LOT AVERAGES AND ARE OBTAINED BY DIVIDING THE LOT-AVERAGE FLOODED-CELL NEGATIVE PLATE CAPACITY BY THE MAXIMUM THEORETICAL NEGATIVE PLATE CAPACITY (AS DESCRIBED EARLIER).
- NO SPEC MINIMUM OR MAXIMUM.
- UTILIZATION HAS INCREASED BY 5 - 10 %.
- HIGH UTILIZATION (> 88%) CORRELATES WELL WITH HIGH N/P RATIO (> 1.9), A LOW RATIO OF NEGATIVE LOADING WEIGHT TO TOTAL NEGATIVE PLATE WEIGHT, AND THE ANOMALOUS NASA STANDARD 50 A.H. CELL LOTS.
- HIGH UTILIZATION ALSO HAS A FAIR CORRELATION TO LIGHTER LOADING LEVELS.

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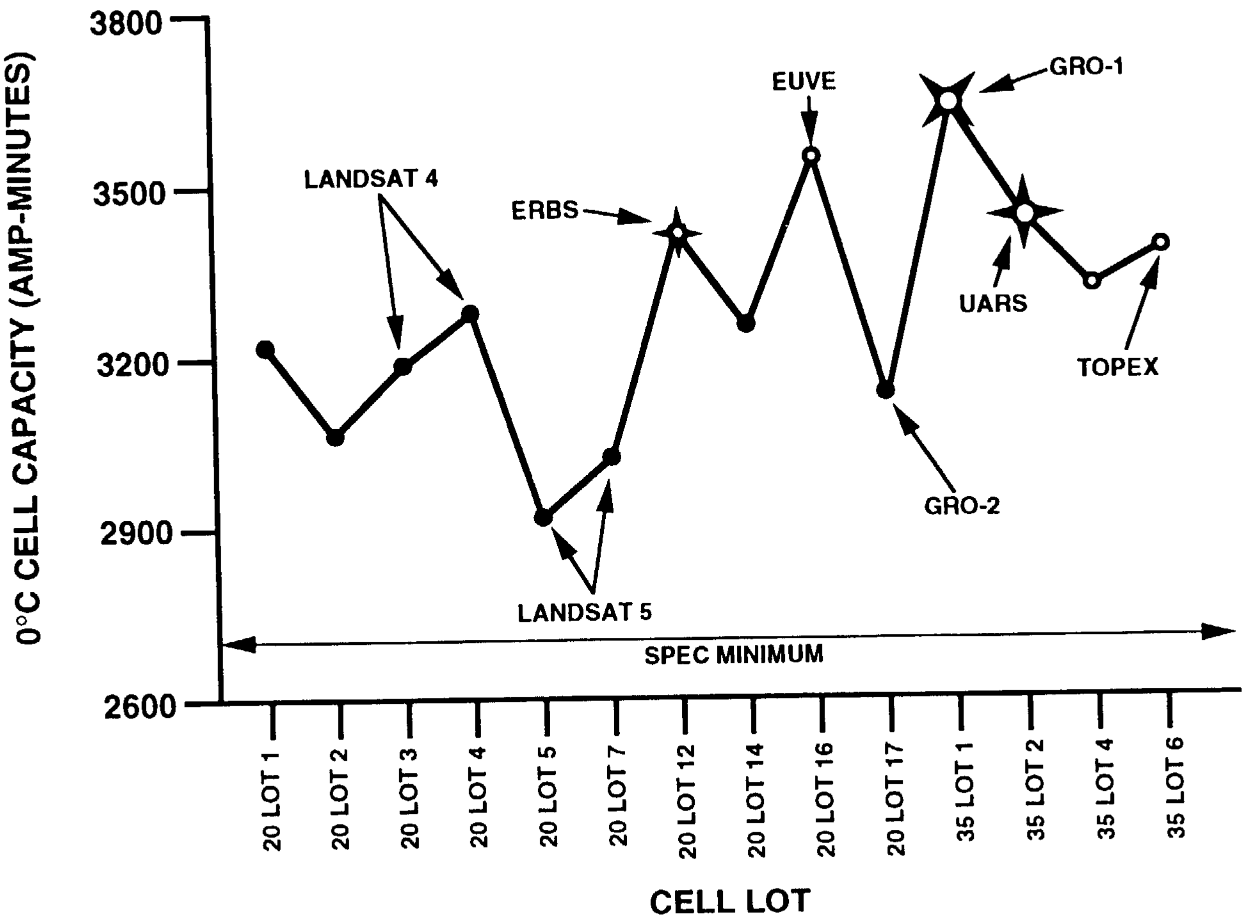
NASA STANDARD 50 A.H. BATTERY CELL HISTORICAL TREND

0°C CAPACITY AT THE CELL LEVEL



- NO SPEC MAXIMUM.
- CELL 0°C CAPACITY HAS VARIED GREATLY AND HAS SHOWN A GENERAL INCREASE WITH TIME.
- THERE IS A VERY GOOD CORRELATION BETWEEN HIGH CAPACITY AT 0°C (> 3400 AMP- MINUTES) AND ANOMALOUS NASA STANDARD 50 A.H. CELL LOTS, WITH SOME LOTS STILL TBD.

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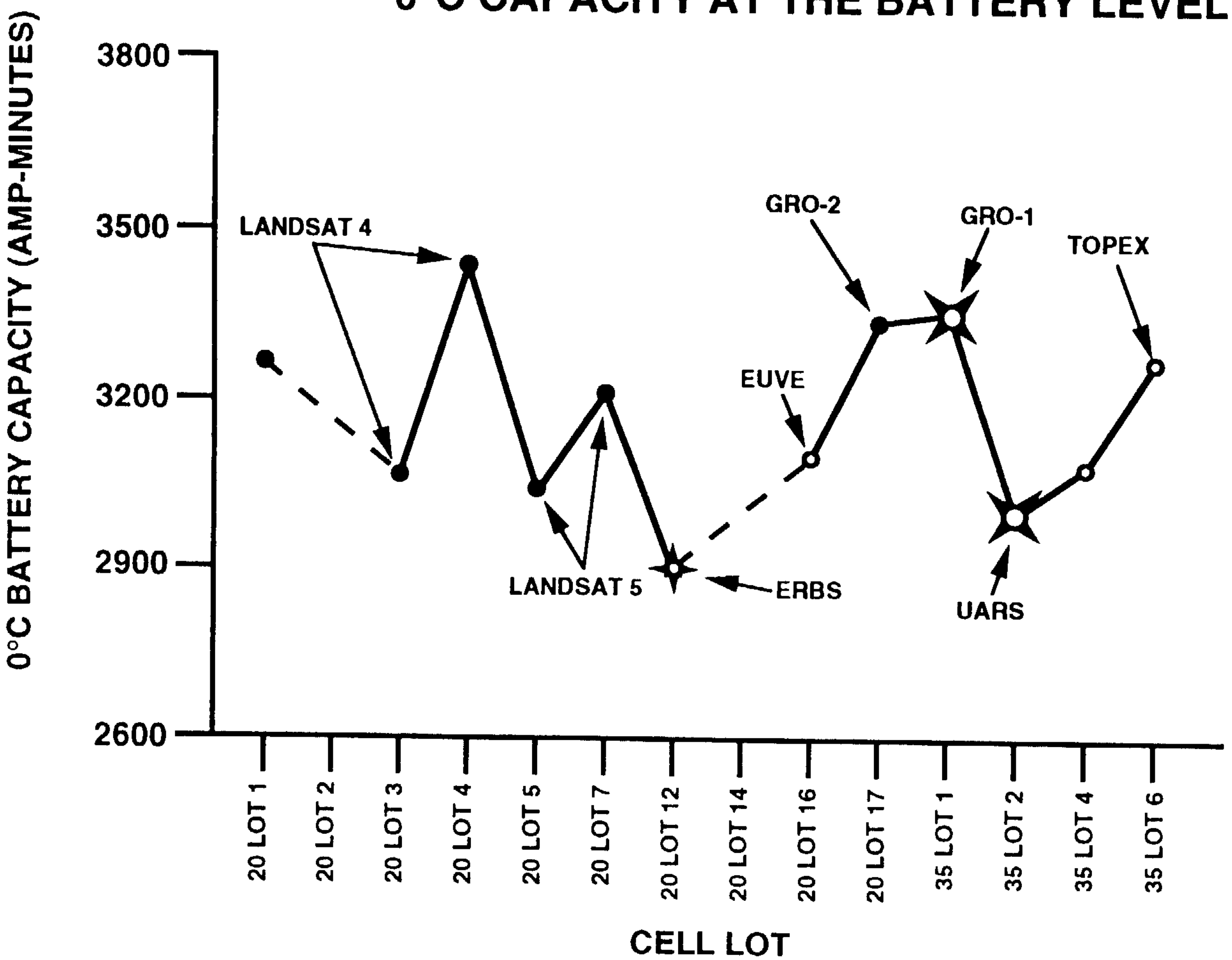
NASA STANDARD 50 A.H. BATTERY CELL HISTORICAL TREND

0°C CAPACITY AT THE BATTERY LEVEL



- BATTERIES FROM 50AB20 LOT 2 AND 50AB20 LOT 14 CELLS WERE NOT TESTED FOR CAPACITY AT 0°C (DESIGNATED AS TEST BATTERIES).
- NO SPEC MAXIMUM.
- SPEC MINIMUM IS TIED TO THE BATTERY CAPACITY MEASURED AT 23°C (MUST BE > 80 % OF THE 23°C CAPACITY). ALL OF THE NASA STANDARD 50 A.H. BATTERIES HAVE MET THIS REQUIREMENT.
- BATTERY CAPACITY HAS ALSO VARIED CONSIDERABLY FROM LOT TO LOT, BUT NOT AS MUCH AS AT THE CELL LEVEL.
- THERE IS NO KNOWN CORRELATION BETWEEN BATTERY CAPACITY AT 0°C AND ANY PAST OR PRESENT ANOMALOUS NASA STANDARD 50 A.H. CELL LOTS

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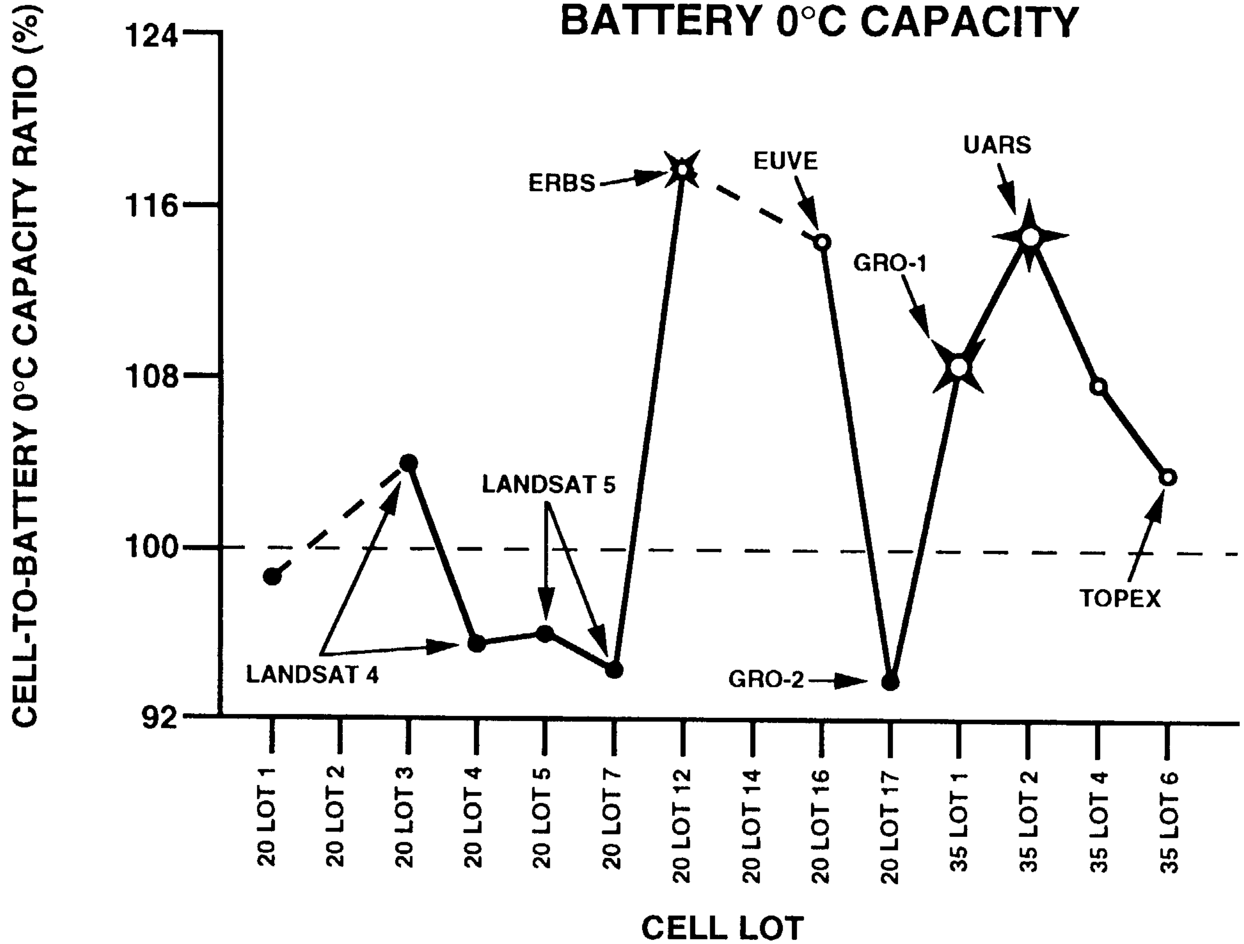
NASA STANDARD 50 A.H. BATTERY CELL HISTORICAL TREND

RATIO OF CELL 0°C CAPACITY TO BATTERY 0°C CAPACITY



- BATTERIES FROM 50AB20 LOT 2 AND 50AB20 LOT 14 CELLS WERE NOT TESTED FOR CAPACITY AT 0°C (DESIGNATED AS TEST BATTERIES).
- NO SPEC MINIMUM OR MAXIMUM.
- THIS RATIO INDICATES HOW MUCH MORE CAPACITY A GIVEN LOT HAD AT 0°C AT THE CELL LEVEL VERSUS AT THE BATTERY LEVEL. IT CAN ALSO BE THOUGHT OF AS "% OF CAPACITY LOST" BETWEEN THE CELL LEVEL AND BATTERY LEVEL.
- RATIOS > 100 % REPRESENT A NET GAIN IN CAPACITY.
- THERE IS A VERY GOOD CORRELATION BETWEEN A CAPACITY LOSS OF > 8 % (AS DETERMINED BY THIS METHOD) AND THE ANOMALOUS NASA STANDARD 50 A.H. CELL LOTS.

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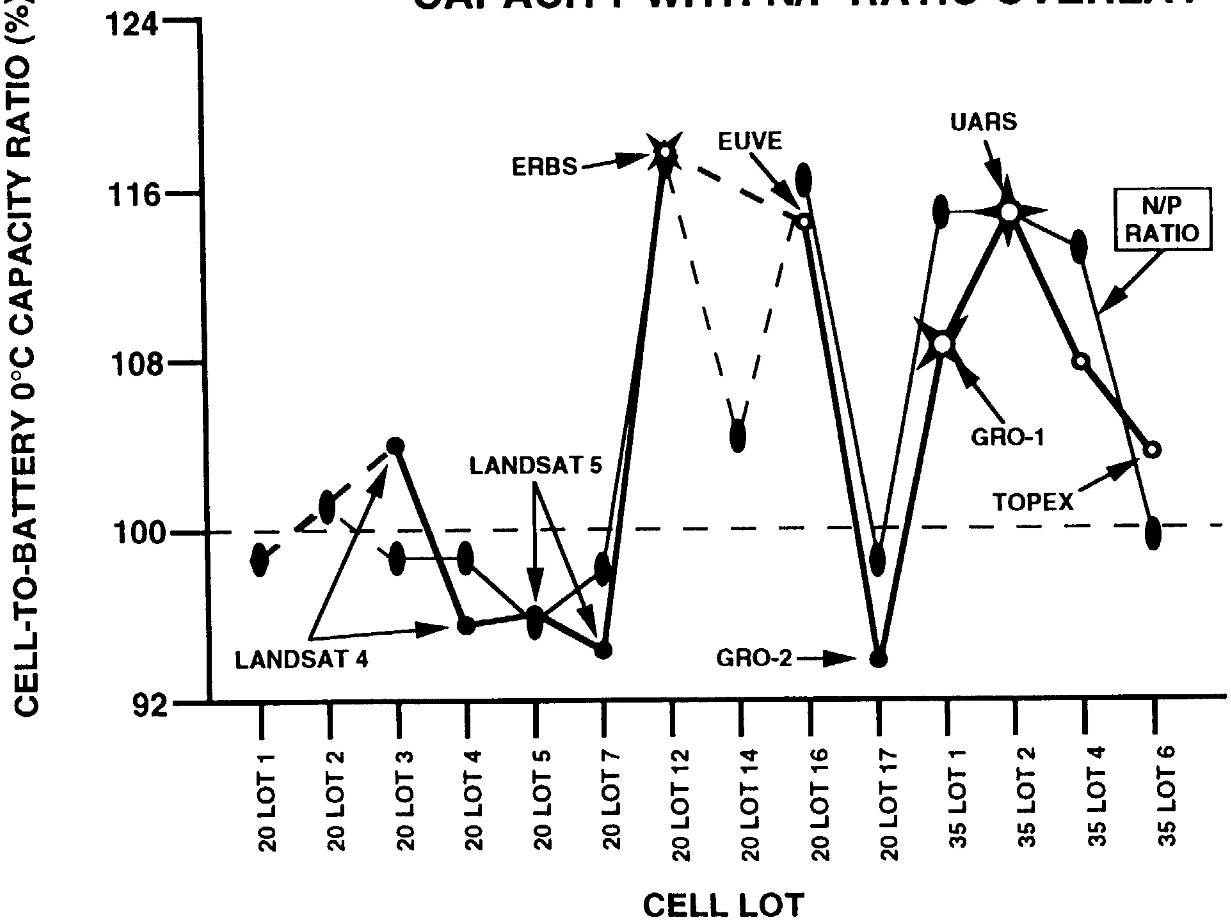
NASA STANDARD 50 A.H. BATTERY CELL HISTORICAL TREND

RATIO OF CELL 0°C CAPACITY TO BATTERY 0°C CAPACITY WITH N/P RATIO OVERLAY



- BATTERIES FROM 50AB20 LOT 2 AND 50AB20 LOT 14 CELLS NOT TESTED FOR CAPACITY AT 0°C (DESIGNATED AS TEST BATTERIES).
- RESEMBLANCE OF THIS RATIO TO THE N/P RATIO (SIZED HERE TO FIT ON THE SAME SCALE) IS REMARKABLE.
- HOWEVER, N/P RATIO IS NOT THE CONTROLLING INFLUENCE. THE FACTOR(S) THAT MAKE THE N/P RATIO HIGH (E.G. HIGH NEGATIVE UTILIZATION) ARE INFLUENCING CAPACITY LOSS.
- EXAMPLE: NASA STANDARD 20 A.H. BATTERY CELL
  - 24ABO6 LOT 4 (SOLAR MAX FLIGHT CELLS)
  - N/P = 2.03
  - NEGATIVE UTILIZATION = 81 %
  - 0°C CELL/BATTERY CAPACITY RATIO = 98.2%
  - LIFE: 2 MONTHS SHORT OF 10 YEARS PRIOR TO ORBITAL RE-ENTRY.

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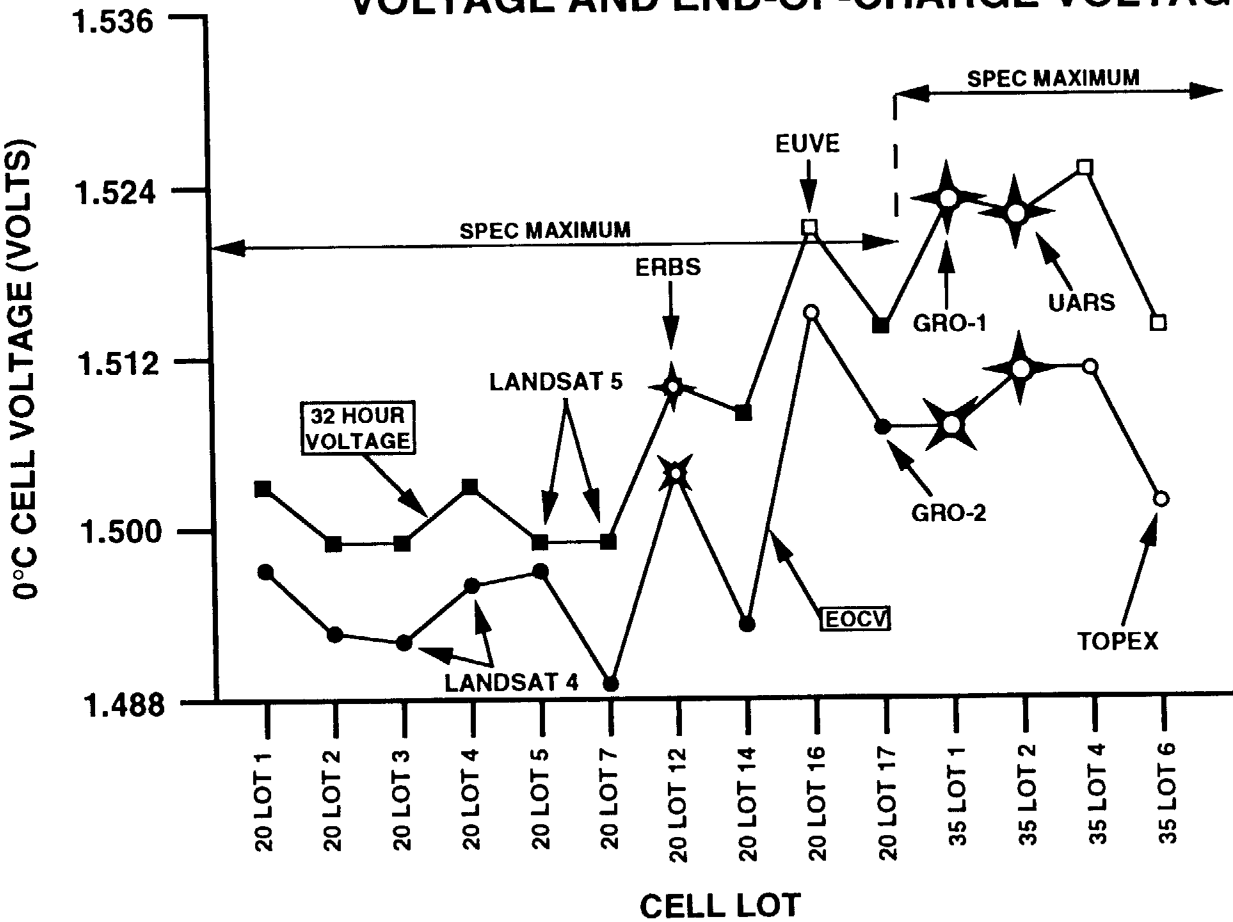
NASA STANDARD 50 A.H. BATTERY CELL HISTORICAL TREND

0°C CELL CAPACITY TEST: 32-HOUR CHARGE VOLTAGE AND END-OF-CHARGE VOLTAGE



- NO SPEC MINIMUM.
- 32 HOUR CHARGE VOLTAGE IS THE NEAREST AVAILABLE DATA FOR PEAK (ROLLOVER) VOLTAGE.
- BOTH PEAK AND END-OF-CHARGE VOLTAGES AT 0°C HAVE BEEN INCREASING, AND ARE 15 - 20 mV HIGHER THAN EARLIER CELL LOTS.
- THE SPEC MAXIMUM WAS CHANGED IN 1989 TO ACCOMMODATE THIS TREND.
- THE TREND RAISES THE CONCERN THAT RECENTLY MADE CELLS MAY NOT BE AS COMPATIBLE WITH NASA STANDARD V/T LEVELS AS OLDER CELLS.
- THERE IS SOME CORRELATION BETWEEN HIGH VOLTAGE IN THE 0°C CAPACITY TEST AND THE ANOMALOUS NASA STANDARD 50 A.H. CELL LOTS, WITH SOME LOTS STILL TBD.

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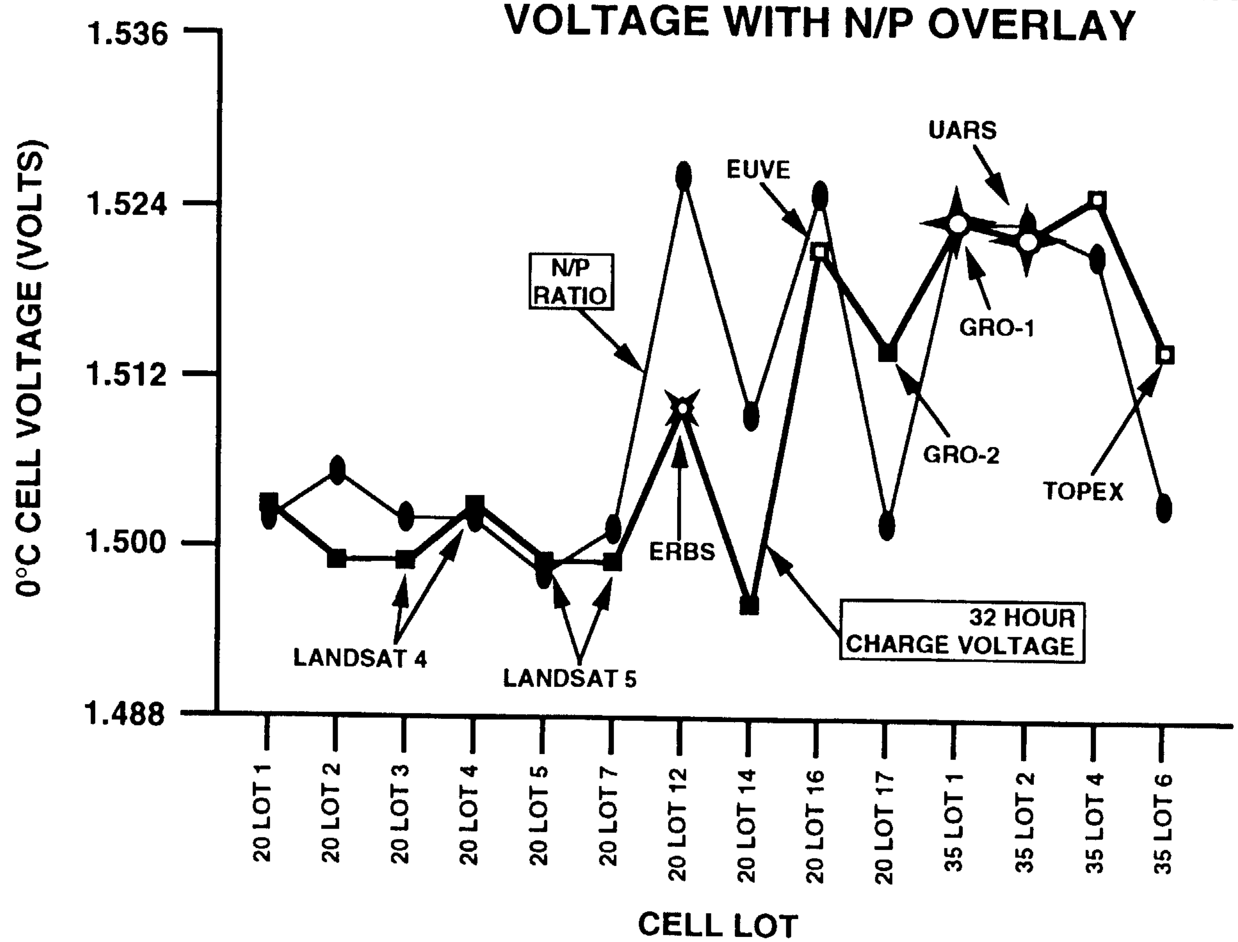
NASA STANDARD 50 A.H. BATTERY CELL HISTORICAL TREND

0°C CELL CAPACITY TEST: 32-HOUR CHARGE VOLTAGE WITH N/P OVERLAY



- THIS TREND ALSO BEARS A CONSIDERABLE RESEMBLANCE TO THE N/P RATIO.

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PRELIMINARY CONCLUSIONS:

- SEVERAL PLATE AND CELL PARAMETERS HAVE MIGRATED WITHIN THEIR SPEC LIMITS OVER THE YEARS (IN SOME CASES, FROM ONE EXTREME TO THE OTHER).
- SEVERAL PARAMETRIC RELATIONSHIPS, NOT GENERALLY MONITORED AND THEREFORE NOT UNDER SPECIFICATION CONTROL, HAVE ALSO MIGRATED OVER THE YEARS.
- MANY OF THESE CHANGES APPEAR TO HAVE TAKEN PLACE AS A NATURAL CONSEQUENCE OF CHANGES IN GE/GAB MATERIALS AND PROCESSES. THE EXACT NATURE OF THESE CHANGES IS STILL UNDER INVESTIGATION.
- SEVERAL OF THESE FACTORS MAY BE "CONSPIRING" TO AGGRAVATE KNOWN CELL FAILURE MECHANISMS (FACTORS SUCH AS HEAVIER PLATE, LESS TEFLON AND/OR LESS-UNIFORM TEFLON, LESS ELECTROLYTE) BUT ALL ARE STILL IN SPEC (WHERE SPECS EXIST)

PRELIMINARY CONCLUSIONS (continued)

- THE WEIGHT OF THE EVIDENCE COLLECTED TO CHARACTERIZE THE ANOMALIES AND TO CHARACTERIZE THE NEGATIVE ELECTRODE ITSELF, STRONGLY SUGGESTS THAT ALTERATIONS TO THE STRUCTURE, COMPOSITION, UNIFORMITY AND EFFICIENCY OF THE NEGATIVE ELECTRODE ARE AT THE HEART OF THE BATTERY PERFORMANCE PROBLEMS CURRENTLY BEING EXPERIENCED.

- FURTHER INVESTIGATION AT ALL LEVELS (PLATE, CELL, BATTERY, AND SYSTEM) CONTINUES TO BE WARRANTED; HOWEVER, PLATE AND CELL INVESTIGATIONS HAVE YIELDED THE MOST USABLE AND CORRELATABLE DATA.

ACKNOWLEDGEMENTS

SINCERE THANKS TO THESE PROFESSIONAL MEN AND WOMEN, FOR THEIR CONTRIBUTIONS OF TIME, EFFORT, INSIGHT AND EXPERIENCE:

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COMSAT LABS

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NORTH CAROLINA STATE UNIVERSITY

DR. PETER FEDKIW

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THE JPL/NASA/TAMU NICKEL-CADMIUM BATTERY MODEL DEVELOPMENT STATUS

JPL

PAUL TIMMERMAN

JET PROPULSION LABORATORY,
PASADENA, CALIFORNIA

NOVEMBER 17-19, 1992

NASA BATTERY WORKSHOP
HUNTSVILLE, ALABAMA

BATTERY SYSTEMS GROUP

JPL

OUTLINE

CELL MODEL DEVELOPMENT

BATTERY MODEL DEVELOPMENT

JPL DEVELOPMENT GOALS

APPROACHES SELECTED

NEGATIVE ELECTRODE

POSITIVE ELECTRODE

ADDITIONAL WORK

SUMMARY

CELL MODEL DEVELOPMENT

TEXAS A&M UNIVERSITY DEVELOPED FIRST PRINCIPLES NI-CD BATTERY MODEL

positive electrode

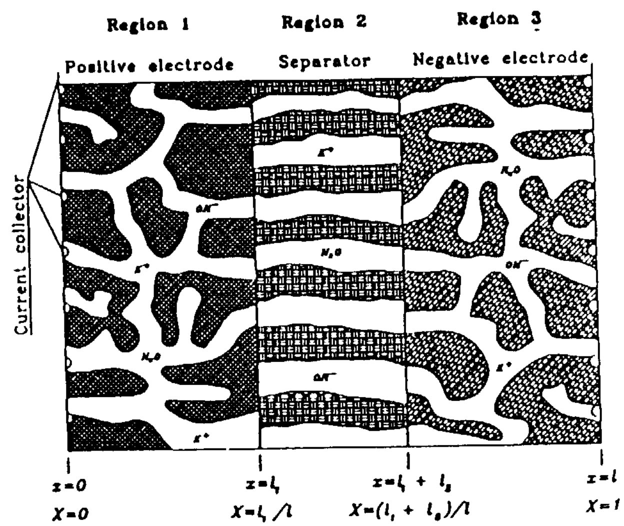
$$NiOOH + H_2O + e^- \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} Ni(OH)_2 + OH^- \quad [1]$$

$$\frac{1}{2} O_2 + H_2O + 2e^- \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} 2\,OH^- \quad [2]$$

negative electrode

$$Cd + 2\,OH^- \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} Cd(OH)_2 + 2e^- \quad [3]$$

$$2\,OH^- \underset{\text{charge}}{\overset{\text{discharge}}{\longleftarrow}} \frac{1}{2} O_2 + H_2O + 2e^- \quad [4]$$



PUBLISHED RESULTS OF EFFORTS

1. D. Fan and R.E. White, "Mathematical Model of a Sealed Nickel-Cadmium Battery", J. Electrochemical Soc., Vol 138, No. 1, pp. 17, January 1991.

2. D. Fan and R.E. White, " Mathematical Modeling of a Nickel-Cadmium Battery: Effects of Intercalation and oxygen Reactions", Vol.138 No. 10, pp. 2952, October 1991.

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BATTERY MODEL DEVELOPMENT

THERMAL MODEL - USES FINITE DIFFENERNCE NODAL MODEL

BATTERY LEVEL MODEL - PROVIDES DESIGN AND CONTROL OPTIONS

CELL DESIGN DATABASE - ALLOWS ENGINEERING LEVEL CELL DESIGN INPUTS

REGIME CONTROL - PROVIDES BATTERY LEVEL REGIME SPECIFICATION

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APPROACHES SELECTED

IMPROVED TREATMENT OF POSITIVE ELECTRODE

- LINEARIZED PROTON DIFFUSION EQUATION IN OXIDE LAYER
- ELECTRONIC CONDUCTIVITY OF OXIDE LAYER

IMPROVE TREATMENT OF NEGATIVE ELECTRODE

- MODIFIED KINETIC EXPRESSION AS PER Pb/PbSO
- IMPROVED SOLID PHASE CONDUCTIVITY

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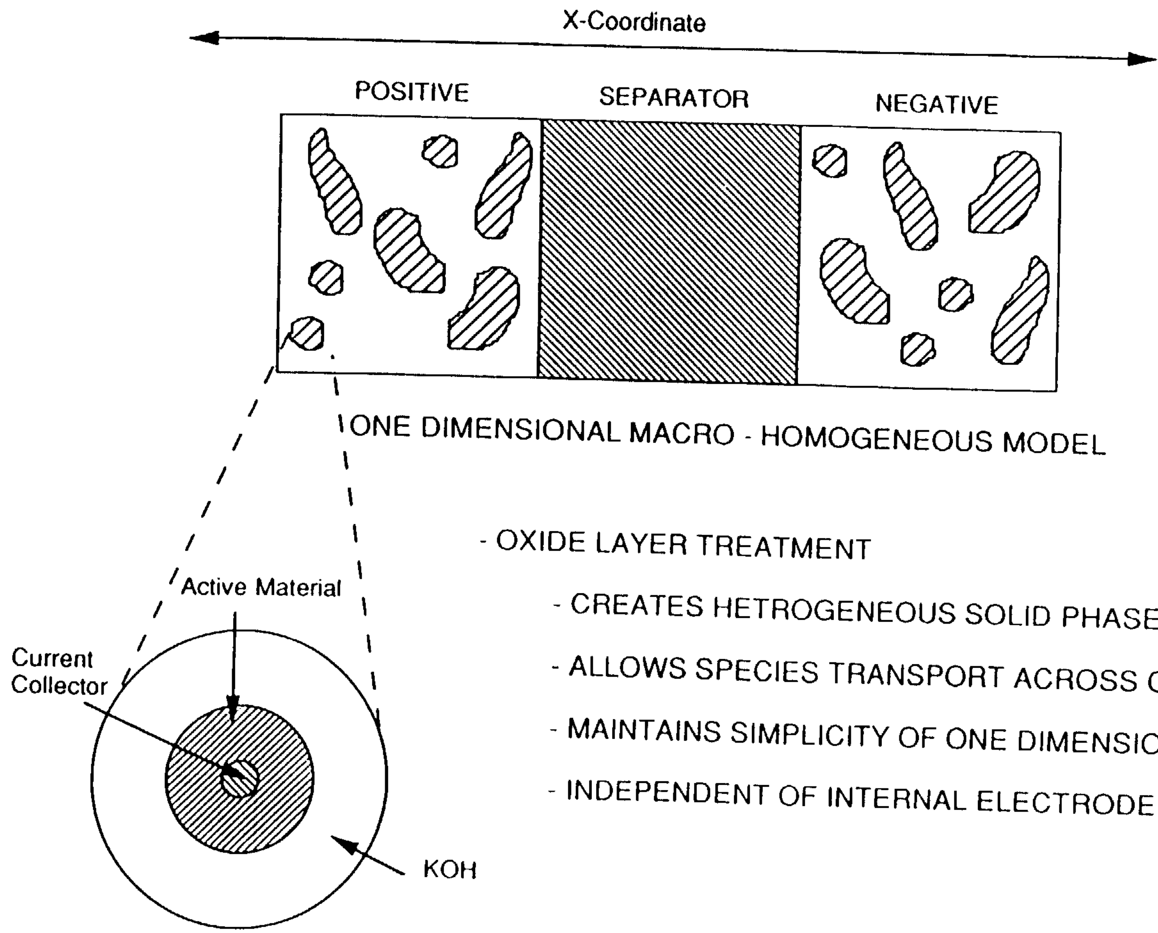
ADDITION OF OXIDE LAYER TO EXISTING MODEL



- OXIDE LAYER TREATMENT
  - CREATES HETROGENEOUS SOLID PHASE
  - ALLOWS SPECIES TRANSPORT ACROSS OXIDE LAYER
  - MAINTAINS SIMPLICITY OF ONE DIMENSIONAL APPROACH
  - INDEPENDENT OF INTERNAL ELECTRODE GEOMETRY

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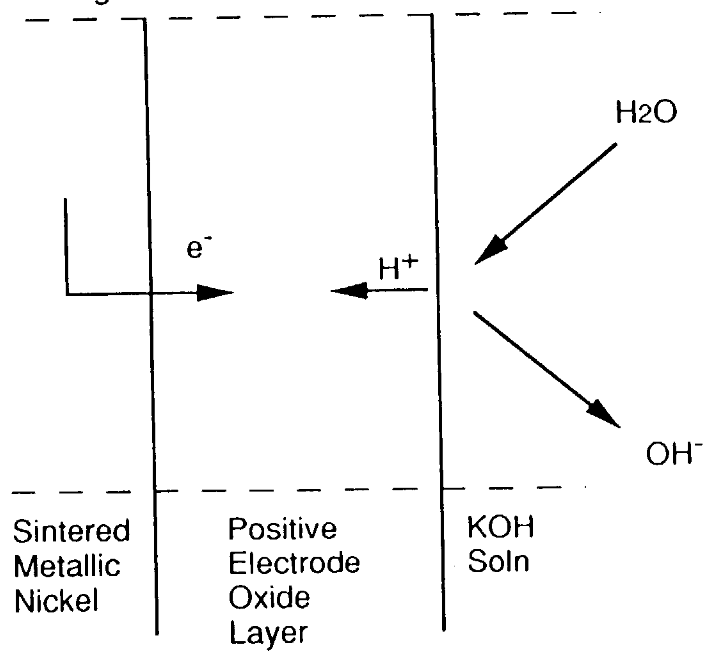
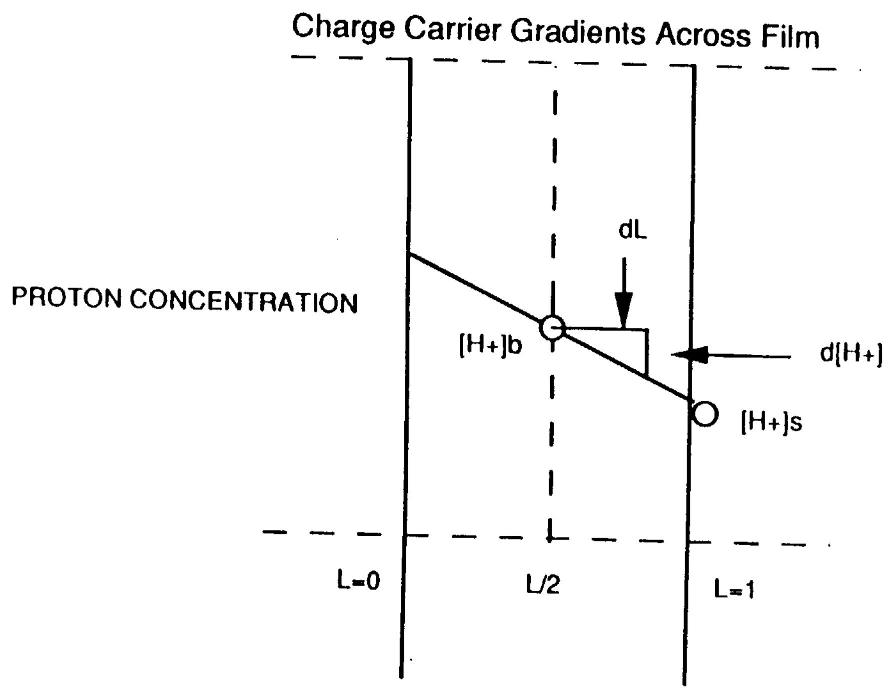
NICKEL OXIDE LAYER CHEMISTRY

Charge Carrier Movement Across Film



- OVERALL REACTION $NiOOH + H_2O + e^- <=> Ni(OH)_2 + OH^-$
- SURFACE REACTION $H_2O <=> OH^- + H^+$
- BULK REACTION $NiOOH + H^+ + e^- <=> Ni(OH)_2$

LINEARIZED PROTON DIFFUSION GRADIENT DIAGRAM



$$[H^+]_S = [H^+]_b - d[H^+] / dL$$

$$d[H^+]/dL = J_{ni} * AL / 2FD$$

Where:
- D is Diffusion Coefficient
- $[H^+]_S$ is Surface Proton Concentration
- $[H^+]_B$ is Bulk Proton Concentration
- L is Film Thickness
- Jni is Reaction Current Density
- A is the Specific Surface Area

ELECTRONIC CONDUCTIVITY OF OXIDE LAYER

$$\left(J_{Ni} + J_{O_2}\right) = -\sigma_{ox} \frac{\partial \phi_{ox}}{\partial y}$$

$$\phi_{ox} = \phi_s - A \int_0^L \frac{\left(J_{Ni} + J_{O_2}\right)}{\sigma_{ox}} \, dy$$

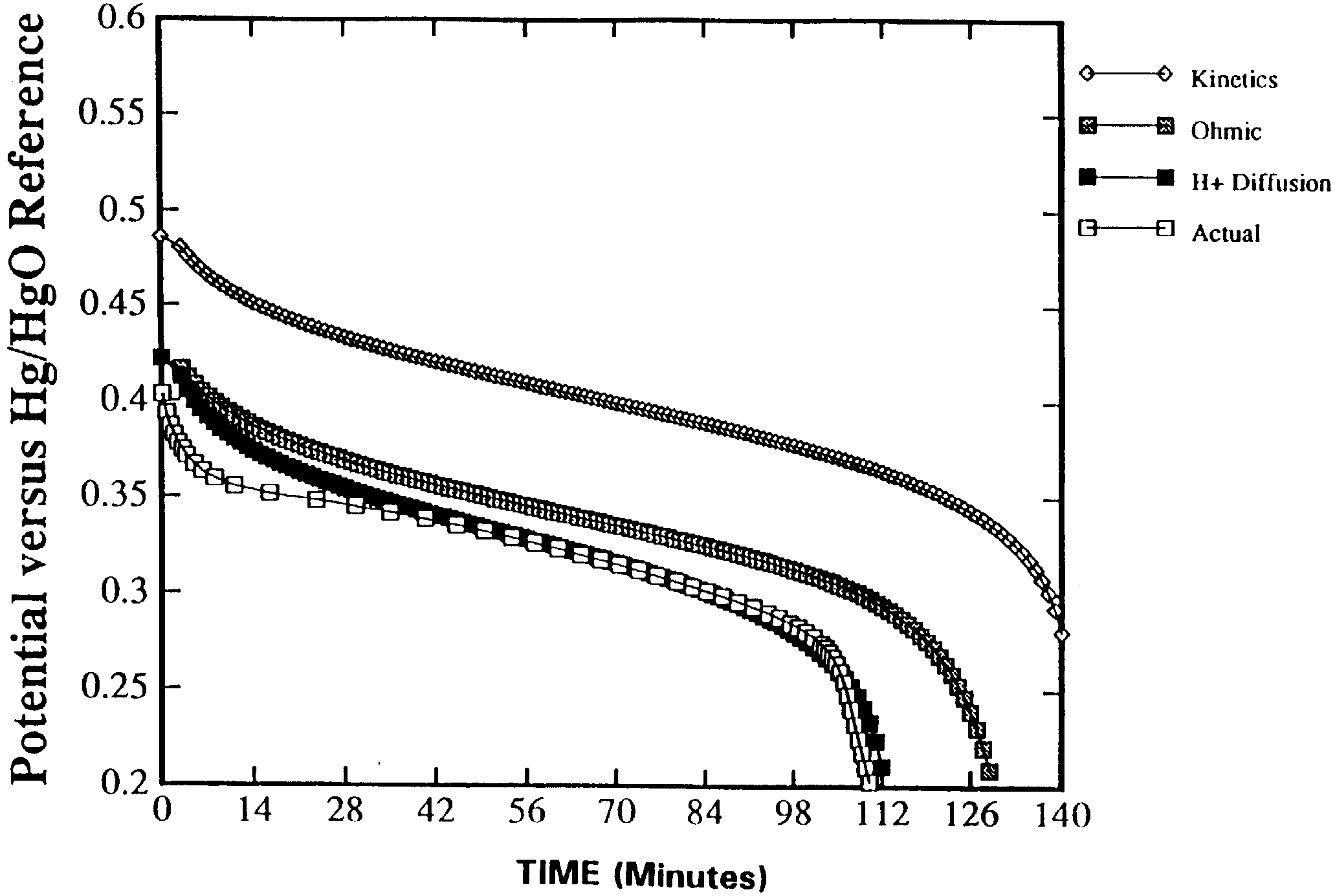
WHERE ϕ_{ox} **IS POTENTIAL IN THE OXIDE PHASE AT THE ELECTROLYTE INTERFACE**
ϕ_s **IS THE POTENTIAL IN THE SOLID MATRIX**
L IS THE OXIDE LAYER THICKNESS
A IS THE SPECIFIC AREA

CONDUCTIVITY OF SOLID OXIDE LAYER IS EXPRESSED AS A SEMICONDUCTOR

$$\sigma_{ox} = \sigma_{\max} e^{-b(1-\theta)^c} \qquad \textit{DISCHARGE}$$

$$\sigma_{ox} = \sigma_{\max} \qquad \textit{CHARGE}$$

Predicted Positive Potentials for Disharge



CADMIUM ELECTRODE KINETICS

MODIFIED AS PER NYUGEN Pb-PbSO4 KINETICS

$$j_{Cd} = i_{0,ref}\, a_{Cd} \left(\frac{\varepsilon_3 - \varepsilon_{03}}{\varepsilon_{max3} - \varepsilon_{03}}\right)^{\zeta 3} \left\{ \left(\frac{C}{C_{ref}}\right)^{\gamma_3} \exp\left[\frac{\alpha_a F}{RT}\eta_3\right] - \left(\frac{\varepsilon_{max3} - \varepsilon_3}{\varepsilon_{max3} - \varepsilon_{03}}\right) \exp\left[\frac{-\alpha_c F}{RT}\eta_3\right] \right\} \quad (5)$$

PRE-EXPONENTIAL AREA TERM INCREASES OVERPOTENTIAL AT LOW STATES-OF-CHARGE

CATHODIC TERM GIVES HIGHER OVERPOTENTIAL AT END-OF-CHARGE

IMPROVES BEGINNING OF LIFE PREDICTIONS

ADDS DEGRADATION / CAPACITY UTILIZATION FUNCTION

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CADMIUM ELECTRODE OHMIC DROP IN X-AXIS

ADDED STATE-OF-CHARGE DEPENDANCE TO OHM'S LAW IN SOLID PHASE

$$\sigma = A * \exp^{-B * (1 - \theta)^C}$$

WHERE σ IS THE CONDUCTIVITY, A,B, AND C ARE CONSTANTS, AND Θ IS SOC

$$i_2 - \sigma_{Cd}\, \epsilon^{exm3} \left(\frac{d\phi_{1,Cd}}{dx} \right) = i_{cell}$$

WHERE i_2 IS CURRENT THROUGH ELECTROLYTE,
i_{cell} IS TOTAL CURRENT FLUX,
exm1 IS THE TORTUOSITY PARAMETER,
ρ_1 IS THE POTENTIAL IN THE SOLID

UTILIZATION ON DISCHARGE NOW DECREASES WITH INCREASED RATE

STRONG EFFECT ON LOCAL CURRENT DENSITY DISTRIBUTION

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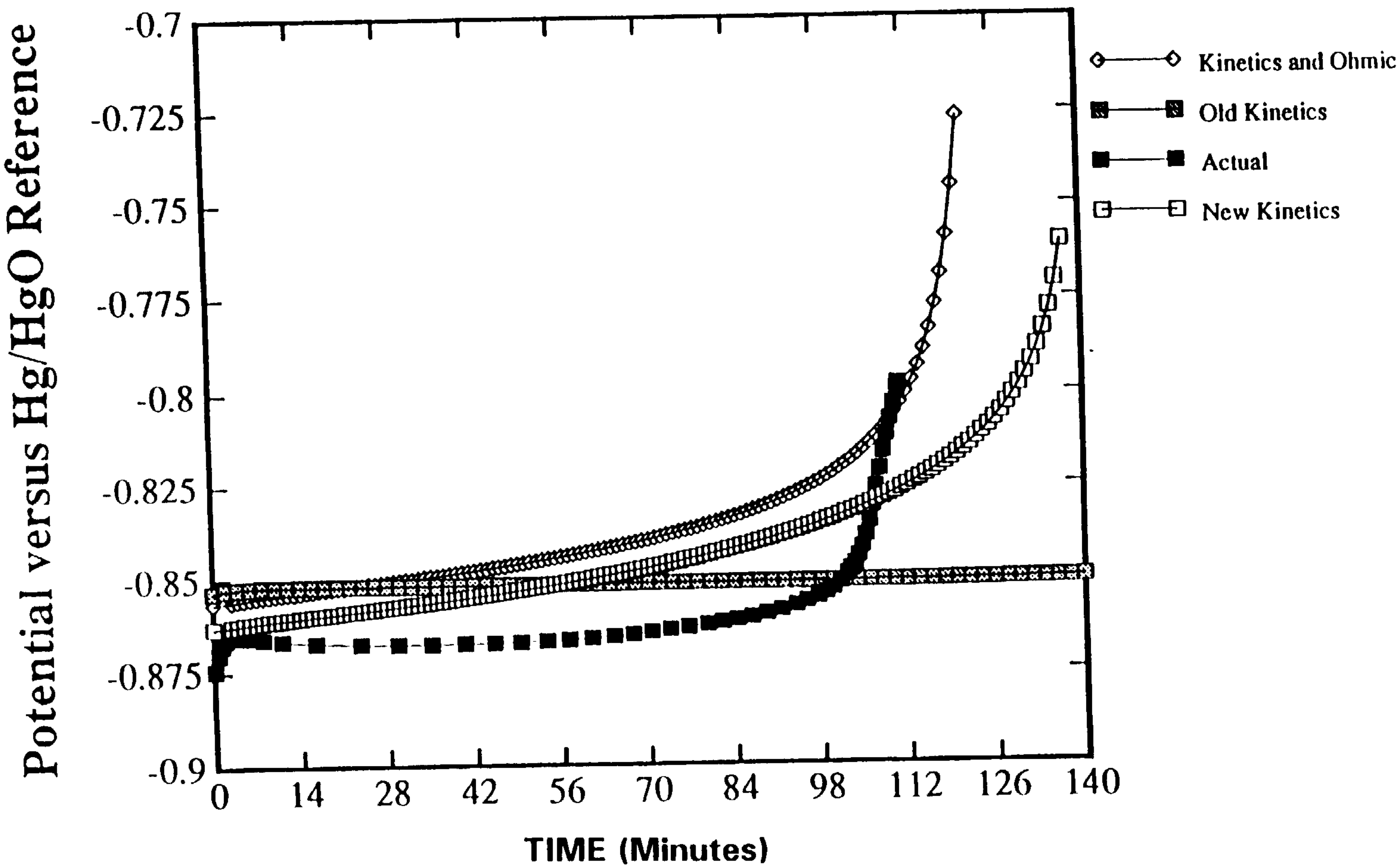
Predicted Negative Potentials for Discharge



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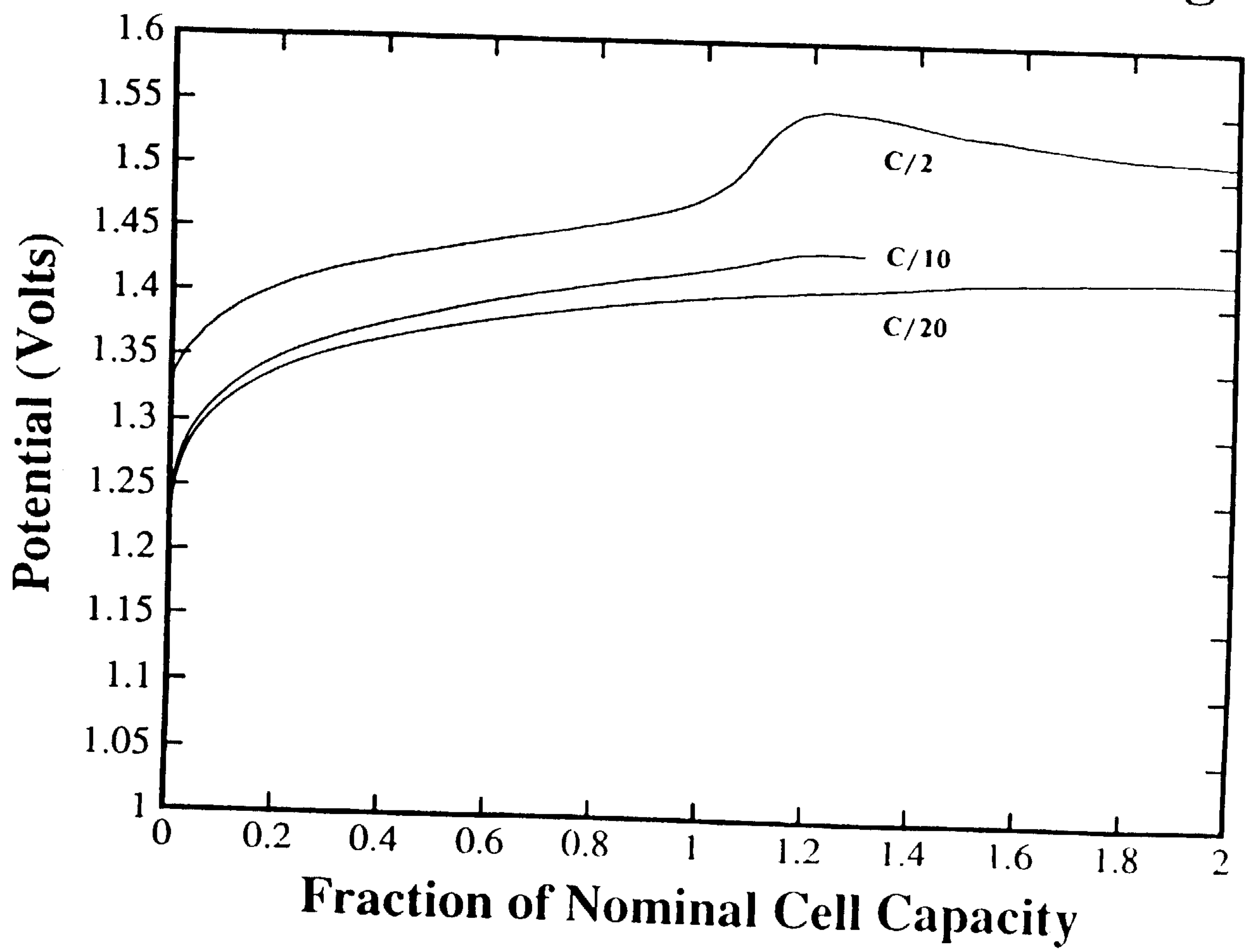
Boilerplate Cell Potentials for Charge



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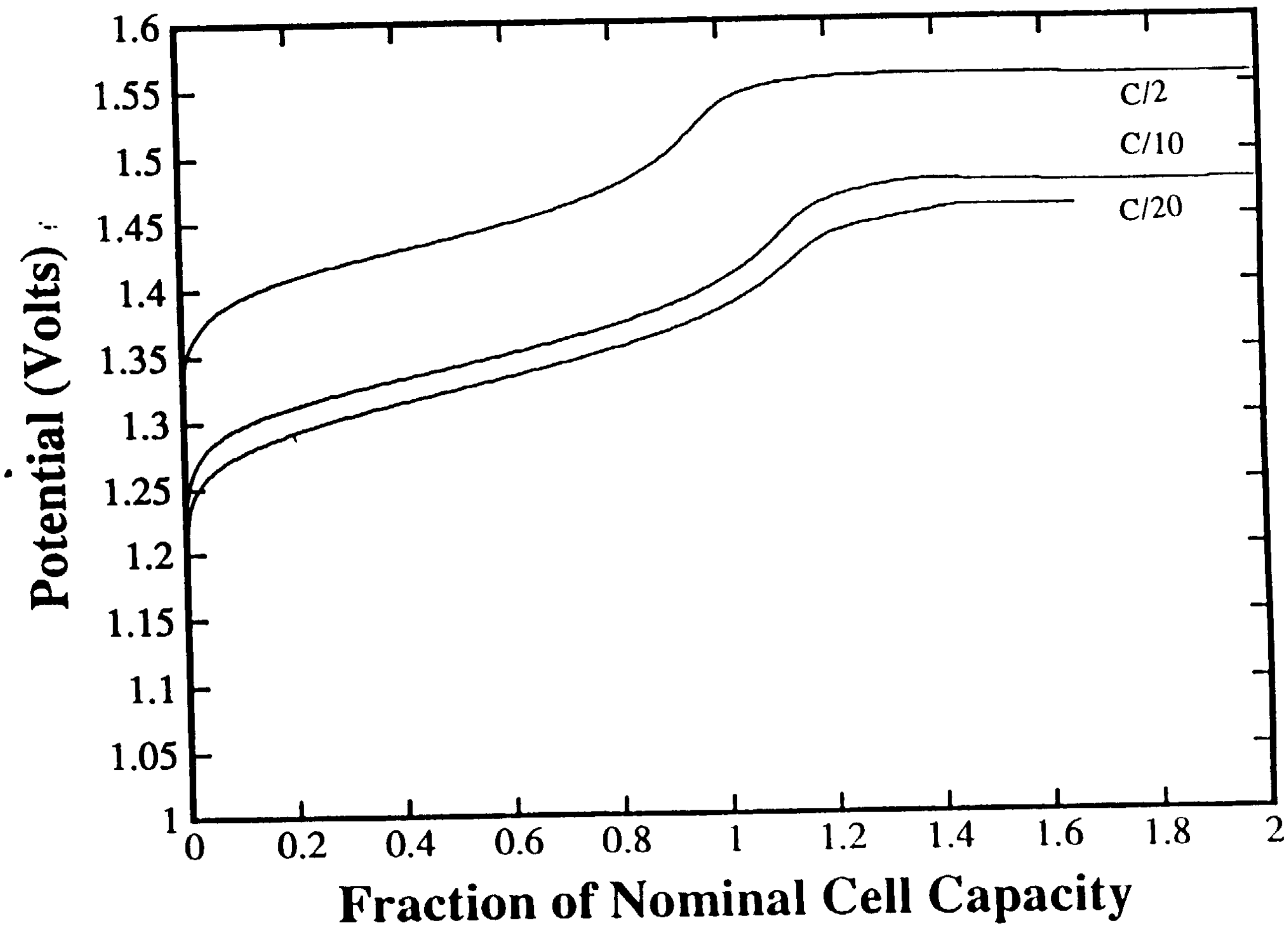
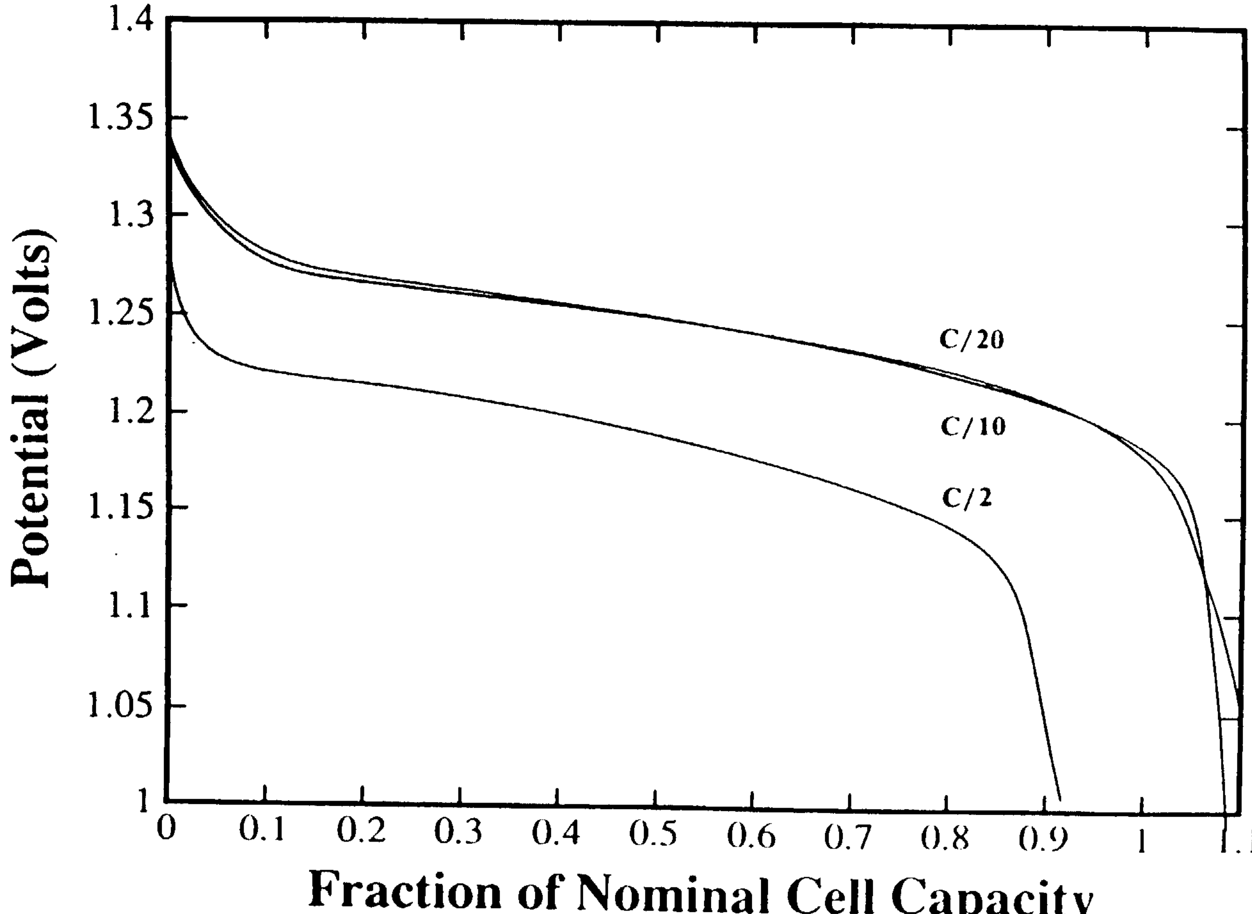
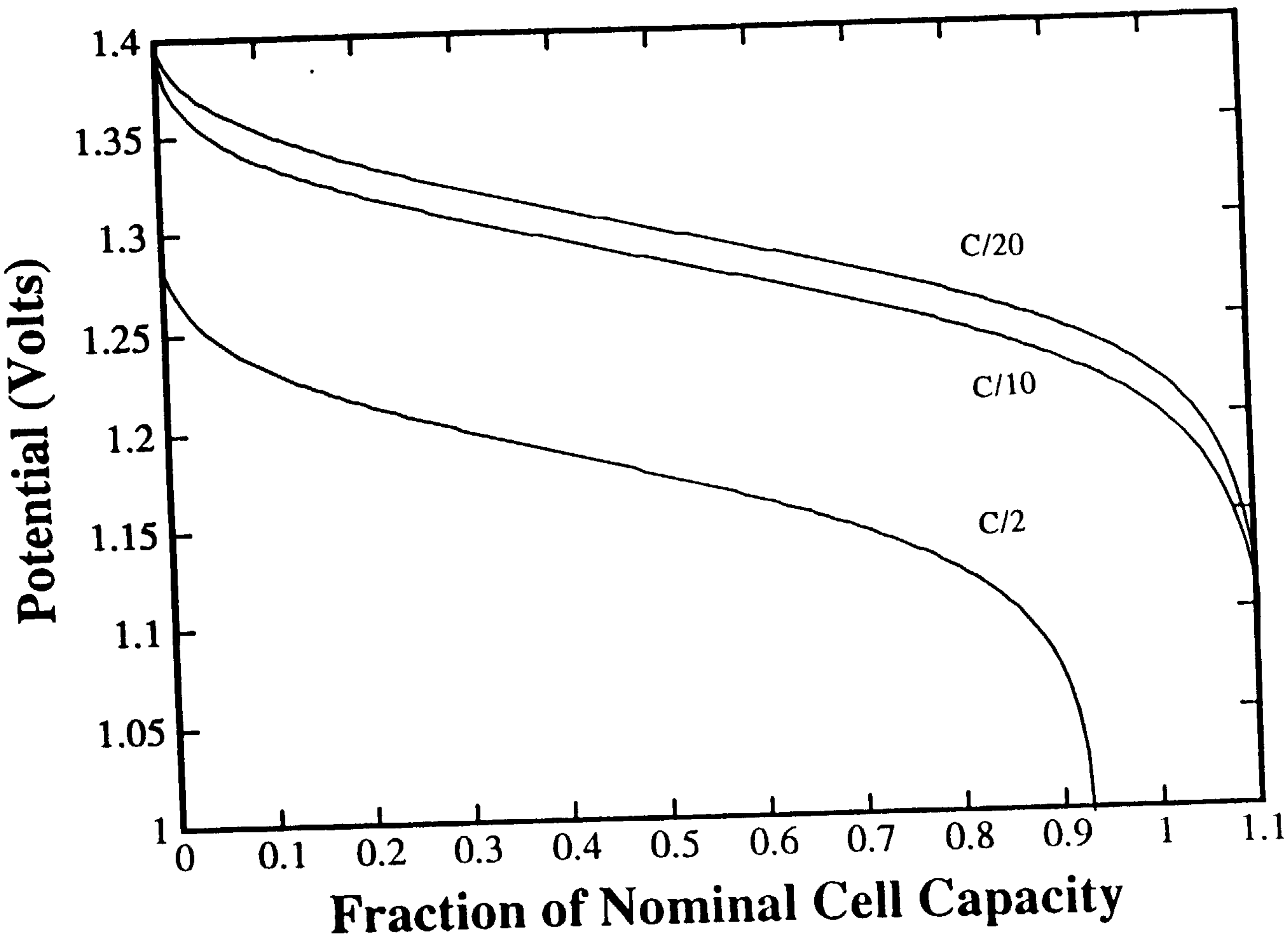
Predicted Cell Potentials for Charge



Boilerplate Cell Potentials for Discharge



Predicted Cell Potentials for Discharge



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SUMMARY

FUNDAMENTAL CELL MODEL DEVELOPMENT CONTINUED

NICKEL OXIDE LAYER DESCRIBED

- ELECTRONIC CONDUCTIVITY OF OXIDE LAYER
- PROTON DIFFUSION THOUGH OXIDE LAYER

CADMIUM ELECTRODE IMPROVED

- IMPROVED KINETIC EXPRESSION
- IMPROVED CONDUCTIVITY EXPRESSION

PERFORMANCE PREDICTIONS ARE SIGNIFICANTLY IMPROVED

BATTERY SYSTEMS GROUP

N93-20510

NiCd CELL RELIABILITY IN THE MISSION ENVIRONMENT

William K. Denson; Reliability Analysis Center, Rome, NY
Glenn C. Klein; Gates Aerospace Batteries, Gainesville, FL

INTRODUCTION

This paper summarizes an effort by Gates Aerospace Batteries (GAB) and the Reliability Analysis Center (RAC) to analyze survivability data for both General Electric and GAB NiCd cells utilized in various spacecraft. For simplicity sake, all mission environments are described as either LEO or GEO. "Extreme value statistical methods" are applied to this database because of the longevity of the numerous missions while encountering relatively few failures. Every attempt has been made to include all known instances of cell-induced-failures of the battery and to exclude battery-induced-failures of the cell. While this distinction may be somewhat limited due to availability of in-flight data, we have accepted the learned opinion of the specific customer contacts to ensure integrity of the common databases.

This paper advances the preliminary analysis reported upon at the 1991 NASA Battery Workshop. That prior analysis was concerned with an estimated 278 million cell-hours of operation encompassing 183 satellites. That paper also cited "no reported failures to date" [see Reference 1]. This analysis reports on 428 million cell hours of operation encompassing 212 satellites. This analysis also reports on seven "cell-induced-failures."

MISSION ENVIRONMENT

Several assumptions have been made concerning both the mission environment and the overall population of cells by which the numbers of cell-hours or cell-cycles are estimated. First for simplicity sake, all mission environments are described as either LEO (predominantly rapid and repetitive cycling) or GEO (predominantly long periods of overcharge followed by brief duty cycles). Generally Polar Orbits are incorporated into the LEO analysis, and Highly Elliptical orbits are incorporated into the GEO analysis. LEO is considered to experience sixteen cycles per day. Second, the analysis assumes twenty-two cells per battery and two batteries per satellite.

The third area of assumption becomes more an area of definition and discrimination. Defining the words *failure, termination,* and *deterioration* can lead to both endless discussion and endless dissension. For purposes of this analysis, *failures* is defined as: outright failure or termination of a cell and/or a battery. Deterioration is defined as: expected performance had deteriorated or degraded to the point that the original mission intention has been significantly limited or compromised either by manifestation of immediate performance deterioration or the limiting of expected life. Discriminating between cell-induced battery failures and battery-induced cell failures encounters the same discussion and dissension. Both definition and discrimination are hampered by different levels of telemetry sophistication for receiving in-flight performance data. This analysis unilaterally accepts both definition and discrimination as proffered by the responsible technical personnel.

It should also be noted that the analysis is being performed at the complete satellite battery level and not the individual cell level, since this is the level for which the data was collected.

MISSION PERFORMANCE

Table 1 contains the detail and arithmetical summary of the 212 satellites reported in this analysis. Details include cell capacity rating, mission environment, launch date and years of operation. Neither customer, program or reason for satellite termination is identified in this listing. Note that four specific indicators of operational life were used since this information was extracted from several sources. They are final or total years of operation, data as of December 1987, data as of January 1991, and data as of April 1992. Total LEI Mission Years reported are 331.7 years; total GEO Mission Years reported are 777.9 years. Note that specific failure data is not included in Table 1.

MISSION SUMMARY

The last page of Table 1 provides the total Mission Summary, the LEO Mission Summary, and the GEO Mission Summary. For 212 spacecraft analyzed, 1109.5 Total Mission Years have accumulated. This equivalent 428 million cell-hours is considerably greater than the 278 million cell-hours reported on last year [Reference 1]. In addition, the previous report did not differentiate between the various mission environments.

For the LEO Mission Environment, 74 spacecraft or satellites were analyzed. Accumulated are 332 Total Mission Years or 85 million Total Cell-Cycles. For the GEO Mission Environment, 138 spacecraft or satellites were analyzed. Accumulated are 778 Total Mission Years or 300 million Total Cell-Hours.

As previously stated, cell-induced failures are not cited or summarized in Table 1. Neither will these failures be tabulated separately due to their sensitive nature. In brief summary, one "long term" GEO has occurred, and six LEO failures have occurred ranging from approximately four thousand to thirty-two thousand cycles. Again note that a cell-induced performance failure does not necessarily imply a mission termination.

STATISTICAL ANALYSIS OF RELIABILITY DATA

A simple method of analyzing reliability data is to determine a failure rate by dividing the number of observed failures by the number of operating hours or cycles. The use of a failure rate inherently assumes that the rate of failures are occurring in a time independent random manner.

Since it is known that batteries typically exhibit wearout characteristics, or an increasing failure rate in time, a failure rate is too simplistic of a metric describing the reliability of the battery.

Weibull analysis is often used to quantify, from empirical time (or cycle) to failures data, the rate of occurrence of failure as a function of time. A complete Weibull analysis usually consists of plotting the cumulative percentage of failures against time on Weibull probability paper when a large percentage of the population has failed. This methodology, however, looses its usefulness when the population contains few or no failures. Since there have been a relatively small percentage of the population failing, alternative analysis methods were required.

The appropriate analysis methodology under these circumstances is the use of confidence limits in conjunction with the Weibull distribution. Nelson [Reference 2] has proposed such a methodology which will be used in this analysis. Background on the Weibull distribution and Nelson's methodology is given in the following paragraphs.

The probability density function f(t) of the Weibull time to failure distribution is;

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

where

α	=	characteristic life, time to 63% population failure
β	=	Weibull shape parameter
t	=	time

The reliability (probability of survival to a time t) is;

$$R(t) = e^{-\left(\frac{t}{\alpha}\right)^{\beta}}$$

And the hazard rate h(t) (or instantaneous failure rate), given the part has survived until time t is;

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

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

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

where

T_i = Time to fail of the i^{th} part or survival time of the i^{th} part if it has not failed

r = Number of failures

n = Total population of parts

Since the database contains few failures, the characteristic life implied by this estimate is suspect. As stated previously, the appropriate analysis methodology to use under these conditions is to apply confidence limits to derive worst case reliability values. From this, lower bound estimates of lifetimes can be made within a given confidence level. To accomplish this, the Chi-square distribution can be utilized. The lower confidence limit for the Weibull distribution is:

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

where

χ^2 = the chi-square percentile at C% confidence and r failures

This value of characteristic life was then calculated for various values of betas and various confidence levels for both LEO and GEO. Table 1 summarizes the data used. The sum of the individual survival times raised to the power beta, as a function of beta, are as follows:

β	$\sum_{i=1} T_i^{\beta}$	
	LEO	GEO
1	331.9	777.9
2	2,911	6,220
3	38,182	57,977
4	624,847	588,803
5	11,472,255	6,357,012
6	2.236×10^8	7.215×10^7

The values of the Chi-square percentiles are given as follows:

C Confidence Level	Chi-Square Percentile	
	LEO (6 failures) 14 Degrees of Freedom	GEO (1 failures) 4 Degrees of Freedom
.25	10.17	1.923
.50	13.34	3.357
.75	17.12	5.385
.90	21.06	7.779
.95	23.68	9.488
.975	26.12	11.14
.990	29.14	13.68
.995	31.32	14.86
.999	36.12	18.47

The resulting lower limit characteristic life estimates as a function of confidence (C) and beta value are summarized in the following table for both LEO and GEO applications.

α FOR LEO APPLICATIONS

β	C								
	.25	.50	.75	.90	.95	.975	.990	.995	.999
1	65.3	49.8	38.8	31.5	28.0	25.4	22.8	21.2	18.4
2	23.9	20.9	18.4	16.6	15.7	14.9	14.1	13.6	12.7
3	19.6	17.9	16.5	15.4	14.8	14.3	13.8	13.5	12.8
4	18.7	17.5	16.4	15.6	15.2	14.8	14.4	14.1	13.6
5	18.6	17.7	16.8	16.1	15.7	15.4	15.1	14.9	14.5
6	18.8	17.9	17.2	16.6	16.3	16.1	15.8	15.6	15.2

α FOR GEO APPLICATIONS

β	C								
	.25	.50	.75	.90	.95	.975	.990	.995	.999
1	809	463	289	200	164	139	117	105	84
2	80.4	60.9	48.1	40.0	36.2	33.4	30.6	28.9	25.9
3	39.2	32.6	27.8	24.6	23.0	21.8	20.6	19.8	18.4
4	28.0	24.3	21.6	19.7	18.8	18.0	17.2	16.8	15.9
5	23.1	20.7	18.8	17.5	16.8	16.2	15.7	15.4	14.7
6	20.5	18.7	17.3	16.3	15.7	15.3	14.9	14.7	14.1

As an example, if a beta value of 4 is assumed, one can be 90% confident that the characteristic life for LEO applications is a minimum of 15.6 years.

If it is desired to calculate the time (t) to the P percentile failure of the population, the following can be used;

$$t = \alpha\left[-\ln\left(1 - \frac{P}{100}\right)\right]^{\frac{1}{\beta}}$$

If the characteristic life is the lower confidence limit as tabulated previously, the time to P percent failure will also be the lower confidence limit. For example, using the characteristic life of 15.6 years for beta = 4 and 90% confidence, the worst case time (at 90% confidence) to reach 1% failure is;

$$t = 15.6\left[-\ln\left(1 - \frac{1}{100}\right)\right]^{\frac{1}{4}} = 4.94 \text{ years}$$

In this example, there is 90% confidence that the time to 1% failure will be greater than 4.94 years.

DISCUSSION ON LONGEVITY OF LEO MISSIONS

Let us assume that five years in LEO environment (29,200 cycles) is a typical mission life time requirement. Then several superlatives can be shown. First, 24 of the 74 LEO missions analyzed were operated beyond that benchmark including one mission for 22 years. Second, testing of a four-cell pack of 26.5 Amp-Hour cells has recently achieved 11.7 years (68,110 cycles) in a LEO test regime. This cell pack (Pack No. 0026G) is currently under test at Crane-NSWC at 10°C and 20% DOD.

SUMMARY AND RECOMMENDATIONS

This database contains substantial updating and upgrading from our previous report. The previous report cited 183 satellites operating for 278 million cell-hours and "no reported failures." This report contains 212 satellites operating for 428 million cell-hours and seven reported failures. We continue to use the extreme value statistical methods of Wayne Nelson as the most viable analysis technique due to relatively few failures.

Predictions of the Characteristic Life and times to percentile failures based upon assumed β values has shown a small decrease in the "predicted life" due to the observance of failures. However, these estimates appear more realistic because any failure improves the estimation of Confidence Intervals; and because the total base of survivability increased 54%.

TABLE 1:GAB NiCd PERFORMANCE IN MISSION ENVIRONMENT

STATUS AS OF JULY, 1992 — ( ) FINAL; unmarked as of 4/92 — * as of 12/87; ** as of 1/91

RATING A-H	MISSION	LAUNCH DATES	YEARS OF OPERATION	LEO YEARS	GEO YEARS
4	LEO	66/02	(1.25)	1.3	
4	LEO	66/02	(4.5)	4.5	
4	LEO	66/10	(2.0)	2.0	
4	LEO	66/12	(20)	20.0	
4	LEO	67/01	(0.9)	0.9	
4	LEO	67/03	(2.4)	2.4	
4	LEO	67/04	(2.8)	2.8	
12	LEO	67/04	[22.0]	22.0	
4	LEO	67/11	17.8*	17.8	
4	LEO	67/11	(2)	2.0	
4	LEO	68/08	(0.2)	0.2	
4	LEO	68/08	(0.9)	0.9	
4	LEO	68/12	(7.2)	7.2	
4	LEO	69/02	(4.8)	4.8	
6	LEO	69/04	(1.75)	1.8	
4	LEO	70/01	(1.4)	1.4	
4	LEO	70/12	(0.7)	0.7	
6	LEO	70/12	(0.8)	0.8	
15	GEO	71/01	14.6*		14.6
15	GEO	71/12	(11.5)		11.5
15	GEO	72/01	13.6*		13.6
15	GEO	72/06	14.0*		14.0
6	LEO	72/07	(5.75)	5.8	
6	LEO	72/10	(2.2)	2.2	
7	GEO	72/11	(10.6)		10.6
6	LEO	72/12	(7.25)	7.3	
7	GEO	73/04	(10.2)		10.2
15	GEO	73/08	(9.8)		9.8
6	LEO	73/11	(2.6)	2.6	
6	LEO	73/12	(5.0)	5.0	
7	GEO	74/04	(9.0)		9.0
7	GEO	74/10	[9.8]		9.8
24	GEO	74/11	10.8*		10.8
6	LEO	75/01	(5.0)	5.0	
7	GEO	75/05	[9.5]		9.5
24	GEO	75/05	10.2*		10.2
6	LEO	75/06	(4.5)	4.5	
12	LEO	75/06	[3.0]	3.0	
24	GEO	75/09	9.9*		9.9
6	LEO	75/10	(0.4)	0.4	
6	LEO	75/11	(5.6)	5.6	
6	LEO	75/?	(1.0)	1.0	
24	GEO	76/01	9.6*		9.6

TABLE 1:Cont'd.

STATUS AS OF JULY, 1992 — ( ) FINAL; unmarked as of 4/92 — * as of 12/87; ** as of 1/91

RATING A-H	MISSION	LAUNCH DATES	YEARS OF OPERATION	LEO YEARS	GEO YEARS
2	LEO	76/03	(4.0)	4.0	
2	LEO	76/03	(1.0)	1.0	
10	GEO	76/03	(3.0)		3.0
6	LEO	76/04	(3.0)	3.0	
24	GEO	76/05	[8.5]		8.5
7	GEO	76/07	[9.1]		9.1
24	GEO	76/07	9.1		9.1
7	GEO	77/03	8.4*		8.4
24	GEO	77/05	8.2*		8.2
6	GEO	77/06	(7)		7.0
6	LEO	77/08	[13]	13.0	
6	LEO	77/12	(3.0)	3.0	
6	GEO	78/01	7.7*		7.7
24	GEO	78/01	7.6*		7.6
15	GEO	78/02	(0.6)		0.6
24	GEO	78/02	14.2		14.2
6	LEO	78/03	(5.5)	5.5	
24	GEO	78/03	7.4*		7.4
4	GEO	78/04	(3.8)		3.8
7	GEO	78/05	7.2**		7.2
15	GEO	78/05	[6.0]		6.0
24	GEO	78/06	[7.2]		7.2
7	GEO	78/08	(0.3)		0.3
6	LEO	78/10	12.2**	12.2	
15	GEO	78/10	11.2**		11.2
15	GEO	78/11	12.2**		12.2
15	GEO	78/12	[2.8]		2.8
17	GEO	78/12	6.7*		6.7
7	GEO	79/08	6.0*		6.0
15	GEO	79/09	10.5		10.5
6	LEO	79/10	[10]	10.0	
15	GEO	80/02	(4.4)		4.4
24	LEO	80/02	[9.8]	9.8	
15	GEO	80/04	9.7**		9.7
6	LEO	80/05	(1.0)	1.0	
6	GEO	80/09	(2.8)		2.8
22	GEO	80/11	4.8*		4.8
35	GEO	80/12	11.3		11.3
24	GEO	81/02	(4.5)		4.5
6	GEO	81/05	(3.6)		3.6
12	GEO	81/05	8.6**		8.6
35	GEO	81/05	10.9		10.9
6	LEO	81/07	11.0	11.0	
5	GEO	81/08	4.0*		4.0

TABLE 1:Cont'd.

STATUS AS OF JULY, 1992 — ( ) FINAL; unmarked as of 4/92; * as of 12/87; ** as of 1/91

RATING A-H	MISSION	LAUNCH DATES	YEARS OF OPERATION	LEO YEARS	GEO YEARS
22	GEO	81/09	4.1*		4.1
17	GEO	81/11	4 .0 *		4.0
35	GEO	81/12	10.4		10.4
17	GEO	82/01	3.85 *		3.9
17	GEO	82/02	10.2		10.2
24	LEO	82/02	0.8	0.8	
35	GEO	82/03	10.1		10.1
12	GEO	82/04	(.8)		0.8
17	GEO	82/06	9.9		9.9
50	LEO	82/07	8.5**	8.5	
17	GEO	82/08	9.7		9.7
35	GEO	82/09	9.6		9.6
24	GEO	82/10	9.5		9.5
35	GEO	82/10	9.5		9.5
17	GEO	82/11	2.8*		2.8
22	GEO	82/11	9.4		9.4
15	GEO	83/02	9.2		9.2
15	GEO	83/02	2.5*		2.5
30	LEO	83/03	9.1	9.1	
6	GEO	83/04	7.8 *		7.8
30	LEO	83/05	1.0	1.0	
12	LEO	83/06	4.2	4.2	
17	GEO	83/06	2.2*		2.2
24	GEO	83/06	8.8		8.8
24	GEO	83/06	8.8		8.8
6	LEO	83/07	9.0	9.0	
21	GEO	83/07	2.1*		2.1
12	GEO	83/08	8.6		8.6
12	GEO	83/08	4.0**		4.0
40	GEO	83/08	8.5		8.5
24	GEO	83/09	8.5		8.5
4	GEO	84/01	(1.6)		1.6
6	LEO	84/02	8.5	8.5	
50	LEO	84/03	6.8**	6.8	
12	LEO	84/04	5.5	5.5	
15	GEO	84/06	7.8		7.8
4	LEO	84/08	3.0**	3.0	
5	GEO	84/08	1.0*		1.0
21	GEO	84/08	1.0*		1.0
25	GEO	84/08	7.7		7.7
15	GEO	84/09	7.6		7.6
12	GEO	84/10	5.0		5.0
17	GEO	84/10	2.6*		2.6
50	LEO	84/10	6.2*	6.2	

TABLE 1:Cont'd.

STATUS AS OF JULY, 1992 | ( ) FINAL unmarked as of 4/92 | * as of 12/87 **as of 1/91

RATING A-H	MISSION	LAUNCH DATES	YEARS OF OPERATION	LEO YEARS	GEO YEARS
15	GEO	84/11	.8*		0.8
17	GEO	84/11	7.6		7.6
25	GEO	84/11	7.6		7.6
24	GEO	85/02	7.2		7.2
35	GEO	85/02	[0.6]		0.6
24	GEO	85/03	2.5**		2.5
25	GEO	85/04	7.0		7.0
21	GEO	85/06	2.8**		2.8
21	GEO	85/06	0.2* *		0.2
35	GEO	85/06	[4.5]		4.5
50	GEO	85/07	7.0		7.0
12	LEO	85/08	[6.0]	6.0	
25	GEO	85/08	6.7		6.7
27	GEO	85/08	6.7		6.7
15	GEO	85/10	6.5		6.5
35	GEO	85/10	6.5		6.5
4	GEO	86/02	[4.0]		4.0
24	GEO	86/03	6.9		6.9
6	LEO	86/09	5.8	5.8	
30	LEO	86/10	5.7	5.7	
12	LEO	86/11	3.1**	3.1	
35	GEO	86/12	6.3		6.3
6	GEO	87/02	5.2		5.2
30	LEO	87/06	4.8	4.8	
50	GEO	87/07	5.0		5.0
12	LEO	87/09	2.2**	2.2	
12	LEO	87/09	2.2**	2.2	
27	GEO	87/09	5.3		5.3
40	GEO	87/11	5.4		5.4
35	GEO	88/02	3.0**		3.0
6	GEO	88/03	(0.8)		0.8
30	LEO	88/03	4.1	4.1	
12	LEO	88/04	1.7	1.7	
12	LEO	88/06	1.5	1.5	
12	LEO	88/06	1.5	1.5	
24	LEO	88/07	4.0	4.0	
12	GEO	88/07	3.7		3.7
12	LEO	88/08	1.3**	1.3	
30	GEO	88/09	3.6	3.6	
40	GEO	88/09	3.5		3.5
35	GEO	88/12	3.3		3.3
35	GEO	89/02	3.1		3.1
40	GEO	89/03	3.0		3.0
30	GEO	89/05	2.9		2.9

TABLE 1:Cont'd.

STATUS AS OF JULY, 1992

( ) FINAL
unmarked as of 4/92

* as of 12/87
**as of 1/91

RATING A-H	MISSION	LAUNCH DATES	YEARS OF OPERATION	LEO YEARS	GEO YEARS
35	GEO	89/06	2.8		2.8
35	GEO	89/06	2.8		2.8
40	GEO	89/06	2.8		2.8
21	GEO	89/08	2.6		2.6
35	GEO	89/08	2.6		2.6
5	GEO	89/09	2.5		2.5
35	GEO	89/09	2.5		2.5
35	GEO	89/10	2.4		2.4
24	LEO	89/11	2.4	2.4	
35	GEO	89/12	2.3		2.3
35	GEO	89/12	2.3		2.3
35	GEO	90/01	2.1		2.1
10	LEO	90/02	2.1	2.1	
35	LEO	90/02	2.1	2.1	
35	GEO	90/03	2.0		2.0
18	GEO	90/06	1.8		1.8
15	LEO	90/07	1.7	1.7	
35	GEO	90/07	1.7		1.7
17	GEO	90/08	1.7		1.7
21	GEO	90/08	1.7		1.7
35	GEO	90/08	1.7		1.7
35	GEO	90/08	1.7		1.7
32	GEO	90/10	1.5		1.5
35	GEO	90/10	1.5		1.5
35	GEO	90/11	1.4		1.4
40	GEO	90/11	1.4		1.4
30	LEO	90/12	1.3	1.3	
35	GEO	91/01	1.2		1.2
32	GEO	91/03	1.1		1.1
50	LEO	91/04	1.0	1.0	
30	LEO	91/05	0.9	0.9	
35	GEO	91/07	0.8		0.8
17	GEO	91/08	0.7		0.8
40	GEO	91/08	0.7		0.7
50	LEO	91/09	0.6	0.6	
40	GEO	91/11	0.3		0.3
50	LEO	91/11	0.3	0.3	

TOTAL LEO MISSION YEARS	331.7	
TOTAL GEO MISSION YEARS		777.9

TABLE 1:Cont'd.

STATUS AS OF JULY, 1992

MISSION SUMMARY:	
TOTAL MISSION YEARS	1109.5
TOTAL MISSION DAYS	0.40 Million
TOTAL MISSION HOURS	9.72 Million
TOTAL BATTERY HOURS	19.44 Million
TOTAL CELL HOURS	427.65 Million
TOTAL SPACECRAFT ANALYZED	212
LEO MISSION SUMMARY:	
TOTAL MISSION YEARS	331.7
TOTAL MISSION DAYS	0.12 Million
TOTAL MISSION CYCLES	1.94 Million
TOTAL BATTERY CYCLES	3.87 Million
TOTAL CELL CYCLES	85.22 Million
TOTAL SPACECRAFT ANALYZED	74
GEO MISSION SUMMARY:	
TOTAL MISSION YEARS	777.9
TOTAL MISSION DAYS	0.28 Million
TOTAL MISSION HOURS	6.81 Million
TOTAL BATTERY HOURS	13.63 Million
TOTAL CELL HOURS	299.81 Million
TOTAL SPACECRAFT ANALYZED	138

This reporting format and analysis technique were the pathfinder for similar databases anticipated for the NiH2 and NiMH Product Lines. We find this format to be sufficiently stable and mature to apply to those product lines. Our expectations are to update on a bi-annual basis and report on the database every four to five years.

REFERENCES

[1] Denson, William K. and Klein, Glenn C., "Analysis of Nickel-Cadmium Battery Reliability Data Containing Zero Failures," Proceedings of the 1991 NASA Battery Workshop.

[2] Nelson, W., "Weibull Analysis of Reliability Data With Few or No Failures," Journal of Quality Technology, Vol. 17, No. 3, July 1985.

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DIVISION ESPACE
SPACE DEPARTMENT
ROMAINVILLE FRANCE

1992- NASA AEROSPACE BATTERY WORKSHOP

CYCLE LIFE STATUS
OF SAFT VOS NICKEL-CADMIUM CELLS

JACQUES GOUALARD

US SPACE AND ROCKET CENTER

HUNTSVILLE - AL

17 - 19 NOVEMBER 1992

SAFT

DIVISION ESPACE — SPACE DEPARTMENT
ROMAINVILLE FRANCE

1992 - NASA AEROSPACE BATTERY WORKSHOP

CONTENT

. LOW EARTH ORBIT CYCLING

ESA TEST - ELAN PROGRAM - 24 AH - 40 AH CELLS
- RESULTS OF DESTRUCTIVE PHYSICAL ANALYSIS

NASA TEST - 20 AH - 24 AH CELLS

AIR FORCE TEST - 24 AH - 40 AH CELLS

. GEOSYNCHRONOUS ORBIT CYCLING

ESA TEST : HIGH DOD 90% - 100 % - 18 AH BATTERIES

AIR FORCE TEST : DOD 80% 24 AH AND 40 AH CELLS

. LIFE TIME EXPECTANCY

CYCLE LIFE STATUS OF SAFT NICKEL-CADMIUM CELLS

Jacques GOUALARD
SAFT - SPACE DEPT. ROMAINVILLE . France

The SAFT prismatic VOS Ni-Cd cells have been flown in geosynchronous orbit since 1977 and in low earth orbit since 1983. In parallel cycling tests are performed by several space agencies in order to determine the cycle life in a wide range of temperature and depth of discharge.

In Low Earth Orbit the ELAN Program is conducted on 24 Ah and 40 Ah cells by CNES and ESA at the European Battery Test Center at temperatures ranging from 0°C to 27°C and DOD from 10 to 40 %, data are presented up to 37000 cycles, one pack (X-80) at 10°C 23% DOD has acheived 49000 cycles.

Results of destructive physical analysis of cells cycled at 27°C and 8° C show that the first cause of failure is the tickness increase of the positive electrode leading to the drying up of the separator. At the negative electrode the overcharge protection is consumed, Hydrogen content in the cell is increased but the negative electrode is not the cause of failure.

In the frame of the qualification program conducted at NSWC-CRANE :

NASA Tests : 3 packs of 20 and 24 Ah have completed 18 400 cycles at 40% DOD

AIR FORCE Tests : 2 packs 24 and 40 Ah have completed 14000 cycles at 40% DOD.

In geosynchronous orbit simulation a high DOD test is conducted by ESA on 3 batteries at 10°C a 70%, 90% and 100% DOD, 31 eclipses seasons have been completed and no sign of degradation is noticed.
The AIR FORCE test at CRANE on 24 Ah and 40 Ah cells at 80% DOD 20°C has acheived 19 shadow periods.

Life time expectancy is discussed, the VOS cell technology could be used for :

in geosynchronous conditions

15 years at 10-15°C 80% DOD

in low earth orbit

10 years at 5-15°C 25-30 % DOD.

SAFT SPACE DEPARTMENT				1992 NASA BATTERY WORKSHOP				
LOW EARTH ORBIT CYCLING - ELAN PROGRAM								
VOS 24A								
TEST NUMBER	50	53	54	55	56	57	58	59
BATTERY NUMBER	X 80	01	02	03	04	05	06	07
DOD %	23	10	10	10	20	20	20	20
TEMPERATURE (°C)	10	+6	+16	+25	+7	+17	+26	-2
DISCHARGE (A) STEP 1 (25 MIN) STEP 2 (10 MIN)	9.15 (35 MN)	3.45 5.77	3.45 5.77	3.45 5.77	3.45 20.0	3.45 20.0	3.45 20.0	3.45 20.0
CHARGE (A)	9.8	8	8	8	8	8	8	8
VOLTAGE LIMIT (V)	1.466	1.456	1.425	1.40	1.49	1.45	1.46	1.523
RECHARGE RATIO	1.06	1.14	1.165	1.17	1.13	1.164	1.078	1.13
CYCLES	49000	37000	37000	37000	37000	37000	37000	36000
END OF DISCHARGE VOLTAGE (V)	1.08	1.25	1.24	1.22	1.07	1.13	1.09	1.13
RECONDITIONING	NO	R1	R1	R2 C 8400	R2 C 4130	R1	No	R1

R1 = RECONDITIONING ON A REGULAR BASIS (3000 CYCLES)
R2 = TEST RECONFIGURATION

SAFT SPACE DEPARTMENT					1992 NASA BATTERY WORKSHOP		
LOW EARTH ORBIT CYCLING - ELAN PROGRAM							
VOS 24A							
TEST NUMBER	60	61	62	63	64	65	66
BATTERY NUMBER	09	10	08	12	15	13	14
DOD %	20	24	30	30	30	40	40
TEMPERATURE (°C)	+17	+17	+8	-1	+17	+8	+27
DISCHARGE (A) STEP 1 (25 MIN) STEP 2 (10 MIN)	3.45 20.0	CONSTANT POWER	7.0 26.0	7.0 26.0	7.0 26.0	7.0 40.0	15.0 20.0
CHARGE (A)	8	MAX:11.4	12	12	12	16	16
VOLTAGE LIMIT (V)	1.475	1.46	1.52	1.52	1.495	1.51	1.464
RECHARGE RATIO	1.16	1.045	1.14	1.07	1.164	1.07	1.14
CYCLES	36000	21000	37000	36000	36000	37000	21000
END OF DISCHARGE VOLTAGE (V)	1.09		1.00	1.03	.97	.80	
RECONDITIONING	No	R2 C 12000	No	R2	No	R2 C 15080	No
						5 FAILED CELLS	DISCONTINUED

SAFT SPACE DEPARTMENT

1992 NASA BATTERY WORKSHOP

LOW EARTH ORBIT CYCLING-ELAN PROGRAM

	VOS 40A				VOS 20B
TEST NUMBER	67	68	69	70	71
BATTERY NUMBER	11	17	18	19	20
DOD %	30	30	10	20	30
TEMPERATURE (°C)	+27	+17	+5	+5	+15
DISCHARGE (A) STEP 1 (25 MIN) STEP 2 (10 MIN)	20 25	20 25	6.80 6.80	13.70 13.70	5.80 21.55
CHARGE (A)	20	20	10	10	10
VOLTAGE LIMIT (V)	1.463	1.48	1.457	1.504	1.48
RECHARGE RATIO	1.13	1.16	1.14	1.08	1.16
CYCLES	31000	31000	28000	27000	27000
END OF DISCHARGE VOLTAGE (V)	0.91	1.03	1.27	1.21	1.01
RECONDITIONING	No	No	R1	R1	No
	3 FAILED CELLS				

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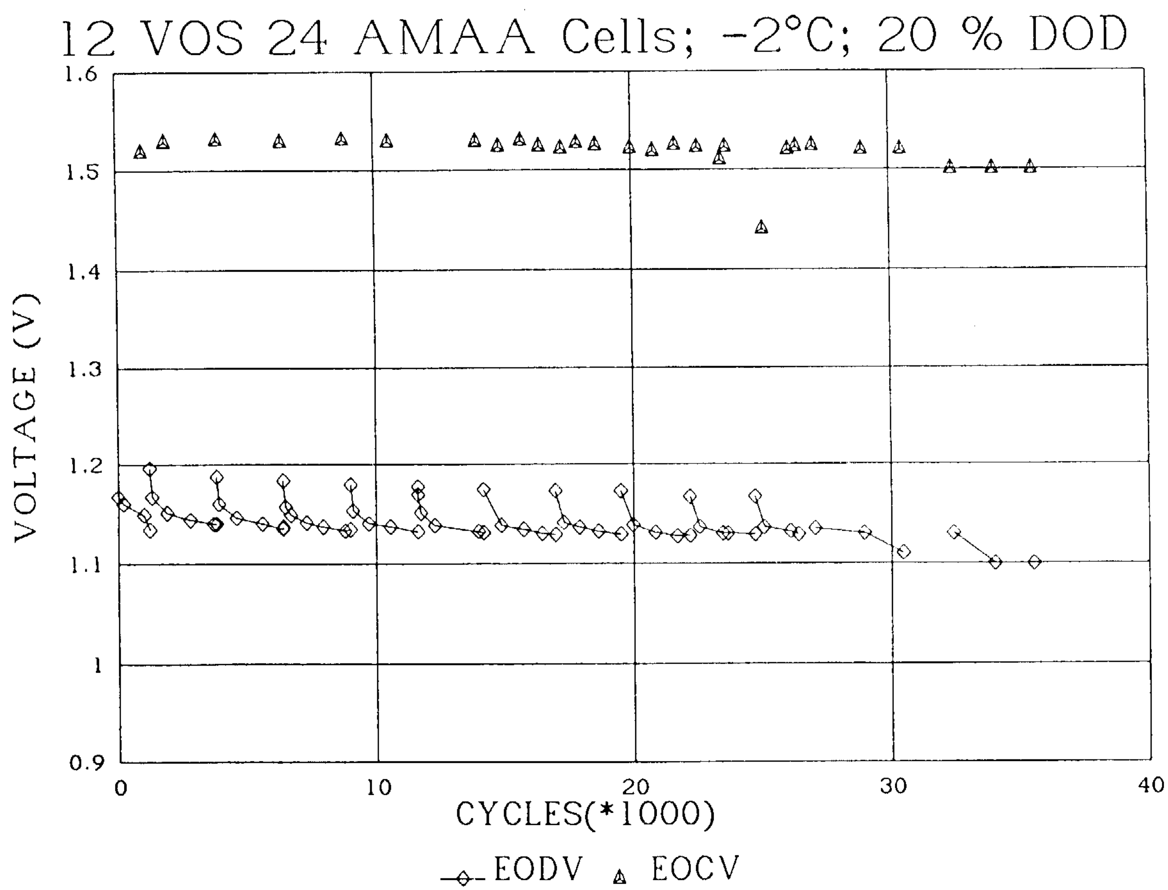
SPACE DEPARTMENT

NiCd Cells	ELAN Program	Low Earth Orbit Cycling



TEST N°59

DISCHARGE:
25 MN AT 3.45A
10 MN AT 20A

CHARGE:
65 MN AT 8A

AS PER SEPTEMBER 1992

NO CELL REMOVED
CYCLING STILL RUNNING

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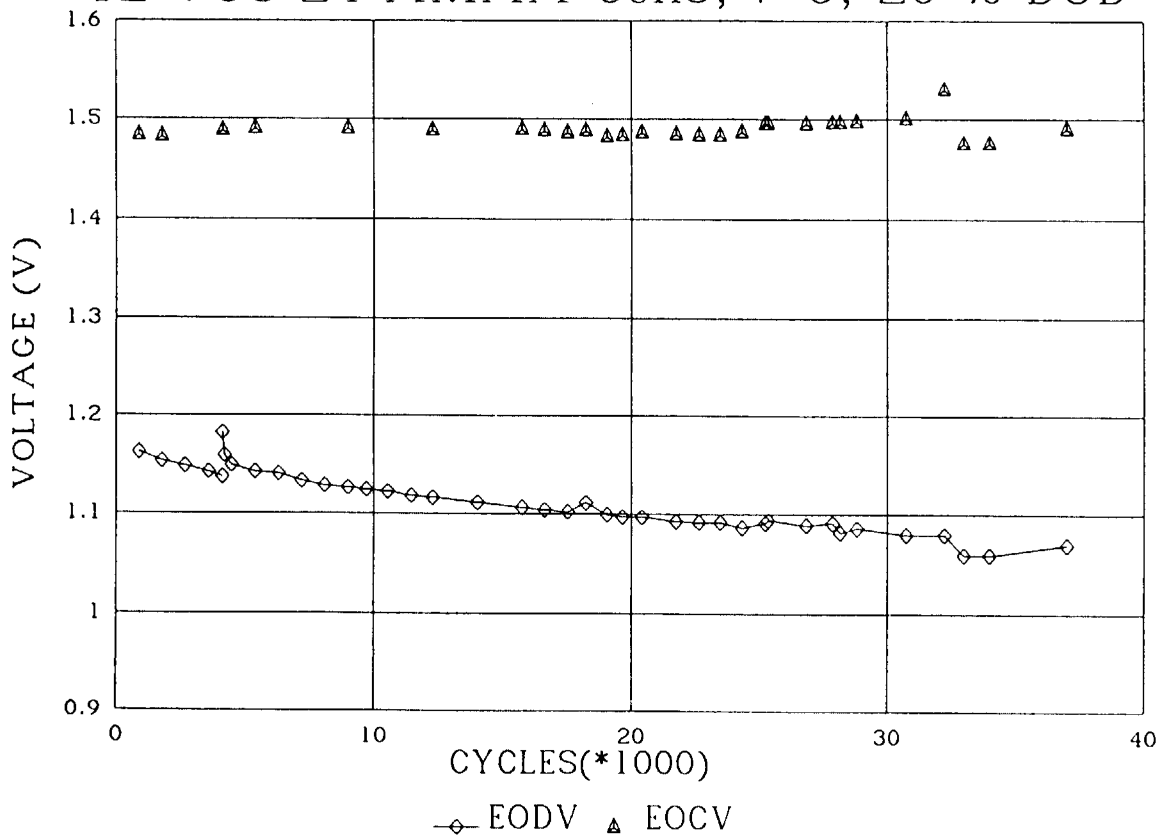
SPACE DEPARTMENT

NiCd Cells	ELAN Program	Low Earth Orbit Cycling

12 VOS 24 AMAA Cells; 7°C; 20 % DOD



TEST N°56

DISCHARGE:
25 MN AT 3.45A
10 MN AT 20A

CHARGE:
65 MN AT 8A MAX
CURRENT TAPERING

AS PER SEPTEMBER
1992

NO CELL REMOVED
CYCLING STILL RUNNING

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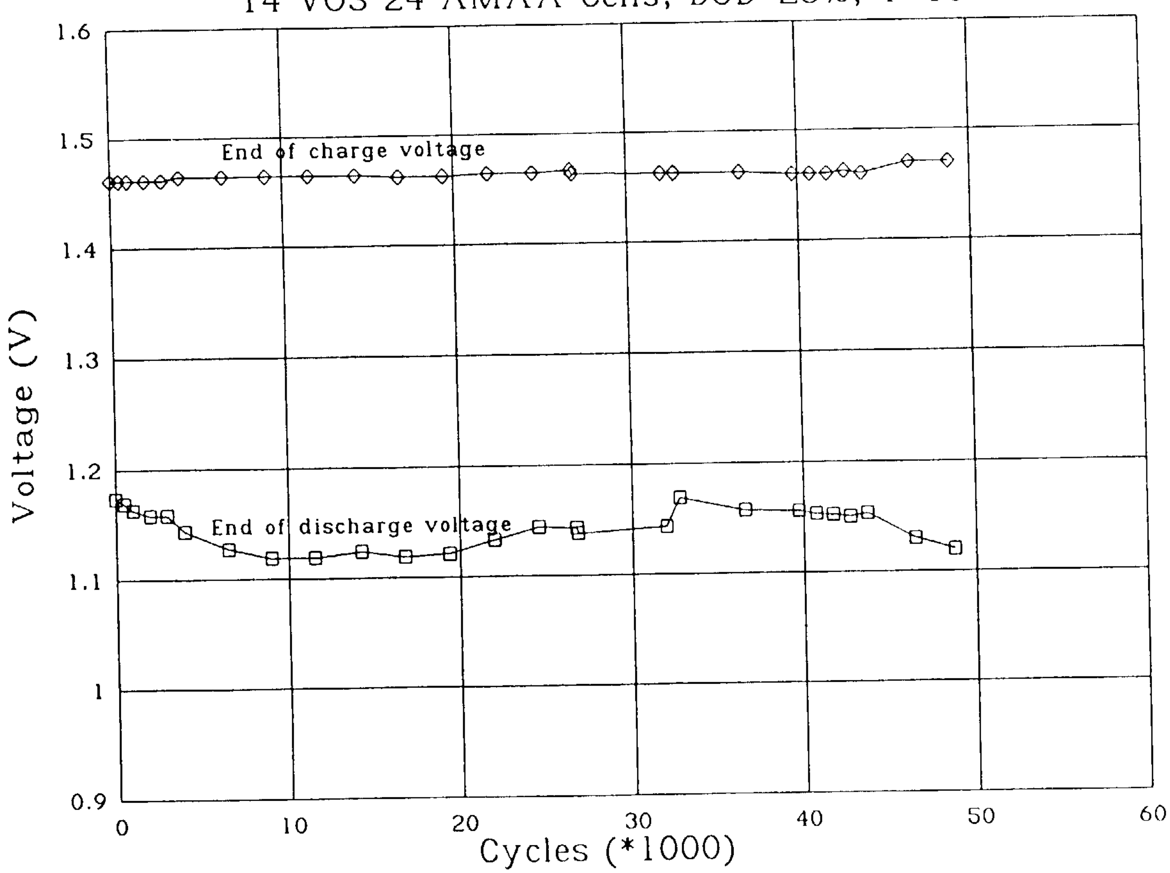
SPACE DEPARTMENT

NiCd Cells	X80 cycling	Low Earth Orbit Cycling

14 VOS 24 AMAA Cells; DOD=23%; T=10°C



TEST N°50

DISCHARGE:
35MN AT ~~5.5A~~ 9.15A

CHARGE:
CURRENT TAPERING

AS PER SEPTEMBER 1992

NO CELL REMOVED
CYCLING STILL RUNINNG

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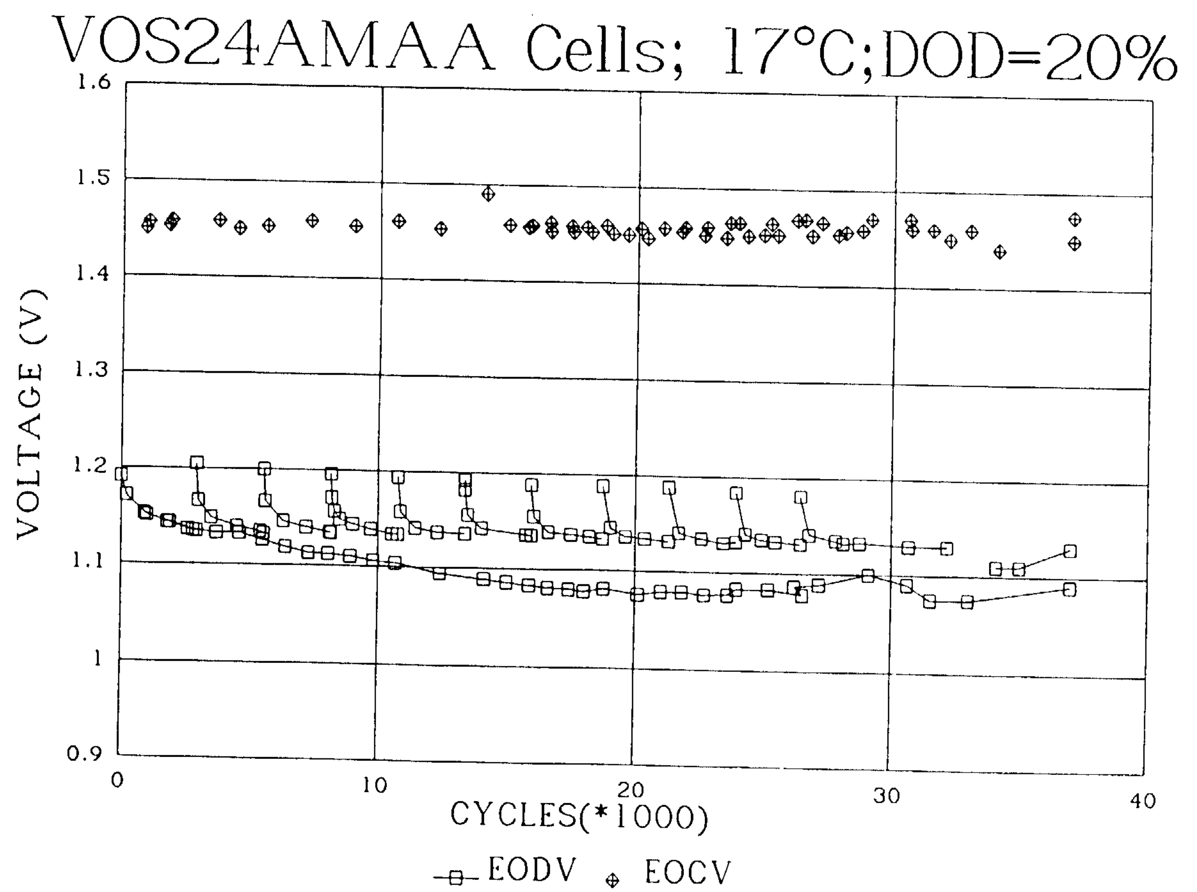
SPACE DEPARTMENT

NICD CELLS	ELAN PROGRAM	LOW EARTH ORBIT CYCLING



TESTS N°57 AND 60

DISCHARGE:
25 MN AT 3.5A
10 MN AT 20A

CHARGE:
65 MN AT 8A MAX
CURRENT TAPERING

WITH AND WITHOUT
RECONDITIONING

AS PER SEPTEMBER 1992

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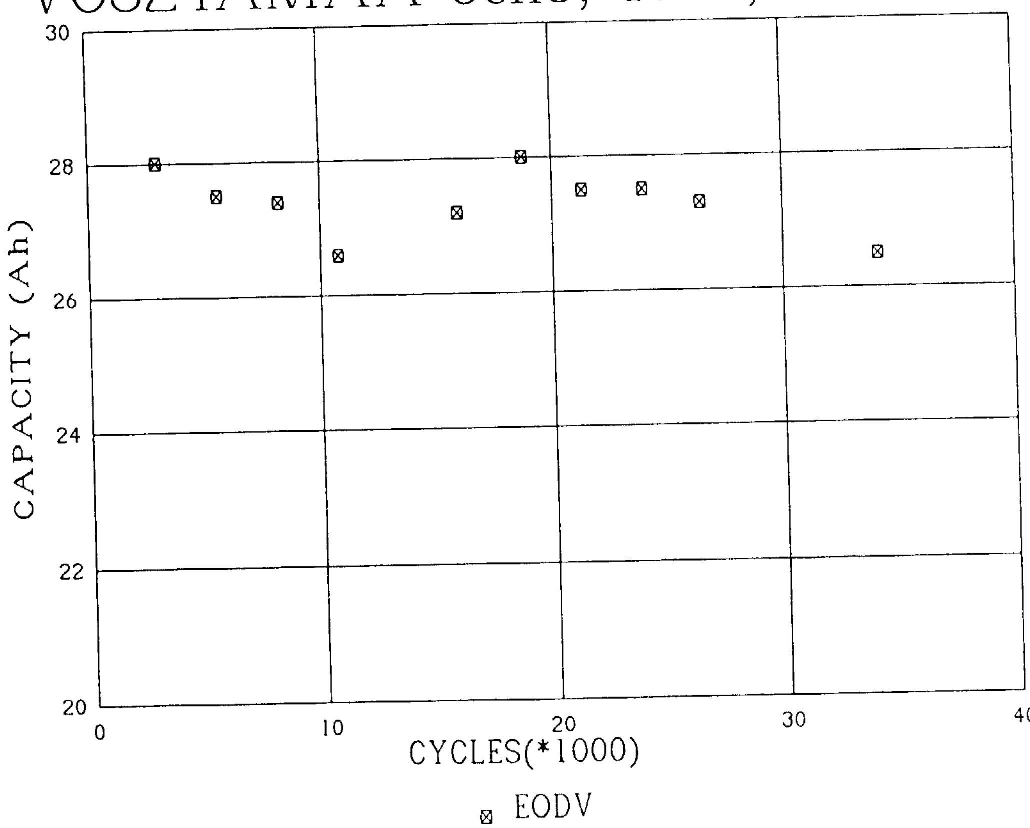
SPACE DEPARTMENT

NiCd CELLS | ELAN PROGRAM | LOW EARTH ORBIT CYCLING

VOS24AMAA Cells; 17°C;DOD=20%



TEST N°57

DISCHARGE AT 3.45 A DOWN TO 1V AFTER CYCLING DISCHARGE

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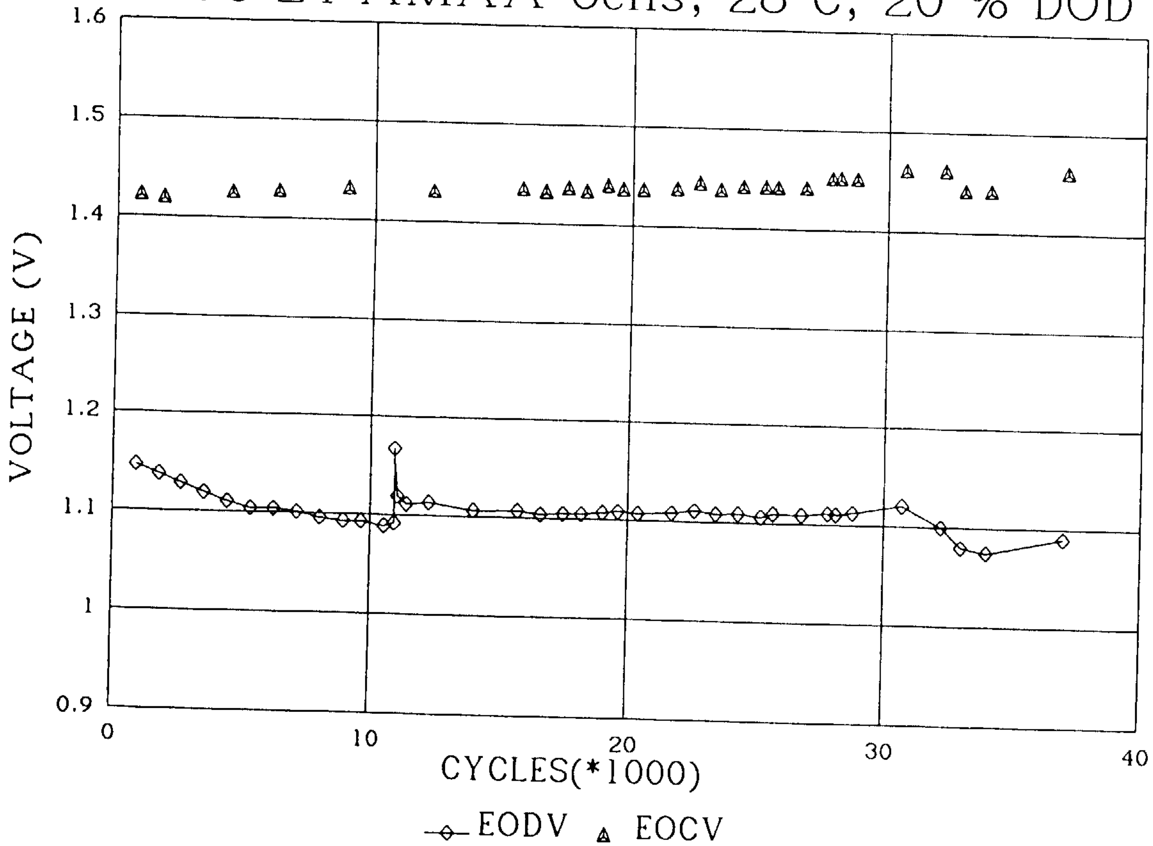
SPACE DEPARTMENT

NiCd Cells	ELAN Program	Low Earth Orbit Cycling

12 VOS 24 AMAA Cells; 28°C; 20 % DOD



TEST N°58

DISCHARGE:
25 MN AT 3.5A
10 MN AT 20A

CHARGE:
65 MN AT 8A MAX
CURRENT TAPERING

AS PER SEPTEMBER
1992

NO CELL REMOVED
CYCLING STILL RUNNING

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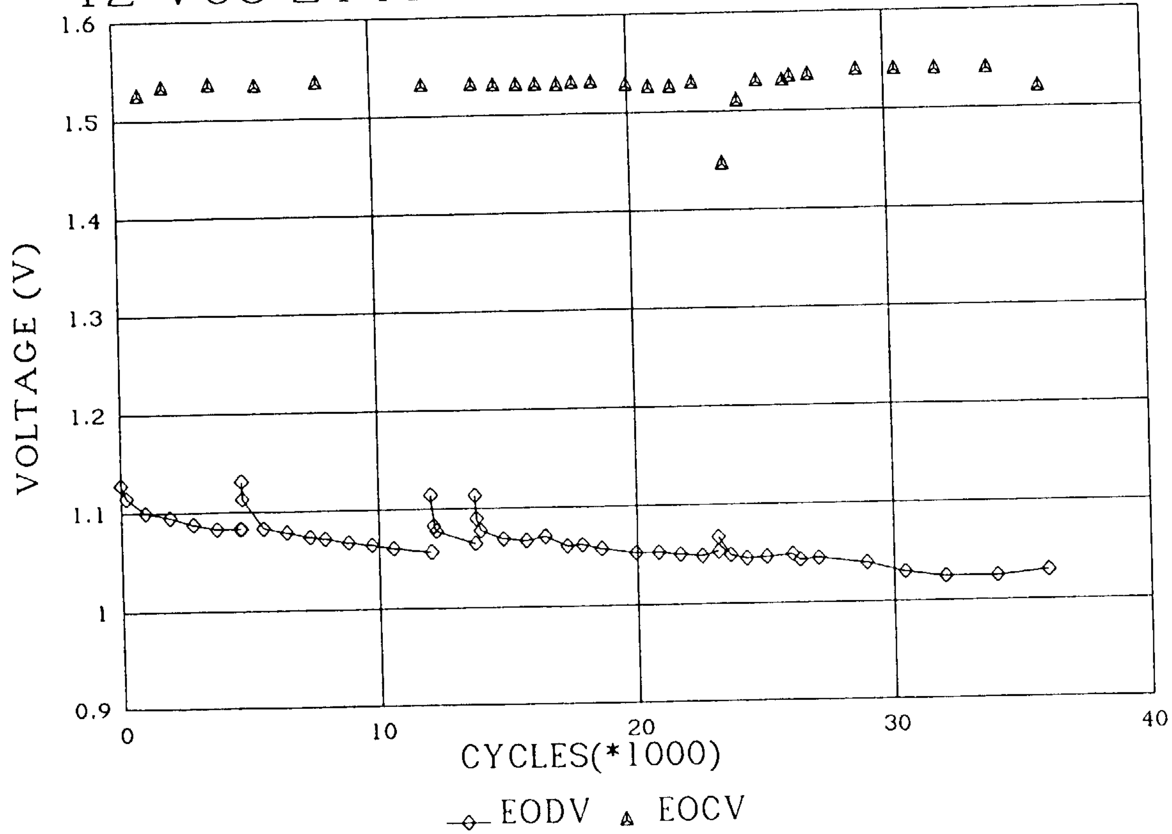
SPACE DEPARTMENT

NiCd Cells	ELAN Program	Low Earth Orbit Cycling

12 VOS 24 AMAA Cells; -1°C; 30 % DOD



TEST N°63

DISCHARGE:
25 MN AT 7A
10 MN AT 26A

CHARGE:
65 MN AT 12A MAX
CURRENT TAPERING

AS PER SEPTEMBER 1992

NO CELL REMOVED
CYCLING STILL RUNNING

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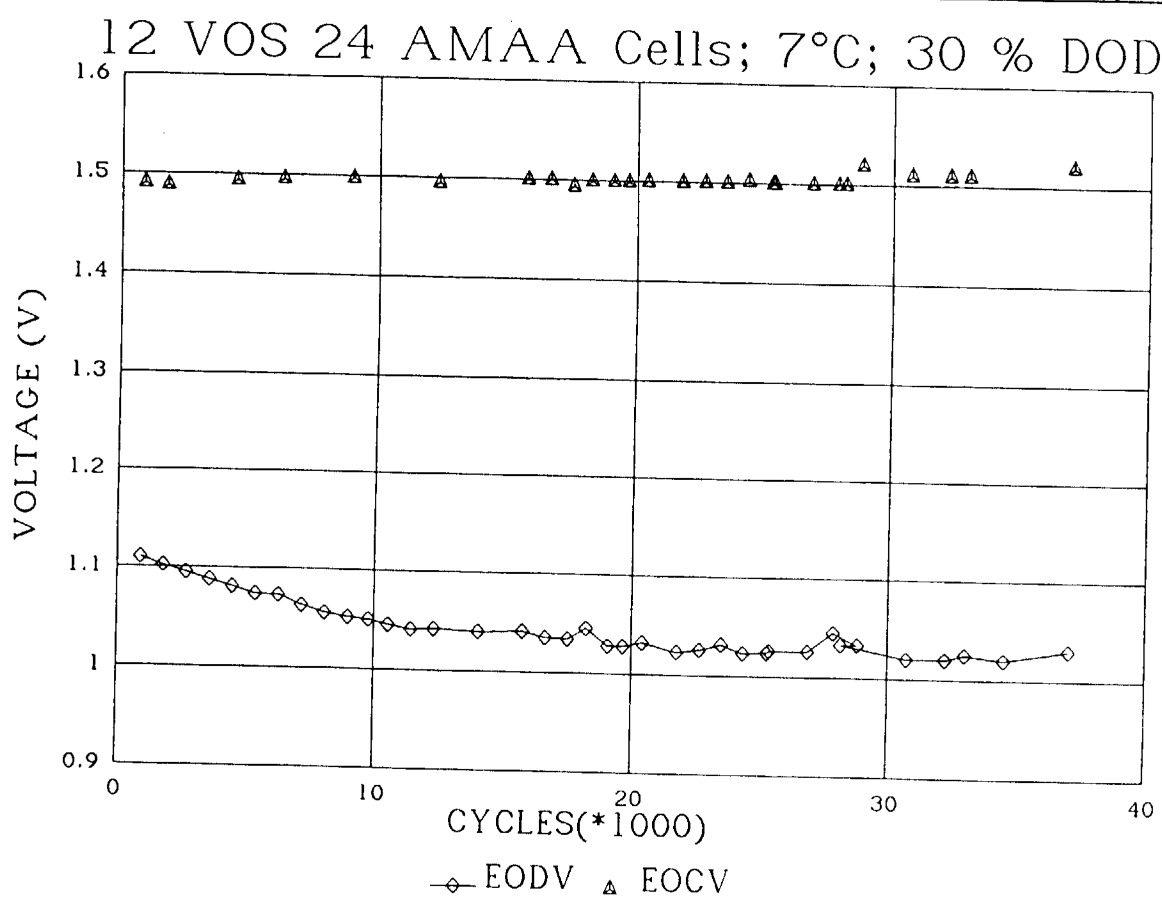
SPACE DEPARTMENT

NiCd Cells	ELAN Program	Low Earth Orbit Cycling



TEST N°62

DISCHARGE:
25 MN AT 7A
10 MN AT 26A

CHARGE:
65 MN AT 12A MAX
CURRENT TAPERING

AS PER SEPTEMBER
1992

NO CELL REMOVED
CYCLING STILL RUNNING

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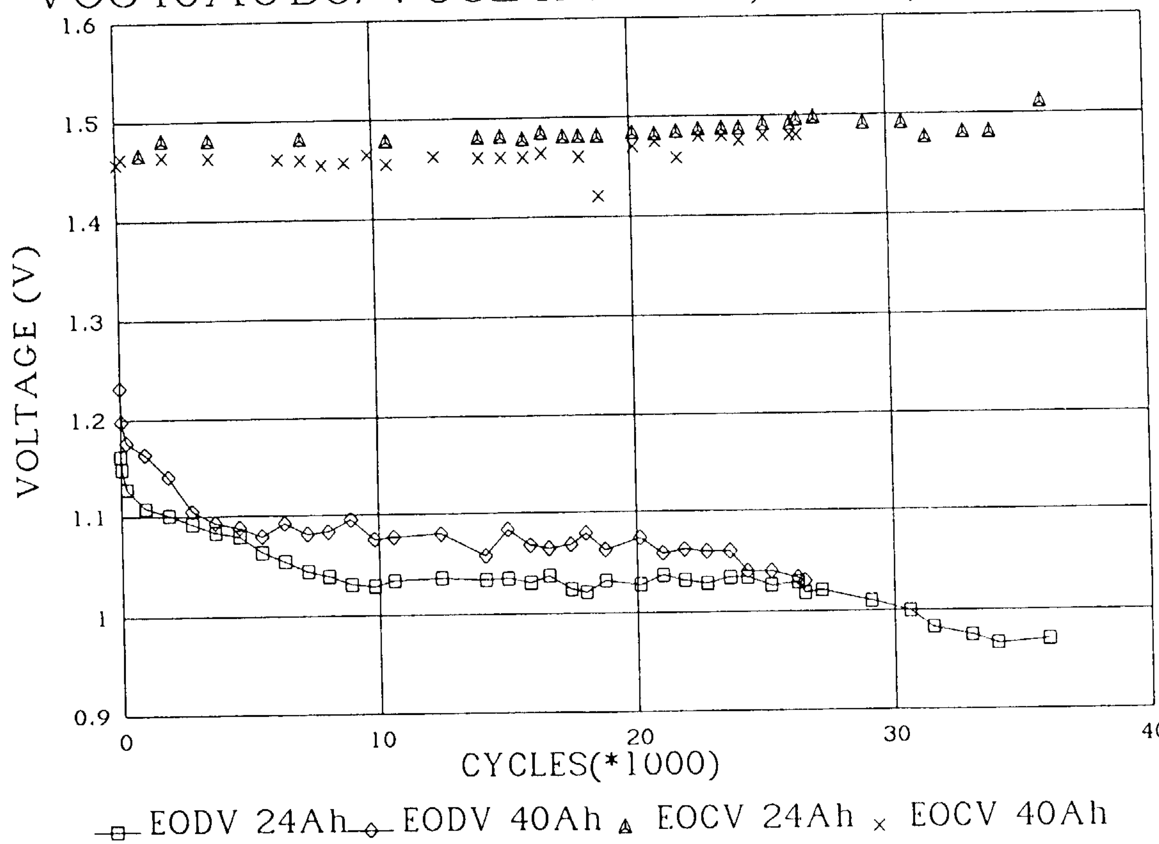
SPACE DEPARTMENT

NiCd Cells | ELAN Program | Low Earth Orbit Cycling

VOS40AGBC/VOS24AMAA; 17°C;30% DOD



COMPARISON

VOS40AGBC/VOS24AMAA

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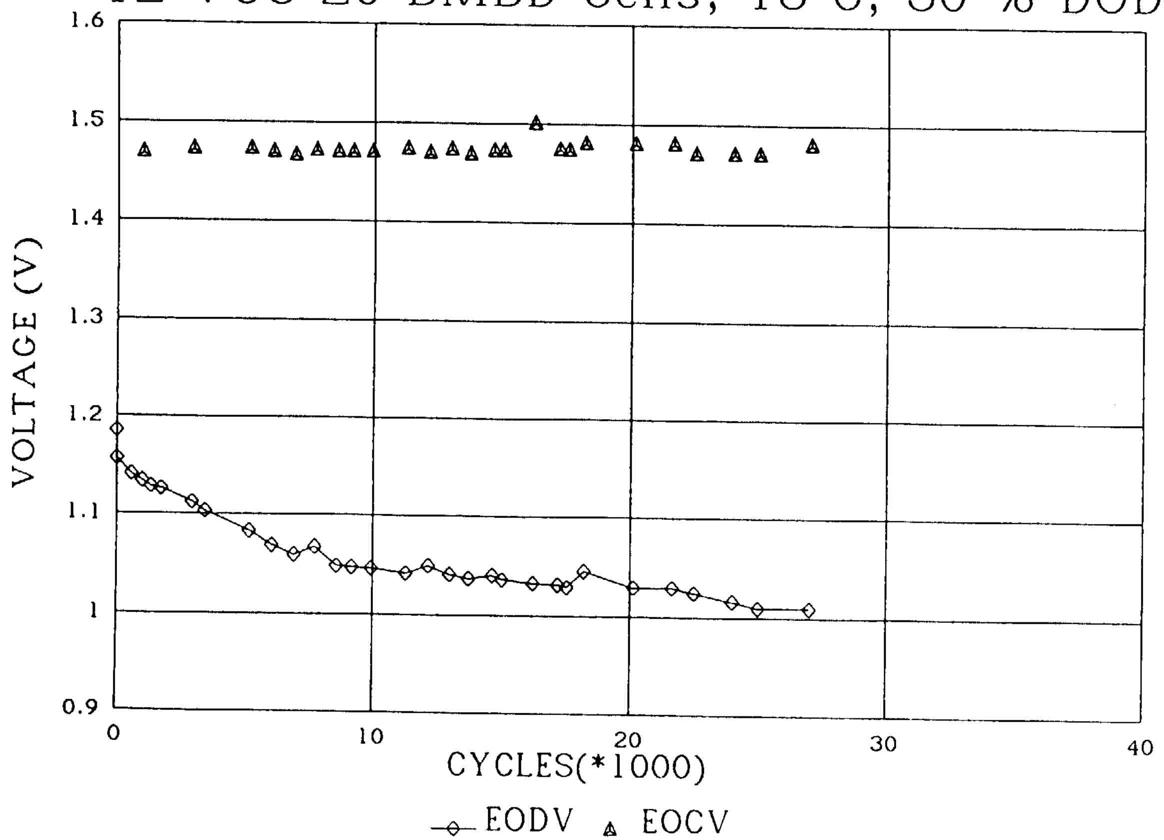
SPACE DEPARTMENT

NiCd Cells	ELAN Program	Low Earth Orbit Cycling

12 VOS 20 BMBD Cells; 15°C; 30 % DOD



TEST N°71

DISCHARGE:
25 MN AT 5.8A
10 MN AT 22A

CHARGE:
65 MN AT 10A MAX
CURRENT TAPERING

AS PER SEPTEMBER
1992

NO CELL REMOVED
CYCLING STILL RUNNING

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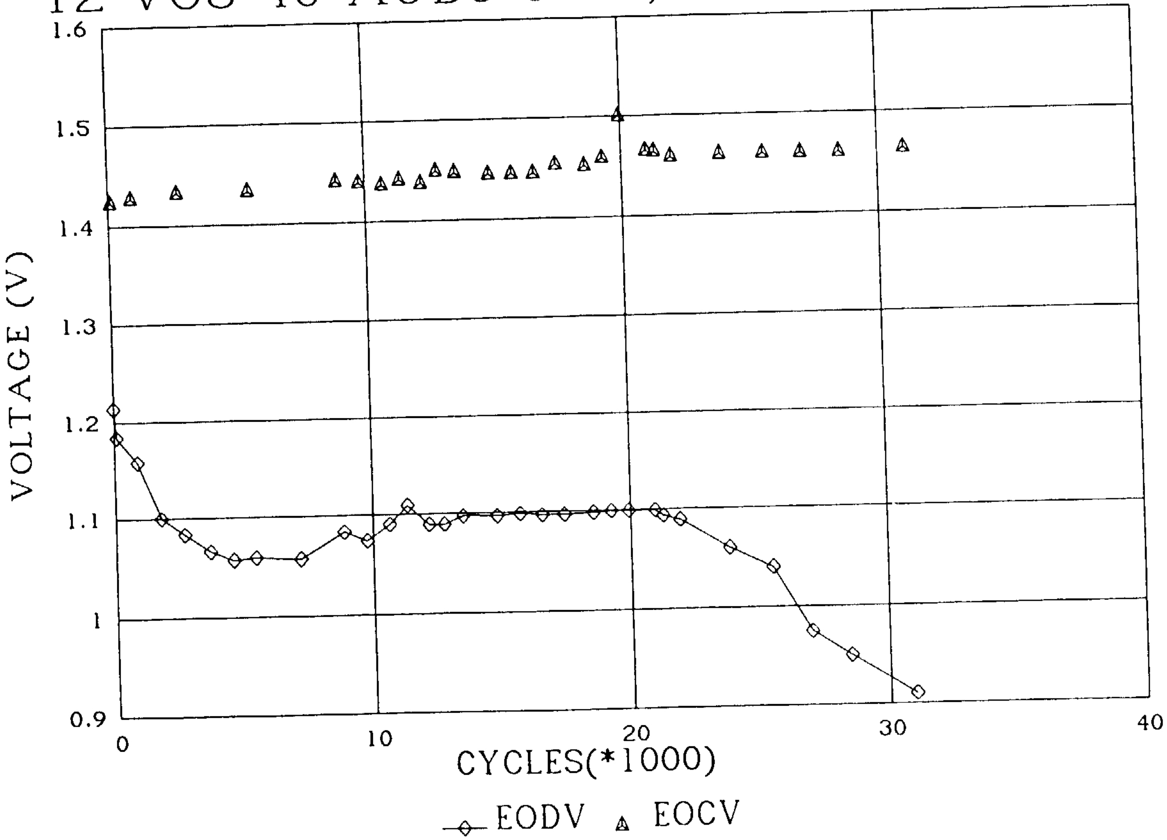
SPACE DEPARTMENT

NiCd Cells	ELAN Program	Low Earth Orbit Cycling

12 VOS 40 AGBC Cells; 27°C; 30 % DOD



TEST N°67

DISCHARGE:
25 MN AT 20A
10 MN AT 25A

CHARGE:
65 MN AT 20A MAX
CURRENT TAPERING

AS PER SEPTEMBER
1992

3 CELLS REMOVED
(CYCLE N°30391, 30394,
30662)

CYCLING STILL
RUNNING

C-6

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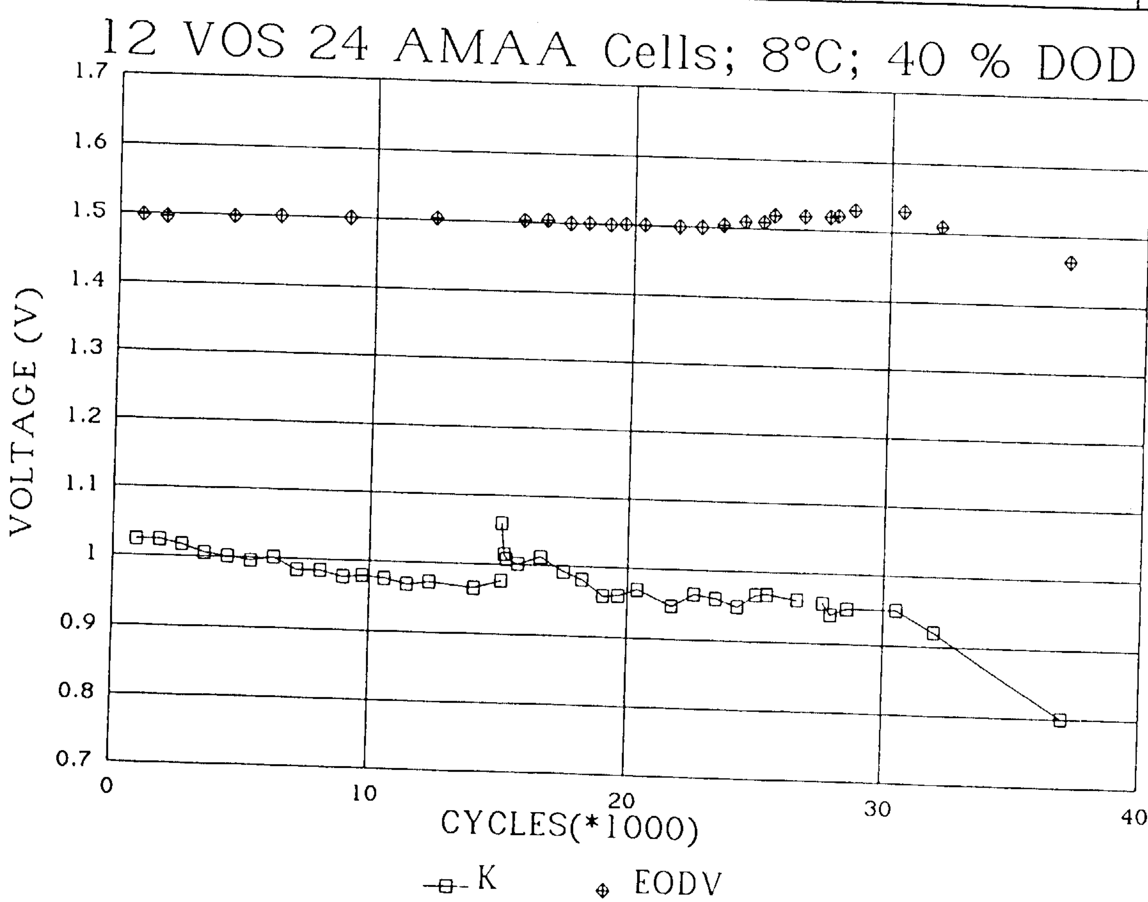
NiCd Cells	ELAN Program	Low Earth Orbit Cycling



TEST N°65

DISCHARGE:
25 MN AT 7A
10 MN AT 40A

CHARGE:
65 MN AT 16A MAX
CURRENT TAPERING

AS PER SEPTEMBER
1992

5 CELLS REMOVED
(CYCLE N° 27039, 29194
31984, 33104, 37098)

CYCLING STILL RUNNING

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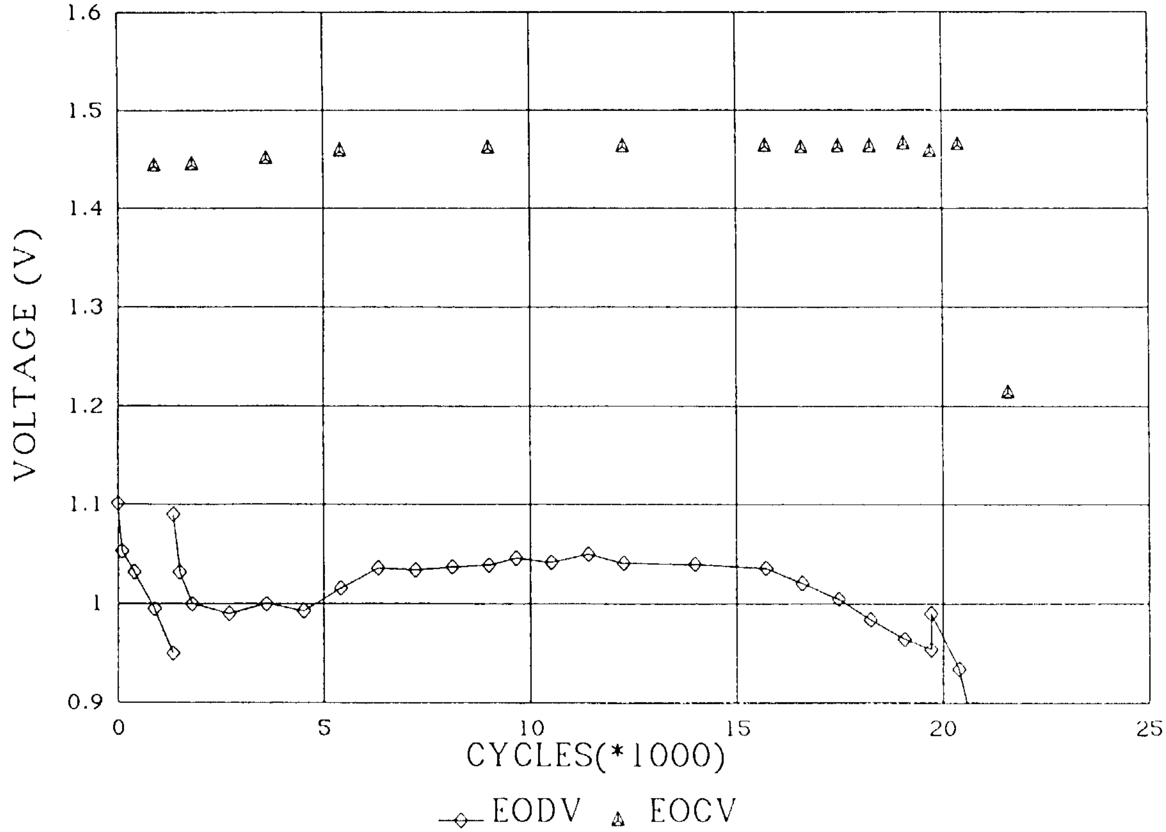
SPACE DEPARTMENT

NiCd Cells	ELAN Program	Low Earth Orbit Cycling

12 VOS 24 AMAA Cells; 27°C; 40 % DOD



TEST n°66

Discharge:
25 mn at 15A
10 mn at 20A

Charge:
65 mn at 16A max
current tapering

As per September
1992

8 cells removed
Cycling stopped

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DIVISION ESPACE — SPACE DEPARTMENT

ROMAINVILLE FRANCE

1992 - NASA AEROSPACE BATTERY WORKSHOP

CHARACTERISTICS OF CELLS COMPONENTS AFTER CYCLING :

ELAN PROGRAM : LOW EARTH ORBIT CYCLING

		VOS 24 AMAA					
		BOL	DOD 40%				
Temperature		–	8 °C		27 °C		
Identification		–	110.179	108.031	109.119	109.123	108.060
Cycles number		0	29194	27039	20169	21604	21424
Capacity Ah		30.5	22.7	27.36	16.32	17.12	10
Internal resistance mohms		3.5	5.2	6.2	5.5	4.2	8.9
H2 %		0			85.6		93.2
Separator aspect		–		dry	dry	dry	dry
Thickness 10^{-2} mm	electr.+	76		88.5(16.4%)	99(30%)	103.5(36%)	100(31.6%)
(swelling %)	electr.–	89		87.5(0%)	103(16%)	104.5(18.5%)	107.5(20.7%)
DIE mm		.26		.21	.0	.0	.0
KOH g/dm2		1		.4	.12	.09	.07

SAFT DIVISION ESPACE SPACE DEPARTMENT ROMAINVILLE FRANCE

1992 - NASA AEROSPACE BATTERY WORKSHOP

MAIN DRIVING PARAMETERS OF CELL DEGRADATION :

(FAILURE CRITERIA EOD VOLTAGE < .8 V)

- Positive electrodes swelling -> 35%
- Inter electrode spacing reduced to zero.
- Separator drying -> High internal resistance -> Low voltage.
- Cd° quantity increasing -> overcharge protection reduction.
  -> H_2 production.

SAFT SPACE DEPARTMENT			1992 NASA BATTERY WORKSHOP		
Ni-Cd CELLS	NSWC PROGRAM		LOW EARTH ORBIT CYCLING		
	NASA/GSFC			AIR FORCE	
	VOS 20 B	VOS 24 A	VOS 24 A	VOS 24	VOS 40
TEST NUMBER	93	94	95	107	108
BATTERY NUMBER	6120S	6024S	6124S	6324S	6340S
DOD (%)	39	39	39	40	40
TEMPERATURE (°C)	20	0	20	20	20
DISCHARGE (A)	16	19.2	19.2	17.2	28.6
CHARGE (A)	16	19.2	19.2	12	20
VOLTAGE LIMIT (V)	1.463	4.489	1.452	1.484	1.494
RECHARGE RATIO	1.056	1.019	1.030	1.07	1.06
CYCLES	18400	18400	18300	14821	12416
END OF DISCHARGE VOLTAGE (V)	1.036	1.12	1.049	1.08	1.115
				DISCONTINUED	DISCONTINUED

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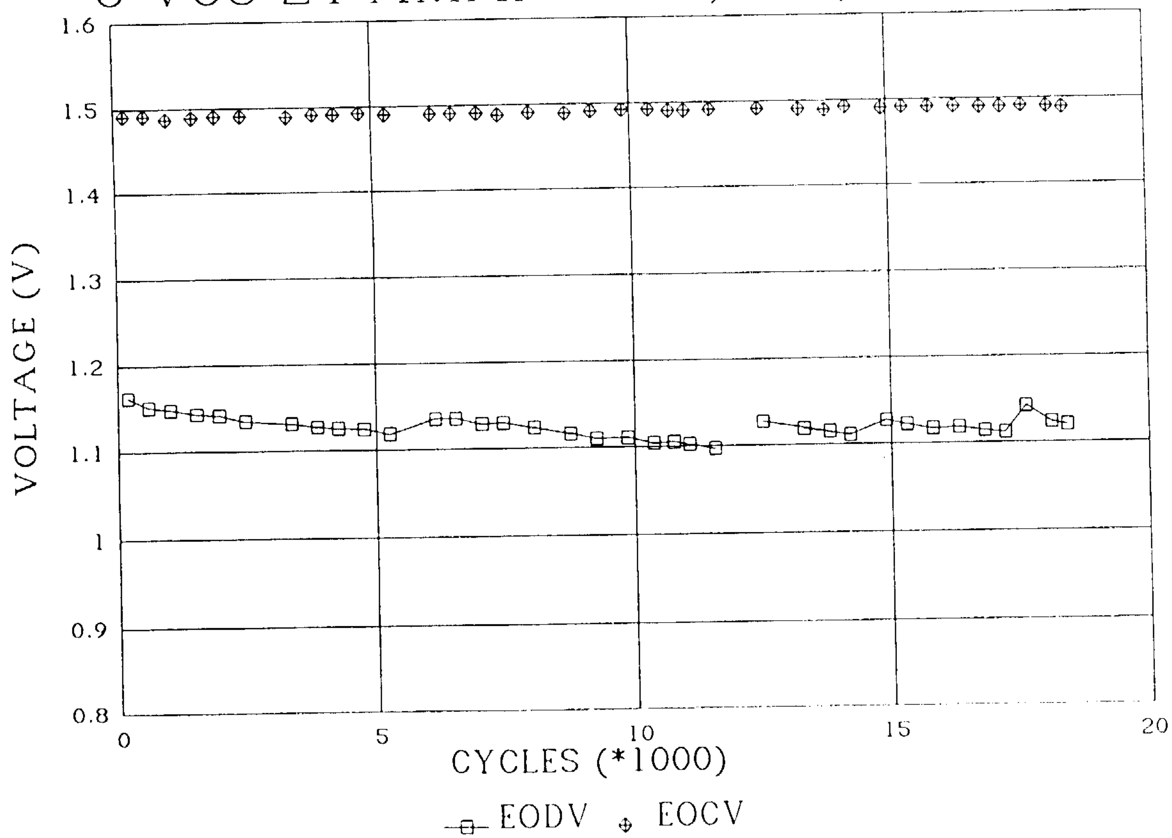
SPACE DEPARTMENT

NiCd Cells	NASA/GSFC Pack 6024S	Low Earth Orbit Cycling

5 VOS 24 AMAA Cells; 0°C; 39% DOD



TEST N°94

DISCHARGE:
29MN AT 19A

CHARGE:
60 MN AT 19A MAX
CURRENT TAPERING

AS PER SEPTEMBER
1992

NO CELL REMOVED
CYCLING STILL
RUNNING

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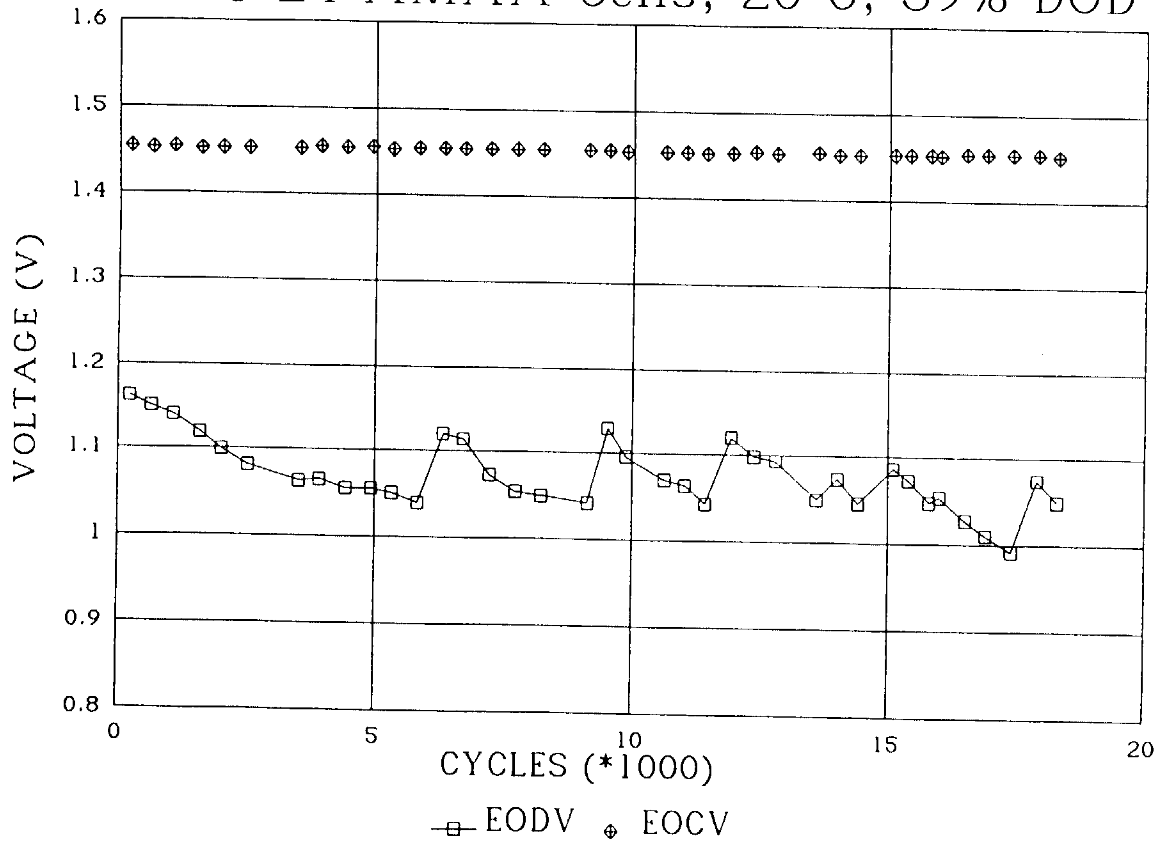
SPACE DEPARTMENT

NiCd Cells	NASA/GSFC Pack 6124S	Low Earth Orbit Cycling

5 VOS 24 AMAA Cells; 20°C; 39% DOD



TEST N°95

DISCHARGE:
29MN AT 19A

CHARGE:
60 MN AT 19A MAX
CURRENT TAPERING

AS PER SEPTEMBER
1992

NO CELL REMOVED
CYCLING STILL
RUNNING

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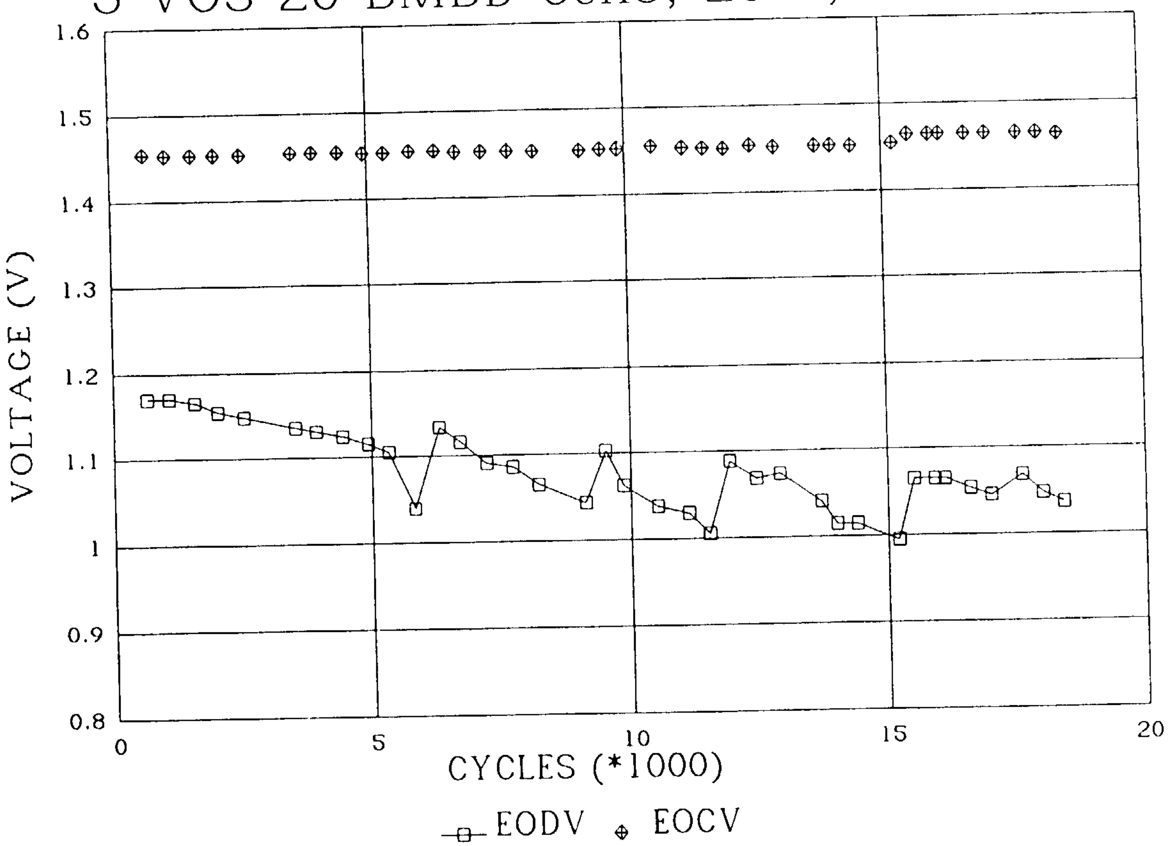
SPACE DEPARTMENT

NiCd Cells	NASA/GSFC Pack 6120S	Low Earth Orbit Cycling

5 VOS 20 BMBD Cells; 20°C; 39% DOD



TEST N°93

DISCHARGE:
29MN AT 16A

CHARGE:
60 MN AT 16A MAX
CURRENT TAPERING

AS PER SEPTEMBER
1992

NO CELL REMOVED
CYCLING STILL
RUNNING

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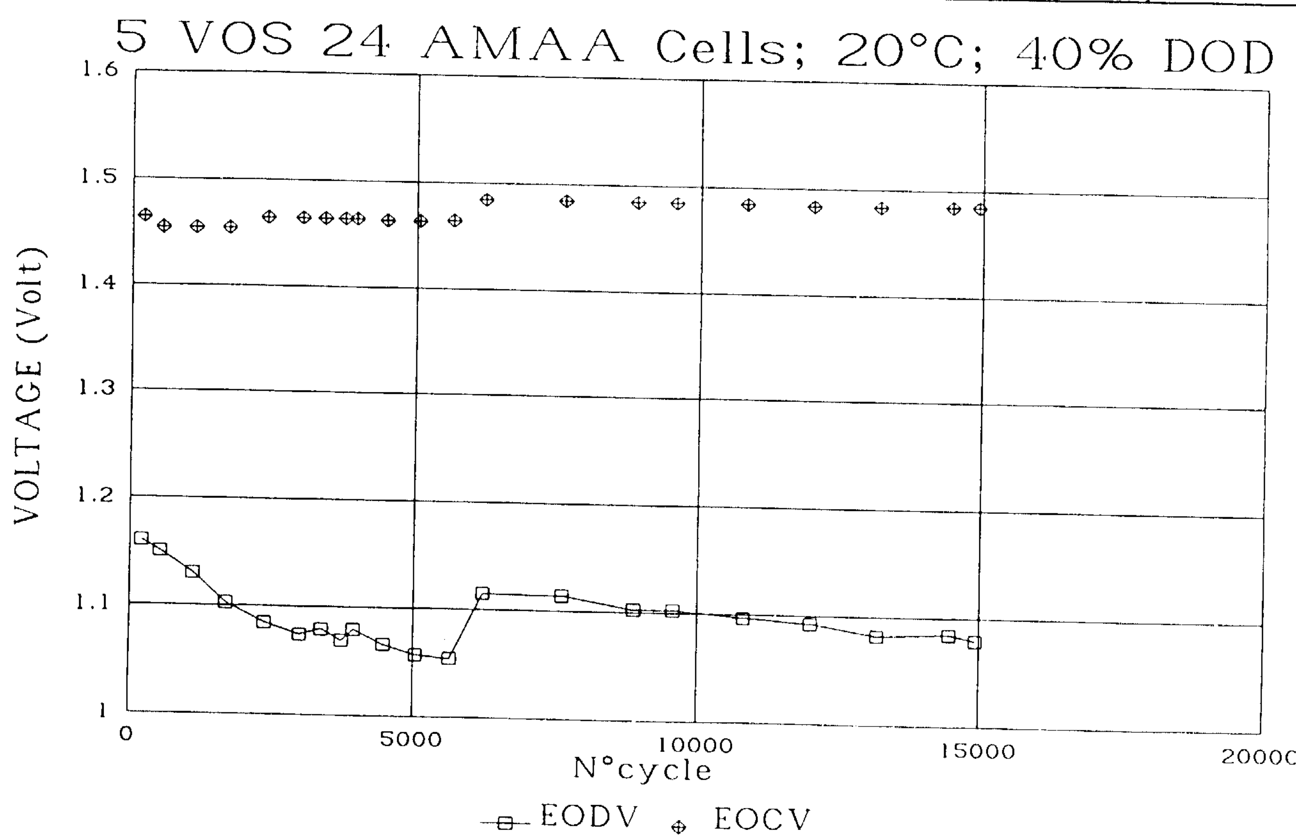
NiCd CELLS	AIR FORCE PACK 6324S	LOW EARTH ORBIT CYCLING



TEST N°107

DISCHARGE:
34 MN AT 17.2 A

CHARGE:
66 MN AT 12 A MAX
CURRENT TAPERING

TEST DISCONTINUED

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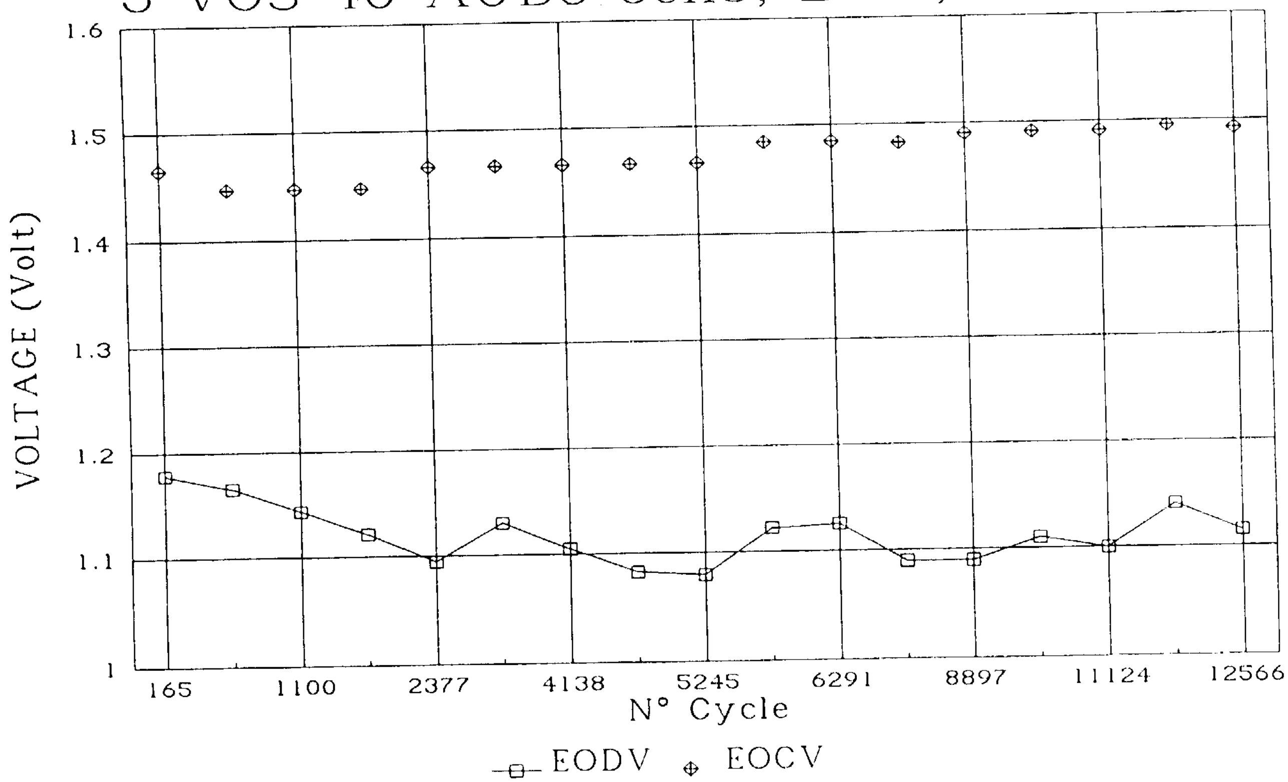
SPACE DEPARTMENT

NICD	AIR FORCE PACK 6340	LOW EARTH ORBIT CYCLING

5 VOS 40 AGBC Cells; 20°C; 40% DOD



TEST N°108

DISCHARGE:
34 MN AT 28.6 A

CHARGE:
66 MN AT 20 A MAX
CURRENT TAPERING

TEST DISCONTINUED

SAFT SPACE DEPARTMENT				1992 NASA BATTERY WORKSHOP	
NiCd CELLS	GEOSTATIONARY ORBIT CYCLING				
	ESA			AIR FORCE	
	VOS 18	VOS 18	VOS 18	VOS 24	VOS 40
TEST NUMBER	43	45	44	109	110
BATTERY NUMBER	ECS-70	ECS-90	ECS-100	6224S	6240S
DOD MAX (%)	70	90	100	80	80
TEMPERATURE (°C)	10°	10°	10°	20°	20°
DISCHARGE (A)				16	26.7
CHARGE (A)				2.4 MAX	4 MAX
VOLTAGE LIMIT (V)	1.52	1.492	1.494	1.41	1.41
RECHARGE RATIO	1.05	1.05	1.05	1.6	1.55
SHADOW NUMBERS	31	31	31	19	19
END OF DISCHARGE VOLTAGE (V)	1.162	1.11	1.084	1.11	1.02

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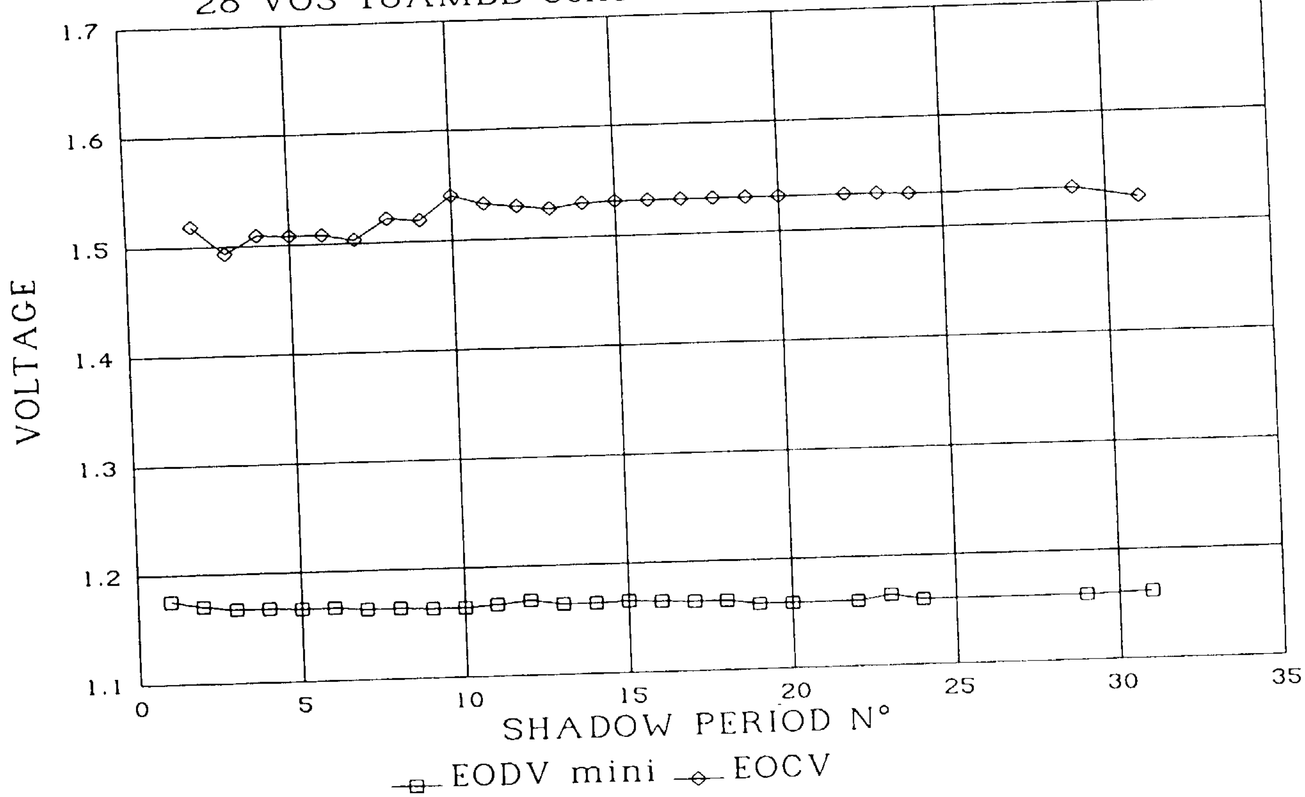
NiCd Cells	ECS SIMULATION	Geostationary Orbit Cycling

28 VOS 18AMBB Cells: DOD=70%; K=1,01; T=10°C



TEST N°43

21 DAYS SHORTEN SOLSTICES WITH TRICKLE CHARGE

Approximated DOD PROFILE

As PER SEPTEMBER 1992

No CELL REMOVED CYCLING STILL RUNNING

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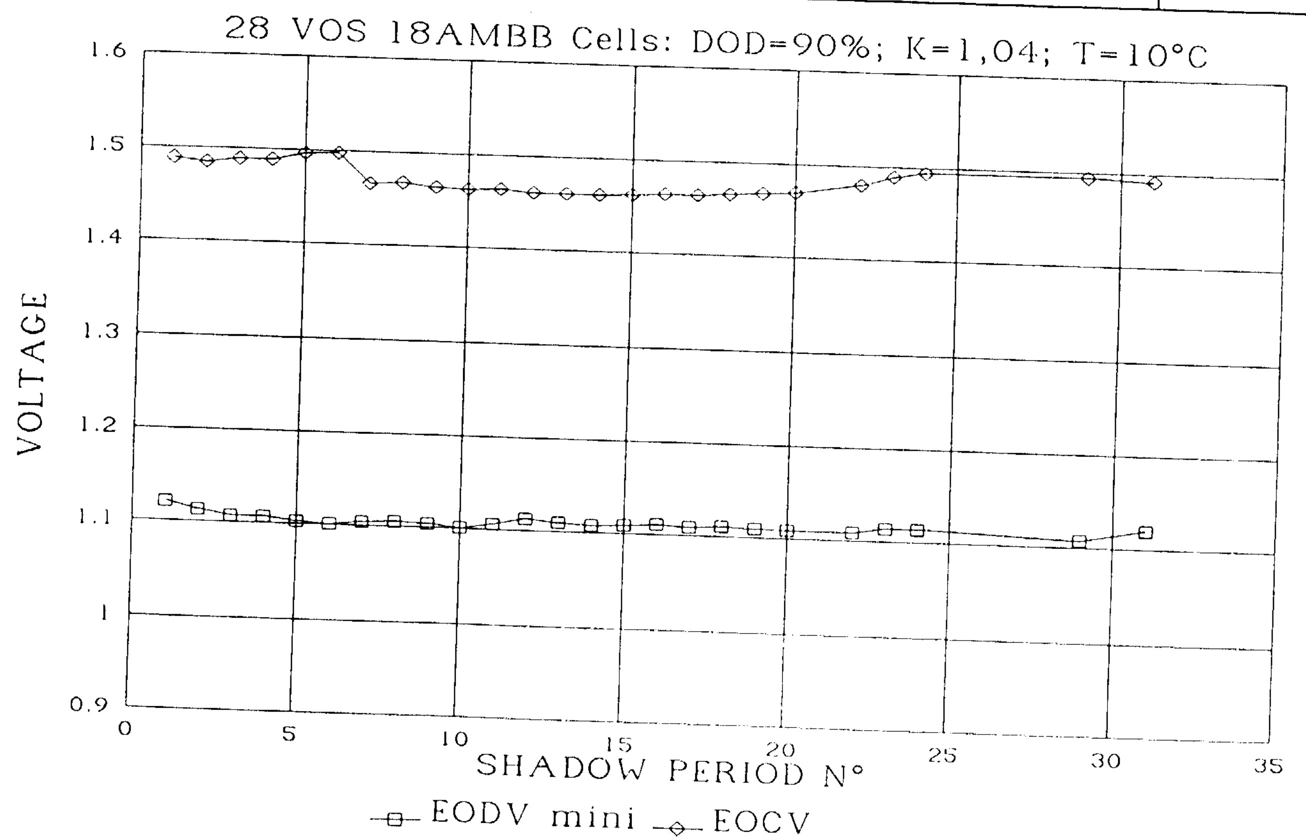
SPACE DEPARTMENT

NiCd Cells	ECS SIMULATION	Geostationary Orbit Cycling



TEST N°45

21 days shorten solstices with trickle charge

Approximated DOD profile

As per September 1992

**No cell removed
Cycling still running**

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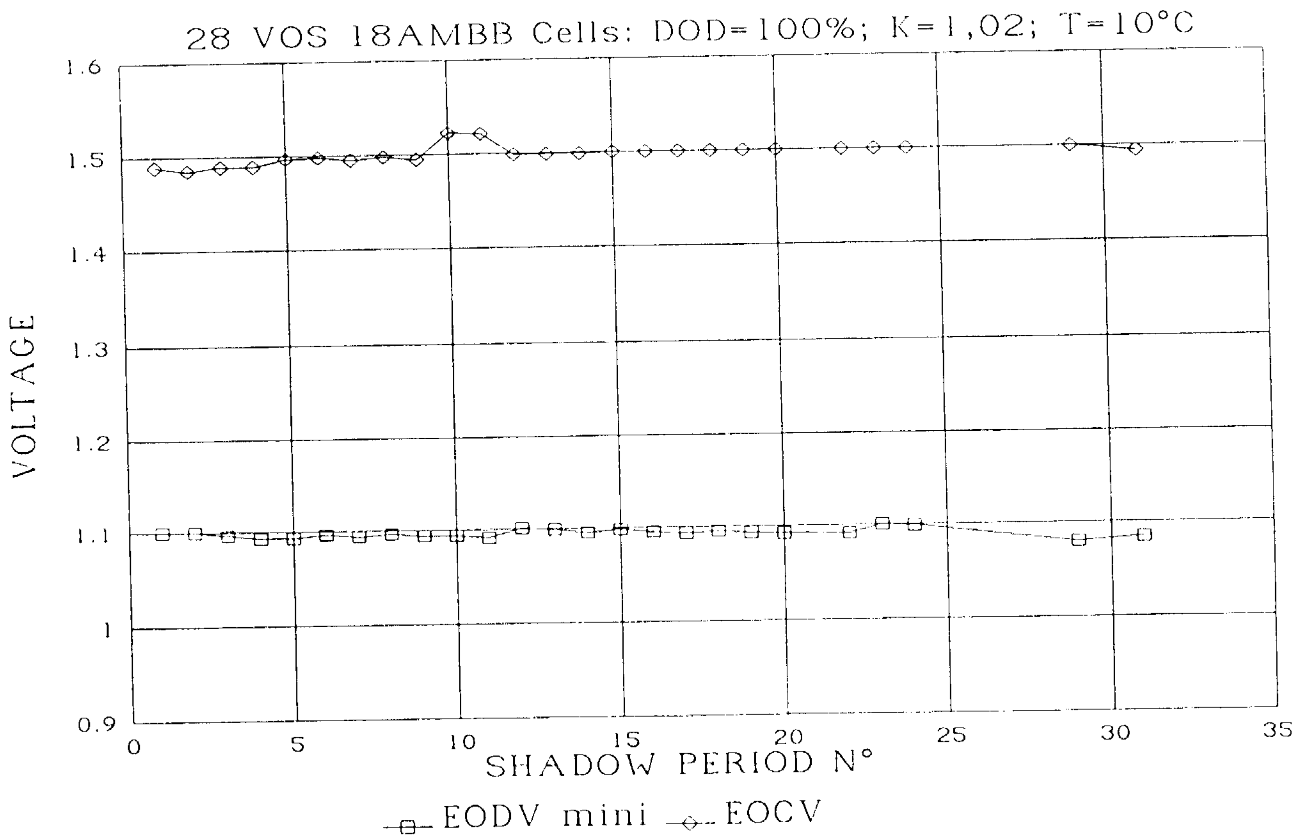
SPACE DEPARTMENT

NiCd Cells	ECS SIMULATION	Geostationary Orbit Cycling



TEST N°44

21 DAYS SHORTEN SOLSTICES WITH TRICKLE CHARGE

APPROXIMATED DOD PROFILE

AS PER SEPTEMBER 1992

NO CELL REMOVED CYCLING STILL RUNNING

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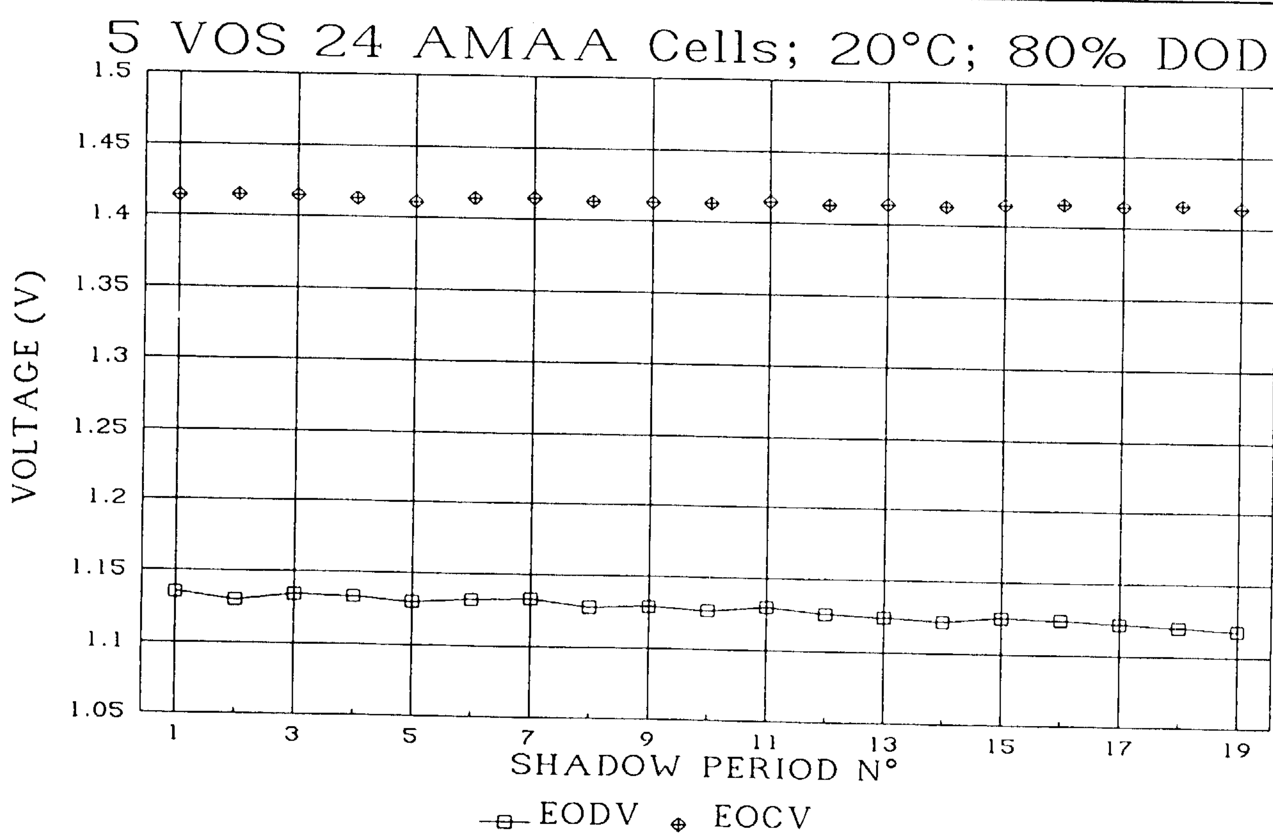
SPACE DEPARTMENT

NiCd CELLS

AIR FORCE PACK 6224S

GEOSTATIONARY ORBIT CYCLING



TEST N°109

REAL DOD PROFILE

2 WEEKS SHORTEN SOLSTICES WITH TRICKLE CHARGE

DISCHARGE: 16 A

CHARGE:
2.4 A MAX
CURRENT TAPPERING

AS PER SEPTEMBER 1992

NO CELL REMOVED
CYCLING STILL RUNNING

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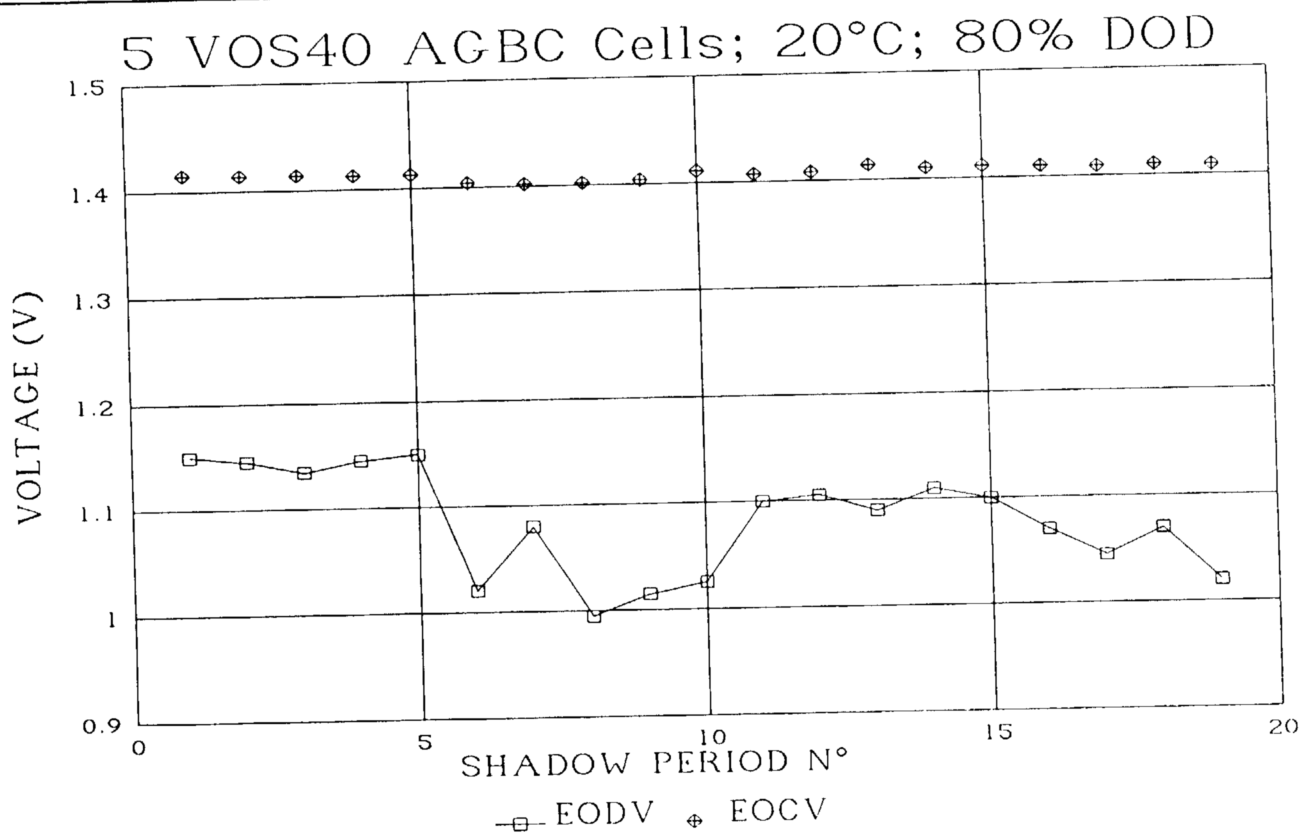
SPACE DEPARTMENT

NiCd Cells	AIR FORCE PACK 6240S	Geostationary Orbit Cycling



TEST N°110

Real DOD profile

2 weeks shorten solsticies with trickle charge

Discharge: 27 A

Charge: 4 A max current tapering

As per September 1992

No cell removed
Cycling still running

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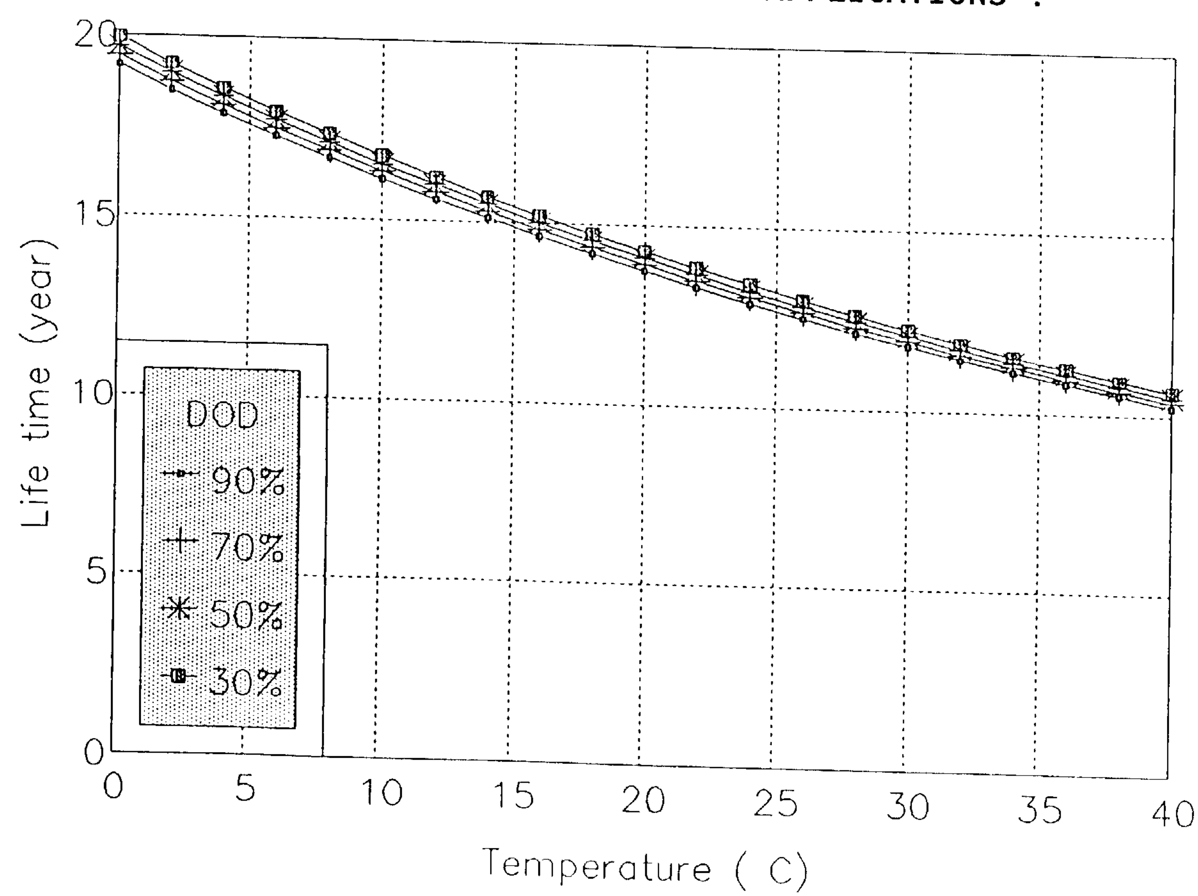
NICD CELL LIFE TIME

OCTOBER 1992

CALCULATED LIFE TIME FOR GEO APPLICATIONS :

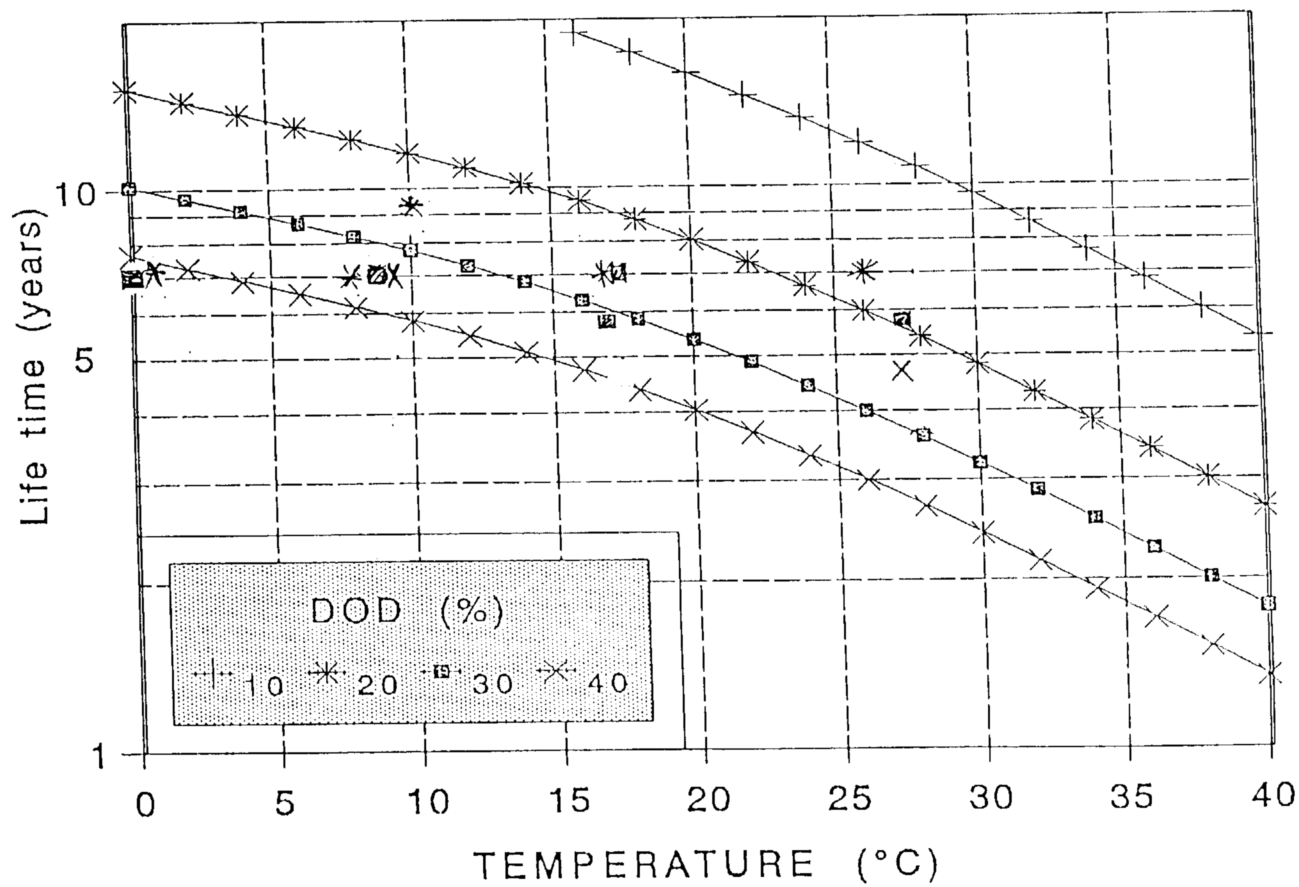


SAFT

NICD CELL LIFE TIME

OCTOBER 1992

CALCULATED LIFE TIME FOR LEO APPLICATIONS :



SAFT SPACE DEPARTMENT

ACKNOWLEDGEMENT

The author would you like to thank Space Agencies and Laboratories for supporting and monitoring the tests :

- European Space Agency and the ESTEC Battery Test Center
- CNES
- US AIR FORCE and Aerospace Corporation
- NASA, Goddard Space Flight Center and Lewis Research Center
- NAVAL Surface Warfare Center-Crane, In.

Nickel-Hydrogen Technologies Session

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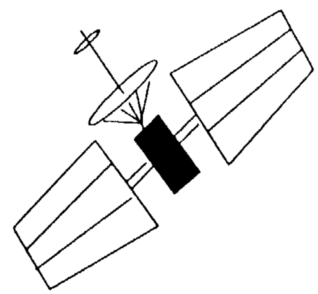
JOPLIN, MO

Advanced Systems Department

NICKEL-HYDROGEN GROUP

2.5 INCH NICKEL-HYDROGEN DEVELOPMENT
1992 NASA BATTERY WORKSHOP



N93-20512

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JOPLIN, MO

Advanced Systems Department

NICKEL-HYDROGEN GROUP

WHY DEVELOP A 2.5 INCH NICKEL-HYDROGEN CELL?

* Provide a Battery Alternative for the Small Satellite Market
* Provide High Reliability Product
* Simplify Charge Control Circuitry
* No Toxic Components
* Provide Better Performance Product for Same Price
* Anticipate Large Growth in Small Satellite Market

EAGLE PICHER Quality First!

2.5 INCH NICKEL-HYDROGEN DEVELOPMENT HISTORY

- Development Started in 1989 thru E.P. Internal Funding
- Development Went Thru three stages:Feasibility, prototype, and Production
- Main Driver Being Cost and Maintaining High Reliability
- On December 18, 1990 Started working with Orbital Sciences Corporation on Battery Development for APEX and SEASTAR Small Sat programs

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NICKEL-HYDROGEN GROUP

2.5INCH NICKEL-HYDROGEN DEVELOPMENT HISTORY

* Delivered the following Flight Qualified Hardware (6AH DESIGN)

20 Flight Qualified Cells	JANUARY 15,1991
4- 10 CELL FLIGHT BATTERIES	JULY 9, 1992
4 Battery Spare Cells	Sept 10,1992

* Contracted with Orbital Science in April 92 to provide Battery Cells for the Orbcomm Program Delivery Scheduled for March 5, 1992

  10AH Design

* In negotiations on two additional Aerospace programs .

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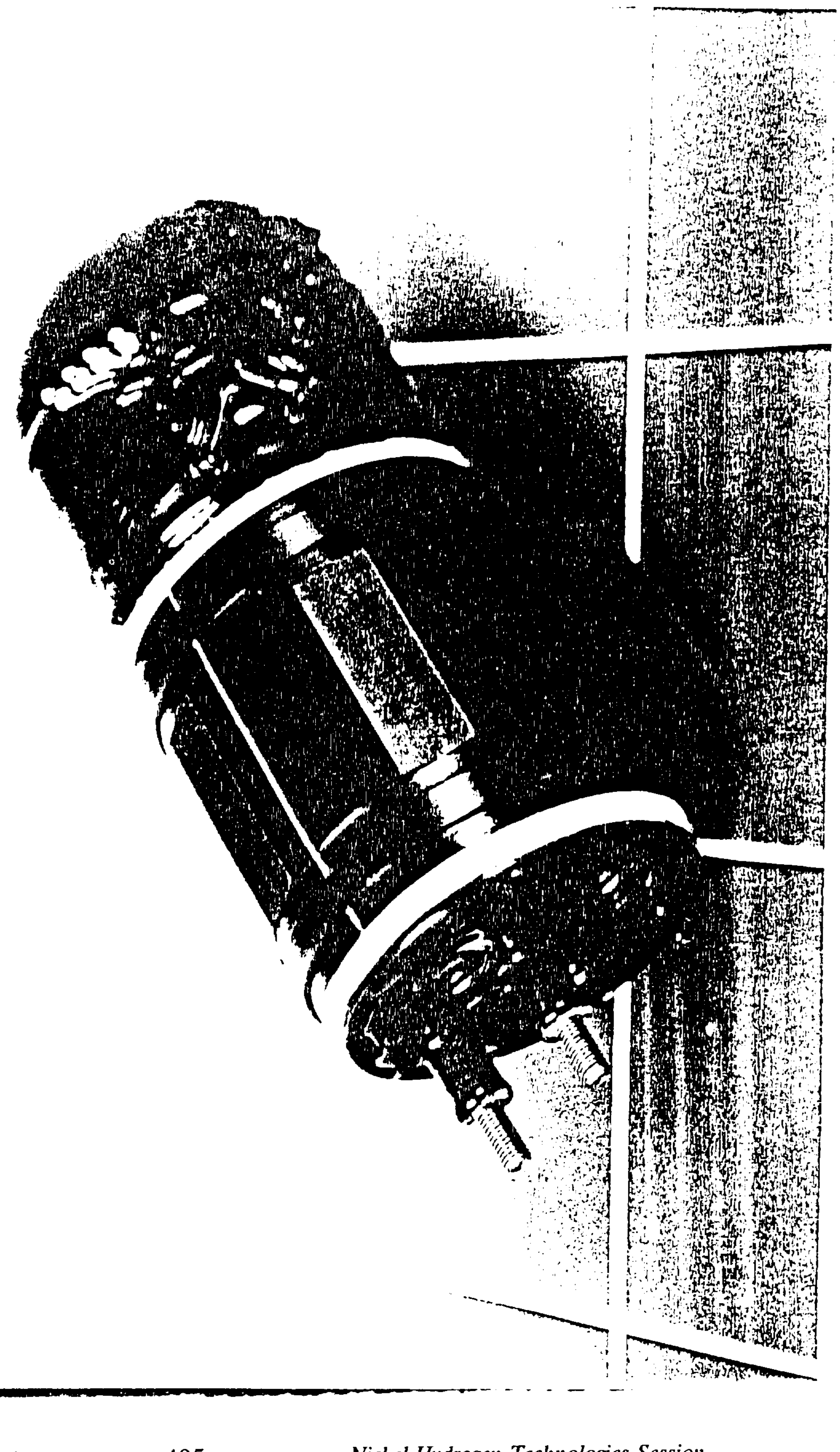

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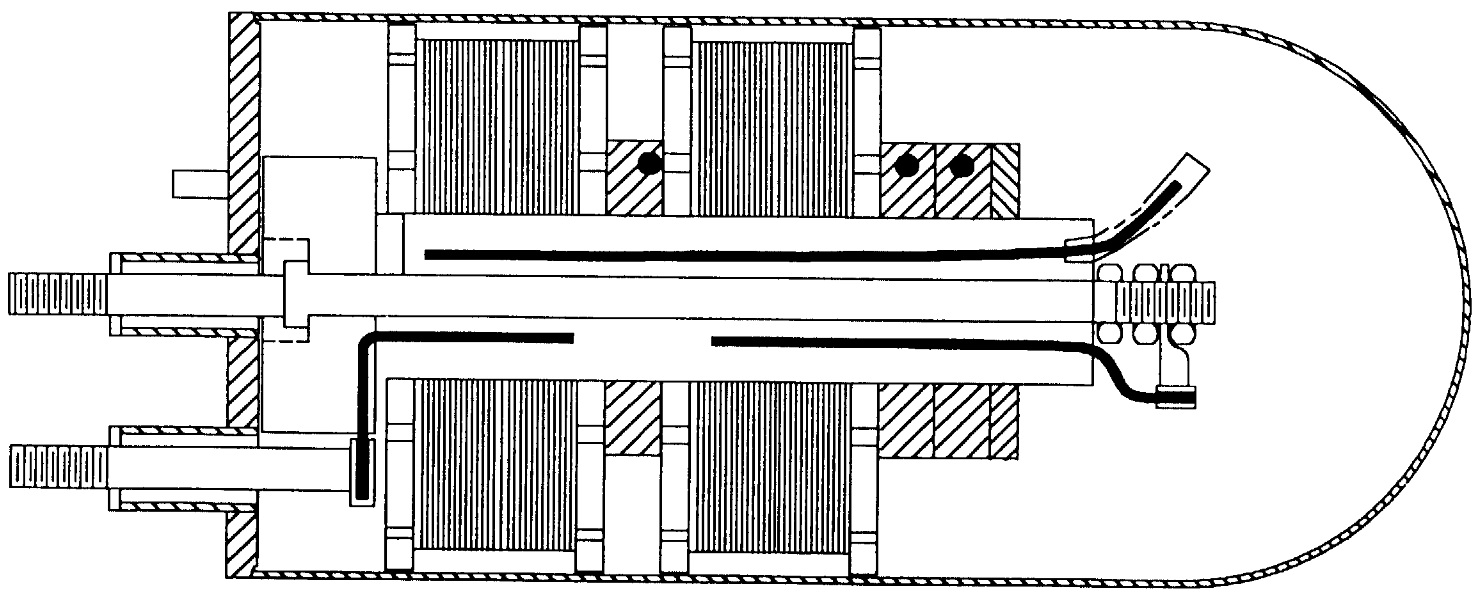
NICKEL-HYDROGEN GROUP

RNHC-6-1 CELL DESIGN



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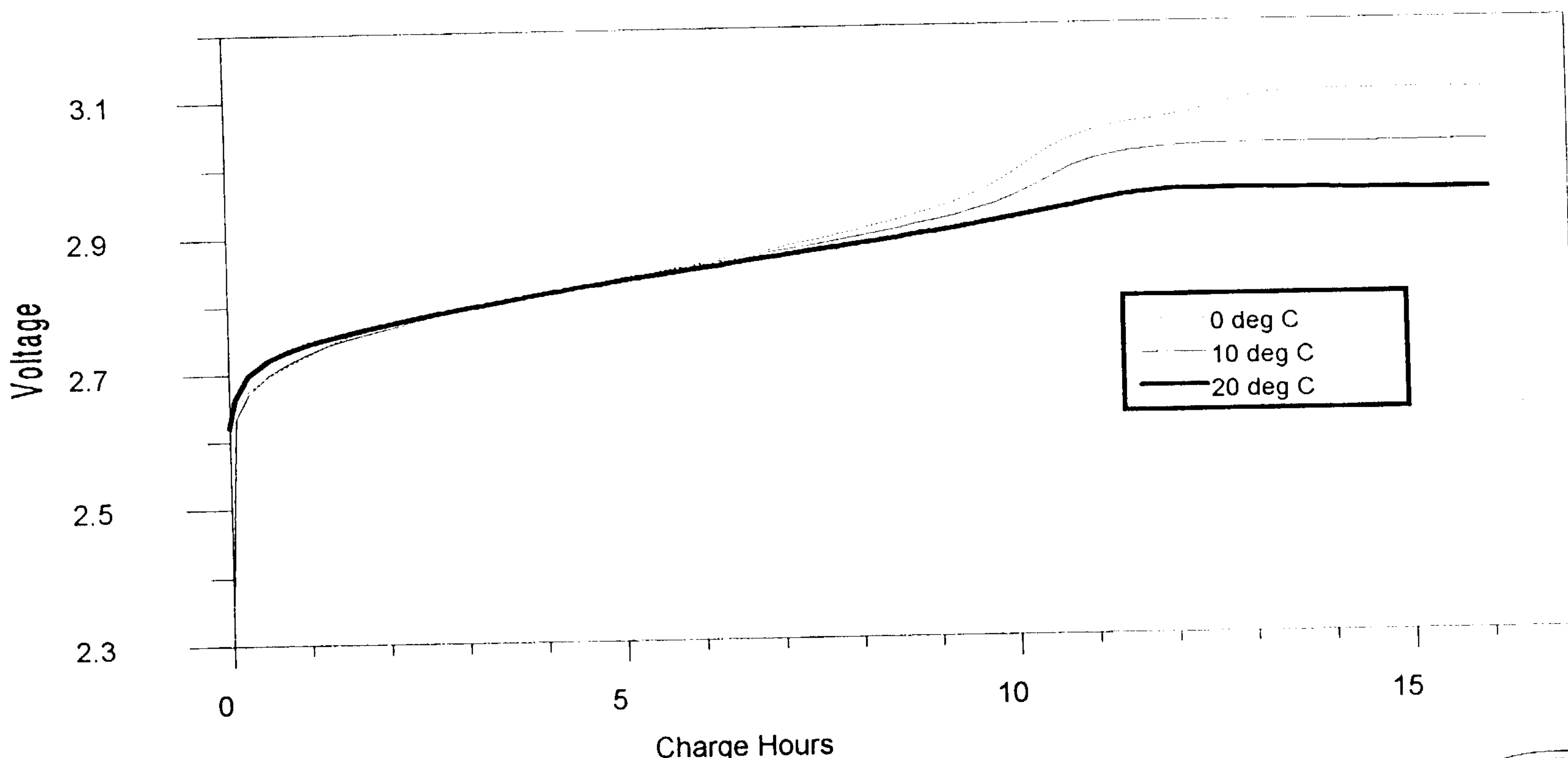
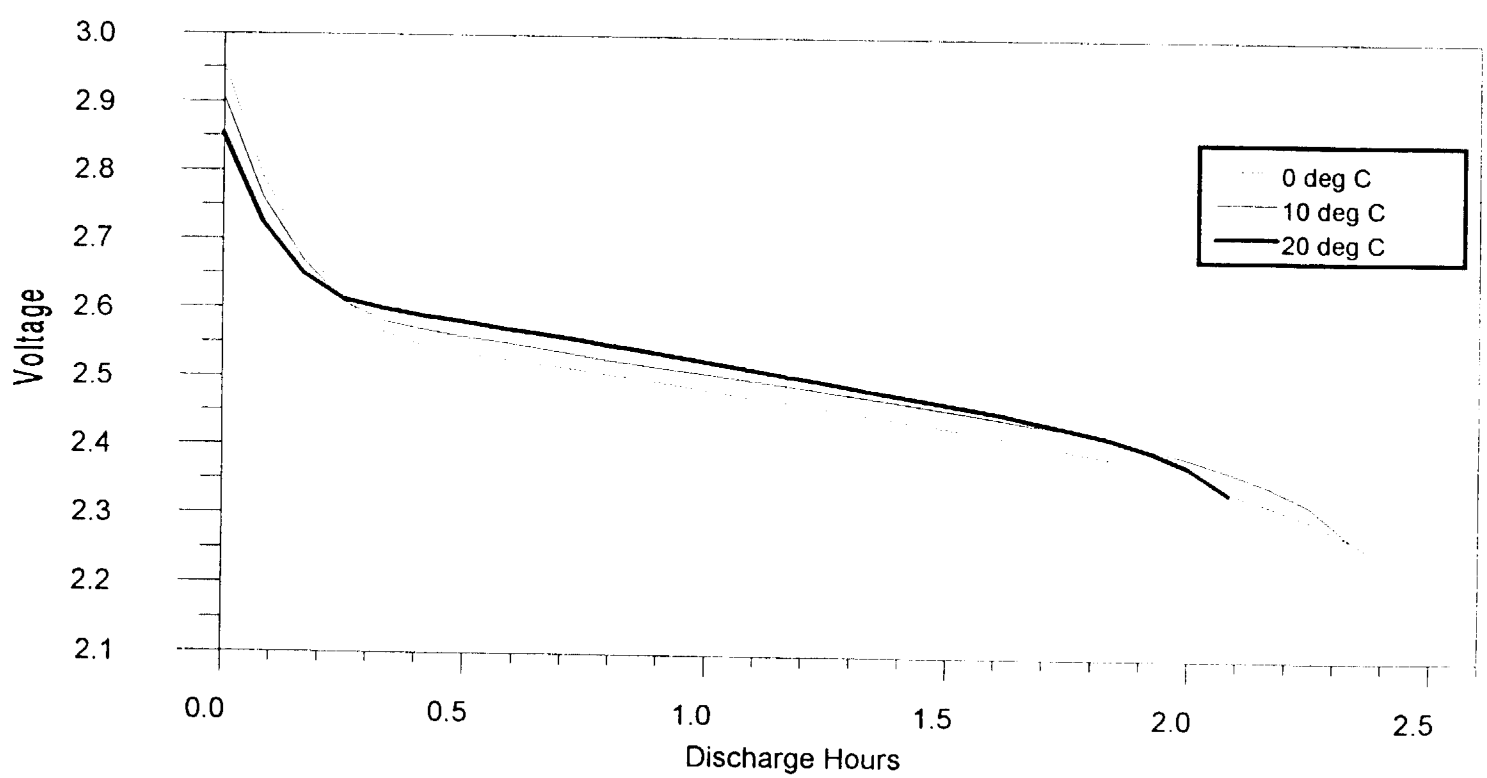
RNHC-6-1 CHARGE VOLTAGE AT 0.6A



RNHC-6-1 DISCHARGE VOLTAGE AT 3.0 AMPS



RNHC-6-1 CELL QUALIFICATION TESTING

* Cell proof pressure to 1.5 times MEOP
* Cell cycle testing to 85,000 cycles at MEOP
* Cell Burst testing > 4/1 safety factor
* Cell Vibration test to 9 GRMS
* Thermal Vaccum Testing 120 hrs
* Performance testing at 0,10,20 degree C
  3.0 amp discharge

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FLIGHT UNIT TESTING

* Pressure Testing 1.5* MEOP
* Leak Check
* X Ray
* 0C Capacity Test
* 10C Capacity Test
* 10C Charge Retention Test
* 20C Capicity Test
* Impedance Check

EAGLE PICHER Quality First!

RNHC-6-1 TECHNICAL DATA

Rated Capacity	6 AH
Nominal Voltage	2.5 Volts
Cell Mass	633 Grams
Diameter	6.48 cm
Length	17.15 cm
Capacity to 2.0 Volts	7.1 AH
Specific Energy	28 WH/KG
Energy Density	39.2 WH/L
Operating Pressure	400 PSIG
Safety Factor	5/1
Cell Case	304LSS
Separator	Zircar
Positive Electrode	Slurry

EAGLE PICHER Quality First!

RNHC-10-1 TECHNICAL DATA

Rated Capacity	10 AH
Nominal Voltage	2.5 Volts
Cell Mass	700 Grams
Diameter	6.48 cm
Length	18.62 cm
Capacity to 2.0 Volts	11.8 A
Operating Pressure	500 PSIG
Safety Factor	5/1
Cell Case	Inconel
Separator	Zircar
Positive Electrode	Slurry

Technical Data for SAR-10027 Battery

Rated Capacity	6AH
Nominal Mass	25.0 Volts
Battery Mass	8467 Grams
Length	40.6 cm
Width	39.4 cm
Height	8.3 cm
Capacity to 2.0 V @ 10C	7.1 AH
Specific Energy	21.20 Wh/Kg
Energy Density	13.5 Wh/L
Vibration	9.0 GRMS
Thermal - Vac	120 hr
Thermistors	2
Heaters	2
Electrical Isolation	Two Levels.

EAGLE PICHER Quality First!

EAGLE-PICHER INDUSTRIES, INC.
JOPLIN, MO

Advanced Systems Department

NICKEL-HYDROGEN GROUP

SAR10027 BATTERY TESTING

* Charge/ discharge capacity test at 20 degree C
* Vibration test to 9Grms (random)
* Thermal-Vaccum test temp cycle for 120 hrs

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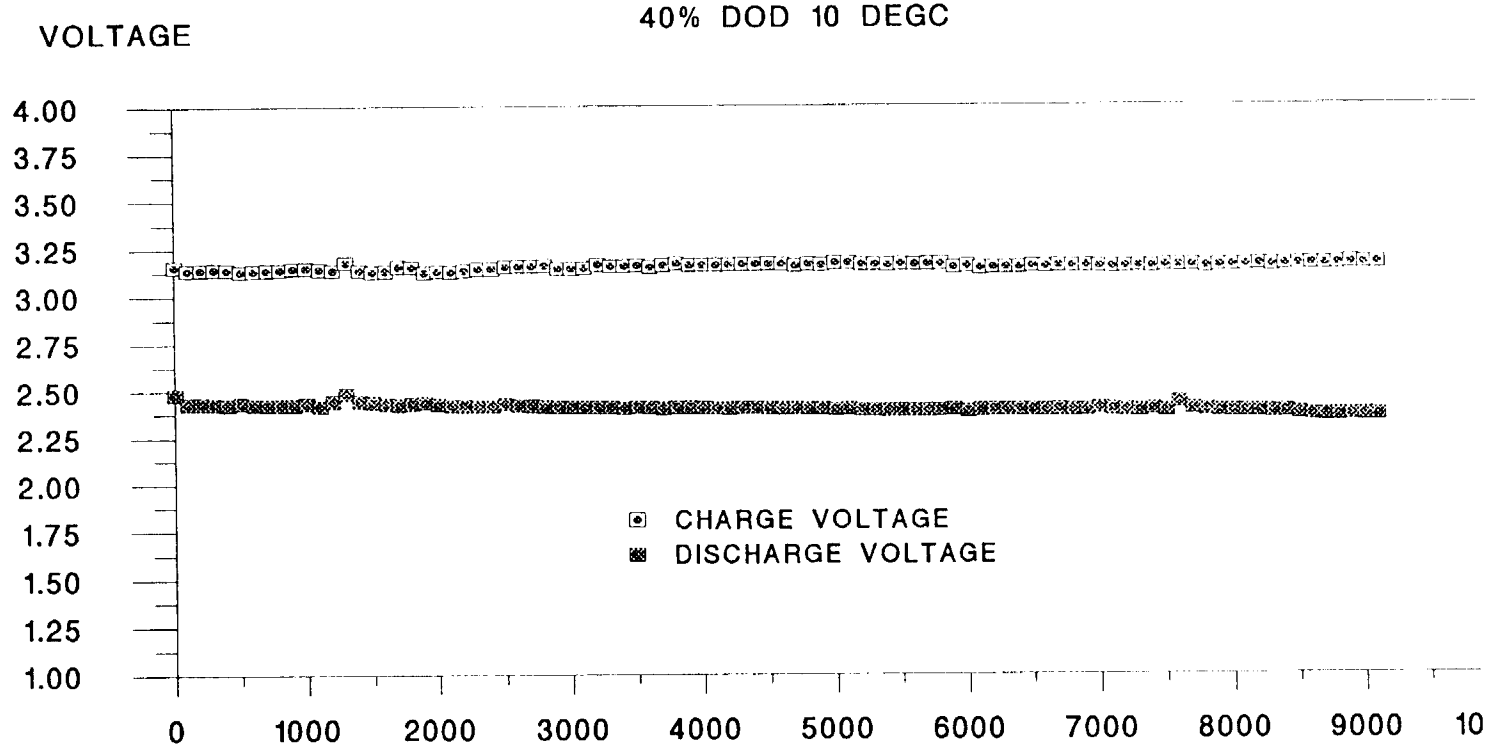
EAGLE-PICHER INDUSTRIES, INC.
JOPLIN, MO

Advanced Systems Department

NICKEL-HYDROGEN GROUP

RNHC-10-1 LIFE TEST AS OF 10/31/92

40% DOD 10 DEGC



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CONCLUSION

Sucessfully developed and manufactured a 6AH and a 10 AH 2.5 Inch CPV

Nickel - HydrogenPressure Vessel for Aerospace and Terrestrial Application

The scheduled flight for the 6 AH cell is JULY 1993

EAGLE PICHER
Quality First!

HUBBLE SPACE TELESCOPE NICKEL HYDROGEN BATTERY SYSTEM BRIEFING

for the 1992 NASA Battery Workshop

David Nawrocki, Lockheed Missiles & Space Co.
David Saldaña, Lockheed Technical Operations Co.
Gopal Rao, Goddard Space Flight Center

18 November 92

BETTY COLHOUN /CSC - GRAPHICS

HST MISSION

LOW EARTH ORBIT OPERATION

96 MINUTE ORBIT	15 ORBITS PER DAY
BETA ANGLES RANGE FROM 0° TO 52°	TRANSLATES TO 26 TO 35 MINUTE DISCHARGE PERIODS

RECHARGE MUST BE ATTAINED IN 60 MINUTES*

STATE-OF-CHARGE

BASED ON ATP CAPACITY OF	88 AMPERE-HOURS AT 0°C
VEHICLE THRESHOLD (OLD)	68 AMPERE-HOURS -- OR 77%
NOMINAL OPERATION (NEW THRESHOLD)	75 AMPERE-HOURS -- OR 85%

* EXCEPT FOLLOWING OFF NORMAL ROLLS

SYSTEM CONSTRAINTS

THERMAL: DISSIPATION OF HEAT GENERATED IN BATTERY CONDUCTED THROUGH TWO INCH HONEYCOMB PANEL PRIOR TO RADIATING TO SPACE

LOUVERS AND MLI ON BAY DOOR INSTALLED ON EXTERIOR BAY DOOR SURFACE TO REDUCE BATTERY HEATER DUTY CYCLES

BATTERIES IN INTIMATE PROXIMITY AND THERMALLY COUPLED

TEMPERATURE OPERATING RANGE: -5°C TO 20°C

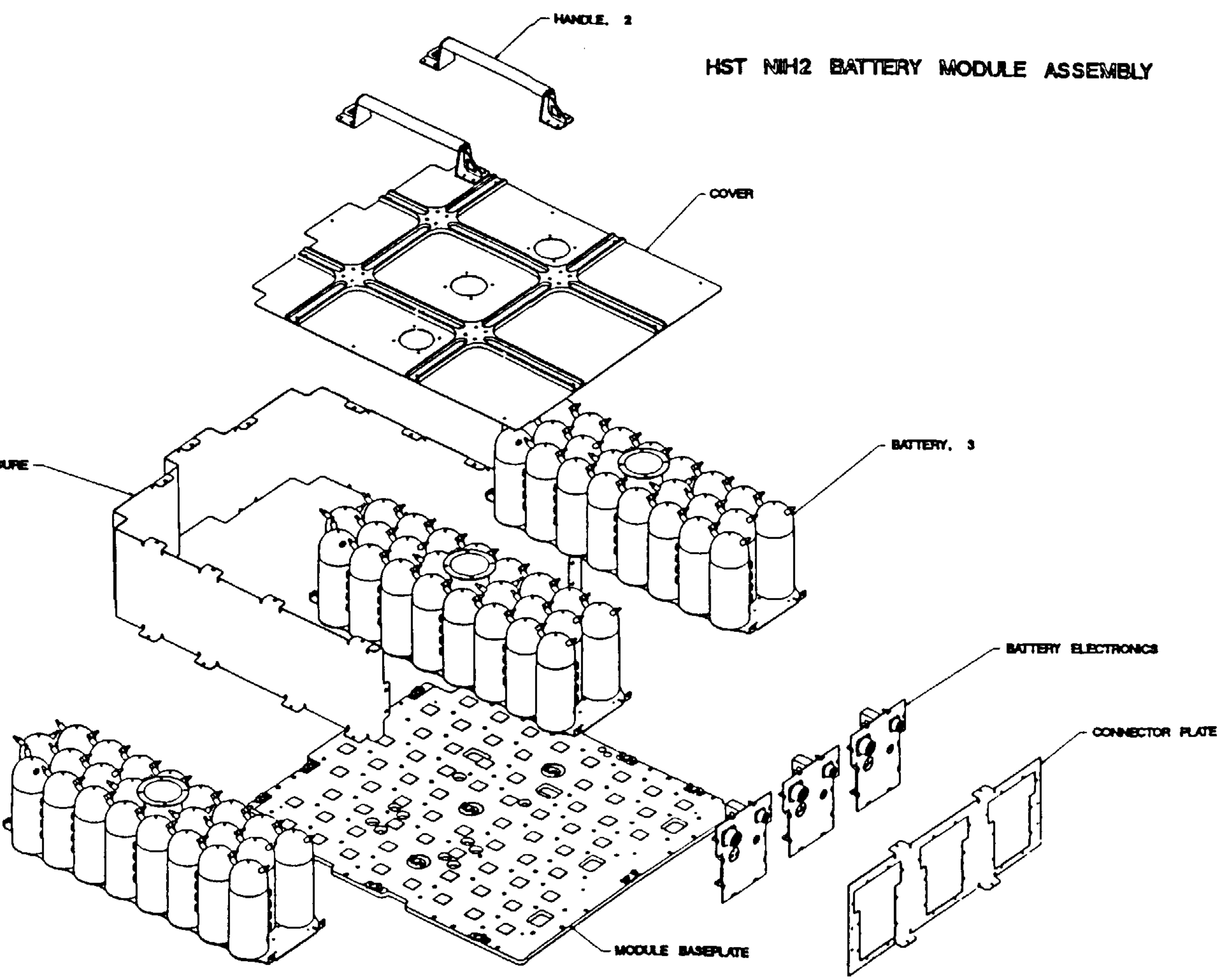
ELECTRICAL: MAXIMUM CHARGE VOLTAGE 34.3 VOLTS DC (SYSTEM CONSTRAINT)
THIS TRANSLATES TO 1.56 VOLTS DC PER CELL
(THERMAL LIMITATION IS 1.53 VOLTS PER CELL)
MINIMUM DISCHARGE VOLTAGE 26.5 VOLTS DC (SYSTEM CONSTRAINT)
THIS TRANSLATES TO 1.20 VOLTS DC PER CELL AND WAS
SECONDARY REASON FOR ADJUSTING ELECTROLYTE CONC.

BATTERY SPECIFICATION

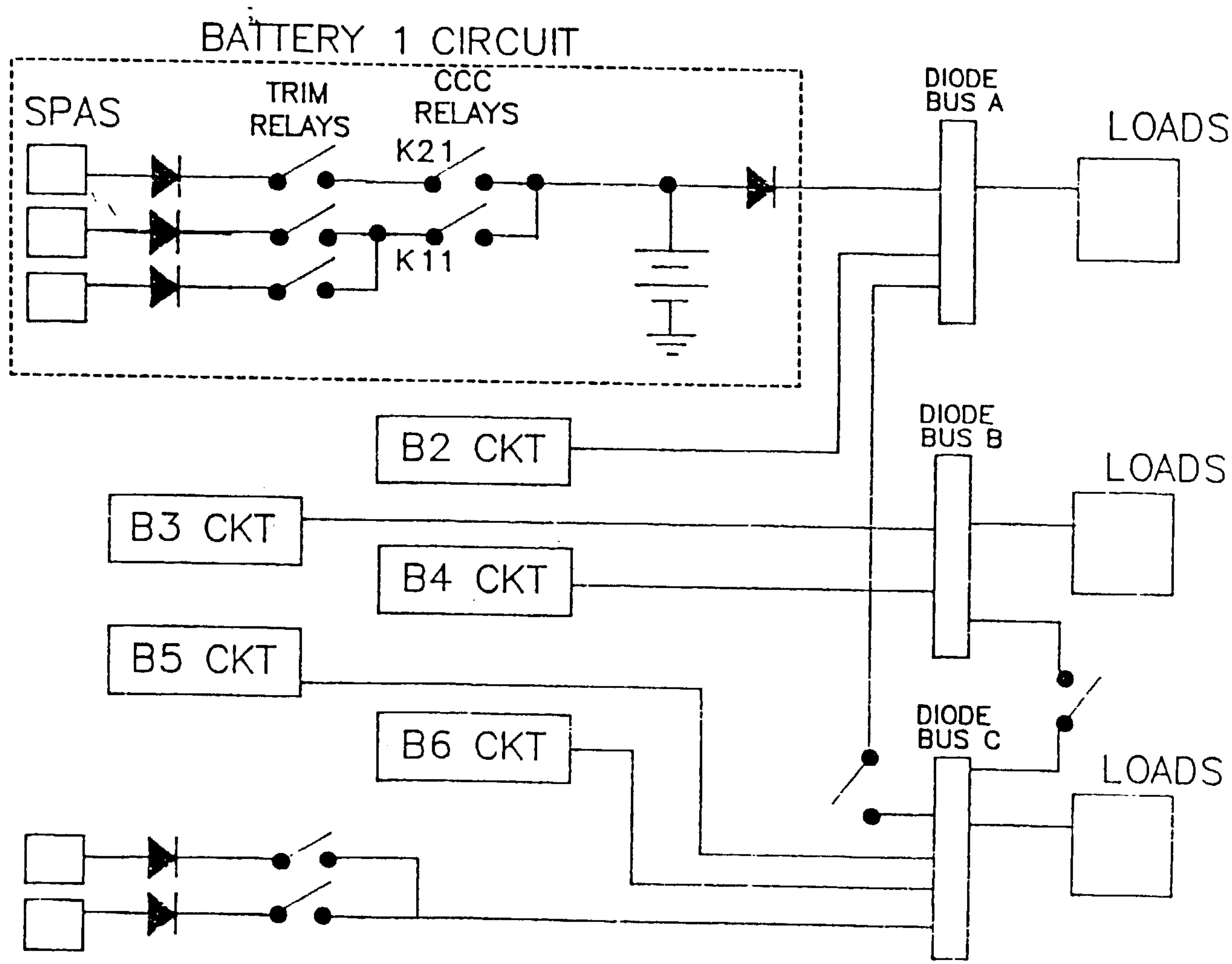
SIX BATTERY SYSTEM	MAXIMUM DOD 14%	WITH ONE BATTERY FAILED
BATTERY CAPACITY AT 0°C	88 AMP-HR	AT 15 AMP (C/6) DISCHARGE RATE
MAX. DISCHARGE CURRENT	20 AMPERES	TO 26.5 VOLTS DC AT BATTERY
PEAK DISCHARGE CURRENT	30 AMPERES	FOR 10 SECONDS MAXIMUM
CHARGING RANGES	5.0 TO 18.0 AMPERES	DURING ORBITAL OPERATIONS
ORBITAL LIFE	FIVE YEARS	27,375--14% DOD CYCLES

BATTERY MODULE

HST NIH2 BATTERY MODULE ASSEMBLY



SIMPLIFIED BLOCK DIAGRAM



CELL DESIGN SUMMARY

AF "Pineapple Slice" Cell Design with the Following Components:

- 48 Dry Sintered Nickel Positive Electrodes (0.035 in. thick)
- 48 Platinum Negative Electrodes (0.006 in. thick)
- Zirconium Oxide Cloth Separators and Gas Screens
- Polysulfone End Plates, Core and Retaining Nut
- Belleville and Whiteley Washers
- Inconel 718 Pressure Vessel (0.040 in. thick)
- Zirconium Oxide Pressure Vessel Wall Wick
- Inconel 718 Terminal Bosses and Weld Ring
- Injection Molded Nylon Terminal Seals

PRESENT STATUS

LAUNCHED: 24 APRIL 1990

ABOUT 2.5 YEARS OF SERVICE // 15 YEAR SPACECRAFT SPEC LIFE

14,012 ORBITS DOY 323 @ 1800 EDT (18 NOV 92)

DOD AVERAGES BETWEEN 8 - 10 % BASED ON NAMEPLATE

HIGHEST DOD 27% FEATHERING TESTS

LOWEST DOD 5% HARDWARE SAFE MODE

TEMPERATURES: 0°C ±3°C NOMINAL

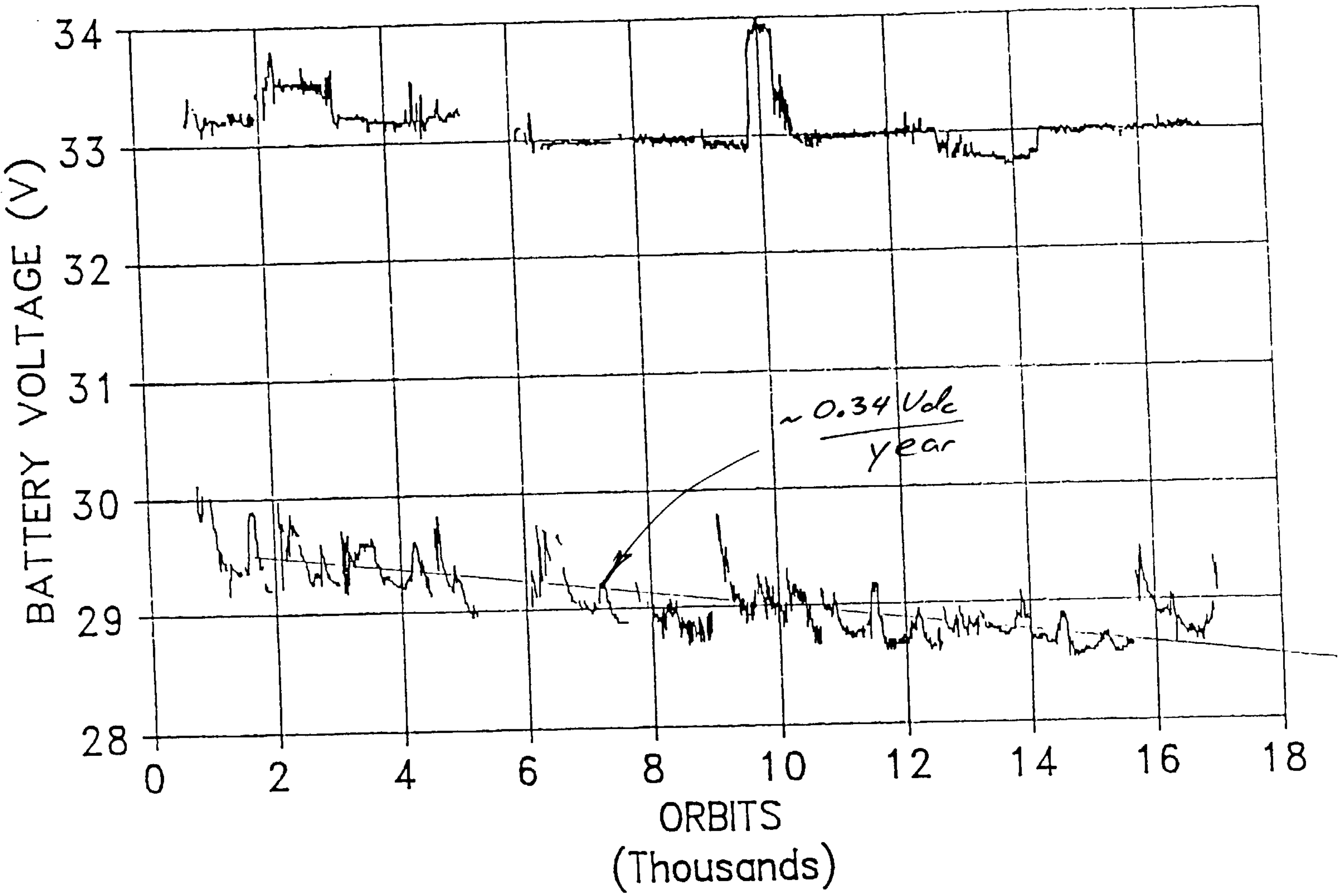
MAX TEMPERATURE: 5°C DURING HARDWARE SAFE MODE

VOLTAGES: EOCV 33 - 33.2 VDC (CONTROLLED)

EODV: DECLINING (SEE NEXT PAGE)

PRESSURES: SEE GRAPH

VOLTAGE DECAY GROUND TEST (MSFC)



⑨

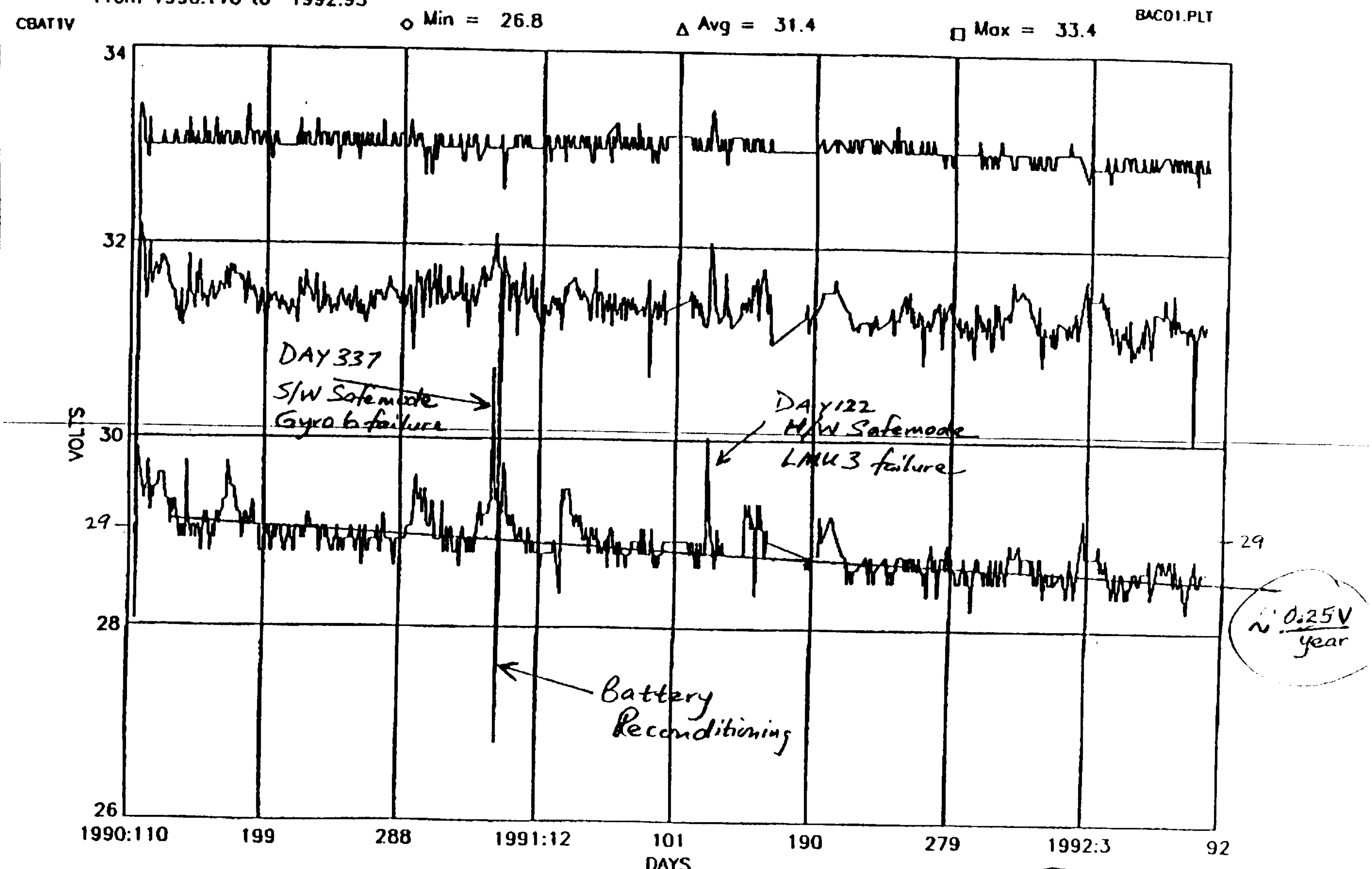
—— END OF CHARGE —— END OF DISCHARGE

HUBBLE SPACE TELESCOPE

On-Orbit Test System

Batt Volt

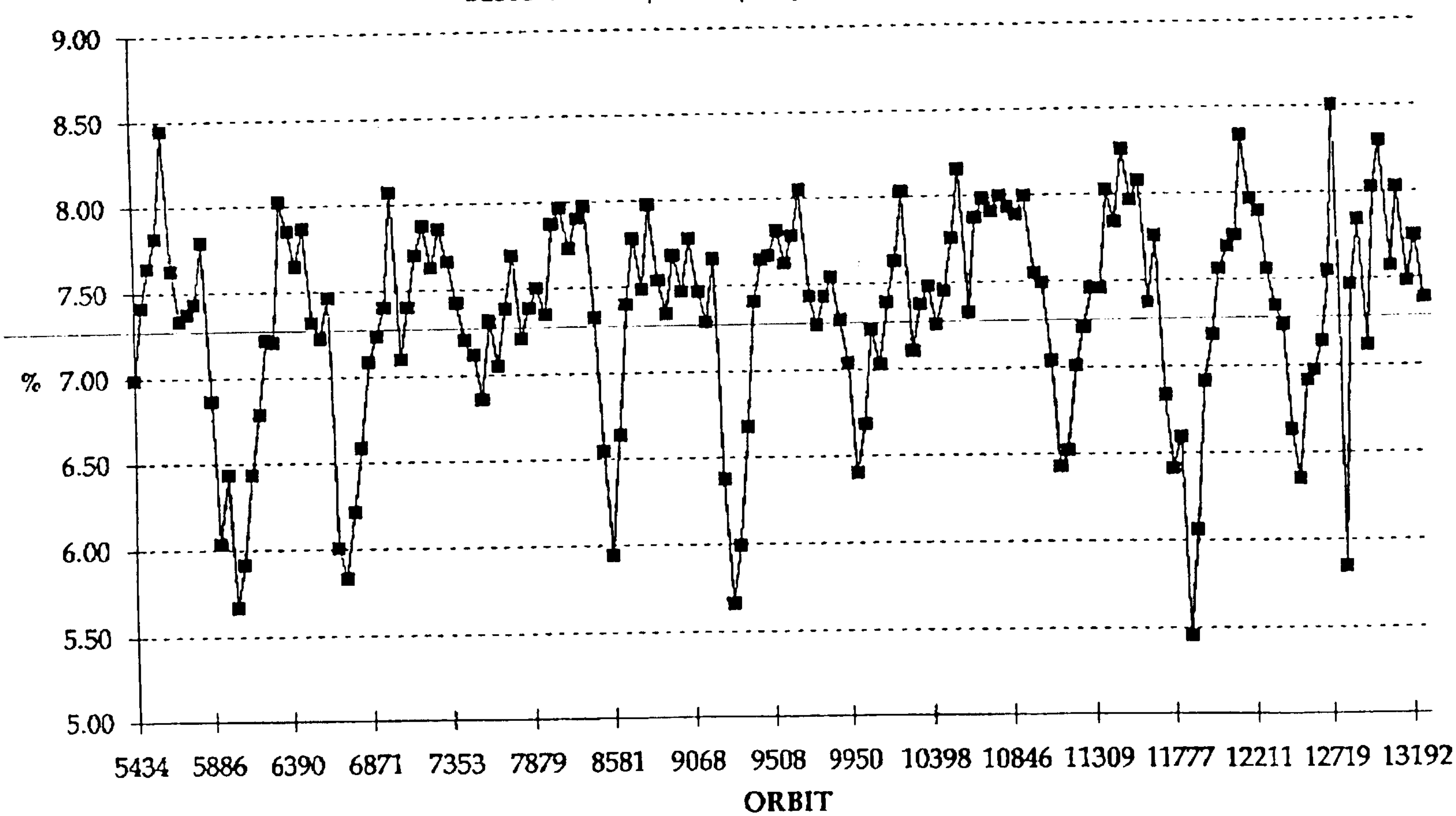
From 1990:110 to 1992:95



SYSTEM DOD

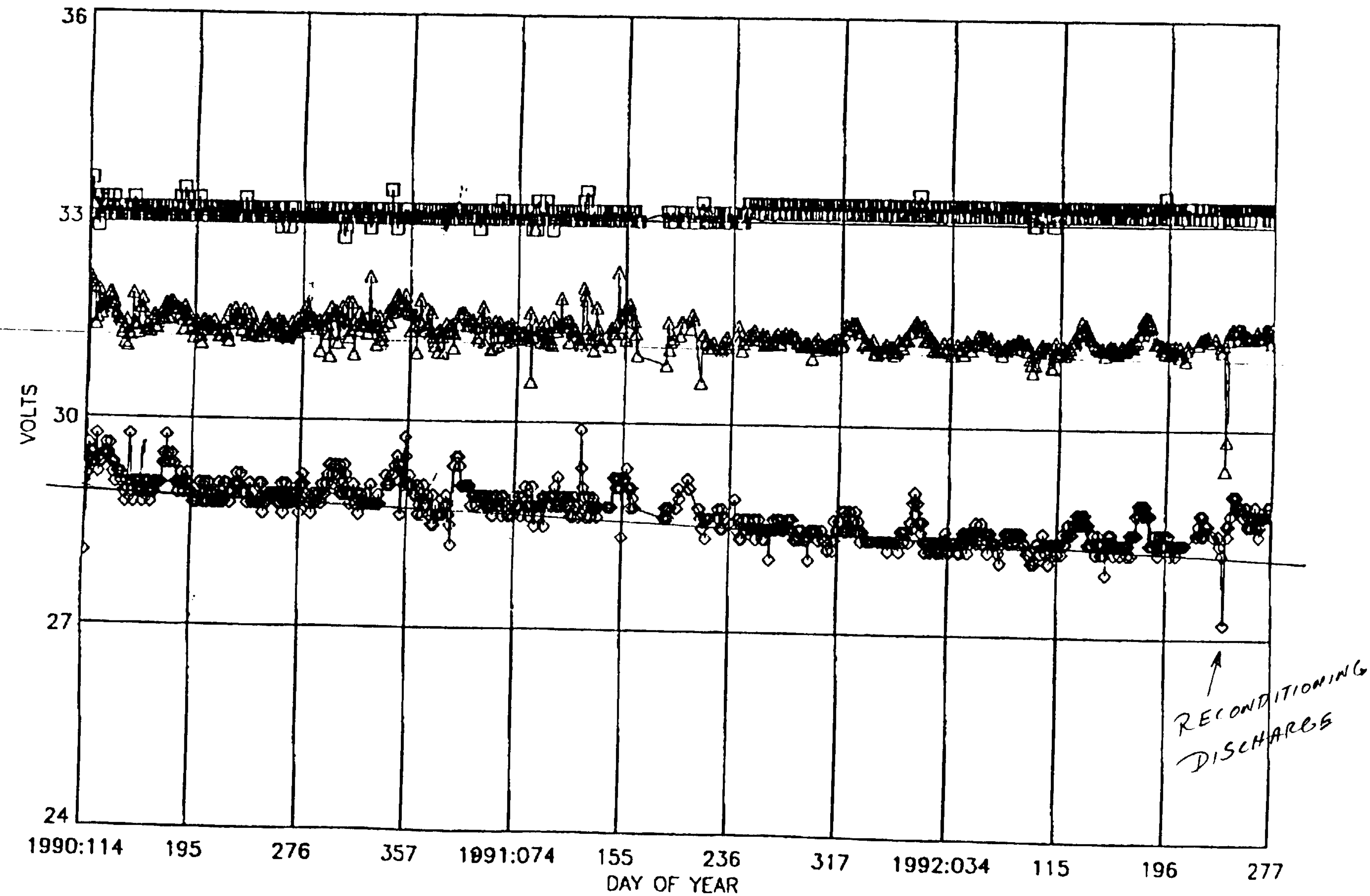
Total Battery Depth-of-Discharge (April 24, 1991- September 30,1992)

Based on nameplate capacity of 6 x 88 = 528 A-h



VOLTAGE DECAY (THRU 10/3/92)

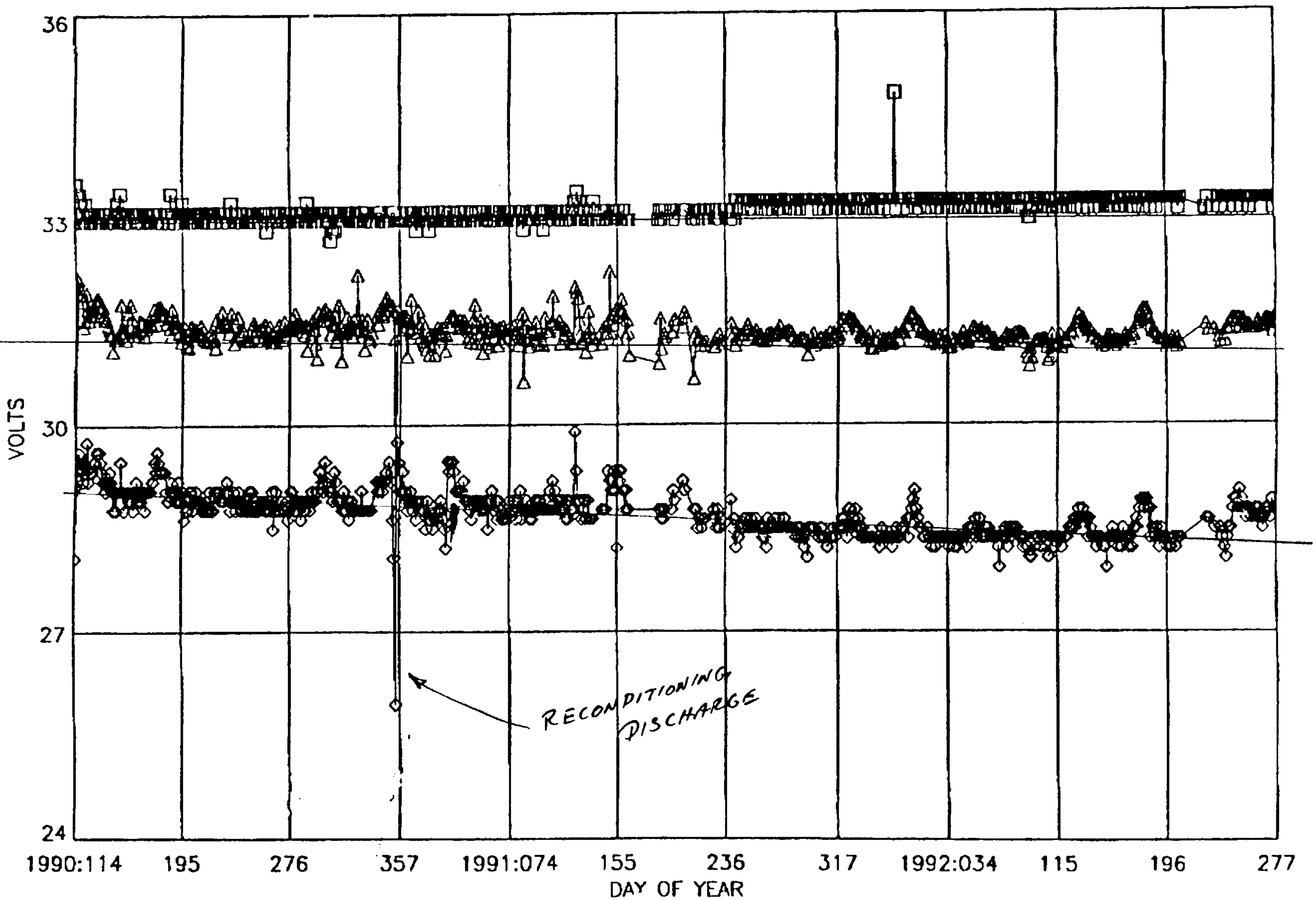
BATTERY #2



HST FS&S

VOLTAGE DECAY (THRU 10/3/92)

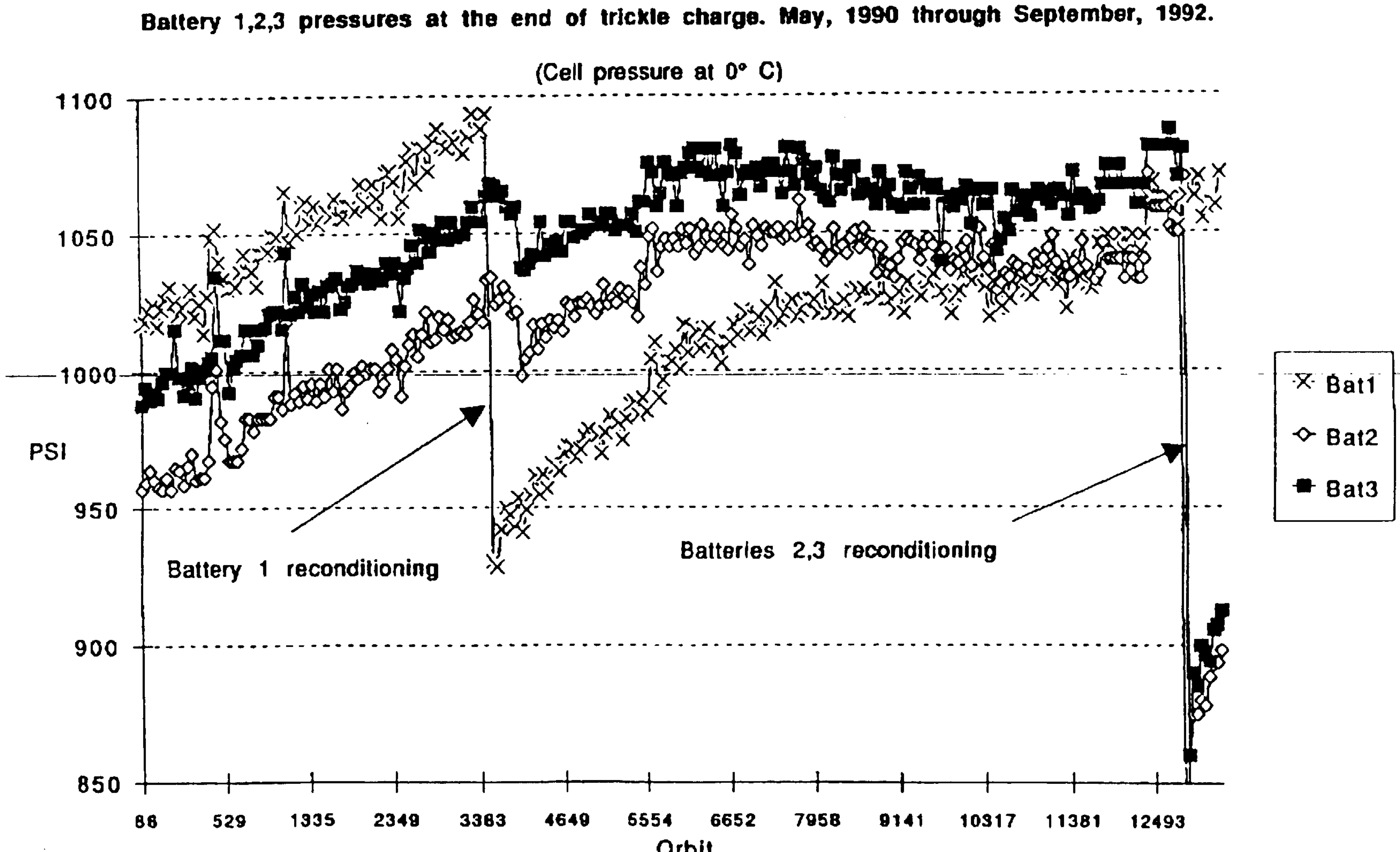
BATTERY #4



HUBBLE SPACE TELESCOPE HST FS&S

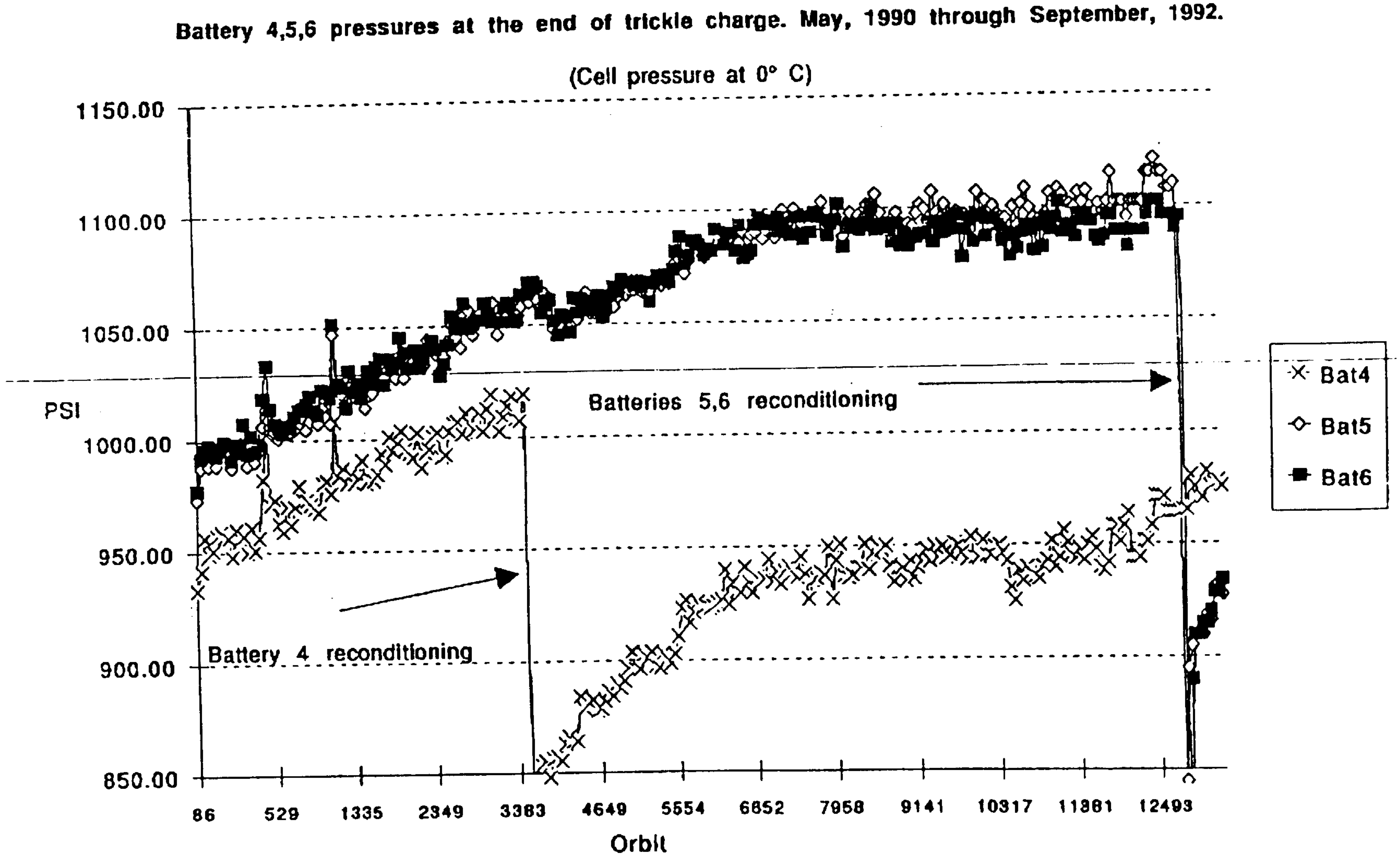
PRESSURE SINCE LAUNCH

BATTERIES 1, 2, & 3



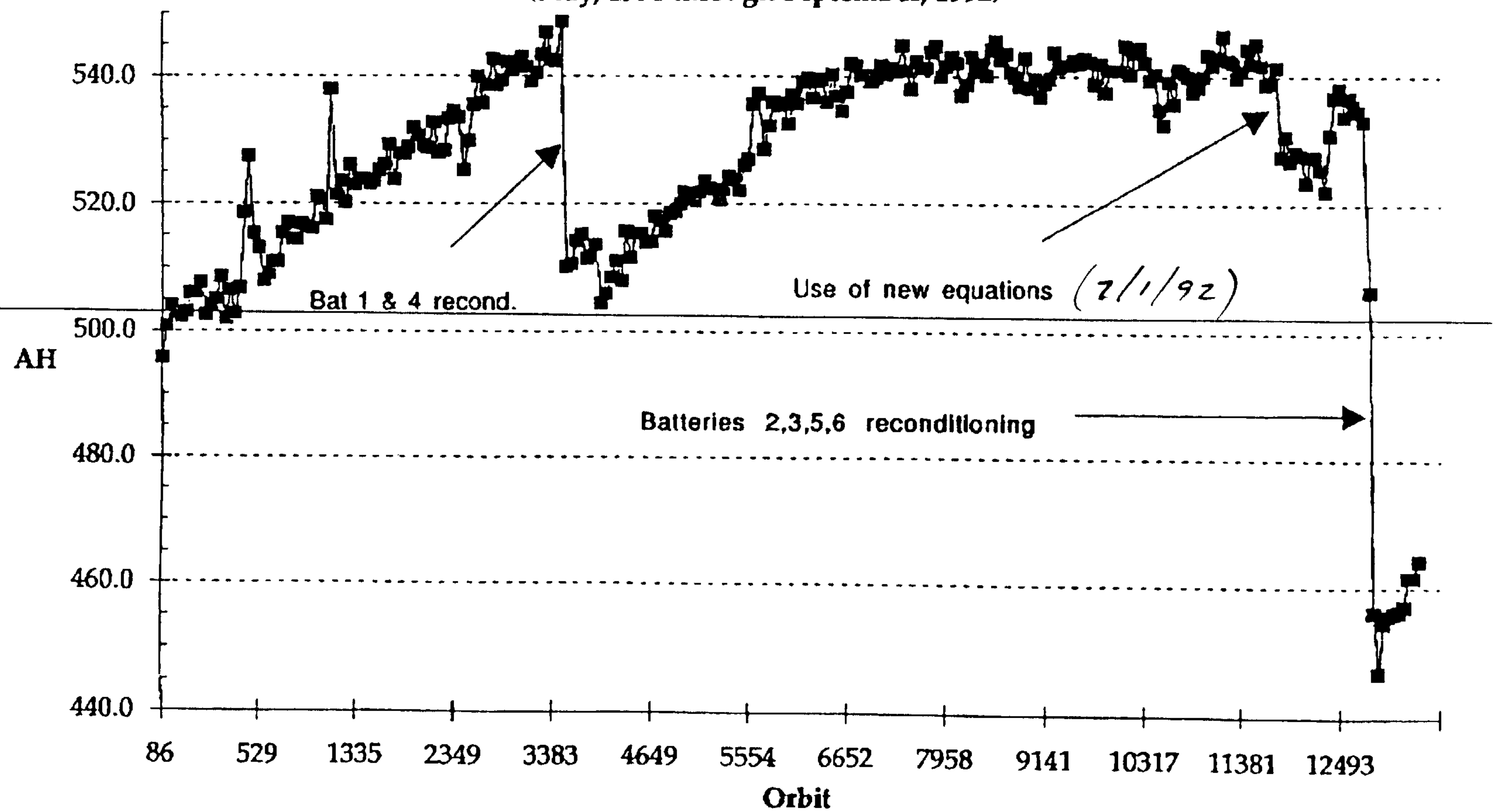
PRESSURE SINCE LAUNCH

BATTERIES 4, 5, & 6

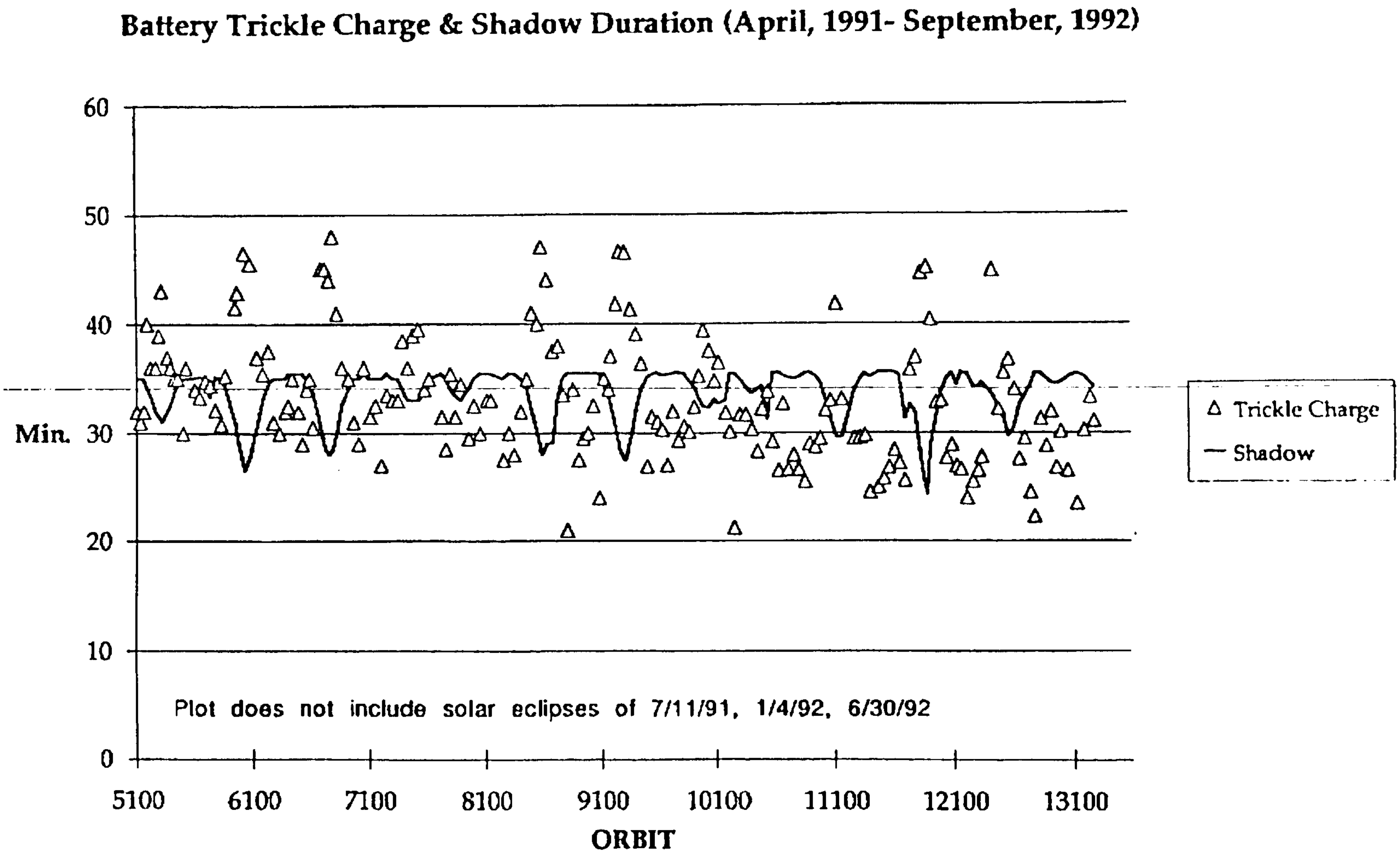


SYSTEM CAPACITY

(May, 1990 through September, 1992)



ECLIPSE TIME VS. TRICKLE CHARGE



CAPACITY TEST OBJECTIVES

Determine the actual capacity of each battery. This is essential for:

a. Establishing trend-analysis baseline for future SM replacement

b. Are the batteries healthy at greater than 7% depth of discharge (the average to which the batteries are normally discharged)?

- Determine if we are starting any soft shorts in cells
- Need to trend end of discharge pressures

c. Defining capacity versus pressure correlation, on a yearly basis.

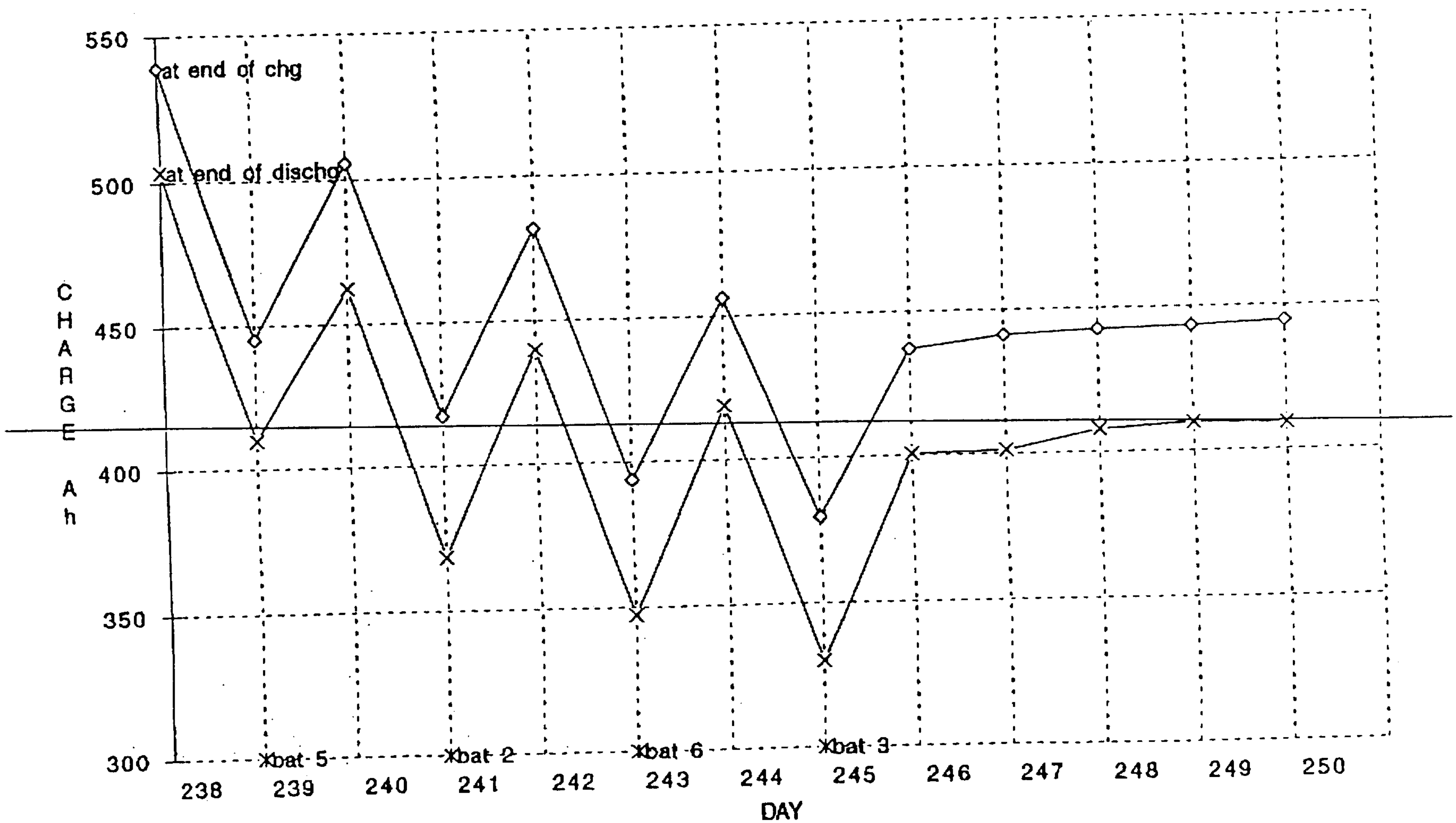
d. Evaluate the Safe Mode power margins.

- New Safe Modes* depend on having plenty of battery capacity
- Safemode trip points must be lowered as known battery capacity declines, thus reducing margins above minimum requirement

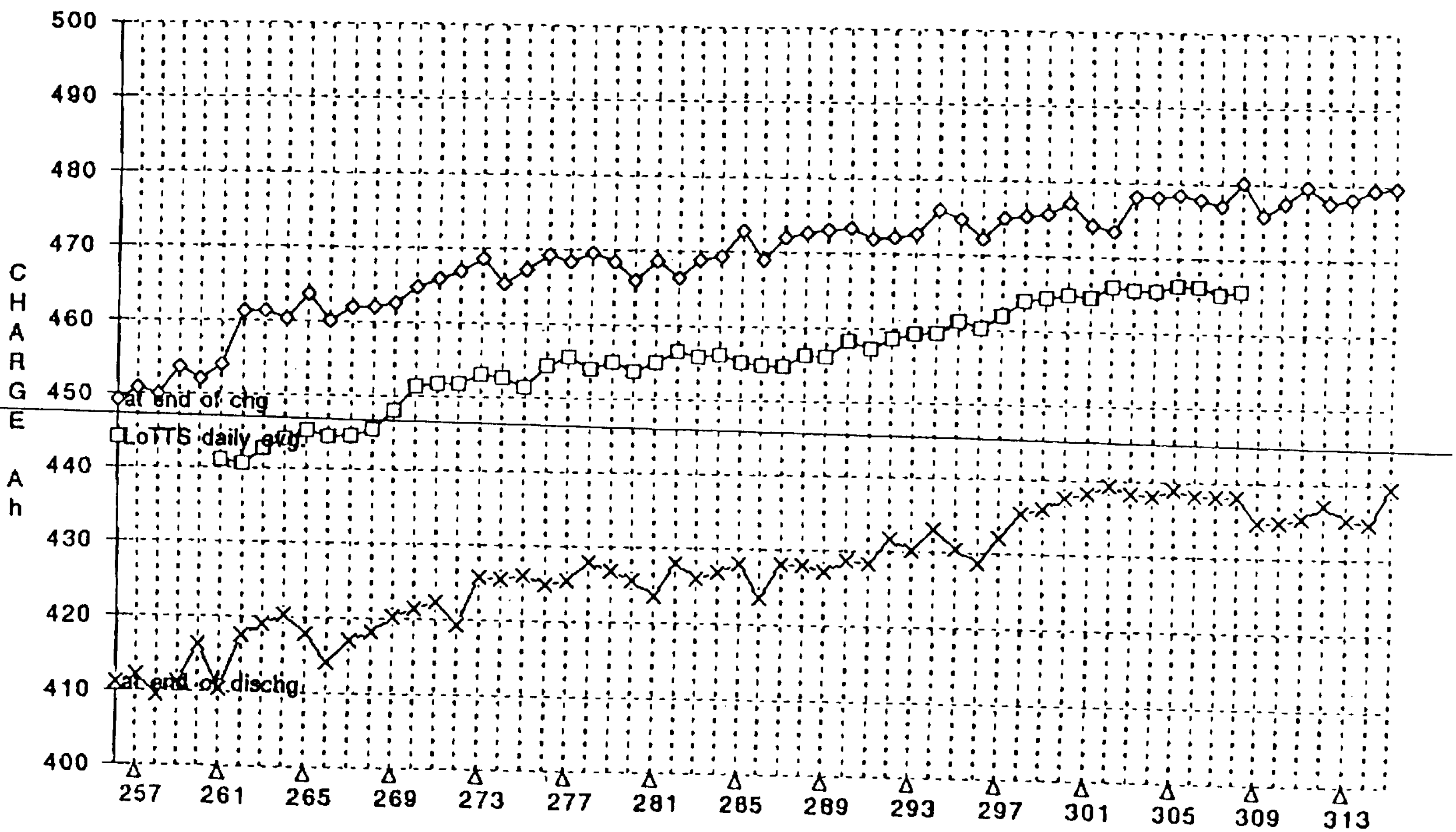
e. Desire to have battery system "balanced"

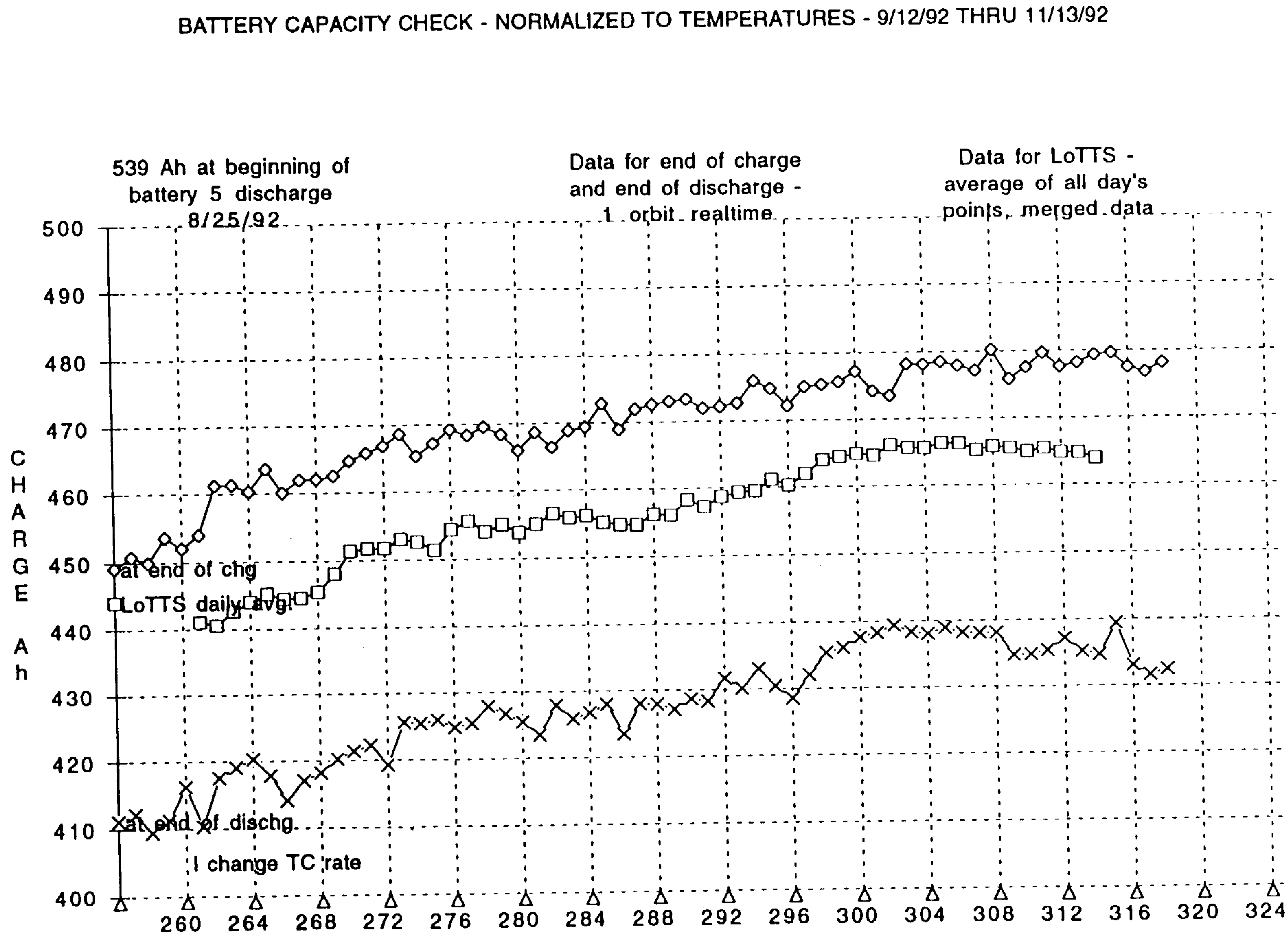
* - Spin Stabilized
  - Zero Gyro

CAPACITY DURING TESTS



PRESENT CAPACITY RECOVERY TREND



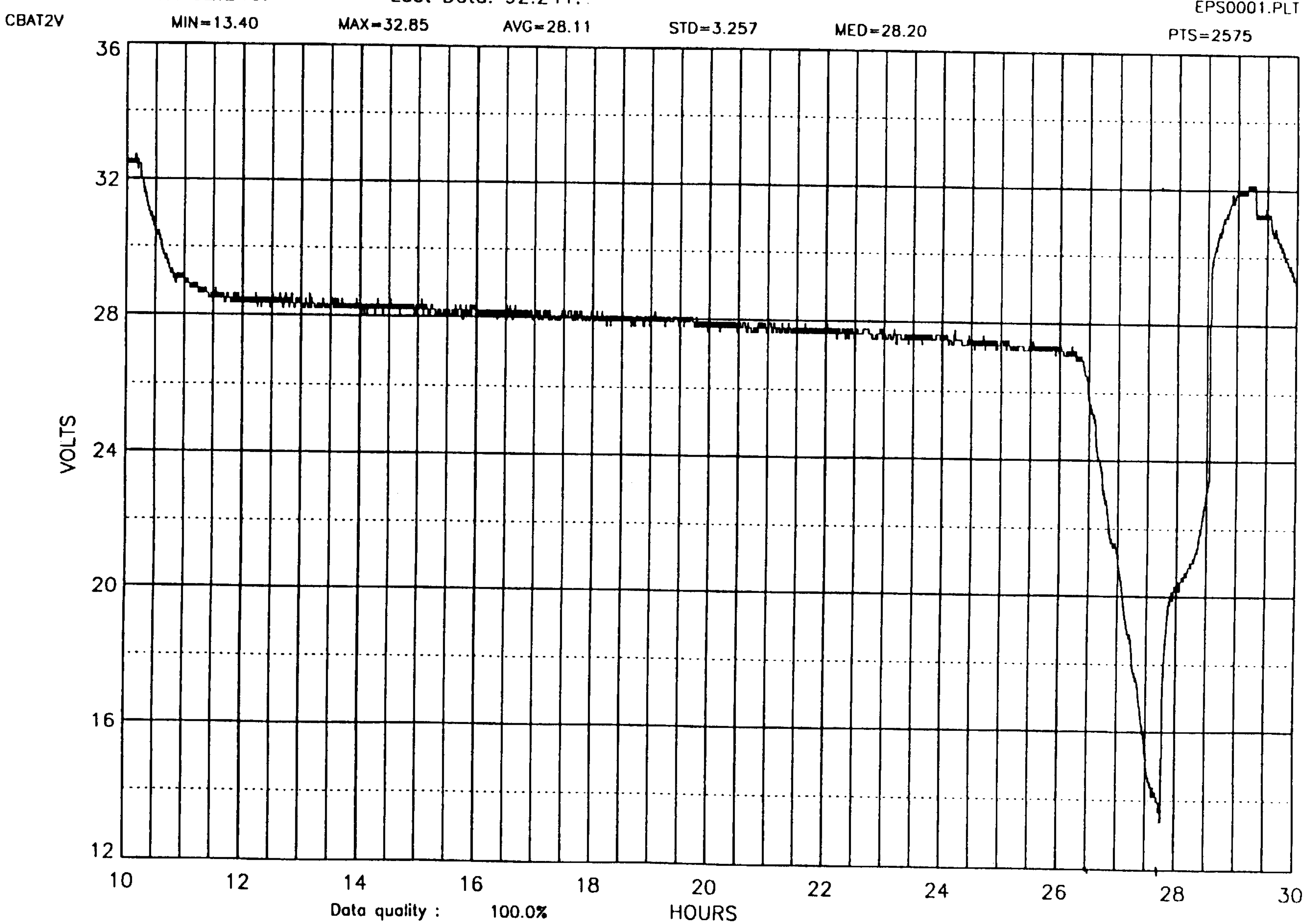

BATTERY CAPACITY CHECK - NORMALIZED TO TEMPERATURES - 9/12/92 THRU 11/13/92
539 Ah at beginning of battery 5 discharge 8/25/92
Data for end of charge and end of discharge - 1 orbit realtime
Data for LoTTS - average of all day's points, merged data
CHARGE Ah
500
490
480
470
460
450
440
430
420
410
400
at end of chg
LoTTS daily avg.
at end of dischg
I change TC rate
260
264
268
272
276
280
284
288
292
296
300
304
308
312
316
320
324

HST LoTTS – ESS
Electrical Power Subsystem
Battery 2 DISCHARGE

First Data: 92:240: Last Data: 92:241:

Data Processed :FRI AUG 28 17:02:00 1992 Merged
Frame quality : 0.00%

EPS0001.PLT



Data quality : 100.0%

Data Processed :FRI AUG 28 17:02:00 1992
Frame quality : 0.00%

Merged

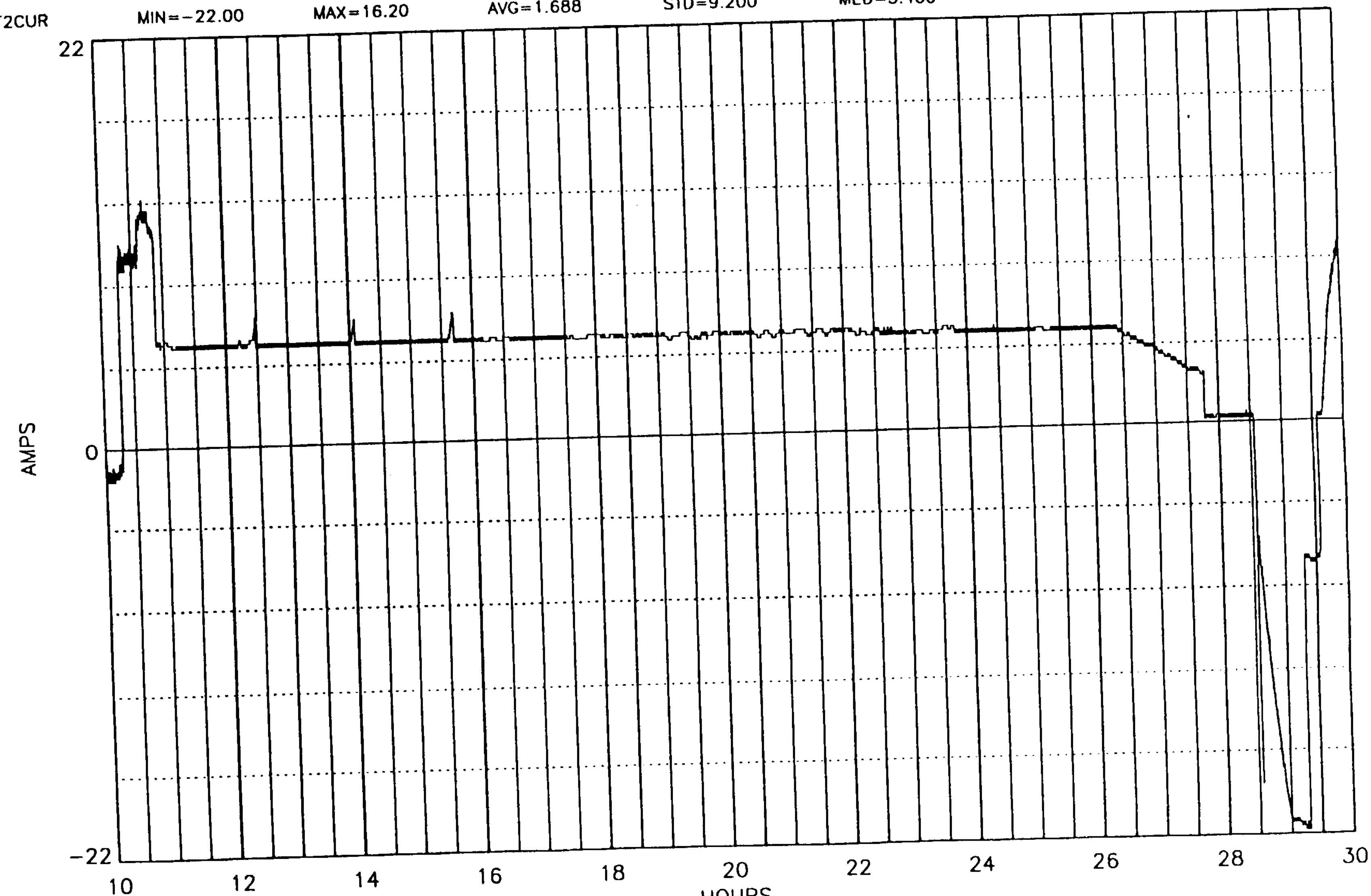
HST LoTTS – ESS
Electrical Power Subsystem
Battery 2 DISCHARGE

First Data: 92:240: Last Data: 92:241:

EPS0002.PLT

PTS=6155

CBAT2CUR MIN=−22.00 MAX=16.20 AVG=1.688 STD=9.200 MED=5.400



Data quality : 100.0%

1992 NASA Aerospace Battery Workshop -531- Nickel-Hydrogen Technologies Session

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AN OVERVIEW OF EIGHT YEARS OF ACTIVITY DEVELOPING FRENCH NICKEL HYDROGEN TECHNOLOGY

Thierry JAMIN

CNES

Jean VERNIOLLE

ESA

presented by Thierry JAMIN

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INTRODUCTION

- THE FRENCH AND EUROPEAN SPACE AGENCIES (CNES, ESA) HAVE BEEN CONTINUOUSLY CONTRIBUTING TO THE DEVELOPMENT OF SAFT NI H2 TECHNOLOGY SINCE 1985.

- AN IMPORTANT EFFORT HAS BEEN DEVOTED TO IMPROVING SCIENTIFIC KNOWLEDGE TO ENHANCING INDUSTRIAL EXPERIENCE AND TO PROMOTING SAFT AS AN OFFICIAL *"BACK UP SOURCE"* FOR THE EUROPEAN DOMESTIC TELECOMMUNICATIONS MARKET AS A BATTERY SUPPLIER.

- FUNDAMENTAL ASPECTS HAVE BEEN INVESTIGATED IN BOTH INDUSTRIAL AND UNIVERSITY LABS AS ESSENTIAL R & D SUPPORTS.

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OBJECTIVES

- WE INTEND TO EXPLAIN WHICH TECHNICAL AREAS, COMPONENTS AND PROCESSES HAVE BEEN COVERED BY OUR STUDIES

- WE INTEND TO SHOW THE RESULTS OF THIS WORK

- WE INTEND TO ESTABLISH THE STATUS WHICH HAS BEEN REACHED AND WHAT THE STANDARD SAFT IPV DESIGN'S MAIN FEATURES ARE

- WE INTEND TO PRESENT OUR PLANS FOR THE NEAR FUTURE

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HISTORICAL BACKGROUND
1984 - 1985 PERIOD

- ACTIVITIES AIMED AT BUILDING A 30-50 Ah IPV CELL DESIGN UNTIL 1984.
- LACK OF MECHANICAL CONCEPT MATURITY AND ELECTROCHEMICAL DISPERSION WERE OBSERVED.
- ENCOURAGING PRELIMINARY LIFE TEST RESULTS PERFORMED ON PROTOTYPES.
- DECISION TO START THE DEVELOPMENT ON A NEW IPV CELL DESIGN IN THE 30-50 Ah RANGE BY EARLY 1985
- SPECIAL ATTENTION GIVEN TO MECHANICAL PART CONSTRAINTS (MATERIAL, SHAPE, THICKNESS) AND PROCESSES IN GENERAL :
  . **MECHANICAL** (MACHINING, THERMAL TREATMENT, WELDING, CONTROL)
  . **ELECTROCHEMICAL** (IMPREGNATION, SORTING, FORMATION)

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1985 - 1992 DEVELOPMENT ACTIVITIES TECHNICAL REQUIREMENTS AND FEATURES

1985 - 1988 30-50 Ah "standard" cell VHS BL		1989 -1992 36-100 Ah "improved" cell VHS CM
. Energy density > 45 Wh/kg . GEO life expectancy : 10 years+	Goals	. Energy density 51-56 Wh/kg . GEO life expectancy : 12-15 years + EP cycles
. Ø 3.2 Inches . 3 piece can . ceramic metal seals (rabbit-ear disposal) . 45° off set filling tube . tig weldings . 75 bars MOP . 2.5 mini safety factor . light Al alloy integral sleeve	Mechanical vessel	. Ø 3.5 Inches . 2 symmetrical hydroformed parts . idem . polar filling tube . idem except filling tube/top dome (Yag) . Idem . 2 mini safety factor (EOL) . idem

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1985 - 1992 DEVELOPMENT ACTIVITIES
TECHNICAL FEATURES
ELECTROCHEMICAL / STACK DESIGN

1985-1988 30 - 50 Ah "standard" cell	1989-1992 36 - 100 Ah "improved"cell
- Mono stack/back to back	- Dual stack above 50 Ah
- Central tie rod/cont.lead assembly	- idem
- Rigid end plates/Belleville washer expansion system	- Light weight shaped end plates/star expansion system
	- Special molded central ring/stack fixture device
- IEC sintered positive electrode	- Thicker positive electrode (same hydroxyde and loading)
- platinized charcoal teflon bonded negative electrode	- Thinner negative electrode (improved catalyst and binder)
- Multi layered non woven polyamid felt separator	- idem
- Woven polyamid gas screen	- idem

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1985 - 1988 DEVELOPMENT ACTIVITIES
30 - 50 Ah range 3.2 inch cell validation results (VHS BL)

- **Medium capacity range IPV SAFT NiH2 cell development achieved by mid 1988**
- **Short term qualification testing realised successfully as follows :**
  . Accelerated fatigue testing on 3 structures : more than 150,000 cycles before leakage.

  . Burst testing on structures (under oil, He, H2 pressure) with/without sleeve : always more than 2.5 BOL security factor.

  . Safety testing on 8 cells (shock, short circuit, over discharge, overcharge) : good behaviour exhibited, cells still under life testing.

  . Thermal testing on 2 specially instrumented thermal prototypes : thermal cartography and correlation with predictive computer models.

  . Vibration testing on 6 cells : qualification loadings. No subsequent electrical or mechanical damage (3 cells life tested).

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1985 - 1992 ACTIVITIES
- 50 Ah CELL LIFE TESTING STATUS

GEO applications

- **9 cells (50 Ah) tested at SAFT facilities** (3 vibrated)
  . 33 eclipse seasons completed under accelerated conditions (70 % DoD, 10° C max.)
  . More than 3 years of testing (Mid 1988-End 1991)
  . Average EOD voltage never below 1.16 V
  . 10 % capacity fading

- **9 cells (50 Ah) tested at AS facilities** (3 abuse tested)
  . 17 eclipse seasons completed under accelerated conditions (70 % DoD, 10°C constant)
  . To be extended to at least 20 seasons
  . capacities remain stable EOD voltage > 1.10 V

LEO applications

- **4 50 cells (50 Ah) tested at ESA/ESTEC facilities** (2 tappered, 2 non tappered) **at 35% DoD, 10 ° C**
  . 1 removed after 17,000 cycles, another after 31, 000 cycles
  . Former submitted to tear-down analysis

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1985 - 1992 ACTIVITIES
30 - 50 Ah CELL LIFE TESTING STATUS (CONT.'D)

LEO APPLICATIONS

- **10 cells (50 Ah) tested at SAFT facilities** (40 % DoD - 15° C) **100 min. cycle, VT gestion**

  . more than 8,000 cycles performed

- **12 cells (50 Ah)** (4 with 26 % KOH) **tested at ESA/ESTEC facilities for Columbus project (90 min cycles, Ict or Pct charge and discharge ; 40 % DoD max and 10 ° C**

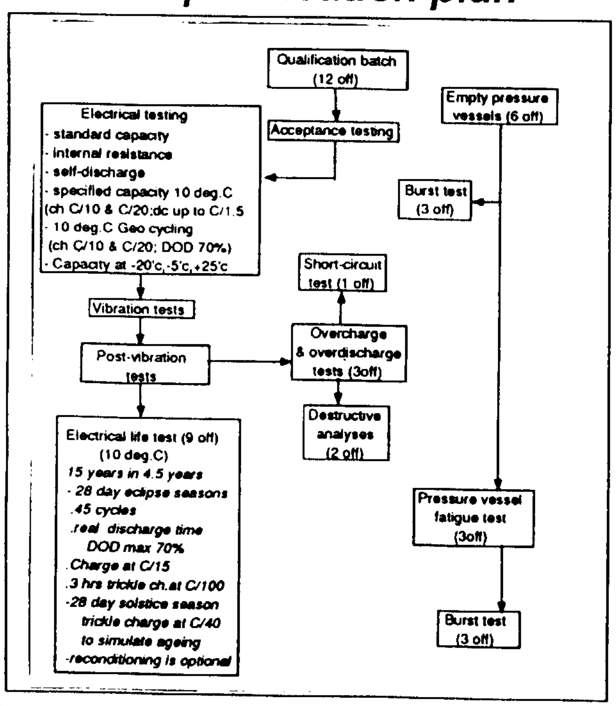
  . more than 6,000 cycles performed

1989 - 1992 DEVELOPMENT ACTIVITIES
36 - 100 Ah 3.5 INCH CELL STATUS (VHS CM)

- High capacity range IPV SAFT Ni-H2 cell development achieved by March 1992.

- Short-term qualification sequence successfully completed

ESA qualification plan



VHS CM features

Capacity	(Ah)	40	50	60	70	80	100
Internal resistance	(mohm)	3.08	2.75	2.52	2.36	2.25	2.08
Mid-point voltage	(V)	1.26	1.25	1.24	1.24	1.23	1.21
Aver. capa. 10 deg.C	(Ah)	44	55	66	77	88	110
Mass	(g)	1097	1270	1467	1666	1865	2269
Height (with tube)	(mm)	169	182	208	234	259	310
Energy density	(Wh/Kg)	51	54	56	57	58	59
Specific energy (vessel only)	(Wh/L)	71	75	78	79	81	82

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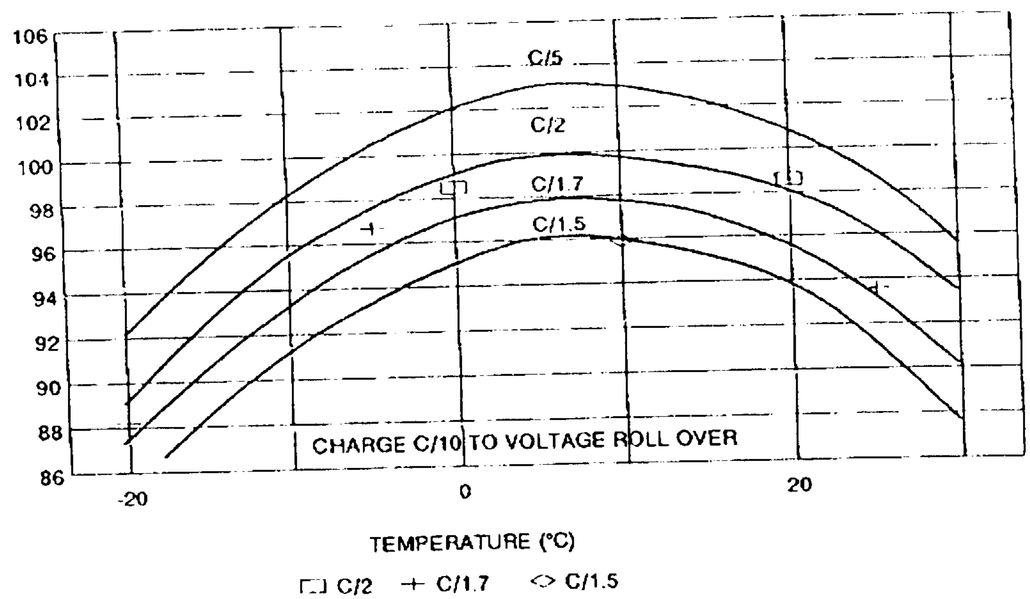
1989 - 1992 DEVELOPMENT ACTIVITIES
36 - 100 Ah O 3.5 INCH CELL STATUS (VHS CM)

VHS 90 CM QUALIFICATION RESULTS

BATCH OF 15 CELLS

CAPACITY TO 1 V VERSUS TEMPERATURE



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1989 - 1992 DEVELOPMENT ACTIVITIES
36 - 100 Ah VHS CM
VHS 90 CM QUALIFICATION RESULTS (CONT.'D)

- **Pressure cycling tests performed on 4 structural vessels**
  . four time mission cycles under pure H2
  . burst pressure in the range 185 - 210 bars (SF > 2.5 EOL)

- **Abuse testing on 5 cells**
  . C/10 24 hours overcharge : max. 94 bars stabilized pressure after 16 H
  . C/1.7 1.2 hours overdischarge : min. 10 bars stabilized pressure
  . short circuit on 1m : 450 A max. peak current, 113 Ah capacity down to 0V
  1/2 H complete discharge step, 137° C max. Tre
  . No direct effects observed, cells under life test

- **Vibration testing on 12 cells**
  . quasi static sine 20 g
  . random 28,7 g rms 200 - 400 Hz > 1 g2Hz peak

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1989 - 1992 ACTIVITIES
90 Ah CELL LIFE TEST AT ESA FACILITIES

Goals

- To demonstrate at least 30 eclipse seasons in 4.5 years under semi accelerated conditions
- To evaluate the comparative effects of P ct versus I ct testing conditions
- To evaluate real thermal profile effects
- To establish pressure evolution and to validate strain gauge reliability mounting
- To simulate electric propulsion constraint

Materials and apparatus

- 20 VHS 90 CM cells split into 2 packs
- Peltier cold plate thermal regulation
- Integral sleeve/individual base plate socket/vertical mounting
- Thermal blanket styrenic foam
- Saturated dry nitrogen atmosphere with O2-controlled level
- 3 cells per battery with gage and pressure transducer

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1989 - 1992 ACTIVITIES
90 Ah CELL LIFE TEST (CONT.'D)

TEST CONDITIONS

Battery 1

Discharge regime	C/15, 60 A
Maximum DoD	80 %
Charge regime	C/15, 6 A
Recharge ratio	1/15
Floating regime	C/100, 0.9 A
Floating time	3 hours
Solstice regime	C/80, 1.12 A
Solstice time	28 days
Average temperature	10° C

Battery 2

Identical except

- constant power discharge
- possibility to replace solstice period by 21 days of 10 daily cycles at 40 % max. DoD for EP operation simulation

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1989 - 1992 ACTIVITIES
90 Ah CELL LIFE TEST (CONT.'D)

Test operations

- Incoming inspection (visual inspection, open circuit voltage, insulation)
- Wake up testing
- Pre-check testings (standard capacity, voltage recovery, charge retention, internal resistance, capacity at mission regime, thermal validation)
- Storage
- Life testing
- Post-check testings (identical to pre-check)

Test chronology

- Batt 1 cells received by the end of may
- Sequences 1 to 4 in June and July
- TRR by the end of July
- Life test started in August
- 2 seasons achieved
- Batt 2 cells received by the end of October

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1985 - 1992 ACTIVITIES

GENERAL TECHNICAL AND MECHANICAL RESULTS

- **Good experience on part weldability (both tig and yag)**
  . validation program on parameter definition
  . leak + burst control
  . four fabrication lots (+ 80 cells)
- **Good knowledge of Inconel sensitivity to H2 brittle effect**
  . ruptural disk method/parametrical studies wrt kinetic loading N2/H2 effect, KOH effect
  . comprehensive experimental program based on 200 coupon tests to establish
    * crack propagation law in an air and hydrogen atmosphere
    * hydrogen and KOH effects on propagation kinetic
    * crack shape ratio effect
    * frequency effects
- **Exhaustive mechanic fracture approach**
  . critical flaw size determination
- **NDI techniques evaluation and feasability studies**
  . RX dye penetrant, ultrasonic examination, eddy current probe, holographic testings

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1985 - 1992 ACTIVITIES

Mechanical results (cont.'d)

- Leak before burst demonstration (Analytical and experimental)
- Fatigue testing and demonstration
- Stack component characterisation versus compressibility and stiffness for dynamic constraint/design and life modelisation
- Study on internal ZrO_2 plasma coatings

Thermal results

- Internal cell measurements and model correlations
- Extensive cell modelisation for prediction and design

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1985 - 1992 ACTIVITIES

ELECTROCHEMICAL RESULTS

- **Evaluation of performances with fibrous felt connector positive electrodes**
  . optimisation of active material loading, thickness, porosity and interconnection
  . boiler plate testing : more than 1200 accelerated cycles
- **Manufacturing and optimisation of a thin negative electrode**
  . new and very divided catalysts, light weight collectors and industrial hydrophobic layer
  . 30 % mass saving versus previous technology, 20 - 30 mV gain at C/2 discharge rate
- **Comprehensive studies on the relation between structural and electrochemical properties**
  . carbonate affinity Co3 effect, proton intercalation, network parameter evolution
  . effect of IEC temperature versus loading efficiency and β ex HN material
- **Patent related to "chimie douce" turbostatic α* new hydroxyde**
  . chemical stability in KOH, high electron efficiency, effect of particle size on cycling stability

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1985 - 1992 ACTIVITIES

ELECTROCHEMICAL RESULTS (CONT.'D)

- Comparative evaluation study on alternate separator material

. characterisation : thickness, porosity, traction resistance, compressibility, perforation resistance, electrolyte absorption and retention/compression effect, OH diffusion, capillary feature, gaseous permeability conductivity pattern/impregnation time, chemical resistance versus KOH and O_2 morphology, analytical composition for organic element

. materials : Zircar cloth, Asbestos felt, polypropylène, polysulfone, polyoléfine, standard non woven polyamid felt

. results : polyamid very competitive but Zircar and polyolefine are possible substitute

* zircar need to be treated because brittle for manipulation

* further investigations needed to assess long term behaviour

1985 - 1992 ACTIVITIES

TEAR DOWN ANALYSIS RESULTS

GOALS

- Establish a BOL reference state
- Explain and quantify component degradation
- Use a technical feedback source on design parameters

OPERATIONS

- Leak test + phenolphthalein test
- Strength test on parts
- Welding controls
- Dimensional controls on stack and mechanical components
- KOH + K2 CO3 concentration and repartition
- Electrical tab controls
- Insulation and resistance controls
- Positive swelling measurement
- X- Ray pattern for active materials at positives
- Porosity, BET and I/V curves on negatives
- Compression curves on expansion system

RESULTS

- one GEO cell failed after 27 seasons
- lack of vessel insulation
  . galvanic coupling
  . O2 evolution and internal short circuit

- positive swelling 2.1 % (0-10 %)
- negative compression 5.4 %
- K2 CO3 in -
- KOH amount in + $\nearrow$ in sep $\searrow$

- support attack level $\nearrow$
- Δ porosity coupled with Δ e at positive
- new micro porosity
- larger cristallite size at +
- separator not altered
- confirmation on LEO cell after 1600 cycles

cnes

FUTURES ACTIVITIES

GEO

- Cycling test on 20 90 Ah cells till 1996 - 1997

LEO

- Cycling test on 10 50 Ah cells till 1995
- Qualifiction on 40 - 70 Ah battery by mid 1993
- Specific LEO design development to be terminated by end 1993
- Selection, testing for LEO/new separator materials (zirfon, PS0 asbestos cloth)
- Definition and study/new foam based positive electrode to reach 65-70 Wh/kg for GEO
- Understanding study on optimisation / new hydroxydes materials-new supports new binding technologies
- Testing on hydrides cells + fundamental studies on new AB materials for improved performances

cnes

1985 - 1992 CNES/ESA NiH2 DEVELOPMENT ACTIVITIES

SUMMARY/CONCLUSIONS

- Since 1985 CNES has been leader in developping basic technologies improving scientific knowledge and entrancing industrial capability with SAFT but also others partners.
- Helpfull ESA participation permit to achieve successfully a generic qualification status on a new broad range (36-100 Ah) GEO cell definition.
- SAFT is providing today a large experience, a serious background and an efficient data base to design new materials and components to fit extensive needs.
- Mechanical and thermal software tools based on experimental correlations to be performed in a general battery qualification program will deliver basis for a full compliant range of batterie for current applications in the next fine years.
- Specific works are on going to develop a LEO design cell while a light weight positive electrode is define to replace traditionnal sintered electrode to achieve mass saving goals for high power future GEO applications

N93-20515

Reliability Study of the NiH2 Strain Gage

Glenn C. Klein, Gates Aerospace Batteries; Gainesville, FL

Donald E. Rash, Jr., Reliability Analysis Center; Rome, NY

INTRODUCTION

This paper summarizes a joint study by Gates Aerospace Batteries [GAB] and the Reliability Analysis Center [RAC]. This study characterizes the reliability and robustness of the temperature compensated strain gages currently specified for sensing of internal pressure of NiH2 cells. These strain gages are characterized as fully encapsulated, metallic foil grids with known resistance that varies with deformation. The measurable deformation, when typically installed on the hemispherical portion of a NiH2 cell, is proportional to the material stresses as generated by internal cell pressures. The internal pressure thus sensed is calibrated to indicate the state-of-charge for the cell. This study analyzes and assesses both robustness and reliability: for the basic design of the strain gage, the installation of the strain gage, and the circuitry involved.

DESCRIPTION OF THE STRAIN GAGE

GAB Part Number 3B84010 defines Micro Measurements' Strain Gage Part Number WK-06-250PD-350. The previous similar part number was 211B2495AB-1. This gage is characterized as (Reference 1.A): dual-element pattern that is fully encapsulated K alloy, equipped with integral, high-endurance beryllium-copper leadwires. The Carrier Matrix [backing] is a high-temperature epoxy-phenolic resin system reinforced with glass fibers. WK-Series gages have the widest temperature range and most extensive environmental capability of any general-purpose strain gage of the self-temperature-compensated type.

Gage length is 0.250 inches, width is 0.240 inches for the grid pair, and resistance is 350 ohms ±0.4%. Operating Range is nominally -269°C to +400°C for Special or Extended Service, and -269°C to +290°C for Normal Service. Backing and adhesive life is projected as $5X10^5$ hours [57 years] at typical Low Earth Orbit [LEO] and Geosynchronous Earth Orbit [GEO] mission environments. Allowable Strain Limit is 1.5%.

GAB Engineering Specification A15B-815 defines Micro Measurements' M-Bond AE-15 Strain Gage Installation Kit. The previous similar part number was 283A6484AE-9. This is characterized as a (Reference 1.B): two-component, 100%-solids epoxy resin system that is recommended for more critical applications. This system is highly resistant to moisture and most chemicals. Typical Elongation Capability is quoted as 10% to 15% at +24°C. A typical set of strain gages as installed is shown in Figure 1.

PURPOSE OF THE STRAIN GAGE

The two strain gage pairs form a typical four-component Whetstone Bridge that is very sensitive to minuscule changes in resistance by forming a null-balance system with two active gages [hard mounted] and two passive gages [soft mounted] for temperature-compensation. Excitation Voltage is generally 6.4±0.005 volts. This excitation voltage is equivalent to 1.6 KW/M^2, and is at the lower side of the optimum range.

The output of the strain gage shows as a resistance change as a function of applied strain level. The strain is directly related to the parent material surface strain, except for the shear -lag of the bonding adhesive. The parent material [i.e., pressure vessel dome] surface stress is a proportional, but indirect, measure of the internal pressure. The internal pressure, created by hydrogen gas, is proportional to the state-of-charge.

Typical expectations for the time dependent GEO mission environment includes: stability and repeatability errors less than 1% over 2000 cycles; and, life expectancy of 15 to 16 years. Different typical expectations for the cycle dependent LEO mission environment includes: repeatability errors less than 1% over life; bridge output voltage drift less than 0.5% per year; and, a life expectancy of approaching forty thousand cycles.

FAILURE MODES, FAILURE CAUSES, and FAILURE EFFECTS

Understanding and defining how a specific failure mechanism produces a discrete failure mode that may effect system operation is important for determining the proper inter-relationship among the events. A proper understanding of this sequence or chain of events is paramount to establishing appropriate corrective actions to prevent recurrence.

In addition, the orientation of the analysis, that is whether to concentrate on system response symptoms or on specific signatures generated by active components, determines both the success of the analysis and the effectiveness of remedial actions. Failure Mode: what aspect, condition, or position is of concern; in what manner does the failure manifest itself. Failure Cause [or Failure Mechanism]: what particular component or part prompts the failure mode to occur and what likelihood of occurrence exists. Failure Effects: what are the effects of the failure, if any, at the interface, on the system, or on the overall mission performance?

ANALYSIS of FAILURE MODES

Other than a substantial accumulation of fatigue characteristics within Tech Note TN-508-1 (Reference 1.C) to be discussed later, the manufacture has not performed any reliability analyses or assessments. MIL-HDBK-217E does not directly address strain gages for the purpose of reliability prediction. Accordingly, a reliability study was performed by RAC (Reference 2) for a specific contractual obligation. The study included a detailed Failure Modes Effects Analysis [FMEA]; a Worst Case Analysis [WCA]; and, a Circuit Stress Analysis [CSA].

Failure Modes Effects Analysis

Generally, the FMEA contains the largest single source of information on discrete failure events. The FMEA involves the listing of potential failure modes, their causes, and the effects upon the components, subsystems, and subsequent systems. The FMEA is a "bottoms-up" analysis of the product design characteristics relative to the planned fabrication, test, and inspection process. This analysis ensures that the resultant product meets the intended need, expectation, and performance goals. When potential failure modes are identified, corrective action can be initiated to eliminate them or continually reduce their risk [or potential occurrence].

This present FMEA encompasses the design, fabrication, and use of the strain gage installation as applied to the GAB NiH2 cell. This analysis covers the use of the strain gage within specific conditions of environment and use of the host cell as it transits throughout test, integration, and the launch and mission environments. The incorporated Failure Modes Effects Analysis of the strain gage contains substantially more detail than a typical FMEA. The following headings are contained within this analysis [Table 1]:

FMEA No.	Failure Cause
Item Name	Failure Detection and Verification
Part Number	Corrective Action -Short Term
Quantity of Parts	Corrective Action -Long Term
Part Function	Failure Effect on the Mission
Failure Mode	Failure Effect on the System
Failure Causes	Failure Effect at the Interface

A more typical FMEA for a NiH2 cell in similar isolated analysis details only two generic failure modes for the strain gage. Those failure modes are cited as: [1] Loss of signal; and, [2] Inaccurate signal. The present FMEA treats the strain gage and installation in isolation upon the cell. As such, the analysis provides details concerning every component, sub-component, and material used during installation of the strain gage on the cell assembly.

Circuit Stress Analysis

The strain gage and installation do not contain the discrete electrical or electronic piece parts that may be subjected to the typical stress derating and application review. Thus, the CSA portion of the RAC study [Reference 2] analyzed installation and application stresses. These stresses were used to predict the base failure rate for the strain gage installation.

The analysis predicted the base failure rate for the strain gage by two different methods. A thermistor model, utilizing handbook principles, predicted a failure rate of 0.13 failures per million hours. RAC databases indicate a failure rate of 0.128 per million hours for a pair of NiChrome resistors. The handbook failure model for the forty-four hand soldered connections in the strain gage subsystem predicted 0.1144 failures per million hours. The total failure rate for the strain gage installation was predicted at 0.2444 failures per million hours.

Worst Case Analysis

The WCA is used to predict the change in performance parameters if all constituent parts were to operate at their extreme stress value, or at the extreme of design tolerance. The addition of the resultant worst case values will provide an end-of-mission performance extreme. Subsequently, insight is gained then as to which extreme values may be modified to reduce inherent risk.

Thus the WCA portion of the RAC study (Reference 2) analyzed environmental profiles and strain gage attributes to predict resistance changes over the mission life. The analysis showed that the 29.3mW that must be dissipated is only 17% of its maximum allowable for high accuracy and only 2% when mounted on the cell as a heat sink. The analysis further predicted a variation in output readings of 1.04% at 5°F at the end of a potential 16.5 year GEO mission.

ANALYSIS of FATIGUE

Expectations for the time dependent GEO mission environment typically includes 2000 cycles over a life expectancy of 15 to 16 years. Expectations for the cycle dependent LEO mission environment includes 30 to 40 thousand cycles approaching a life expectancy of 5 years. The cycle dependency of the LEO mission environment is one area not previously analyzed for the strain gage installation. Thus, the increased cycle requirement for LEO versus GEO mission environments raises the specter of fatigue. Henceforth, our discussion is centered about two specific areas: [1] Fatigue Analysis of the strain gage proper; and [2] Fatigue Analysis of the strain gage installation. "Strain gage installation" may be more correctly referred to as the strain gage mount and periphery installations including the circuitry.

Analysis of Strain Gage Proper

GAB has adopted and applied the manufacturer's recommendations as stated in Tech Note TN 505 (Reference 1.D) for both the strain gage and the installation. In addition, the manufacture has performed substantial testing of strain gages to determine their fatigue characteristics. The following information is paraphrased from their Tech-Note [Reference 1. C].

The metal foils used in strain gages are prone, as are all metals, to fatigue damage when cyclically strained at sufficiently high amplitude. In general, larger grid areas result in higher fatigue life, while higher resistance result in lower fatigue life. Micro Measurements monitors three parameters on strain gages during fatigue testing: "super-sensitivity," gage factor change, and zero-shift. Super-sensitivity results from cracks that are just forming, and that are open only during the tension portion of the loading cycle. Super-sensitivity can only be detected and monitored by using an oscilloscope. Fatigue cracks can also cause increases in the tension gage factor; however, they are easily detected since the compression value will be much lower. For purely dynamic strain measurements, zero-shift is relatively incidental, and strain gages can be considered functionally adequate until fatigue damage has progressed almost to the stage of super-sensitivity. Generally, Nominal Fatigue Life is based upon a zero-shift of $100\mu\varepsilon$.

Figure 2 illustrates those fatigue stress test results. Numerically, Micro Measurements cites a Fatigue Life of 10^6 cycles for a Strain Level of $\pm 2400\mu\varepsilon$, and 10^7 cycles for a Strain Level of $\pm 2200\mu\varepsilon$. This fatigue life data is based on fully reversed strain levels. As a generalized approximation, this data can be used for unidirectional strains, or various mean-strains by taking the indicated peak amplitude and derating by 10 percent. As an example, $\pm 1500\mu\varepsilon$ would be approximately equivalent in gage fatigue damage to strain levels of +2700 to $0\mu\varepsilon$, or 0 to $-2700\mu\varepsilon$, or $+2500/-200\mu\varepsilon$. However, a mean-strain that increases in a tensile direction during cycling will lead to a much earlier failure.

A typical GAB design destined for a LEO mission environment yielded the following characteristics. Internal cell pressure varies according to MCP[1-DOD], where MCP is the maximum cell pressure and DOD is the depth-of-discharge. For a typical LEO mission:

MCP = 950 PSIG @ BOL [beginning of life];

MCP = 1000 PSIG @ EOL [end of life]; and,

DOD = 30% for a nominal 89 A-H.

The Worst Case pressure varies between 700 to 1000 PSIG [850±150 PSIG]. Therefore, for a minimum thickness of 0.019 inches the strain varies from 1595 to 2277$\mu\varepsilon$ [or, 1936±341$\mu\varepsilon$]. Thus, $5X10^4$ cycles at 1595 to 2277$\mu\varepsilon$ appear well below the manufacturer's point of concern.

Analysis of Strain Gage Mount and Periphery Installations

Appendix A of Tech-Note TN-508-1 provides numerous installation recommendations for Maximum Strain Gage Fatigue Life. This appendix refers to an additional series of both Tech Notes and Tech Tips for hands-on installation techniques and tips. These tips and hints include:

1. Avoiding excess adhesive films;
2. Soft solders with low melt points;
3. Using auxiliary bondable terminals;
4. Leadwire attachment techniques; and,
5. Use of overcoatings.

GAB has adapted all the installation techniques into their current MCD's. The installation process is controlled and basic instruction techniques were provided by Micro Measurements. The soldering process is certified to NHBB 5300.5[3A-1].

CONCLUSIONS and RECOMMENDATIONS

1. The expanded Failure Modes & Effects Analysis, the Circuit Stress Analysis, and the Worst Case Analysis each show the design, fabrication and installation of the strain gage to be conservative in view of the manufacture's available equipment list and installation recommendations.

2. The Root Cause of numerous Failure Modes identified within the FMEA could be traced to potential fatigue damage. The Fatigue Analysis of the strain gage shows the gage usage and environment to be well below even the manufacturer's points of minimum concern. Significant test data exists for the prediction of fatigue life of the strain gage. However, this gage installation and periphery, while following all possible recommendations, have not been tested for fatigue life.

3. The end result of this analysis is the recommendation for two life test regimes for the strain gage and installation. A LEO test of 2000 cycles at Room Temperature has already been scheduled for completion by year end. A GEO test is being devised with expected completion by Mid-1993. Success and failure criteria are being determined, and test results will be reported in a later paper.

TABLE 1: Expanded Strain Gage FMEA

No.	Item Name	Part Number	Qty	Function	Failure Mode	Failure Causes
STR-1	Strain gage	211B2495AB1	2	Strain gage	Open	Corrosion; Mishandling; Shipping damage; Cracked die; Lifted or broken solder joint
STR-2					Intermittent open	Cracked die (gage); Cracked solder joint
STR-3					Short (hard)	Extraneous particles; Solder whiskering
STR-4					Intermittent or soft short	Extraneous particles; Solder whiskering; Ionic contam.; Cracked or voided epoxy
STR-5	Soldereze wire	283A6484WA	10	Soldereze wire connections	Open	Mishandling; Shipping damage; Broken wire; Lifted or broken solder joint
STR-6					Intermittent open	Cracked wire; Cracked solder joint; Cold solder joint
STR-7	Balco wire	283A6484WC	1	Balco wire temperature compensation	Open	Mishandling; Shipping damage; Broken wire; Lifted or broken solder joint
STR-8					Intermittent open	Cracked wire; Cracked solder joint; Cold solder joint
STR-9					Improper length	Wire cut too long; Wire cut too short
STR-10	Strain gage wires [cupron]	283A6484WD	1	Cupron wire balance	Open	Mishandling; Shipping damage; Broken wire; Lifted or broken solder joint
STR-11					Intermittent open	Cracked wire; Cracked solder joint; Cold solder joint

No.	Item Name	Part Number	Qty	Function	Failure Mode	Failure Causes
STR-12					Improper length	Wire cut too short; Wire cut too long
STR-13	Terminal strip	2B72001	1	External connections	De-bonding of copper foil & backing	High g-field [shock]
					Cracked solder joint	High strain field
STR-14	Terminal strip	2B72002	2	Bridge intra-connect	De-bonding of copper foil & backing	High g-field [shock]
					Cracked solder joint	High strain field
STR-15	Polyimide Tape	A23C-801	A/R	Electrical insulation	Intermittent or soft short	Mishandling; Shipping damage
STR-16	Control shim	2B74008	1	Installation support	De-bonding of installation	Mishandling, improper mix or handling of epoxy
STR-17	Adhesive	A15B-815	A/R	Structural bonding	De-bonding of gage or terminal strips	Improper mix or application
STR-18	Adhesive	A15F-801	A/R	Structrural bonding	De-bonding of control shim installation	Improper mix or application
STR-19	Solder	2C93001	A/R	Electrical connections	De-bonding or corrosion	Improper solder flux
STR-19	Polyurethane	A8B-801	A/R	Installation overcoat	De-bonding	Improper mix or application

No.	Failure Detect/Verf	C/A Short Term	C/A Long Term	Failure Effect [Mission]
STR-1	Electrical and visual tests	Electrical tests	Certified soldering process, epoxy control requirements	Loss of pressure reading from cell
STR-2	Electrical/thermal, material, final vibr./integration testing	Electrical tests	Certified soldering process, epoxy control requirements	Intermittent pressure readings from cell
STR-3	Electrical measurements	Electrical tests	Certified soldering process, epoxy control requirements	Lowered pressure reading from cell (discharge indication)
STR-4	Electrical measurements & calibration cycle	Electrical tests, stabilization bake	Certified soldering process, epoxy control requirements	Intermittent low pressure reading from cell (discharge indication)
STR-5	Electrical and visual measurements	Electrical tests	Certified soldering process	Loss of pressure reading from cell
STR-6	Electrical/thermal measurements	Electrical tests	Certified soldering process	Intermittent (loss of) pressure reading from cell
STR-7	Electrical and visual measurements	Electrical tests	Certified soldering process	Incorrect pressure reading from cell
STR-8	Electrical/thermal measurements	Electrical tests	Certified soldering process	Fluctuation in pressure reading from cell
STR-9	Electrical and visual measurements	Electrical tests	Control cutting process	Incorrect pressure reading from cell
STR-10	Electrical and visual measurements	Electrical tests	Certified soldering process	Incorrect pressure reading from cell
STR-11	Electrical/thermal measurements	Electrical tests	Certified soldering process	Fluctuation in pressure reading from cell

No.	Failure Detect/Verf	C/A Short Term	C/A Long Term	Failure Effect [Mission]
STR-12	Electrical/thermal measurements	Electrical tests	Control cutting process	Fluctuation in pressure reading from cell
STR-13	Electrical/thermal, material, final vibr./integration testing	Care and handling, protective cap	Shock indicators in shipping containers	Intermittent pressure readings from cell
	Electrical/thermal, material, final vibr./integration testing	Electrical tests	Use 'half-terminal' technique [see Note 2]	Intermittent pressure readings from cell
STR-14	Electrical/thermal, material, final vibr./integration testing	Care and handling, protective cap	Shock indicators in shipping containers	Intermittent pressure readings from cell
	Electrical/thermal, material, final vibr./integration testing	Electrical tests	Use 'half-terminal' technique [see Note 2]	Intermittent pressure readings from cell
STR-15	Electrical/thermal, material, final vibr./integration testing	Protective cap	Protective cap	Intermittent low pressure reading from cell (discharge indication)
STR-16	Electrical/thermal, material, final vibr./integration testing	Protective cap, epoxy control requirements	No futher action required	Intermittent pressure readings from cell
STR-17	Electrical/thermal, material, final vibr./integration testing	Electrical tests	Epoxy control requirements	Intermittent pressure readings from cell
STR-18	Electrical/thermal, material, final vibr./integration testing	Electrical tests	Epoxy control requirements	Intermittent pressure readings from cell
STR-19	Electrical/thermal, material, final vibr./integration testing	Electrical tests	Certified soldering process	Intermittent pressure readings from cell
STR-19	Visual inspection	Visual inspection	Epoxy control requirements	Minimal-to-no effect

No.	Failure Effect [System]	Failure Effect [Interfaces]
STR-1	Loss of strain gage reading	Loss of strain gage voltage
STR-2	Intermittent strain gage reading	Intermittent strain gage voltage
STR-3	Lowered strain gage reading	Lowered strain gage voltage
STR-4	Intermittent low strain gage reading	Intermittent loss of strain gage resistance (see note 1)
STR-5	Loss of strain gage reading	Loss of strain gage voltage
STR-6	Intermittent strain gage reading	Intermittent strain gage voltage
STR-7	Inaccurate strain gage reading when temperature changes	Improper reading due to loss of temperature compensation
STR-8	Voltage fluctuation	Improper pressure indication, intermittent temperature compensation
STR-9	Inaccurate strain gage reading when temperature changes	Improper reading due to incorrect temperature compensation
STR-10	Loss of differential voltage zeroing	Intermittent pressure loss from loss of voltage compensation
STR-11	Voltage fluctuation	Intermittent pressure indication due to voltage compensation

NOTES:
1. During shock, vibration, and thermal vacuum environment
2. Alternate Technique when using bondable terminals

No.	Failure Effect [System]	Failure Effect [Interfaces]
STR-12	Voltage fluctuation	Incorrect voltage compensation
STR-13	Intermittent strain gage reading	Intermittent strain gage voltage
	Intermittent strain gage reading	Intermittent strain gage voltage
STR-14	Intermittent strain gage reading	Intermittent strain gage voltage
	Intermittent strain gage reading	Intermittent strain gage voltage
STR-15	Intermittent low strain gage reading	Intermittent loss of strain gage resistance (see note 1)
STR-16	Intermittent strain gage reading	Intermittent strain gage voltage
STR-17	Intermittent strain gage reading	Intermittent strain gage voltage
STR-18	Intermittent strain gage reading	Intermittent strain gage voltage
STR-19	Intermittent strain gage reading	Intermittent strain gage voltage
STR-19	Minimal-to-no effect	Minimal-to-no effect [@ ground environment only]

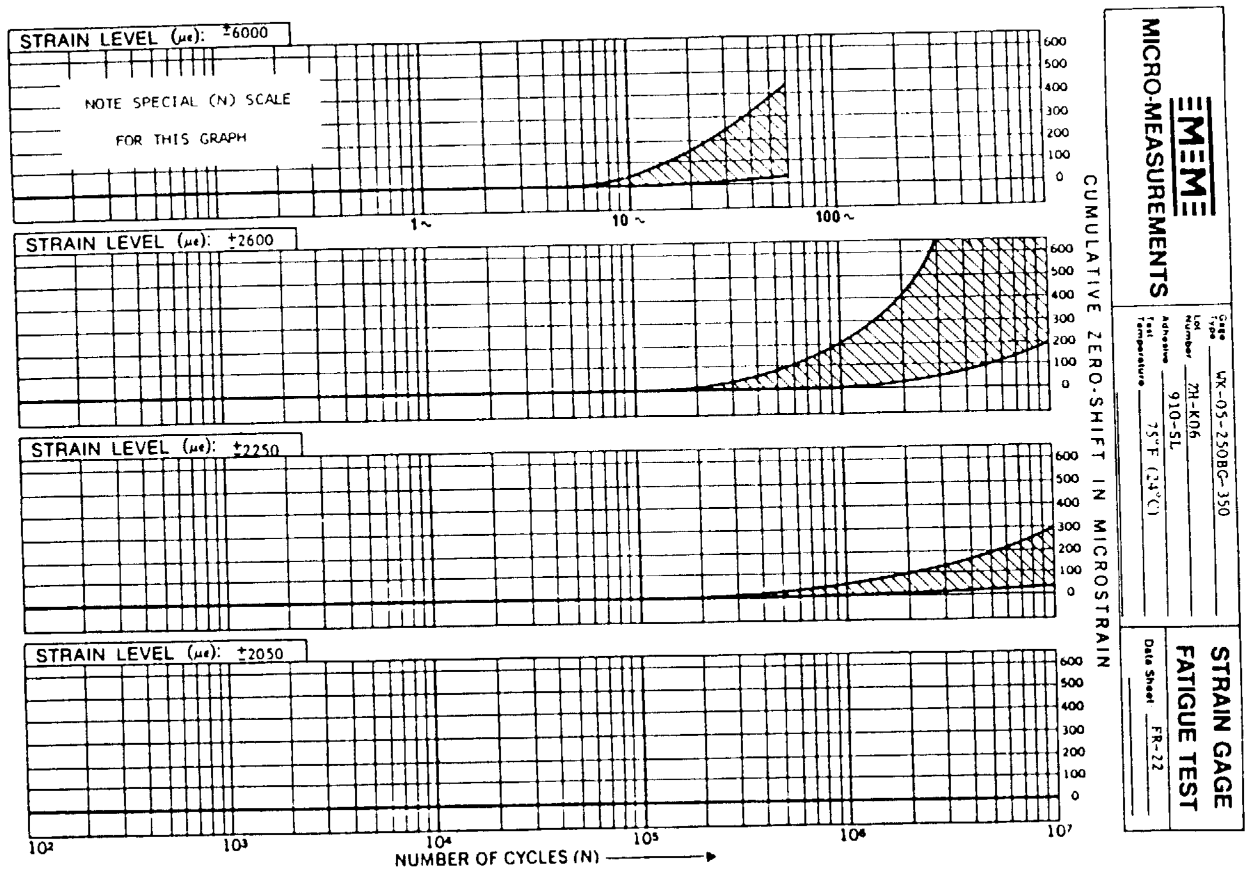

Figure 2 --Strain Gage Fatigue Test Results

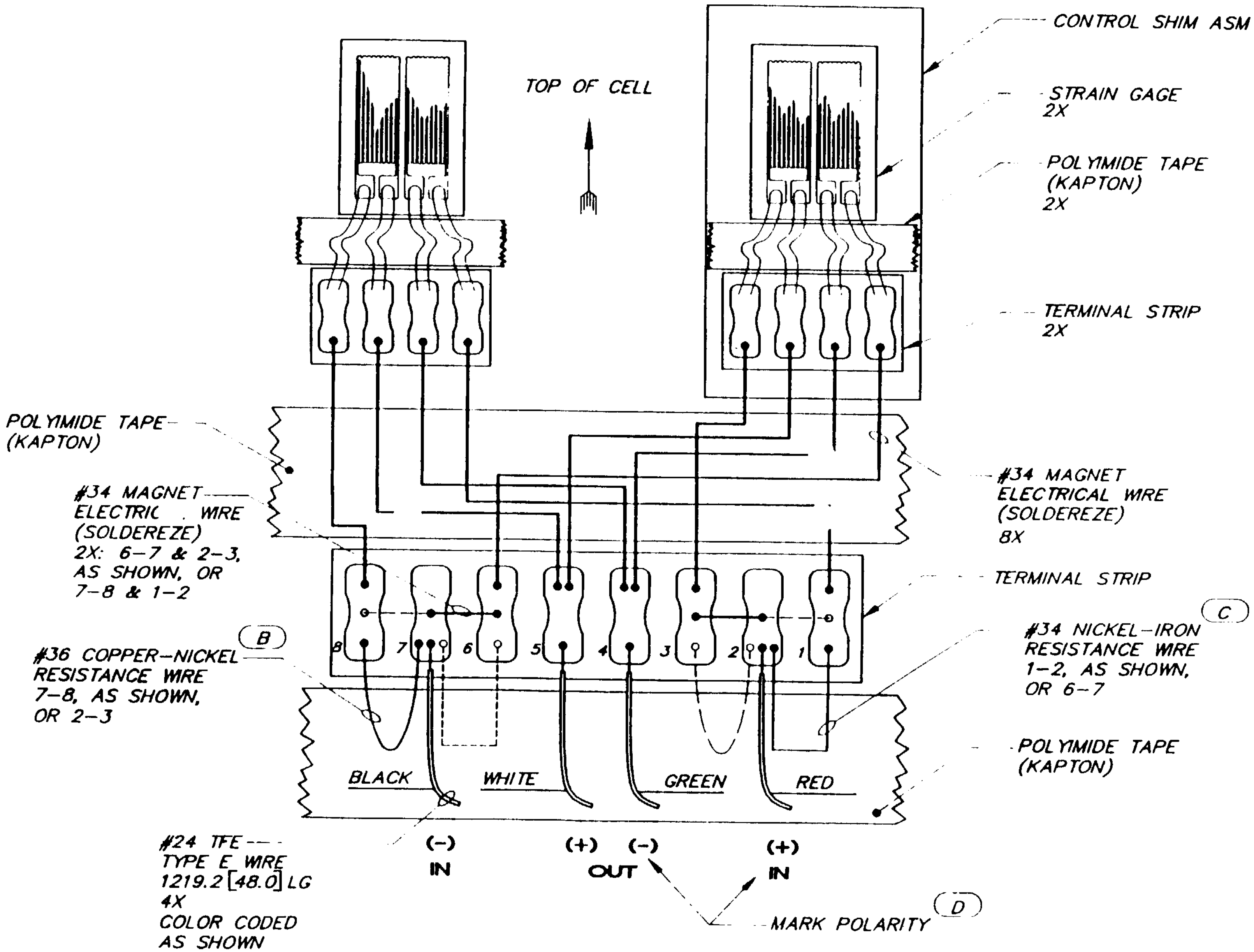

Figure 1 --Typical Strain Gage and Installation

REFERENCES

1. Strain Gage Technology Manual; Measurements Group -*Vishay*, Raleigh, NC; 1991:

    A. Catalog 500, Parts A & B.

    B. Catalog A-110-5.

    C. Tech Note TN-508-1, "Fatigue Characteristics of Micro-Measurements Strain Gages."

    D. Tech Note TN-505, "Strain Gage Selection Criteria, Procedures, Recommendations."

2. Reliability Study of the NiH2 Strain Gage; Reliability Analysis Center, Rome, NY; 1992.

High Specific Energy, High Capacity Nickel-Hydrogen Cell Design

N93-20516

James R. Wheeler
Eagle Picher Industries, Joplin MO

Abstract

A 3.5 inch rabbit-ear-terminal nickel-hydrogen cell has been designed and tested to deliver high capacity at a C/1.5 discharge rate. Its specific energy yield of 60.6 wh/kg is believed to be the highest yet achieved in a slurry-process nickel-hydrogen cell, and its 10°C capacity of 113.9 AH the highest capacity yet made at a discharge rate this high in the 3.5 inch diameter size. The cell also demonstrated a pulse capability of 180 amps for 20 seconds. Specific cell parameters, performance and future test plans are described.

Cell Description

A program was desired to maximize power and specific energy for 3.5 inch diameter nickel-hydrogen cells while still retaining the long-cycle life and ruggedness of the positive slurry electrode. Eagle-Picher designed the cells as part of a joint project with a major aerospace company. We have now completed and tested a 100 ampere-hour cell design in two separator versions. One version has a single layer of asbestos separator for each positive electrode, and one has a single Zircar separator, but they are otherwise identical and were made from the same lots of electrodes and other components. Four Zircar cells and three asbestos cells were built and activated with a standard solution of KOH.

A photograph of a sample cell (both versions are externally the same) and a table of weight and dimensions are provided by Figure 1 and Table 1. All of the cells were equipped with strain gage pressure monitors.

Figure 1

CELL DESCRIPTION	TYPE SEPARATOR	
	Single Zircar	Single Asbestos
Weight (grams)*	2279	2236
Cell Length (in) Dome to Dome	10.97	10.97
Cell Length (in) Overall	11.56	11.56

* strain gage weight subtracted (17g)

Table 1

The internal cell design is a dual stack with a back-to-back electrode configuration and continuous leads to rabbit-ear terminals. The rabbit-ear terminal is a feature which permits a shorter battery height and therefore a shorter thermal path when the cells are vertically mounted. Thus, the high specific energy can be further improved at the battery level by reducing the length of the cell sleeve mountings and cell inter-connections. If the cells are mounted parallel to a baseplate, the rabbit-ear terminals help there as well because the cells can be rotated to minimize the length of the interconnects.

The positive electrodes are only slightly thicker and more porous than Eagle-Picher's standard high-bend-strength slurry plaque, but are still approximately double the bend-strength of dry sinter. A catalyzed wall wick is incorporated for improved thermal operation and gas management, making the cell suitable for either LEO or GEO applications. The electrolyte levels for the two versions are about the same, with the single Zircar version holding, on average, only 1% more per cell than the single asbestos version.

The pressure vessel is Inconel 718. MEOP translates to a minimum burst safety factor of 2.5. The actual maximum pressure reached by the highest Zircar version cell under conditions of severe overcharge was 3% greater than the value for the asbestos.

Cell Testing

The cells were tested to the customer's performance specification. Performance data are summarized in Tables 2 and 3.

CAPACITIES TO 1.0V (AH) AT 68 AMPS	SEPARATOR TYPE	
	Zircar	Asbestos
30°C	81.3	82.9
20°C	99.1	99.7
10°C	113.9	111.3
0°C	117.6	113.1
-10°C	115.6	108.2

Table 2

Standard capacity charges were 9 amps for 16 hours. The discharge rate used was C/1.5, or 68 amps. Average discharge voltage performance for each type of cell is shown by the curves in Figure 2. Mid-discharge values (45 minutes) are comparable to those achieved in shorter 3.5 inch cells, indicating a good cross-section of internal bussing. The voltage advantage of Zircar over asbestos is apparent, and is essentially the same for the single Zircar configuration as would be expected from a double Zircar design.

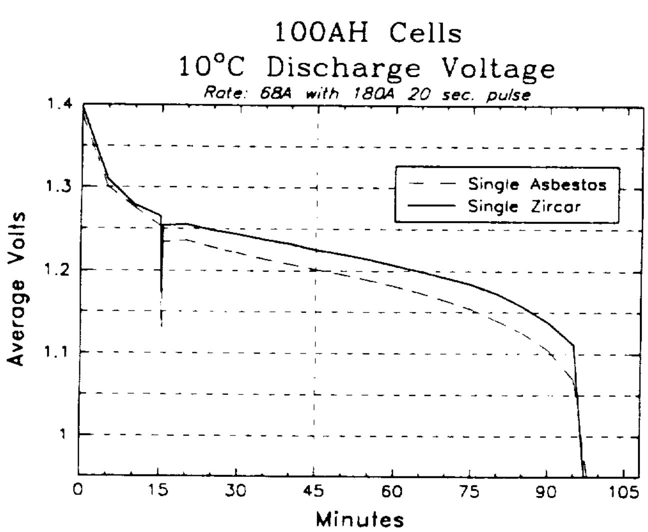

Figure 2

Testing (See Figure 2) also included a 180 amp pulse test. The test was nominally a 10°C capacity test (16 hour, 9 amp charge), with the pulse conducted 15 minutes after start of the discharge. Pulse duration was 20 seconds. Minimum terminal voltages reached at the end of the pulse were 1.17 V for the Zircar version cells, and 1.13 V for the asbestos cells.

The Zircar version achieved 60.1 watt-hours per kilogram at 10°C to 1.0 V at a discharge rate of C/1.5 (68 amps). (Watt-hour values were measured by the automated data collection software, not calculated on mid-point voltages.) In the same test the asbestos version achieved 59.0 watt-hours per kilogram. (Of course capacities would have been somewhat greater and discharge voltage higher at a more-normal C/2 rate.)

PERFORMANCE DATA	TYPE SEPARATOR	
	Zircar	Asbestos
180 Amp Pulse, Minimum Voltages	1.173	1.130
WH/Kg	60.1	59.0
WH/Kg*	60.6	59.4
* Strain gage weight subtracted		

Table 3

If the strain gages had not been installed, the values would be 60.6 wh/kg and 59.4 wh/kg respectively. These are believed to be the highest energy densities yet achieved at the cell level for nickel-hydrogen cells with slurry-process positive electrodes.

The evolution of size and power of slurry-type cells at Eagle-Picher is shown in Figure 3. This progression has been chronological, from small to large, over the last 10 years.

Capacity retention was measured by charging the cells for 16 hours at 9.0 amps and 10°C, and, after an open circuit stand of 72 hours, discharging at 68 amps to 1.0 V. The percentages of capacity retained, when compared to the standard 10°C test, were 84.6% for Zircar, and 85.8% for asbestos.

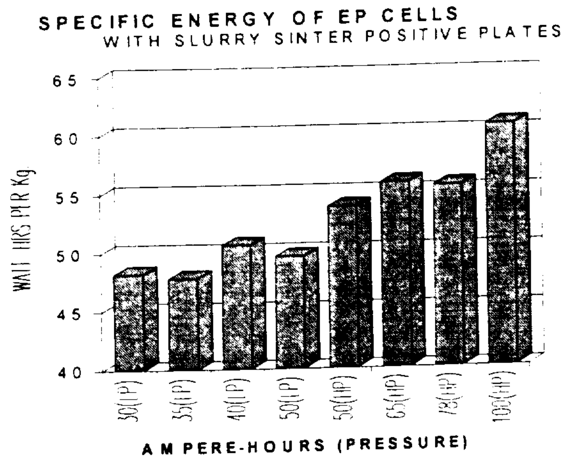

Figure 3

Conclusions

By using single-layer separator and slightly thicker, more-porous positive electrodes, specific energies of 3.5 inch nickel-hydrogen cells can exceed 60 Watt-hours per kilogram and provide good, all-around performance, even at discharge rates of C/1.5. At lower current densities, performance would of course be even better.

Also, it is shown that the 3.5 inch cell can be made to yield capacities above 110 AH. This is important to spacecraft designers who are requiring larger-capacity batteries for many applications. If these demands can be satisfied by a 3.5 inch design, thermal characteristics will be better than with a thicker cell.

Using our activation process, the electrolyte quantity for single layer Zircar is just slightly larger than the single layer asbestos version, and this augers well for cycle life. At Eagle Picher, single-layer Zircar cells have exceeded 13,400 cycles at a depth of discharge of 15%. That test is continuing.

Plans

Three cells of each version are presently undergoing characterization testing at the facilities of a major aerospace corporation, and then will undergo qualification and life testing. Characterization testing includes 100 amp discharge cycles, which have reportedly been completed with capacities comfortably above 100 AH. Life testing is planned for up to 15 years and will be to a GEO regime (real-time eclipse cycling to an 80% depth of discharge with shortened sun-times).

EAGLE PICHER | Advanced Systems Department | *NICKEL-HYDROGEN GROUP*

EAGLE-PICHER SPV DEVELOPMENT

NASA BATTERY WORKSHOP

November 1992

EAGLE PICHER Quality First!

N93-20

DEVELOPMENT PLAN

LICENSING AGREEMENT WITH COMSAT LABORATORIES

PARALLEL DEVELOPMENT OF EAGLE-PICHER TECHNOLOGY

EAGLE PICHER | Advanced Systems Department | NICKEL-HYDROGEN GROUP

EAGLE-PICHER HERITAGE - SPV TECHNOLOGY

- Over 2300 IPV Cells Currently in Flight
- Over 97 Nickel-Hydrogen Batteries in Flight
- Two-Cell CPV Manufacture and Testing
  - $>$18000 Cycles at 50% DOD
  - $>$ 9100 Cycles at 30% DOD
- Common Pressure Batteries - Silver Zinc Technology
- Proven Electrode Designs

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SPV UNITS IN PROCESS AT EAGLE-PICHER

TEN 40 AH CELLS FOR CHARACTERIZATION AND LIFE TESTS, 3 TO BE TESTED AT EAGLE-PICHER AND 7 AT COMSAT LABORATORIES.
5 Currently on test. Balance to be placed on test by 12/1/92.

TWO 10 CELL BATTERIES TO BE DELIVERED TO COMSAT LABORATORIES FOR CYCLE TESTING.
Estimated Completion - January 1993

ONE 22 CELL BATTERY FOR CHARACTERIZATION AND CYCLE TESTING AT EAGLE-PICHER.
Estimated Completion - January 1993

ONE 22 CELL BATTERY FOR DELIVERY TO A PRIME CONTRACTOR.
Estimated completion - May 1993

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DESIGN FEATURES

10 INCH DIA., 40 AH, 22 CELL BATTERY

WEIGHT	22.2 KG
LENGTH	58.4 CM(23.0 IN.)
SPECIFIC ENERGY	57 WH/KG
ENERGY DENSITY	60.8 WH/L

EAGLE PICHER Quality First!

BASIC BATTERY DESIGN FEATURES

- 10 inch diameter thin-wall pressure vessel, hermetically sealed using two weld rings and proven EB welding methods. Terminal seals use the flight-proven Ziegler compression method.
- Plurality of individually packaged Ni-H2 cells (half-circle shape), enclosure provided with gas permeable port to hydrogen reservoir.
- Thermally conductive heat fins or rack providing a path from the surface of each individual cell to inner surface of pressure vessel.
- Flexure springs to provide loading of the cell stack radially (for thermal considerations) and axially (for stack compression).
- COMSAT design uses an insulated feedthrough terminal to provide intercell connection of hermetically sealed cell packets.

CELL DEVELOPMENT CONSIDERATIONS

POSITIVE ELECTRODES:

Selection of Type: Slurry vs. Dry Sinter
Selection of Thickness
Selection of Target Loading

NEGATIVE ELECTRODES:

Integration of EPI patented substrate design for optimized current collection.

SEPARATOR:

Selection of Type: Asbestos vs. Zircar
Consideration of alternative types

GAS DIFFUSION SCREEN:

Selection of Type and Number of Layers

WELDING TECHNIQUES FOR BUS ASSEMBLY

Development of EB and Laser Welder Methods

Early Development Activity

Boilerplate tests run to verify expected plate performance

- Full Capacity Cycles at 20 Degrees C

- Full Capacity Cycles at 10 Degrees C

- Full Capacity Cycles at 0 Degrees C

(Boilerplate units were activated with 31% KOH)

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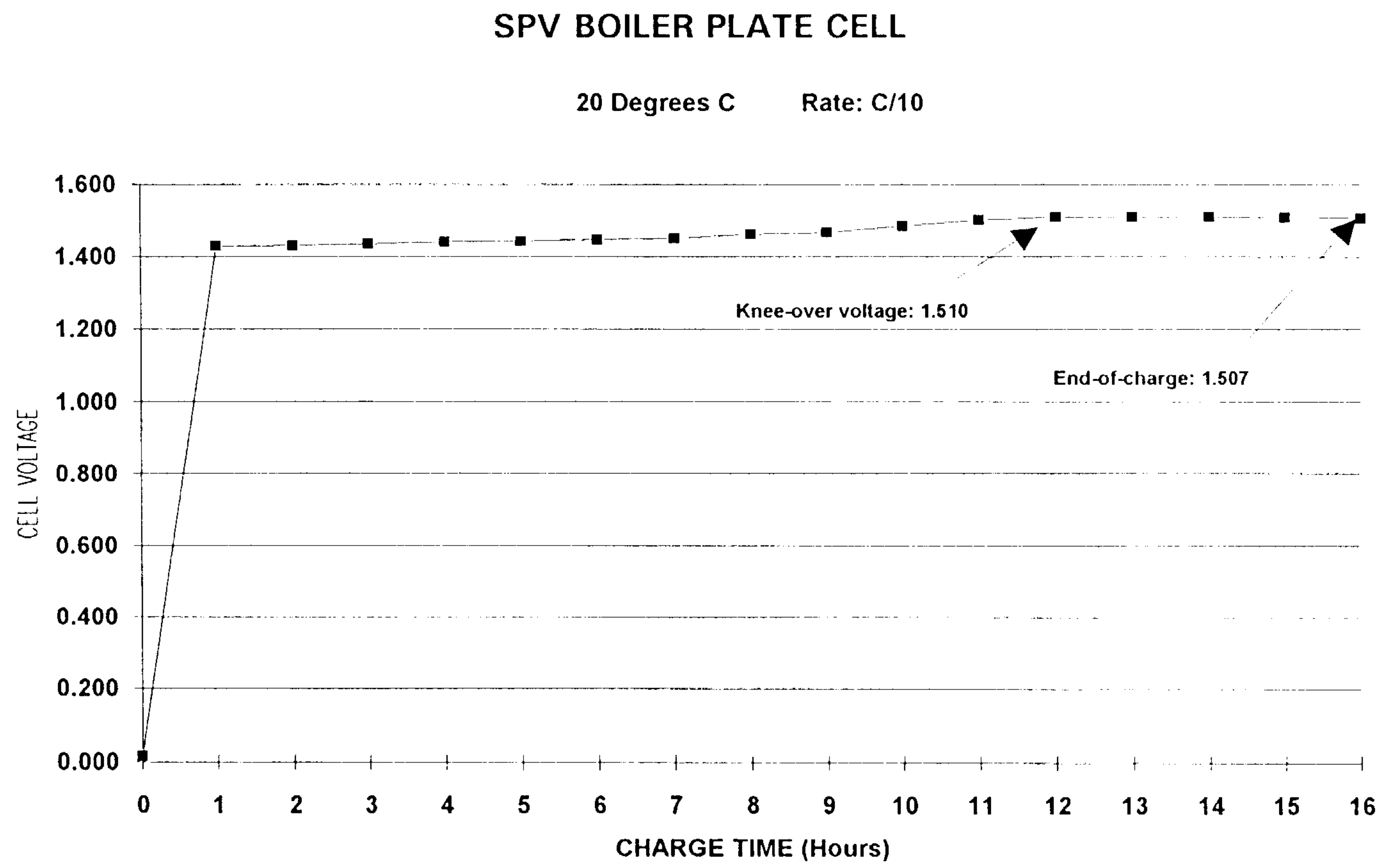
EAGLE PICHER **Advanced Systems Department** *NICKEL-HYDROGEN GROUP*



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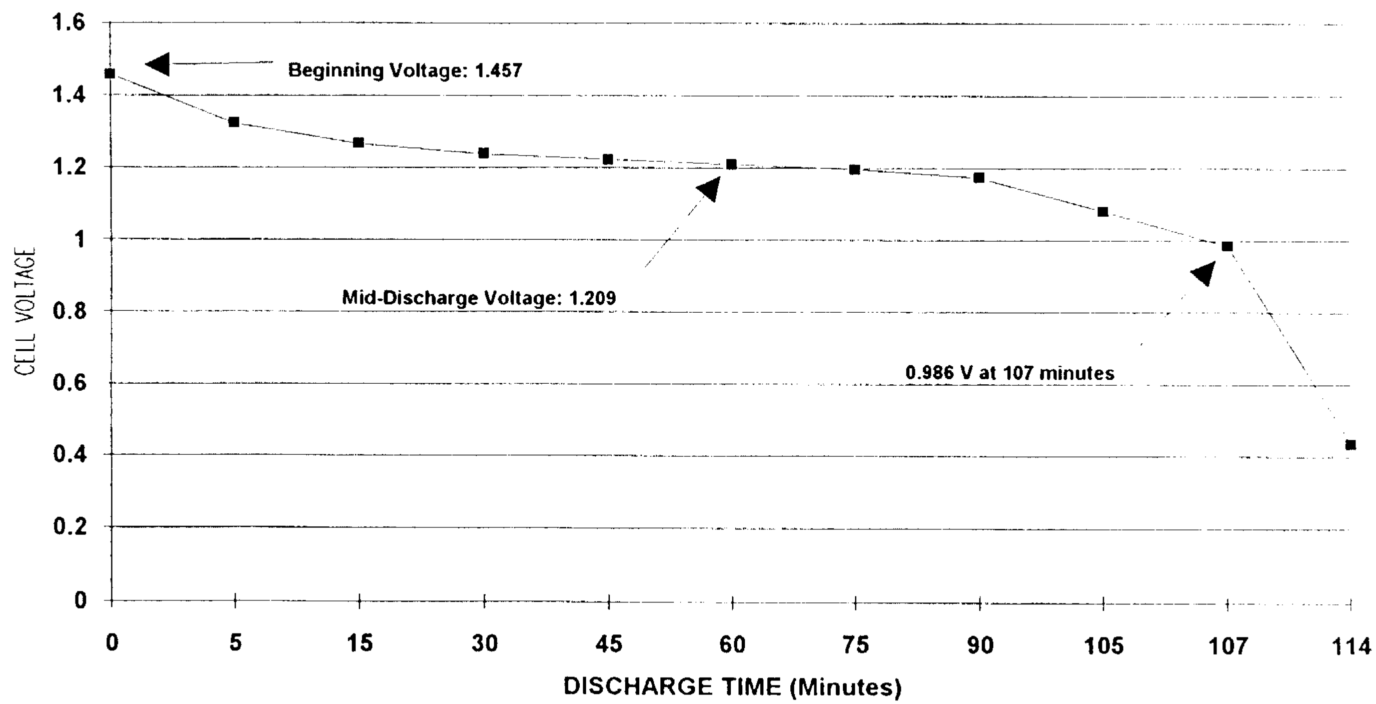
SPV BOILER PLATE CELL

20 Degrees C Rate: C/2



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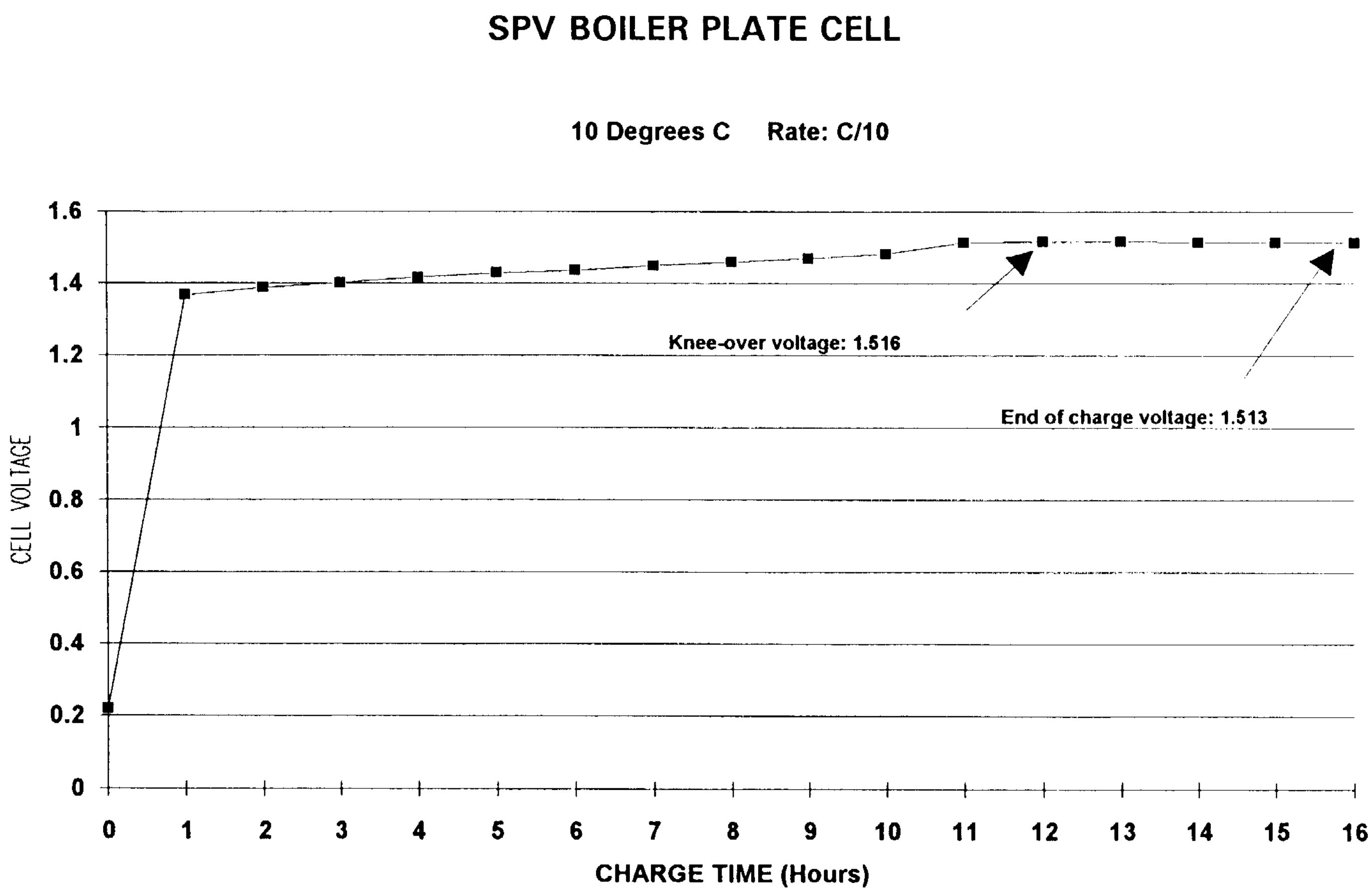
SPV BOILER PLATE CELL
10 Degrees C Rate: C/10
CELL VOLTAGE
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
CHARGE TIME (Hours)
Knee-over voltage: 1.516
End of charge voltage: 1.513
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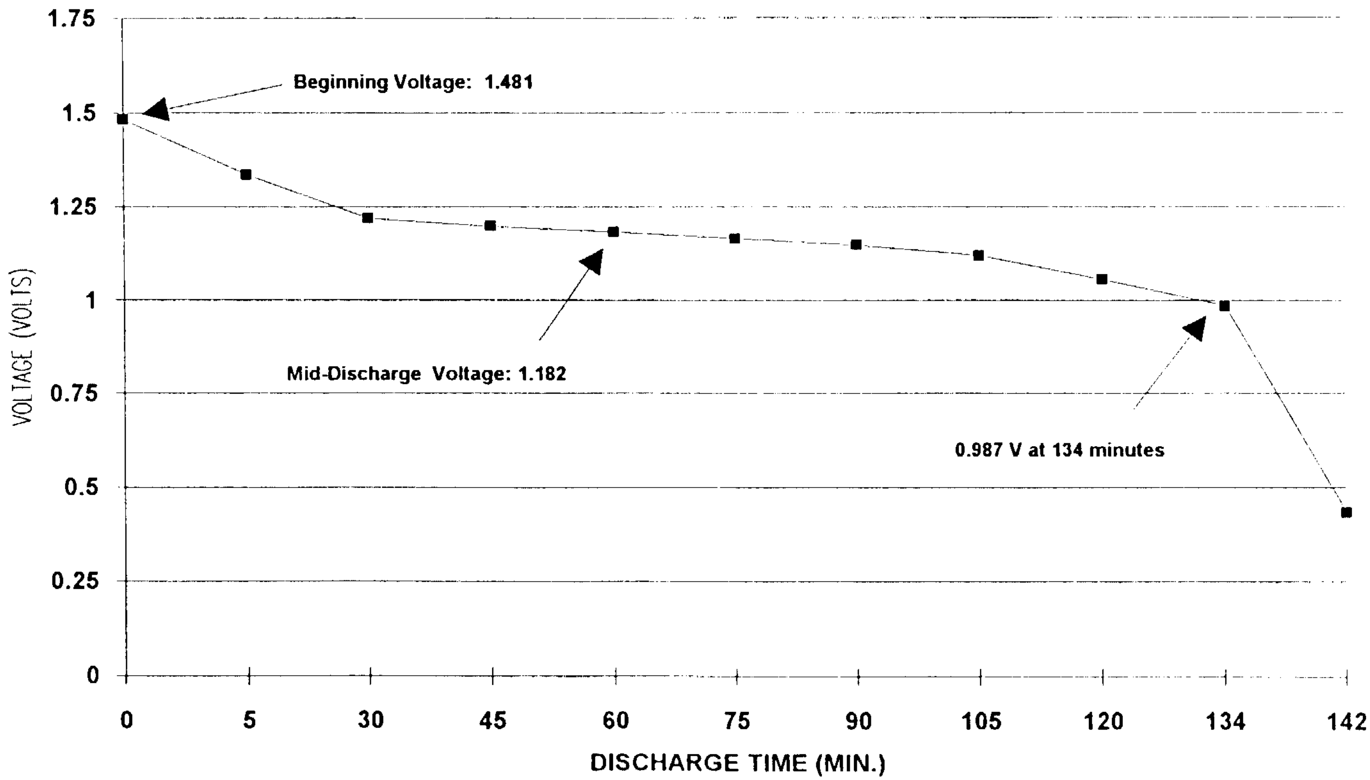
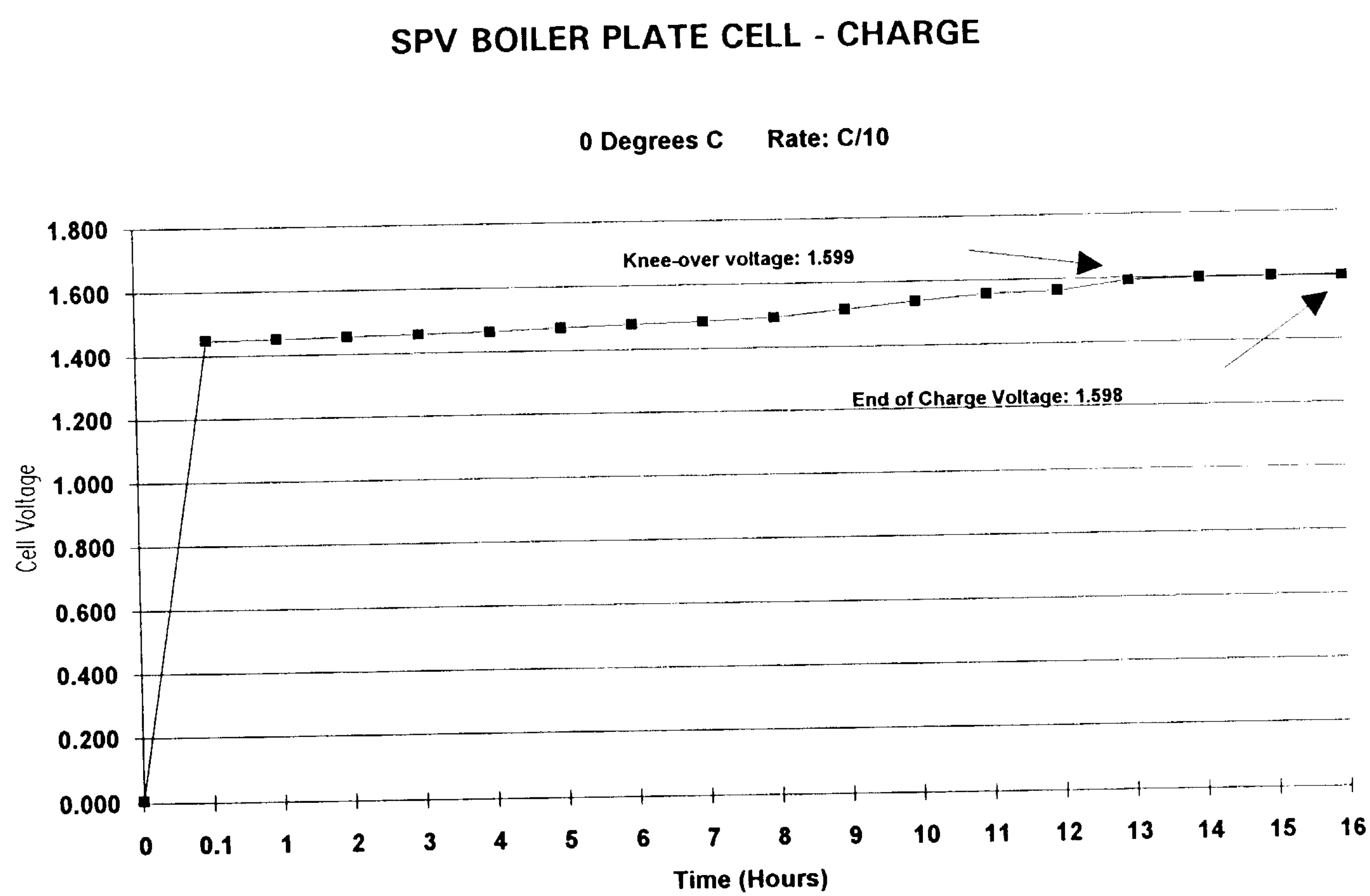
SPV BOILER PLATE DISCHARGE

10 DEG. C Rate: C/2




SPV BOILER PLATE CELL - CHARGE
0 Degrees C Rate: C/10
Knee-over voltage: 1.599
End of Charge Voltage: 1.598
Cell Voltage
1.800
1.600
1.400
1.200
1.000
0.800
0.600
0.400
0.200
0.000
0
0.1
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Time (Hours)
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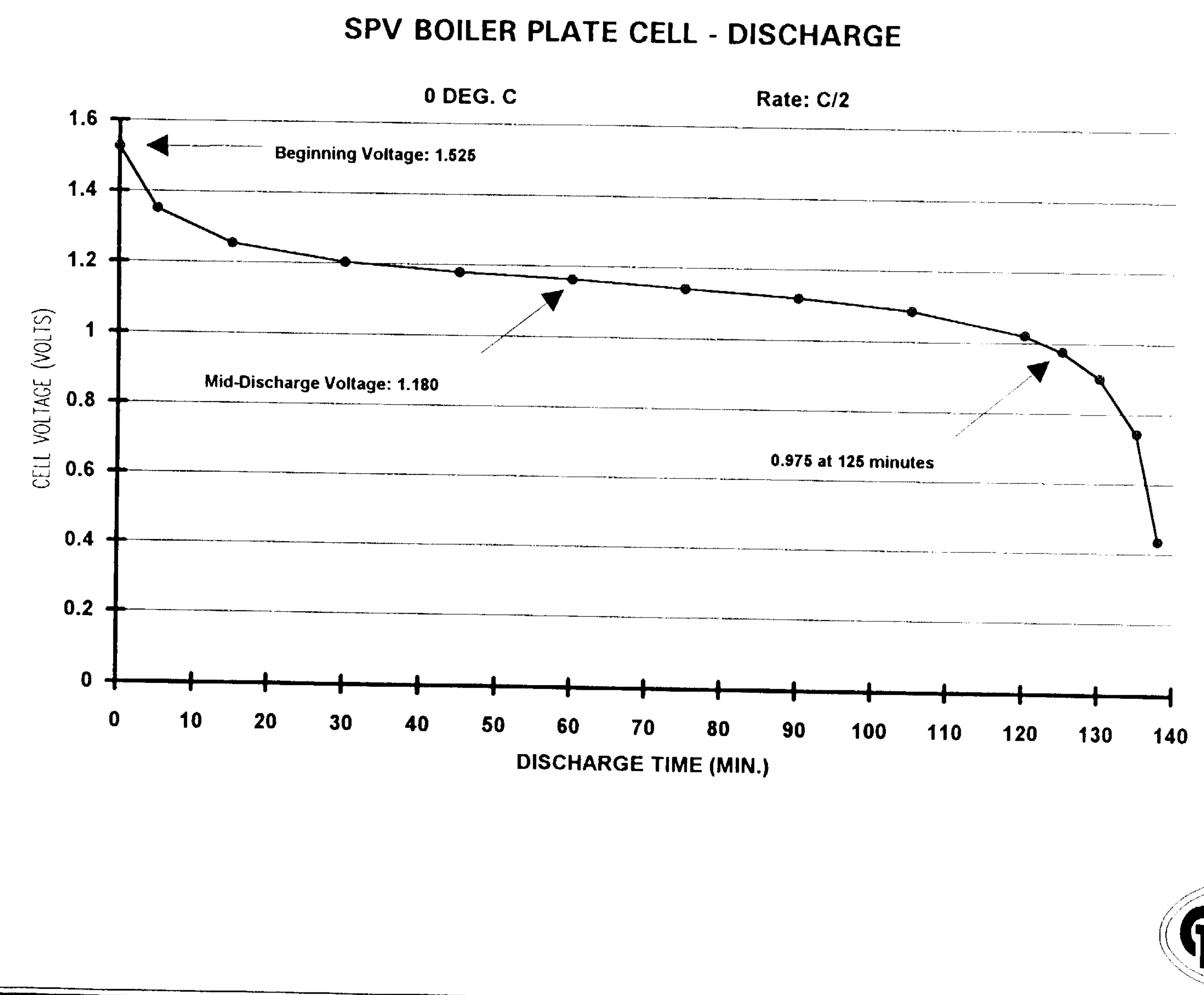

CELL DEVELOPMENT ACTIVITY

10 cells manufactured per the COMSAT design for characterization and cycle tests:

3 Cells at EPI - Activated

2 Cells at COMSAT - Activated (31% KOH)
2 Vented Cycles

15 GEO Cycles: 10.8 Hr Charge at C/10 - Typical EOCV - 1.492
72 minute Discharge at C/2 - Typical EODV - 1.205

1 Capacity Cycle: Capacities measured at Room Ambient Temperature - 40. 2 and 40.3 AH

5 Cells - To be activated later this month

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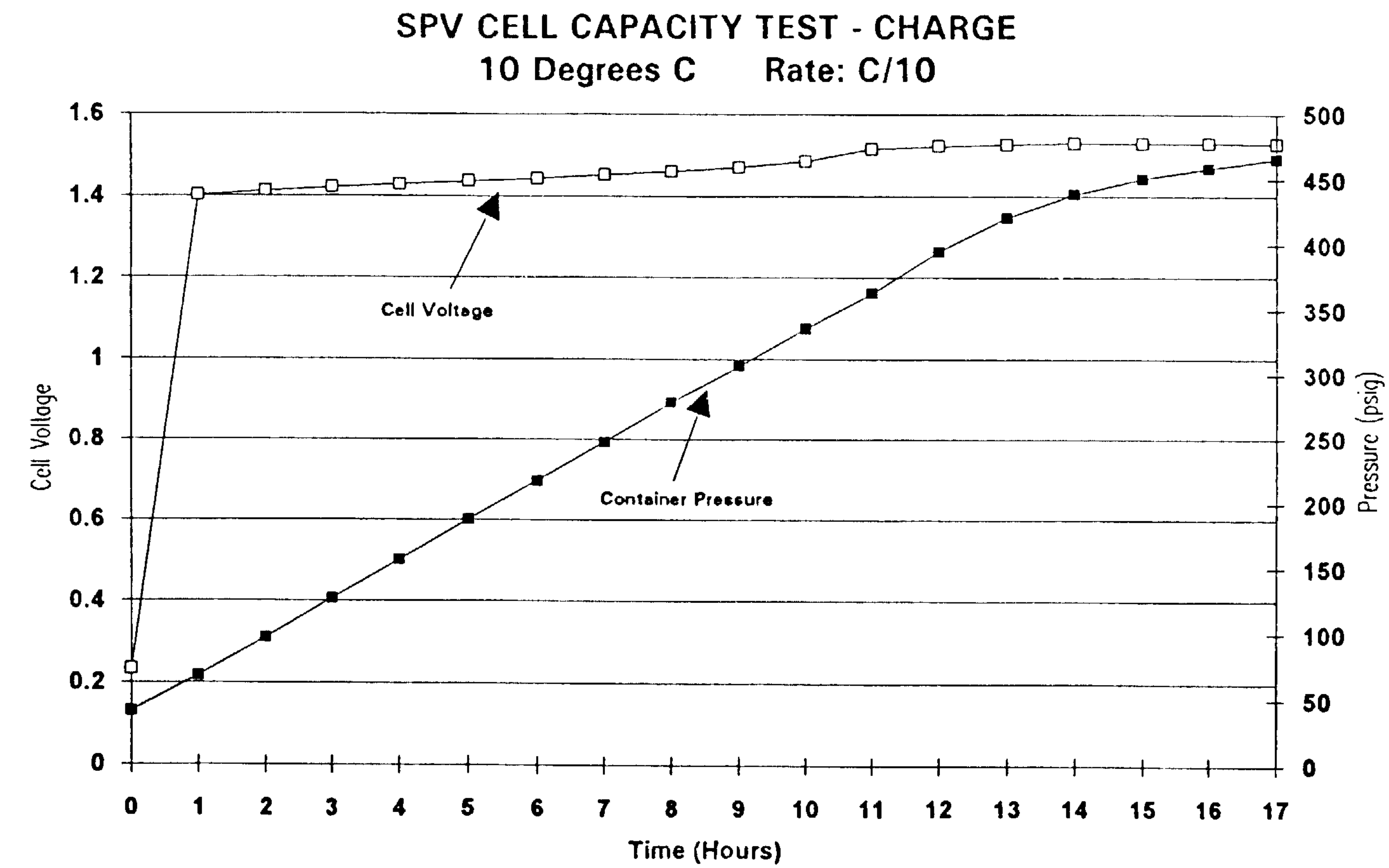
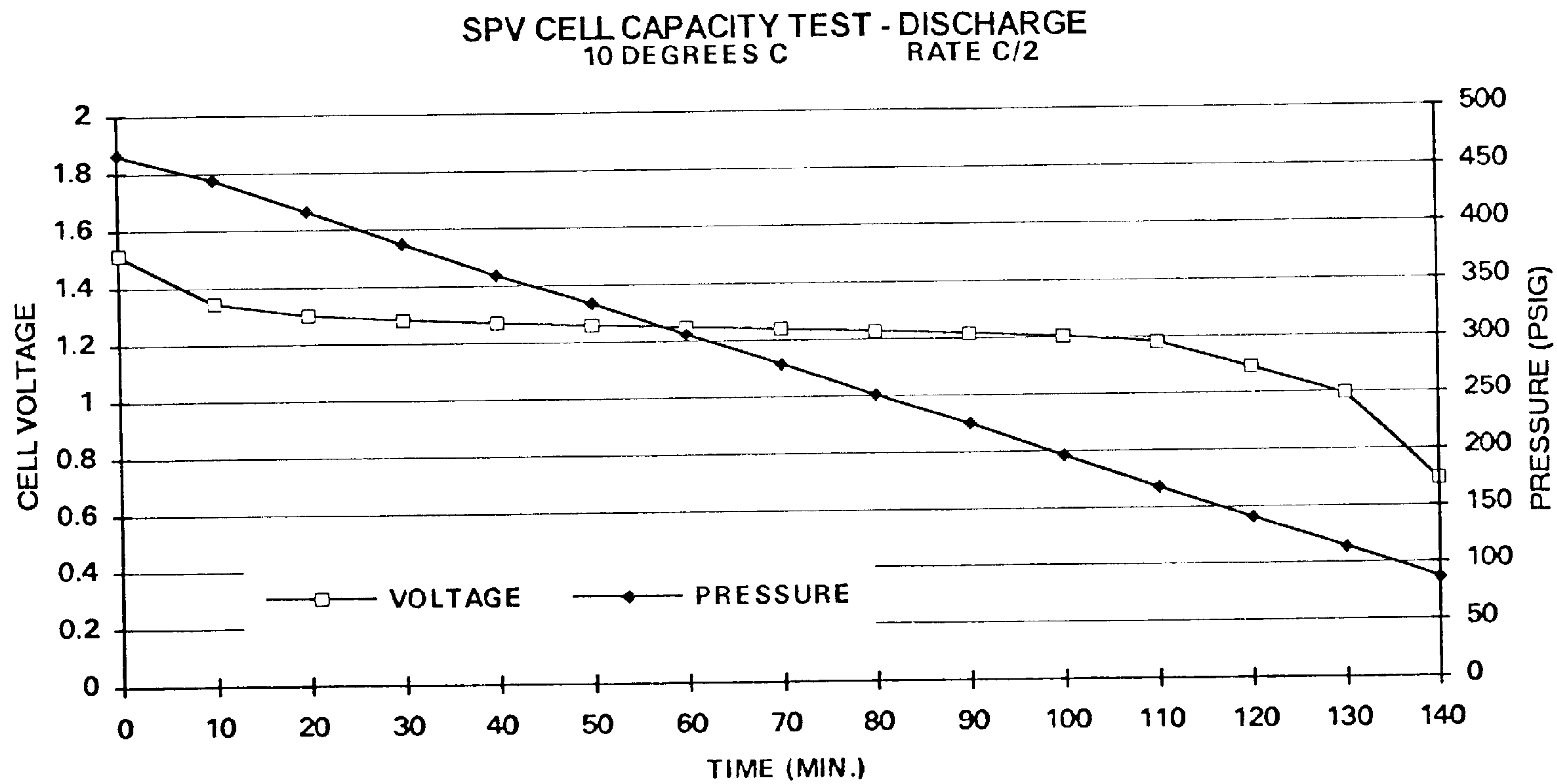


Data Provided By Comsat Laboratories, Clarksburg, MD

EAGLE PICHER | Advanced Systems Department | NICKEL-HYDROGEN GROUP



Data Provided by Comsat Laboratories, Clarksburg, MD

CURRENT PLANS

- Completion of units currently in process
- Continue development of alternate design concepts, including rigid case and alternate separator material
- Continue development for and manufacture 5" diameter 15 AH prototype using similar technology

CONCLUSION

Eagle-Picher is participating in the development and manufacture of a 10 inch diameter SPV Ni-H2 battery. Testing has been completed which verifies electrode performance and cell design.

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NICKEL-HYDROGEN CPV BATTERY UPDATE

Johnson Controls Battery Group, Inc.
P.O. Box 591, Milwaukee, WI 53201
Kenneth R. Jones and Jeffrey P. Zagrodnik
(414/783-2604) (414/783-2605)

N93-20518

The multicell common pressure vessel (CPV) nickel hydrogen battery manufactured by Johnson Controls Battery Group, Inc. has completed full flight qualification, including random vibration at 19.5 g for two minutes in each axis, electrical characterization in a thermal vacuum chamber, and mass-spectroscopy vessel leak detection. A first launch, is scheduled for late in 1992 or early 1993 by the Naval Research Laboratory (NRL). Specifics of the launch date are not available at this time due to the classified nature of the program. Release of orbital data for the battery is anticipated following the launch.

Three 5" diameter 22-cell, 12 Ah batteries (figure 10 have been fabricated and tested to various degrees as the qualification, flight and flight spare batteries for the NRL program. As part of the qualification, NRL has attached a strain gauge as a parallel means of pressure monitoring with the pressure transducer installed by Johnson Controls during fabrication of the battery.

Several additional units of similar design have been fabricated or a scheduled for fabrication in early 1993 as part of a variety of programs for several customers. Battery specific energy based on the delivered capacity and average discharge voltage delivered by the battery is 50.4 Wh/kg.

Fabrication of several 10" diameter CPV's, ranging in capacity from 25 Ah to 50 Ah, has also been initiated. These batteries incorporate an expandable stack design which is designed to accommodate the possible expansion of the nickel electrodes during long-term cycling (25,000 cycles or more) typical of LEO missions. A prototype 50 Ah test cell (48.2 Ah theoretical capacity), delivered 50 Ah to 1.0 volt/cell (104% utilization) and 51.6 Ah to 0.5 volt/cell (107% utilization) on a standard 10°C C/2 discharge characterization cycle (Figure 2) while maintaining an average discharge voltage of 1.25 V/cell. The 104% utilization is up considerably from the 95% utilization that had been more typical of previous cells and batteries. The improvement is attributed to minor process optimizations incorporated into the positive electrode fabrication processes. The higher utilization will translate directly into further improvement in specific energy.

Two 2-cell batteries dating back to the time of the original CPV battery prototype [1], were retrieved from a 1.5 year storage period and put back on test. The batteries had been discharged to 1.0 volt/cell average prior to storage. Storage conditions were open circuit at room temperature in an uncontrolled warehouse setting. Full capacity was achieved on the second cycle following reinitiation of testing. These two-cells have now been placed back on a 40% DOD LEO cycle and have accumulated 13,000 and 9,000 total cycles, respectively. A third 2-cell, which has been cycled continuously since 1989, remains on test at COMSAT Laboratories. Although we no longer receive formal reports on the test status, it is our understanding that the battery remains on test and has surpassed 22,000 cycles.

References:

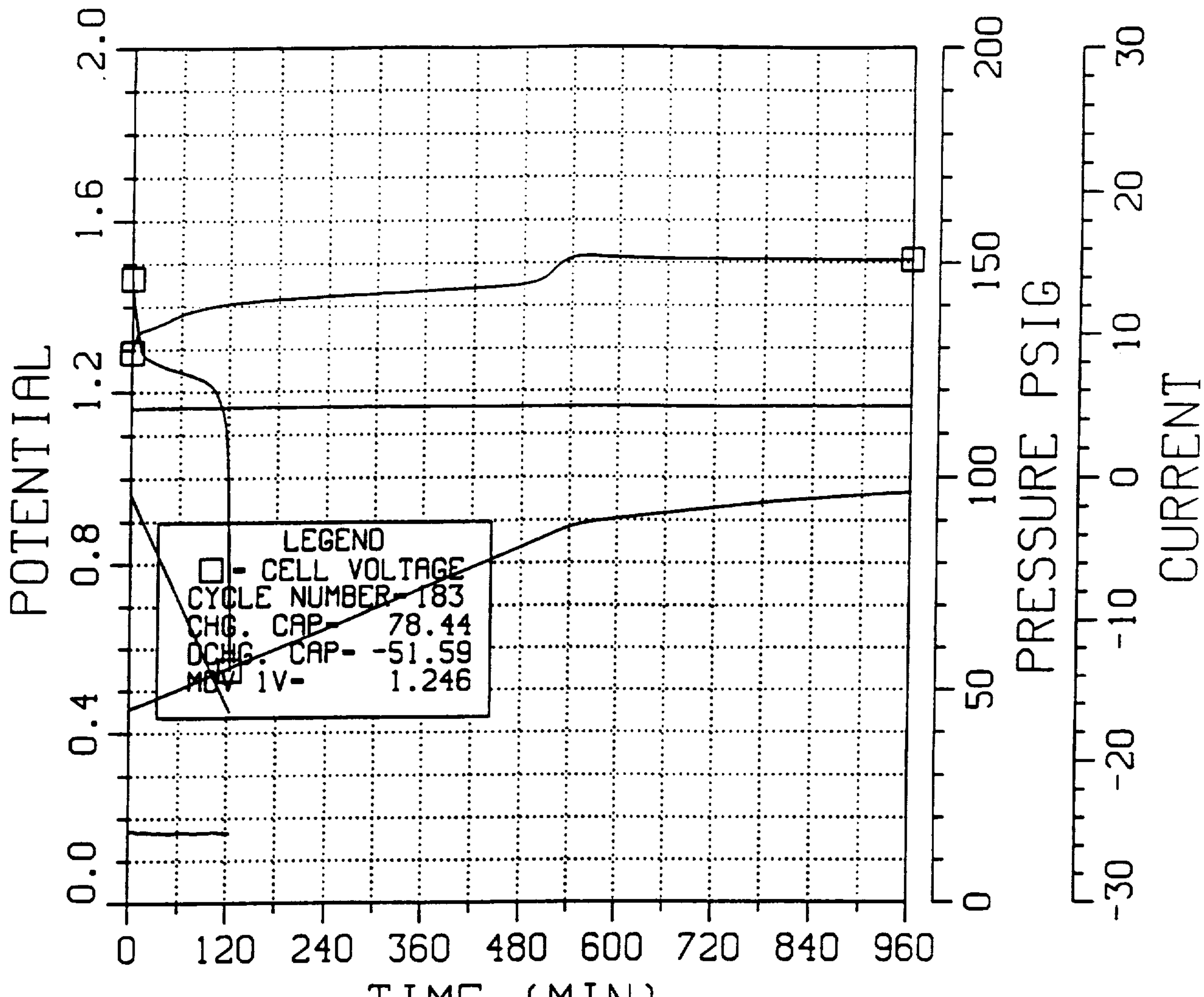
Zagrodnik, J.P., Jones, K.R., "Advances in the Design of Common Pressure Vessel Nickel Hydrogen Batteries for Aerospace Applications," 26th Intersociety Energy Conversion Conference (IECEC), August, 1991.

Acknowledgement:

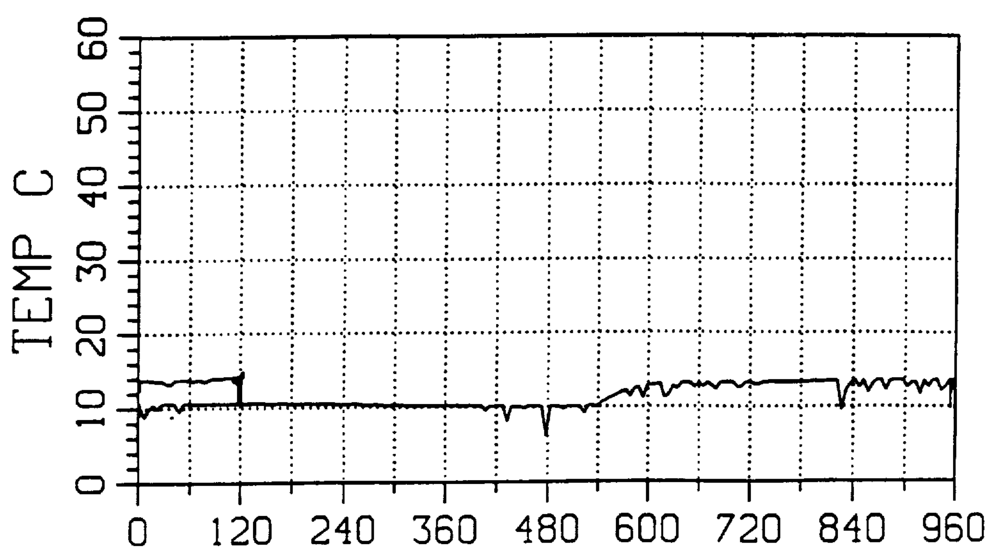
The authors gratefully acknowledge the support of Chris Garner at the Naval Research Laboratory.

CELL S106

C/10, 16-hour charge
C/2 discharge to 0.5 volt/cell
10°C



TEMPERATURE PROFILE



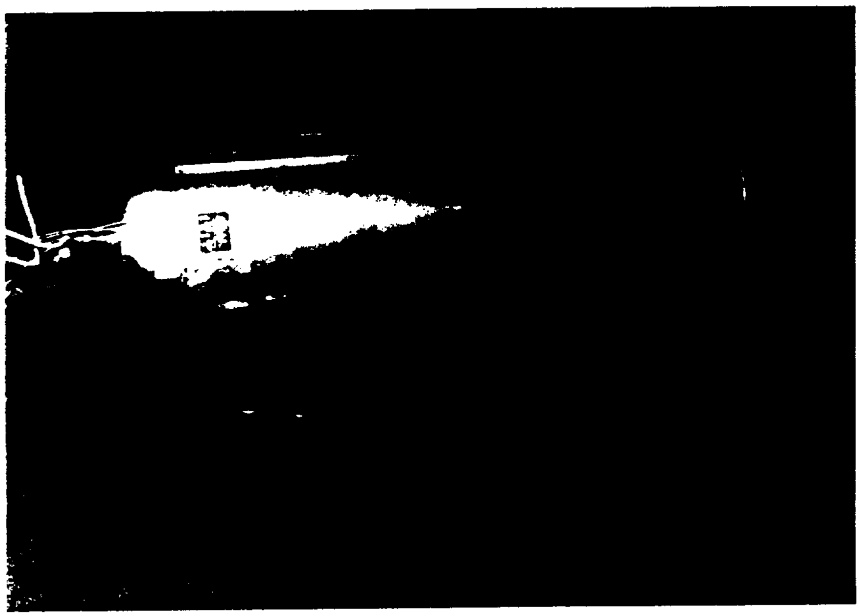


Figure 2:

5" Diameter, 22-Cell CPV Battery
With Pressure Transducer and Strain Gauge

Advanced Technologies Session

Organizers: Sal Di Stefano
Jet Propulsion Laboratory

Michelle Manzo
Marshall Space Flight Center

NASA Johnson Space Center

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BATTERY REVIEW BOARD

THE 1992 NASA AEROSPACE BATTERY WORKSHOP

NOVEMBER 19, 1992

THE STORAGE BATTERY IS, IN MY OPINION, A CATCH-PENNY, A SENSATION, A MECHANISM FOR SWINDLING THE PUBLIC STOCK COMPANIES. THE STORAGE BATTERY IS ONE OF THOSE PECULIAR THINGS WHICH APPEAL TO THE IMAGINATION, AND NO MORE PERFECT THING COULD BE DESIRED BY STOCK SWINDLERS THAN THAT VERY SELF-SAME THING....JUST AS SOON AS A MAN GETS WORKING ON THE SECONDARY BATTERY IT BRINGS OUT HIS LATENT CAPACITY FOR LYING...SCIENTIFICALLY, STORAGE IS ALL RIGHT, BUT, COMMERCIALLY, AS ABSOLUTE A FAILURE AS ONE CAN IMAGINE.

THOMAS A. EDISON - JANUARY 1883

NASA Johnson Space Center

BATTERY REVIEW BOARD

AGENDA

- CHARTER
- MEMBERSHIP
- CHRONOLOGY
- BACKGROUND
- STATEMENT OF THE PROBLEM
- ASSESSMENT/RECOMMENDATIONS FOR NEAR TERM FLIGHTS
- ASSESSMENT/RECOMMENDATION FOR FUTURE ACTIVITIES
- NASA BATTERY STEERING COMMITTEE
- SUMMARY

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NASA BATTERY REVIEW BOARD CHARTER

- REVIEW THE STATUS OF Ni-Cd, Ni-H_2 and Ni- METAL HYDRIDE AEROSPACE BATTERIES WITH EMPHASIS ON RELIABILITY, PRODUCIBILITY AND PERFORMANCE
- DETERMINE BEST DIRECTION FOR FUTURE NASA PROGRAM WITH RESPECT TO THESE SECONDARY BATTERIES

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JOHN DAY	GSFC

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BOARD CHRONOLOGY

8/19-21/92	BOARD DELIBERATION AND SITE VISIT AT GSFC
8/20/92	SITE VISIT AT COMSAT CORPORATION
8/25/92	BOARD TELECON
8/28/92	SITE VISIT AT LEWIS RESEARCH CENTER
8/31/92	SITE VISIT AT EAGLE-PICHER INDUSTRIES IN COLORADO SPRINGS, CO
9/1/92	SITE VISIT AT JET PROPULSION LABORATORY
9/2/92	SITE VISIT AT HUGHES, ELECTRON DYNAMICS DIVISION IN TORRANCE, CA
9/2/92	SITE VISIT AT AEROSPACE CORP IN LOS ANGELES, CA
9/9/92	SITE VISIT AT MDESC IN ST. CHARLES, MO
9/10/92	SITE VISIT AT EAGLE-PICHER INDUSTRIES IN JOPLIN, MO
9/17/92	SITE VISIT AT GATES IN GAINESVILLE, FL
9/18/92	BOARD DELIBERATION
9/23-25/92	BOARD DELIBERATION
9/25/92	MEETING WITH SAFT PERSONNEL AT GSFC
10/22/92	FINAL REPORT BRIEFING TO ACTING DEPUTY ADMINISTRATOR
11/17/92	ENGINEERING MANAGEMENT COUNCIL
NOV. '92	FEEDBACK TO PARTICIPANTS

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BACKGROUND

- LARGE NUMBER OF APPLICATIONS IN THE 60'S AND 70'S. SIGNIFICANT BATTERY PERFORMANCE ISSUES ENCOUNTERED - MOST APPLICATIONS ABLE TO MANAGE BATTERY PROBLEMS BY REDUCING POWER CONSUMPTION AND MANAGING CHARGE CONTROL
- GSFC IMPLEMENTED GSFC STANDARD SPEC AND GROUND TEST APPROACH FOR THE 20 AH CELLS AND BATTERIES
- 1975 - GSFC CONTRACT WITH FOUR MANUFACTURES (GE, E-P, GULTON, AND YARDNEY) FOR STANDARD 20 AH CELL. ONLY GE (GATES) PASSED CERTIFICATION
- 1976 - MANUFACTURE OF PELLON 2505 SEPARATOR MATERIAL DISCONTINUED- CELL/BATTERY COMPANIES STOCKPILE ENOUGH TO LAST THROUGH THE 80'S
- LATE 1970'S - GSFC 50 AH SPEC FOR STANDARD CELLS AND BATTERIES DEVELOPED
- 1980-85 - MANY PROBLEMS WITH PLATES AND CELLS AT GE. THEIR COMMERCIAL LINE, WHICH ALSO PRODUCES PLATES FOR AEROSPACE APPLICATIONS, WAS SHUT DOWN FOR THREE MONTHS IN SEPTEMBER OF 1984 TO CORRECT DEFICIENCIES
- 1985 - NASA ADMINISTRATOR (MR. BEGGS) REQUESTED AND RECEIVED SURVEY OF BATTERY PROBLEMS - NASA AEROSPACE FLIGHT BATTERY STEERING COMMITTEE ESTABLISHED - BATTERY PROGRAM PLAN ESTABLISHED
- 1986 - GE SOLD TO GATES

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BACKGROUND (CONT.)

- 1985-91
  - BATTERY STEERING COMMITTEE CONVERTED GSFC STANDARD SPEC'S AND MCD TO NASA STANDARDS
  - SEARCH FOR NEW SEPARATOR MATERIAL TO REPLACE PELLON 2505 LED TO DEVELOPMENT OF PELLON 2536 AND 2538
  - Ni-H_2 TECHNOLOGY MATURING - SPACE STATION SELECTED Ni-H_2 BASELINE
  - ADVANCED Ni-Cd TECHNOLOGY MATURING
    - GSFC SELECTED ADVANCED Ni-Cd (9 AH) FOR SAMPEX APPLICATION
    - JPL SELECTED 37 AH ADVANCED Ni-Cd AS BACKUP FOR MARS OBSERVER
    - GSFC SELECTED 50 AH ADVANCED Ni-Cd AS BACKUP FOR EUVE
- 1975-1991
  - LARGE NUMBER OF SUCCESSFUL FLIGHT PROGRAMS (LEO & GEO) UTILIZING NASA STANDARD Ni-Cd BATTERIES (LANDSAT-ERBS, SMM, TIROS)
- 11/91 TO PRESENT
  - PROBLEMS ENCOUNTERED WITH 50 AH CONVENTIONAL Ni-Cd BATTERIES AND CELLS
  - GSFC HAS SELECTED 50 AH ADVANCED Ni-Cd FOR XTE AND TRMM AND 9 AH ADVANCED Ni-Cd FOR FAST AND TOMS

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STATEMENT OF PROBLEM

- INSUFFICIENT/NON REPEATABLE Ni-Cd BATTERY CHARGE/DISCHARGE CYCLE CAPABILITY FOR LEO APPLICATIONS
  - EARLIEST FAILURE TO DATE ~ 2000 CYCLES; DIVERGENCE >200 MV
- WHEN DIVERGENCE OCCURS, TLC (TENDER LOVING CARE) CAN PROLONG THE LIFE. HOWEVER, ON EXISTING IN-FLIGHT SPACECRAFT, THERE IS LIMITED BATTERY CHARGE/DISCHARGE CONTROL CAPABILITY.
- ACCEPTANCE TEST PROCEDURE (ATP) INSUFFICIENT TO SCREEN FOR CYCLE LIFE CAPABILITY - SIGNIFICANT AMOUNT OF TIME REQUIRED TO VALIDATE LIFE CAPABILITY
- GENERAL CONSENSUS IS THAT THE PROBLEM IS WITH NEGATIVE PLATE
- CELL ELECTRICAL BEHAVIOR AND DPA'S (DESTRUCTIVE PHYSICAL ANALYSIS) OF CELLS FROM GROUND TEST SHOW SYMPTOMS OF A FAILED CELL AT THE END OF ITS LIFE
- ROOT CAUSE OF THE FAILURE IS UNKNOWN

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SUMMARY OF PROBLEMS WITH 50 AH STANDARD Ni-Cd

FLIGHT VEHICLES

- GRO
  - TWO MODULAR POWER SYSTEMS (MPS); THREE BATTERIES EACH
  - NOMINAL OPERATION FOR 7 MONTHS (~3000 CYCLES)
  - DEC 91, ~ 80 MV DIFFERENTIAL
  - CURRENTLY - MPS 1: BATTERY 2 OFF LINE > 750 MV
BATTERIES 1 AND 3 (STILL ON LINE 150 - 300 MV)
MPS 2: NOMINAL FLIGHT PERFORMANCE
- UARS
  - 1 MPS
  - NOMINAL OPERATION FOR 2,000 CYCLES
  - JAN '92 - OCT '92, 80 MV UP TO 400 MV
  - CURRENTLY - APPROMIMATELY 200 MV

GROUND TEST

- GRO
  - CELLS FROM MPS 1 LOT EXHIBIT CELL DIVERGENCE (30 MV) AFTER 6600 CYCLES; THEN IMPROVED
  - CELLS FROM MPS 2 LOT NOMINAL
- UARS
  - CELLS FROM FLIGHT LOT EXHIBIT CELL DIVERGENCE AFTER 2000 CYCLES
  - THREE UARS CELLS DPA'D FROM FLIGHT LOT AT APPROX 5000 CYCLES
    - 2 FROM STRESS PACK (EXCESSIVE MIGRATION IN ONE, OTHER WAS NOMINAL)
    - 1 FROM MISSION SIM PACK (SOFT SHORTS WITH LOCALIZED Cd MIGRATION)

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ACTIVITIES FOR NEAR TERM PROGRAMS UTILIZING CONVENTIONAL Ni-Cd

ASSESSMENT:

- UNCERTAINTY ASSOCIATED WITH LEO LIFE CYCLE CAPABILITY OF ALL NASA STANDARD Ni-Cd CELLS

RECOMMENDATIONS:

- ON-ORBIT VEHICLES IN LOW EARTH ORBIT - MINIMIZE STRESS OF THE BATTERY (TLC)
  - MINIMIZE OVERCHARGE AND AVOID HIGH TRICKLE CHARGE CURRENT - STRONG EVIDENCE THAT THIS ENHANCES LIFE - THIS SHOULD BE DONE ON ALL PROGRAMS UTILIZING NASA STANDARD Ni-Cd BATTERIES
  - CODE S OPERATIONS COMMITTEE APPOINTED BY DR. FISK TO CO-ORDINATE OPERATIONAL ACTIVITIES IS ON-GOING. - DETAILED SUGGESTIONS HAVE BEEN DISCUSSED WITH THAT GROUP

- CONTINUE SEARCH FOR ROOT CAUSE(S)
  - CONTINUE TO PARTICIPATE WITH GOVERNMENT TEAM LOOKING FOR CORRELATION BETWEEN APPARENT GOOD LOTS AND THE PROBLEM LOTS
  - PERFORM CELL DPA'S AT OTHER LOCATIONS
    - MSFC, JPL, LeRC

- RE-EVALUATE PLANNED LAUNCHES UTILIZING ALREADY MANUFACTURED NASA STANDARD Ni-Cd BATTERIES

- PERFORM 2 YEAR CELL STRESS TEST OR A MISSION SIMULATION TEST ON FLIGHT LOT CELLS PRIOR TO FLIGHT

BATTERY REVIEW BOARD

PRESENT PROJECTS SCHEDULED TO USE NASA STANDARD Ni-Cd

PROJECT	LAUNCH DATE	RESOLUTION	# CYCLES REQUIRED
WIND (26.5A-H)	12/93	7 ECLIPSE ORBIT. EVALUATING PLATE, CELL AND BATTERY DATA, BUT SHOULD BE ACCEPTABLE	7
POLAR (26.5A-H)	8/94	<300 ECLIPSE ORBIT. EVALUATING PLATE AND CELL DATA, BUT SHOULD BE ACCEPTABLE	300
GOES (12A-H)	12/93, 12/94, 98, 99	GEO ORBIT. CONV. Ni-Cd ACCEPTABLE PROVIDED TEST DATA IS ACCEPTABLE	<1000
TDRSS (40A-H)	1/93, 1/95	GEO, PLATE FABRICATED PRIOR TO 1987. CONV. Ni-Cd ACCEPTABLE. CELL PACKS IN TEST	<1000
NOAA I (26.5A-H)	3/93	BATTERIES MANUFACTURED FROM LOT 14 PLATES; SAME AS NOAA D (16 MONTHS IN ORBIT), ONE BATTERY ON H (FOUR + YEARS IN ORBIT); 22 MONTH SUCCESSFUL LIFE TEST. ACCEPTABLE FOR FLIGHT.	10,000
NOAA J (26.5A-H)	'94	22 MONTH MISSION SIM TEST IN PROGRESS; EVALUATING POSSIBLE USE OF SAFT OR SUPER Ni-Cd	10,000
NOAA K (47A-H)	'95	24 MONTH MISSION TEST WILL BE DONE; EVALUATING SUPER Ni-Cd (POSSIBLY M.O.), SAFT Ni-Cd AND Ni-H_2 AS ALTERNATIVES	10,000
ACTS	6/93	GEO ORBIT MISSION OF APPROXIMATELY 4 YEARS USING 2 NASA STANDARD 19 AH Ni-Cd at 50% DOD WITH RECONDITIONING AND INDIVIDUAL CELL VOLTAGE MONITORING AVAILABLE	400

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OTHER NEAR-TERM NASA PROGRAMS REQUIRING SECONDARY BATTERIES

PROGRAM	CELL MANF	BATTERY MANF	TYPE	ORBIT	AH	LAUNCH DATE	COMMENT
GSFC							
FAST	EP-CS	HAC	Su Ni-Cd	LEO	9	8/94	
SWAS	TBD	TBD	Ad Ni-Cd	LEO	21	6/95	
TOMS	EP-CS	HAC	Su Ni-Cd	LEO	9	8/94	
XTE	EP-CS	HAC	Su Ni-Cd	LEO	50	12/95	
TRMM	EP-CS	HAC	Su Ni-Cd	LEO	50	8/97	
ACE	TBD	TBD	TBD	L1	TBD	8/97	
LeRC							
SSF	GATES	LORAL	$Ni\text{-}H_2$	LEO	81	3/96	6.5 YEARS @ 35% DOD ~36,400 CYCLES
JSC							
TESS	EP-J	MDESC	$Ni\text{-}H_2$	15-60% DOD FOR .5-1.5 HOURS	78	6/96	4755 CYCLES/ 10 YEARS

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BATTERY REVIEW BOARD

RECOMMENDED DIRECTION FOR FUTURE PROGRAMS

RECOMMENDATION: MAKE SELECTION(S) BASED ON REQUIREMENT TRADE STUDY RESULTS COMBINED WITH MARKET PLACE COMPETITION

- CONVENTIONAL Ni-Cd
  - USER BEWARE WITH RESPECT TO NASA STANDARD Ni-Cd CELLS FOR LEO APPLICATION UNLESS ON-GOING ACTIVITY IDENTIFIES ROOT PROBLEM(S) WHICH CAN BE CORRECTED
- ADVANCED Ni-Cd
  - ACCEPTABLE FOR FLIGHT USAGE
  - QUANTITY OF DATA ON ADVANCED Ni-Cd IS LIMITED AND MORE TESTING SHOULD BE PERFORMED
  - GROUND HANDLING/STORAGE PROBLEM NEEDS RESOLUTION
- Ni-H_2
  - EXCELLENT SYSTEM FOR LEO IN TERMS OF CAPABILITY; (CYCLE LIFE, DEPTH OF DISCHARGE, ETC)
- Ni-MH
  - MONITOR PROGRESS OF Ni-MH
- EACH PROGRAM SHOULD PERFORM A SPECIFIC BATTERY QUALIFICATION TEST. ALSO PERFORM A MISSION SIMULATION TEST, AND/OR A CELL STRESS TEST ON <u>FLIGHT LOT CELLS</u> PRIOR TO FLIGHT
- PROVIDE MORE FLEXIBLE CHARGE CONTROL AT A BATTERY LEVEL, e.g. DESIGN CHARGE CONTROL SYSTEMS TO LIMIT OVERCHARGE AND GENERALLY MINIMIZE STRESS ON BATTERY
- DESIGN Ni-Cd SYSTEMS TO ALLOW FOR RECONDITIONING OF BATTERIES IN LEO IF PRACTICAL

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BATTERY REVIEW BOARD

FUTURE CELL/BATTERY PROCUREMENT STRATEGY

ASSESSMENT

- THE CURRENT STRATEGY OF A NASA STANDARD CELL AND BATTERY SPECIFICATION AND NASA CONTROL OF A STANDARD MANUFACTURING CONTROL DOCUMENT FOR Ni-Cd IS UNWARRANTED

RECOMMENDATIONS

- TREAT BATTERY/CELL LIKE OTHER SPACECRAFT COMPONENTS
- LET PRIME OR IN-HOUSE PROJECT OFFICE (S) DECIDE ON SPECIFICATIONS, MCD'S, ETC.
- USE CONTRACT INCENTIVES TO INSURE PERFORMANCE, SCHEDULE, AND LIFE CHARACTERISTICS ARE MET
- BATTERY STEERING COMMITTEE SHOULD REORIENT 8073.1 SPECIFICATION AS A CHECKLIST/HANDBOOK FOR PROCURING CONVENTIONAL Ni-Cd, ADVANCED Ni-Cd, AND $Ni\text{-}H_2$
- RELINQUISH NASA CONTROL OF DASH 87 AND DASH 88 MANUFACTURER'S CONTROL DOCUMENT (MCD)

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BATTERY REVIEW BOARD

FUTURE CELL/BATTERY PROCUREMENT STRATEGY (CONT.)

PRO'S

- PLACES RESPONSIBILITY AND ACCOUNTABILITY WITH THE PRIMES AND THEIR SUBCONTRACTORS
- ALLOWS IMPROVEMENTS DEVELOPED IN COMMERCIAL AND OTHER GOVERNMENT PROGRAMS TO BE INCORPORATED INTO NASA PROGRAMS MORE QUICKLY
- DECREASES RESPONSE TIME FOR NECESSARY MCD CHANGES AT THE VENDOR
- UTILIZES MARKET PLACE FOR COMPETITION
- ALLOWS NASA AEROSPACE CELLS TO BE MORE LIKE COMMERCIAL AND OTHER GOVERNMENT AEROSPACE CELLS
- MORE LIKE HOW WE ARE CURRENTLY OPERATING

CON'S

- POTENTIALLY LESS NASA CONTINUITY BETWEEN PROGRAMS
- POTENTIALLY FEWER LONG TERM BUSINESS ARRANGEMENTS
- BATTERY TEAM IN '85 RECOMMENDED USE OF STANDARDS

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BATTERY REVIEW BOARD

NASA BATTERY PROGRAM

ASSESSMENT:

THE NASA BATTERY STEERING COMMITTEE WAS ESTABLISHED IN 1985 TO PROVIDE FOR AN INTEGRATED, WELL MANAGED NASA AEROSPACE BATTERY PROGRAM. THIS GROUP CONTINUES TO PROVIDE OVERSIGHT FOR THE NASA BATTERY PROGRAM (INITIALLY FUNDED IN 1988) AND PERFORMS AN ESSENTIAL SERVICE FOR NASA AND AEROSPACE BATTERY COMMUNITY

RECOMMENDATIONS:

- CONTINUE BATTERY PROGRAM EVALUATION OF ADVANCED Ni-Cd, NI-H2 AND NI-MH CELLS TO SUPPORT FUTURE NASA MISSIONS
- ABANDON THE NASA STANDARD BATTERY CONCEPT WITH RESPECT TO NASA CONTROL OF THE CELL SPECIFICATION AND THE MANUFACTURING CONTROL DOCUMENT
- REVISE NHB 8073.1 (NASA STANDARD CELL SPECIFICATIONS) TO CELL/BATTERY PROCUREMENT GUIDELINES
- FOCUS ON COORDINATION OF LESSONS LEARNED AND MAINTAINING AND UPDATING AGENCY WIDE BATTERY DATA BASES
- EXPAND CURRENT BATTERY PROGRAM PLAN TO INCLUDE AUTOMATED FLIGHT/GROUND TEST, GOVERNMENT AND INDUSTRY CELL/BATTERY DATA BASE
- PROVIDE INDEPENDENT VERIFICATION OF MANUFACTURING FLIGHT CELLS BY PROCURING AND TESTING REPRESENTATIVE CELLS FROM VARIOUS MANUFACTURERS
- AUGMENT LIFE CYCLE TESTING OF GOVERNMENT OWNED EXISTING SUPER AND CONVENTIONAL Ni-Cd CELLS
- DEVELOP AN APPLICABLE CELL STRESS TEST FOR Ni-H_2 and Ni-MH

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BATTERY REVIEW BOARD

SUMMARY

- HISTORICAL REVIEW OF Ni-Cd USAGE INDICATES "GOOD OLE DAYS" WERE ONLY PARTIALLY GOOD
- SEVERAL ON-ORBIT AND GROUND TEST CYCLE LIFE PROBLEMS WITH NASA STANDARD Ni-Cd CELLS - ROOT CAUSE REMAINS ELUSIVE
  - ON-ORBIT CYCLE LIFE CAN BE PROLONGED WITH TENDER LOVING CARE (TLC)
- SIGNIFICANT NUMBER OF NASA STANDARD Ni-Cd CELLS ALREADY MANUFACTURED FOR FUTURE APPLICATIONS - EACH PROGRAM IS EVALUATING EXISTING DATA AGAINST SPECIFIC APPLICATION REQUIREMENTS.
- BATTERY CHOICES FOR NEAR-TERM, NEW PROGRAMS INCLUDE $Ni-H_2$, ADV Ni-Cd, AND CONVENTIONAL Ni-Cd
- CD ENVIRONMENTAL RULING ACCEPTABLE BUT SHOULD EXPECT CONTINUING PRESSURE
- FUTURE APPLICATIONS SHOULD EMPHASIZE $Ni-H_2$
- NASA POLICY FOR IMPLEMENTATION OF NASA STANDARD CELL AND BATTERY UNWARRANTED - SHOULD ALLOW SPACECRAFT REQUIREMENTS AND MARKET PLACE COMPETITION TO DRIVE SELECTION

N93-20520

DEVELOPMENT OF FIRST GENERATION

AEROSPACE NiMH CELLS

Lawrence Tinker, Dan Dell

Tony Wu, Guy Rampel

Gates Aerospace Batteries

Gates Energy Products, Inc.

Presented at the 1992 NASA Battery Workshop

November 19, 1992

Program Description

- Gates Energy Products involved in NiMH development since 1987
- GAB aerospace cell development program begun in 1990 in conjunction with GEP
- Prismatic cell testing begun in 1991
- Initial work aimed at demonstrating feasibility and identifying problem areas
- Recent work focused on improvements to alleviate identified problems

Gates Aerospace Batteries in conjunction with Gates Energy Products has been developing NiMH technology for aerospace use since 1990. GEP undertook the development of NiMH technology for commercial cell applications in 1987. This program focused on wound cell technology for replacement of current NiCd technology.

As an off shoot of this program small wound cells were used to evaluate initial design options for aerospace prismatic cell designs. Early in 1991, the first aerospace prismatic cell designs were built in a 6 Ah cell configuration. These cells were used to initially characterize performance in prismatic configurations and begin early life cycle testing. Soon after the 6 Ah cells were on test several 22 Ah cells were built to test other options. The results of testing of these cells were used to identify potential problem areas for long lived cells and develop solutions to those problems.

Following these two cell builds a set of 7 Ah cells was built to evaluate improvements to the technology. To date results from these tests are very promising. Cycle lives in excess of 2,200 LEO cycles at 50% DoD have been achieved with cells continuing on test.

Results from these cell tests are discussed and data presented to demonstrate feasibility of this technology for aerospace programs.

Table I

NiMH Prismatic Cell Design Summary

Item	6 Ah	22 Ah	7 Ah
Positive Electrodes			
Number	14	15	14
Thickness (mm)	0.71	0.71	0.71
Capacity (Ah) theoretical	7.5	27.6	9.31
Negative Electrodes			
Number	15	16	15
Thickness (mm)	0.32	0.32	0.32
Capacity (Ah)	11.5	42.2	14.4
Separator			
Type	Nylon-2538	Nylon-2538	Nylon-2538 Others
Negative to Positive			
Capacity Ratio (nominal)	1.5	1.5	1.5
Electrolyte			
Type	KOH	KOH	KOH
Concentration (%)	31	31	31
Cell Dimensions (mm)			
Overall Height	69.9	112.5	70.1
Case Height	59.2	101.8	58.8
Width	53.8	75.7	54.2
Depth	20.8	22.6	21.1

Table I summarizes the design parameters for the three types of cells tested to date. The 6 Ah and 22 Ah cell sizes were initial test bed sizes and the 7 Ah size is planned to be used for initial qualification testing. The 6 Ah cells were used to test three configurations of positive electrodes with two separator types. The 22 Ah cells continued these tests in a larger cell configuration to identify any potential problems with scaling up of the cell size.

The initial baseline separator used was nylon 2538 and the electrolyte 31% KOH. Cell dimensions are conventional NiCd cell dimensions although for lower rated cells.

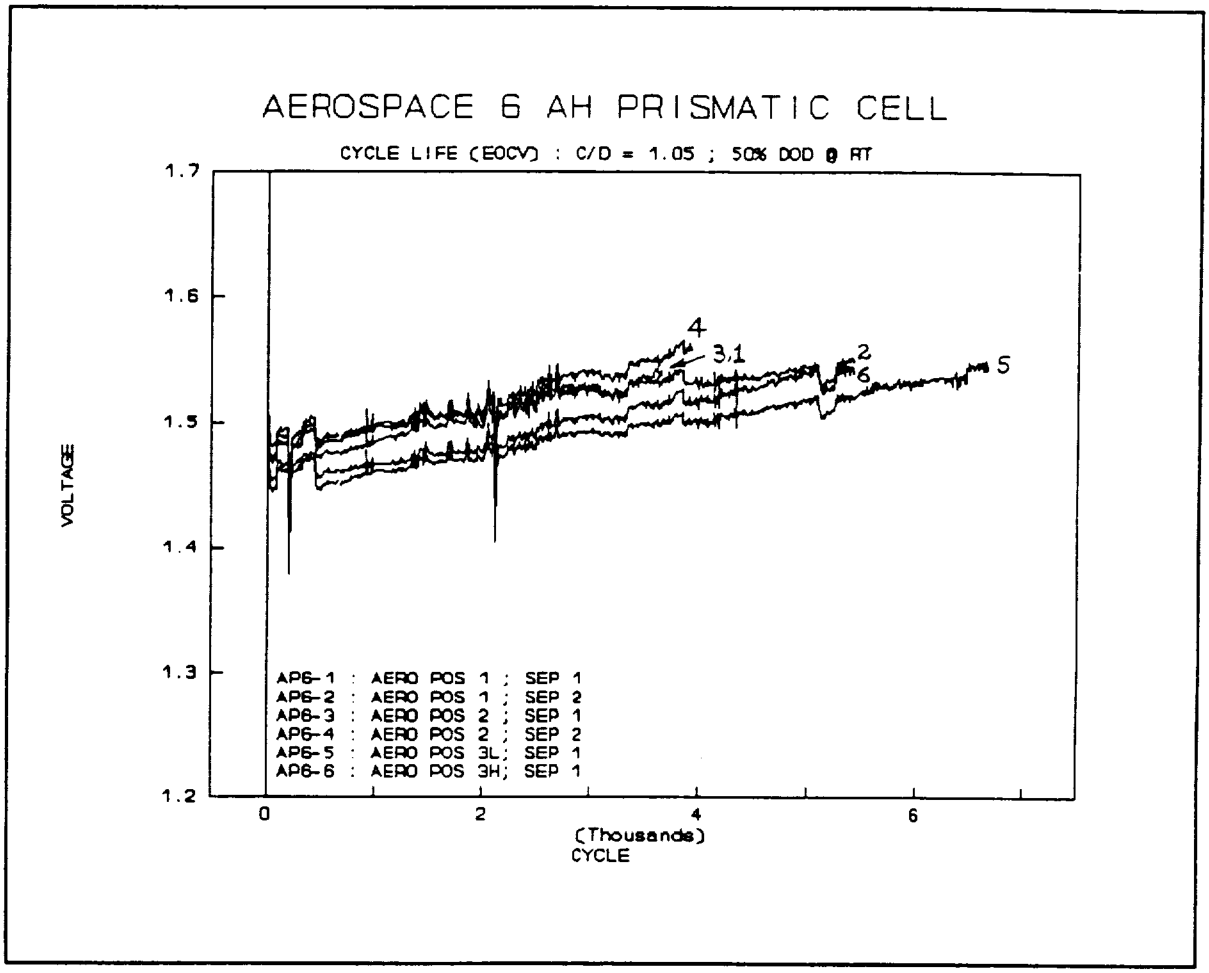


Figure 1 Performance of 6 Ah Cells in Initial Configuration

Cycling of all cells included in this paper was performed in a LEO simulation regime using an integrator controlled cycler. Each cell is monitored using a FLUKE scanning multimeter interfaced to a PC based data collection system. Cell pressures are monitored by direct reading of gauges (Ashcroft A1S1) attached to the cells. Pressure data is manually entered into the correct data file.

This figure illustrates the EOCV performance for the initial build of 6 Ah NiMH prismatic cells. One cell of this group provided greater than 6,000 LEO cycles at 50% DoD. Three primary failure modes were observed in these cells, end of charge pressure increases, shorts, and declining EODV. These cells included three types of positive electrodes with one alloy type and two separators.

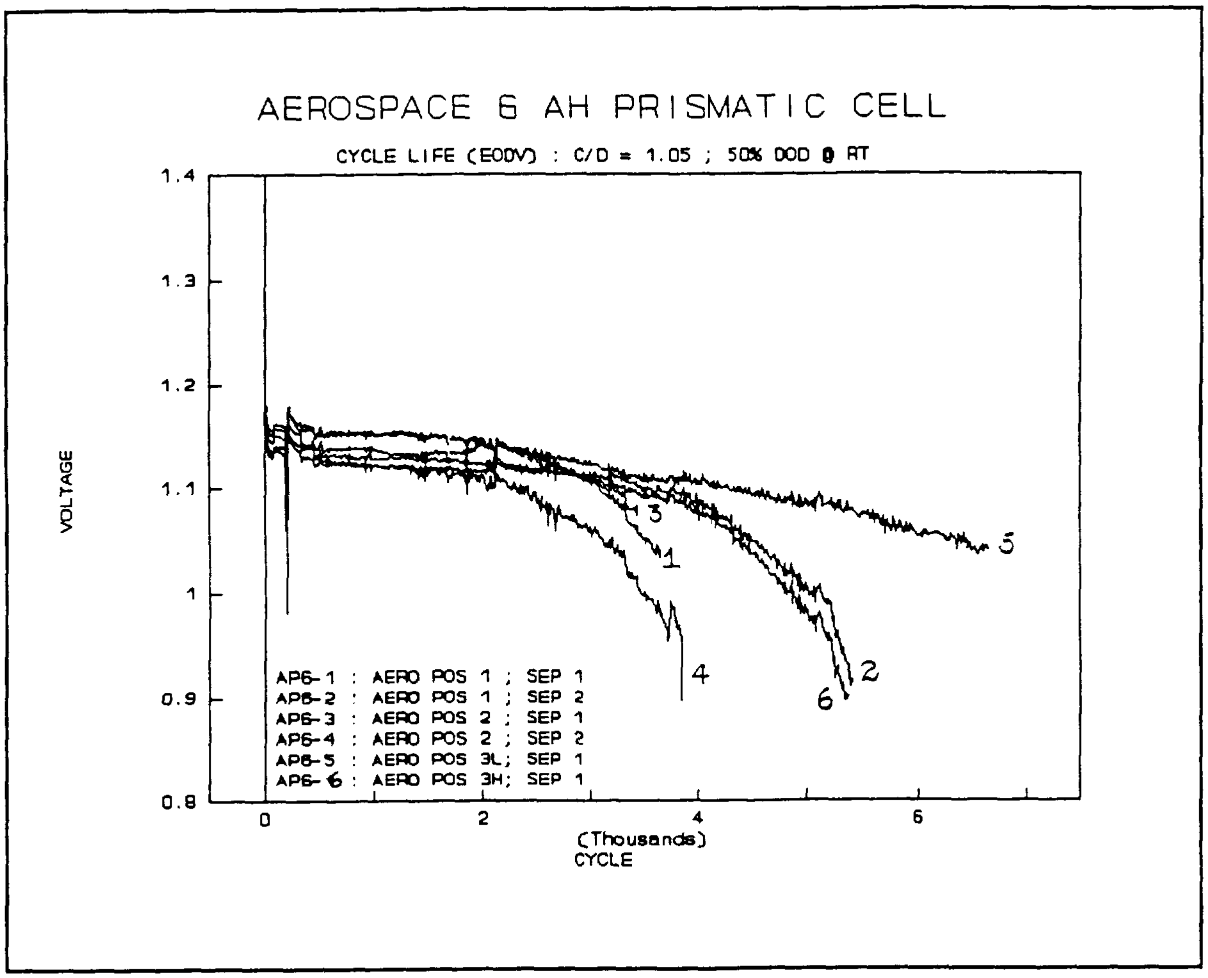


Figure 2 EODV Performance for 6 Ah Cells in Initial Configuration

This figure illustrates the EODV performance trend for the same cells identified in Figure 1. As can be seen from the curves the earliest failures were at about 3500 cycles due to shorts. These shorts were identified to be caused by the substrate in use and this problem has been corrected for future cells. Three cell configurations were terminated due to low EODV and high EOCP and the last cell was terminated due to high EOCP (Figure 3).

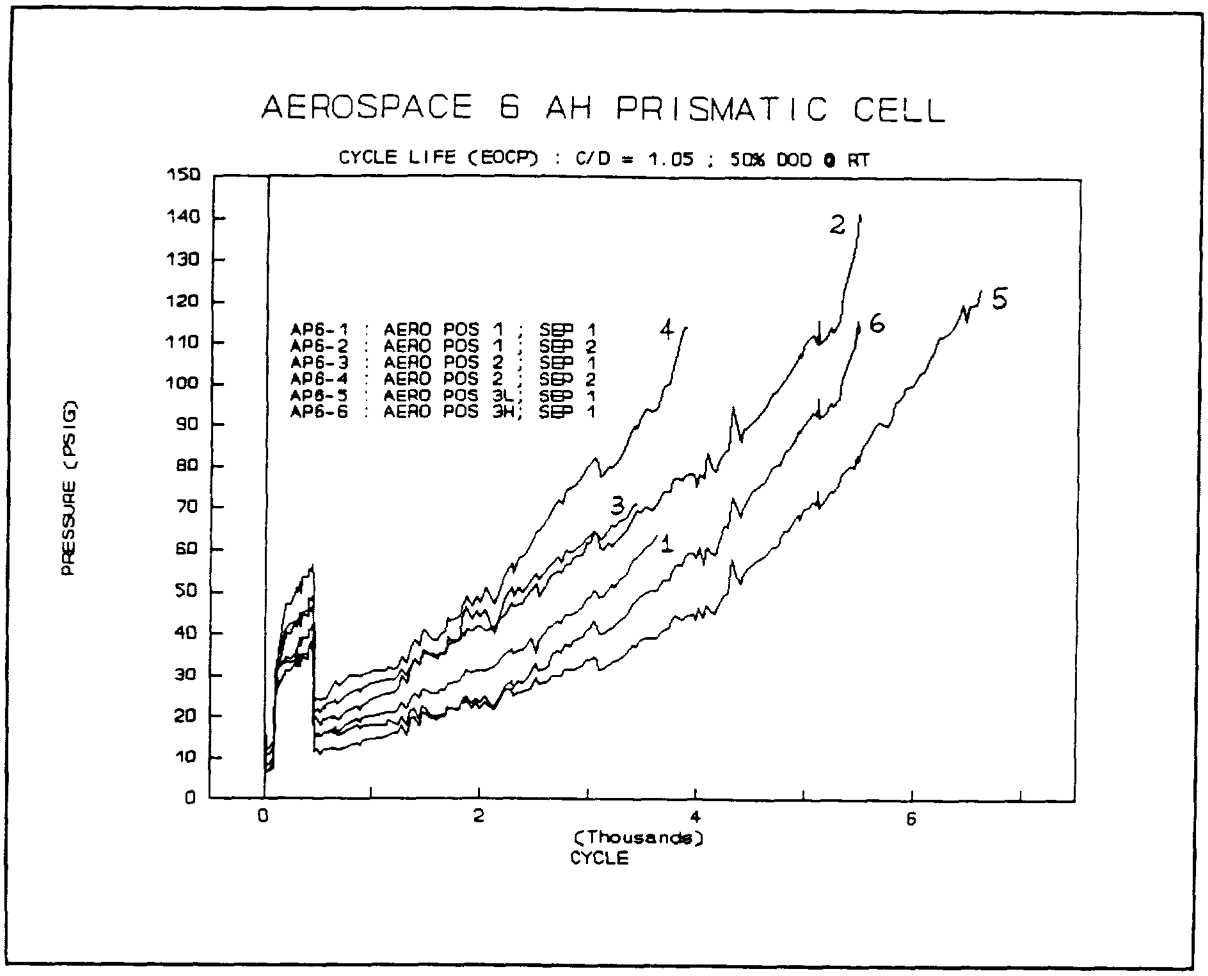


Figure 3 EOCP Performance of 6 Ah Cells in Initial Configuration

This figure shows the increase in EOCP as a function of cycle life for the initial 6 Ah cell configurations. Initially, the recharge ratio was 1.10 and the pressures appeared to rise rapidly early in life. The ratio was reduced to 1.05 at about 500 cycles and the performance improved. However, the cells exhibited a steady increase in pressure with cycling that eventually led to termination of the tests. The increase in pressure has been attributed to a slow degradation of the metal hydride alloy and low negative to positive ratio in the cells. These issues have been addressed in recent cell designs and are reflected in lower EOCP performance with cycle life.

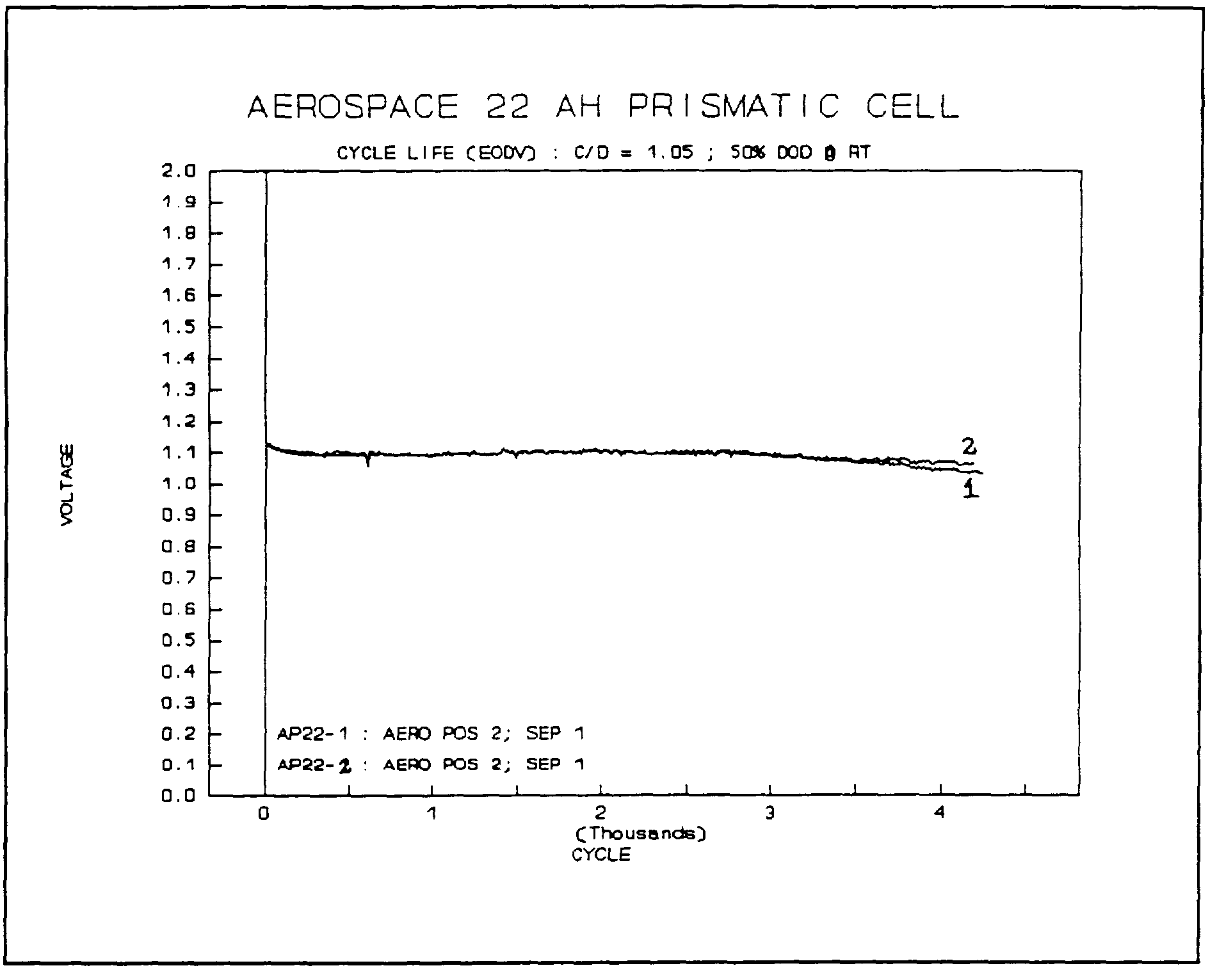


Figure 4 EODV Performance for 22 Ah Cells

The second set of test cells evaluated were 22 Ah cells. These cells were built in 15 Ah equivalent NiCd cases using one type of alloy and one type of positive and separator. This figure illustrates the EODV performance for the cells in 50% DoD LEO cycling. As can be seen from the curves the voltage was stable at about 1.10 V over the cycle life with minor dispersion appearing at about 3600 cycles and continuing until termination of the test.

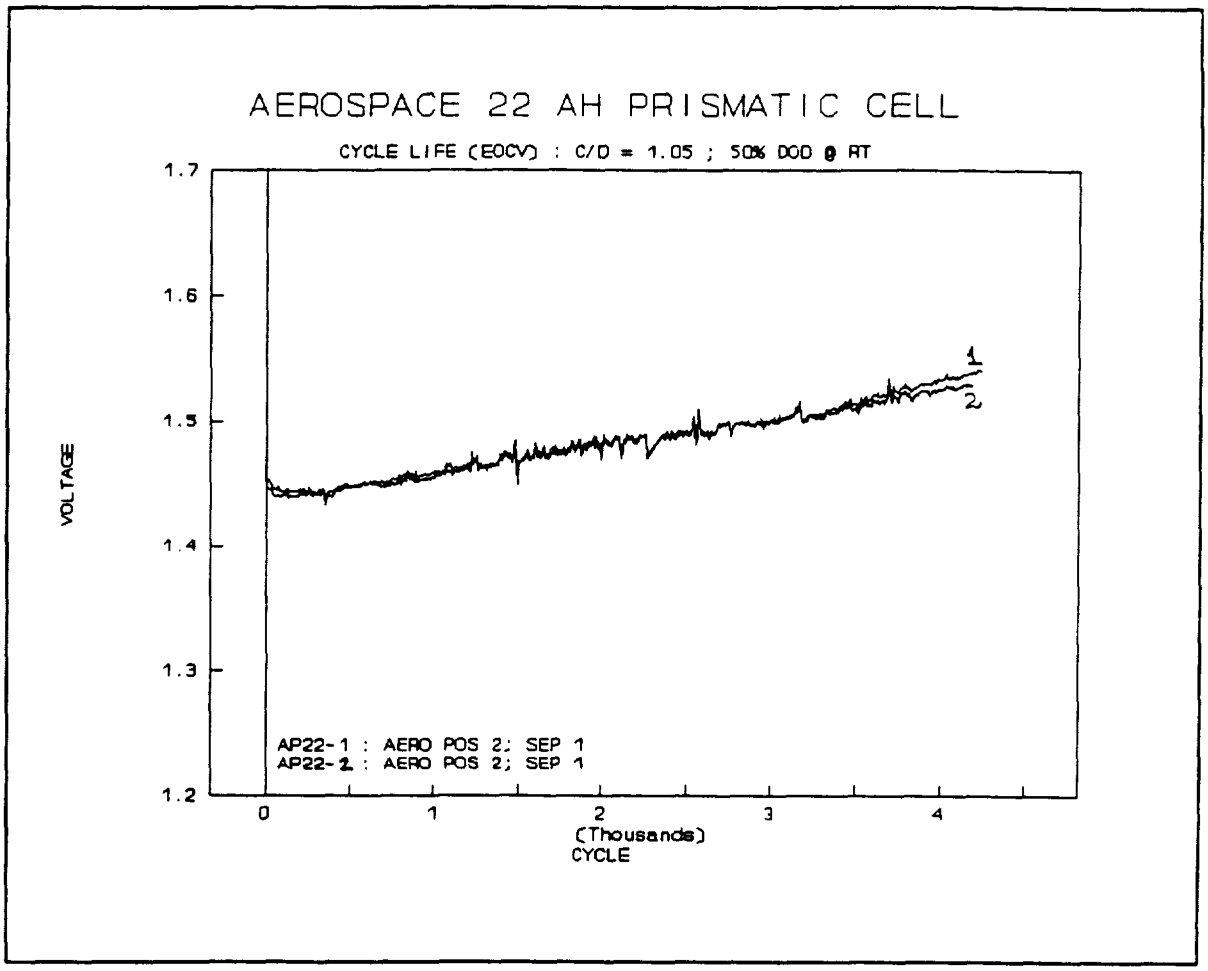


Figure 5 EOCV Performance for 22 Ah Cells

Shown here is the EOCV performance for the 22 Ah cells tested. The data shows an increasing trend over the 4,236 cycles tested. This trend is not desirable for long cycle life. Improvement of the EOCV trend was one of the primary issues addressed in subsequent cell designs that are being tested.

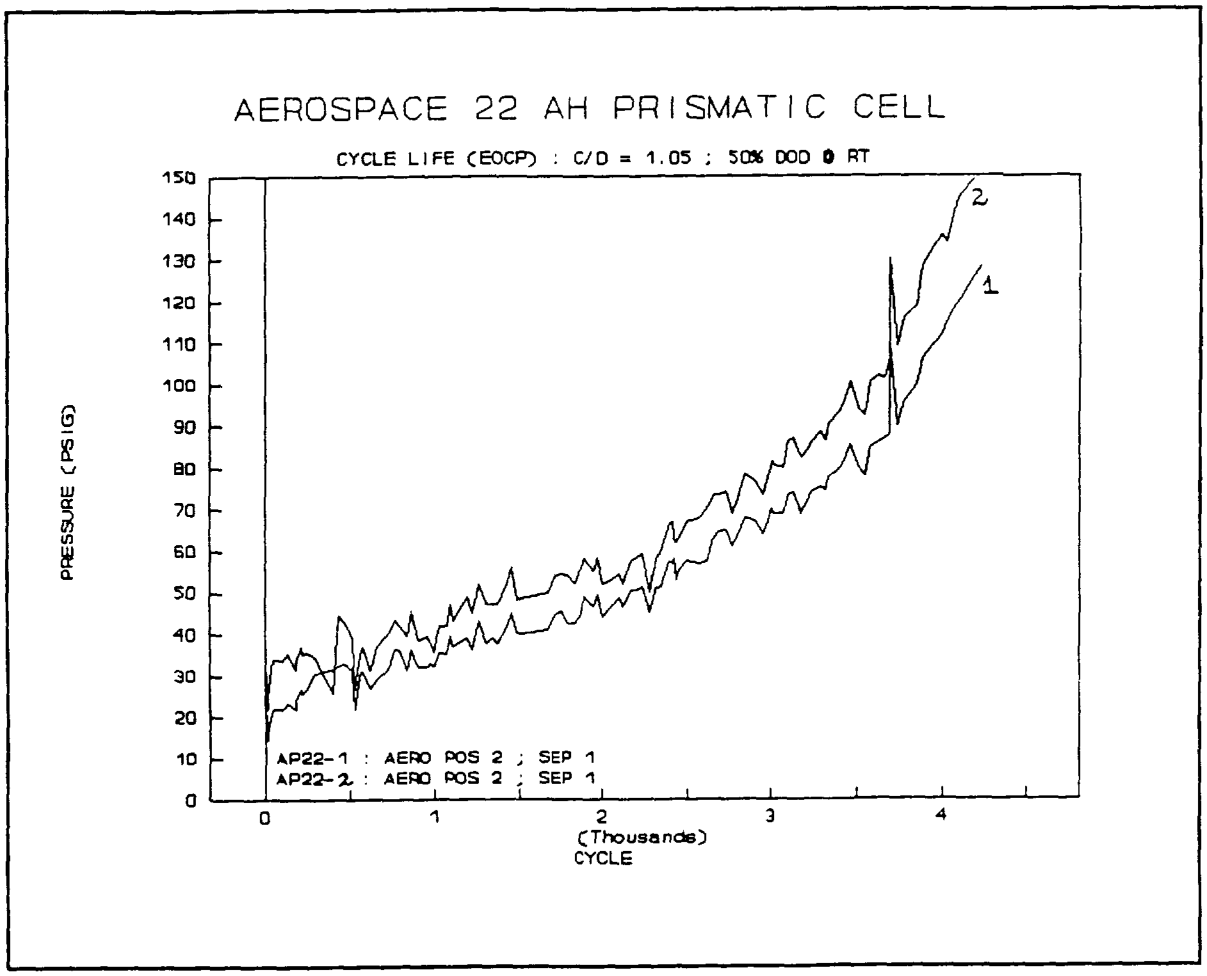


Figure 6 EOCP Performance for 22 Ah Cells

This figure illustrates the EOCP performance for the 22 Ah cells. The trend of increasing EOCP has been the limiting factor in the testing of these cells. Although there have been increases observed in the EOCV the primary reason for termination of the testing of these cells was EOCP. The changes have been attributed to the slow degradation of the alloy being tested combined with a low negative to positive ratio.

Table II

7 Ah NiMH Capacity Performance

Cell Type	Discharge Rate	Mid-Point Voltage	Capacity Ah	Alloy	Sep
AP7-5	C/2	1.201	7.47	MH-2	Sep 1
	C	1.133	6.04		
AP7-6	C/2	1.198	7.33	MH-2	Sep 2
	C	1.131	5.75		
AP7-7	C/2	1.199	7.25	MH-2	Sep 2
	C	1.132	5.62		
AP7-8	C/2	1.209	7.34	MH-2	Sep 3
	C	1.149	6.62		
AP7-9	C/2	1.202	7.31	MH-2	Sep 3
	C	1.135	5.91		

This table illustrates the capacity performance of the 7 Ah cells in initial testing. All tests were performed at room temperature. Mid-point Voltages were similar at both the C/2 and C rate with the best performance seen in the AP7-8 cell configuration.

Capacity delivery was similar also with the best C/2 performance seen in the AP7-5 cell and the best C rate capacity in the AP7-8 cell. All cells tested were from one alloy of the AB_2 type. The AP7-6,7 cells are the same configuration and the AP7-8,9 cells are of the same configuration.

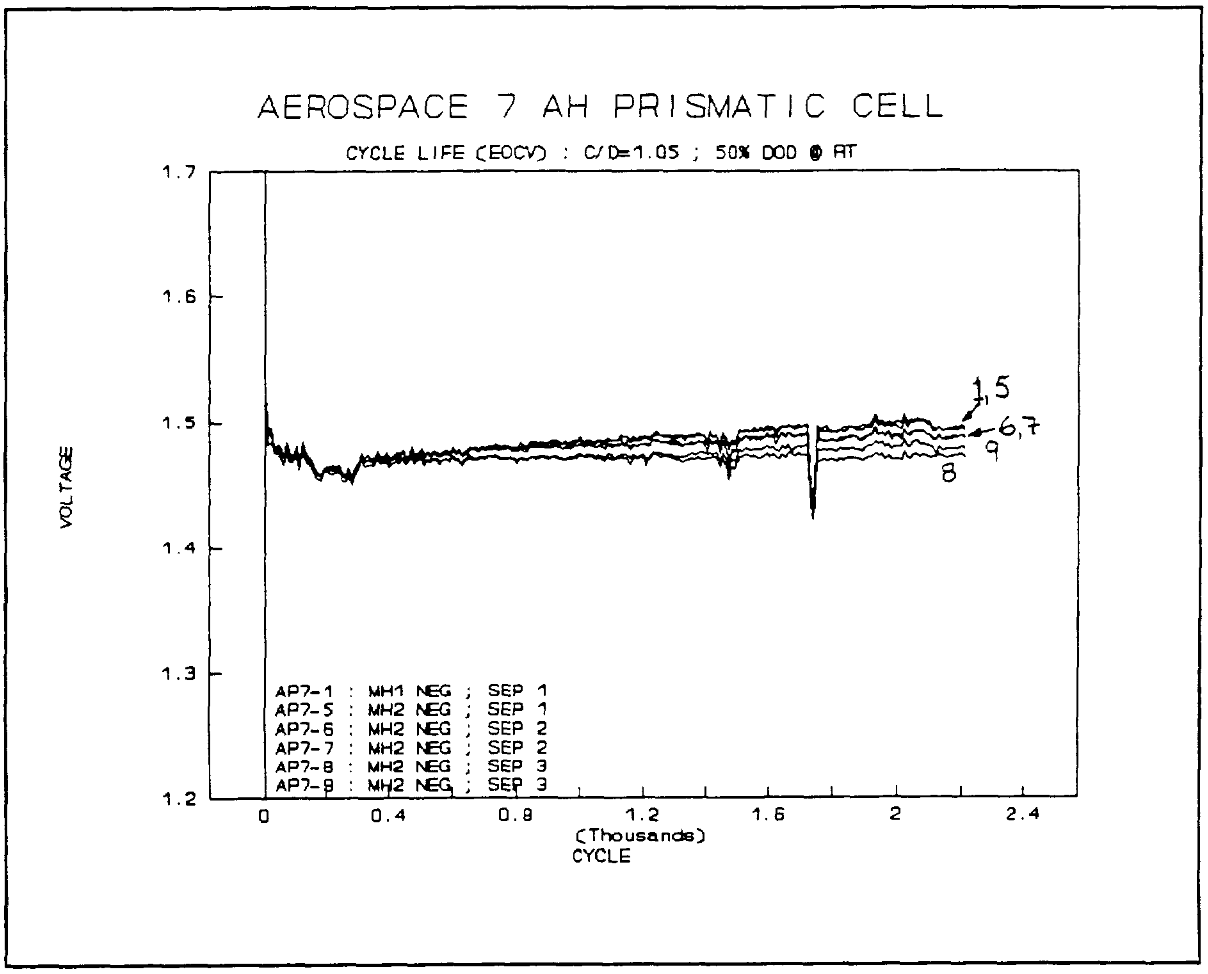


Figure 7 EOCV Performance for 7 Ah Prototype Cells

The 7 Ah cells described in Table II plus one similar cell with alloy type MH-1 were placed in LEO life cycle testing at 50% DoD at room temperature. This figure illustrates the EOCV performance of these cells with cycle life. In general the voltage has been steady with a very slight increase shown for all cells. Within similar cell configurations the EOCV is tracking well except for the AP7-8,9 configurations. These two cells have different electrolyte levels and this is believed to be the cause of the difference. The overall spread across all of the cells is about 0.030 V.

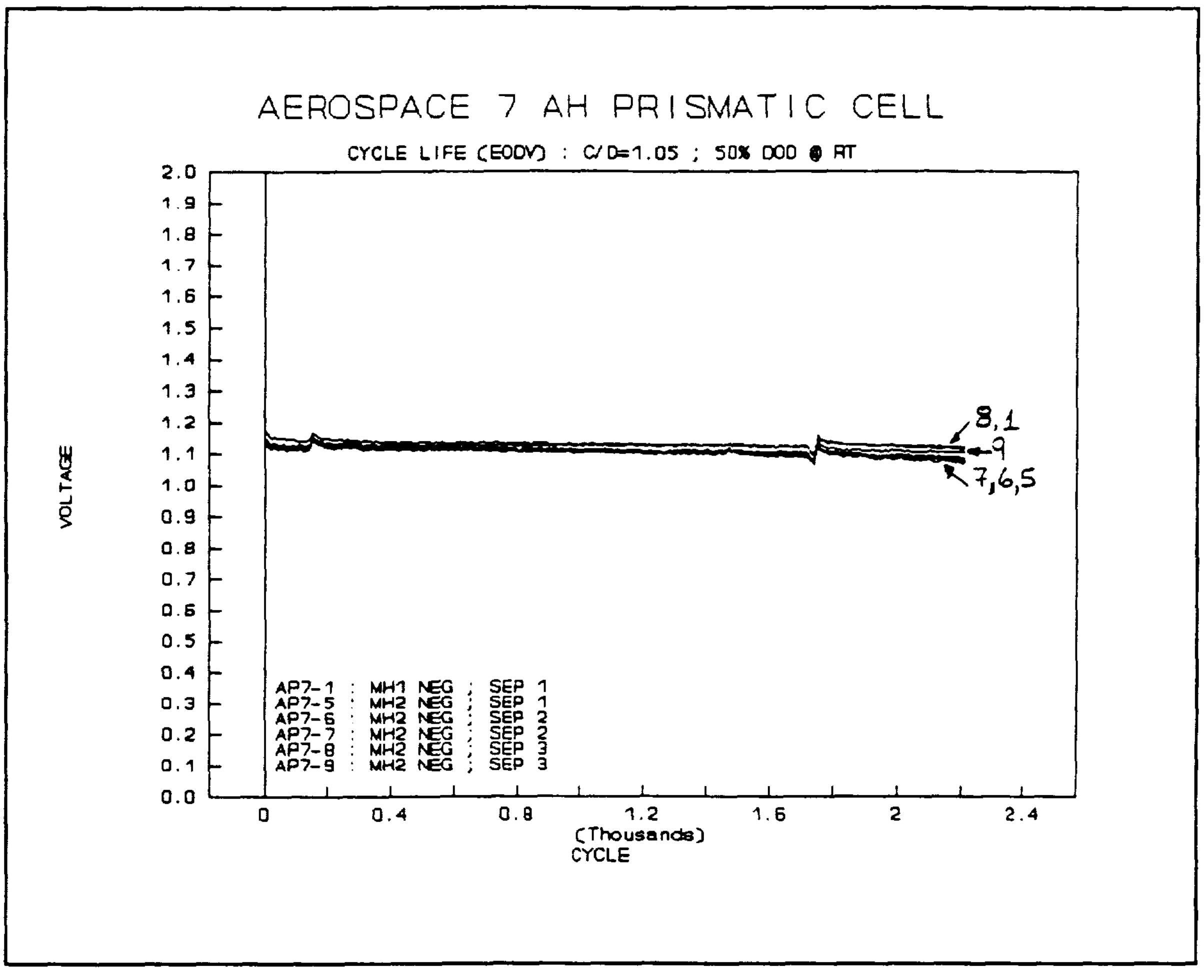


Figure 8 EODV Performance for 7 Ah Prototype Cells

This figure illustrates the EODV performance with cycle life for the 7 Ah cells. The voltage has remained steady over the cycle life to date with only a slight dispersion between cells. The C/D ratio has been maintained at 1.05 during the tests and this has maintained the EODV. The EODV is at 1.06 V for the lowest cell and 1.12 for the highest cell. The performance is similar to that seen in the 6 Ah and 22 Ah cell designs to this point in cycling.

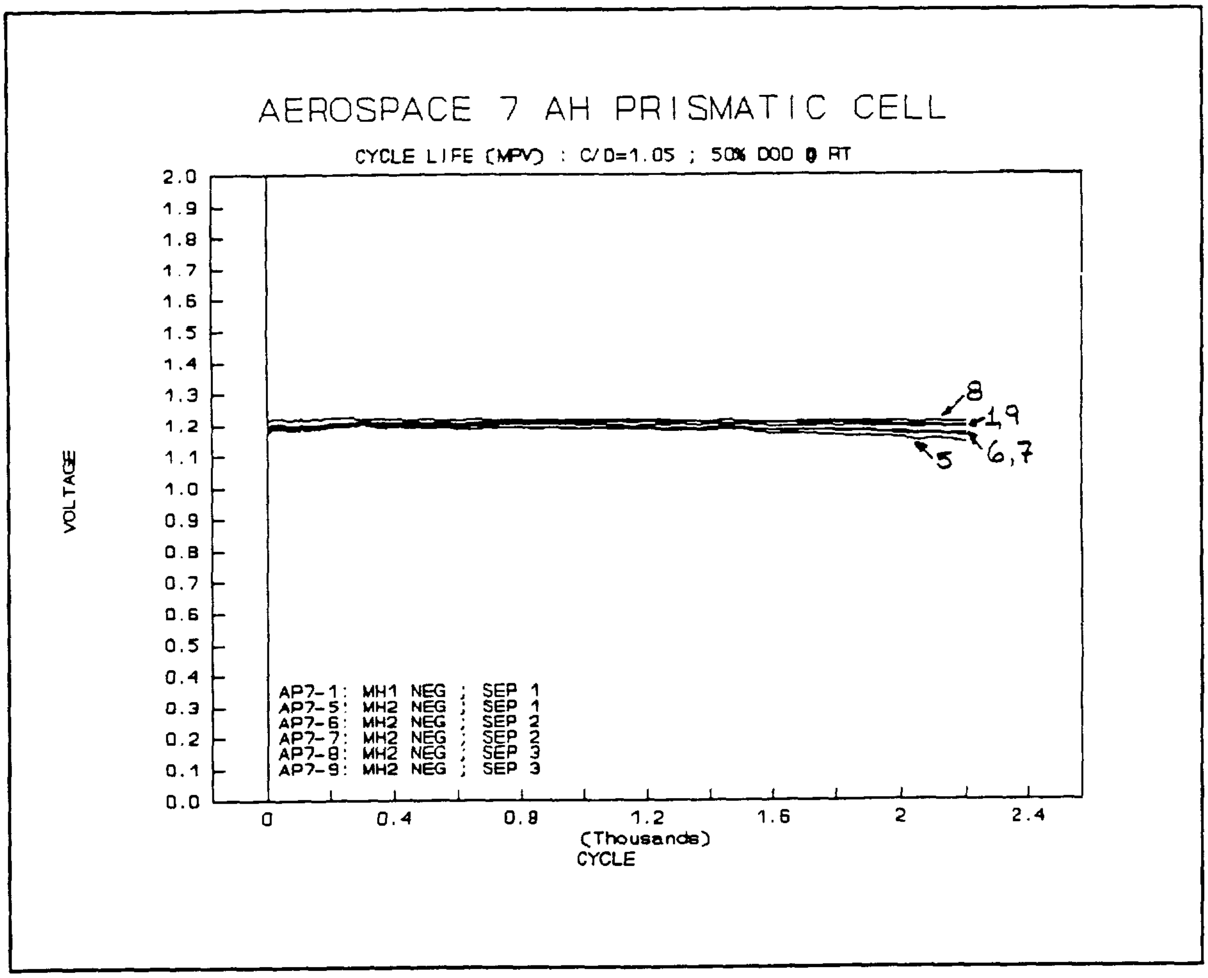


Figure 9 Mid-Point Voltage Performance for 7 Ah Prototype Cells

This figure illustrate the mid-point voltage trend over the cycles completed to date. This voltage is measured at the equivalent of 25% DoD during the discharge. The MPV is currently at 1.14 V for the worst cell and at 1.21 V for the best cell. Within each cell configuration the performance is similar.

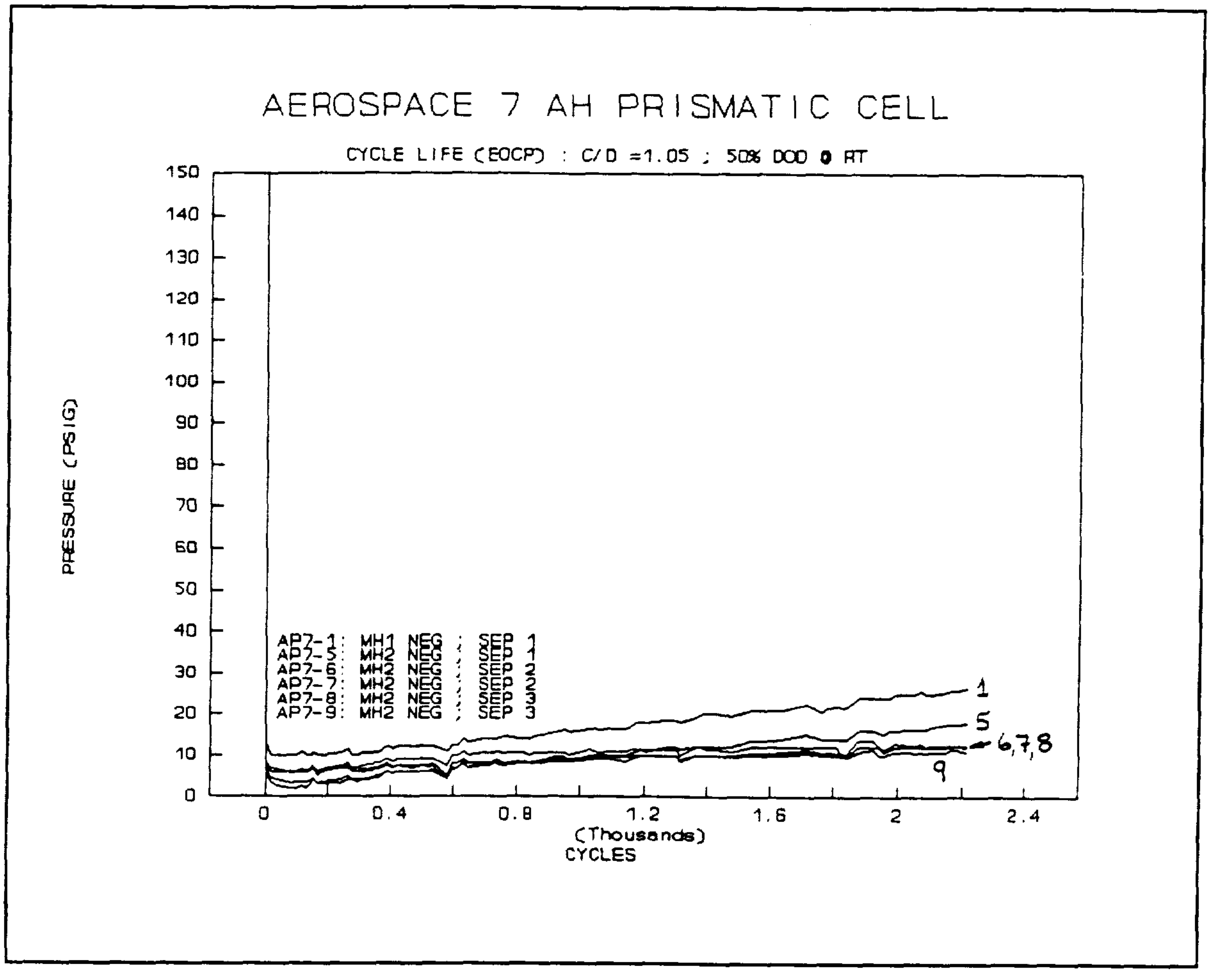


Figure 10 EOCP Performance for 7 Ah Prototype Cells

Increase in pressure with cycle life has been the primary reason for termination of testing on earlier cell configurations. This figure shows the EOCP for all of the 7 Ah cells on test. The data trend shows that the pressure is below 20 psig in all cells except for the one with alloy MH-1. Cells AP7-1 and AP7-5 are showing steady increases with life, however, the four remaining cells are maintaining level performance at less than 10 psig. The 6 Ah and 22 AH cells were showing 20 to 70 psig (Figures 3 and 6), at this point in life. The improvement is very encouraging and is a result of design adjustments made to improve the response over time.

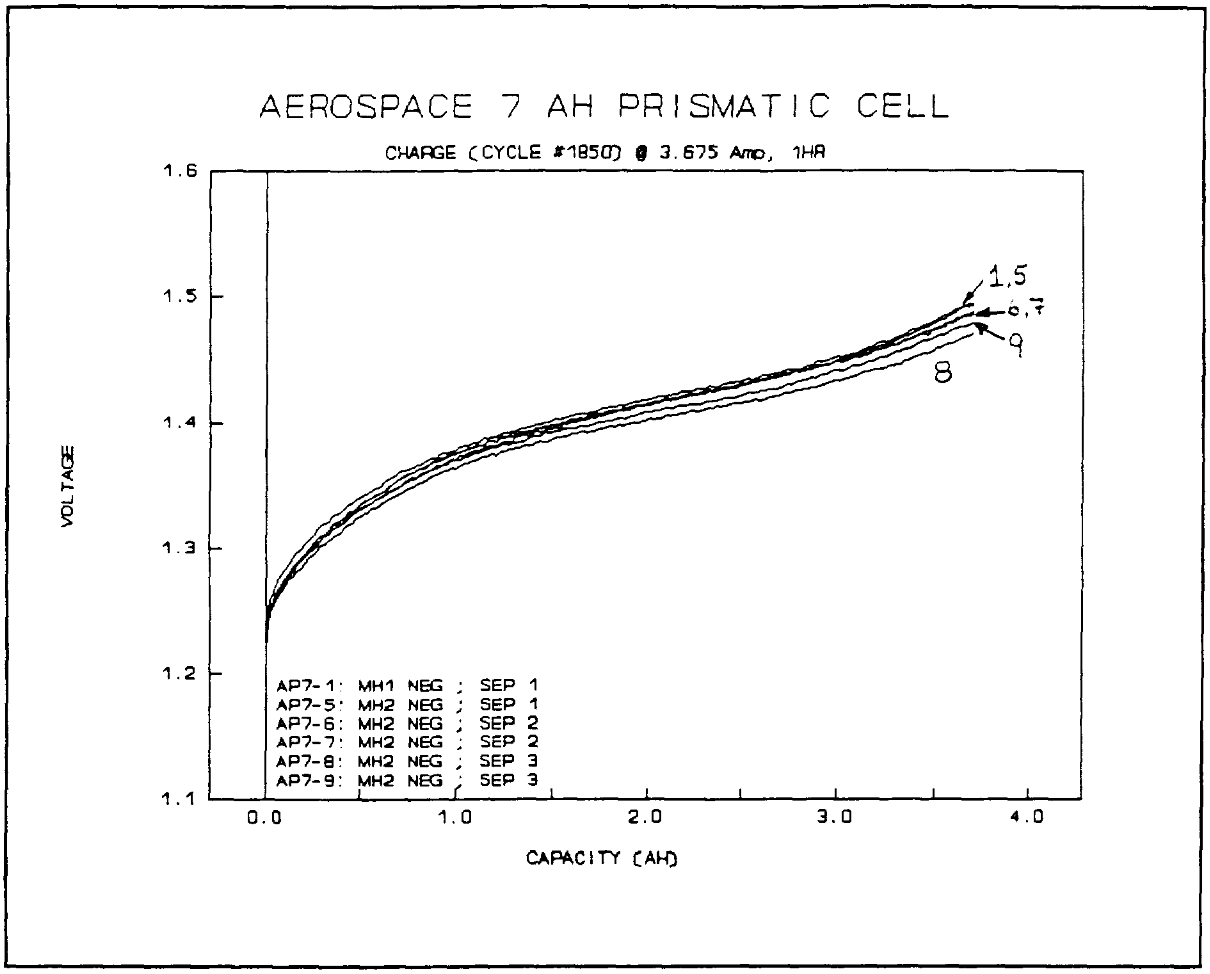


Figure 11 Charge Voltage Profile for 7 Ah Prototype Cells, Cycle 1,850

This figure shows the charge voltage profile for cycle number 1,850. The voltage ranges from 1.47 to 1.49 V at EOC. The curve is relatively smooth and increasing with time and has a slight upturn at the end of charge. This curve is similar to those seen for NiCd cells under similar test conditions and is further evidence of the ability of the NiMH system to replace NiCd cells.

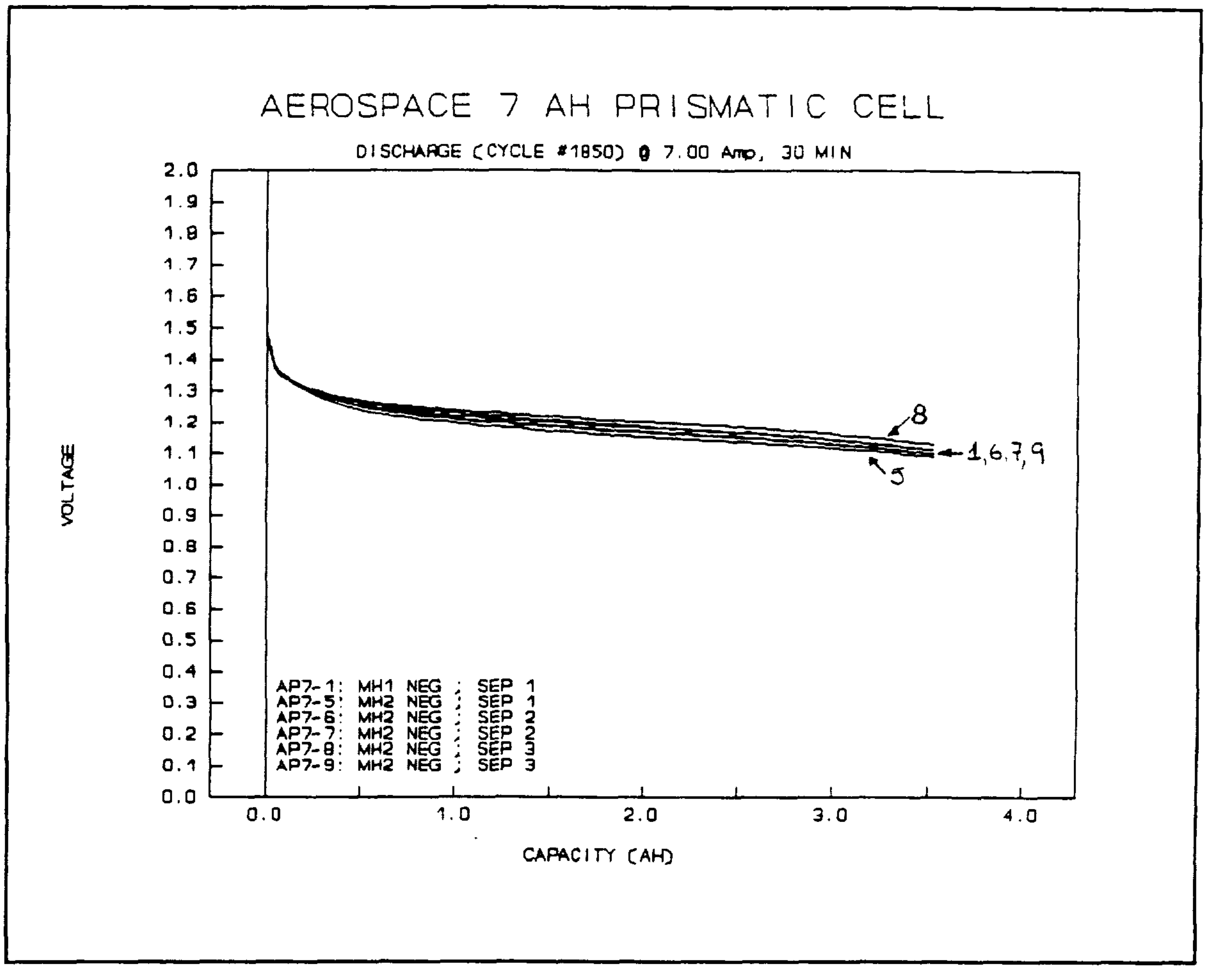


Figure 12 Discharge Voltage Profile for 7 Ah Prototype Cells, Cycle 1,850

This figure shows the corresponding discharge voltage profiles for cycle 1,850 for all cells in test. The curves are relatively flat with mid-point voltages of 1.16 to 1.21 V. The EODV ranges from 1.09 to 1.14 V. The highest discharge voltages are seen with the AP7-8 and AP7-9 cell configurations. Again, this data is very similar to that seen for NiCd cells of similar design.

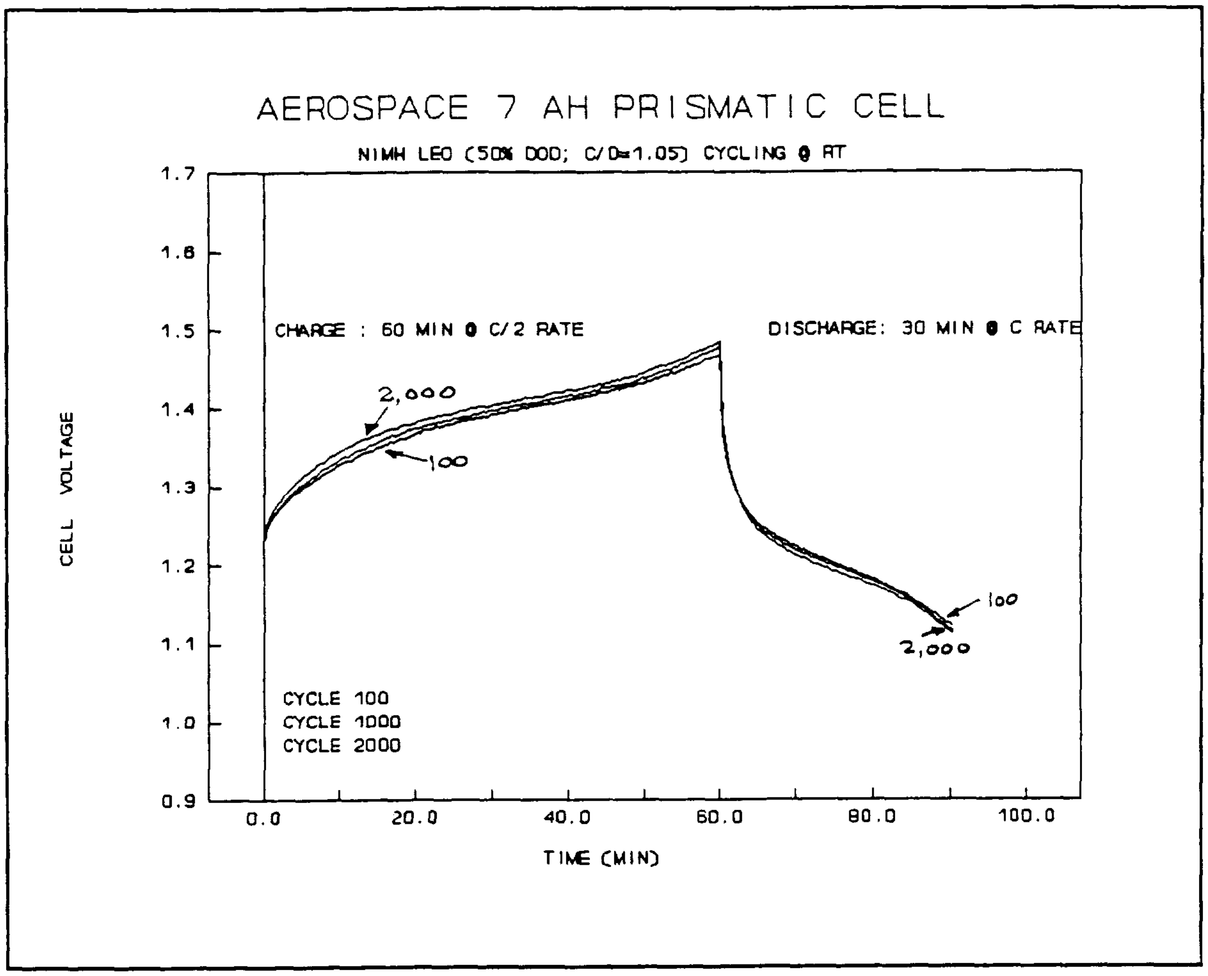


Figure 13 Charge/Discharge Voltage Profile Over Life for 7 Ah Prototype Cells

This figure illustrates the change in voltage profile for one cell during a single cycle at three points in cycle life, 100, 1,000 and 2,000 cycles. These curves are shown to illustrate the stability of the cells during cycle life testing. There is very little change observed relative to the shape of the curve or the voltages obtained. At the 2,000 cycle point there has only been a 0.020 V increase in EOCV and a 0.010 V decrease in EODV.

Aerospace NiMH Cells *Gates Aerospace Batteries*

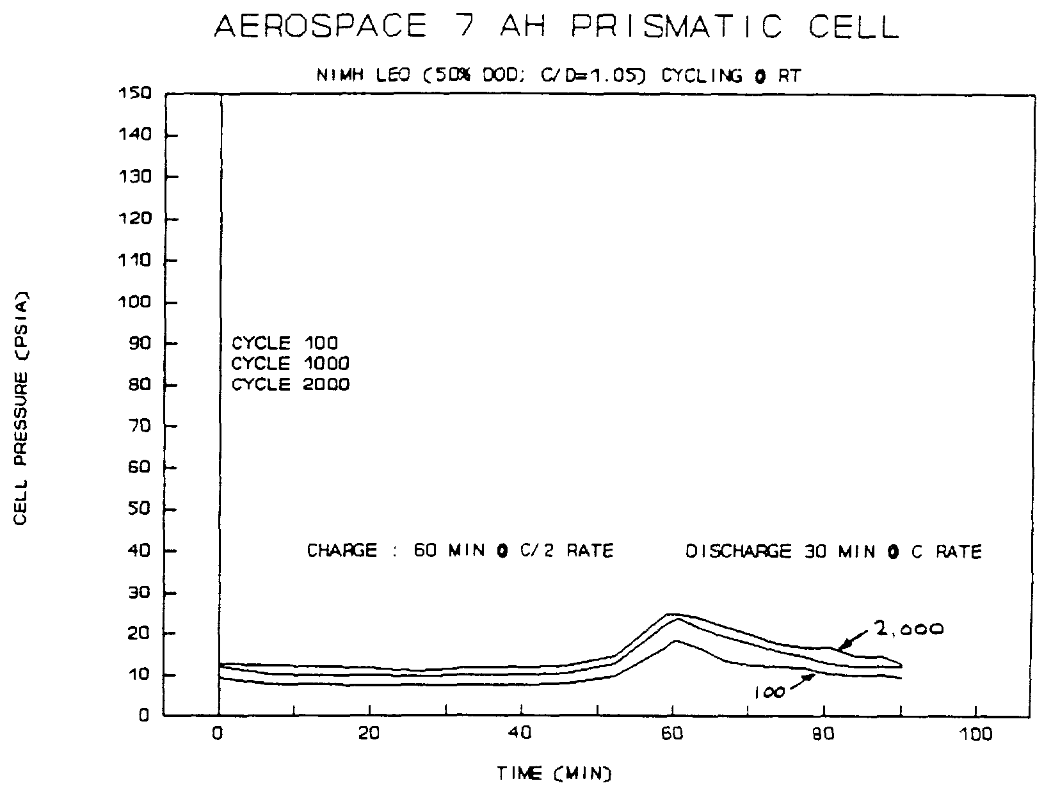


Figure 14 Pressure Response Profiles for 7 Ah Prototype Cells

This figure illustrates the pressure response profiles for one of the 7 Ah cells on test at 100, 1,000 and 2,000 cycles. The overall change in EOCP has been 7 psia over the first 2,000 cycles. As indicated earlier, increasing EOCP has been the primary failure mode observed in previous cell builds. The low pressure results seen here are a significant improvement over the earlier 6 Ah and 22 Ah cell configurations. With pressure performance this low at 2,000 cycles significantly improved cycle life is anticipated.

Summary and Conclusions

- Prototype 7 Ah NiMH cells have demonstrated >2,000 LEO 50% DoD cycles with excellent voltage and pressure performance
- 7 Ah cells size to be used for initial test configuration for qualification testing
- Designs for 24 Ah and 35 Ah cells based on scale up of 7 Ah cells in progress
- Development program continuing with goal of >10,000 LEO 50% DoD cycles by 1995
- NiMH appears to be excellent candidate for use in aerospace cells

Cycle life testing of prototype NiMH cells in 6, 7, and 22 Ah sizes has been discussed. As indicated in the results to date the 6 and 22 Ah cell designs were used as initial test vehicles to identify potential performance issues so that subsequent cell configurations could address those issues. Even though these cells were early designs, cycle lives in excess of 4,000 50% DoD LEO cycles were achieved in both designs. The improvements in design for the 7 Ah cells are reflected in the excellent performance to date.

This 7 Ah cell design will be used to begin initial qualification testing in 1993. In addition, 24 Ah and 35 Ah cell designs are in progress and will also be evaluated in qualification testing. GAB plans to continue this development effort with a goal of achieving >10,000, 50% DoD, LEO cycles in qualification hardware by mid 1995.

Based on the results achieved to date NiMH appears to be a viable alternative to NiCd and NiH_2 cell technology for aerospace applications.

Future Direction

- Continue evaluation of Alloy/Separator/Positive Combinations

  AB_2 and AB_5 Type alloys

  Other non-nylon separator materials

- Expand parametric database using 7 Ah and 24 Ah cells

  Voltage and Capacity performance vs temperature

  Charge retention and overcharge tolerance

- Begin qualification testing on 7 Ah and 24 Ah cells in mid 1993

- Expand available range of NiMH cell designs

Although results of NiMH cell testing to date are promising, qualified designs are still on the horizon. As such GAB intends to continue its development program in order to establish those qualified designs. Future work will be aimed at evaluation of various alloy combinations with different types of separators to optimize the designs.

Testing of current designs will continue in order to establish the database needed for cell qualification. This will include various parametric tests including capacity and voltage performance at various temperatures, self-discharge, and overcharge tolerance. It is GAB's intention to have cells available to begin internal qualification testing in mid-1993.

GAB will also develop an expanded range of NiMH cell designs in 1993.

N93-20521

DEVELOPMENT OF NICKEL-METAL HYDRIDE CELL

Saburo Kuwajima, Nolimits Kamimori
National Space Development Agency of Japan
Tsukuba Space Center
Tsukuba, Ibaraki, 305 Japan

Kensuke Nakatani, Yoshiaki Yano
Sanyo Electric Co., Ltd.
Satellite Battery Section
Sumoto, Hyogo, 656 Japan

ABSTRACT

National Space Development Agency of Japan(NASDA) has conducted the research and developments(R&D) of battery cells for space use. We have started a new R&D program about a Nickel-Metal Hydride(Ni-MH) cell for space use from this year, based on good results in evaluations of commercial Ni-MH cells in Tsukuba Space Center(TKSC). This paper describes the results of those commercial Ni-MH cell's evaluations and recent status about the development of Ni-MH cells for space use.

INTRODUCTION

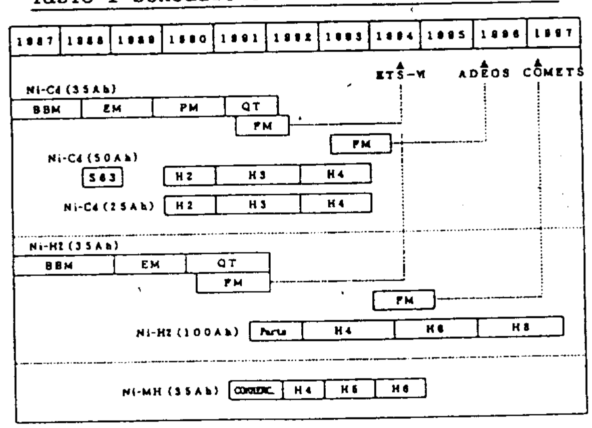
NASDA/TKSC has conducted R&Ds of Nickel-Cadmium(Ni-Cd) and Nickel-Hydrogen(Ni-H2) cells for space use. The recent schedule of the R&Ds is shown in Table-1.

The development of the 35 Ah Ni-Cd cell has finished, and these Ni-Cd cells will be used for Engineering Test Satellite-VI(ETS-VI) to be launched in 1994, and Advanced Earth Observation Satellite(ADEOS) to be launched in 1996. Now we are expanding this technology of the space Ni-Cd cell to wide capacity range of approximately 20 to 50 Ah. Life tests of 25 and 50 Ah cells have been performed, and so far getting good results.

The development of the 35 Ah Ni-H2 cell has also finished already, and these Ni-H2 cells will be tested on ETS-VI flight experiment, and will be used for Communication Engineering Test Satellite(COMETS) to be launched in 1997. The technology of space Ni-H2 cell will be expanded up to 100 Ah, to improve energy density and to reduce cost.

And we have started new programs about new type battery systems. These battery systems are a Ni-MH cell and a secondary Lithium cell, etc., which recently come to be popular for commercial use. Before starting these new programs, we have performed preliminary tests to examine electrically whether these cells can be used

Table-1 Schedule of Batteries Development



Prepared for the 1992 NASA Aerospace Battery Workshop held in Huntsville, AL, USA, 17-19 November, 1992. (Report No.; NASDA-TK-E92043) for space or not. Unlike the space cells, commercial cells generally have some different properties such as small capacity, cylindrical shape, and crimp sealing with a nylon gasket. But we think it enough to evaluate only a feasibility for space use.

On the Ni-MH cells, we have tested commercial cells from 1991 as the TKSC's in-house R&D. And we have started a development program under contract with SANYO Electric Company(Sanyo) from this year, getting good results from the in-house R&D.

Also on the secondary Lithium cell, we are going to adopt the same procedure, so now preparing the evaluation of some commercial lithium cells in order to start evalution tests in the next year.

EVALUATION OF COMMERCIAL Ni-MH CELLS

Sample Cell Description

The test samples are 4/3A-size commercial Ni-MH cells, which were shaped cylindrical with 17mm in diameter, and 67mm in height. The rated capacity was 2.2 Ah when these samples were offered from Sanyo last year. Each 5 cells are alloted for GEO and LEO life tests respectively.

For reference, C-size rated 1.8 Ah commercial Ni-Cd cells were tested in the same test packs and the same number of samples in order to compare the Ni-MH cell with the Ni-Cd cell.

Test Conditions

The purpose of these tests was to evaluate the capability of a Ni-MH cell for space use. So we adopted our usual GEO and LEO test conditions that were the same as the space Ni-Cd cell's life tests.

The conditions of GEO test are 0.1C charge for 9 hours and 0.5C discharge for 1.2 hour, so depth of discharge(DOD) is 60% and charge return ratio is 150%. The rated capacity "C" used to define charge and discharge current in these tests is selected 2.2 Ah. A reconditioning discharge and a capacity check are performed in every 45 cycles. The condition of the reconditioning discharge is 1/80C constant current discharge after cycling charge. And conditions of a capacity check are 0.1C charge for 16 hours and then 0.5C discharge to 1.0 V for each cells, after reconditioning discharge.

The conditions of LEO test are 0.3C charge for 52.5 minutes and 0.5C discharge for 30 minutes, so DOD is 25% and charge return ratio is 105%. Capacity checks are performed in 1,000 cycles and then in approximately every 5,000 cycles. The capacity check in a LEO test consist of two kinds of capacities. One of two types is a residual capacity that is obtained by immediate discharge with 0.5Crate after charge of cycling test. Another type of capacity is full-charged capacity that is obtained by 0.5C discharge to 1.0 V after every cells are full-charged with 0.1C rate for 16 hours. These conditions are summarized in Table-2.

Table-2 Test Conditions of Commercial cells

TEST TYPE / CONDITION	GEO	LEO
Charge	0.1C, 9 hours	0.3C, 52.5 min
Discharge	0.5C, 1.2hours	0.5C, 30 min
DOD	60 %	25 %
Charge Return	150 %	105 %
Temperature	20℃ (COOLING PLATE TEMP.)	
Capacity Check	RECONDITIONING CAPACITY	RESIDUAL CAPACITY
	FULL-CHARGED CAPACITY	FULL-CHARGED CAPACITY
	EVERY 45 CYCLES	ABOUT EVERY 5,000 CYCLES

(C=2.2Ah)

Photo-1 Test Set-up on Cooling Plate

Both cells under GEO and LEO tests are mounted together on a cooling plate whose temperature is maintained about 20 degree C. The set-up of GEO and LEO tests is shown in Photo-1.

GEO Test Result

GEO test started on May-1991, and is over 900 cycles so far with no failures to continue cycling. Charge and discharge characteristics about cell voltages and temperature at 134 cycles are shown in Fig-1 and Fig-2. End of charge voltage(EOCV) and end of discharge voltage(EODV) versus number of cycles about all Ni-MH and Ni-Cd cells are shown in Fig-3. And reconditioning capacities and full-charged capacities in every 45 cycles are shown in Fig-4 and Fig-5.

Cell Voltage; The overcharge voltage of the Ni-MH cell is higher than that of the Ni-Cd cell. The discharge voltage of the Ni-MH cell is also higher than that of the Ni-Cd cell. And EOCV and EODV of the Ni-MH cells are higher than those of Ni-Cd cells. Moreover all voltages of the Ni-MH cells shows a good uniformity during charge and discharge periods. One of the Ni-Cd cells shows gradually degradation of EODV. The reason of degradation is suspected that the No.4 Ni-Cd cell's internal impedance at 1kHz increases larger than the other cells as shown in Table-3.

Cell Temperature; In charge period the temperature behavior of the Ni-MH cell is almost same as the Ni-Cd cell. And in discharge period the temperature of the Ni-MH cell becomes as same as the cooling plate. The temperature of the Ni-Cd cell is balanced above the temperature of the cooling plate due to heat generation during discharge period.

Cell Capacity; It is thought to be reasonable that reconditioning capacities of Ni-Cd cells are less than full-charged capacities, because 0.5C discharge rate of full-charged capacity check is larger than 1/80C rate of reconditioning discharge. But in the case of Ni-MH cell, both capacities are observed identically. The reason is suspected that a rate of self-discharge in the Ni-MH cell is larger than that of the Ni-Cd cell.

Table-3 Change of Cell Internal Impedance

Number of Cycles	Ni-MH Average (5cells)	Ni-Cd No.4	Ni-Cd Average (others)
Initial	1.6 mΩ	2.2 mΩ	2.1 mΩ
225	1.6 mΩ	8.4 mΩ	2.0 mΩ
540	6.0 mΩ	24.5 mΩ	2.2 mΩ
675	10.1 mΩ	41.7 mΩ	7.8 mΩ
900	9.4 mΩ	97.0 mΩ	2.9 mΩ

LEO Test Result

LEO test started on May-1991, and is over 8,000 cycles so far with no failures as well as GEO test. Charge and discharge characteristics about cell voltages and temperature at 7,975 cycles are shown in Fig-6 and Fig-7. EOCV and EODV versus number of cycles about 5 Ni-MH and 5 Ni-Cd cells are shown in Fig-8. Results of capacity checks are shown in Fig-9.

Cell Voltage; During charge period, the voltage of the Ni-MH cell is almost same as the Ni-Cd cells. And the discharge voltage of the Ni-MH cell is higher than the Ni-Cd cell. So it shows no difference of EOCV between the Ni-MH and Ni-Cd cells, but EODV of the Ni-MH cells are higher than the Ni-Cd cells. Moreover voltages of both cells show good uniformities respectively.

Cell Temperature; In charge period the temperature of the Ni-MH cell is balanced above the temperature of the cooling plate, though the temperature of the Ni-Cd cell is gradually decreasing below temperature of the cooling plate. And in discharge period it is observed the temperature of the Ni-MH cell is decreasing, but the temperature of the Ni-Cd cell is reversely increasing. These thermal properties of the Ni-MH cell implies heat generation during charge and heat absorption during discharge which is contrary to the property of the Ni-Cd cell. These thermal property is thought to be caused by reaction of hydrogen absorbing metal, but a quantitative discussion on the thermal property can not be derived from these data.

Cell Capacity; According to the capacity trend of Fig-9, all Ni-MH cells show a very good performance though all Ni-Cd cell shows a gradual degradation. The reason of Ni-Cd cell's degradation is thought that cadmium electrodes are easy to degrade by agglomeration of active materials.

Summary of Commercial Ni-MH Tests

It is recognized that the Ni-MH cell has a good performance about charge/discharge cycling, especially about capacity remainning. So the Ni-MH cell is electrically thought to has capability for space use. On overcharge characteristics for GEO application, a test of continuous charge for commercial Ni-MH cells has been initiated recently.

DEVELOPMENT OF Ni-MH CELLS FOR SPACE USE

Cell Design

At the first phase of development, the Ni-MH cell with rectangular shape and large capacity has been designed in order to evaluate its characteristics and to examine an issues related to large-scale cell. As a cell case and terminal for the trial Ni-MH cell, those of the 25 Ah Ni-Cd cell of H2 phase on Table-1 are utilized in order to compare the Ni-MH cell with the Ni-Cd cell. So dimensions of the Ni-MH cell for space use are 95.0 mm in case height, 106.9mm in width, and 25.2 mm in thickness.

A positive electrode is manufactured using a nickel sinter plate and a chemical impregnation method, and has the same electrode parameters as the Ni-Cd cell's that are 85% of porosity and 2.4 g/cc-void of loading level, except thickness that has been modified to 0.60mm from 0.63mm of the Ni-Cd cell. Dimensions of an electrode are 80.0mm in height, and 104.4mm in width, and 16 positive electrodes are used in a cell.

A Negative electrode is manufactured using a Mischmetal Nickel5(MmNi5) based alloy as the Hydrogen Absorbing Metal and a stripped metal sheet. 17 negative electrodes are used in a cell.

A separator is selected a nylon as same as the Space Ni-Cd cells. And thickness of separator is 0.21mm in a cell.

The trial Ni-MH cell has 35.5 Ah of designed cell capacity, compared with 27.5 Ah of the Ni-Cd cell when the cell case with same dimensions is used. Another saying, the designed energy density of 50.7 Wh/kg is larger than the space 35Ah Ni-Cd cell's 44.1 Wh/kg. The cell design for space use is summarized in Table-4.

Table-4 Design of Ni-MH Cell for Space

Ni-MH CELL DESIGN	(+)	(-)
Active Material	$Ni(OH)_2$	$MmNi_5$
Plate Area	80.0×104.4 mm	
Plate Thickness	0.60 mm	0.43 mm
Sinter Porosity	85 %	—
Loading Level	2.4g/cc-void	—
Number of Plates	16	17
Electrodes Capacity (actual)	38.6 Ah	75.2 Ah
Separator	Nylon	
Electrolyte	31%KOH	
Cell Dimension (case)	95.0H×106.9W×25.2T mm	
Cell Weight	840 g	
Cell Capacity	35.5 Ah	
Energy Density (Actual)	50.7 Wh/kg	

REFERENCE (35Ah Space Ni-Cd Cell)	
Cell Dimension (case)	115.2H×106.9W×25.2T mm
Cell Weight	max. 1050 g
Cell Capacity	38.6 Ah
Energy Density (Actual)	44.1 Wh/kg

Test Description

Testing consists of two steps; the first step is to evaluate an electrical characteristics of electrodes stack using dummy cells; the second step is full-evaluation using flight type cells.

The dummy cell is composed of two endplates of stainless steel, a cell-wall of poly-acryl, and electrodes stack, and then fasten these elements with bolts & nuts, so it can be assembled easily. The external view of a dummy cell are shown in Photo-2. But this dummy cell cannot be used for life test because a sealing between 2 end-plates and a cell-wall is not enough for long time. Pressure value of a dummy cell is not equal to a flight type cell because of a

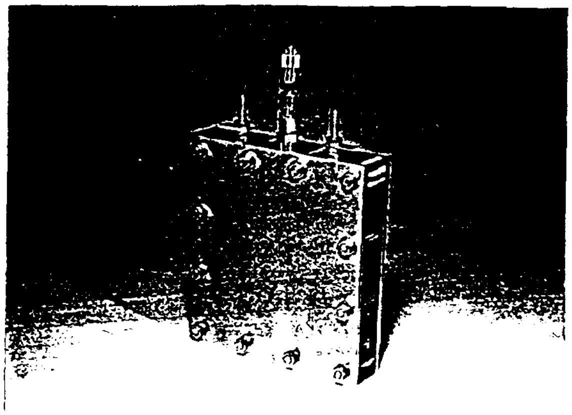


Photo-2 External View of Ni-MH Dummy Cell

difference of free spaces. Moreover electrical resistance of terminal is larger than flight type cell's one, so we must revise the cell voltage in order to compare with flight type cell. So tests of dummy cells are purposed to get only initial characteristics of the charge/discharge voltage and capacity versus temperature. The charge conditions of these tests are 0.1C rate for 24 hours at the cell temperature of 20 and 35 degree C, and 0.05C rate for 48 hours at -5 degree C. And the discharge condition is 0.5C rate to 1.0 V at every temperatures. The rated capacity "C" in this test is tentatively selected 35 Ah. Cell temperature is controlled by computer using a temperature chamber.

The flight type cells will be assembled after reviewing dummy cell's data. The flight type cell are planned to get correct pressure values, and then get to long term performance. After initial performance tests, the flight type cells will be subjected to life tests in TKSC.

Test Results of Ni-MH Dummy Cell and Comparison with Space Ni-Cd Cell

Charge and discharge characteristics at -5, 20, and 35 degree C of dummy cells are shown in Fig-10 and Fig-11. These dummy cell's voltages are revised to cancel for increase of terminal resistance compared with flight type cell's terminal. For reference, those of the 35 Ah space Ni-Cd cell are shown in Fig-12 and Fig-13.

Charge Voltage and Pressure; Charge voltage of the Ni-MH dummy cell becomes higher at lower temperature. And charge pressures at 20 and -5 degree C start to increase when overcharging starts. Charge pressure at 35 degree C is gradually increasing. The trend of these characteristics in charge period is almost same as the space Ni-Cd cell shown in Fig-12. Charge characteristics is thought to be mainly dominated by Nickel electrodes.

Discharge Voltage and capacity; Discharge voltages and capacities at 20 and 35 degree C are almost identical, and it can confirm that the measured capacity almost meets the designed capacity 35.5 Ah. But the discharge voltage and capacity at -5 degree C are about 50 mV and 20% lower than those at the other temperatures. And these characteristics versus temperature are different from the space Ni-Cd cell's discharge data shown in Fig-13. The reason is suspected that activity or capacity of the hydride metal decreases at lower temperature.

CONCLUSION

The results of evaluations and comparison of commercial Ni-MH and Ni-Cd cells show that Ni-MH cell system has a capability for space use. As a result of Ni-MH cell design for space use, the Ni-MH cell has advantages of small size and light weight compared with the space Ni-Cd cell, so the Ni-MH cell is thought to be promising battery cell.

We will confirm the cell characteristics at various temperatures, especially at lower temperatures, cycling life and failure modes, and mechanical strength using flight type cells. As the first technology demonstration, we are now proposing Ni-MH cells to be applied to a small satellite for NASDA mission.

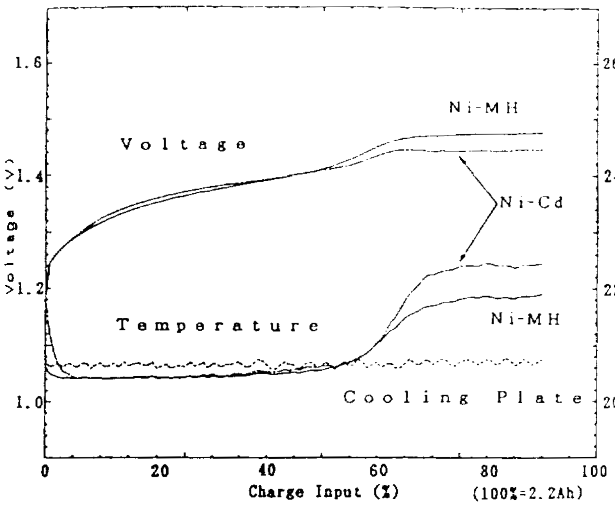


Fig-1 Charge Characteristics of Commercial Ni-MH & Ni-Cd Cells in GEO Test

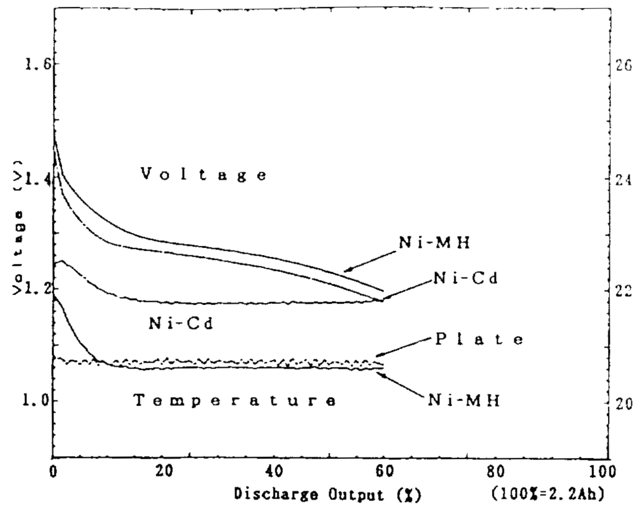


Fig-2 Discharge Characteristics of Commercial Ni-MH & Ni-Cd Cells in GEO Test

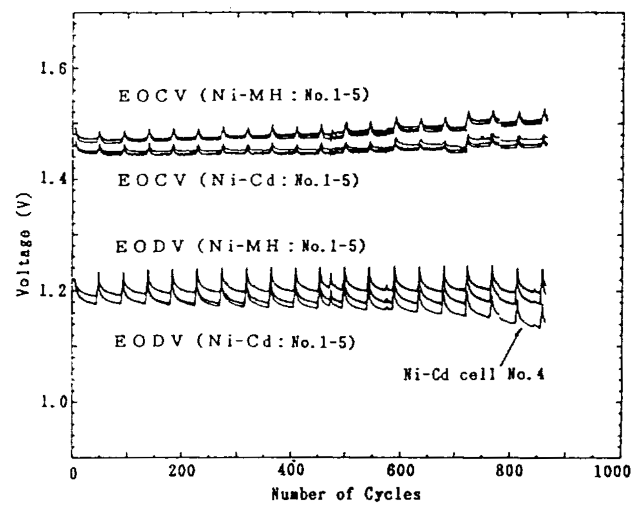


Fig-3 EOCV & EODV Trend of Commercial Ni-MH & Ni-Cd Cells in GEO Test

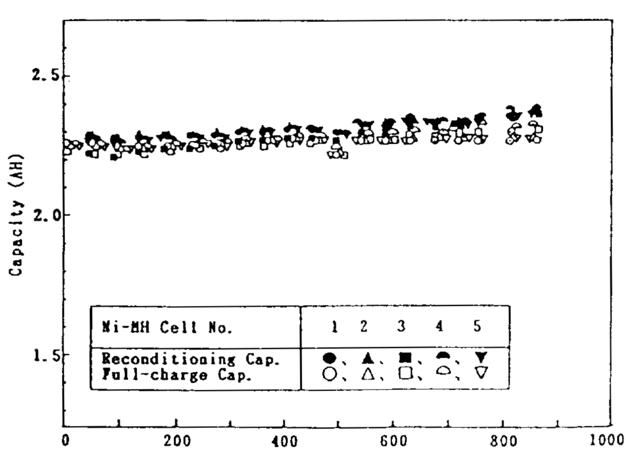


Fig-4 Capacity Trend of Commercial Ni-MH & Ni-Cd Cells in GEO Test

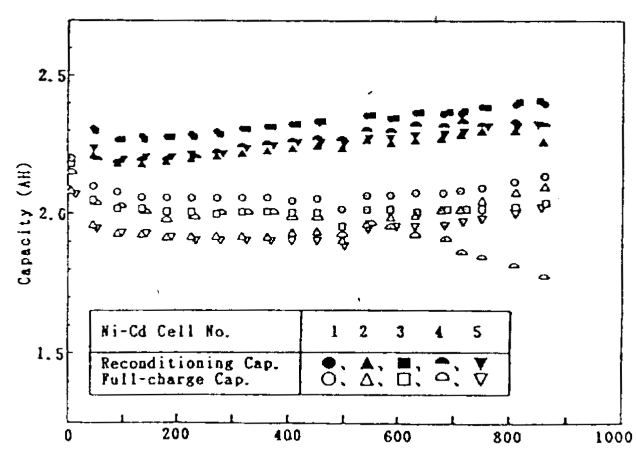


Fig-5 Capacity Trend of Commercial Ni-MH & Ni-Cd Cells in GEO Test

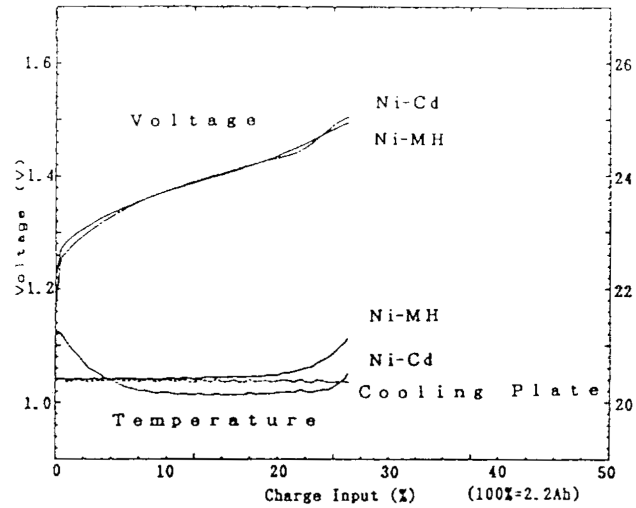


Fig-6 Charge Characteristics of Commercial Ni-MH & Ni-Cd Cells in LEO Test

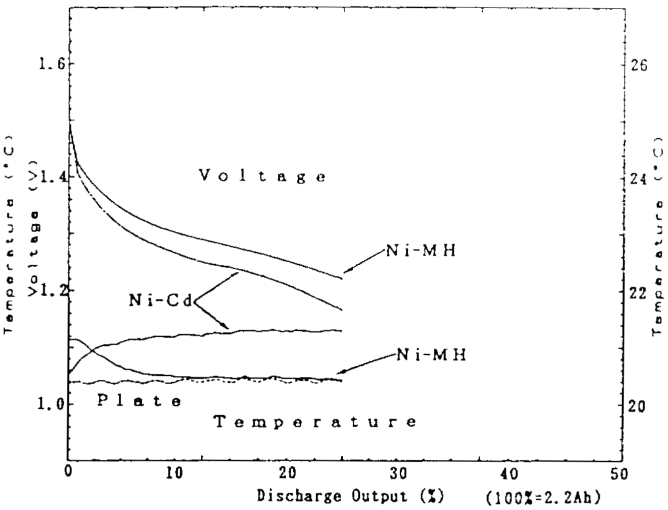


Fig-7 Discharge Characteristics of Commercial Ni-MH & Ni-Cd Cells in LEO Test

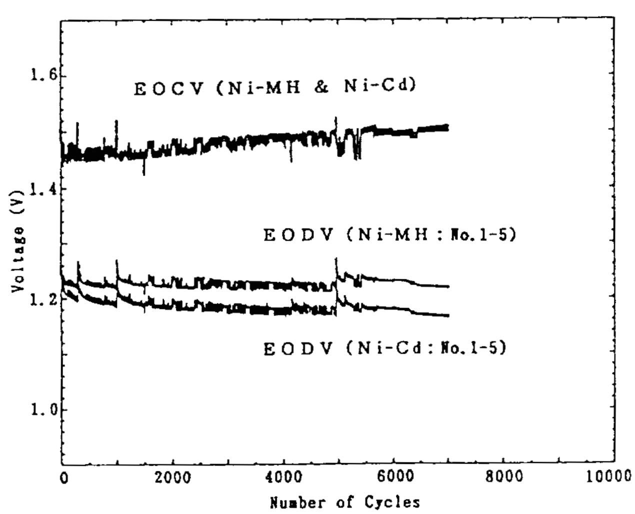


Fig-8 EOCV & EODV Trend of Commercial Ni-MH & Ni-Cd Cells in LEO Test

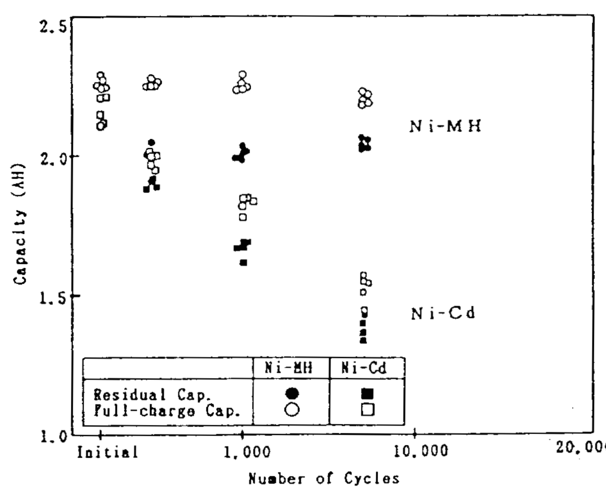


Fig-9 Capacity Trend of Commercial Ni-MH & Ni-Cd Cells in LEO Test

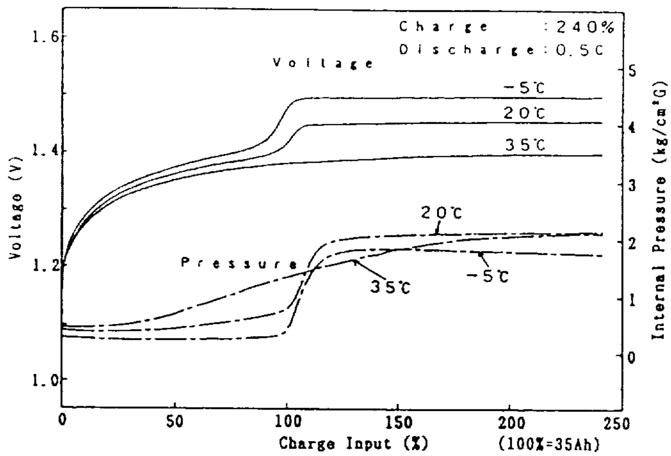


Fig-10 Charge Characteristics of Ni-MH Dummy Cell

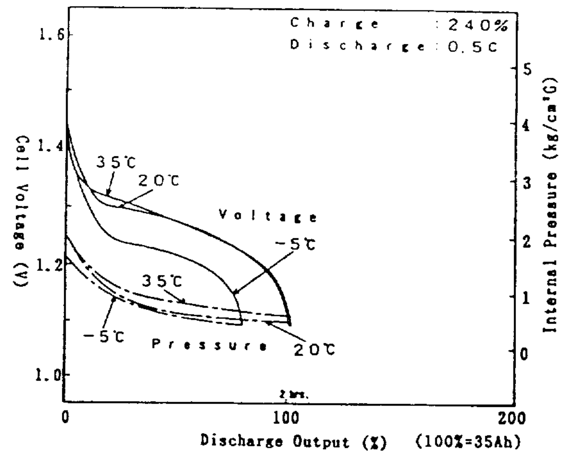


Fig-11 Discharge Characteristics of Ni-MH Dummy Cell

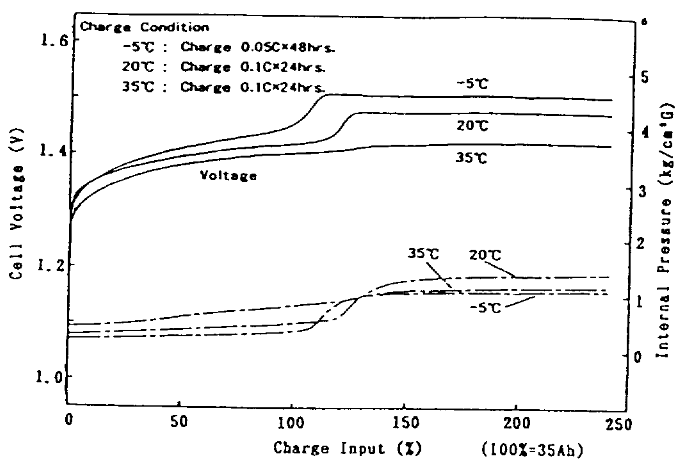


Fig-12 Charge Characteristics of the 35Ah Space Ni-Cd Cell

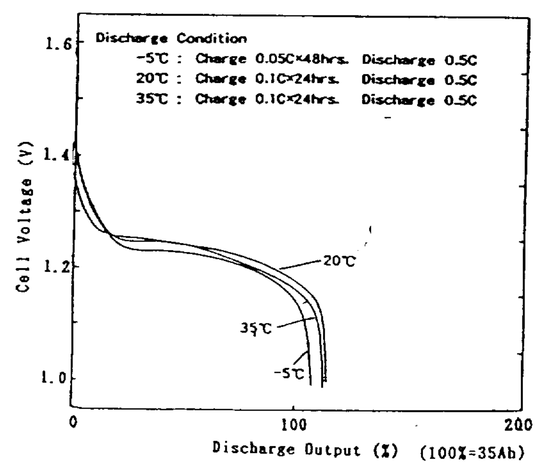


Fig-13 Discharge Characteristics of the 35Ah Space Ni-Cd Cell

N93-20522

Nickel Metal Hydride, A Flight Experiment

Presented at the NASA Aerospace Battery Workshop, Huntsville, Al., Nov.19,1992

Edward A. Fitzgerald

Senior Systems Engineer
Teledyne-Brown Engineering
Cummings Research Park
300 Sparkman Drive, NW
P.O. Box 070007 ; MS#70
Huntsville, Alabama 35807-7007

Dr. Francis C. Wessling

Professor of Mechanical Engineering
University of Alabama in Huntsville
Consortium for Materials Development in Space
Huntsville, Alabama 35899

Abstract

A Nickel Metal Hydride battery was discharged at high rate in a microgravity environment. Data from the flight is compared to data taken on the earth's surface.

Introduction

The sounding rocket program at the Consortium for Materials Development in Space (CMDS) at the University of Alabama in Huntsville (UAH) needed to improve the power system used to support experiments. Also SEDSAT, a small satellite program at UAH needed new battery technology. Currently, commercial Nickel Cadmium (NiCd) "F" cells are used to power the Consort and Joust series of sounding rockets. The goal of this work is to reduce the weight and volume of the battery packs and, thereby, allow more payload (experiments).

Trade studies quickly limited the choices of new batteries due to the budget constraints of these programs. The new batteries had to be functionally equivalent to NiCd in cost and performance. Nickel Metal Hydride (NiMH) promised a weight reduction of 20% and a volume reduction of 30% over commercial NiCd. NiMH has a specific energy of 50 watt-hrs per kilogram compared to 25 for aerospace NiCd and 40 for commercial NiCd. NiMH has an energy density of 2.4 watt-hrs per cubic inch compared to 1.2 - 1.7 for NiCd. [1&2]

NiMH is a low pressure Nickel Hydrogen technology which lacks the volumetric inefficiencies attendant with the storage of hydrogen in the gaseous state. This emerging technology has seen some success in cellular phones and laptop computers. NiMH meets or exceeds NiCd performance in all areas except peak discharge current. NiMH is capable of 5 "C" continuous current and NiCd is capable of 10 to 20 "C" continuous current where a "C" is the one hour current. The NiMH performance should improve as the process matures. In the commercial market NiMH is twice the cost of NiCd but is expected to be equal in the future. In the aerospace market NiMH is expected to cost less than NiCd. Pending OSHA decisions may in the near future make the domestic manufacture of NiCd unattractive and cause its cost to rise.

The only significant environmental parameter which can not be adequately simulated on earth is the absence of gravity. Gravity causes convection and without convection the behavior of liquids and gasses is changed dramatically. Due to the lack of experience with this couple in space, a simple experiment was devised to test its performance so we could gain the confidence necessary to allow it to power the experiments. The proof of performance would be launched on the Consort IV rocket from White Sands Missile Range in New Mexico.

Six cells would be sufficient to prove performance while minimizing the size and weight of the experiment and, a "C" rate discharge would be initiated during the seven minutes of microgravity. One voltage and two temperature measurements were available from the on-board computer.

Lacking the time for a normal purchasing cycle, parts were procured in local stores and Bill Powellson, mechanical engineer, had to machine the parts he had designed. The establishment of a non-disclosure agreement with Gates Aerospace Batteries (GAB) and the procurement of a NiMH Materials Safety Data Sheet for White Sands range safety proved to be projects in themselves.

In order to have vibration qualification performed on the experiment , it was necessary to build two experiments. The first model was built in two weeks with NiCd cells and sent to vibration. The second or flight model was finished just as GAB delivered the samples. The 24 samples had been cycled 5 times before delivery and this data was used to select 6 cells with the same capacity and self discharge characteristics. The NiMH cells were installed in the flight experiment and 10 days of testing was performed, including four additional charge/discharge cycles, to characterize the battery and experiment.

The flight experiment was conceived on Aug. 8 ,1991, delivered to UAH on Sept.19,1991 and launched on Nov.16,1991. Sounding rockets do, indeed, allow rapid access for experiments to low gravity !

The Rocket

Consort launches and experiments are funded by a cooperative arrangement between the NASA Office of Commercial Programs (OCP), industries, universities, and other government agencies. The Consort program [3] is managed by the Consortium for Materials Development in Space (CMDS) at the University of Alabama in Huntsville. The Consortium is one of seventeen Centers for the Commercial Development of Space (CCDS) established by the NASA-OCP to promote commercial uses of space.

The launch vehicle for Consort IV was a Starfire sounding rocket (Fig 1). The two-stage solid-propellant launch vehicle was 52 feet tall and carried 1000 lbs of payload to 200 miles altitude. After achieving a ten micro-g environment for seven minutes the payload section re-entered the atmosphere and parachuted to the earth 50 miles from the launch site. It was recovered by helicopter and returned to the launch site within 2 hrs. The payload module was approximately 3.6 m in length and 0.44 m in diameter and contained nine experiments packages.

The Cell

Nickel Metal Hydride is a low pressure Nickel Hydrogen (NiH) technology. It is very economical compared to NiH. The specific energy is the same as NiH but it has double the energy density. The cell used in this experiment was a standard sub C size of cylindrical construction. The cell had a diameter of 0.87in. and a height of 1.66in. It was provided by Gates Aerospace Batteries and has an aerospace nickel plate, an Ovonic Metal Hydride plate and a Nylon 2538 separator. The average output voltage per cell is 1.2 volts and its capacity is 2 amp-hrs. All charging of the cell was done at the 20 hour rate with a current of 180 ma.

The Experiment

A battery of six cells was housed in a Delrin honeycomb with a chamber for the electronics. The experiment had a height of 2.5in., a depth of 1.5in. and a width of 14.5in. Its weight was 2.6 lbs. The electronics were designed to connect a resistive "C" rate load (2 amps) to the battery whenever the microgravity signal was present. The microgravity signal was available from the sounding rocket which contained the facility to record the voltage and the two temperatures every second. The sounding rocket also recorded its internal ambient temperature.

Figure 2 is a schematic of the experiment. The discharge is initiated when the signal "MICROG" goes high. This forward biases the photodiode (U1) and causes the phototransistor (U1) to conduct. The current flow through the phototransistor (U1) forward biases the darlington transistor (Q1) which turns on the electromechanical relay (K1) and connects a wire wound resistive load of 3.9 ohms to the battery. The voltage is now present on connector P1-pins 7&8 , and is proportional to the battery voltage. The relationship between the true battery voltage and the voltage measured was characterized during testing to correct for wire and relay contact resistance. Thermisters were in surface contact with two of the cells and measured their temperatures. Connector (P2) was used for battery charging which was performed on the ground only. Launch was specified to be accomplished within 72 hours of charging.

The Data

The launch occurred 25 hours after charging. Graphs have been included which characterize the discharge performance of NiMH in the lab and during the flight.

Figure 3 is a graph of discharge voltage vs. time (60 min) for the initial lab capacity discharge and is typical of this NiMH cell.

Figure 4 is a graph of the cell temperature vs. time for the lab discharge of figure 3. The experiment was in an air conditioned lab at 24 C.

Figure 5 is a graph of discharge voltage vs. time for the seven minute flight discharge. The lab data graphed for comparison was taken after the flight with an identical standtime of 25 hrs. The five volt full scale analog input had a resolution of 8 bits, therefore the flight data has a granularity of 20 millivolts.

Figure 6 is a graph of the cell temperature vs. time for the seven minute flight discharge. The data shows a higher rate of heating in flight (3.4 C in 7 min). The curve of figure 4 showed rates of heating that varied between 0.7 C and 2.1 C in 7 minutes. The rocket's internal ambient temperature was higher than the temperature of the battery at the beginning of discharge and is graphed to explain the source of this additional heating.

Figure 7 is a graph of discharge voltage vs. time (60 min) before and after the flight. It indicates that the 1 hour capacity was essentially unchanged by the flight.

Conclusions

1 . The graphs of battery voltage versus time (Fig 5) proved to be very similiar on earth and in space. The higher voltage at the beginning of flight discharge occurred because the flight battery was six degrees Celsius colder at the beginning of its discharge.[4]

2 . Capacity measurements before and after flight did not show any degradation (Fig 7). The slightly higher voltage in the "after" curve occurred because of small differences in the cells' internal temperature.

3 . The graphs of battery temperature versus time show a higher rate of heating in flight than in the lab but this is attributed to still air and conducted heat from the ambient. (Fig 6).

4 . The experiment was dissassembled and examined for anomalies. The cells did not exhibit any swelling or leakage. At this time, they had a total of fifteen charge/discharge cycles accrued.

The NiMH battery performed well in space during this test and appears suitable for powering the experiments in the sounding rockets. The sounding rocket has been the first test of this new battery technology in space and soon will become its first application in space.

Future Experiments

Teledyne-Brown is looking for a partner to participate in a new battery technology experiment that will fly on-board the shuttle in the near future. The experiment will consist of multiple charge and discharge cycles of a new battery technology. The experiment will demonstrate the practical use of the new technology as well as gathering scientific data. It will be among several Teledyne Brown material science experiments to be flown on a GAS can (Get Away Special can) (Fig. 8). The new technology will be either Nickel Metal Hydride or Silver Metal Hydride. Twelve charge and discharge cycles are planned on a 105 hr. timeline. The first ten cycles will use the other GAS can experiments as the load and then two cycles will be performed using fixed resistive loads.

The authors acknowledge the support given on this project by the NASA Office of Commercial Programs under grant # NAGW-812.

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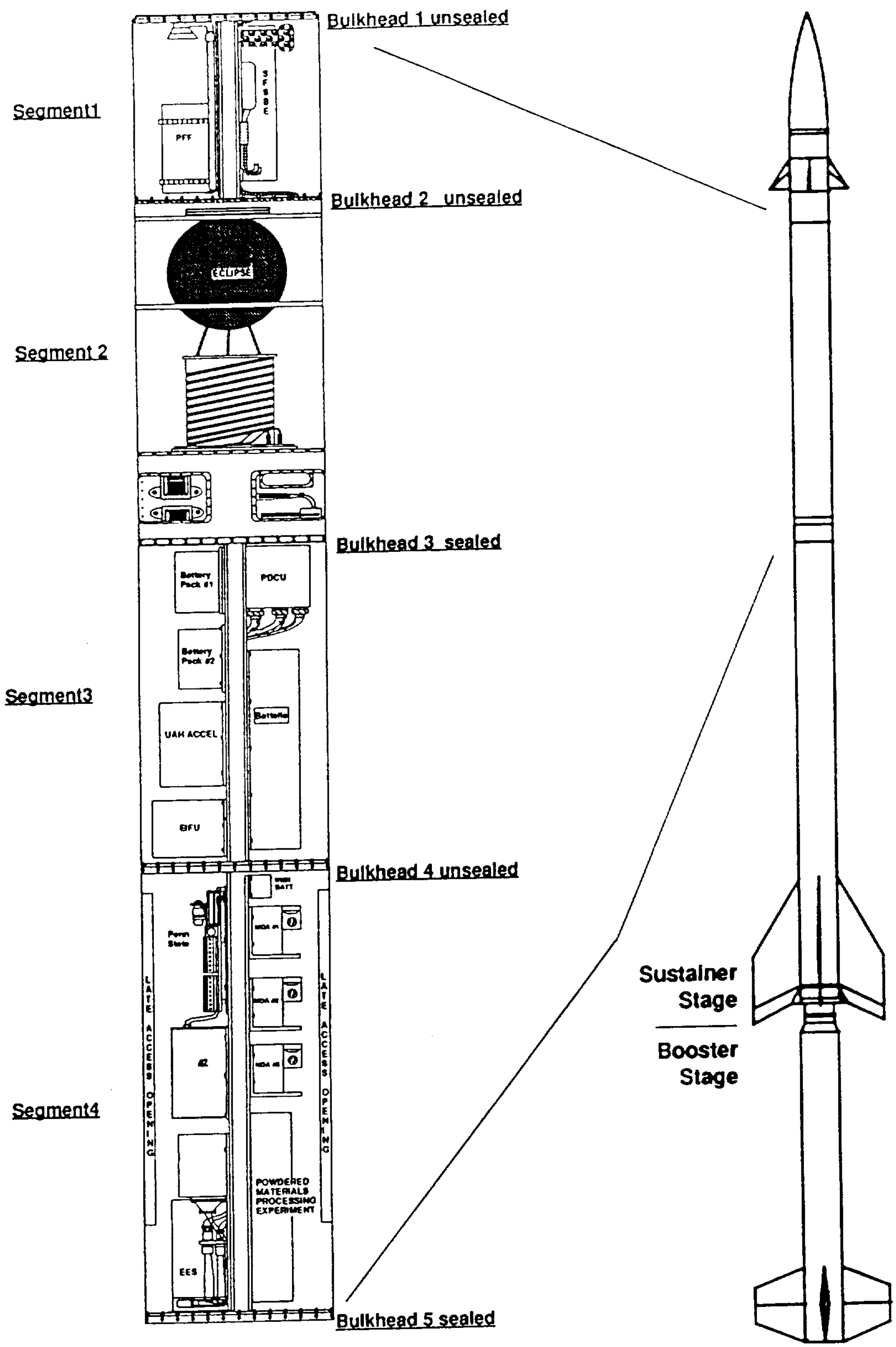
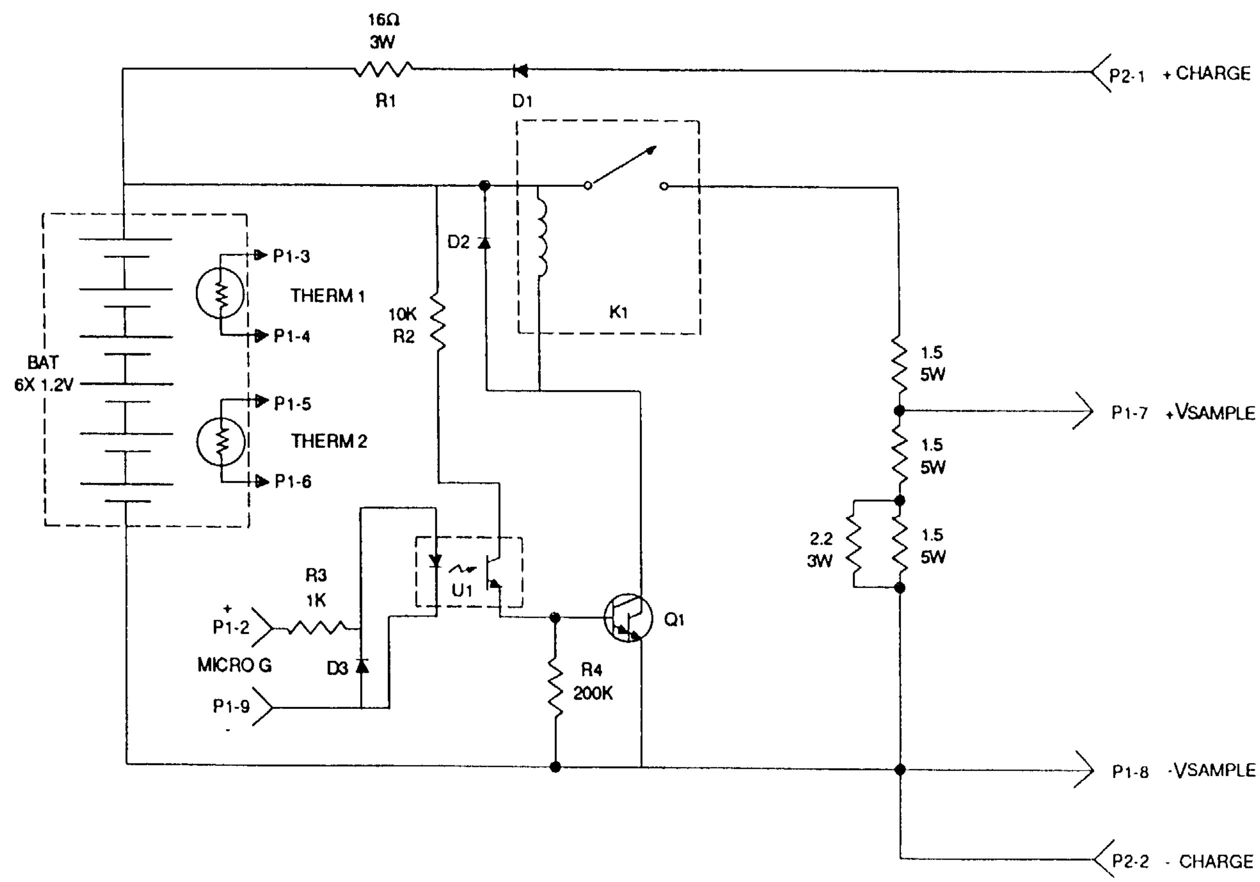


CONSORT IV

FIGURE 1

FIGURE 2	Nickel Metal Hydride, A Flight Experiment	Ed Fitzgerald



CONSORT BATTERY EXPERIMENT SCHEMATIC

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FIGURE 3	Nickel Metal Hydride , A Flight Experiment	Ed Fitzgerald

NiMH Battery , Discharge Voltage vs. Time

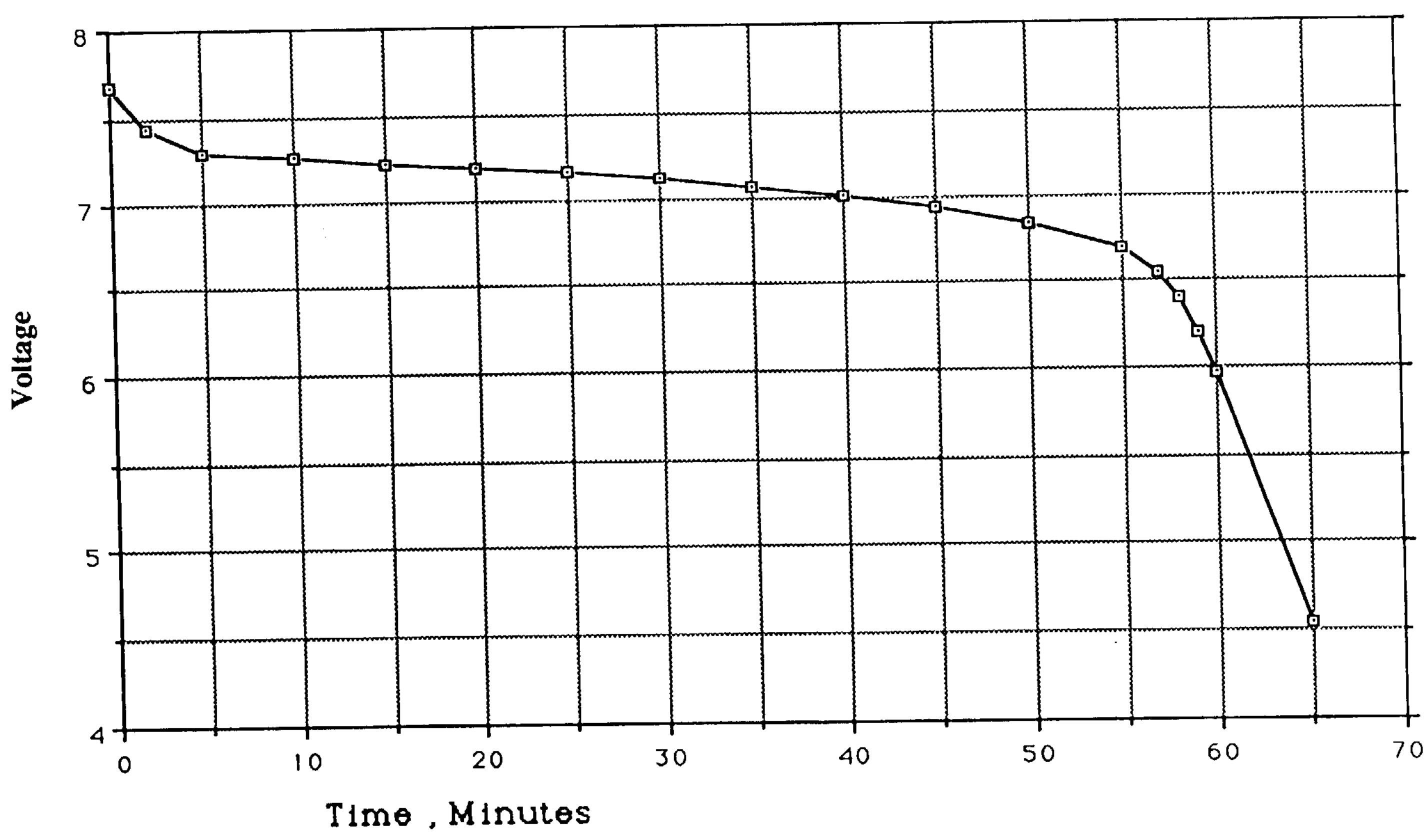

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FIGURE 4	Nickel Metal Hydride , A Flight Experiment	Ed Fitzgerald

NiMH Battery, Discharge Temperature vs Time

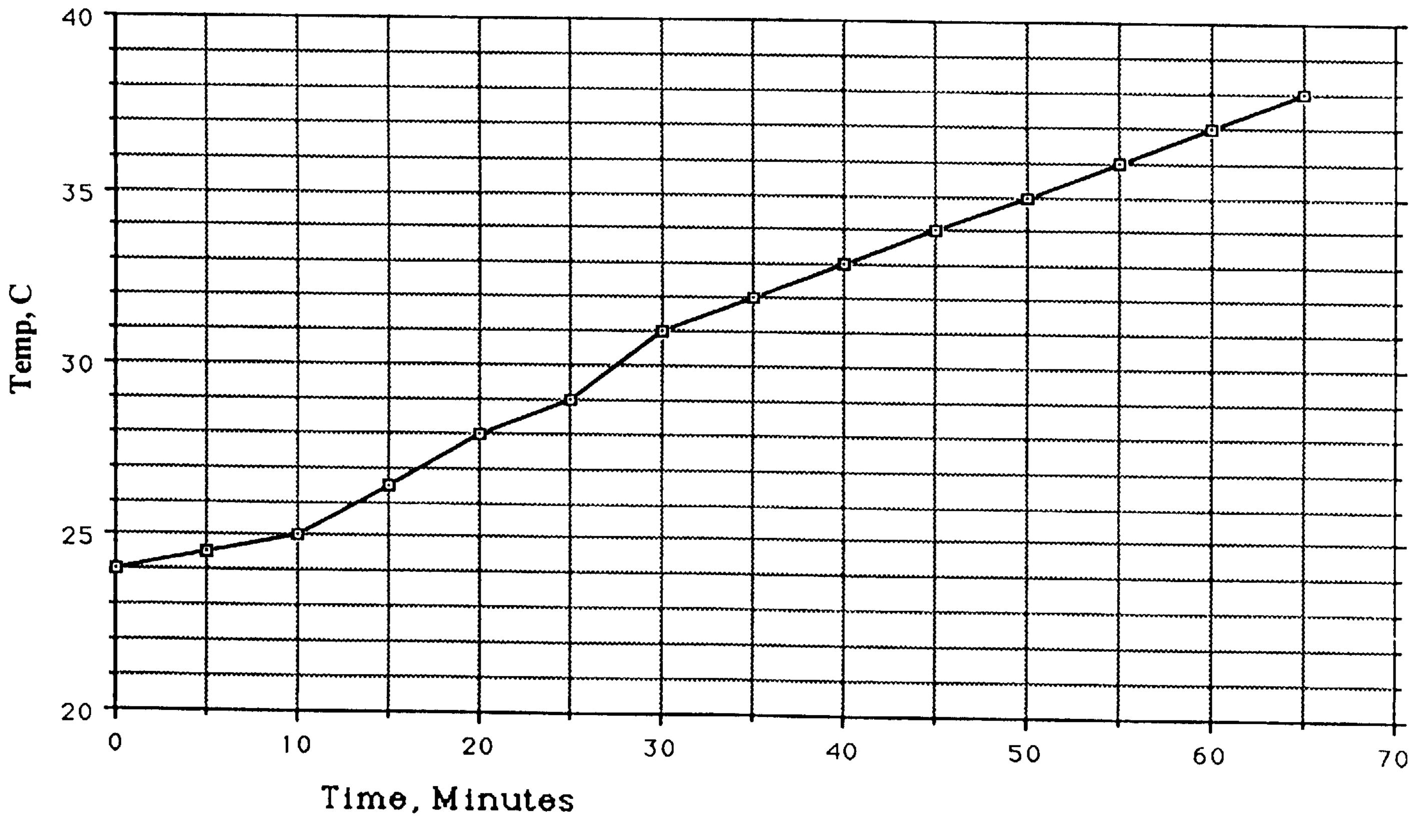

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FIGURE 5 | Nickel Metal Hydride , A Flight Experiment | Ed Fitzgerald

NiMH Battery, Comparison Flt vs Lab

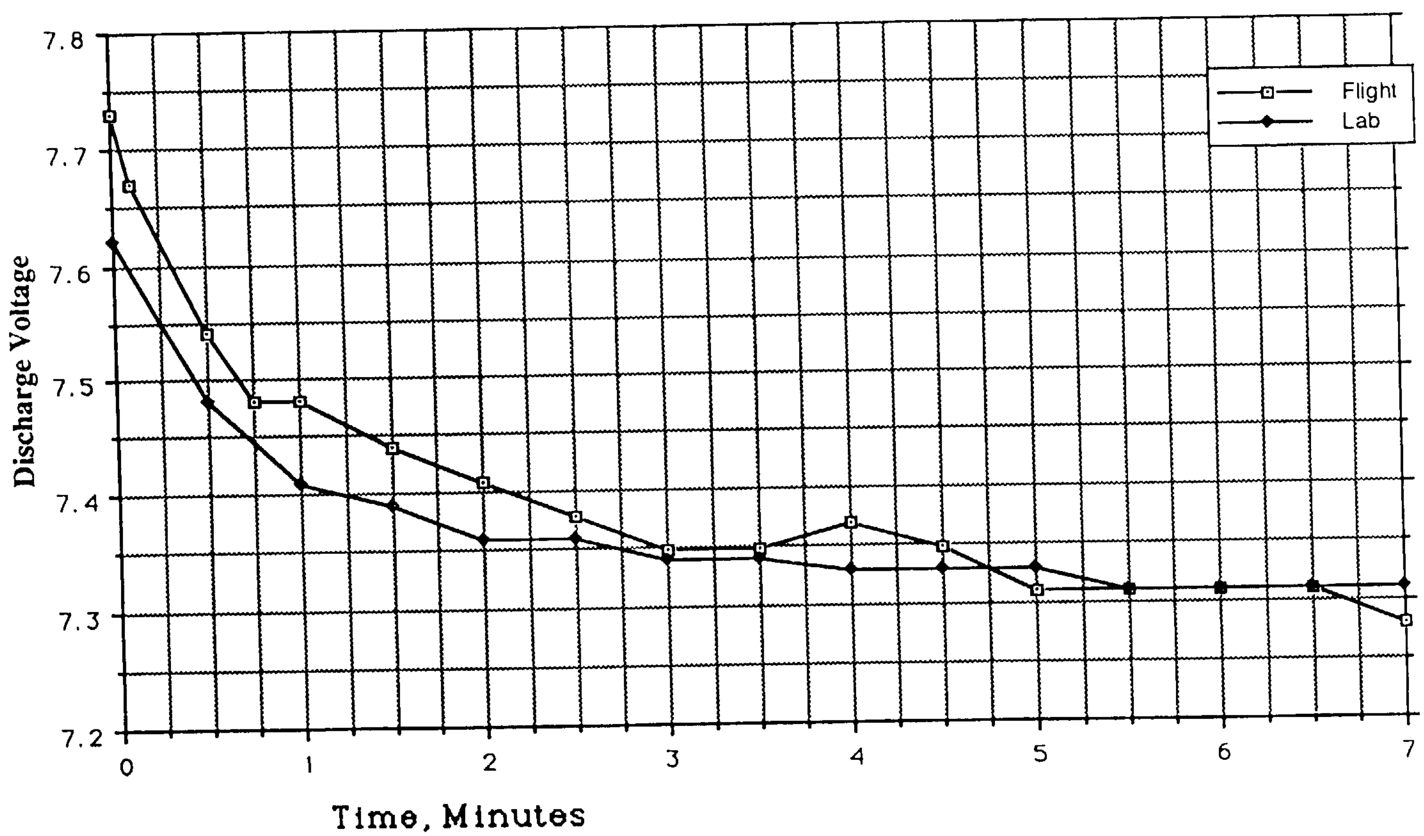

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FIGURE 6 | Nickel Metal Hydride , A Flight Experiment | Ed Fitzgerald

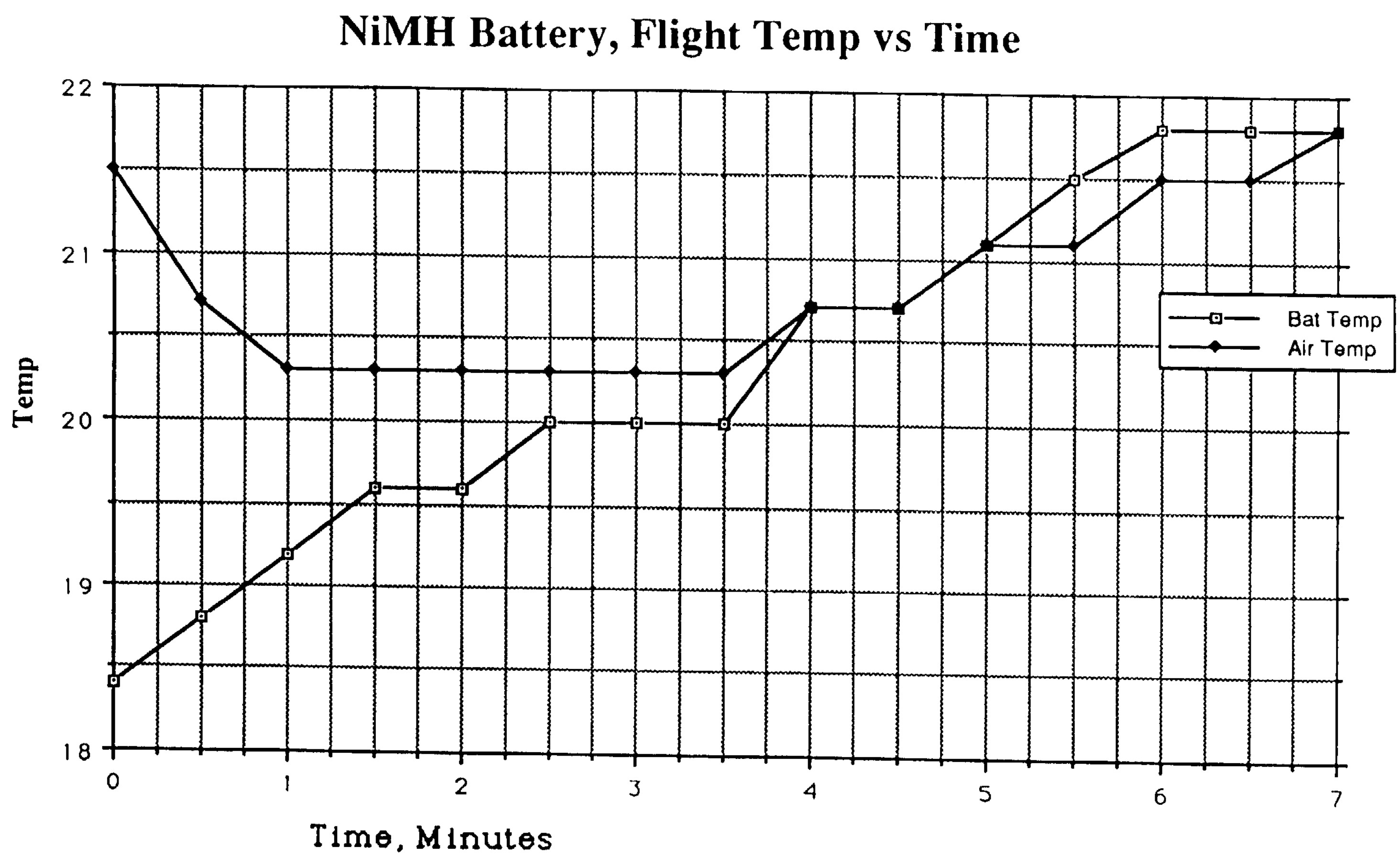

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FIGURE 7	Nickel Metal Hydride , A Flight Experiment	Ed Fitzgerald

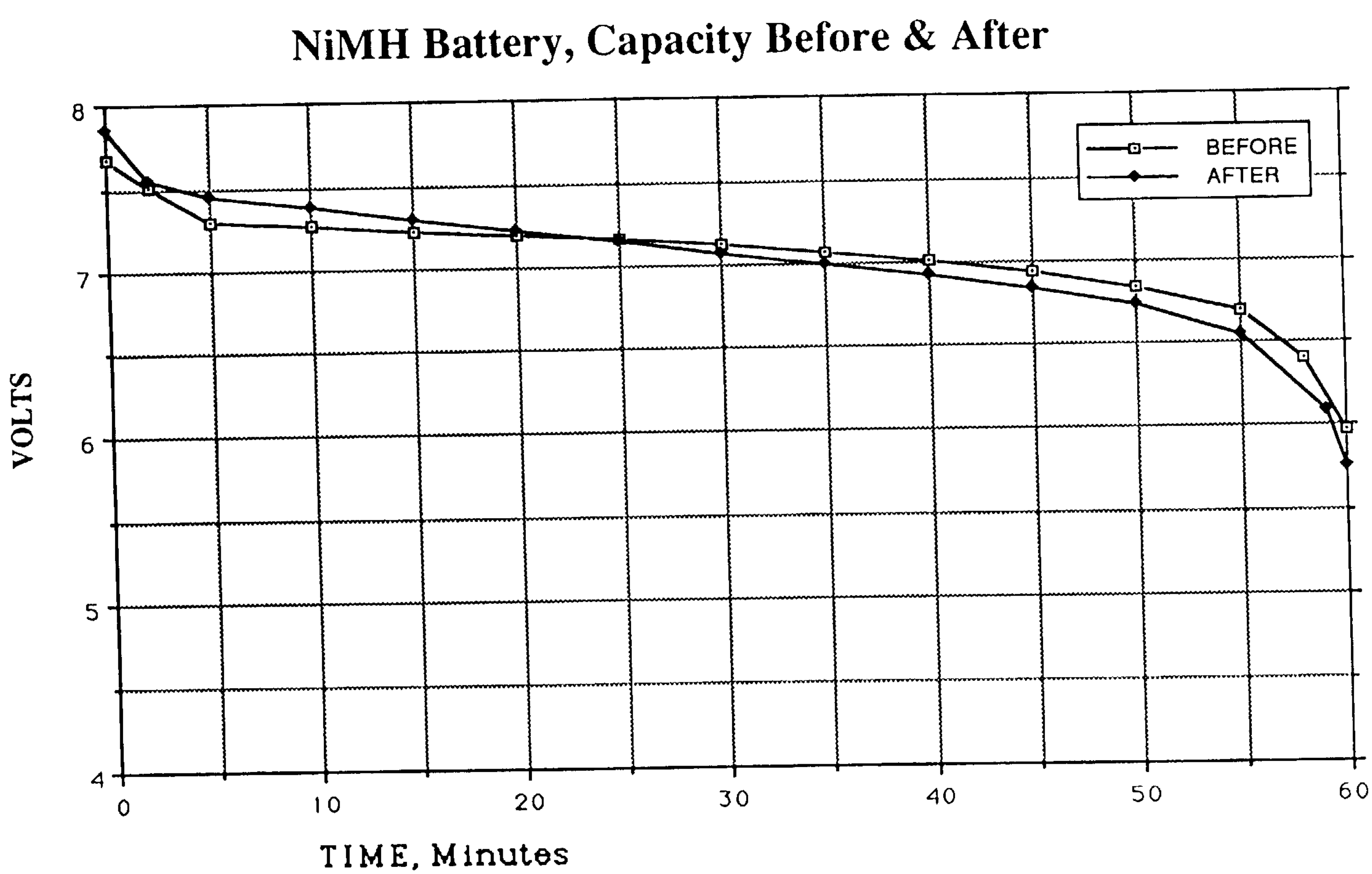

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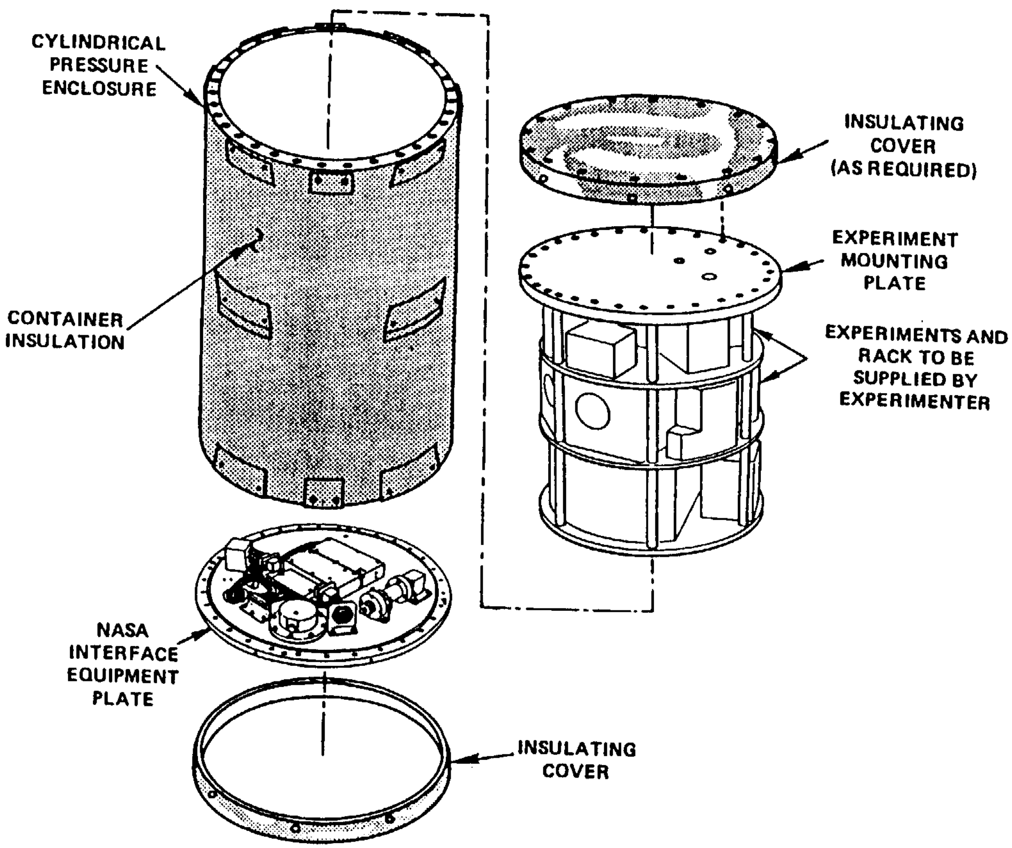
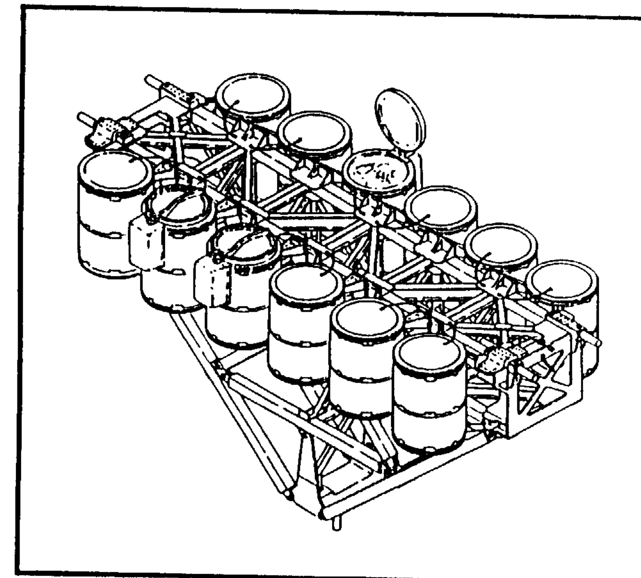
FIGURE 8	Nickel Metal Hydride , A Flight Experiment	Ed Fitzgerald

GET AWAY SPECIAL
SMALL SELF-CONTAINED PAYLOADS
CONTAINER CONCEPT





GAS BRIDGE PAYLOAD

TELEDYNE
BROWN ENGINEERING

ADVANCED SYSTEMS OPERATION

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SODIUM-SULFUR GROUP

EPI SODIUM SULFUR PROGRAM

- NaS program initiated in 1986.
- EPI selected by USAF as sole developer for NaS LEO cells.
- Over 200 cells constructed for a variety of applications.
- Developed a β" electrolyte production capability.

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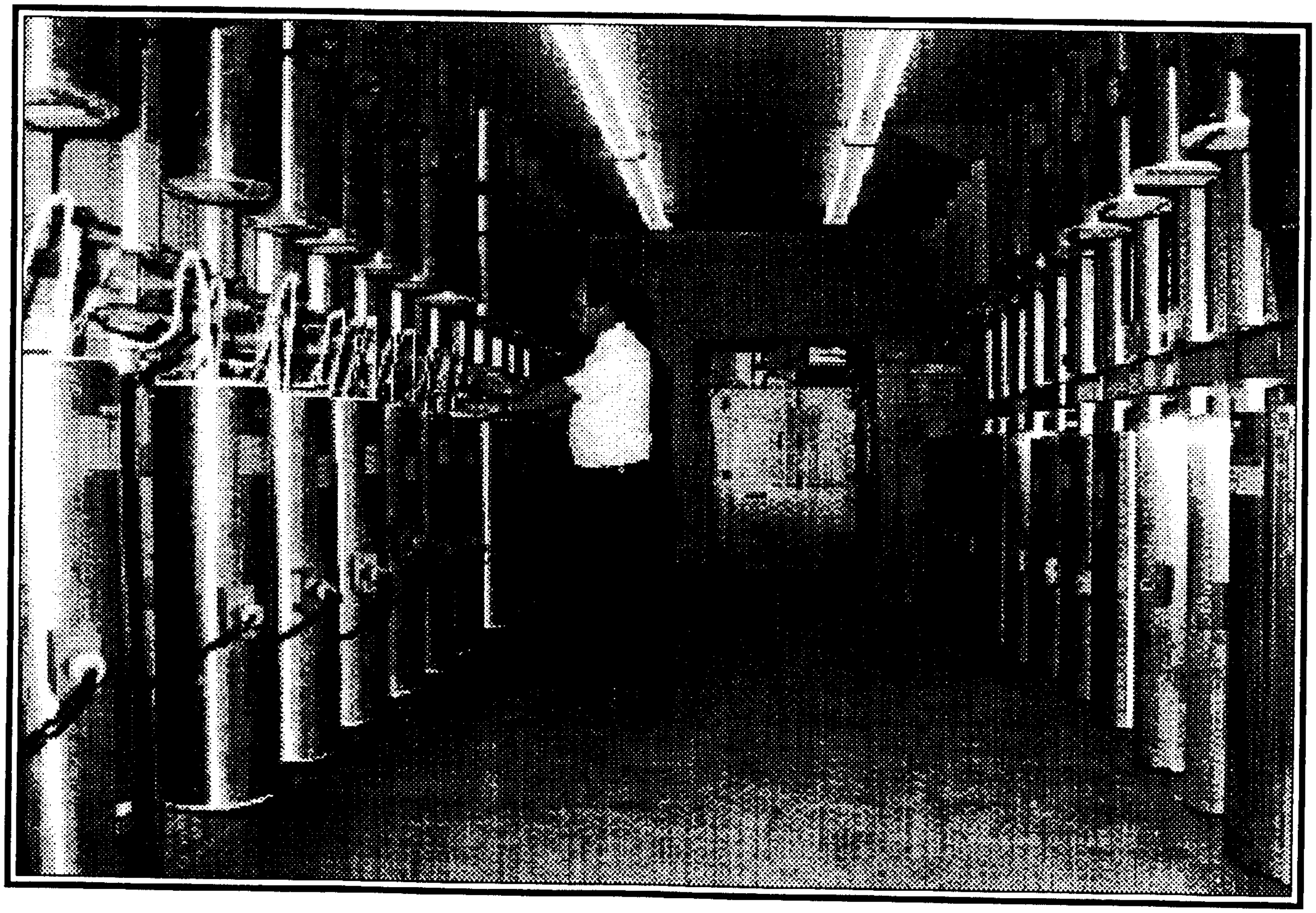

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CELL SIZES MANUFACTURED

50 AH	1.4" D X 12.3" L	600 gms (1.31 lbs)
40 AH	1.4" D X 9.0" L	500 gms (1.10 lbs)

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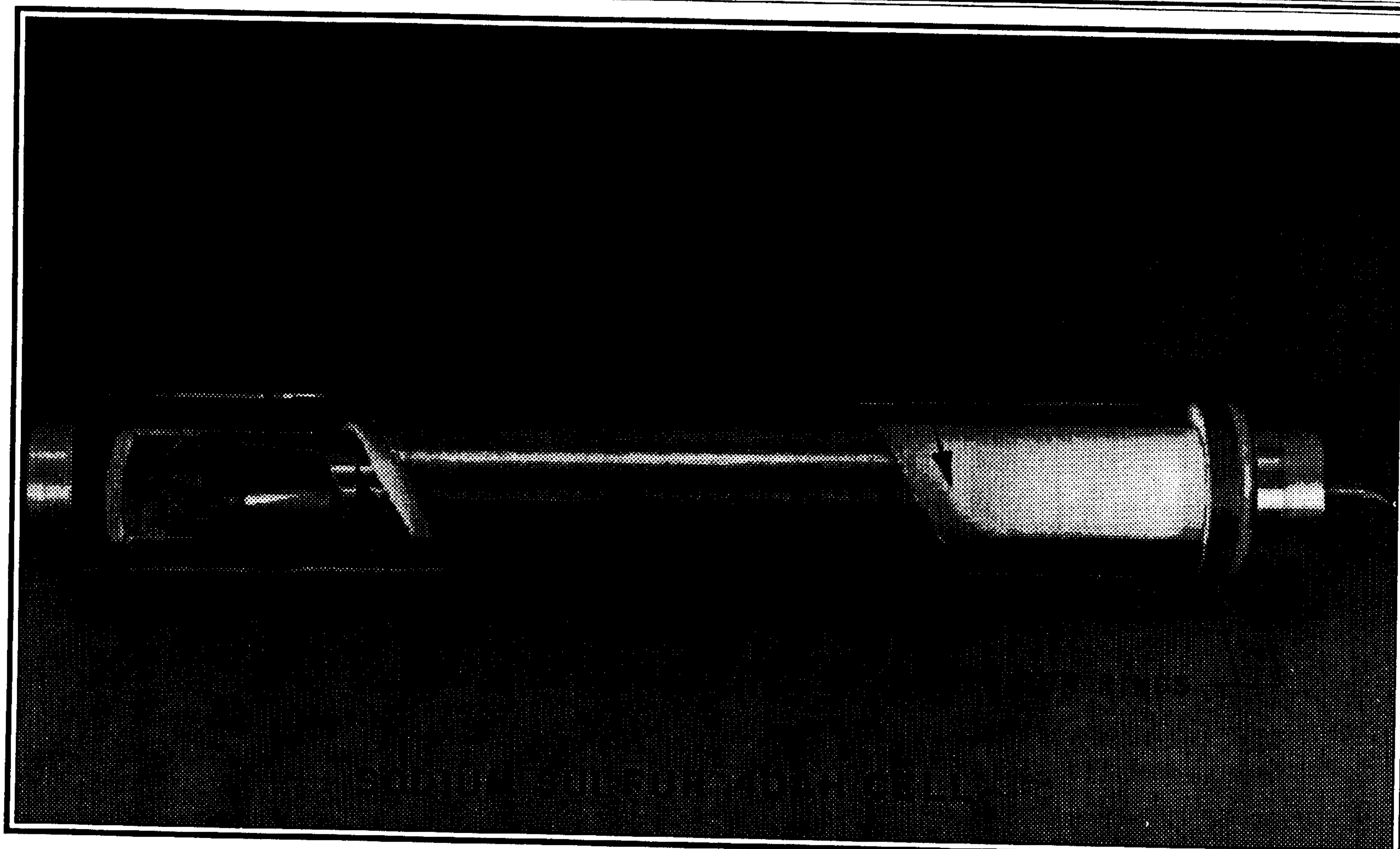

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

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ORIGINAL PAGE IS OF POOR QUALITY

AREAS OF IMPROVEMENT

- Resistance
- Cathode Performance
- Parts Count
- Weight
- Seals

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Performance Improvement Demonstrated (16 Amp Discharge)

	Weight (grams)	Avg. Volts (Discharge)	Resistance (mOhms)	Spec. Energy (Whr/Kg)	Energy Dens. (Whr/L)
Baseline	509	1.64	17.6	119.1	266.9
Intermediate	506	1.74	10.6	127.3	283.6
Improved	500	1.89	6.7	139.8	307.8
State-of-the-Art	455	1.95	5.8	158.5	334.0

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50 AHR CELL — "IMPROVED" DESIGN

- 8,400 Cycles (>95% LEO, 60% DOD)
- On test 33 months
- Discharge resistance 8.3 milliohms (7.3 milliohms BOL)
- F1% 16.1 (14.0 BOL)
- Capacity 53.3 AHr (52.1 BOL)

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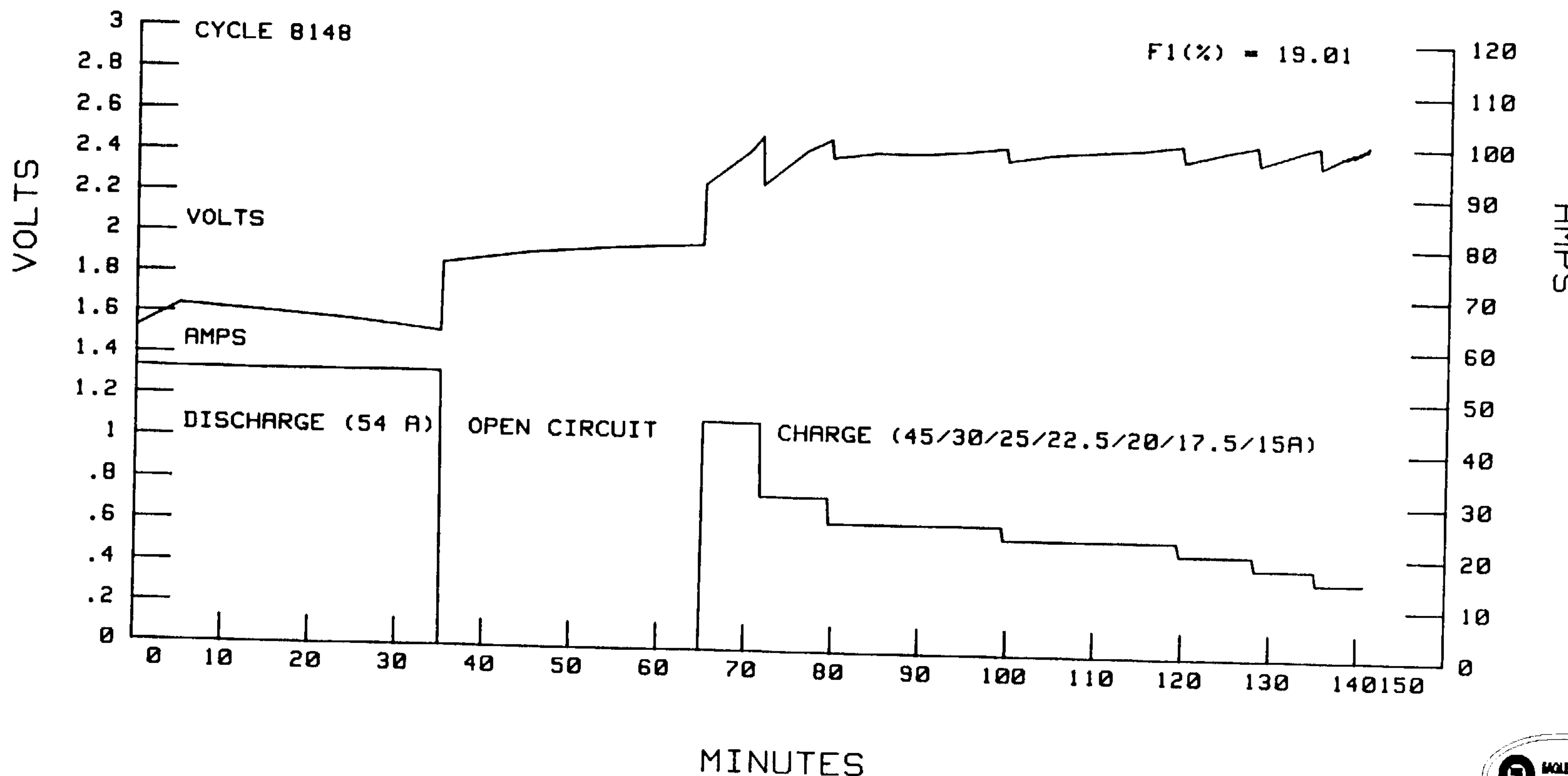
IMPROVED CELL PERFORMANCE (LEO 60% DOD)



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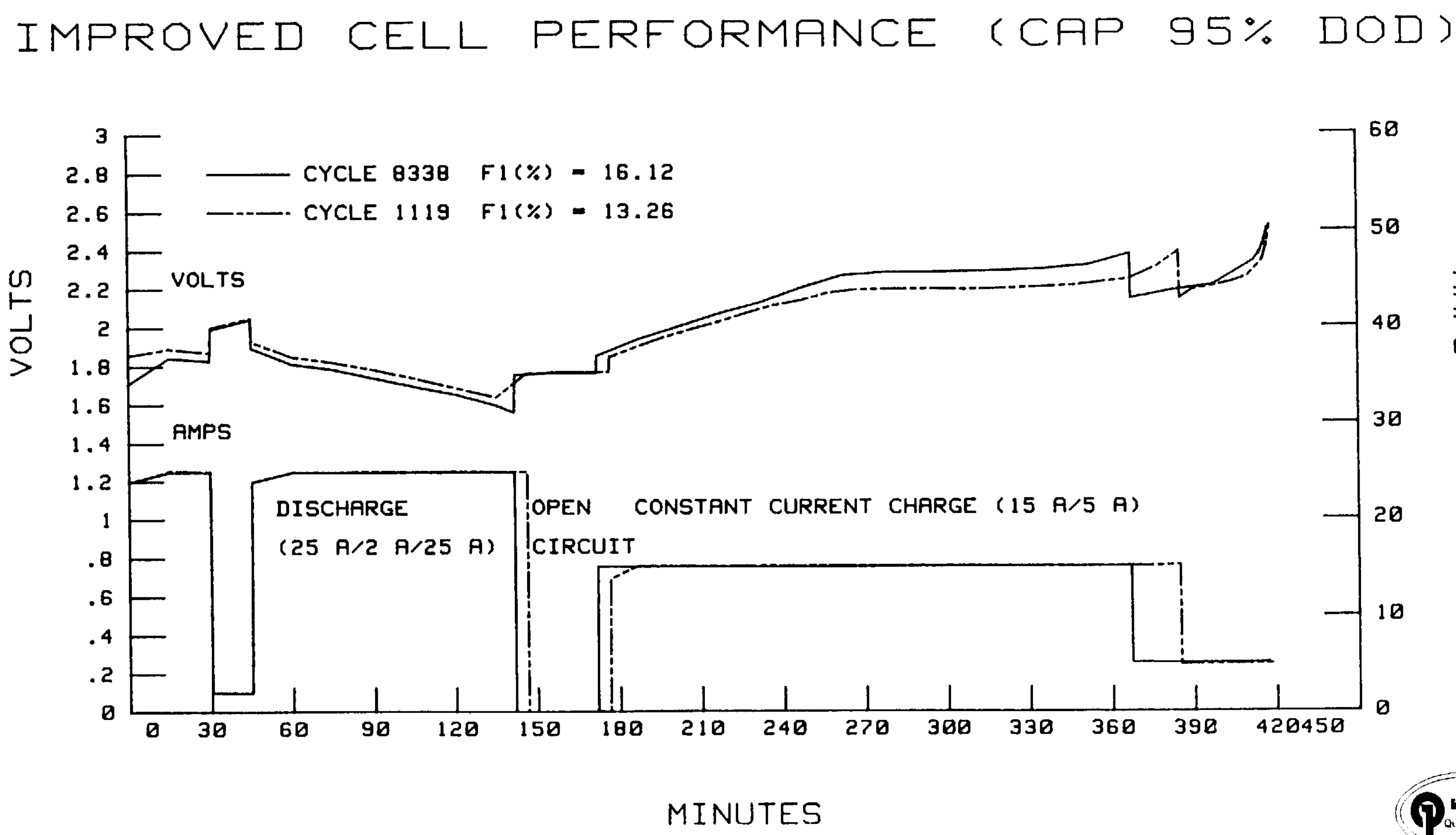

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ADVANCED SYSTEMS OPERATION

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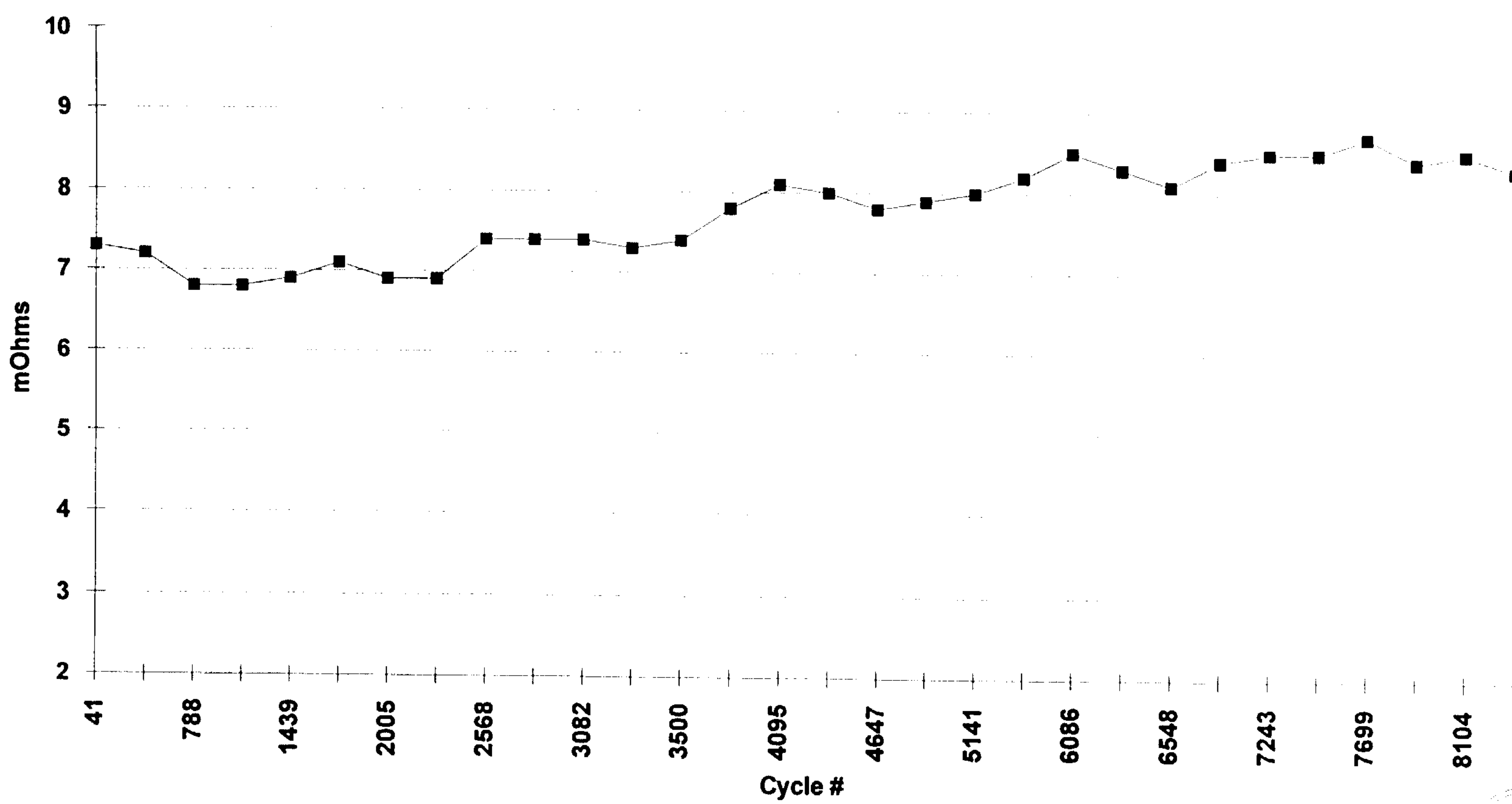
Resistance - 50AHr "Improved" Cell



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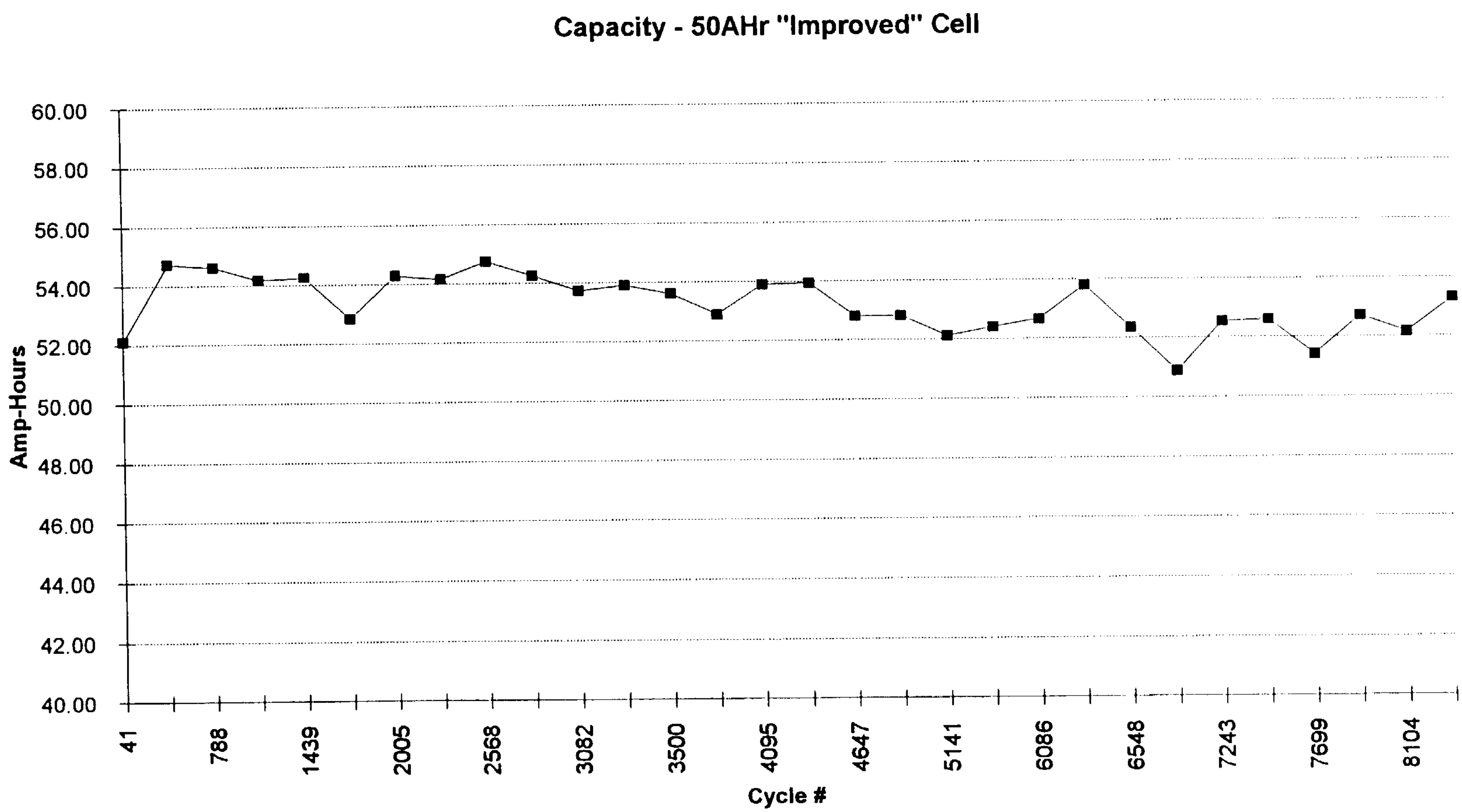

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SINGLE CELL TEST MILESTONES

- Over 11,000 cycles to date
- 43 month calendar life
- 3,130 AHr/cm^2 in cell testing
- 5,900 AHr/cm^2 in sodium-sodium testing
- Discharge resistance < 5 milliohms
- F1 of less than 5 (low rate charge)

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ENVIRONMENTAL TESTING ACCOMPLISHED

- Shock .... 30g's, 11ms
- Acceleration .... 15g's, 5 min.
- Random Vibration.......... $0.25g^2$/Hz, 300-1200Hz (0A=19.5g RMS)
- Sine Vibration................. 7.5g peak, 5-2000Hz
- Humidity .... MIL-STD-810B, Method 507
- Freeze/Thaw .... 20 Cycles

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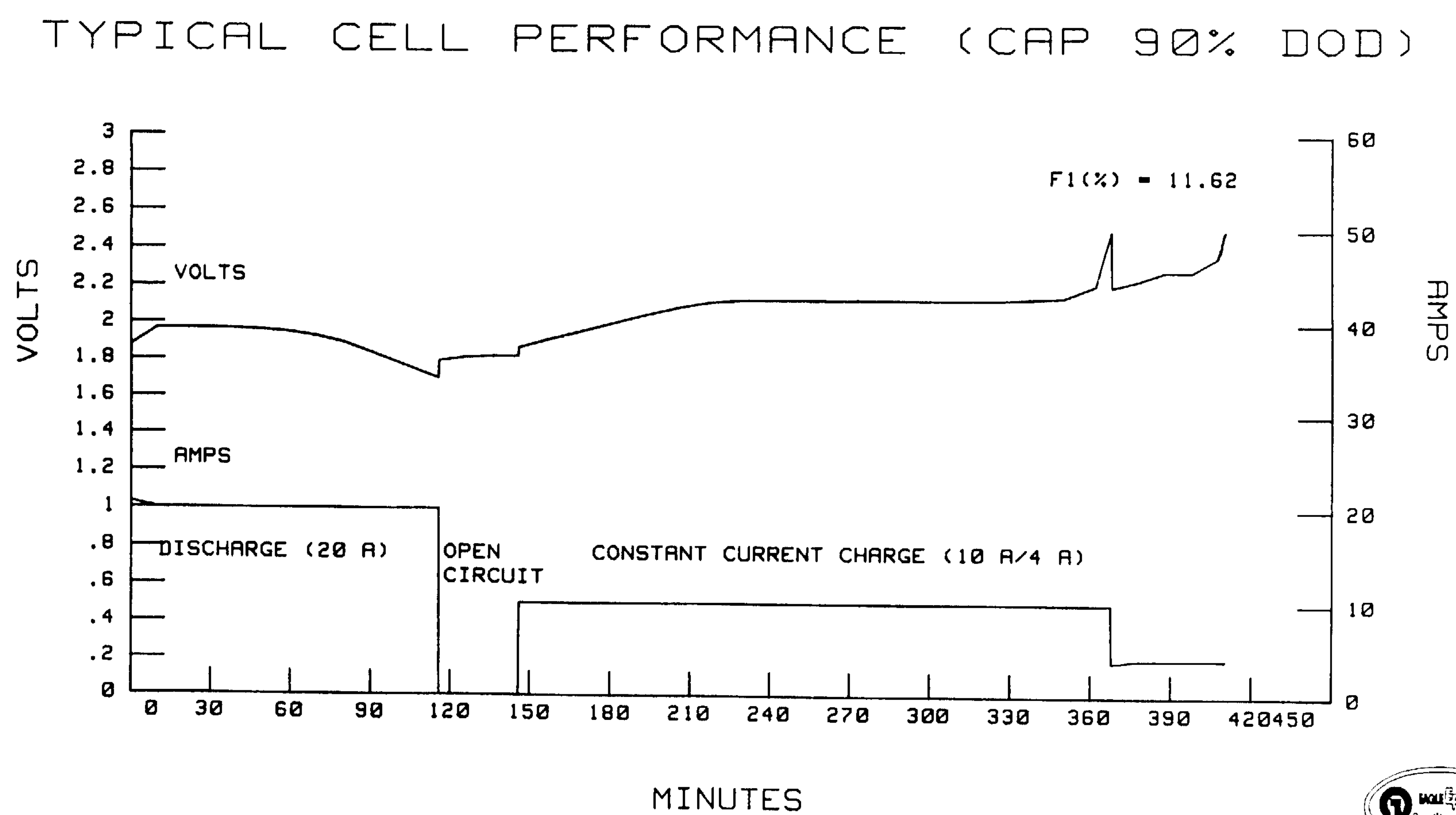
STATE-OF-THE-ART CELL



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ADVANCED SYSTEMS OPERATION

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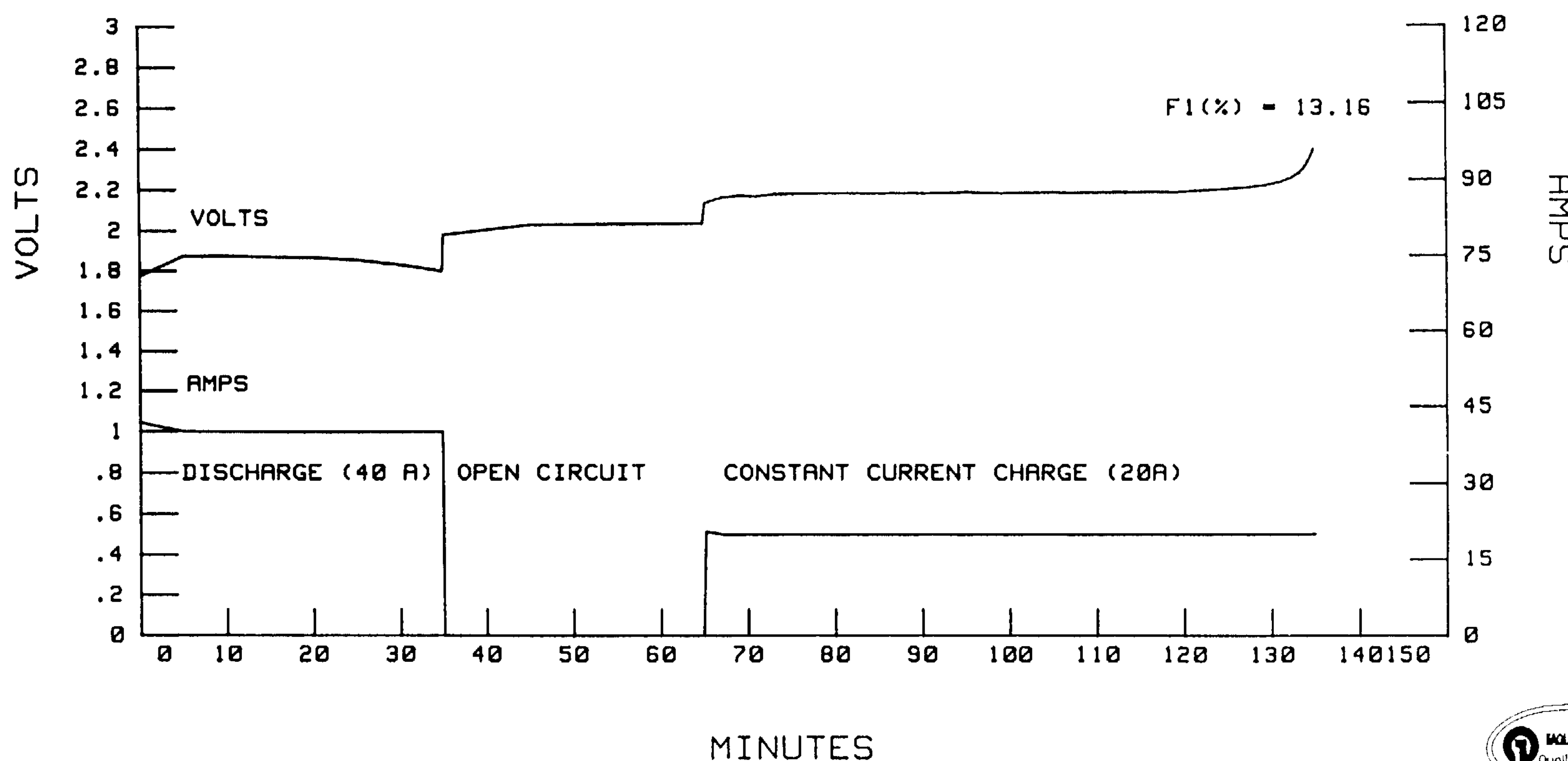
STATE-OF-THE-ART CELL

TYPICAL CELL PERFORMANCE (LEO 60% DOD)



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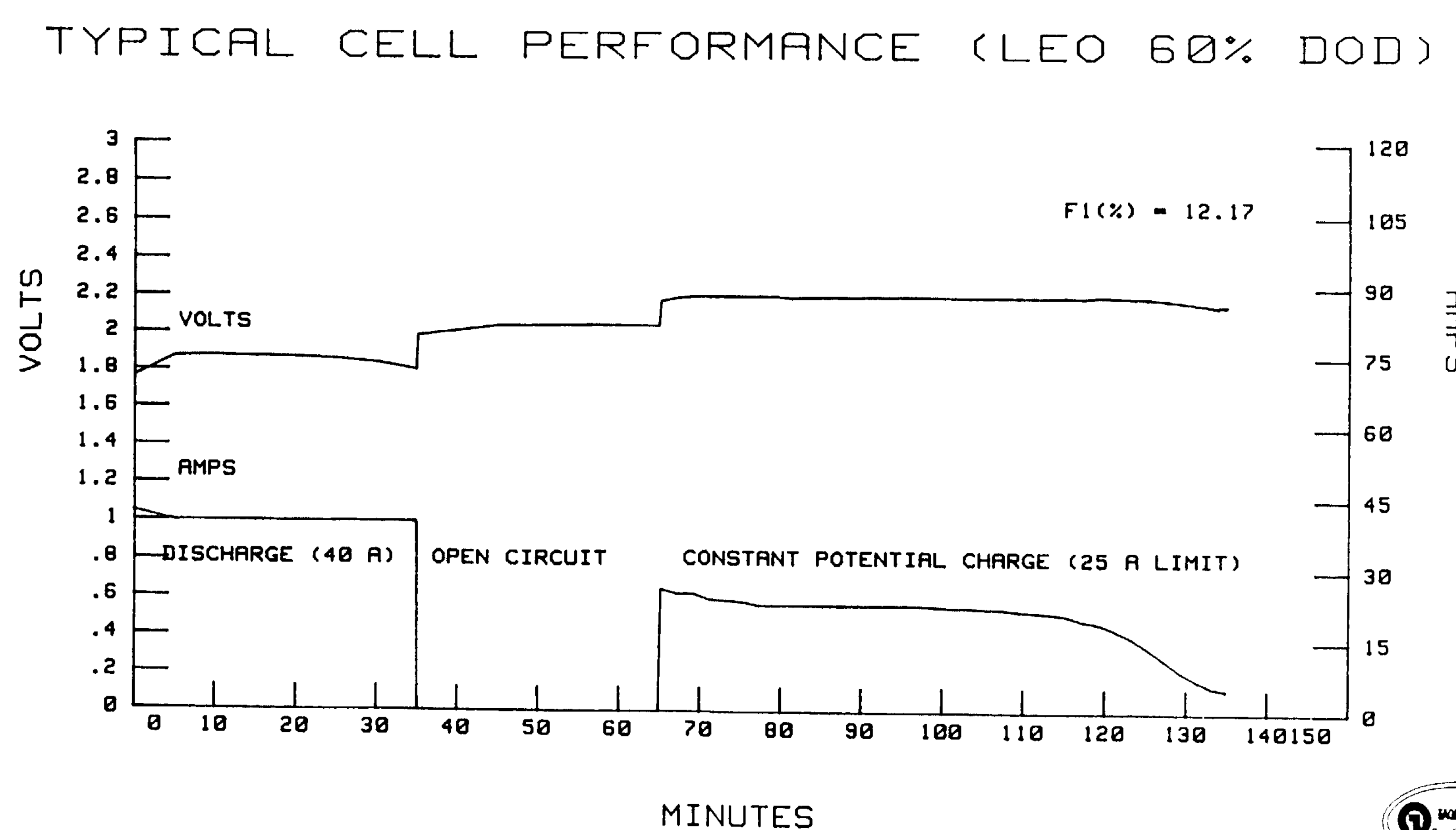
STATE-OF-THE-ART CELL



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ENTRY LEVEL BATTERY

- Effort funded internally 1990-1991
- Three cell module
- 1,000 cycles achieved
  Constant current charge/discharge
  Nominal 60% DOD (=30AHr)
- 30 Whr/Kg
- Calendar life: 6 months

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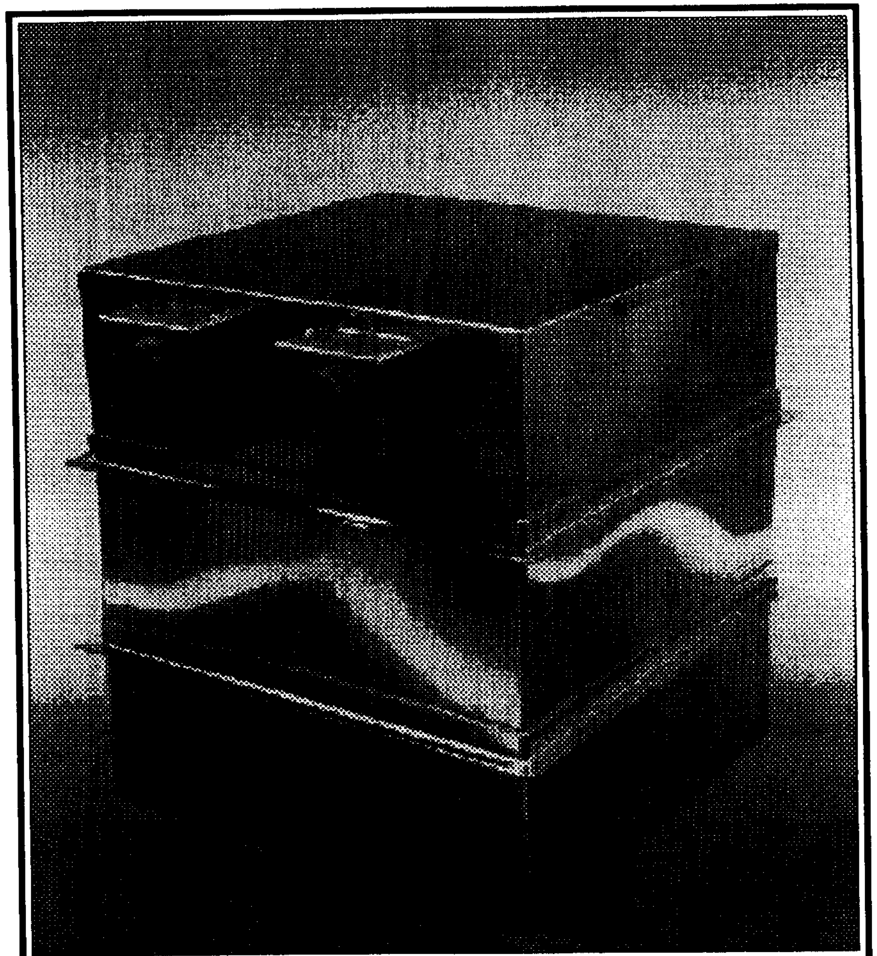
Advanced Systems Operation

Sodium-Sulfur Group



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NEXT GENERATION BATTERY PERFORMANCE PROJECTIONS

- 35 Amp-Hour cells
- 20 cell series string
- Battery OCV: 42 Volts
- Battery working volts: 38 Volts
- Weight: 13.5 Kg
- Volume: 30 L
- Energy Density: 100 Whr/Kg, 45 Whr/L

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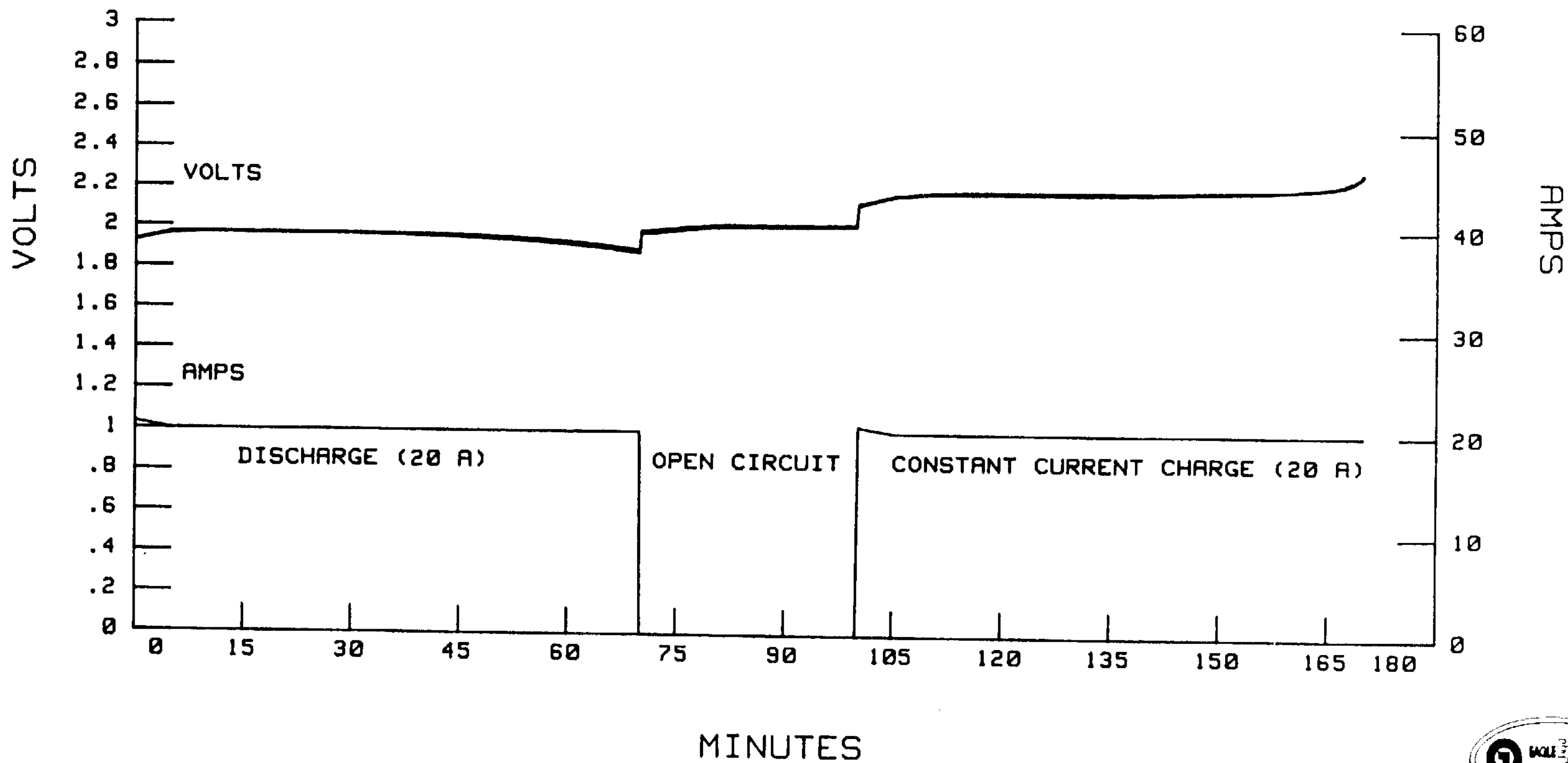
ADVANCED SYSTEMS OPERATION

SODIUM-SULFUR GROUP

STATE-OF-THE-ART CELL

TYPICAL THREE CELL GROUP



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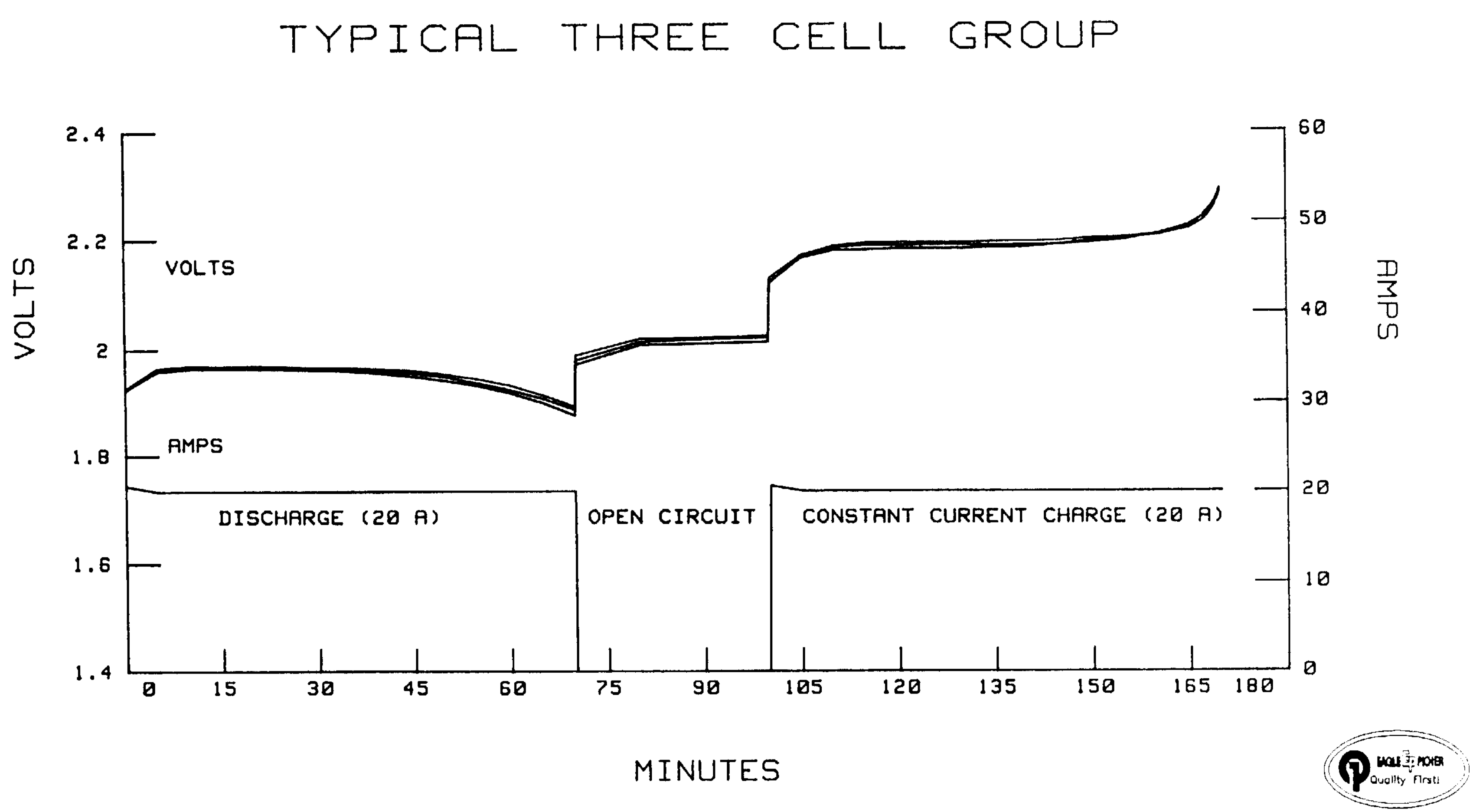
STATE-OF-THE-ART CELL



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SUMMARY

Sodium Sulfur cell and battery designs continue to evolve with significant improvement demonstrated in:

- Resistance
- Rechargeability
- Cycle Life
- Energy Density
- Electrolyte Characterization

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Thermal Composites Division

ESLI

Phase-Change Composite TES for Nickel-Hydrogen Batteries †

Date: November 19, 1992

Presented at: NASA Aerospace Battery Workshop, MSFC

Presented by: Richard A. Meyer
Energy Science Laboratories Inc. (San Diego, CA)

† Contract No: F29601-92-C-0065 (USAF SBIR Phase I)
Technical Monitor: Mary Corrigan (PL/VTPT)
Prin. Investigator: Timothy R. Knowles (619/552-2034)

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Ni-H2 Thermal Control Problems

Passive Thermal Control with TES

Phase-Change Composites (PCC)

Candidate Materials

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Fabrication & Freeze-Melt Cycling

Thermal Modeling

System Benefits

Applications

Ni-H2 THERMAL CONTROL PROBLEMS

Ni-H2 thermal characteristics:

- cycle life sensitive to temperature control
- need lower temperatures (≈0°C) than NiCads (≈21°C)
- high T transients at end of charge and during discharge
- T gradients in cell & across battery are detrimental

Cold-bias design is typical for aerospace battery thermal control

- radiators sized for larger than average heat dissipation
- high T transients remain
- heaters needed to prevent excessive low T
- option = VCHP, louvers also used to reduce heating

Passive high-heat-capacity option:

- thermal inertial reduces high and low T variations
- the heating needs are reduced
- the radiator may be sized for average load with low heating

PASSIVE THERMAL CONTROL WITH TES

Add thermal energy storage (TES) to the battery
- reduce temperature variations, both hot and cold
- time-average the heat delivered to the radiator

A phase-change material (PCM) makes TES light weight
- PCMs have 20x-40x higher specific heat than batteries

Phase-change composite (PCC) = PCM matrix + conductive fins
- high heat conductance and high heat capacity
- capillary gaps control position of fluid and voids

Potential benefits of PCC-TES are
- improved battery temp control, efficiency, cycle life
- reduced battery heater power
- reduced radiator area and system weight

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PHASE-CHANGE COMPOSITES (PCC)

Composite a high conductivity (k) material with a high heat capacity (c) material for high speed TES = thermal capacitor.

Figure of Merit for a TES material is the kc-product.

Thermal time constant $\tau = RC = (C/A)^2 / kc$

Thermal flux $F \propto 1/\tau \propto kc$

Flux / Weight $F/W \propto kc^2/\rho$

where $R = L/kA$, $C = cLA$, $c = \rho c_p$, ρ = density, L = TES thickness, A = heat transfer area

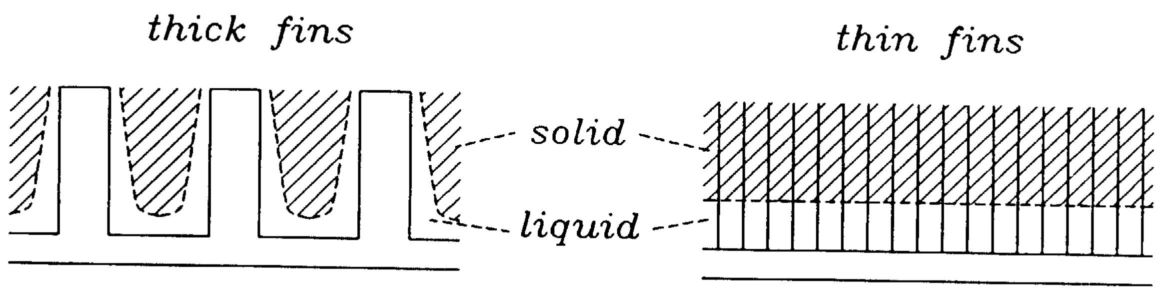
TABLE: Combine high-k and high-c materials (illustrative values)

MATERIAL	k	c	$F \propto kc$	ρ	F/W
high-k (metal, carbon)	100	1	100	3	33
high-c (PCM)	1	100*	100	1	10,000
50-50 composite (PCC)	50	50*	2,500	2	62,500
25-75 composite (PCC)	25	75*	1,875	1.5	93,750

* effective over a limited temperature range around the phase-change temperature

PCC STRUCTURE

Performance is best when homogeneous, with planar isotherms



Requires fins so thin that the thermal resistance across the PCM layer is less than the thermal resistance along the fin.

Fin widths required: <10 microns, for 5 mm TES thickness.

PCC thermal properties obey simple rule of fractions

$$k_{PCC} = k_F\, x + k_{PCM}\,(1 - x) \quad \text{(parallel)}$$

$$c_{PCC} = c_F\, x + c_{PCM}\,(1 - x)$$

$$\rho_{PCC} = \rho_F\, x + \rho_{PCM}\,(1 - x)$$

$$H_{PCC} = H\,(1 - x)$$

F = fin

x = fin volume fraction

ρ = density

H = latent heat

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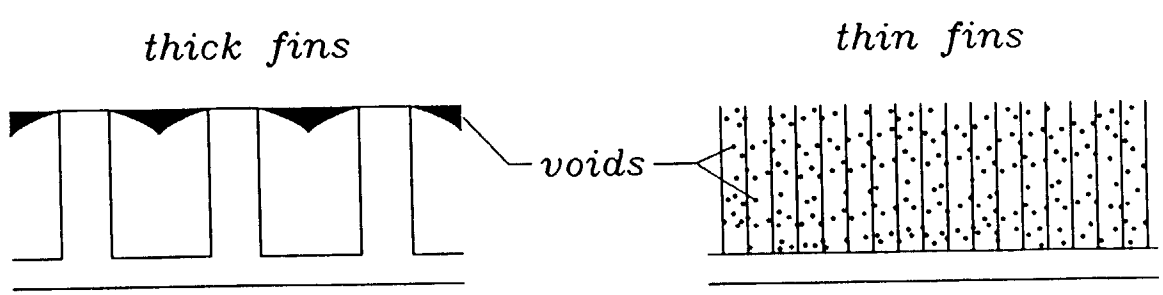
SHRINKAGE VOIDS, STRESS RELIEF

High capacity PCMs generally have large volume changes ~10% during solid-liquid phase change causing expansion stress.

Fine capillary structure in PCC prevents expansion stress

- capillary forces $\gg$ gravity forces for small gaps
- shrinkage voids are finely distributed
- expansion into distributed voids avoids stress
- light weight encapsulation is adequate



CANDIDATE MATERIALS

Many PCMs are available between -20°C and 10°C

- Encyclopedia of Organic Chemistry cites 975
- Aldrich Chemical Company offers ~440

Two candidates currently under study are:

- WATER (H_2O, D_2O)
  - high latent heat, but high stress potential
  - MP = 0 - 3.8°C (range); BP = 100-101°C;
  - H = 334 J/g; c = 4.19 J/g-K; ρ = 0.92 g/cm^3, ice @ 0°C
- n-TETRADECANE ($C_{14}H_{30}$)
  - a benign paraffin that wets carbon fiber
  - MP = 5.6°C; BP = 254°C; FP = 99°C; MW = 198.4
  - H = 227 J/g; c = 2.21 J/g-K; ρ = 0.763 g/cm^3 @ 20°C

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PCC DESIGN OPTIONS

PCC-TES LOCATION OPTIONS

cell sleeve	good thermal control; simple retrofit
cell interior	recommended for Common Pressure Vessels
pockets	use open space between cells
baseplate	interferes with wiring, heat pipes, fasteners

SLEEVE LINER OPTIONS

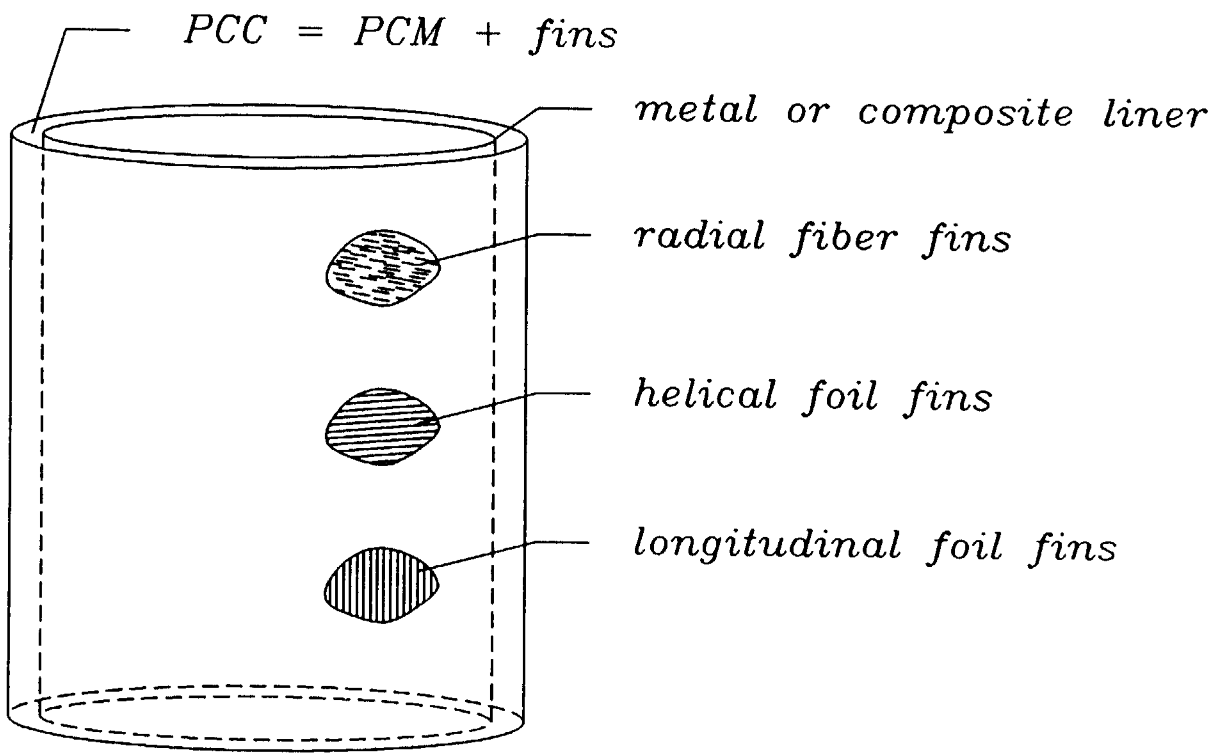
thin metal	good heat transfer; corrosion?
fiber composite	light weight; reliable encapsulation?

FIN STRUCTURE OPTIONS

radial fibers	good heat transfer, void control; low cost
axial fins	too conductive, higher cost metal fabrication
helical fins	good heat transfer; adequate stress control?
helical tubing	poor heat transfer; low stress in poly tubing

PCC SLEEVE FOR IPV

Retrofit PCC-TES sleeves on IPVs. Increase volume 10%.
Sleeve conductivity design options:



SLEEVE THERMAL RESISTANCE

Conventional aluminum sleeve needs thick walls for heat conductance, and is 11% of battery weight

PCC-TES sleeve stores heat, then releases it at ≈constant temp
☞ PCC-TES does NOT need thick conductive walls

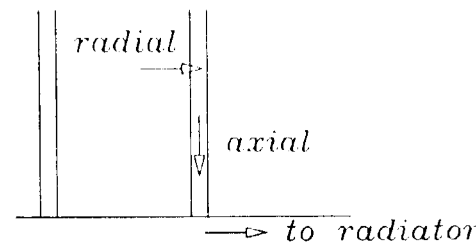


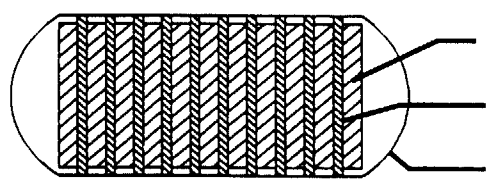
TABLE: Axial and radial sleeve thermal resistances.

	Axial	Radial
conventional 1-mm aluminum sleeve =	6.15	0.00010
3-mm water =	675.74	0.10365
2.75-mm PCC (361% of cell heat cap.) =	442.9	0.00207
PCC-TES: 0.25-mm Al + 2.75 mm PCC =	23.40	0.00178

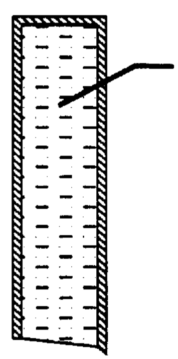
PCC PLATE FOR MULTICELL CPV

CPV has same heat generation in more compact geometry.
Interior PCC-TES plates reduce transients, average heat release.

COMMON PRESSURE VESSEL (eg 22 cells)



OPTION: PCC-TES Plates



* high capacity
* low weight
* improved Temp control
* reduced GEO heating requirement

FABRICATION & TESTING

Phase 1 progress: fabrication of subscale sleeves and demonstration of freeze-melt survival for limited cycling

- sleeve size = 10 cm long, 2.3 cm ID, 3.9 cm OD.
- aluminum liner, polymer encapsulation.
- PCMs = tetradecane, water
- fin material = high-k carbon fiber felt

Without fins, expansion stress causes fracture and leak during first freeze/melt cycle.

Fin structures have been developed for which no fracture or leak has occurred in all 16 cycles run.

PCMs encapsulated in polyethylene also can survive freeze/melt cycling, but the heat conductance is too low.

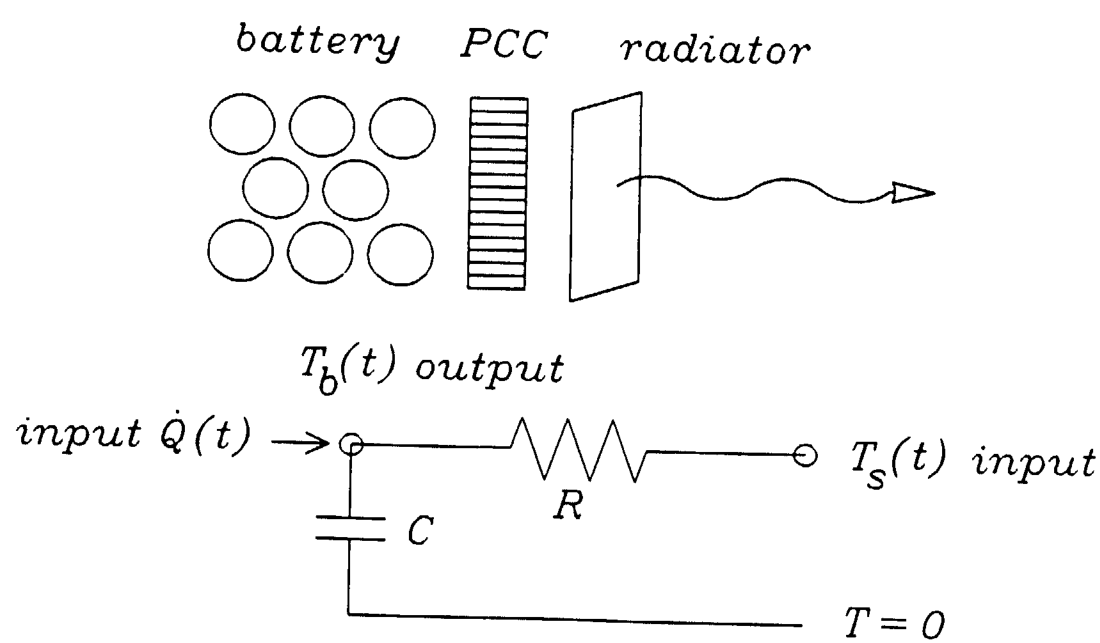
Phase 2 objectives

- PCC-TES prototype development
- reliability testing

THERMAL MODELING

For qualitative system study use two-node RC model

- lump battery and TES capacity into single node
- couple node to space node via radiator resistance
- input cell heat record and space temperature
- predict battery transient temperatures

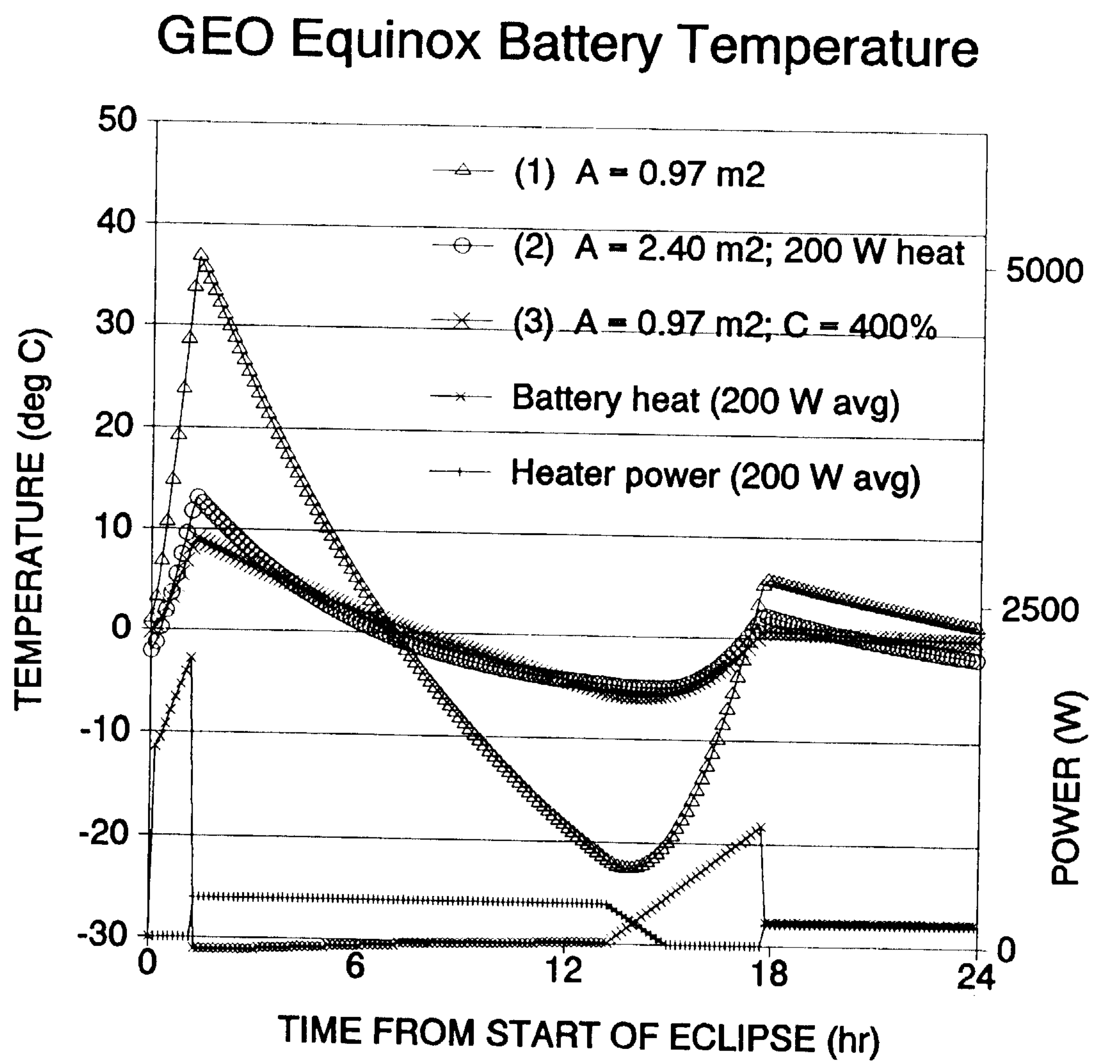


GEO Ni-H2 BATTERY TEMPERATURES

Calculate temperature response of battery using 2-node model for different heater, radiator and TES configurations.

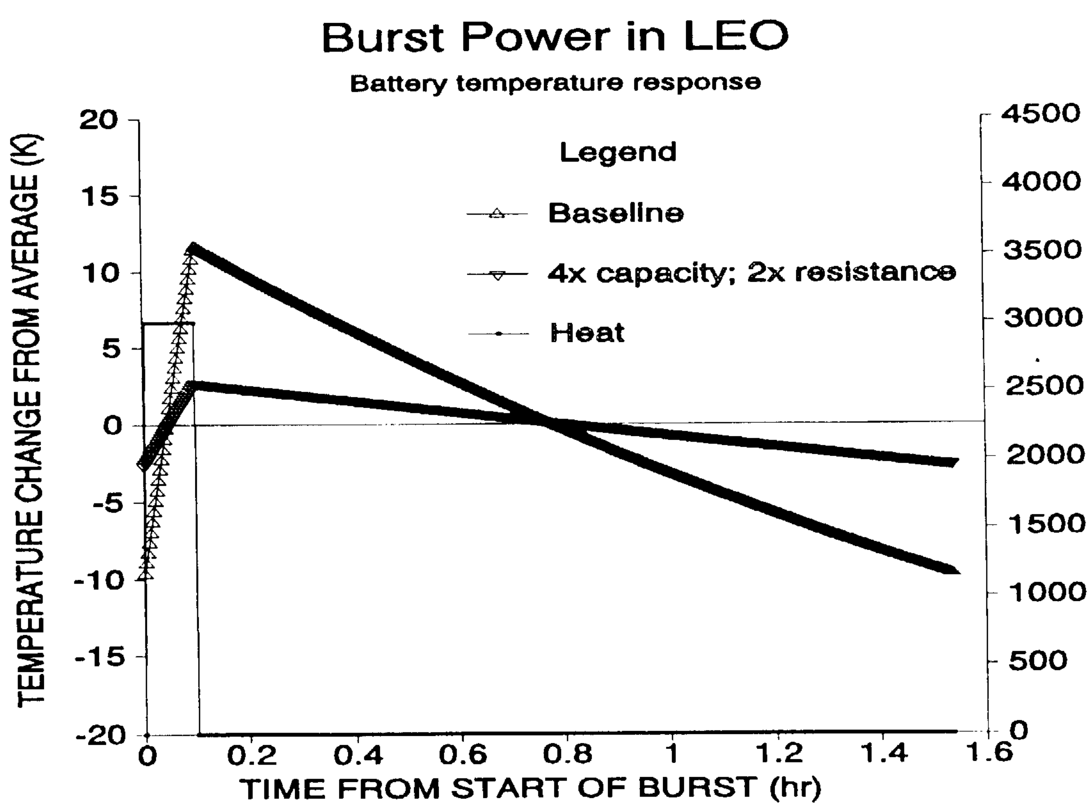
	COMPONENT WEIGHT (lbs)					
	Battery	Thermal Control System (TCS)				Battery + TCS
		Radiator + heat pipes	Heater subsystem	PCC-TES subsystem	Total TCS	
Case 1	450	26	0	0	26	476
Case 2	450	65	66	0	131	581
Case 3	450	26	0	43	69	519

PCC-TES option (case 3) offers improved temperature control and 62 lb weight saving = 47% weight reduction of the TCS


GEO Equinox Battery Temperature
(1) A = 0.97 m2
(2) A = 2.40 m2; 200 W heat
(3) A = 0.97 m2; C = 400%
Battery heat (200 W avg)
Heater power (200 W avg)
TEMPERATURE (deg C)
50
40
30
20
10
0
-10
-20
-30
POWER (W)
5000
2500
0
0
6
12
18
24
TIME FROM START OF ECLIPSE (hr)

LEO Ni-H2 SURGE POWER BATTERY TEMPERATURES

Calculated temperature response of battery with 1 m2 radiator, compared with temperature response for 400% capacity.



SYSTEM BENEFITS SUMMARY

Potential system benefits:

- Improved cell temp control during high rate discharge
- Improved temperature uniformity across the battery
- Smaller, lighter radiator sized for average load
- Less heater power required
- Less reliance on active louvers, VCHPs
- More options for high rate, deep discharge use
- Less satellite repositioning for thermal control
- Fewer active control functions
- More satellite resources available for primary function

HIGH-C thermal control (PCC-TES) is best for short transients.
LOW-R thermal control (heat pipe radiators) is best for steady state.

Ni-H2 batteries do benefit from HIGH-C option, but PCC-TES components are not space qualified.

POTENTIAL APPLICATIONS

Retrofitting Ni-H2 for Ni-Cd batteries

- TES lowers peak load to radiator and may allow existing NiCad radiator area to be used for Ni-H2

GEO communications and data relay satellite

- TES may reduce battery temperature transients, reduce heater requirement, and reduce radiator size.

Multicell CPV batteries

- TES inside the vessel may reduce temperature gradients and reduce heat flux through vessel wall

LEO satellite surge battery power

- TES may lower peak battery temperatures in mobile telephone satellites over high traffic centers
- TES may lower peak battery temperatures in Space Based Radar

Other battery applications

- Na-S, Ni-MH2

1992 NASA Aerospace Battery Workshop

N93-20525

November 17-19, 1992
U.S. Space and Roket Center
Huntsville, AL

Cathodes For Molten-Salt Batteries

CONTRACT NO. DAAL01-91-C-0111
US ARMY LABCOM, ETDL
SLCET/PR (Dr. W.K. Behl)
FORT MONMOUTH, NJ 07703-5000

SHYAM D. ARGADE
TECHNOCHEM COMPANY
203-A CREEK RIDGE ROAD
GREENSBORO, NC 27406-4419

This presentation is related to research on cathodes for molten-salt rechargeable lithium batteries for pulse power applications. The support of this Phase I SBIR program by the US Army Labcom, ETDC is gratefully acknowledged.

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CATHODES FOR MOLTEN SALT BATTERIES

- INTRODUCTION
- EXPERIMENTAL CELL
- RESULTS AND DISCUSSION
- PERFORMANCE PROJECTION
- CONCLUSIONS

For the cathode reactions in molten-salt cells, chlorine-based and sulfur-based cathodes reactants have relatively high exchange current densities. Sulfur-based cathodes, metal sulfides and disulfides have been extensively investigated. Primary thermal batteries of the Li-alloy/FeS_2 variety have been available for a number of years. In this research effort chlorine based rechargeable cathodes have been investigated for the pulse power application. A brief introduction is followed by the experimental aspects of research, and the results obtained. Performance projections to the battery system level are discussed and the presentation is summarized with conclusions.

INTRODUCTION

PHASE I SBIR PROGRAM OBJECTIVE

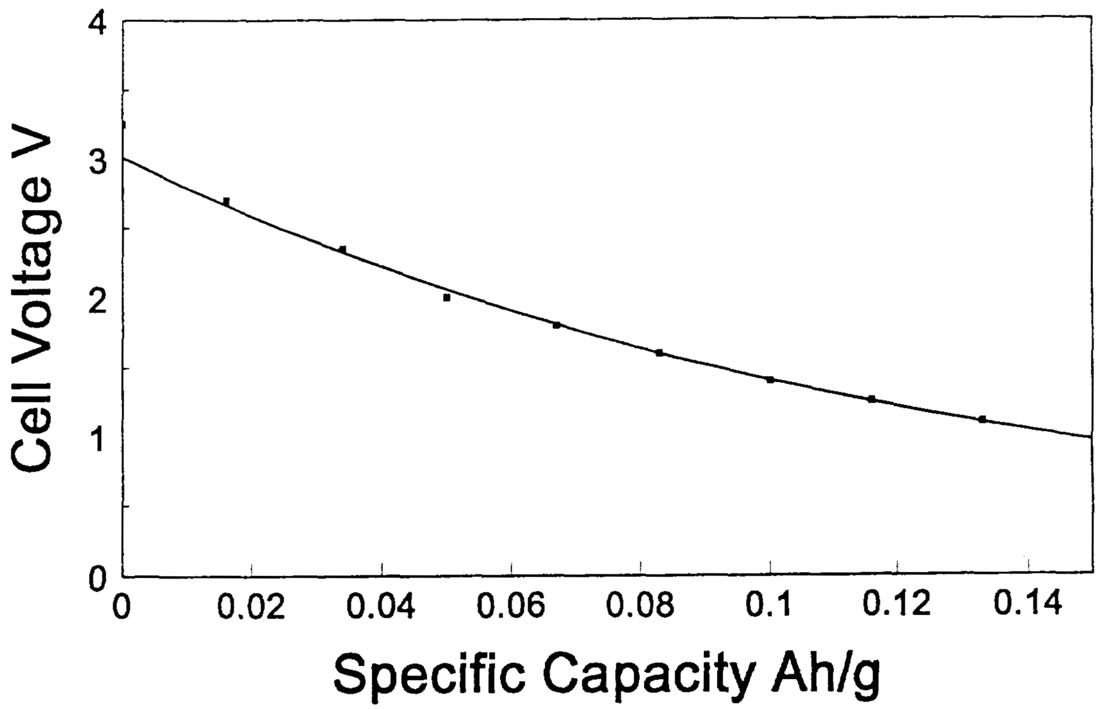
- RECHARGEABLE CHLORINE CATHODE ADDITIVES
- HIGH RATE CARBON CATHODES

In this battery system, during charge lithium is deposited to form the lithium aluminum alloy and chlorine formed is stored by adsorption on a high surface area carbon cathode. During discharge, lithium and chlorine dissolution reactions produce lithium chloride. Chlorine can be stored during charge as adsorbed chlorine or as a chlorine adduct. The objectives of this Phase I program are (1) to identify chlorine cathode additives to augment the storage capacity and (2) develop high rate carbon cathode structure while incorporating these additives.

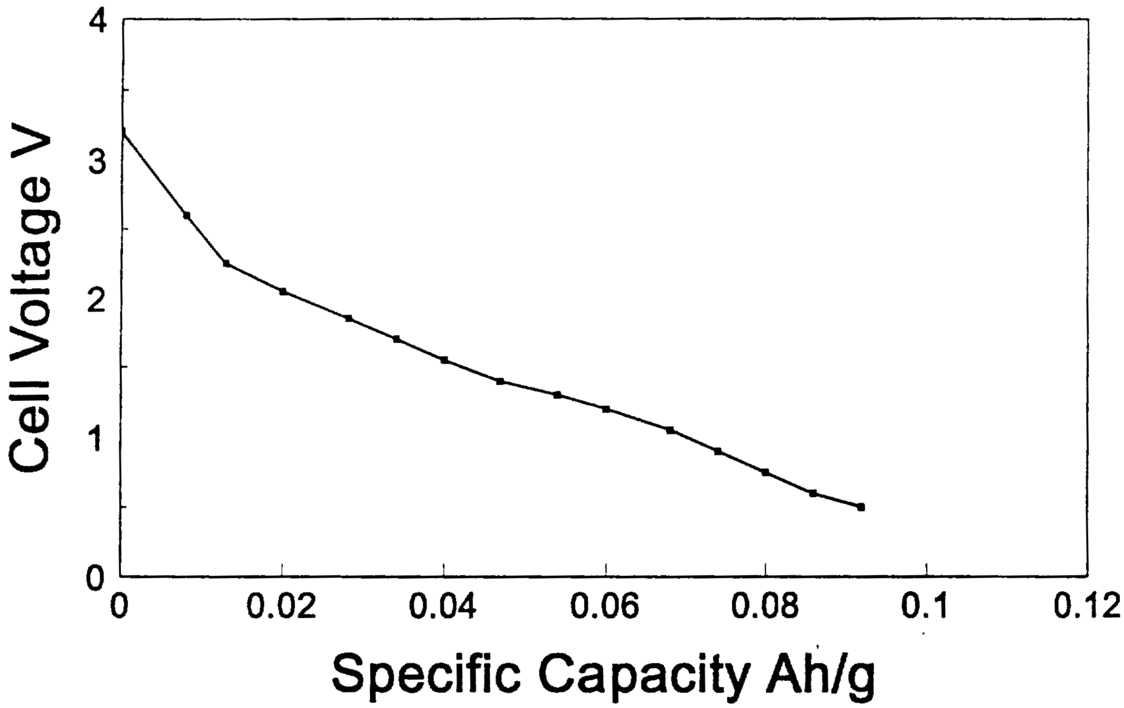
EXPERIMENTAL

- WAFER-STACK CELL
- NOMINAL 2" DIAMETER CELLS
- Li-Al ALLOY WAFERS
- CARBON BASED CATHODES
    - Tungsten carbide
    - Tungsten Disulfide
    - Molybdenum Disulfide
    - Vanadium Oxide
    - Tungsten Oxide
- LiCl-KCl SALT SEPARATOR WAFERS

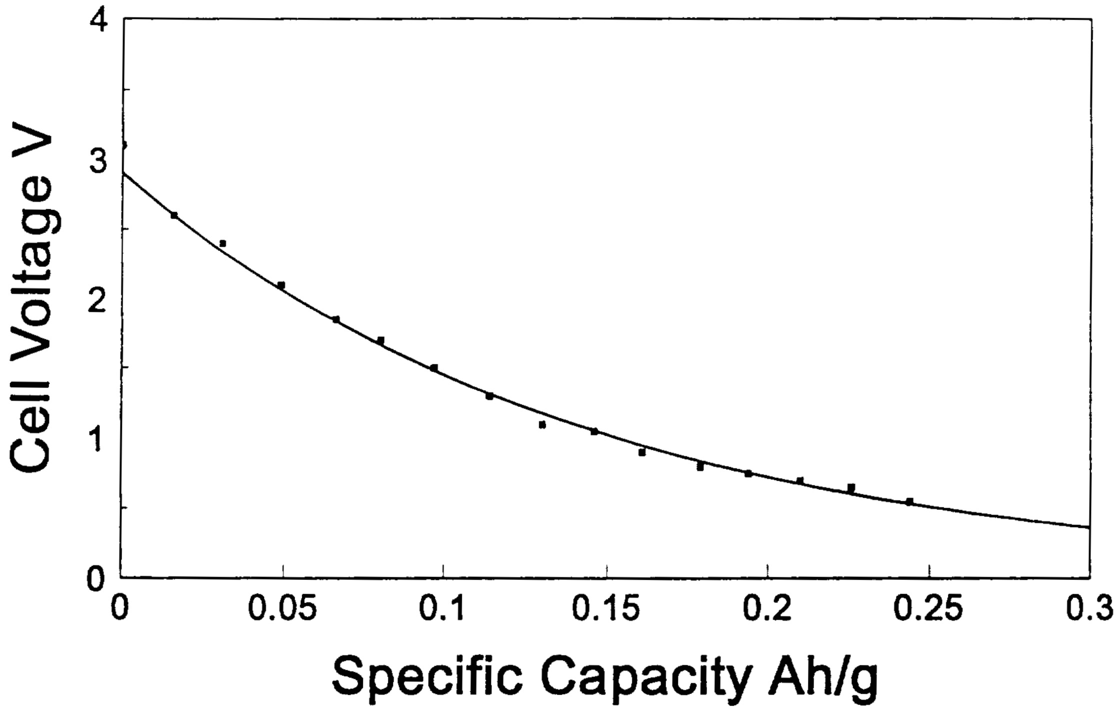
Experimental work was carried out with nominally 2" diameter wafer stack configuration cells, Li-Al anode wafer, LiCl-KCl salt separator wafer containing a molten-salt immobilizer compound and the carbon cathode wafer were used to form the cell. Additives identified above were incorporated in the carbon cathode wafers, using standard techniques.



Cell discharge profile for a Li-Al/carbon cathode cell, after being charged to a constant voltage of 3.30 V, is shown in this viewgraph. The cell voltage versus specific cathode capacity at 62 mA/cm^2 is shown for a plain carbon cathode. Please note the specific capacity is for cathode weight alone.



This viewgraph shows a similar discharge profile for a carbon cathode, incorporating tungsten carbide as the additive. The lower specific cathode capacity can be ascribed to the high specific gravity of tungsten carbide.



This discharge is for a cell consisting of a cathode that has tungsten disulfide as the additive. This cathode yields good capacity, while functioning as a chlorine cathode.

RESULTS

Discharge Capacities at Constant Current for Carbon + Additive Cathodes in Li-Al Molten Salt Cells

Cathode Type	OCV, V	Current Density, mA/cm^2	Sp. Cath. Cap. Ah/g
Carbon	3.30	62	0.18
VO_x + C	2.60	62	0.18
WO_3 + C	2.85	62	0.17

This table shows specific cathode capacity for three cathodes, carbon, VO_x + C, and WO_3 + C

RESULTS

Discharge Capacities at Constant Current for Carbon + Additive Cathodes in Li-Al Molten Salt Cells

Cathode Type	OCV, V	Current Density, mA/cm^2	Sp. Cath. Cap. Ah/g
WC + C	3.20	62 186	0.10 0.09
MoS_2 + C	2.80	62 124	0.14 0.14

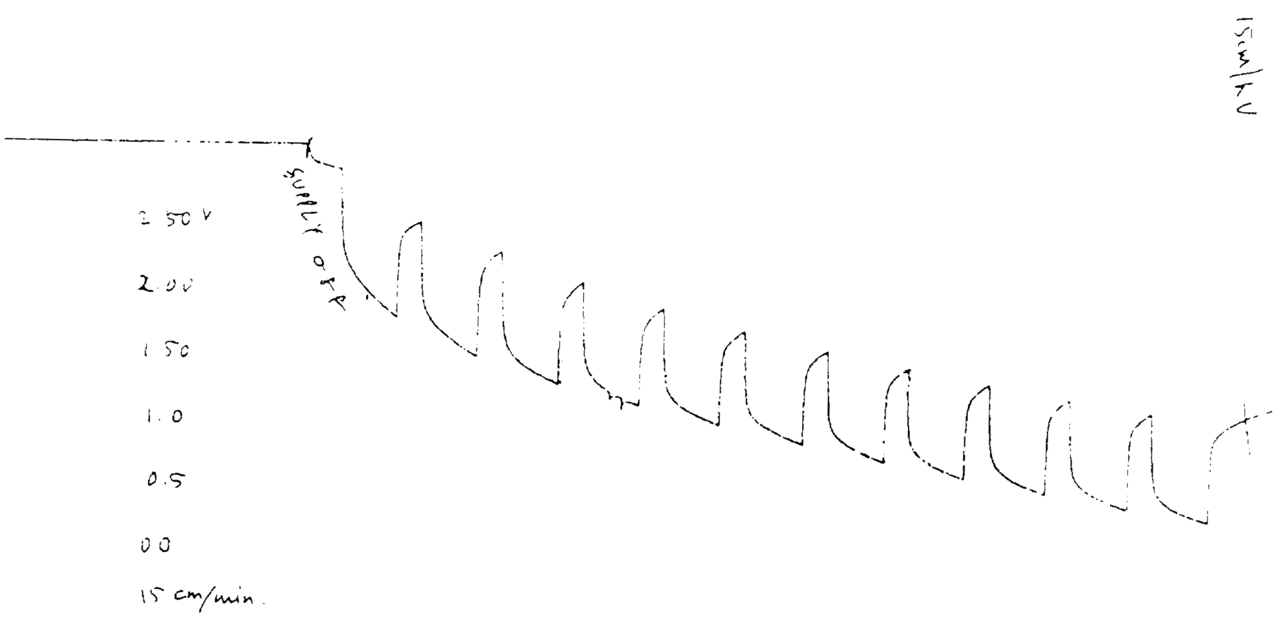
This viewgraph shows the specific cathode capacity for WC and MoS_2 as cathode additives.

RESULTS

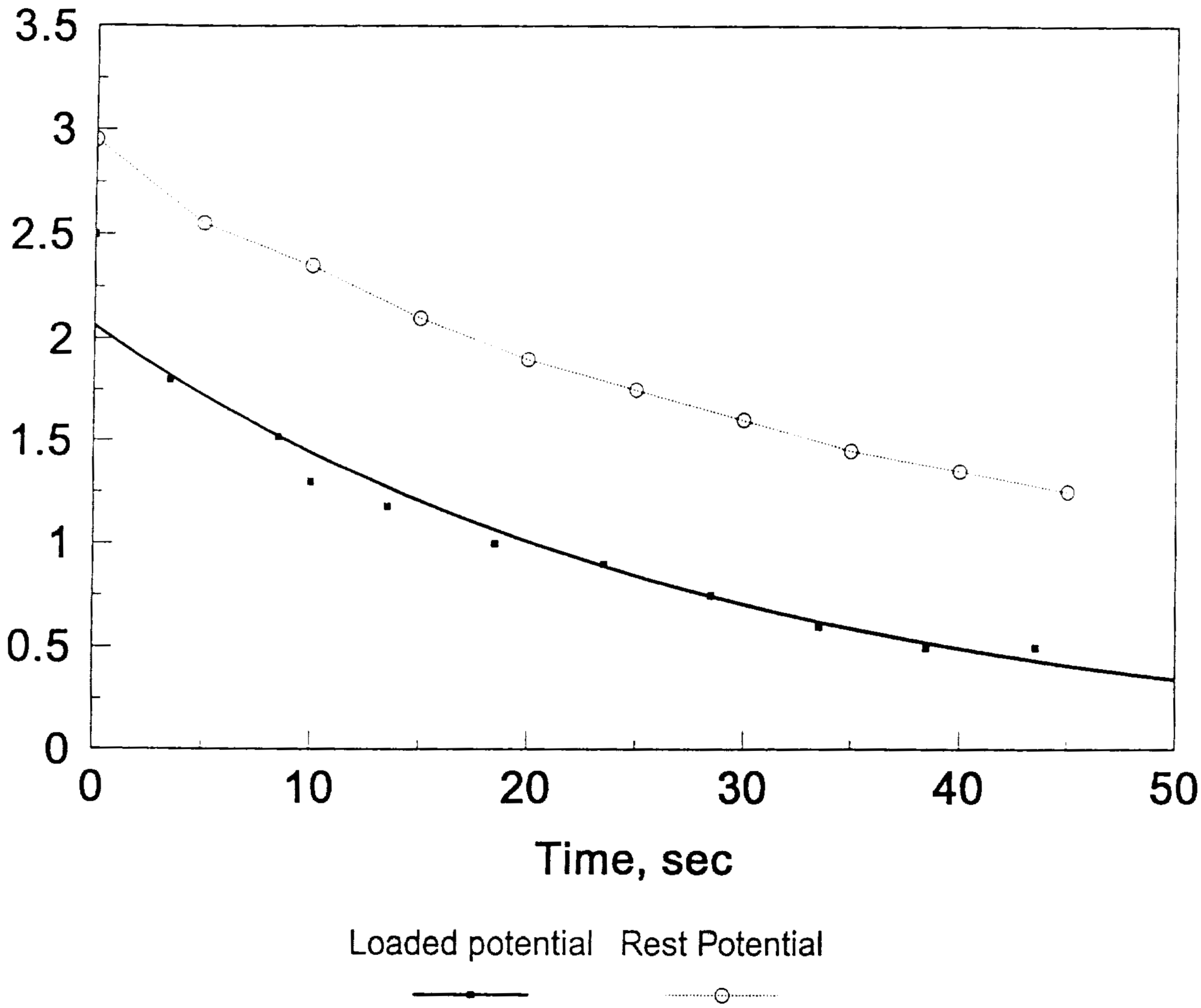
Discharge Capacities at Constant Current for Carbon + Additive Cathodes in Li-Al Molten Salt Cells

Cathode Type	OCV, V	Current Density, mA/cm^2	Sp. Cath. Cap. Ah/g
WS_2 + C	3.10	62	0.17
		124	0.21
		186	0.13
		248	0.17

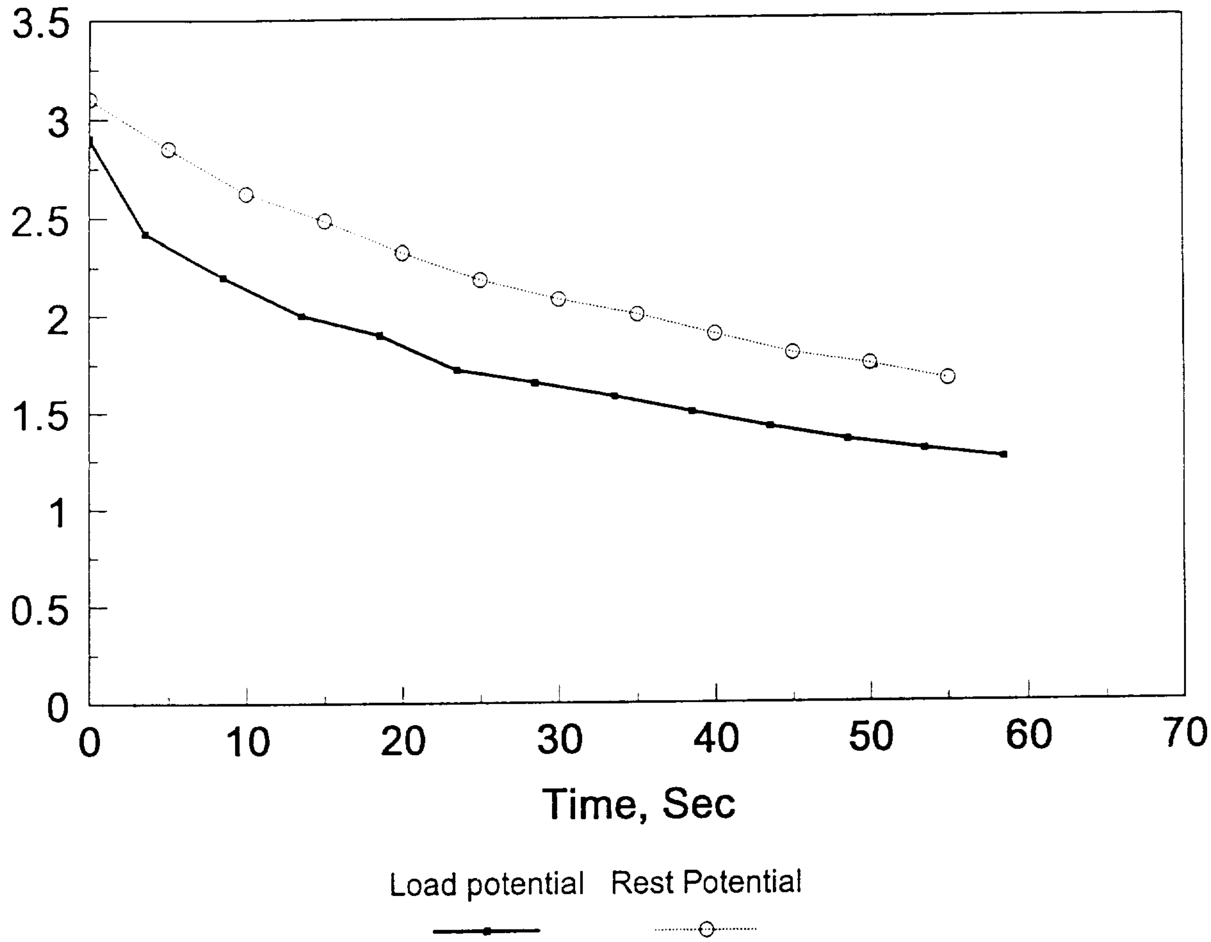
WS_2 additive gave good results. Even at relatively high discharge rates the delivered capacity does not decline significantly.



This work was oriented towards a pulse power batteryapplication. This viewgraph shows the recorder trace for repetitive pulse discharges for a WS_2 additive containing cathode. The pulse current density is 1 A/cm^2 with the pulse duration of 3.5 seconds and 1.5 seconds between pulses.



The same figure is shown as loaded cell voltage as a function time. The profile is similar in shape to the steady state discharge curve. The rest potential between pulses behaves in a similar manner.



This viewgraph shows the pulse discharge profile for a WC - carbon cathode containing cell operating at 310 mA/cm^2, 3.5 second pulse width, 5 seconds/pulse.

RESULTS
Pulse Delivery Characteristics of Cathodes Li-Al Molten Salt Cells

Cathode Type	Pulse Duration sec.	Current Density A/cm^2	No. of Pulses to (Volts)	Power Density W/cm^2	Total Energy Joules
WC-C	3.5 (5 s/pulse) 8 (10s/pulse)	0.248 0.372 0.372	12 (1.6) 10 (1.4) 4 (1.5)	0.64 1.13 0.93	340 483 370
VO_x-C	8 (10s/pulse)	0.312 0.625	5 (1.2) 7 (0.8)	0.5 0.9	292 488

This viewgraph shows the pulse delivery characteristics for various cathodes.

RESULTS
Pulse Delivery Characteristics of Cathodes Li-Al Molten Salt Cells

Cathode Type	Pulse Duration sec.	Current Density A/cm^2	No. of Pulses to (Volts)	Power Density W/cm^2	Total Energy Joules
Carbon	5	0.94	1	1.9	150
WS_2-C	3.5 (5 s/pulse)	0.312	14 (1.5)	0.7	439
		0.500	19 (1.5)	1.1	833
		0.625	19 (1.0)	1.4	812
		0.75	14 (0.5)	1.7	746
		1.00	10 (0.5)	2.0	619

This table exhibits the pulse delivery data for WS_2 - carbon cathode containing cells. For 625 mA/cm^2 current density pulses, the cell delivered a total energy of 812 joules in 19 pulses. At 1 A/cm^2 it exhibited a pulse power density of 2 W/cm^2.

Performance Projections

- Bipolar Cell stack 3" Diameter Based on Experimental Results
- 3.5 s Pulses, 0.625 A/sq.cm

Based on Improved Performance

- 8-s Pulses, 0.625 A/sq.cm above 1.50 V

For performance projection, 3" diameter bipolar cell stack is used with the experimental results obtained and performance improvement using 8-second duration pulses.

Performance Projection
System Level, 1 A/sq. cm

	Specific Power	Power Density
1 st pulse	3.2 kW/kg	5.5 kW/L
Av. Pow. 10 pulses	1.8	3.0

Specific power and power density are shown.

Performance Projection
System Level

	Specific Energy	Energy Density
Present	82 kJ/kg	140 kJ/L
Improved	145	248

Specific energy and energy density for the two cases are shown here.

CONCLUSIONS

- CARBON-BASED CHLORINE CATHODES WITH ADDITIVES
- SPECIFIC CATHODE CAPACITY 0.14 Ah/g-0.20 Ah/g
- REPETITIVE 3.5-S AND 8-S PULSES WITH 1.5 AND 2 SEC INTERVAL RESPECTIVELY
- POWER PERFORMANCE 1.5-2 W/sq.cm.
- PROJECTION TO THE SYSTEM LEVEL
  - 82 kJ/kg, 140 kJ/L - PRESENT RESULT
  - 145 kJ/kg, 248 kJ/L - IMPROVED RESULTS

This viewgraph summarizes the presentation.

Bipolar Rechargeable Lithium Battery For High Power Applications

Presented to the

NASA Aerospace Battery Workshop

NOVEMBER 17–19, 1992

U.S. Space and Rocket Center

Huntsville AL

S. Hossain, G. Kozlowski and F. Goebel

Yardney Technical Products, Inc.

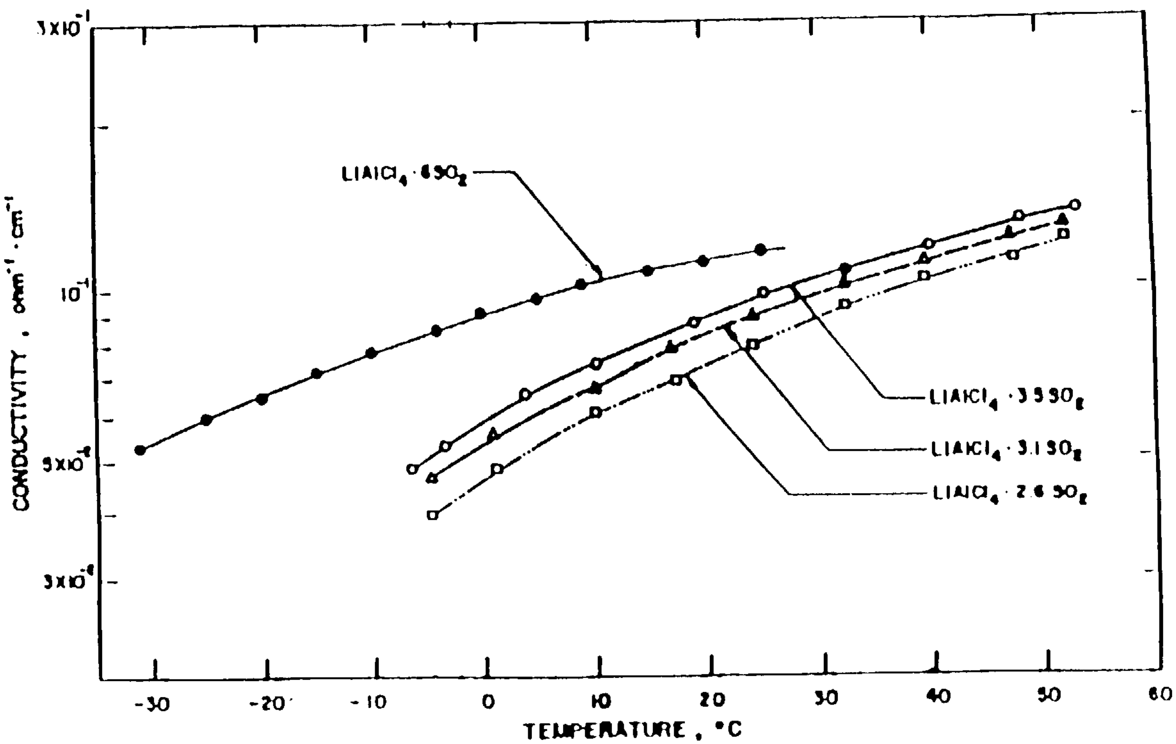
82 MECHANIC STREET, PAWCATUCK CT 06379

Bipolar Rechargeable Lithium Battery: CELL CHEMISTRY

Anode or Negative Electrode	:	Li
Cathode or Positive Electrode	:	$CuCl_2$
Electrolyte	:	SO_2 based $LiAlCl_4$
OCV	:	3.45V versus Li

NO organic electrolytes offer as high conductivity as SO_2-based electrolytes

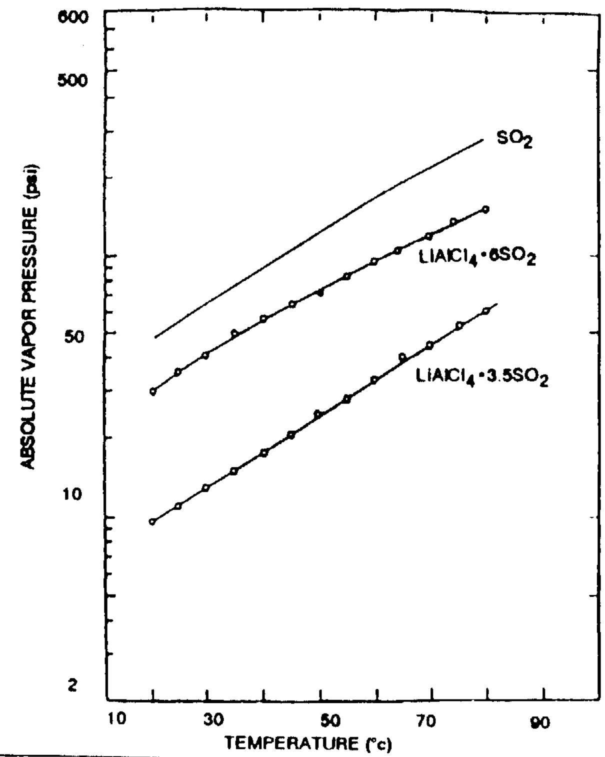
Conductivity of $LiAlCl_4/SO_2$ Electrolytes at Various Temperatures



Kuo et al, Duracell Final Report, Contract No. DOE-DE-AC01-80ER-10191 (1985)

Vapor-pressure lower than atmospheric pressure can be achieved with SO_2-based electrolytes.

Vapor Pressures of $LiAlCl_4/SO_2$ Electrolytes at Various Temperatures



Kuo et al, Duracell Final Report, Contract No. DOE-DE-AC01-80ER-10191 (1985)

Bipolar Rechargeable Lithium Battery: ELECTROLYTE ADVANTAGE

SO_2 based Li–ion conducting electrolytes offer several advantages

- High ionic conductivity ($1 \cdot 1 \times 10^{-2}$ Scm^{-1})
- Excellent electrochemical voltage window
- Limited overcharge tolerance
- Very low shelf–discharge rate (<0.1% per month)
- Insignificant Li–anode passivation

Bipolar Rechargeable Lithium Battery: REACTION MECHANISMS

The use of high surface area carbon and SO_2−based $LiAlCl_4$ electrolyte provides extra capacity before SO_2−reduction occurs.

Discharge

Anode: $Li \rightarrow Li^+ + e^-$

Cathode:

1. $Cu^{++} + e \rightarrow Cu^+$ (~ 3.4 versus Li)
2. $LiAlCl_4 \bullet 3SO_2 + xC + 3e^- \rightarrow LiClAl \left\langle \begin{array}{c} OSO \\ OSO \\ OSO \end{array} \right\rangle Cx + 3Cl^-$
3. $2SO_2 + 2e^- \rightarrow S_2O_4^{=}$ (~ 2.8V versus Li)
4. $Cu^+ + e \rightarrow Cu^0$ (~ 2.5V versus Li)

Charge

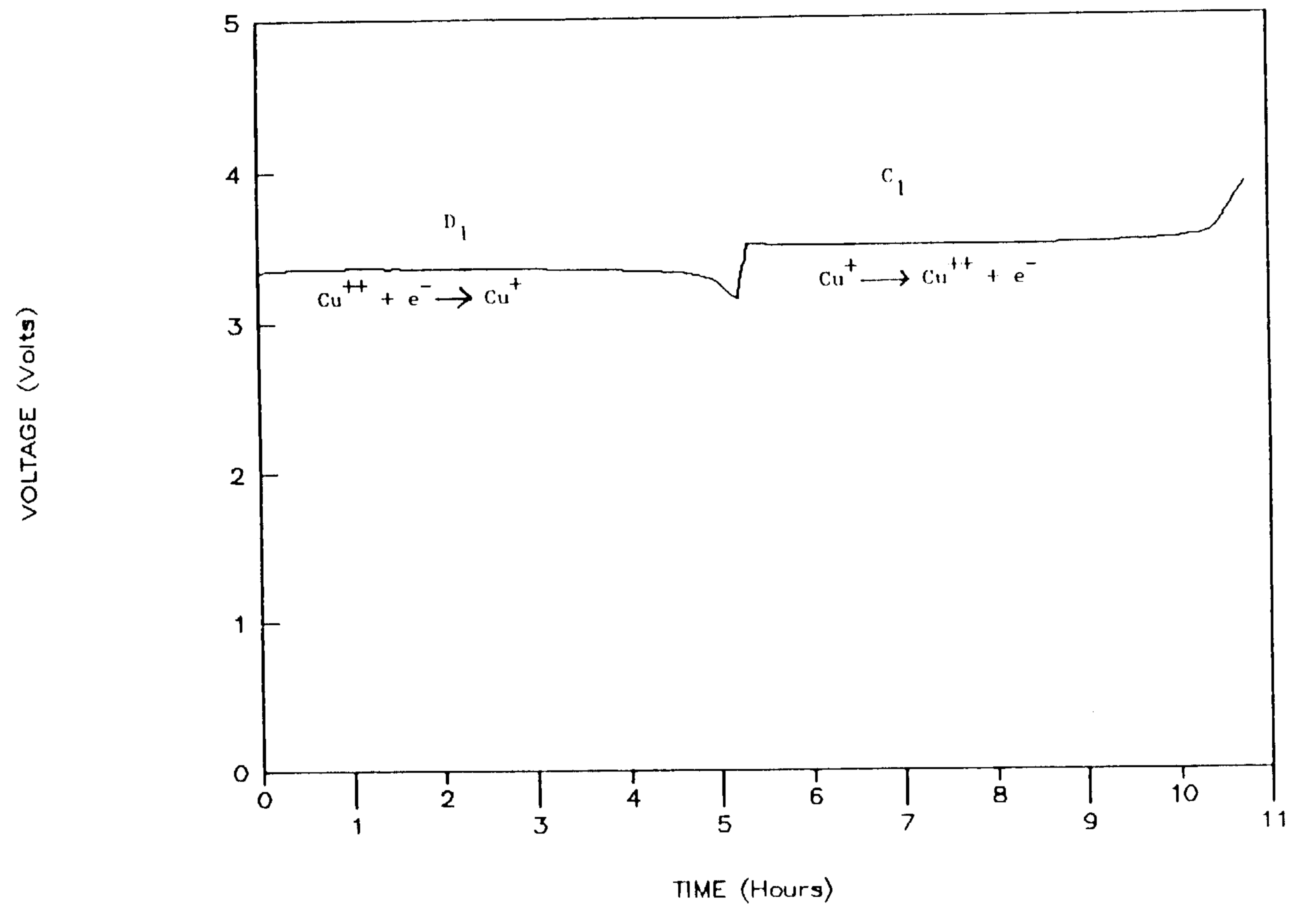
Anode: $Li^+ + e \rightarrow Li$

Cathode: $Cu^+ \rightarrow Cu^{++} + e$ (~ 3.5V versus Li)

$LiClAl(OSO)_3 \bullet xC + 3Cl^- \rightarrow LiAlCl_4 \bullet 3SO_2 + xC + 3e^-$ (~ 3.65V versus Li)

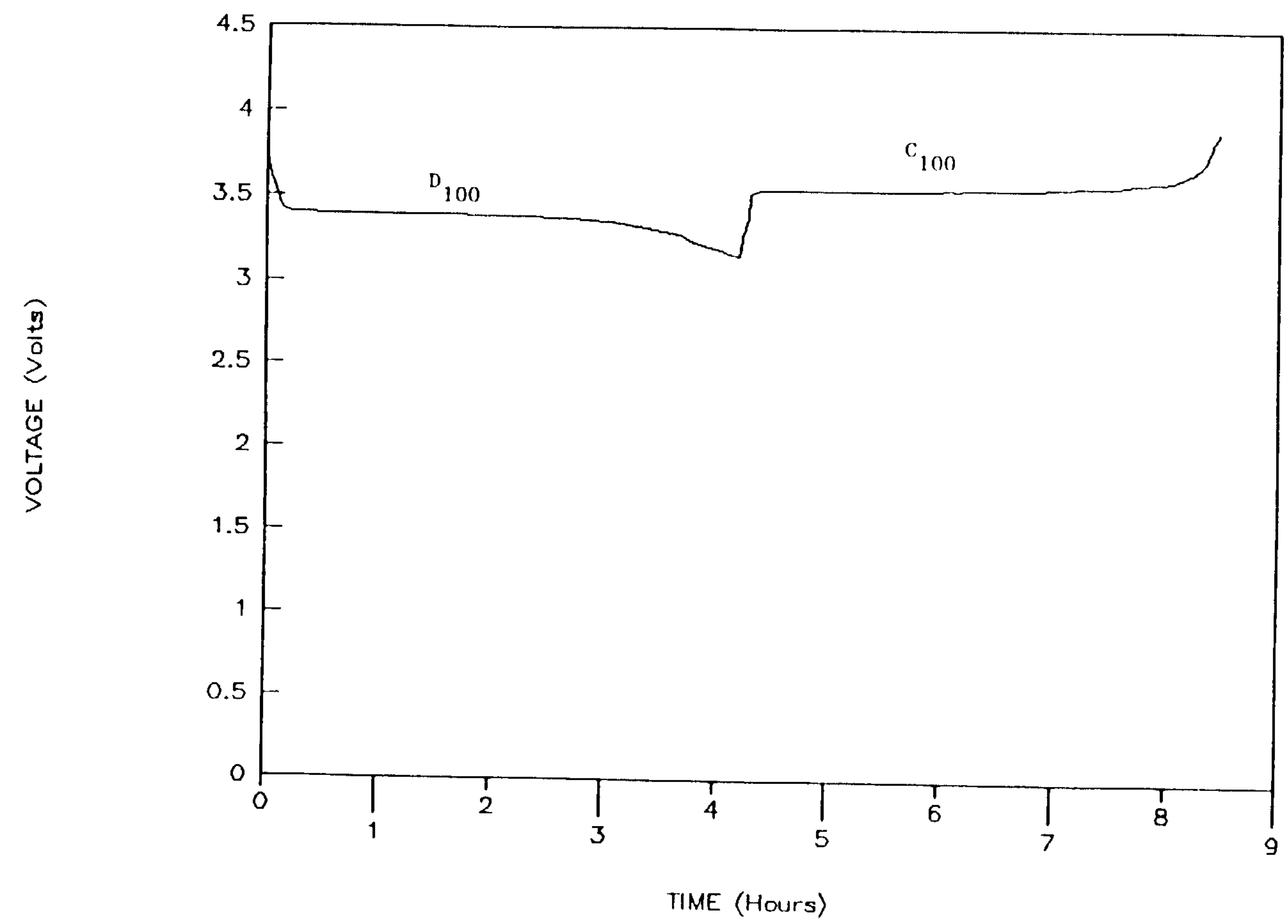
$LiAlCl_4 \rightarrow Li^+ + AlCl_3 + \frac{1}{2}Cl_2 + e^-$ (~ 3.9V versus Li)

$Li/CuCl_2$ Rechargeable Cells: CYCLING BEHAVIOR



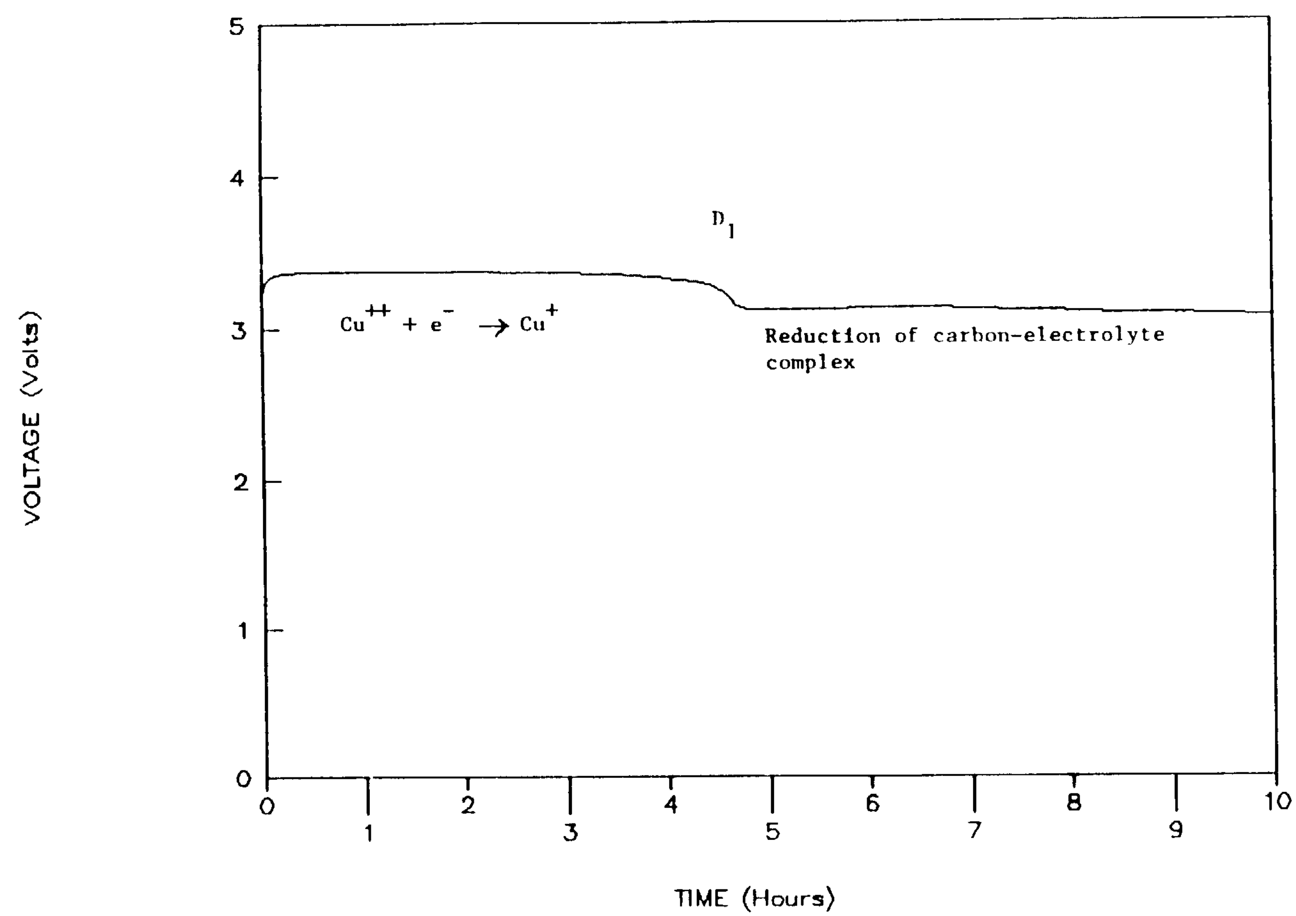
Discharge/charge behavior of a $Li/CuCl_2$ cell in $LiAlCl_4 \bullet 6SO_2$ electrolyte at 1mA/cm^2

Li/$CuCl_2$ Rechargeable Cells: CYCLING BEHAVIOR



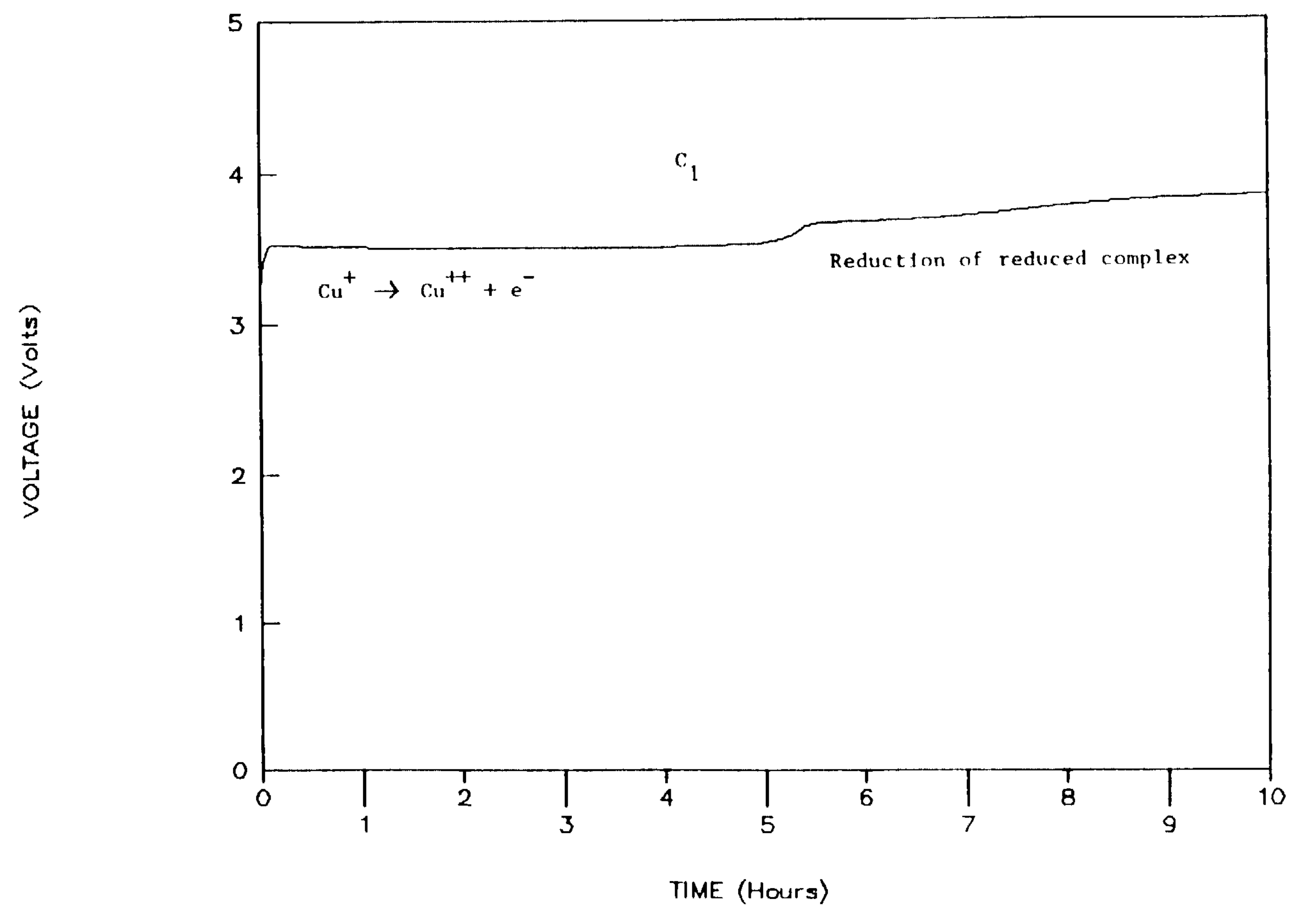
Discharge/charge behavior of a Li/$CuCl_2$ cell in $LiAlCl_4 \bullet 6SO_2$ electrolyte at 1mA/cm^2

$Li/CuCl_2$ Rechargeable Cells: CYCLING BEHAVIOR



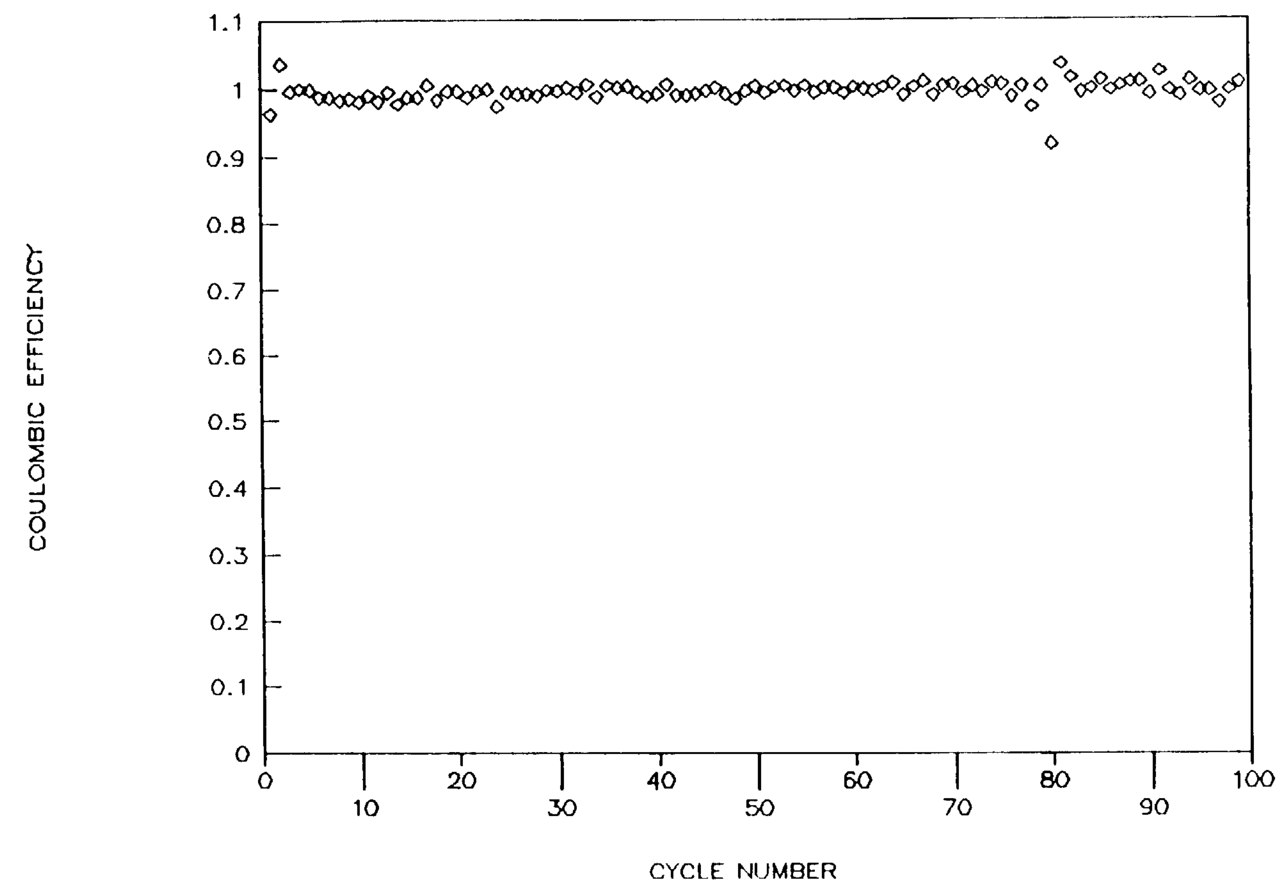
Discharge behavior of a $Li/CuCl_2$ rechargeable cell in $LiAlCl_4 \bullet 6SO_2$ electrolyte at $1 mA/cm^2$

$Li/CuCl_2$ Rechargeable Cells: CYCLING BEHAVIOR

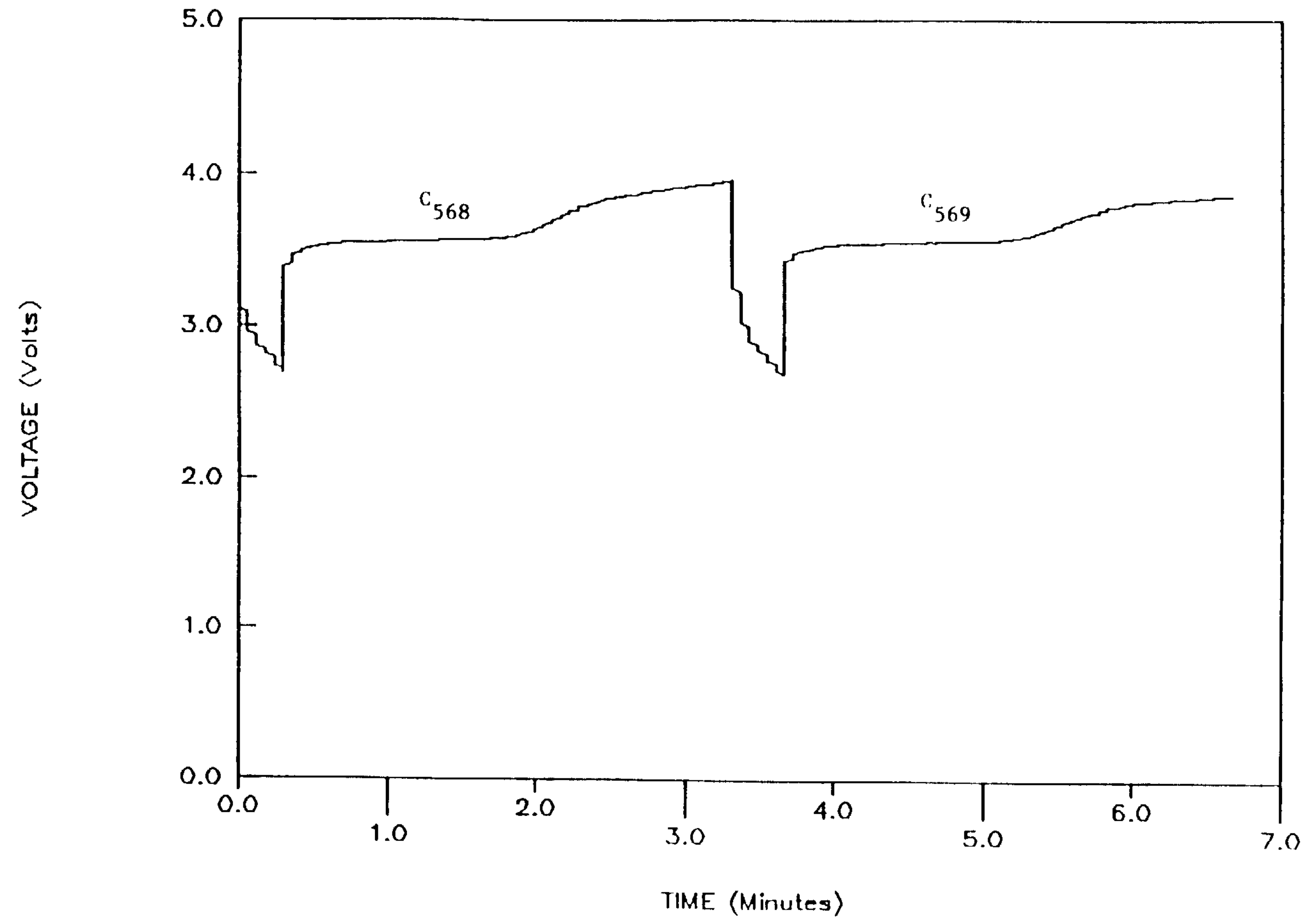


Charge behavior of a $Li/CuCl_2$ cell in $LiAlCl_4 \bullet 6SO_2$ at $1 mA/cm^2$

Coulombic efficiency of 1 shows excellent cycling behavior

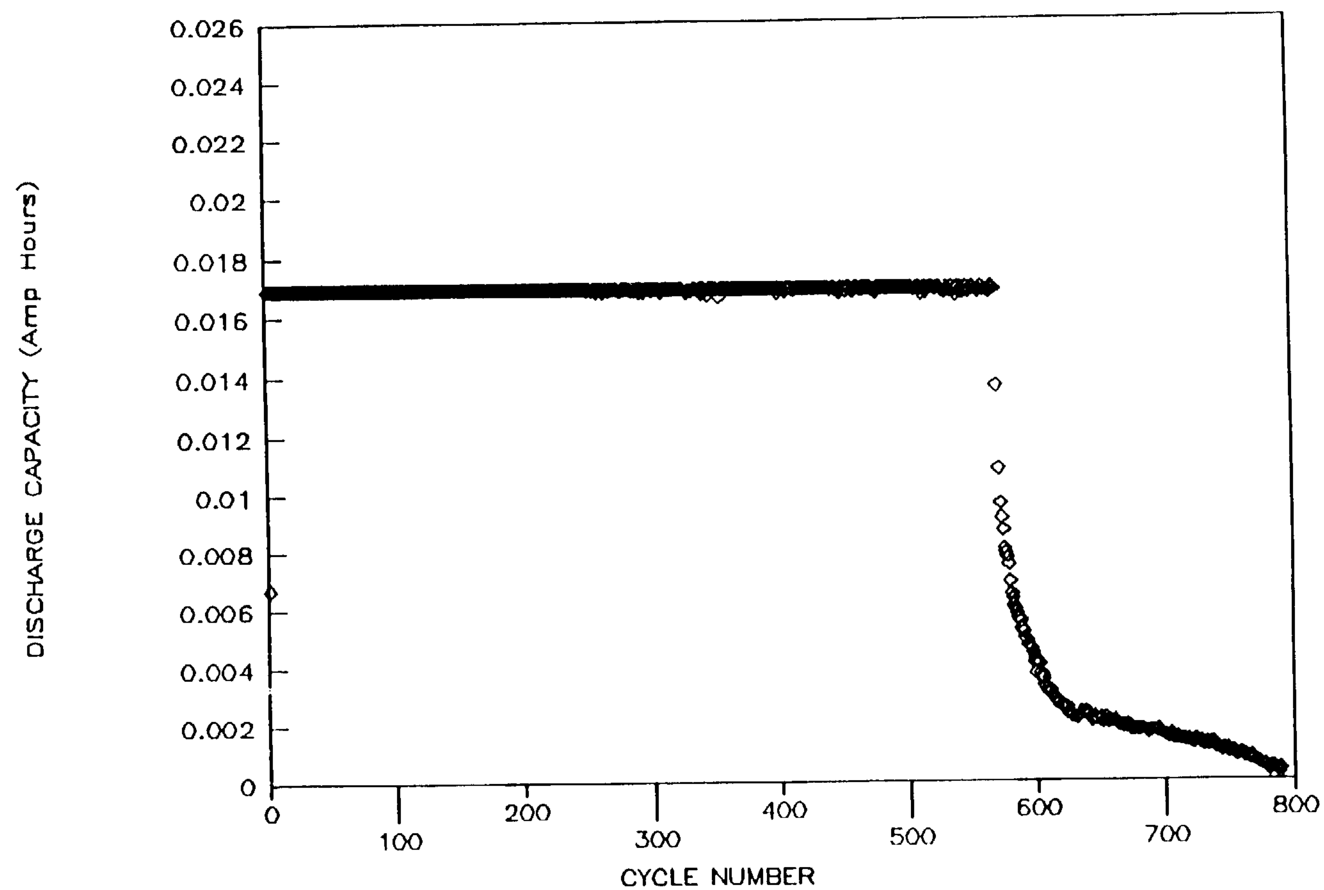


Coulombic efficiency of a Li/$CuCl_2$ cell at 1mA/cm^2 discharge/charge rate



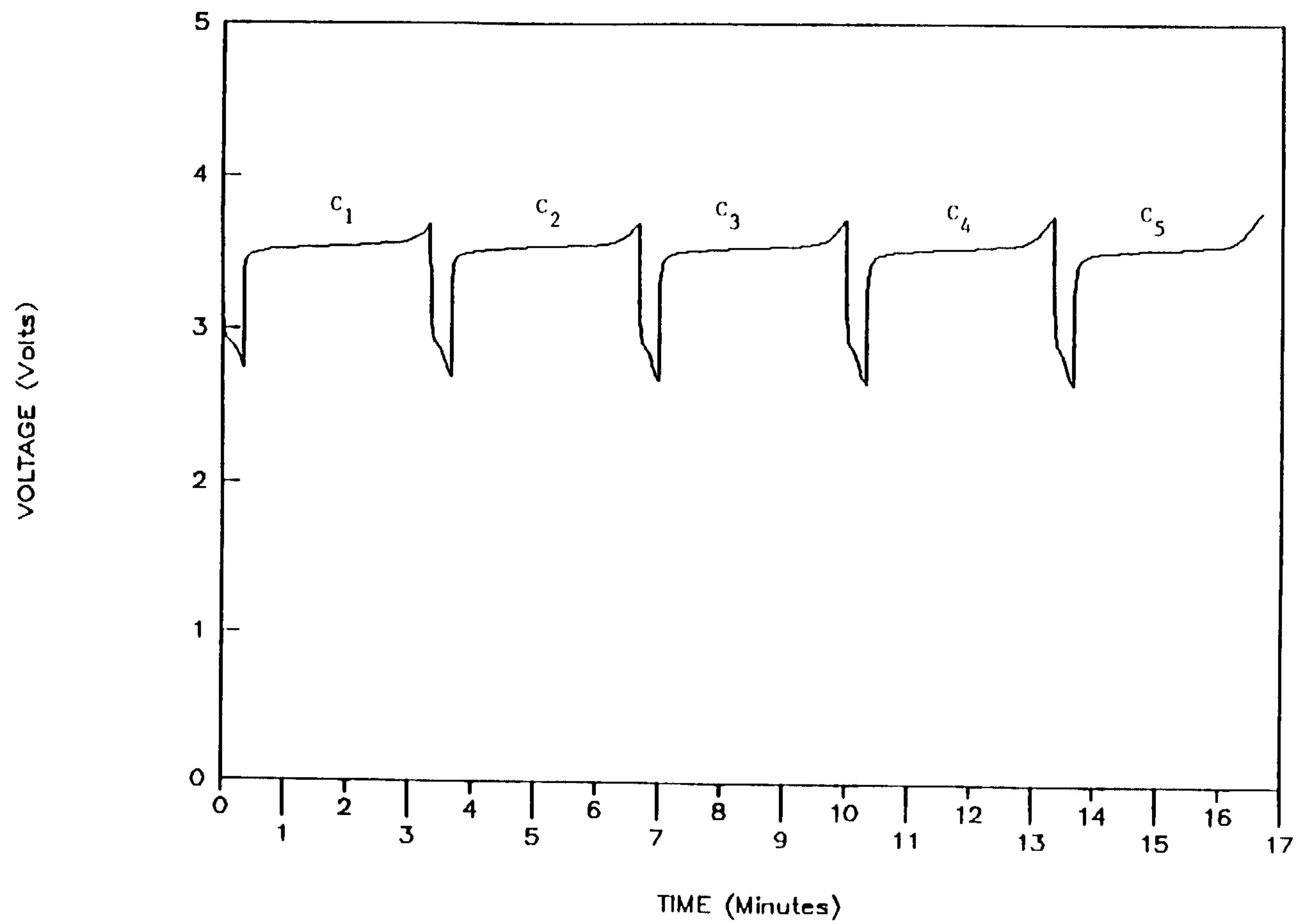
Discharge/charge behavior of a Li/$CuCl_2$ cell at 40mA/cm^2 discharge for 20 seconds and 4.44mA/cm^2 charge for 180 seconds.

Bipolar Lithium Rechargeable Batteries: CYCLE LIFE



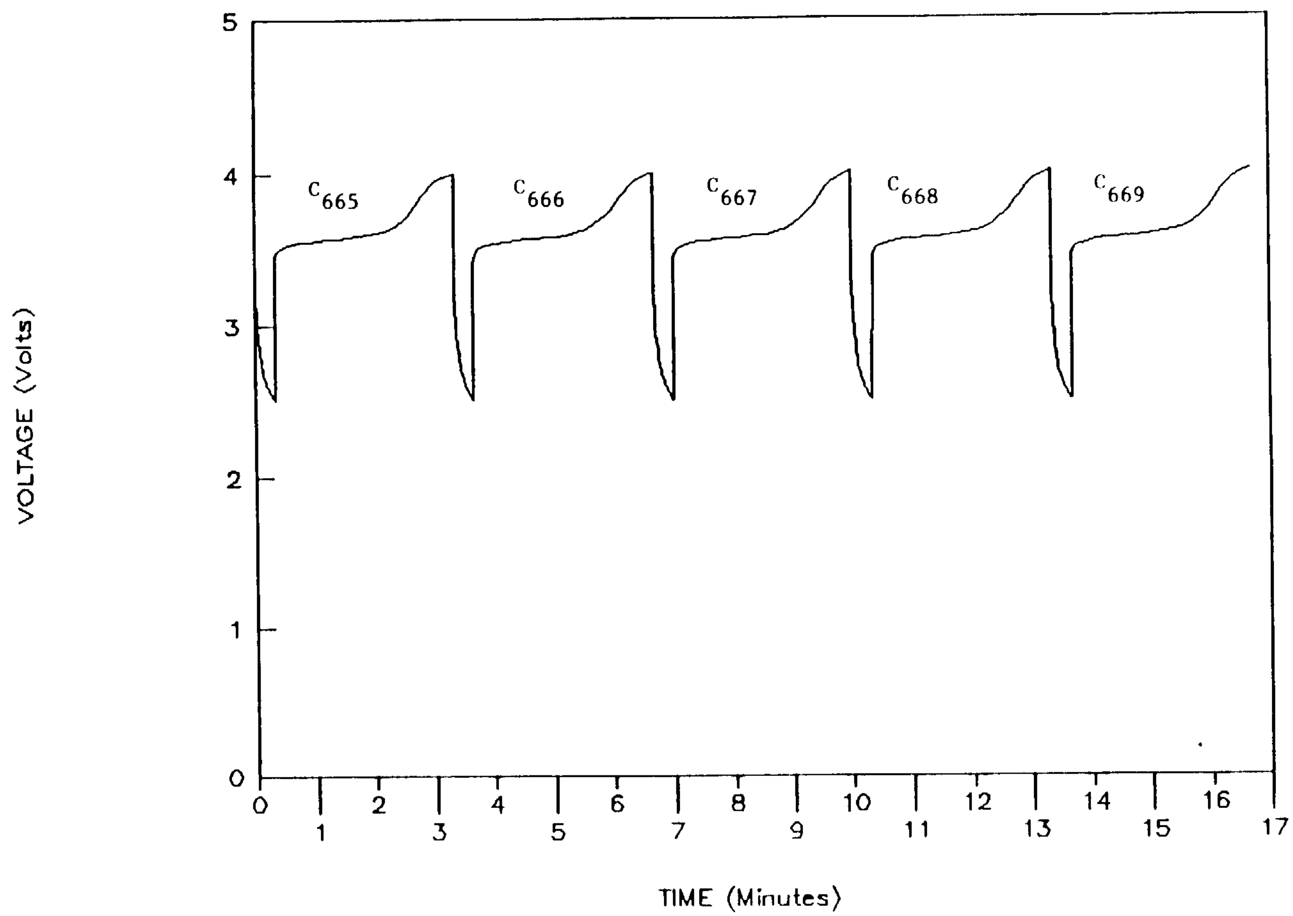
Cycle number vs capacity of a $Li/LuCl_2$ cell at $40mA/cm^2$ discharge for 20 seconds and $4.44mA/cm^2$ charge for 180 seconds. Voltage limits 2.5–4.0 V.

Bipolar Lithium Rechargeable Batteries: CYCLING BEHAVIOR



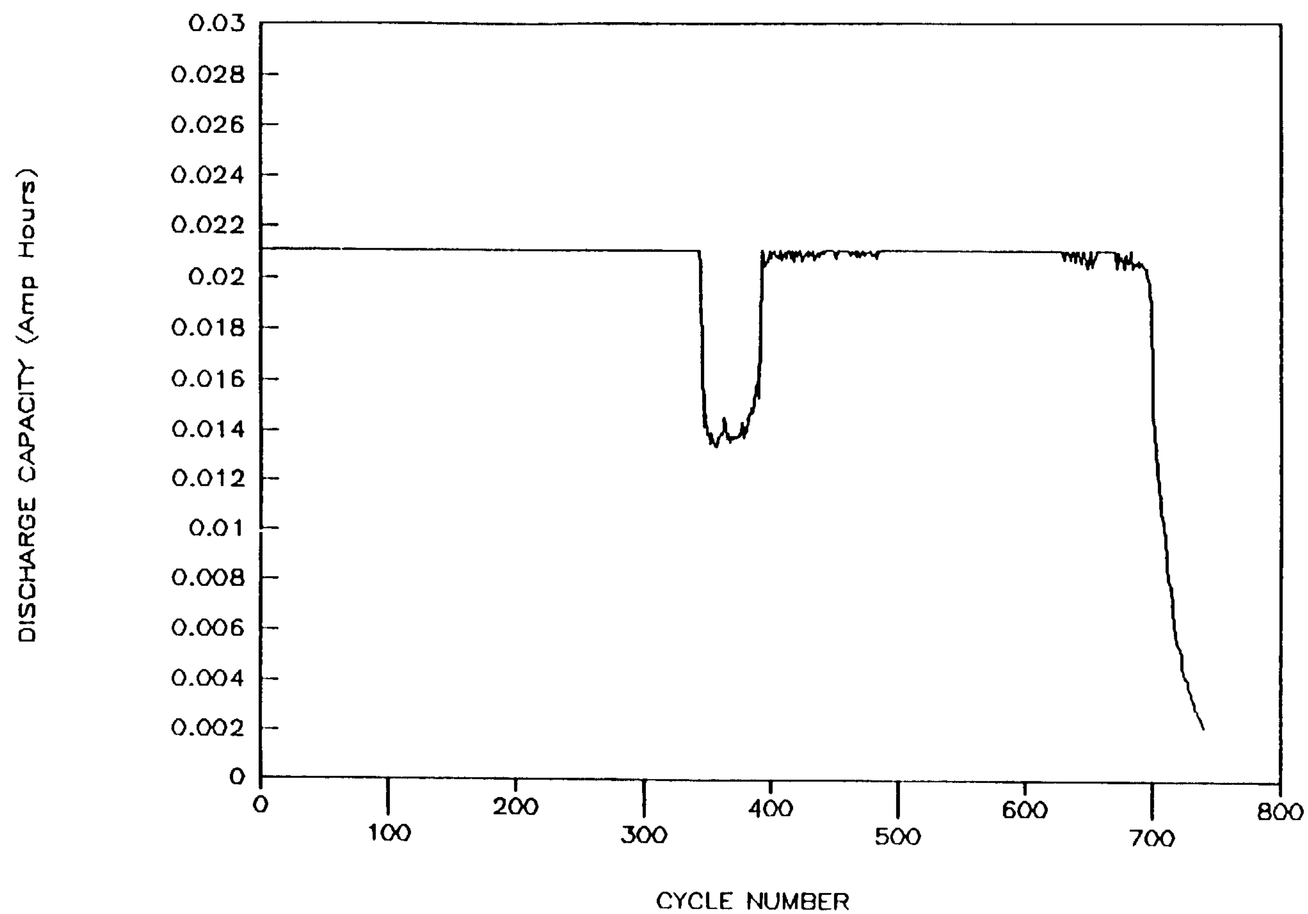
Discharge/charge behavior of a Li/$CuCl_2$ cell at 50mA/cm^2 discharge for 20 seconds and 5.56mA/cm^2 charge for 180 seconds.

Bipolar Lithium Rechargeable Batteries: CYCLING BEHAVIOR

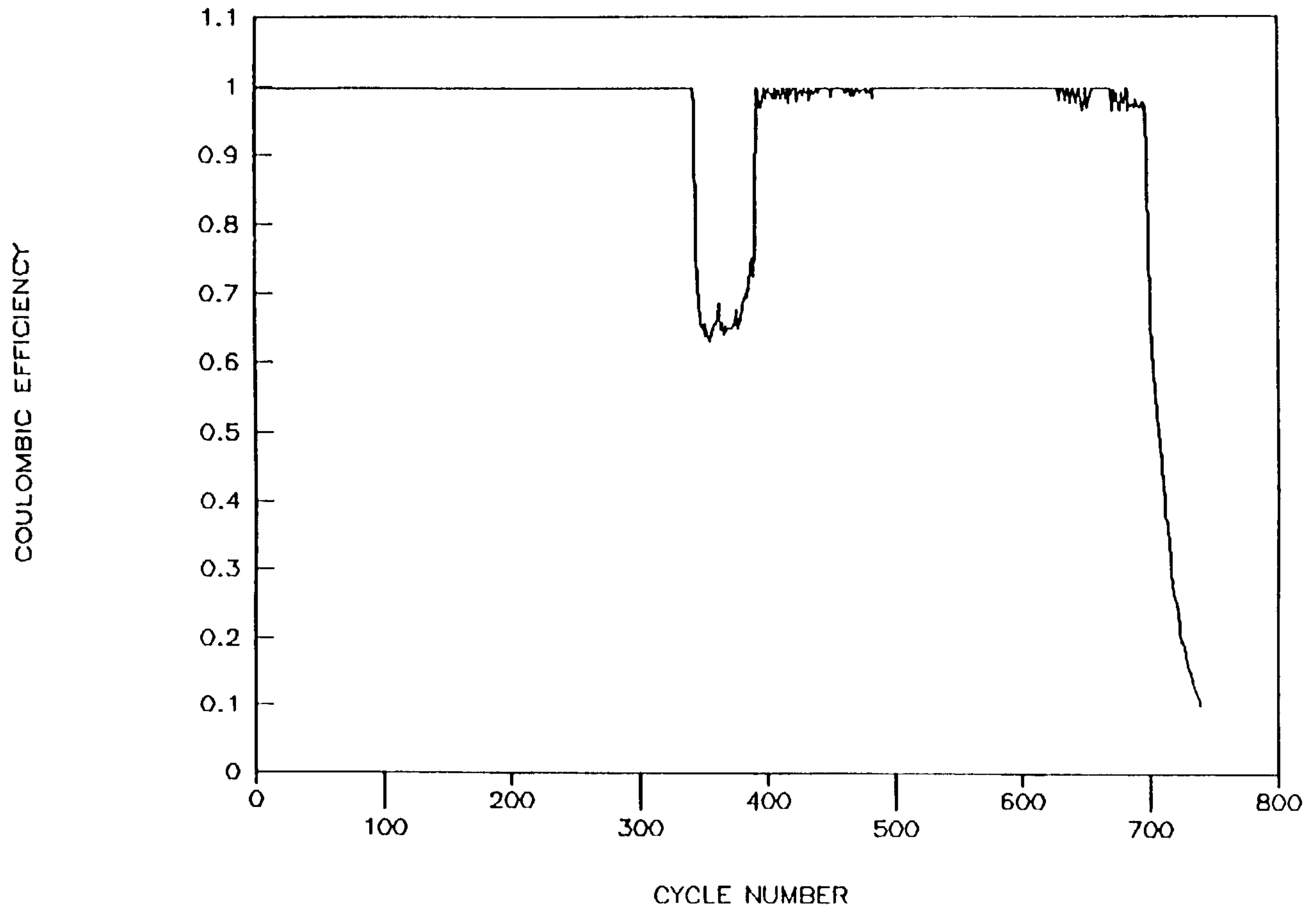


Discharge/charge behavior of a Li/$CuCl_2$ cell at 50mA/cm^2 discharge for 20 seconds and 5.56mA/cm^2 charge for 180 seconds.

Bipolar Lithium Rechargeable Batteries: CYCLE LIFE

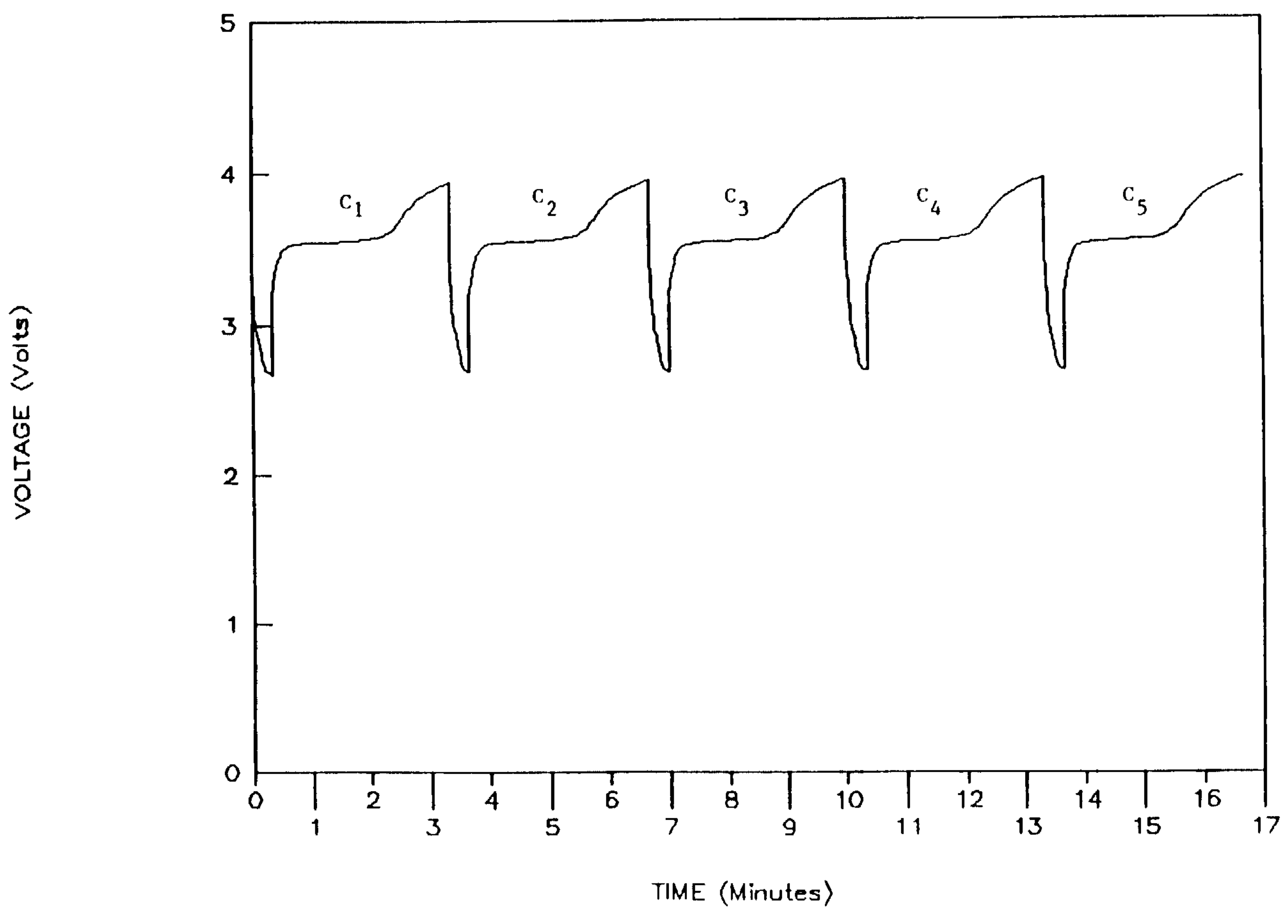


Cycle number vs capacity of a Li/$CuCl_2$ cell at 50mA/cm^2 discharge and 5.56mA/cm^2 charge for 180 seconds. Voltage limits: 2.5–4.0 V.



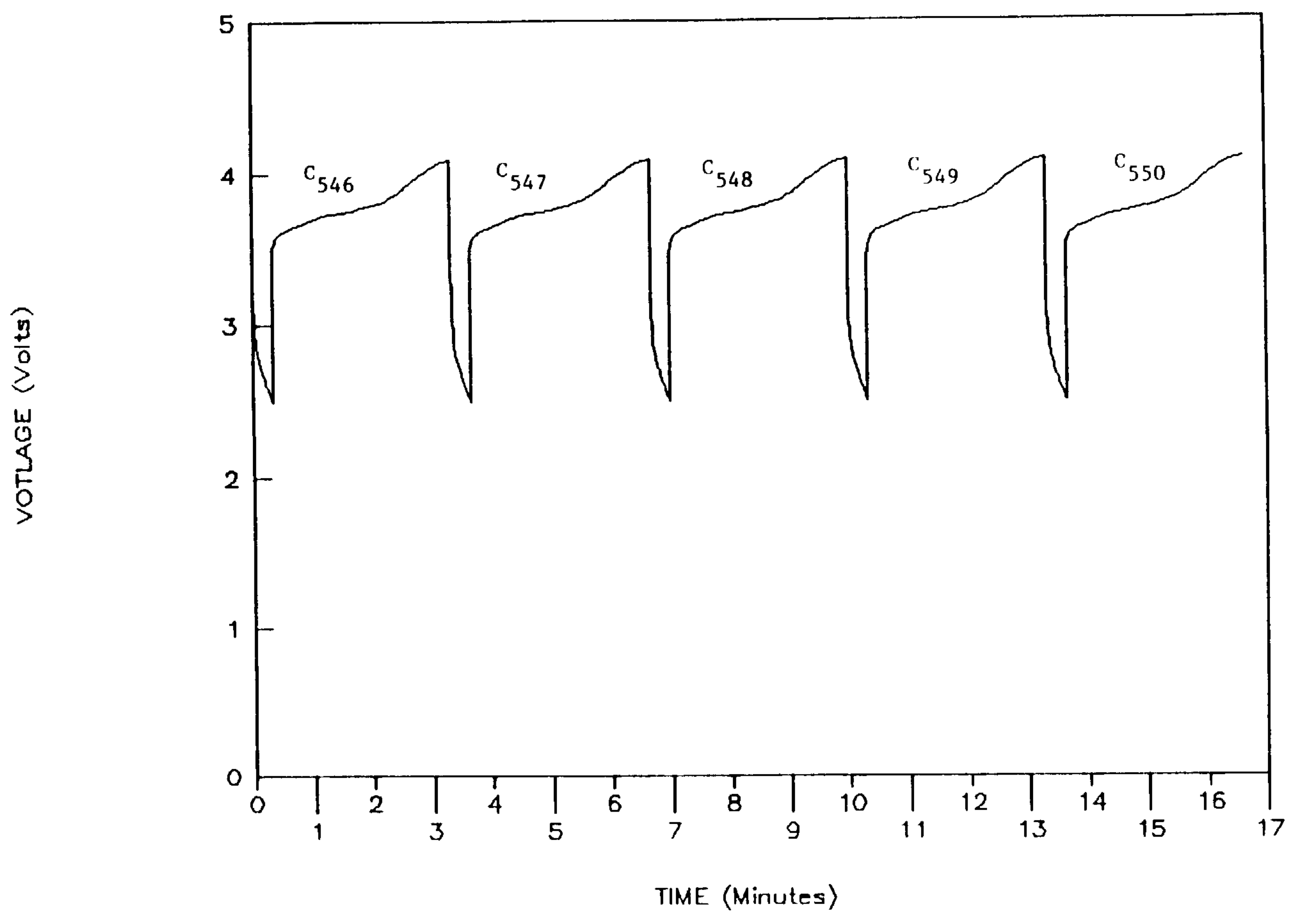
Coulombic efficiency of a Li/$CuCl_2$ cell discharged at 50mA/cm^2 for 20 seconds and charged at 5.56mA/cm^2 for 180 seconds

Bipolar Lithium Rechargeable Batteries: CYCLING BEHAVIOR



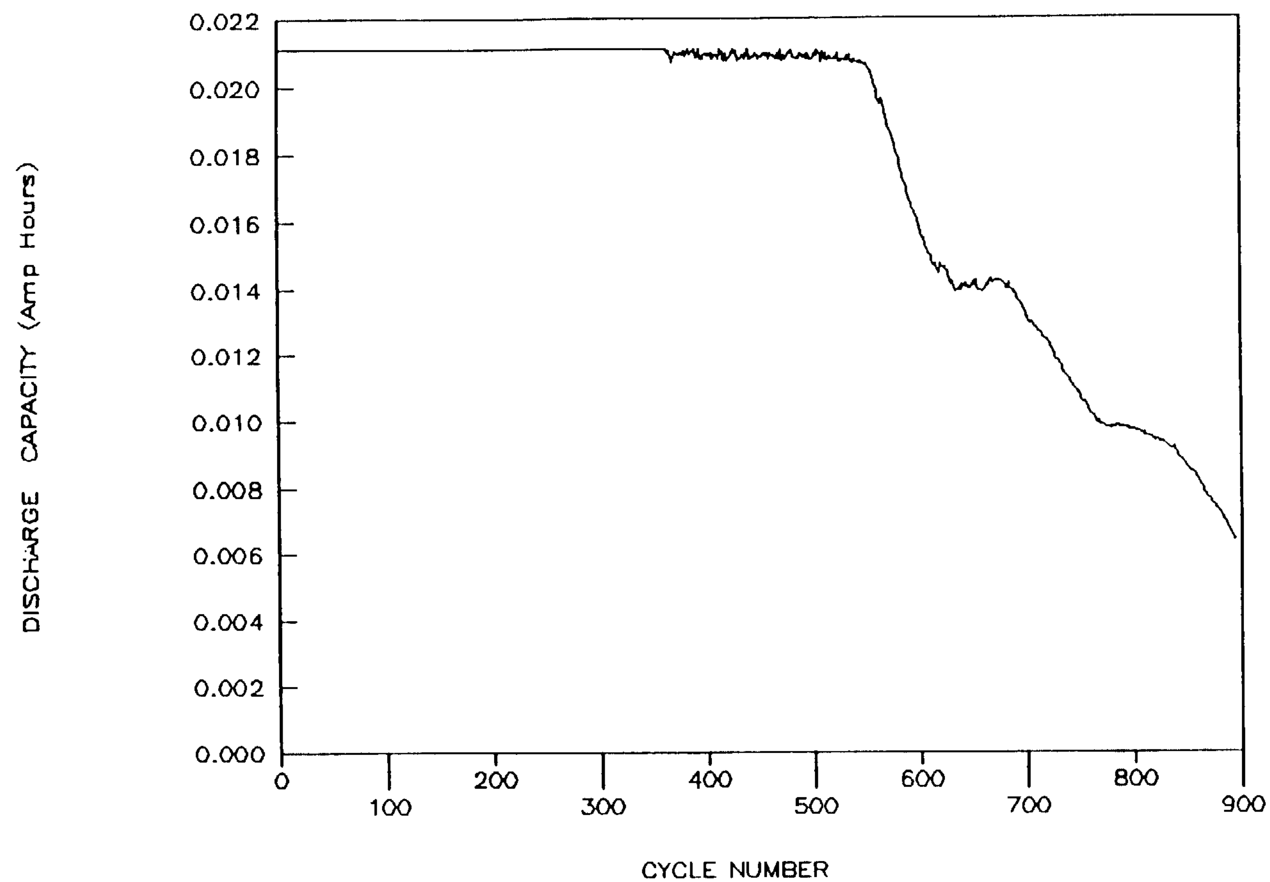
Discharge/charge behavior of a $Li/CuCl_2$ cell at 50mA/cm^2 discharge for 20 seconds and 5.56mA/cm^2 charge for 180 seconds

Bipolar Lithium Rechargeable Batteries: CYCLING BEHAVIOR



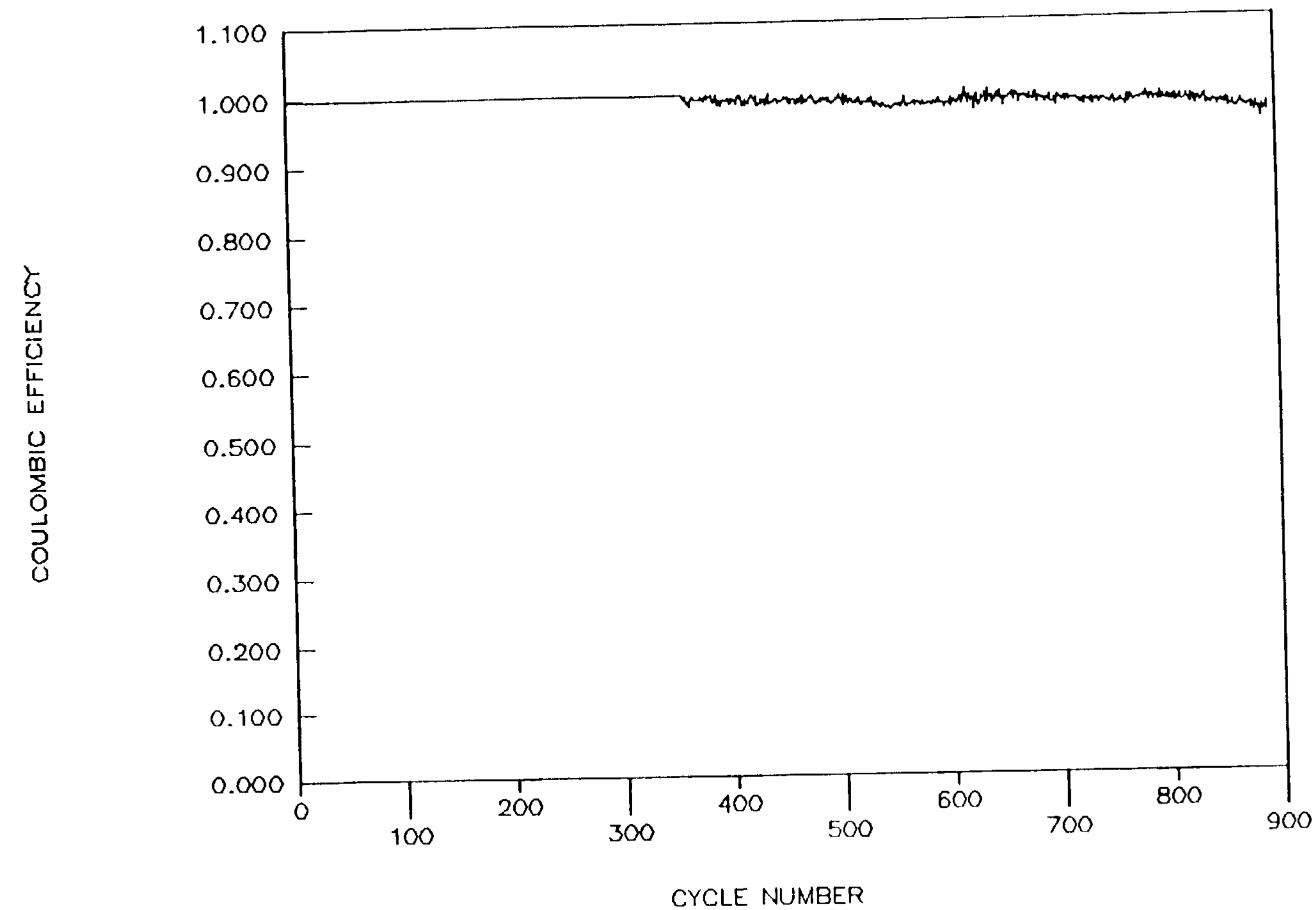
Discharge/charge behavior of a Li/$CuCl_2$ cell at 50mA/cm^2 discharge for 20 seconds and 5.56mA/cm^2 charge for 180 seconds

Bipolar Lithium Rechargeable Batteries: CYCLE LIFE



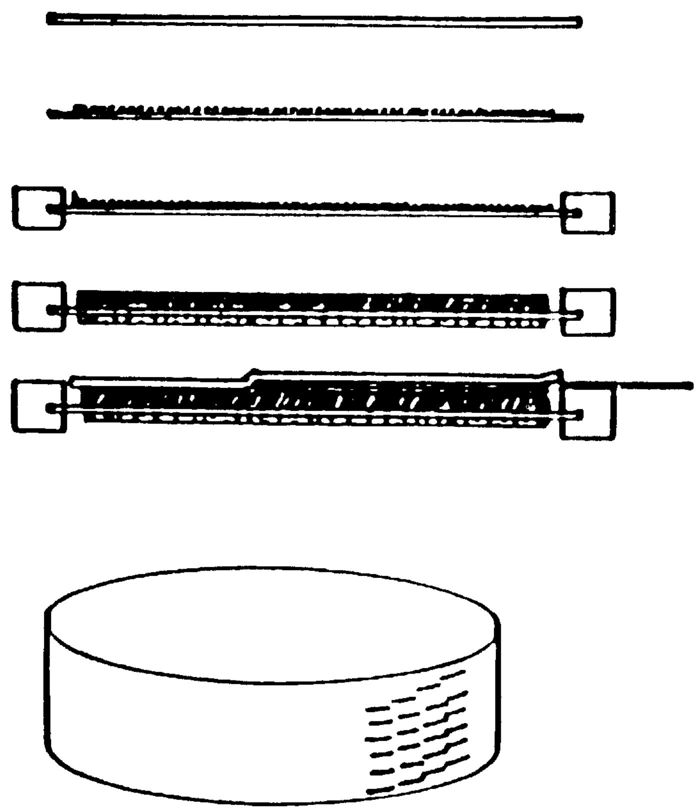
Cycle number vs capacity of a $Li/LuCl_2$ cell at $50mA/cm^2$ discharge for 20 seconds and $5.56mA/cm^2$ charge for 180 seconds. Voltage limits 2.5–4.0 V.

Bipolar Lithium Rechargeable Batteries: CYCLING BEHAVIOR



Coulombic efficiency of a $Li/CuCl_2$ cell discharged at $50 mA/cm^2$ for 20 seconds and charged at $5.56 mA/cm^2$ for 180 seconds

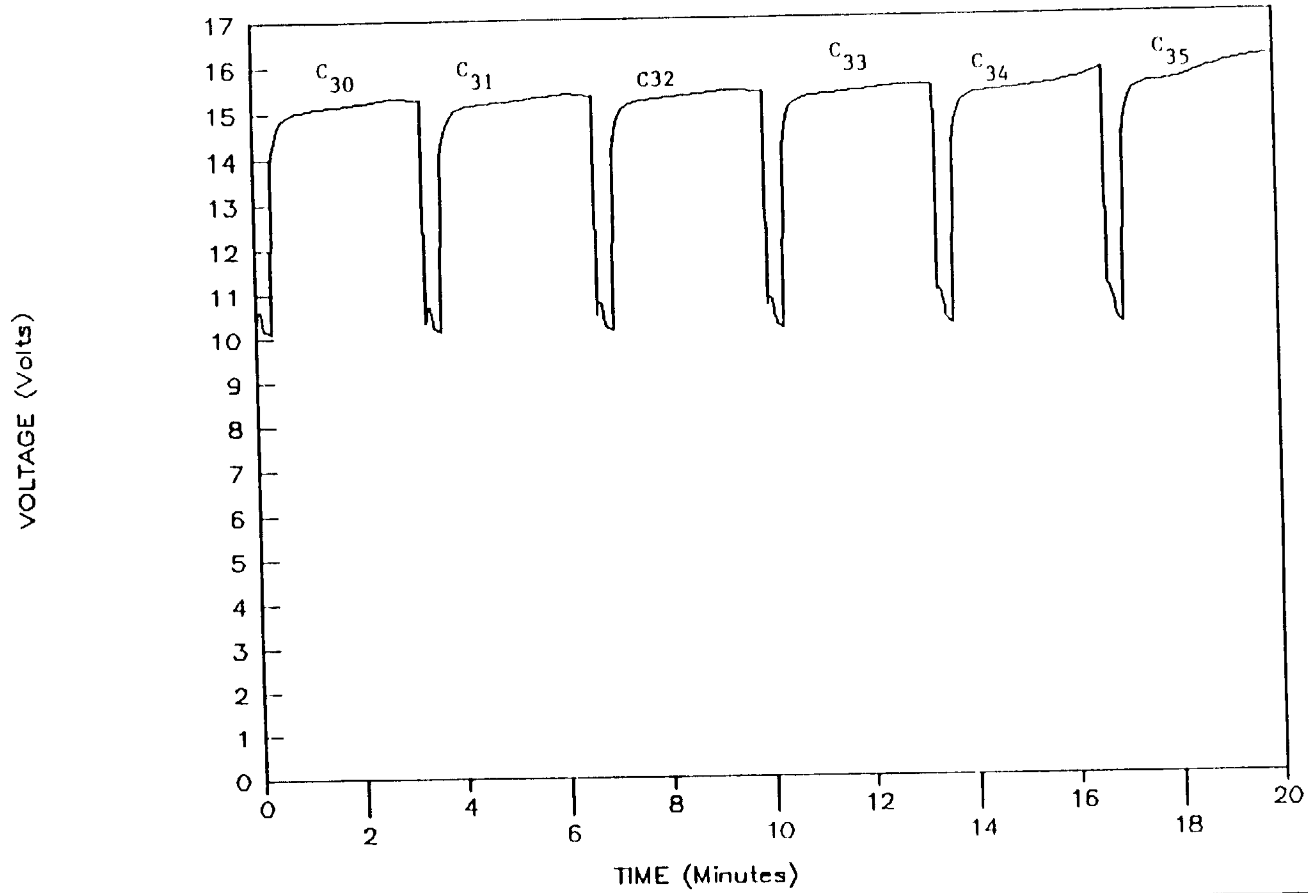
Bipolar Lithium Rechargeable Batteries: CELL ASSEMBLY



1. Nickel substrate
2. Carbon/TFE undercoat
3. Tefzel insulator
4. Anode and cathode
5. Fill tube and separator
6. Stack sealed except in fill tube area, then activated. Final.

BIPOLAR STACK ASSEMBLY SEQUENCE

Bipolar Lithium Rechargeable Batteries: CYCLING BEHAVIOR



Discharge/charge behavior of a bipolar Li/$CuCl_2$ battery (4−cell stack) at 50mA/cm^2 discharge for 20 seconds and 5.56mA/cm^2 charge for 180 seconds. Voltage limits 10.0−16.0 V.

Bipolar Rechargeable Lithium Battery

Based on the present state–of–the–art of bipolar rechargeable lithium batteries, a cumulative specific power of 1mW/kg and specific energy of 6kWh/kg can be achieved

Develpment of a 270V bipolar rechargeable battery

REQUIREMENTS:

Discharge:	20 seconds at 50mA/cm^2 (Total = 30A)
Average operating voltage:	270 V
Charge:	180 seconds at 5.56mA/cm^2 (Total=3.33A)
Charge cut–off voltage:	360 V
Total number of cycles:	800 cycles

TOTAL WEIGHT OF BIPOLAR BATTERY: 6 kg

$$\textbf{SPECIFIC POWER} = \frac{270 \times 30}{6}\ \text{w/kg} = 1.35\text{kW/kg}$$

DESIGN CONSIDERATIONS FOR RECHARGEABLE LITHIUM BATTERIES

JPL

D. H. SHEN, C.-K. HUANG, E. DAVIES
D. PERRONE, S. SURAMPUDI, and G. HALPERT

Jet Propulsion Laboratory,
California Institute of Technology
Pasadena, California

THE 1992 NASA AEROSPACE BATTERY WORKSHOP
MARSHALL SPACE FLIGHT CENTER
HUNSVILLE, ALABAMA
NOVEMBER, 1992

BATTERY SYSTEMS GROUP

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OUTLINE

* OBJECTIVE
* CELL BASELINE DESIGN & TESTING
* CELL DESIGN PARAMETERS STUDIES
* CELL CYCLING PERFORMANCE
* SUMMARY AND CONCLUSIONS

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OBJECTIVE

DETERMINE THE INFLUENCE OF CELL DESIGN PARAMETERS ON THE PERFORMANCE OF Li-TiS_2 CELLS

Li-TiS$_2$ CELL BASELINE DESIGN

RATED CAPACITY	1 Ah CELL
TiS$_2$ CAPACITY	1.2 Ah (Theoretical) 1.0 Ah (Practical)
LITHIUM CAPACITY	6 Ah
Li:TiS$_2$ CAP. RATIO	6
ELECTROLYTE	1.5M LiAsF$_6$/ 10%EC + 90%2-MeTHF
SEPARATOR	CELGARD 2400
ELECTROLYTE QTY.	7.5 cc
CURRENT COLLECTOR	Ni EXMET
CAN & COVER MAT'LS	SS
SEAL	GLASS TO METAL

CELL DESIGN PARAMETERS STUDIED

DESIGN PARAMETERS	VARIATIONS
ANODE TO CATHODE CAPACITY RATIO	4:1, 6:1, and 9:1
PACK TIGHTNESS	Tight, medium, and loose
TYPE OF ELECTROLYTE Salt: 1.5 M $LiAsF_6$	2-MeTHF, 10% EC + 90% 2-MeTHF, THF + 2% 2-MeF, THF + 2-MeTHF + 2% 2-MeF, Diox + 2-MeTHF + THF + 2% 2-MeF, and EC + PC.
QUANTITY OF ELECTROLYTE	4, 7.5, and 9 c.c.
SEPARATOR	Microporous Polypropylene Microporous Polyethylene Sub-microporous Polypropylene Thermal separator
BINDER CONCENTRATION	2 and 1 weight %
CASE POLARITY	Isolated, floating, and positive.

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CELL TESTING CONDITIONS

*	DISCHARGING	1 Ah CELLS
	TYPE:	CONSTANT CURRENT
	CURRENT DENSITY (mA/cm^2):	1
	CUTOFF VOLTAGE (V)	1.7
	DEPTH OF DISCHARGE	50%
*	CHARGING	
	TYPE:	CONSTANT CURRENT
	CURRENT DENSITY (mA/cm^2):	0.5
	CUTOFF VOLTAGE:	2.7 V
*	TEMPERATURE	25° C

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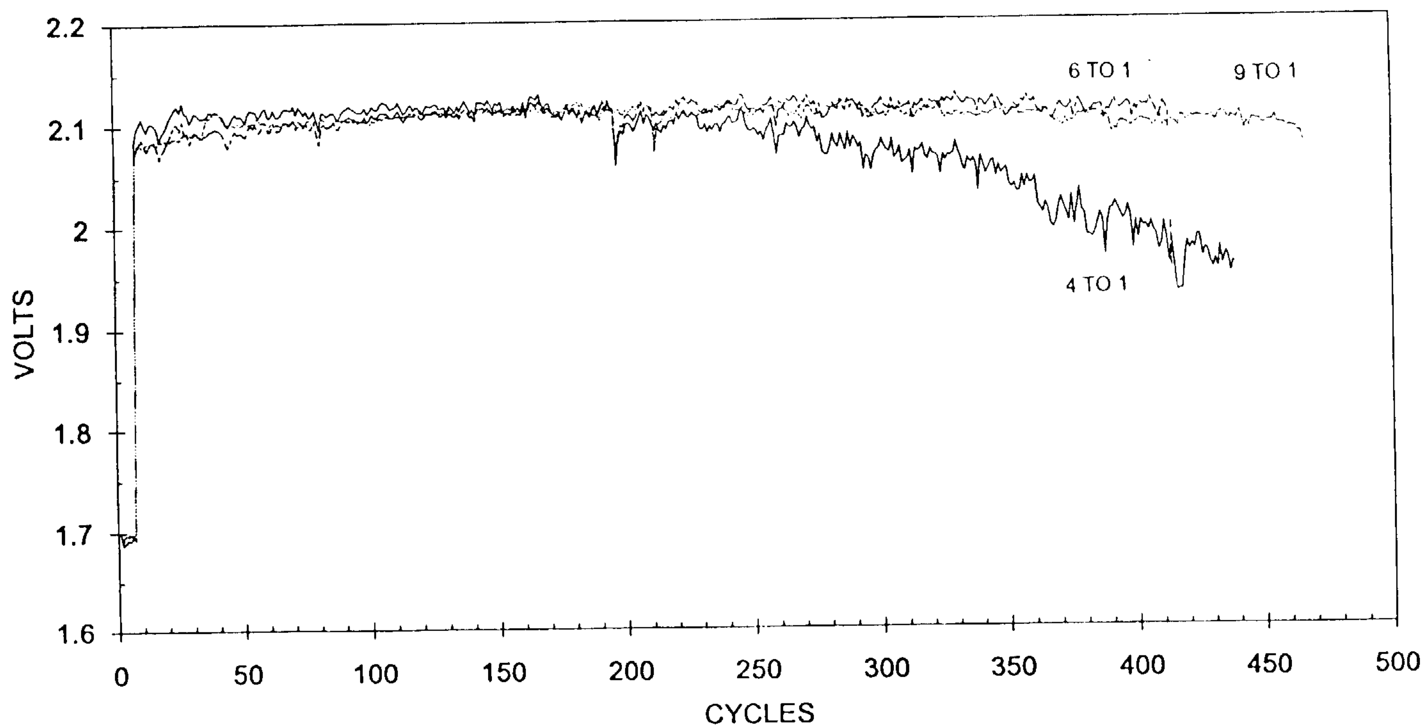
DESIGN PARAMETER STUDIES

EFFECT OF ANODE TO CATHODE CAPACITY RATIO
ON END-OF-DISCHARGE VOLTAGE



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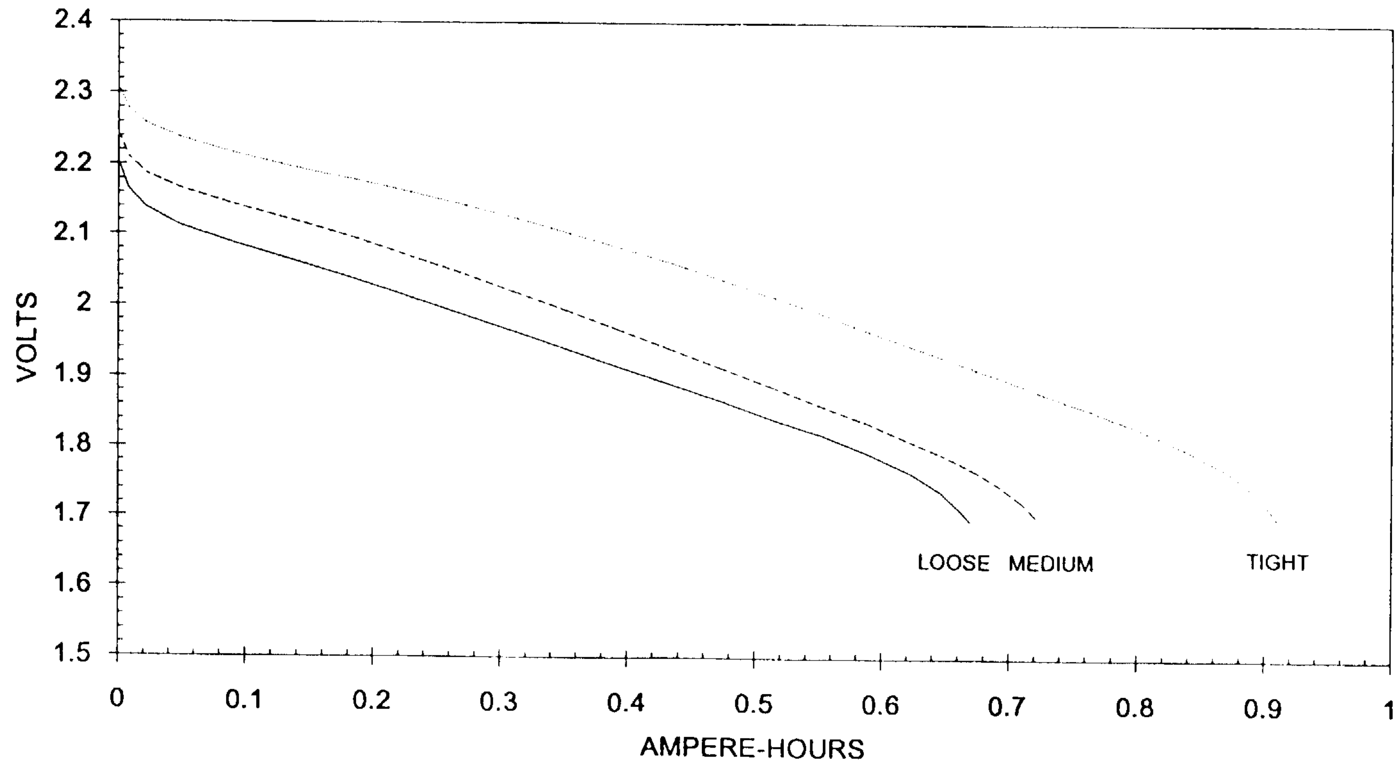
DESIGN PARAMETER STUDIES

EFFECT OF PACK TIGHTNESS ON C/5 CAPACITY AT CYCLE 10



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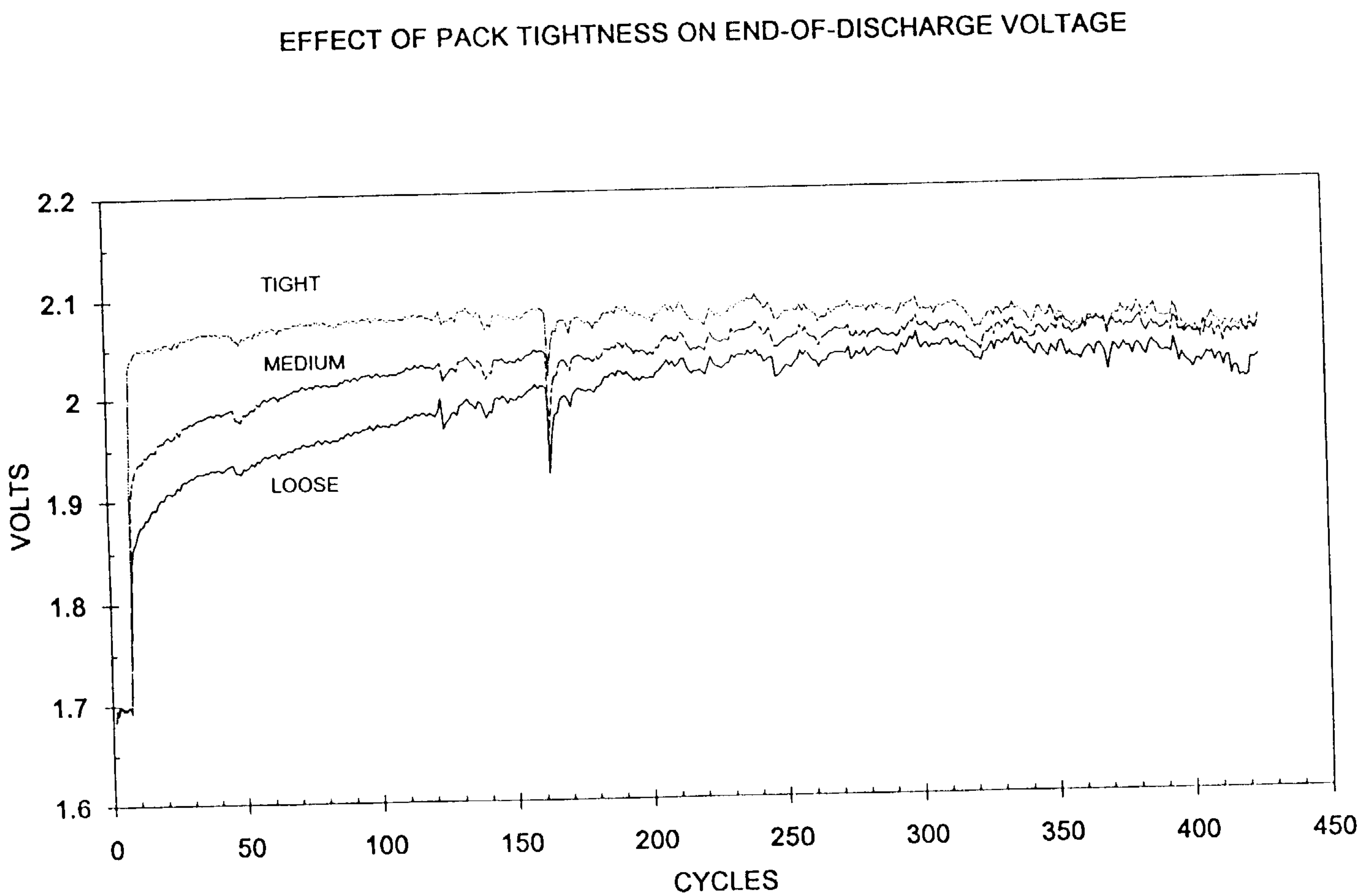
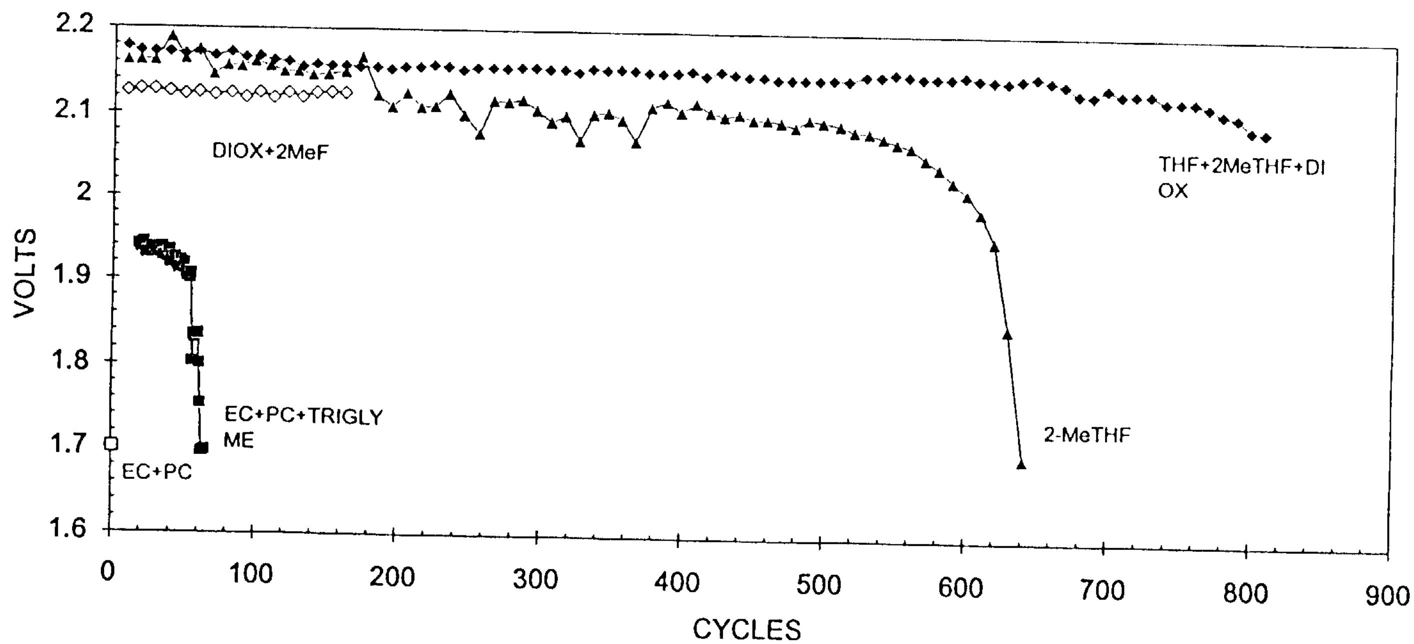
DESIGN PARAMETER STUDIES



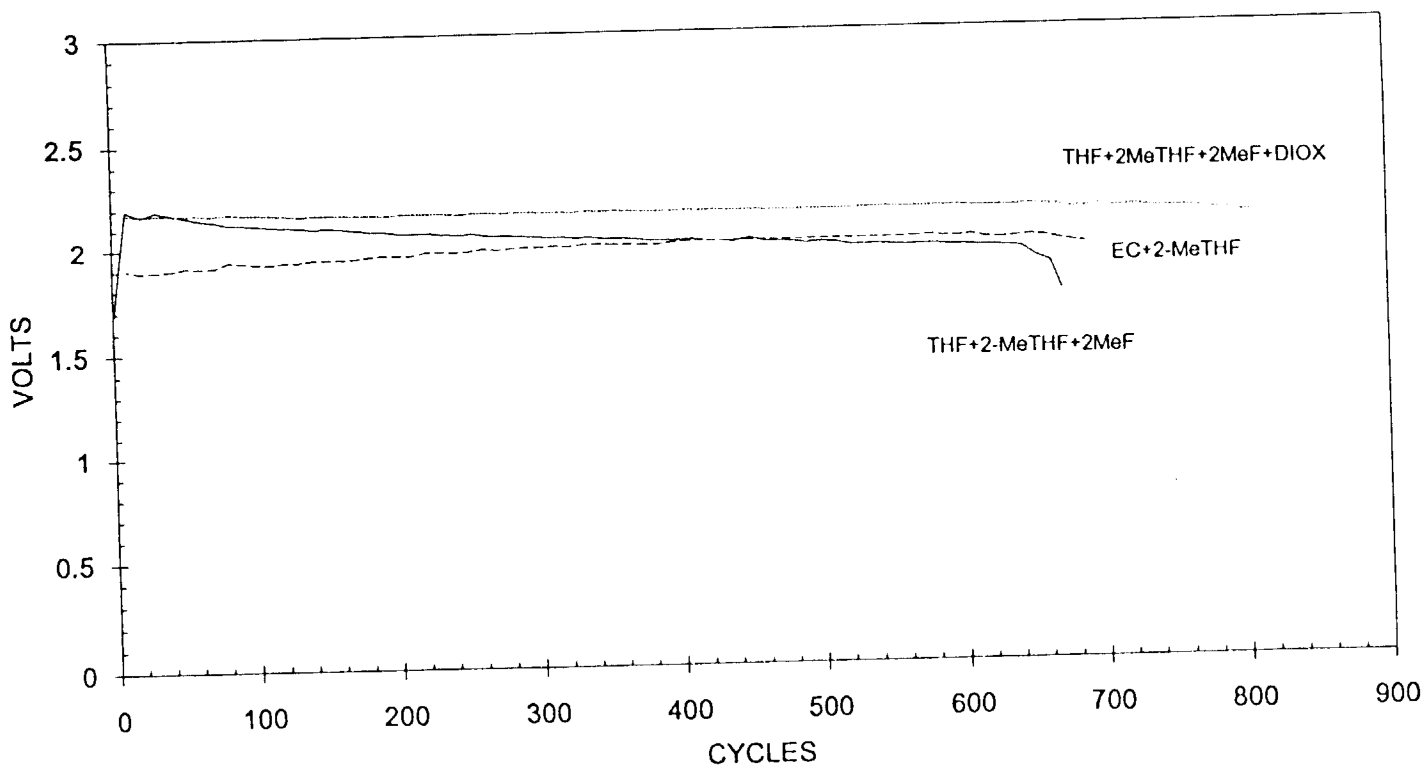
DESIGN PARAMETER STUDIES

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



DESIGN PARAMETER STUDIES

END-OF-DISCHARGE VOLTAGE OF CELLS WITH SELECTED ELECTROLYTES



BATTERY SYSTEMS GROUP

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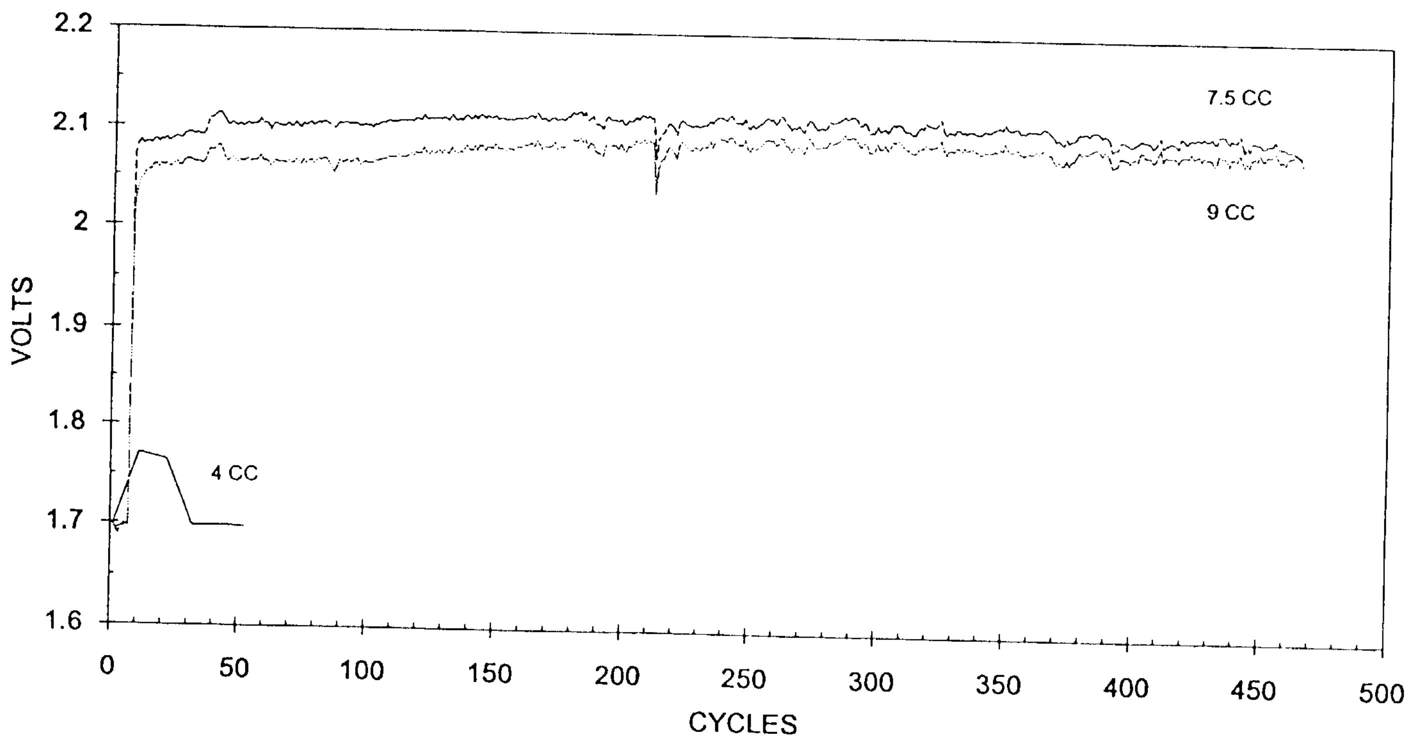
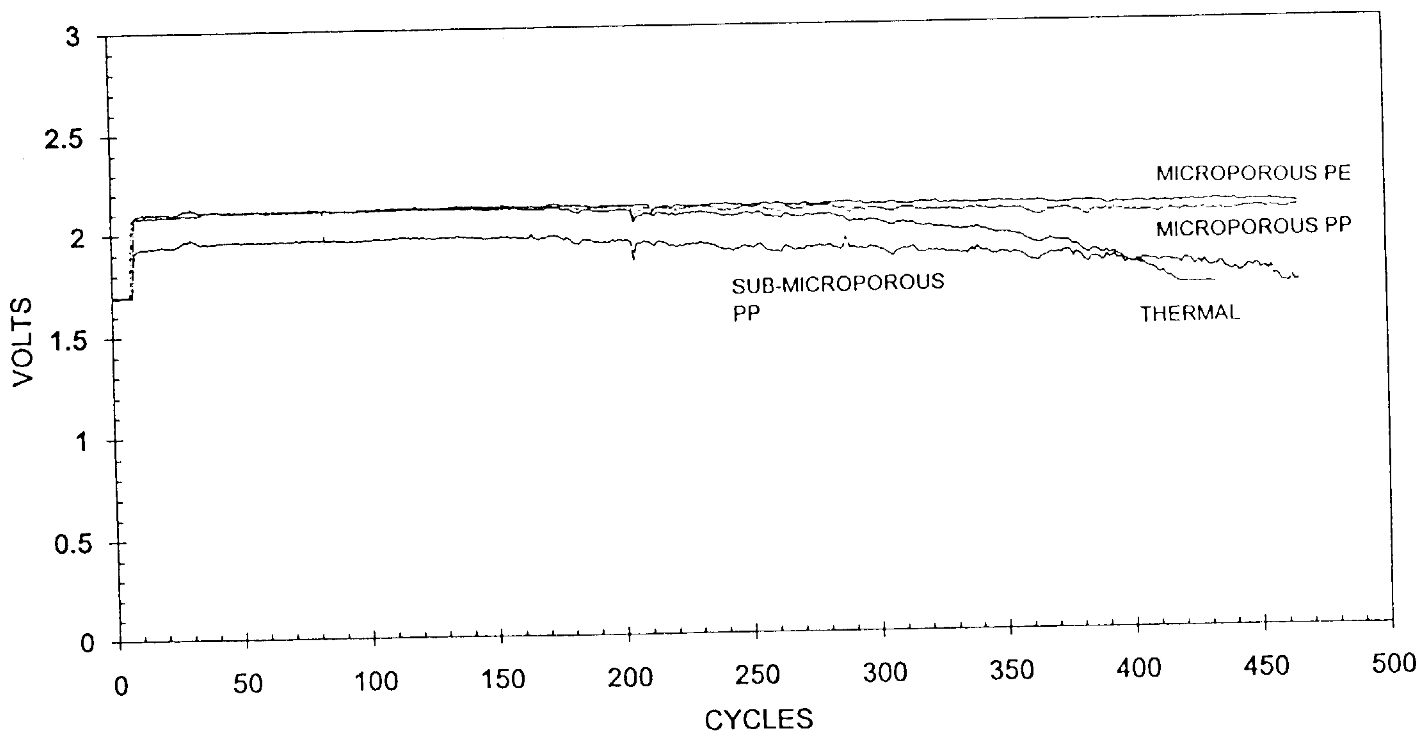
DESIGN PARAMETER STUDIES

EFFECT OF ELECTROLYTE VOLUME
ON END-OF-DISCHARGE VOLTAGE



DESIGN PARAMETER STUDIES

EFFECT OF SEPARATOR ON END-OF-DISCHARGE VOLTAGE



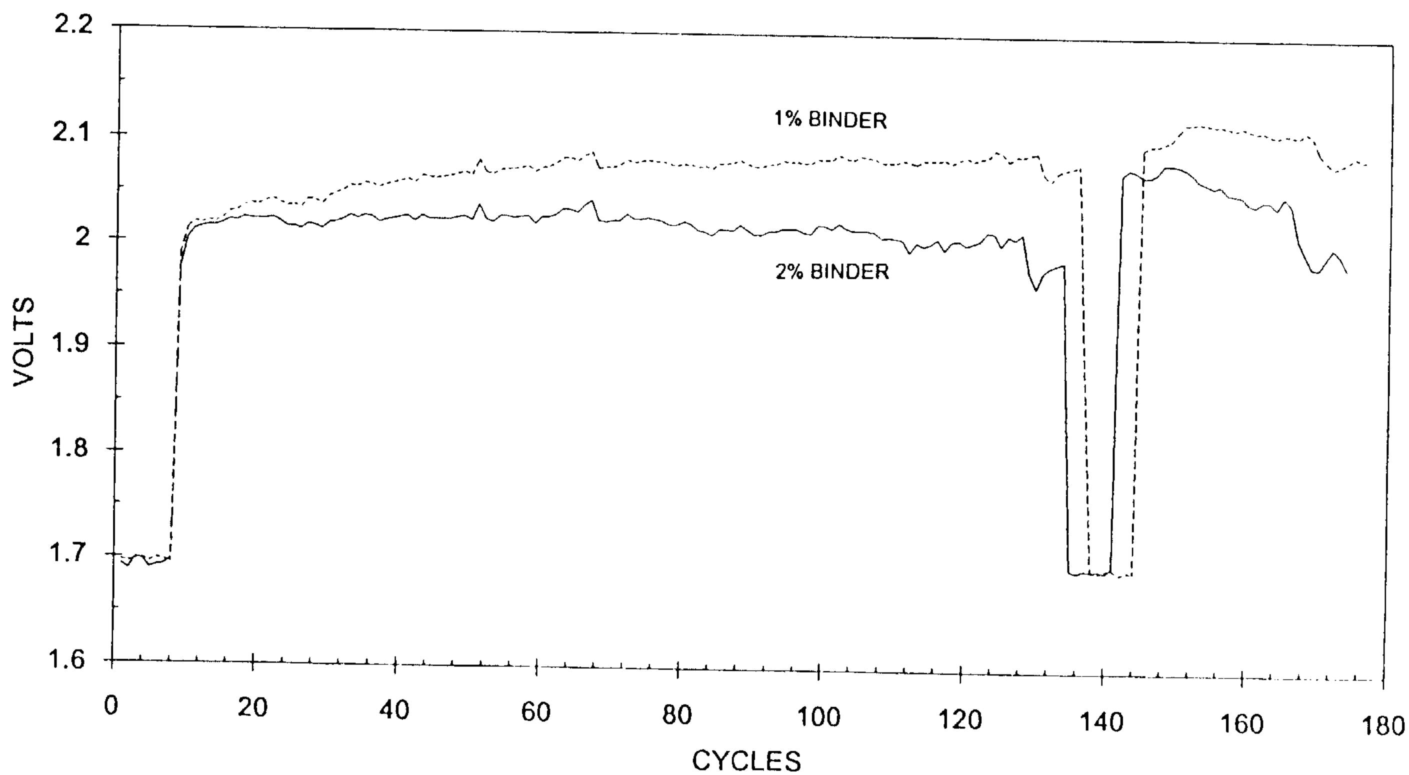
1992 NASA Aerospace Battery Workshop

Advanced Technologies Session

C-9

DESIGN PARAMETER STUDIES

EFFECT OF CATHODE BINDER CONCENTRATION ON END-OF-DISCHARGE VOLTAGE



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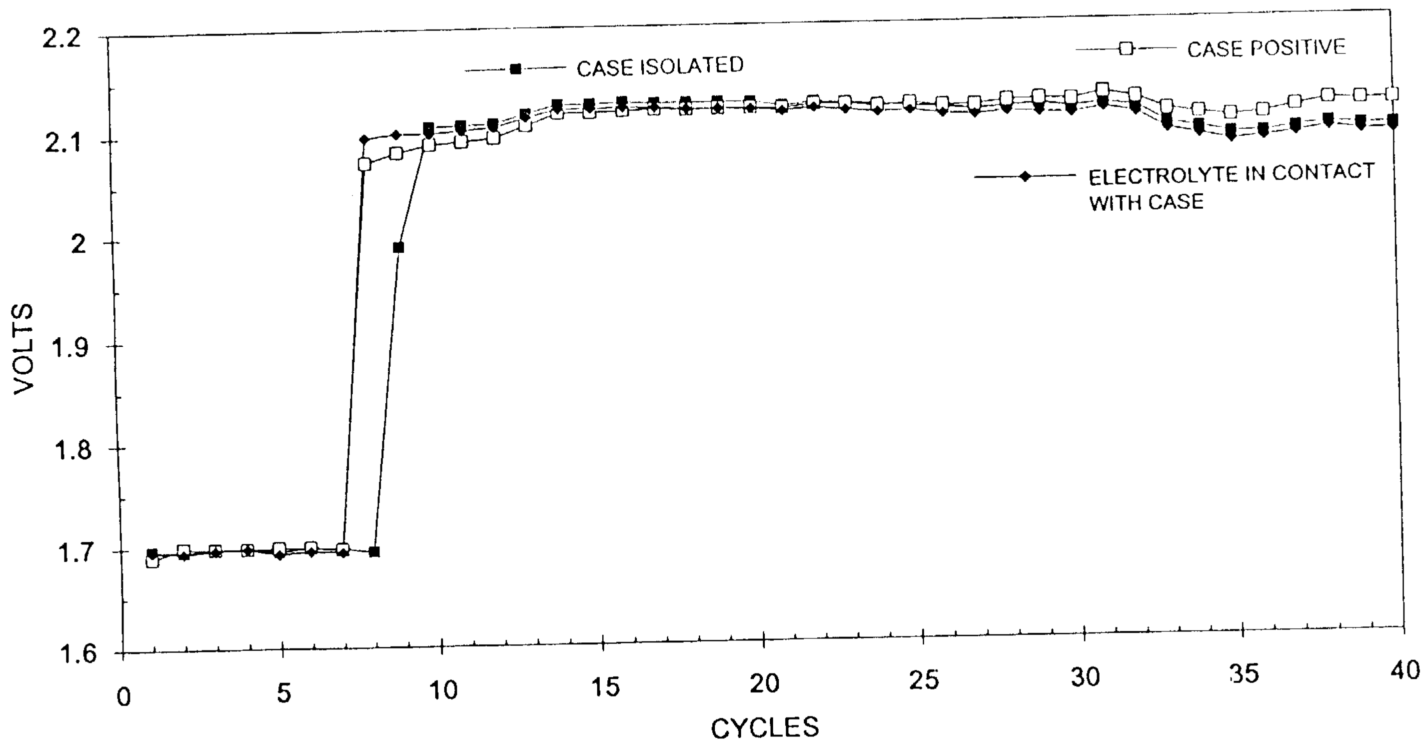
DESIGN PARAMETER STUDIES

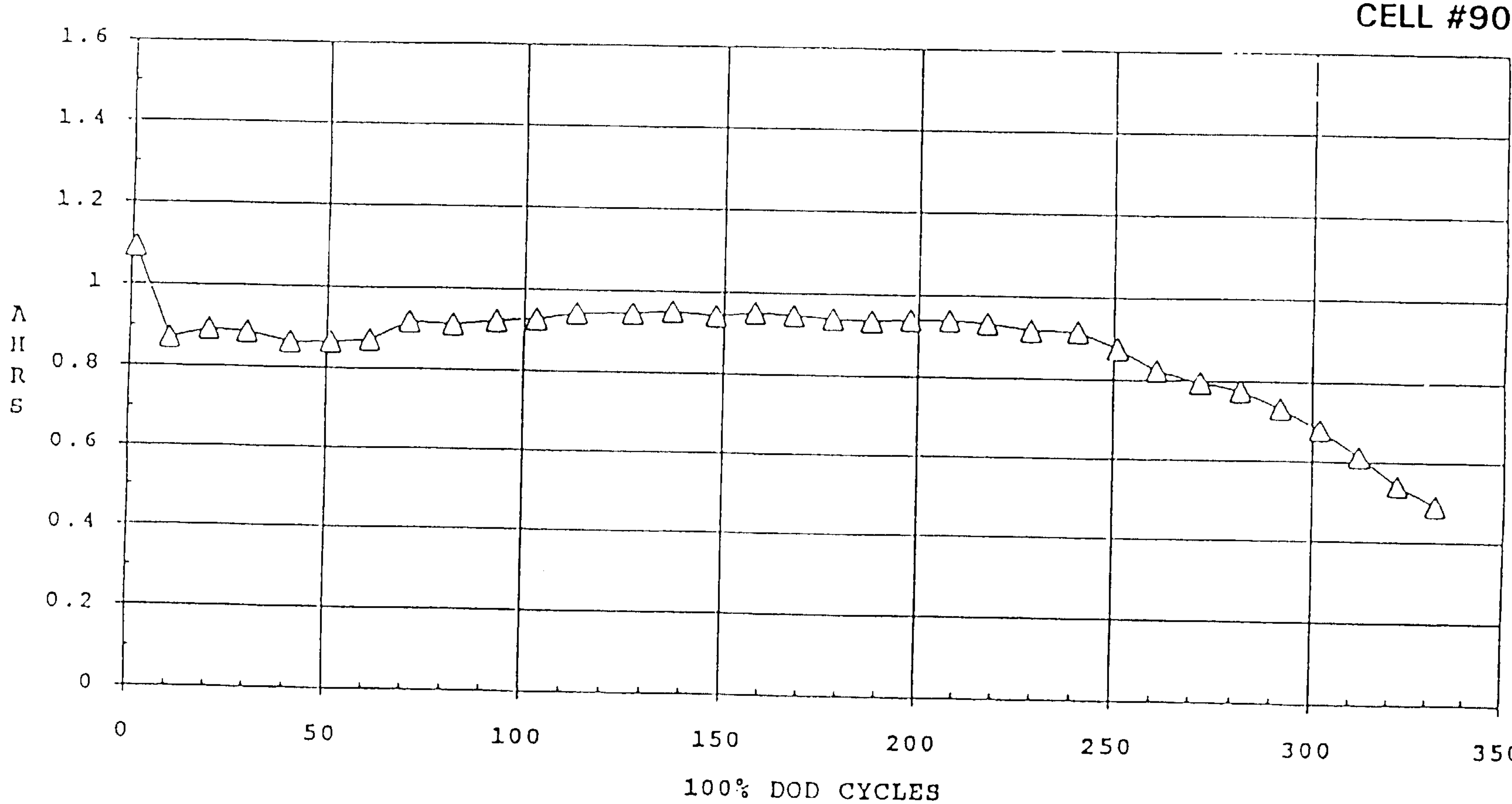
EFFECT OF CASE POLARITY ON END-OF-DISCHARGE VOLTAGE



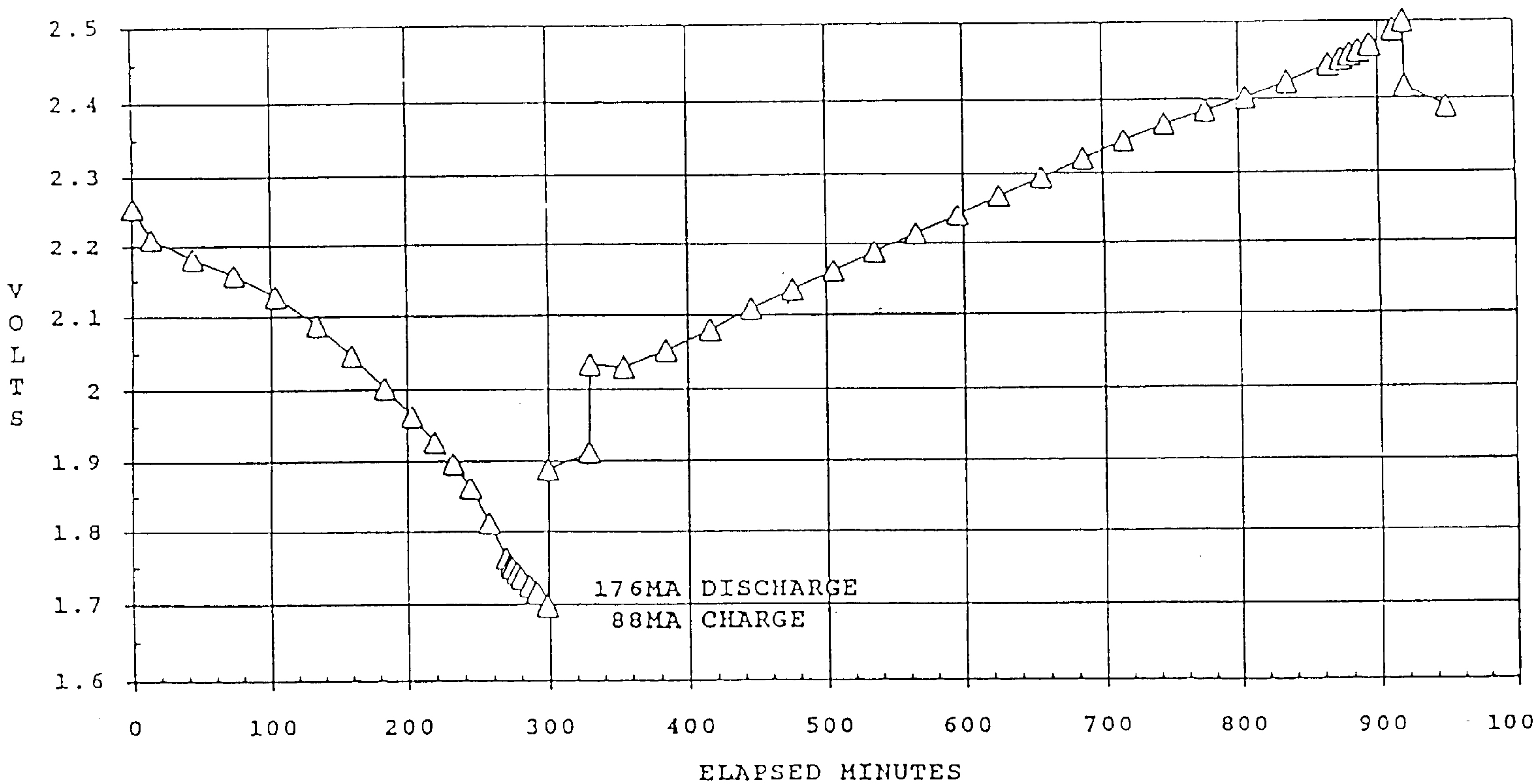
CYCLE LIFE CHARACTERISTICS OF 1 Ah Li-TiS_2 CELL

(C/5 DISCHARGE, C/10 CHARGE - AT 100% DOD)

CELL #9005



TYPICAL CHARGE/DISCHARGE CURVE FOR 1 Ah Li-TiS_2 CELL



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SUMMARY

SUGGESTED CELL DESIGN PARAMETERS

DESIGN PARAMETERS	VARIATIONS
ANODE TO CATHODE CAPACITY RATIO	6:1
PACK TIGHTNESS	Tight
TYPE OF ELECTROLYTE Salt: 1.5 M $LiAsF_6$	10% EC + 88% 2-MeTHF + 2% 2-MeF THF + 2-MeTHF + 2% 2-MeF, DIOX + 2-MeTHF + THF + 2% 2-MeF
QUANTITY OF ELECTROLYTE	7.5 c.c.
SEPARATOR	Microporous Polypropylene Microporous Polyethylene Sub-microporous Polypropylene
BINDER CONCENTRATION	1 % by weight
CASE POLARITY	floating or positive.

List of Attendees

Russ Aikins
Hughes Electron Dynamics Division
555 Republic Drive, Ste 200
Plano, TX 75074
214-423-3357

Jim Ames
Eagle-Picher Industries
C & Porter Streets
Joplin, MO 64801
417-623-8000 EXT353

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

Wilbert L. Barnes
Naval Research Laboratory
Code 8134
4555 Overlook Ave. SW
Washington, DC 20375-5000
202-767-6517

Charles W. Bennett
GE Astro Space
MS NP-2I
POB 800
Princeton, NJ 08543-0800
609-951-7597

David Bernard
GE American Communications
POB 479
6950 Bradley Rd.
Somis, CA 93066
805-386-4199

Samuel Birken
The Aerospace Corporation
MS M4/986
POB 92957
Los Angeles, CA 90009-2957
310-336-6080

Bernard Bregman
The Aerospace Corporation
MS M6/216
POB 92957
Los Angeles, CA 90009-2957
310-416-7239

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

Marc G. Brideau
Martin Marietta
POB 179
Denver, CO 80201
303-971-8286

Harry Brown
Naval Surface Warfare Center - Crane Div.
Code 6095
Crane, IN 47522-5001
812-854-1593

Quang Bui
U.S. Air Force
USAF LMC (AFSC) / SDES
POB 92960
Los Angeles AFB
Los Angeles, CA 90009-2960
310-363-3100

David Burns
Marshall Space Flight Center
EB13
Marshall Space Flight Center, AL
35812
205-544-4807

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

John E. Casey
Lockheed Engineering & Sciences Co.
2400 NASA Rd. 1, C51
Houston, TX 77058-3799
713-483-0446

Alan Cash
Teledyne Brown Engineering
MS #50
300 Sparkman Dr.
Huntsville, AL 35807-7007
205-726-3506

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

Everton Collins
McDonnell Douglas
7404 Executive Place
Seabrook, MD 20706-0001
301-464-7400

William D. Cook
Eagle-Picher Industries, Inc.
C and Porter Streets
Joplin, MO 64801
417-623-8000

Dennis B. Cooper
INTELSAT
3400 International Dr. NW
Box 34
Washington, DC 20008-3098
202-944-7349

Mark Darty
McDonnell Douglas Space Systems Co.
MS 23B2
689 Discovery Dr.
Huntsville, AL 35806
205-922-7475

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

Sal DiStefano
Jet Propulsion Laboratory
MS 277-212
4800 Oak Grove Drive
Pasadena, CA 91109
818-354-6320

G. J. Dudley
European Space Agency
POB 299
2200 AG Noordwijk
The Netherlands
31-1719-83834

Andrew F. Dunnet
INTELSAT
MS 33A
3400 International Dr. NW
Washington, DC 20008
202-944-7245

Tim A. Edgar
Eagle Picher Industries, Inc.
3820 South Hancock Expressway
Colorado Springs, CO 80911
719-392-4266

Blake A. Emmerich
Zircar Products, Inc
110 N. Main St.
Florida, NY 10921
914-651-4481 EXT 229

Marlon L. Enciso
Goddard Space Flight Center
Code 421
Greenbelt, MD 20771
301-286-5070

Tetsuya Enomoto
Sanyo Energy Co.
333 Pierce Rd. #175
Itasca, IL 60143
708-285-0333

Ed Fitzgerald
Teledyne Brown Engineering
MS 70
300 Sparkman Dr. NW
Huntsville, AL 35807
205-726-2865

Nicanor A. Flordeliza
GE American Communications
4 Research Way
Princeton, NJ 08540
609-987-4453

Daniel Gallagher
MRJ, Inc.
10455 White Granite Dr.
Oakton, VA 22124
703-218-0308

Chris Garner
Naval Research Laboratory
4555 Overlook Ave. SW
Washington, DC 20375-5320
202-767-9075

Dr. William O. Gentry
Johnson Controls, Inc.
POB 591
Milwaukee, WI 53201
414-228-2228

Eugena Goggans
Marshall Space Flight Center
EB13
Marshall Space Flight Center, AL
35812
205-544-3386

Guillermo A. Gonzalez
Langley Research Center
MS 433
1 North Dryden St.
Hampton, VA 23665-5225
804-864-7107

Jacques Goualard
SAFT
156 Avenue De Metz
93230 Romainville, France
33-1-49-42-34-17

Edwin Guasp
Sverdrup / NASA-LeRC
MS 309-1
21000 Brookpark Road
Cleveland, OH 44135
216-433-5249

Shahid Habib
NASA Headquarters
Code QE
Washington, DC 20546
202-358-0536

Charles Hall
Marshall Space Flight Center
EB12
Marshall Space Flight Center, AL
35812
205-544-3330

David Hall
Marshall Space Flight Center
EB12
Marshall Space Flight Center, AL
35812
205-544-4215

Steve Hall
Naval Surface Warfare Center - Crane Div.
Code 6095
Crane, IN 47522
812-854-1593

Gerald Halpert
Jet Propulsion Laboratory
MS 277-212
4800 Oak Grove Drive
Pasadena, CA 91109
818-354-5474

Jeff Hayden
Eagle Picher Industries, Inc.
3820 South Hancock Expressway
Colorado Springs, CO 80911
719-392-4266

Ed Hendee
Telesat Canada
1601 Telesat Court
Gloucester, Ontario
Canada K1B 5P4
613-748-0123 EXT 2366

Gary L. Hickman
Naval Research Laboratory
Code 8134
4555 Overlook Ave. SW
Washington, DC 20375-5000
202-767-6517

Carole A. Hill
The Aerospace Corporation
MANZ/210
POB 9045
Albuquerque, NM 87119-9045
505-846-7063

Christopher G. Hoffman
Swales & Associates, Inc.
5050 Powder Mill Road
Beltsville, MD 20705
301-595-5500 EXT.2239

Sohrab Hossain
Yardney Technical Products, Inc.
82 Mechanic Street
Pawcatuck, CT 06379
203-599-1100

Lorna Jackson
Marshall Space Flight Center
EB12
Marshall Space Flight Center, AL
35812
205-544-3318

Thierry Jamin
CNES
18 Avenue Edouard Belin
31055 Toulouse Cedex
France
CNES/CST/TE/AE/SE/AC
61 27 49 38

Dr. Philip J. Johnson
British Aerospace, Inc.
POB 405
Alachua, FL 32615-0405
904-462-3607

Nolimits Kamimori
National Space Development Agency of Japan
Tsukuba Space Center
2-1-1 Sengen, Tsukuba, Ibaraki 305
Japan
81-298-52-2285

Bobby Kennedy
Marshall Space Flight Center
EB13
Marshall Space Flight Center, AL
35812
205-544-3384

Visvaldis Klasons

POB 260159
Plano, TX 75026-0159

Glenn Klein
Gates Aerospace Batteries
POB 147115
Gainesville, FL 32614-7115
904-462-3569

Roy Lanier
Marshall Space Flight Center
EB11
Marshall Space Flight Center, AL
35812
205-544-3301

John W. Lear
Grumman
MS T01-12
South Oyster Bay Rd.
Bethpage, NY 11714
516-575-5460

H.S. Lim
Hughes Aircraft Company
Bldg 231 MS 1921
POB 2999
Torrance, CA 90509-2999
310-517-7620

Eric Lowery
Marshall Space Flight Center
EB12
Marshall Space Flight Center, AL
35812
205-544-0080

Chuck Lurie
TRW
MS R4/1082
One Space Park
Redondo Beach, CA 90278
310-813-4888

Dr. Tyler X. Mahy
U.S. Government
c/o OTS–2S83, NHB
Washington, DC 20505
703-874-0739

Michelle Manzo
Lewis Research Center
MS 309-1
21000 Brookpark Rd.
Cleveland, OH 44135
216-433-5261

Mike Martin
Marshall Space Flight Center
EB13
Marshall Space Flight Center, AL
35812
205-544-3341

Dean W. Maurer
AT&T / Bell Labs
379 Princeton-Hightstown Rd.
Cranbury, NJ 08512
609-448-0687

Louis C. Maus
Marshall Space Flight Center
PD14
Marshall Space Flight Center, AL
35812

Bryon T. Maynard
Kennedy Space Center
MS CS-TMO-2
Kennedy Space Center, FL 32899
407-867-2223

Kate McGinnis
Analex Corporation
3005 Aerospace Parkway
Brook Park, OH 44142
216-977-0488

David D. McGuire
Martin Marietta
9390 S. Warhawk Rd.
Conifer, CO 80433
303-977-8647

Sid Megahead
Ray-O-Vac
630 Forward Dr.
Madison, WI 53711

George Methlie

2120 Natahoa Ct.
Falls Church, VA 22043
202-965-3420

Dr. Richard A. Meyer
Energy Science Laboratories, Inc.
1706 Morocco Dr.
San Jose, CA 95125
408-723-0159

John Meyer
Johns Hopkins University / APL
Bldg 23/205
Johns Hopkins Rd.
Laurel, MD 20723-6099
301-953-5000 EXT8604

Scott D. Miller
GE Government Services
GE - UARS FOT
Code 425.9; Bldg. 3, Rm. S-26
Goddard Space Flight Center
Greenbelt, MD 20771
301-286-3854

Kensuke Nakatani
Sanyo Electric Co., Ltd.
221-1 Kaminaizen, Sumoto, Hyogo 570
Japan
(011-81) 799-23-2851

Dave Nawrocki
Lockheed Missiles & Space Co., Inc.
808 Loyalton Dr.
Campbell, CA 95008
408-743-0170

Mike Nemcek
Loral Aerosys
25111 Country Club Blvd., Suite 236
North Olmsted, OH 44070
216-979-5018

Al Norton, Jr.
Marshall Space Flight Center
EB13
Marshall Space Flight Center, AL
35812
205-544-3362

Al Norton
Marshall Space Flight Center
EB13
Marshall Space Flight Center, AL
35812
205-544-3355

Pat O'Donnell
Lewis Research Center
MS 309-1
21000 Brookpark Rd.
Cleveland, OH 44135
216-433-5248

Burton Otzinger

857 E. Sierra Madre Ave.
Glendora, CA 91740
310-797-3724

George Pack
Lockheed Missiles & Space Co., Inc.
POB 3504
O/7910 B551
Sunnyvale, CA 94089-3504
408-743-7157

Victor Patton

74 Mountain Shadows Lane
Castle Rock, CO 80104

Catherine Penafiel
Loral Aerosys
7375 Executive Place
Seabrook, MD 20706
301-286-9316

David F. Pickett
Hughes Aircraft Co.
Electron Dynamics Division
MS 231/1040
POB 2999
Torrance, CA 90509-2999
310-517-7601

Joseph M. Potak, Jr.
Booz, Allen, & Hamilton, Inc.
Crystal Square 2, Suite 1100
1725 Jefferson Davis Highway
Arlington, VA 22202
703-271-1665

Dick Radzwill
Hughes
3100 Lomita
Torrance, CA
310-517-6237

Gopal Rao
Goddard Space Flight Center
Code 734.5
Greenbelt, MD 20771
301-286-6654

Kathleen M. B. Robbins
COMSAT Laboratories
22300 Comsat Dr.
Clarksburg, MD 20871

Dr. Howard H. Rogers
Hughes Aircraft Co.
MS 231/1720
POB 2999
Torrence, CA 90509-2999
310-517-7614

B. Rutkauskas
MDESC
POB 426
St. Charles, MO

David Saldaña
Lockheed Technical Operations Co.
1721 Tipton Dr.
Crofton, MD 21114
410-721-5637

David F. Schmidt
Gates Aerospace Batteries
POB 147115
Gainesville, FL 32614-7115
904-462-4752

Ronald L. Silvey
Eagle-Picher Industries, Inc.
POB 47
Joplin, MO 64801
417-623-8000

Walter L. Smeton
Martin Marietta
MS S4012
POB 179
Denver, CO 80201
303-971-8108

Ron Smith
Eagle-Picher Industries
C & Porter Streets
Joplin, MO 64801
417-623-8000

Ken Stephens
Marshall Space Flight Center
EB11
Marshall Space Flight Center, AL
35812
205-544-6616

Joe Stockel
Office of Research & Development
MS 4123
Washington, DC 20505
703-351-2065

Kohei Takagi
Toshiba Corporation
1. Komukai, Toshiba-Cho
Saiwaiku, Kawasaki, 210
Japan
81-44-548-5133

Benjamin Tausch
Martin Marietta
MS S4001
POB 179
Denver, CO 80201
303-971-8706

Steve Tesney
Marshall Space Flight Center
EB12
Marshall Space Flight Center, AL
35812
205-544-3400

Lawrence Thaller
Aerospace Corporation
MS M2/275
POB 92957
Los Angeles, CA 90009
310-336-5180

Paul Timmerman
Jet Propulsion Laboratory
MS 303-300
4800 Oak Grove Dr.
Pasadena, CA 91109
818-354-5388

Dr. Lawrence Tinker
Gates Aerospace Batteries
POB 147115
Gainesville, FL 32614-7115
904-462-4715

Mark R. Toft
McDonnell Douglas Electronic Systems
MS 500 4174
POB 426
St. Charles, MO 63301
314-925-7692

Greta Tracinski
Applied Power International
1236 N Columbus Ave., #41
Glendale, CA 91202
818-243-3127

Walter A. Tracinski
Applied Power International
1236 N. Columbus Ave., Suite 41
Glendale, CA 91202-1672
818-243-3127

Dr. Hari Vaidyanathan
COMSAT Laboratories
22300 Comsat Dr.
Clarksburg, MD 20878
301-428-4507

Chester A. Vaughan
Johnson Space Center
MS EP
NASA Rd. 1
Houston, TX 77058

Charles Richard Walk
Tracor Technology Resources
1601 Research Blvd.
Rockville, MD 20850
301-251-4875

Harry Wannemacher
McDonnell Douglas
7404 Executive Place
Seabrook, MD 20706-0001
301-464-7400

William Wells
Vitro Corporation
Suite 825
400 Virginia Ave SW
Washington, DC 20024
202-646-6350

James R. Wheeler
Eagle-Picher Industries, Inc.
1215 West B Street
Joplin, MO 64802
417-623-8000 EXT 359

Dr. Ralph E. White
Texas A&M University
Dept. of Chemical Engineering
College Station, TX 77843-3122
409-845-3307

Tom Whitt
Marshall Space Flight Center
EB12
Marshall Space Flight Center, AL
35812
205-544-3313

Don Williams
Marshall Space Flight Center
PD14
Marshall Space Flight Center, AL
35812

Doug Willowby
Marshall Space Flight Center
EB12
Marshall Space Flight Center, AL
35812
205-544-3334

Daniel G. Wise
GE - UARS FOT
Code 425.9
Goddard Space Flight Center
Greenbelt, MD 20771
301-286-3875

Bart Wright
Martin Marietta
MS S4012
POB 179
Denver, CO 80120

Yoshiaki Yano
Sanyo Energy Co.
Kaminaizen 222-1
Sumoto-City Hyogo, Japan

Jeff Zagrodnik
Johnson Controls, Inc.
POB 591
Milwaukee, WI 53201
414-783-2605

Albert H. Zimmerman
The Aerospace Corporation
MS M2/275
POB 92957
Los Angeles, CA 90009-2957
310-336-7415

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Jeffrey C. Brewer, Compiler

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George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

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Washington, DC 20546

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13. ABSTRACT *(Maximum 200 words)*

This document contains the proceedings of the 23rd annual NASA Aerospace Battery Workshop, hosted by the Marshall Space Flight Center on November 15-19, 1992. The workshop was attended by scientists and engineers from various agencies of the U.S. Government, aerospace contractors, and battery manufacturers, as well as international participation in like kind from a number of countries around the world.

The subjects covered included nickel-cadmium, nickel-hydrogen, nickel-metal hydride, and lithium based technologies, as well as advanced technologies including sodium-sulfur and various bipolar designs.

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