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The 1994 NASA Aerospace Battery Workshop

Compiled by
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Proceedings of a workshop sponsored by the
NASA Aerospace Flight Battery Systems Program,
and held in Huntsville, Alabama
November 15–17, 1994

National Aeronautics and Space Administration
Marshall Space Flight Center • MSFC, Alabama 35812

February 1995

Preface

This document contains the proceedings of the 27th annual NASA Aerospace Battery Workshop, hosted by the Marshall Space Flight Center on November 15-17, 1994. 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.

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 1994 Workshop was held on three consecutive days and was divided into four sessions. The first day consisted of a General Session and a Nickel-Hydrogen Design Session. The second day consisted exclusively of an Advanced Technologies Session. The third and final day was devoted to a Nickel-Hydrogen / Nickel-Cadmium Test and Flight System Data 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.
>
> **Bob Bechtel** and **Eric Lowery**, NASA Marshall Space Flight Center; **Michelle Manzo**, NASA Lewis Research Center; and **Gerald Halpert**, Jet Propulsion Laboratory, for serving as Session Organizers, which involved soliciting presentations, organizing the session agenda, and orchestrating the session during the workshop;
>
> **Huntsville Marriott**, 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 Session

NASA CENTER UPDATE
GODDARD SPACE FLIGHT CENTER

Presented to
1994 NASA AEROSPACE BATTERY WORKSHOP

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

November 15, 1994

NASA GODDARD SPACE FLIGHT CENTER UPDATE

- OPERATING SPACECRAFT
- CURRENTLY BASELINED SPACECRAFT
- LIFE TESTING AT NAVAL SURFACE WARFARE CENTER (NSWC), CRANE, INDIANA

OPERATING SPACECRAFT

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

SAMPEX

- Single 9 Amp-hour Super NiCd battery
- 22 series-connected cells
- Plate fabrication (EPI): 10/90
- Cell activation: 5/91
- Launched: 7/3/92
- Completed 10655 eclipse orbits and 2160 full-sun orbits
- Nominal performance: Alternating between VT 4 and VT 5; recharge ratio 1.04; temperature between 1 °C and 11 °C; DOD between 0% and 17.2% (average 12%)

EUVE

- Three 50 Amp-hour conventional NiCd batteries in parallel (Modular Power Subsystem (MPS))
- 22 series-connected cells per battery
- Plate fabrication (GE/GAB): 1/85 - 5/85
- Cell activation: 3/88
- Launched: 6/7/92
- Completed 13482 eclipse orbits
- Completed six months of operation without incident at VT 4, with C/D ratios between 1.06 and 1.09, temperatures between -2 °C and +7 °C and average DOD of 9%

EUVE - continued

- Half-battery differential voltages began to diverge in 12/92, following a period of relatively shallow discharge and soon exceeded 50 mV
- Battery heater thermostats deliberately bypassed less than five months after launch to change battery operating temperature from -2 °C to 7 °C
- Half-battery differential voltages have approached and occasionally exceeded 100 mV, beginning 9 months after launch

EUVE - continued

- Maximum battery charge rates are controlled by Solar Array offsets or by commanding a 3 amp Constant Current charge mode at S/C sunrise
- C/D ratio control is obtained by using CCM (trickle) at the end of each S/C sunlight period, after a desired C/D ratio (calculated on-board) has been reached
- Flight software regularly adjusted to result in acceptable C/D ratios during shorter eclipse periods (shallower DOD)
- Current status and operational mode: VT 3; recharge ratio 1.05 - 1.08; temperature ~7 °C (heat pipes); maximum DOD 10% (average 9%)

UARS

- Three 50 Amp-hour conventional NiCd batteries in parallel (Modular Power Subsystem (MPS))
- 22 series-connected cells per battery
- Plate fabrication (GE/GAB): 8/88 - 1/89
- Cell activation: 10/30/89
- Launched: 9/12/91
- Completed 17363 orbits
- Completed 4 months of operation without incident, employing a combination of VT 5 & 6, with recharge ratios between 1.09 and 1.15, temperatures between 0 °C and 5 °C and DOD ranging from 0% to 20%

UARS - continued

- In 1/92, after first full-sun period, half-battery differential voltages diverged and quickly exceeded 50 mV
- Continued use of VT 5 & 6 caused battery temperature and load-sharing divergence; half-battery differential voltages approached 500 mV
- VT 4 established as new nominal operating level seven months after launch; C/D ratios still ranged from 1.02 to 1.10
- Battery heater thermostats deliberately bypassed in 4/92 to change battery operating temperature from 0 °C to 5 °C

UARS - continued

- Maximum charge rate reduced to 25 amps or less beginning 7/92 via Solar Array Offsets, then 20 amps or less beginning in 1/93
- Implemented conditioning discharges (10% - 40% DOD) during 12/92 full-sun period to minimize continuous battery overcharge and improve battery performance; deep conditioning discharges (25% - 40% DOD) are performed at least once during full-sun periods that occur twice a year

UARS - continued

- C/D ratios are controlled by switching between VT 3 and VT 4 as needed (VT 3 when DOD < 15%) or commanding low (trickle) constant current charging for the end of each S/C sunlight period, after a desired C/D ratio (calculated on-board) has been reached
- Current status and operational mode: Switching between VT 3 and VT4 as noted above, C/D ratios between 1.01 and 1.06, temperatures between 1 °C and 7 °C and DOD between 0% and 20% (average 15%)

CGRO

- Two sets of three 50 Amp-hour conventional NiCd batteries in parallel (each set in a Modular Power Subsystem (MPS-1 and MPS-2))
- 22 series-connected cells per battery
- Launched: 4/5/91
- Completed 20558 orbits on 5 of 6 batteries (6th battery (battery 2 of MPS-1) off-line)

CGRO MPS-1

- Plate fabrication (GE/GAB): 6/88 - 11/88
- Cell activation: 7/89
- Nominal performance up to 3174 eclipse orbits under VT 5, with C/D ratios 1.1 - 1.2 (uncorrected), temperatures between 0 °C and 3 °C; average DOD 10% (maximum 13%)
- Half-battery differential voltage reached and exceeded 50 mV by 11/91; C/D ratios increasing
- Reduced to VT 4 in 2/92; half-battery differential voltages continued to grow and were exceeding 450 mV by 6/92; C/D ratios between 1.2 and 1.35

CGRO MPS-1 - continued

- Reduced to VT 3 in 5/92; half-battery differential voltages and C/D ratios continue to be divergent
- On 7/2/92, batteries 1 & 3 exhibited half-differential voltages between 200 and 400 mV, while battery 2 exceeded 700 mV (detector saturated)
- Battery 2 developed a short (in one or more cells) while nearing the end of the charge portion of one orbit on 7/16/92, and was taken off the spacecraft bus

CGRO MPS-1 - continued

- Maximum charge rate reduced beginning 2/93 through the use of CCM (0.75 amps between two batteries) at S/C sunrise; VT control is restored 15 - 20 minutes later
- Control of C/D ratios has also been effected since launch+22 months by commanding low (trickle) constant current charging for the end of each S/C sunlight period, after a desired net charge (calculated on-board) has been reached under VT control

CGRO MPS-1 - continued

- Current status and operational mode: VT 3, C/D ratios between 1.10 and 1.20 (uncorrected), temperatures between 1 °C and 3 °C; DOD between 7% and 14% (average 10%)

CGRO MPS-2

- Plate fabrication (GE/GAB): 1/85- 7/85
- Cell activation: 11/88
- Nominal performance through 20558 eclipse orbits under VT 5 (occasionally VT 6, as required), with C/D ratios 1.1 - 1.15 (uncorrected), temperatures between 2 °C and 4 °C and average DOD 12% (maximum 15%)

ERBS

- Two 50 Amp-hour conventional NiCd batteries in parallel
- 22 series-connected cells per battery
- Plate fabrication (GE/GAB): 6/83 - 9/83
- Cell activation: 11/83
- Launched: 10/5/84
- Completed 55080 orbits (one battery with two failed cells)
- Completed 5 years of nominal performance under VT 6: average C/D ratios 1.16, average temperatures 10 °C and average DOD 9% (maximum 14%)

ERBS - continued

- Half-battery differential voltages began to diverge in 9/89 and increased to over 200 mV in battery 1 and over 450 mV in battery 2 by 7/90; battery current-sharing began to diverge on both charge and discharge, with battery 1 accepting more charge and contributing less on discharge
- VT level reduced from 6 to 5 during 1/92, then 5 to 4 during 7/92
- After cell short in battery 1 on 8/7/92, VT level lowered from 4 to 3

ERBS - continued

- After second cell short in battery 1 on 9/4/92, and failed attempts to keep both batteries on-line, battery 1 was taken off the spacecraft bus
- First cell short in battery 2: 6/93
- After second cell short in battery 2 during 7/93, VT level switched from 3 to 1 and the use of Constant Current was re-introduced as a means to achieve desired C/D ratio
- In 8/93, implemented a combination of 11.4 Amp and 3 Amp Constant Current charge modes to attain desired C/D ratio of 1.10

ERBS - continued

- C/D goal of 1.02 established 3/94 to further minimize overcharge
- Beginning in 1994, employed techniques to force battery discharge during shallow discharge periods (DOD < 7%) and/or full-sun periods
- Current status and operational mode: C/D ratios between 1.00 and 1.02, temperatures between 3 °C and 5 °C; DOD between 7% and 14% (average 11%)

HST

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

HST - continued

- Battery performance has been nominal:
- Completed 24876 orbits
- Operated system on VT levels K1L3 and K2L3 from launch through 3/93 in step-to-trickle charge mode with trickle charge current of 12 amps (2 amps per battery) and trickle charge period approximately 40 minutes
- Operated system on VT levels K1L4 and K2L3 from 3/93 to present in step-to-taper mode; temperature 0 $\pm$ 3 °C; average DOD 5 - 8 % (maximum 8.5%); system capacity over 500 AH

HST - continued

- Reconditioned batteries through 5.1 ohm load

DATE	BATTERY NUMBER	END OF DISCHARGE VOLTAGE	AVERAGE DISCHARGED CAPACITY AT 26.4V
12/90	1 & 4	19 VOLTS	94 AMP-HOURS
8/92 - 9/92	2, 3, 5 & 6	13 VOLTS	88 AMP-HOURS
8/94 - 10/94	1 & 4	15 VOLTS	77 AMP-HOURS

CURRENTLY BASELINED SPACECRAFT

SPACECRAFT	BATTERY TYPE	BATTERY/CELL MANUFACTURER	ORBIT	LAUNCH DATE
TOMS	NiCd, 9 Ah (Super)	HAC/EPI	LEO	3/95
FAST	NiCd, 9 Ah (Super)	HAC/EPI	LEO	8/95
NOAA - J	NiCd, 26.5 Ah	ASD(MM)/GAB	LEO	12/94
GGS (WIND)	NiCd, 26.5 Ah	ASD(MM)/GAB	LEO	11/94
GOES - J)	NiCd, 12 Ah	SSL/GAB	GEO	4/95
TDRSS - 7	NiCd, 40 Ah	TRW/SAFT, France	GEO	6/95
SWAS	NiCd, 21 Ah (Super)	HAC/EPI	LEO	6/95
XTE	NiCd, 50 Ah (Super)	HAC/EPI	LEO	8/95

CURRENTLY BASELINED SPACECRAFT - continued

SPACECRAFT	BATTERY TYPE	BATTERY/CELL MANUFACTURER	ORBIT	LAUNCH DATE
NOAA - K	NiCd, 37 Ah (Super)	ASD(MM) / HAC/EPI	LEO	12/95
GGS (POLAR)	NiCd, 26.5 Ah	ASD(MM)/GAB	LEO	12/95
TRMM	NiCd, 50 Ah (Super)	HAC/EPI	LEO	8/97
ACE	NiCd, 12 Ah	APL/SAB, Gainesville	GEO	9/97
HST	NiH2, 88 Ah	LMSC/EPI	LEO	12/97
EOS - AM	NiH2, 50 Ah	ASD(MM)/EPI	LEO	6/98
LANDSAT - 7	NiH2, 50 Ah	ASD(MM)/EPI	LEO	12/98

LIFE TESTING AT NSWC, CRANE

- Advanced NiCd cells:
  - Hughes Aircraft Company (Torrance, CA) / Eagle Picher Industries, Inc. (Colorado Springs, CO)
  - Eagle Picher Industries, Inc. (Colorado Springs, CO)
- Conventional NiCd cells:
  - Gates (now SAFT) Aerospace Batteries (Gainesville, FL)
  - General Electric BBD (Gainesville, FL - now SAFT)
  - SAFT-France
- NiH_2 cells from Eagle Picher Industries, Inc. (Joplin, MO)
- Data as of 11/8/94

ADVANCED NICD CELL LIFE TEST

Testing in Progress:

- Hughes / EPI:
  - Pack # 6000A - 21 AH, Polypropylene, PBI, Magnum©
  - Pack # 6001A - 21 AH, Zircar/Polysulfone
  - Pack # 6003A - 21 AH, Zircar/Polysulfone
  - Pack # 6004A - 21 AH, Zircar/Polysulfone
  - Pack # 6090T - 9 AH, Zircar/PBI w/additive, Super©
  - Pack # 6091T - 9 AH, Zircar/PBI w/additive, Super©
  - Pack # 0090B - 9 AH, Zircar/PBI w/additive, Super©
- EPI:
  - Pack # 6106M - 10 AH, Magnum©
  - Pack # 6122M - 10 AH, Magnum©
  - Pack # 6506M - 50 AH, Magnum©
  - Pack # 6522M - 50 AH, Magnum©

ADVANCED NICD CELL LIFE TEST - continued

Hughes / EPI: Cycling Discontinued Since 1992

- Pack # 6002A - 21 AH, Zircar/PBI
- Pack # 6005A - 21 AH, Zircar/Polysulfone
- Pack # 6006A - 21 AH, Zircar/PBI w/additive, Super©
- Pack # 6053A* - 50 AH, Zircar/PBI w/additive, Super©
- Pack # 0090A - 9 AH, Zircar/PBI w/additive, Super©

* Cells procured, batteries manufactured by McDonnell Douglas Electronic Systems Company, St. Louis, MO

ADVANCED NICD CELL LIFE TEST - continued

Pack #	Size (AH)	Orbit	DOD (%)	Temp (°C)	C/D	VT	Minimum EODV	Cycle #
6000A	21	LEO	40	20	1.07.	7.5	1.121	26692
6001A	21	LEO	40	20	1.08	7	0.985	26639
6003A	21	LEO	40	20	1.09	7	0.980	24329
6004A	21	LEO	25	30	1.06	7	0.871	25020
6090T**	9	LEO	50	20	1.10	7	1.164	6282
6091T	9	LEO	0 - 32	20	1.11	6	1.154	5638
0090B*	9	LEO	12	5	1.14	5.5	1.229	8880
6106M	10	LEO	10	0	1.07	4	1.248	751
6122M	10	LEO	40	20	1.06	5.5	1.098	2627
6506M	50	LEO	10	0	1.07	4	1.263	760
6522M	50	LEO	40	20	1.08	6	1.078	1960

* On cycle 7137, switched from SAMPEX mission profile to FAST mission profile (134 minute orbit, 40 minute discharge), one cell removed for high voltage at cycle 7171

** One cell removed due to leak at cycle 4110

ADVANCED NICD CELL LIFE TEST - continued

Discontinued Packs

Pack #	Size (AH)	Orbit	DOD (%)	Temp (°C)	C/D	VT	Avg EODV	Last Cycle #	Key
6002A	21	LEO	40	20	1.27	7	1.128	25357	1
6005A	21	LEO	40	30	1.13	7.5	1.040	18969	2
6006A	21	LEO	40	20	1.05	7.5	0.987	21601	2
6053A	50	LEO	40	20	1.07	7	1.192	13283	3
0090A	9	LEO	40	30	1.10	7	1.056	13090	2,4

Key: 1 - Cells bulging; 2 - EOCV divergence; 3 - Low EODV; 4 - Cells leaking; 5 - Low recharge; 6 - High EOCV; 7 - Discontinued by request

GAB NICD CELL LIFE TEST

Pack #	Size (AH)	Orbit	DOD (%)	Temp (°C)	C/D	VT	Minimum EODV	Cycle #
0002S	26.5	LEO	40	20	1.09	7	1.005	9226
0003S	26.5	LEO	40	20	1.04	6	1.020	5480
0027A	12	LEO	40	20	1.08	7	0.989	9705
0052E	50	LEO	20	0	1.03	5	1.193	8787
0052F	50	LEO	20	0	1.03	5	1.184	8834
0052G	50	LEO	20	0	1.05	5	1.211	8815
0347N*	47	LEO	12-18	0	1.07	5	1.183	3872
0647N**	47	LEO	12-18	0	1.13	6	1.191	4381
6052C	50	LEO	20	0	1.03	5	1.146	8500
6052D	50	LEO	20	0	1.03	5	1.191	8517

* One cell removed at cycle 2757 for low EOCV, 1 of 4 remaining cells exhibiting EOCV divergence; multiple reconditioning

** 3 of 5 cells have exhibited EOCV divergence; multiple reconditioning

GAB NICD CELL LIFE TEST - continued

Pack #	Size (AH)	Orbit	DOD (%)	Temp (°C)	Minimum EODV	Shadow #
0001S	26.5	GEO	40	5	1.201	8
6227B	12	GEO	60	5	1.184	15
6227C	12	GEO	60	0	1.193	14

Discontinued Packs

Pack #	Size (AH)	Orbit	DOD (%)	Temp (°C)	Avg EODV	Shadow #	Key
0231A	6	GEO(IUE)	80	10	1.179	30	6
0232A	40	GEO(TDRSS)	50	0	1.187	29	7
0232B	40	GEO(TDRSS)	50	15	1.187	26	7

Key: 1 - Cells bulging; 2 - EOCV divergence; 3 - Low EODV; 4 - Cells leaking;
5 - Low recharge; 6 - High EOCV; 7 - Discontinued by request

GAB NICD CELL LIFE TEST - continued

More Discontinued Packs

Pack #	Size (AH)	Orbit	DOD (%)	Temp (°C)	Avg EODV	Shadow #	Key
0232C	40	GEO(TDRSS)	75	0	1.153	24	7
0232D	40	GEO(TDRSS)	75	0	1.153	4	7
6232A	40	GEO(TDRSS)	50	0	1.184	24	7
6232B	40	GEO(TDRSS)	50	0	1.181	5	7
6232C	40	GEO(TDRSS)	50	10	1.181	54	7
6232D	40	GEO(TDRSS)	50	15	1.186	49	7

Key: 1 - Cells bulging; 2 - EOCV divergence; 3 - Low EODV; 4 - Cells leaking;
5 - Low recharge; 6 - High EOCV; 7 - Discontinued by request

GAB NICD CELL LIFE TEST - continued

More Discontinued Packs

Pack #	Size (AH)	Orbit	DOD (%)	Temp (°C)	C/D	VT	Avg EODV	Last Cycle #	Key
6051C	50	LEO	40	20	1.01	7	0.957	21541	3
6051D (EUVE)	50	LEO	40	20	1.06	8	0.947	22991	3
6051E	50	LEO	40	20	1.01	8	0.921	19545	3
6051F	50	LEO	40	20	1.03	7	0.929	18577	3
6051G (GRO-2)	50	LEO	40	20	1.03	8	0.912	20852	3
6051H (GRO-1)	50	LEO	40	20	1.01	6	1.002	11941	7
6051I (EUVE & GRO-2)	50	LEO	15	15	1.17	6	1.212	28632	7

Key: 1 - Cells bulging; 2 - EOCV divergence; 3 - Low EODV; 4 - Cells leaking; 5 - Low recharge; 6 - High EOCV; 7 - Discontinued by request

GAB NICD CELL LIFE TEST - continued

More Discontinued Packs

Pack #	Size (AH)	Orbit	DOD (%)	Temp (°C)	C/D	VT	Avg EODV	Last Cycle #	Key
6053B	50	LEO	40	20	1.06	8	0.962	13220	3
6085A	20	LEO	20	15	1.12	6	1.162	15022	5
6085B	20	LEO	28	15	1.09	7	1.133	11123	5
6085C	20	LEO	40	20	1.01	6	1.026	19057	5
0004H	4	HEO	40	15	NA	6	1.167	4525	7
0026G	26.5	LEO	20	10	1.01	3.5	1.076	71658	2
0026I	26.5	LEO	18.5	10	1.01	4	1.193	46553	2
0026J	26.5	LEO	25	10	1.04	6	1.153	32793	2

Key: 1 - Cells bulging; 2 - EOCV divergence; 3 - Low EODV; 4 - Cells leaking; 5 - Low recharge; 6 - High EOCV; 7 - Discontinued by request

SAFT-France NICD CELL LIFE CYCLE TEST

Pack #	Size (AH)	Orbit	DOD (%)	Temp (°C)	C/D	VT	Minimum EODV	Cycle #
6024S	24	LEO	40	0	1.03	7.5	1.026	30128
6140S	40	LEO	40	20	1.08	7	1.024	8241

Discontinued Packs

Pack #	Size (AH)	Orbit	DOD (%)	Temp (°C)	C/D	VT	Avg EODV	Last Cycle #	Key
6120S	20	LEO	40	20	1.16	8.5	1.039	20998	3
6124S	24	LEO	40	20	1.07	8.5	1.009	26091	3

Key: 1 - Cells bulging; 2 - EOCV divergence; 3 - Low EODV; 4 - Cells leaking; 5 - Low recharge; 6 - High EOCV; 7 - Discontinued by request

NiH2 CELL LIFE CYCLE TEST

Pack #	Size (AH)	Orbit	DOD (%)	Temp (°C)	C/D	VT (V)	Minimum EODV	Cycle #
3600H (FSM)	93	LEO	9	-5	1.04	1.514	1.292	12811
3601H (FM2)*	93	LEO	9	-5	1.07	1.514	1.292	12680

* Reconditioned twice. 80.7 Ah removed first time and 77.5 Ah removed second time.

SUMMARY OF BATTERY ACTIVITIES AT THE JET PROPULSION LABORATORY

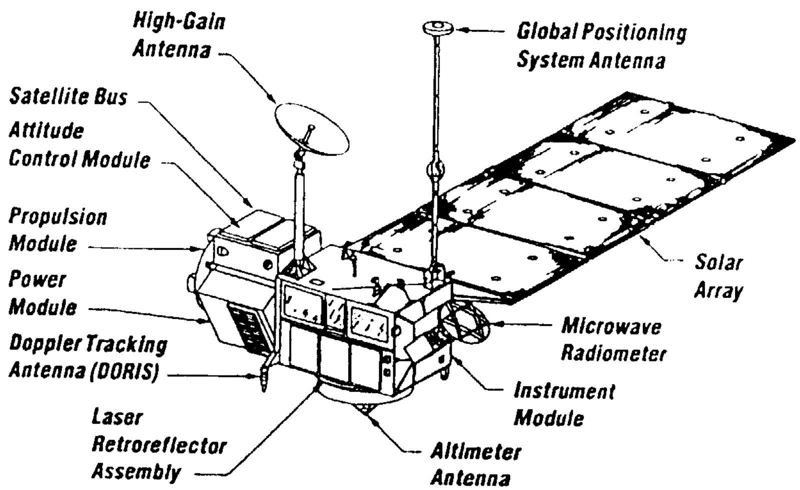
PRESENTED BY
Sal Di Stefano

JPL

1994 NASA AEROSPACE BATTERY WORKSHOP
November 15-17, 1994
Huntsville Marriott
Huntsville, Al

JPL

TOPEX POSEIDON



BATTERY DEFINITION

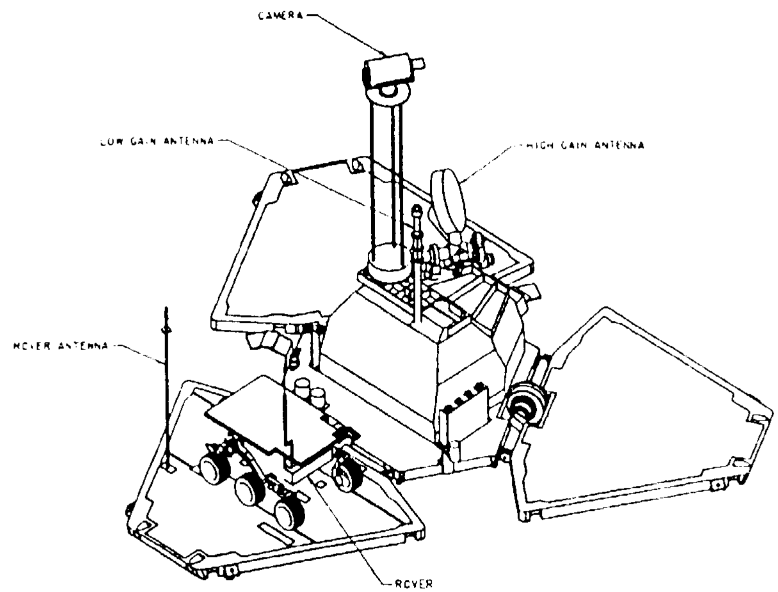
- PRIME CONTRACTOR - FAIRCHILD / McDONNELL DOUGLAS MPS (BATT)
- BATTERY DESIGN
  - MODULAR POWER SUBSYSTEM (3 x 22 CELL 50 Amp-Hr BATT)
  - CELL DESIGN
    - GATES AEROSPACE - NASA STANDARD NiCd
    - 16 POS / 17 NEG
    - PELLON 2505 SEPARATOR
    - NONPASSIVATED POS / TEFLONATED NEG
- BATTERY CYCLE REGIME
  - MEDIUM ALTITUDE ORBIT - VARIABLE OCCULTATIONS AND SOME ÍFULL SUN PERIODS

- 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

ENERGY STORAGE SYSTEMS GROUP

MARS PATHFINDER

JPL

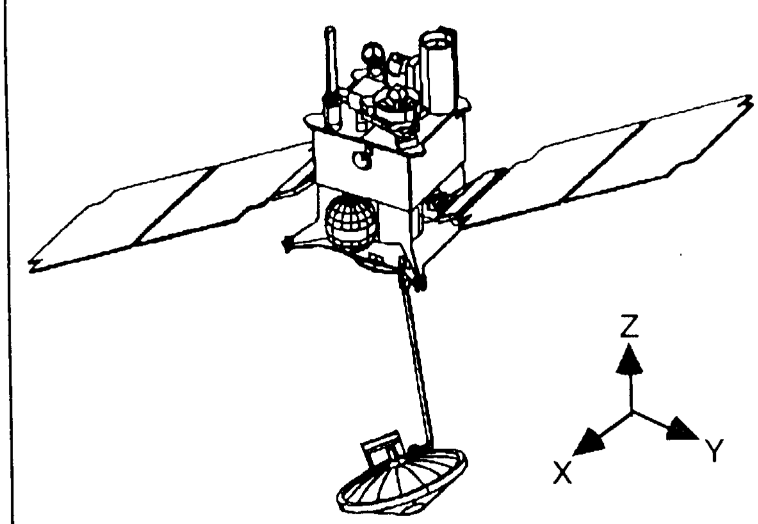


- THREE BATTERIES REQUIRED FOR MISSION
  - LANDER AND CRUISE POWER
    - » 40 AH Ag-Zn / MODIFIED BST SYSTEMS INC. DESIGN
      - 18 CELLS - GOAL IS 30 50% DOD CYCLES ON SURFACE OF MARS
  - PYRO EVENTS
    - » OFF THE SHELF THERMAL ($LiFeS_2$) Eagle-Picher
      - TESTING WA PERFORMED TO VERIFY MISSON PULSE SEQUENCE REQUIREMENTS WERE MET
  - ROVER BATTERY
    - » NINE 'D' SIZE PRIMARY $LiSOCl_2$ CELLS
    - » SAFT 6590 CELL DESIGN BASELINED
      - TESTING TO VERIFY BATTERY CAPABILITIES TO BE PERFORMED

ENERGY STORAGE SYSTEMS GROUP

JPL

MARS GLOBAL SURVEYOR



•PRIME CONTRACTOR - MARTIN MARIETTA

•BATTERY DESIGN

–CELL DESIGN

»3.5" NiH_2 TWO CELL CPV (EAGLE-PICHER)

»16 ELECTRODE PAIR PER CELL

»16 ELECTRODE PAIR / CELL

»31% KOH / 2 LAYER ZIRCAR

–BATTERY

»2 BATTERIES / 8 VESSELS (16 CELLS PER BATTERY)

»VOLTAGE MONITORED @BATTERY & HALF BATTERY LEVEL

»2 STRAIN GAUGES AND 2 TEMPERATURE SENSORS PER BATTERY

»CHARGE CONTROL: PRESSURE WITH V/T AND AHR INTEGRATION BACK-UP

–BATTERY CYCLE REGIME

»11 MONTH CRUISE (THREE 40% DOD CYCLES)

»~8500 MAPPING CYCLES (29% DOD) AND 14,000 RELAY CYCLES (24% DOD)

ENERGY STORAGE SYSTEMS GROUP

NASA AEROSPACE FLIGHT BATTERY PROGRAM

JPL

JPL ACTIVITIES IN SUPPORT OF THE NASA BATTERY STEERING COMMITTEE AND PROGRAM.

WITH THE
OBJECTIVES OF MAINTAINING AND ENHANCING THE QUALITY RELIABILITY
AND
MAINTAINABILITY OF AEROSPACE BATTERIES FOR NASA APPLICATIONS.

ACTIVITY / FY	88 89 90 91 92 93 94 95 96 97 98	REMARKS
NICKEL CADMIUM BATTERY MODEL	Phase I model; Phase II model; Phase III model	Increase fundamental understanding. Enhance safety & reliability
JPL TEST FACILITY	HP 9000 based ten test station system; Mission simulation Tests; NASA MPS Test bed; NWSCC stress tests	Enhance reliability assist flight programs in minimizing risk
ADVANCED FLIGHT TECHNOLOGY	Super NiCd procurement; NiMH survey task; NiMH Technology Verification task; Crane data analysis; NHB revision NASA data task; Advanced $NiCd/NiH_2$ Testing	Provide advanced technology for flight use
NICKEL HYDROGEN BATTERY MODEL	Phase I model; Phase II model; Phase III model	Increase fundamental understanding. Enhance relliability

ENERGY STORAGE SYSTEMS GROUP

JPL

- **BATTERY CHALLENGES FOR FUTURE NASA SPACECRAFT**
  - INCREASE SPECIFIC POWER AND POWER DENSITY (REDUCED MASS / VOLUME)
  - INCREASE ACTIVE STORAGE AND CHARGE RETENTION
  - EXTEND OPERATION TO EXTREME ADVANTAGES
- **PROJECTED APPLICATIONS**
  - SMALL PLANETARY ORBITERS "MICROSPACECRAFT" CLASS
  - LANDER / ROVERS
  - ASTRONAUT EQUIPMENT

STATUS OF Li TECHNOLOGY @ JPL

	Li-TiS2	*Li-ION*	*Li-Polymer*
ANODE	Li	LiC	LiC
CATHODE	TiS2	LiCoO2	LiCoO2
ELECTROLYTE	LiAsF6/EC + 2-MeTHF	LiPF6/EC+DMC+DEC	LiAsF6/PAN+EC+MeS
VOLTAGE	2.1	3.8	3.8
CAPACYTY (AH)	ONE TO 3	one to 3	<0.2
OPERATING TEMPERATURE	60°C TO -20°C	60°C TO -20°C	RT TO 60°C
SPECIFIC ENERGY (Wh/Kg)	132	85	~150
ENERGY DENSITY (Wh / l)	260	240	~350

ENERGY STORAGE SYSTEMS GROUP

JPL

AGENDA

- FLIGHT PROJECT SUPPORT ACTIVITIES
  - TOPEX
  - MARS PATHFINDER
  - MARS GLOBAL SURVEYOR (MGS)
- RESEARCH / DEVELOPMENT AND ENGINEERING ACTIVITIES
  - SUPPORT FOR NASA's FLIGHT BATTERY SYSTEMS PROGRAM (CODE Q)
    - » BATTERY MODELING
    - » NASA BATTERY TESTBED
    - » ADVANCED FLIGHT TECHNOLOGY ASSESSMENT
- RECHARGEABLE LITHIUM BATTERIES FOR SPACE APPLICATIONS

ENERGY STORAGE SYSTEMS GROUP

1994 NASA Aerospace Battery Workshop
November 15-17, 1994
Huntsville, AL

NASA Johnson Space Center
B. J. Bragg

Johnson Space Center Battery Programs Overview

Shuttle Orbiter Programs

Space Station Programs

Advanced Technology Programs

Shuttle Orbiter Programs

- Support DDT&E and Qualification for GFE Flight Applications
  - Variety of Cell Chemistries and Sizes Utilized
    - Lithium (all types), Ag-Zn, Ni-Cd, Ni-MH, Alkaline
    - Sizes from Button Cells up to 25 AH
  - Improve Cell Performance and Safety
  - Major Applications:
    - Helmet Lights
    - Advanced Helmet Light
    - Helmet TV
    - SAFER
    - Crew Comm Unit
    - Survival Radio
    - EMU Backpack
    - Experiment Power

- Support Orbiter Payload Activity
  - Provide Consultation for Battery Selection and Design
  - Review Payload Hazard Reports for JSC Safety Panel
  - In-house Payload Battery Development and Qualification

- Support Development of Payload Battery Safety Policies/Requirements
  - Preparation & Implementation of JSC 20793, Battery Safety Handbook
  - Redefine Payload Battery Safety Policies for Small Batteries

- Support Mission Operations
  - In-flight Problem Resolution
  - Post-flight Failure Analysis/Corrective Action

Shuttle Orbiter Programs:

Shuttle Orbiter program support involves the design, development, testing and evaluation and eventual qualification of battery systems for GFE (Government Furnished Equipment). These batteries include a wide variety of chemistries and sizes, as noted in the view graph. The applications listed are crew equipments, experiments, and payloads, any of which could be used in the cabin or on EVA (Extra-Vehicular Activity) in space vacuum. A major part of this activity involves efforts to improve the performance and safety of the batteries directed at these applications.

Payload support is provided in the areas of safety reviews and hazard report reviews. Consultation for the selection and design of payload batteries is provided, as is support for the development and qualification of in-house payloads.

Support is also provided for the preparation and implementation of battery safety requirements documentation (JSC 20793, "Manned Space Vehicle Battery Safety Handbook"), and for the safety policy determination of various categories of batteries; i.e., small batteries.

Finally, mission operational support is provided for the purpose of in-flight problem solving, hardware corrective action , and crew de-briefing activities.

Space Station Programs (ISSA)

- Monitor ISSA Ni-H2 Cell/Battery Development, Fabrication, Test & Delivery
  - Saft Cell Contract
  - Eagle-Picher Industries Cell Contract
  - Loral Battery ORU Contract

- Maintain Cognizance of NASA-LeRC ISSA Support Tasks
  - Crane Testing of Ni-H2 Technology Cells
  - LeRC In-house Ni-H2 Testing
  - Advanced Ni-H2 Technology Development

- Support Development of Russian Segment Battery Specs & Standards
  - Safety Requirements for Ni-Cd, Ag-Zn, and Small Batteries
  - Verification Mechanisms Development
  - Safety Issues Identification

- DDT&E and Qualification of GFE Batteries for ISSA Applications
  - Advanced Development for EMU Backpack
  - Small Secondary Batteries for GFE (Ni-MH, Ag-Zn, Ni-Cd, Li-Ion, etc.)
  - Charger Development for Small Batteries

Space Station Programs (ISSA):

The development, fabrication, test and delivery of ISSA Ni-H2 cells and batteries are monitored in support of the Space Station Program Office at NASA-Johnson Space Center. There are two cell contractors; Saft Aerospace Batteries, and Eagle-Picher Industries. Both have delivered qualification cells and are beginning to deliver flight cells. Additionally, the power systems contractor, Loral, is testing the battery ORU (Orbital Replacement Unit), and starting to build flight ORU's. This activity is conducted under a task agreement with SSPO (Space Station Program Office).

NASA-LeRC is also supporting the SSPO under task agreements by testing current Ni-H2 cell technology at Crane and in-house, and by in-house testing of advanced technology under development at LeRC. At JSC, cognizance is maintained of this work.

Support is also provided to the SSPO in the area of developing specs and standards for the battery systems on the Russian Segment Modules. This support involves defining the safety requirements for the major battery systems used on the Russian Segments (Ni-Cd and Ag-Zn batteries); understanding the design of the various systems; developing verification mechanisms; and determining the safety issues to be resolved.

Finally, effort is provided for the design, development, test and evaluation and eventual qualification of GFE batteries for the numerous ISSA applications. Examples of these are an advanced EMU backpack battery, an advanced helmet light, and small secondary batteries (Ni-MH, Ag-Zn, Ni-Cd, etc.) for GFE. Work is being performed to investigate new charger technology for the new chemistries being developed; particularly for small batteries.

Advanced Technology Programs

- Evaluation of Performance/Safety of Advanced Chemistries:
  - Li-Ion
  - Ag-MH
  - Li-Polymer
  - Small $Ni\text{-}H_2$
  - Ni-MH
  - Rechargeable Alkalines
  - Advanced Ag-Zn
  - CPV $Ni\text{-}H_2$

- SBIR Programs in Secondary Battery Technology - Phase I/Phase II
  - EIC - $Zn\text{-}O_2$, Phase I & Phase II
  - EIC - Li-Solid State, Phase I & Phase II
  - MATSI - $Zn\text{-}O_2$, Phase I & Phase II
  - Electro Energy, Inc. - Ag-MH, New Phase I
  - TPL, Inc. - Carbon Electrodes for Li-Ion, New Phase I
  - Past Phase I's - Electrochimica, YTP, Ovonic, Technochem, Energy Innovations

- Lithium Cell Internal Short Circuit Hazard Control Development
  - Lower Shorting Capability, but Keep Reasonable Capacity at C/8 Rate
  - Flight Li-BCX II D Cell with 0.4M Electrolyte with WGL
  - Projected Program in Flight Li-BCX II C & DD Cells with WGL
  - Consider Same Approach with Alternate Vendor's $Li\text{-}SOCl_2$ Cells

- Evaluation of Advanced Charger Technologies

- Projected NASA-University-Industry Partnerships with Potential Grant Funding

Advanced Technology Programs:

A major activity of these programs is the evaluation of performance and safety of the various advanced battery chemistries now becoming available to users. These include those listed in the briefing chart. Mission environmental simulations over the rate, temperature and pressure conditions are conducted to cover the extremes of operating conditions encountered. Also, abuse tests, such as short circuit, over discharge, charging and overcharging, and extreme temperature exposure. Hazard controls are evaluated for these cells as well.

SBIR programs are listed in the briefing chart. JSC has three active Phase II programs in place; with two new Phase I programs about to be initiated. These programs allow the investigation of new battery innovations which have the potential of becoming viable commercial products. A major effort should be made by all NASA centers involved in the SBIR program to make sure resulting activities are shared for the benefit of all.

Lithium batteries have demonstrated the highest energy density available; however, the hazard potential is also high. A program to control this hazard is under way at JSC, primarily for the hazard of internal and external short circuit. Currently, flight C, D, and DD cells of the WGL Li-BCX chemistry are flown with a waiver for the hazard of an internal cell short, for which there is no positive control. The institution of a 0.4 molarity electrolyte in a Li-BCX D cell has demonstrated a level of control for this hazard not previously achieved. This electrolyte selection still allows sufficient performance in capacity to allow its use for the present applications on the Shuttle Orbiter. Final verification of this design is in progress; future programs will be directed at the flight C and DD cells of a Li-BCX II chemistry, as well as at alternate Li-LOCl2 cells now under evaluation as alternate flight cells. Final verification of this control feature would allow the deletion of the waiver and thus allow greater use of this high energy density cell for flight applications.

As noted earlier, evaluation of new charger technologies is under way, required to a great extent by the special charging requirements of the various new cell chemistries such as Ni-MH and Li-Ion. New pulse charging techniques are also touted as having performance advantages, and need to be evaluated for potential application.

Finally, new commercially oriented partnerships are being promoted between NASA, Universities, and Industries. Space Act Agreements constitute one form of these partnerships; but with no associated funding currently available. University grant funds may help to make these new agreements viable. Progress will be reported as these programs develop.

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POWER
TECHNOLOGY
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1994 NASA AEROSPACE BATTERY WORKSHOP

LEWIS RESEARCH CENTER BATTERY PROGRAM AN OVERVIEW

BY

MICHELLE MANZO

AND

DR. PATRICIA O'DONNELL

HUNTSVILLE MARRIOT,

HUNTSVILLE, ALABAMA

NOVEMBER 15-17, 1994

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AGENDA

POWER TECHNOLOGY DIVISION

- LeRC ORGANIZATION
- ADVANCED COMMUNICATIONS TECHNOLOGY SATELLITE (ACTS)
- INTERNATIONAL SPACE STATION ALPHA (ISSA)
- ELECTROCHEMICAL TECHNOLOGY BRANCH
- PARTNERSHIP FOR A NEW GENERATION OF VEHICLES (PNGV)
- ADVANCED IPV NICKEL-HYDROGEN DEVELOPMENT
- LIGHTWEIGHT NICKEL ELECTRODE DEVELOPMENT
- ADVANCED LIGHTWEIGHT CPV NICKEL-HYDROGEN DEVELOPMENT
- METAL HYDRIDE EVALUATION
- BIPOLAR NICKEL-METAL HYDRIDE BATTERY DESIGN
- NASA AEROSPACE FLIGHT BATTERY SYSTEMS PROGRAM

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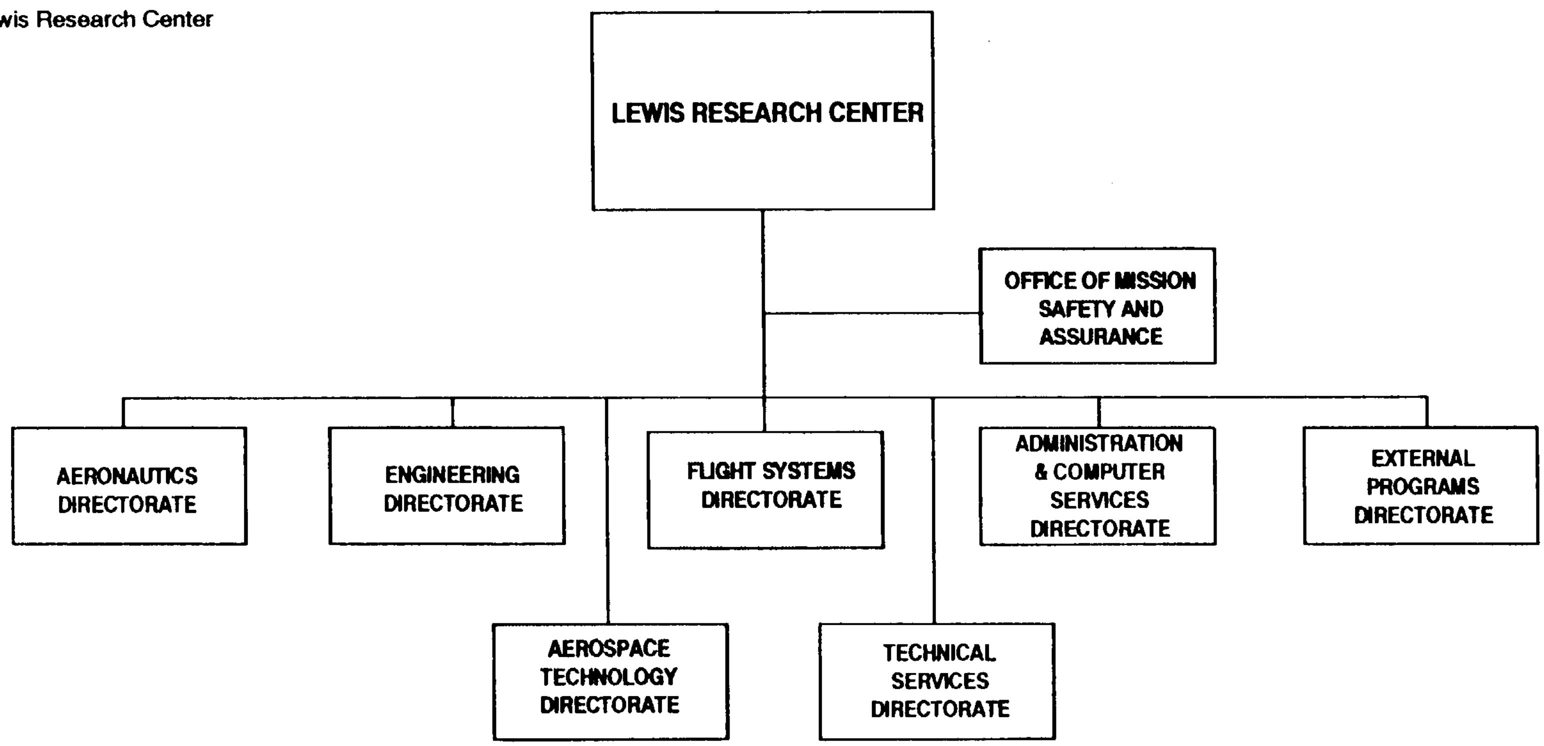
NASA LEWIS RESEARCH CENTER

POWER TECHNOLOGY DIVISION



☐ BATTERY POWER SYSTEM PROGRAMS

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ACTS

ADVANCED COMMUNICATIONS TECHNOLOGY SATELLITE

ADVANCED COMMUNICATIONS TECHNOLOGY SATELLITE

POWER SYSTEM: MARTIN MARIETTA (GE ASTRO SPACE)

BATTERY KEY PARAMETERS:

- 2 Ni-Cd BATTERIES WITH 19 Ah NAMEPLATE CAPACITY (22 CELLS EACH)
- 50% DEPTH-OF-DISCHARGE MAXIMUM
- MISSION REQUIREMENT 4 YEAR GEO REGIME WITH <400 CYCLES
- RECONDITIONING AVAILABLE
- INDIVIDUAL CELL VOLTAGE MONITORING AVAILABLE
- 4 CHARGE RATES AVAILABLE: C/7, C/20, C/30 C/60
- PLATE MANUFACTURING DATE: 1/90 (+) AND 2/90 (-)
- CELL FILL DATE: 8/17/90

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ACTS

- LAUNCHED SEPTEMBER '93
- SUN EARTH ACQUISITION MANEUVER A SUCCESS
- THREE ECLIPSE SEASONS
- 108 CHARGE/DISCHARGE CYCLES
- OPERATING AT <50% DOD
- TRICKLE CHARGE AT C/60
- TEMPERATURE AT <8°C
- CELLS REMAIN BALANCED
- NO ANOMALIES WITH POWER SYSTEM TO DATE

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INTERNATIONAL SPACE STATION ALPHA

Ni/H_2 BATTERY and CELL TESTING

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POWER TECHNOLOGY DIVISION

ISSA GOALS AND PROGRAMS

- IN MARCH OF 1986, NICKEL-HYDROGEN (Ni/H_2) CELLS WERE CHOSEN AS THE ENERGY STORAGE SYSTEM FOR ISSA

- GOALS
  - OBTAIN EXPERIENCE IN HANDLING AND TESTING Ni/H_2 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/H_2 TEST FACILITY IN BLDG. 309
    - Ni/H_2 CELL TESTING AT THE NAVAL SURFACE WARFARE CENTER (NSWC) AT CRANE, IN

  - PRIME
    - CELL DEVELOPMENT PROGRAM WITH VENDORS
    - ENGINEERING MODEL PROOF-OF-CONCEPT TEST AT NASA LeRC/PSF

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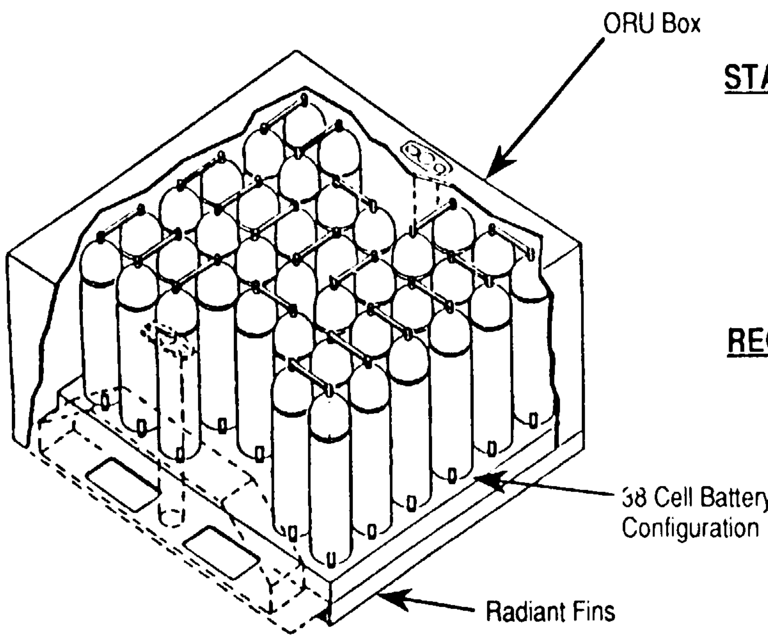
ENERGY STORAGE SUBSYSTEM Ni/H_2 BATTERY ORU



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"x36"x17"
• BATTERY ORU ASSEMBLY MASS	349.9 lbs
• NOMINAL BATTERY CELL CAPACITY	81Ah
• MEAN TIME BETWEEN REPLACEMENT	5.0 yrs
• DESIGN LIFE	6.5 yrs
• DESIGN CYCLE LIFE	37,960 cycles
• STORAGE LIFE	4 yrs
• NOMINAL DEPTH OF DISCHARGE	35%

BATTERY ORU PROVIDES STATION POWER DURING SOLAR ECLIPSE PERIODS

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NASA
C-91-07931

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IPV NICKEL HYDROGEN CELL TESTING INTERNATIONAL SPACE STATION ALPHA SUPPORT

POWER TECHNOLOGY DIVISION

CRANE TESTING

- LEO LIFE TESTS
  CHARGE CONTROL INVESTIGATIONS
  STORAGE INVESTIGATIONS
- 380 IPV $Ni-H_2$ CELLS TESTED
- 65 Ah AND 81 Ah CAPACITY
- 3 COMMERCIAL VENDORS
- 10^oC and -5^oC TEMPERATURES
- 35% AND 60% DEPTH-OF-DISCHARGE
- 26% AND 31% KOH
- 5 CELL DESIGN VARIATIONS
- 1 50 Ah CPV $Ni-H_2$ BATTERY

IN-HOUSE TESTING

- LEO LIFE TESTS
- 39 IPV $Ni-H_2$ CELLS TESTED
- 50 Ah AND 65 Ah CAPACITY
- 3 COMMERCIAL VENDORS
- 10^oC AND -5^oC TEMPERATURES
- 35% DEPTH-OF-DISCHARGE
- 26% AND 31% KOH
- 13 CELL DESIGN VARIATIONS

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ELECTROCHEMICAL TECHNOLOGY BRANCH

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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

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ELECTROCHEMICAL TECHNOLOGY BRANCH

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BATTERIES

- NICKEL-CADMIUM
- NICKEL-METAL HYDRIDE
- NICKEL-HYDROGEN
- SODIUM-SULPHUR
- LITHIUM-POLYMER
- LITHIUM-CARBON DIOXIDE

FUEL CELLS

- PEM
- MOLTEN CARBONATE
- SOLID OXIDE

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NEW GENERATION VEHICLE TECHNOLOGY

POWER TECHNOLOGY DIVISION

PEAKING POWER STORAGE

ISSUES
- HIGH PEAK POWER
- LIGHTWEIGHT
- CHARGE/DISCHARGE CYCLE LIFE
- UTILIZATION OF REGENERATIVE BRAKING (RAPID RECHARGE)
- RECYCLABILITY/DISPOSAL
- MANUFACTURABILITY/COST

POWER STORAGE SOURCES
- BATTERIES
- ULTRACAPACITORS
- FLY WHEELS
- REGENERATIVE FUEL CELLS

APPROACH
- EVALUATE SOA POWER MANAGEMENT DEVICES
- DESIGN AND DEVELOP LIGHTWEIGHT COMPONENTS
- DEVELOP DESIGN OPTIONS FOR MAXIMUM PERFORMANCE
- IMPROVE CURRENT EFFICIENCY
- OPTIMIZE RAPID CHARGE/DISCHARGE PERFORMANCE
- UTILIZE UNIQUE THERMAL MANAGEMENT SCHEMES
- EVALUATE ADVANCED DESIGNS
- INTEGRATE SELECTED DESIGNS INTO EV SYSTEM CONCEPT
- STUDY POWER MANAGEMENT INTERFACES (MOTOR/CONTROLLER)
- FOCUS ON TECHNOLOGY OPTIONS TO REDUCE COSTS

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ADVANCED BATTERIES
AUTOMOTIVE APPLICATIONS

INITIAL THRUST

- ADVANCED Ni ELECTRODES FOR Ni-MH BATTERIES
  - SPACE ACT AGREEMENT (SAA) WITH USABC
  - NASA DEVELOPED HIGH PERFORMANCE LIGHTWEIGHT Ni ELECTRODES - COSTLY
    - TERRESTRIAL ELECTRODES LOW COST - LOW PERFORMANCE
    - PROVIDE OPTIMIZED PERFORMANCE IN 2 YEARS

LONG TERM ACTIVITIES

- PURSUE ADVANCED NaS TECHNOLOGIES
  - ~300 W-hr/kg
- Li-SOLID POLYMER
  - INCREASED ENERGY DENSITY
  - PACKAGING

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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

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ADVANCED IPV NICKEL HYDROGEN BATTERY CELL DESIGN

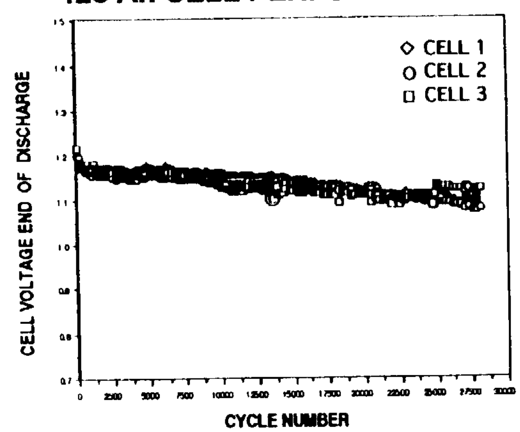
POWER TECHNOLOGY DIVISION

- INNOVATIVE CELL DESIGN CONCEIVED AND PATENTED AT NASA LeRC
- ADVANCED FLIGHT CELLS CYCLED AT 60% DOD, WITH NO CELL FAILURE

SIGNIFICANCE: DECREASE IN LIFE CYCLE COST

BREAKTHROUGH IN LEO CYCLE LIFE

125 Ah CELL PERFORMANCE



CELL FEATURES

- 26% KOH - IMPROVES CYCLE LIFE
- 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

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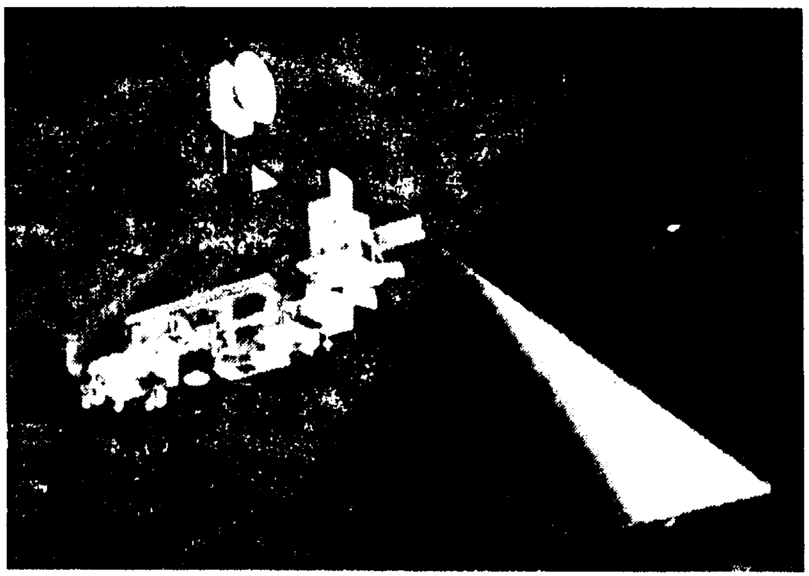
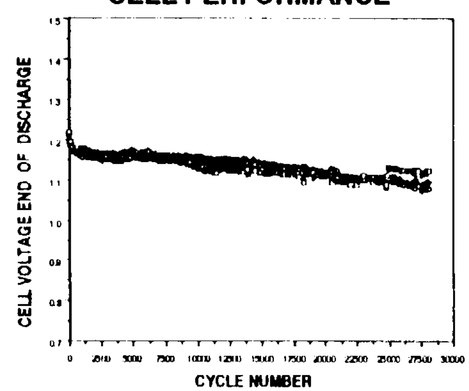
NASA LEWIS ADVANCED DESIGN NICKEL HYDROGEN BATTERY TECHNOLOGY SELECTED FOR EARTH OBSERVING SATELLITE (EOS)

POWER TECHNOLOGY DIVISION



EOS
LAUNCH 1998

ADVANCED NICKEL HYDROGEN SELECTED AS BASELINE FOR EARTH OBSERVING SATELLITE - EOS



- **INNOVATIVE CELL DESIGN CONCEIVED AND PATENTED AT NASA LEWIS**
- **CELL FEATURES A CATALYZED WALL WICK FOR**
  - IMPROVED OXYGEN MANAGEMENT
  - IMPROVED ELECTROLYTE MANAGEMENT
  - IMPROVED THERMAL MANAGEMENT
- **CATALYZED WALL WICK FLIGHT CELLS PASS 5 YEAR MARK AT 60% DOD WITH NO CELL FAILURES**

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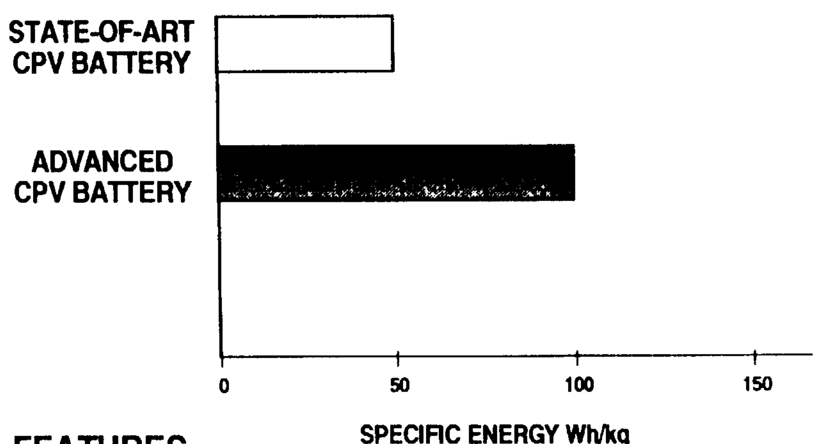
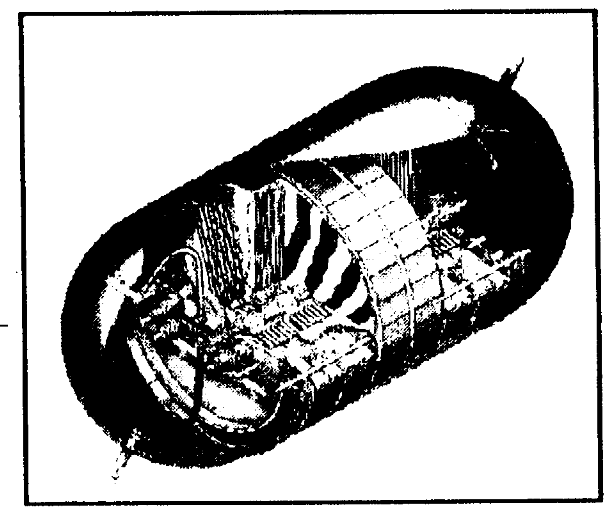
ADVANCED LIGHTWEIGHT CPV BATTERY





FEATURES

- ADVANCED THERMAL MANAGEMENT
- LIGHTWEIGHT NICKEL ELECTRODE
- LOW COST DESIGN
- LONG CYCLE LIFE

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POWER TECHNOLOGY DIVISION

CPV NiH_2 MILESTONES

YEAR	1994	1995	1996	1997
	▼ 50 Wh/kg SOA CPV Batteries Procurred From Vendors	▼ Testing Initiated; ▼ Advanced Component Development	▼ Testing Completed; ▼ Advanced Cell Components Available	▼ 100 Wh/kg CPV Design

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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 FOCUSED PROGRAM IN 94
    - PLATFORM POWER AND THERMAL MANAGEMENT

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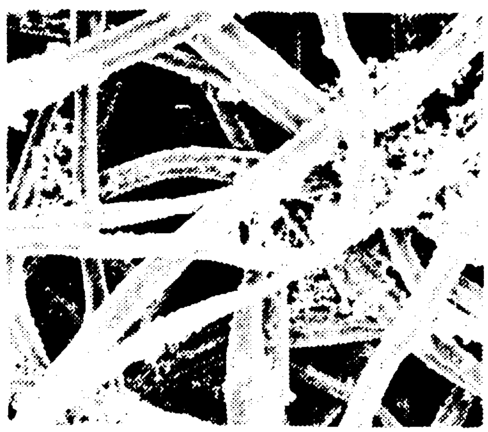
LIGHTWEIGHT NICKEL HYDROGEN CELL

POWER TECHNOLOGY DIVISION



CUSTOMERS

- NASA Mission Offices
- Commercial Aerospace Companies (Communication Satellites)
- Commercial Battery Companies

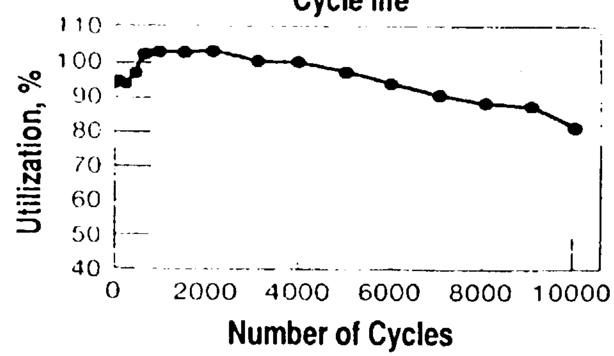
OBJECTIVE

Develop and demonstrate a nickel electrode for Ni-H_2 cell which will increase the specific energy from 50 Whr/kg (SOA) to 100 Whr/kg.

PROGRESS

- Selected lightweight nickel electrode structure
- Utilized pore size engineering
- Increased specific energy
- Verified performance
- Demonstrated 10,000 cycles at 40% DOD

Cycle life



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LIGHTWEIGHT NICKEL-HYDROGEN CELL

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

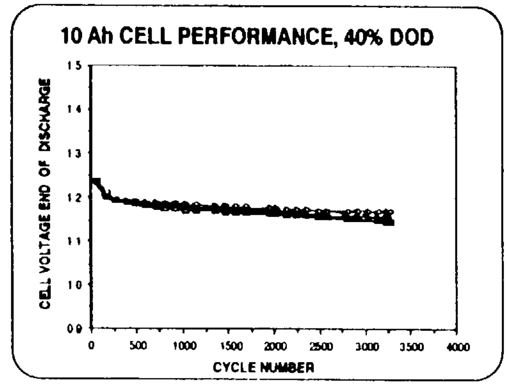
National Aeronautics and
Space Administration

Lewis Research Center

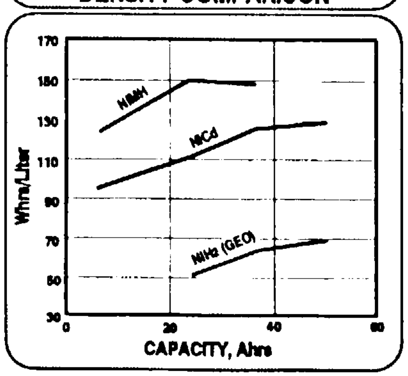
Power Technology Division

STATE-OF-THE-ART NICKEL METAL HYDRIDE BATTERY

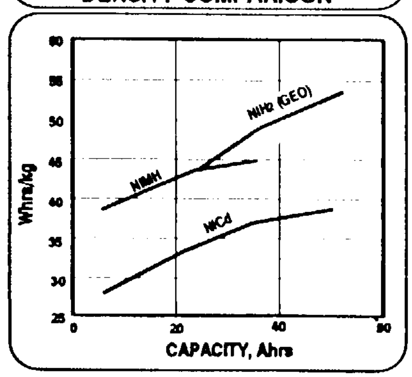
- ADVANTAGEOUS FOR SMALL GEO SPACECRAFT REQUIRING LESS THAN 1 kW OF POWER
- IMPROVED VOLUMETRIC AND GRAVIMETRIC ENERGY DENSITY
- REDUCED BATTERY COST
- CYCLED FOR OVER 3300 CYCLES WITH NO CELL FAILURE



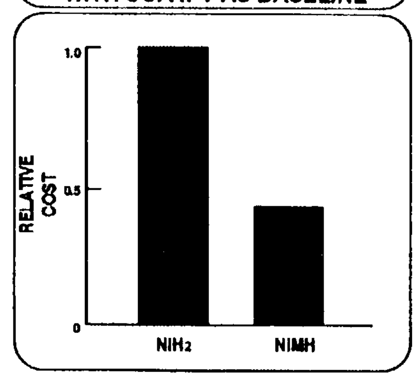
VOLUMETRIC ENERGY DENSITY COMPARISON



GRAVIMETRIC ENERGY DENSITY COMPARISON



RELATIVE COST COMPARISON WITH SOA IPV AS BASELINE



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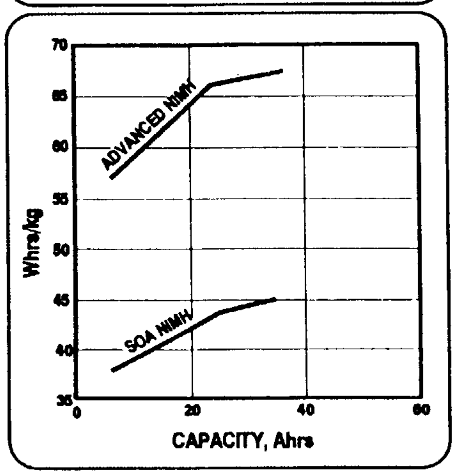
POWER TECHNOLOGY DIVISION

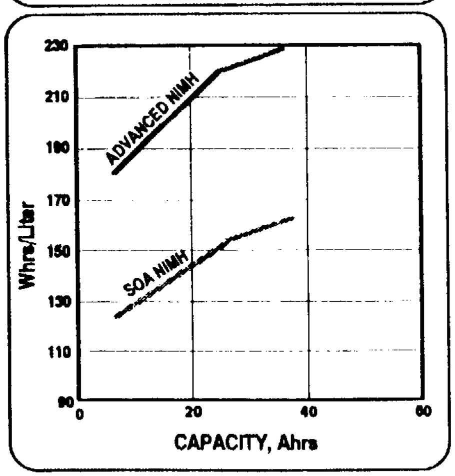
ADVANCED LIGHT WEIGHT, LOW COST NICKEL METAL HYDRIDE BATTERY

- IMPROVE GRAVIMETRIC AND VOLUMETRIC ENERGY DENSITY 50% COMPARED TO SOA NiMH BATTERIES BY USING LIGHTWEIGHT COMPONENTS
- IMPROVE CYCLE LIFE BY INCREASING STABILITY OF NEGATIVE ELECTRODE HYDRIDE MATERIAL
- REDUCE BATTERY COST FOR COMMERCIAL SATELLITES

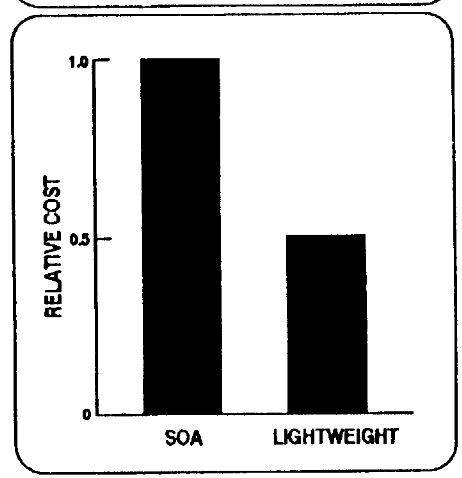
GRAVIMETRIC ENERGY DENSITY COMPARISON



VOLUMETRIC ENERGY DENSITY COMPARISON



RELATIVE COST COMPARISON WITH SOA NIMH AS BASELINE



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AEROSPACE METAL HYDRIDE CELLS

OBJECTIVE:

- EVALUATE METAL HYDRIDE SOA TECHNOLOGY

APPLICATIONS:

- FUTURE SPACECRAFT AND SCIENCE MISSIONS THAT USE NICKEL CADMIUM

STATUS/ACCOMPLISHMENTS:

- 6, 10 Ah EAGLE PICHER Ni-MH CELLS HAVE BEEN CYCLED FOR OVER 6000 LEO CYCLES (40% DOD, 10°C) WITH NO CELL FAILURE. THE AVERAGE END OF DISCHARGE VOLTAGE IS 1.144
- 5, 24 Ah Ni-MH CELLS ORDERED FROM GATES HAVE BEEN DELIVERED TO LeRC
- 6, 10 Ah EAGLE PICHER Ag-MH CELLS HAVE COMPLETED TESTING AT CRANE
- 21, 35 Ah AEROSPACE DESIGN Ni-MH CELLS HAVE BEEN ORDERED FROM SANYO

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BIPOLAR NICKEL-METAL HYDRIDE BATTERY DEVELOPMENT

GOAL:

- ADVANCE NICKEL BATTERY TECHNOLOGY TO MEET NASA/CUSTOMER REQUIREMENTS

OBJECTIVE:

- DEVELOP DESIGN FOR FLIGHT-WEIGHT NICKEL METAL HYDRIDE BATTERY
- DELIVER FLIGHT HARDWARE AS FOLLOW ON

APPROACH:

- INTEGRATE COMPONENT DEVELOPMENT (IN-HOUSE AND CONTRACT) WITH THE BIPOLAR Ni-MH CONTRACT
- BIPOLAR Ni-MH CONTRACT (1995 AWARD)
    - TRADE STUDY
    - HYDRIDE DEVELOPMENT
    - BIPOLAR BATTERY DESIGN
    - FLIGHT HARDWARE (CONTRACT OPTION)

STATUS:

- RFP RELEASE- NOVEMBER
- COMPONENT DEVELOPMENT IS ONGOING

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BIPOLAR NICKEL-METAL HYDRIDE MILESTONES

YEAR	1994	1995	1996	1997	1998	1999	2000
CONTRACT		Contract Award; Trade Study	Preliminary Design	Hardware Demo; Improved Design	Final Design		Battery Hardware
COMPONENT DEVELOPMENT	Initiate Component Development		Component Improvement		Component Selection		

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NASA AEROSPACE FLIGHT BATTERY SYSTEMS PROGRAM

National Aeronautics and
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POWER TECHNOLOGY DIVISION

PROGRAM OBJECTIVES

ENHANCE CELL/BATTERY SAFETY, PERFORMANCE AND RELIABILITY OF BATTERIES FOR SPACE POWER SYSTEMS

MAINTAIN CURRENT BATTERY TECHNOLOGY

INCREASE FUNDAMENTAL UNDERSTANDING OF PRIMARY AND SECONDARY CELLS

PROVIDE A MEANS TO BRING FORTH ADVANCED TECHNOLOGY FOR FLIGHT USE

ASSIST FLIGHT PROGRAMS IN MINIMIZING BATTERY TECHNOLOGY RELATED FLIGHT RISKS

ENSURE THAT SAFE, RELIABLE BATTERIES ARE AVAILABLE FOR NASA's FUTURE MISSIONS

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APPROACH

ESTABLISH SPECIFICATIONS, DESIGN AND OPERATIONAL GUIDELINES FOR PRIMARY AND SECONDARY CELLS AND BATTERIES

PROVIDE FOR IMPROVED CELL/BATTERY MANUFACTURING PROCESS CONTROL

OPEN AND MAINTAIN COMMUNICATION LINES WITHIN NASA AND THE AEROSPACE COMMUNITY

PROVIDE FOR QUALIFICATION OF NEW TECHNOLOGIES - COORDINATE BATTERY TECHNOLOGY ACTIVITIES BETWEEN CODE X AND CODE Q

INCREASE THE FUNDAMENTAL UNDERSTANDING OF PRIMARY AND SECONDARY CELLS

IMPLEMENT INDEPENDENT CHECKS AND BÀLANCES FOR CELL VERIFICATIONS

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NASA AEROSPACE FLIGHT BATTERY SYSTEMS PROGRAMS

LEWIS RESEARCH CENTER TASKS

NICKEL-HYDROGEN GUIDELINES DOCUMENT

BATTERY DATA BASE

IMPEDANCE NDE

NICKEL-CADMIUM VERIFICATION OF SECONDARY CELLS

NICKEL-HYDROGEN CELL COMPONENT AND DESIGN EVALUATION

NICKEL-HYDROGEN CPV TECHNOLOGY EVALUATION

DEVELOPMENT OF SEPARATOR TEST PROCEDURES

NICKEL METAL-HYDRIDE TECHNOLOGY EVALUATION

National Aeronautics and
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SUMMARY

THE LEWIS RESEARCH CENTER BATTERY ACTIVITIES INTEGRATE TOGETHER TO FORM A PROGRAM THAT SUPPORTS THE LEWIS RESEARCH CENTER ROLE AS "CENTER OF EXCELLENCE FOR SPACE POWER"

MSFC Flight Programs and Battery-Related Activities

Jeffrey C. Brewer

Marshall Space Flight Center

NASA Aerospace Battery Workshop

Huntsville Marriott, Huntsville, AL

November 15, 1994

Outline

- **MSFC Flight Programs**
- **Battery-Related Activites**
  - *Program Activities Status*
  - *Test Descriptions*
  - *Test Objectives*
  - *Test Results*

MSFC Flight Programs

- Hubble Space Telescope
- Advanced X-ray Astrophysics Facility -- Imaging
- Solid Rocket Booster and External Tank

Hubble Space Telescope

Program Activities Status

- Maintaining extensive testbed for GSFC
- Engineering support to GSFC through experience with testbed

Hubble Space Telescope

Test Descriptions

- Six-battery system test
- Flight spare battery test
- Three 4-cell packs test
- Six Ni-Cd 4-cell packs test

Hubble Space Telescope

Test Objectives

- **Six-battery system test**
  - ***Determine operating characteristics of the batteries***
  - ***Investigate on-orbit anomalies***
  - ***Test proposed variations prior to implementation on orbit***
- **Flight spare battery test**
  - ***Flight cell life test***
  - ***Observe aging characteristics***

Hubble Space Telescope

Test Objectives

- **Three 4-cell packs test**
  - ***Similar to six-battery system test, but more aggressive in its investigations***
- **Six Ni-Cd 4-cell packs test**
  - ***Continue life test of original flight-type Ni-Cd cells***

Hubble Space Telescope

Test Results

- **Six-battery system test**
  - ***Nominal performance of batteries***
  - ***Value of full EPS testbed proven immeasurable***
  - ***Over 29850 cycles completed***
- **Flight spare battery test**
  - ***Nominal performance of battery***
  - ***Over 29350 cycles completed***

Hubble Space Telescope

Test Results

- **Three 4-cell packs test**
  - ***Nominal performance of cells often through extreme test conditions***
  - ***Over 29700, 31500, and 30500 cycles completed on FSB, TM1, and TM2 packs, respectively***
- **Six Ni-Cd 4-cell packs test**
  - ***Over 41400 cycles completed***
  - ***No failures -- over 40 Ah capacity***

Advanced X-ray Astrophysics Facility -- Imaging

Program Activities Status

- **Currently in PDR**
- **Flight cell procurement to begin mid-1995**
- **Launch planned for September 1998**

Advanced X-ray Astrophysics Facility -- Imaging

Test Descriptions

- Five-cell pack (30 Ah EP $Ni\text{-}H_2$) accelerated mission simulation test
- EPS breadboard test to begin in 1995

Advanced X-ray Astrophysics Facility -- Imaging

Test Objectives

- **Five-cell pack test**
  - ***Accelerated life test for flight design cells***
- **EPS breadboard test**
  - ***Evaluate and verify EPS algorithms***
  - ***Design evaluation and mission operations support***
  - ***Evaluate battery performance under mission profile***

Advanced X-ray Astrophysics Facility -- Imaging

Test Results

- **Five-cell pack test**
  - ***Exceptional performance through first half of mission***
  - ***Electrical characterization proceeding well***

Solid Rocket Booster and External Tank

Program Activities Status

- BST Ag-Zn qualified for SRB Range Safety System (RSS)
- Effort continuing on ET RSS battery
- OFI/DFI alternate source qualification proceeding

Solid Rocket Booster and External Tank

Test Description

- Three-vendor (BST, EP, YTP) characterization test

Test Objectives

- Characterize capacity vs. wet life on RSS-design cells

Solid Rocket Booster and External Tank

Test Results

- Initial testing completed
- Test results being delivered to manufacturers
- Not currently available for public dissemination

Battery-Related Activities

- Students for the Exploration and Development of Space Satellite (SEDSAT)
- Center Director's Discretionary Fund (CDDF)
- Code Q Battery Program

SEDSAT

Program Activities Status

- **Providing technical expertise**
- **Launch scheduled for June 1997**
- **Baselined Ni-MH for flight**
  - ***EP 10 Ah prismatic cells***
  - ***32 cells from CDDF funding for flight and characterization***

SEDSAT

Test Descriptions

- **One 16-cell EP 10 Ah prismatic Ni-MH pack (CDDF)**
- **Two 16-cell (SAFT & Gates) 7 Ah cylindrical Ni-Cd packs**
- **System breadboard**
- **Twelve EP 10 Ah prismatic Ni-MH cells (CDDF)**

SEDSAT

Test Objectives

- **Ni-MH and Ni-Cd packs**
  - ***Characterize electrical performance of each***
  - ***Provide data to aide in flight cell selection***
- **System breadboard test**
  - ***EPS characterization and verification***
- **Twelve EP Ni-MH cells**
  - ***Flight cell characterization***

SEDSAT

Test Results

- **EP Ni-MH pack**
  - ***Over 6100 cycles completed***
- **SAFT/Gates Ni-Cd packs**
  - ***Over 6200 cycles completed***
- **System breadboard test**
  - ***Not yet started***
- **Twelve EP Ni-MH cells**
  - ***Not yet started***

CDDF

Program Activities Status

- **Investigating metal hydride technologies**
  - ***Ni-MH -- 48 cells (20 dedicated to SEDSAT flight battery and spares, 28 for SEDSAT testing)***
  - ***Ag-MH -- 8 cells***
- **Currently in fourth year of funding**

CDDF

Test Descriptions

- One 16-cell EP 10 Ah prismatic Ni-MH pack (SEDSAT)
- Twelve EP 10 Ah prismatic Ni-MH cells (SEDSAT)
- Eight EP 20 Ah prismatic Ag-MH cells

CDDF

Test Objectives

- **EP Ni-MH pack**
  - ***Characterize electrical performance***
  - ***Provide data to aide in flight cell selection***
- **Twelve EP Ni-MH cells**
  - ***Flight cell characterization***
- **Eight EP Ag-MH cells**
  - ***Cell characterization***

CDDF

Test Results

- EP Ni-MH pack
  - *Over 6100 cycles completed*
- Twelve EP Ni-MH cells
  - *Not yet started*
- Eight EP Ag-MH cells
  - *Not yet started*

Code Q Battery Program

Program Activities Status

- NASA Aerospace Battery Workshop
- Ni-H_2 Stress Test Definition
- Ni-H_2 and Ni-Cd DPA Guidelines Document

Code Q Battery Program

Test Description

Ni-H_2 stress test definition

- ***Six 5-cell 48 Ah EP Ni-H_2 packs***
- ***Three at 20 °C -- 40, 50, and 60 % DOD***
- ***Three at 10 °C -- 50, 60, and 70 % DOD***

Code Q Battery Program

Test Objectives

- Supplement existing data from which a 2-year stress profile can be defined
- Characterize identical cells in likely stress profile range

Code Q Battery Program

Test Results

- Test cells were delivered late October
- Test cells are in storage at MSFC
- Test will begin in January 1995

A RE-EXAMINATION OF THE CAPABILITIES OF SILVER-OXIDE/ZINC CELLS FOR POTENTIAL AEROSPACE APPLICATIONS

HARLAN LEWIS, MARK THOMAS, AND WM. JOHNSON
NAVAL SURFACE WARFARE CENTER DIVISION, CRANE

1994 NASA AEROSPACE BATTERY WORKSHOP
HUNTSVILLE, ALABAMA
15 NOVEMBER 1994

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SILVER OXIDE/ZINC CELL CAPABILITIES

* INTRODUCTION

- # RECENT PROBLEMS WITH CYCLE LIFE AND WET-STAND LIFE FOR DOMESTIC TECHNOLOGY RECHARGEABLE CELLS
- # CLAIMS OF DR. V. BAGOTZKY OF THE FRUMKIN INSTITUTE FOR ELECTROCHEMISTRY, OF SUBSTANTIALLY GREATER LIFETIMES FOR AgO/Zn CELLS, AND THEIR USE IN RUSSIAN UNMANNED SATELLITES FOR POWER REQUIREMENTS
- # AVAILABILITY OF CELLS FROM FRUMKIN INSTITUTE FOR TESTING
- # RUSSIAN TECHNOLOGY CELLS STATED AS 100 Ahr RATING, DRY, UNCHARGED (NO OTHER INFORMATION PROVIDED)
- # DOMESTIC CELLS AVAILABLE WERE 110 Ahr RATING, HIGH-RATE, DRY, CHARGED

SILVER OXIDE/ZINC CELL CAPABILITIES

* EXPERIMENTAL

  # CELLS WEIGHED, FILLED, AND SUBJECTED TO TOP-OFF CHARGE (10A RATE TO 2.03V DC)

  # TWO CONDITIONING CYCLES APPLIED (20A RATE DISCHARGE TO 1.20V DC, 10A RATE CHARGE TO 2.03V DC)

  # TEST REGIME SELECTED SIMILAR TO THAT FOR ET (ELECTRONICS) BATTERY CELLS FOR THE SEAL DELIVERY VEHICLE (SDV)

SILVER OXIDE/ZINC CELL CAPABILITIES

- CYCLE LIFE - LOW RATE CELLS: C/5 DISCHARGE, C/10 CHARGE, 5-RUSSIAN, 3-DOMESTIC
  - EVERY 10TH CYCLE, A PERFORMANCE DISHCARGE TO 1.20V DC (FIRST ON 5TH CYCLE, SECOND, ETC. ON 10TH, 20TH) REMAINING NINE CYCLE DISCHARGES TO 50% DoD ALL CHARGES "BALANCED" (TO 2.03V DC)

- WET LIFE: 3-RUSSIAN, 3-DOMESTIC
  - THIRTY DAY STAND-IN-CHARGE STATE PERFORMANCE DISCHARGE AT C/5 RATE TO 1.20V DC, 2 HR OPEN CIRCUIT, BALANCED C/10 CHARGE TO 2.03V DC.
  - MATERIAL ANALYSIS FOR PLATE CHEMISTRY, ADDITIVES
  - DPA ON FAILED CELLS TO DETERMINE FAILURE MODES

SILVER OXIDE/ZINC CELL CAPABILITIES

* RESULTS AND DISCUSSION

DESIGN OF RESPECTIVE CELLS

ELECTROLYTE COMPOSITION FOR RESPECTIVE CELLS

MATERIAL ANALYSIS OF RESPECTIVE CELLS

CYCLE LIFE AND WET-STAND LIFE DATA

- RUSSIAN CELLS CYCLED AT TWICE THE CURRENT DENSITY OF DOMESTIC CELLS (8.4mA/cm^2 vs. 4.5mA/cm^2), THUS RUSSIAN CELLS WERE "STRESSED"

TABLE 1
COMPARISON OF RUSSIAN AND DOMESTIC CELLS

DOMESTIC CELLS	RUSSIAN CELLS
U-Wrap Positives	U-Wrap Negatives
Negatives use no visible binder	Negatives use porous paper and a PVA binder
Plates are placed parallel to face of cell	Plates are perpendicular to face of cell
Grid collector on dry charged	Wire loop collector on dry uncharged
Positive plates use a nylon wick stagger folded	Positive plates use a nylon slip cover sonic weld sealed
Electrolyte uses few/no additives	Electrolyte uses ZnO, LiOH, and $Na_2B_4O_7$ additives
Cellophane separator 1.0mil wood pulp type/silver treated	Cellophane separator is 1.5mil cotton linter type/non-treated
Plates are specially designed for each application	Plates are standardized and selected for each application (?)
Cases are specially designed for each application	Cases are standardized and selected for each application (?)

TABLE 2
COMPOSITION OF RUSSIAN ELECTROLYTE

Potassium Hydroxide	530±10g/l
Zinc Oxide	40±5g/l
Lithium Hydroxide	15±3g/l
Sodium Tetraborate (anhydrous)	55±5g/l

TABLE 3
CHARGED CATHODE COMPOSITIONS†

Sample	AgO	Ag_2O	Ag_2CO_3	Ag	Hg	Cu(ppm)
Domest1	60.72	25.12	4.98	4.43	0	5.8
Domest2	63.27	28.17	4.25	4.03	0	5.4
Domest3	58.36	31.83	3.47	4.52	0	5.3
Avg	60.78	28.37	4.23	4.33	0	5.5
Russ1	46.88	38.86	9.82	3.03	0.08	1.3
Russ2	61.25	28.13	4.93	2.67	0.11	1.5
Russ3	48.46	35.74	8.73	3.29	0.11	1.2
Avg	52.20	34.24	7.83	3.00	0.10	1.3

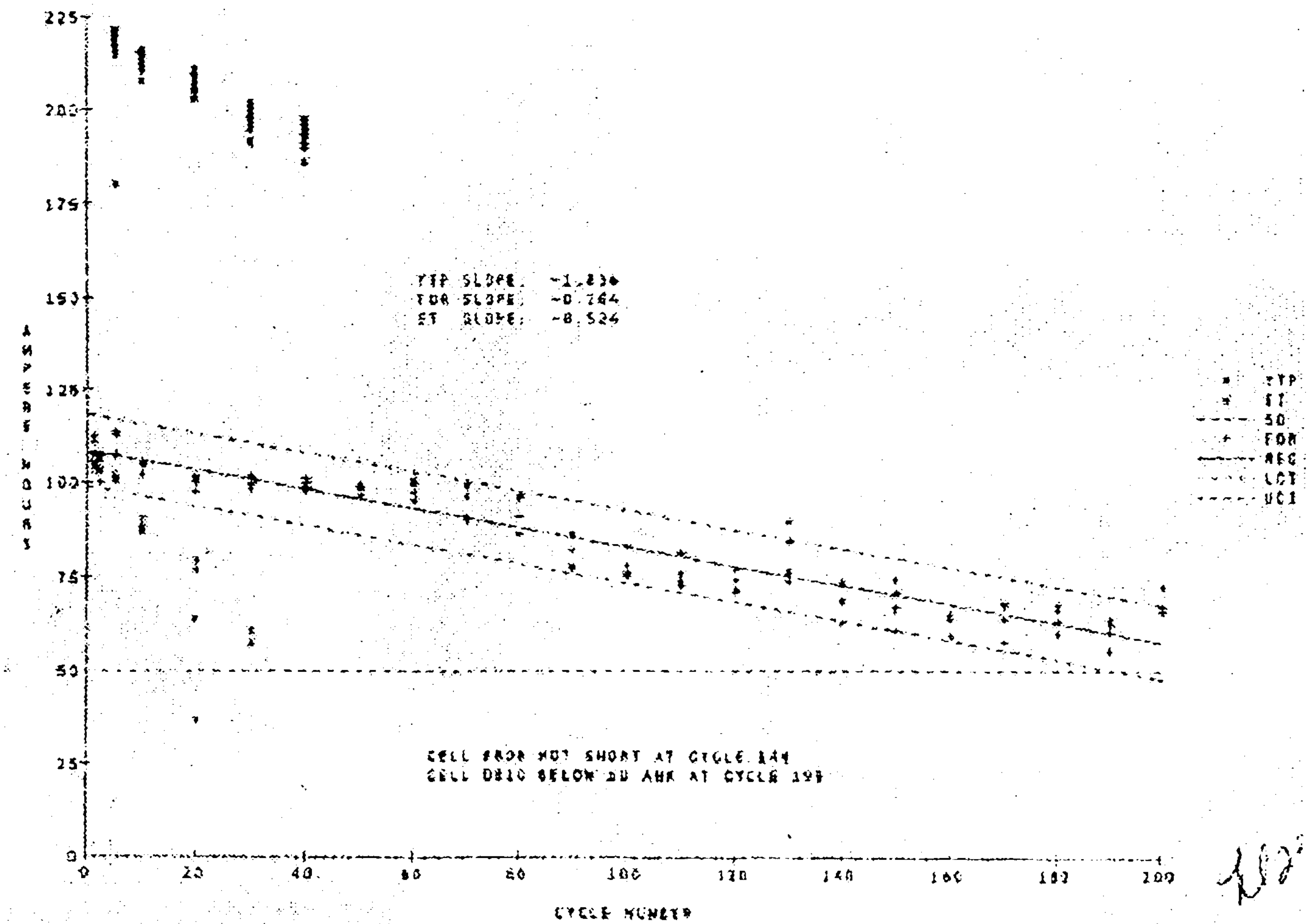
†After top-off and two conditioning cycles, composition in percent unless indicated otherwise

TABLE 4
CHARGED ANODE COMPOSITIONS‡

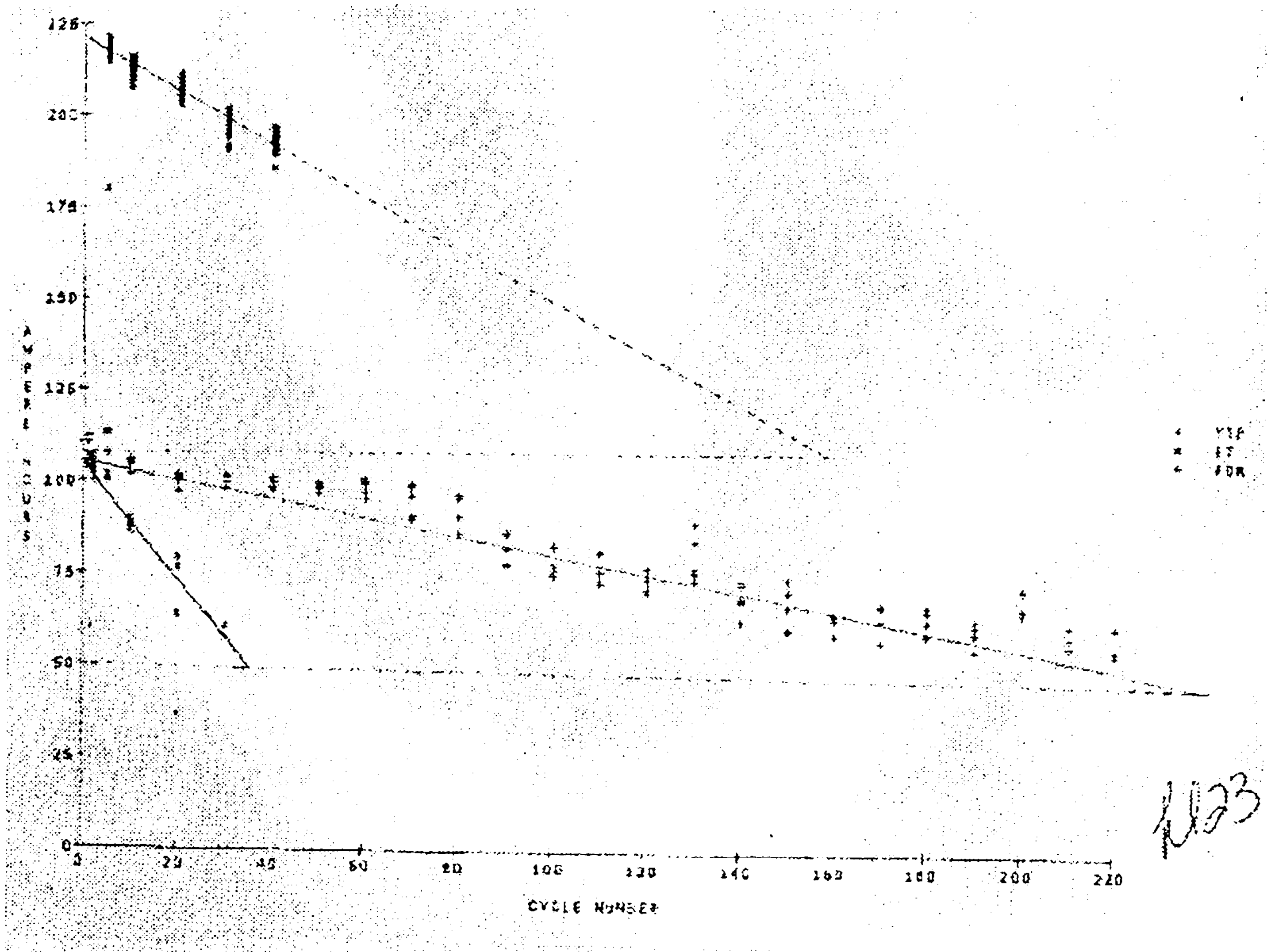
Sample	Total Zn	ZnO	$ZnCO_3$	Hg	Ag(ppm)
Domest1	94.54	17.38	1.88	1.10	202.3
Domest2	93.94	16.76	1.81	1.10	144.5
Domest3	92.94	19.06	2.04	1.14	73.7
Avg	93.81	17.73	1.91	1.11	140.3
Russ1	88.81	23.09	1.54	1.68	13.89
Russ2	85.83	24.26	1.42	1.47	7.83
Russ3	88.95	28.57	1.27	1.72	7.61
Avg	87.86	25.31	1.41	1.62	9.78

‡After top-off and two conditioning cycles, composition in percent unless indicated otherwise

PERFORMANCE DISCHARGE COMPARISONS OF 100 AHR CELLS REPRESENTATIVE OF BOTH DOMESTIC AND FOREIGN TECHNOLOGY



PERFORMANCE DISCHARGE COMPARISONS OF 100 AHR CELLS FROM FOREIGN SOURCES, 100 AHR CELLS FROM DOMESTIC SOURCES, AND 200 AHR DOMESTIC CELLS OF THE SAME VOLUME (ET)



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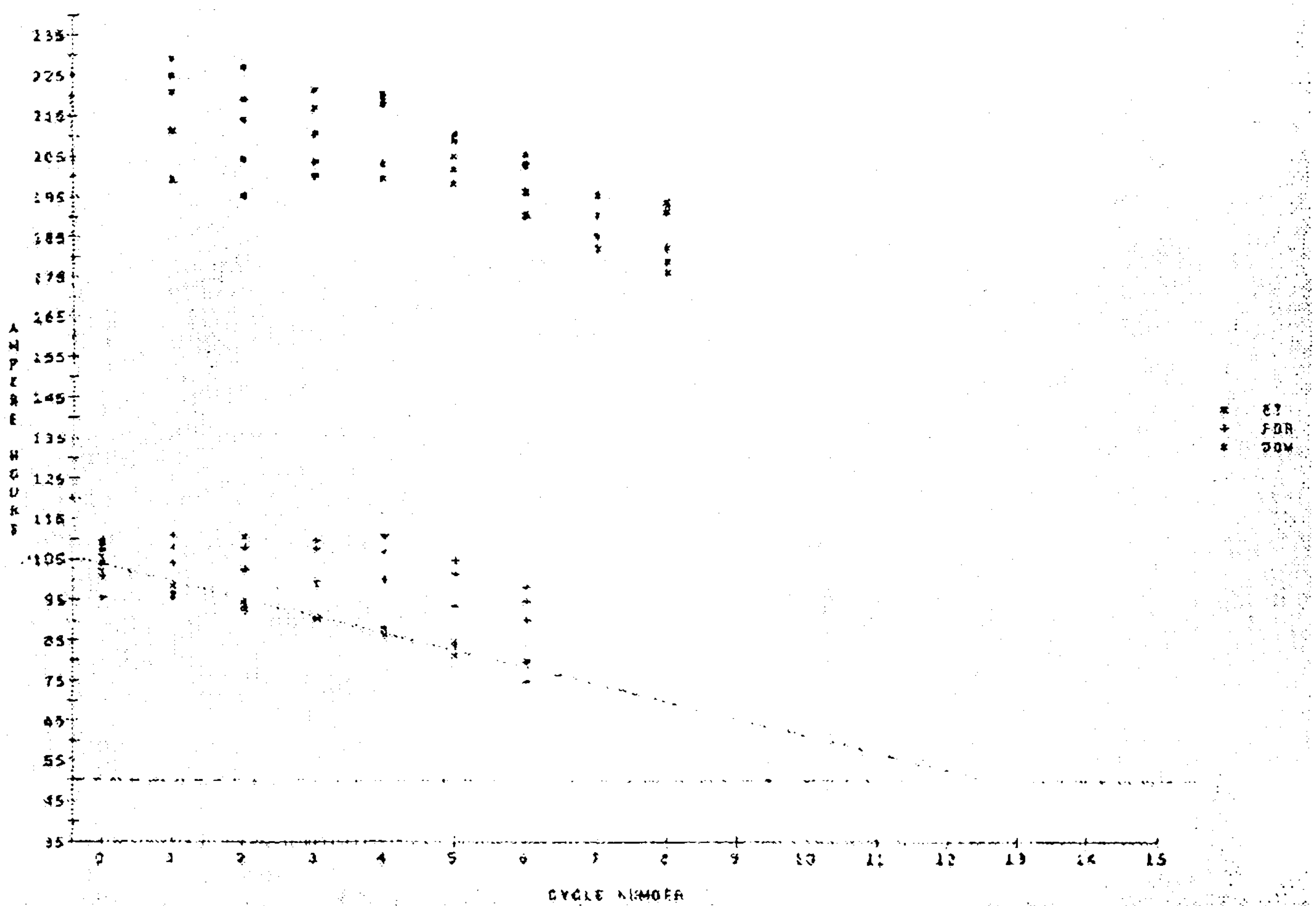
WETLIFE DISCHARGE COMPARISONS OF 100 AHR CELLS FROM DOMESTIC SOURCES, AND 200 AHR DOMESTIC, AND 200 AHR DOMESTIC CELLS OF THE SAME VOLUME (ET)



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SILVER OXIDE/ZINC CELL CAPABILITIES

* CONCLUSIONS

SILVER OXIDE/ZINC RECHARGEABLE TECHNOLOGY APPEARS CAPABLE OF AT LEAST 200 CYCLES TO 50% DoD

FOREIGN TECHNOLOGY CELLS ARE PROBABLY CAPABLE OF GREATER CYCLE LIFE AT CURRENT DENSITIES MORE APPROPRIATE TO TECHNOLOGY STANDARDS

SEPARATOR SOURCE/COMPOSITION HAS BEEN SHOWN PREVIOUSLY TO BE CAPABLE OF A SIGNIFICANT CONTRIBUTION TO CELL LIFE

ELECTROLYTE COMPOSITION MAY RETARD ZINC SOLUBILITY AND THUS RESULT IN RETENTION OF ANODE "SHAPE" AND REDUCTION OF DENDRITE GROWTH

DOMESTIC CELLS WERE NOT REPRESENTATIVE OF DOMESTIC CAPABILITY

Primary Zinc-Air Batteries

Ron Putt, MATSI
Terrill Atwater, ARL
Bob Bragg, NASA-JSC

MATSI 11/15/94 NASA

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OVERALL CELL REACTION

$$Zn + \frac{1}{2}O_2 \rightarrow ZnO \qquad 1.2V$$

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CHARACTERISTICS

- Excellent Specific Energy
  - 300-500 Wh/kg
- Moderate Power
  - C/10 - C/100 Rates Preferred
- Safe
  - Rate-Limited By Oxygen Transport
- Inexpensive
  - Lowest Cost Per Wh In Production
- Low Environmental Impact
  - Factory Recycling Will Be Available

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CELL COMPONENTS

- Anode
  - 67.5% Battery-Grade Zinc Powder
  - 35 W% Potassium Hydroxide
  - 0.6% Gellant
- Separator
  - EPM Impregnated PVA
- Cathode
  - Two-Layer PTFE-Bonded Gas Diffusion Electrode

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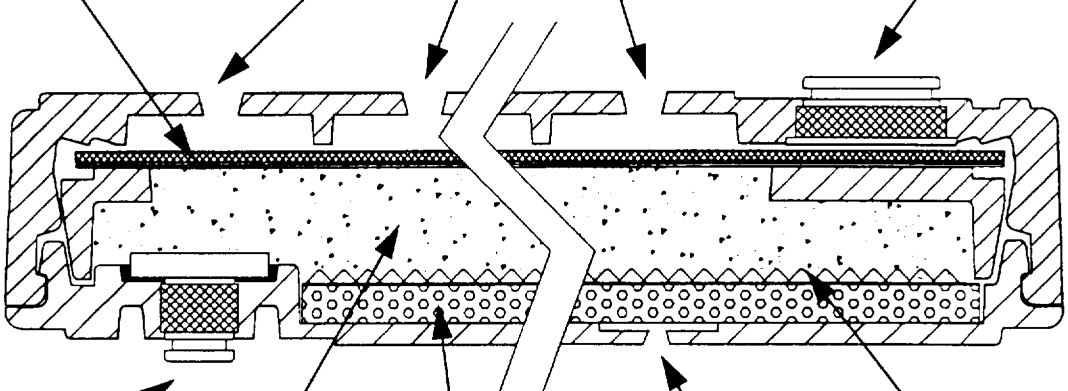
CELL DESIGN*



* U.S. PATENT 5,328,778. FOREIGN AND OTHER U.S. PATENTS PENDING.

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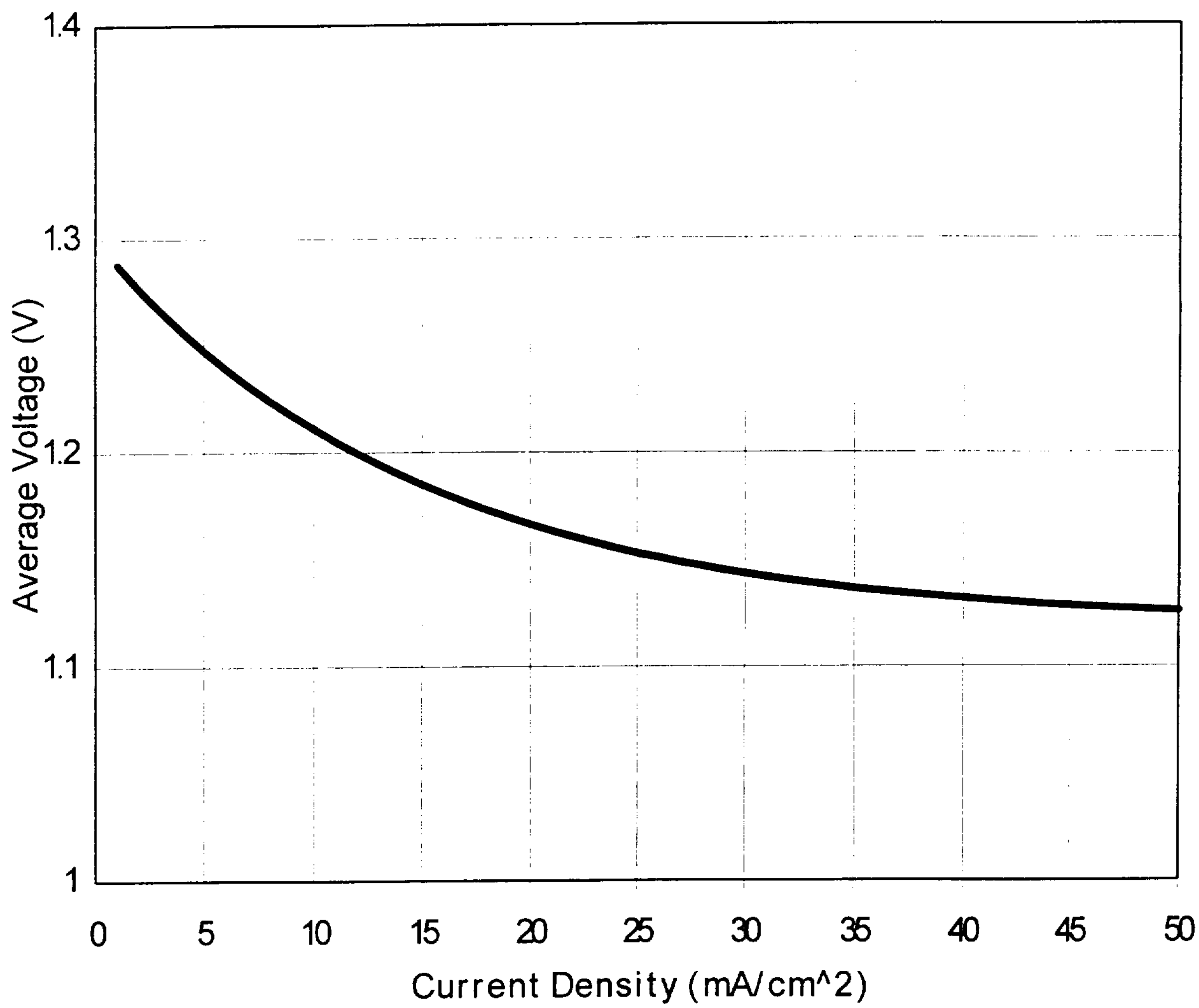
Average Cell Voltage vs. Current Density

$$V = 1.3 - 0.18\,[1 - \exp(-.068i)]$$



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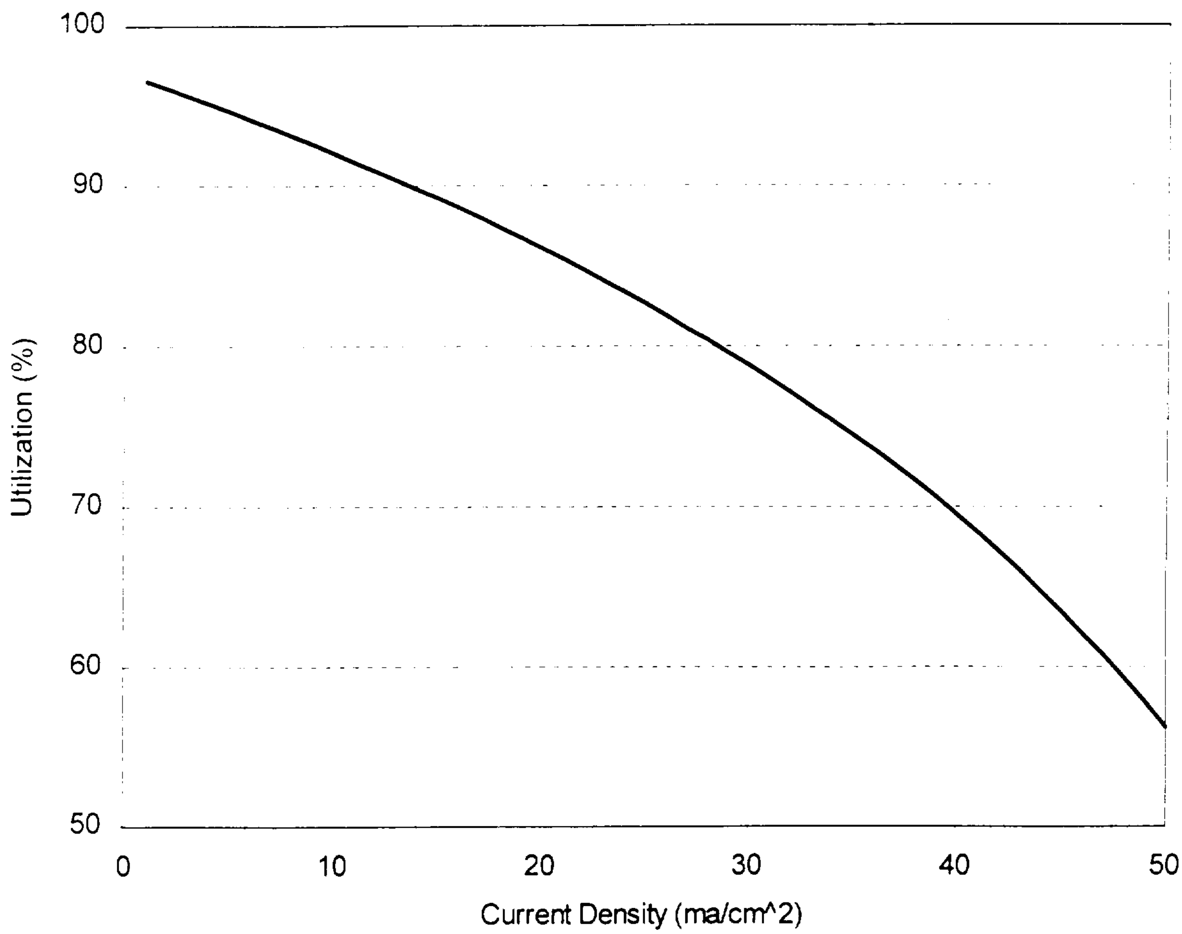
ANODE UTILIZATION vs. CURRENT DENSITY

$$U = 97 + 32.5 \ln (1 - i/70)$$



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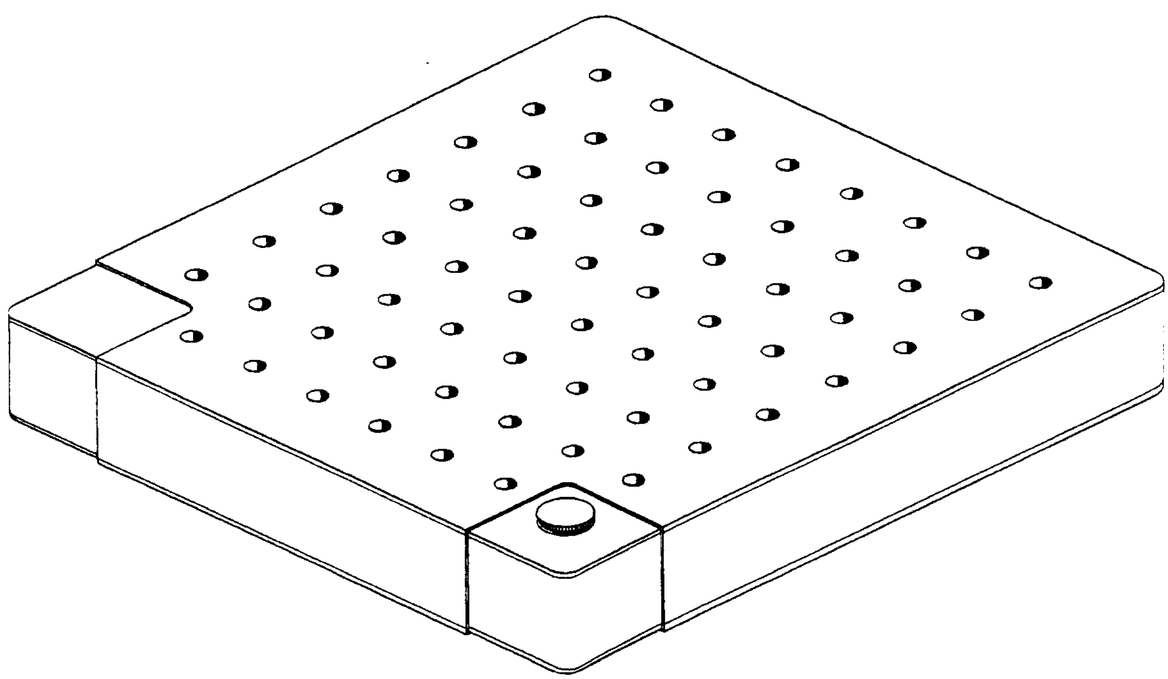
M CELL



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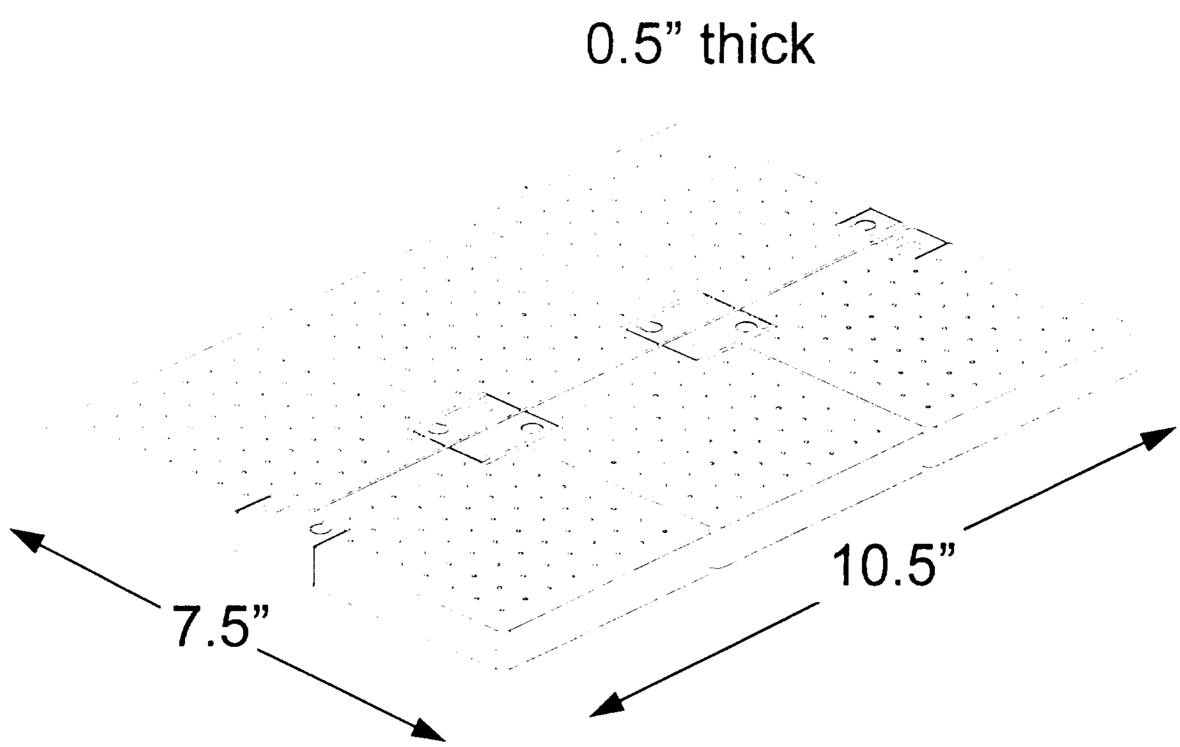
M-6 BATTERY CELL LAYOUT



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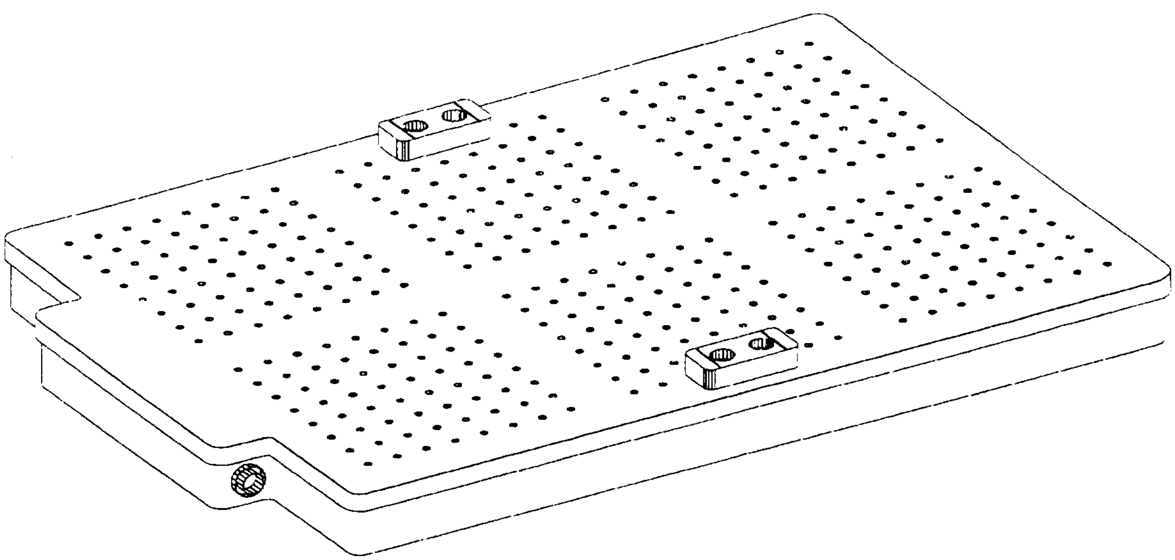
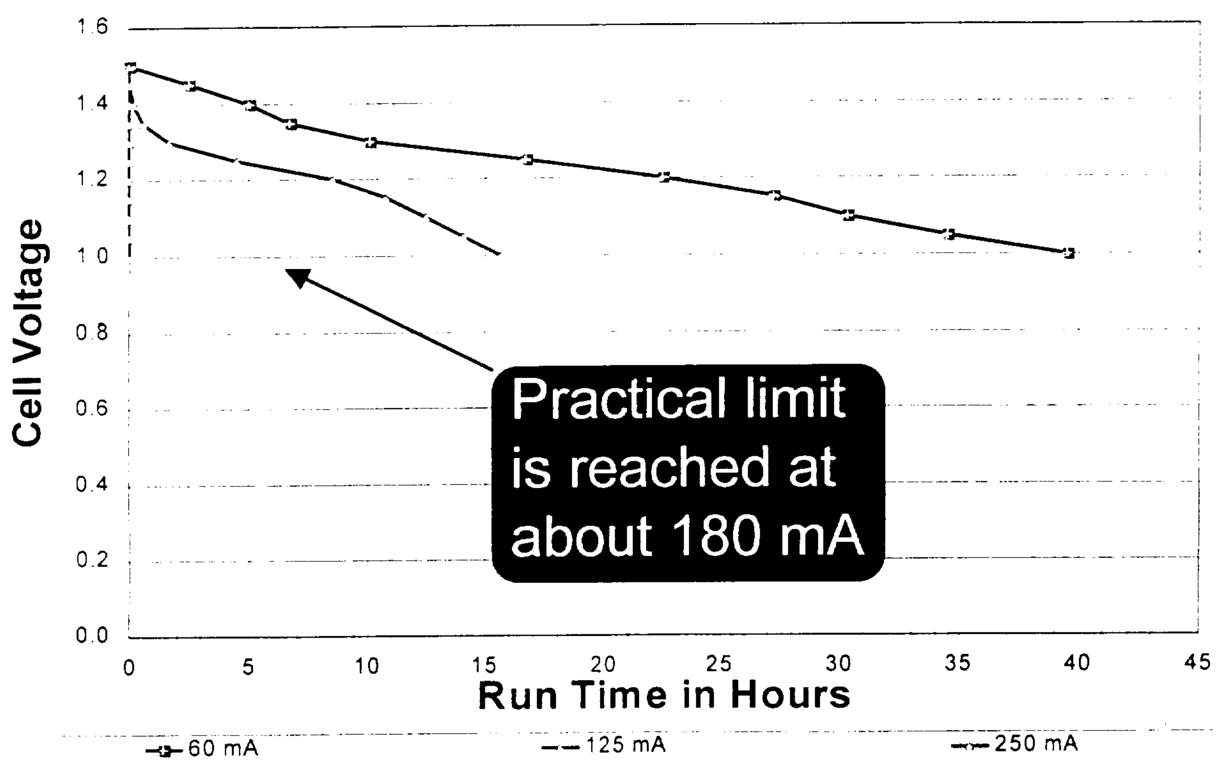
M-6 ALKALINE-AIR™ BATTERY



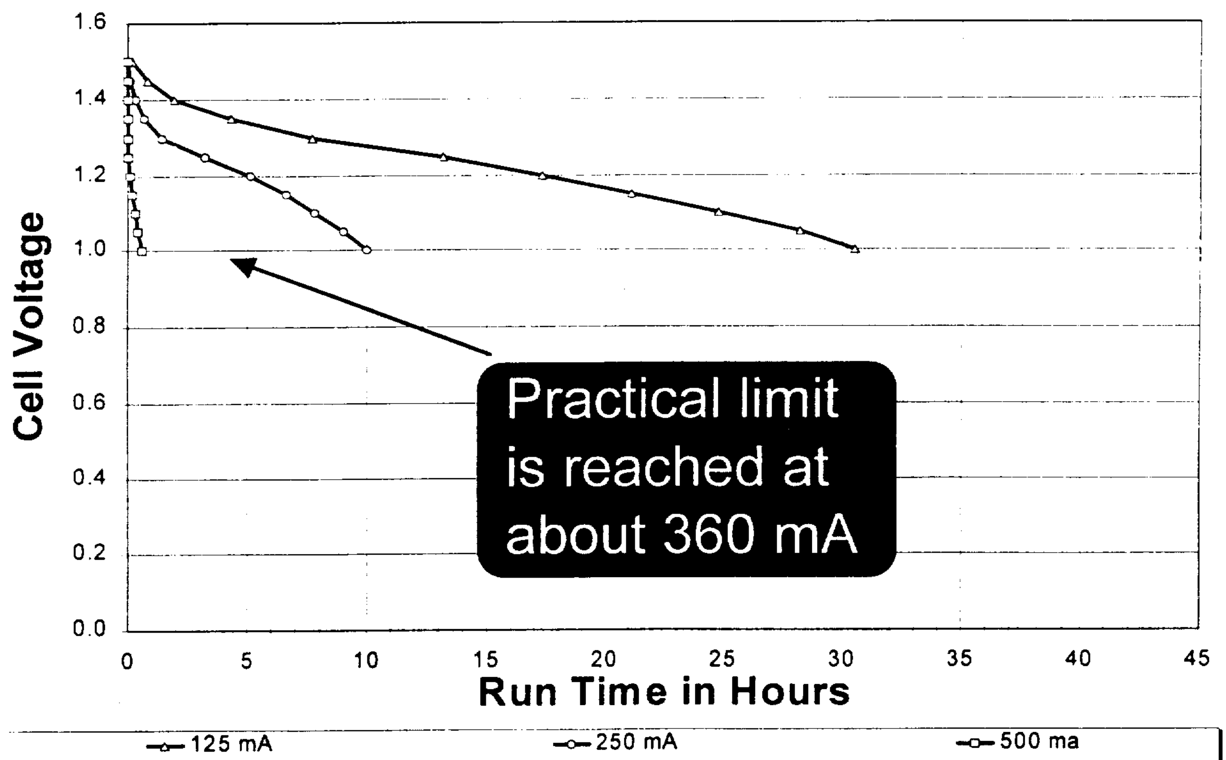
MATSI 11/15/94 NASA

CARBON-ZINC "D" CELL PERFORMANCE



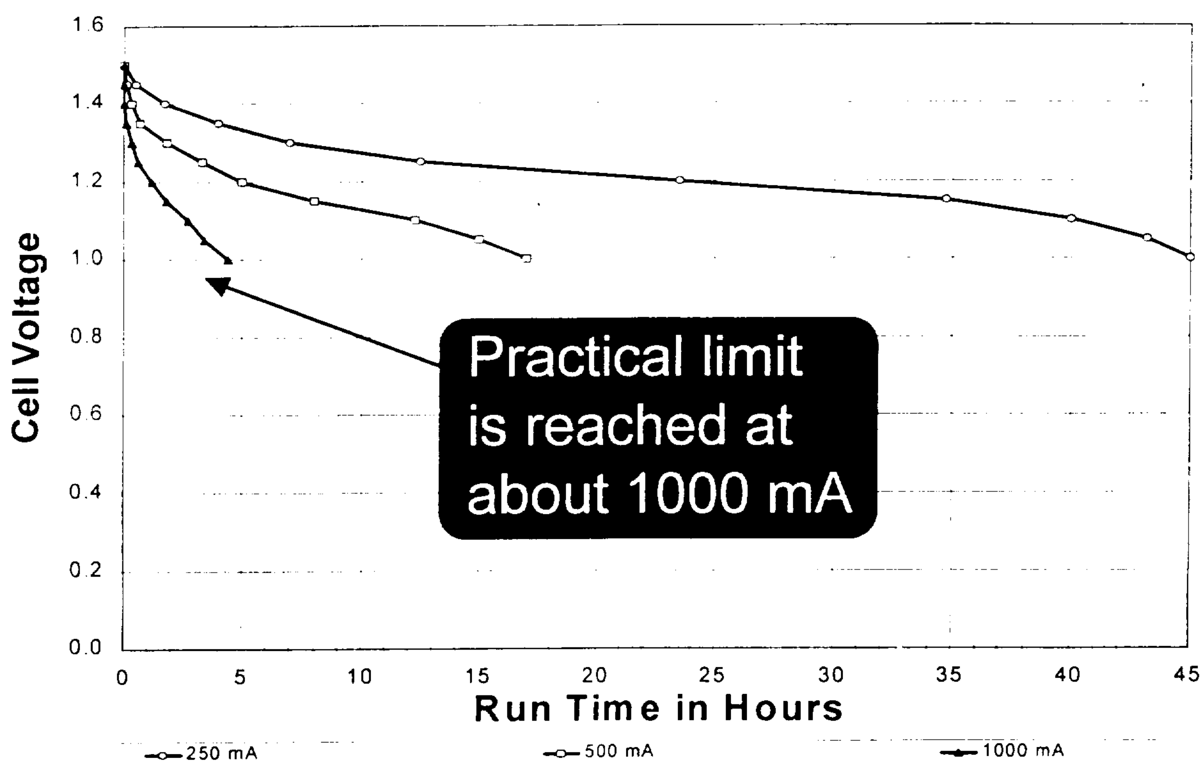
MATSI 11/15/94 NASA

HEAVY DUTY "D" CELL PERFORMANCE



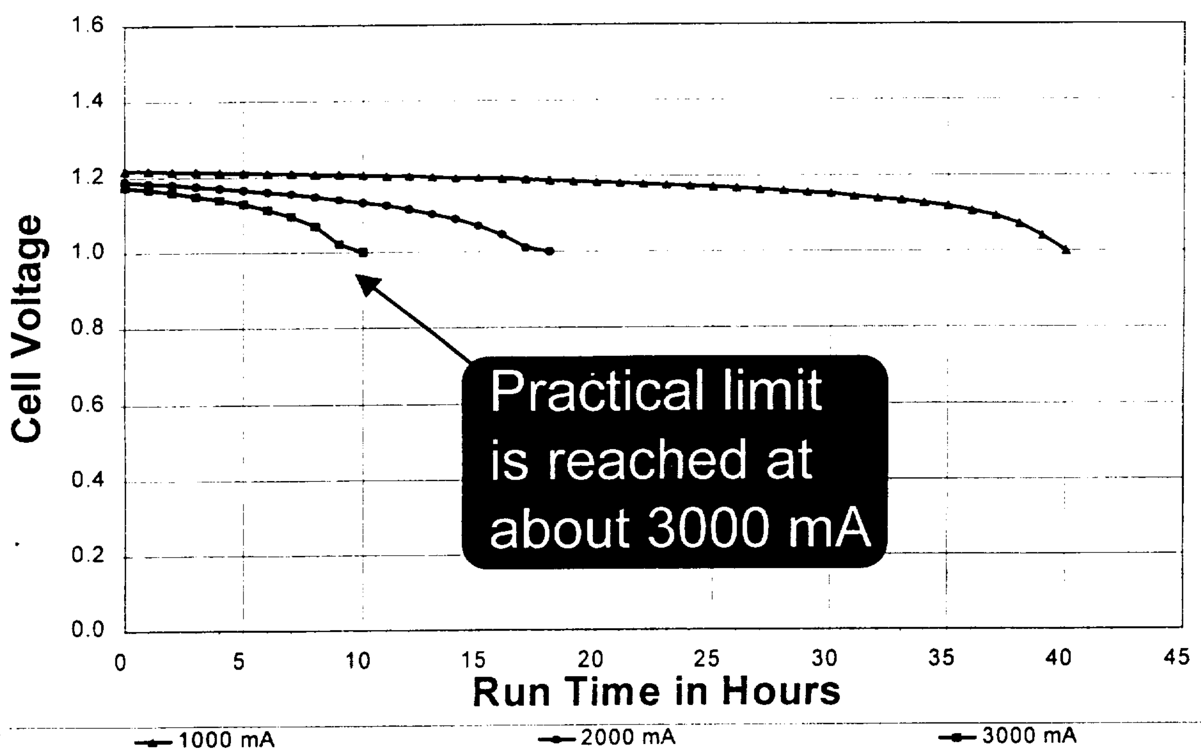
MATSI 11/15/94 NASA

ALKALINE "D" CELL PERFORMANCE



MATSI 11/15/94 NASA

MATSI "M" CELL PERFORMANCE



MATSI 11/15/94 NASA

Nickel-Hydrogen Design Session

A FIRST PRINCIPLES NiH_2 BATTERY MODEL:

A NEW APPROACH

1995 NASA BATTERY WORKSHOP
HUNTSVILLE, ALABAMA

NOVEMBER 15, 1994

Paul Timmerman
Jet Propulsion Laboratory / California Institute of Technology

John Weidner
University of S. Carolina / Department of Chemical Engineering

OUTLINE

GOALS OF BATTERY MODEL DEVELOPMENT

HISTORY OF FINITE DIFFERENCE BATTERY MODELS

APPROACH

COMPARISONS TO EARLIER APPROACHES

ADVANTAGES OF PLANAR MODEL

DISADVANTAGES OF PLANAR MODEL

RESULTS

PORT TO PERSONAL COMPUTERS

CONCLUSIONS

GOALS

DEVELOP FIRST PRINCIPLES MODEL FOR NI-H2 AEROSPACE BATTERY

AVOID UNNECESSARY COMPLEXITY AND COMPUTATION

PROVIDE DETAILED DESCRIPTION OF ALL LIMITING CONDITIONS

ENABLE RAPID CHANGES TO MODEL TO SPEED DEVELOPMENT

HISTORY OF FINITE DIFFERENCE BATTERY MODELS

- FIRST BATTERY MODELS OF LEAD-ACID IN 1970'S (TIEDEMAN AND NEWMAN)
- THE TYPICAL BATTERY MODEL IN 1980'S
  - USED NEWMAN'S BANDJ ROUTINE TO SOLVE POROUS ELECTRODE PROBLEM
  - TREATED EACH COMPONENT AS A POROUS REGION
  - FAN AND WHITE ADAPTED TECHNIQUE FOR NICAD CELL MODEL
  - JPL EXPANSION OF CELL MODEL TO INCLUDE BATTERY FEATURES
- IMPROVED ACTIVE MATERIAL TREATMENT IN THE 1990'S
  - SOLVE TRANSPORT THROUGH THIN FILM PROBLEM
  - REQUIRES ADDITIONAL NUMERICAL SOLUTION FOR FILM TREATMENT
  - PSEUDO 2-D MODELS SOLVED BOTH POROUS ELECTRODE AND THIN FILM TRANSPORT
  - MAO AND WHITE: NICKEL HYDROGEN DISCHARGE PERFORMANCE MODEL
  - DEVIDTS AND WHITE: NICKEL CADMIUM PERFORMANCE MODEL

PLANAR MODEL APPROACH

ACHIEVE AN ANALYTICAL SOLUTION TO TREATMENT OF FILM

REPLACE NUMERICAL TREATMENTS SUCH AS BANDJ AND PSEUDO2

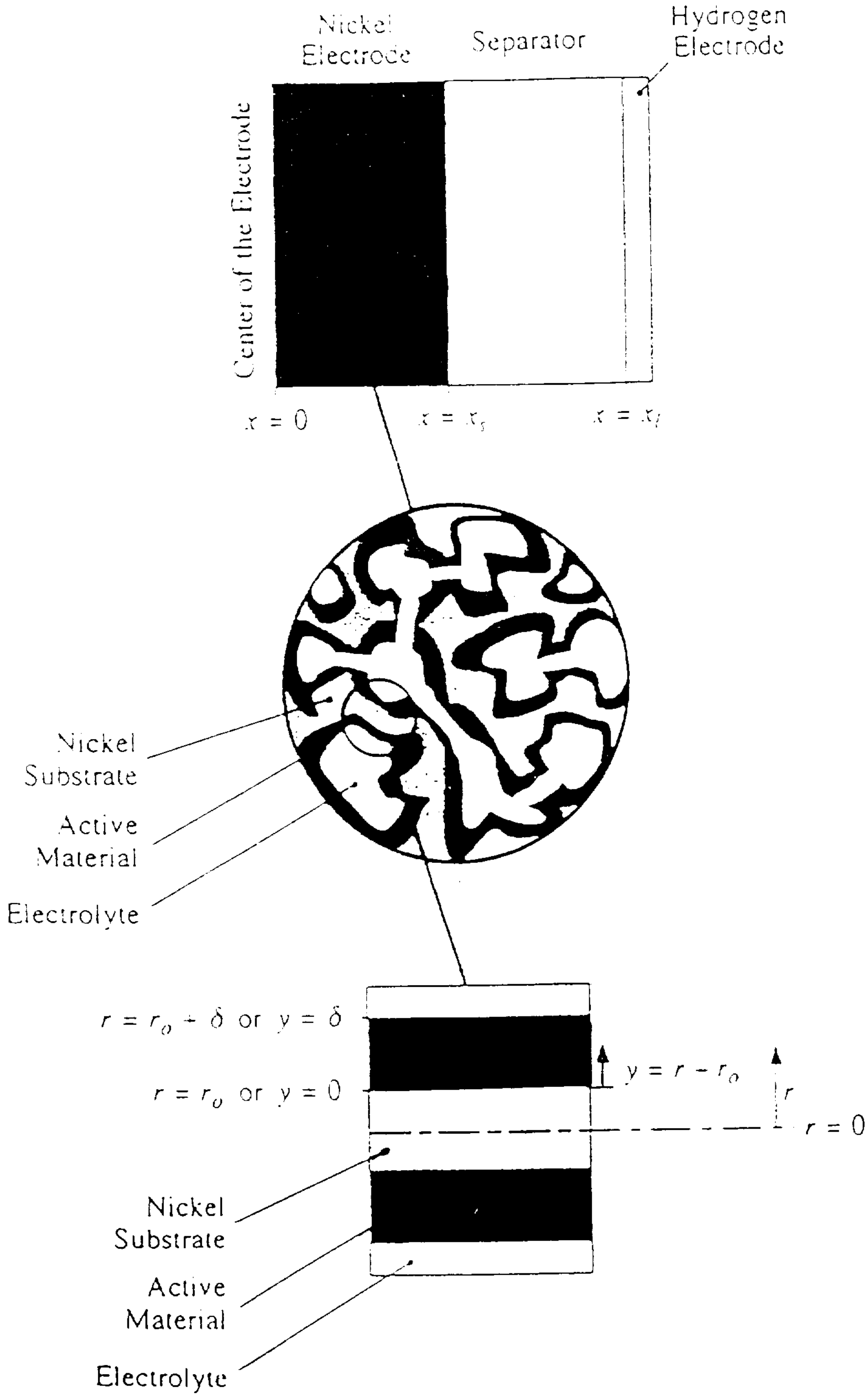
INCLUDE DIFFUSION OF PROTONS AND CONDUCTION OF ELECTRONS

ANALYTICAL SOLUTION TO FILM PROTON TRANSPORT PROBLEM IS
- SMALLER
- FASTER
- EASIER TO MODIFY

IGNORES POROUS ELECTRODE CONTRIBUTIONS - IONIC TRANSPORT

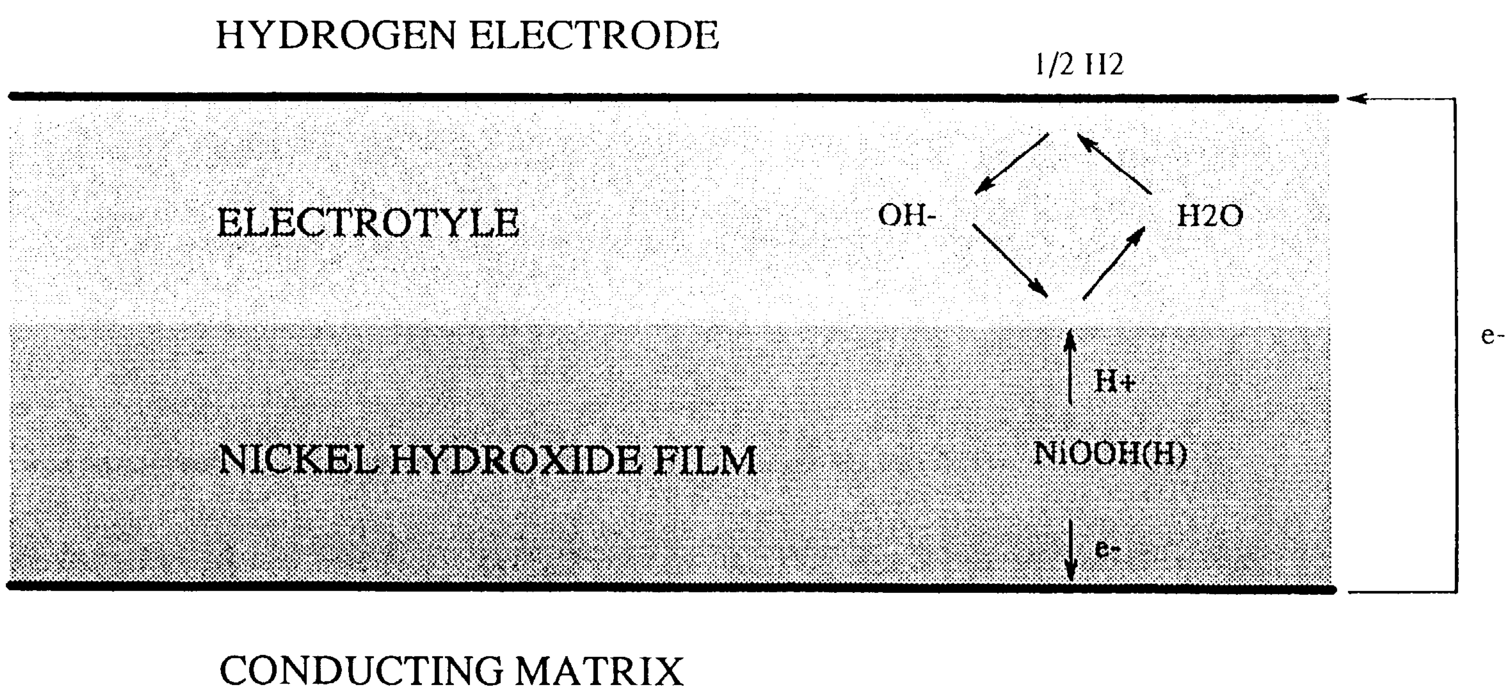
J.W. WEIDNER AND P.J. TIMMERMAN, JECS VOL. 141, NO. 2, FEBRUARY 1994.

POROUS ELECTRODE MODEL SCHEMATIC



1.) MAO-Z, DEVIDTS-P, WHITE-RE, NEWMAN-J, THEORETICAL ANALYSIS OF THE DISCHARGE PERFORMANCE OF A NIOOH/H-2 CELL, JOURNAL OF THE ELECTROCHEMICAL SOCIETY, VOL: 141 (1):54-63(1994)

SCHEMATIC OF PLANAR ELECTRODE MODEL OF NIH2 CELL



PJT 11-2-94

COMPARISONS: TRANSPORT

PSEUDO-TWO DIMENSIONAL MODEL

- PROTON TRANSPORT IN X- DIMENSION IS NEGLECTED
- LIQUID PHASE TRANSPORT IN Y-DIMENSION NEGLECTED

PLANAR ELECTRODE MODEL

- POROUS ELECTRODE STRUCTURE NEGLECTED
- OHMS LAW IN SUBSTRATE IGNORED
- OHMS LAW IN SOLUTION IGNORED

DISADVANTAGES

LACK OF POROUS ELECTRODE TREATMENT IS LARGEST EFFECT

ANALYTICAL SOLUTION FOR LIQUID PHASE MAY ALSO BE DEVELOPED

HIGH CURRENT RATES MAY SHOW SLIGHTLY LESS OVER-POTENTIALS

NICKEL SUBSTRATE CONDUCTION IS NOT INCLUDED

ADVANTAGES OF PLANAR MODEL

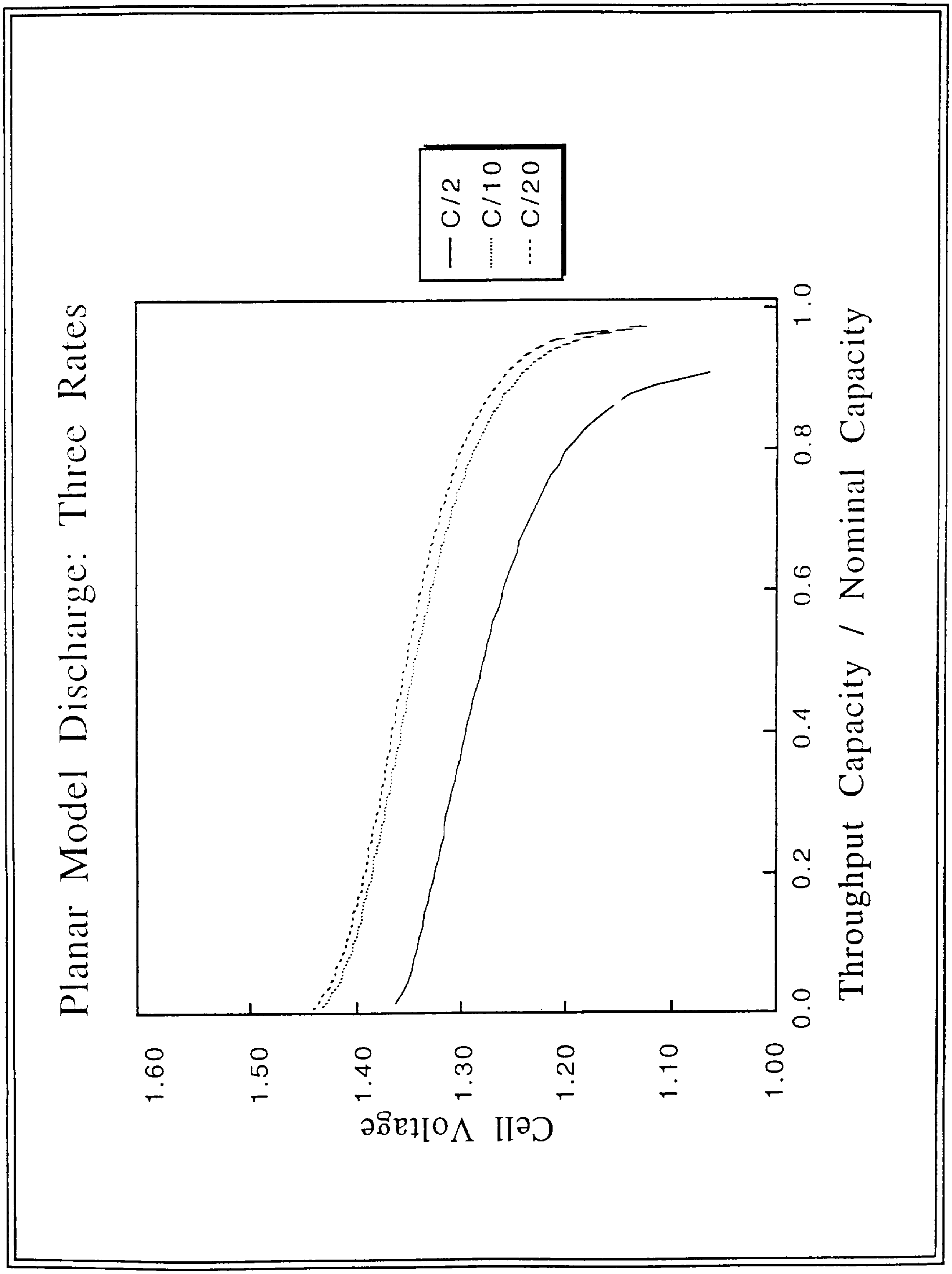
FASTER EXECUTION

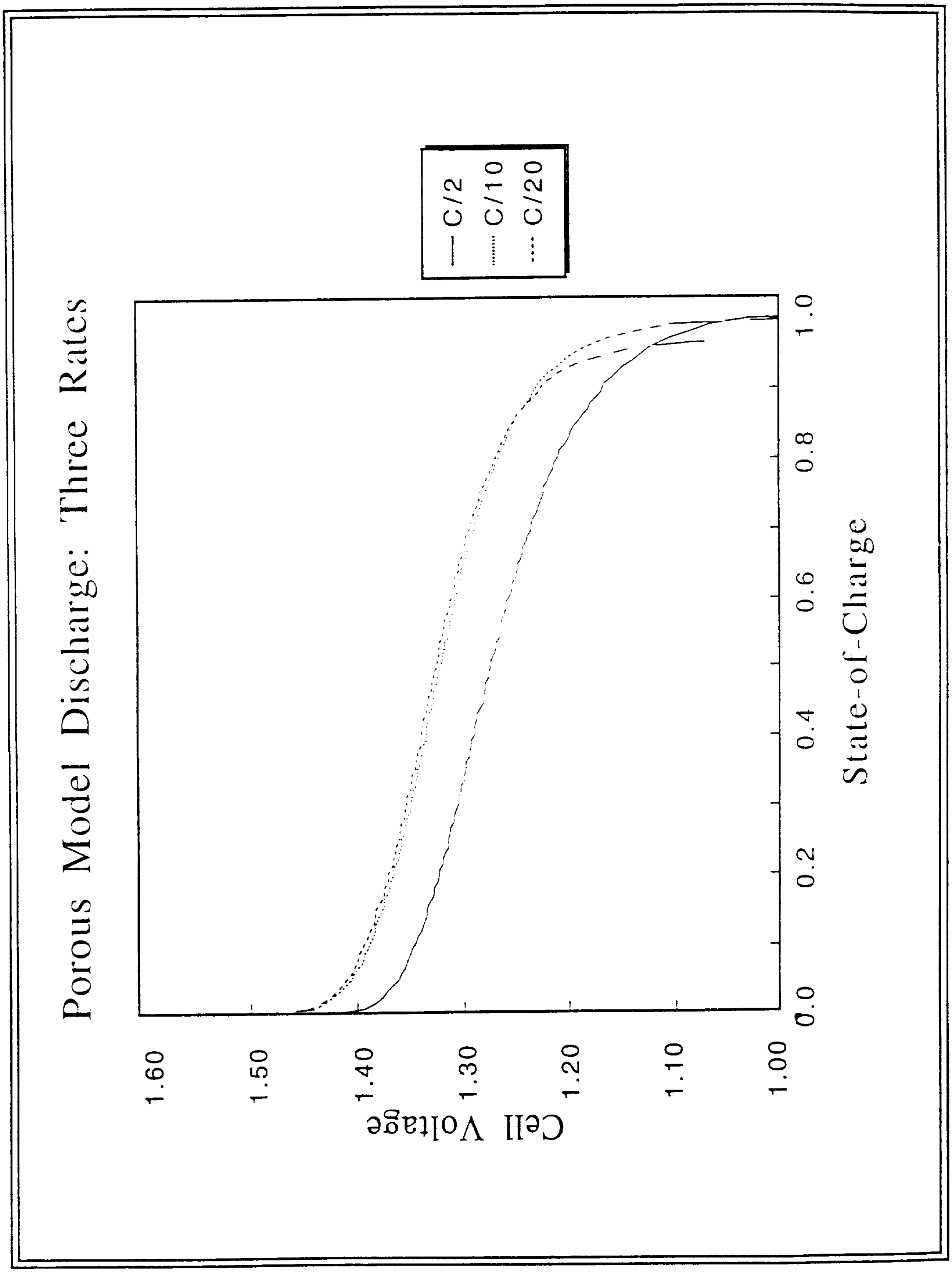
SMALLER MEMORY REQUIREMENTS

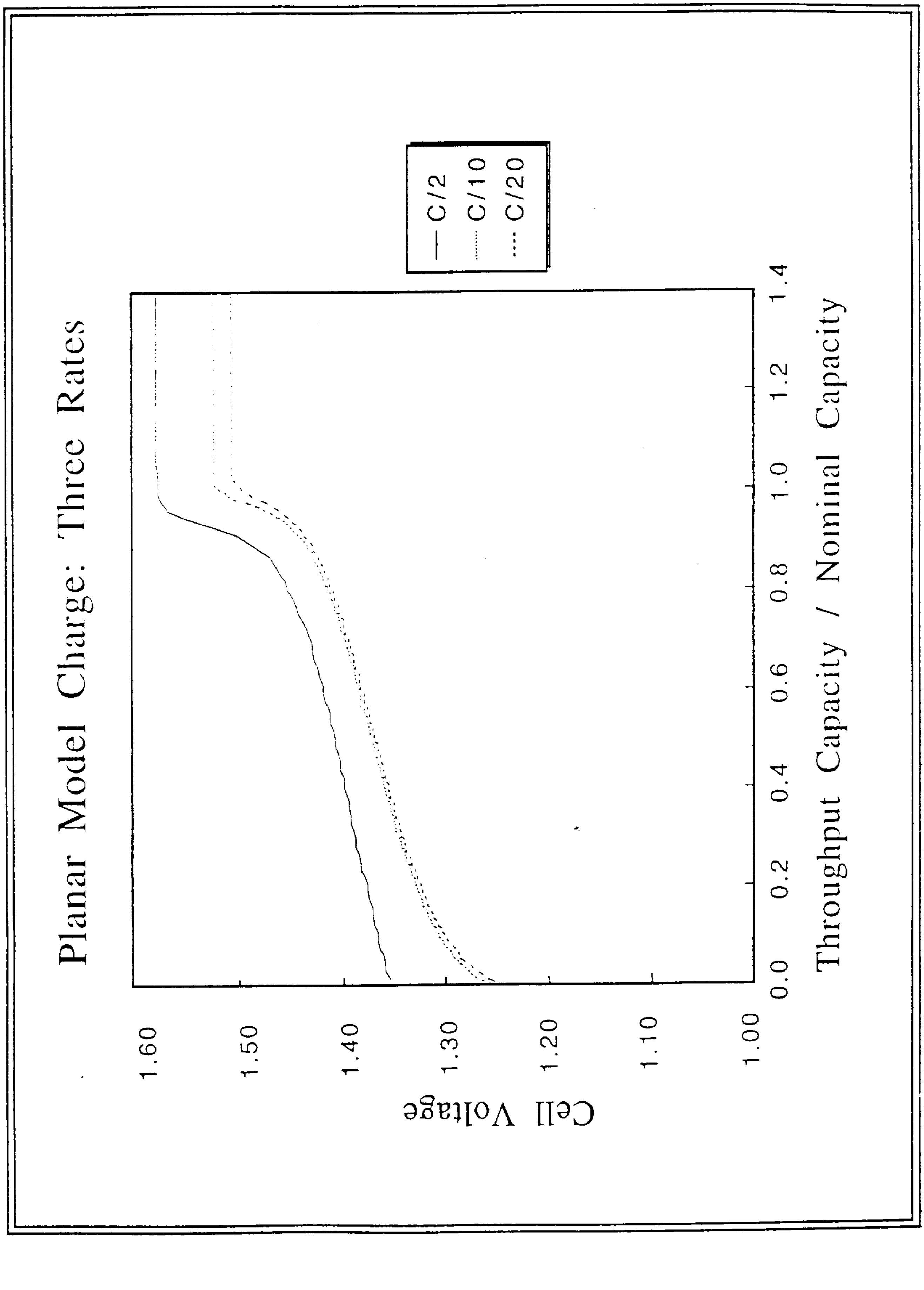
EASIER TO CHANGE FUNDAMENTAL EQUATIONS

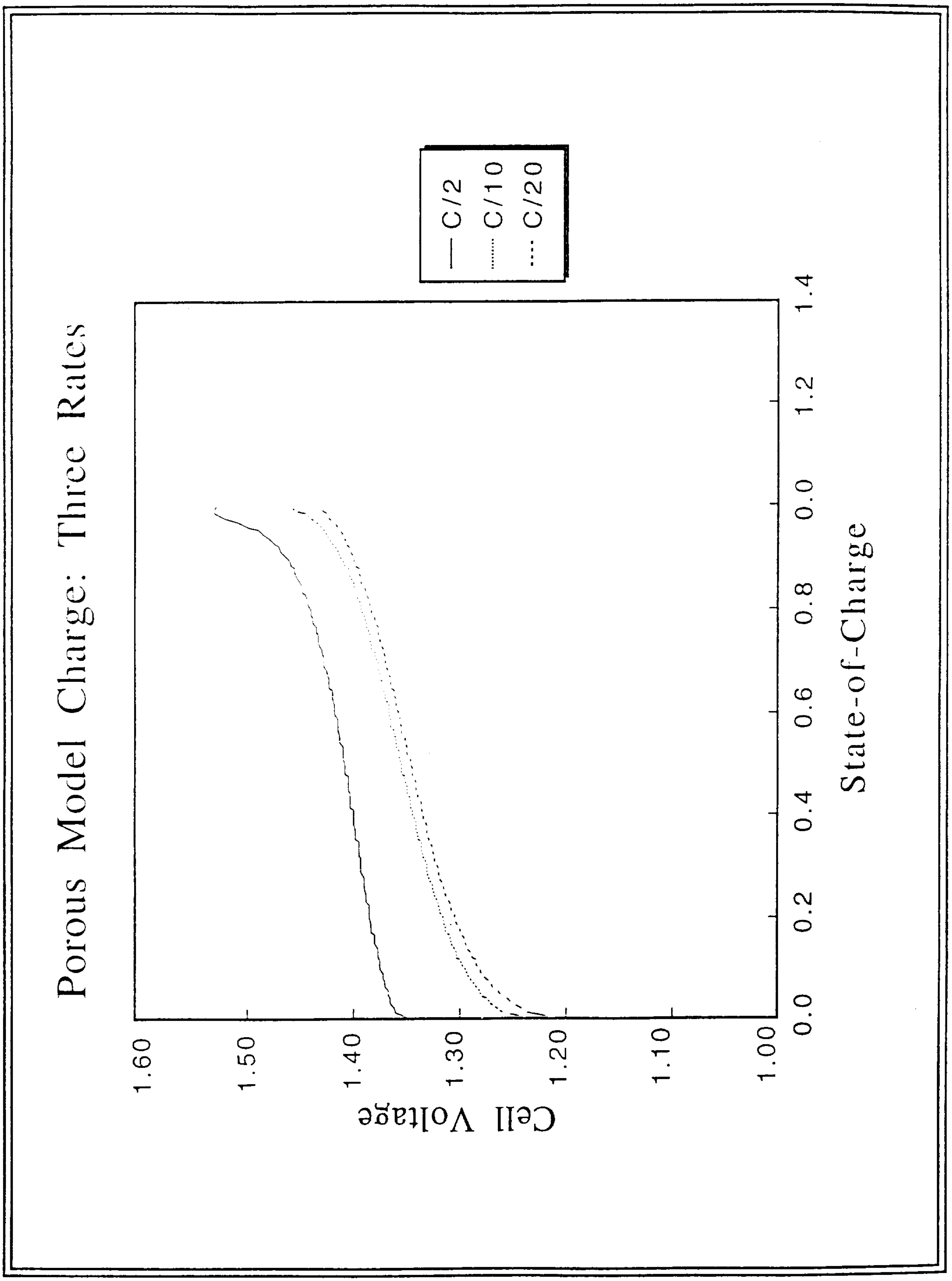
EASIER TO WRITE BATTERY MODEL AROUND

NEW MODELS CAN BE BUILT CHEAPER, FASTER, BETTER


Planar Model Discharge: Three Rates
Cell Voltage
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.0
0.2
0.4
0.6
0.8
1.0
Throughput Capacity / Nominal Capacity
C/2
C/10
C/20


Porous Model Discharge: Three Rates
C/2
C/10
C/20
Cell Voltage
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.0
0.2
0.4
0.6
0.8
1.0
State-of-Charge


Planar Model Charge: Three Rates
Cell Voltage
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Throughput Capacity / Nominal Capacity
C/2
C/10
C/20


Porous Model Charge: Three Rates
Cell Voltage
State-of-Charge
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.0
0.2
0.4
0.6
0.8
0.0
1.2
1.4
C/2
C/10
C/20

COMPARISONS OF POROUS AND PLANAR MODELS

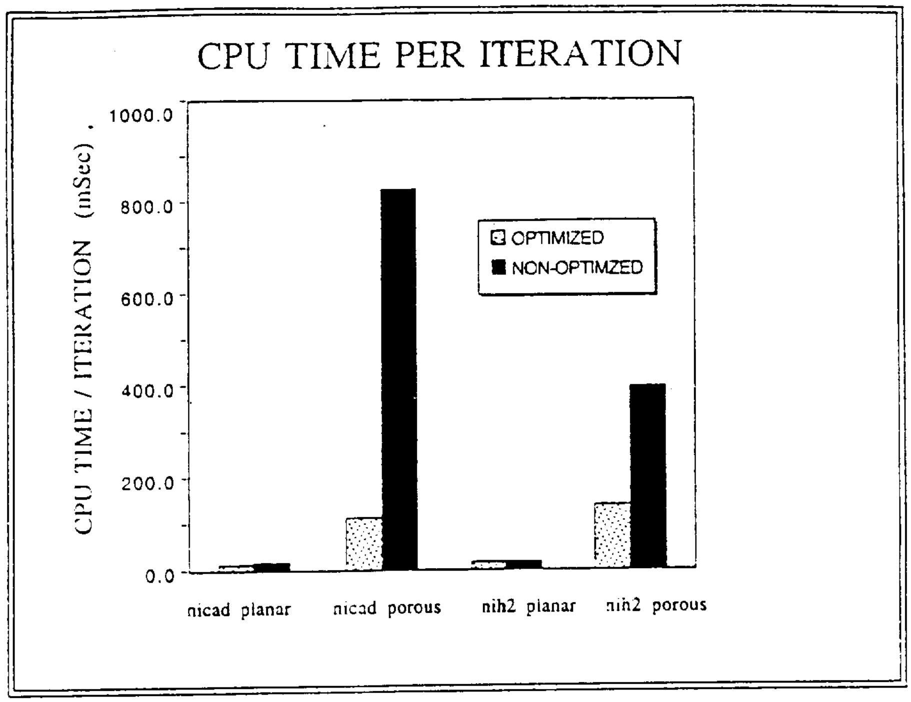
ITEM	POROUS MODEL WITH FILM	PLANAR MODEL
PAGES OF CODE	4750	900
THERMODYNAMICS	FULL TREATMENT	FULL TREATMENT
KINETICS	FULL TREATMENT	FULL TREATMENT
SOLID TRANSPORT	X- AND Y- AXIS	Y- AXIS ONLY
LIQUID TRANSPORT	X- AXIS	NON-POROUS X- AXIS
LEARNING CURVE	STEEP	SHALLOW

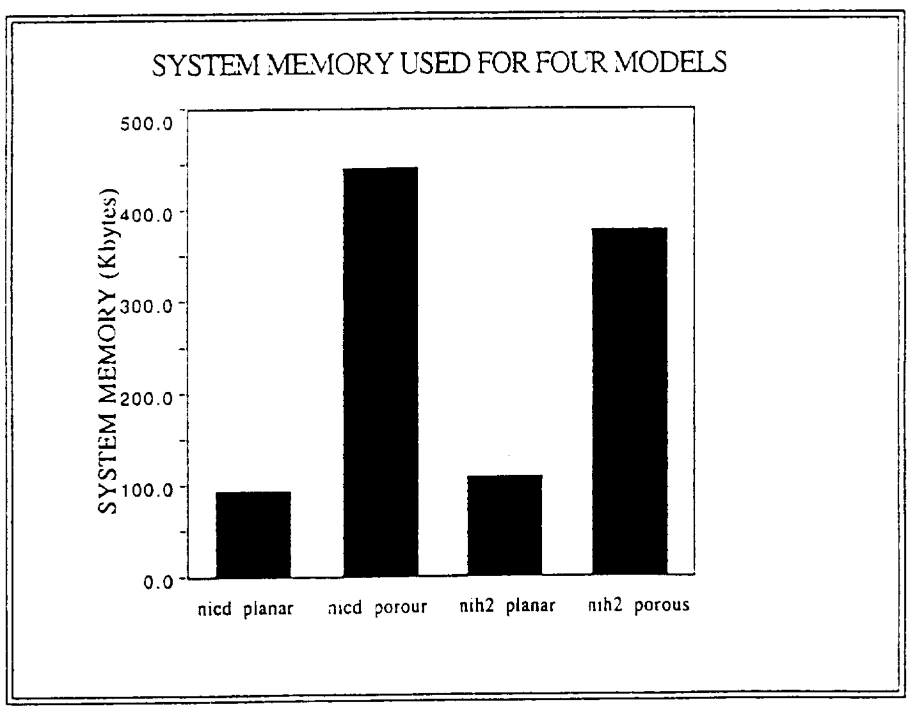
COMPARISON OF FOUR MODELS

PROGRAM NAME	OPTIM LEVEL	EXECUT SIZE	CPU TIME	MEMORY SIZE	NUMBER OF ITERATIONS	TIME PER ITERATIONS
nicad_0d	FAST	114 kb	7.07 sec	n/a	387	18.3 mSec
nicad_0d	NONE	181 kb	8.71 sec	94.1 kb	387	22.5 mSec
nicad_1d	FAST	271 kb	38.9 sec	n/a	339	115 mSec
nicad_1d	NONE	752 kb	275 sec	437.4 kb	339	811 mSec
nih2_0d	FAST	128 kb	9.9 sec	n/a	501	19.4 mSec
nih2_0d	NONE	220 kb	10.2 sec	107.5 kb	501	20.3 mSec
nih2_2d	FAST	389 kb	37.5 sec	n/a	269	139 mSec
nih2_2d	NONE	506 kb	105 sec	369.9	269	390 mSec

Notes:

1.) Comparisons were made for a simple C/2 discharge at 20oC.
2.) They were performed on a Sun Microsystems SPARCstation Model 10.
3.) F77 Compiler vers 2.0 and Optimization Flags (-cg92 -fast -O4).
4.) Memory size not available in optimized case.


CPU TIME PER ITERATION
CPU TIME / ITERATION (mSec)
1000.0
800.0
600.0
400.0
200.0
0.0
OPTIMIZED
NON-OPTIMZED
nicad planar
nicad porous
nih2 planar
nih2 porous


SYSTEM MEMORY USED FOR FOUR MODELS
SYSTEM MEMORY (Kbytes)
500.0
400.0
300.0
200.0
100.0
0.0
nicd planar
nicd porour
nih2 planar
nih2 porous

PORT TO PERSONAL COMPUTERS

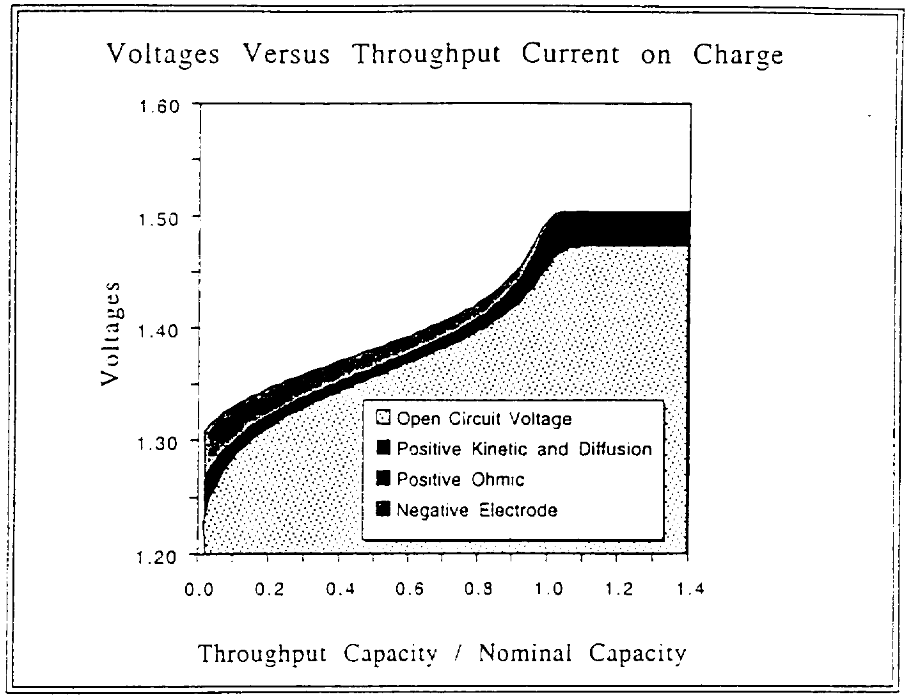
PLANAR ELECTRODE MODEL PORTED TO MACINTOSH COMPUTERS

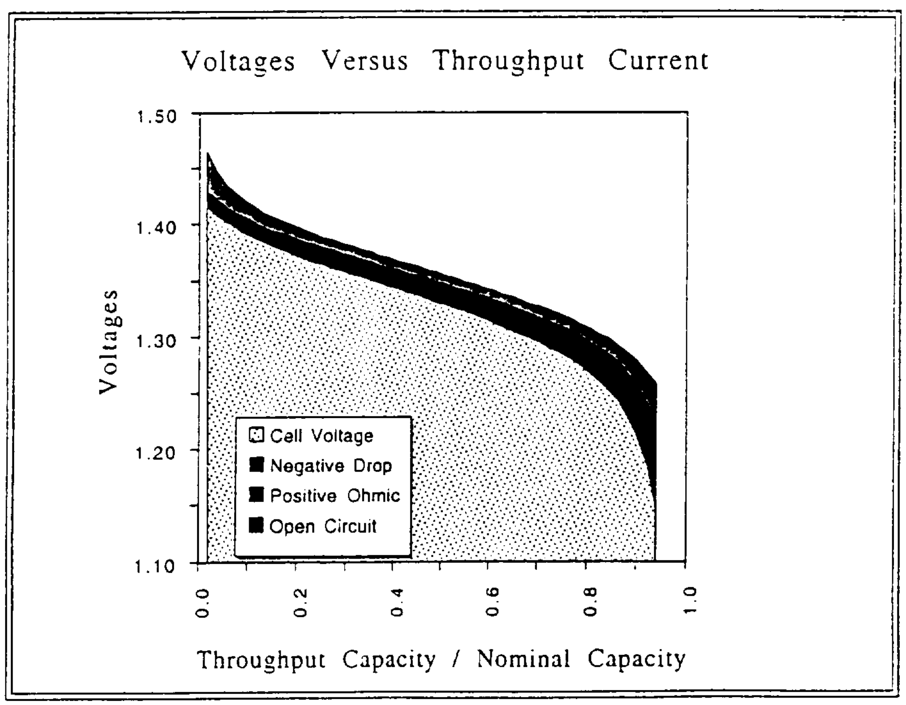
TIME REQUIRED FOR COMPLETE CHARGE COMPLETED

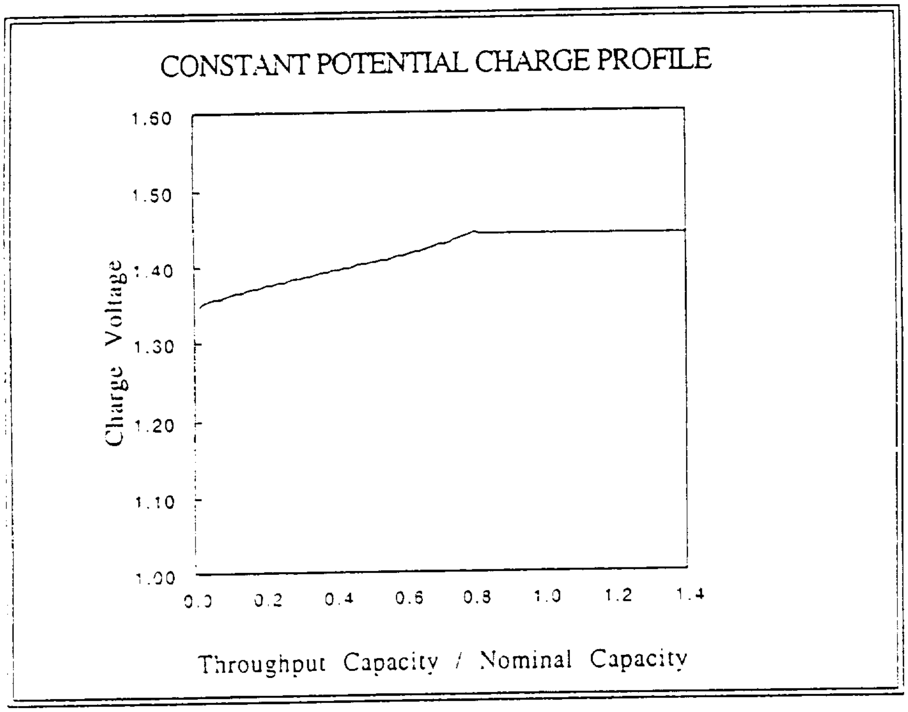
- ~200 SECONDS FOR Mac II si (with FPU)
- ~60 seconds for Mac II fx (with FPU)

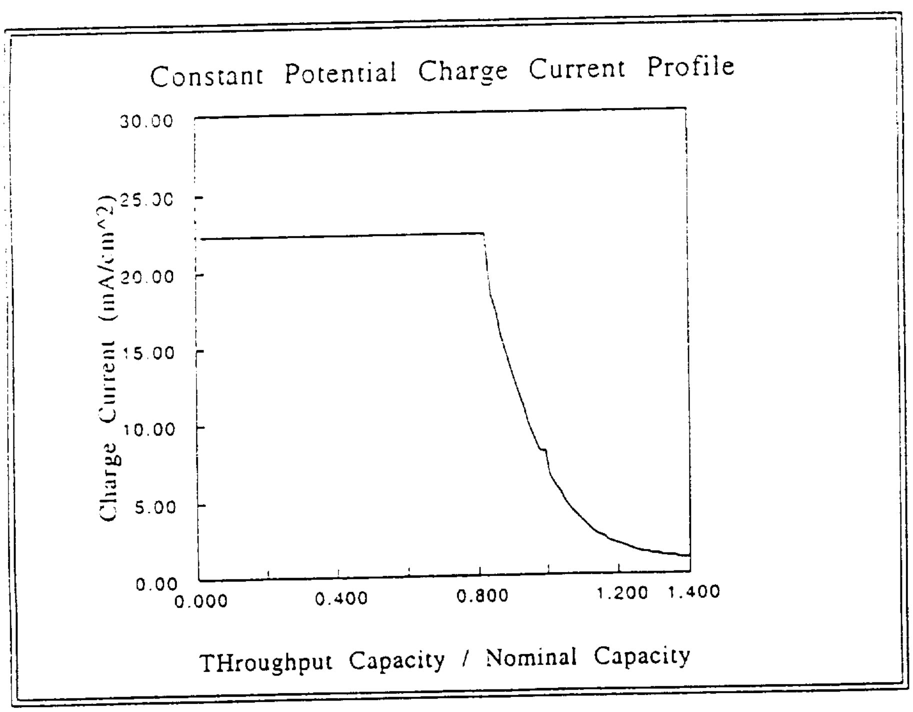
ALSO SHOWN TO RUN ON PORTABLE COMPUTERS

GRAPHICS SUPPORT ALSO DEVELOPED

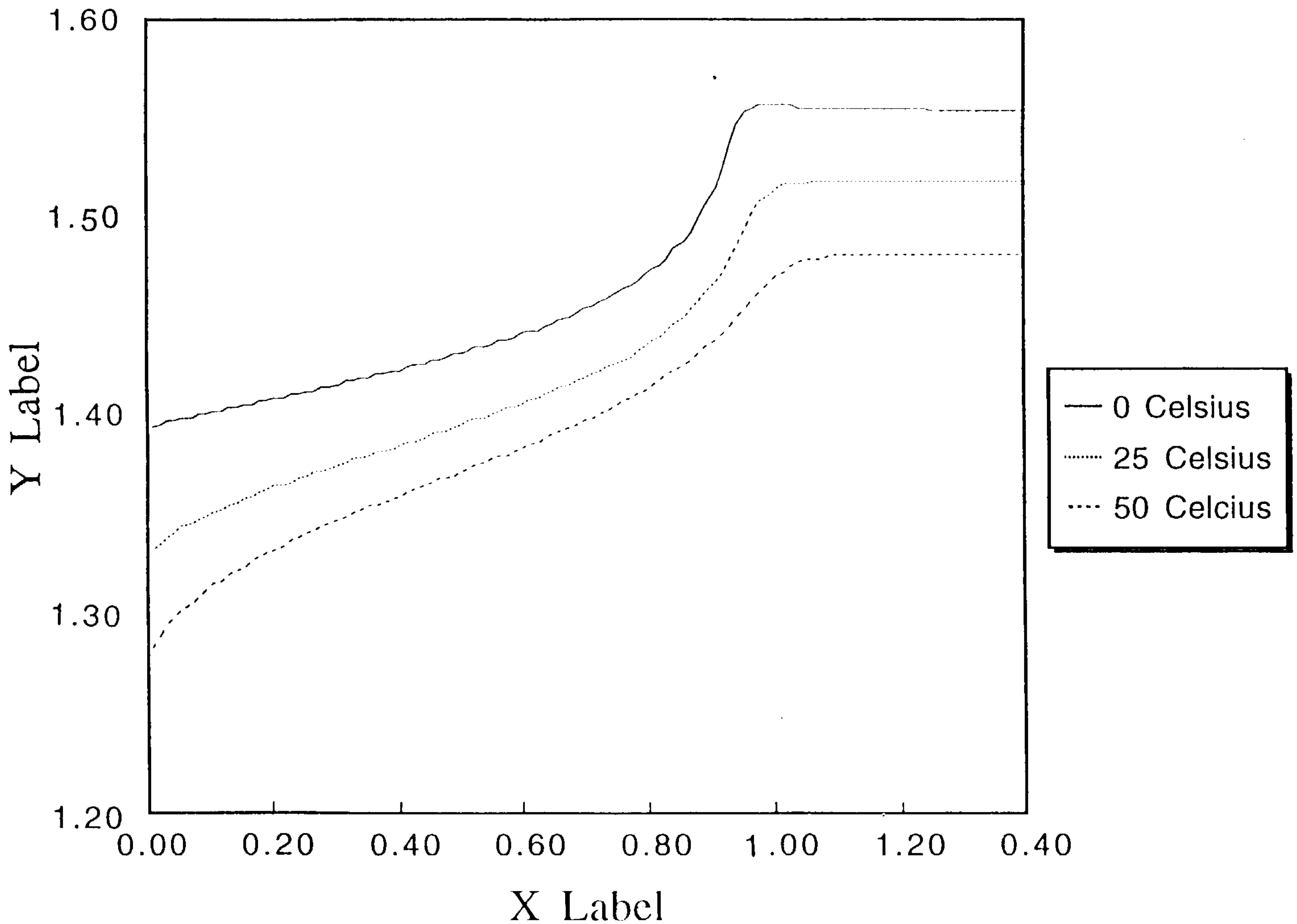

Voltages Versus Throughput Current on Charge
Voltages
1.60
1.50
1.40
1.30
1.20
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Open Circuit Voltage
Positive Kinetic and Diffusion
Positive Ohmic
Negative Electrode
Throughput Capacity / Nominal Capacity


Voltages Versus Throughput Current
Voltages
1.50
1.40
1.30
1.20
1.10
0.0
0.2
0.4
0.6
0.8
1.0
Cell Voltage
Negative Drop
Positive Ohmic
Open Circuit
Throughput Capacity / Nominal Capacity


CONSTANT POTENTIAL CHARGE PROFILE
Charge Voltage
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Throughput Capacity / Nominal Capacity


Constant Potential Charge Current Profile
Charge Current (mA/cm^2)
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0.000
0.400
0.800
1.200
1.400
THroughput Capacity / Nominal Capacity

Planar Model: Temperature Effects



CONCLUSIONS

NEW, PROMISING METHOD OF BATTERY MODELING DEMONSTRATED

INITIAL PERFORMANCE VERY SIMILAR TO MORE RIGOROUS MODEL

BATTERY MODELS AND CELL MODELS ARE BEING DEVELOPED

PROTOYPES DEMONSTRATED ON WORKSTATION AND MACINTOSH

THE FUTURE

PLANAR CELL MODELS OF NI-CD, NIH2, NI-MH ARE BEING DEVELOPED

AEROSPACE BATTERY MODELS BEING DEVELOPED ATOP CELL MODELS

ADDITIONAL DETAIL IN THE POSITIVE ELECTRODE CAN BE ADDED

- MULTIPLE PHASES
- SCHOTTKY JUNCTION EQUATIONS
- VARIABLE PROTON DIFFUSION COEFFICIENT

IMPROVED GAS AND LIQUID PHASE TREATMENTS ARE ALSO POSSIBLE

BOILERPLATE DATA WILL BE GENERATED FOR USE IN CALIBRATION

ACKNOWLEDGEMENTS

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N95- 26786

Progress Towards Computer Simulation of NiH_2 Battery Performance Over Life

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The Aerospace Corporation
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The long-term performance of rechargeable battery cells has traditionally been verified through life-testing, a procedure that generally requires significant commitments of funding and test resources. In the situation of nickel hydrogen battery cells, which have the capability of providing extremely long cycle life, the time and cost required to conduct even accelerated testing has become a serious impediment to transitioning technology improvements into spacecraft applications. The utilization of computer simulations to indicate the changes in performance to be expected in response to design or operating changes in nickel hydrogen cells is therefore a particularly attractive tool in advanced battery development, as well as for verifying performance in different applications.

Computer-based simulations of the long-term performance of rechargeable battery cells have typically have very limited success in the past. There are a number of reasons for the lack in progress in this area. First, and probably most important, all battery cells are relatively complex electrochemical systems, in which performance is dictated by a large number of interacting physical and chemical processes. While the complexity alone is a significant part of the problem, in many instances the fundamental chemical and physical processes underlying long-term degradation and its effects on performance have not even been understood. Second, while specific chemical and physical changes within cell components have been associated with degradation, there has been no generalized simulation architecture that enables the chemical and physical structure (and changes therein) to be translated into cell performance. For the nickel hydrogen battery cell, our knowledge of the underlying reactions that control the performance of this cell has progressed to where it clearly is possible to model them. The recent development of a relatively generalized cell modeling approach[1] provides a framework for translating the chemical and physical structure of the components inside a cell into its performance characteristics over its entire cycle life. This report describes our approach to this task in terms of defining those processes deemed critical in controlling performance over life, and the model architecture required to translate the fundamental cell processes into performance profiles.

Model Architecture

The general architecture for the modeling method employed here has been described in detail in Refs. 1 and 2. This modeling approach breaks a nickel hydrogen cell into a number of finite elements that encompass all internal cell components and materials.[2] These include gas spaces, wall wicks, nickel electrodes, separators, and hydrogen electrodes. The reagents that move through these components are electrolyte, hydrogen gas, and oxygen gas. These materials move throughout the cell under the combined forces of migration, convection, capillary pressure, and diffusion.

The performance of the nickel electrode, which typically limits cell life, is critical in defining performance over life. The nickel electrode model used here is based on the finite element model described in Ref. 1. This model describes the active material in the nickel electrode as a porous deposit within pores of a given diameter in a nickel metal substrate. Charge transport is allowed by movement of holes and protons in the solid active material grains, and movement of ions in the electrolyte. The charge transfer processes considered at the interface between the active material grains and the electrolyte include oxidation of β-$Ni(OH)_2$, oxidation and reduction of β-NiOOH, reduction of γ-NiOOH, oxidation and thermal decomposition of α-$Ni(OH)_2$, oxygen evolution from both β-NiOOH and γ-NiOOH, and the reaction of hydrogen gas with the charged materials. At the interface between the sintered nickel substrate and the active material, corrosion of nickel is allowed, as well as catalytic oxidation of hydrogen gas and catalytic reduction of oxygen gas.

Models that have been previously utilized to describe the nickel electrode[1,3] are based on a one dimensional layer of active material placed in contact with a substrate surface. While this is clearly an excellent local description of the physical structure of the nickel electrode, as indicated in Fig. 1 there is a wide distribution of layer thicknesses and substrate structures occurring in real nickel electrodes. We have found that there are significant performance differences between the results from model simulations for the realistic structure of Fig. 1 and the simplistic one-dimensional approach that has been used in the past. As indicated in Fig. 2, a model based on the 3-dimensional structure cross-sectioned in Fig. 1 provides much more realistic charge behavior, particularly charge efficiency as the fully charged state is approached, than does the idealized one-dimensional model. Thus, a key aspect of simulating performance over life is to include in the simulation the real structure of the sinter substrate, as well as all other cell components. It is not realistic to expect a model to be capable of predicting performance over life without also providing that model a complete description of the internal structure of all cell components. Thus, a three-dimensional model of the pores within the nickel electrode will be used in this study. The structure of these pores will be measured from actual nickel electrodes of the same type as those being simulated in the operating cells.

Degradation Modes

The model described in the above paragraphs has been demonstrated[1,2,4] to be capable of accurately predicting cell performance for any specific structures within the nickel electrodes or the nickel hydrogen cell. Thus, the remaining task in simulating performance over life is to predict how the chemical and physical structure of the internal cell components change over life. The degradation modes that will be focussed on in this study involve the nickel electrode and are: (1) substrate corrosion, (2) active material phase changes, (3) substrate swelling, (4) active material extrusion, (5) electrode cracking, and (6) short-circuiting through the separator. The rate of each of these degradation processes will be based on the underlying driving forces for the processes, such as voltage, density changes, pressure differentials, and chemical gradients.

Substrate corrosion is assumed to be occurring on a passivated nickel surface, on which the rate of corrosion is linearly dependent on the voltage. In addition it is assumed that the volume changes from oxidation and reduction of the oxides on the nickel surface will periodically fracture the passivation layer. Thus, corrosion will occur over the surface area of the sintered substrate at a rate proportional to the active material voltage at the interface with the substrate, and also at an additional rate proportional to the changes in density of the active material immediately adjacent to the metal surface. In this model, the layer of active material immediately adjacent to the sinter is about 100

Angstroms thick. Sinter corrosion will decrease substrate area, increase active material density near the substrate, decrease cobalt additive levels near the substrate, increase electrolyte concentration, and increase cell hydrogen pressure. The increase in active material from corrosion can, in some instances, cause increased capacity to be available in the nickel electrode. The model described above will be used to determine the combined effect of all these changes on performance when a realistic three-dimensional sintered structure is used.

Phase changes in the nickel electrode active material will occur during the simulation process in response to gradients that develop in electrolyte concentration, temperature, and potential through the cell. The electrochemical reactions discussed above and programmed into the nickel electrode simulation module will assure that the different phases will interconvert during cycling in the manner expected in a real battery cell.

Nickel electrode swelling will be allowed to occur at a rate based on the difference between the positive and negative forces normal to the electrode surface. Forces that drive swelling are expansion of active material during discharge or phase changes, and electrolyte hydrodynamic forces, and gas pressure differentials. The swelling of the electrode structure will be based on the magnitude of these forces that are calculated by the model, along with the mechanical strength properties of the electrode itself. Swelling within each element of the electrode will be assumed to occur via a homogenous expansion of the three-dimensional structure of the sinter.

Active material extrusion will be driven by essentially the same forces as nickel electrode swelling, but is based on the elasticity of the active material. Additionally, the active material will be allowed to extrude not only from one element into another within the nickel electrode, but into the separator as well. Extrusion of active material into and through the separator can produce short circuit paths, with the short circuit current being dependent on the resistivity of the active material. In a properly constructed nickel hydrogen cell, such short circuits are probably the ultimate failure mode, since they can cause the cell state of charge to drop below that needed to sustain cycling. The physical extrusion of active material from the sintered substrate will result in a decrease in available active material for charge discharge cycling.

Cracking of nickel electrodes can occur as a result of swelling if the sintered structure if forced past its yield point, or if corrosion etches away interconnecting metal. For this approach to effectively model cell capacity loss due to cracking of the sinter structure, the cumulative deformation forces in the sinter structure relative to the force needed to cause separation of the sinter must be modeled. The plan at present is to track these forces as the sinter structure is allowed to swell, and to adjust the conductivity paths to reflect separation of the conductive matrix. Cracking of the conductive matrix will force more current to be carried through the active material, thus will result in earlier depletion and lower utilization.

Present Degradation Model Status

The present life cycle degradation model consists first of a three dimensional cell model, that includes a three dimensional microscopic model of the nickel electrode. The nickel electrode model, which is most critical to modeling the performance of the nickel hydrogen cell, can track the formation of different active material phases through the cell stack (or stacks), the charge efficiency, the self-discharge, and the voltage vs. capacity behavior during cycling if it has the physical and chemical state of the internal cell components well defined. The second part of this life cycle model defines how the physical and chemical state of the internal cell components are to be adjusted as the cells cycles. This portion of the model is now under development, with the adjustments in sinter structure due to corrosion having been put into a preliminary simulation model. This preliminary model is consistent with about 40% corrosion of a typical sinter structure after 40,000 LEO cycles at 80% depth of discharge. The various degradation modes discussed above are each being developed as individual modules that are capable of making small adjustments to the state of the cell components after each cyclic interval.

The computational approach used here for simulating a nickel hydrogen cell life test is to utilize two work-stations. These networked work-stations will be programmed to run a cell model through a life test, periodically calculating updated cell performance and stress forces. The stress forces are used to adjust the physical and chemical state of the cell components, with these adjustments being typically 0.1 to 1% over a cyclic interval. Cyclic intervals would vary according to the rate of change of cell performance parameters. Early in the cycling the computers will update cell performance every few cycles, while after thousands of cycles, 10-100 cycles may be allowed to elapse between computational updates. When the cell begins to fail after extensive cycling, computational updates will again be performed relatively frequently. This approach is expected to give a full life test in about 1 month of time using a two-processor approach, assuming that individual cycles can be run at about a real time rate (as suggested in preliminary calculations).

Conclusions

An approach to simulating a life test of a nickel hydrogen battery cell in a computer system has been outlined. This approach is based on two key elements. The first of these is a model of the nickel hydrogen cell that can very accurately predict performance from a detailed knowledge of the physical and chemical states of the internal cell components. This first element is now largely developed and ready to integrate into a life test simulation. The second key element is a degradation model that utilizes internal stresses and forces that are obtained from the dynamic cycling of the cell model, to periodically adjust the physical and chemical state of the cell components to reflect the key degradation processes. While at present the second part of this effort is not fully developed, we are confident that this general simulation approach can successfully be used to follow and predict the performance of battery cells during their operational life. We anticipate applications of this approach to the characterization and validation of design advances, the design of power systems, and the operational management of nickel hydrogen batteries in spacecraft power systems.

Acknowledgement

The support of the Aerospace Corporation is gratefully acknowledged for funding this work through the Aerospace Supported Research program.

References

1. A. Zimmerman, *Proc. of the 29th IECEC*, American Inst. of Aeronautics and Astronautics, ISBN 1-56347-091-8, 1994, pp. 63-69.

2. A. H. Zimmerman, *Proc. of the 1993 NASA Aerospace Battery Workshop*, NASA Conf. Pub. 3254, 1993, p. 295.

3. D. Fan and R. E. White, *J. Electrochem. Soc.*, **138**, 17 (1991); **138**, 2952 (1991).

4. A. H. Zimmerman and A. H. Phan, *Ext. Abstr. of the Fall 1994 Meeting of the Electrochemical Society*, The Electrochemical Society, Inc., Pennington, N.J. Vol. 94-2, 1994, p. 101.

Figure 1. Cross Section of Nickel Sinter Showing Metal As White Regions

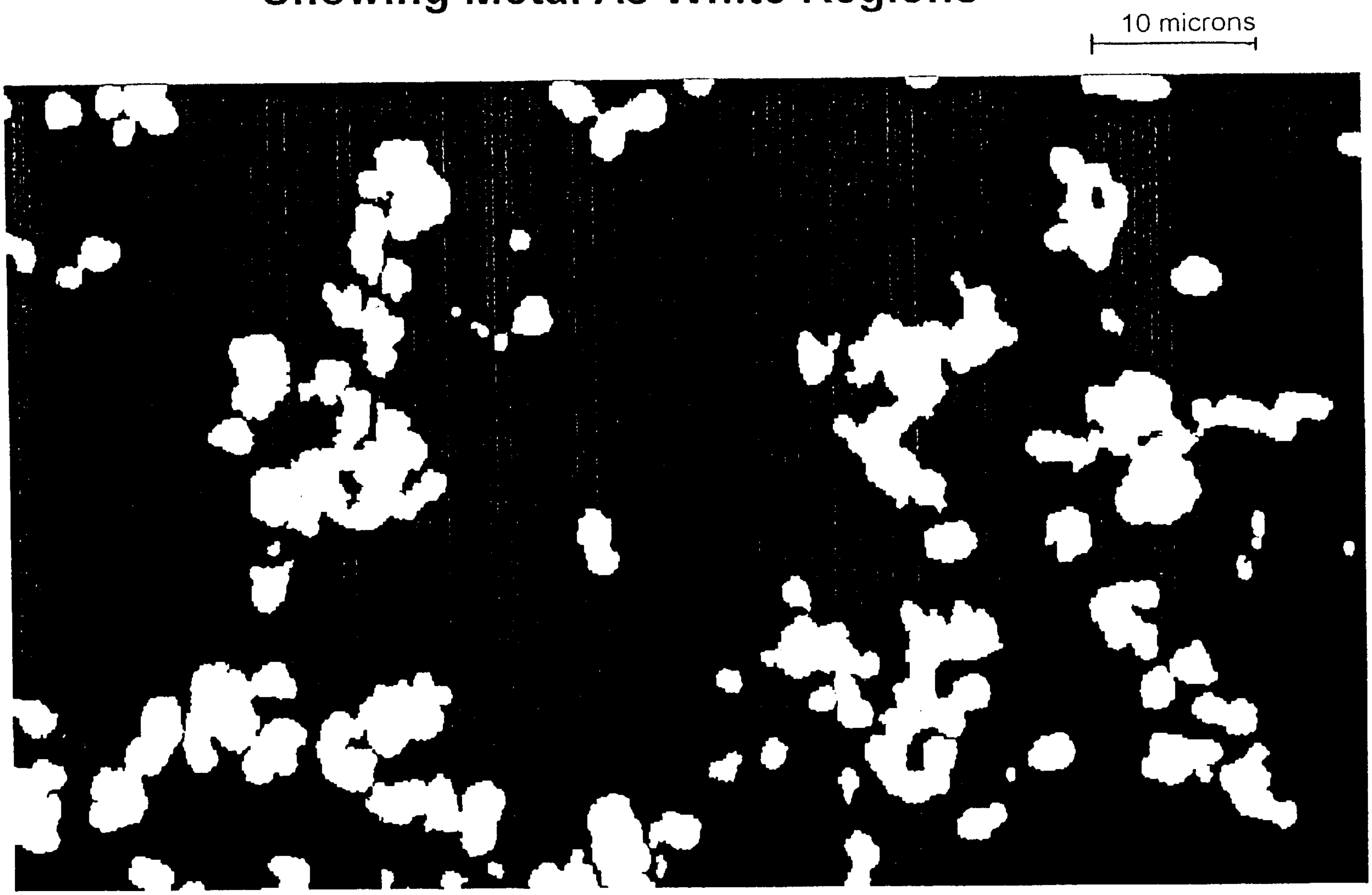
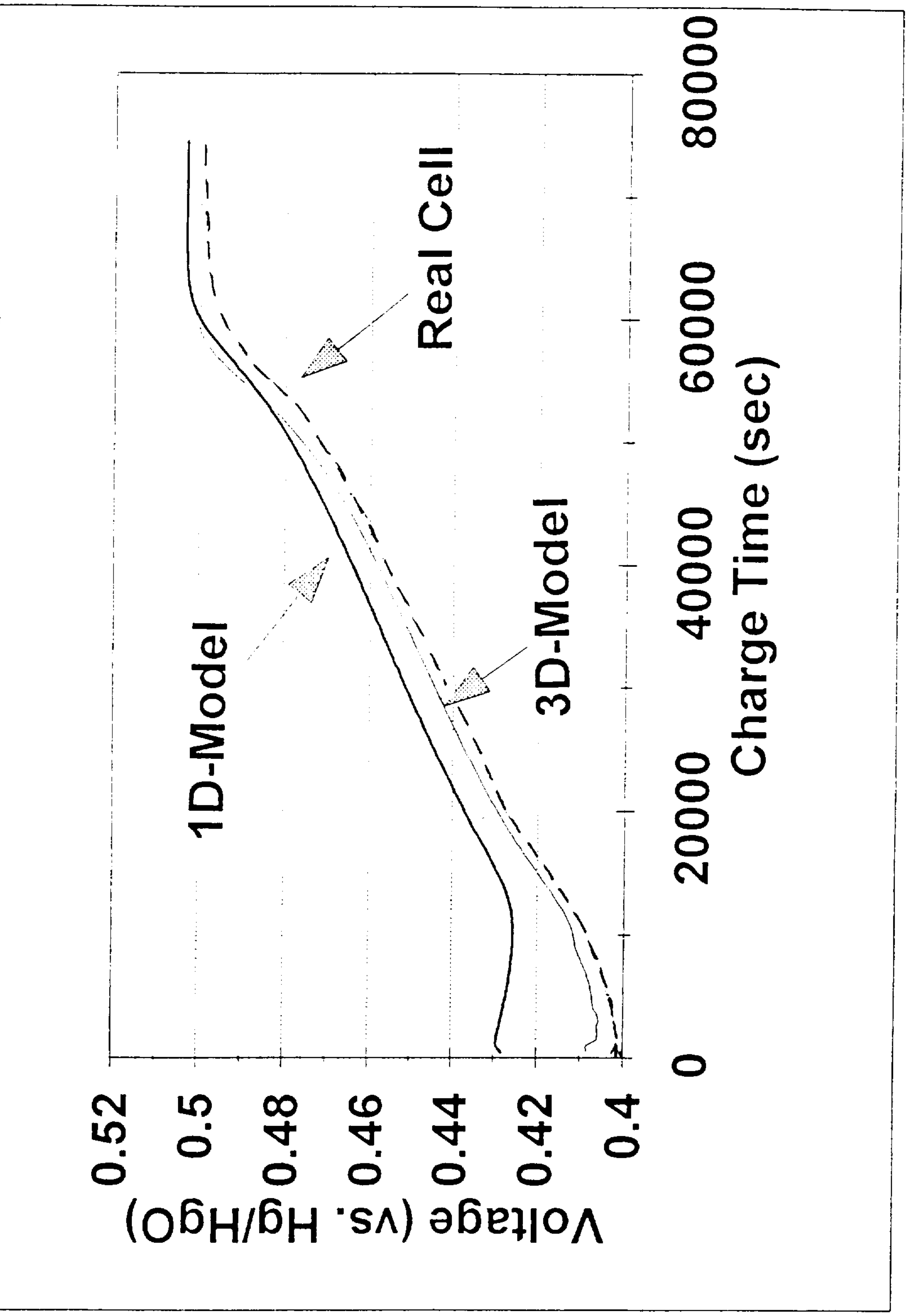


Figure 2. C/10 Charge Voltage



N95- 26787

LONG LIFE 80Ah STANDARD IPV NiH2 BATTERY CELL

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SUMMARY

A standard Nickel-Hydrogen (NiH2) Individual Pressure Vessel (IPV) battery cell is needed to meet future low cost, high performance mission requirements for NASA, military, and civil space programs. A common or standard cell design has evolved from the heritage of HST, Milstar and other Air Force Mantech cell designs with substantial flight experience, while incorporating some of the historical COMSAT cell design features described in Reference (1). Key features include slurry process nickel electrodes having high strength, long life and high yield (lower cost), and dual layer Zircar separators for improved KOH retention, uniformity and longer life. The cell design will have a zirconium oxide wall wick inside the pressure vessel to redistribute electrolyte and extend life. The slurry electrode will be 35 mils thick to take advantage of qualified cell mechanical configurations and proven assembly and activation techniques developed by Eagle Picher Industries (EPI) for the Hubble Space Telescope (HST) RNH-90-3 and "Generic HST" RNH-90-5 cell designs with back-to-back nickel electrodes produced by the dry sinter process. The 80Ah common cell design can be scaled to meet capacity requirements from 60Ah to 100Ah. Producibility, commonality and long life performance will be enhanced with the robust cell design described herein.

BACKGROUND

The battery cell technology flow shown in Figure 1 summarizes evolution of various battery cell designs at LMSC beginning with the Air Force NiH2 Flight Experiment. This led to development of the RNH-76-3 cell design by EPI. Back-to-back truncated disk slurry aqueous (Bell) process nickel electrodes developed in the 1970s by COMSAT were combined with asbestos separator material for the RNH-76-3 cell design. Back-to-back pineapple slice dry sinter aqueous (Bell) process nickel electrodes were later developed in the 1980s by EPI for HST and Milstar battery applications. These applications utilize Zircar separators in conjunction with cell stack design concepts developed by Hughes Aircraft Corporation and the Air Force, which were later qualified for the HST RNH-90-3, "Generic HST" RNH-90-5 and Milstar RNH-76-11 Mantech cells.

Performance advantages of the Mantech cell type used by LMSC include lower cell impedance from use of Zircar material in place of asbestos separator used for the COMSAT cell, greater yield in cell build due to decreased sensitivity to electrolyte quantity, and greater energy density due to the high porosity (84%) dry sinter plaque. The COMSAT cell design, using slurry 80% porosity plaque with improved strength properties, has improved plate yield (lower cost) versus the dry sinter plaque cell design. A desire to combine the best characteristics of the COMSAT and Mantech cell configurations has led to the common cell design described herein.

GENERAL CELL DESCRIPTION

The standard cell design described herein has been designated an RNH-90-9 cell by EPI based on similarity to the RNH-90-5 cell design. The design builds upon heritage of HST, Milstar and other Air Force Mantech cell designs with substantial flight experience, while incorporating some of the historical COMSAT cell design features described in Reference (1). The 80Ah NiH2 battery cell will have 48 slurry process nickel electrodes contained in a 9.0 inch long pressure vessel with a 0.030 inch nominal wall thickness. Key features include slurry process nickel electrodes with 80% porosity for high strength, long life and high yield (lower cost), and dual layer Zircar separators for improved KOH retention, uniformity and longer life. The electrolyte concentration will be 31% KOH in the discharged state for improved low temperature discharge voltage performance. The cell design will have a zirconium oxide wall wick inside the pressure vessel to redestribute electrolyte and extend life. While LMSC has chosen a 48-electrode version of the common cell to avoid mechanical requalification, this design could be easily scaled to meet capacity requirements from 60Ah to 100Ah. The slurry electrodes will be 35 mils thick to take advantage of qualified Mantech cell mechanical configurations, and proven assembly and activation techniques identified in Reference (2) for the HST RNH-90-3 cell design with back-to-back nickel electrodes produced by the dry sinter process. The common cell design will have 5/16 inch terminals and four electrode tab thicknesses of 5, 7, 9 and 11 mils for lower cell impedance at discharge rates greater than 40A. The cell will weigh approximately 2072g and have a rating of 80Ah at a 40A (C/2) discharge rate to 1.10V/cell (24.2V/Battery) following a standard charge at 0°C. Nickel precharge in the range from 15% to 20% should result in a maximum expected operating pressure (MEOP) of 1075 psi at beginning of life (BOL) for this cell design. It has been demonstrated that pressure vessels made with 0.030 inch base Inconel 718 material provide a nominal safety margin of 3X for an MEOP of 1100 psi on RNH-76-3 cells.

The common cell is not optimized for minimum weight for BOL capacity performance, however, in theory, stronger plate material should have longer life under similar operating conditions. This would allow greater DOD operation for the common cell in both geosynchronous and low earth orbit (LEO) applications which should minimize or eliminate the weight penalty. Test data summarized in Reference (3) show operational performance characteristics over the temperature range from -10°C to +20°C for the RNH-90-5 cell design with back-to-back nickel electrodes produced by the dry sinter process. The common cell, designated as RNH-90-9, should have similar electrical performance characteristics as the "Generic HST" RNH-90-5 cell design. The cell would have a rating of 80Ah at a 40A (C/2) discharge rate to 1.10V/cell (24.2V/battery) following a standard charge at 0°C. Testing of the RNH-90-5 cell was accomplished to identify usefulness of the common cell in a generic LEO application. This short term testing identified advantages over the COMSAT cell type which the common cell will replace. Other predicted performance and operating characteristics of the cell are discussed in the following section.

PERFORMANCE PREDICTION

The electrical and thermal performance of an RNH-90-5 cell similar to that used on HST was initially characterized over a matrix of operating conditions from -10°C to +20°C. Testing included standard capacity tests and electrical cycling using 12-hour cycling regimens incorporating constant DOD cycles with step changes in the cell current at three points in the discharge as described in Reference (3). Subsequently, cycling was performed to characterize cell voltage under both constant charge/constant discharge conditions required for a LEO operating environment at +10°C. Four discharge rates (40A, 55A, 75A and 90A) were used in a cyclic scheme which subjected cells to a constant 44 percent DOD each cycle. Because of the relatively high charge rate (38A) required to maintain energy balance for the LEO test, it was necessary to raise the voltage/temperature (V/T) charge termination level to 1.54V/cell (33.9V/battery) to achieve stabilization during the test. Post +10°C capacity testing shows a usable capacity of 70Ah for a recharge ratio of 1.02 to 1.20V/cell (26.4V/battery) at a 40A (C/2) discharge rate. V/T optimization should allow for a greater usable capacity. The discharge scheme for the four distinct cycles was as follows:

Cycle A: 40A for 13.3 min., 75A for 7.1 min.
55A for 9.7 min., 90A for 5.9 min.

Cycle B: 55A for 9.7 min., 90A for 5.9 min.
40A for 13.3 min., 75A for 7.1 min.

Cycle C: 90A for 5.9 min., 40A for 13.3 min.
75A for 7.1 min., 55A for 9.7 min.

Cycle D: 75A for 7.1 min., 55A for 9.7 min.
90A for 5.9 min., 40A for 13.3 min.

Cycles were performed in the order A,B,C,D,A,B,C,D etc. Cycling was repeated until "stability" was reached. Stability is reached when time to charge off for consecutive cycles does not differ by more than 4 minutes and the discharge voltage is stable. Data shown in Attachment 1 summarize test results obtained at the four discharge rates for these operating conditions. These data demonstrate capability of the "Generic HST" RNH-90-5 cell design to operate at a maximum DOD of 44% and meet a peak 80A load for a 22-cell battery over a voltage range from 26.4V to 33.9V at +10°C. It is expected that the standard 80Ah NiH2 battery cell described herein will have similar electrical performance characteristics as the "Generic HST" RNH-90-5 cell.

REFERENCES

(1) J. D. Dunlop, G. M. Rao and T. Y. Yi, NASA Handbook for Nickel-Hydrogen Batteries, NASA Reference Publication 1314, September 1993.

(2) D. E. Nawrocki and J. D. Armantrout, "The Hubble Space Telescope Nickel-Hydrogen Battery Design," 25th IECEC, Reno, NV, August 1990.

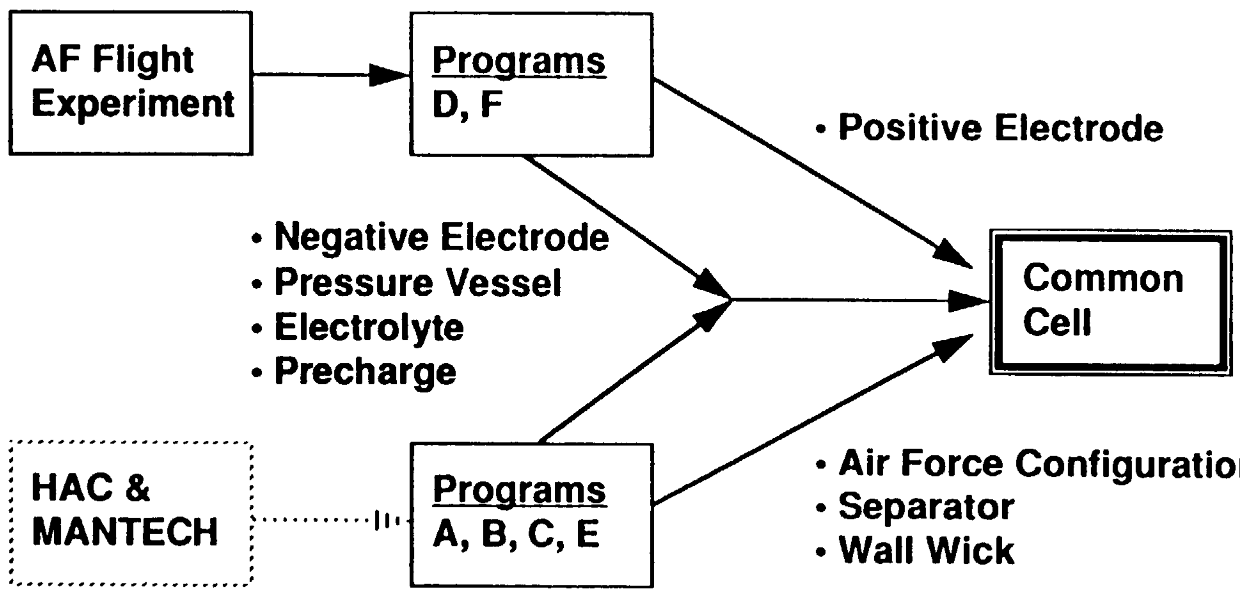
(3) J. D. Armantrout and D. P. Hafen, "Performance Characterization of an 80Ah Nickel-Hydrogen Cell," 27th IECEC, Atlanta, GA, August 1993.

ATTACHMENTS

(1) RNH-90-5 Characterization Tests Conducted By Eagle Picher Industries

(2) Presentation Charts

FIGURE 1. CELL TECHNOLOGY FLOW



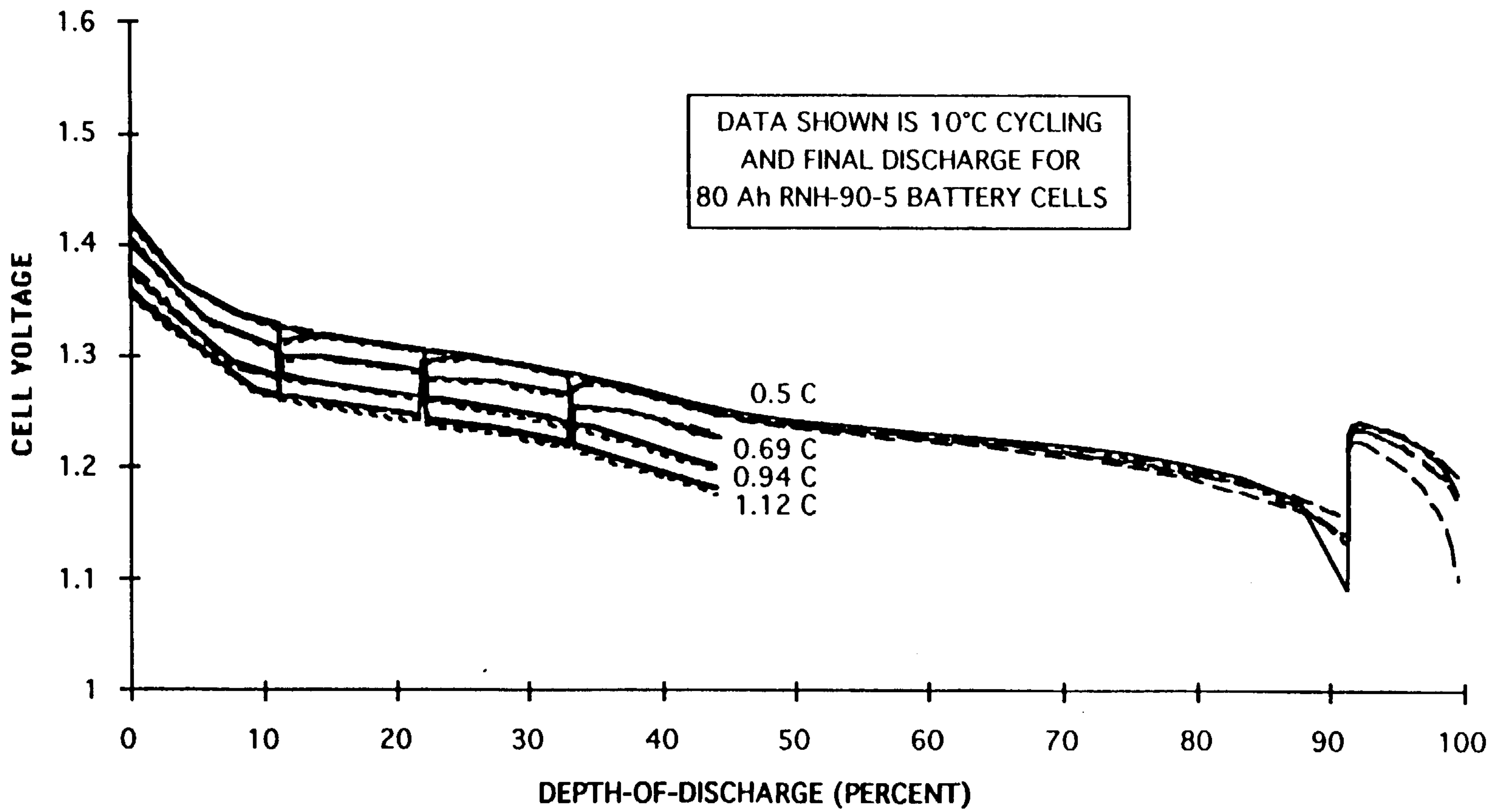
OPTIONS

- Electrodes (position and diameter)
- Rated capacity
- Vessel thickness

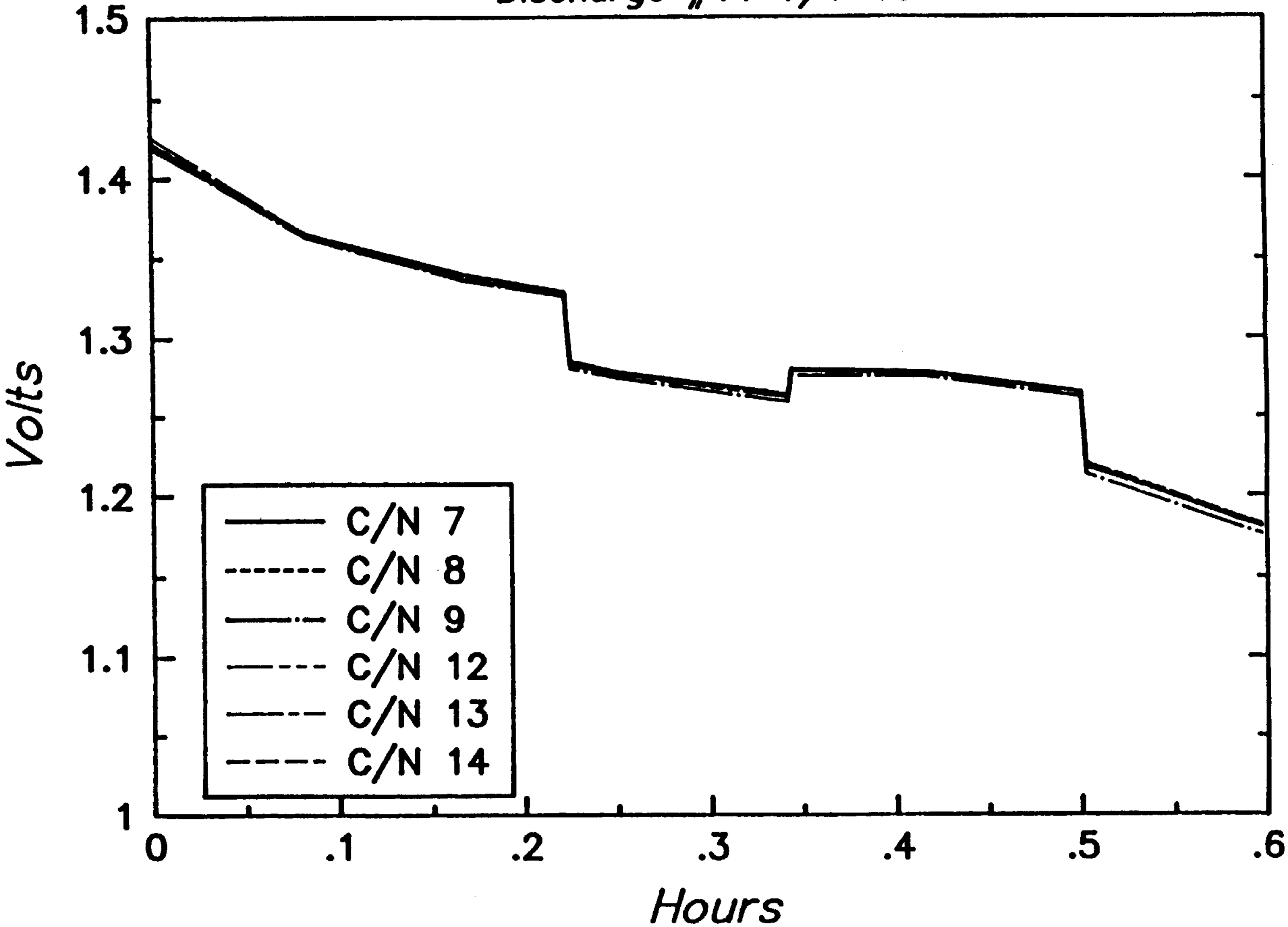
ATTACHMENT 1.

RNH-90-5 CHARACTERIZATION TESTS
CONDUCTED BY EAGLE PICHER INDUSTRIES

COMMON BATTERY CELL PERFORMANCE



RNH-90-5
Characterization Tests
10°C Cycle A
Discharge #11 V/T 10



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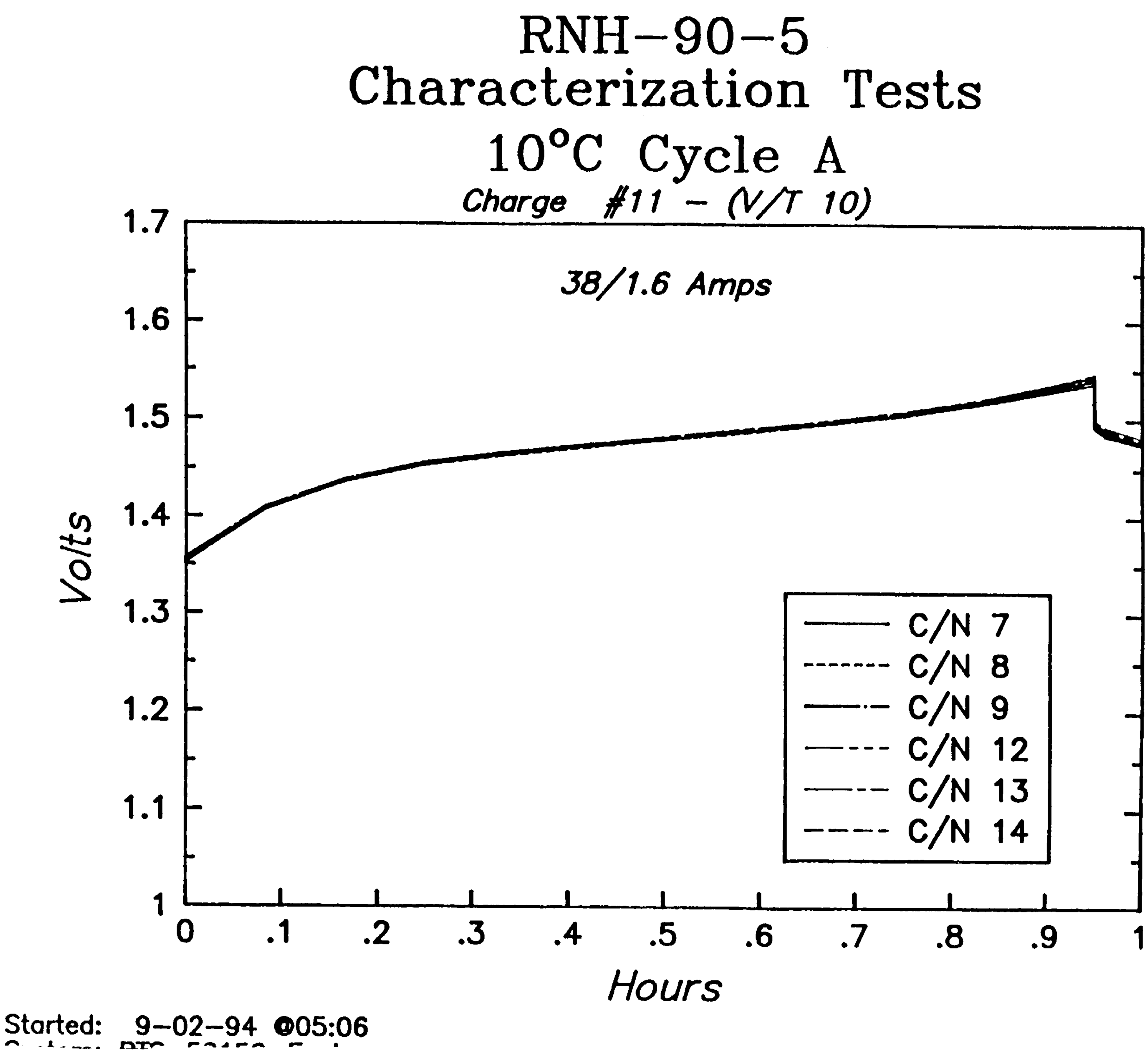
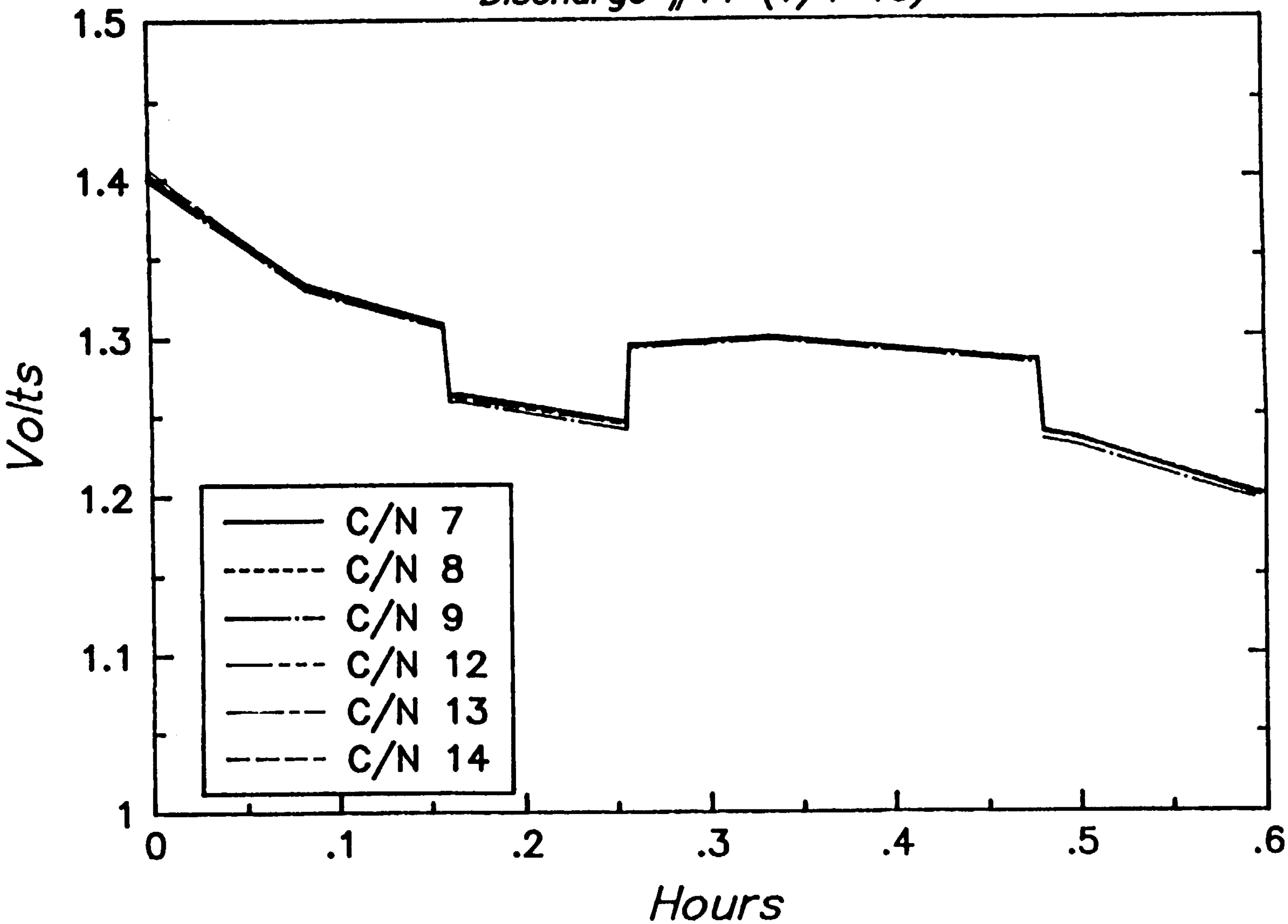
RNH-90-5 Characterization Tests 10°C Cycle A



RNH-90-5
Characterization Tests
10°C Cycle B

Discharge #11 (V/T 10)



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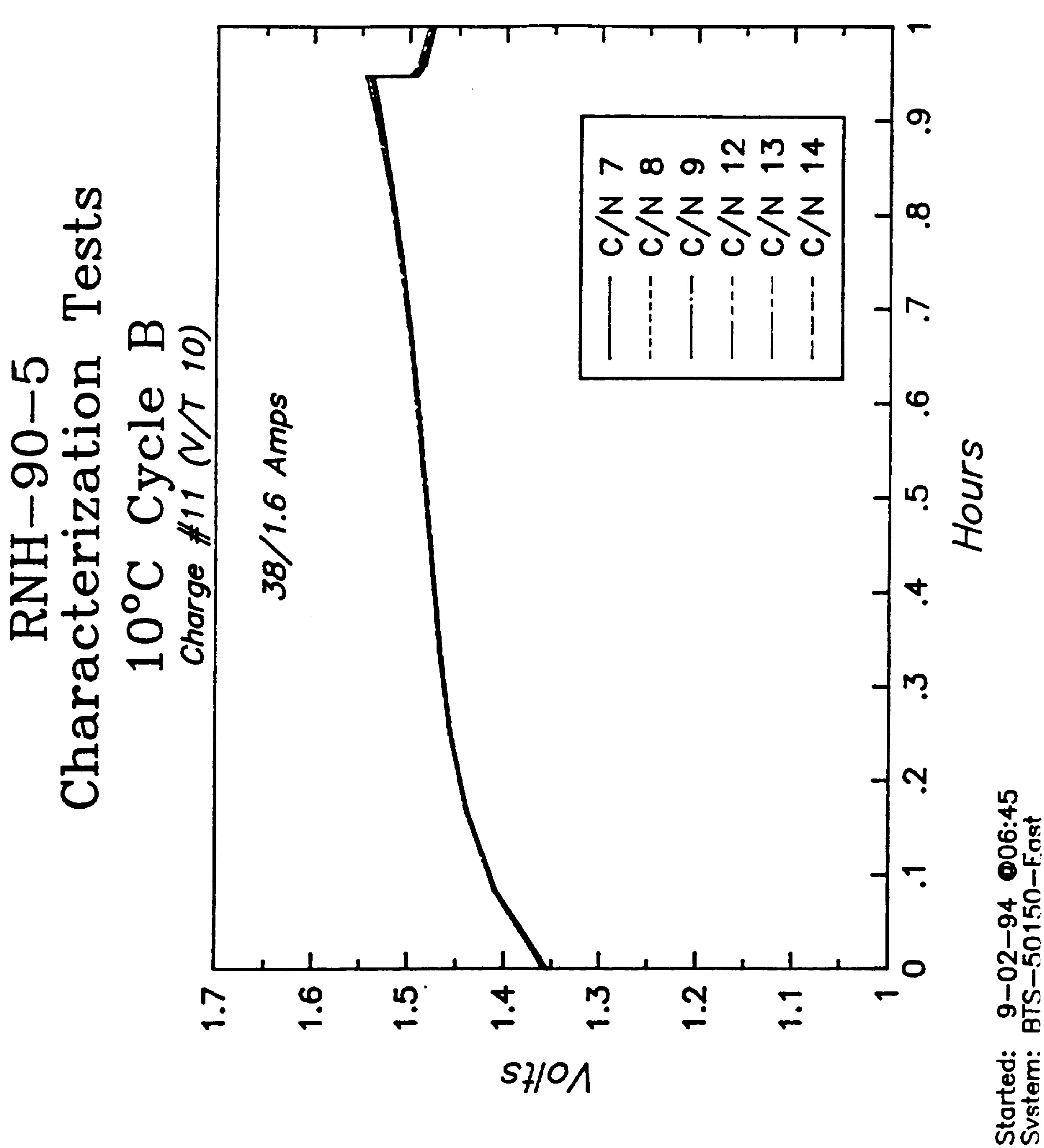
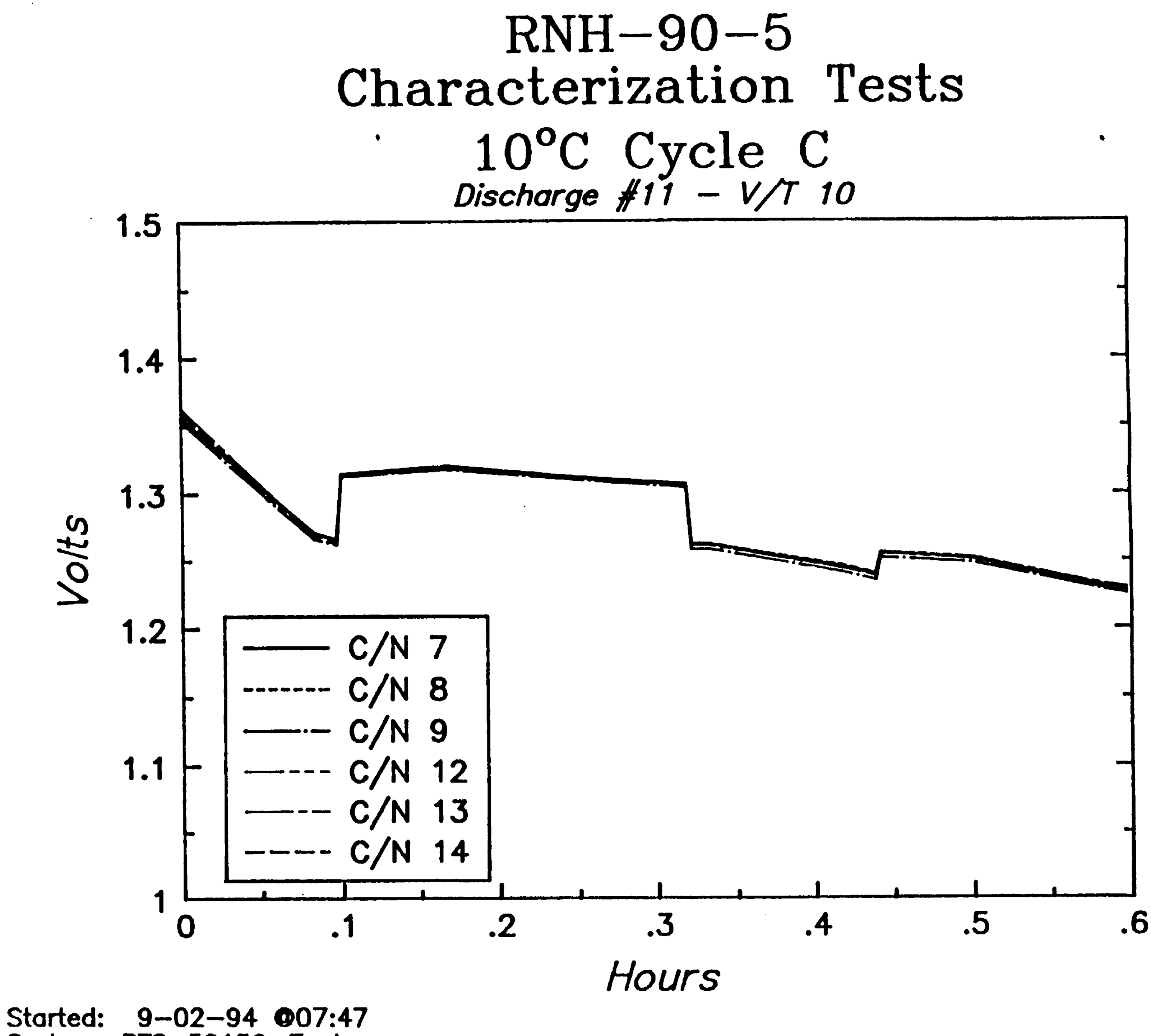
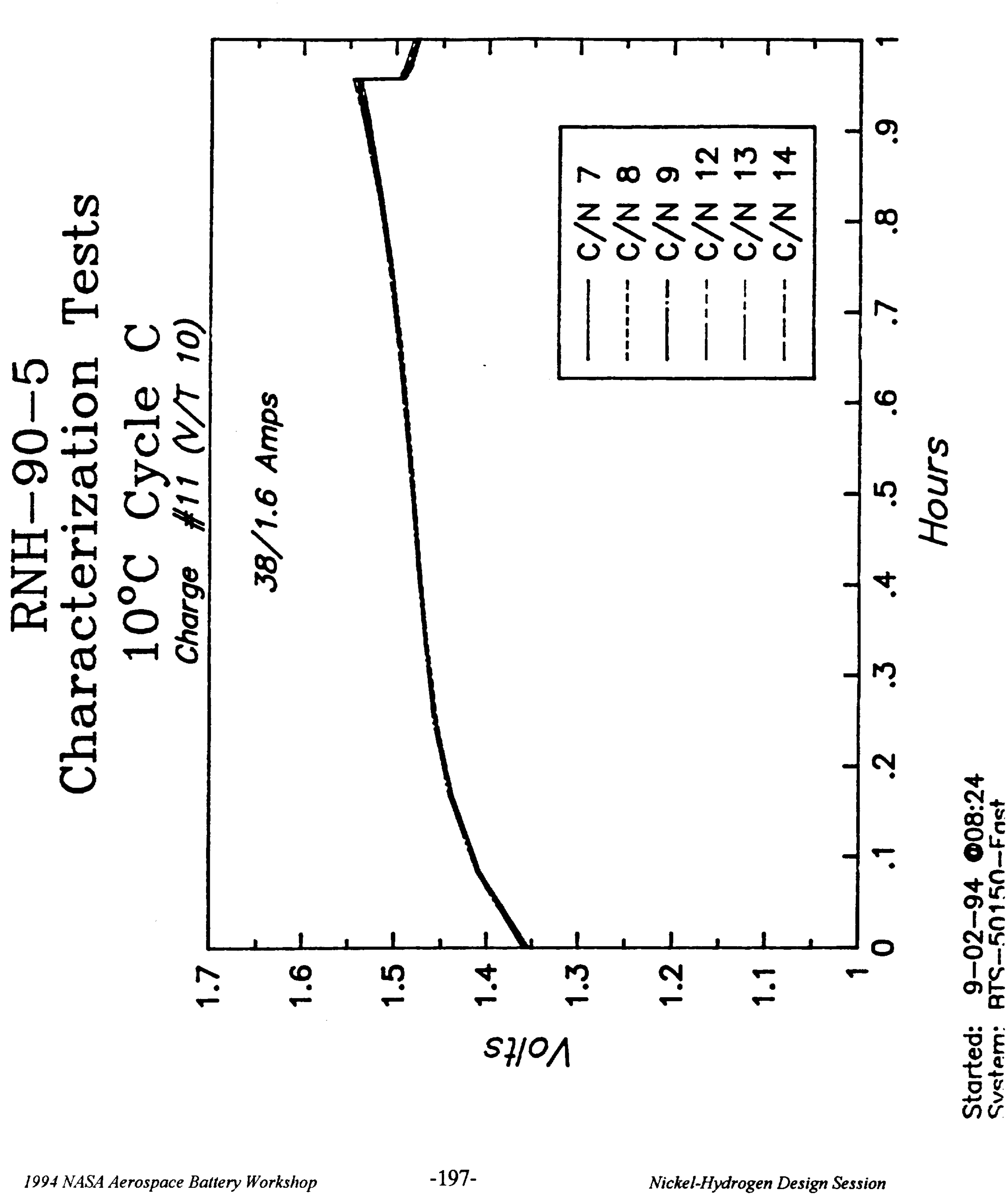
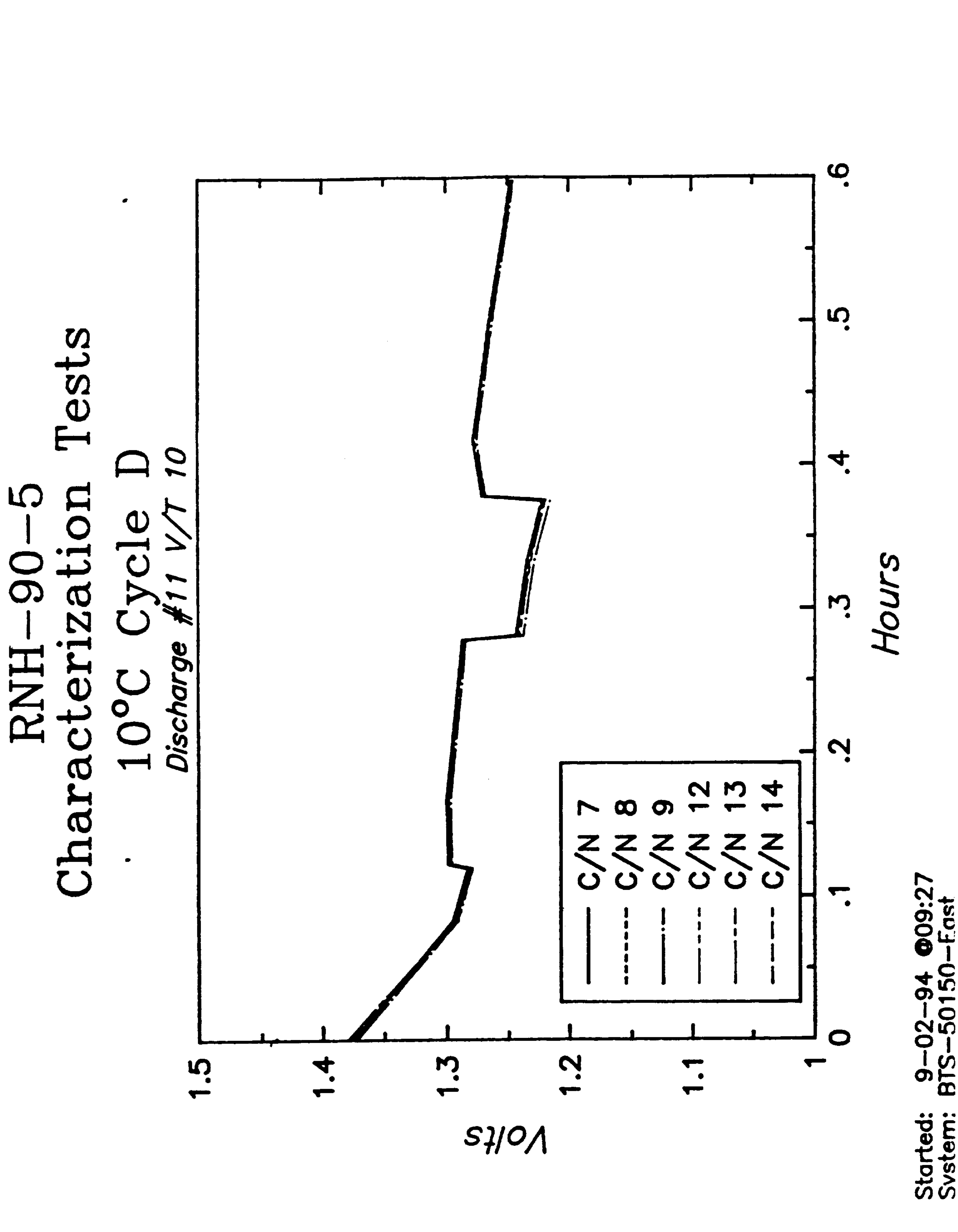
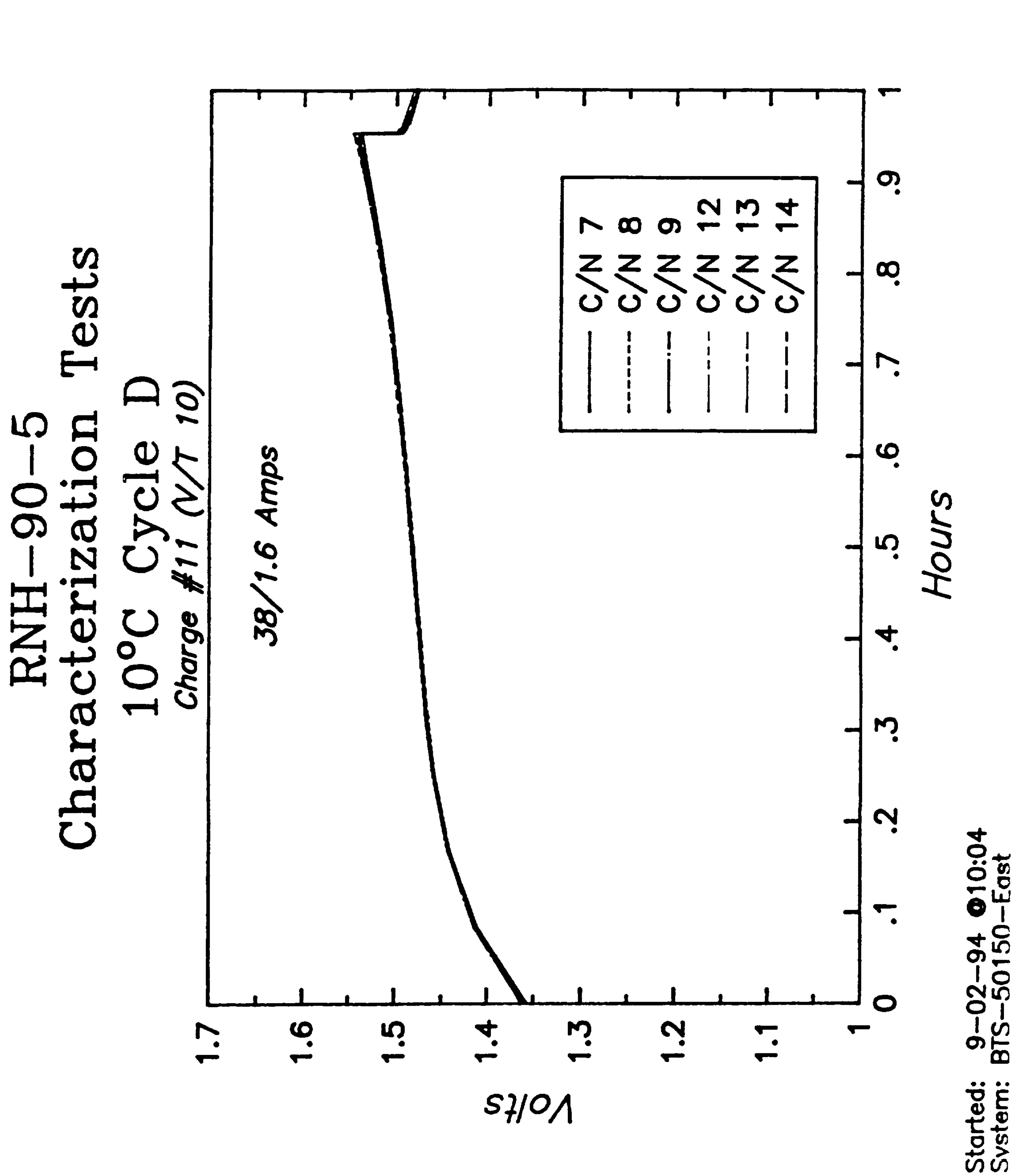

RNH-90-5
Characterization Tests
10°C Cycle B
Charge #11 (V/T 10)
38/1.6 Amps
Volts
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1
Hours
C/N 7
C/N 8
C/N 9
C/N 12
C/N 13
C/N 14
Started: 9-02-94 @06:45
System: BTS-50150-Fast



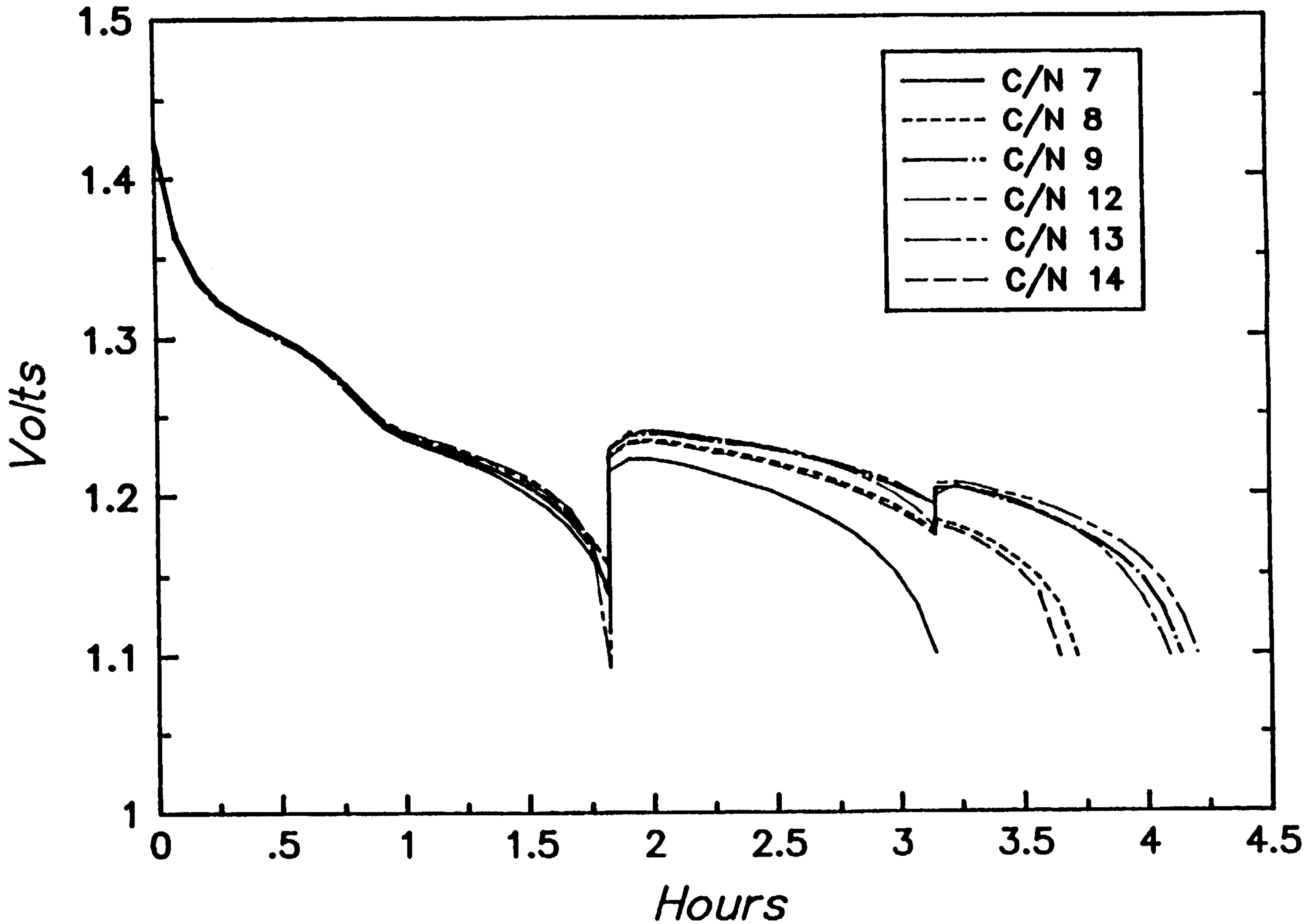
RNH-90-5
Characterization Tests
10°C Cycle C
Discharge #11 - V/T 10
1.5
1.4
1.3
1.2
1.1
1
Volts
0
.1
.2
.3
.4
.5
.6
Hours
C/N 7
C/N 8
C/N 9
C/N 12
C/N 13
C/N 14
Started: 9-02-94 @07:47


RNH-90-5
Characterization Tests
10°C Cycle C
Charge #11 (V/T 10)
38/1.6 Amps
Volts
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
Hours
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1
C/N 7
C/N 8
C/N 9
C/N 12
C/N 13
C/N 14
Started: 9-02-94 08:24


RNH-90-5
Characterization Tests
10°C Cycle D
Discharge #11 V/T 10
Volts
1.5
1.4
1.3
1.2
1.1
1
Hours
0
.1
.2
.3
.4
.5
.6
C/N 7
C/N 8
C/N 9
C/N 12
C/N 13
C/N 14
Started: 9-02-94 @09:27
System: BTS-50150-Fast


RNH−90−5
Characterization Tests
10°C Cycle D
Charge #11 (V/T 10)
38/1.6 Amps
Volts
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
Hours
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1
C/N 7
C/N 8
C/N 9
C/N 12
C/N 13
C/N 14
Started: 9−02−94 @10:04
System: BTS−50150−East

RNH-90-5
Characterization Tests
10°C Final Discharge V/T 10



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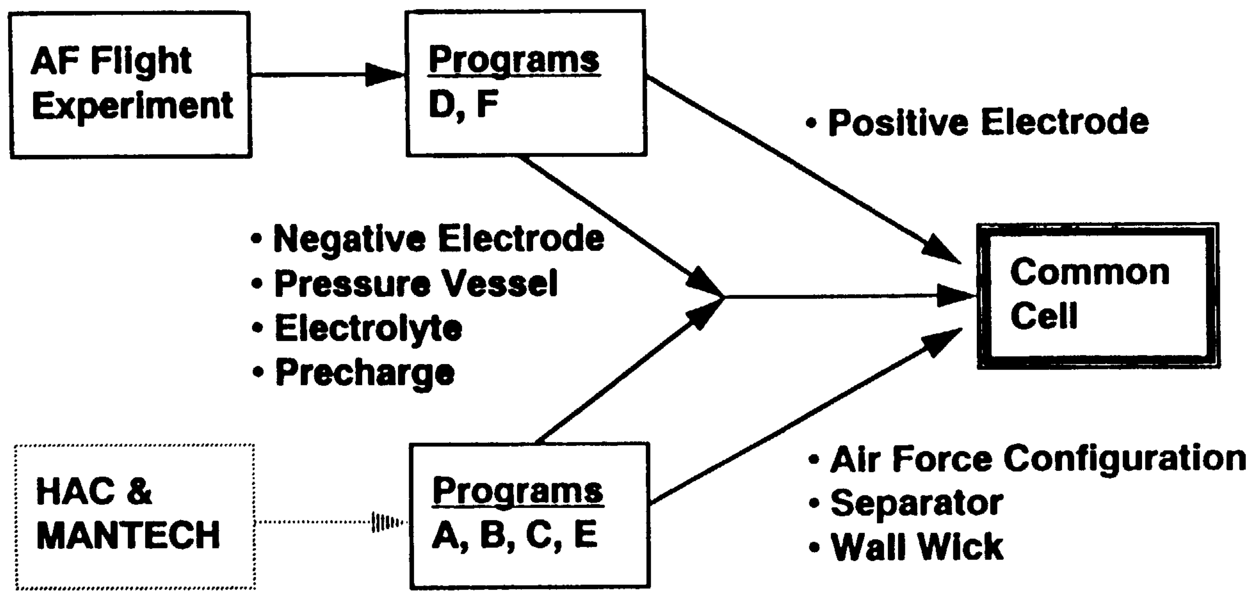
ATTACHMENT 2.

PRESENTATION CHARTS

CELL TECHNOLOGY FLOW



OPTIONS

- Electrodes (position and diameter)
- Rated capacity
- Vessel thickness

LMSC NIH2 BATTERY DESIGN APPLICATIONS

PROGRAM*	CELL TYPE	POSITIVE	SEPARATOR	TERMINAL
A	AF(76AH)	DRY SINTER	ZIRCAR	AXIAL
B	AF(80AH)	DRY SINTER	ZIRCAR	RABBIT
C	AF(88AH)	DRY SINTER	ZIRCAR	RABBIT
D	COMSAT(83AH)	SLURRY	ASBESTOS	RABBIT
E	AF(40AH)	SLURRY	ZIRCAR	RABBIT
F	COMSAT(90AH)	SLURRY	ASBESTOS	RABBIT

*EXCLUDES AF FLIGHT EXPERIMENT NIH2 BATTERY

PRESENT COMSAT ARCHITECTURE

- COMSAT NiH2 CELL ARCHITECTURE SELECTED OVER AIR FORCE (AF) CELL DESIGN IN 1986 DUE TO ACCELERATED GROUND TEST DATA FROM 1970'S AND GEOSYNCHRONOUS EARTH ORBIT (GEO) FLIGHT EXPERIENCE IN THE 1980'S
  - MORE THAN 50,000 LOW EARTH ORBIT (LEO) CYCLES COMPLETED AT 30% DEPTH-OF-DISCHARGE (DOD) ON RNH-30-1 COMSAT CELL DESIGN
  - SIX INTELSAT V COMMERCIAL SATELLITES LAUNCHED BETWEEN 1983 AND 1985 WITH RNH-30-1 BATTERY CELLS OPERATED AT 60% DOD
- TRUNCATED DISK ELECTRODE STACK COMPONENTS WITH TEFLONATED CELL CASE USED IN COMSAT BACK-TO-BACK CELL DESIGN WITH WET SLURRY PLAQUE SINTERING PROCESS AND ASBESTOS SEPARATOR FOR RNH-76-3 CELL

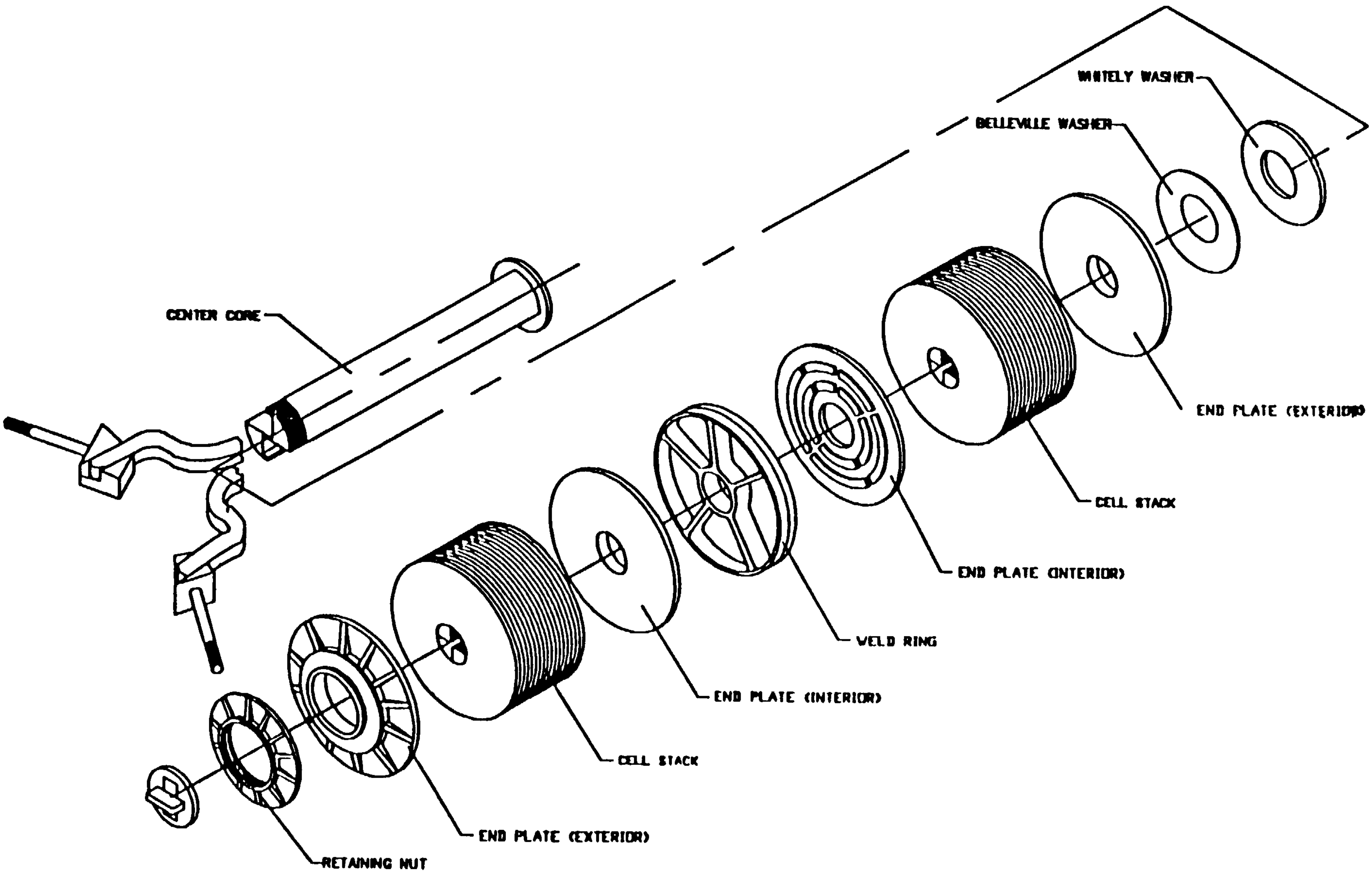
USAF/MANTECH ARCHITECTURE

- HUGHES AIRCRAFT COMPANY (HAC) BEGAN DEVELOPMENT OF NIH2 CELLS FOR LEO APPLICATIONS AT SAME TIME AS COMSAT/INTELSAT DEVELOPMENT EFFORT IN 1970'S
  - AF NIH2 FLIGHT EXPERIMENT LAUNCHED IN 1977
- USAF MANTECH CELL DEVELOPMENT STARTED IN 1981 AT YARDNEY USING COMSAT AND AF DESIGN TECHNOLOGY
- EAGLE-PICHER INDUSTRIES (EPI) MANTECH CELL DESIGN COMBINED TECHNOLOGY FROM COMSAT AND USAF MANTECH DESIGNS FOR MILSTAR AND HST BATTERY CELLS
- ELECTRODE STACK COMPONENTS (PINEAPPLE-SLICE CONFIGURATION) USED IN AF BACK-TO-BACK CELL DESIGN WITH DRY SINTER AQUEOUS PROCESS AND ZIRCAR SEPARATOR MATERIAL FOR "GENERIC HST" RNH-90-5 CELL

LMSC NiH2 COMMON CELL SUMMARY

- SHARED DEVELOPMENT AND PROCUREMENT WILL REDUCE COST AND RISK FOR 80Ah RNH-90-9 CELL DESIGN
- LMSC WILL USE/PROPOSE ON ALL CURRENT HI-POWER NASA AND MILITARY NiH2 BATTERY APPLICATIONS
- STANDARD BATTERY CELL DESIGN FEATURES INCLUDE:
  - SLURRY NICKEL ELECTRODES FOR LONG LIFE AND HIGH YIELD (LOWER COST) BASED ON FLIGHT PROVEN DESIGNS DEVELOPED OVER LAST 20 YEARS
  - DUAL LAYER ZIRCAR SEPARATORS FOR IMPROVED KOH RETENTION, UNIFORMITY AND LONGER LIFE
  - ZIRCONIUM OXIDE WALL WICK TO REDISTRIBUTE ELECTROLYTE AND EXTEND LIFE PERFORMANCE

RNH-90-5 CELL ASSEMBLY CONFIGURATION



POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

Corinne DENNIG and Thierry JAMIN

SAFT ADVANCED BATTERIES
POITIERS FRANCE

CNES
TOULOUSE FRANCE

1994 NASA AEROSPACE BATTERY WORKSHOP
US SPACE AND ROCKET CENTER
HUNTSVILLE AL
NOVEMBER 15-17, 1994

SAFT

POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

INTRODUCTION

SINCE 1965, SAFT HAS USED POLYAMID SEPARATORS IN ITS NiCd AND NiH2 CELLS.

CYCLABILITY OF THIS SEPARATOR IS PROVEN.

OBJECTIVES OF THE STUDY :

- CLEARLY IDENTIFY MODIFICATIONS OF THE SEPARATOR DURING CYCLING.
- SHOW THAT THEY HAVE NO IMPACT ON THE CELL CYCLABILITY.

CONTENT :

- COMPARISON BETWEEN NEW AND AGED SEPARATORS (FROM CELLS WHICH HAVE BEEN CYCLED).
- COMPARISON BETWEEN SEPARATORS LOCATED IN CONTACT WITH POSITIVE OR NEGATIVE ELECTRODES IN THE CELL.

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POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

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POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

1-SEPARATOR CHARACTERISTICS

1.1 - CHEMICAL :   FTR 3

FELT : NON WOVEN TISSUE ⟶ MIXTURE OF POLYAMID 6-6 (NYLON 6-6) AND POLYAMID 6

POLYAMID 6-6

$$-\left[HN-(CH_2)_6-NH-\underset{\underset{O}{\|}}{C}-(CH_2)_4-\underset{\underset{O}{\|}}{C} \right]_n-$$

1.2 - DIMENSIONNAL :

SPECIFICATION : 0.14 ∓ 0.03 mm (LHOMARGY : micrometer)
DOUBLE LAYER

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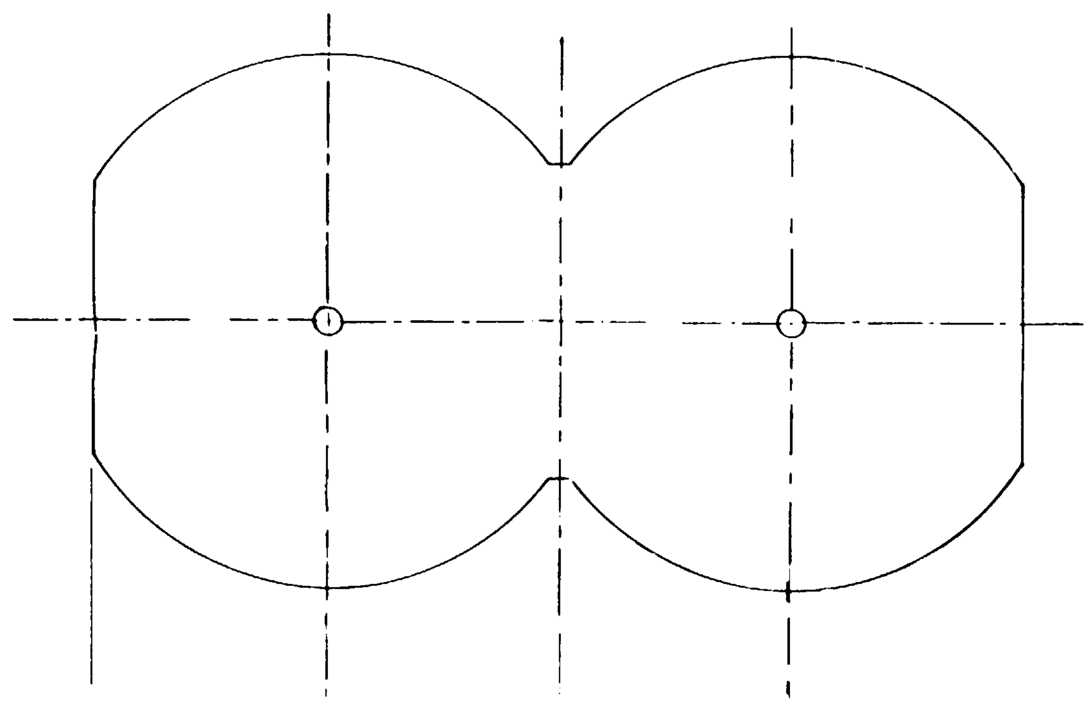
POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS



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POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

FAILED CELLS FROM TWO CYCLING TESTS WERE USED TO PERFORM THIS STUDY.

2 TYPE OF CYCLING

2.1-TESTS PERFORMED

PARTS OF THESE RESULTS HAVE BEEN PRESENTED LAST YEAR BY Y.BORTHOMIEU AND D.DUQUESNE

GEO

- VHS50BL CYCLING : 20 PERIODS PERFORMED IN ACCELERATED CONDITIONS (T=10°C)

Demonstrate the GEO life cycle with a constant DOD profile (70 %) for 18 GEO seasons
Between season 19th and 20 th : GEO cycle with real 70 % DOD
Reconditionning after each season

LEO

- HRN42 CYCLING BEGUN IN 1985 : 38,000 CYCLES PERFORMED (T=10°C, DOD=40 %) ; TEST still running

Test the suitability of HRN design (electrochemistry) for LEO missions
Compare taper versus cut-off charge management
Test in horizontal position

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POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

2- TYPE OF CYCLING

2-2 DPA RESULTS

Cell Type	CYCLING	TEST Performer	Number of Cycles completed	Reason of Removal	DPA Observations
VHS50BL n°9	GEO	AE/SP	20 seasons	EOD Voltage below 1 V Low EODV since the beginning of cycling	Ageing of electrochemical components: - drying negative electrode **due to acceptance test deviation :** **H2 leakage on test equipment** No critical ageing of the separator
HRN42 n°5	LEO	ESA	31629	Short circuit	Short due to the positive swelling : **Old design limitation :** **no positive expansion accommodation system** No critical ageing of the separator :

S.A.F.T

POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

3.1 - SIZE

3.1.1 - THICKNESS

3.1.2 - SURFACIC DENSITY

3.1.3 - APPARENT DENSITY

3.1.4 - CONCLUSION

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POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

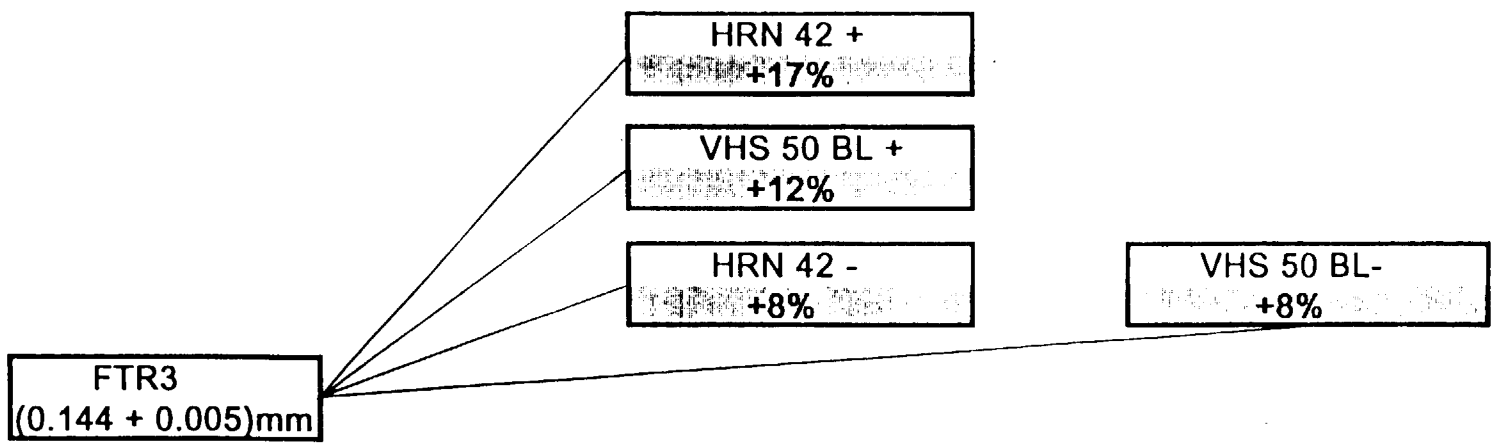
3-SEPARATOR CHARACTERIZATION
3.1-SIZE

3.1.1.- THICKNESS

LHOMARGY MI 20 (electrical micrometer) --> 2 sqcm contact surface, 1 bar pressure service, 4 seconds time lag
SEPARATORS IN A DRY STATE
FOUR MEASUREMENTS FOR EACH SEPARATOR
MEASUREMENTS ON 20 SEPARATORS ABOUT

RESULTS

NEW | AGED



NEW SEPARATOR, NEVER IMPREGNATED
NOT AN ABSOLUTE INITIAL REFERENCE

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POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

3-SEPARATOR CHARACTERIZATION
3.1- SIZE
3.1.1- THICKNESS (CONT'D)

A. SEPARATORS SWELLING

- MODIFICATION OF TEXTURE FIBER DURING CYCLING

B. POSITIVES/NEGATIVES DIFFERENCES

- DUE CERTAINLY TO O2 EVOLUTION DIFFERENCES

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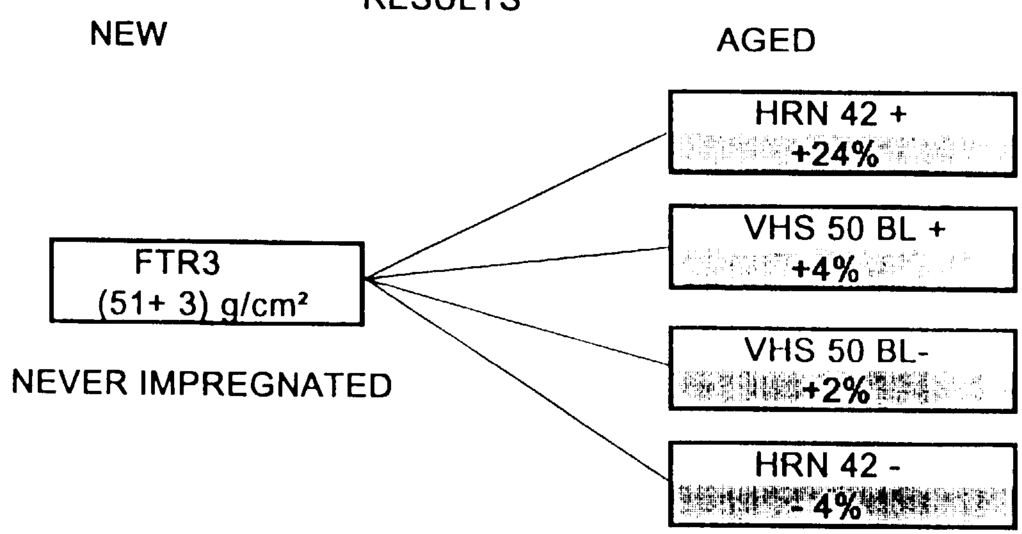
POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

3-SEPARATOR CHARACTERIZATION
3.1-SIZE (CONT'D)

3.1.2.- SURFACIC DENSITY : WEIGHT PER SURFACE UNIT

SEPARATORS IN A DRY STATE
MEASUREMENTS ON 20 SEPARATORS ABOUT
WEIGHTING ON EACH SEPARATOR (S = 92.5 sqcm)

RESULTS



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POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

3-SEPARATOR CHARACTERIZATION
3.1 SIZE
3.1.2-SURFACIC DENSITY (CONT'D)

A. TRENDS ARE THE SAME THAN FOR THICKNESS :

- DEPENDS ON NUMBER OF CYCLE

B. HIGHER SURFACIC DENSITY FOR THE POSITIVE SEPARATOR OF HRN 42 CELL

- POSITIVE HYDROXYDE DEPOSIT

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POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

3-SEPARATOR CHARACTERIZATION
3.1 SIZE (CONT'D)

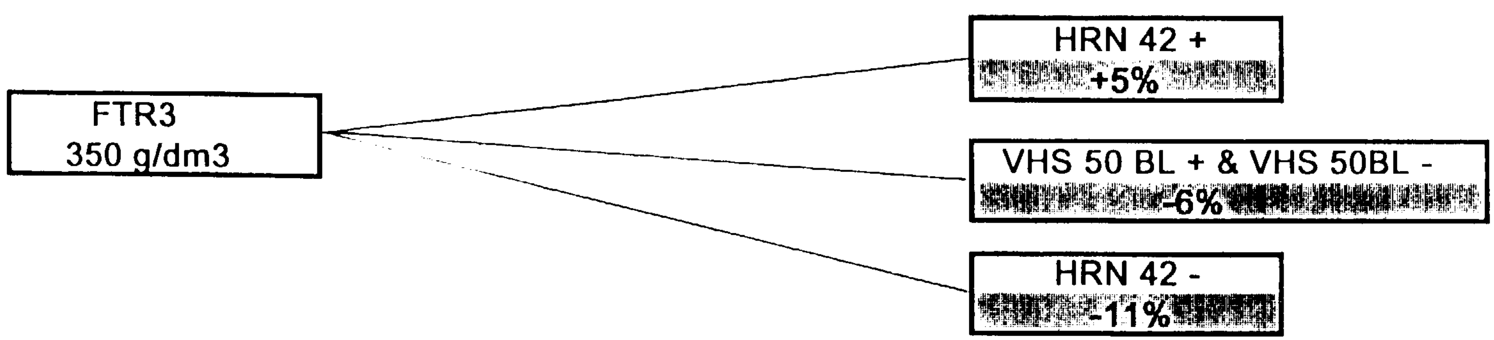
3.1.3.- APPARENT DENSITY : WEIGHT PER VOLUME UNIT

APPARENT DENSITY RO IS LINKED TO SURFACE DENSITY μ AND THICKNESS THROUGH THE RELATION :

$$Rd0 = \mu \times 10/e$$

RESULTS

NEW | AGED



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POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

3-SEPARATOR CHARACTERIZATION
3.1.4-CONCLUSION

SEPARATOR MODIFICATIONS WITH CYCLING ARE CHARACTERIZED BY :

- THICKNESS AND SURFACIC DENSITY INCREASE

- HIGHER THICKNESS FOR THE POSITIVE SEPARATOR

REMARK : THE POSITIVE AND NEGATIVE SEPARATORS BEHAVIOUR IS THE SAME FOR ALL LOCATION INSIDE TH CELL.

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POLYAMID SEPARATOR BEHAVIOUR IN NiH_2 CELLS

3.2 - MECHANICAL CHARACTERISTICS

3.2.1 - MECHANICAL RESISTANCE

3.2.2 - COMPRESSIBILITY MEASUREMENTS

3.2.2.1 - WITH DRY SEPARATORS

3.2.2.2 - WITH KOH ELECTROLYTE

3.2.3 - CONCLUSION

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POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

3-SEPARATOR CHARACTERIZATION
3.2- MECHANICAL CHARACTERISTICS

3.2.1.- MECHANICAL RESISTANCE

TRACTION APPARATUS : LHOMARGY DI 20 (RATE 30 mm/mn, LENGTH BETWEEN JAWS : 110 mm)
DETERMINATION OF THE BREAKING LOAD FOR THE WHOLE SEPARATOR

RESULTS

	SEPARATORS TYPE	STRENGTH (daN)	VARIATION (%)	ELONGATION	VARIATION (%)
NEW SEPARATORS	FTR 3	6.5	/	31	/
	Impregnated FTR 3	6.2	-5	30	-3
AGED SEPARATORS	HRN 42 +	4.1	-37	18.8	-39
	HRN 42 -	3.8	-41.5	20.8	-33
	VHS 50 +	6.6	1.5	23.8	-23.2
	VHS 50 -	7	8	25.6	-17

SAFT

POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

3-SEPARATOR CHARACTERIZATION
3.2 MECHANICAL CHARACTERISTICS (CONT'D)

3.2.2.- COMPRESSIBILITY MEASUREMENTS

DRY AND IMPREGNATED SEPARATORS COMPRESSION BETWEEN 0 AND 100 daN

--> THE CELL REPRESENTATIVE STRENGTH IS FROM 10 TO 30 daN

ONE SAMPLE : FIVE SEPARATORS WITH 28.3 sqcm

COMPRESSION SURFACE : 4.9 sqcm

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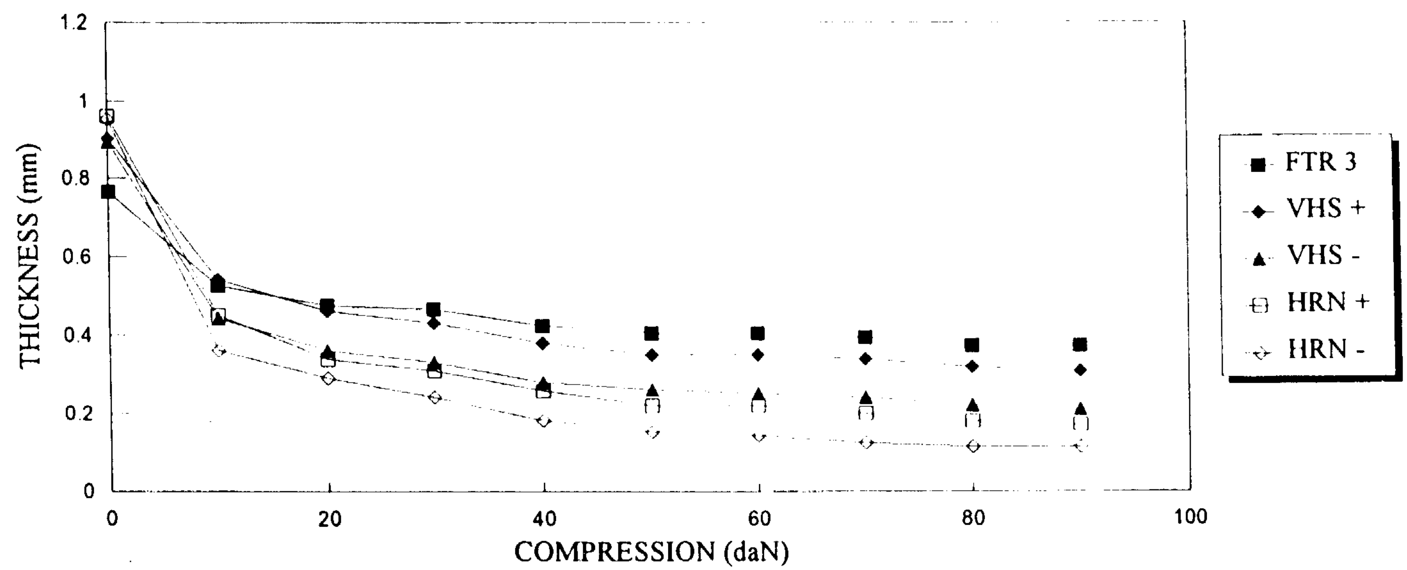
POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

3-SEPARATOR CHARACTERIZATION
3.2- MECHANICAL CHARACTERISTICS
3.2.2.- COMPRESSIBILITY MEASUREMENTS (CONT'D)

3.2.2.2.- DRY SEPARATORS

THICKNESS=F(COMPRESSION)

DRY SEPARATORS



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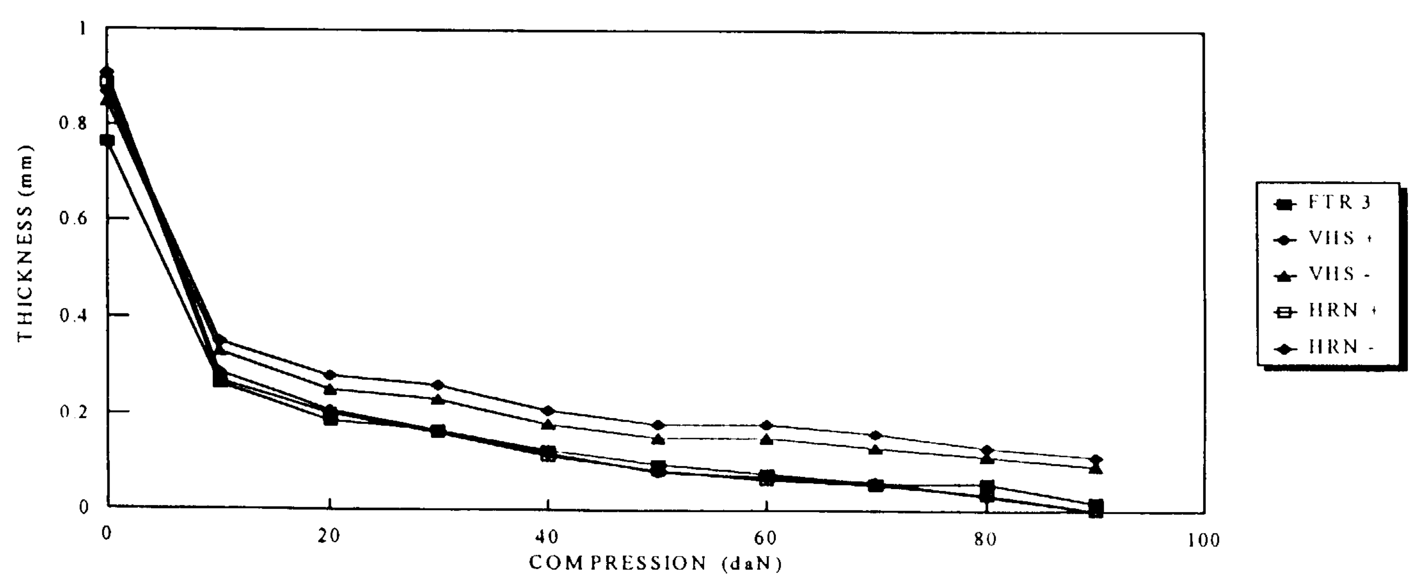
POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

3-SEPARATOR CHARACTERIZATION
3.2- MECHANICAL CHARACTERISTICS
3.2.2- COMPRESSIBILITY MEASUREMENTS (CONT'D)

3.2.2.3.- WITH KOH ELECTROLYTE

THICKNESS = F(COMPRESSION)
KOH impregnated separators



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POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

3-SEPARATOR CHARACTERIZATION
3.2- MECHANICAL CHARACTERISTICS
3.2.2.- COMPRESSIBILITY MEASUREMENTS (CONT'D)

3.2.2.3.- WITH KOH ELECTROLYTE (CONT'D)

WE DEDUCT THE COMPRESSIBILITY AT 90 daN :

	COMPRESSIBILITY AT 90 daN	
SEPARATORS	DRY	IMPREGNATED
FTR 3	50,9%	98%
VHS 50+	65,4%	87,3%
VHS 50-	76,1%	89,3%
HRN 42+	81,4%	99%
HRN 42-	88,1%	99,9%

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POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

3.2.3 - CONCLUSION

- THE KOH SEPARATORS CYCLING LEAD TO A SLIGHT DECREASE OF

  THEIR MECHANICAL RESISTANCE AND AN INCREASE OF THE COMPRESSIBILITY LEVEL.

- BOTH, NEW OR AGED SEPARATORS ARE NOT BRITTLE AND EASY TO HANDLE.

SAFT

POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

3.3 - PHYSICO - CHEMICAL MEASUREMENTS

3.3.1 - ELECTROLYTE ABSORPTION

3.3.2 - ELECTROLYTE DIFFUSION

3.3.3 - ELECTROLYTE RETENTION

3.3.4 - CHEMICAL ANALYSIS

3.3.5 - CONCLUSION

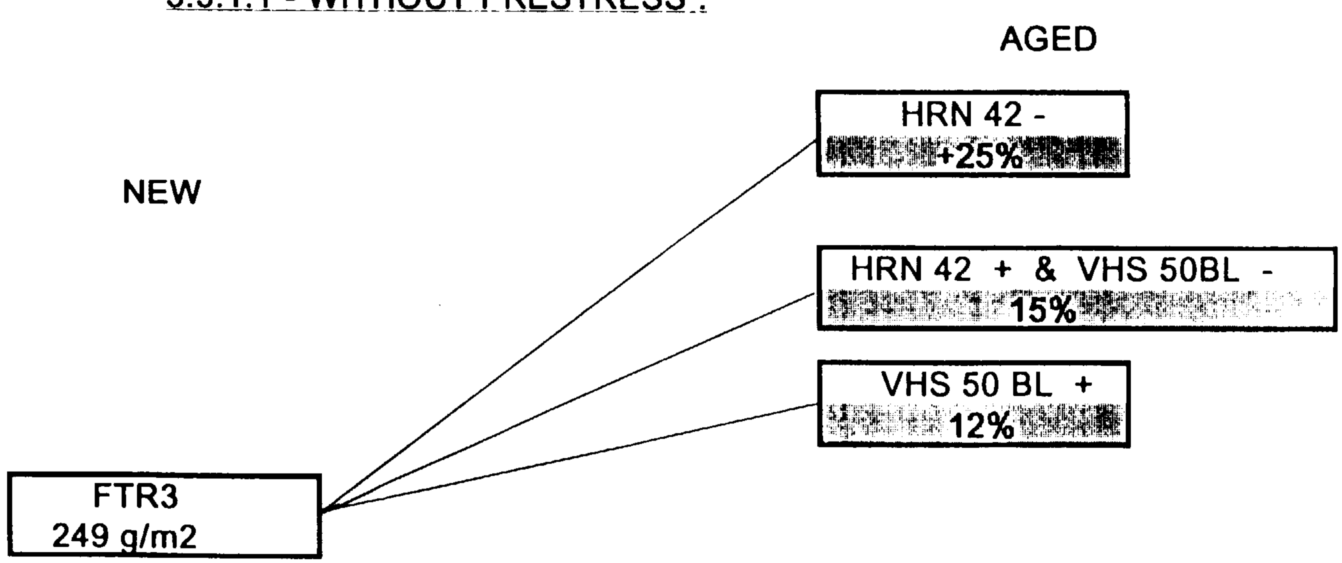
SAFT

POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

3 - SEPARATOR CARACTERIZATION
3.3 - PHYSICO-CHEMICALMEASUREMENTS

3.3.1 - ELECTROLYTE ABSORPTION :

3.3.1.1 - WITHOUT PRESTRESS :



ABSORPTION BETTER FOR : HRN 42 / VHS 50 BL / FTR 3
NEGATIVES / POSITIVES SEPARATORS

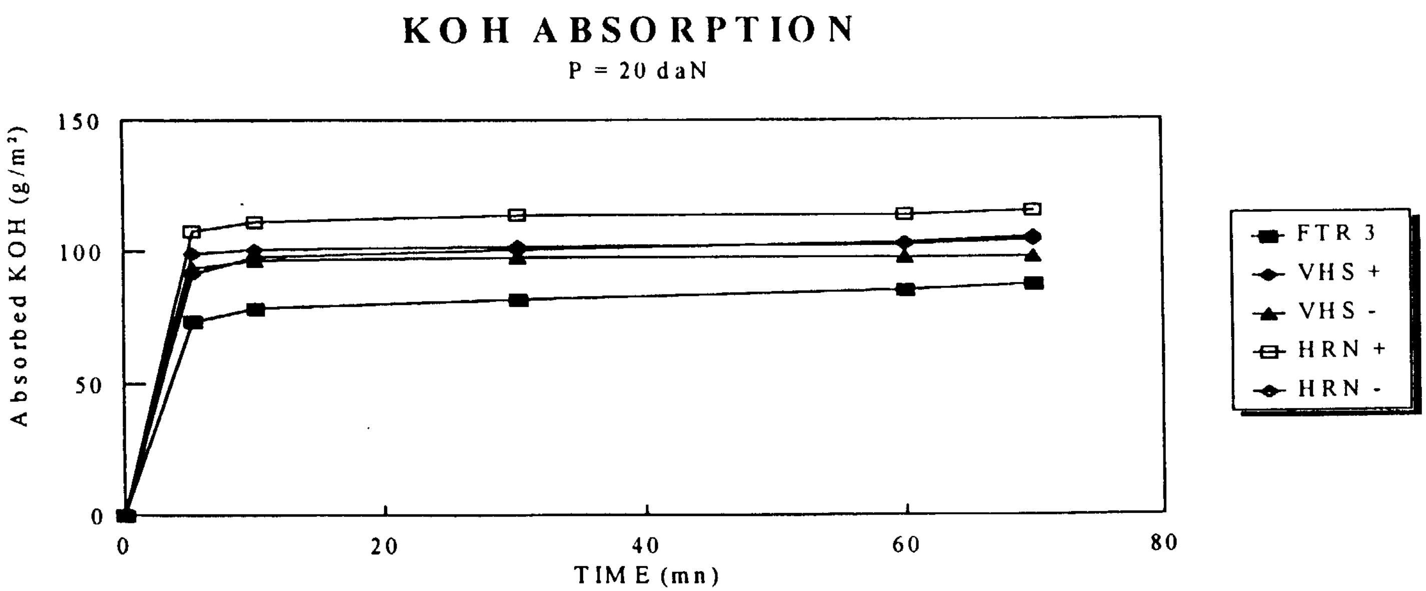
SAFT

POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

3 - SEPARATOR CARACTERIZATION
3.3.1 - ELECTROLYTE ABSORPTION

3.3.1.2 - WITH PRESTRESS :

One sample : 5 separators (6 sqcm each) stack
Compression strength : 5, 10 and 20 daN



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POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

3 - SEPARATOR CARACTERIZATION
3.3.1 - ELECTROLYTE ABSORPTION
3.3.1.2 - WITH PRESTRESS (CONT'D)

AT 70 MN OF ABSORPTION :

	ABSORPTION AT 5 daN		ABSORPTION AT 20 daN	
SEPARATOR	AVERAGE (g/m^2)	INCREASE (%)	AVERAGE (g/m^2)	INCREASE (%)
HRN 42 +	143.2	18	115.5	32
HRN 42 -	141.1	16	104.5	21
VHS 50 +	147.4	21	105.3	20
VHS 50 -	138.1	14	98.2	12
FTR 3	121.6	/	87.4	/

KOH ABSORPTION

LOWER ► HIGHER
NEW ► AGED SEPARATORS
NEGATIVES ► POSITIVES

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POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

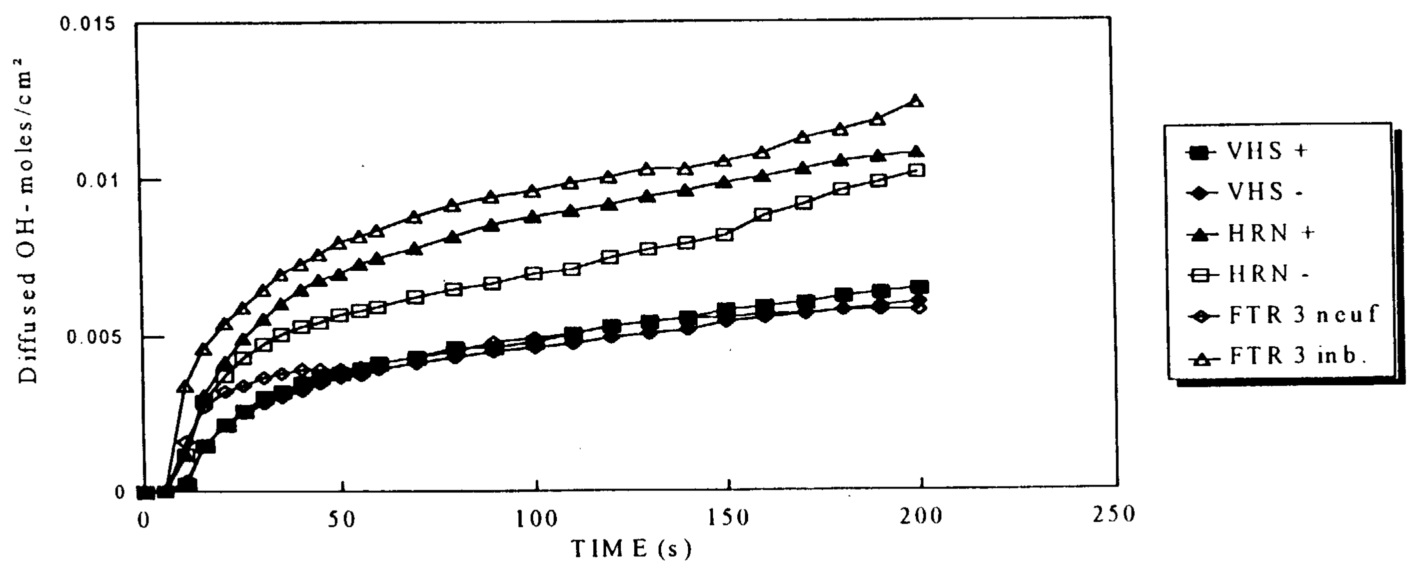
3 - SEPARATOR CARACTERIZATION
3.3.2 - ELECTROLYTE DIFFUSION

Sample surface : 3.14 sqcm

Double compartement : some water on one side, KOH (1.55 %) on the other side.

pH measurement = f(time)

KOH DIFFUSION = F(TIME)



IONIC DIFFUSION : DRY FTR3 (FIBERS NOT REORGANIZED)

IMPREGNATED FTR3 > HRN 42 > VHS 50 BL

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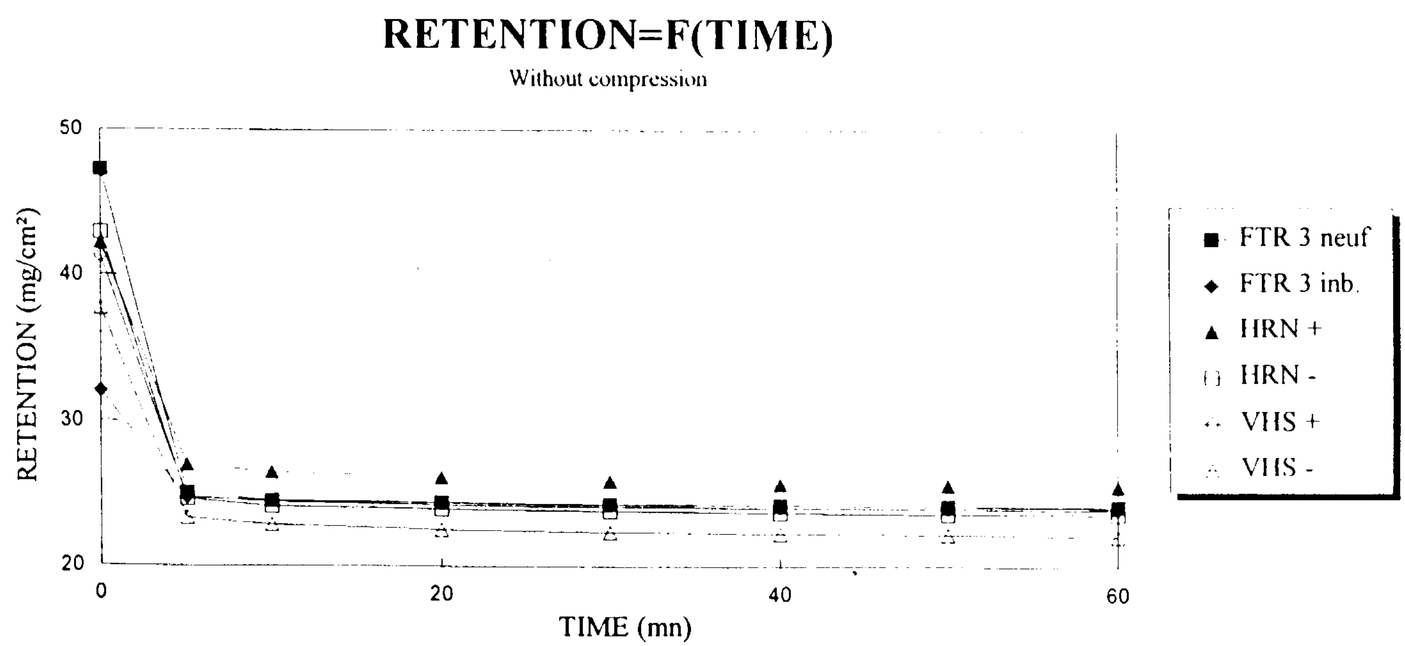
POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

3 - SEPARATOR CARACTERIZATION
3.3.3 - ELECTROLYTE RETENTION

Impregnated sample one night
Gravity effect

3.3.3.1 - WITHOUT COMPRESSION :



S.A.F.T

POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

3 - SEPARATOR CARACTERIZATION
3.3.2 - ELECTROLYTE RETENTION

AFTER ONE HOUR :

SEPARATORS	KOH LOSS (%)	VARIATION (%)
IMPREGNATED FTR 3	74.9	/
HRN 42 +	60.4	-19
HRN 42 -	54.9	-27
VHS 50+	57.9	-23
VHS 50 -	58.4	-22

KOH RETENTION :

AGED > IMPREGNATED FTR3
POSITIVE > NEGATIVE SEPARATOR

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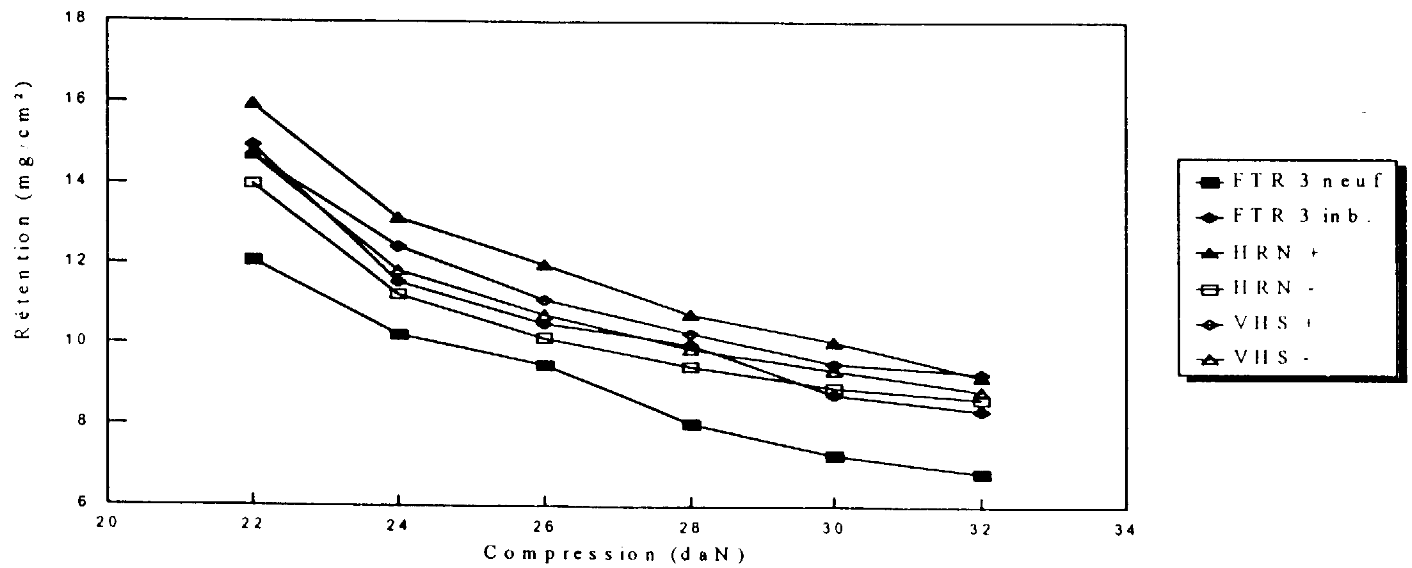
POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

3 - SEPARATOR CARACTERIZATION
3.3.3 - ELECTROLYTE RETENTION (CONT'D)

3.3.3.2 - WITH COMPRESSION :

RETENTION = F(COMPRESSION)



RETENTION : IMPREGNATED FTR 3 > NEW FTR 3
AGED SEPARATORS > NEW FTR 3

POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

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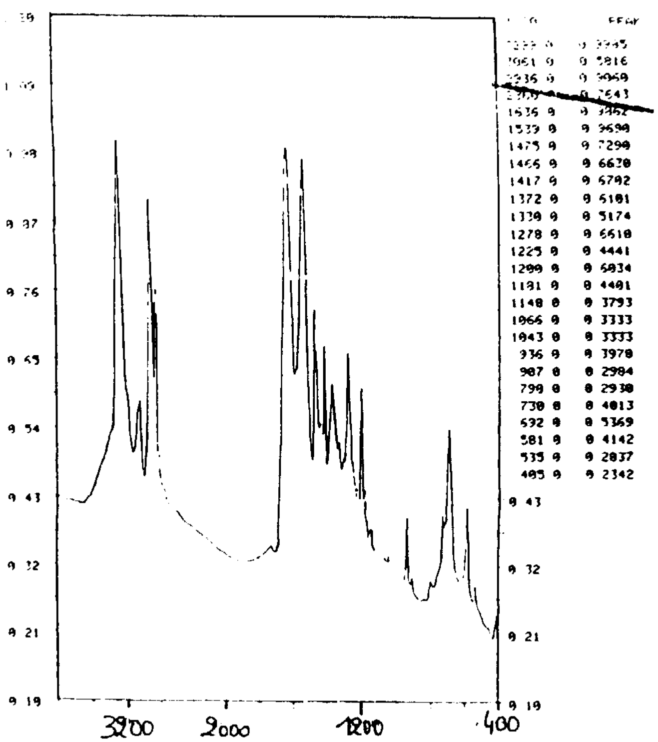
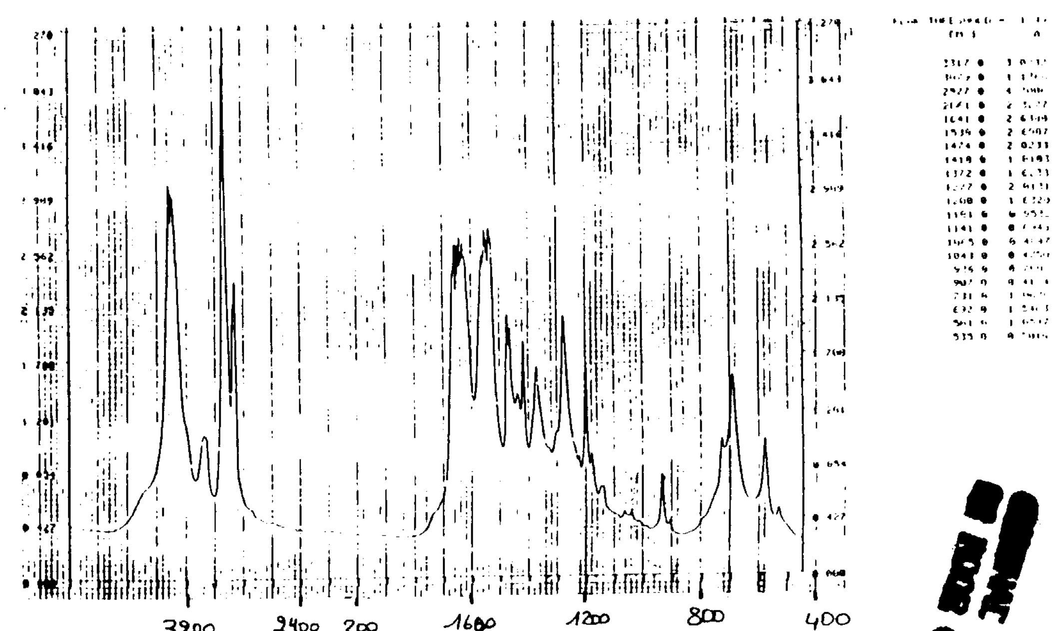
3 - SEPARATOR CARACTERIZATION
3.3.4 - PHYSICO-CHEMICAL MEASUREMENTS
INFRA-RED ANALYSIS

HRN 42 : INFRA-RED SPECTRUM

AGED SEPARATOR (HRN 42 CELL)



NEW SEPARATOR



NO VISIBLE DIFFERENCE

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POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

3 - SEPARATOR CARACTERIZATION
3.3.5 - CONCLUSION

<u>CYCLING :</u>

KOH ABSORPTION INCREASES WITH OR WITHOUT PRESTRESS.

KOH DIFFUSION DECREASES.

POSITIVE > NEGATIVE FOR : ABSORPTION
DIFFUSION
RETENTION

NO DIFFERENCE IN THE INFRA-RED SPECTRUM.

SAFT

POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

4 - CONCLUSION

SIZE :

- THICKNESS, SURFACIC DENSITY INCREASE.

MECHANICAL CHARACTERISTICS :

- EASY TO HANDLE
- SLIGHT DECREASE IN MECHANICAL RESISTANCE
- INCREASE IN COMPRESSIBILITY

PHYSICO - CHEMICAL MEASUREMENTS :

- KOH ABSORPTION, RETENTION INCREASE
- KOH DIFFUSION DECREASES
- NO CHANGE IN THE CHEMICAL ANALYSIS

SAFT

POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS

4 - CONCLUSION (CONT'D)

- ►CHANGES IN THE SEPARATOR CHARACTERISTICS AFTER CYCLING HAVE BEEN IDENTIFIED.
- ►THIS INCREASES OUR KNOWLEDGE OF THE POLYAMID SEPARATOR BEHAVIOUR IN NiH2 CELLS.
- ►ONLY SLIGHT DIFFERENCES BETWEEN NEW AND AGED SEPARATORS WERE NOTICED.
- ►THIS STRENGTHENS SAFT CHOICE TO USE THIS SEPARATOR IN NiH2 AND NiCd CELLS.

N95- 26788

High-Rate/High-Temperature Capability of a Single-Layer Zircar-Separator Nickel-Hydrogen Cell

James R. Wheeler
Eagle Picher Ind., Joplin MO

Abstract

A 50 ampere-hour nickel-hydrogen cell with a single-layer Zircar separator stack design was fully charged and then discharged at a 2C current rate to an end voltage of 1 volt. This extreme test resulted in high temperatures which were recorded at three locations on the cell, i.e., the cell wall, the boss (barrel of the compression seal), and a terminal. The results provide new information about the high-temperature and high-discharge-rate capabilities of nickel-hydrogen cells. This information also adds to the growing data base for single-layer zirconium-oxide-cloth (Zircar) separator cell designs.

Cell Description

The cell used in the tests described here is a 3½ inch-diameter RNH 50-49Z ManTech design with a nominal capacity of 50 Ah. A typical cell is shown in figure 1.

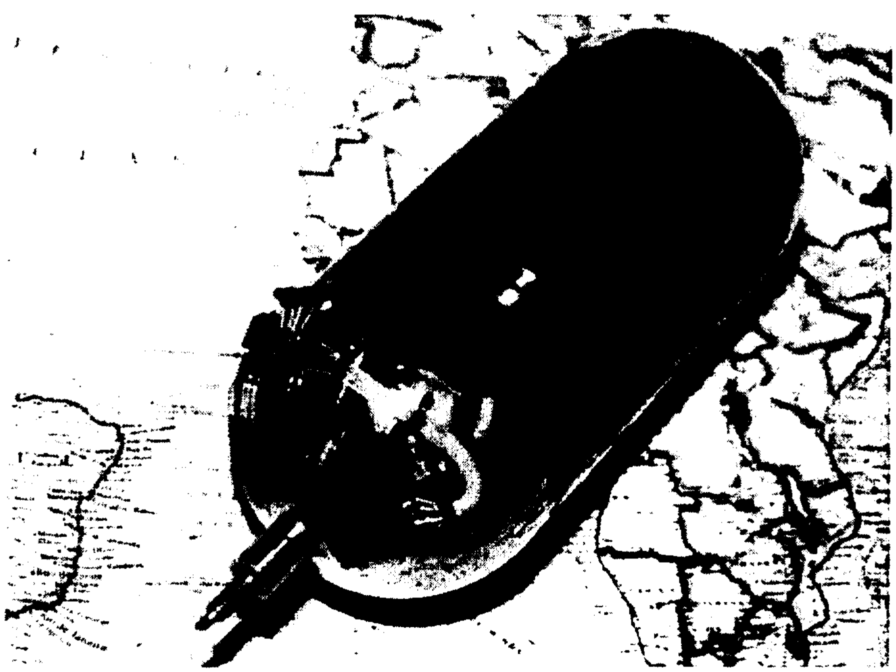

Figure 1. RNH 50-49 Nickel Hydrogen Cell

By "ManTech" is meant an Eagle Picher design which uses pineapple-slice-shaped electrodes and stack elements, a central polysulfone core, continuous nickel-foil leads on electrodes, and a wall-wick to ensure a recirculating path to return and equilibrate electrolyte throughout the cell stack. Other features include a spring washer for uniform stack compression, a small wall gap and separator/electrolyte contact with the cell wall to facilitate heat transfer. One feature in this cell that makes it slightly different from other ManTech production cells is the application of a thin, plated coating of gold to the hemispheres on either end. The purpose of this is to lower the thermal emittance of the normally-cooler cell ends and thereby reduce the thermal gradient within the cell.

The development cell chosen for this test differs from the production version in that its stack contains one layer of zirconium-oxide cloth per positive electrode instead of one layer of asbestos. The cell was constructed with a production lot and all other materials were identical to those in the production cells. This design is notable for having the highest ratio of conductor resistance to area of electrode of any other 3.5-inch diameter size cell currently in production at Eagle Picher. The reason for this is weight-savings. The design, with either separator, successfully met all acceptance-test requirements.

Test Design

The test described here was performed primarily to confirm the 2C current-carrying rating of a ¼-inch nickel terminal in a 50 Ah nickel-hydrogen cell. Secondary objectives were to confirm the survivability of the terminal seals and the cell itself at high rates and temperatures, and to test the robustness of single-layer Zircar separator under the same conditions.

The test was conducted in the open air of an air-conditioned test laboratory, and no special effort was made to cool it during this period of testing. The cell was instrumented with thermocouples on the cell wall (opposite the cell stack), on the boss (barrel of the compression seal), and on the tip of the negative terminal. It was given a standard charge (5.25 amps for 16 hours) and then discharged to 0.7 volts at 100 amps. Capacity was measured to 1.0 volts, and also to 0.7 volts in anticipation of the voltage depression caused by high current and the resultant high IR drop in stack and leads.

The cell was then shorted down to below 0.1 volts with a 0.2 ohm resistor, and the test was repeated. The discharge rate the second time was increased to 125 amps to provide an over-test and to increase performance confidence. To detect any leakage which might result from the softening of the Nylon terminal seals by the high test temperatures, a phenolphthalein leak test was performed on the terminal seals at the end of all charges and discharges.

Following the high-rate cycles the cell was given a phenolphthalein leak check, placed in a cooling cart and given a standard cycle using the same charge regime as before, but a normal 30 amp discharge. This was intended to indicate whether any performance decline had resulted from the testing.

Test Results

The cell delivered appropriately good capacity on all cycles. No leaks occurred despite temperatures as high as 189°F. See tables 1 and 2 for summaries of capacity and temperature. A graph of the thermocouple temperatures on the second high-rate cycle are shown in figures 2 and 3. The plots for the first cycle were similar, but not quite so high. The evident late rise in the terminal temperature in figure 3 was due to a connection problem with the thermocouple.

Table 1
Cell Capacity (Ah)

	0.7 volts	1.0 volts
Test 1 (100 amps)	60.0	53.3
Test 2 (125 amps)	55.6	41.6
Standard 10°C (30 amps)	------	64.4

Table 2
Thermocouple Temperature (°F)

	100 amp discharge	125 amp discharge
Negative Terminal	110	143
Boss (seal)	156	176
Cell Wall	189	188

Conclusions

The warm starting temperature and the selection of a cell with thin leads made it a severe test. Despite the fact that the test cell has electrode leads lighter than any other Eagle Picher production cell, it performed well at the 2C and 2.5C rates without any decline in performance at a normal temperature. The final standard capacity of 64.4 Ah compares favorably, within normal test variance, with the cell's original 10°C ATP capacity of 65.2 Ah. Finally, its Nylon seals did not leak despite exposure to at least 176°F.

The results support the conclusion that this type of cell, including its single Zircar separator design, and the Ziegler Nylon compression seal are robust under harsh conditions. The seal withstood a temperature of 176°F and the cell a temperature of 189°F. The actual temperatures internal to the seal and cell stack were certainly higher than this, although they could not be measured directly.

It is generally recognized that temperature has some effect on the cycle life of batteries in general,[1] and it should be reassuring that this type of cell can endure this kind of exposure with no apparent degradation of performance. The presence of the wall wick in the design affords a mechanism to re-distribute any water displaced by the temperature extremes. While a judgment about the long-term effects of high temperatures is not within the scope of this paper, there is no reason to expect the ultimate cycle life to be degraded by a short-term exposure as in the test described here, particularly since this cell design has a wall wick to redistribute any electrolyte which might be displaced by temperature gradients during testing.

Acknowledgments

Gary Nowlin assisted in test design and conducted the testing described. His contribution is gratefully acknowledged.

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[1] David Linden, *Handbook of Batteries and Fuel Cells,* para. 3.2.6, p. 3-9, McGraw Hill, 1984.

N95- 26789

Air Force Ni-H_2 Cell Test Program

State of Charge Test

Presented at: 1994 NASA Aerospace Battery Workshop
Huntsville, AL

Prepared by: Bruce Moore, NSWC Crane Div.
Capt. Douglas Smellie, USAF

Nickel Hydrogen cells are being cycled under a LEO test regime to examine the benefits of operating the cells at lower States of Charge (SOC) than typically used. A group of four cells are being cycled using a voltage limiting charge regime that limits the State of Charge that the cells are allowed to reach. The test cells are being compared to identical cells being cycled at or near 100% State of Charge using a constant current charge regime.

Air Force Ni-H_2 Cell Test Program

State of Charge Test

Purpose

Examine the benefits of operating Nickel Hydrogen cells at lower States of Charge (SOC) than identical cells being cycled at similar LEO conditions approaching 100% SOC.

Goals

Determine the effects of lower SOC on cell performance.

Exceed the number of cycles that the sister cells reach before failure.

Four 50 AmpHr 3.5" diameter cells manufactured by Eagle Picher in Joplin Mo. are being used for the test, part numbers RNH50-43 and RNH50-53. RNH50-43 uses a back-to-back stack design with a 26% KOH electrolyte concentration . RNH50-53 uses an alternating stack with an electrolyte concentration of 31% KOH.

Each of the two designs were originally split up into two packs of ten cells each, 3314E and 3214E. They are running an identical constant current test regimes with a C/D ratio of 1.03 to 1.04 at 40% Depth of Discharge and 10 degrees C. Approximately one year or 5000 cycles later the four cell SOC test pack, 3001C, was started. Two cells from each design were combined into one pack. The charge and discharge for the SOC test pack are identical to the original packs with a voltage limit placed on the charge cycle that will cause the current to taper towards the end of the charge.

Air Force Ni-H_2 Cell Test Program

State of Charge Test

Manufacturer	Eagle Picher, Joplin	
Capacity	50 AmpHr	
Size	3 1/2 "	
Separator	Asbestos	
Part #	RNH 50-43	RNH 50-53
Stack Configuration	Back to Back	Alternating
KOH Concentration	26%	31%

Air Force Ni-H_2 Cell Test Program

State of Charge Test

Pack ID	3001C SOC Test	3214E	3314E
# of Cells	4	10	10
Part #	RNH50-43 RNH50-53	RNH50-43	RNH50-53
DOD	40%		
Temperature	10 Degrees C		
Discharge	40 A for .5 Hr		
Charge	26.11 A with taper for 1 Hr (Voltage Limited)	26.11 A for .766 Hr 2.58 A for .233 Hr Recharge = 103%	

Air Force Ni-H_2 Cell Test Program

State of Charge Test

State of Charge Definition

100% SOC - The point during a C/2 Charge that the cell pressure no longer increases at a linear rate.

0% SOC - The point during a C rate Discharge that the cell voltage reaches 1.0 volt.

SOC will be checked prior to life cycle and will be checked every 5000-10000 cycles.

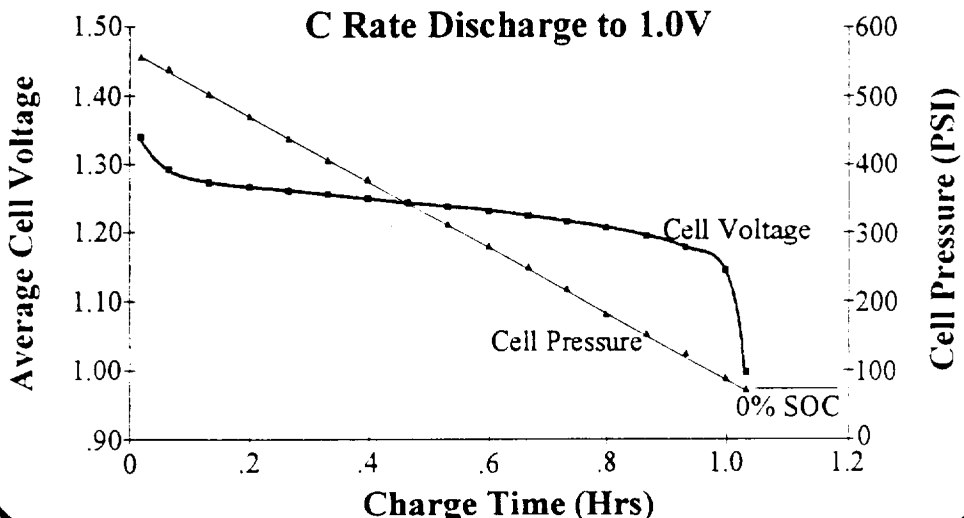
For the purposes of this test, 100% state of charge is defined as the point during a C/2 charge that the cell pressure no longer increases at a linear rate. 0% state of charge is the point during a C rate discharge that the cell voltage reaches 1.0 volts. Prior to starting life cycle, the four cells destined for the SOC test were cycled to find the zero and one hundred percent SOC points. According to the results the pressures related to those points are 80 and 590 psi respectively. Although this data is probably accurate for the cell in its current state it is not useful information for the purposes of life cycle testing.

An examination of the Trend Plot for 3314E shows that at the beginning of life, the End of Charge (EOC) pressures were at the same 590 psi for the SOC test cells. After only 1000 cycles the EOC pressures were reduced to approximately 425 psi. It appears that changes occur very quickly during the first 1000 cycles of a life cycle regime. Since the SOC test cells seem to follow the characteristics of their sister cells, the 425 psi EOC pressure value was assumed for 100% SOC.

The target SOC for the test cells is 60 to 70%. This value was chosen to keep the cells at significantly below 100% SOC and to provide for a reserve capacity at the end of discharge, in this case 20 to 30% of rated capacity. Assuming the previously stated values of 425 psi for 100% SOC and 80 psi for 0% SOC, the pressure should be maintained at 304 psi for 65% SOC.

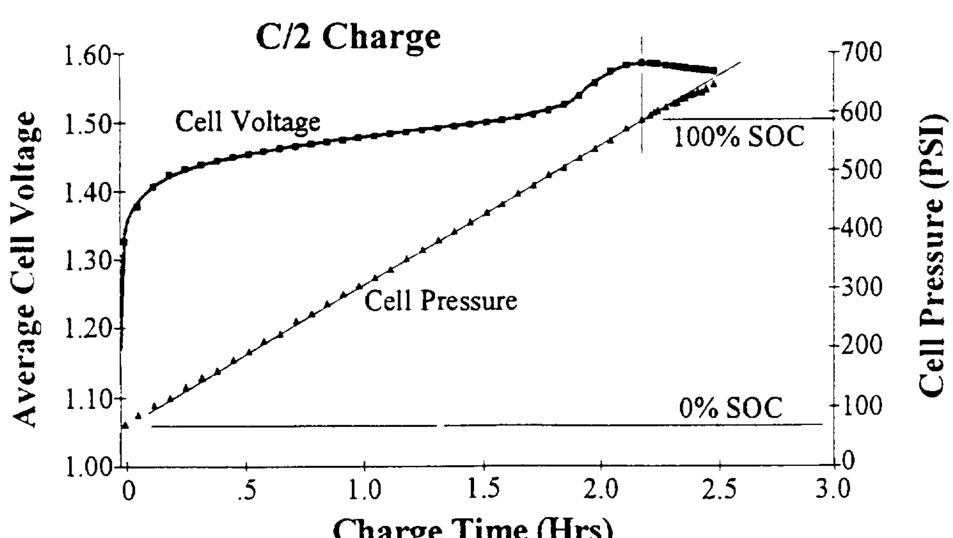
Air Force Ni-H_2 Cell Test Program

State of Charge Test



Air Force Ni-H_2 Cell Test Program

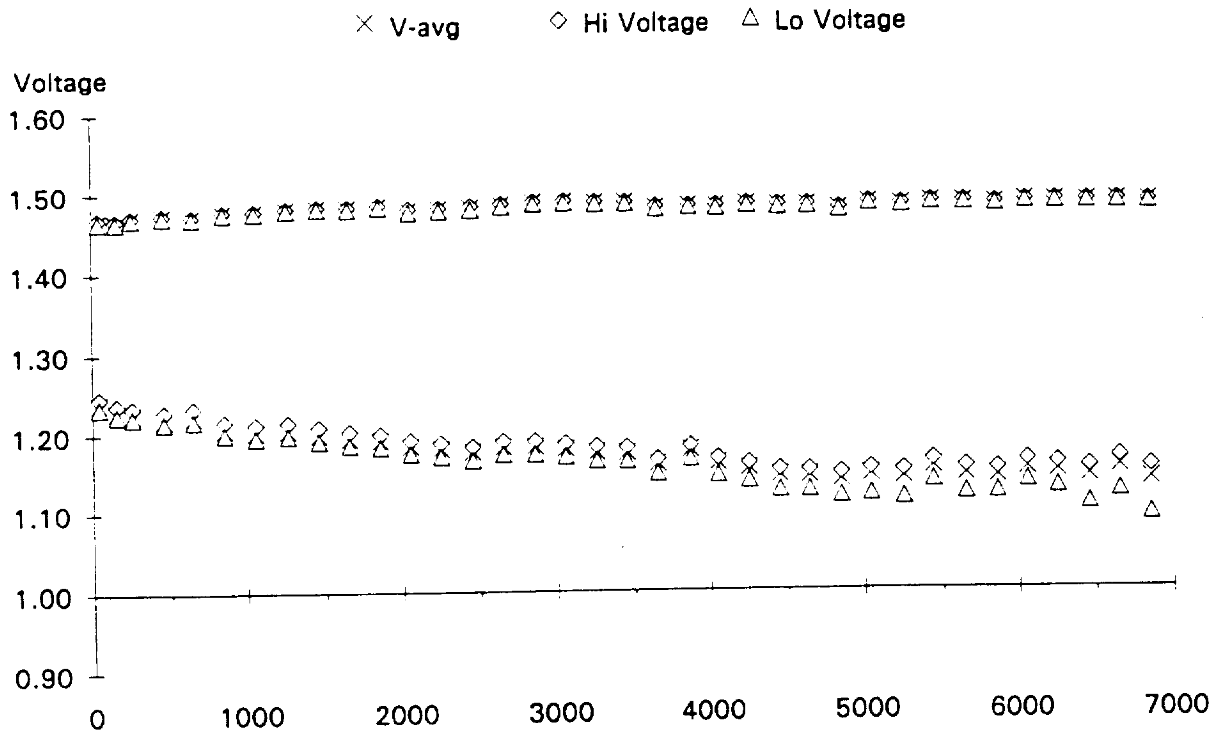
State of Charge Test

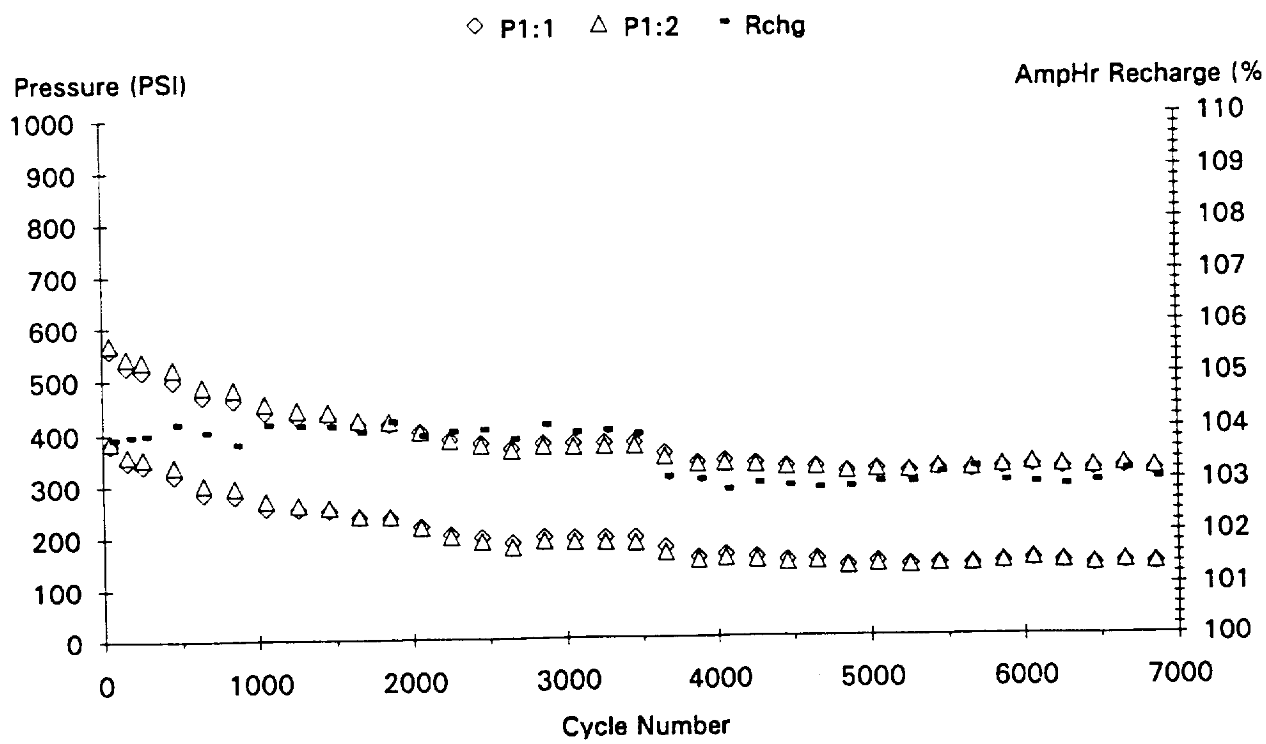


NSWC Crane **Pack ID 3214E** **10 cells**

Voltage/Pressure/Recharge EOC/EOD Trend Plot 08/05/93 - 10/25/94

EPI 50 AmpHr 3.5" 40% DOD 10 Deg C 26% KOH Back2Back Stack

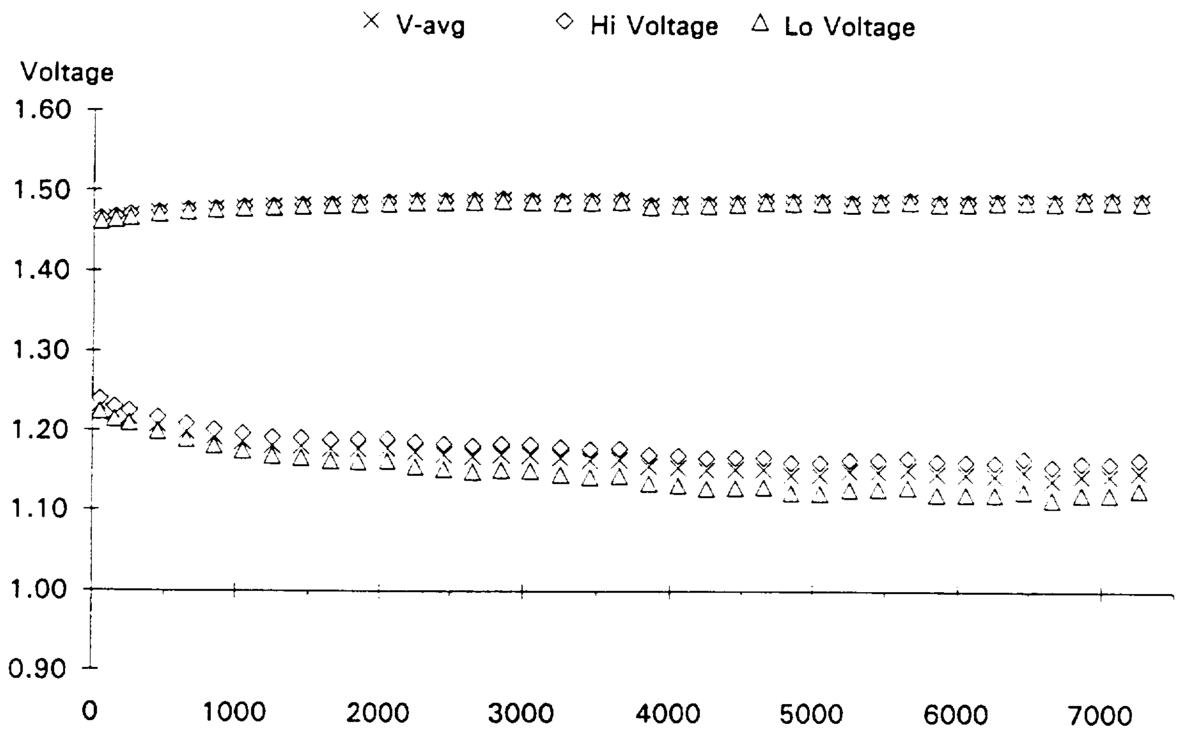


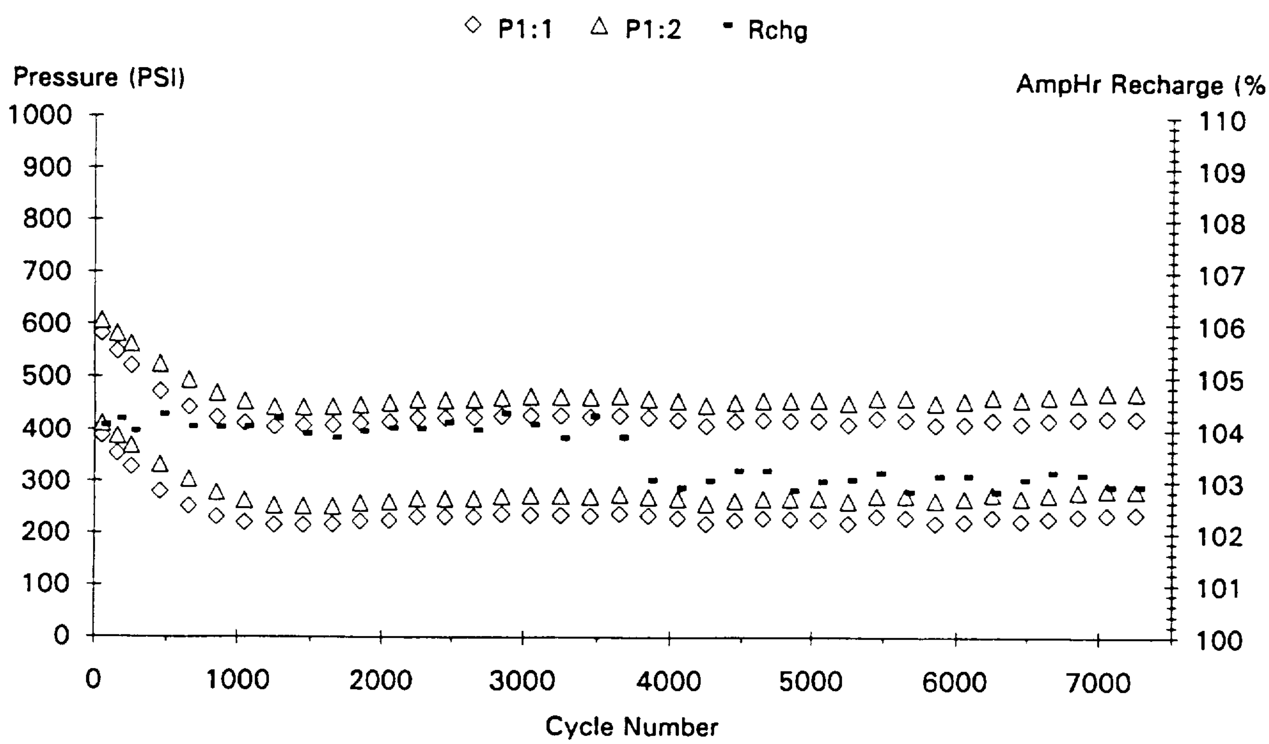


NSWC Crane Pack ID 3314E 10 cells

Voltage/Pressure/Recharge EOC/EOD Trend Plot 07/23/93 - 10/21/94

EPI 50 AmpHr 3.5" 40% DOD 10 Deg C 31% KOH Alternating Stack

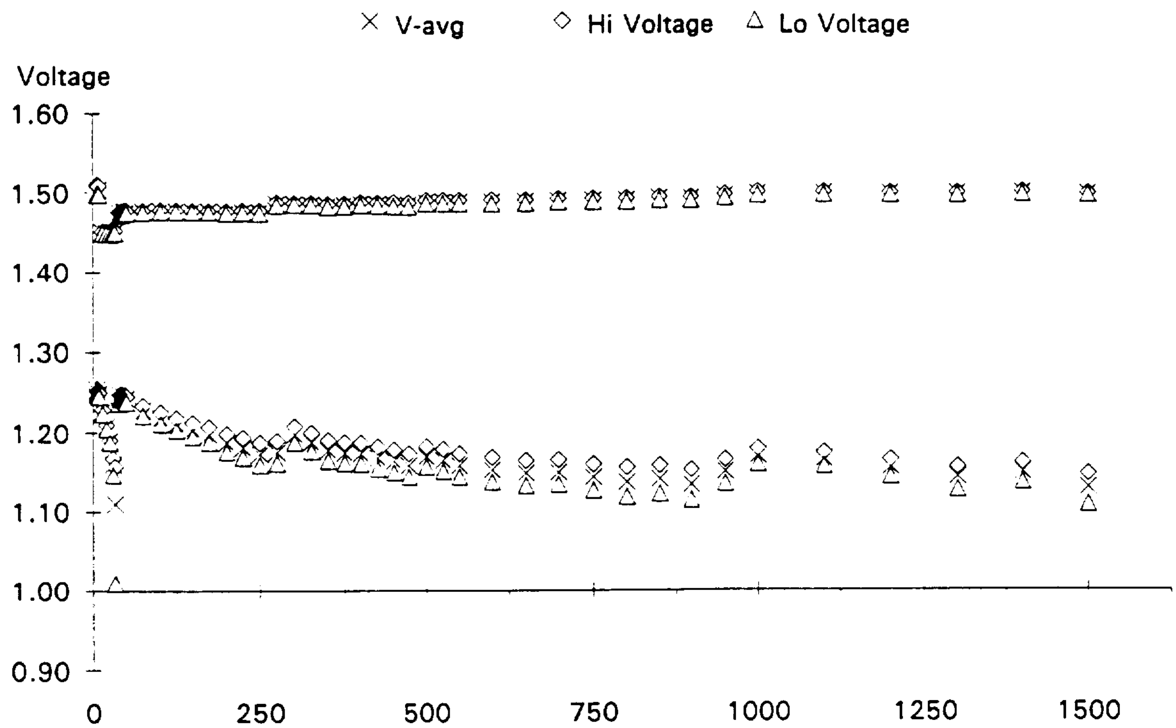


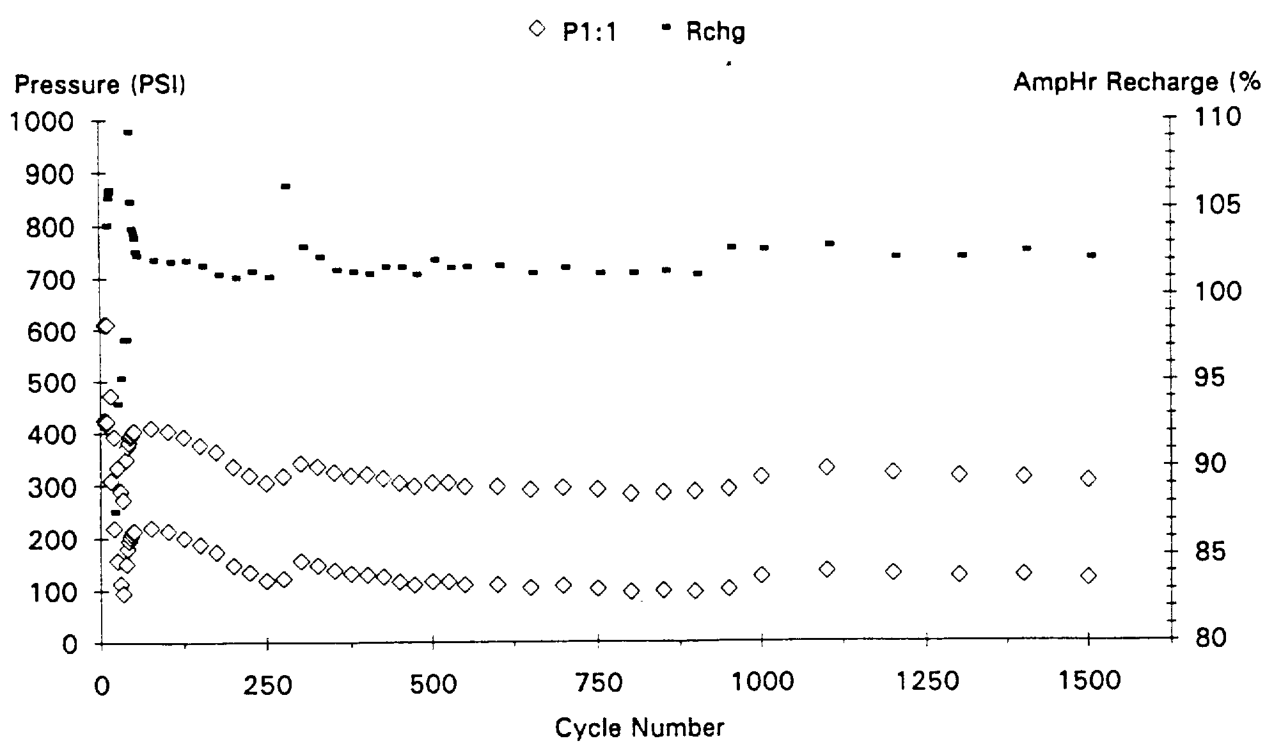


NSWC Crane   Pack ID 3001C   4 cells

Voltage/Pressure/Recharge EOC/EOD Trend Plot   07/21/94 - 10/26/94

Eagle Picher 50 AmpHr   3.5"   40% DOD   10 Deg C   SOC Test





Air Force Ni-H_2 Cell Test Program

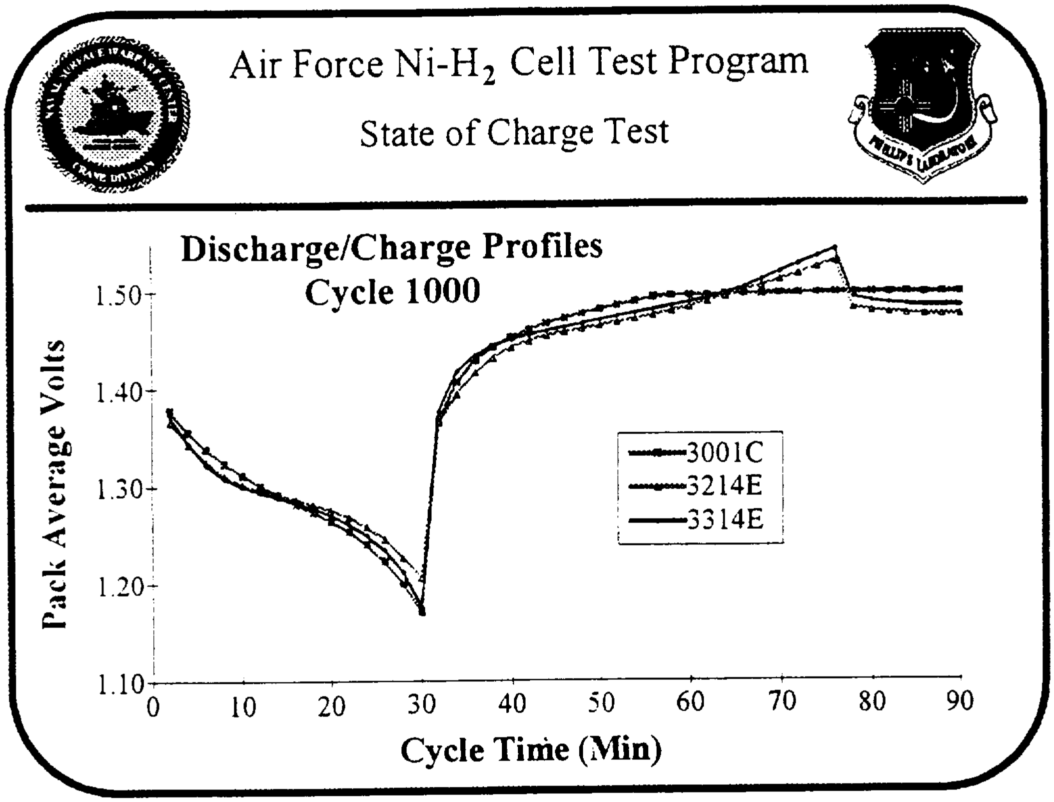
State of Charge Test

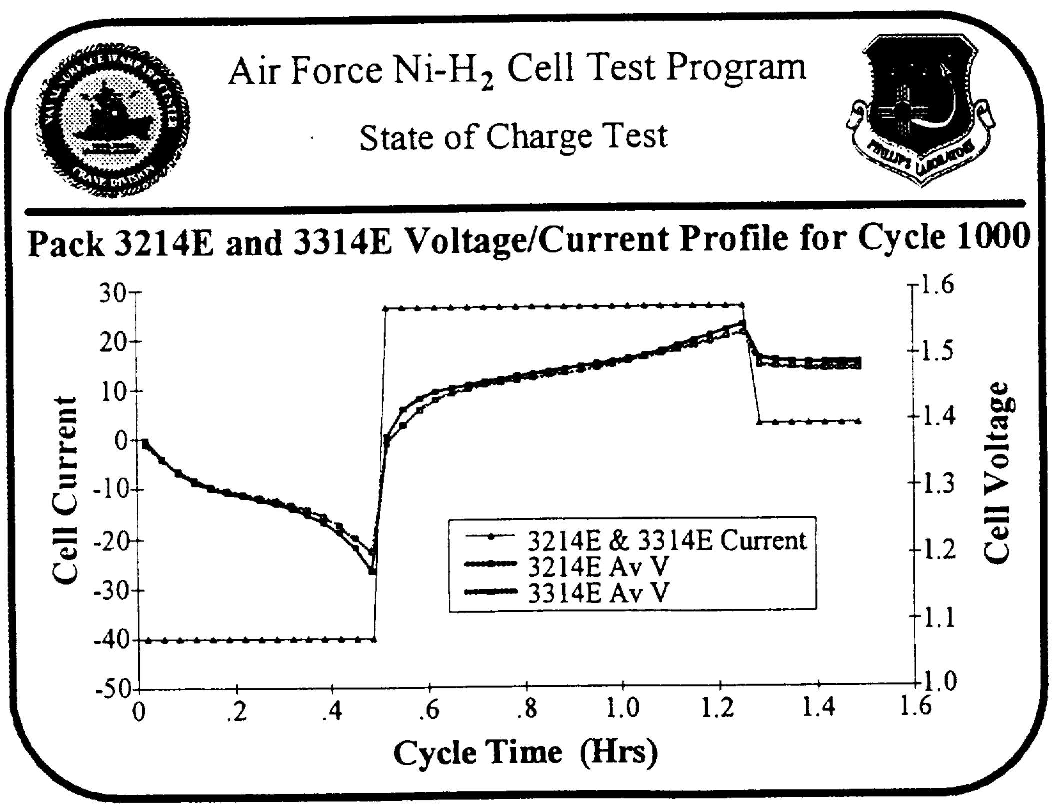
Pre Life Cycle Cell Capacities C Rate to 1.0 Volt				
	RNH50-43		RNH50-53	
Temp	3314E	3001C	3214E	3001C
-5 °C	62.94	60.84	65.69	65.23
0 °C	68.64	67.33	74.14	75.60
10 °C	58.10	55.68	64.98	62.41
20 °C	51.58	52.30	59.15	58.78
30 °C	49.37	49.83	53.56	55.11

Capacities for pack 3001C were measured after 1 year standing open circuit, discharged at 5 degrees C.

The SOC test cells will be cycled with a C/2 charge and C rate discharge again at 5000 cycles to determine the pressure values for 0 and 100% SOC. The SOC/pressure relationship will also be checked again every 5000 to 10000 cycles.

Prior to life cycle testing the four SOC test cells were stored discharge, open circuit at 5 degrees centigrade for one year. Comparison of the sister cells that started life cycle testing one year before the SOC test cells show very little difference in the capacities. The reported capacity values for the SOC test cells in pack 3001C are after the one year stand. The capacity was not checked when they were received.

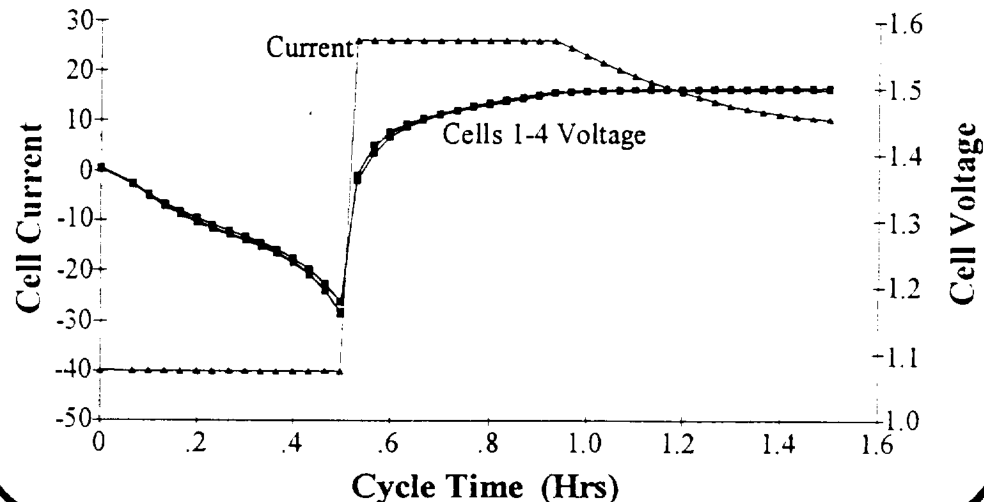

Air Force Ni-H_2 Cell Test Program
State of Charge Test
Discharge/Charge Profiles
Cycle 1000
Pack Average Volts
1.50
1.40
1.30
1.20
1.10
0
10
20
30
40
50
60
70
80
90
Cycle Time (Min)
3001C
3214E
3314E


Air Force Ni-H_2 Cell Test Program
State of Charge Test
Pack 3214E and 3314E Voltage/Current Profile for Cycle 1000
Cell Current
30
20
10
0
-10
-20
-30
-40
-50
Cell Voltage
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
Cycle Time (Hrs)
3214E & 3314E Current
3214E Av V
3314E Av V

Air Force Ni-H_2 Cell Test Program

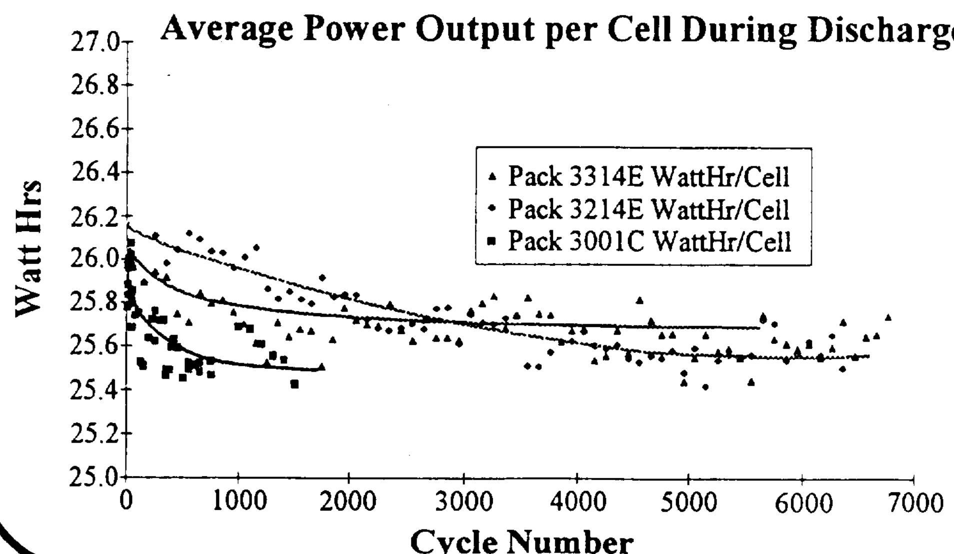
State of Charge Test

Pack 3001C Voltage/Current Profile for Cycle 1000



Air Force Ni-H_2 Cell Test Program

State of Charge Test



Air Force Ni-H_2 Cell Test Program

State of Charge Test

Concerns

- Sample is small. Only four cells are being used for the comparison of the SOC charge regime.
- Possibility of voltage divergence because of the different cell designs.
- Possible effect of capacity checks on life of cell.

Design and Fabrication of the EOS–AM1 Battery Assembly

by

D.J. Keys, G.M. Rao, H.E. Wannemacher, R.B. Wingard
NASA/GSFC

C.W. Bennett, W.M. Gibbs, E.W. Grob and A.F. Mucciacciaro
MARTIN MARIETTA ASTRO SPACE

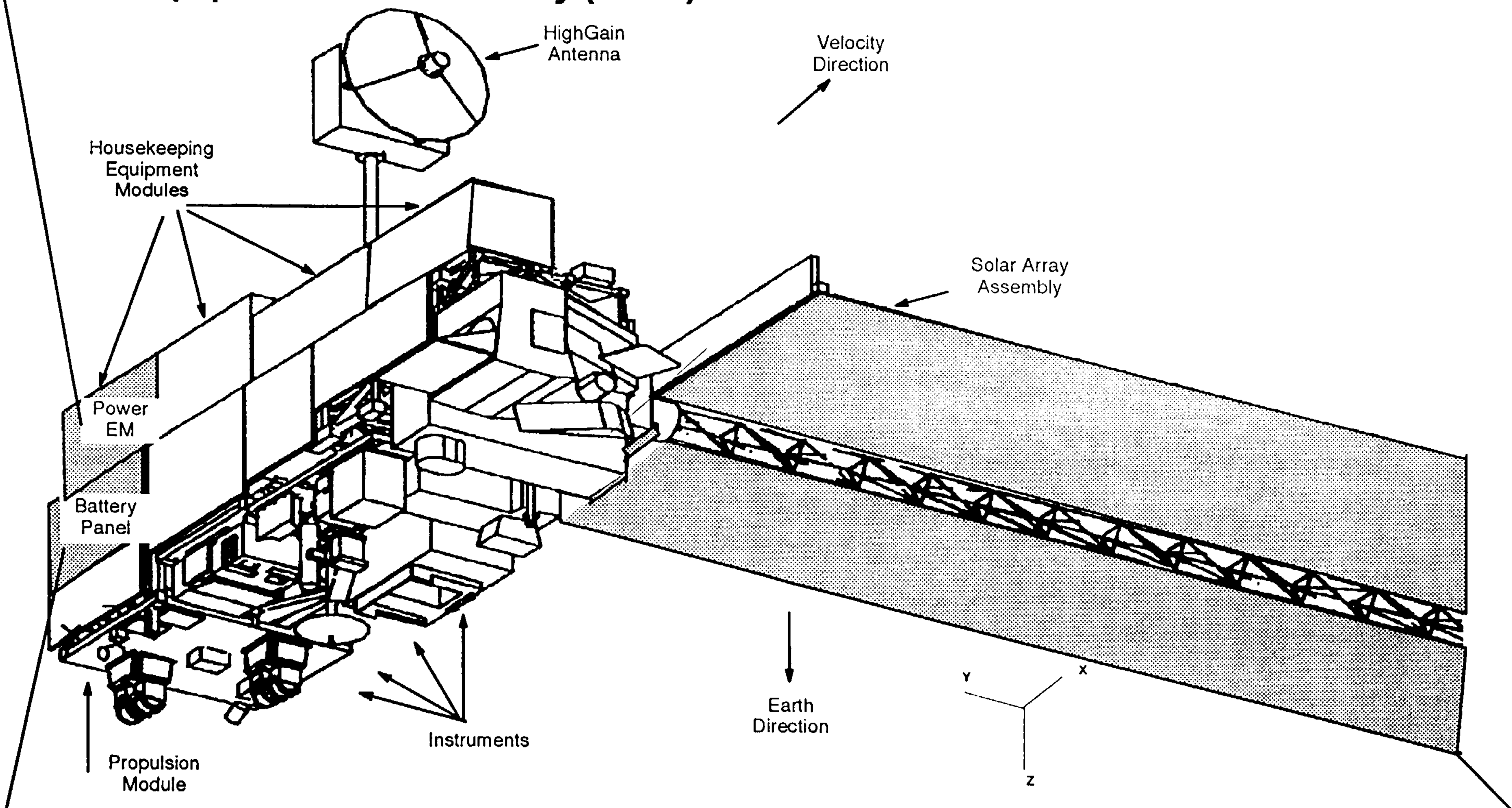
(Performed under NASA Contract NAS5–32500)

Outline

- Spacecraft Interfaces
- Top Level Requirements
- Design Summary
  - Electrical
  - Thermal
  - Mechanical
  - Battery Assembly
- Design Drivers

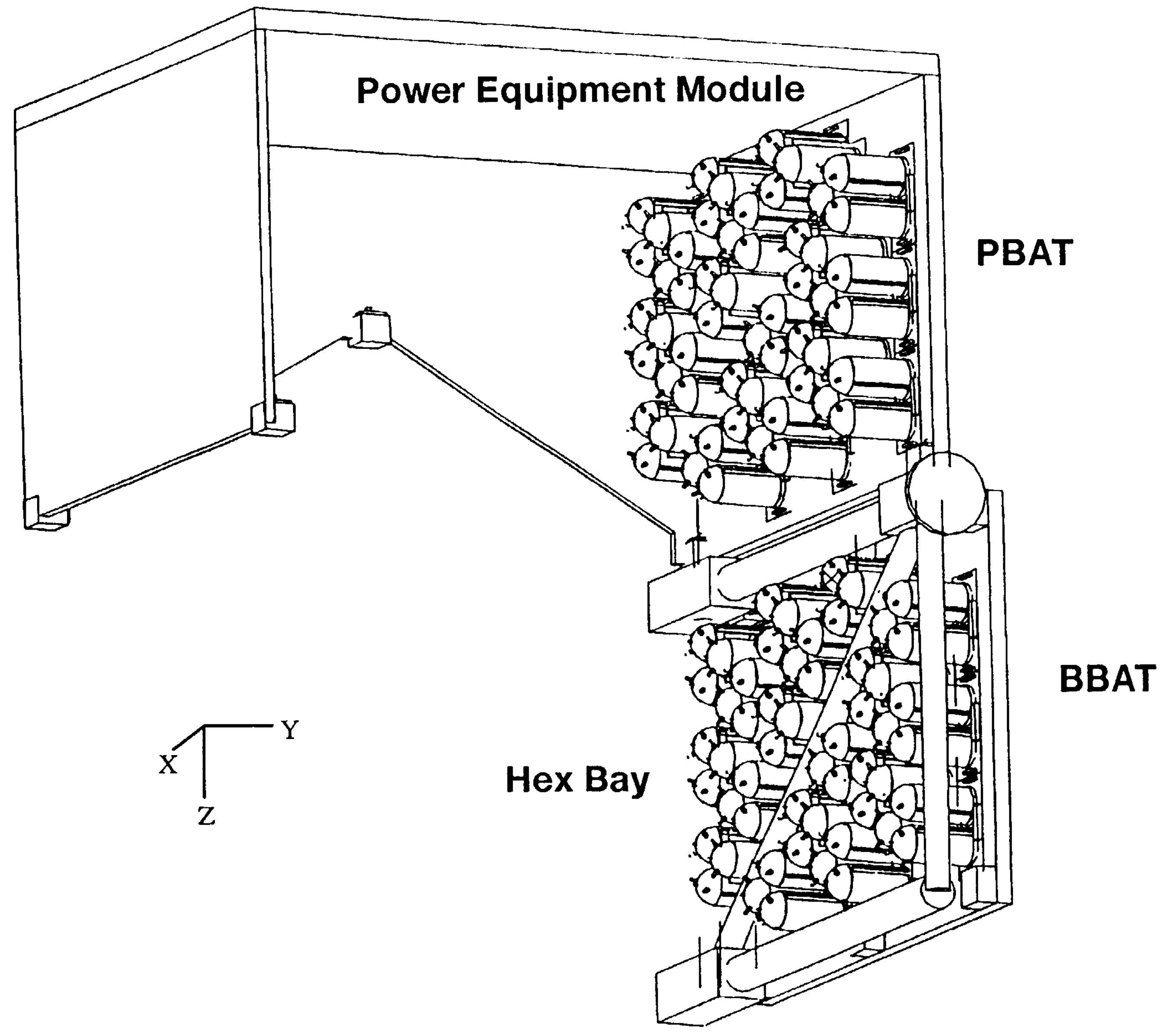
Battery Assembly/Spacecraft Interface

Power Equipment Module Battery (PBAT)



Hex Bay Battery (BBAT)

Integrated Battery Assemblies



Top Level Requirements

Electrical Requirement	Actual or Prediction
– Capacity (Amp Hours Minimum)	
– – 58.8 at 0°C	65.0
– – 57.0 at 10°C	64.5
– – 50.0 at 20°C	54.5
– – 42.0 at 30°C	51.5
– Voltage	
– – 54.0 to 89.1	70.2 to 80.4 (Max Science)
– – 54.0 to 89.1	71.8 to 80.9 (Survival and Safe)
– Depth of Discharge	
– – 30% Max	19.1% (Max Science, 54 cells)
– – 35% Max	19.6% (Max Science, 53 cells)
– – 30% Max	10.0% (Survival and Safe)
– Current	
– – 30 Amps Max Discharge	20.7 Amps (Max Science, 53 cells)
– – 23 Amps Max Charge	12.2 Amps (Max Science, 53 cells)

Top Level Requirements

Requirement	Actual or Prediction
• Mechanical Requirement	Actual or Prediction
– Mass (Maximum)	
– – 310.1 (PBAT)	299.7 (10.4 lbs Contingency)
– – 315.9 (BBAT)	304.7 (11.2 lbs Contingency)
– Structural Load Cases	
– – Launch acceleration environment	
– – Qualification level acoustic loading	
• Thermal Requirement	Actual or Prediction
– Operating Temperature Limits	
– – –5°C to 10°C	2.6°C to 4.7°C (Min Science)
– – –5°C to 10°C	1.2°C to 3.9°C (Max Science)
– Thermal Gradients	
– – Cell to Cell 3°C max	2.4°C (EOL Cold)
– – Stack to Dome 7°C max	2.1°C (EOL Cold)
– – Dome to Dome 10°C max	2.3°C (EOL Cold)
– – PBAT to BBAT 3°C max	1.5°C (EOL Cold)

Design Summary

Parameter	Implementation
• Four fused outputs	Fuse Board
• Isolated pyro bus	Pyro bus relay assembly
• Conductive thermal design	Cell/sleeve assembly & baseplate
• Open cell protection	Bypass switch assembly (one per cell)
• Cell pressure telemetry	BPM (4 per BAT)
– GSE/Flight isolation	GSE/Flight transfer relay assembly
• Heater control	Separate primary and backup circuits
– multiple cells per circuit	Six cells per circuit
– Nine primary circuits	Through HCE5A
– Nine backup circuits	Through HCE5A
– Thermistor control	one thermistor per cell (controls Pri. & B/U)
– Over and under temp. protection	High and low temp. T–stats/circuit
• Flight cell voltage telemetry	Through HCE5A (for each cell)
• Flight cell temp. telemetry	Through HCE5A (for each cell)

Design Summary

Parameter	Implementation
• Ground cell voltage monitor	GSE/letdown relay assembly
• Ground letdown function	GSE/letdown relay assembly
• Ground BPM cell temp. monitor	GSE T_{zero} umbilical
• Verifiable double insulation	TP1, TP2, TP3 via GSE T_{zero} umbilical
• Charge power connection	Charge power diode assembly
• Redundant V/T control	Three circuits to PDU
• BAT health status telemetry	Via PDU
– Battery current	Primary and backup via meter shunt
– Battery voltage	Primary and backup
– Battery voltage (expanded)	Primary and backup
– Battery panel temperature	Primary and backup
• Connector interface	Seventeen (17) connectors
– Isolated power and signals	Yes
– Isolated primary and backup	Yes

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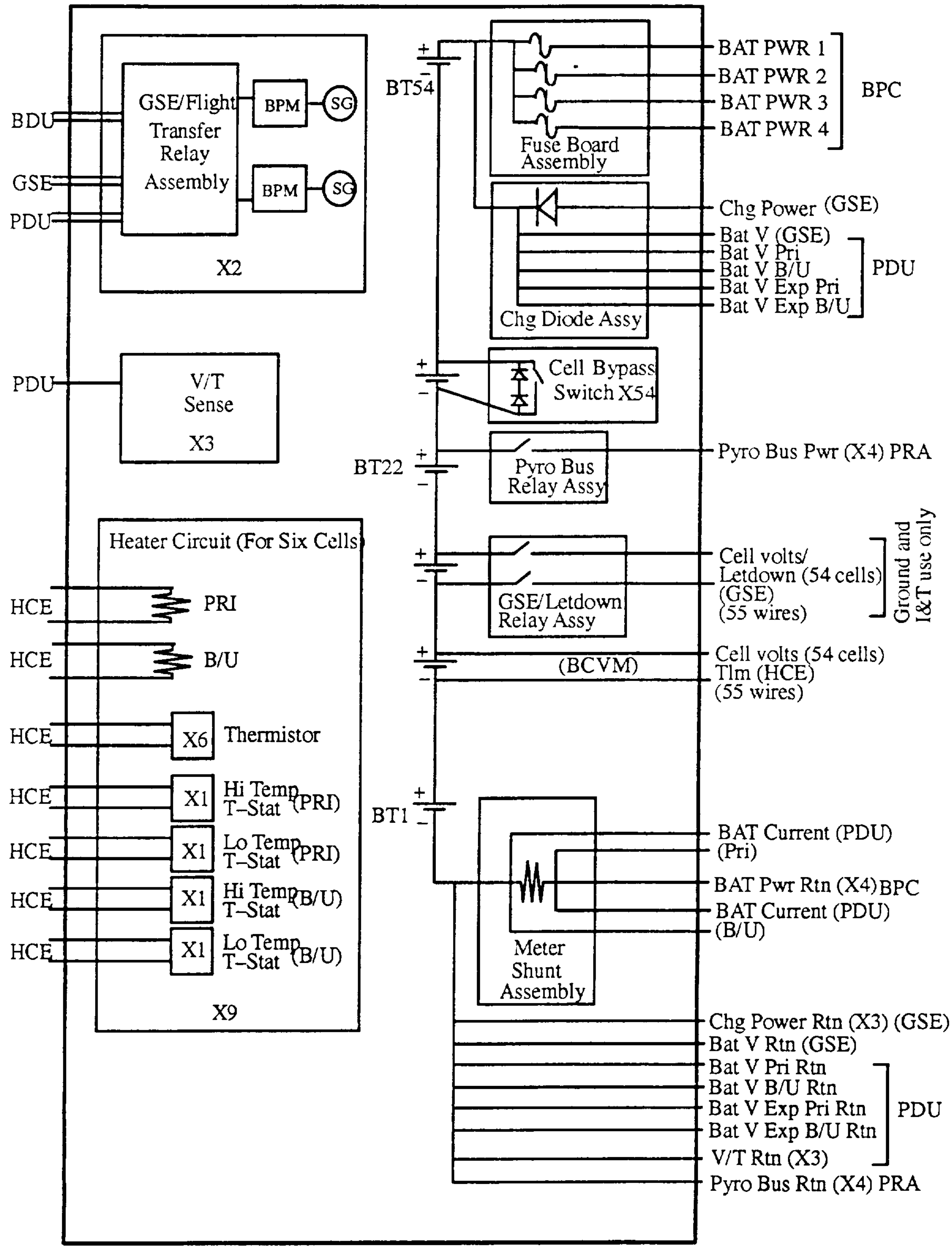
Functional Block Diagram



Signal, Command and Telemetry Interfaces

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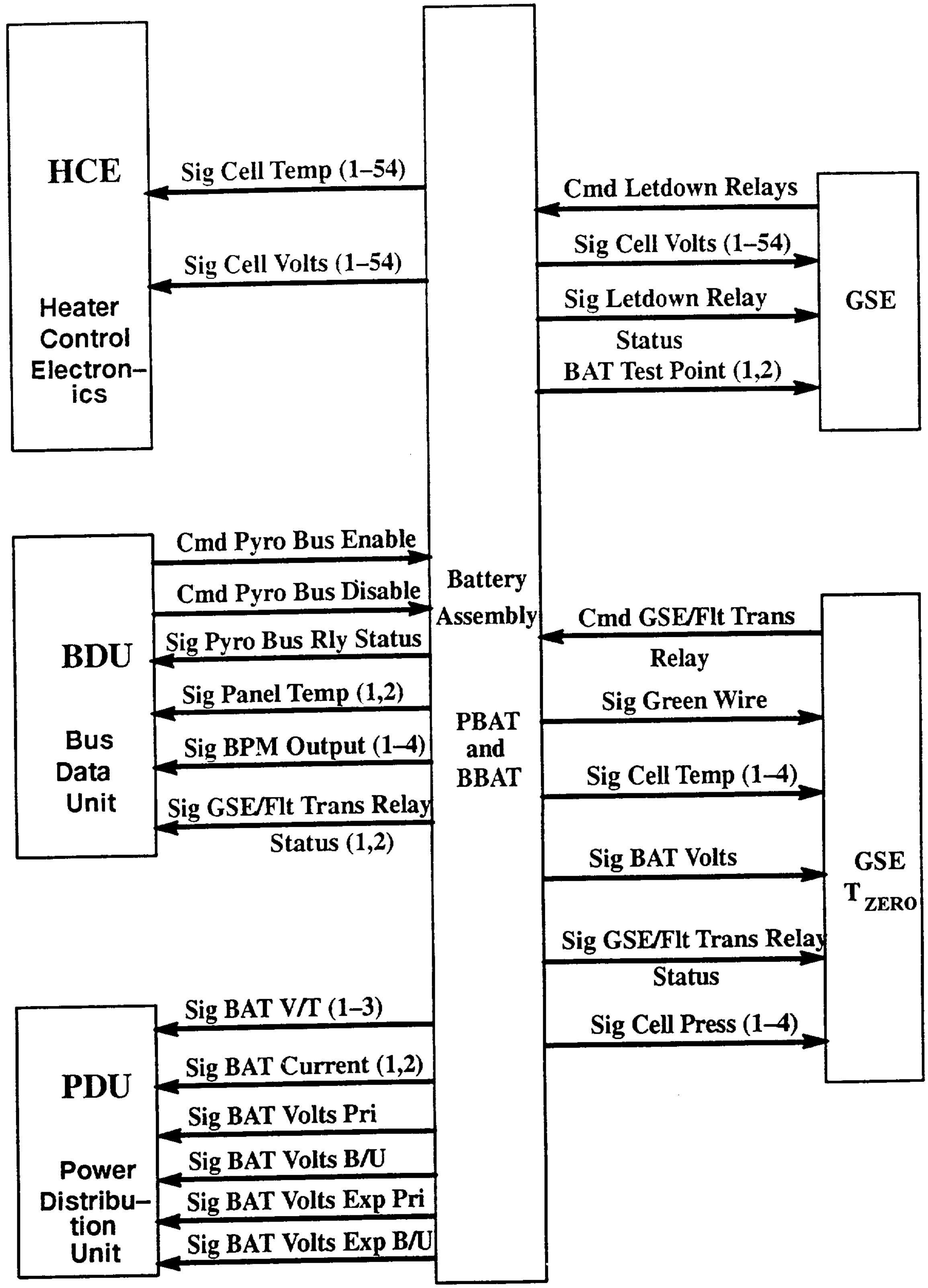

Signal, Command and Telemetry Interfaces

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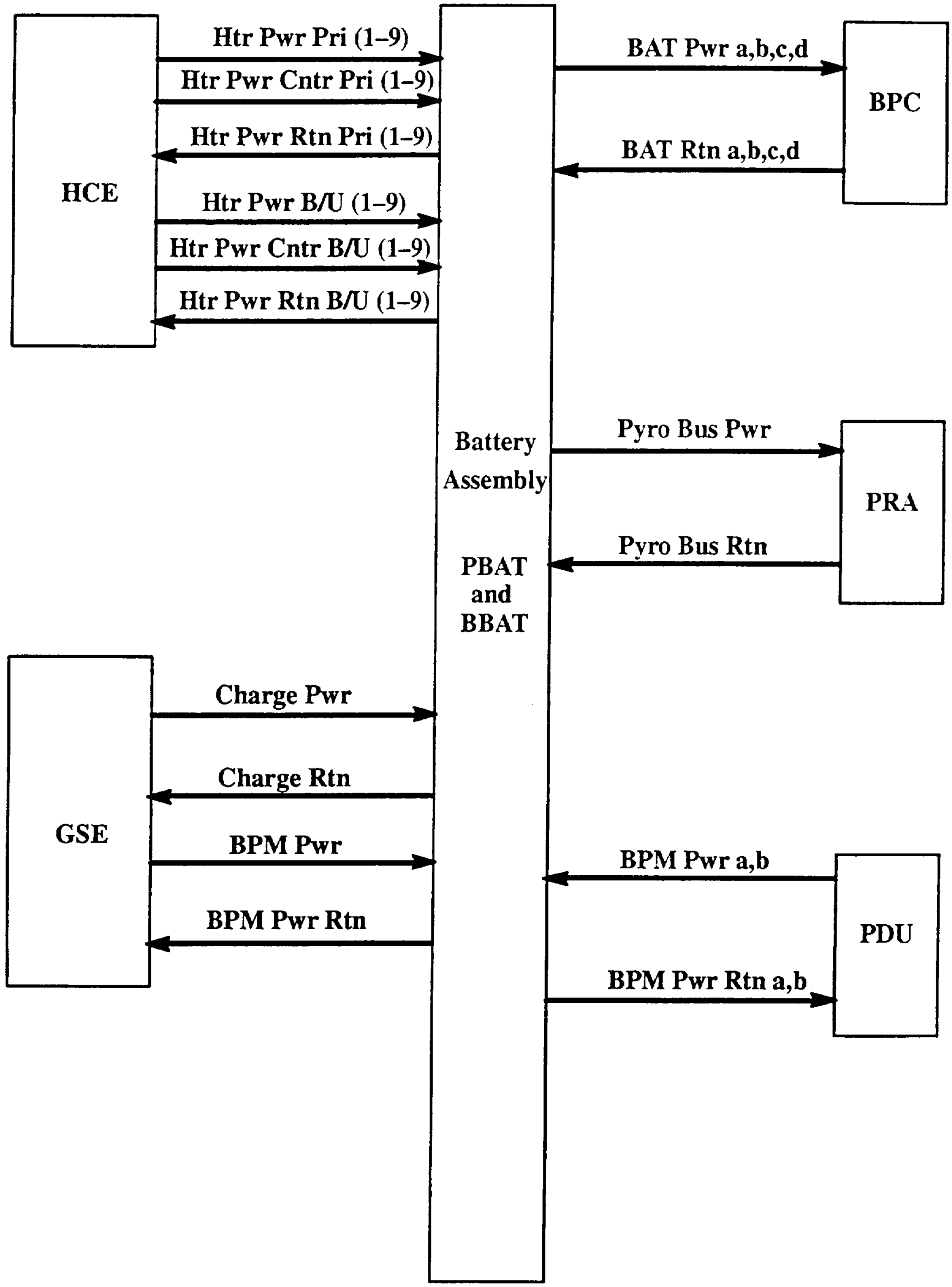

Three Cell Pack Electrical Design

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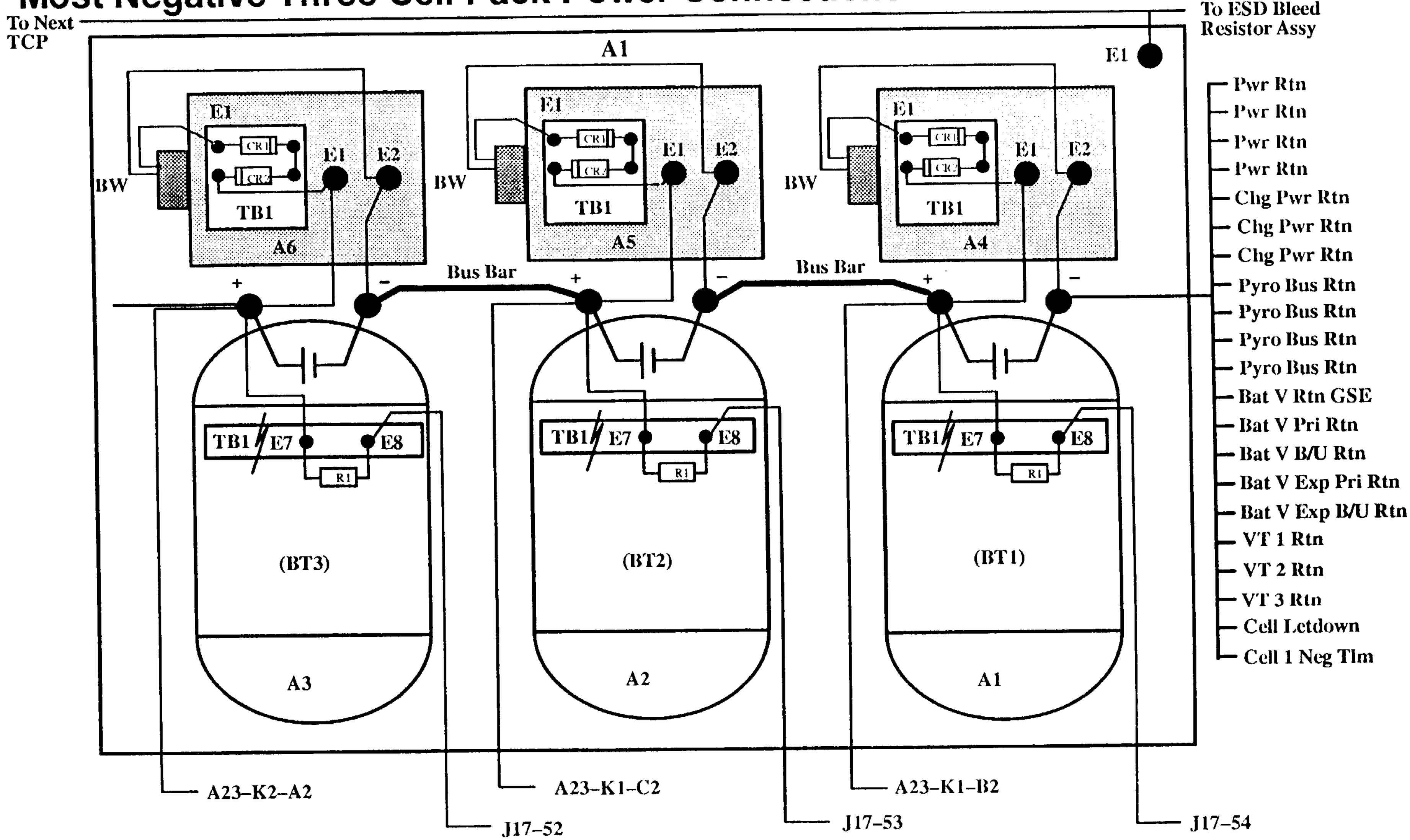
Most Negative Three Cell Pack Power Connections



Verifiable Double Insulation

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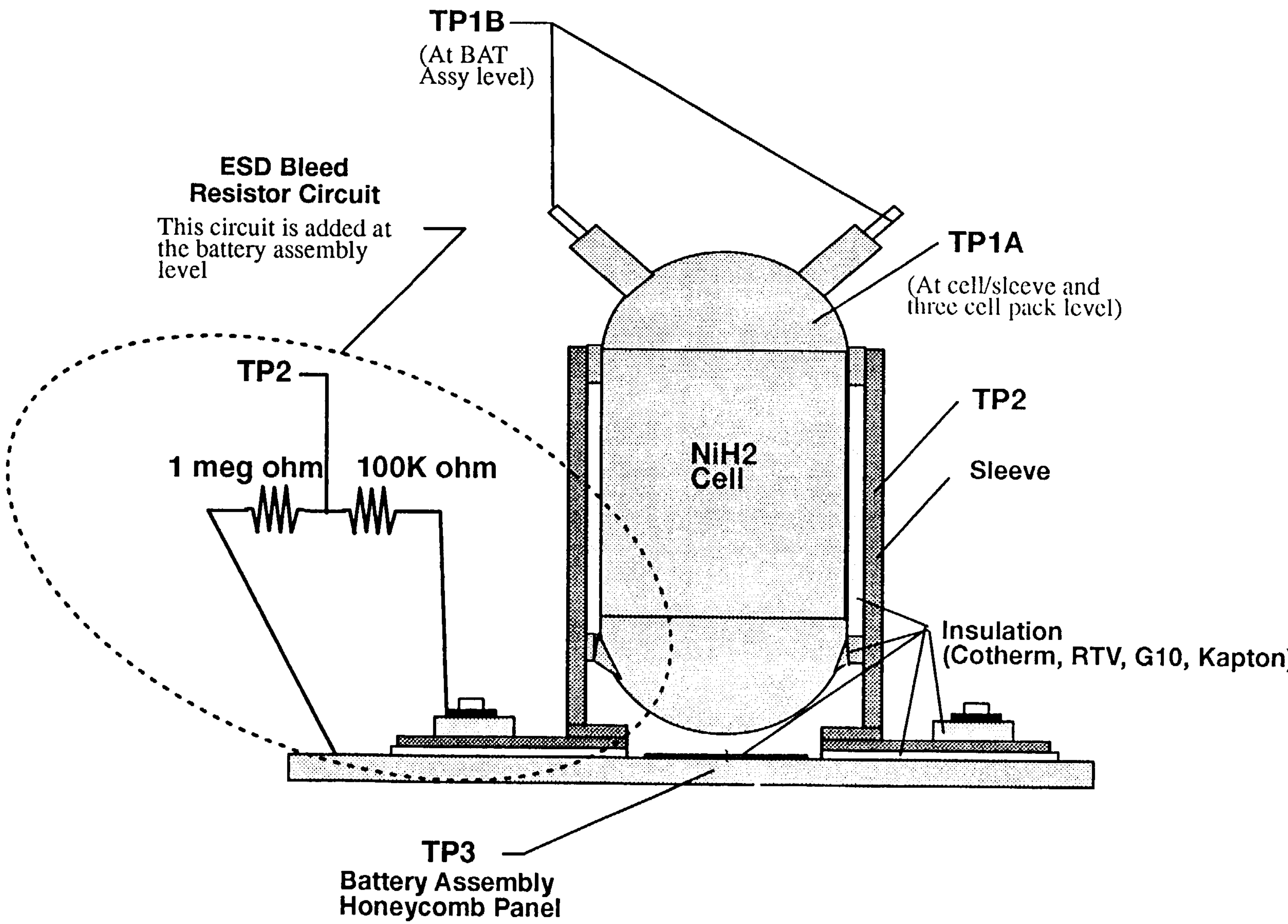

Three Cell Pack Heater Circuits

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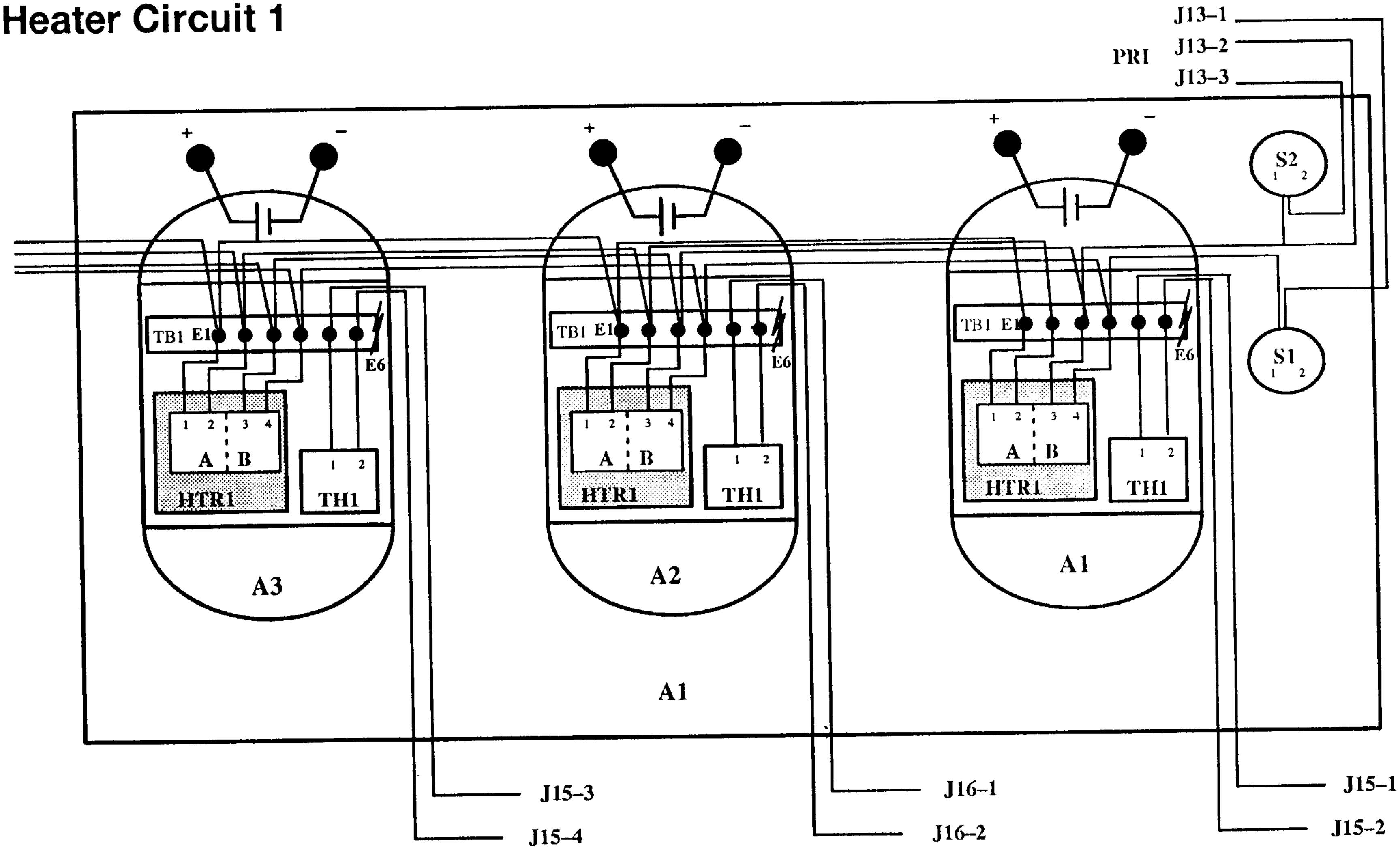
Heater Circuit 1



Three Cell Pack Heater Circuits

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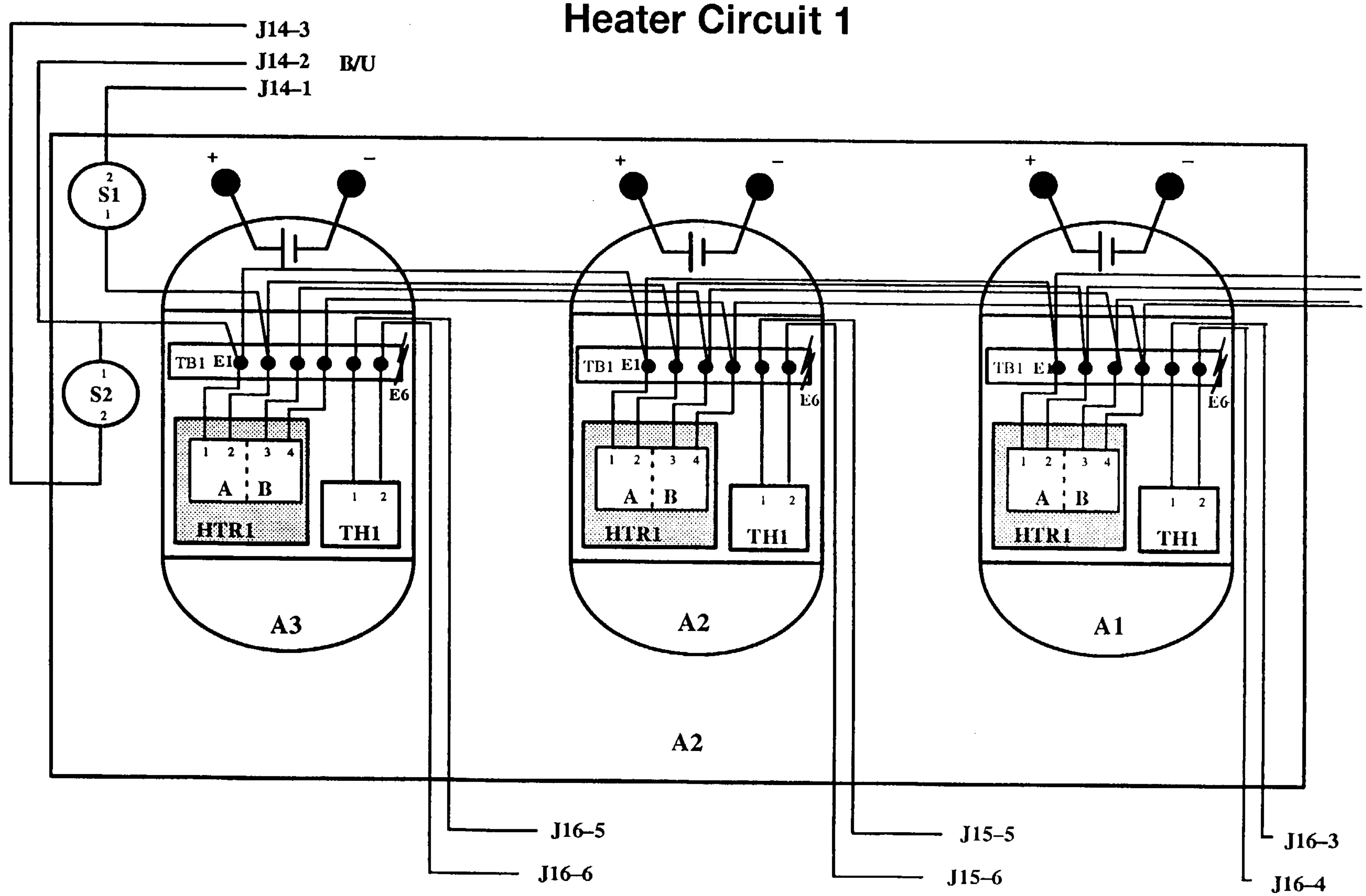
Heater Circuit 1



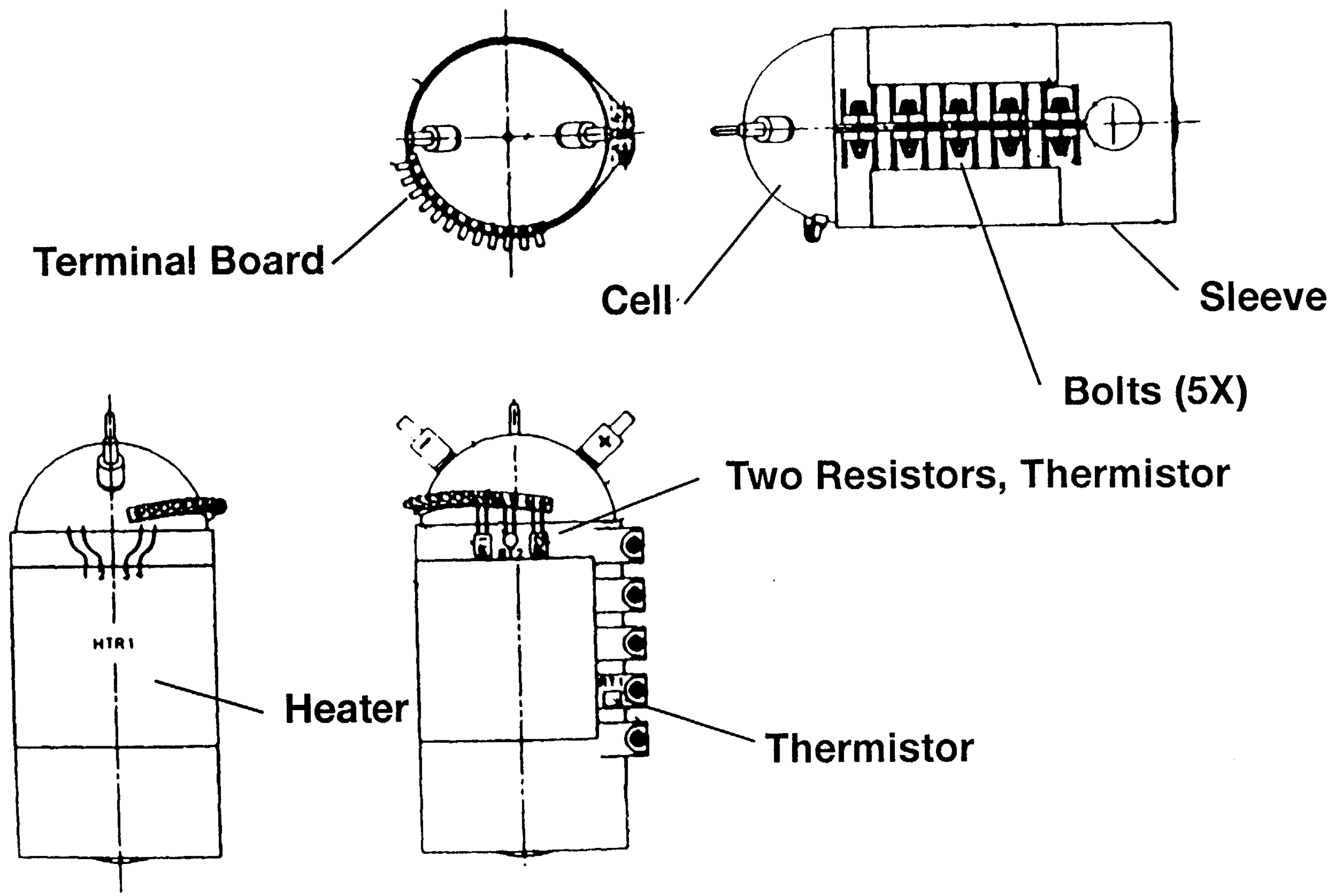
Battery Assembly Modular Design

- 54 Cell/Sleeve assemblies
  - 54 Bypass switch assemblies
- 18 Three cell pack assemblies
- Electrical subassemblies
  - 4 Battery Pressure Monitor Assembly (BPM)
  - 1 Meter Shunt Assembly
  - 2 GSE/Flight Transfer Assembly
  - 1 GSE/Letdown Relay Assembly
  - 1 Pyro Bus Relay Assembly
  - 1 Charge Power Diode Assembly
  - 1 ESD Bleed Resistor Circuit Assembly
- Cover/Connector Box Assembly (with 17 connectors)
  - 1 Fuse Board Assembly
- Built and test all subassemblies
  - Cell/sleeve assemblies
  - Three cell pack assemblies
  - Electrical subassemblies

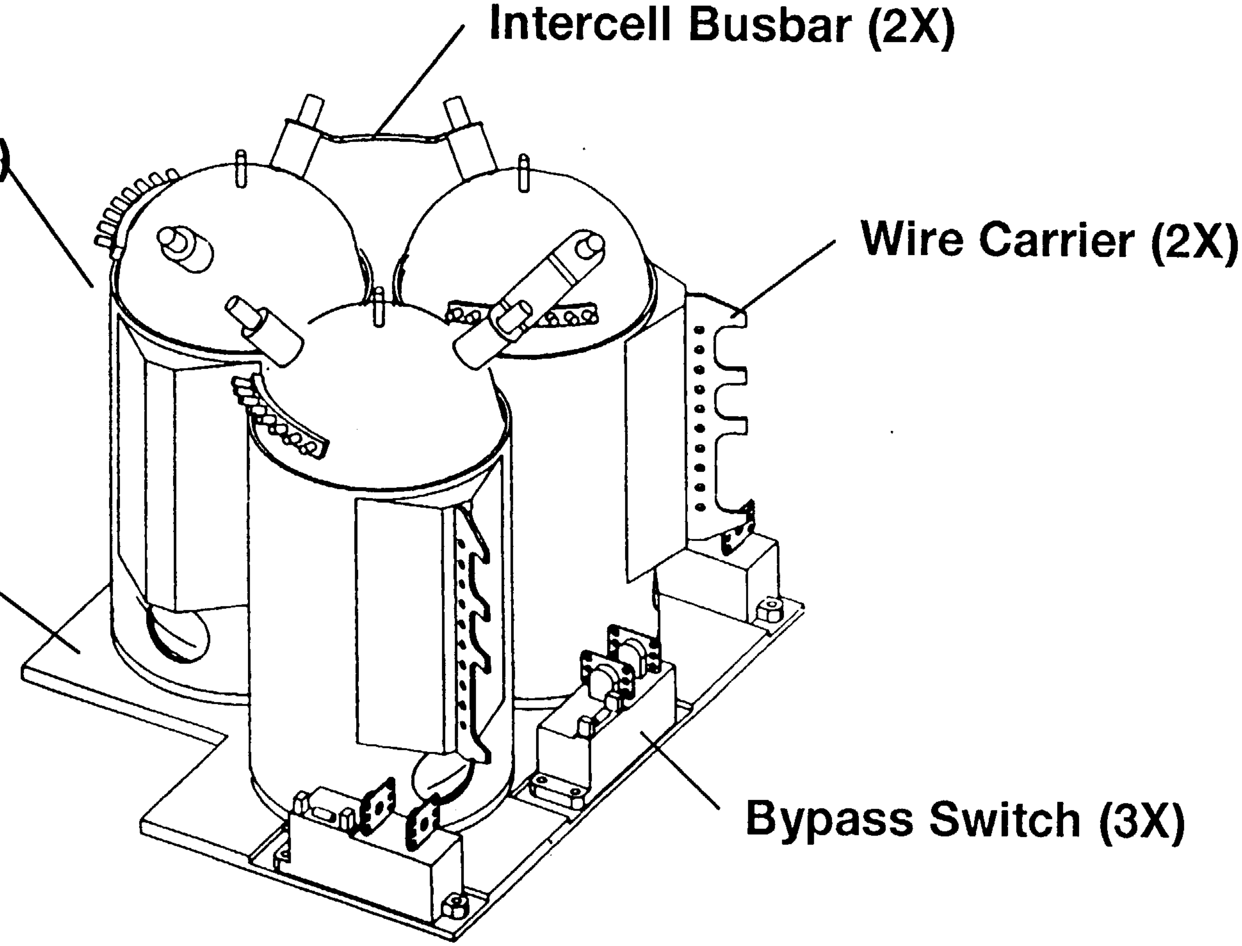
Battery Assembly Modular Design

- Integrate at the battery assembly level
  - Install Three Cell Packs to honeycomb panel
  - Install electrical subassemblies to honeycomb panel
  - Complete final point to point wiring
  - Route wires to connectors
  - Install battery cover
  - Tape all cover seams with copper tape for EMC requirement

Cell/Sleeve Assembly



Three Cell Pack



Battery Assembly

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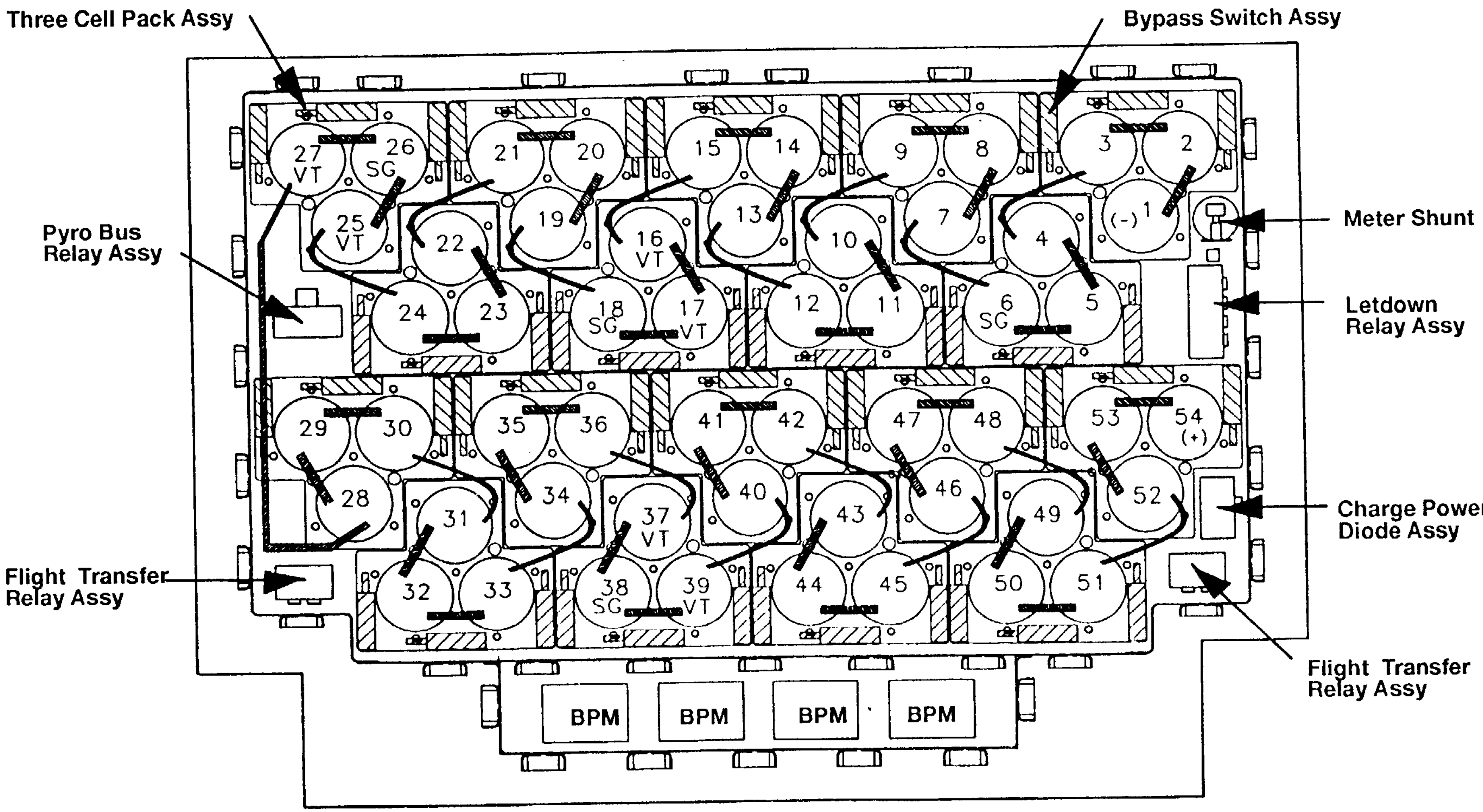
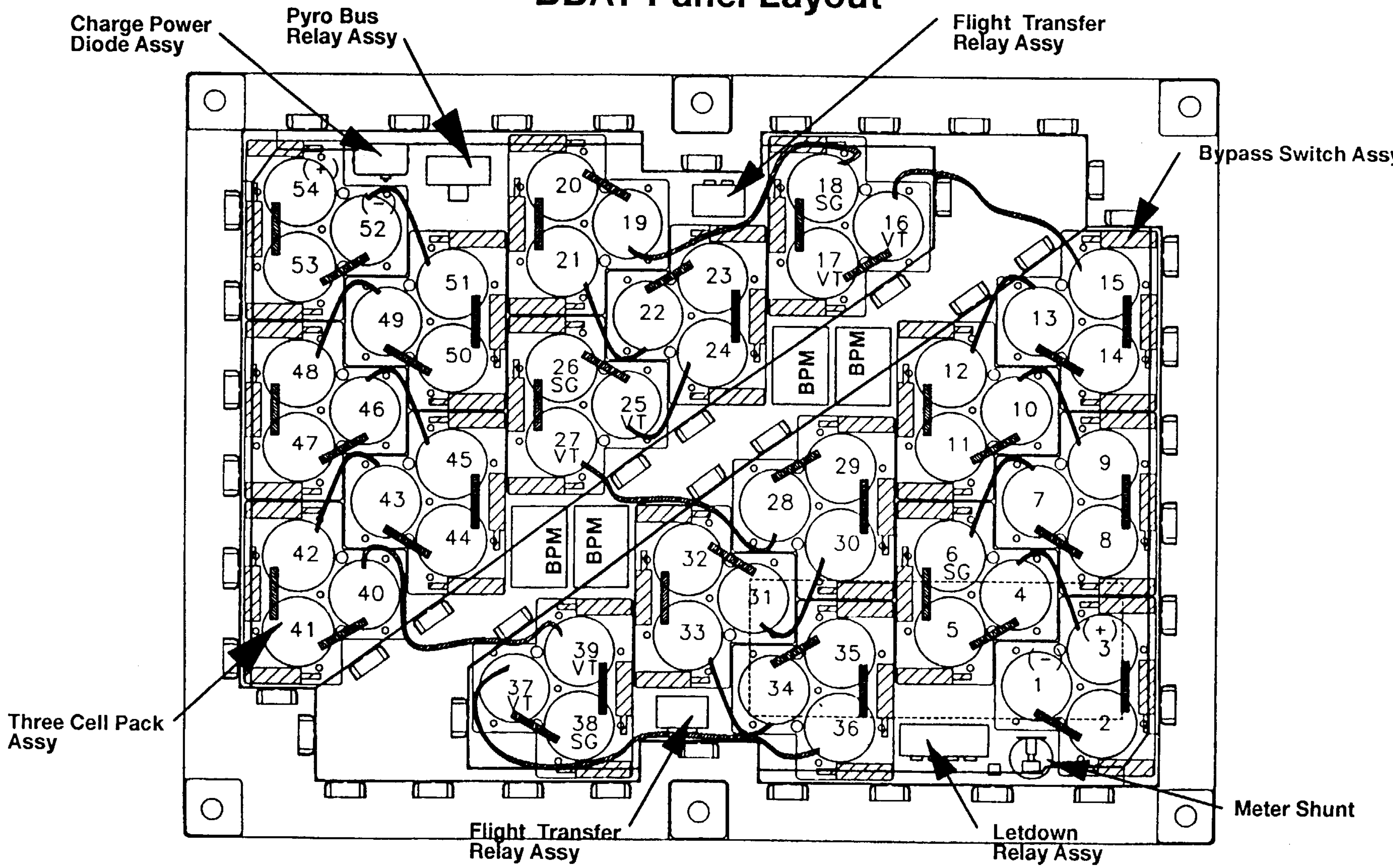
PBAT Panel Layout



Battery Assembly

BBAT Panel Layout



Power Module Battery Cover

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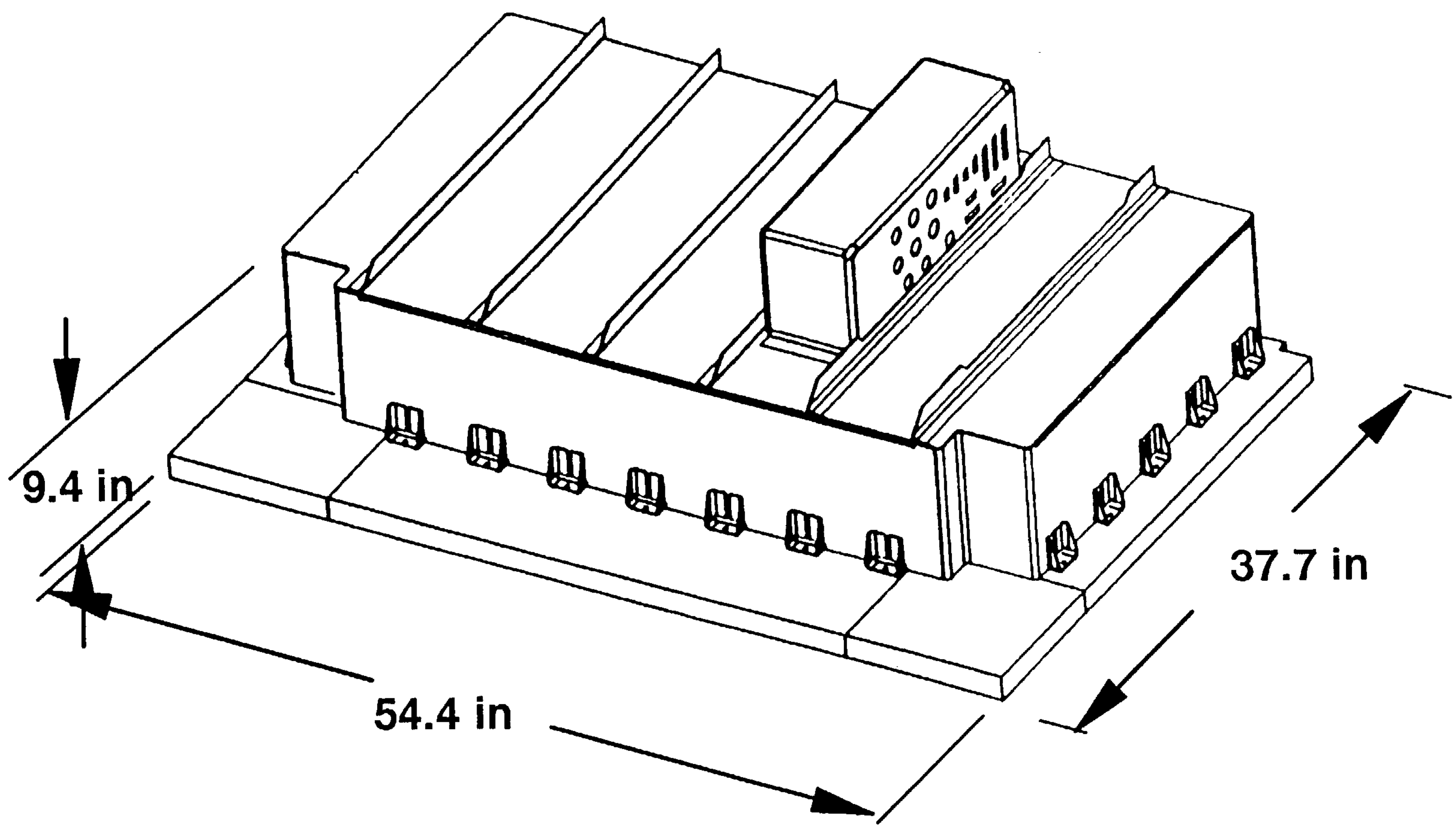
Panel and Cover
299.7 lbs



Hex Bay Battery Cover

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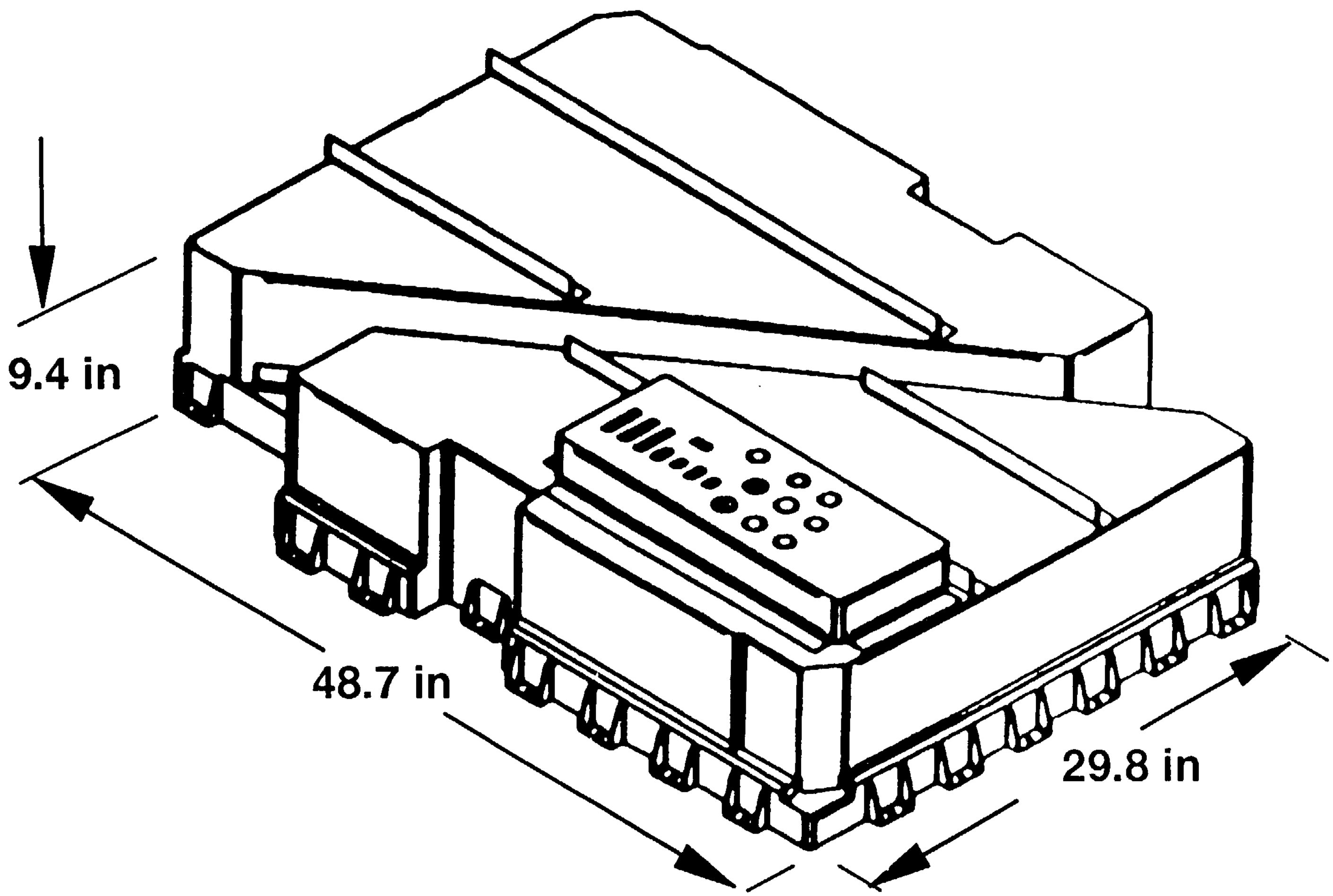
Panel and Cover
304.7 lbs



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Design Drivers

- Tight thermal gradient requirements drive battery design
  - Conductive design
  - Material selection
  - Mechanical design impact
  - Heater circuit design
  - Increased electrical complexity
- Electrical Complexity
  - modular design approach
  - individual cell voltage and temperature telemetry
  - 17 connectors with 428 wires for spacecraft interface
  - open cell protection device
- EMC
  - .063" thick cover required
  - large weight impact
  - gold plated sintered washers
  - copper tape at seams

Advanced Technologies Session

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SILVER CADMIUM BATTERY CAPACITY AND HOW TO KEEP IT

Geoff Dudley & Max Schautz
European Space research and Technology Centre
Noordwijk, The Netherlands

1994 NASA Aerospace Battery Workshop

Huntsville Marriott
Huntsville, Alabama, USA

November 15-17, 1994

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HISTORY OF USE BY ESA

Silver cadmium batteries have been used on a considerable number of ESA scientific spacecraft where high levels of magnetic cleanliness were mandatory:

SPACECRAFT	*LAUNCH DATE*	*Number of batteries*
HEOS -1	*Dec. 1968*	*1 (5 Ah)*
HEOS - 2	*Jan 1972*	*1 (5 Ah)*
GEOS 1	*April 1977*	*1 (16 Ah)*
ISEE -B	*Oct 1977*	*1 (10 Ah)*
GEOS 2	*July 1978*	*1 (16 Ah)*
GIOTTO	*July 1985*	*4 (16 Ah)*
CLUSTER (x4 S/C)	*Dec. 1995*	*4 x 5 (16 Ah)*

Yardney silver cadmium cells have been used on all the above spacecraft. Geos, Giotto and Cluster use the YS16(S)-4 16 Ah cell. The battery design for Cluster is identical to Giotto. The 4 Cluster spacecraft will be in elliptical 66 hour polar orbits. During the 2.5 year mission the batteries will see a total of about 35 charge-discharge cycles with a maximum depth of discharge of 65%. 32 of these will take place during 4 short eclipse seasons which occur roughly every 6 months.

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CLUSTER BATTERIES

- ***7 EM + 3 QM + 20 FM + 2 FS = 32 BATTERIES***
- ***Each Battery contains 14 16 AH Yardney Ag-Cd cells (identical battery design to Giotto)***
- ***Min 22 cells required in order to make matched battery of 14 cells. Additional 44 cells procured for special tests***
- ***748 dry cells fabricated Dec. 1991***
- ***EM cells activated Jan. 1992. Capacity nominal***
- ***QM cells activated June 1992. Capacity nominal***

Cell activation entails filling with electrolyte, 3.5 formation cycles, cell sealing, last formation discharge, 5 stabilization cycles, and 2 acceptance cycles. This is carried out in groups of 22 cells. Matching cycles are then performed and the 16 best matched cells shipped for battery manufacture (14 cells + 2 spares).

BATTERY MANAGEMENT COMPARISON

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Based on expected spacecraft conditions, the following standard capacity cycles were defined:

- ***GIOTTO:***
  - *Charge: 0.53 A to 1.51 V (average) followed by taper charge ending when current reaches 0.18 A*
  - *Discharge 8A constant current to 0.9 V (average)*
- ***CLUSTER:***
  - *Charge: 0.53 A to 1.51 V (average), no taper charge*
  - *Discharge 4A constant current to 0.9 V (average)*

In contrast to the Giotto program, taper charging is not implemented for Cluster. Both programs employ a trickle charge when the battery voltage falls below 19.43 (1.39 V/cell).

CLUSTER BATTERY FABRICATION Problem 1

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- ***EM 1-5 Battery construction June-Nov. 1992***
- ***Battery electrical tests in Oct. 1992 :***
  - *Expected capacity:* 16 - 17 Ah
  - *Acceptance minimum capacity:* 15.2 Ah
  - *Measured capacity:* 11.5- 12.2Ah !
- ***EM 6-7 & QM battery construction Oct.-Nov. 1993***
- ***Battery electrical tests in Nov. 1993:***
  - *Measured capacity:* 13.4- 14.8 Ah !

Cells were not cycled by the battery manufacturer until after battery construction, which involves potting the cells into the aluminum structure. The low capacity was found both before and after battery vibration and thermal vacuum tests.

INVESTIGATION PLAN

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- ***ESTEC Energy Storage Section was asked for practical assistance May 1993. 3 parallel activities initiated:***
  - *Comparative cycling of spare EM and Giotto cells which had been in cold storage in the ESTEC European Space Battery Test Centre for 8 years followed by tear-down analyses*
  - *Review of cell activation data, procedures and QA documentation*
  - *Extraction of relevant cell and battery data from earlier programs in order to establish a norm against which to compare the Cluster data*

Cells were immersed in a water bath at 20 deg.C for all electrical tests. The reference electrodes were pieces of cadmium wire, mechanically cleaned and washed in hydrochloric acid, water and potassium hydroxide immediately before insertion into the cell. Inside an oxygen - filled glove box, cell tops were pierced with a 1 mm drill and a 0.4 ml electrolyte sample taken with a syringe. The reference electrode, sheathed in PTFE tubing except for the last 1 cm, was inserted and the cell re-sealed with epoxy cement.

INITIAL CYCLE RESULT SUMMARY

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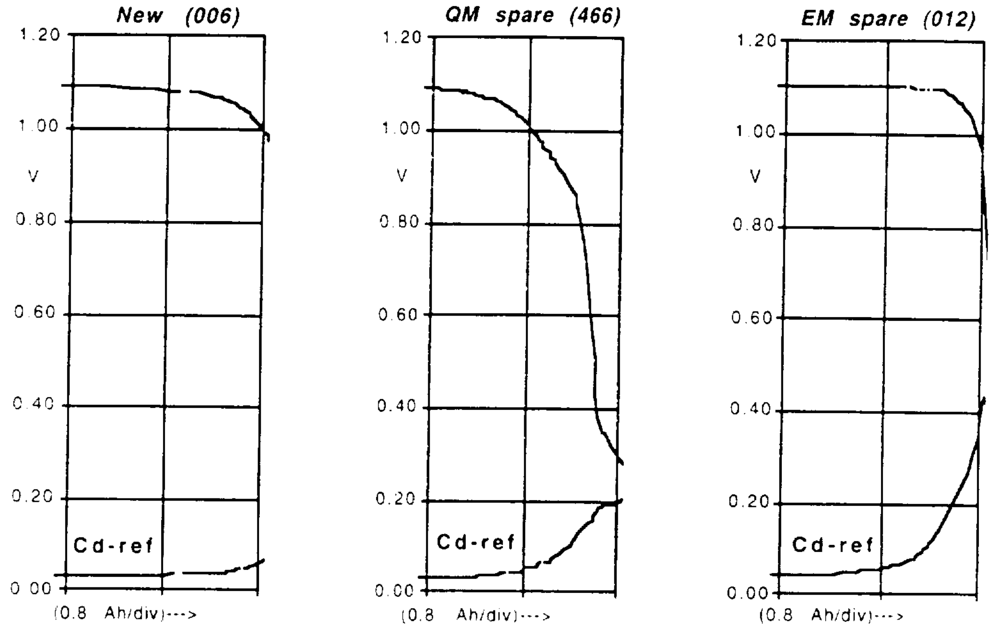
CELL	Storage time	Capacity (Ah)	Chg.-limiting electrode	Disch.-limiting electrode	K2CO3 (wt%)
OLD CELL 022	10.5 y	11.8	Ag	Cd	13.7
GIOTTO 451	8 y	12.4	Ag	Cd	7.6
CLUSTER EM 012	20 m	13.8	Ag	Cd	10.0
CLUSTER QM 466	14 m	15.8	Ag	Ag	9.8
FRESH CELL 006	1 m	18.5	Ag	Ag	9.8

It is noteworthy that the lower capacity cells are all cadmium - limited on discharge. As cells age, carbonate ions build up in the electrolyte as a by-product of oxidation of the cellophane separators. The level of carbonate present was considered an important parameter both as an indicator of the extent of the attack and because high levels are known to impede operation of the cadmium electrodes. The concentrations measured in the test cells were unexpectedly high, but the activation of cell 006 at ESTEC revealed that the levels already reach about 6 wt.% at the time cells are first sealed. This is formed presumably during the deliberate overcharge that takes place during the first formation charge.

REFERENCE ELECTRODE RESULTS (end of 4A discharge)



Cycles with reference electrodes were extended to 1.56V on charge and 0.2V on discharge (except for cell 006 which only went to 0.9 V on discharge). In all cases charge was limited by the silver electrode since the cadmium reference - cadmium electrode potential remained within +/- 20 mV right up to the end of charge. On discharge (above), both electrodes can be seen eventually to polarize with respect to the cadmium reference. On the basis of which electrode polarized first, one could conclude that the discharge capacities of the two electrodes were within 0.5 Ah of each other in all cases including the 'fresh' cell 006 (the curves for which can be superimposed upon those of QM 466). This is not enough to explain the differences in capacity. However, fresh cells should have a much larger excess cadmium capacity than the result for cell 006 suggestes. so it is probably not valide to estimate quantitative electrode capacity differences from this type of data.

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CONCLUSIONS FROM INITIAL CYCLE TESTS

- ***STORAGE DISCHARGED AT -12 DEG.C IS EFFECTIVE***
- ***EM CELL AND CELLS STORED FOR LONG TIME ARE CADMIUM-LIMITED ON DISCHARGE***
- ***QM AND 'FRESH" CELLS ARE SILVER-LIMITED ON DISCHARGE***
- ***DIFFERENCE IN CAPACITY BETWEEN GIOTTO AND CLUSTER STANDARD CYCLE IS <0.5 Ah***

The question was raised as to the best storage temperature and state of charge for silver cadmium cells. The remarkably high capacities still available from the cells stored for many years at ESTEC confirm that -12 deg. C is a suitable temperature. Although most probably discharged when put into storage, we cannot confirm this with certainty.

CELL TEARDOWN ANALYSIS

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- *No significant differences between cells found:*
  - *State of cellophane separators similar for all cells*
  - *Surface appearance of electrodes (electron scanning microscopy) very similar*

Cells were dismantled in the oxygen-filled glove box to avoid further carbonation. A sample of the electrolyte was recovered for analysis and the components were washed in distilled water and allowed to dry. The extent of silver penetration of the cellophane separator was estimated from its appearance and later by atomic absorption analysis. Electrode surfaces were examined under a scanning electron microscope. The results did not show any abnormalities in any of the cells studied. Cell 006, which had not been stored long and had seen only moderate cycling showed somewhat less silver penetration of the cellophane but the electrode surfaces were indistinguishable from the stored cells.

REVIEW OF EM & QM CELL FORMATION

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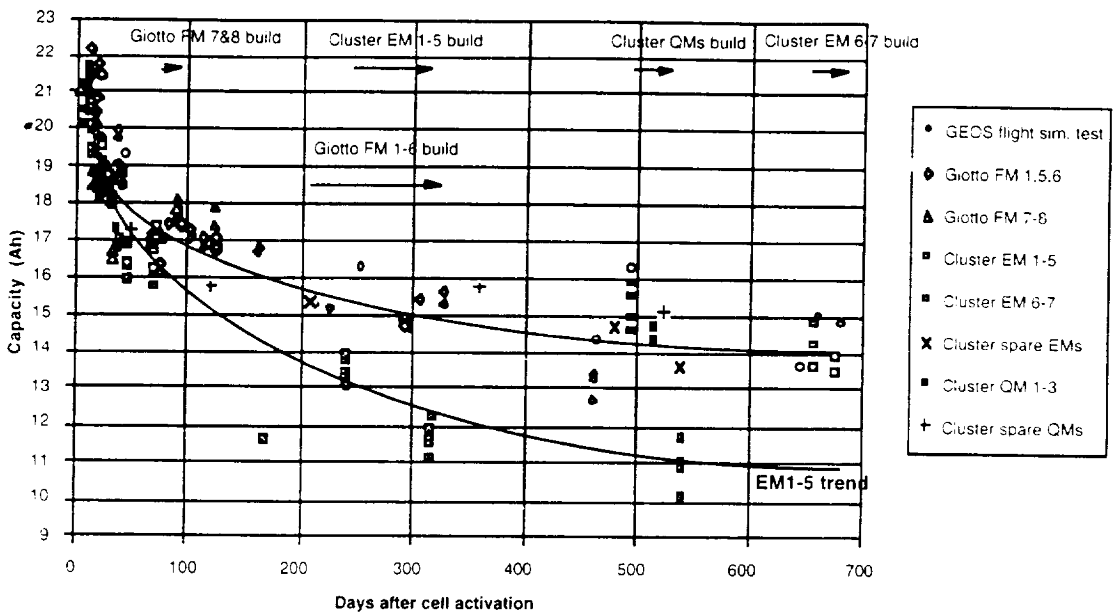
- ***Dry cell build nominal***
- ***During activation the following could have impacts on subsequent performance:***
  - *Over temperature during parts of EM 1-4 formation (slightly less for EM 5-7)*
  - *Interruptions during first formation charge of QM cells.*
  - *Cell wetting procedure identified as critical (procedures changed from program to program*
- ***None of the above could be conclusively linked to the differences in subsequent behaviour of EM and QM cells and batteries***

The factors above could all play a role in subsequent performance. In particular, the first attempt to activate dry Cluster cells at ESTEC confirmed how sensitive the obtained capacity is to the thoroughness of the electrolyte filling step.

CAPACITY COMPARISON WITH EARLIER PROGRAMS



It can be seen that the capacities of Cluster EM batteries 1-5 fall significantly below the trend for all other cells and batteries. Spare EM cells and Cluster QM cells and batteries, on the other hand, are not anomalous. Cluster EM batteries 6,7 which also gave capacities below the acceptance level (15.2 Ah), nevertheless show capacities which are nominal when the (nearly 2 years) interval since activation is taken into account. Since the cells in EM 6,7 were activated in parallel with battery EM 5, this suggests that the difference may have more to do with the storage conditions since activation than with the cell formation. Whilst batteries were generally stored discharged at ambient temperature, detailed records of time batteries spent at different temperatures and states of charge and are not available (and were not required).

CONCLUSIONS FROM INITIAL INVESTIGATIONS

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- *THERE IS NOTHING WRONG WITH THE DRY CELLS*
- *CLUSTER EM 1-5 BATTERY CAPACITIES ARE ABNORMALLY LOW*
- *CLUSTER EM 6-7 AND QM BATTERY CAPACITIES, (AS WELL AS SPARE EM & QM CELL CAPACITIES), ALTHOUGH LOW, ARE WHAT WOULD BE EXPECTED FROM PAST EXPERIENCE WHEN TIME SINCE CELL ACTIVATION IS TAKEN INTO ACCOUNT*
- *IT SHOULD BE POSSIBLE TO MAKE FLIGHT BATTERIES WITH REQUIRED CAPACITY PROVIDED:*
  - *Time between activation and battery acceptance < 6 months*
  - *Storage of cells and batteries cold when not in use*
  - *Cell formation carried out precisely to specification*

CLUSTER EM BATTERY INTEGRATION TESTS **Problem 2**

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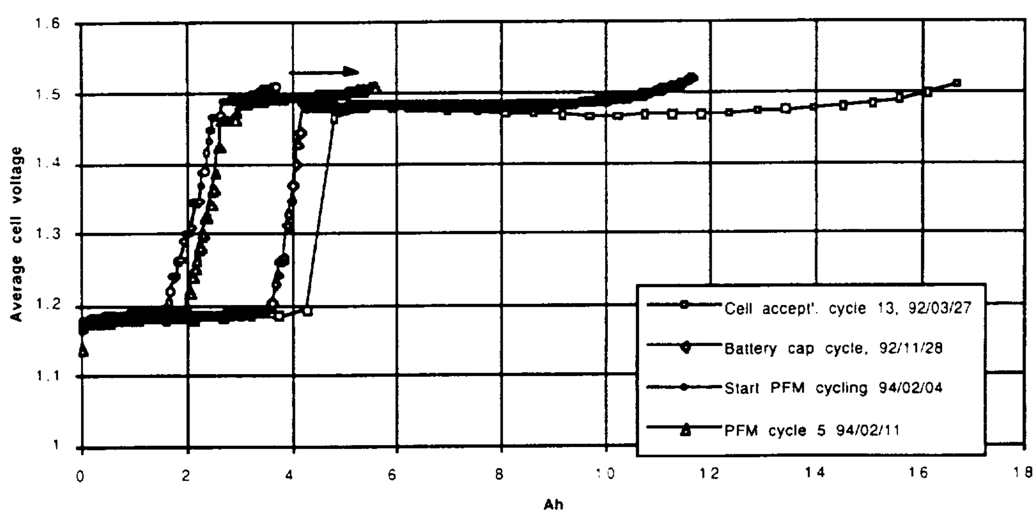
- ***At the start of integration tests in July 1993, the EM battery capacities had declined further to between 10.1 and 11.7Ah***
- ***By Feb. 1994, at the start of cycling on the Cluster PFM, capacities down to 3.5 to 4.2 Ah !***
- ***The capacity needed at end of mission is estimated as 10 Ah***

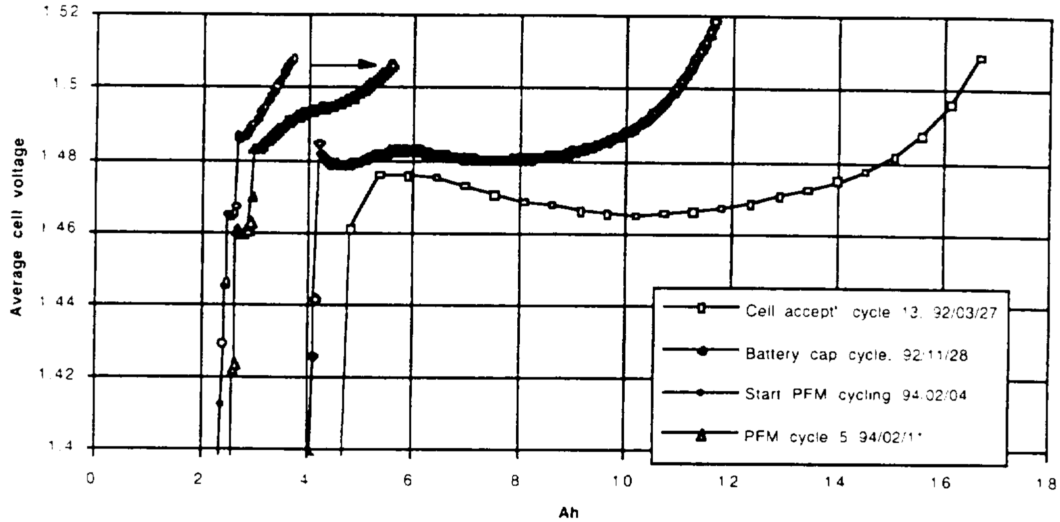
Since their construction, the EM batteries had been stored discharged at ambient temperature for 4 months before they were needed for integration testing. Before the start of these tests, a further standard capacity check was carried out and revealed a further drop in capacity of all 5 batteries. By February 1994, at the start of cycling test on the Cluster proto-flight model, capacities had fallen dramatically. Comparing the shapes of the battery voltage curves during cycling at various times reveals significant changes, particularly during charge in the second plateau region.

Battery EM 4 Cell Voltage During Charge



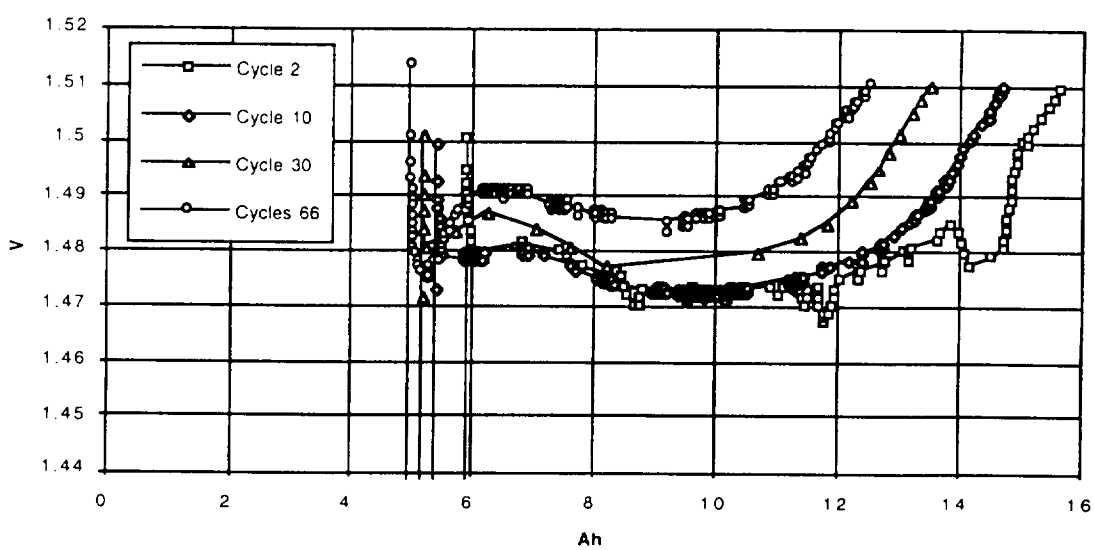
This compares the average cell voltage charge curves of the cells used to make battery EM 4 with the curves measured at battery level before the start of integration testing. The curves are dominated by the transition from the first plateau (Ag ----> Ag2O) to the second (Ag2O----> AgO). Although these over-simplified reactions would suggest a ratio of the capacity of the second to the first plateau as 1;1, in practice a cell a fresh cell gives a ratio of about 2.5:1 as was the case for the EM 4 cells immediately after activation. It can be seen that this ratio has fallen to about 0.5:1. While the capacity of the first plateau has also fallen, the majority of the capacity reduction is associated with the second plateau, charge being terminated when the average cell voltage reaches 1.51 V.

Battery EM 4 Second Plateau Charge (enlarged scale)



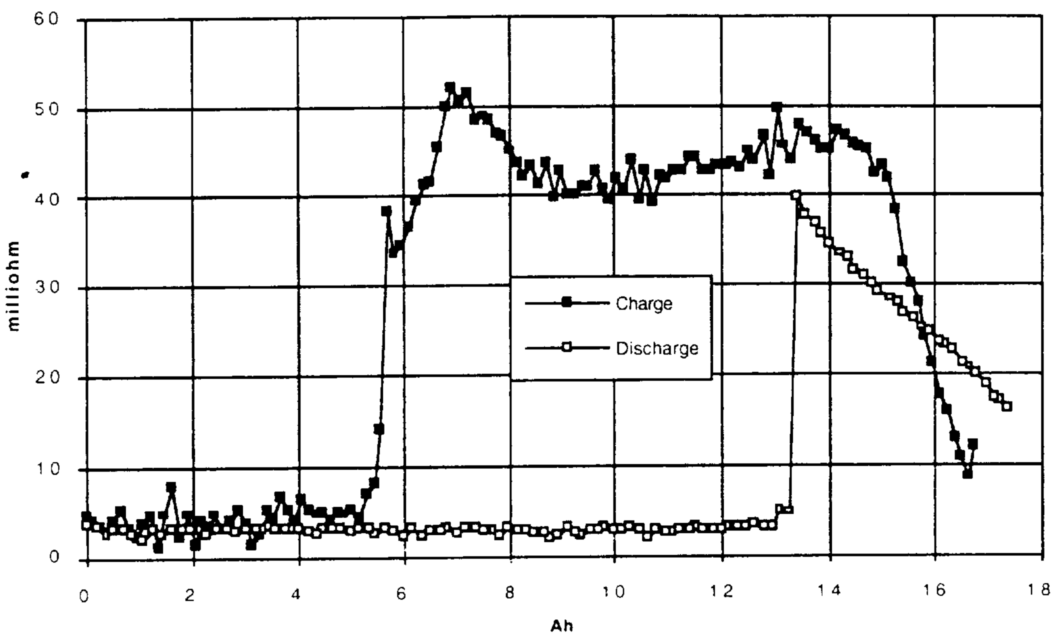
Here the same second plateau charge data is shown on an expanded scale. The change in shape of the charge voltage curves can now be seen clearly. From the reference electrode data from single cell tests we believe that these changes are due only to the silver electrode. (EM batteries are not yet available for reference electrode tests). The last curve shows that it is possible to regain some lost capacity by repeat cycles.

Second Plateau Charge During Life Cycle Test at 20 deg.C



Second plateau average cell voltage charge curves are shown from a 100% DoD life cycle test on two cells at ESTEC. (Fluctuations during cycle 2 were due to instabilities in the temperature of the water bath). Although the cell voltage increases with number of cycles, the increase is rather uniform and the fall in capacity of the second plateau is moderate. The capacity of the first plateau falls by less than 1 Ah after 66 cycles. These results demonstrate the cell's capability to meet the capacity requirements at the end of the mission. The observation that storage could cause more capacity loss than continuous cycling had, however, not been anticipated and therefore needed further investigation.

Internal Resistance as Function of State of Charge (cell 006)



The change in charge voltage curve with storage was considered most likely to be the result of silver electrode kinetic limitations caused, for example by morphological changes or surface contamination. Internal ohmic resistance measurements should provide useful information. The 'fresh' cell (006) was subjected to current-interruption internal resistance measurements during one complete charge - discharge cycle. Results are shown for charge (solid squares) , going from left to right and discharge (open squares), going from right to left. Results are based upon voltage measurements 2 mS before and after the current was reduced to zero by an electronic switch. Reference electrode measurements in the same cell confirmed that the large resistance changes are associated with the silver electrode. This is a known feature of the couple, but it explains how sensitive the second plateau voltage could be to small changes in the silver electrode surface. (The fall in resistance towards the end of charge is probably associated with the onset of oxygen evolution. Comparative resistance data are not yet available for cells exhibiting second plateau capacity loss.

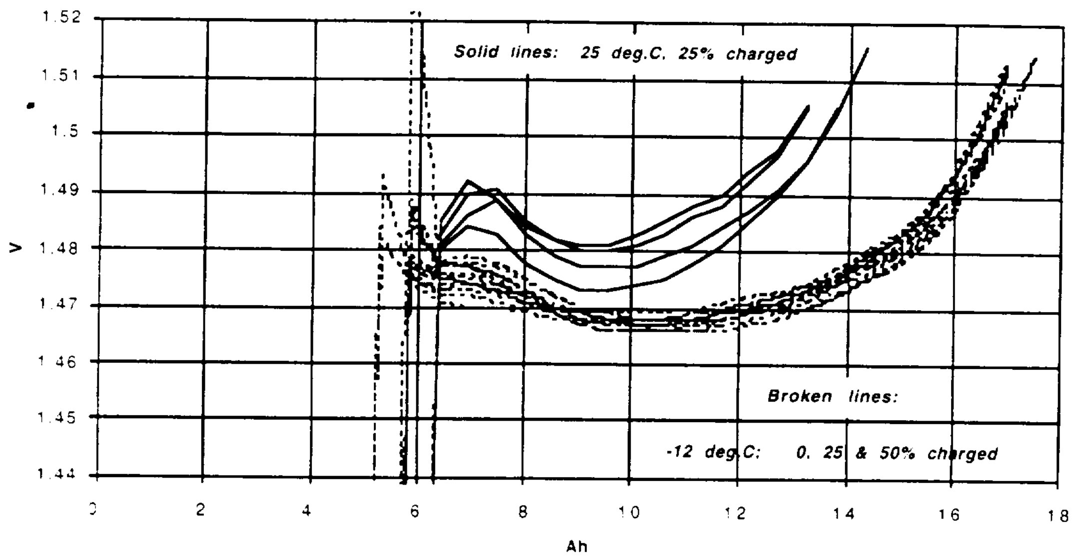
SUMMARY OF OBSERVATIONS

esa

- ***Cells meet life/capacity requirements after accelerated life tests at 100% DoD***
- ***The shape of the charge curve changes more with storage at ambient temperature than with life-cycling .***
- ***The majority of capacity loss on storage is a result of the increase in second plateau charge voltage***
- ***Available reference electrode measurements on single cells lead us to believe that this is due to the silver electrode.***
- ***The effect is partially reversible with extra cycling***

Cell Storage test at Yardney

Cell Second Plateau Charge after storage for 6 months



To settle remaining doubts over the best storage conditions, Yardney stored 5 groups of 4 cells for 6 months at 0%, 25%, 50% and 100% charged at -12 deg.C.
Standard capacity cycles at 20 deg. C, after removal from storage were performed, and the second plateau charge region is shown above. It can be seen that all cells stored at -12 deg.C irrespective of state of charge, showed little change whereas the group stored at 25 deg. C show a loss of 3 to 4 Ah from the second plateau. The charge curve was rather similar to that of a cell subjected to 66 cycles (see vu-graph 17). (The variability in voltage near to the plateau transition is due to the low number of measurements (one per hour)).

Dependence of Charge Voltage Curve on Storage Conditions

esa

- ***Confirms storage at -12 deg. C. is desirable***
- ***State of charge has less effect on charge curve (but storage highly charged is expected to accelerate separator degradation rate)***
- ***The capacity of the lower charge plateau is not affected at all***
- ***Flight cells and batteries will be stored discharged at -12 deg.C whenever not in use***

As a result of these findings, strict rules for storage of flight cells and batteries are in preparation.

RECOVERY OF CAPACITY POSSIBLE?

esa

- ***Special charge techniques aimed at improving charge voltage curve investigated at ESTEC:***
  - *High current (1 A) followed by taper charge at 1.51 V*
    - *gave no improvement*
  - *"Reflux" pulse charge*
    - *gave modest improvement (~ 1Ah)*
- ***Details will be reported elsewhere***

A natural question is whether the capacity loss is recoverable or permanent. So far, only slight recovery has been possible, so it is essential to avoid such losses in the first place.

CONCLUSIONS

esa

- *Confirms that cells and batteries should be stored cold and discharged*
- *Full recovery of capacity loss due to poor storage conditions does not appear possible*
- *Main concern is effect of long non-eclipse periods during mission (5 months at ~ 20 deg.C)*
- *BUT: GEOS had similar non-eclipse periods and gave no battery problems during mission*

Whereas long periods of non-use at ambient temperature and a charged state can easily be avoided on the ground, they are unavoidable during the mission, where the temperature during eclipse-free periods is expected to be in the region of 20 deg.C.

CHANGES TO ON-BOARD MANAGEMENT

esa

- *Decision to cycle batteries more during non-eclipse periods (minimum 2/5 batteries have to be available charged at any time):*
  - *original plan: 2 months charged, 3 months discharged*
  - *new plan: 1 month charged, 1 - 2 months discharged.............*
- *Mission simulation battery test in progress at Yardney modified to conform to new plan*

The change in plan reduces the maximum time any battery will be left charged and un-cycled from 2 months to 1 month.

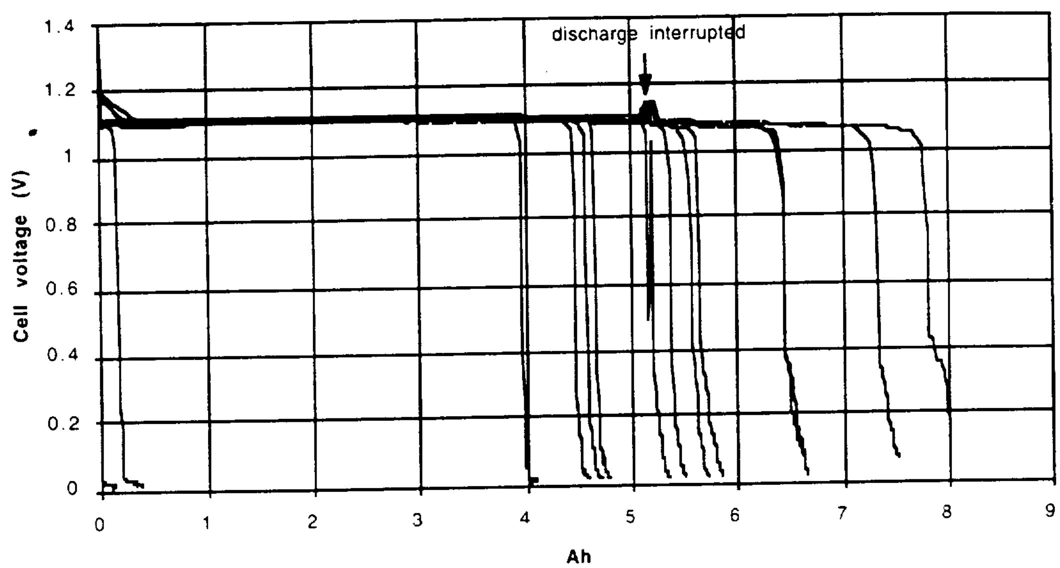
AFTER EM INTEGRATION TESTS **Problem 3**

esa

- *Integration tests involved intermittent cycling with irregular interruptions*
- *After PFM cycling tests, battery capacity less than 1 Ah !*
  - *Obvious severe mismatch between the states of charge of the different cells.*
  - *Some cells must have been overcharged and others reversed during cycling*

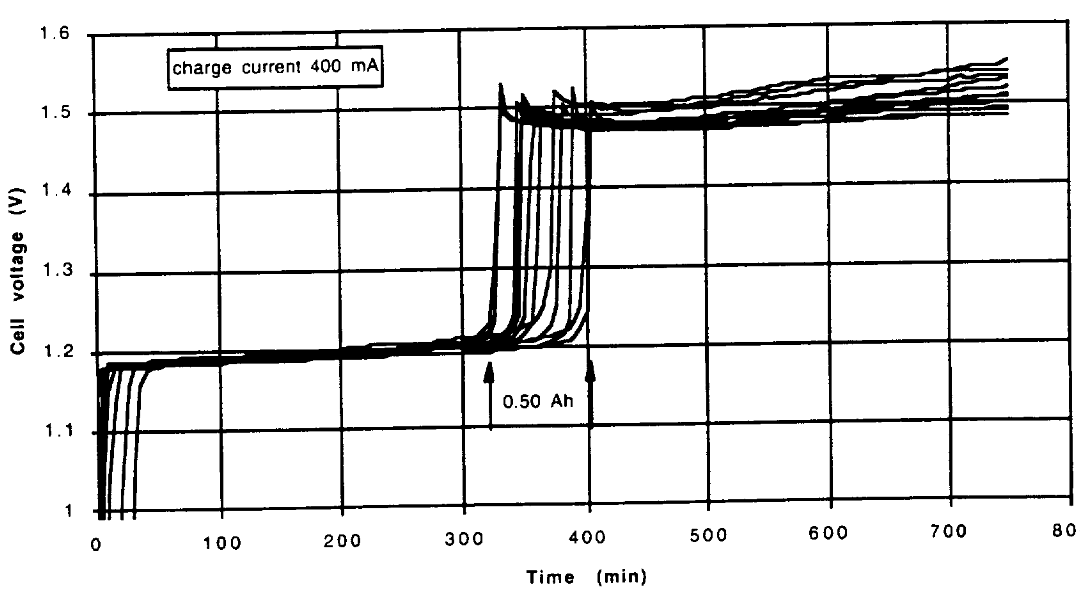
During integration tests, battery cycling was started and stopped according to the needs of the equipment under test. Consequently batteries sometimes remained for prolonged periods at intermediate states of charge. As a result individual cell's state of charge began to diverge. This in turn led the most charged cells tending to be overcharged and the least charged cells reversed in subsequent cycles, because maximum and minimum voltages are defined only at battery level.

Discharge of Battery EM 4 with Individual Cell resistors



Battery EM 4 was discharged connecting 2.8 ohm resistors across each cell. The voltage curves show an enormous dispersion of 8 Ah between the extreme cells.

Battery EM 4 Charge After Reconditioning



Following the above 'reconditioning' discharge, the next charge was normal again in the sense that the dispersion in plateau transition times between cells in the battery was 0.50 Ah, very close to that observed immediately after battery manufacture (0.53 Ah) and even to that during acceptance cycling of the cells that were made into the battery. This is quite remarkable considering the abuse some cells had suffered.

CELL MATCHING WITHIN BATTERY

- ***Extra capacity loss due to cell mis-match recovered by individual cell discharge***
- ***Problem due to overcharge and reversal of some cells.***
- ***Before PFM cycle testing, spread of individual cell plateau transition times had remained between 0.45 and 0.65 Ah, remarkably constant***

Cells in a battery maintain their relative state of charge during normal cycling and storage. Prolonged periods at intermediate states of charge will eventually lead to mis-match, but the overcharge and reversal some cells evidently suffered during the PFM cycle test were probably the main cause. Reconditioning has restored cell's relative states of charge but not the capacity lost during storage and due to cell overcharge and reversal.

MAXIMUM SAFE CHARGE VOLTAGE

- ***Cell capacity can be increased by using higher charge voltage cut-off limit***
- ***BUT dangerously high cell voltages could be reached in case of cell mis-match***
- ***AND individual cell voltages not accessible by telemetry***

Tests on battery EM 3, in which the end of charge voltage limit had been slightly raised, showed that the capacity could be increased by several ampere-hours because it was then possible to get past the 'hump' in the second plateau charge curve. It is nevertheless essential to avoid any cell in a battery being charged into the region where oxygen is evolved from the silver electrode, because the recombination reaction in such a 'flooded' cell is too slow to prevent the build up of dangerously high pressure in the cell. .

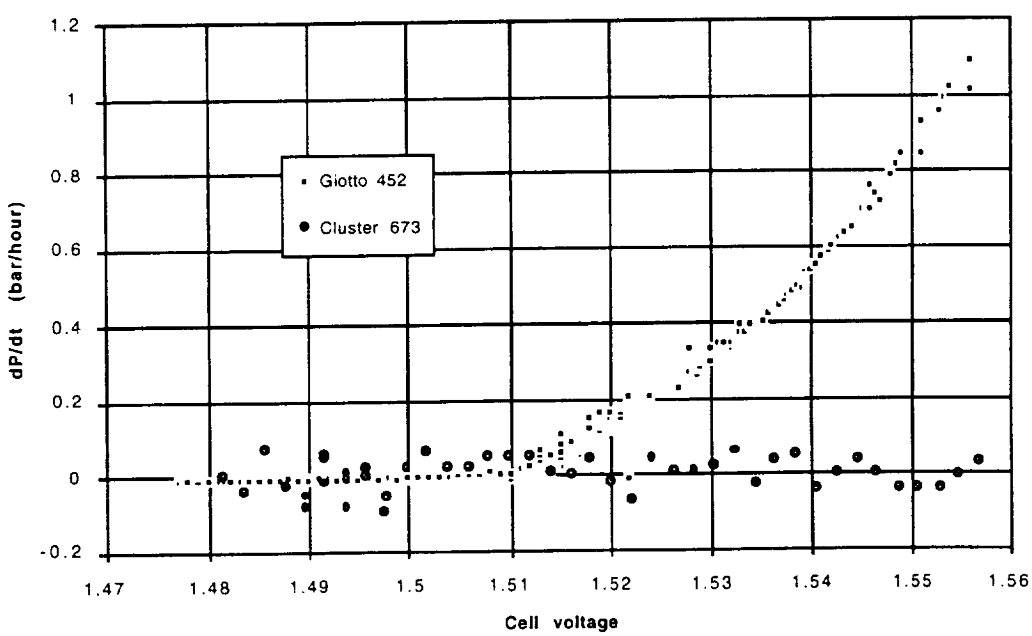
esa

DECISIONS

- ***To add cell level reconditioning hardware on board***
  - ***Battery discharge every month to include individual cell deep discharge to ensure cell match***
- ***To determine maximum safe cell voltage***
  - ***Tests begun at ESTEC to determine voltage at which oxygen evolution begins to occur***

Because of the experience with cell mis-match and the unavailability of individual cell voltage data during the mission, it was decided to implement individual cell reconditioning on board the Cluster spacecraft. In addition it was decided to determine at what charge voltage (at normal charge current) oxygen evolution begins to occur.

CELL PRESSURE TEST RESULTS



Cells were opened in an oxygen filled glove box and a pressure transducer fitted through a hole drilled in the fill tube and sealed with epoxy cement. Since the cells were clamped across their large faces and the free space in the cell plus pressure transducer remained practically constant, the rate of generation of oxygen is roughly proportional to the rate of pressure increase. There is a clear difference in the behavior of the old Giotto cell, which begins oxygen evolution at 1.51 V at normal charge rates, and the Cluster cell. Since it appears that this voltage decreases with aging, it will be necessary to carry out further measurements on Cluster cells in an "end of life" condition.

CONCLUSIONS

- ***This investigation has to a considerable extent been a re-learning process***
- ***Recommendations have been made for activation, storage and handling of flight cells and batteries***
- ***We are confident that when the above are observed problems will not recur.***

Because of the infrequent use of silver cadmium batteries, continuity in knowledge of how to handle them has been hard to maintain and this exercise has been somewhat of a re-learning process. Whilst we believe we know how to avoid these problems during preparation of the flight batteries, it is intended to continue these investigations with the aim of better understanding the underlying processes responsible for them.

ACKNOWLEDGEMENTS

- ***Thanks go to Andre Sepers and Sean Clarke for laboratory assistance and to Dave Collins from ESTEC Materials Division for cell teardown analyses***
- ***We thank Mssrs Nietner, Gallantini and Serenyi, respectively from Dornier, Fiar and Yardney for their willing assistance and supply of data***
- ***We thank the Cluster project team, in particular Horst Fiebrich and Gus Mecke, for their patience during the laboratory work and to the head of the project John Credland, for permission to publish this paper.***

Design and Performance Data for Sealed Fiber Nickel-Cadmium (FNC) Cells

Menahem Anderman
Acme Electric Corporation
Aerospace Division

Sal Di Stefano & D. Perrone
Jet Propolsion Laboratories

FNC

Who is Acme Aerospace

- Acme Aerospace is a division of the Acme Electric Corporation, featuring four product lines:

  * Sealed Fiber Ni-Cd cells for aviation, space, and the specialty market.
  * Industrial vented Fiber Ni-Cd cells.
  * Airborne battery charges power converter and related equipment.
  * Custom power system engineering.

- Acme Aerospace owns the exclusive license to manufacture and sell the sealed FNC (Fiber Nickel-Cadmium) batteries from DAUG Hoppecke of Germany for the aerospace military market.

- Battery production commenced in 1991.

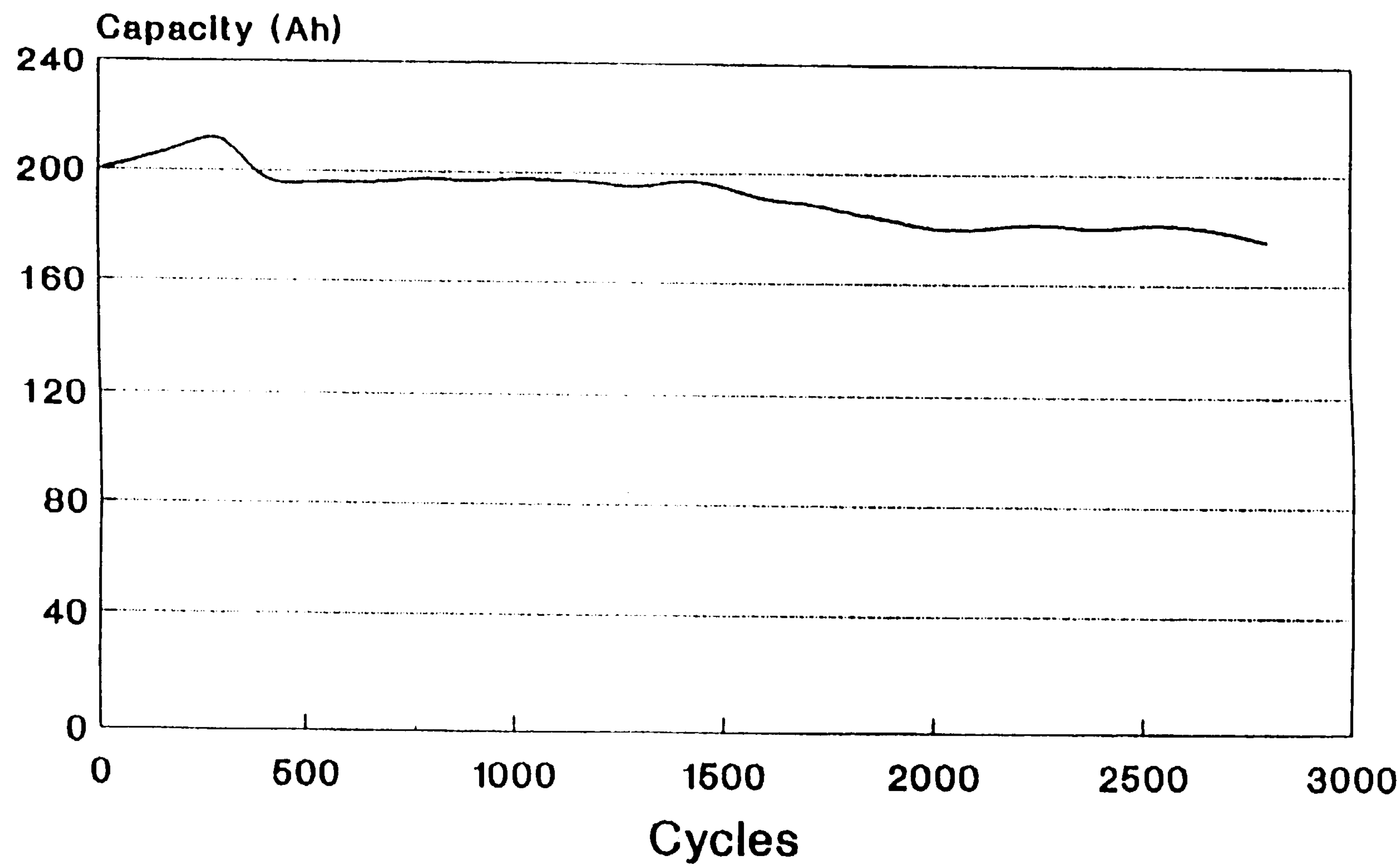
- The FNC Battery, unknown in North America until 1990, has been selected as the OEM battery for the:

Boeing 777	Longbow Apache
MD-90	F-22

- Several space quality cells under test and more in development and under contract.

FNC

Cycle Life Data
200 Ah FNC Traction Cell (KFMP 200)
100 % DOD, Discharge Load 100 Amp



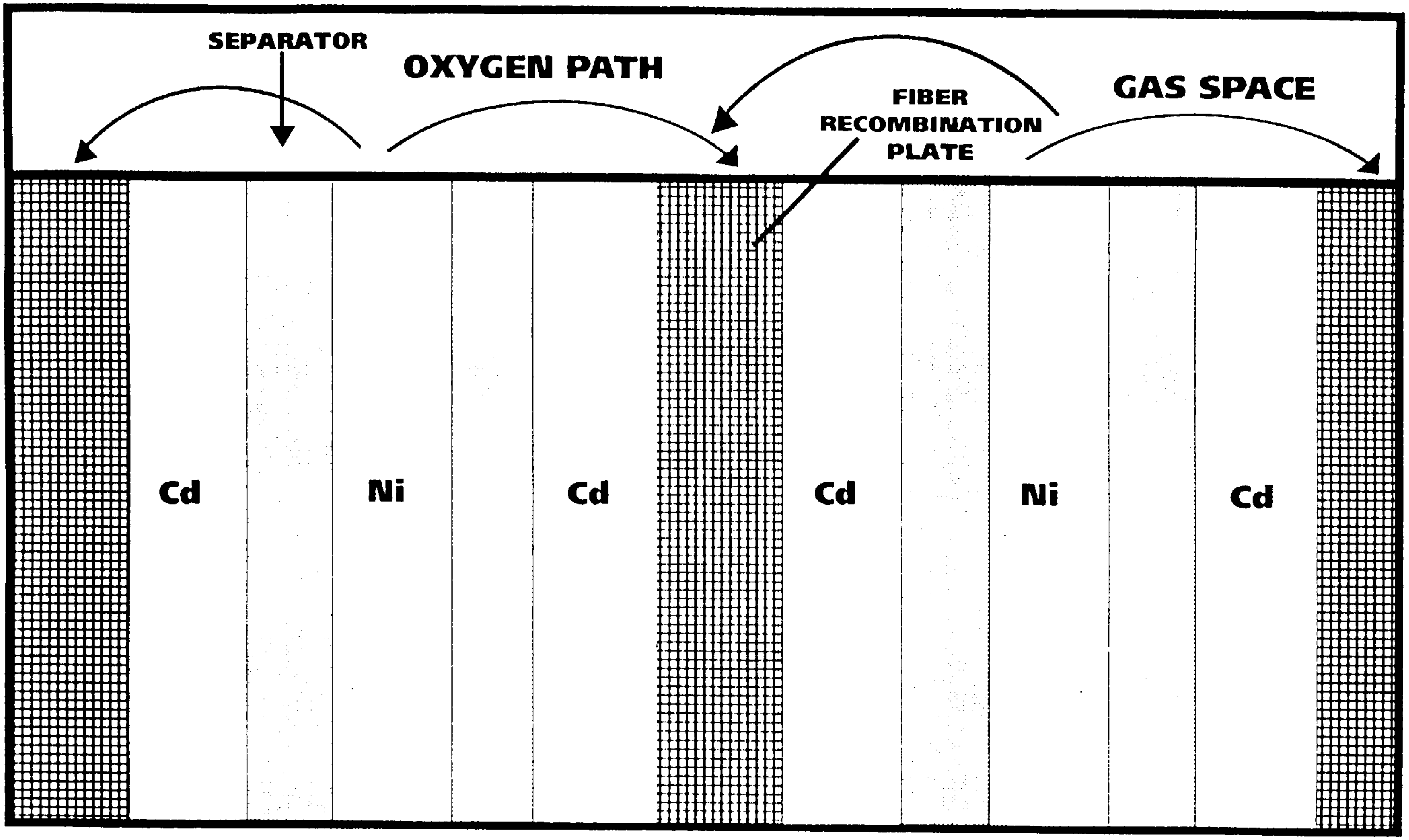
DAUG Laboratory, 1989-1990

FNC Main Features

- Use of Fiber Plate (negative and positive)
- Use of Recombination Plates
- Use of Fully Wet Separator
- Larger Amount of Electrolyte per Ahr.
- Negative Internal Pressure
- Hydrogen Removal Catalyst

FNC

Sealed FNC Cells



SCHEMATIC STACK DESIGN OF A SEALED FNC RECOMBINATION CELL

FNC

Ni-Cd Cells
Component Comparison

	NASA Standard	*Acme FNC*
Plaque	Sintered Nickel	Nickel-plated Felt
Impregnation	Chemical/Electrochemical	Mechanical
Positive Loading	2g/cc Void	1.5g/cc Void
Separator	30-80 micron pore size nylon	2-5 micron pore size PP or 20-40 micron pore size nylon

FNC

Space Ni-Cd Cells
Stack Comparison

	NASA Standard	Acme FNC
Recombination Plates	NO	YES
Overcharge Pressure	> 30 PSIA	< 5 PSIA
Hydrogen Removal Capability	NO	YES
Inner Electrodes Distance	8-10 mil	11-13 mil
Electrolyte ml/Ah	2.5 - 3.5	4 - 4.5
Measured Negative/Positive Capacity	1.5 - 2	2 - 2.4

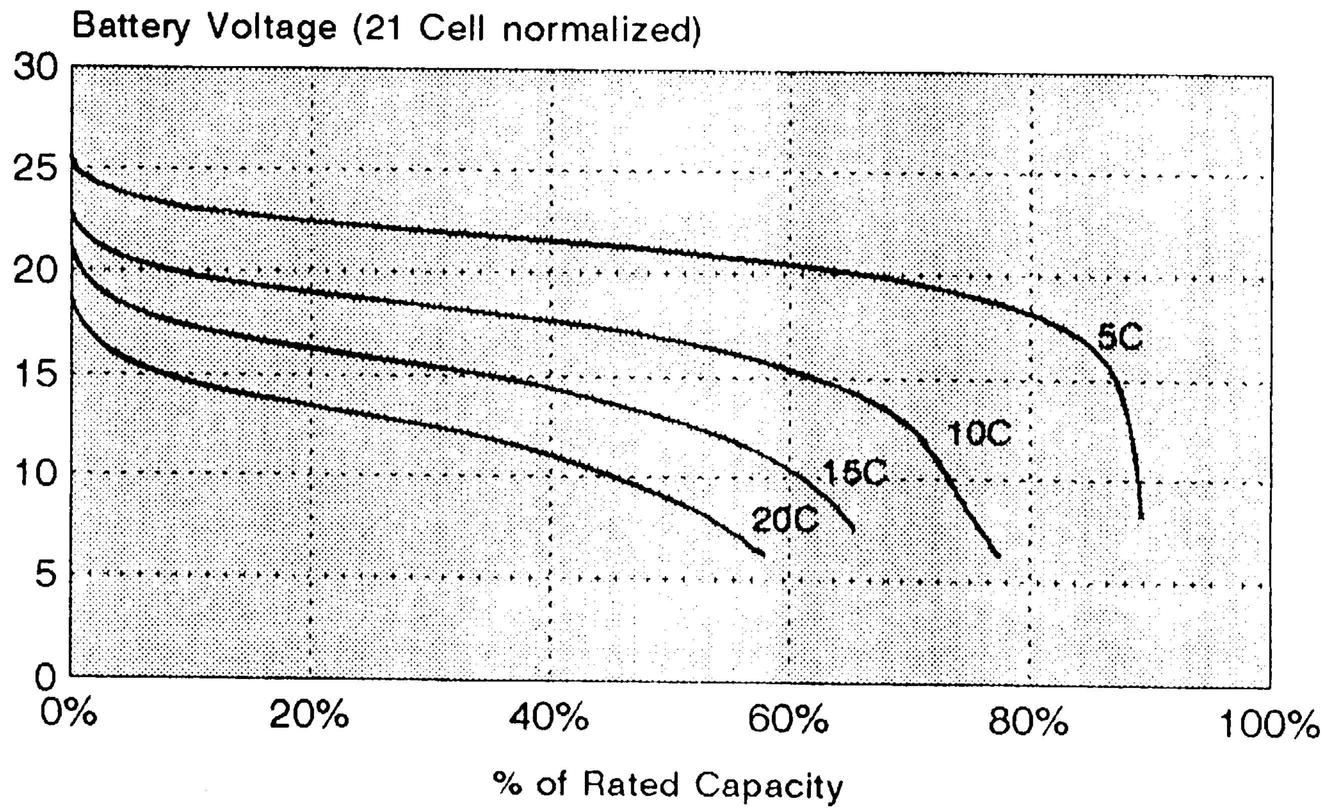
FNC

Typical Design Parameters
SPFNC Cells

Electrodes Active Area	55 cm^2/Ah
Positive Electrode Loading	1.5g/cc Void
Positive Electrode Charge Density	0.15 Ah/g
Negative Electrodes Theoretical Capacity	3.3 Rated Capacity
Negative Electrodes Flooded Capacity	2.5 Rated Capacity
Separator Material	PP or Nylon
Inner Electrode Distance	11 - 13 Mil
Electrolyte Concentration	30 - 32% KOH 2 - 3% LiOH
Electrolyte Volume	4.3 ml/Ah
Cell Impedance (mohm Ah)	30
Specific Energy (Cell Level)	34 - 43 Wh/kg

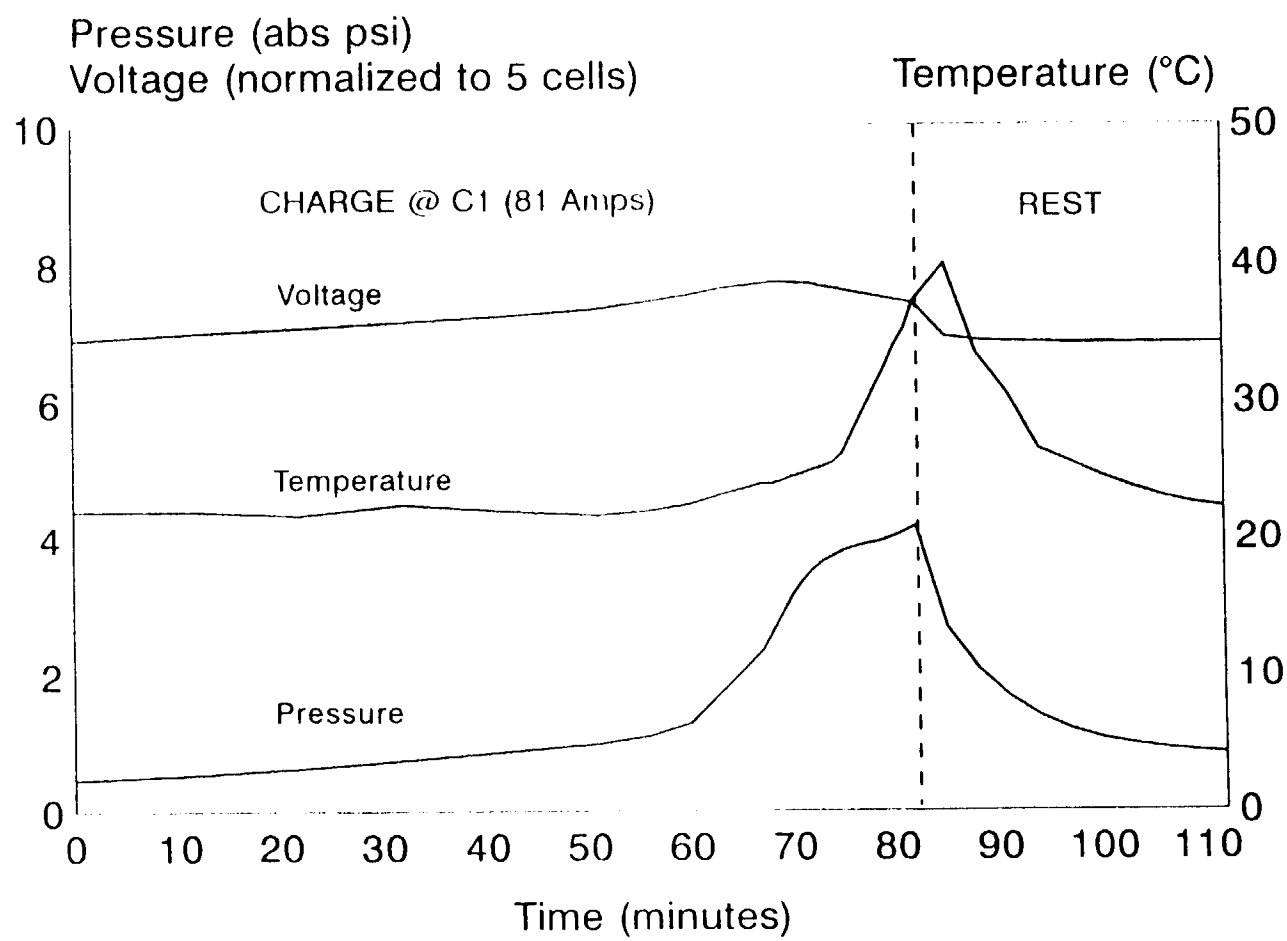
FNC

Typical Discharge Characteristics
for FNC Sealed X-type Cells



FNC

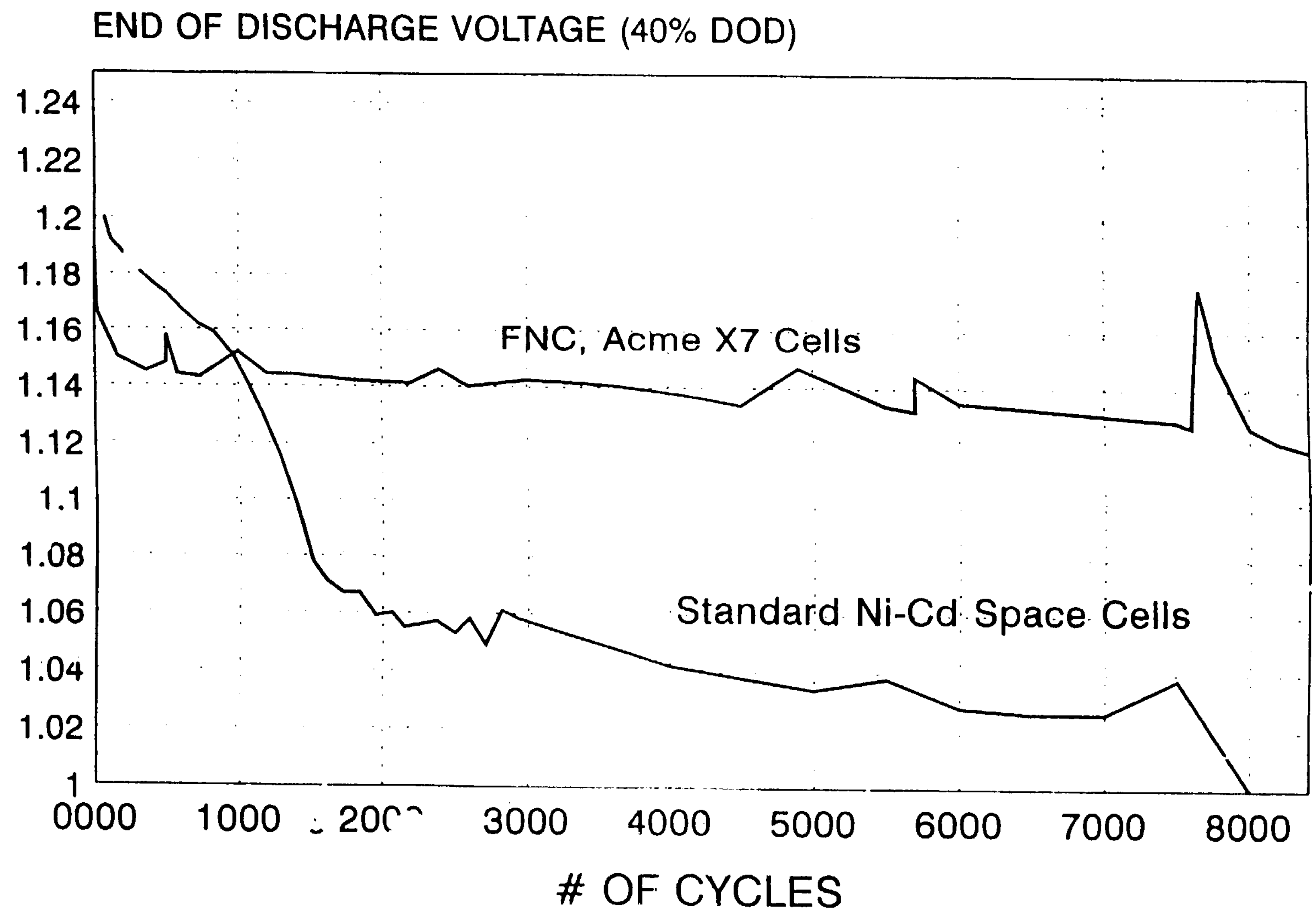
Charging Characteristics
X81 Cell, 24°C



FNC

Accelerated LEO Stress Test
20°C / 40% DOD

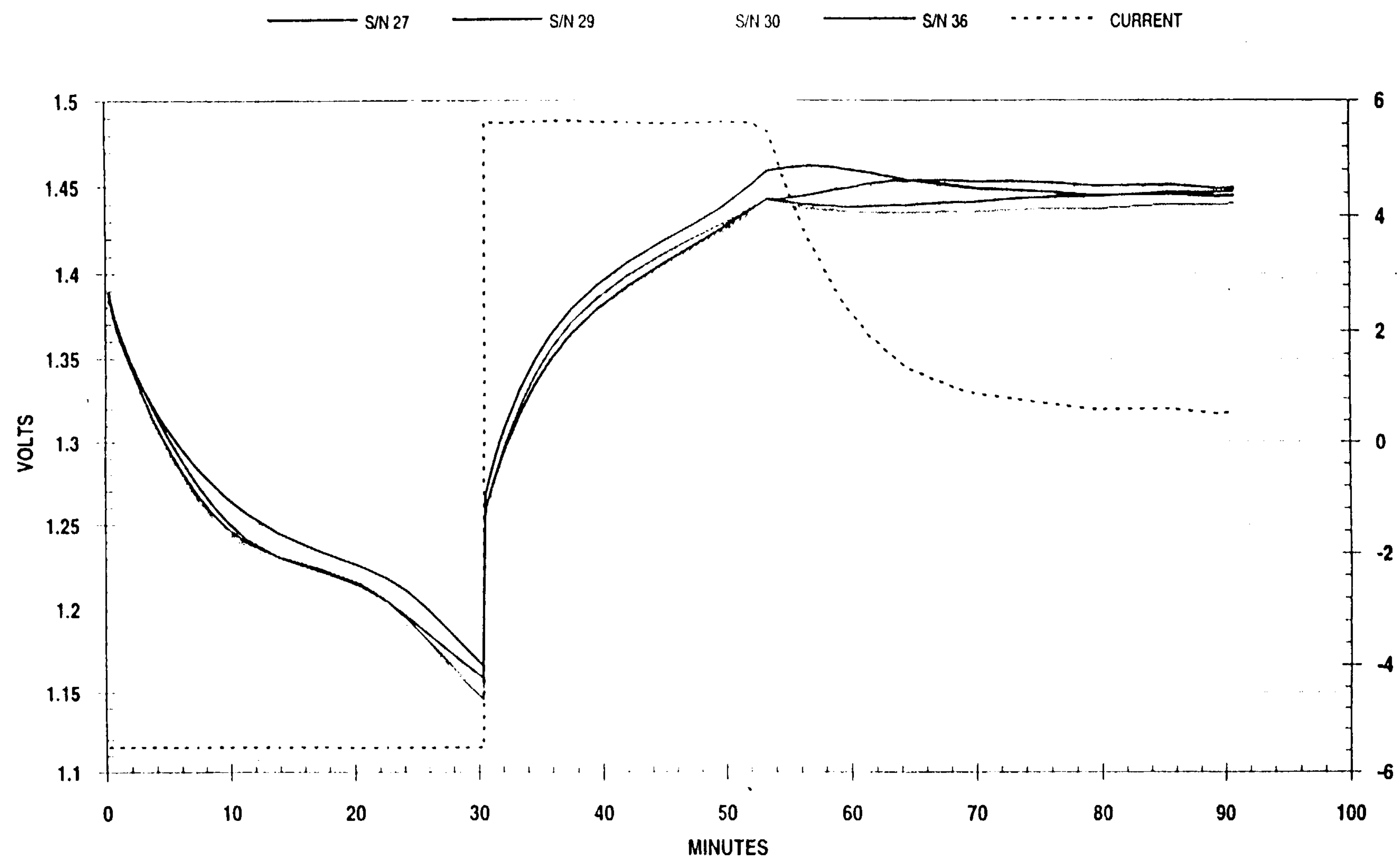
FNC



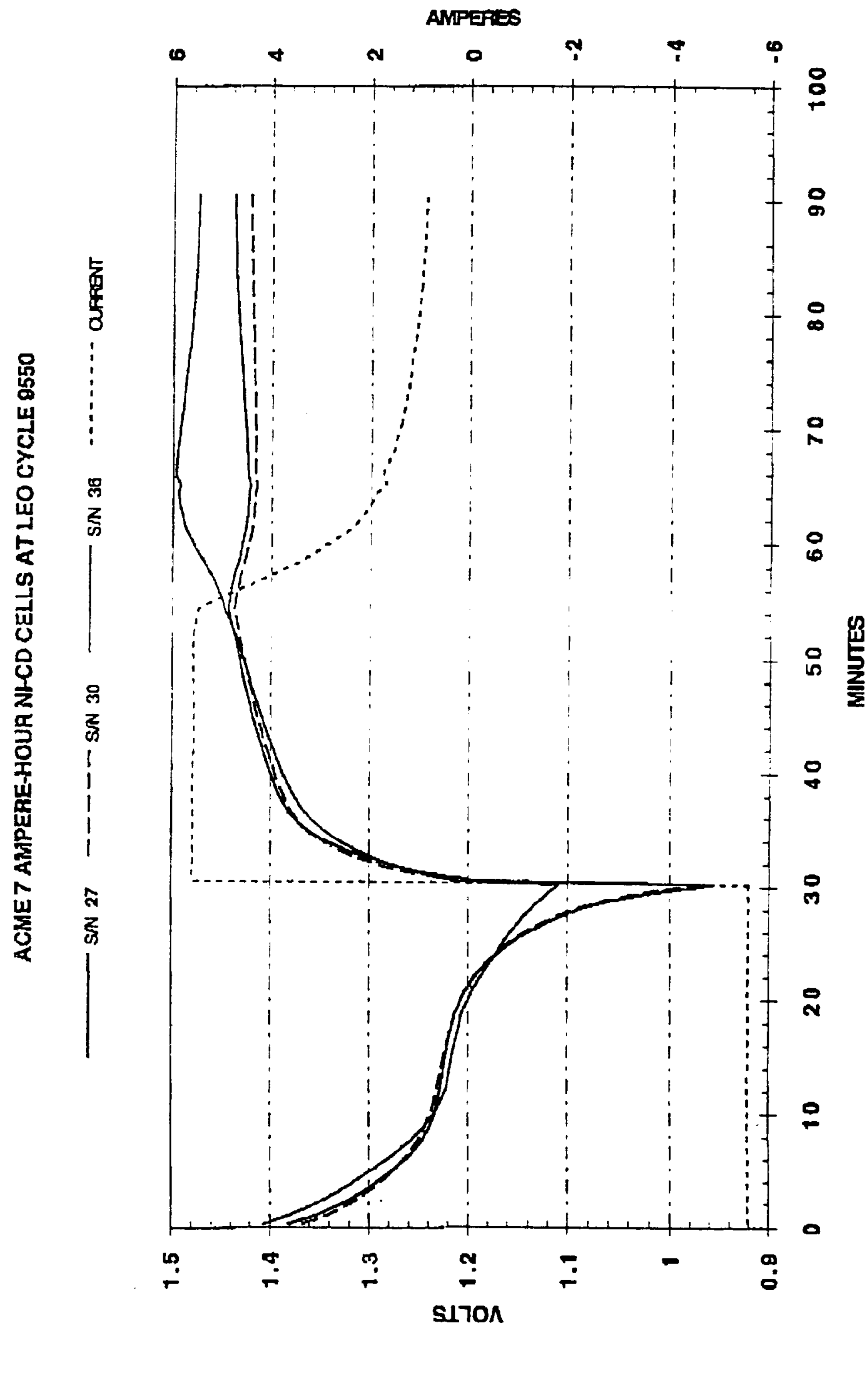
JPL Data 1991 - 1994

JPL

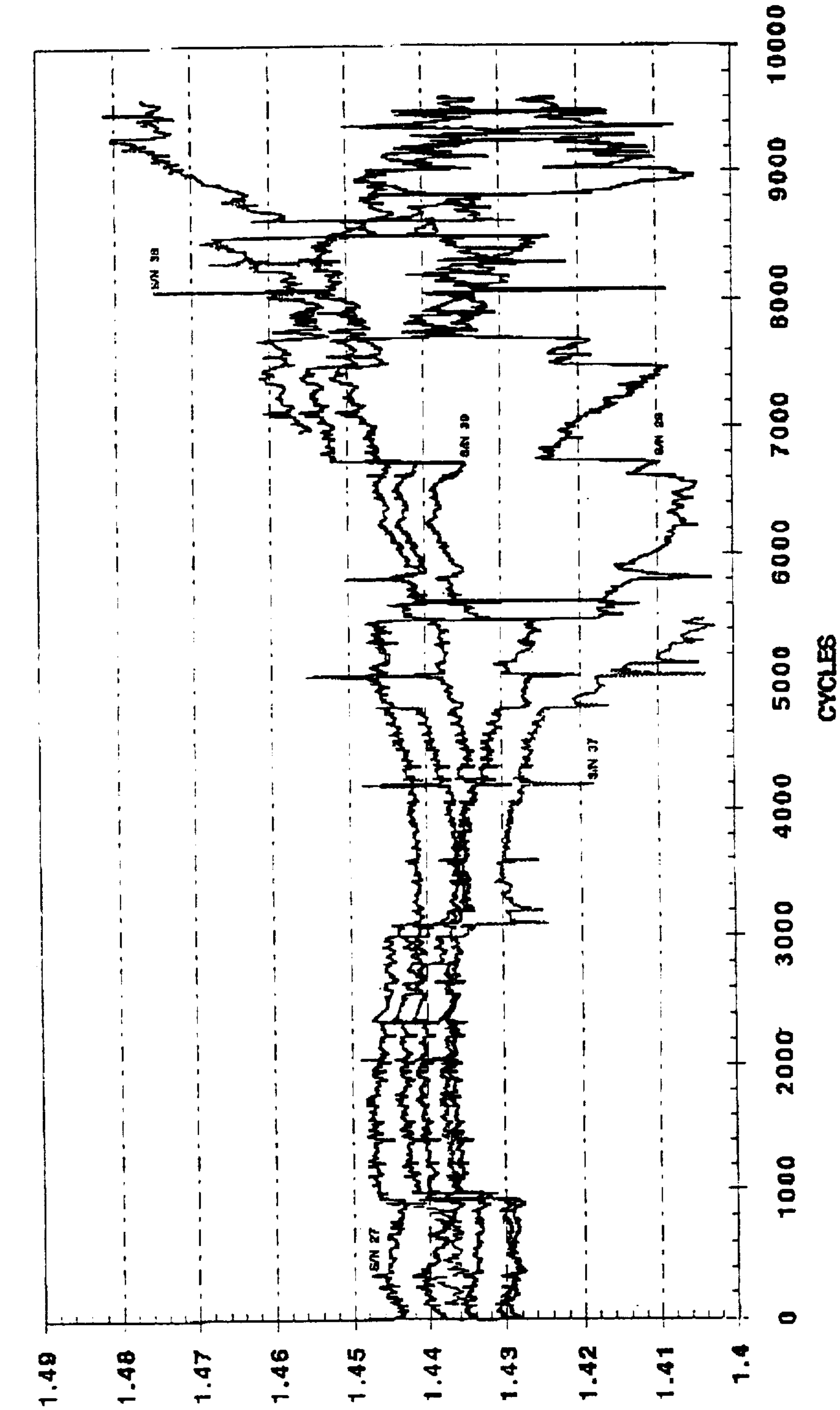
ACME 7 AMPERE-HOUR NI-CD CELLS AT LEO CYCLE 8500

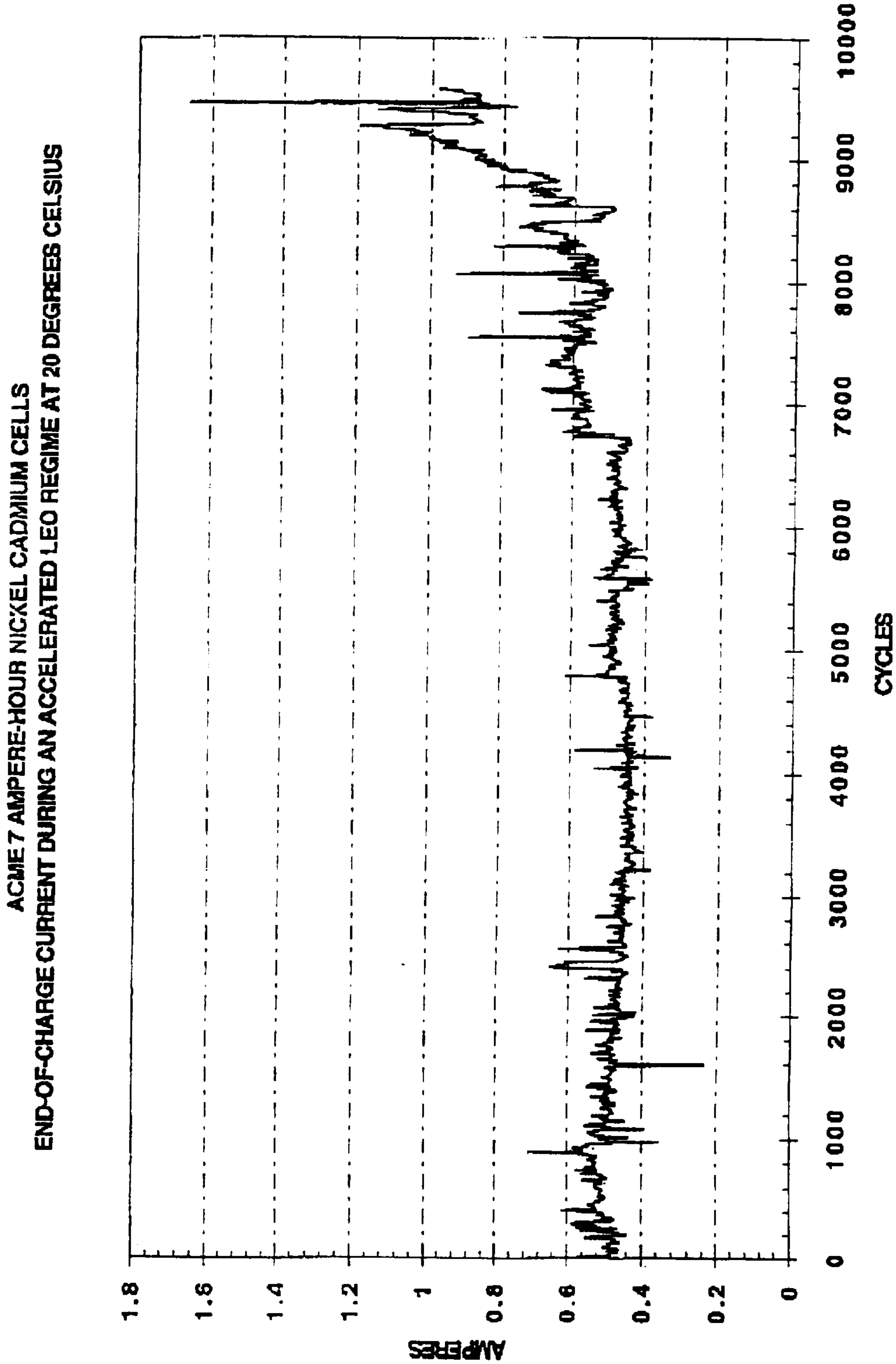


ENERGY STORAGE SYSTEMS GROUP


ACME 7 AMPERE-HOUR NI-CD CELLS AT LEO CYCLE 9550
S/N 27
S/N 30
S/N 36
CURRENT
VOLTS
1.5
1.4
1.3
1.2
1.1
1
0.9
AMPERES
6
4
2
0
-2
-4
-6
MINUTES
0
10
20
30
40
50
60
70
80
90
100

ACME 7 AMPERE-HOUR NICKEL CADMIUM CELLS
END-OF-CHARGE CELL VOLTAGES DURING AN ACCELERATED LEO REGIME AT 20 DEGREES CELSIUS

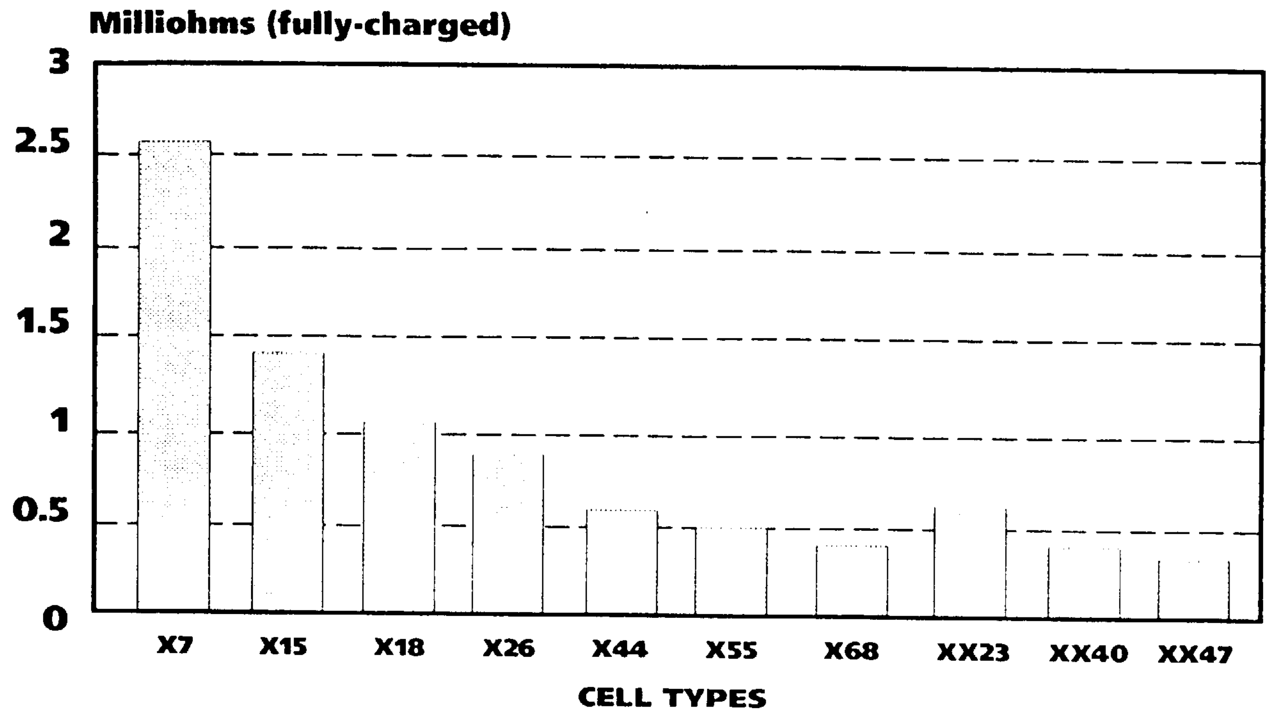



ACME 7 AMPERE-HOUR NICKEL CADMIUM CELLS
END-OF-CHARGE CURRENT DURING AN ACCELERATED LEO REGIME AT 20 DEGREES CELSIUS
AMPERES
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
CYCLES
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000

Sealed FNC Cells

CELL TYPE	RATED CAPACITY (Ah/1h to1.0Vpc)	WEIGHT (lbs.)	WEIGHT (kg)	WIDTH (inches)	WIDTH (mm)	LENGTH (inches)	LENGTH (mm)	TOTAL HEIGHT (inches)	TOTAL HEIGHT (mm)
X7	6.5	0.63	0.28	2.24	57	.94	24	4.12	105
X15	15	1.25	0.57	2.41	61	1.14	29	7.03	178
X18	17	1.62	0.73	2.66	67	1.41	36	5.79	147
X26	26	2.50	1.13	4.53	115	.99	25	6.61	168
X44	44	3.80	1.72	4.53	115	1.62	41	6.61	168
X55	55	4.52	2.05	4.53	115	2.13	54	6.52	166
X68	68	5.71	2.59	4.53	115	2.33	59	6.52	166
X81	81	6.90	3.13	4.53	115	2.13	54	8.82	224
XX23	23	2.50	1.13	4.53	115	.99	25	6.61	168
XX40	40	3.79	1.72	4.53	115	1.62	41	6.61	168
XX47	47	4.52	2.05	4.53	115	2.13	54	6.52	166

FNC



CELL IMPEDANCE
TEMPERATURE +25°C

FNC

FNC

FNC Peripheral Advantages

- More tolerable to manufacturing variations.
- Potential for shorter development and qualification time for new cells.
- Lower cost.
- Capacity up to 150 Ah possible.

FNC

SUMMARY

- Improved fiber plates are utilized in Ni-Cd cells for a variety of applications.
- Sealed cell design uses oxygen recombination plates that allow the use of a dendrite-resistive fully wet separator.
- Conservative design: low positive mass loading, high negative to positive capacity ratio, high electrolyte per Ah.
- Negative cell pressure at all times.
- Robust against manufacturing variations.
- Cycle life testing ongoing.
- Potential for increased reliability with reduced cost compared to standard cells.
- Ready for full space qualification programs.

FNC

NASA BATTERY TESTBED CAPABILITIES AND RESULTS

JPL

Frank Deligiannis, Sal DiStefano,
and Dave Perrone

1994 NASA Aerospace Battery Workshop
Huntsville Marriott
Huntsville, Alabama
November 15-17, 1994

JPL

BACKGROUND

- A COUPLE OF NASA SATELLITES (UARS & CGRO) EXPERIENCED ANOMALIES WITH THEIR Ni-Cd BATTERIES - EARLY 1992
- BATTERIES DEVELOPED LARGE HALF-BATTERY VOLTAGE DIFFERENTIALS (>100 mV) EARLY IN LIFE (<1 YR)
- A BATTERY ON CGRO WAS REMOVED OFF LINE DUE TO THE HALF-BATTERY VOLTAGE DIFFERENTIAL EXCEEDING 750 mV
- UPCOMING LAUNCHES OF EUVE & TOPEX WITH SIMILAR DESIGN BATTERIES - MID 1992
- BATTERY MANAGEMENT WAS INITIATED ON MOST MISSIONS
  - -MANY NON-TRADITIONAL METHODS OF OPERATION APPEARED
- NASA BATTERY TESTBED EFFORT WAS INITIATED

ENERGY STORAGE SYSTEMS GROUP

JPL

NASA TESTBED OBJECTIVE

- DETERMINE ON THE GROUND THE IMPACT OF VARIOUS OPERATIONAL STRATEGIES PRIOR TO IMPLEMENTATION ON THE SPACECRAFT

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APPROACH

- DEVELOP COMPUTER CONTROLLED TESTING WHICH WILL ENABLE FAST RECONFIGURATION TO MODEL VARIOUS BATTERY SYSTEMS: CGRO, UARS, EUVE TOPEX AND OTHER FUTURE NASA MISSIONS
- OBTAIN & OPERATE IMBALANCED BATTERIES WITH HIGH HALF-BATTERY VOLTAGE DIFFERENTIALS
- IMPLEMENT VARIOUS OPERATIONAL STRATEGIES SUCH AS
  - DEEP DISCHARGES DURING FULL SUN PERIODS
  - CONSTANT CURRENT MODES OF CHARGING
  - ETC.

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TESTBED CAPABILITIES

- CURRENTLY CONFIGURED TO HANDLE THREE 50 Ah NiCd BATTERIES IN PARALLEL
- SIMULATION THROUGH COMPUTER HARDWARE & SOFTWARE
- VARIOUS CHARGE/DISCHARGE MODES CAN BE IMPLEMENTED (CONSTANT CURRENT, CONSTANT POWER, CONSTANT VOLTAGE etc)
- SIMULATION OF ORBIT PROFILES WITH VARYING OCCULTATION PERIODS
- TEMPERATURE, VOLTAGE, CURRENT LIMITS CAN BE SET
- 24 HOUR AUTOMATED OPERATION

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TESTBED CAPABILITIES (cont.)

- POWER & ORBIT PROFILES EASILY CHANGED BY COMPUTER COMMAND
- MONITORING & DATA COLLECTION OF INDIVIDUAL CELL VOLTAGES, BATTERY CURRENTS, TEMPERATURES & VOLTAGES INCLUDING PARAMETERS SUCH AS PEAK CHARGE CURRENT, TAPER CURRENT, C/D RATIO, NET OVERCHARGE etc.
- THERMAL ENVIRONMENT CONTROLLED BY AN ENVIRONMENTAL CHAMBER
- SYSTEM HAS MAX 40 A PER BATTERY CURRENT CAPABILITY
- SYSTEM HAS MAX 60 V PER BATTERY VOLTAGE CAPABILITY

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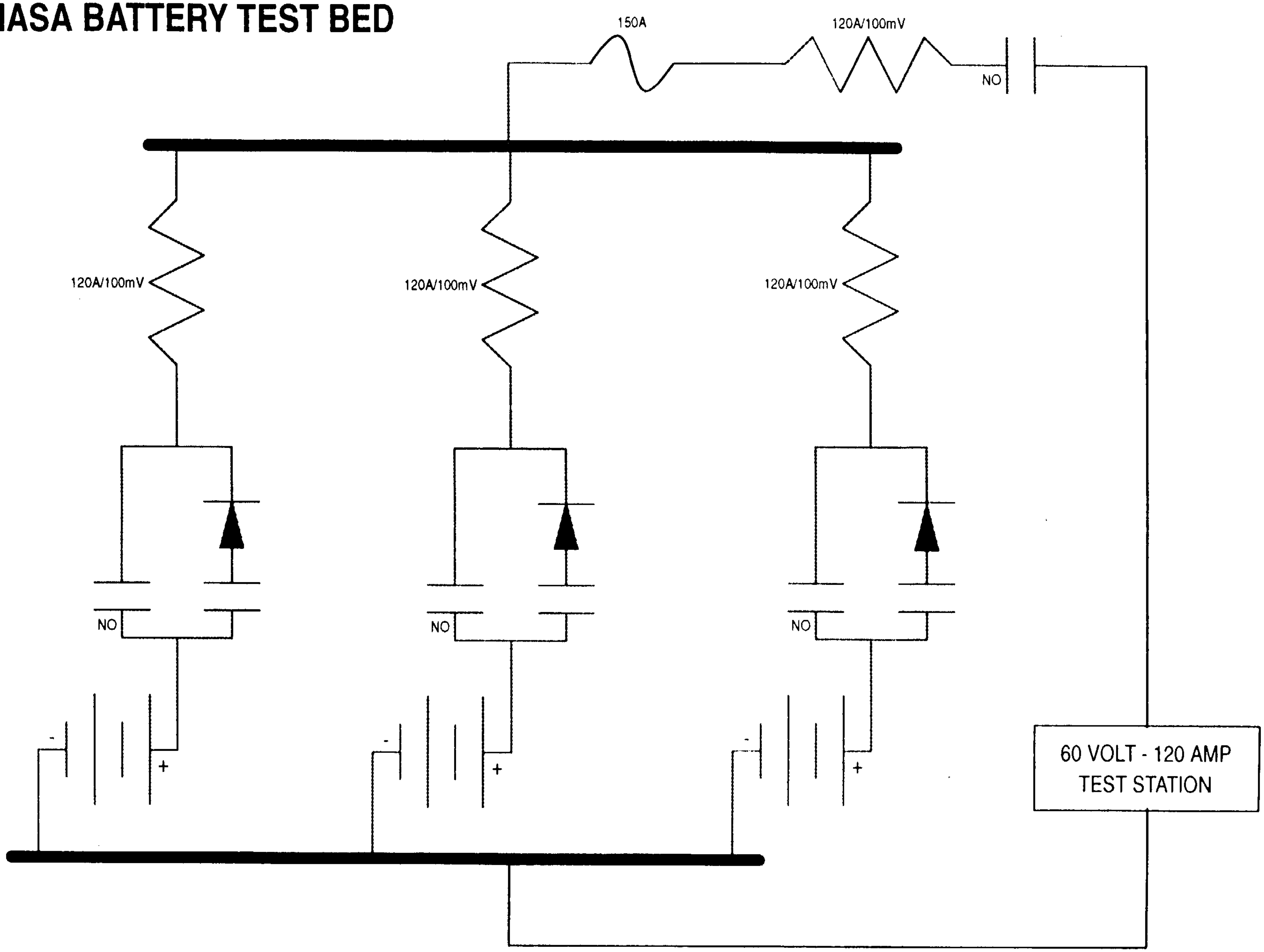
NASA BATTERY TEST BED



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CURRENT TEST REGIME & BATTERIES

- THREE 22-CELL 50 Ah BATTERIES
  - TWO BATTERIES APPROXIMATELY 8 YEARS OLD, HAVE BEEN USED AS TEST BATTERIES ON CGRO AND TOPEX
  - ONE BATTERY WAS BUILT WITH CELLS FROM FOUR LOTS CGRO LOT, UARS LOT, EUVE FLIGHT LOT, EUVE LOT MOST CELLS WERE CYCLED FOR AT LEAST 1 YEAR
- IMPLEMENTED ONE OF THE ORIGINAL UARS PROFILE
  - 18% DOD
  - 95.5 MINUTE ORBIT
  - V/T 5
  - 3° C
  - 34 A PEAK CHARGE CURRENT

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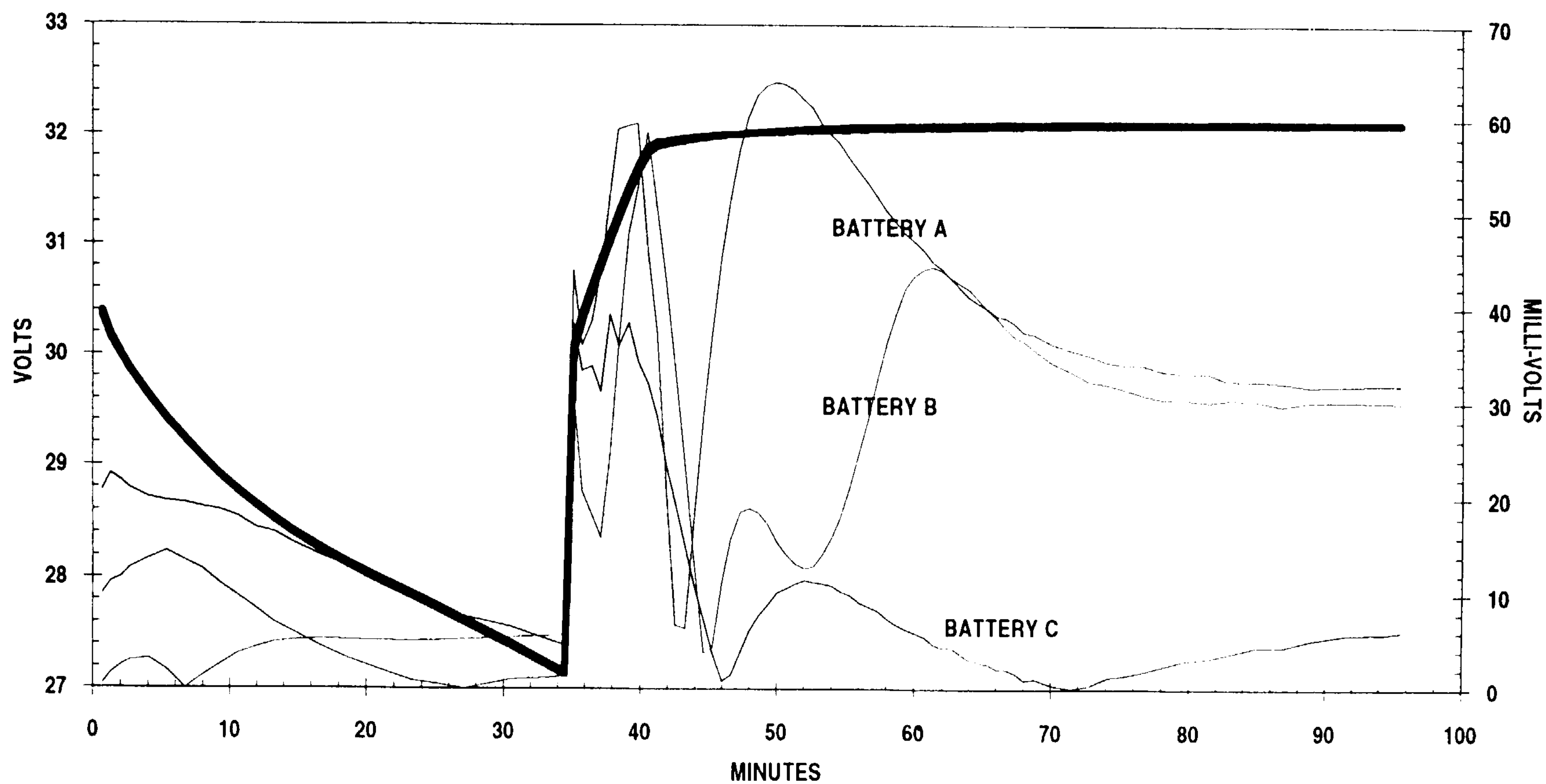
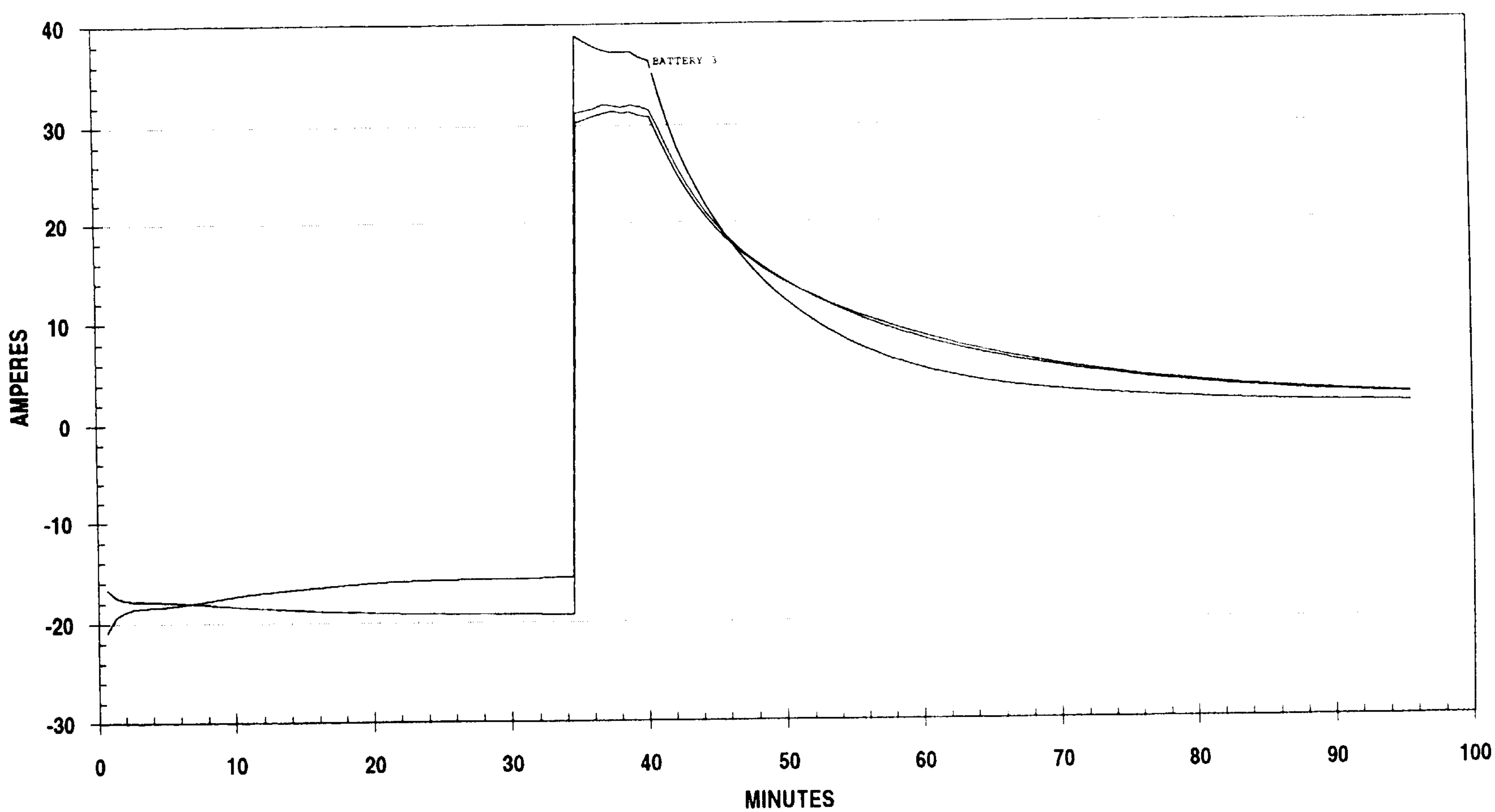
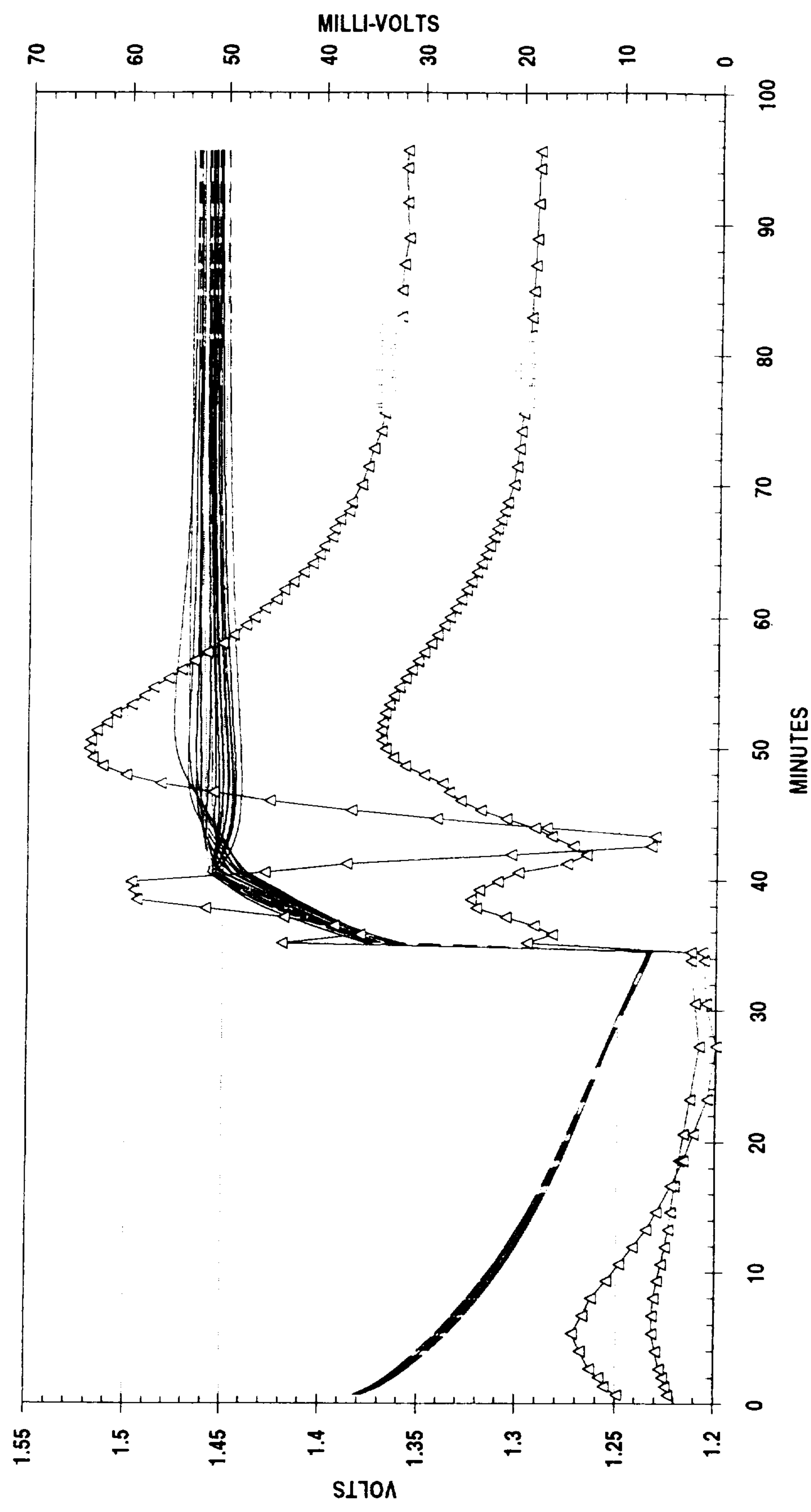
NASA BATTERY TEST BED -- BATTERY A, B & C
CYCLE 400 AT 18% DOD AT 3 DEGREES CELSIUS
BATTERY VOLTAGE & HALF BATTERY DIFFERENTIAL



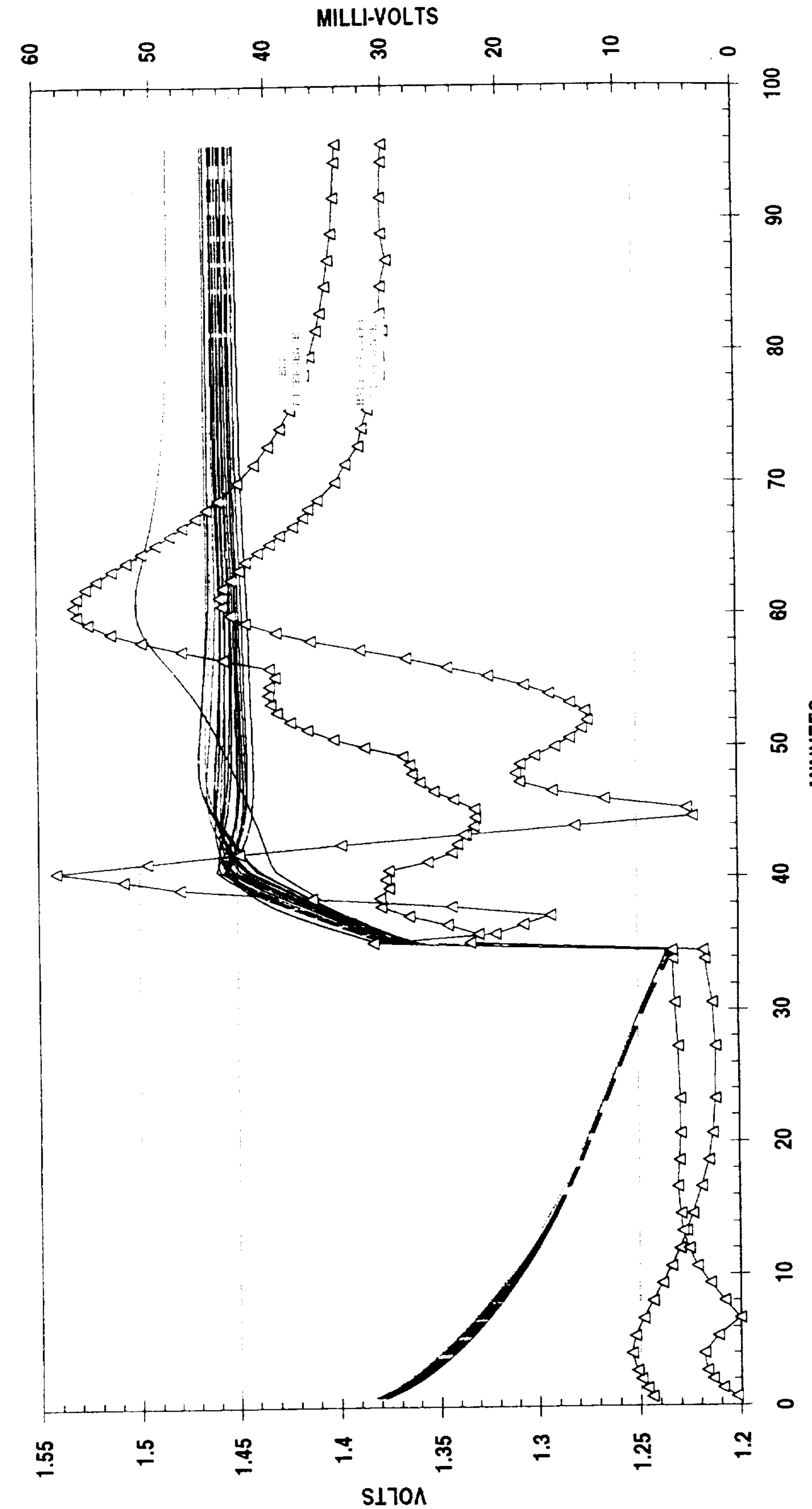
NASA BATTERY TEST BED
CYCLE 400 AT 18% DOD AT 3 DEGREES CELSIUS



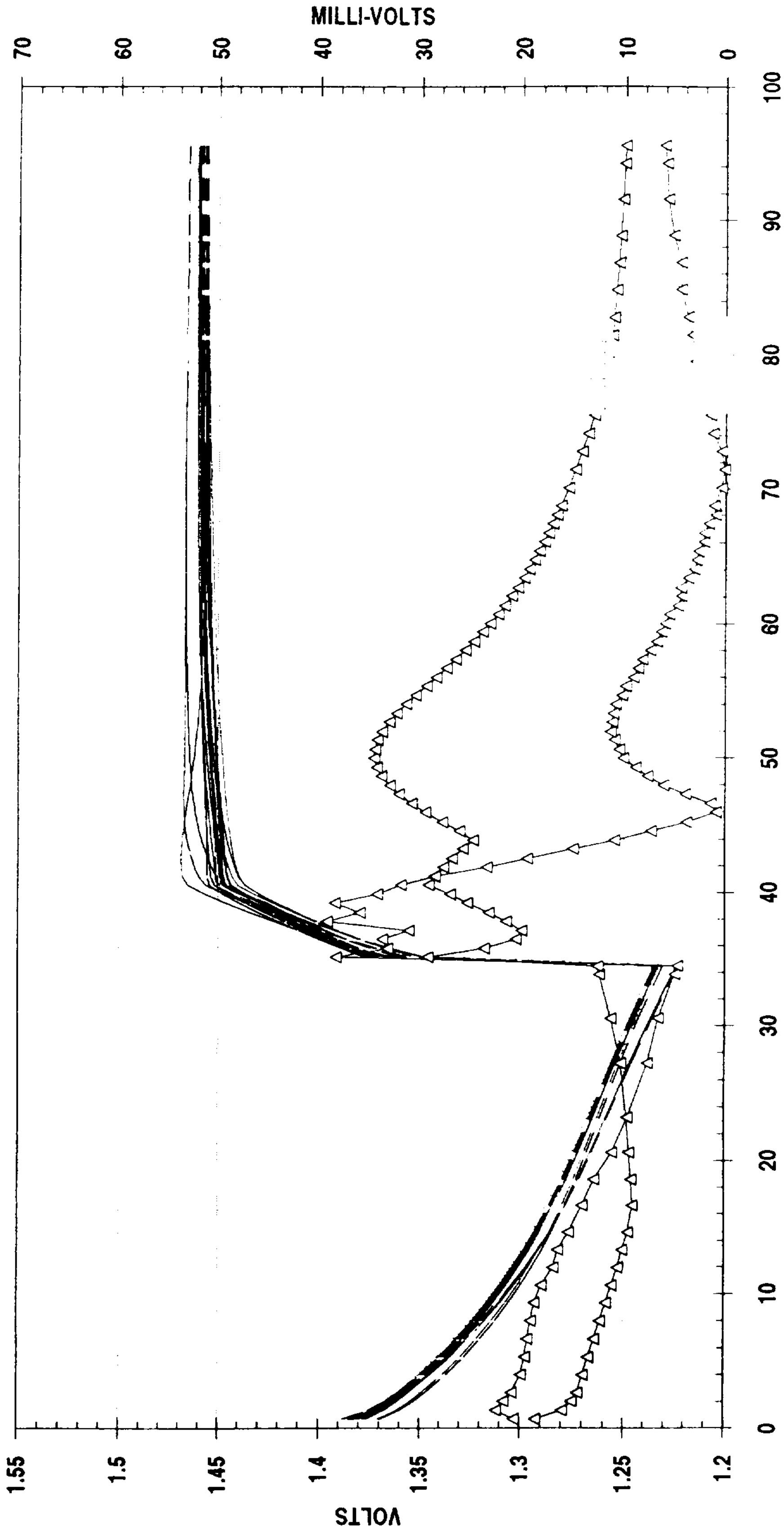
NASA BATTERY TEST BED -- BATTERY A
CYCLE 400 AT 18% DOD AT 3 DEGREES CELSIUS



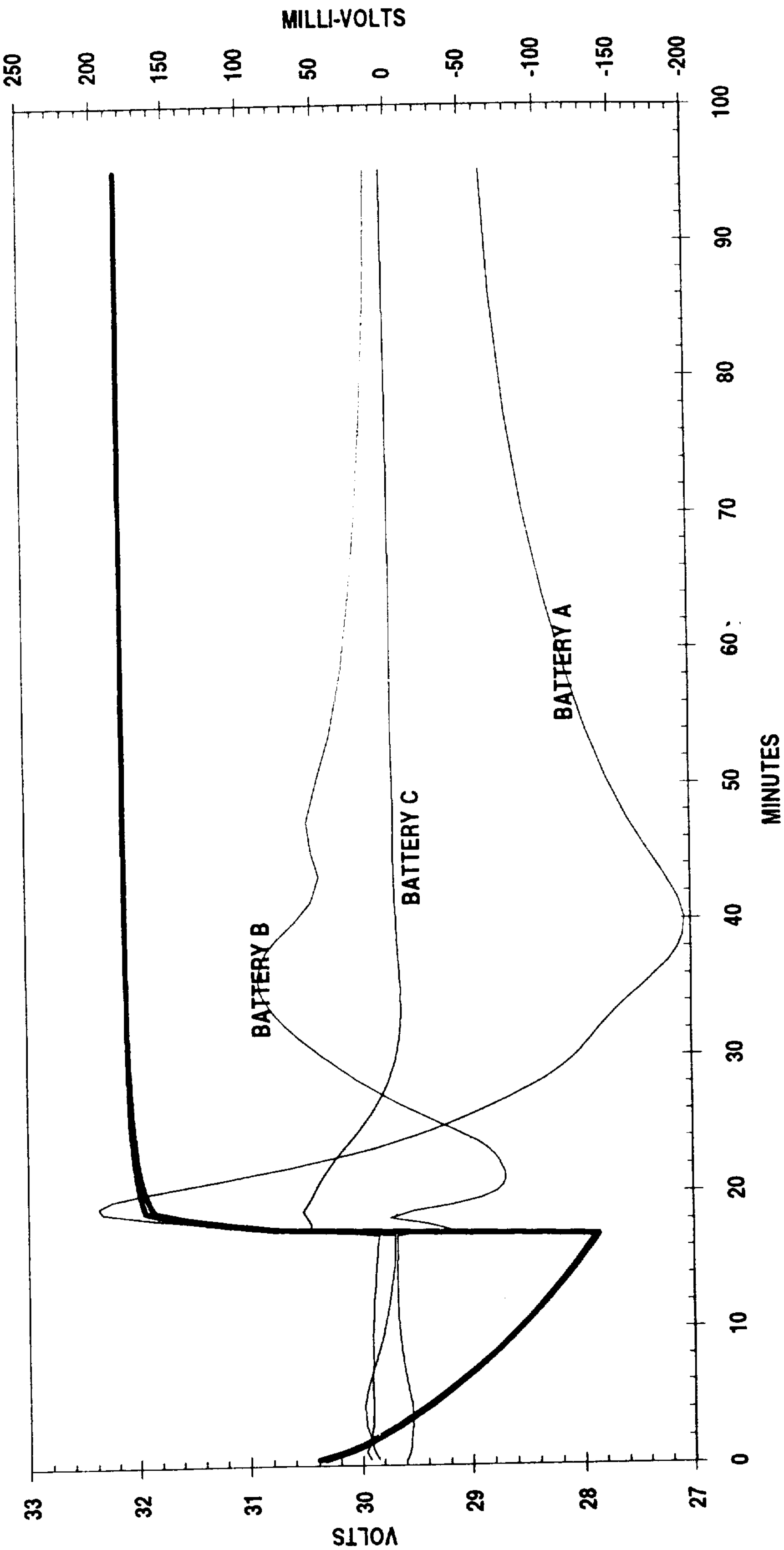
NASA BATTERY TEST BED -- BATTERY B
CYCLE 400 AT 18% DOD AT 3 DEGREES CELSIUS

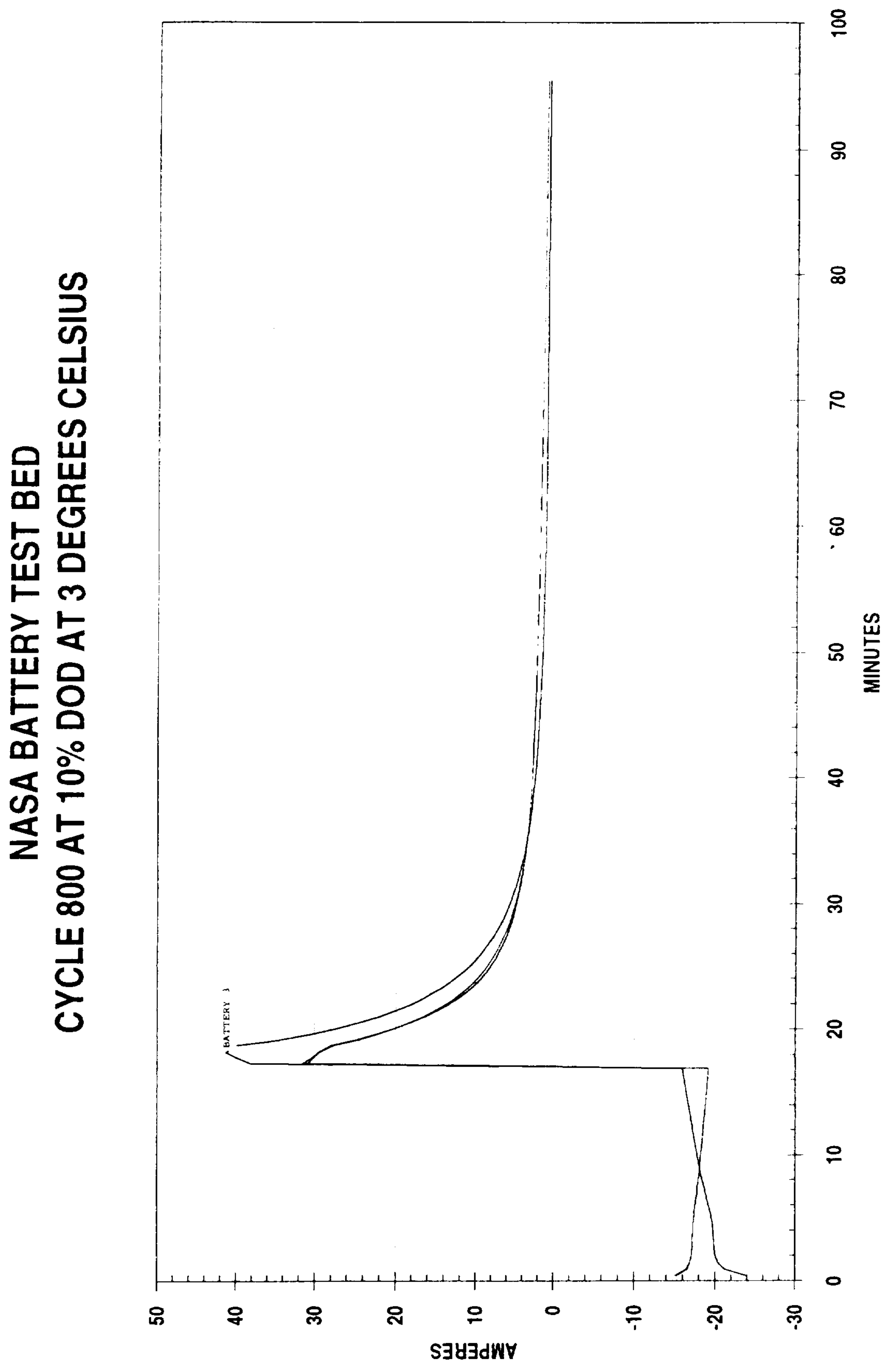


NASA BATTERY TEST BED -- BATTERY C
CYCLE 400 AT 18% DOD AT 3 DEGREES CELSIUS

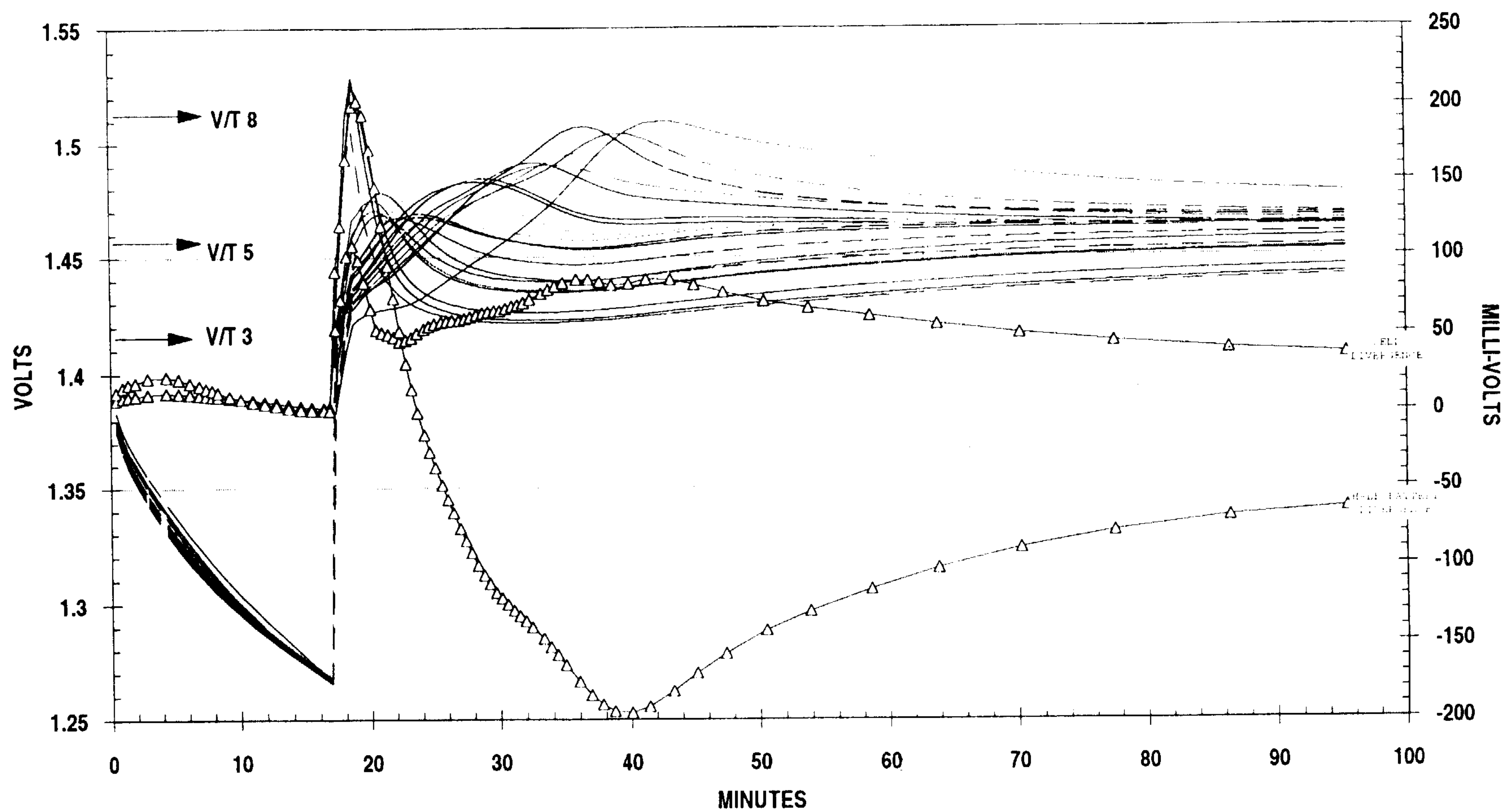


NASA BATTERY TEST BED -- BATTERY A, B & C
CYCLE 800 AT 10% DOD AT 3 DEGREES CELSIUS
BATTERY VOLTAGE & HALF BATTERY DIFFERENTIAL

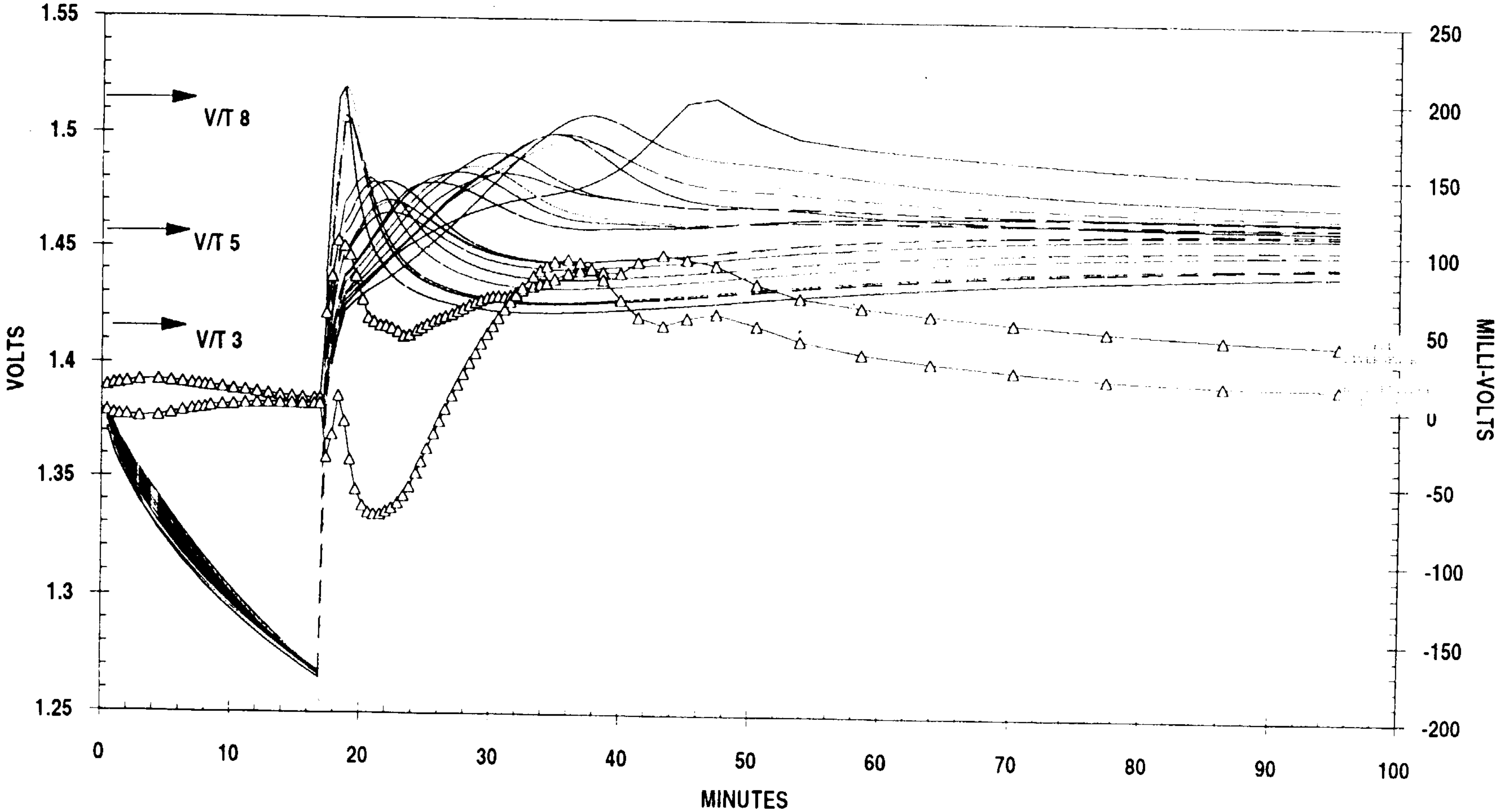



NASA BATTERY TEST BED
CYCLE 800 AT 10% DOD AT 3 DEGREES CELSIUS
BATTERY 3
AMPERES
50
40
30
20
10
0
-10
-20
-30
MINUTES
0
10
20
30
40
50
60
70
80
90
100

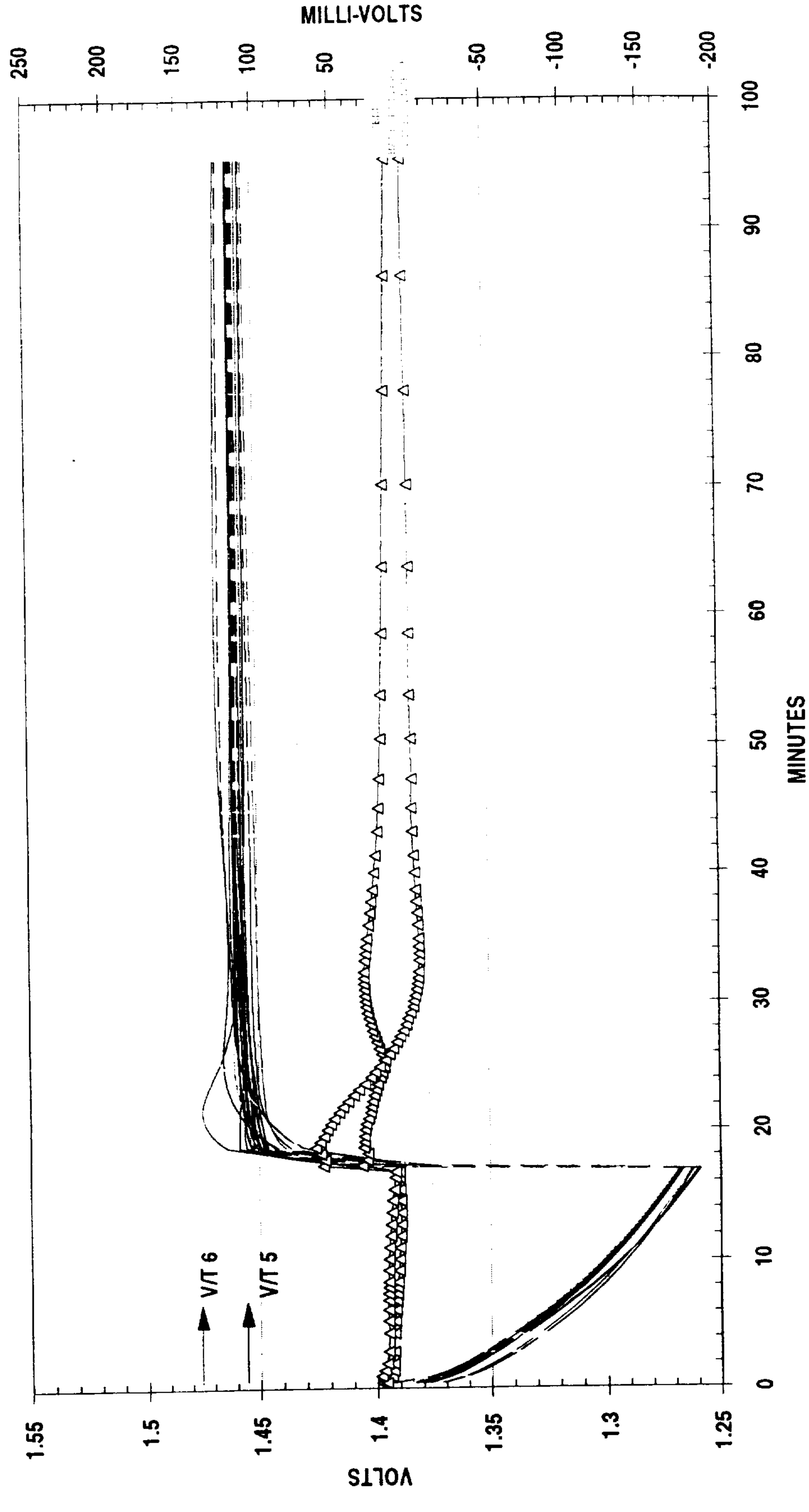
NASA BATTERY TEST BED -- BATTERY A
CYCLE 800 AT 10% DOD AT 3 DEGREES CELSIUS



NASA BATTERY TEST BED -- BATTERY B
CYCLE 800 AT 10% DOD AT 3 DEGREES CELSIUS



NASA BATTERY TEST BED -- BATTERY C
CYCLE 800 AT 10% DOD AT 3 DEGREES CELSIUS



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SUMMARY

- COMPLETED THE COMPUTER SOFTWARE & HARDWARE
- OBTAINED THREE BATTERIES FOR TESTING
- ESTABLISHED A PERFORMANCE DATABASE OF THE THREE BATTERIES UNDER THE UARS PROFILE
- CREATED A IMBALANCED BATTERY SYSTEM
- FUTURE PLANS ARE TO IMPLEMENT VARIOUS OPERATIONAL STRATEGIES TO CORRECT THE IMBALANCE

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SUMMARY

- SUCCESSFULLY DEMONSTRATED THE OPERATION OF A SPACECRAFT BATTERY TESTBED
  - HARDWARE IS CONFIGURED TO ACCOMMODATE MULTIPLE BATTERIES (i.e. 3 X 22 CELL NiCd)
  - SOFTWARE CAN IMPLEMENT ANY ORBITAL PROFILE
- ESTABLISHED A PERFORMANCE DATA BASE FOR THE MODULAR POWER SUBSYSTEM (MPS) CHARACTERISTIC OF SEVERAL NASA ORBITING SATELLITES (GRO,UARS,EUVE, TOPEX/Poseidon)
  - UARS ORBITAL PROFILE IMPLEMENTED ON TEST BATTERIES
  - INITIATED ANALYSIS OF BATTERY MANAGEMENT TECHNIQUES

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ACKNOWLEDGMENT

- This work was performed at The Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautic and Space Administration . The work was sponsored by the Office of Safety Reliability and Maintainbility,Code Q,of NASA.
- Test Batteries and useful discussions were provided by Dr. Gopalakrishna M. Rao and Mr. Mark Toft of the Power Branch at Goddard Space Flight Center.

ENERGY STORAGE SYSTEMS GROUP

Eric Darcy
11/16/94

Calorimetric Evaluation

of

Commercial Ni-MH Cells and Chargers

with
Brent M. Hughes
Lockheed Engineering & Sciences Company

N95- 26790

The test objectives are to evaluate the electrical and thermal performance of commercial Ni-MH cells and to evaluate the effectiveness of commercial charge control circuits. The ultimate design objectives are to determine which cell designs are most suitable for scale-up and to guide the design of future Shuttle and Station based battery chargers.

Outline

- Description of Ni-MH cells and chargers
- Cycling experiment using Taguchi techniques
- Calorimetric comparison of best performing cells
- Summary conclusions

The cells tested were those most readily available. Some were purchased while others were sampled to us. The most notable exclusion are Panasonic cells. Efforts are under way to obtain these for future evaluation.

Description of Cells

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Cell Manufacturer	Cell Size	Ah rating	DoM	Hydride formulation
Ovonic	C	3.25	92	AB_2
Harding*	A	1.8	93	AB_2
Gold Peak*	7/5A	2.5	94	AB_2
Maxell	4/3A	2.3	94	AB_2
Sanyo*	4/3A	2.3	93	AB_5
Sanyo	4/3AU	2.4	94	AB_5
Toshiba*	4/5A	1.5	93	AB_5
Furukawa	Prismatic	0.55	93	AB_5
Yuasa*	Prismatic	3.0	94	AB_5
Yuasa*	4/3A	2.4	94	AB_5

* have limited cycling performance data.

This Austrian product uses a novel fast charge approach which starts fast and declines in a stair-step manner. The technique reduces the maximum charge voltage (power) needed. Unfortunately, this charger sometimes failed to terminate when the current was adjusted from its factory setting. Thus, only C-cells where tested with this charger.

Enstore Charger	Propulsion and Power Division	
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Model # - ECS-II by Enstore, Inc.

Input - constant voltage AC (110 V or 220V) or DC (11 V)

Output - continuously pulsing charge current with 4 step sequence.
- Step 1 - 100% of initial setting to about 75% SOC
- Step 2 - 75% of initial setting to about 95% SOC
- Step 3 - 38% of initial setting to about 100% SOC
- Step 4 - lower duty cycle of pulses at step 3 level maintained indefinitely

Charge Rates - 2 to 8 A, but with Evaluation Board only successful at 4 A

Charge Termination Methods
- proprietary voltage inflection
- maximum voltage
- maximum temperature

Other Features/Limits
- can be set to charge Ni-Cd and Pb/PbO_2 batteries
- termination was inconsistent at any setting other than 4 A.
- requires a 6 kΩ NTC thermistor.

This declining stair-step current profile results in a camelback heat profile which minimizes peak charge voltage and heat. Enstore, Inc., acknowledged this termination problem and is performing further development to correct it.

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Enstore Charger Sequence

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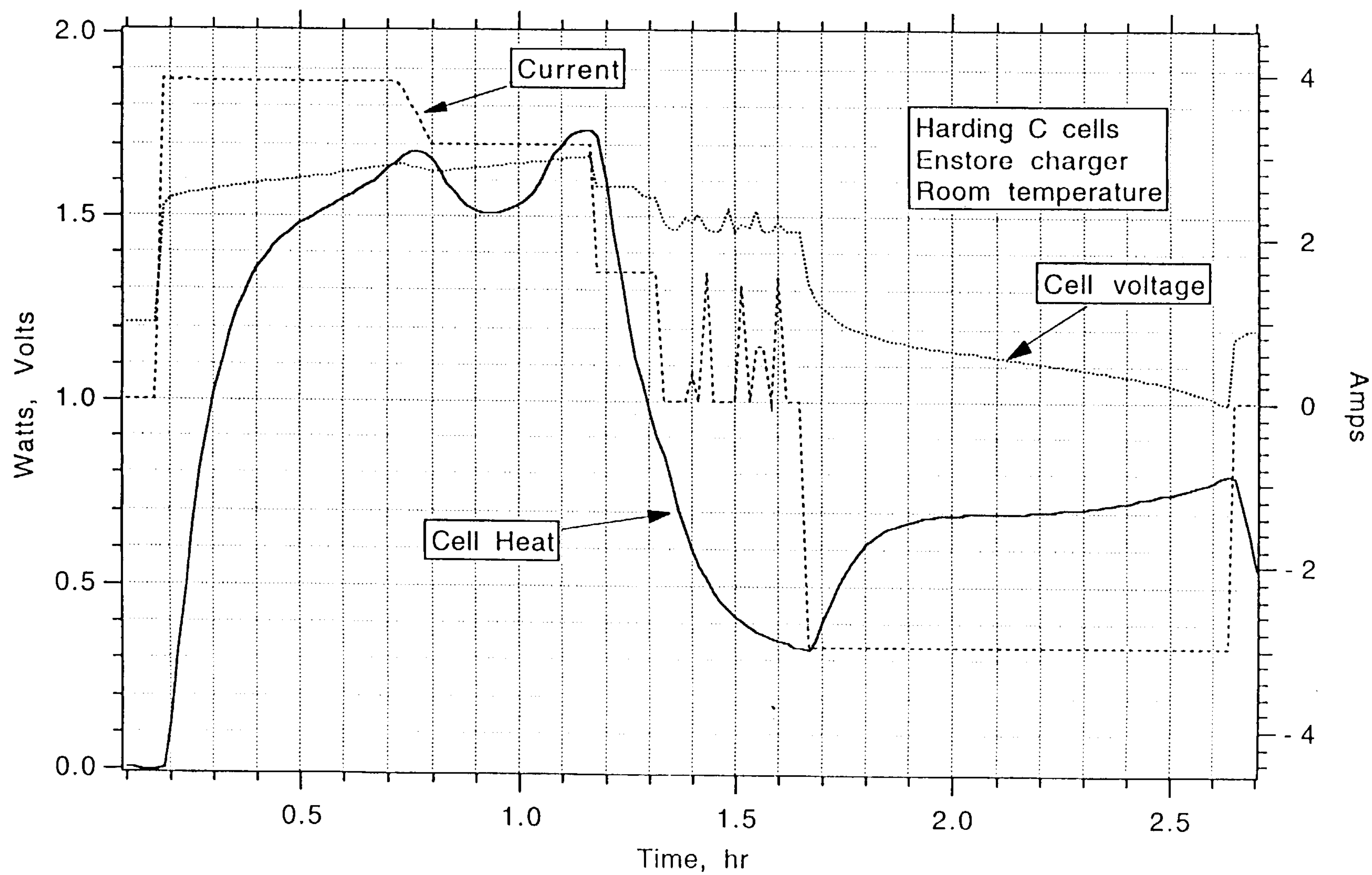

The Benchmarq charger uses a negative slope algorithm, which has proven successful with Ni-Cd cells, and couples it with a cell temperature rise algorithm. Besides the Enstore charger, it has the least amount of current rate settings. The chip has an input pin to activate discharge of a battery before initiating charge.

Benchmarq Charger	Propulsion and Power Division	
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Model # - bq2003 by Benchmarq Microelectronics, Inc.

Input - constant voltage of 11 V (or constant current with additional circuitry)

Output - constant current set by user with resistors

Charge Rates - C/4, C/2, C, 2C, and 4C

Primary Charge Termination Methods
- temperature rise ($\Delta T/\Delta t$)
- negative voltage slope ($-\partial V/\partial t$)

Secondary Charge Termination Methods
- maximum temperature (user tweakable)
- maximum voltage (user tweakable)
- timer (360, 180, 90, 45, and 23 minutes)

Top-off and Trickle Charge
- top-off is set equivalent to 1/10 the duty cycle of fast charge
- trickle rate constant (user configurable with resistors)

Other Features/Limits
- discharge before charge initiation

The Maxim charger is the simplest tested. It has the least amount of features. Charge current fluctuations can occur if the power transistor is not carefully matched to the control circuit. The resulting voltage fluctuations troubles the zero slope algorithm.

Maxim Charger	Propulsion and Power Division	
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Model # - Max 712 by Maxim Integrated Products

Input - Constant voltage of 11 V (No constant current capability)

Output - Constant current set by user with resistor(s)

Charge Rates - 3C, 2C, 1.5C, 1C, C/2, C/2.5, and C/4

Primary Charge Termination Methods
- maximum voltage point ($\Delta V/\Delta t \leq 0$)
- max temperature (user tweakable)

Secondary Charge Termination Methods
- max voltage (user tweakable)
- timer (22, 33, 45, 66, 90, 132, 180, and 264 minutes)

Trickle Charge
- built-in trickle set to 1/8 of fast charge rate.
- can be set to other values with additional circuitry

Other Features/Limits
- Power transitor must be carefully matched to the control circuit to prevent instabilities in the output.

The ICS charger is the most complex and feature-packed of the lot tested. An important feature is its acceptance of constant current input. This feature exists with the Benchmarq charger with some reworking of the circuitry around the chip, but is not available with the Maxim or Enstore chargers.

ICS Charger	Propulsion and Power Division	
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Model # - ICS 1702 by Integrated Circuits Systems, Inc.

Input - Constant current or constant voltage of 11 V. Configured by user.

Output - Constant current with discharge pulses (Reflex).
Current is limited by size of external transitor.

Charge Rates - C/4, C/3, C/2.5, C/2, C/1.5, 1C, 1.3C, 2C, and 4C

Primary Charge Termination Methods
- voltage inflection ($\partial^2V/\partial t^2 = 0$)
- temperature slope approximately = 0.7°C/min
- negative voltage slope ($-\partial V/\partial t$)

Secondary Charge Termination Methods
- maximum voltage (user tweakable)
- maximum temperature (user tweakable)
- timer (273, 242, 210, 142, 107, 73, 55, 37, and 19 minutes)

Trickle Charge - 2 hr topping and indefinite maintenance charge available

Other Features/Limits
- discharge pulse current is set by user
- 2 min soft start period prevents false voltage inflection termination

The typical Reflex current profile uses a discharge pulse level set at -2.5 times the charge current.

Reflex charge profile

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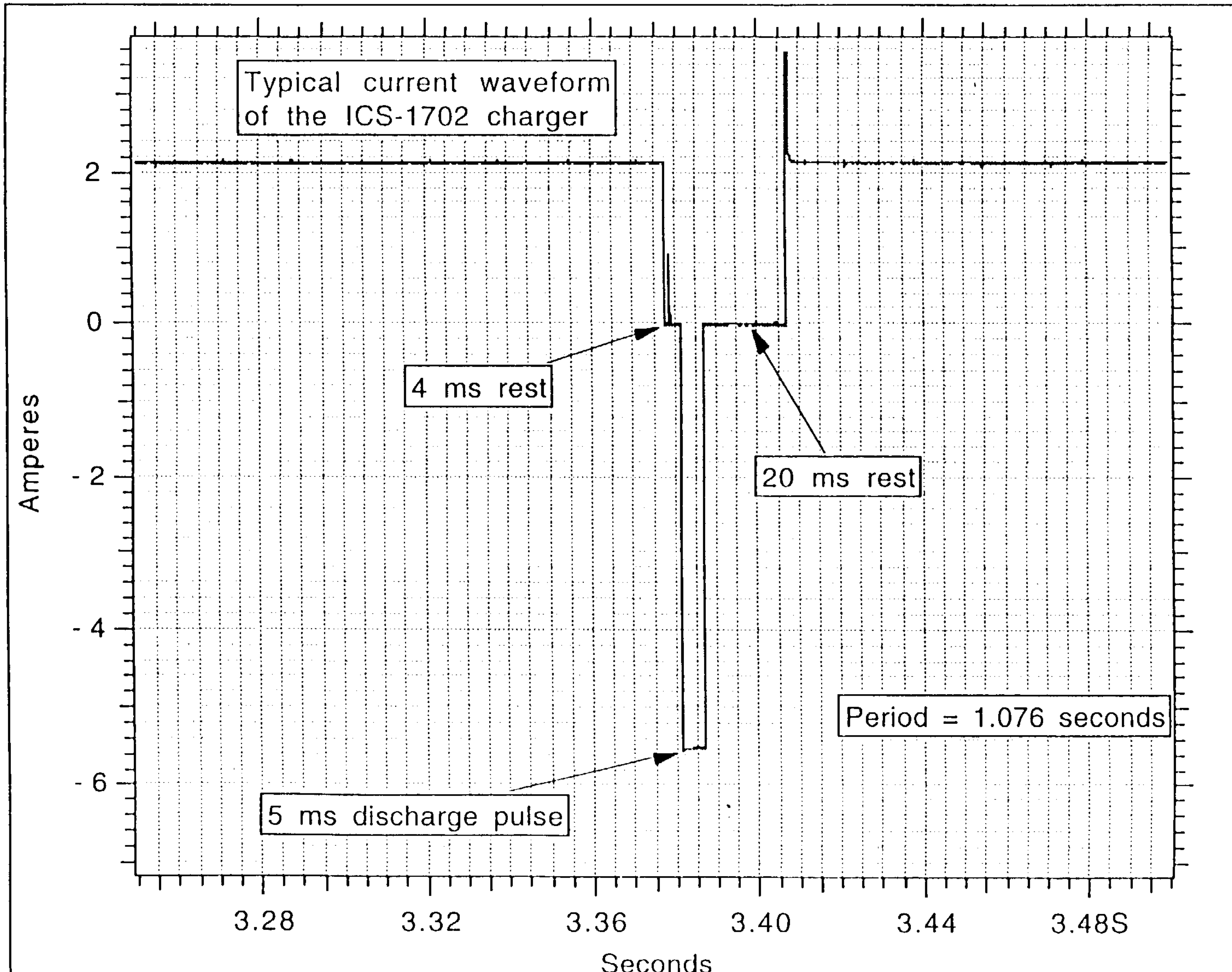

The objective of the experiment is to determine which combination of factors contribute to maximum discharge capacity as a % of nameplate capacity after 100 cycles. A secondary objective was to determine the Ah C/D ratios of each combination. All three Harding batteries (consisting of A-cells) failed within 80 cycles to deliver appreciable capacity. They were replaced with Gold Peak cells.

Cycling experiment using Taguchi techniques	Propulsion and Power Division	
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1 st Performance Evaluation using L18 Taguchi Matrix

- 3 cell types - Harding A, Sanyo 4/3A, and Toshiba 4/5A
- 3 chargers - Benchmarq, ICS, and Maxim
- 3 charge rates - 3/C, C, and 2C
- 3 trickle charge rates - C/100, manufacturer setting, and C/10
- 3 trickle charge times - 5 min, 1 hr, and 2 hr
- 3 charge and discharge rest times - 2 min, 15 min, 30 min
- 2 temperatures - 25 and 5 deg C
- 1 discharge rate - C rate to 1 volt/cell

Performance criteria

- Discharge capacity (as % of nameplate) vs cycle number

After Harding cells failed, they were replaced with Gold Peak 7/5A cells.

This plot shows the cycling performance of Sanyo 4/3A batteries with 3 different chargers at room temperature. Sanyo cells performed very consistently. Benchmarq terminated after 85-87% charge input at a C rate probably due to its sensitive temperature rise termination algorithm. Interestingly, ICS achieved a lower C/D Ah ratio at 2C than Maxim did at C/3, while discharge output was nearly identical.

Sanyo 4/3A cell cycling

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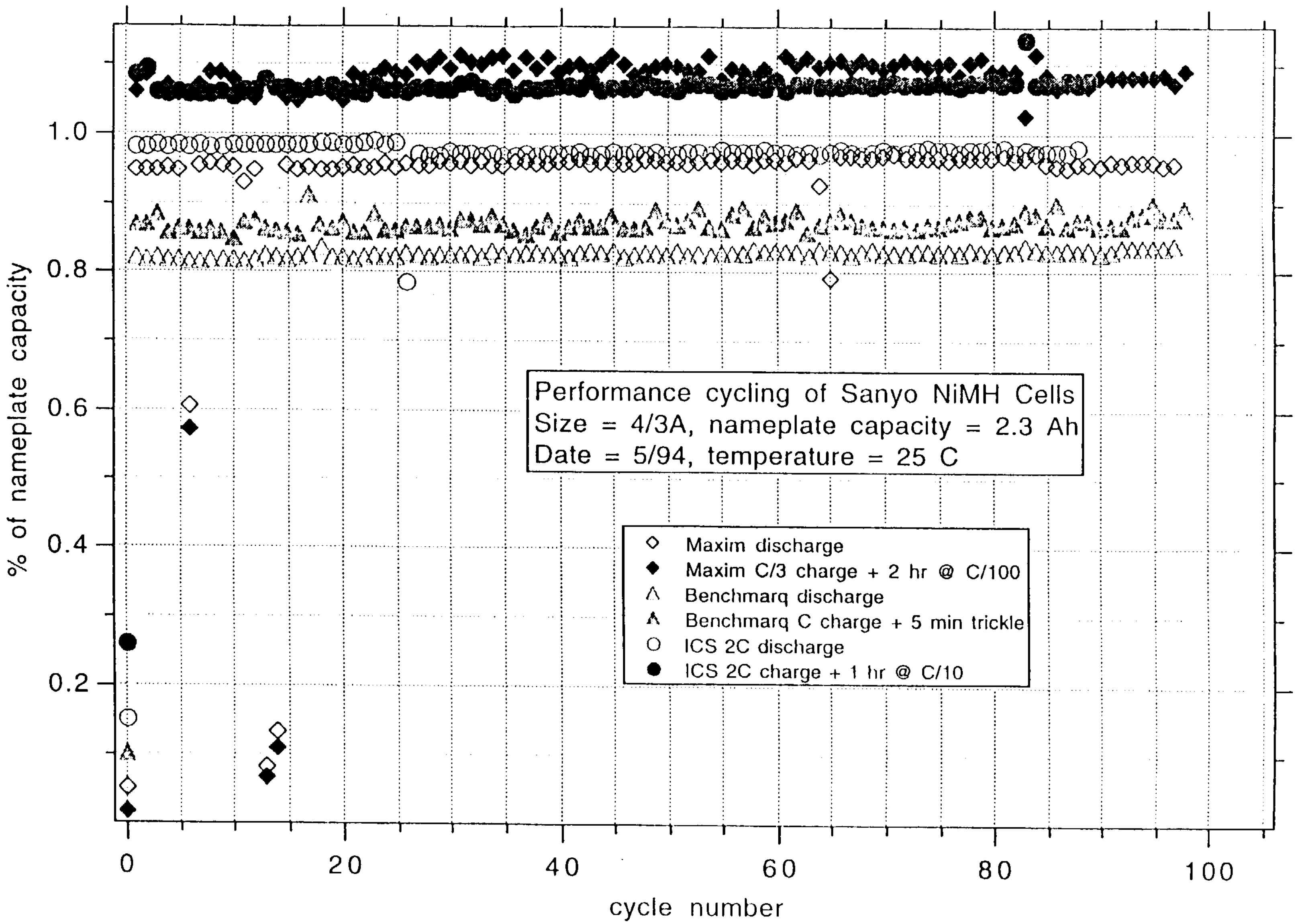

Toshiba batteries were also consistent performers with all the chargers. Curiously, the rate of charge did not effect the discharge output (90% of nameplate capacity). ICS inconsistencies were due to a "testing" bug.

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Toshiba 4/5A cell cycling

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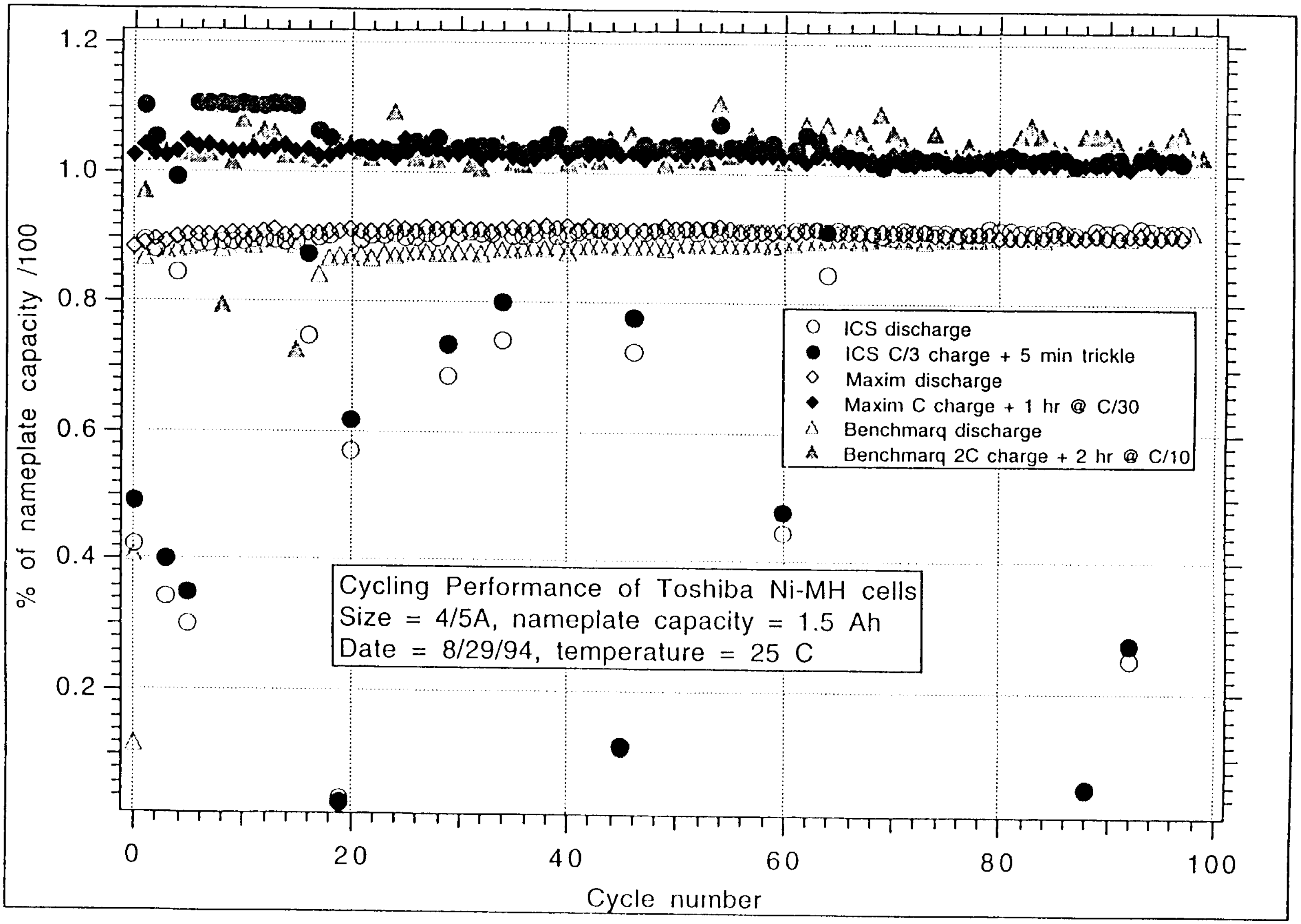

Gold Peak batteries did not perform much better than Harding cells. At C/3 rate, they faded. At C rate, they failed abruptly. At the 2C rate, they only accepted a 60% charge input.

Gold Peak 7/5A cell cycling

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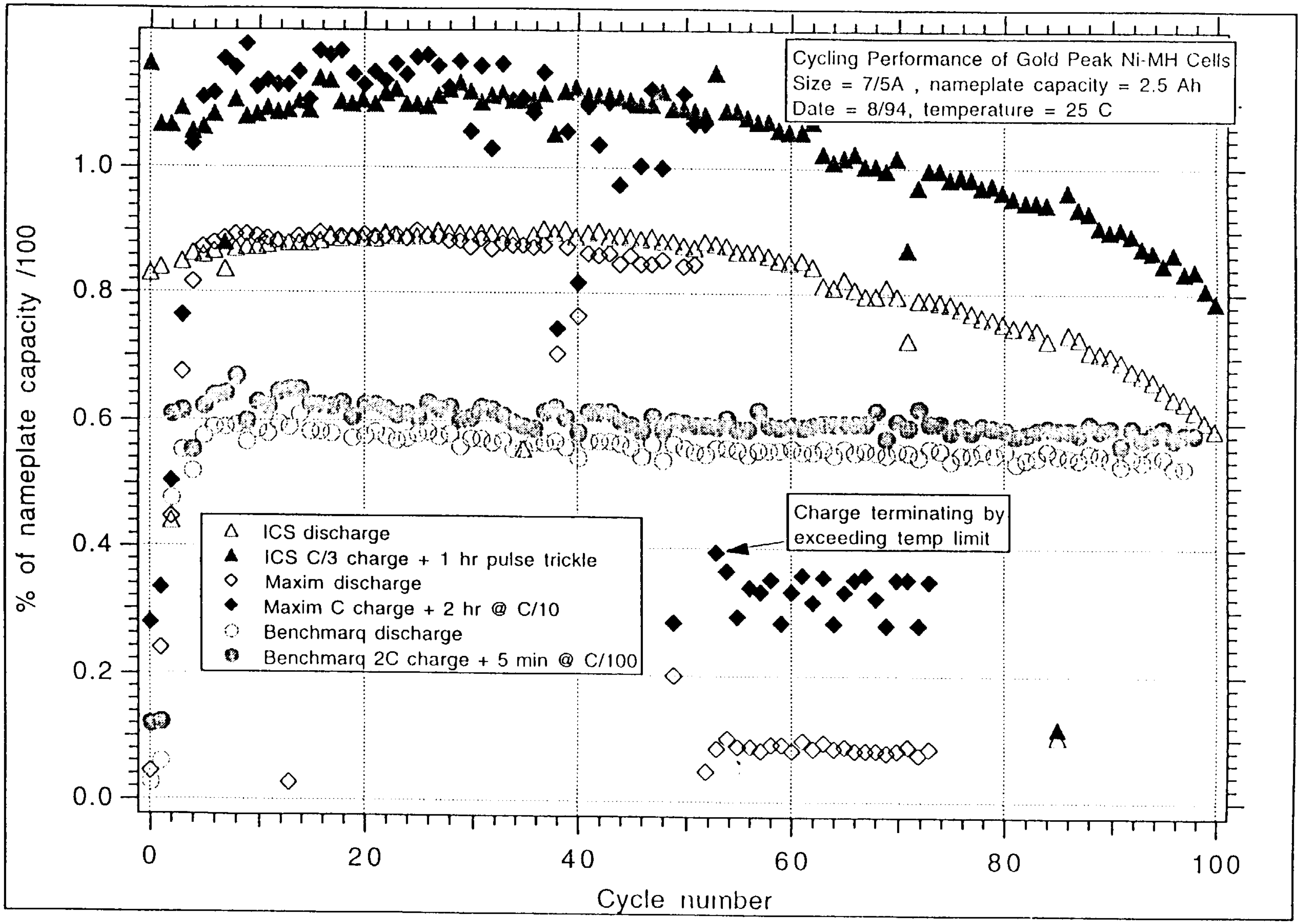

At 10 °C, Sanyo cells were consistent like at room temperature. Note that the discharge output of the Benchmarq C/3 charge was identical to the Maxim 2C charge. Both benefited from C/100 trickle period. ICS terminated at 90% charge input, and thus, fared weakly at this lower temperature.

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Sanyo 4/3A cell cycling at 10°C

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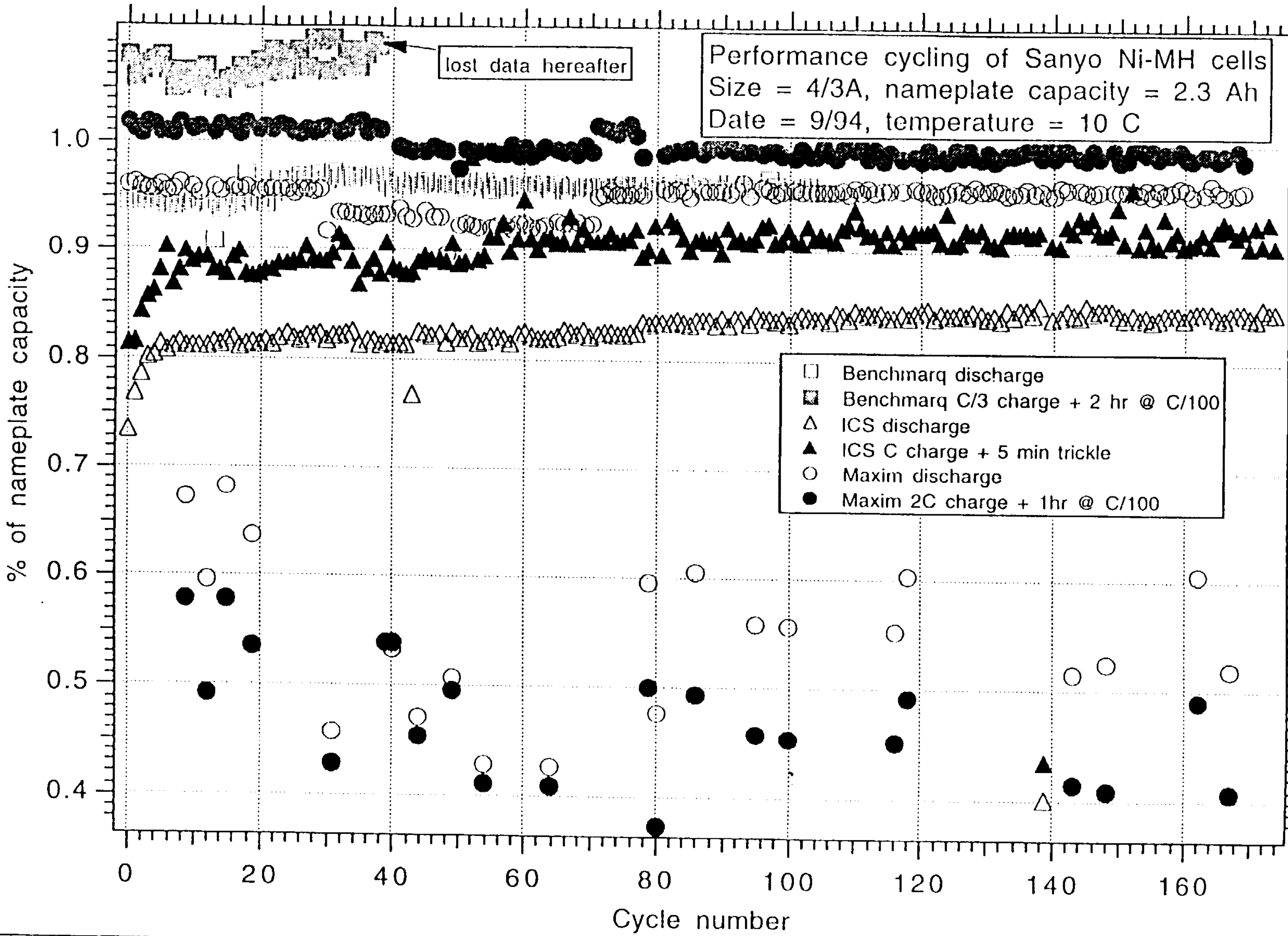

Toshiba cells showed signs of capacity degradation. Note that these cycles where accumulated on top of those done at room temperature. ICS at a C rate has a good C/D ratio with a 85% discharge output.

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Toshiba 4/5A cell cycling at 10°C

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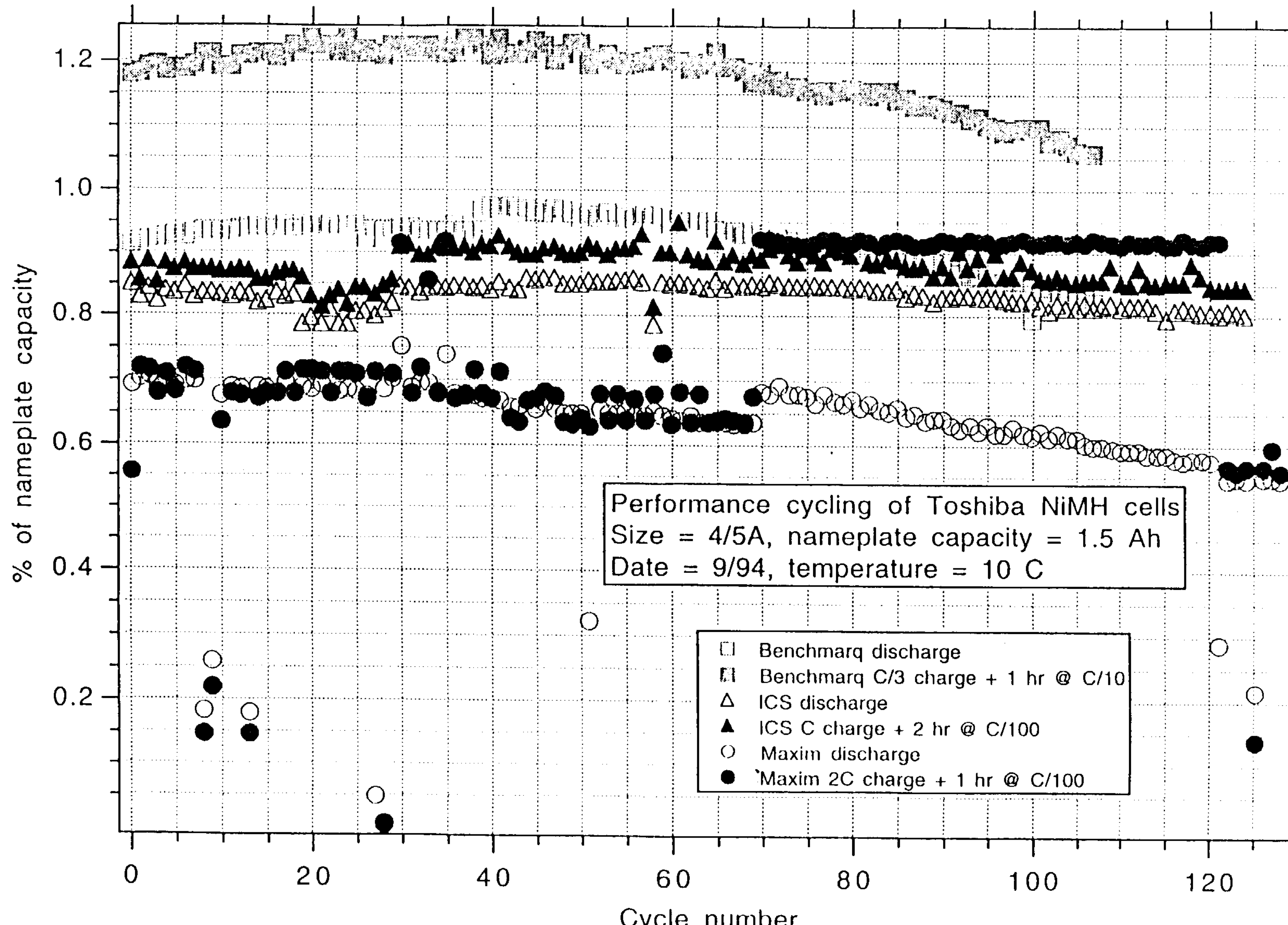

Gold Peak performance at 10 °C was dismal.

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Gold Peak 7/5A cells at 10°C

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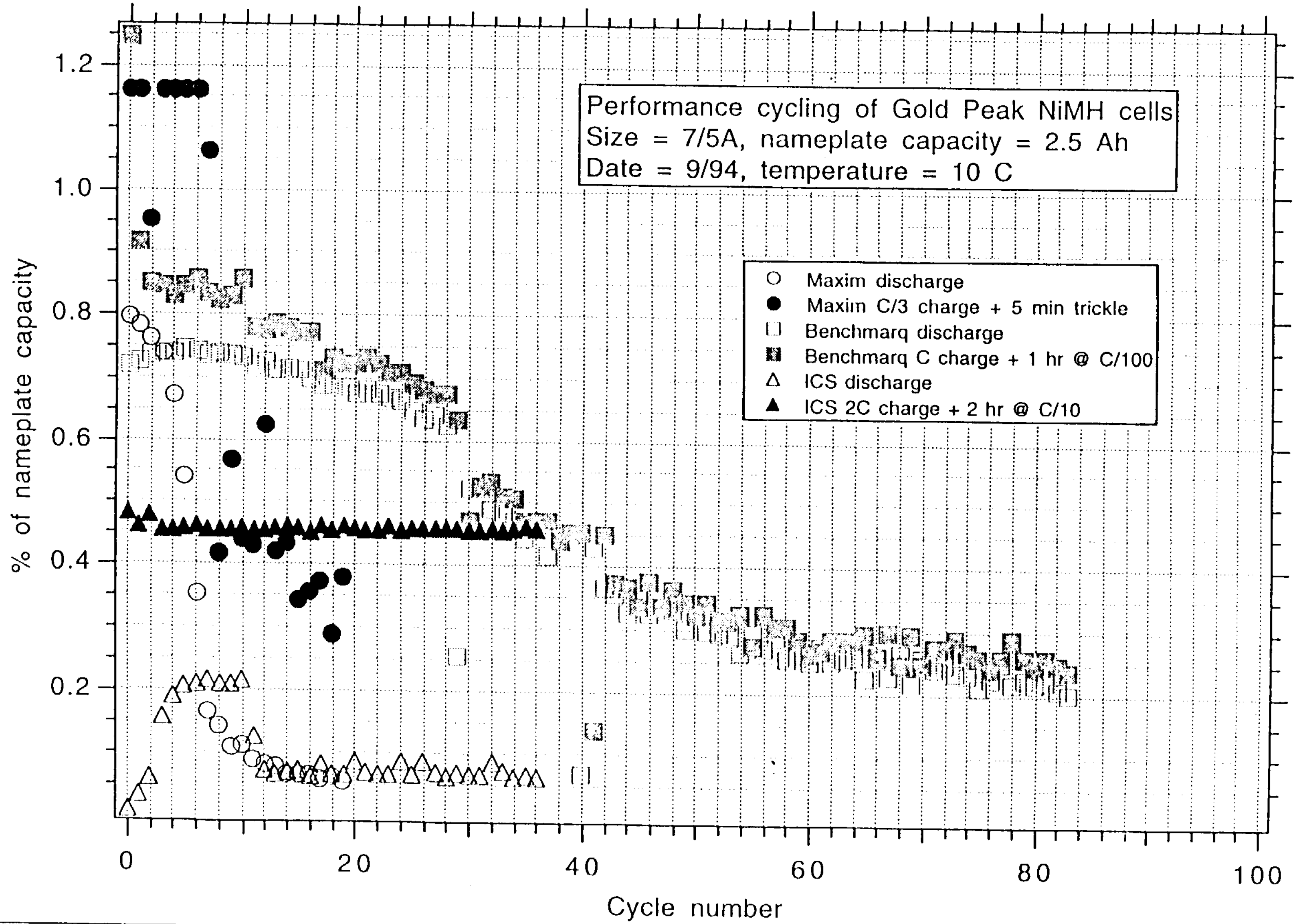

Cell type was the overwhelming factor affecting discharge output after 100 cycles because the Gold Peak cells performed so poorly. The contribution attributed to experimental error was higher than all other factors.

Main Effects Analysis

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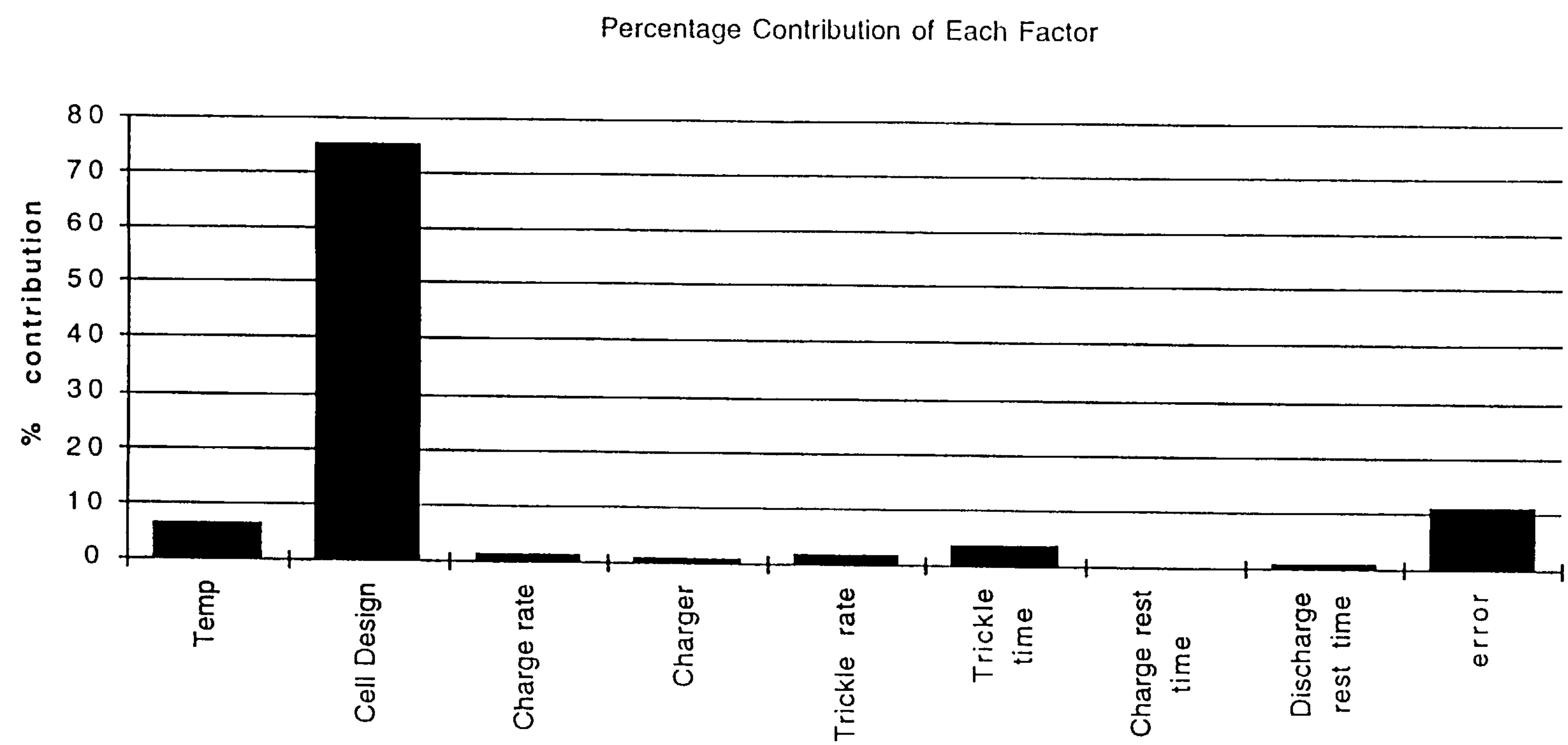

- Cell type was the most important factor effecting % of discharge capacity
- All other factors were less important than experimental error

Nevertheless, the effects of varying the levels of each factor can be observed. Room temperature was 20% better than 10 °C. Strangely, the three hour and 2C rates were better than C rate. Benchmarq and ICS chargers faired better than Maxim. A future experiment is needed with only one cell type to more accurately pin point the effects of the chargers, charge rate, etc.

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Effects of Varying Levels

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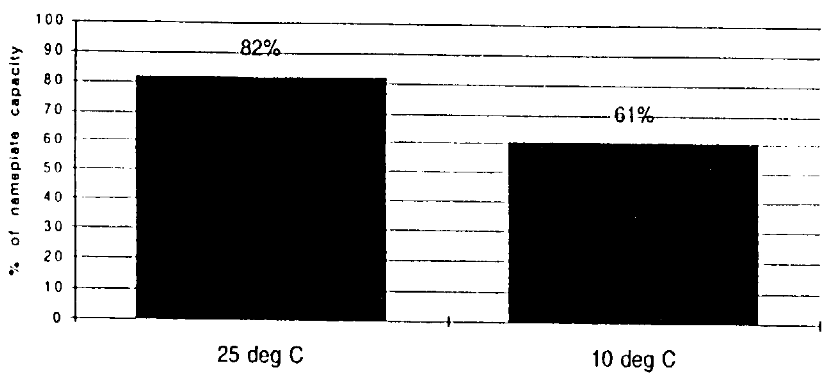
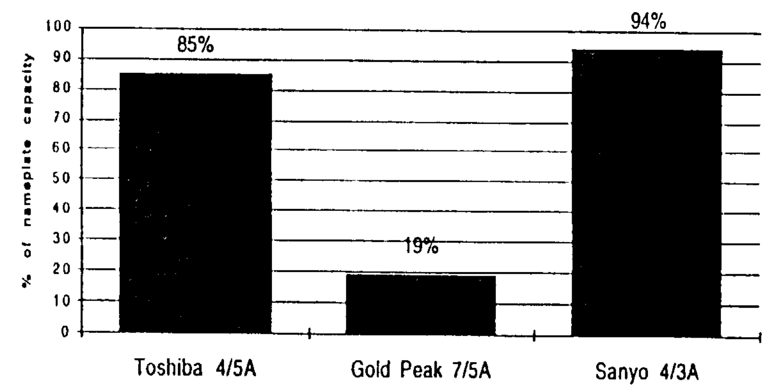
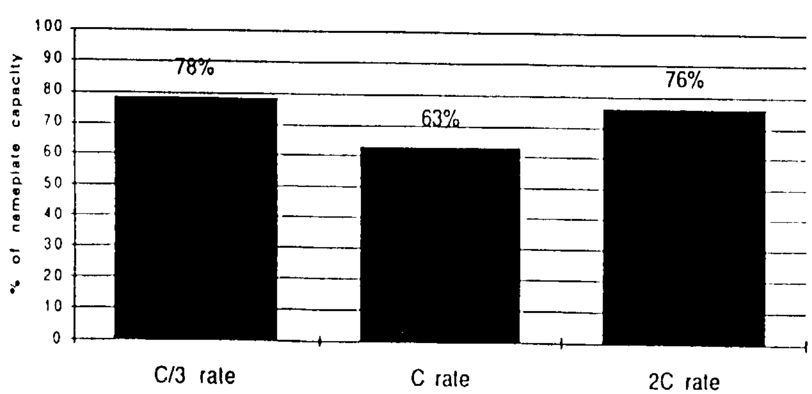
Temperature Effects on Discharge Capacity



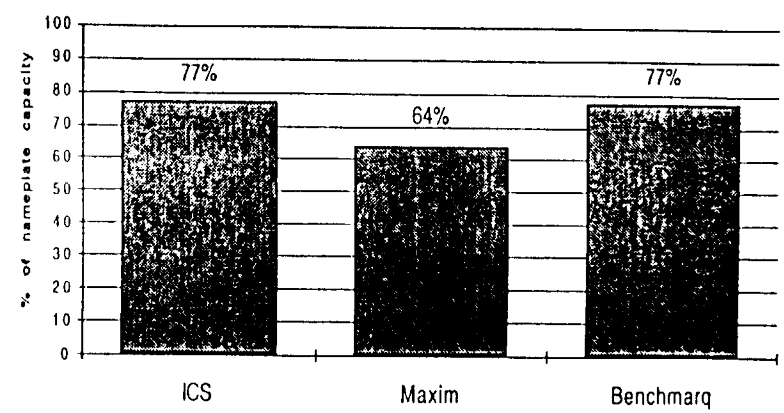
Effect of Cell Design on Discharge Capacity



Effect of Charge Rate on Discharge Capacity



Effect of Charger Type on Discharge Capacity



The cells and chargers listed have been evaluated in the calorimeter. Only the best performing cells will be discussed today. The majority of the cells were tested with the ICS charger because of its performance and its constant current input made current adjustments very convenient. The cycling conditions included long rest periods after trickle charge and discharge to allow integration of the heat profile to calculate thermal energy.

Experimental Plan - Calorimetry	Propulsion and Power Division	
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Cell types tested to date
- Ovonic C
- Sanyo 4/3A and 4/3AU
- Gold Peak 7/5A
- Yuasa 4/3A and prismatic
- Toshiba 4/5A
- Maxell 4/3A
- Sanyo Ni-Cd C

Chargers
- Benchmarq Microelectronics, bq2300
- Integrated Circuit Systems, ICS-1702
- Maxim Integrated Products, Maxim712

Cycling conditions
- C charge and discharge rates
- 0.1 A trickle charge for 1 hour immediately after charge
- 2 hr rest after trickle charge and discharge
- 1 volt/cell discharge cut-off
- Room temperature water bath controlled environment

The Sanyo 4/3A cell had the lowest steady state heat rate on charge and discharge. However, it was significantly overcharged by the ICS charger as is evident by the severe heat spike. This overly influences the total charge thermal energy calculation. At a C rate this cell only delivered 94% of its 2.3 Ah nameplate capacity. Sanyo says that the cell N/P ratio is nearly 2.0 and that the nickel electrode is the sintered type. This is clearly a low impedance cell but with limited capacity delivery at higher rates.

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Sanyo 4/3A cells with ICS charger

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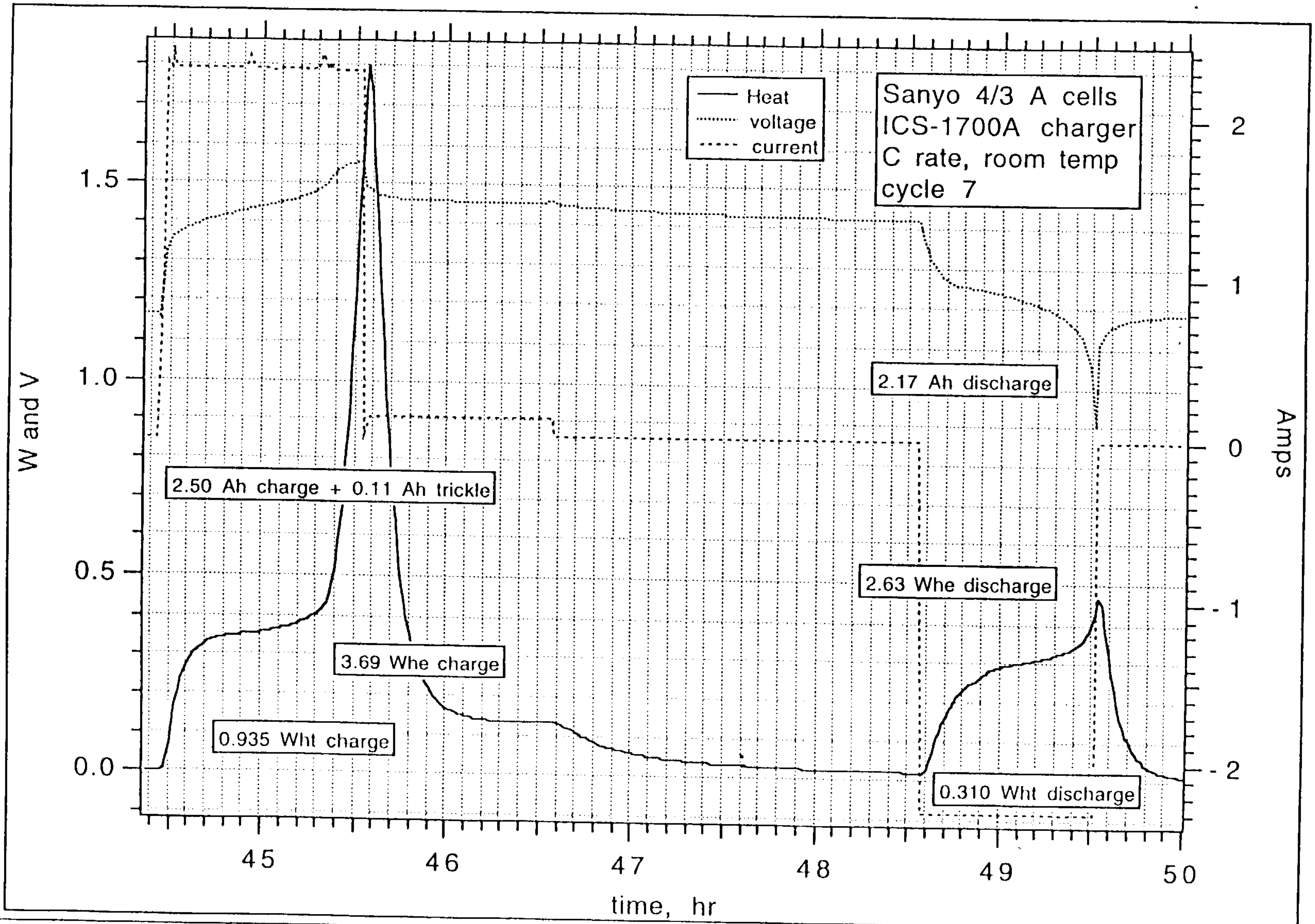

The new Sanyo 4/3AU cell yields a 0.1 Ah more capacity at the same rate but runs very much hotter. Specifically, 1.85 times hotter, in terms of steady state heat, on discharge and 2.43 times hotter on charge. Sanyo says the nickel electrode is non-sintered. Clearly, impedance changes alone can not account for this difference. I suspect hydride modifications have changed the heat of hydriding and dehydriding. Interestingly, this cell suffered less overcharge heat than the 4/3A, maybe because temperature algorithms terminated the AU cell.

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Sanyo 4/3AU cell with ICS Charger

Propulsion and Power Division

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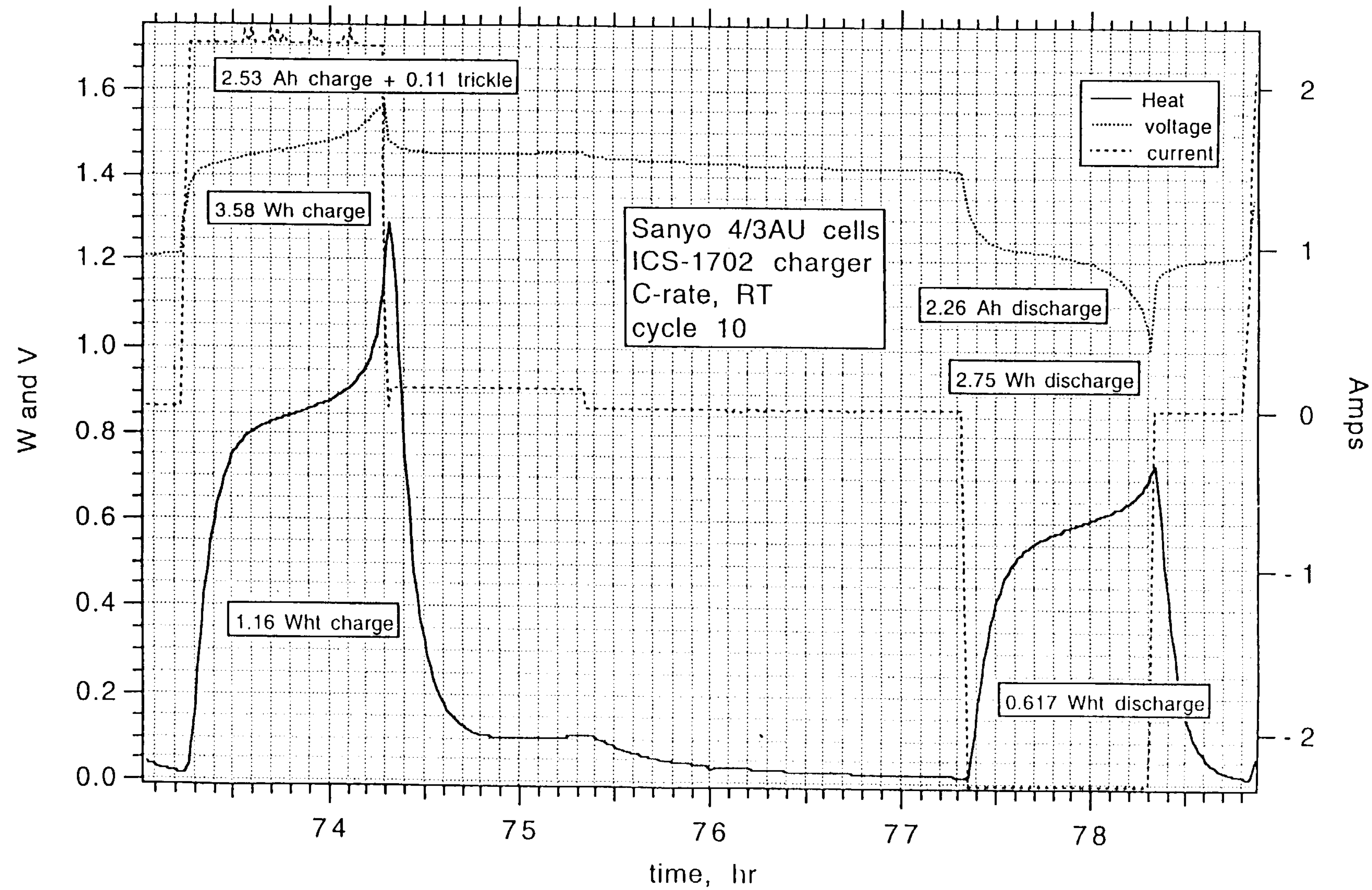

Yuasa 4/3A cell capacity delivery is nearly identical with the Sanyo 4/3A. However, the Sanyo cell runs 1.16 and 1.91 times hotter (steady-state heat) during discharge and charge, respectively. Yuasa has informed me that the cell's N/P ratio is 1.5. This cell appears to suffer the least amount of overcharge heat compared to the Sanyo cells. Yuasa says that the nickel electrode uses a high surface area powder material doped with CoO and pasted onto a porous foam substrate. Again, the difference between heat rates of charge and discharge indicates that their hydride electrodes are different as well.

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Yuasa 4/3A cell with ICS charger

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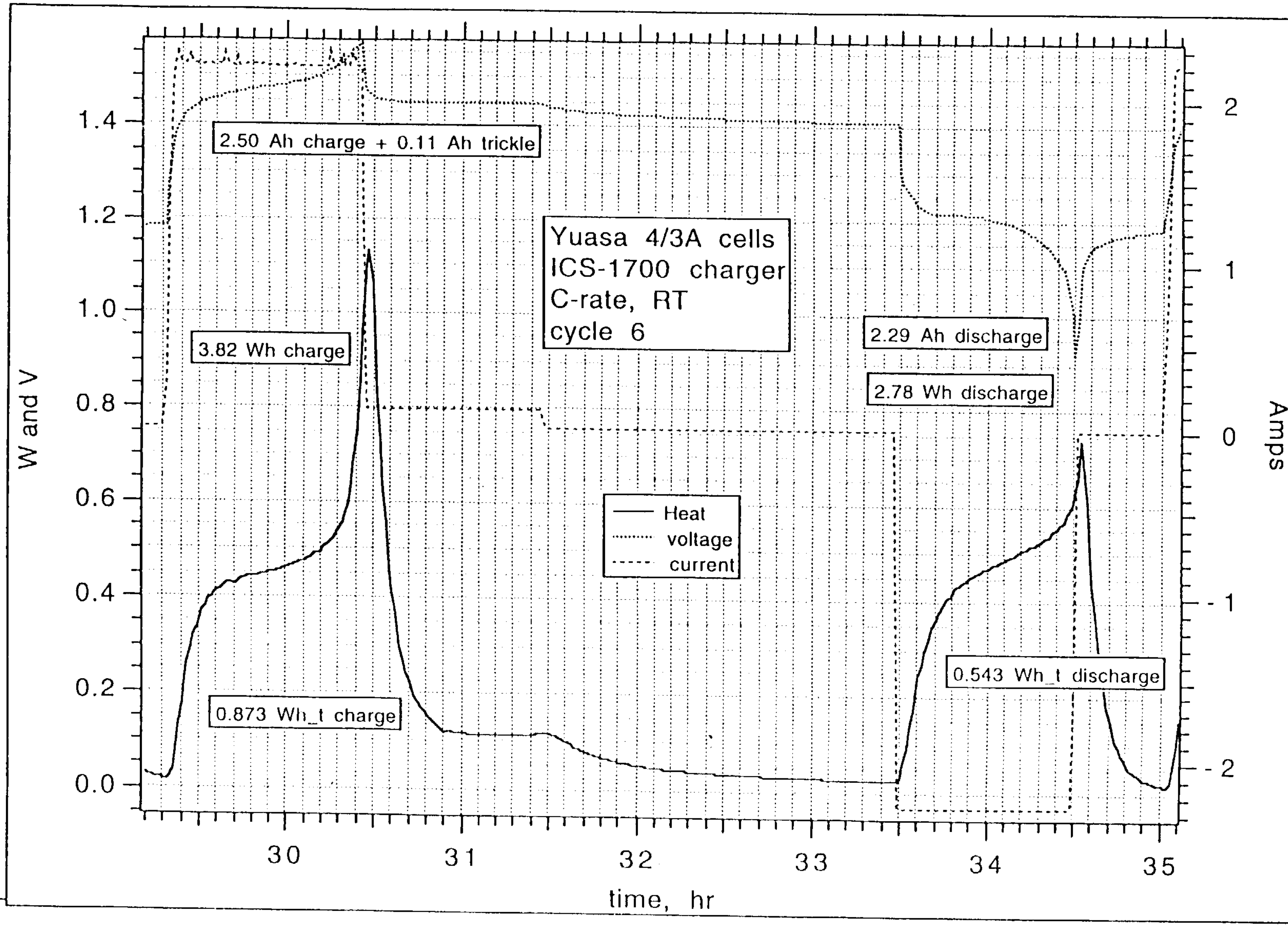

The Yuasa prismatic cell rated at 3.0 Ah delivered slightly less capacity than its cylindrical relative and was not as thermally efficient. This mostly likely due to the higher impedance of the prismatic construction. Yuasa says its N/P ratio is 1.75 and it received more overcharge than its 4/3A relative.

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Yuasa prismatic cell with ICS charger

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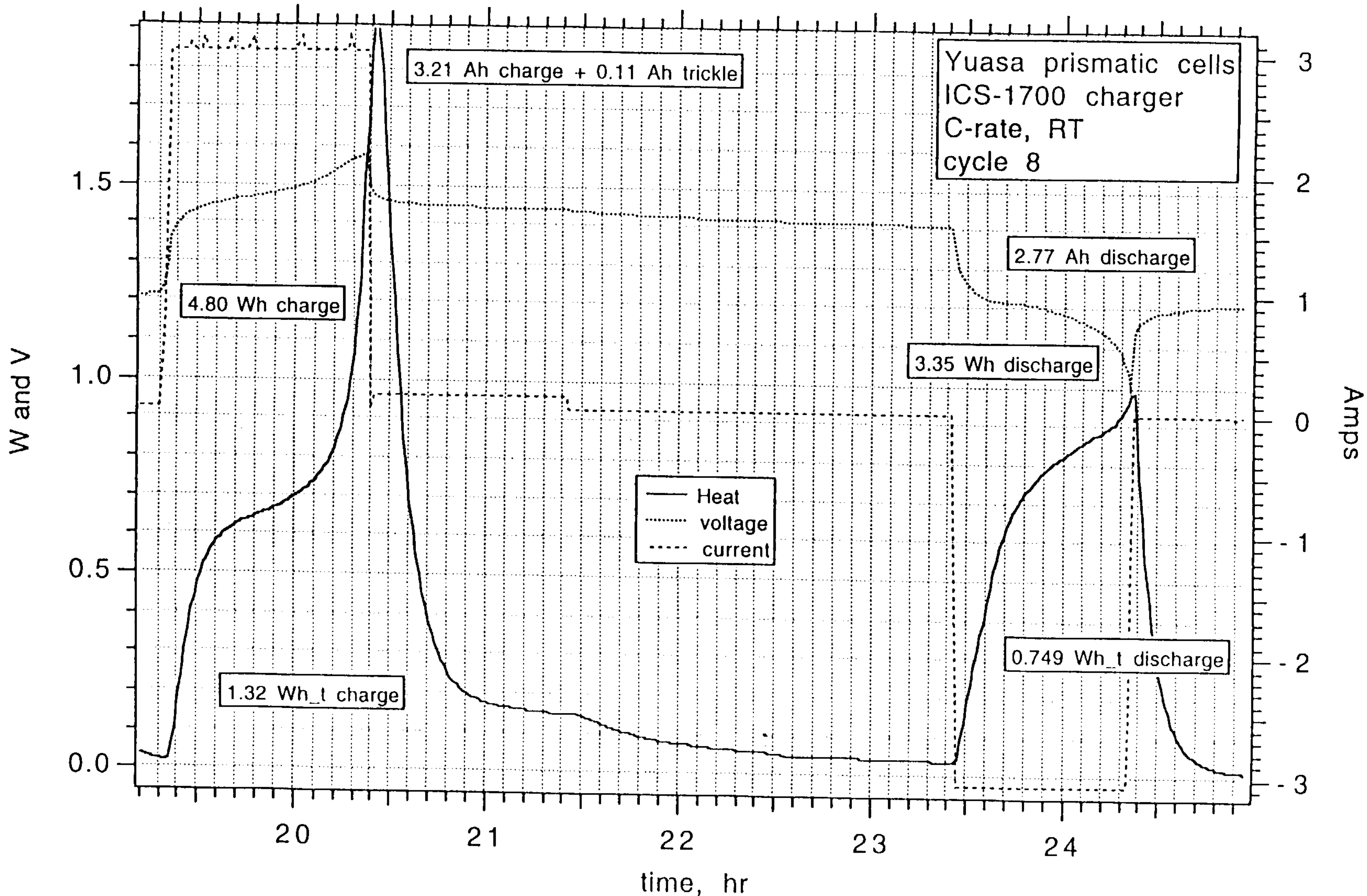

This table compares the four best performing cells. Electrical and thermal potentials are parameters I devised to compare the integrated electrical and thermal energy on a per Ah delivered basis. This allows for comparing cells of varying capacity. On charge, the electrical potentials were nearly identical while the Sanyo 4/3AU clearly generated more heat per Ah than the others. On discharge, the Sanyo 4/3A cell generated less heat per Ah delivered. But the telling parameter is the midway heat rate value determined halfway during charge and discharge. Differences in midway voltage were minimal compared to the midway heat. This comparison demonstrates the wide difference in the thermal characteristics of Ni-MH cells all using similar hydride formulations (AB_5).

Comparison of 4 best cells

Propulsion and Power Division

Eric Darcy **11/16/94**

	Sanyo 4/3A	Sanyo 4/3AU	Yuasa 4/3A	Yuasa Prismatic
Charge characteristics				
Ampere-hours, Ah	2.61	2.55	2.61	3.32
Watt-hours, Wh	3.82	3.69	3.69	4.8
Electrical potential Wh/Ah, V	1.46	1.45	1.41	1.45
Watt-hours thermal, Wht	0.935	1.26	0.873	1.32
Thermal potential Wht/Ah, V	0.358	0.494	0.334	0.398
Midway voltage, V	1.44	1.46	1.47	1.47
Midway heat, W	0.36	0.875	0.459	0.65
Discharge characteristics				
Ampere-hours, Ah	2.17	2.26	2.29	2.77
Watt-hours, Wh	2.63	2.8	2.78	3.35
Electrical potential Wh/Ah, V	1.21	1.24	1.21	1.21
Watt-hours thermal, Wht	0.31	0.587	0.543	0.749
Thermal potential Wht/Ah, V	0.143	0.26	0.237	0.27
Midway voltage, V	1.23	1.219	1.21	1.2
Midway heat, W	0.295	0.547	0.472	0.78

Comparison findings	Propulsion and Power Division	
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Sanyo 4/3A vs Sanyo 4/3AU

- AU cell yields 0.1 Ah more on discharge at C rate
- AU cell runs 1.85 and 2.43 times hotter during discharge and charge
- impedance changes alone can not account for this difference
- difference probably due to a change in ΔH of hydriding/dehydriding

Yuasa 4/3A vs Sanyo 4/3AU

- capacity delivery is nearly identical
- Sanyo cell runs 1.16 and 1.91 times hotter during discharge and charge

Yuasa Prismatic vs Yuasa 4/3A

- Prismatic delivered slightly less Ah relative to its nameplate (3 Ah)
- Prismatic not as thermally efficient due to higher impedance

Most thermally efficient cells

- Yuasa 4/3A cell during charge (0.78)
- Sanyo 4/3A cell during discharge (0.88)

$$e = \frac{Wh - Wh_{thermal}}{Wh}$$

Summary Conclusions	Propulsion and Power Division	
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Performance Cycling
- AB_5 (Sanyo, Yuasa, Toshiba) cells cycled more consistently than AB_2 cells
- Yuasa 4/3A and Sanyo 4/3AU yielded best energy (56 Wh/kg, 193 Wh/L)

Taguchi Experiment
- Cell Design was most important factor due to poor performance of AB_2 cell
- ICS and Benchmarq chargers are better than Maxim charger

Calorimetric Study
- AB_5 cells are more thermally efficient than AB_2 cells
- Nevertheless, thermal performance varies widely within AB_5 cell designs.

Future tests

Propulsion and Power Division

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- Calorimetric evaluation of other viable cells and chargers
- Convert test stand to ICS chargers and cycle test the following cells
  - Yuasa 4/3A
  - Yuasa Prismatic
  - Sanyo 4/3AU
  - improved Toshiba 4/3A cells
  - Furukawa prismatic cells
- DPA's to correlate performance to cell design

Back-up charts

DPA plan	Propulsion and Power Division	
	Eric Darcy	11/16/94

Purpose: Determine why Yuasa cells are thermally different from Sanyo cells

Part I - Determine general cell design characteristics
- Cell gas composition and pressure (gas chromatograph)
- KOH conc of electrolyte (titration) and ion composition (ion chromatography)
- Weight and volume distribution of dry cell components

Part II - Analysis of the negative
- Grain structure (optical and SEM techniques)
- Elemental composition (Mass Spectroscopy)
- Specific surface area (BET)
- Porosity and pore distribution (Hg porosimetry)
- Elemental and molecular composition of surface (XPS)
- Composition depth profiling of the surface (AES)
- Electrochemical capacity, mAh/g (electrode test)
- Heat of hydriding/dehydriding (calorimetry)

Part III - Analysis of the positive
- Electrochemical capacity, mAh/g (electrode test)
- Porosity and pore distribution (Hg porosimetry)

Test Stand Description	Propulsion and Power Division	
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Automated Battery Cycler Capabilities

- 10 independent battery cycling stations
- Each station equipped with bipolar power supply = 20 V and ±10 A
- Charge control options for each station
  - user software controlled with power supply as source, or
  - controlled by IC chargers using battery voltage and temperature inputs
- Data Acquisition = 40 channels, 15 to 30 sec single scan rate
- Stand Computer is a Macintosh IIci, 20 MB RAM, 100 MB HD, 25 MHz
- LabVIEW software for stand control and data acquisition
  - 5 state cycle; discharge, discharge rest, charge, trickle charge, charge rest
  - Charge parameters = current with time, voltage, and temperature limits
  - Discharge parameters = current with voltage and time limits
  - Trickle charge parameters = current with time, voltage, and temp limits
  - Number of cycles entered by user
- LabVIEW for datalogging
  - Battery state time, voltage, current and temperature read each scan
  - Uses fencepost and deadband features to minimize stored data.
  - Logs battery state t, V, I, and T at the end of each state.

Battery environment maintained with water and air bath

- 1355 cc (83 in^3) available for all ten batteries
- range; 0 to 100 °C

Calorimeter Capabilities	Propulsion and Power Division	
	Eric Darcy	11/16/94

Twin Cell Heat Conduction Calorimeter

- made by Hart Scientific, Inc.
- can accommodate D-cells or smaller
- no messy immersion of battery in heat conductive liquids needed
- water bath temperature range is 0 to 100 C
- water bath stabilizes temperature to $\pm$ 0.01 °C
- walls of twin cells measure heat with thermoelectric sensors
- 200 second time constant
- 100 μW resolution
- 10 channel data acquisition; bath temp, heat, and 8 other user selected
- twin cell design cancels effects of external undesired thermal inputs
- other measurement cell is used for calibration, or
- two batteries can be tested simultaneously with lower resolution

Yuasa 4/3A and prismatic cell cycling

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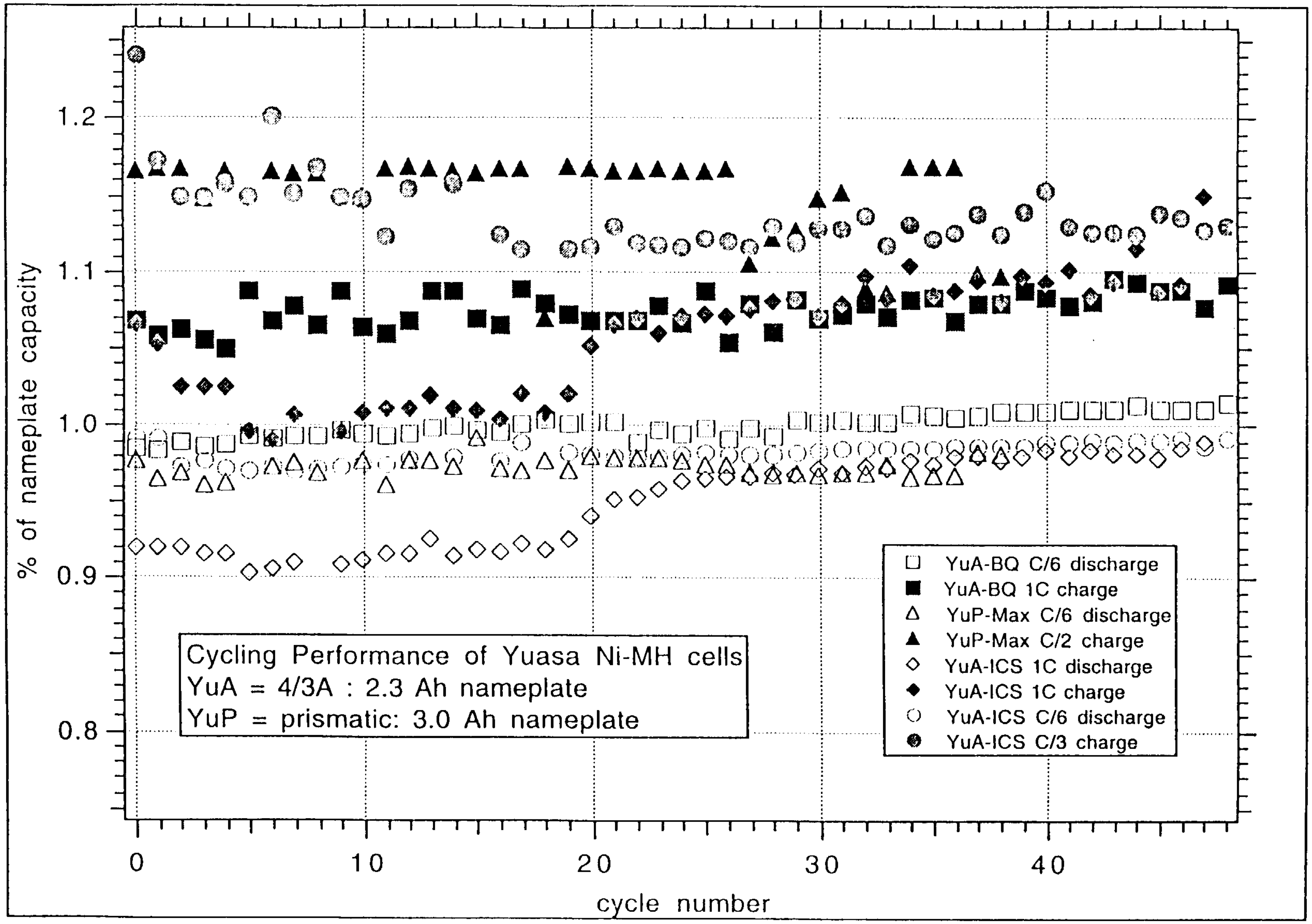

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Tabular comparison of all cells tested

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		AB2	AB5	AB5	AB5	AB5	AB5	AB2	AB2
	Ni-Cd	Ovonic C	Sanyo 4/3A	Sanyo 4/3AU	Yuasa 4/3A	Yuasa P	Toshiba 4/5A	Gold Peak 7/5A	Maxell 4/3A
Nominal cell weight (g)	80	84	49.2	50.6	49.9	75.7	32	47.4	49.3
Nominal cell volume (L)	0.0241	0.0241	0.014	0.0145	0.0147	0.0202	0.00976	0.0153	0.0145
Benchmarq bq2300 charger									
Discharge output (% of nameplate)	107	78	87						
Ah C/D ratio	1.15	1.23	1.12						
Wh C/D ratio	1.35	1.83	1.38						
Wh_t C/D ratio	0.96	2.68	2.1						
Charge efficiency	0.85	0.63	0.77						
Discharge efficiency	0.78	0.75	0.85						
Specific energy (Wh/kg)	32.8	33.2	48						
ICS-1700A charger									
Discharge output (% of nameplate)	109	77	94	94	95	92	87	78	87
Ah C/D ratio	1.18	1.44	1.2	1.13	1.14	1.2	1.2	1.3	1.2
Wh C/D ratio	1.34	2.05	1.4	1.32	1.33	1.42	1.32	1.68	1.43
Wh_t C/D ratio	1.06	2.89	3.02	2.15	1.53	1.66	2.31	2.68	2.83
Charge efficiency	0.83	0.69	0.75	0.658	0.78	0.73	0.78	0.69	0.61
Discharge efficiency	0.78	0.79	0.88	0.79	0.81	0.77	0.87	0.8	0.8
Specific energy (Wh/kg)	33.4	32.4	52.6	55.3	55.6	44.4	48	47.4	48.7
Energy density (Wh/L)	111	113	185	193	189	166	157	147	166
Maxim 712 charger									
Discharge output (% of nameplate)	107	78	93						
Ah C/D ratio	1.13	1.3	1.17						
Wh C/D ratio	1.34	1.83	1.42						
Wh_t C/D ratio	0.97	2.71	2.62						
Charge efficiency	0.84	0.63	0.75						
Discharge efficiency	0.78	0.75	0.86						
Specific energy (Wh/kg)	33	33.2	52.4						
Enstore ECS-II charger									
Discharge output (% of nameplate)		90							
Ah C/D ratio		1.32							
Wh C/D ratio		1.92							
Wh_t C/D ratio		2.4							
Charge efficiency		0.721							
Discharge efficiency		0.777							
Specific energy (Wh/kg)		39							

Note: All figures obtained while charging/discharging at C rates

Eric Darcy

Abuse Tolerance Determination

of

Commercial Ni-MH cells

Outline

- Objectives
- Test Matrix
- Overcharge
- Reversal
- Short Circuit
- Heat-to-Vent
- Conclusions

Test Matrix

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Manufacturer	Shape	Capacity, Ah	Overcharge	Reversal	Short Circuit	Heat-to-Vent
Furukawa	prismatic	0.55	x	x	x	x
Furukawa	AA	1.1				x
Gates	4/5A	1.5				x
Goldpeak	7/5A	2.5			x	x
Harding	AA	1.1	x	x	x	x
Harding	A	1.8	x	x	x	x
Harding	C	3.25	x	x	x	x
Maxell	4/3A	2.3				x
Ovonic	C	3.25	x	x	x	x
Sanyo	4/3A	2.3	x	x	x	x
Toshiba	4/5A	1.5	x	x	x	x
Yuasa	4/3A	2.4				x
Yuasa	prismatic	3				x

Overcharge Tests

Propulsion and Power Division

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Overcharge reactions

negative MH electrode; $2\ H_2O + O_2 + 4e^- \longrightarrow 4\ OH^-$

positive NiOOH electrode; $4OH^- \longrightarrow 2H_2O + O_2 + 4e^-$

Conditions
- Charge input > 200% of nameplate capacity
- 4 tests run per cell type
  - low rate (C/3) at room temperature (RT) and at 0 °C
  - high rate (2C) at RT and at 0 °C

Results
- At C/3 and RT, no cells leaked and found no evidence of leaking
- At C/3 and 0 °C, only Toshiba and Harding C cell leaked a bit of KOH
- At 2C rate, only the Harding C cell leaked at both temperatures
- Max cell temp = 88 °C by Sanyo and Ovonic cells at high rate, RT
- None of the cells leaked profusively or ruptured

Overdischarge/Reversal Tests	Propulsion and Power Division	
	Eric Darcy	11/16/94

Overdischarge reactions

negative MH electrode; $H_2 + 2OH^- \longrightarrow 2e^- + H_2O$

positive NiOOH electrode; $2H_2O + 2e^- \longrightarrow 2OH^- + H_2$

Conditions

- Forced discharge > 200% of nameplate capacity
- 4 tests run per cell type
  - low rate (C/3) at room temperature (RT) and at 0 °C
  - high rate (2C) at RT and at 0 °C

Results

- All the cells leaked some electrolyte
- Max cell temp = 95 °C with Sanyo cell at high rate, RT
- None of the cells leaked profusively or ruptured

Short Circuit Tests

Conditions

- 4 tests run per cell type
  - low rate (0.1 Ω) at room temperature (RT) and at 0 °C
  - high rate (<0.05 Ω) at RT and at 0 °C

Results

- None of the cells leaked detectable amounts of electrolyte during all tests
- Max cell temp (91 °C) with Harding A cell at high rate, RT (peak I = 12.4A)
- Max peak current was 28.4 A (max T = 79 °C) with Sanyo cell at high rate, RT

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Harding A cell

Propulsion and Power Division

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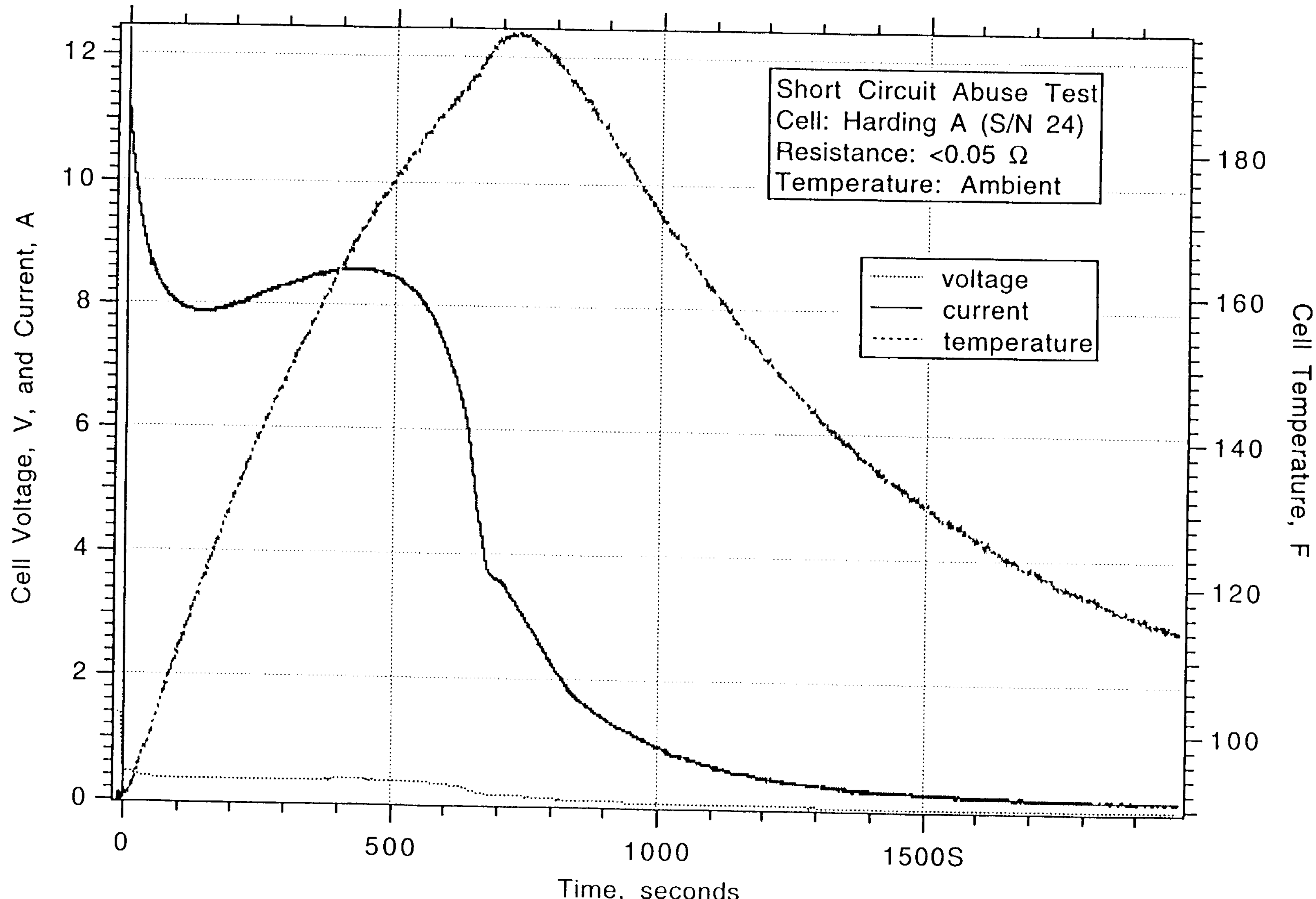

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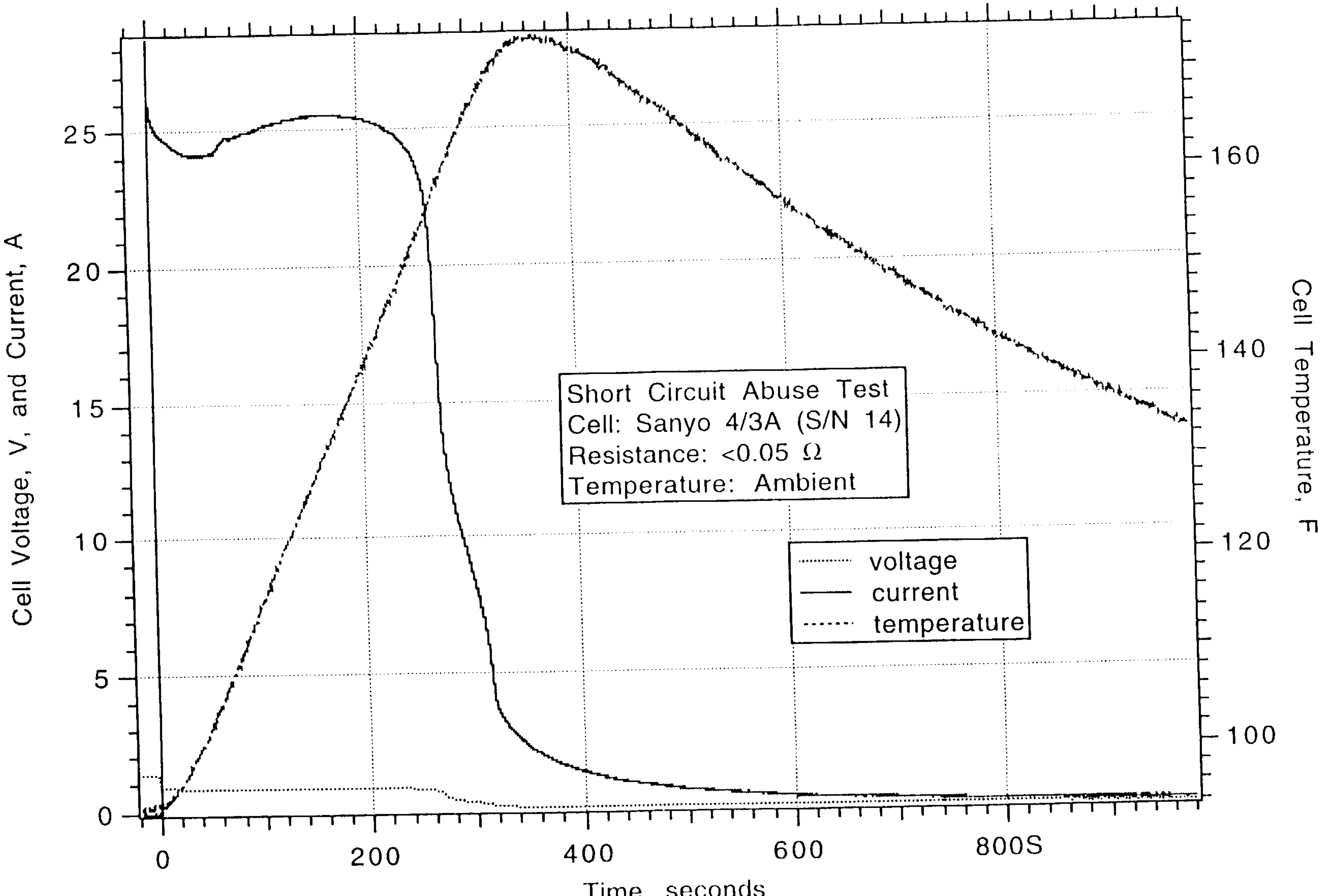
Sanyo 4/3A cell	Propulsion and Power Division	
	Eric Darcy	11/16/94



Heat-to-Vent Tests	Propulsion and Power Division	
	Eric Darcy	11/16/94

Conditions
- cells pre-charged at C/2 for 130 min within 48 hours of oven test.
- cell were placed in evacuated pressure vessel
- pressure vessel and cell were heated in thermal chamber
- Temperature profile
    - RT to 177 °C in 4-5 hours
    - > 1 hour at 177 °C
    - 177 °C to RT overnight
- Vents detected as small sudden increases in vessel pressure

Results
- All cells vented, some gradually, other discreetly from 130 to 171 °C
- Prismatic cells and Ovonic's C-cell lost the most electrolyte
- Outer insulation of all cells was burnt and cracked
- None of the cells ruptured

Heat-to-Vent Results

Propulsion and Power Division

Eric Darcy 11/16/94

Manufacturer	Shape	mass, g	mass lost, %	Vent temperatures, deg F
Furukawa	prismatic	17.4	4	340
Furukawa	AA	27.5	0.7	304, gradual vent
Gates	4/5A	33.4	1.1	gradual vent
Goldpeak	7/5A	47.5	0.6	300
Harding	AA	23.9	0.4	gradual vent
Harding	A	34.8	0.6	gradual vent
Harding	C	83	0.1	gradual vent
Maxell	4/3A	49.3	1.2	269, 272, 281, 328, 330, 331, 332, 334, 336, and 340
Ovonic	C	82.7	4	270 and 285
Sanyo	4/3A	52.7	2.5	272 and 350
Toshiba	4/5A	32.5	3.1	293, 301, and 311
Yuasa	4/3A	49.9	1.8	266, 276, and 284
Yuasa	prismatic	75.8	3.8	gradual vent

Conclusions

Propulsion and Power Division

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- Commercial Ni-MH cells are very tolerant to short circuits
- Overcharge and reversal tests resulted in very benign KOH leakage
- Cells vent noticeably and benignly at temperatures over 130 °C

Summary of Commercial Ni-MH Cell Abuse Test Results

Introduction

The purpose of this test was to determine the abuse tolerance characteristics of various commercially available nickel-metal hydride (Ni-MH) cells. Cells from Furukawa, Gold Peak, Gates, Harding, Maxell, Ovonic, Sanyo, Toshiba, and Yuasa were tested. The tests were conducted as sub portion of test number 2P807 at B352 of the Thermochemical Test Area and included overcharge, overdischarge, short circuit, and heat-to-vent cell tests. The tests were started on 4/14/94 and finished on 8/26/94. Table 1 describes the type of cells evaluated and which tests each type was submitted to.

Table 1

Manufacturer	Shape	Capacity, Ah	Overcharge	Reversal	Short Circuit	Heat-to-Vent
Furukawa	prismatic	0.55	x	x	x	x
Furukawa	AA	1.1				x
Gold Peak	7/5A	2.5			x	x
Gates	4/5A	1.5				x
Harding	AA	1.1	x	x	x	x
Harding	A	1.8	x	x	x	x
Harding	C	3.25	x	x	x	x
Maxell	4/3A	2.3				x
Ovonic	C	3.25	x	x	x	x
Sanyo	4/3A	2.3	x	x	x	x
Toshiba	4/5A	1.5	x	x	x	x
Yuasa	4/3A	2.3				x
Yuasa	prismatic	3.0				x

Overcharge Test

A total of four overcharge tests were performed covering two rates, C/3 and 2C, and two temperatures, room and 0 °C. Each test lasted until a 200% charge input into each cell was achieved. At the C/3 rate, only the low temperature run caused the Toshiba 4/5 A and Harding C cells to lose weight indicating a small venting of electrolyte. At the higher 2C rate only the C cells leaked at both temperature. During the high rate, room temperature test, the Sanyo 4/3A and Ovonic C reached temperatures over 88 °C all others were lower. None of the cells leaked profusely or ruptured.

Reversal Test

A total of four cell reversal test were performed covering two rates, C/3 and 2C, and two temperatures, room and 0 °C. Each test lasted until a >100% reverse charge was drawn from the cell from the point of voltage reversal. Nearly all the cells lost a bit of weight during the tests indicating a venting of some electrolyte. During the high rate, room temperature tests the Sanyo 4/3A reached 95° C. However, none of the cells ruptured.

Short Circuit Test

A total of four cell short circuit test were performed covering two loads, 0.12Ω and >0.05Ω, and two temperatures, room and 0 °C. None of the cells leaked or ruptured during any of the short circuit tests. At the high rate and room temperature, the Harding A cell reached the highest temperature of the all the cells, 91 °C, and its peak current was 12.4 A. Under the same conditions, the Sanyo 4/3A cell had a peak current of 28.4 A while attaining 79 °C.

Heat-to-Vent Test

All the cells listed in Table 1 were charged at C/2 rate for 2 hr and 10 min. and then submitted to this test within 48 hours. This test was performed by placing the cell in a pressurized vessel equipped with feed-throughs for cell voltage and temperature measurements. A roughing pump was used to pull a light vacuum on the cell so as best detect changes in pressure from a transducer connected to the vessel. The vessel was placed in an automated thermal chamber. This massive vessel took about 4-5 hours to heat to 177 °C (350 °F) from room temperature. It was maintained there for an hour before letting the vessel naturally cool off. Prior to opening the vessel, it was purged with nitrogen for over 5 min.

All the cells vented, presumably hydrogen, and varying amounts of electrolyte. These vents were sometimes very gradual over the entire heating process, while some cells vented in very discreet events easily associated with a particular temperature. Table 2 lists the weight loss incurred during the test and any discreet vent temperatures for all the cells tested. Exempting the Ovonic C-cell which is an obsolete cell design, the prismatic cells lost the most weight percent during the ventings. Outer insulation of all the cells was burnt and cracked, but none of the cells ruptured. The Sanyo and Toshiba cells showed evidence of forceful vents. The Sanyo cell's terminal insulator cap on its positive was separated from the lid of the case during the vent. The Toshiba cell's vent products left white deposits covering the positive end of the cell. Including these last two cells, the venting were very benign and uneventful.

Table 2

Cell	Size	Weight, g	Weight loss	Vent temperatures, °F
Furukawa	prismatic	17.4	4.0%	340
Furukawa	AA	27.5	0.7%	304, gradual
Gold Peak	7/5A	47.5	1.1%	gradual vent
Gates	4/5A	33.4	0.6%	300
Harding	AA	23.9	0.4%	gradual vent
Harding	A	34.8	0.6%	gradual vent
Harding	C	83.0	0.1%	gradual vent
Maxell	4/3A	49.3	1.2%	269, 272, 281, 328, 330, 331, 332, 334, 336, and 340
Ovonic	C	82.7	4.0%	270 and 285
Sanyo	4/3A	52.9	2.5%	272 and 350
Toshiba	4/5A	32.5	3.1%	293, 301, 311
Yuasa	4/3A	49.9	1.8%	266, 276, 284
Yuasa	prismatic	75.8	3.8%	gradual vent

Conclusions

The commercial Ni-MH cells tested behave very benignly when abused electrically and thermally. Their main hazards are the vent of a small amount of hydrogen (>0.1g for the largest cell which is equivalent to 2.5 liters at ambient pressure and temperature) and the leakage of KOH electrolyte. These hazards were not present during the short circuit tests. Overall, these cells are very safe to use in well ventilated applications.

Measurement

of

Thermal properties of Space Ni–MH cell

1994 NASA Aerospace Battery Workshop
November 15–17,1994

S.Kuwajima & K.Koga
National Space Development Agency of Japan

NASDA
Space Subsystems and Technology Department

Contents

Ni–MH Cell evaluation test : An Update

Measurement of Thermal Properties of Space Ni–MH Cell

- Objectives
- Experimental Method
- Test Condition
- Measurement result
- Findings
- Summary and Future Work

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35Ah Ni–MH BBM Evaluation Test

Test Conditions

	25% DOD–LEO	40% DOD–LEO
Cell	3 BBM–A + 3 BBM–B	2 BBM–A + 2 BBM–B
Charge	0.3C, 52.5 min.	0.48C, 52.5 min.
Discharge	0.5C, 30 min.	0.8C, 30 min.
DOD	25%	40%
Charge Return	105%	
Cell Temp.	20°C (Maintained by Chamber)	
Capacity check	Residual Capacity, Full–Charged Capacity at 1,000 cycles 3,000 cycles and then about every 5,000 cycles	

Residual Capacity : 0.5C discharge to 1 Volt after LEO cycle

Full–Charged Capacity : 0.5C discharge to 1 Volt after full–charging with 0.1C for 16 hours

BBM–A : Capacity–stabilizing cycle after electrolyte filled

BBM–B : Precharge arrangement of MH electrode prior to stabilizing cycle

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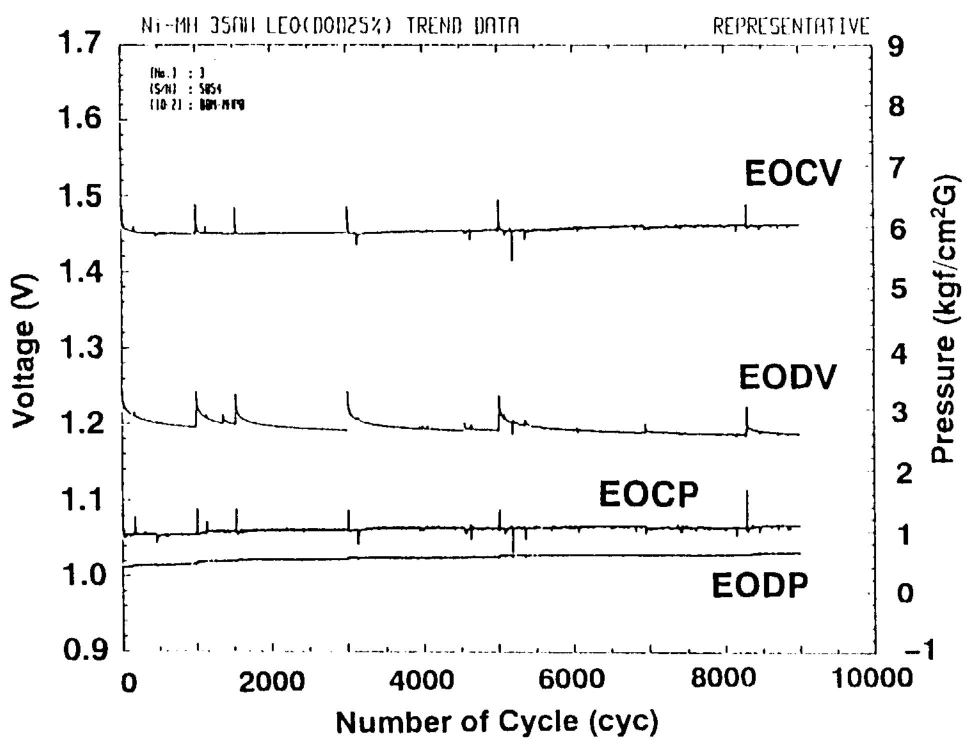
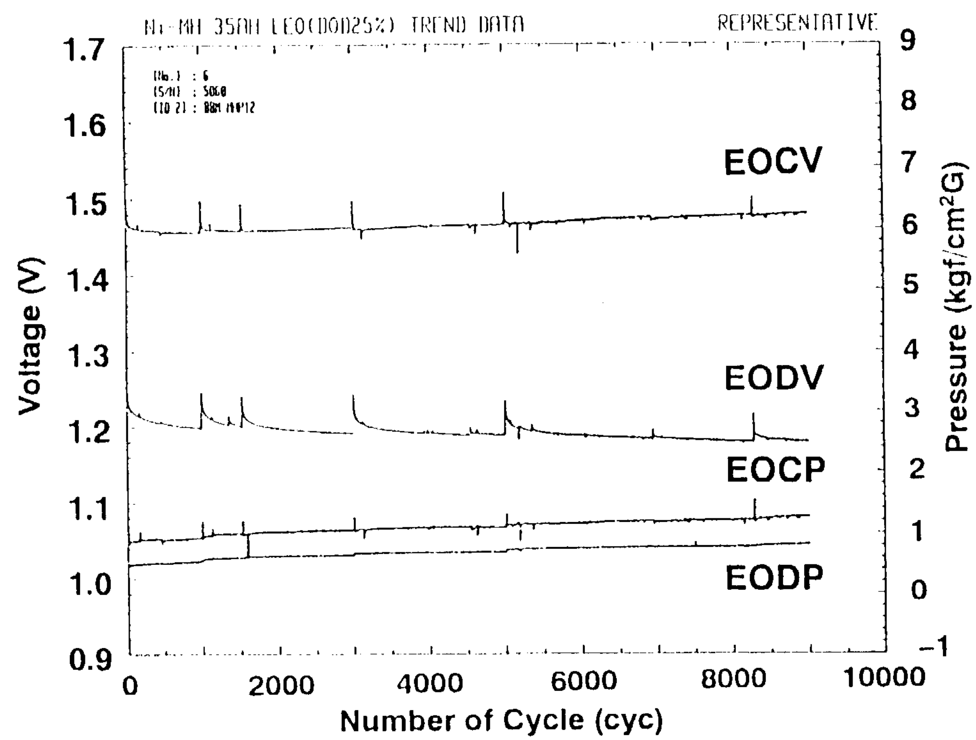
35Ah Ni–MH BBM LEO Cycle Test (DOD 25%)

Trend of EOCV,EODV,EOCP & EODP

All cells have good performance.



BBM–A



BBM–B

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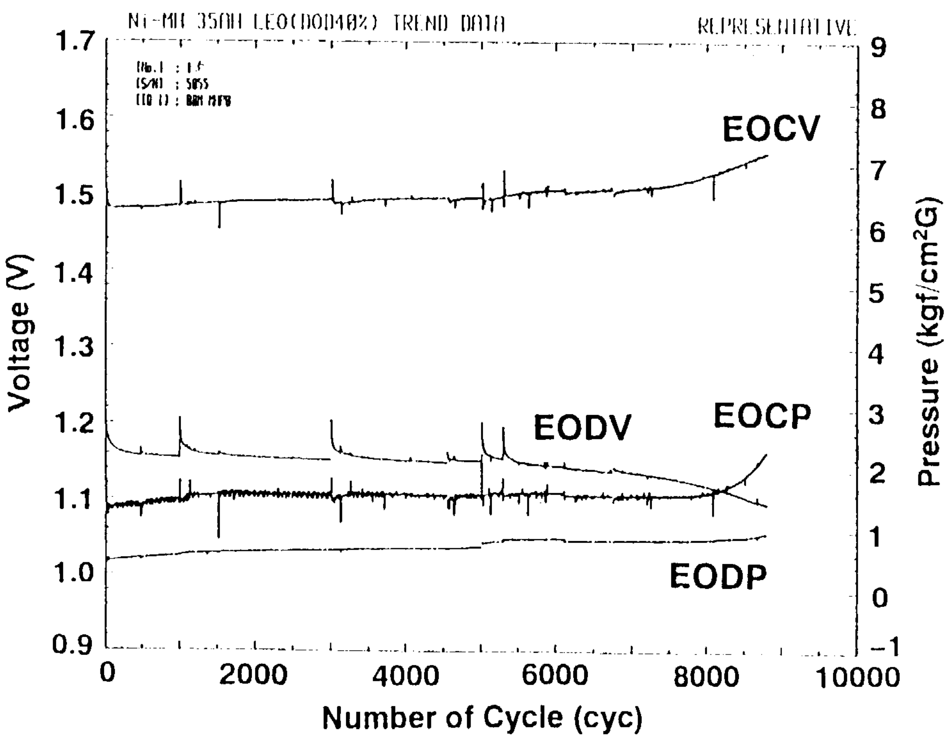
35Ah Ni-MH BBM LEO Cycle Test (DOD 40%)

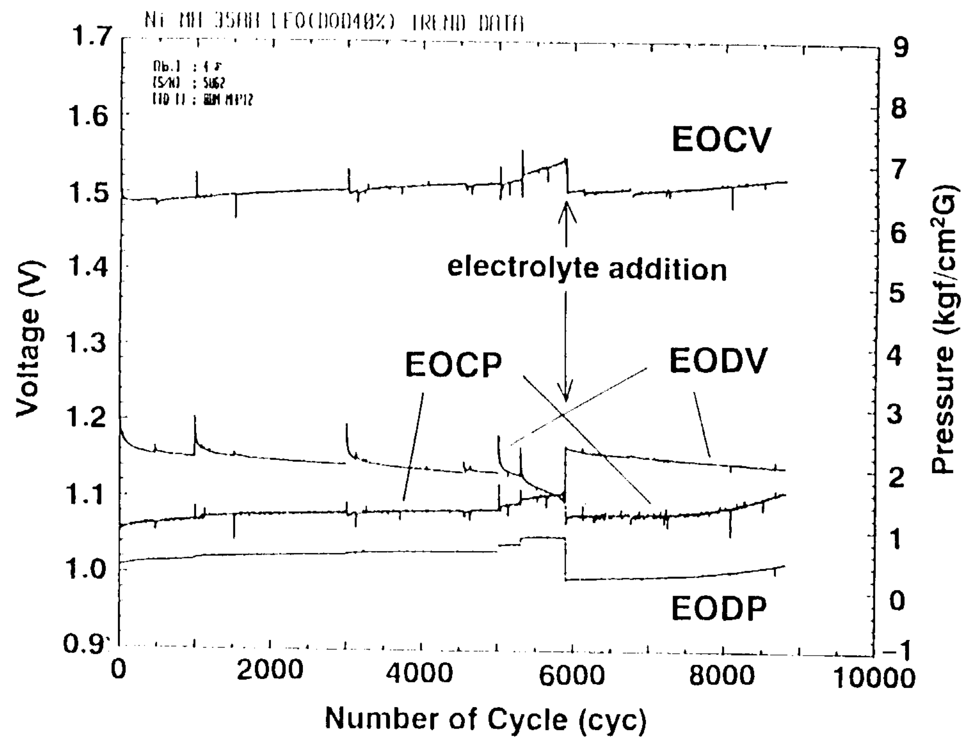
Trend of EOCV,EODV,EOCP & EODP

BBM-A: EOCV and EOCP increased from about 7,000 cycle

BBM-B: One cell was subjected to DPA at 5294cyc to examine degradation mechanism
The other cell was added electrolyte at 5893cyc and continue cycle.



BBM-A



BBM-B

NASDA 35Ah Ni-MH BBM LEO Cycle Test

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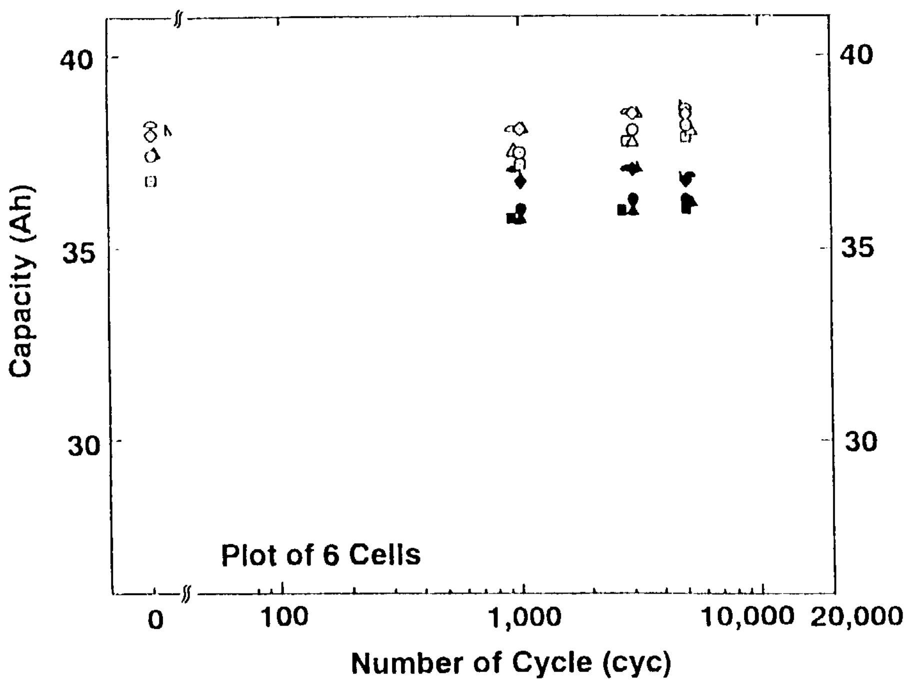
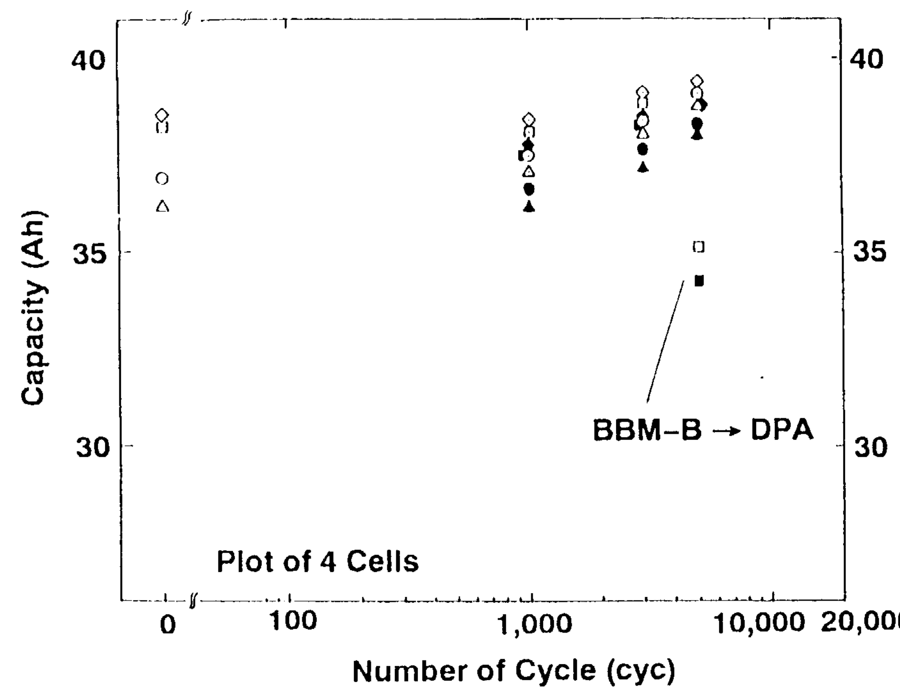
Trend of Capacities

25% DOD



40% DOD



White-mark : Full-Charged Capacity
Black-mark : Residual Capacity

35Ah Ni–MH BBM Evaluation Test

Current Status of Cycling test

LEO (DOD 25%)

EOCV,EODV,EOCP and EODP are all stable .

So far, capacity trend are better than Ni–Cd Cell

LEO (DOD 40%)

BBM–B

Before DPA, we added electrolyte tentatively, and then capacity, EOCV and EODV were restored. From result of DPA, there isn't another cause of degradation. So that the degradation was caused by dryout of electrolyte.

Then we added electrolyte to the cell at 5893cyc and continued cycling test, and it works well after that.

BBM–A

EOCV and EOCP increased from about 7000cyc, and it seems like phenomenon of electrolyte dryout.

We added electrolyte at 8799cyc.

Objectives

NASDA has been developing space Ni–MH cell on contract with SANYO.

1st manufactured cell shows initial capacity of over 35Ah and specific energy of about 50 Wh/kg(about 860g of weight).

Ni–MH cell was decided to be used for OICETS(Optical Inter–orbit Communications Engineering Test Satellite) to be launched in 1998.

When applying new cell to satellite, we have to know the thermal properties of the cell.

Therefor we survey the thermal property of space Ni–MH cell and compare with Ni–Cd cell.

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Experimental Method

Using thermopile–type heat sensor for evaluating the calorie from the cell.

Thermopile–type heat sensor measures temperature difference, and it generates a dc voltage directly proportional to the rate of heat flow by using "$mV/W \cdot m^{-2}$"

Insulating thermally from open air by using formed styrene.

Almost heat from the cell goes through the heat sensor along the aluminum cell stack and the bottom of the cell to the cold plate.

This way is convenient, simple, and simulate the actual mounting state and heat flow of satellite battery.

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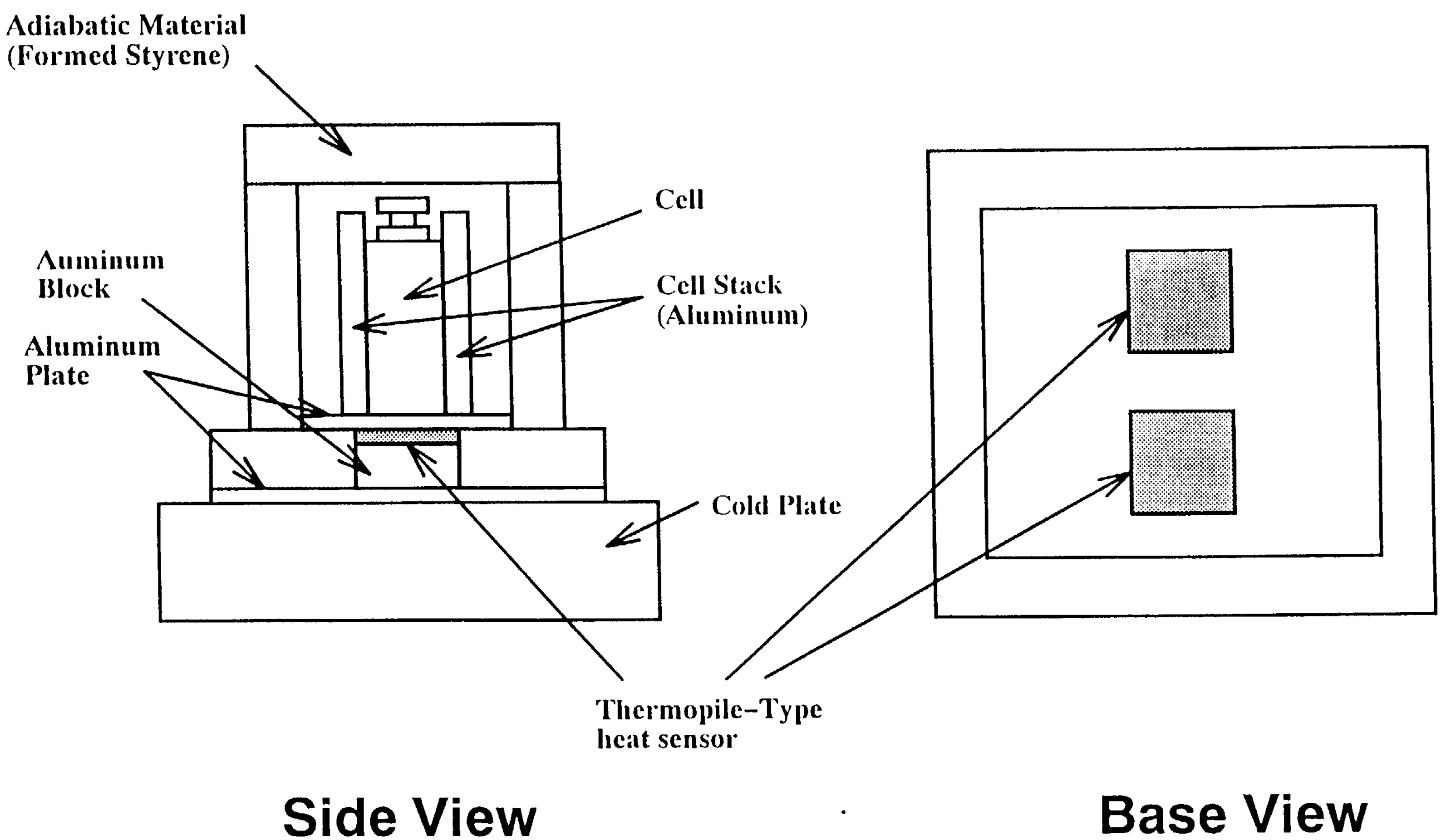
Configuration of the equipment



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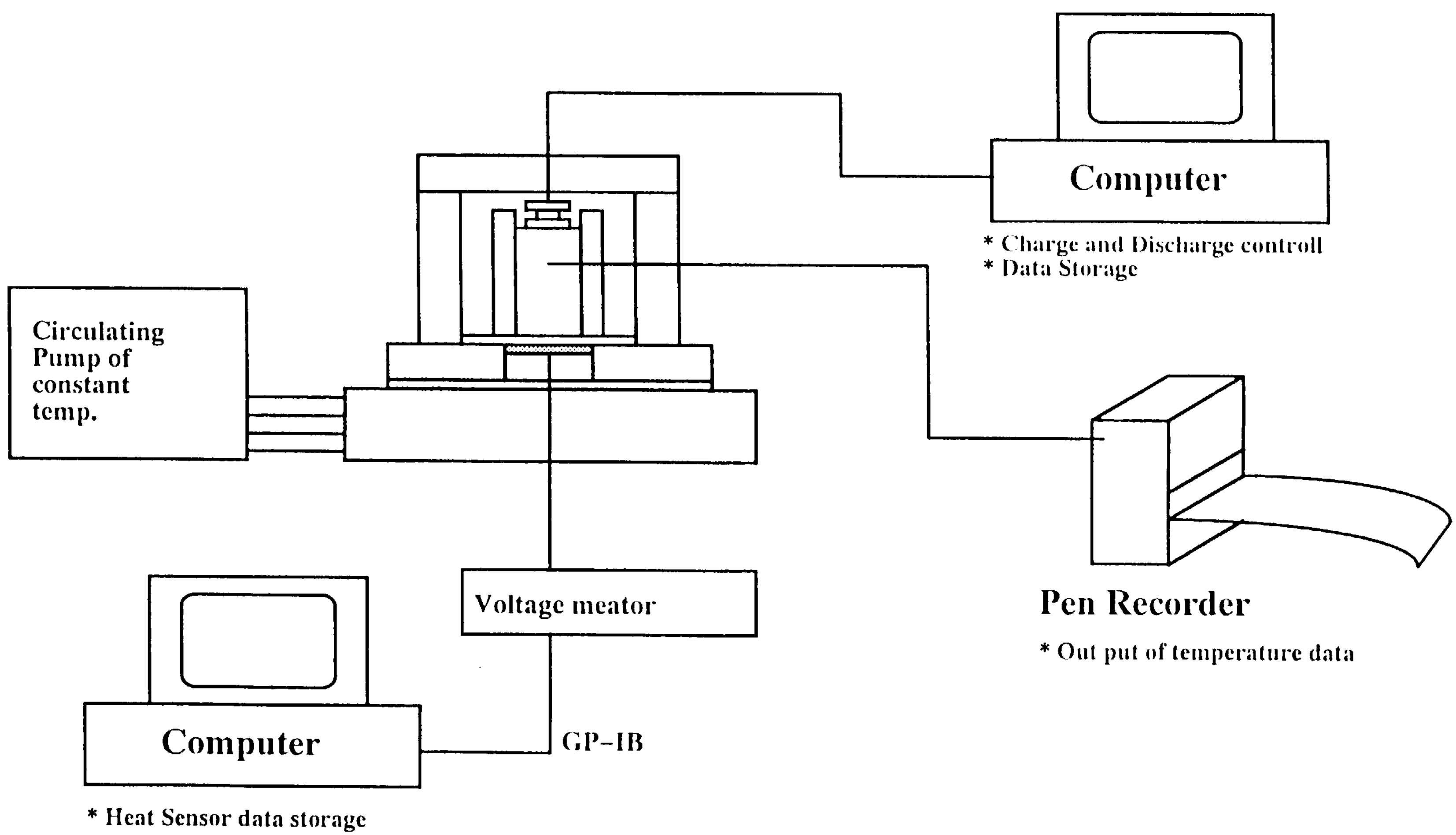
Schematic of the equipment



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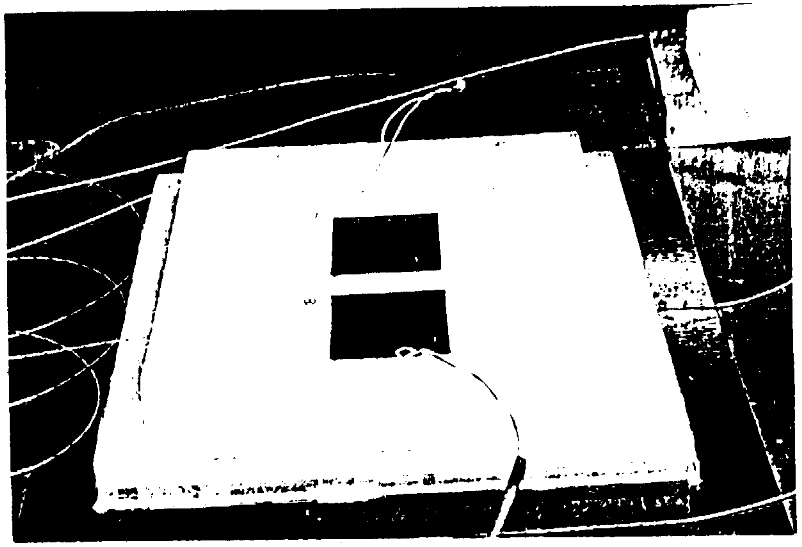
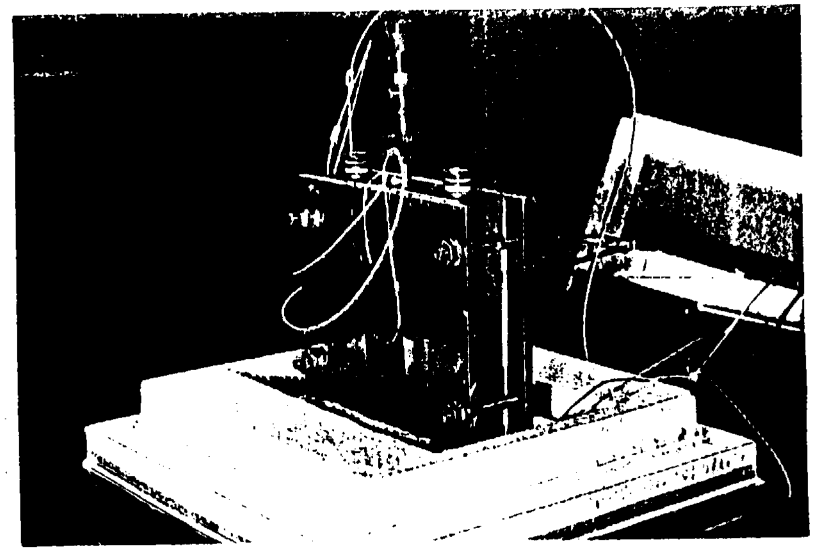
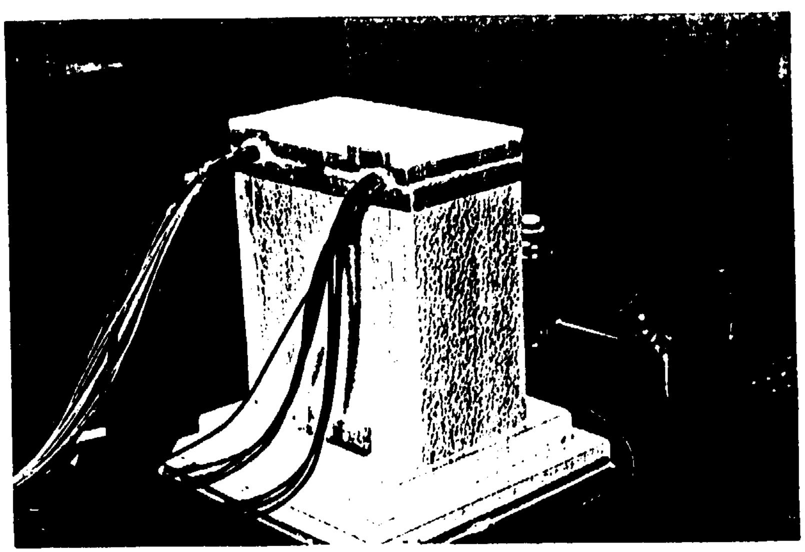
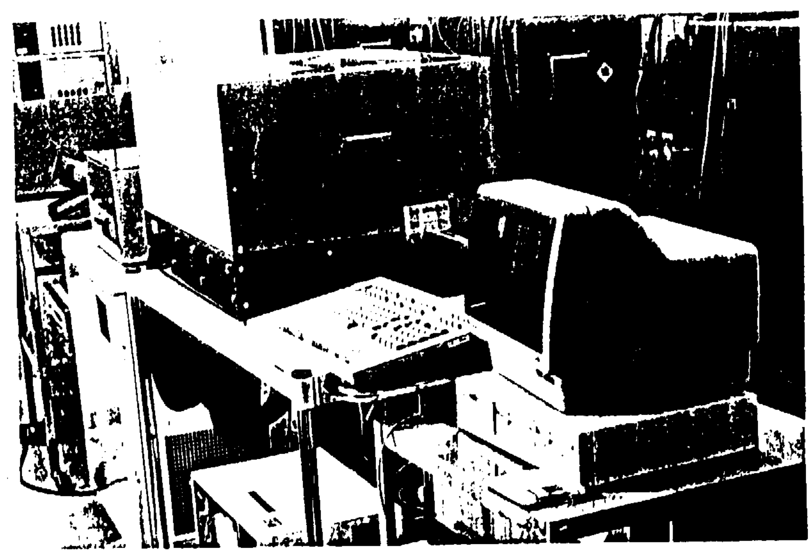
Outer View of Equipment









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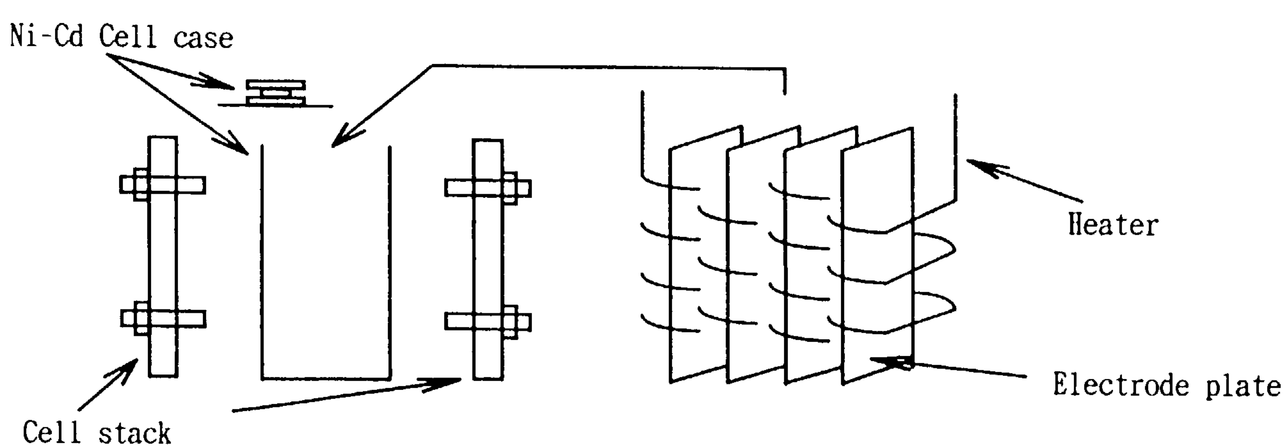
Evaluation of heat leak from BOX

There is some heat leak from styrene BOX.

To evaluate this leak, we use the dummy cell which has 35Ah cell case, and in it, the heater is tied around the electrode plate.

Using this dummy cell, we calibrate the measurement value of heat sensor to real generated heat.



Structure of dummy cell

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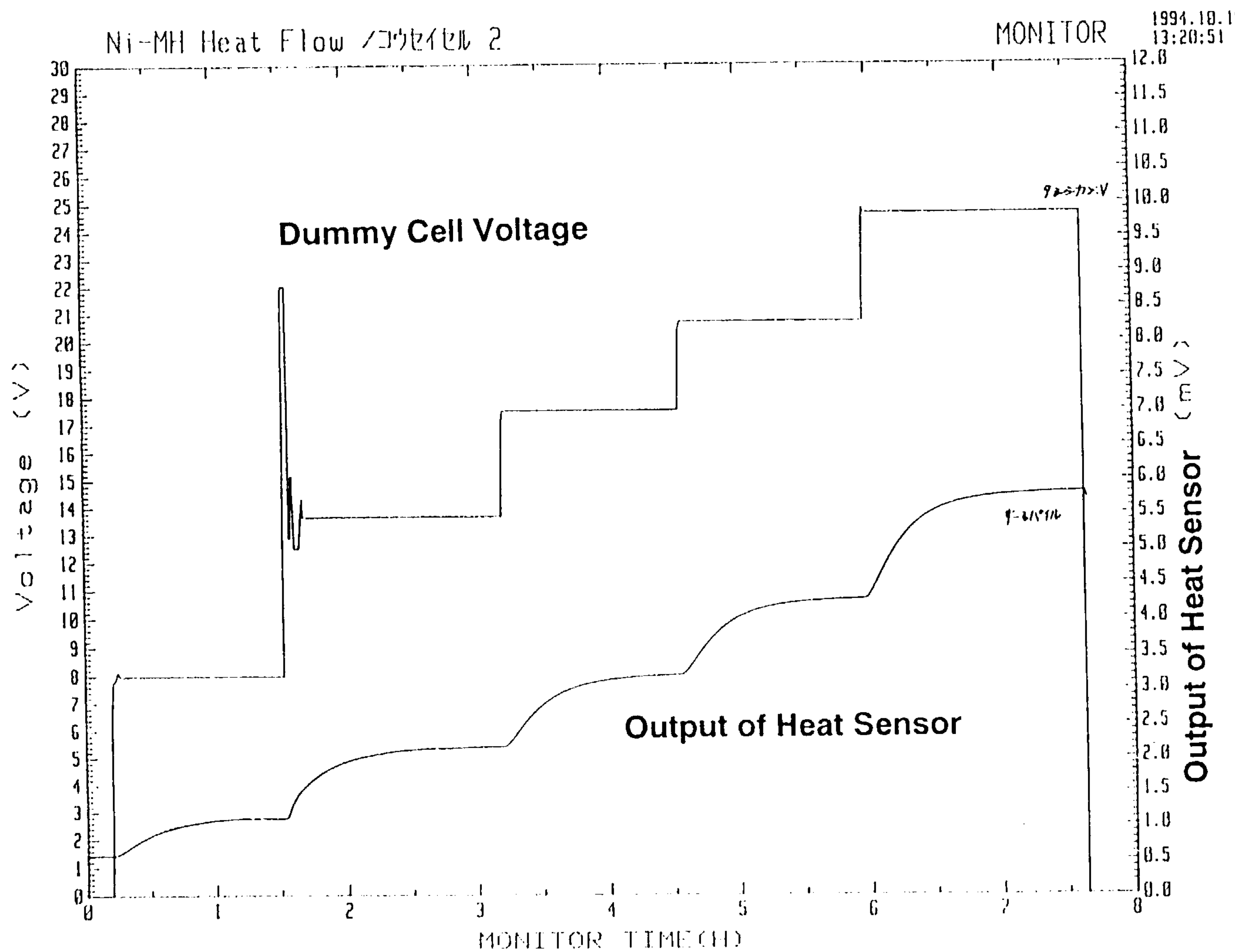
Result of Dummy Cell Test



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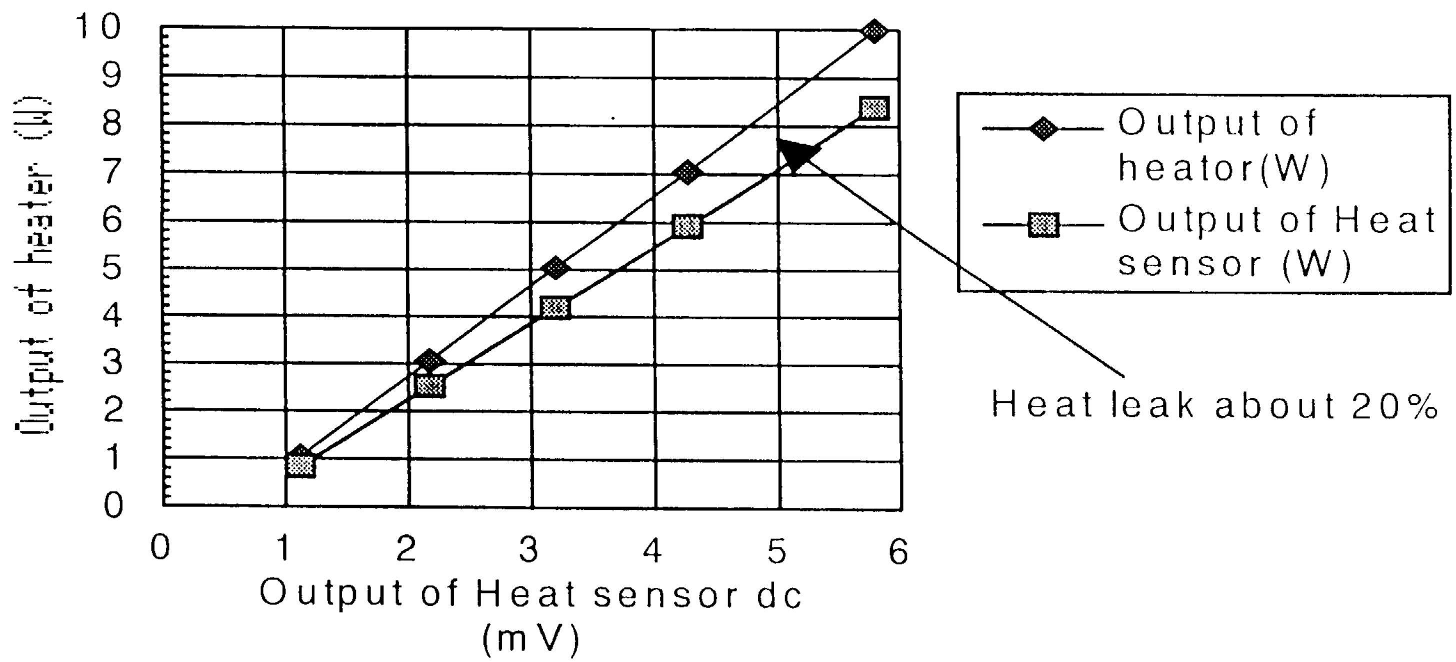
Result of heat leak measurement from BOX



- We got result that measurement value is linear to output of heater, and proportional constant is about 0.8(sensor/heater).
- The response time that output reaches steady heat rate is about two hours.
- Therefor output heat of cell does not always indicate instanteous heat rate.

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Test Condition (Cycling test)

Specimen : 35Ah Ni–Cd and Ni–MH cell (SANYO)

Cold Plate Temperature : 10°Centigrade

We chose the test condition to simulate the Low Earth Orbit Cycling which may be used by OICETS.

Cycling Test Condition

	Condition 1	Condition 2	Condition 3
Charge	C/3(11.67A) 31.5 min.	C/3 (11.67A) 47.5 min.	C/3 (11.6A) 19.0 min.
Trickle Charge	C/50 (0.7A) 28.5 min.	C/50 (0.7A) 12.5 min.	C/50 (0.7A) 41.0 min.
Discharge	C/3 (11.67A) 30.0 min.	C/2 (17.5A) 30.0 min.	C/5 (0.7A) 30.0 min
DOD	17%	25%	10%

NASDA Result of Cycling Condition 1 (DOD17%)

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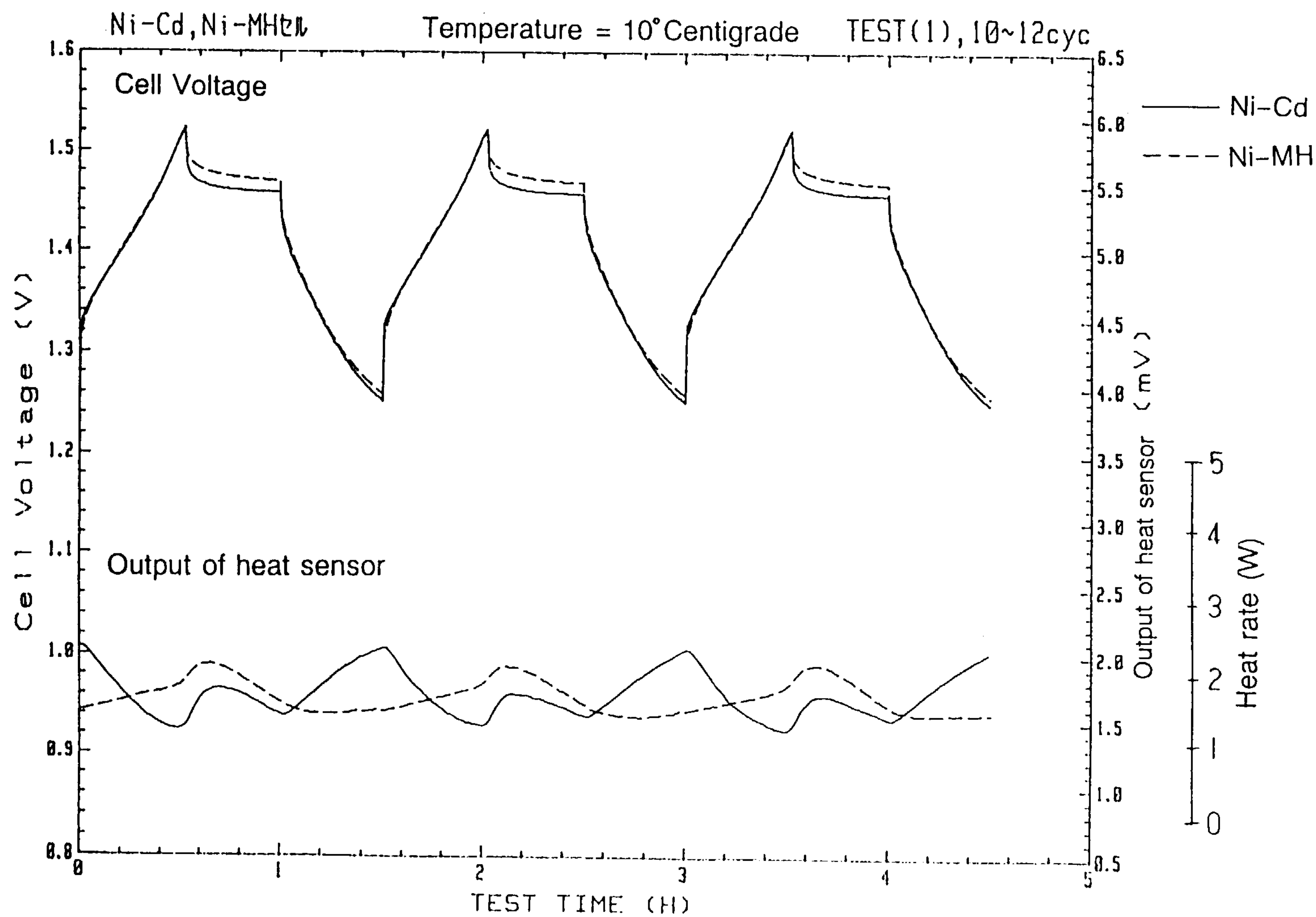
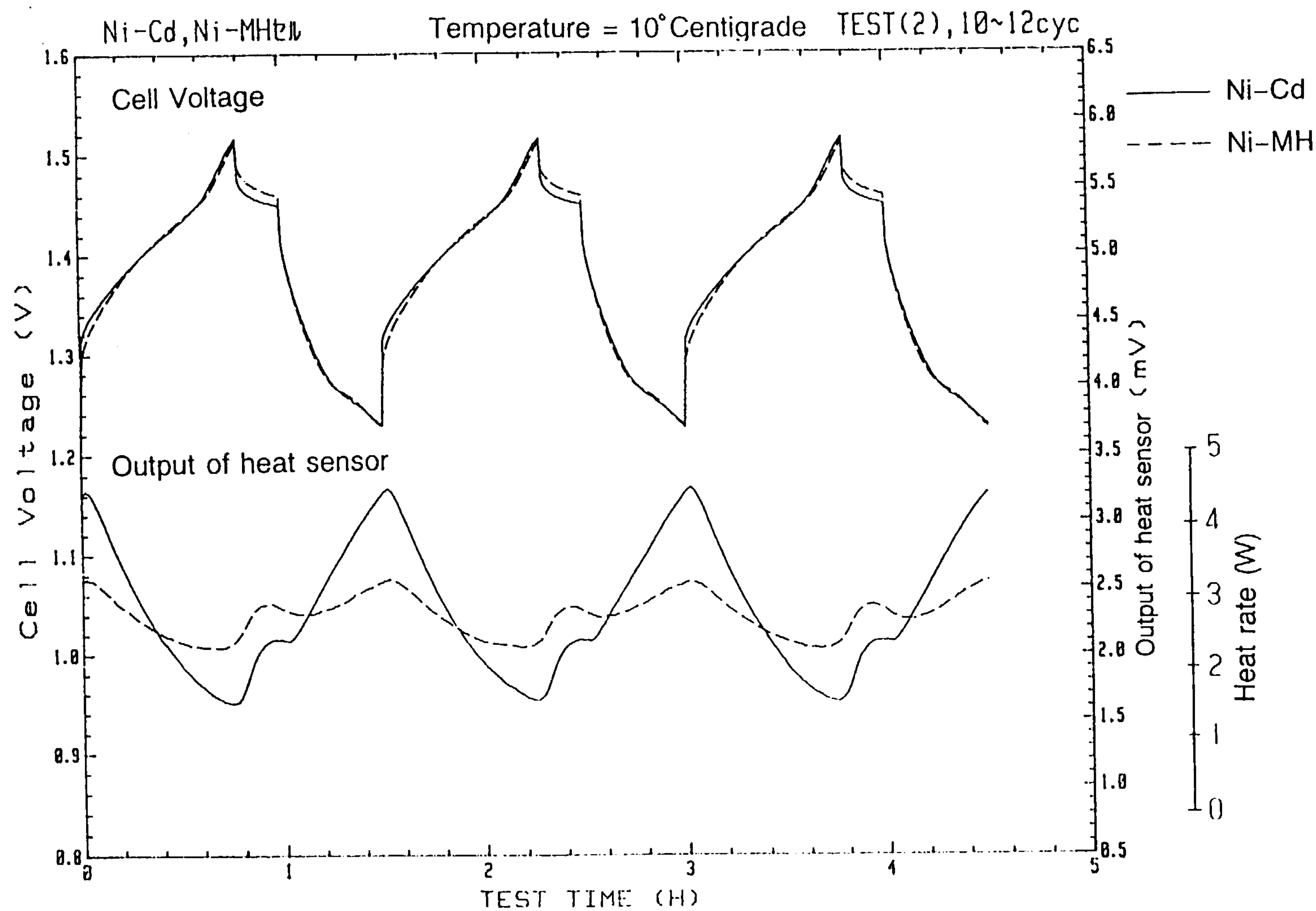


NASDA Space Subsystems and Technology Department — Result of Cycling Condition 2 (DOD25%)



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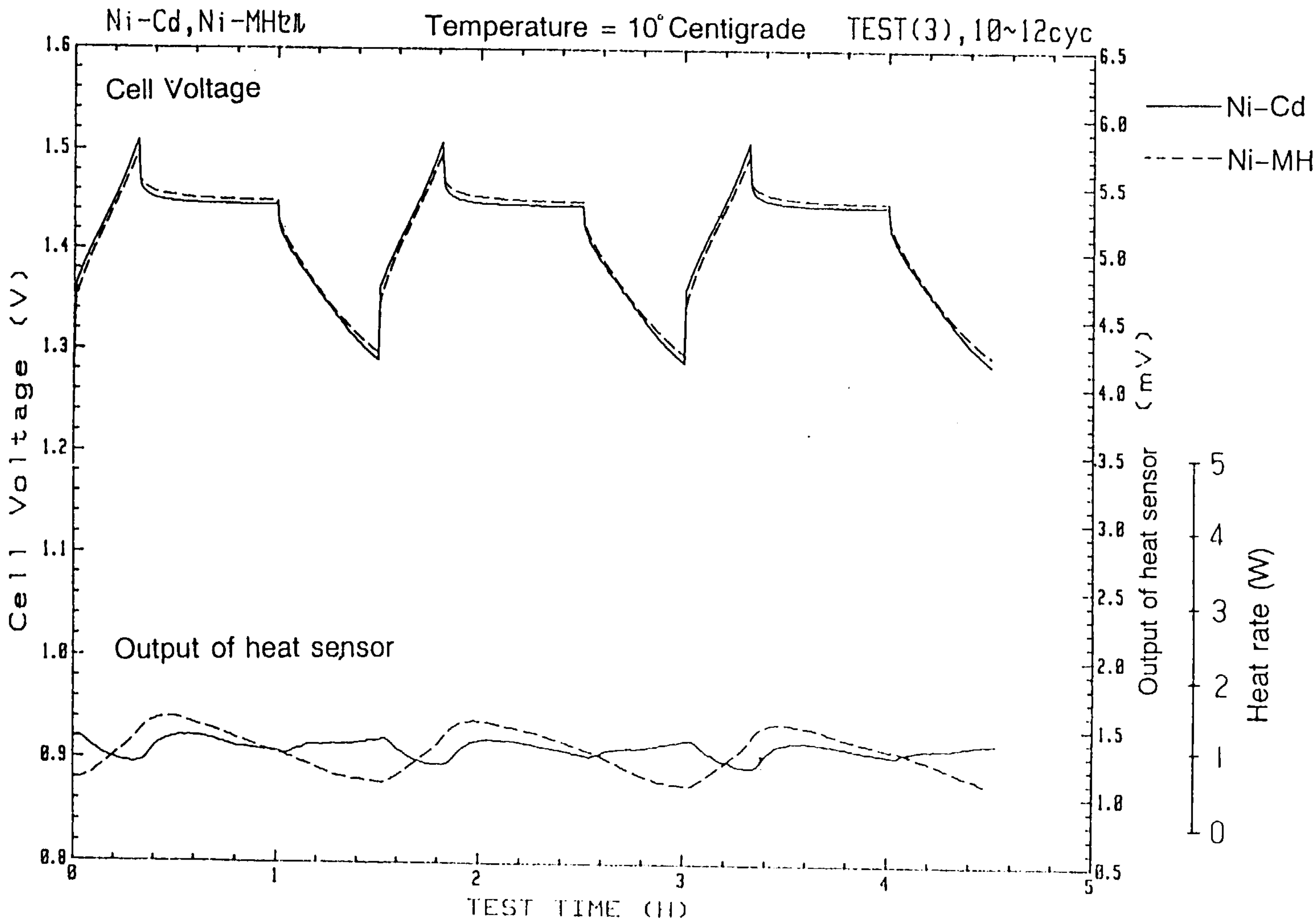
Result of Cycling Condition 3 (DOD10%)



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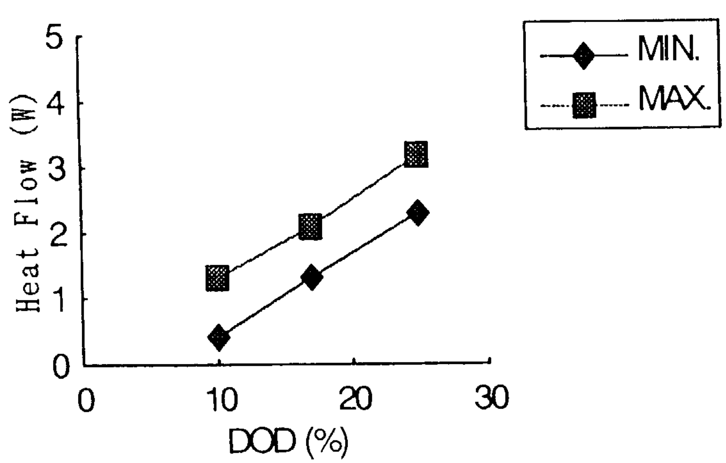
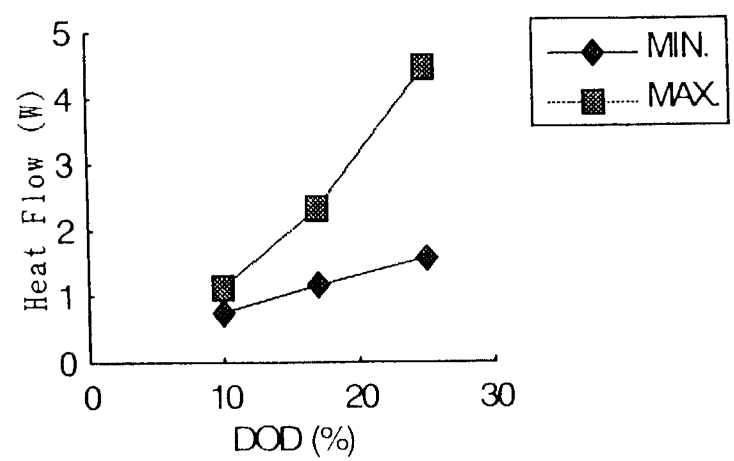
Findings (Cycling test)

Cycling Test

DOD vs. Heat flow (Ni-MH)



DOD vs. Heat flow (Ni-Cd)



- Concerning the width between min. and max. of heat flow, Ni–MH is bigger than Ni–Cd at DOD 10%, and smaller at DOD 25% and 17%.
- Cell heat became large as DOD is deeper.
- Amplitude and variation of cell heat is different between Ni–MH and Ni–Cd cell but heat average is almost same.
- Ni–MH heat characteristic of charge and discharge seems different from Ni–Cd.

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Test Condition (various charge and dischrage)

- Heat characteristic at cycling test indicate heat average due to the response time.
- To evaluate the detail characteristics under different charge and discharge rate, we chose the condition as follows,

160% Full Charge

Charge	C/10 (3.5A) 16 hours
Discharge	C/2 (17.5A) 1 Volt cut

C/3,C/5,C/8 charge and C/2,C/3,C/5 discharge

	Condition 1	Condition 2	Condition 3	Condition 4
Charge	C/5 (7.0A) 6 hours	C/5 (7.0A) 6 hours	C/8 (4.4A) 9.6 hours	C/3 (11.7A) 3 hours
Discharge	C/3 (11.67A) 1 Volt cut	C/5 (7.0A) 1 Volt cut	C/2 (17.5A) 1 Volt cut	C/2 (17.5A) 1 Volt cut

There is cell open state for two hours between charge and discharge.

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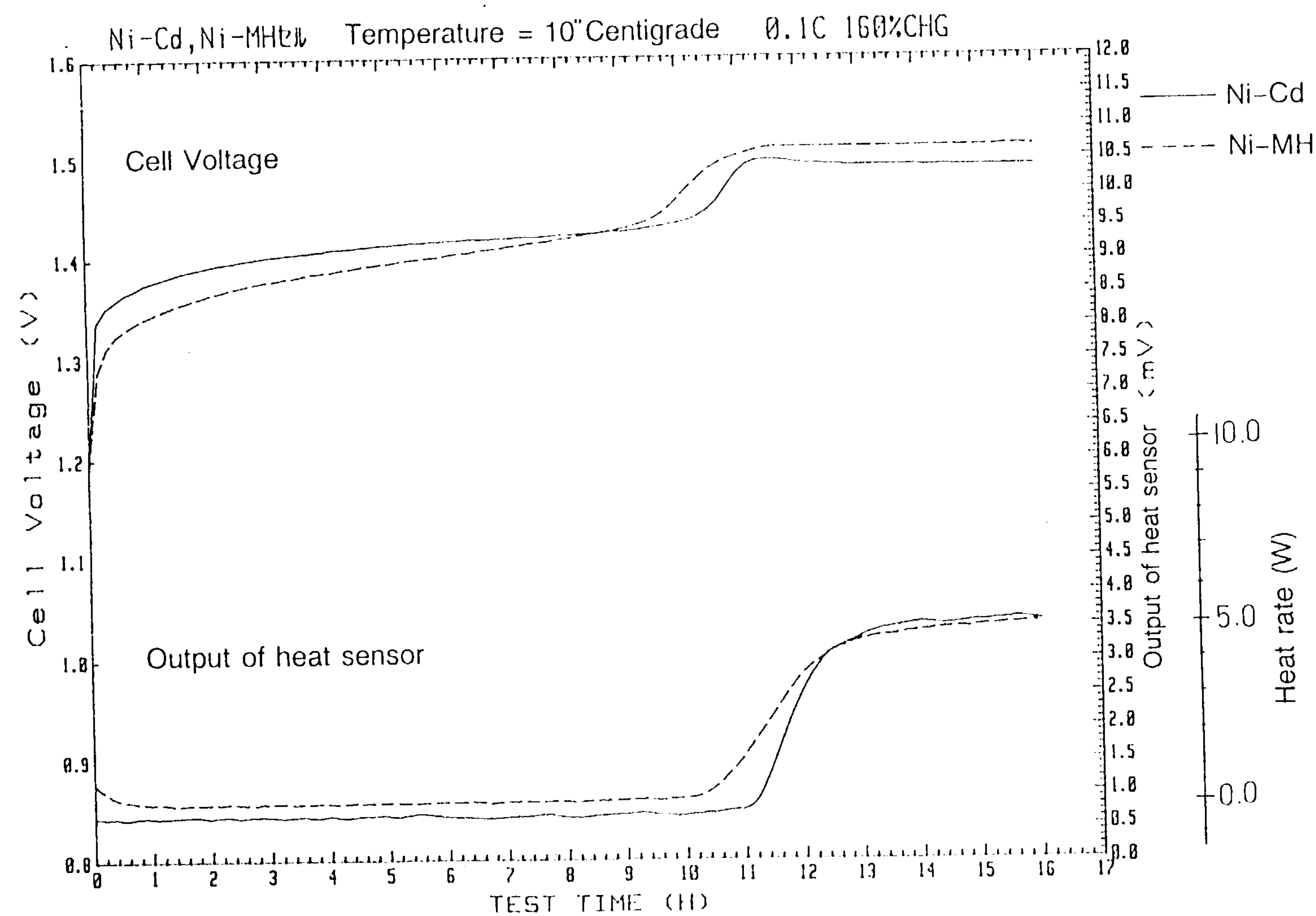
Result of 160% Full Charge



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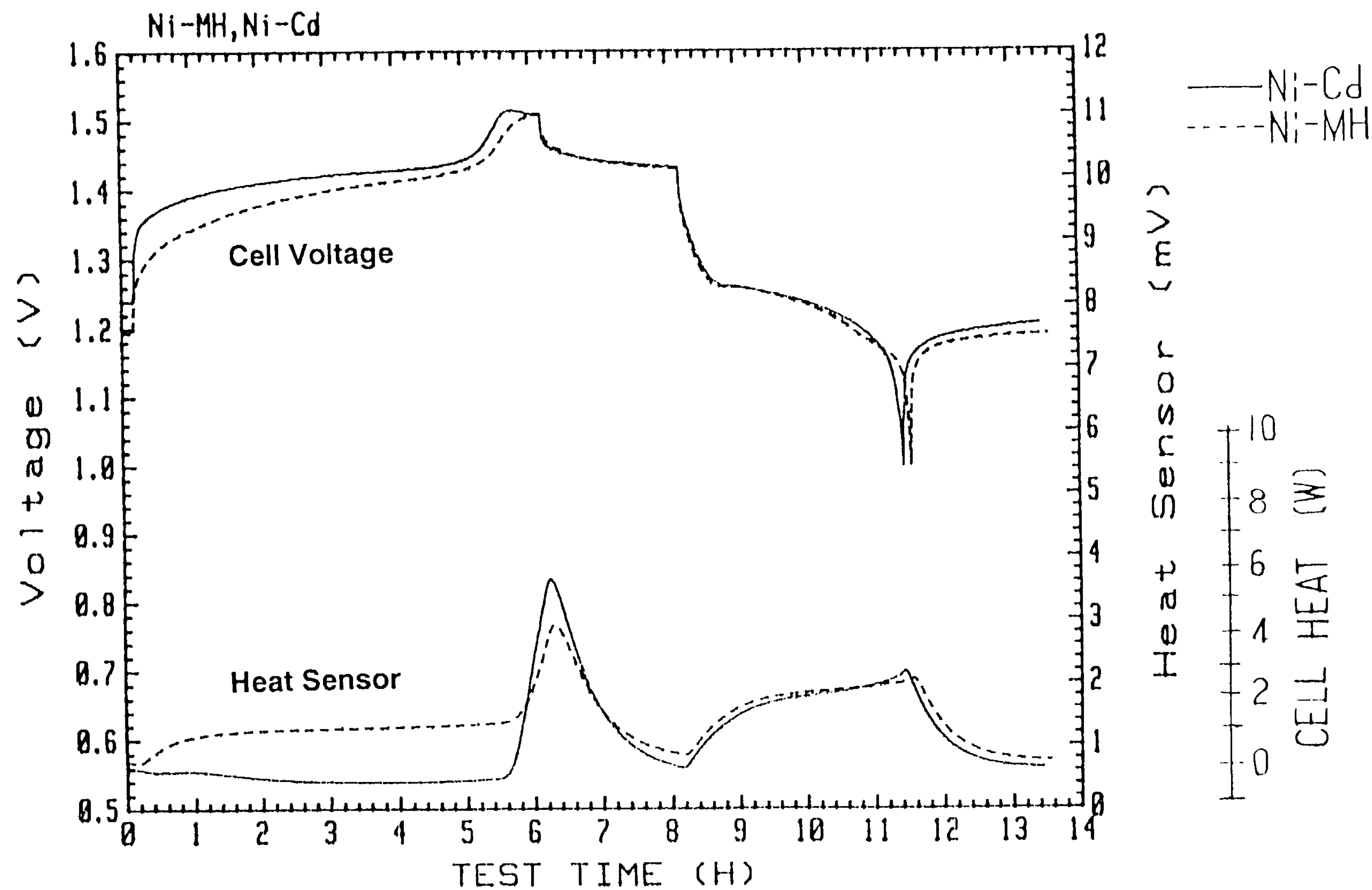
Findings (160% Full charge test)

160% Full charge Test

Heat flow during over charge state is almost same (5W) between Ni–Cd cell and Ni–MH cell, and this value is as same as that all of charge power became heat.

NASDA Space Subsystems and Technology Department — C/5 charge and C/3 discharge (Condition 1)



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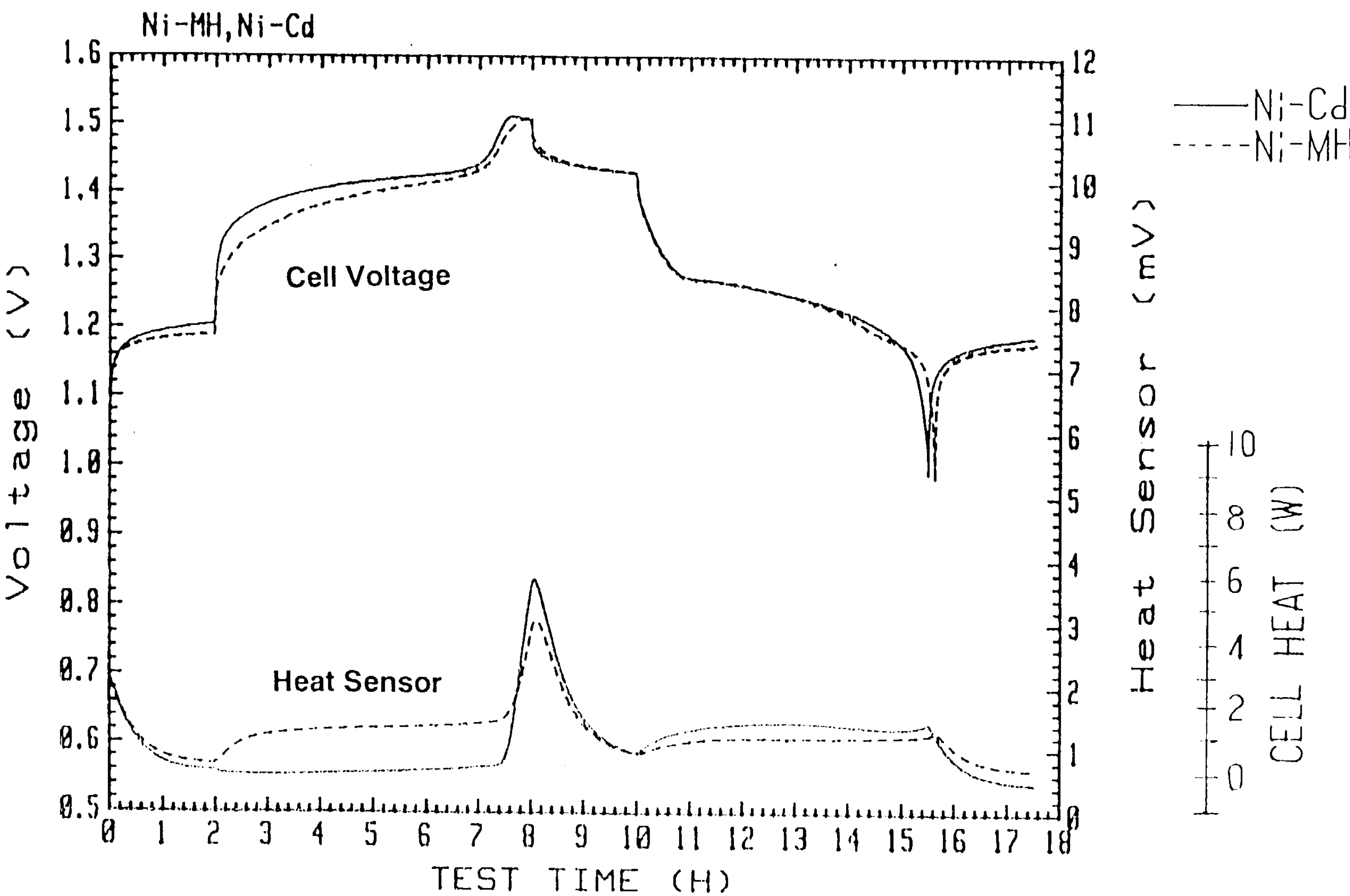
C/5 charge and C/5 discharge (Condition 2)



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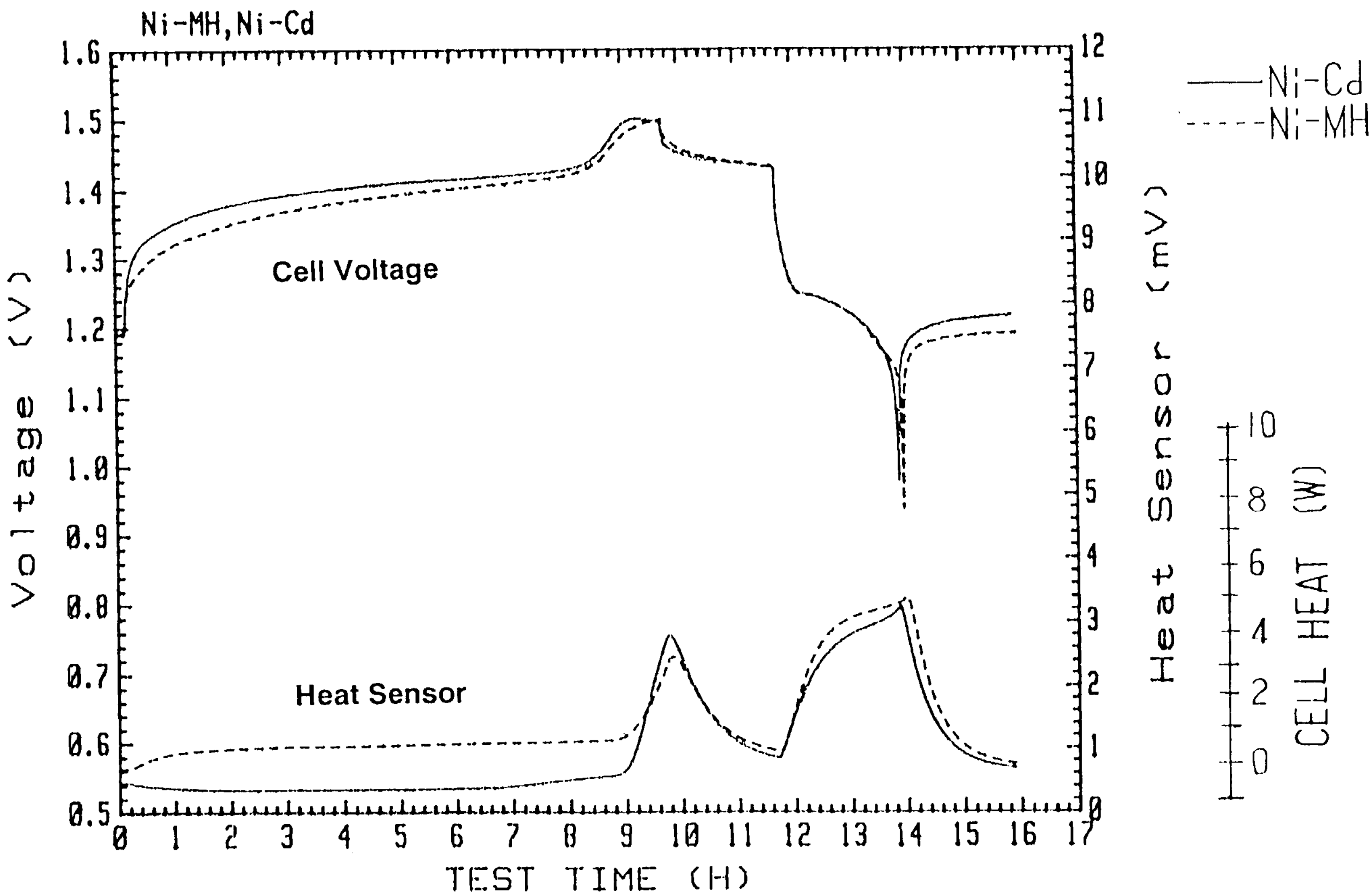
C/8 charge and C/2 discharge (Condition 3)



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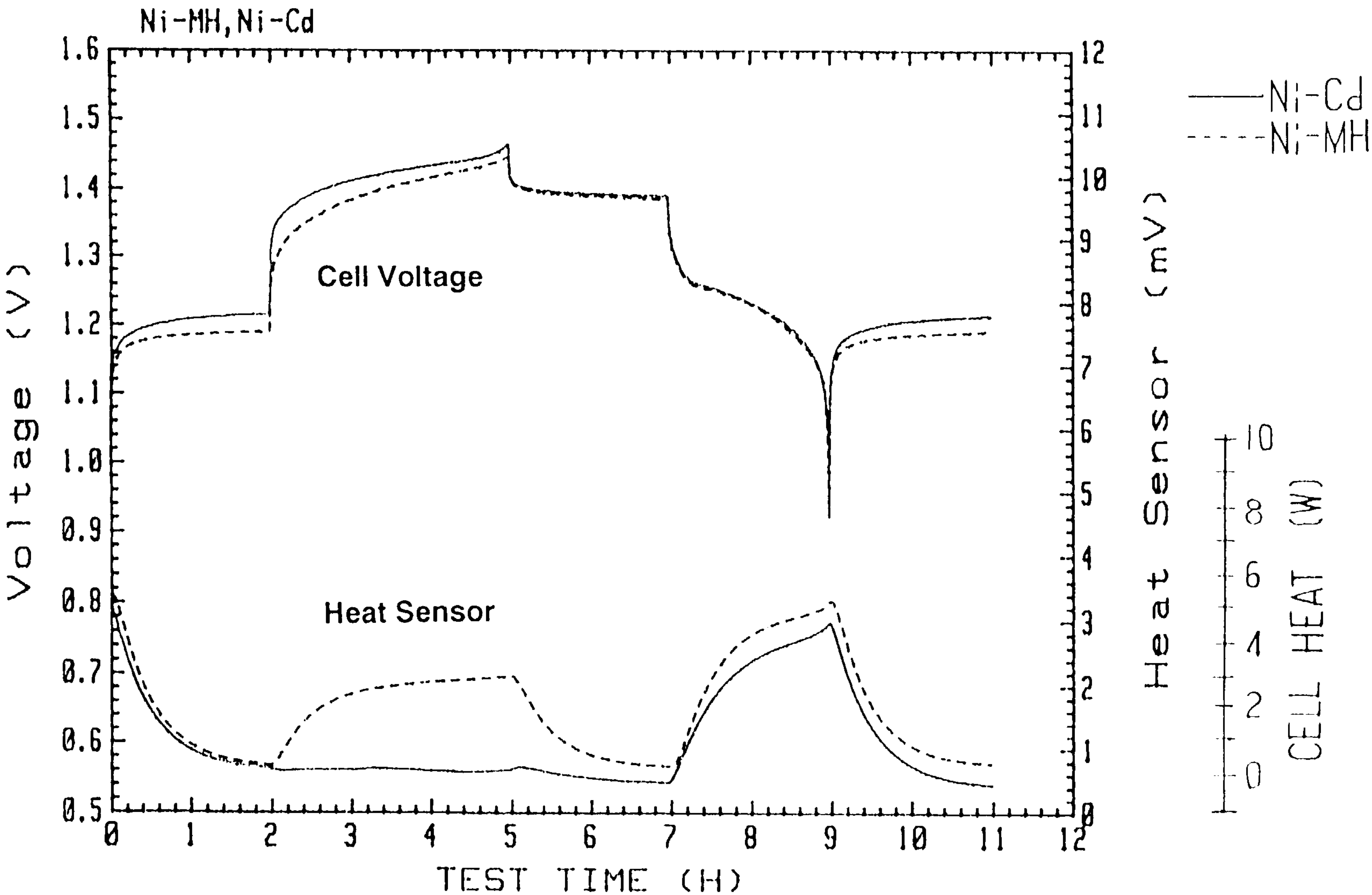
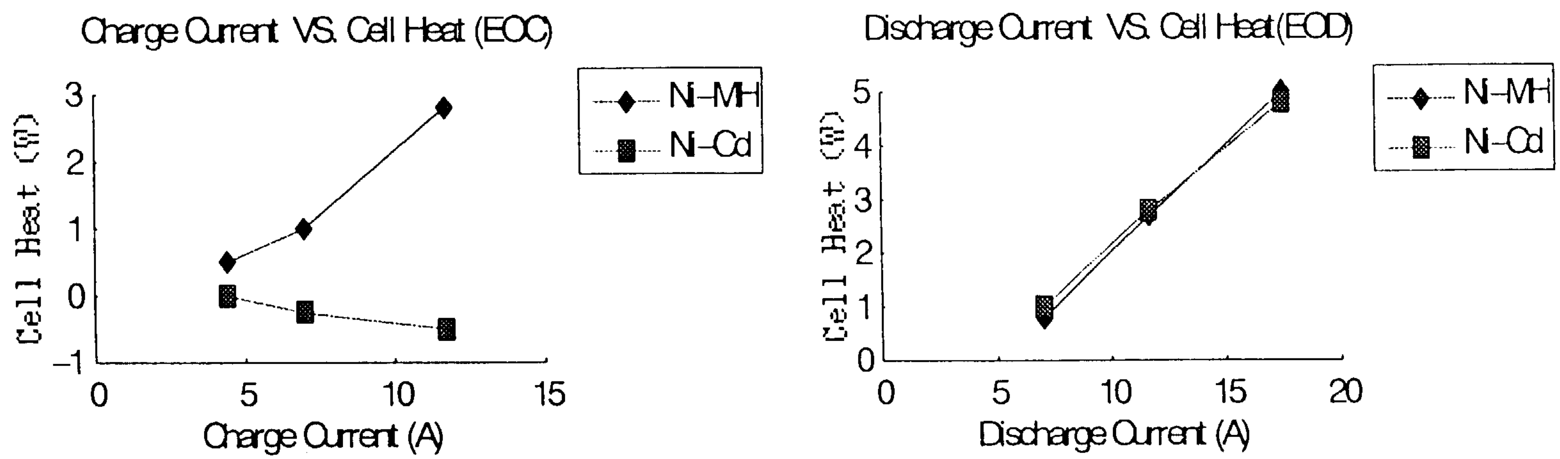
C/3 charge and C/2 discharge (Condition 4)



NASDA Space Subsystems and Technology Department

Findings (various charge and discharge)

C/2,C/3,C/5 discharge and C/3, C/5, C/8 charge test



- Cell heat of Ni–MH during effective charging time is larger than Ni–Cd cell at any discharge ratio.
- Cell heat of Ni–MH becomes large according to charge rate, but cell heat of Ni–Cd is almost 0 W at any charge rate.
- In the case of discharging time, cell heat of two kind of cell is almost same.

NASDA Space Subsystems and Technology Department

Summary and Future work (1/2)

Summary

Cycling test

Average of heat is almost same between Ni–MH and Ni–Cd cell.
Amplitude of heat is different between Ni–MH and Ni–Cd cell.

C/3,C/5,C/8 charge test

Cell heat of Ni–MH is bigger than Ni–Cd at any charge rate.

C/2,C/3,C/5 discharge test

Cell heat of Ni–MH is almost same as Ni–Cd at any discharge rate.

Concerning the amplitude difference at cycling test

The heat of Ni–Cd cell at charge is lower than Ni–MH and cell heat at discharge is same, so at cycling condition, amplitude of Ni–Cd cell heat becomes larger than Ni–MH. This explain the result at cycling (except DOD 10%).

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Summary and Future work (2/2)

Concerning the same heat average at cycling test

From the result of charge and discharge test, cell heat of Ni–MH was exothermic during charge, and in addition, discharge heat is same as Ni–Cd. This suggest that the heat average becomes more than Ni–Cd cell, but result at cycling test shown same level. Two kind of test result is not compatible.

To evaluate these result more detail, we must do quantitative analysis like computer simulation of cycling test using the result of charge and discharge test.

Future work

- For quantitative analysis, we need more measurement data.
- Simulation of Ni–MH thermal property by use of dummy cell.
- Computer simulation in the same parameter as test condition.

N95- 26791

Nickel Metal Hydride LEO Cycle Testing

Eric Lowery

NASA
George C. Marshall Space Flight Center

1994 NASA Aerospace Battery Workshop
Huntsville Marriott
Huntsville, AL
November 16, 1994

The George C. Marshall Space Flight Center is working to characterize aerospace AB5 Nickel Metal Hydride (NiMH) cells. The cells are being evaluated in terms of storage, low earth orbit (LEO) cycling and response to parametric testing (high rate charge and discharge, charge retention, pulse current ability, etc.). Cells manufactured by Eagle Picher are the subjects of the evaluation.

There is speculation that NiMH cells may become direct replacements for current Nickel Cadmium cells in the near future. Flight application of the subject NiMH cells is planned on a small university student satellite in 1997.

Electrodes Reactions

NiCd Charge

@Positive Electrode (Nickel):

$$2Ni(OH)_2 + 2OH^- \rightarrow 2NiOOH + 2H_2O + 2e^-$$

@Negative Electrode (Cadmium):

$$Cd(OH)_2 + 2e^- \rightarrow Cd + 2OH^-$$

Overall:

$$2Ni(OH)_2 + Cd(OH)_2 \rightarrow 2NiOOH + Cd$$

NiMH Charge

@Positive Electrode (Nickel):

$$Ni(OH)_2 + OH^- \rightarrow NiOOH + H_2O + e^-$$

@Negative Electrode (Metal Hydride):

$$Hydride + H_2O + e^- \rightarrow Hydride(H) + OH^-$$

Overall:

$$Ni(OH)_2 + Hydride \rightarrow NiOOH + Hydride(H)$$

The energy density of the metal hydride cell is approximately 1.2 - 1.5 times the energy density of the NiCd cell. The actual ratio is dependent upon the packaging required. The Environmental Protection Agency has no objections to the disposal of spent NiMH cells. The mature NiMH cell is expected to be an order of magnitude less expensive than a comparable NiCd cell.

The operation of the NiMH cell is similar to the operation of the Nickel Cadmium (NiCd) cell. The reaction at the positive nickel electrode in the NiCd is the same as at the positive nickel electrode in the NiMH. Cadmium is oxidized and reduced at the negative electrode in the NiCd cell. In the NiMH cell, hydrogen is adsorbed and desorbed by the active hydride metal of the negative electrode.

Nickel Metal Hydride - Alloy

AB_2

Primarily Nickel Titanium (NiTi) or Iron Titanium (FeTi) with various mischmetal percentages of Zirconium (Zr), Nickel (Ni), Vanadium (V), Chromium (Cr) and transition metals generally referred to as X and Y components.

AB_5

Primarily Lanthanum Nickel5 (LaNi5) or Cerium Nickel^5 ($CeNi_5$), with various mischmetal percentages of Cobalt (Co), Silicon (Si) etc.

The two primary hydride classes that are used to manufacture NiMH cells are AB_2 and AB_5. Most of the early work with NiMH was with the AB_2 alloy. This alloy is found most prominently in the cylindrical cells manufactured for the consumer market. The AB_5 alloy was developed later. The AB_5 alloy seems to have properties better suited to aerospace applications. The cycle life and mechanical integrity of the AB_5 alloy seems to be greater.

Aerospace NiMH vs. Commercial NiCd

	Metal Hydride Eagle-Picher AB5, Prismatic	Nickel Cadmium Gates, Cylindrical	Nickel Cadmium Saft, Cylindrical
Rated Capacity @ avg volt = 1.25	10 Ampere Hrs.	7 Ampere Hrs.	7 Ampere Hrs.
Length	2.591 cm	8.778 cm	8.852 cm
Width/Dia.	5.192 cm	3.226 cm	3.231 cm
Height	7.999 cm		
Mass	349.56 g	225.67 g	202.48 g
Energy Density	116.2 Wh/l	121.9 Wh/l	120.6 Wh/l
Specific Energy	35.7 Wh/kg	38.8 Wh/kg	43.21 Wh/kg

An effort is being made to utilize commercial technology wherever possible to reduce the cost of programs and bring them to fruition faster. This chart is a comparison of two commercial NiCd cells with an aerospace NiMH. The relatively low energy density of the NiMH is due to heavier packaging; however, if use of commercial technology is possible, a large cost and weight saving may be realized.

EPI RMH-10

10 Ampere Hour Nickel Metal Hydride Cell Produced by Eagle-Picher Ind, Joplin, MO.

10 Positive (Nickel) plates and 11 Negative (Hydride) plates.

Polypropylene Separators.

31% Potassium Hydroxide Electrolyte.

Orbit Profile

Highly Elliptical, 99 minute length.

69 Minutes Sun, 30 Minutes Eclipse.

Constant Power Load = 17.0 watts.

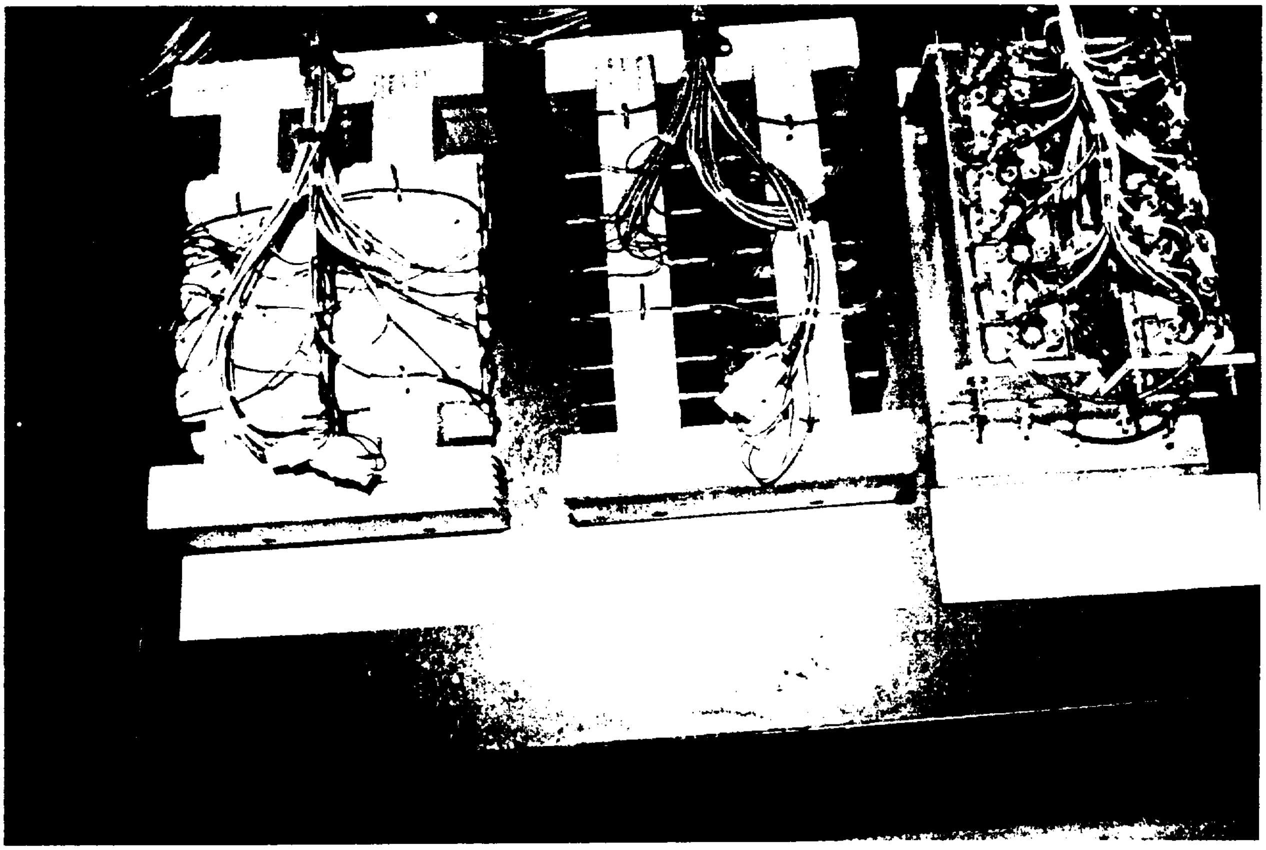
4% DOD (NiMH), 5.6% DOD (NiCd)

5300 LEO Orbits Annually.

The planned application of the NiMH batteries is on a small amateur radio satellite built by the Students for the Exploration and Development of Space (SEDS). The name of the satellite built by the group is the Students for the Exploration and Development of Space Satellite (SEDSAT). This small satellite is designated to be launched from the Space Shuttle in early 1997 as the effective endmass for a flight of NASA's Small Expendable Deployer System (also SEDS). The student SEDS group is composed of university students from around the world working cooperatively to further their understanding and interest in space. This small satellite is a practical application of all new technologies possible.

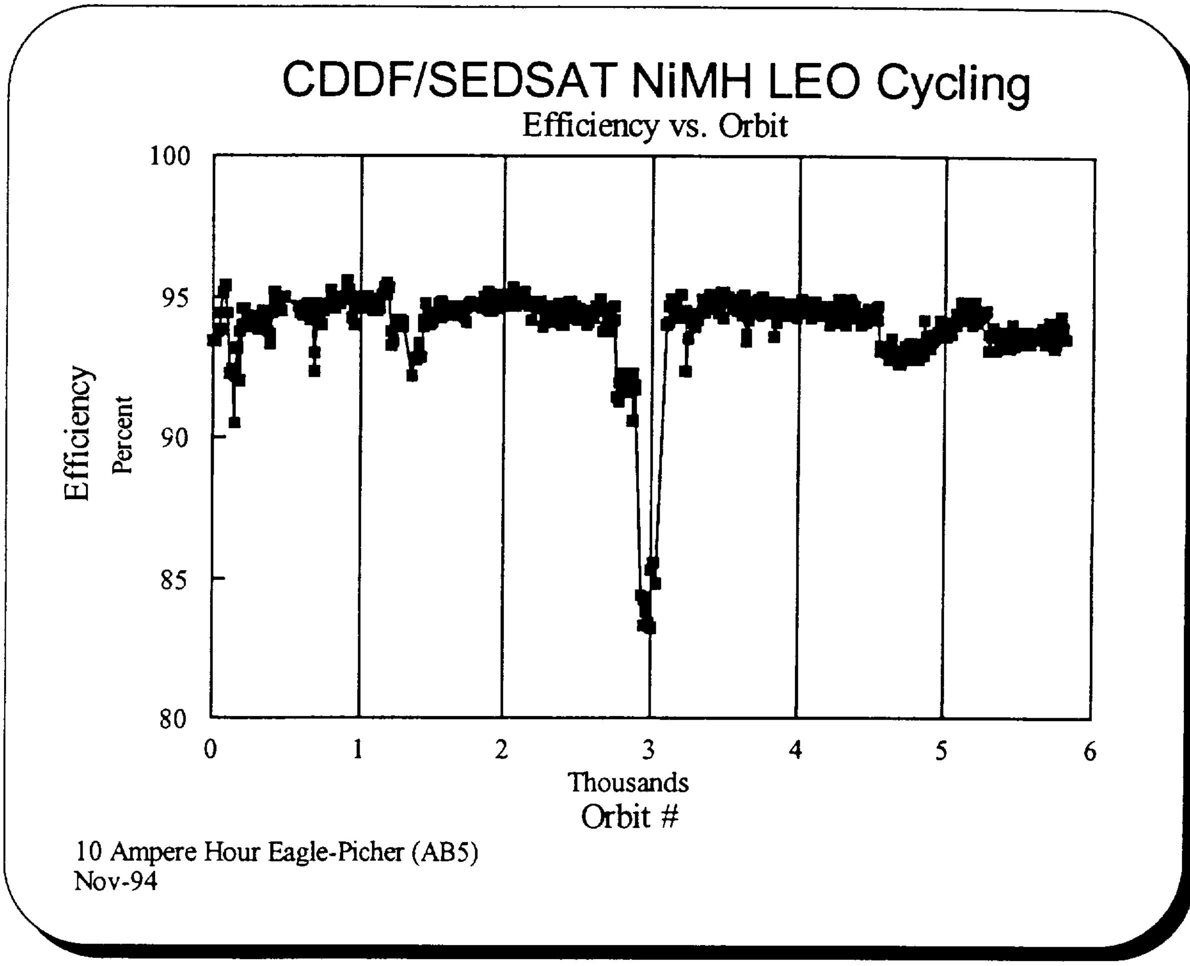
The power system baselines NiMH battery cells because of their energy density. The spacecraft power bus can operate between 16 and 40 volts because of voltage converters; however, the solar array capability can only charge 16 battery cells.

A 16 cell NiMH battery is being LEO cycled in a simulated power system in support of the anticipated launch. Two commercial NiCd batteries are also being cycled in the same manner for comparison and as possible alternative flight batteries.



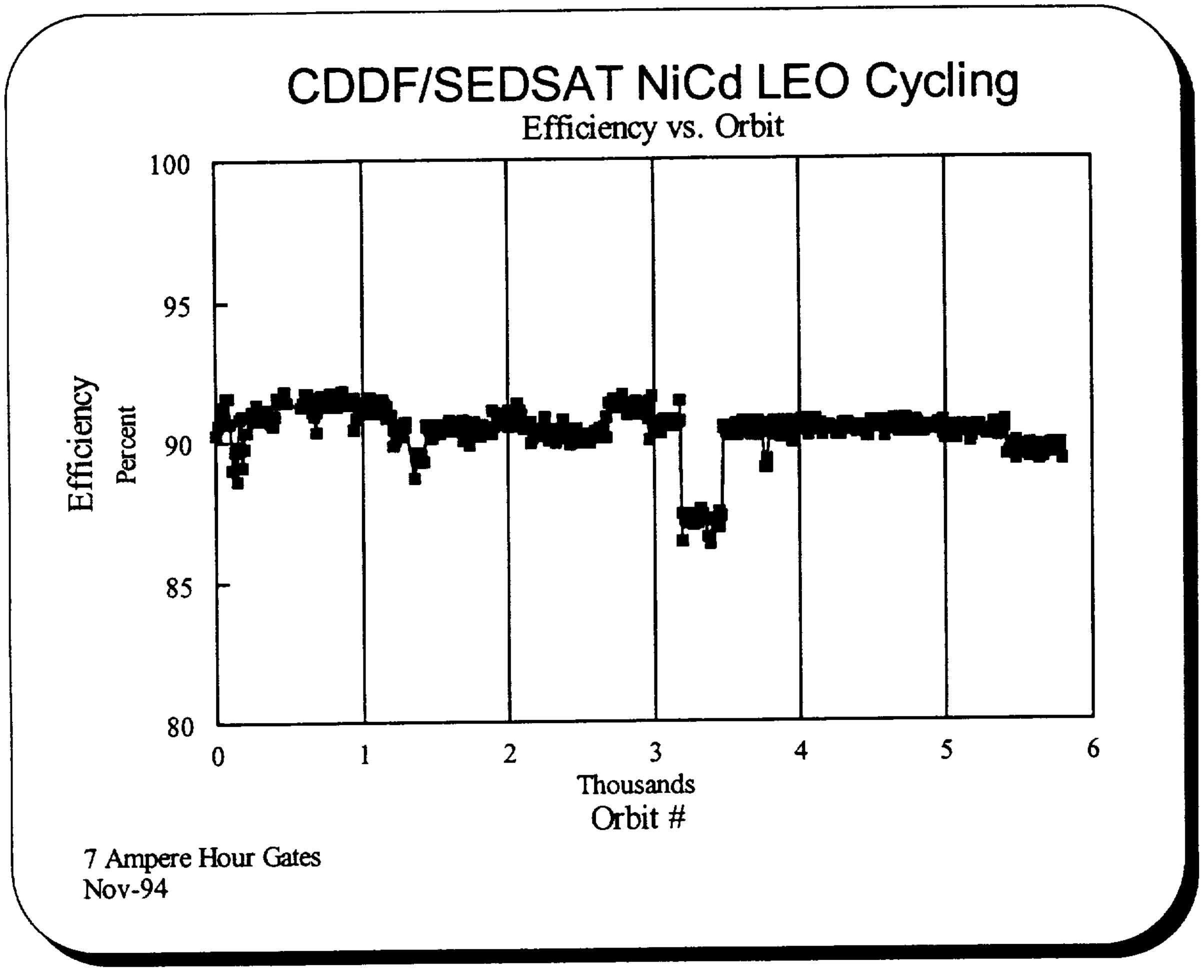
THE PHOTOGRAPH ON THIS PAGE ILLUSTRATES THE TEST BATTERIES.

The battery on the left is composed of commercial 7 amphere hour cylindrical NiCd cells manufactured by Gates Energy. The middle battery is composed of commercial 7 ampere hour cylindrical NiCd cells manufactured by Saft. The battery on the right is composed of aerospace 10 ampere hour NiMH cells manufactured by Eagle-Picher. Instrumentation for the batteries includes battery voltage, cell voltage, battery current and temperature. The batteries have been cycled 5800 real time orbits.

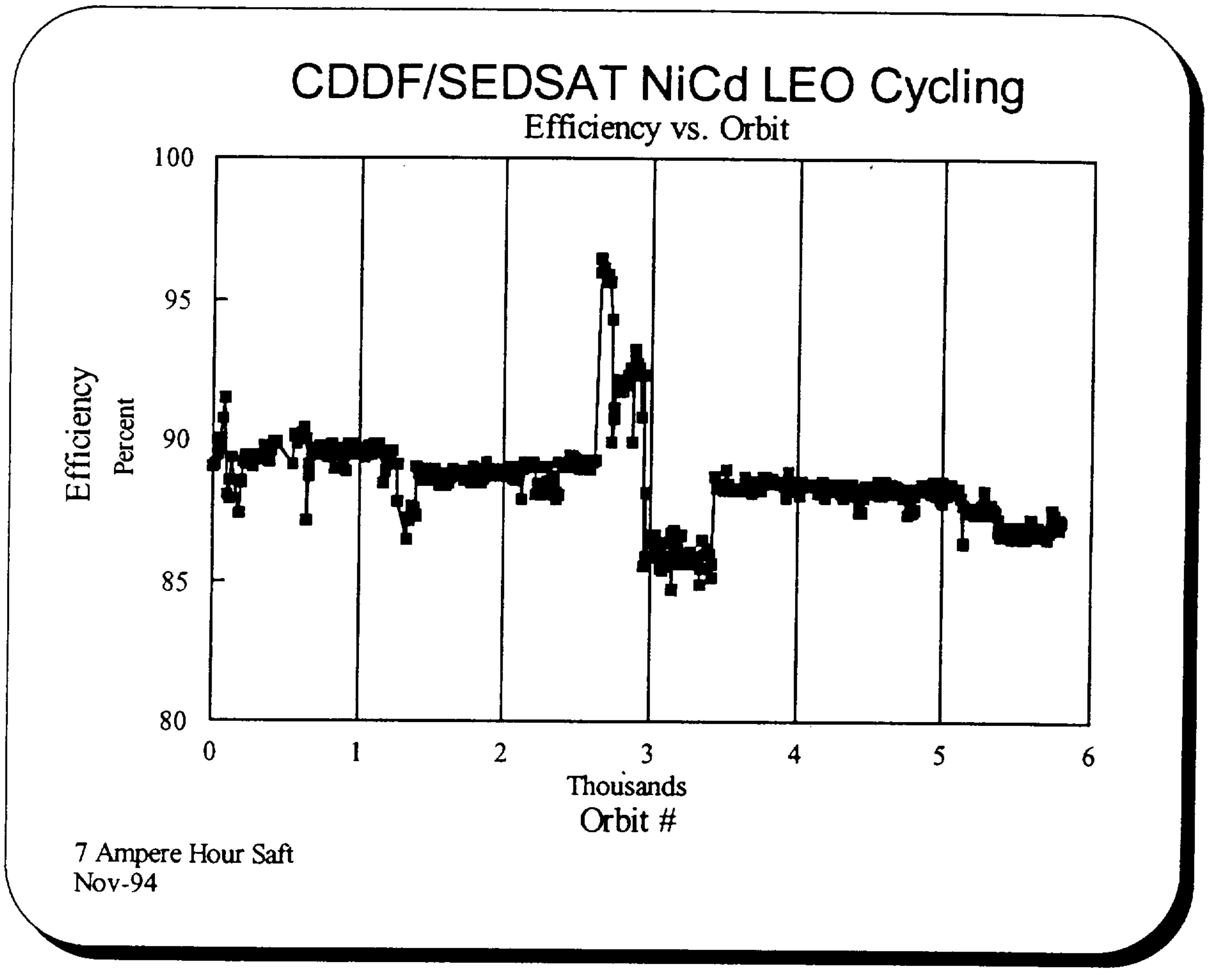


The NiMH battery is very efficient. The average watt hour efficiency over the 5800 orbits has been 94%. The depth of discharge is very low (4%) and the load during discharge has not caused the voltage to decrease very much from the charge value. The battery efficiency on an ampere hour basis is 91%. The recharge ratio was adjusted to minimize overcharge and to maximize the efficiency.

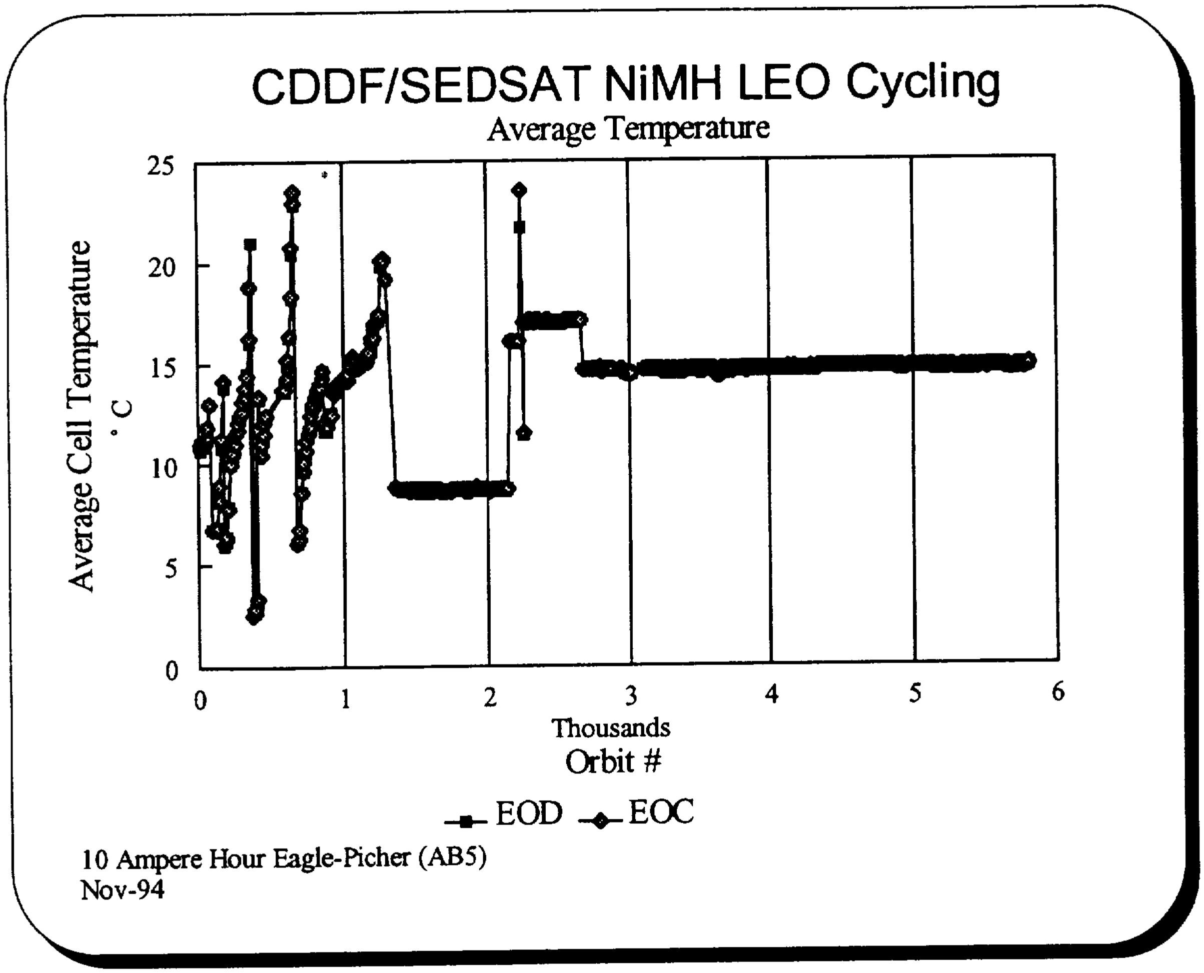
The decrease in efficiency at 3000 cycles was caused by a loss of two of the cells. The first cell began to show degraded performance at 2950 cycles. The cell began to develop an impedance during charge and exhibited a severe loss of capacity during discharge. The poor performance of the cell is attributed to degradation of the separator. The cell was removed from the battery after 2990 cycles. A second cell began to exhibit the same type of behavior at 3030 cycles. This cell also began to develop an impedance during charge and exhibited a severe loss of capacity during discharge. The second cell was removed from the pack at 3070 cycles.



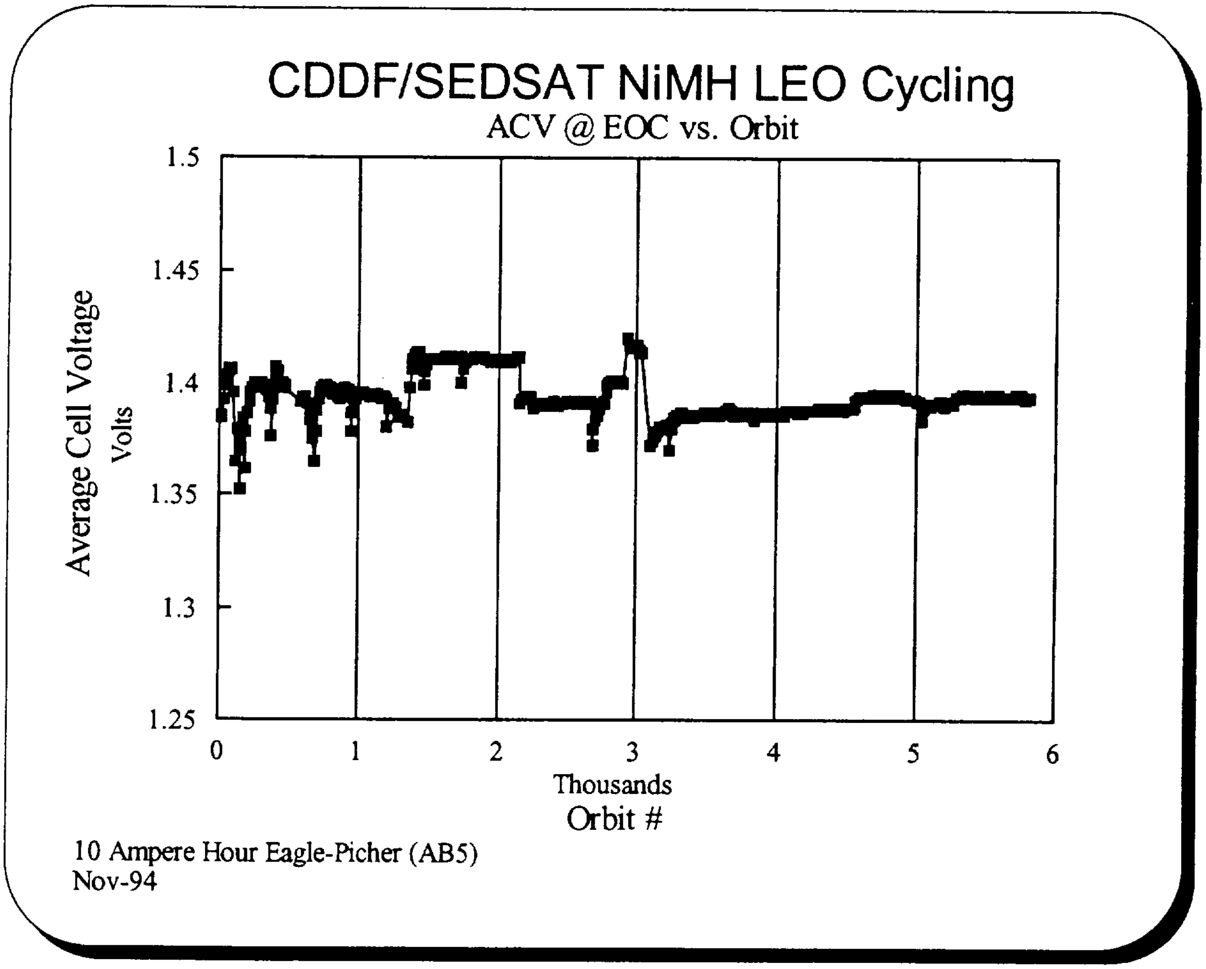
The commercial NiCd cells did not perform as well as expected. The light load and the minimal overcharge were hoped to produce a higher watt hour efficiency. The efficiency of the 7 ampere hour commercial NiCd cells manufactured by Gates averaged 91% over the first 5800 real time LEO cycles. The depth of discharge for the 7 ampere hour cells is 5.6%. The recharge ratio during the 5800 cycles was set at 1.04. The recharge ratio was adjusted based on the performance of the NiMH cells. The charge acceptance efficiency may have been a factor in the performance of the NiCd cells. All three of the batteries were charged to a recharge ratio of 1.04 at a moderate rate with less than five minutes of trickle charge. The NiMH cells charge acceptance efficiency is very high at moderate charge rates. The charge acceptance efficiency of the NiMH cell is also very high at high rates of charge. The charge acceptance efficiency of the NiCd cell is high at high charge rates but decreases substantially at lower rates of charge.



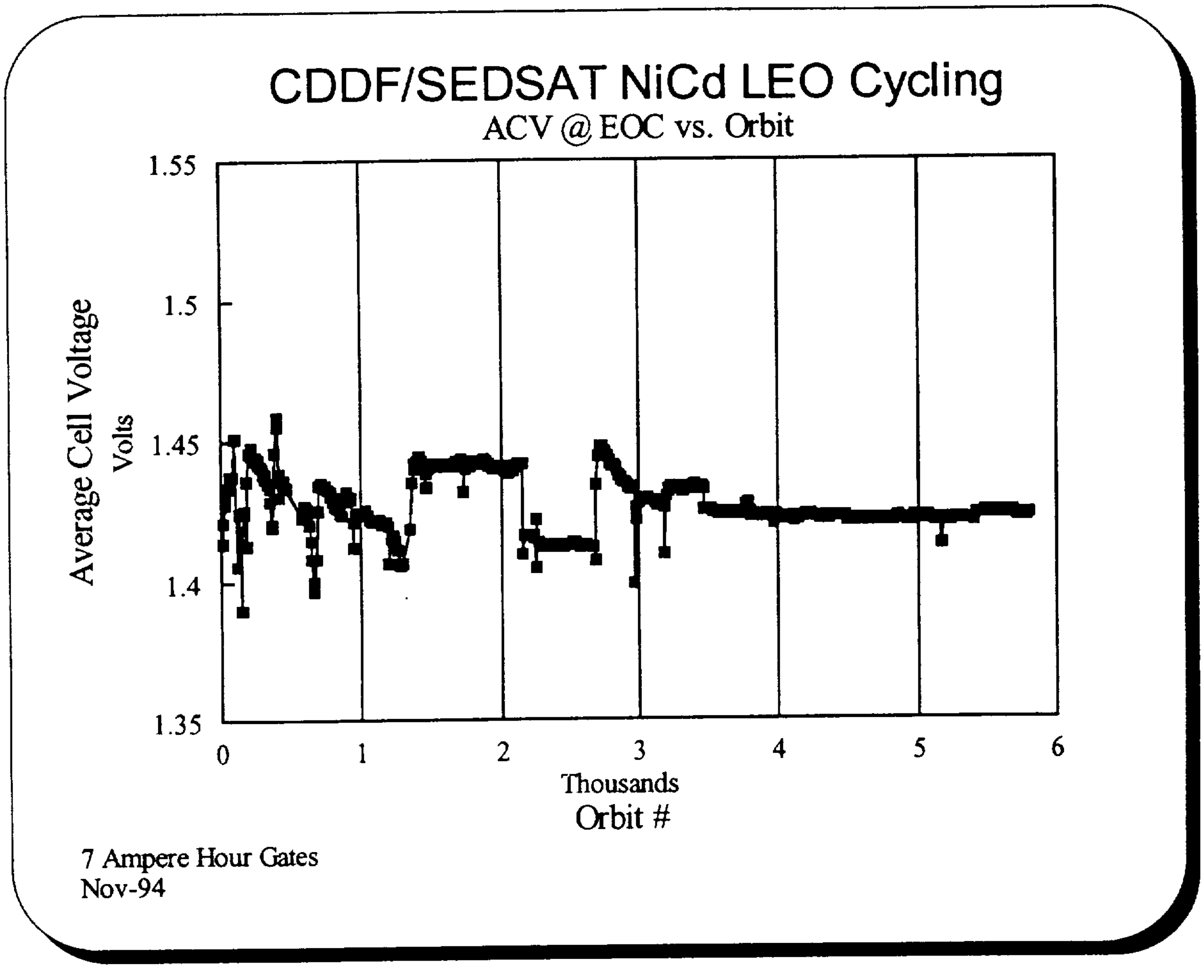
The watt hour efficiency of the commercial NiCd cells produced by Saft was not as high as the efficiency of the commercial cells produced by Gates. The average watt hour efficiency of the Saft cells over the 5800 orbits was 89%.



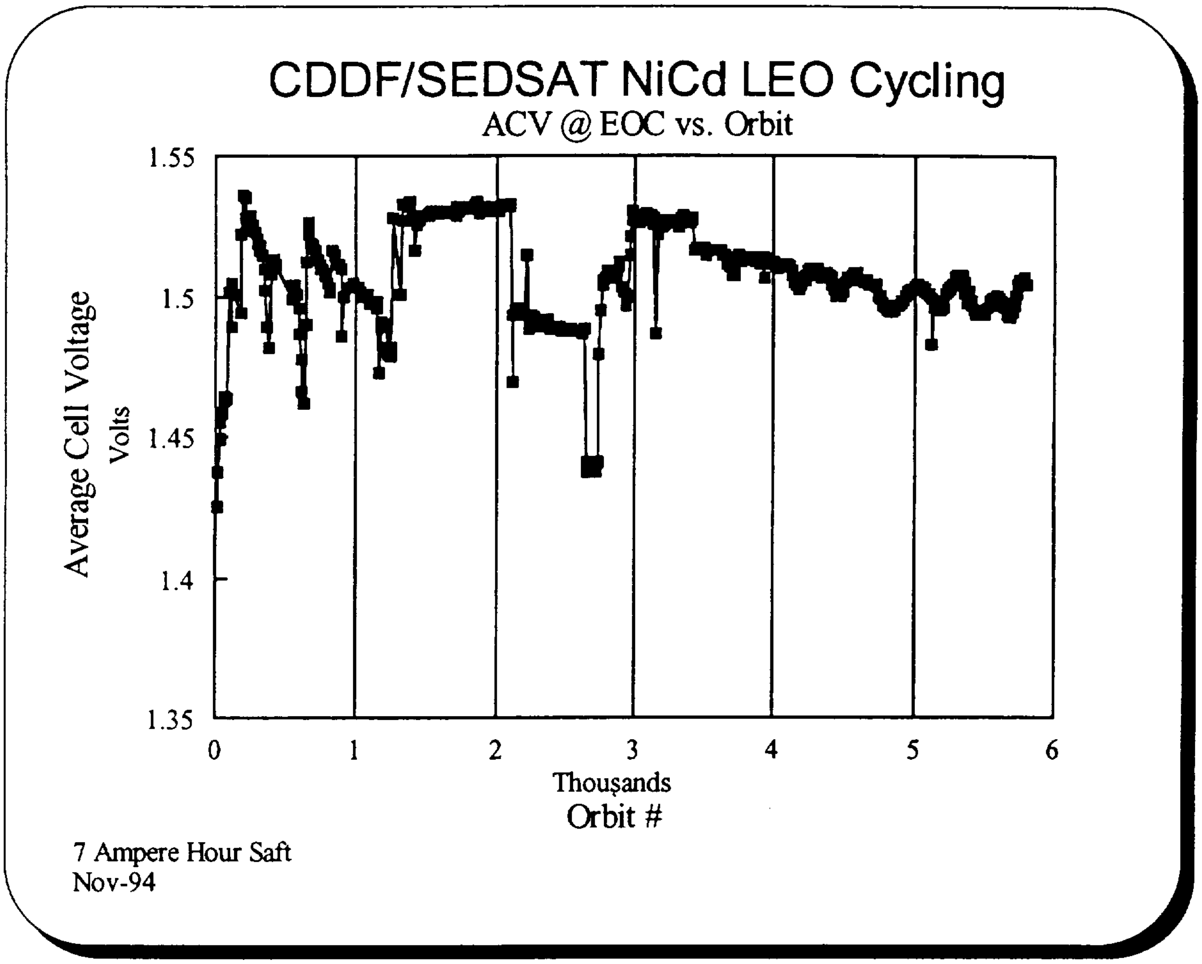
The temperature of the test batteries fluctuated greatly during the first 1000 cycles; however, the efficiency of the batteries was not affected. The efficiency of all three batteries was constant during the period of thermal variance. The early thermal variation was due to problems with the environmental chamber providing thermal control. Temperature did not appear to have a significant effect on performance of the NiMH or the NiCd batteries during the first 5800 LEO cycles.



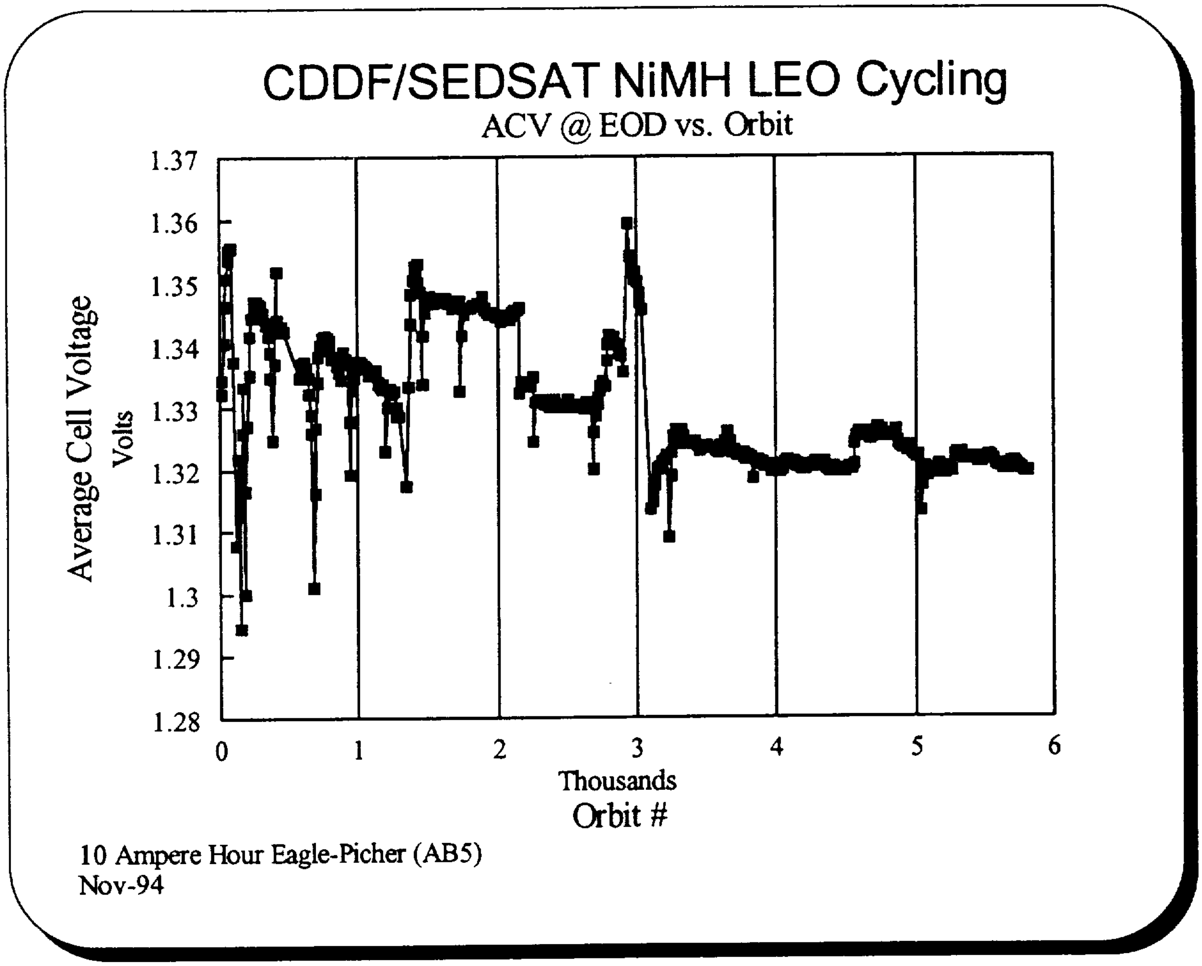
This chart shows the average cell voltage at the end of the high rate charge period. The NiMH cell does not show a large variation from its initial value. This data indicates that the cells are not developing an internal impedance operating under the test conditions. The lack of variation in the end of charge voltage may indicate that the active hydride material has remained stable and that there has been little movement.



The average cell voltage at the end of the high rate charge period for the NiCd cells manufactured by Gates was 1.43 volts. This voltage is three millivolts higher than the average voltage of the NiMH cells. This difference would be .5 volts at the battery level. This difference is partially responsible for the lower efficiency of the NiCd cells. Internal impedance is responsible for this voltage differential.

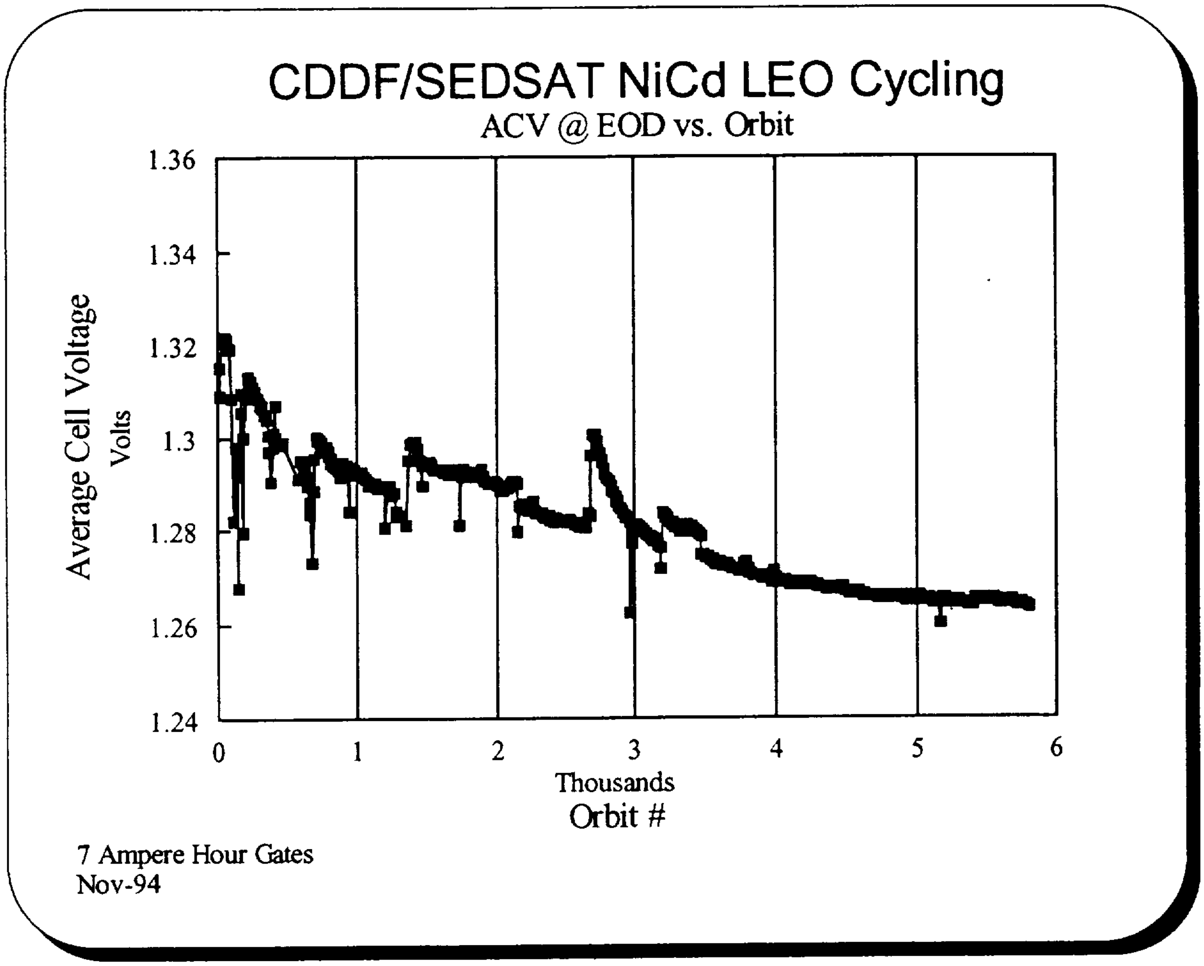


The average cell voltage at the end of the high rate charge period for the NiCd cells manufactured by Saft was 1.52 volts. This difference from the comparable commercial NiCd cell is thought to be attributable to separator impedance.

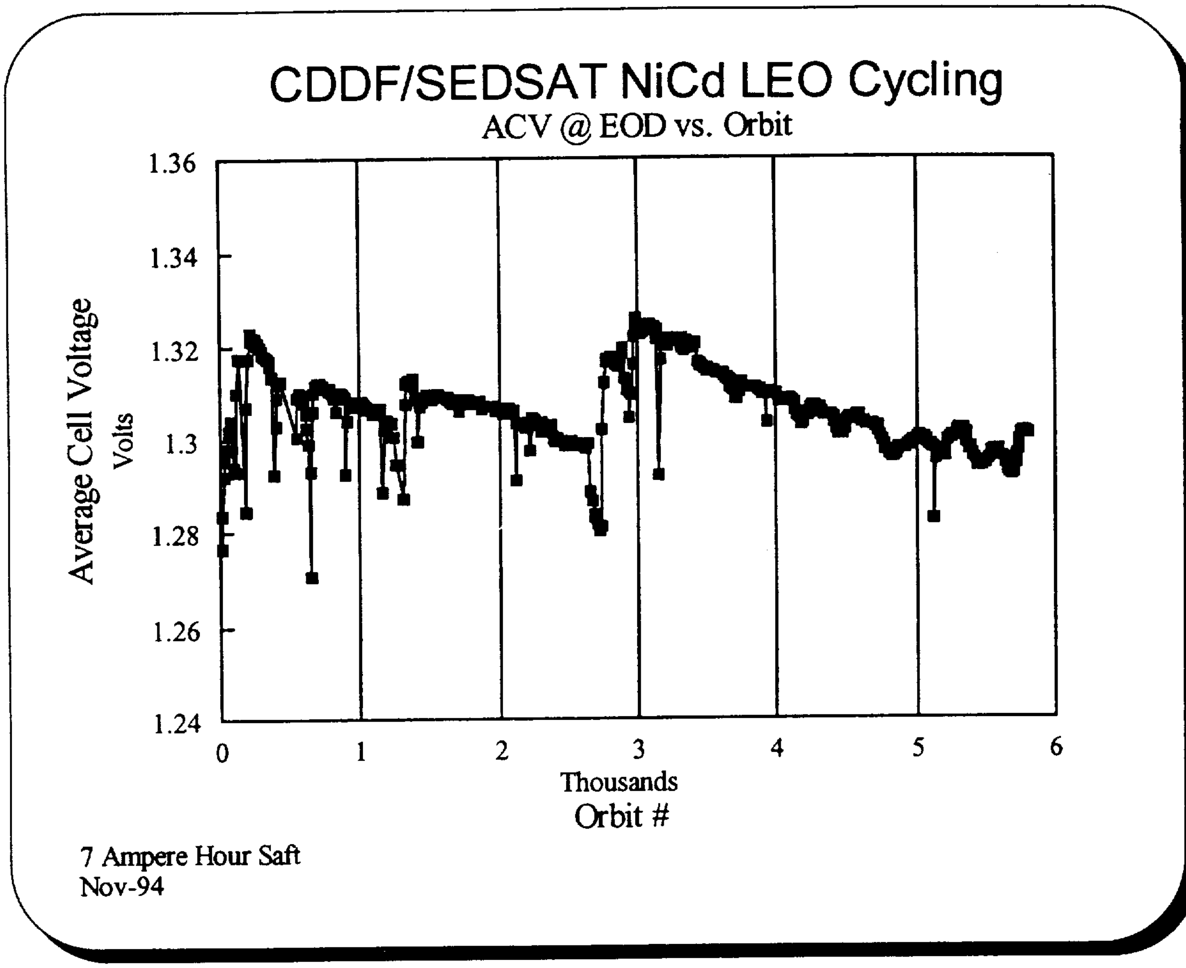


The average cell voltage at the end of discharge is a good general indicator of the true health of a battery. A number of factors can affect the end of discharge voltage. To use the end of discharge voltage as specific indicator of health, the effects of variables such as recharge ratio, amount of overcharge, life history, system operation, anomalies, etc. must be quantified. Understanding the relationship of all of the variables related to the performance of the battery is very complex.

The end of discharge voltage has decreased an average of two millivolts over the 5800 cycles. This decrease is attributable to normal degradation.



The Gates NiCd end of discharge voltage has decreased an average of six millivolts over the 5800 cycles. This loss is normal and expected in commercial cells. The cells are exhibiting normal aging and wearout mechanisms.



The Saft commercial NiCd cells have not exhibited the expected decrease in end of discharge voltage. This phenomena may be due to an excess of active material in the cell present since manufacturing.

The performance of the NiMH cells is very satisfactory at this point. The comparison between the NiCd and NiMH cells favors use of the NiMH cells. The present results indicate that NiMH cells are feasible direct replacements for NiCd cells in many applications.

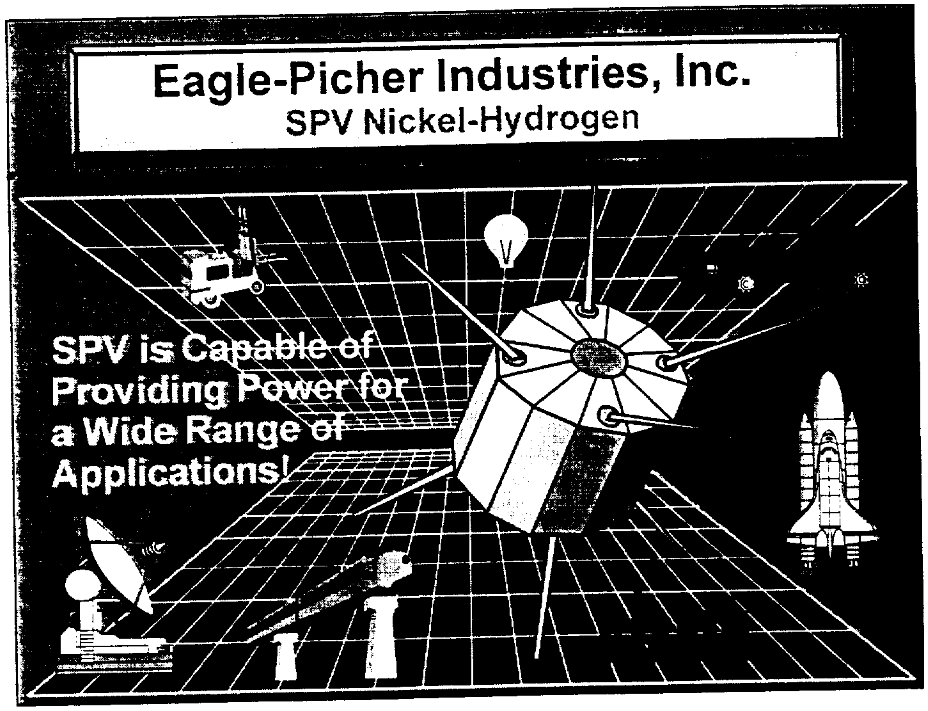
EAGLE - PICHER 1843

EP150

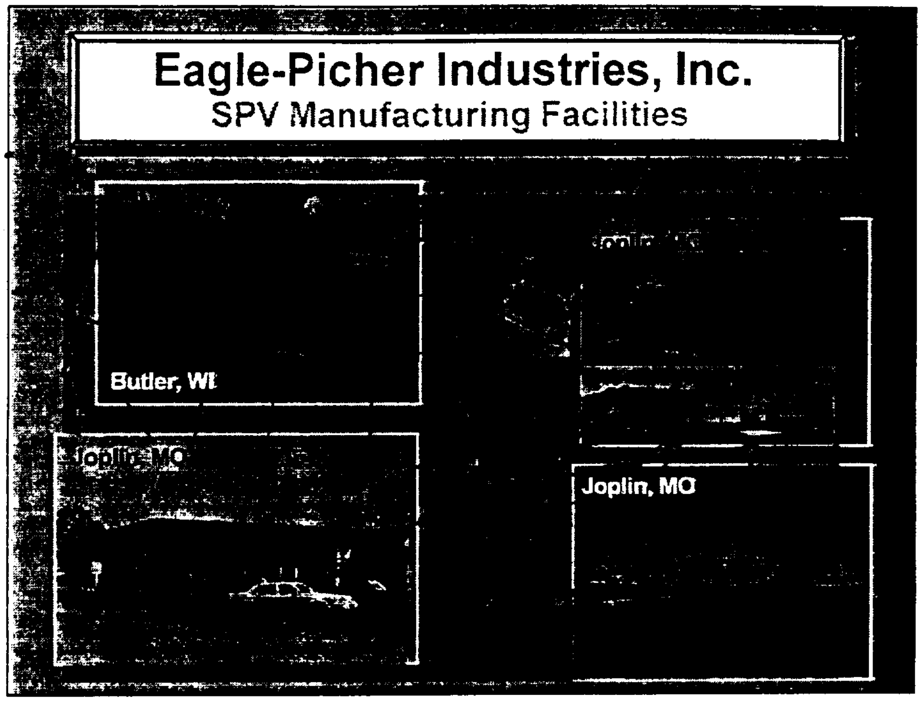
1993 INDUSTRIES, INC.

Nickel-Hydrogen ($Ni-H_2$) System
Single Pressure Vessel (SPV) Technology

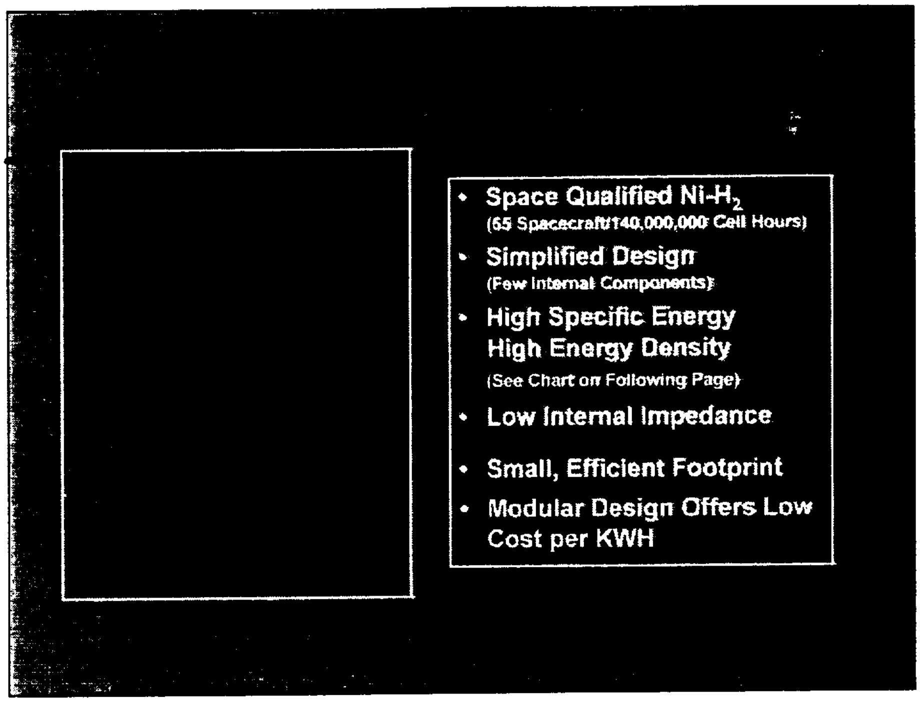
- Founded in 1843, Cincinnati, OH
- 1993 Revenues $661.5 Million
- 15 Operating Divisions
- Approximately 6500 employment (1500 associated with battery manufacturing)
- 55 Manufacturing Facilities (11 Batteries)
- 50 Domestic - 5 International Locations



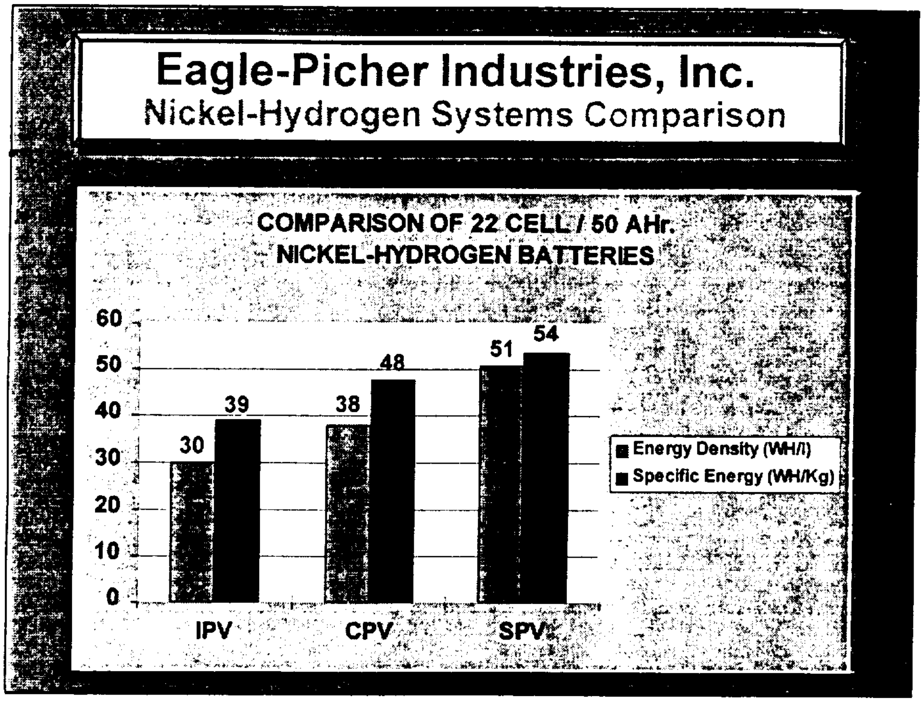
- Satellite Power
- Electric Vehicles (Cars, buses, trains, utility vehicles)
- Terrestrial Applications
    - Telecommunications Equipment
    - "Fiber-in-the-loop"
    - Remote repeater/antenna array backup power
    - Utility Load Leveling
    - Uninterruptible Power Systems (UPS)



- Eagle-Picher Acquired Former Johnson Controls Ni-H2 Space Battery Assets in Butler, WI June 1, 1994.
- Merging of Respective SPV Technologies Has Produced a Superior Battery Design.
- Acquisition will produce a hybrid design SPV.
- Both technologies are COMSAT licensed. The Butler facility continued with flexible, thin film cell case design. EPI went another direction and developed a rigid cell case design.
- Two (2) lower cost, Commercial Aerospace, manufacturing plants (located in Joplin, Missouri and Butler, Wisconsin) have now been designated to support the industries requirements.

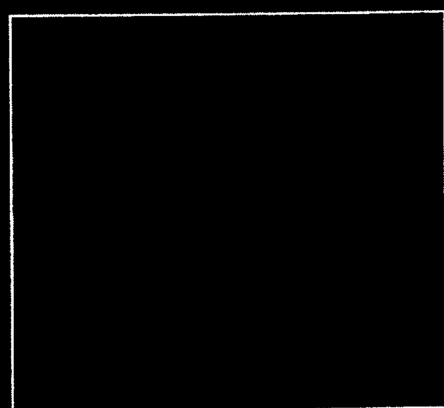


- Battery utilizes the same proven nickel-hydrogen electrode technology which has currently been demonstrated on over 65 satellite launches and has accumulated an excess of 140,000,000 successful cell hours in space
- When compared to IPV and CPV batteries, there are fewer components.
- Internal impedance is lower due to shortened conductor path within the battery. (SPV 20 mOhms/ IPV 30-35 mOhms)
- Higher specific energy when compared to Ni-Cd, IPV and CPV

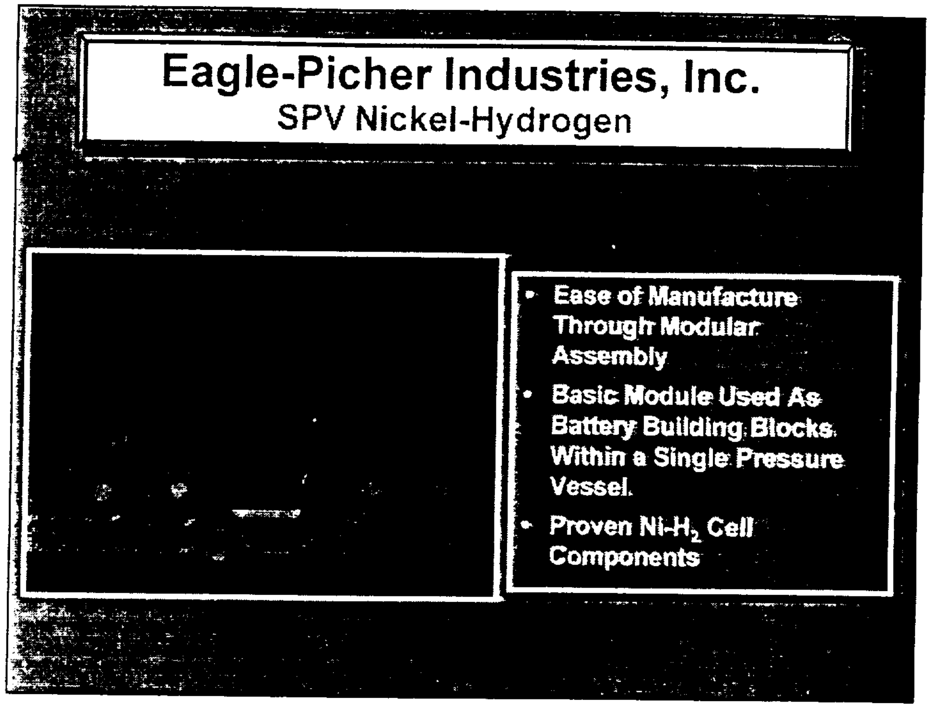


- For Ni-H2 comparison, assumed equal power capability (conductor IR loss) plus same pressure vessel safety margin.
- Ni-Cd projection assumed current available cell technology and "frame" type battery design.

Eagle-Picher Industries, Inc.
SPV Nickel-Hydrogen

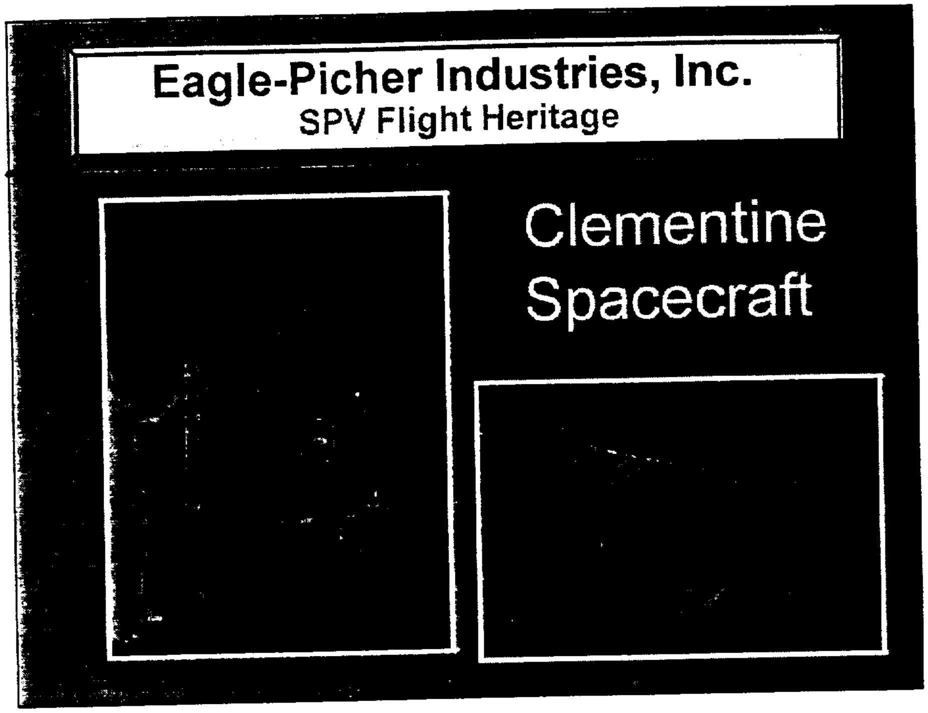


- Each Cell Enclosed Within an Individual Cell Container
- Radial Thermal Fin for Internal Cell Heat Transfer
- Cell Container is Vented Allowing for Common Hydrogen Access

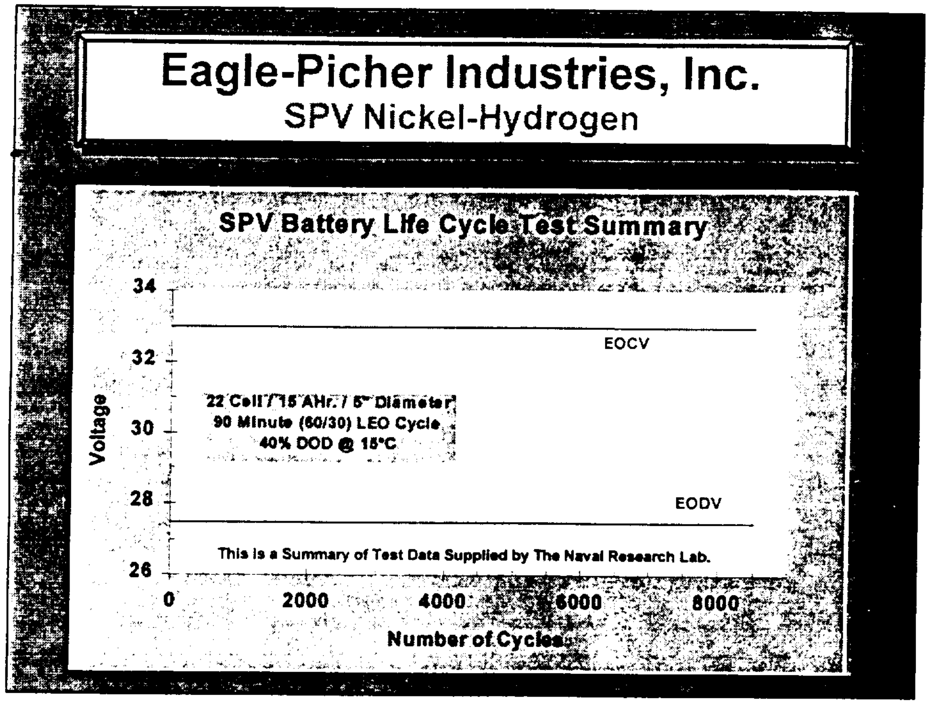


Modular assembly allows:

- Various battery capacity sizes to share common components.
- Ease of assembly.
- Critical cell functional testing prior to battery assembly (Joplin).
- Butler battery is assembled as a stack before activation takes place. Testing is possible at this level before insertion into PV.

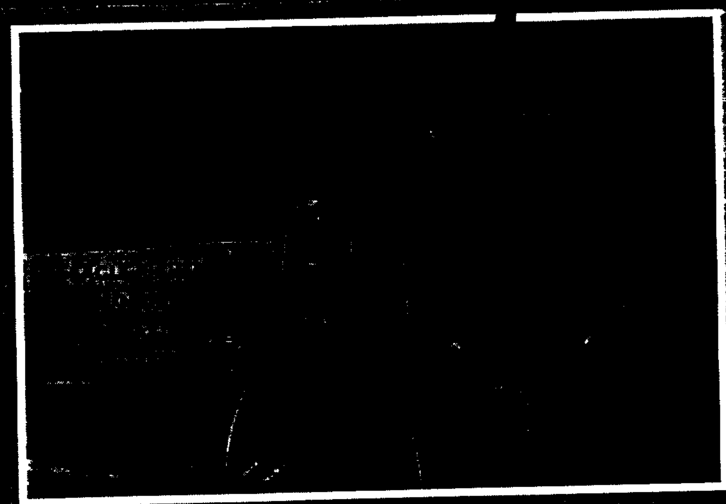


- SPV Technology has been space flight qualified.
- Clementine (NRL) 15 AHr./ 28 Volt
- IRIDIUM® (Iridium, Inc.) 50 AHHr. / 28 Volt

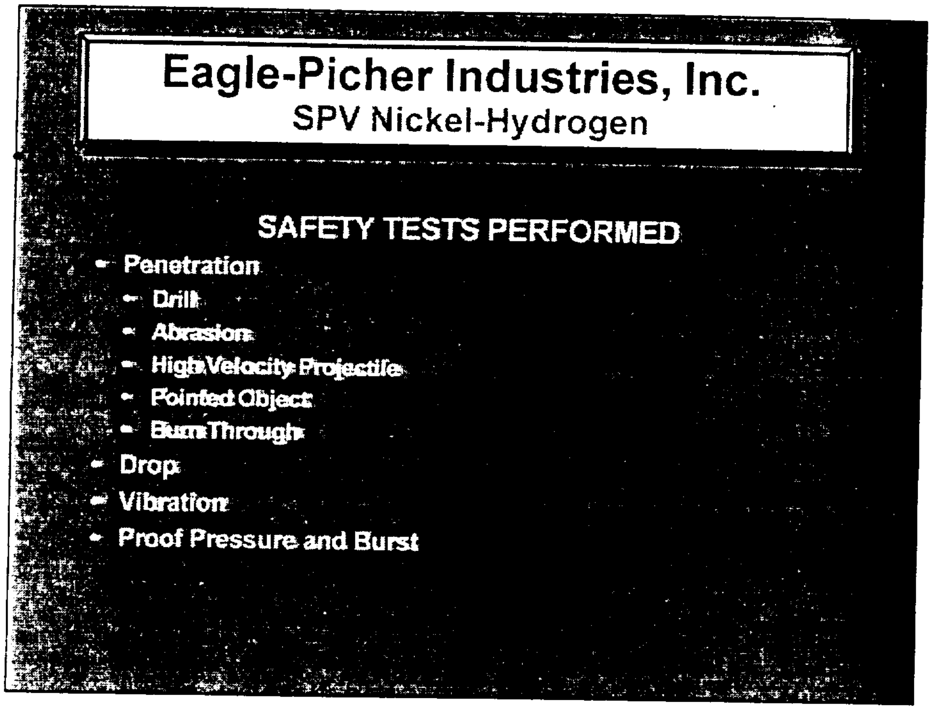


- Test performed by the Naval Research Laboratory.
  - Depth of Discharge = 40%
  - Test Temperature = 15°C
  - Cycles Completed = 8,500
- Additional Life Cycling data is on file from COMSAT Labs:
  - 30,000 cycles on a 2 cell SPV

Eagle-Picher Industries, Inc.
SPV Nickel-Hydrogen



- Test performed on charged 10" diameter, 50 AHr. battery
- 5A discharge during vibration
- 19 GRMS in 2 axes (Y and Z)

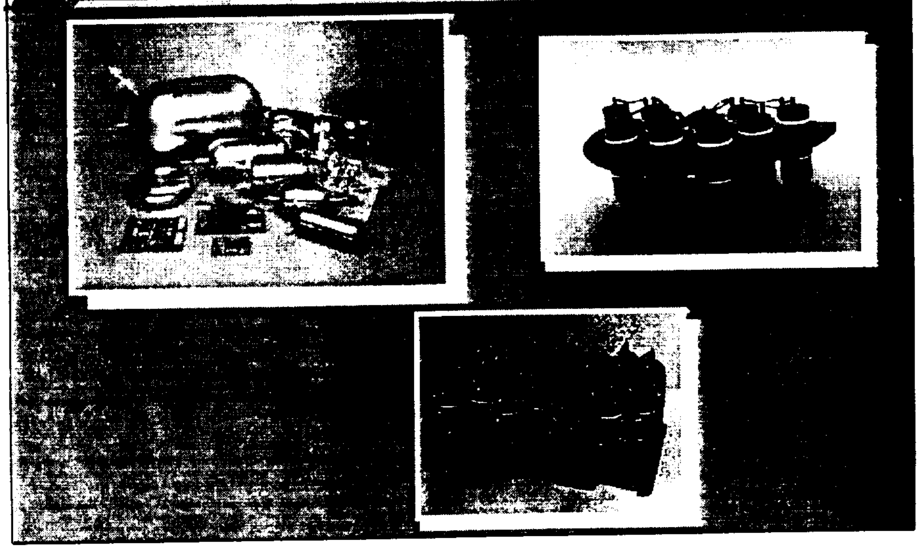


Fatigue/Burst:

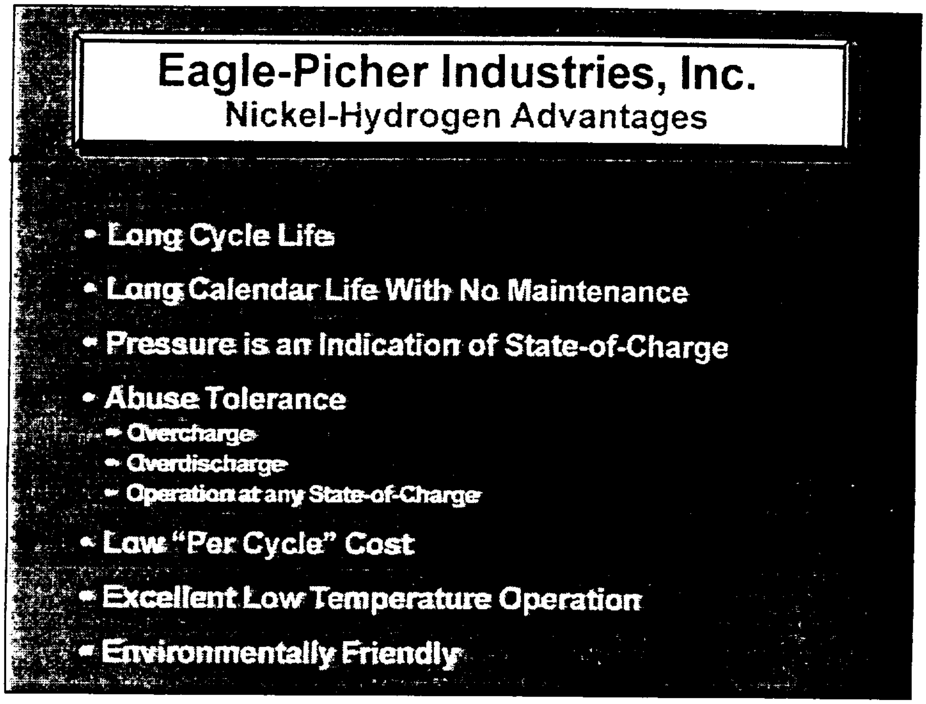
- >2.0 x Maximum Expected Operating Pressure (MEOP) burst pressure after 100,000 fatigue cycles per MIL-STD-1522A.

Eagle-Picher Industries, Inc.

SPV & Complementary Ni-H_2 Designs



- Currently the only domestic manufacturer of the SPV (and CPV) Technology.
- Licensed from COMSAT and Johnson Controls.
- Other Ni-H2 designs manufactured:
    - IPV
    - CPV
    - DPV
    - Low Pressure Vessel (LPV) Under development
- Other Space Qualified Products Manufactured:
    - Intelligent Battery Charger
    - Charge/Discharge Controller Circuitry
    - Special Test Equipment
    - Heater Controllers
    - Temperature Monitoring Systems
    - Strain Gage assemblies
    - Strain Gage signal amplification circuitry



- **Long Cycle Life**
  - 100K+ cycles demonstrated
- **Long Calendar Life With No Maintenance**
- **Pressure is an Indication of State-of-Charge**
  - Approximately 50 to 1200 psig
- **Abuse Tolerance**
  - Overcharge
  - Overdischarge
  - Operation at any State-of-Charge
- **Low "Per Cycle" Cost**
- **Excellent Low Temperature Operation**
  - -10°C preferred (excursions to -20°C are permissible) OLYMPUS spacecraft was frozen and successfully recovered
- **Environmentally Friendly**
  - No Cadmium, Lead or Mercury in the system
  - Hermetically Sealed System

N95- 26792

50 Ah NiH_2 CPV Qualification Tests

J.C. Garner, W. Barnes, G. Hickman
U.S. Naval Research Laboratory

In 1992, the Naval Research Laboratory (NRL) started a program to qualify a large diameter common pressure vessel (CPV) nickel hydrogen (NiH_2) batteries for use on future Navy/NRL spacecraft electrical power subsystems. NRL's involvement with the qualification of CPV NiH_2 batteries dates back to 1988 when COMSAT and Johnson Controls Inc., initiated a joint effort to fly the first ever NiH_2 CPV in space. A later NRL-JCI cooperative research and development agreement led to the launch of a space experiment in 1993 and to the use of a single NiH2 CPV battery on the BMDO Clementine spacecraft in 1994. NRL initiated procurement of two, 50 Ah CPV NiH_2 batteries in the Fall of 1992. The two batteries were delivered to NRL in June 1994. NiH_2 CPV batteries have almost 2x the specific energy (Wh/kg) of nickel cadmium batteries and 2x the energy density (Wh/l) of individual pressure vessel NiH_2 CPV's. This presentation discusses the results of electrical and mechanical qualification tests conducted at NRL. The tests included electrical characterization, standard capacity, random vibration, peak load, and thermal vacuum. The last slides of the presentation show initial results from the life cycle tests of the second NiH2 CPV battery at 40% depth of discharge and a temperature of 10 deg Celsius.

50Ah NiH_2 CPV Qualification Tests

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Washington, D.C. 20375-5354

INTRODUCTION

- Discuss Preliminary Qualification Test Results Conducted On Eagle Picher (Johnson Controls Inc.) 50 Ah NiH_2 CPV Batteries
- Discuss Follow On Work With 50 Ah NiH_2 CPV
- Additional NiH2 CPV Work @ NRL

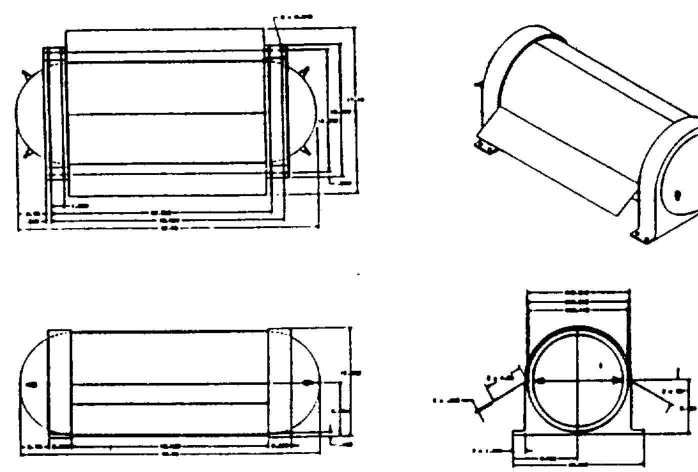
Purpose

- **Risk Reduction Effort To Qualify The 50 Ah Common or Single Pressure Vessel Battery For Use In Future Navy/NRL Spacecraft**

50 Ah CPV Advantages

	110 Ah IPV NiH_2	50 Ah CPV NiH_2
Number Of Batteries	1	2
Cells/Battery	24	22
Bare Battery Mass	141.36 lbs	126 (63 lbs/Bat)
Mechanical/Thermal Mounting Hardware	70.68 lbs	25.2 lbs
Total Battery Mass	212.04 lbs	151.20 lbs
Mass Savings		60.84 lbs

50 Ah CPV Mechanical/Thermal Spacecraft Interface



Program Schedule

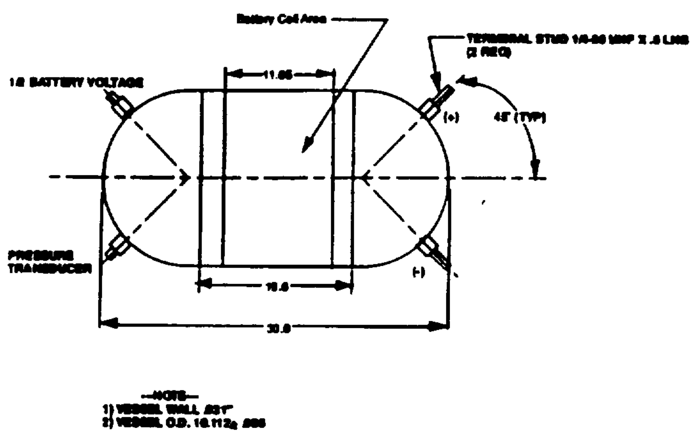
- 1992 September - Released Procurement Package
- 1993 January - Awarded Contract To Johnson Controls Inc., For Two (2) 50 Ah NiH_2 CPV Batteries
- 1993 February - Preliminary Design Review
- 1993 April NRL Preliminary Design Review
- 1993 August - Critical Design Review
- 1993 August - December
  - Pressure Vessel Qualification
  - Cell Build
  - Electrolyte Fill Determination Tests
- 1994 January - March End Plate Problems
  - Complete Mass Simulator, Conduct Qualification Vibration
- 1994 March - June Assemble Batteries/Acceptance Test
- 1994 July - September Qualification Tests On S/N 144
- 1994 September Start Life Cycle Test S/N 145

Eagle Picher (Johnson Controls Inc.)
50 Ah NiH2 CPV Battery

- Capacity — 50 Ampere-Hours*
- Number Of Cells — 22
- Back-To-Back Positive Electrodes
- Separator — Dual Layer Zircar
- Electrolyte — 31% KOH
- Pressure Vessel — 30 mil Inconel 718 Tube w/ Hydroformed End Domes
  - Diameter — 10.0 inches
  - Length — 30.0 inches
- Mass — 63 lbs (28.58 kg)
- Terminal — Positive, Negative, 1/2 Battery Voltage
- Pressure — Kuhlite ETM-341-375-1000 Pressure Transducer

* When Discharged @ C/2=25.0 Amps To 22.0 Volts @ 10°C, After A 16 Hour Charge @ C/10=5.0 Amps

Battery Exterior Dimensions



Electrolyte Fill Level Tests (1 Of 2)

- Earlier Experience W/Clementine Batteries Showed Oxygen Recombination Damage (Popping)To Electrolyte Containment Bags Will Occur W/Too Much Electrolyte
  - Cell Stack Must Be Removed From Pressure Vessel
  - Electrolyte Containment Bags Need Replacement
- Electrolyte Fill Level Determined By Calculation
  - Based On Nominal Component Dimensions
  - Assumes Vendors Supply Components Within Tolerance Specification
- Per NRL Request, EP (JCI) Initiated Electrolyte Fill Level Tests Before Adding Electrolyte To First Battery
  - EP Performed Electrolyte Fill Calculation (g/Ah)
  - Build 6 Boilerplate Test Cells, Sim-LEO Cycle

» 1.	2.9 g/Ah	4.	3.5 g/Ah
» 2.	3.0 g/Ah	5.	*3.8 g/Ah (calculated)*
» 3.	3.4 g/Ah	6.	4.0 g/Ah

Electrolyte Fill Level Tests (2 Of 2)

- Capacity Measurement After 24 Cycles
  - 2.9 g/Ah 10.50 Ah
  - 3.0 g/Ah 12.96 Ah
  - 3.4 g/Ah 11.68 Ah
  - 3.5 g/Ah 13.11 Ah
  - 3.8 g/Ah 13.04 Ah
  - 4.0 g/Ah 13.40 Ah
- Continued Cycling the 3.0 g/Ah, 3.5 g/Ah, and 3.8 g/Ah
- 1000 Cycle Capacity
  - 3.0 g/Ah
  - 3.5 g/Ah
  - 3.8 g/Ah
- Selected 3.65 g/Ah For Electrolyte Fill Level

Pressure Vessel Qualification

- Qualify Battery Pressure Vessel To MIL-STD-1522A
- Pressure Cycle Vessel From 0 To MEOP* For 4 x Expected Cycle Life
  - 0 to 700 psi
  - 4 x 25,000 Cycles = 100,000 Cycles
- Provide Safety Factor > 2.5 :1 For Burst
- Tests Conducted At Milwaukee School Of Engineering (FPI)
- 3 Vessels Failed Before Successful Cycle Test
  - Design Of Support For Cell Stack
  - Design Of Weld Ring
  - Shape Of Pressure Cycle Curve
- Burst Pressure of 2320 psi After 105,000 Cycles
  - Safety Factor 3.3 : 1

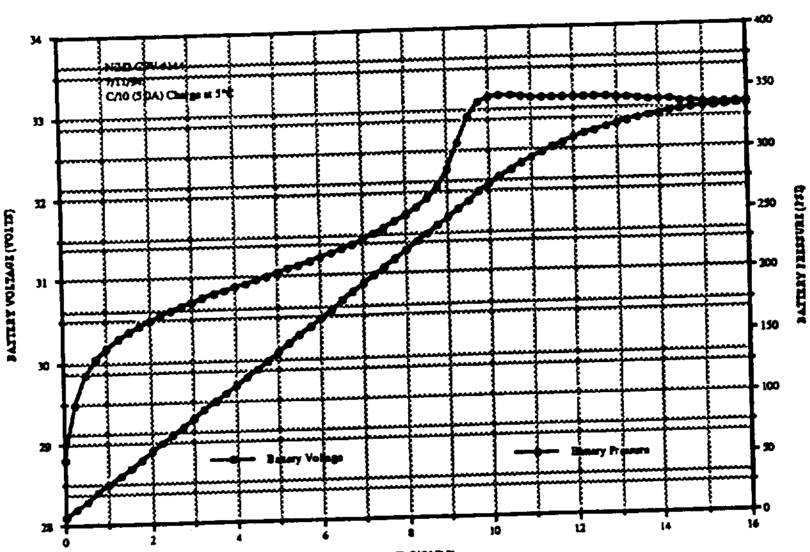
Eagle Picher (JCI) Acceptance Tests

- Visual Inspection Dimensional and Weight Check
- Insulation Resistance Test
- Conditioning Capacity
- Capacity & Overcharge @ 25°C
- Capacity & Overcharge @ 35°C (Deleted)
- Capacity & Overcharge @ 0°C
- Impedance
- Charged Open Circuit Stand
- Electrolyte Leakage
- Pressure Transducer Calibration

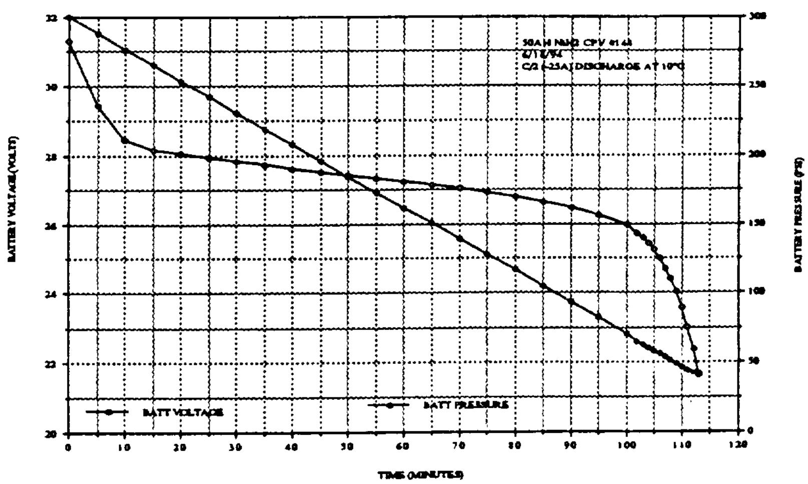
NRL Acceptance Test Plan

- Receipt & Inspection
- Installation Of Thermal Control Hardware
- Initial Capacity
  - 5.0 Amp Charge For 10 Hours + 2.5 Amp Charge For 14 Hours
  - -25 Amp Discharge to 22.0 Volts
- Capacity @ -10°C, -5°C, 0°C,5°C, 10°C, 20°C
- LEO Cycle 40% DOD, 10°C
- Charge Retention Test
  - 5.0 Amp Charge 16 Hours, 72 Hours Open Circuit, -25 Amp Dischsrge To 22.0 Volts
- Peak Load Test
  - -25 Amp Discharge For 1 Hour Followed By - 100 Amp Discharge For 5 Minutes
- Random Vibration
  - -10 Amp Discharge, 18.9 Grms For 180 Seconds In Each Axis
- Thermal Vacuum

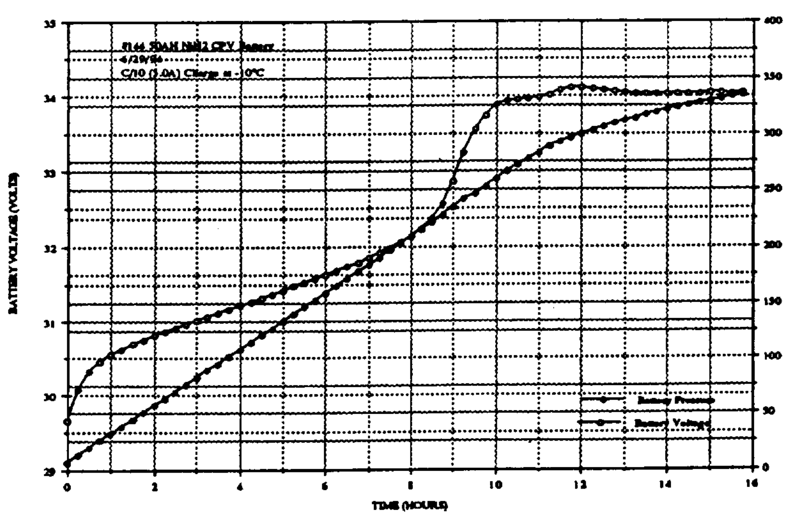
5.0 Amp Charge For 16 Hours @ 5°C



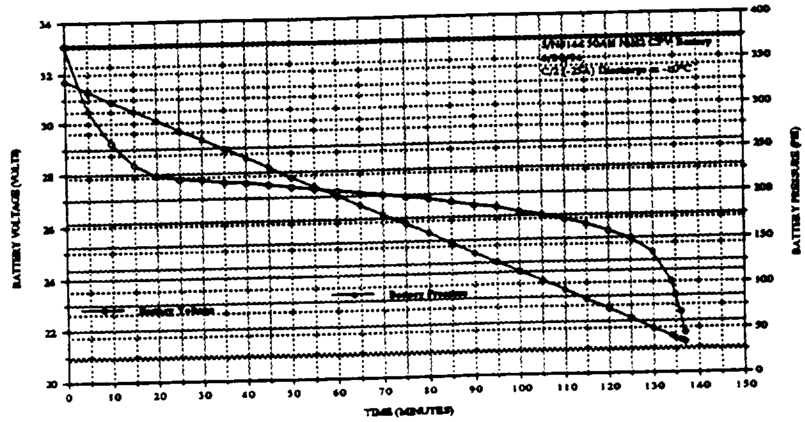
-25.0 Amp Discharge @ 10°C



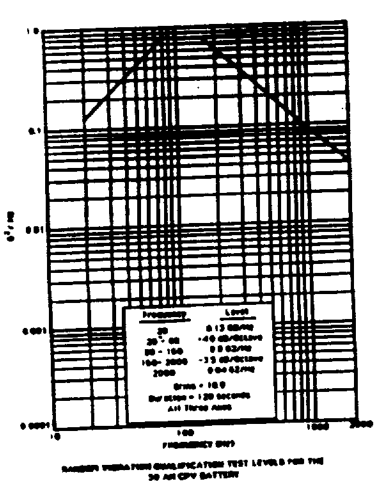
5.0 Amp Charge For 16 Hours @ -10°C

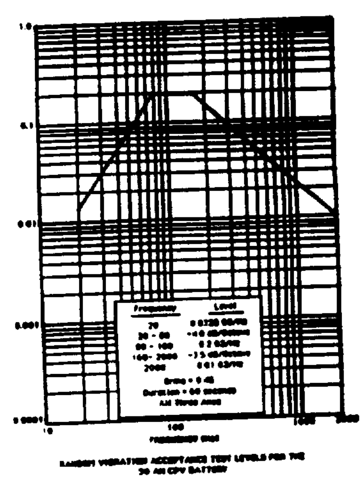


-25.0 Amp Discharge @ -10°C

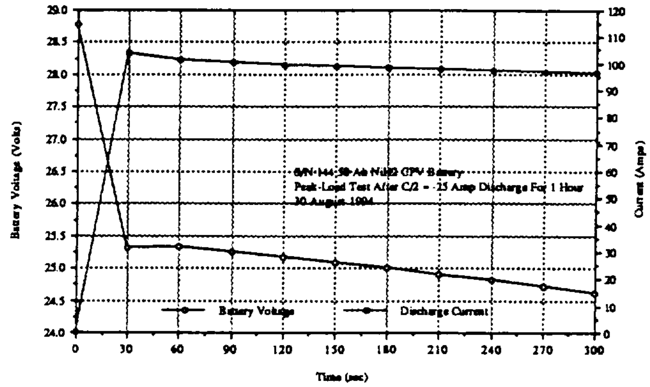


Random Vibration Test Levels

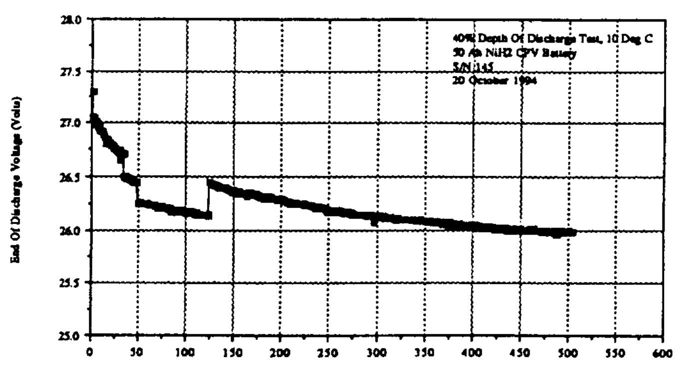




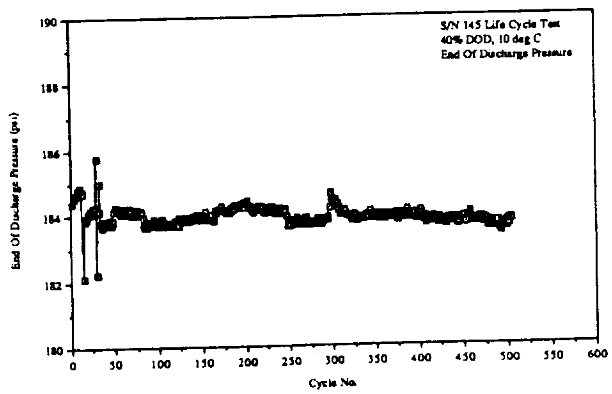
Post Vibration Peak Load Test



S/N 145 Life Cycle Test 40% DOD @ 10°C (EODV)



S/N 145 Life Cycle Test 40% DOD @ 10°C (EODP)



Qualification Test Program Status

- S/N 144 Completed All Environmental Tests
  - Life Cycle Test @ 60% DOD, 0°C
- Qualification Test Report In Progress
- S/N 145 Continue On Life Cycle Test, 40% DOD @10°C

Other NiH_2 SPV Work At NRL

- S/N 144 To Be Returned To EP (Milwaukee) For Partial DPA & Thermocouple Instrumentation
- Thermal Design Verification Tests w/S/N 144 Planned
- Qual Flight Experiment Battery (10.5 Ah NiH_2 SPV) Life Cycle Tests Continues (+8500 Cycles)
- Clementine Qual & Flight Spare Batteries To Be Returned To EP (Milwaukee) For Partial DPA
  - NRL Receive Qual For Life Cycle Test
  - USAF PL Receives Flt Spare For Test @ NWSC Crane
- Procurment Of EP(Joplin) 50Ah SPV In Progress For Qualification Test

Unique Features of a New Nickel-Hydrogen 2-Cell CPV

James R. Wheeler
Eagle Picher Ind., Joplin MO

Abstract

Two-cell nickel-hydrogen common pressure vessel (CPV) units with some unusual design features have been successfully built and tested. The features of interest are half-normal platinum loading for the negative electrodes, the use of rabbit-ear terminals for a CPV unit, and the incorporation of a wall wick. The units have a nominal capacity of 20 Ah and are 3.5 inches in diameter. Electrical performance data is provided. The data support the growing viability of the 2-cell CPV design concept.

Cell Description

The unit described in the tests described here is a 3½ inch-diameter RNHC 20-5. It is a two-cell common-pressure-vessel design with a nominal capacity of 20 Ah. Its construction is identical to that of a 40 Ah tandem-stack ManTech cell, except that the two stack-halves are internally connected in series rather than parallel. One of the units is shown in figure 1. As can be seen, this unit has rabbit-ear terminals, which has the advantage of reducing battery height and cell-to-cell interconnection mass.

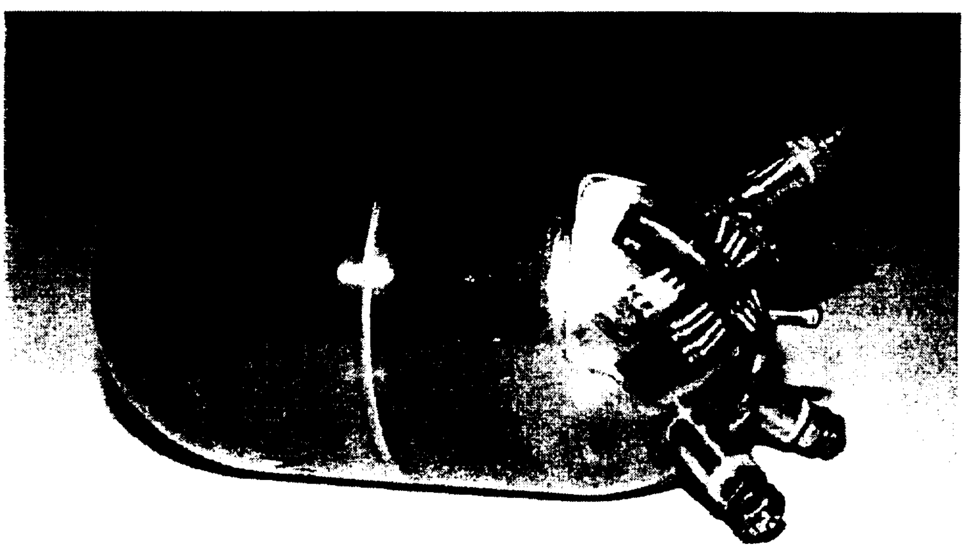


Figure 1.
RNHC 20-5

By "ManTech" is meant an Eagle Picher design which uses pineapple-slice-shaped electrodes and stack elements, a central polysulfone core, continuous nickel-foil leads on electrodes, and a wall-wick to ensure a recirculating path to return and equilibrate electrolyte throughout the cell stack. Also unlike an IPV, there is no separator/electrolyte bridge provided between the cell stacks. Although not present in these units, a hydrophobic Teflon strip adjacent to the weld ring on either side is planned for future units to discourage any possible long-term ionic migration through electrolyte film between the two internal cells.

Other features include a spring washer for uniform stack compression and separator/electrolyte contact with the cell wall to facilitate heat transfer. The positive electrode material is 80% slurry. The active material loading was a standard 1.65 g/ccv.

The separator material is two layers of zirconium-oxide cloth per positive electrode. Having two layers was desired because the intended functions were for operation in low earth orbit (LEO). The double separator design results in more weight for the unit, much of which is electrolyte.

Unusual Features

These units have some unusual features which distinguish them from normal production:

The use of a wall wick in a 2-cell CPV unit.

The negative electrodes were loaded to a platinum level of 4 g. per cm^2, which is half the normal loading.

This is the first 3.5 inch-diameter CPV unit with rabbit-ear terminals to be built by Eagle Picher. The third terminal on this unit is a special test terminal (center voltage tap) which is connected internally between the two cells. It is not necessary to the unit's function and would not be present in flight units.

The slurry plaque for the positive electrodes was manufactured in Eagle Picher's Range-Line plant in Joplin, Missouri. This is notable since all of EP's flight production thus far has come from its Colorado plant. The plaque design is otherwise identical however.

Performance

Seven units of this design were built and tested using conventional acceptance-type tests and a 2C (40 amp) pulse test. The pulse was applied for 20 seconds after 15 minutes of discharge at the normal rate of 10 amps (C/2). The performance of the units in testing was essentially what would be expected for individual-pressure-vessel cells, allowing for the double voltage of these units. The test results are shown in table 1, and the charge and discharge curves at 10°C and 0°C are shown in figures 2 through 5. It is noteworthy that the charge retention of these units, at 88% for a 72-hour open-circuit stand, is virtually the same as for an IPV with the same separator. The cells showed no ill effects of the 2C (40 amp) pulse. Average minimum voltage at the end of the pulse was 2.36 volts (IPV equivalent: 1.18 volts).

Table 1.
RNHC 20-5 CPV
AVERAGE PERFORMANCE

Test	2.0 Volts	2.2 Volts	Max. Chg. Volts
10°C Capacity (Ah)	22.19	21.99	3.051
0°C Capacity (Ah)	24.34	23.81	3.132
10°C High Rate (Ah)	23.77	23.61	3.046
10°C 72-Hr. C.R.*	20.91	20.77	3.045

* 88.0%

Conclusions

The results of the tests support the viability of the 2-cell CPV design at a time when interest in this concept for nickel-hydrogen batteries is growing. With half as many interconnects in a 2-cell CPV battery and somewhat less pressure-vessel weight per cell, they represent a significant potential weight-savings at the battery level[1]. Fears of internal electrolyte bridging in two-cell unit have proven unfounded, and now the compatibility of the wall wick with the 2-cell CPV concept has also been demonstrated.

Two cell CPV's have already flown in the MISTI, TUBSAT and APEX programs[2], and common use in the future seems likely. The use of single rather than double layer separator would be appropriate for GEO applications and would make the weight of the battery more attractive. Had this unit been a single-layer design, its weight would have been 1146.6g., a savings of 106.3g (computer-design projection). The cost would be improved as well since the separator is an expensive component.

The successful manufacture and testing of the units documented here add to the growing literature for 2-cell CPV's, and in addition show that reduced platinum loading of negative electrodes can be combined with the CPV concept. The compatibility of the rabbit-ear terminal configuration is also affirmed with this work. The use of slurry plaque from a different source was shown to perform to the same standards as that from the more-usual one.

Acknowledgments

David Cooke managed the assembly and testing of the RNHC 20-5. His contributions are gratefully acknowledged.

[1] Otzinger, B. M., and Wheeler, J. R., "Common Pressure Vessel Nickel Hydrogen Battery Development", Vol. III, p. 1381, IECEC Proceedings, 1989.
[2] Coates, D. K., and Fox, C. L., "Current Status of Nickel-Hydrogen Battery Technology Development", Part 1, pp. 75-80, IECEC Proceedings, 1994

Status Of Bipolar
Nickel-Metal Hydride Development

November 15, 1994

Martin Klein

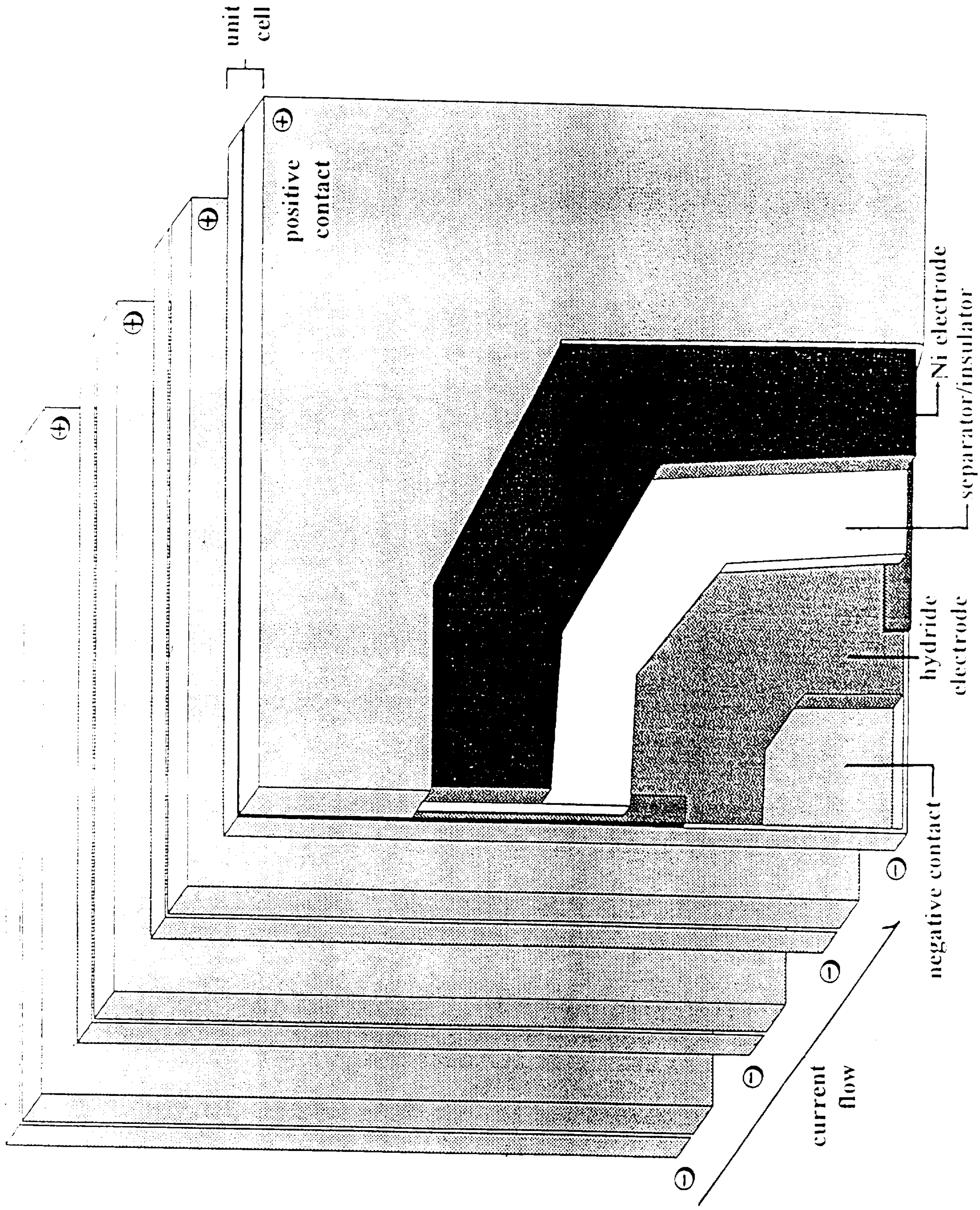
Electro Energy, Inc.
Shelter Rock Lane
Danbury, CT 06810
203-797-2699

$$Ni(OH)_2 + OH^- \text{ ----------- } NiOOH + H_2O + e^-$$

$$M + e^- \text{ ----------- } 1/2\ MH + OH^-$$

$$Ni(OH)_2 + M \text{ ----------- } NiOOH + 1/2\ MH$$

Cell Reactions



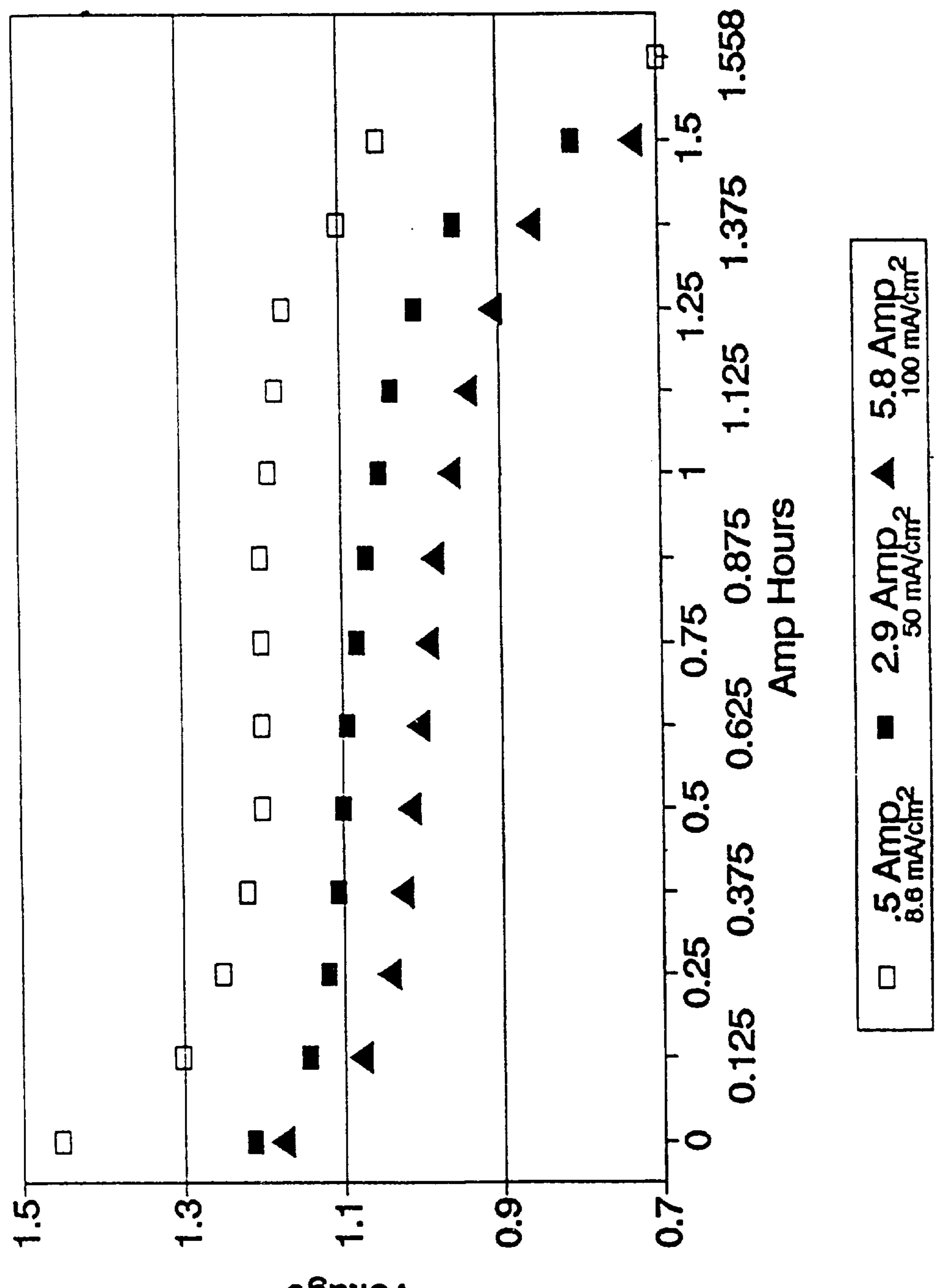
Bipolar Wafer Cell Concept

- Commercial sintered nickel electrodes
- Plastic-bonded nickel electrodes fabricated at EEI
- Pasted nickel foam electrodes fabricated at EEI
- Separator material consisting of non-woven nylon, polypropylene, or plastic-bonded inorganic compounds
- Hydride materials consisting of various rare earth AB_5 alloys similar to the International Common Samples.

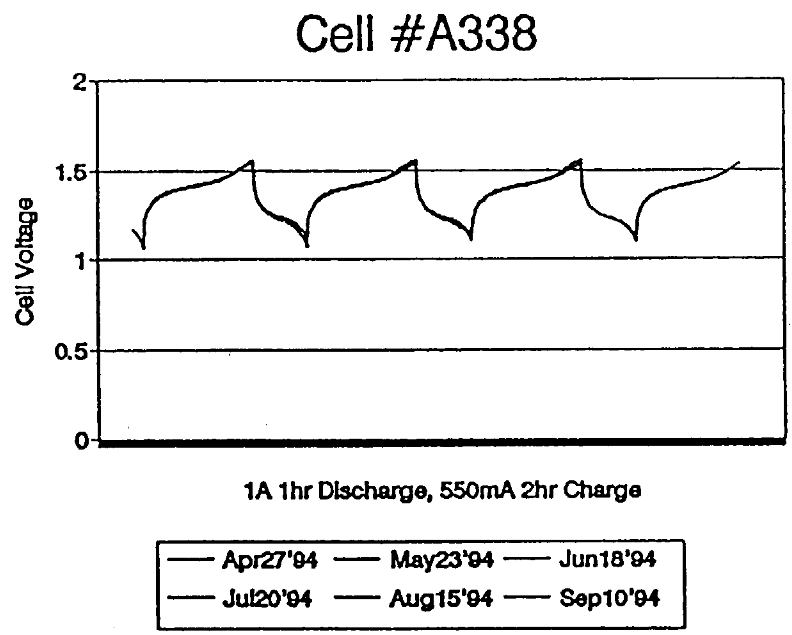
Major Component Variables

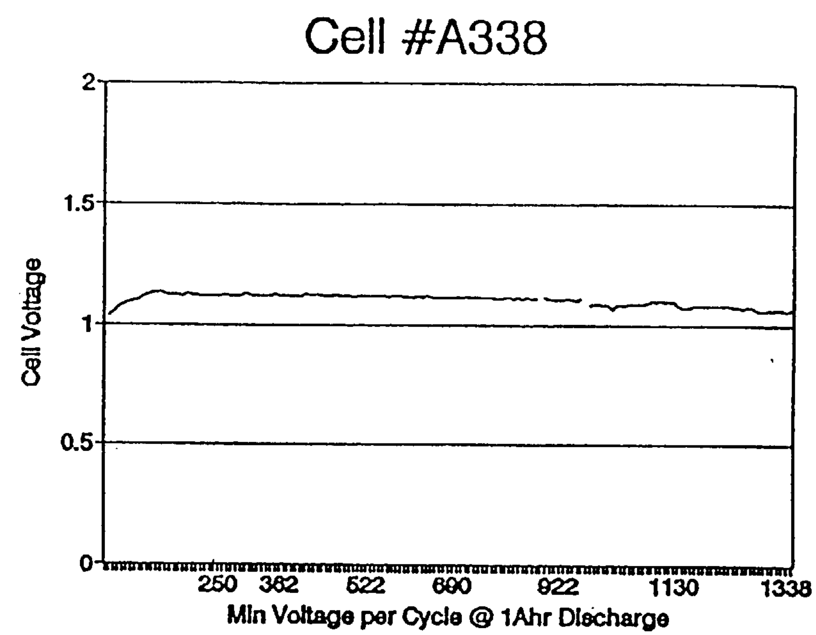
(1)	IBA MH No. 1	$MmNi_{3.55}Co_{0.75}Mn_{0.4}Al_{0.3}$
(2)	IBA MH No. 2	$MmNi_{3.5}Co_{0.7}Al_{0.8}$
(3)	IBA MH No. 3	LmNi alloy
(4)	IBA MH No. 4	$Ti_{1.6}V_{2.2}Zr_{1.6}Ni_{4.2}Cr_{0.7}$
(5)	IBA MH No. 5	$MmNi_{3.5}Co_{0.7}Al_{0.8}$
(6)	IBA MH No. 6	$MmNi_{3.5}Co_{0.8}Mn_{0.4}Al_{0.3}$

International Common Samples of MH Alloys



Bipolar Cell Rate Tests

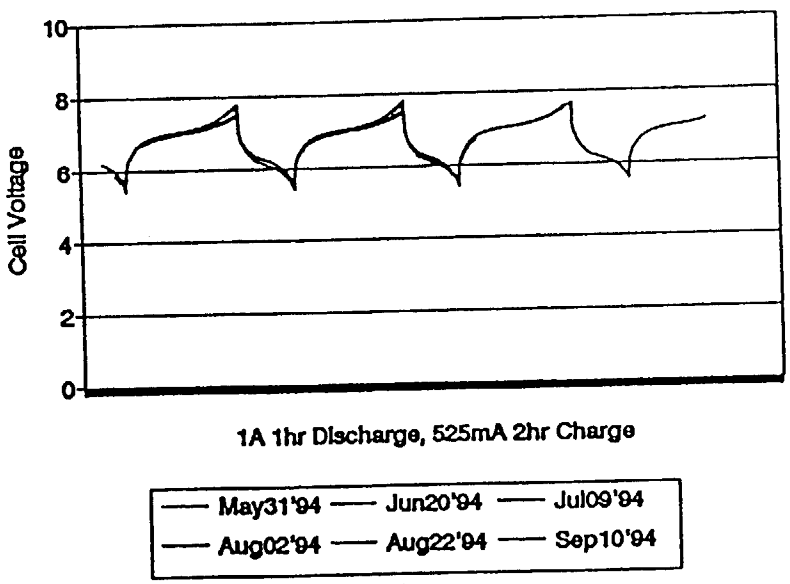




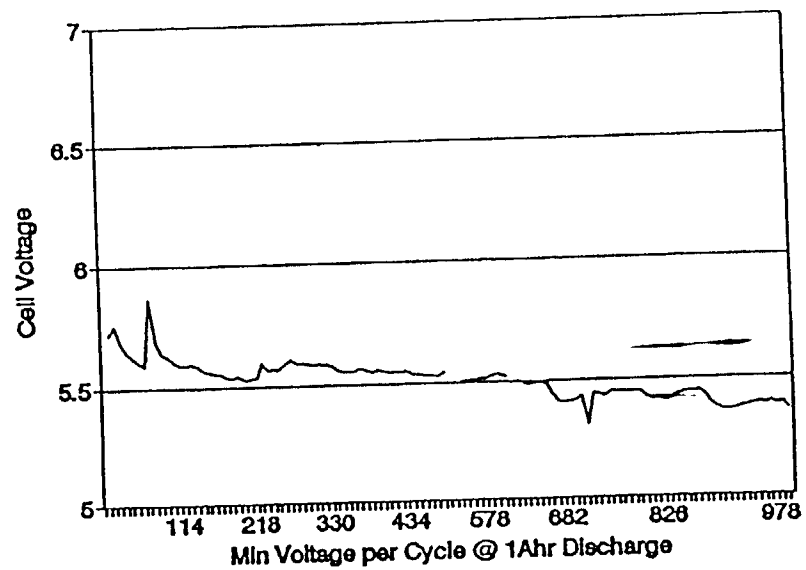
Single Vented Wafer Cell 3" x 3" Electrodes
1.5 Ah Nominal Capacity
Cycle 66% DoD, 1 h Discharge/2 h Charge

Plastic Bonded, Nickel Electrode, Life Test

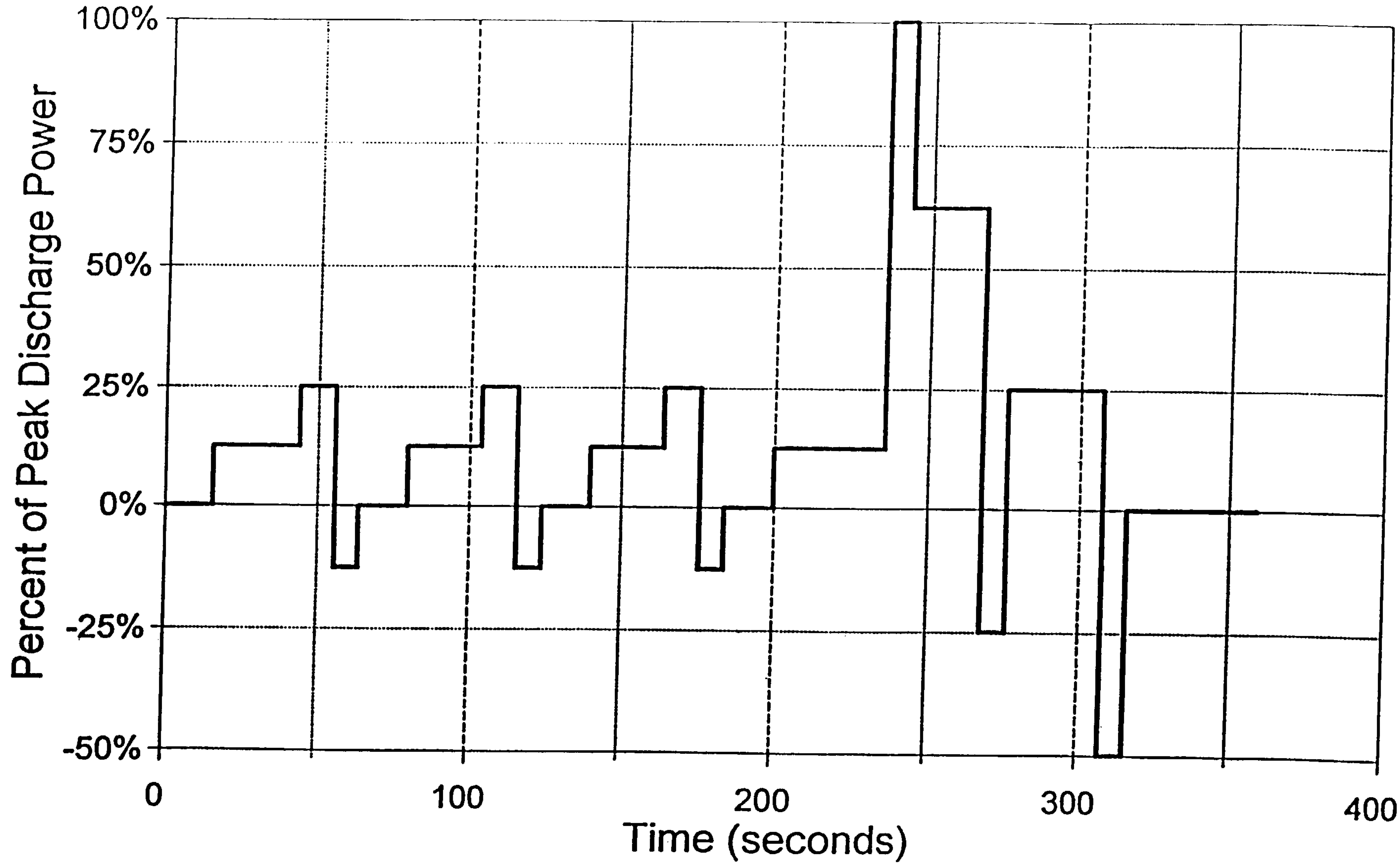
Cell #D370^



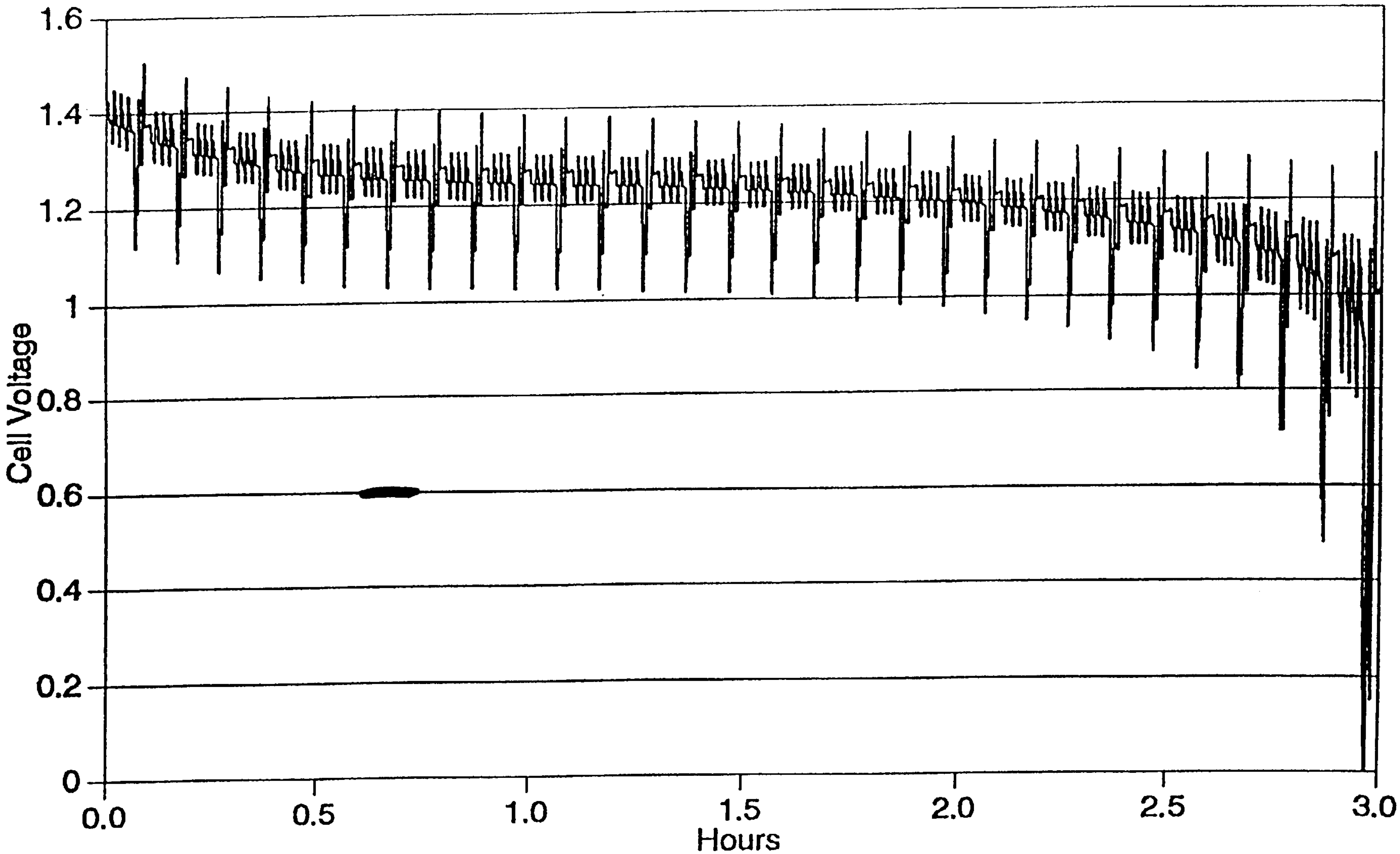
Cell #D370^



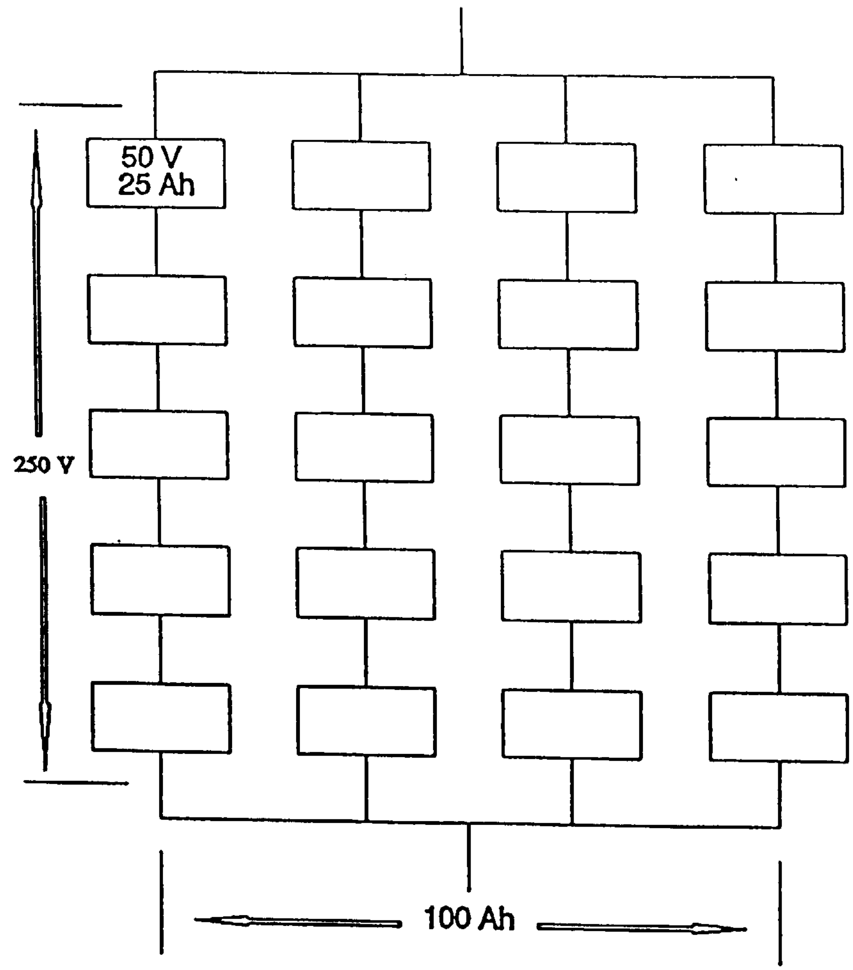
Vented 5 Cell Pack, Life Test



Dynamic Stress Test (DST) Cycle



DST Discharge Profile

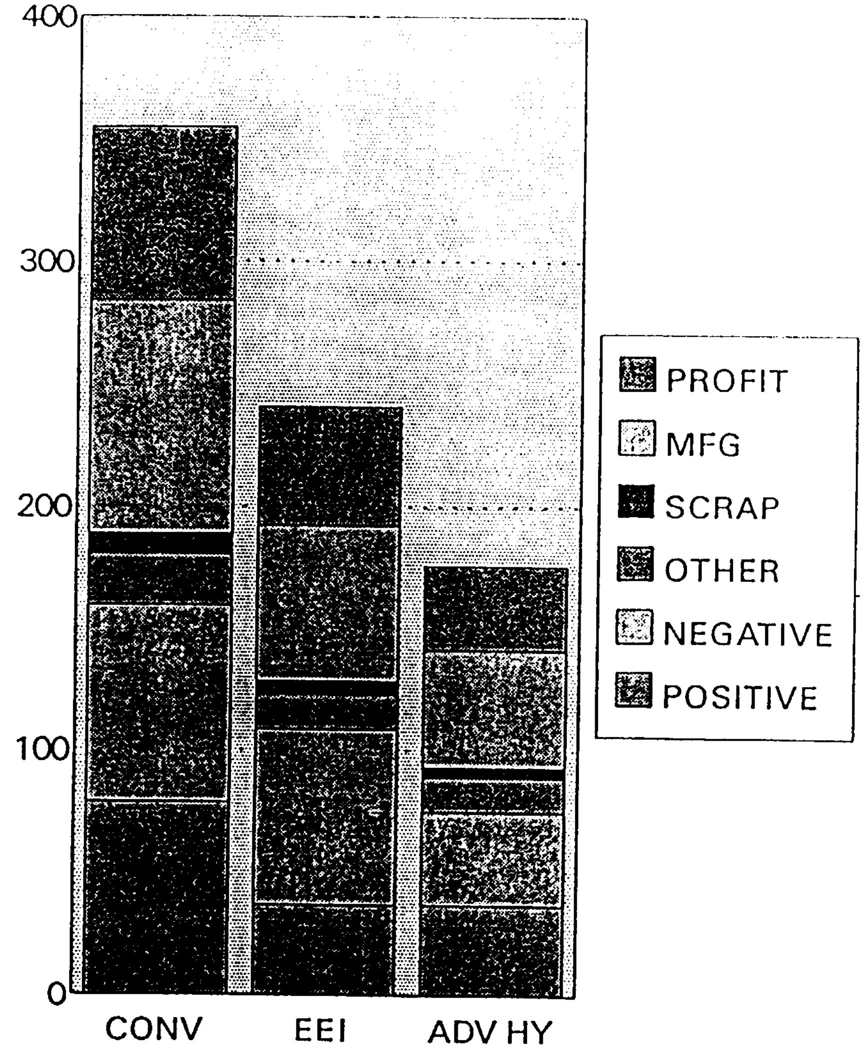


Electric Vehicle Battery Arrangement

100 Ah 250 V BATTERY PARAMETERS

NO. PARALLEL MODULES	4
VOLTAGE, CAPACITY,	250 V, 100 Ah
ENERGY	25 kWh
DIMENSION (in.)	10 x 40 x 23 (150 l)
WEIGHT (inc. hardware)(5%)	420 kg
E.D. GRAVIMETRIC	60 Wh/kg
E.D. VOLUMETRIC	167 Wh/l

100 Ah 250 V Battery Parameters



Estimated Ni-MH Cost Analysis ($/kWh)

Summary

- Nickel-Metal Hydride Battery System a leading contender for EV Applications.
- Bipolar approach has cost and power advantages.
- Results of single and multi-cells demonstrate stabioity of materials of construction and power capability.
- Growth potential
  Improved Nickel and Hydride
  80 to 100 Wh/kg

RECHARGEABLE LITHIUM - STATUS OF SAFT ACTIVITIES

J.L. FIRMIN
SAFT

C. BASTIEN
SAFT

1994 NASA WORKSHOP
HUNTSVILLE, ALABAMA

PRESENTATION CONTENT

- HISTORY
- LI - ION TECHNOLOGY
- SAFT STRATEGY
- SAFT SPACE PLAN
- ELECTRONICS
- PRODUCT PERFORMANCES AND CHARACTERISTICS

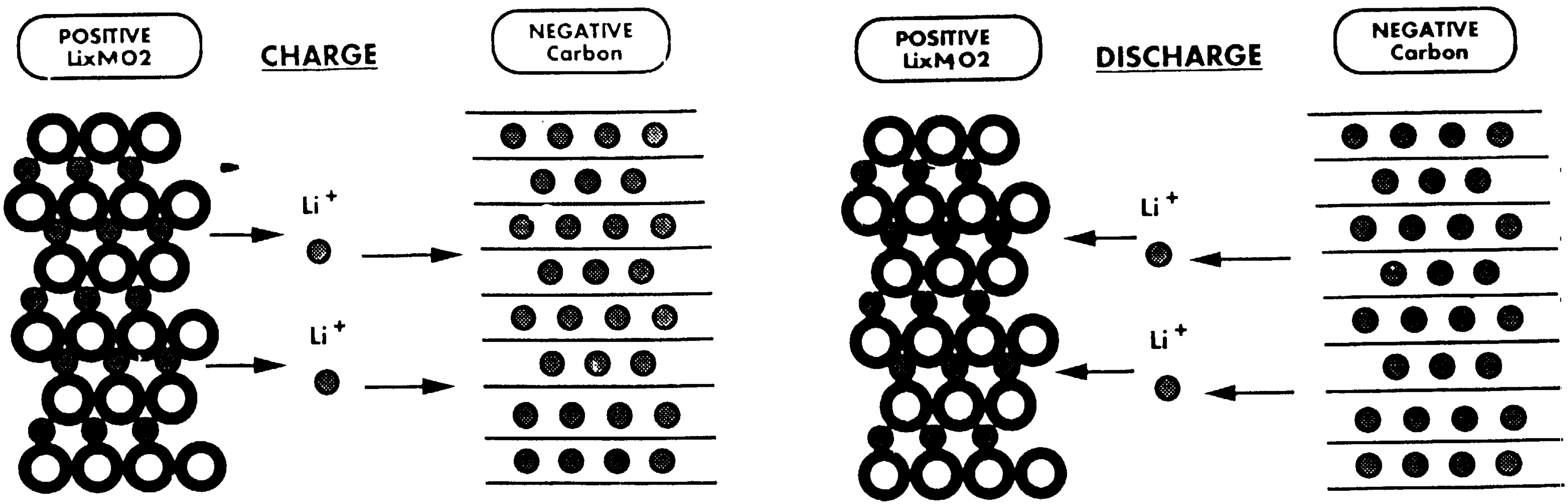
HISTORY

SINCE 1964, SAFT HAS BEEN ONE OF THE PIONEERS OF THE LITHIUM BATTERY CHEMISTRY.

- **TODAY**, SAFT IS THE WORLD LEADER OF $LiSO_2$ AND $LiSOCL_2$ PRIMARY BATTERIES
- **OVER THE LAST TWO YEARS**, SAFT HAS DEVELOPPED LiV_2O_5 AND $LiNiO_2$ RECHARGEABLE CELLS FOR MILITARY APPLICATIONS.
- **MORE RECENTLY**, A NEW TYPE OF RECHARGEABLE LITHIUM HAS BEEN DEVELOPPED FOR LONGER LIFE AND IMPROVED SAFETY : **Li -ION**

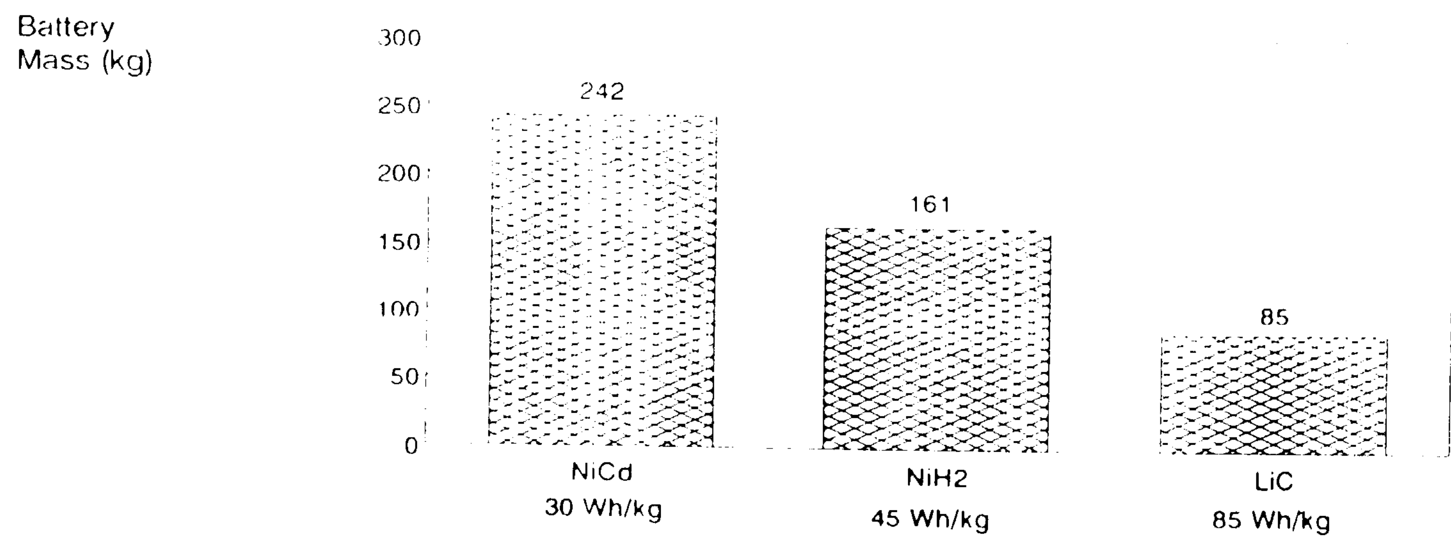
Li - ION TECHNOLOGY

- Li -ION operating principles



Li - ION TECHNOLOGY

- **A lighter energy : Estimation of a 4.5 kW geostationary satellite battery mass in function of the electrochemical couple.**



MASS GAIN BETWEEN A NiH2 AND LiC BATTERY : **76 kg** (for a 4.5 kW powerful satellite)

FACTOR 2

LI - ION TECHNOLOGY

- **And more than that !**

		Alkaline family			Lithium
		Standard Ni-Cd	Enhanced Ni-cd	Ni-MH	Li-Ion
1	Nominal capacity (mAh)	+	++	+++	-
2	Volumetric Energy (Wh/l)	-	+	++	+++
3	Weight Energy Density (Wh/Kg)	-	+	++	+++
4	Nominal Voltage	1.2V	1.2V	1.2V	3.6V
5	Charge retention	+	++	+	+++
6	Cycle life	+++	++	++	+
7	High rate charge	+++	++	++	+
8	Memory effect	-	-	+	+++
9	Overcharge ability	+++	++	+	-
10	Overdischarge ability	+++	++	++	-
11	Internal resistance during cycling	+++	++	+	+
12	Cost per Wh (in same shape) + cost of the charger / electronics	++	++	+	- (today)

A GENERAL PURPOSE TEÇHNOLOGY

LITHIUM RECHARGEABLE ...

... A NEW, GENERAL PURPOSE, ELECTROCHEMISTRY

WHICH CAN HAVE AS BRIGHT A FUTURE AS

NiCd HAS EXPERIENCED IN THE LAST 20 YEARS.

SAFT STRATEGY

SAFT PERCEIVE RECHARGEABLE LITHIUM AS A GENERAL PURPOSE TECHNOLOGY

- ➔ 1 Electrochemistry
- ➔ 1 Electrode definition and process
- ➔ 1 Kind of equipment
- ➔ Several applications : PORTABLE, ELECTRIC VEHICLE, SPACE
- ➔ Several shapes : Cylindrical, Prismatic, Plastic battery
- ➔ Several sizes : Small, Medium, Large
- ➔ The R&D effort can be supported by a larger turn over

GUIDELINES

❶ SAFT WILL HAVE ITS OWN PROPRIETARY TECHNOLOGY ($LiNiO_2$ / Graphite)

❷ THINK DIFFERENTLY

➔ Rechargeable lithium has unique features :
- Voltage
- Thin, flexible electrodes
- Electronics control
- Cost advantages

➔ New concepts : format, plastic can, battery design, association cell / electronics ...

❸ CLOSE COOPERATION WITH CUSTOMERS

ORGANISATION

RESEARCH	ALCATEL ALSTHOM CORPORATE	
	RESEARCH CENTER - MARCOUSSIS (France)	
MARKETING	MARKETING STRATEGIC COMMITTEE	
	SAFT WORLDWIDE SALES & SUBSIDIARIES NETWORK	
DEVELOPMENT ENGINEERING	CYLINDRICAL CELLS	Valdese North Carólina (USA)
	PLASTIC BATTERY	
	MEDIUM PRISMATIC	
	ELECTRIC VEHICLE	Poitiers (France)
	SPACE	
GENERAL MANAGEMENT OF THE PROGRAM	SAFT ADVANCED BATTERIES GROUP	

SAFT SPACE PLAN

2 APPLICATIONS : GEOSTATIONARY SATELLITES

Low earth orbit (LEO) 2 years missions, LAUNCHERS, PROBES

1 STRATEGY :

- USE MULTI-APPLICATION TECHNOLOGY (PORTABLE, ELECTRIC VEHICLE, SPACE)
- INCLUDE FLIGHT VALIDATIONS IN DEVELOPMENT PLANS
- HAVE A GROUND BATTERY QUALIFICATION IN 1998

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RECHARGEABLE LITHIUM - Status of SAFT Activities

CELL OFFER

GEOSTATIONARY SATELLITES

40 Ah - 200 Ah

Based on Electric Vehicle experience

Same basic materials and electrodes process

Specific space cell development

Space Battery and Electronics development

Technical Objectives :

Battery : 100 Wh/kg, 150 Wh/l
Cell : 140 Wh/kg, 260 Wh/l

Cycle life : 1500 cycles - 80% DOD - 15 years + Ionic propulsion (TBD)

LEO 2 years missions, LAUNCHERS, PROBES

5 Ah

Same cell as for military and commercial applications

No specific space cell development

Space Battery and Electronics development

Battery : 70 Wh/kg, 120 Wh/l
Cell : 100 Wh/kg, 240 Wh/l

Cycle life : 10 000 cycles - 20% DOD

RECHARGEABLE LITHIUM - Status of SAFT Activities

RESEARCH :

- Increase cycle life (storage and fading)
- Increase gravimetric energy
- Limit corrosion
- Study charge & discharge control parameters and their aging

CELL DEVELOPMENT :

- Electric & Mechanical connection with thin electrodes supports
- Stack blocking
- Formation mode (no plates formation available)
- Charge mode

BATTERY & ELECTRONICS:

- Electronics management design
- Promote new concepts

1994 NASA Aerospace Battery Workshop

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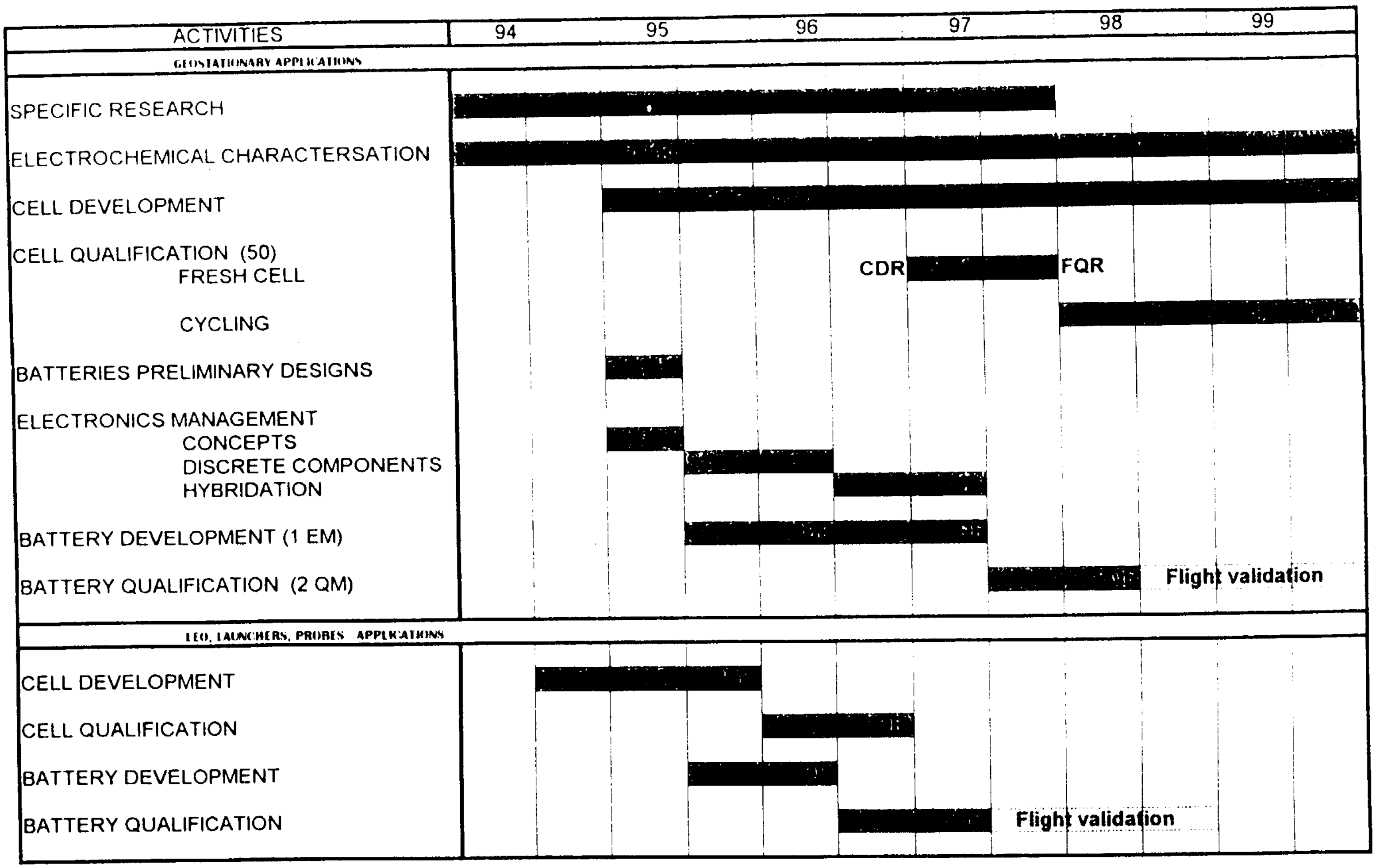
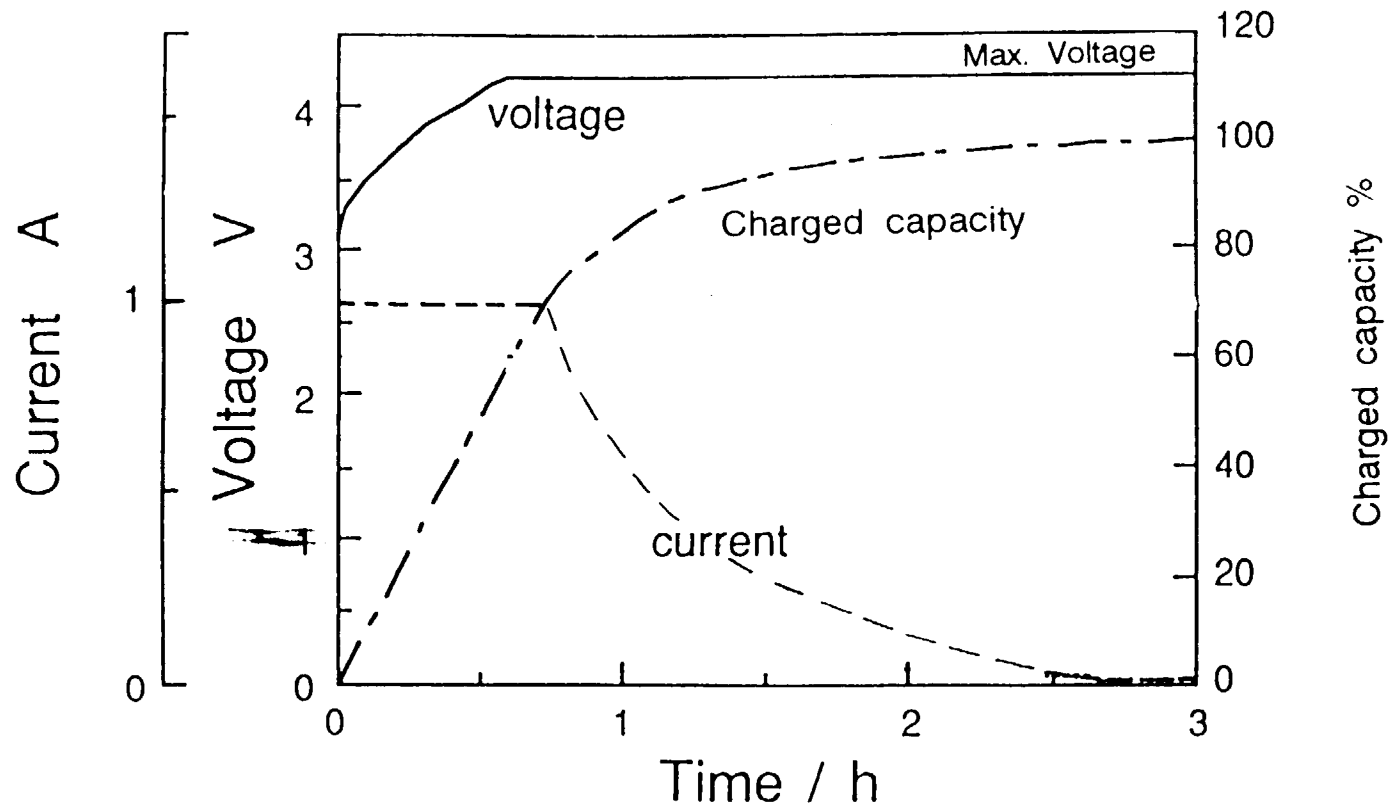
RECHARGEABLE LITHIUM - Status of SAFT Activities

SCHEDULE



LI - ION CHARGE MODE



ELECTRONICS

ELECTRONICS CONCEPTS :

The difficulty comes from the voltage management mode for cells in series

2 families of concepts :

➔ *BATTERY CHARGE MODE WITHOUT CELL BY-PASS* :
Management by the cell with highest voltage

- Constant current
- Constant current by steps
- Constant current and battery constant voltage

👍 Easy to manage (same as NiCd & NiH_2)

👎 Limit cell capacity performances

ELECTRONICS

➔ *BATTERY CHARGE MODE WITH CELL BY-PASS* :
Management of each cell

- Constant current and constant voltage ensured on each cell by electronic control

👍 Guaranteed to use the maximum cell capacity
Compensate cells dispersion

👎 New Electronic concept to study
Cost (to be evaluated at system level)

SAFT's AIM IS TO DELIVER A COMPLETE BATTERY SYSTEM

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PRODUCT PERFORMANCES AND CHARACTERISTICS

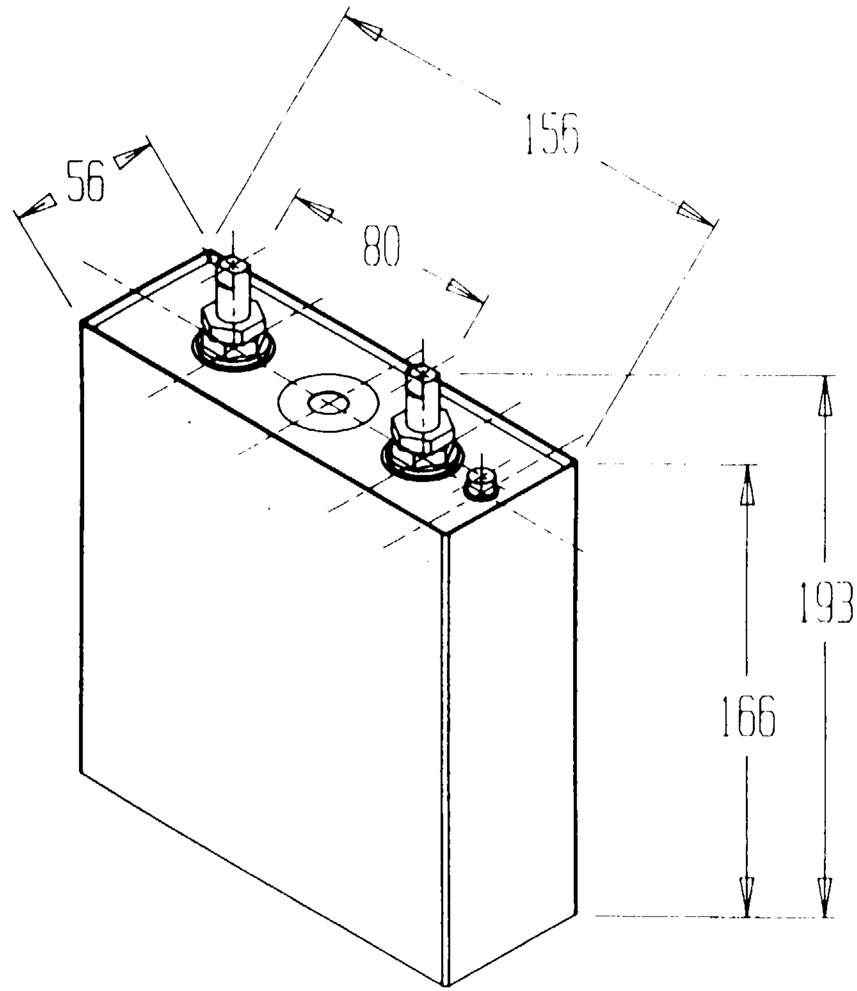
MAIN REQUIREMENTS COMPARISON

Requirements	PORTABLE	ELECTRIC VEHICLE	SPACE
Charge rate	C/20 to C	C/10 to C	C/20 to C/1.5
Discharge rate	C/8 to C	C/5 to 2C	C/1.5
Peak discharge	Up to 3C	up to 3C	Up to C
Charge Temperature range	0°C to 50°C	- 20°C to + 50°C	tbd
Discharge Temperature range	-20°C to +60°C	id.	tbd
Storage Temperature range	-40°C to +85°C	id.	tbd
Gravimetric Energy	> 120 Wh/kg (Beg.of life) Cell	140 Wh/kg (Beg. of life) Battery	100 Wh/kg (End of life) Battery
Life time	>1000 cycles 100%DOD with >70% Nominal Capacity 4 years	>1000 cycles 100%DOD with >80% Nominal Capacity 10 years	1500 cycles 80 % DOD + ionic propulsion 15 years
Charge retention	< 10 % after 1 month 20°C < 10 % after 8 days 45°C		< 25 % after 72 h 20°C

Specific Space requirement:
- **135 days rest period in between 45 days use**
- **Launchers vibrations & shocks**
- **15 years life time and more than 10 000 cycles**

Li - ION 100 Ah CELL SCHEMATIC

Dimensions in mm



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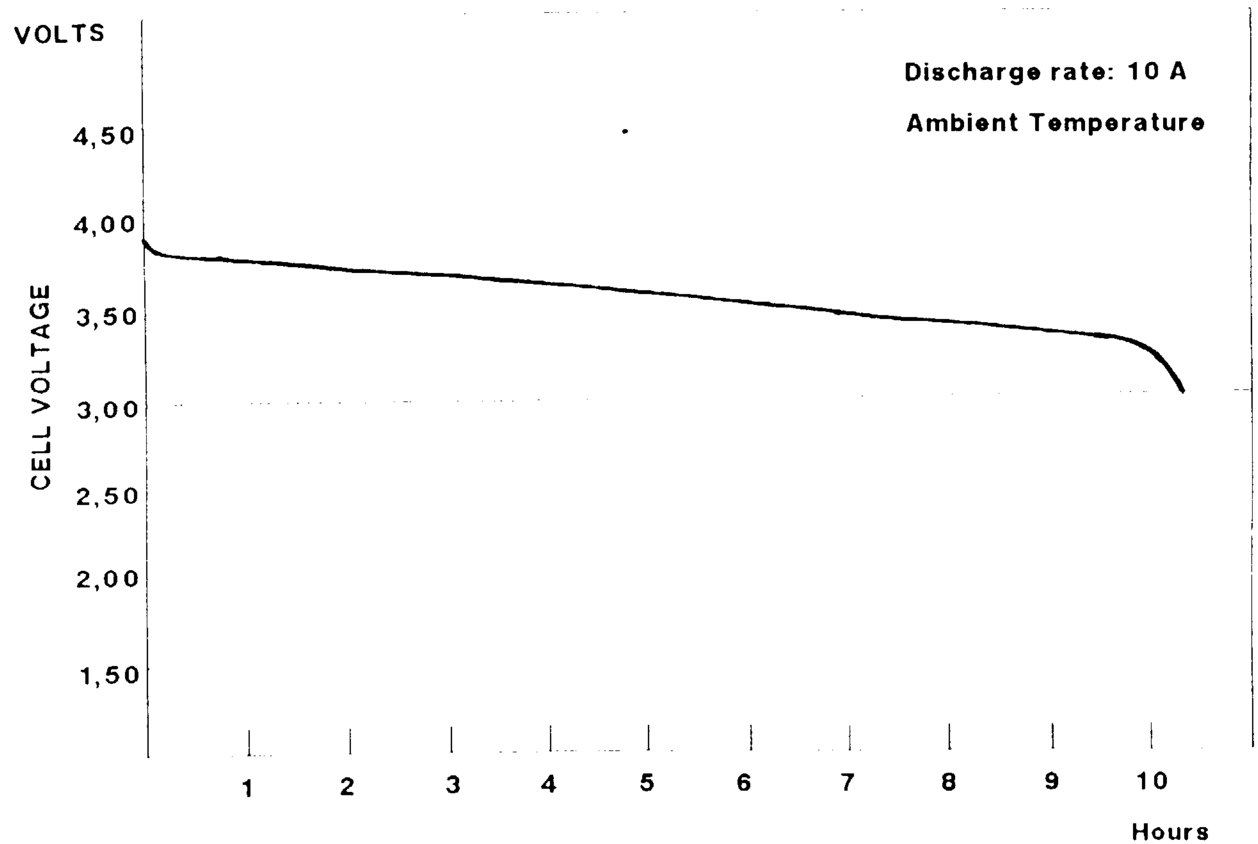
RECHARGEABLE LITHIUM - Status of SAFT Activities

100 AH DISCHARGE CURVE



DISCHARGE PROFILE OF A 100 AH LINIO2/GRAPHITE PRISMATIC CELL (CYCLE 5)

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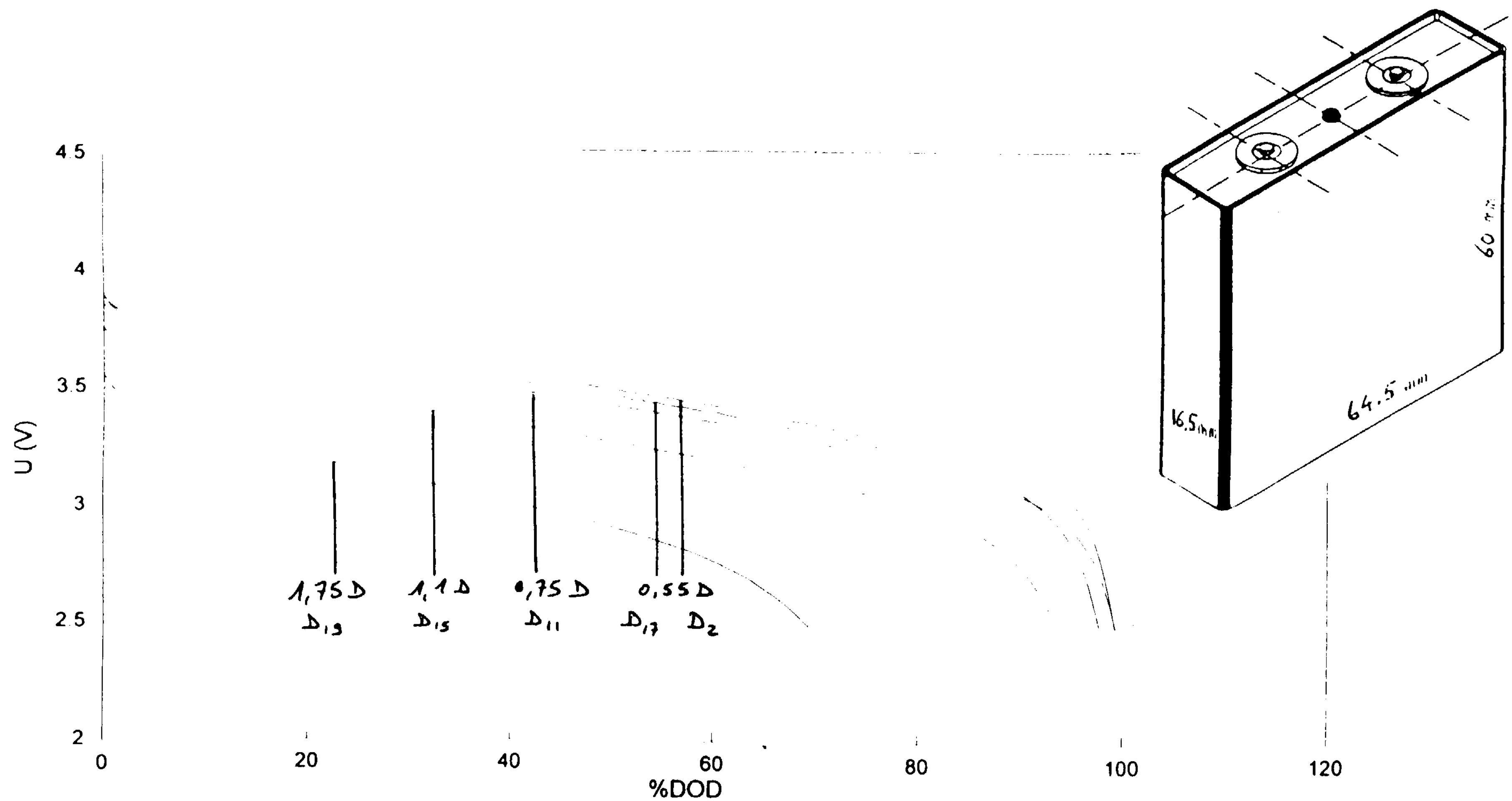
RECHARGEABLE LITHIUM - Status of SAFT Activities

5 Ah CELL DISCHARGE CURVE



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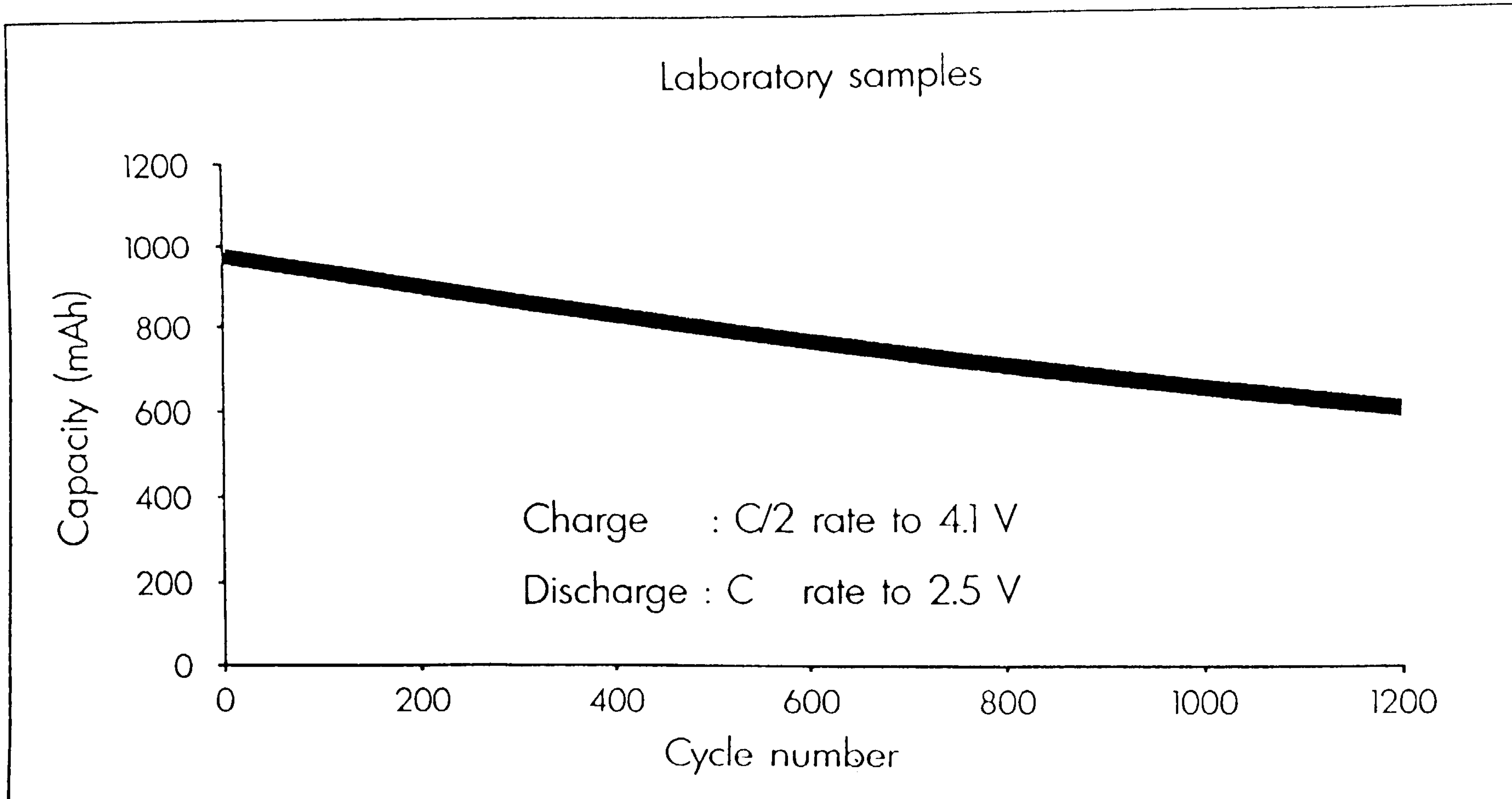
CYCLE LIFE ON LABORATORY SAMPLES



AA CELL PERFORMANCES COMPARISON

	Standard NiCd	Top of the range NiCd	Nickel metal hydride	Li-Ion
Nominal capacity (mAh)	600 - 700	900	1200	400 to 550
Nominal voltage (volts)	1.2	1.2	1.2	3.6
Weight energy density (Wh/kg)	35 - 40	50	60	80 - 110
Volumetric energy density (Wh/l)	100 - 110	140	180	190 to 260
Cycle life (number of cycles)	1000	1000	500 - 1000	500 - 1000

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CYCLE LIFE PERFORMANCE EVALUATION OF Li-ION CELLS

Rao Surampudi, Dave Perrone, Ron Nauman, Chen-Kuo Huang
Ratnakumar Bugga, Gerald Halpert

NASA Battery Workshop
Huntsville Alabama
November 15-17, 1994

JPL

Outline

- Objective
- Cell Description
- Test Plans
- Charge/Discharge Characteristics
- Cycle Life Performance
  - 100% DOD
  - 40% DOD
- Summary

ENERGY STORAGE SYSTEMS GROUP

Objective

Determine Cycle Life Performance of Lithium Ion Cells at 100% DOD and 40% DOD (NASA stress test)

Cycling Parameters 100% DOD Test

Charging

- Constant Current @ 100mA
- EOC Voltage to 4.2 volts cutoff

Discharging

- Constant Current @ 200mA
- EOD Voltage to 3.0 volts cutoff

Open Circuit Period

- End of Charge: 30 minutes
- End of Discharge: 30 minutes

Cell Description

Type I

Anode: Carbon (Coke)

Cathode: $LiCoO_2$

Electrolyte: EC-Based Electrolyte

Rated Capacity: 1 ampere-hour

OCV: 3.8 volts

Dimensions

Length= 64.1 mm

Diameter = 18.2 mm

Weight = 40 grams

Manufactured by Sony

Specific Energy: 70.0 Watt-Hours/Kg

Cell Description

Type II

Anode: Carbon (Coke)

Cathode: $LiCoO_2$

Electrolyte: EC-Based Electrolyte

Rated Capacity: 1 ampere-hour

OCV: 3.8 volts

Dimensions

Length= 51 mm

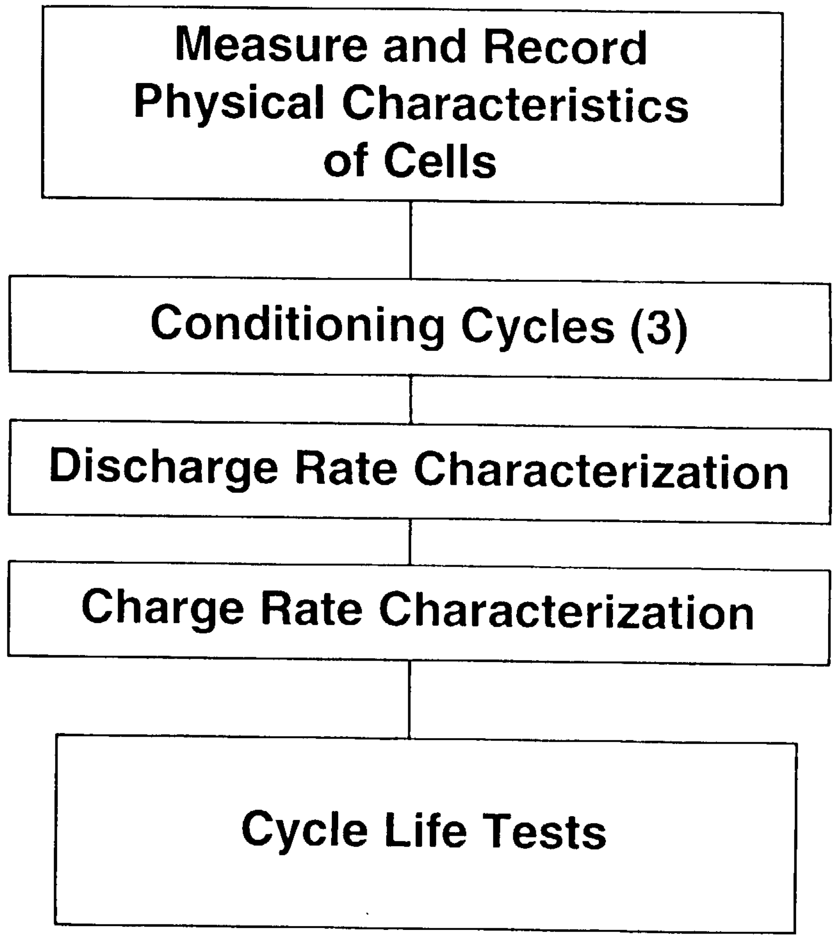
Diameter = 21 mm

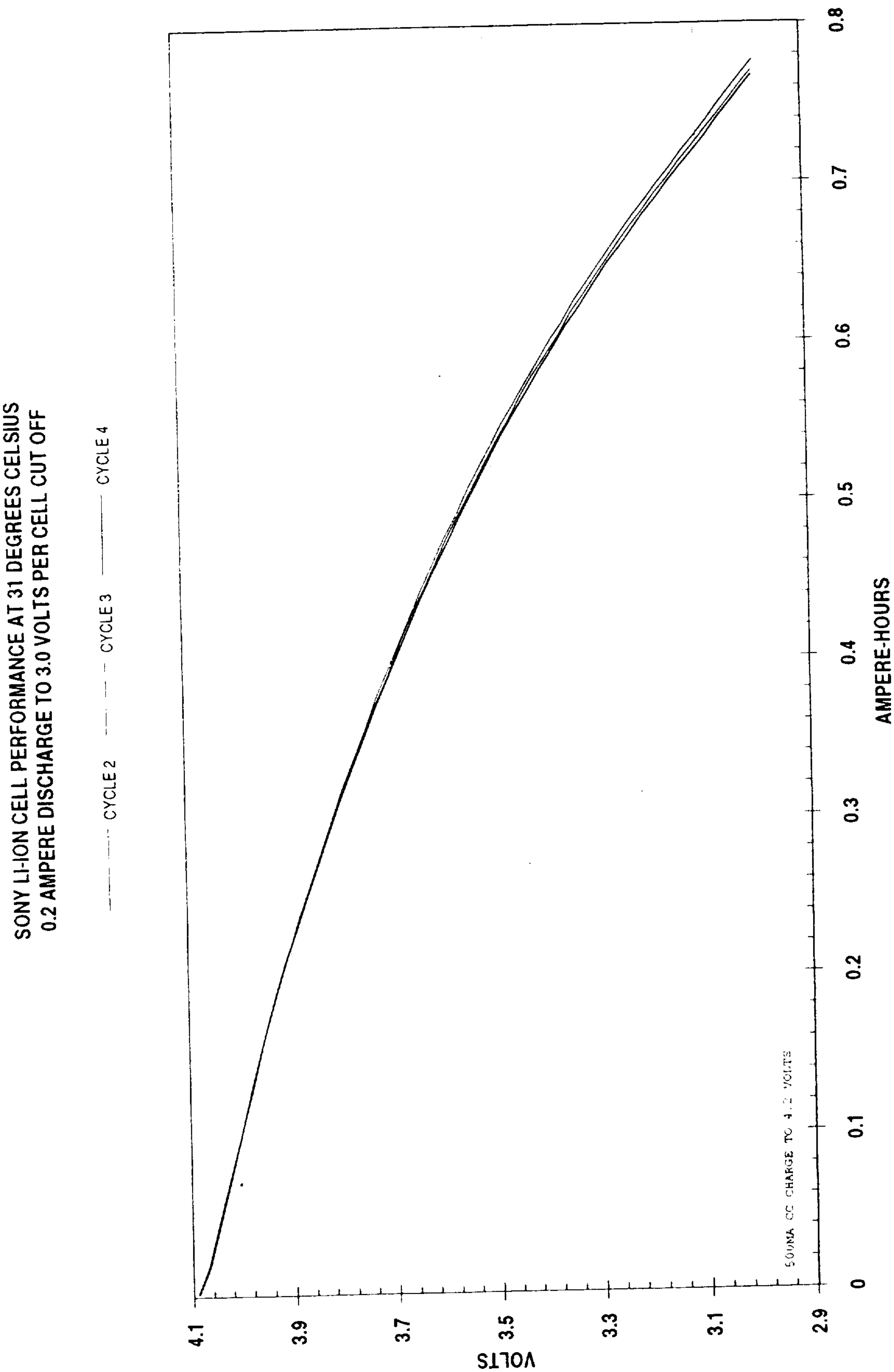
Weight = 40 grams

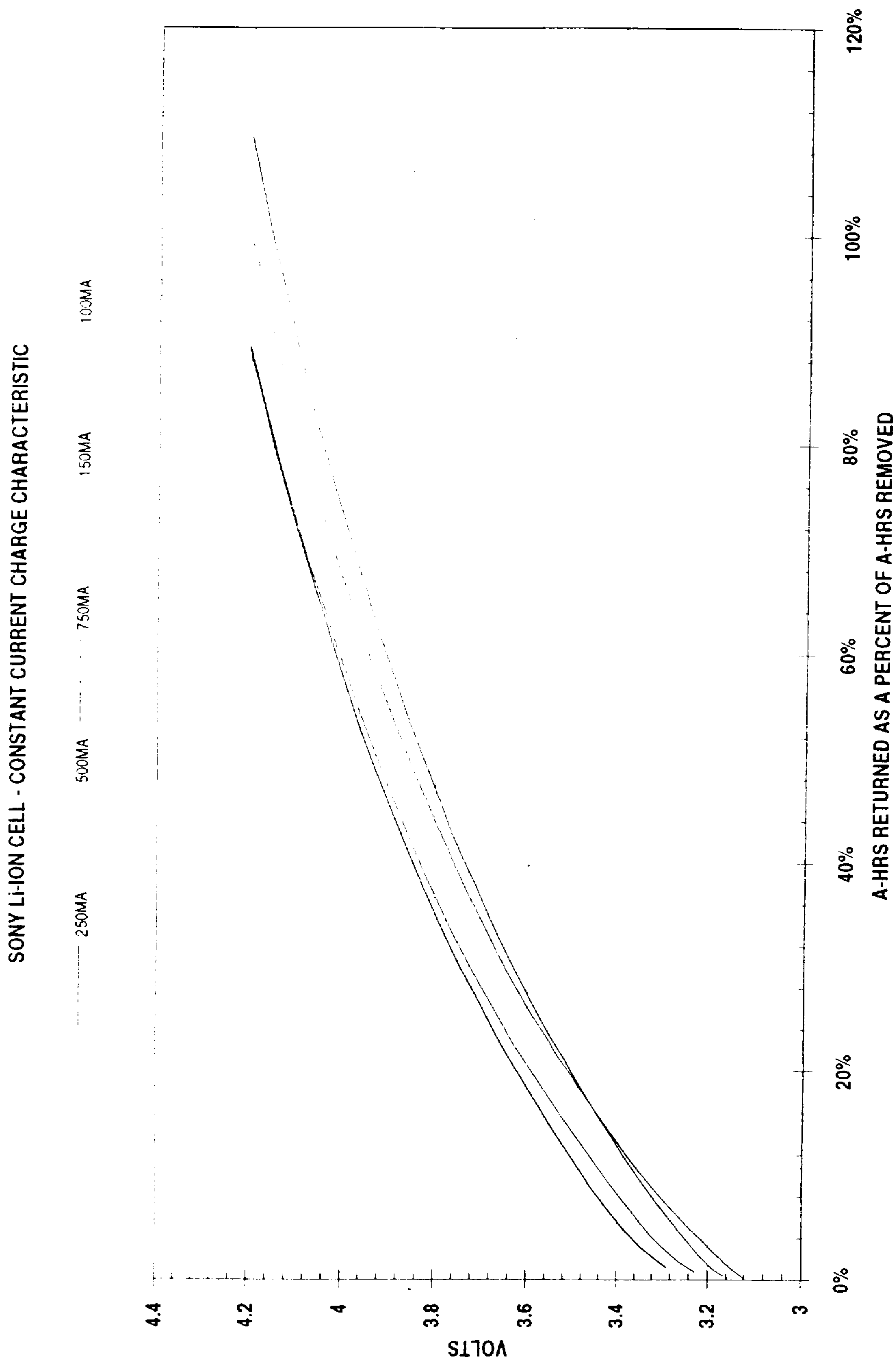
Manufactured by Sony

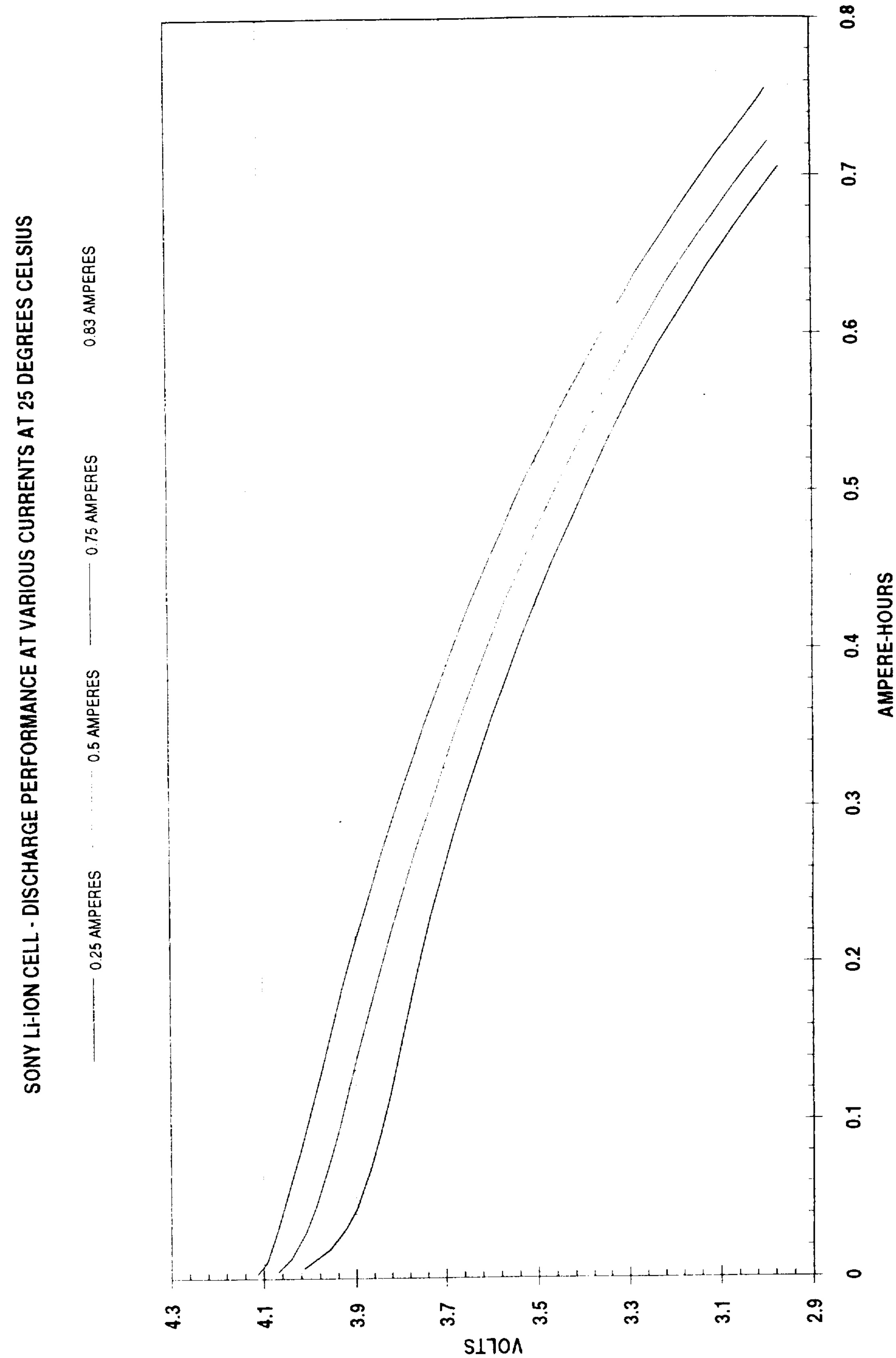
Specific Energy: 80.5 Watt-Hours/Kg

Test Plan Overview



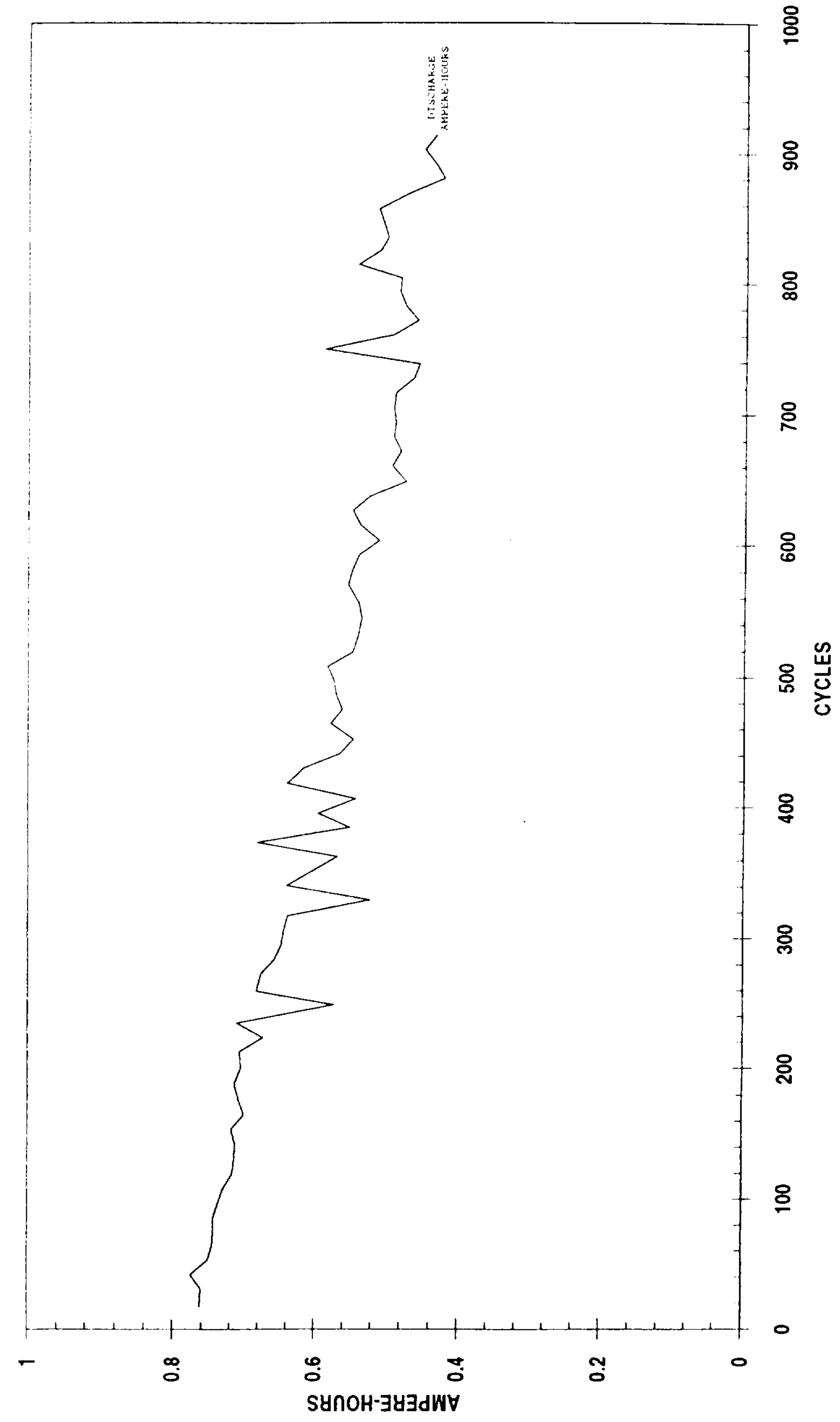

SONY LI-ION CELL PERFORMANCE AT 31 DEGREES CELSIUS
0.2 AMPERE DISCHARGE TO 3.0 VOLTS PER CELL CUT OFF
CYCLE 2
CYCLE 3
CYCLE 4
500MA CC CHARGE TO 4.2 VOLTS
VOLTS
4.1
3.9
3.7
3.5
3.3
3.1
2.9
AMPERE-HOURS
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

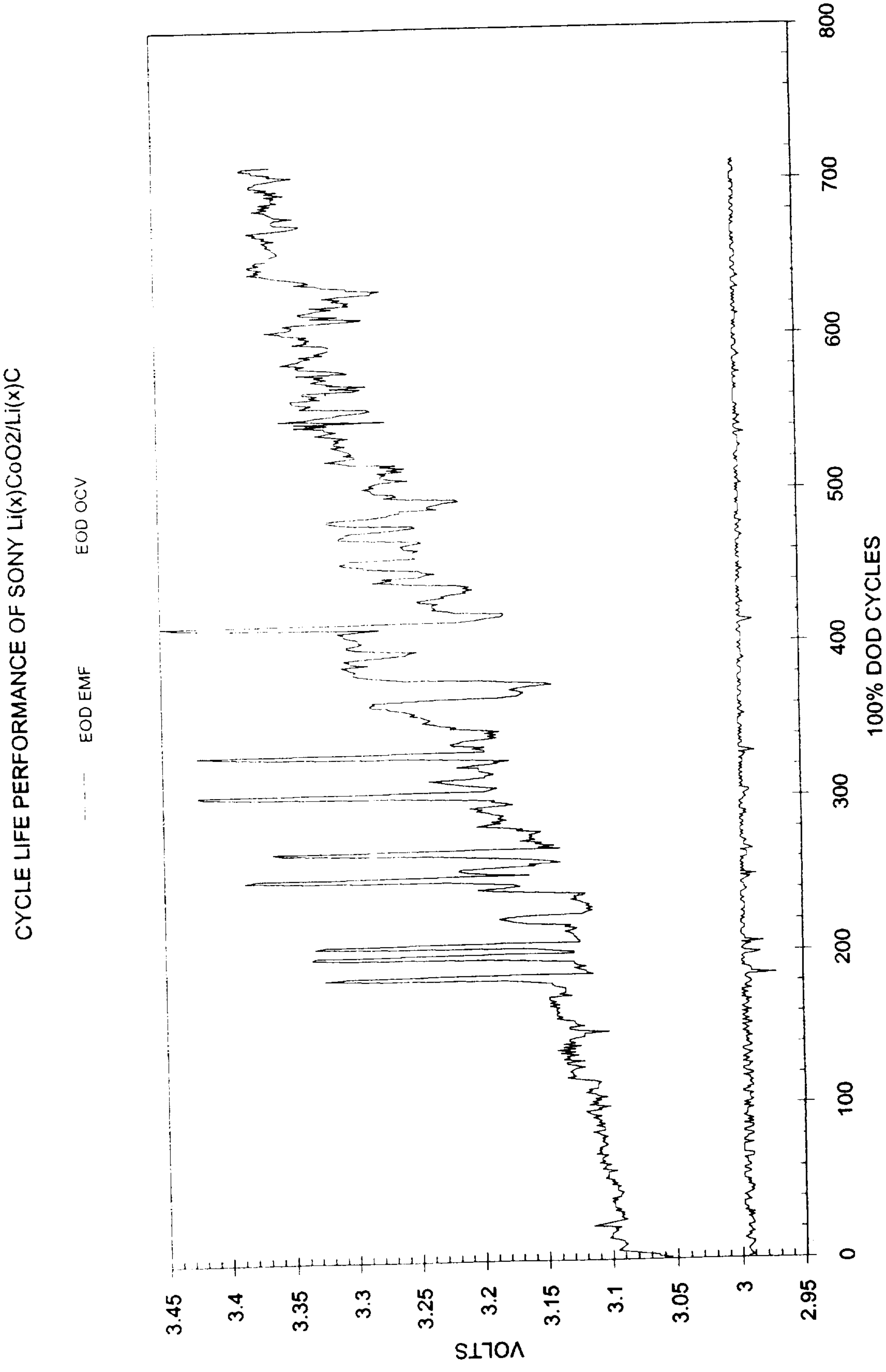

SONY Li-ION CELL - CONSTANT CURRENT CHARGE CHARACTERISTIC
250MA
500MA
750MA
150MA
100MA
VOLTS
4.4
4.2
4
3.8
3.6
3.4
3.2
3
0%
20%
40%
60%
80%
100%
120%
A-HRS RETURNED AS A PERCENT OF A-HRS REMOVED

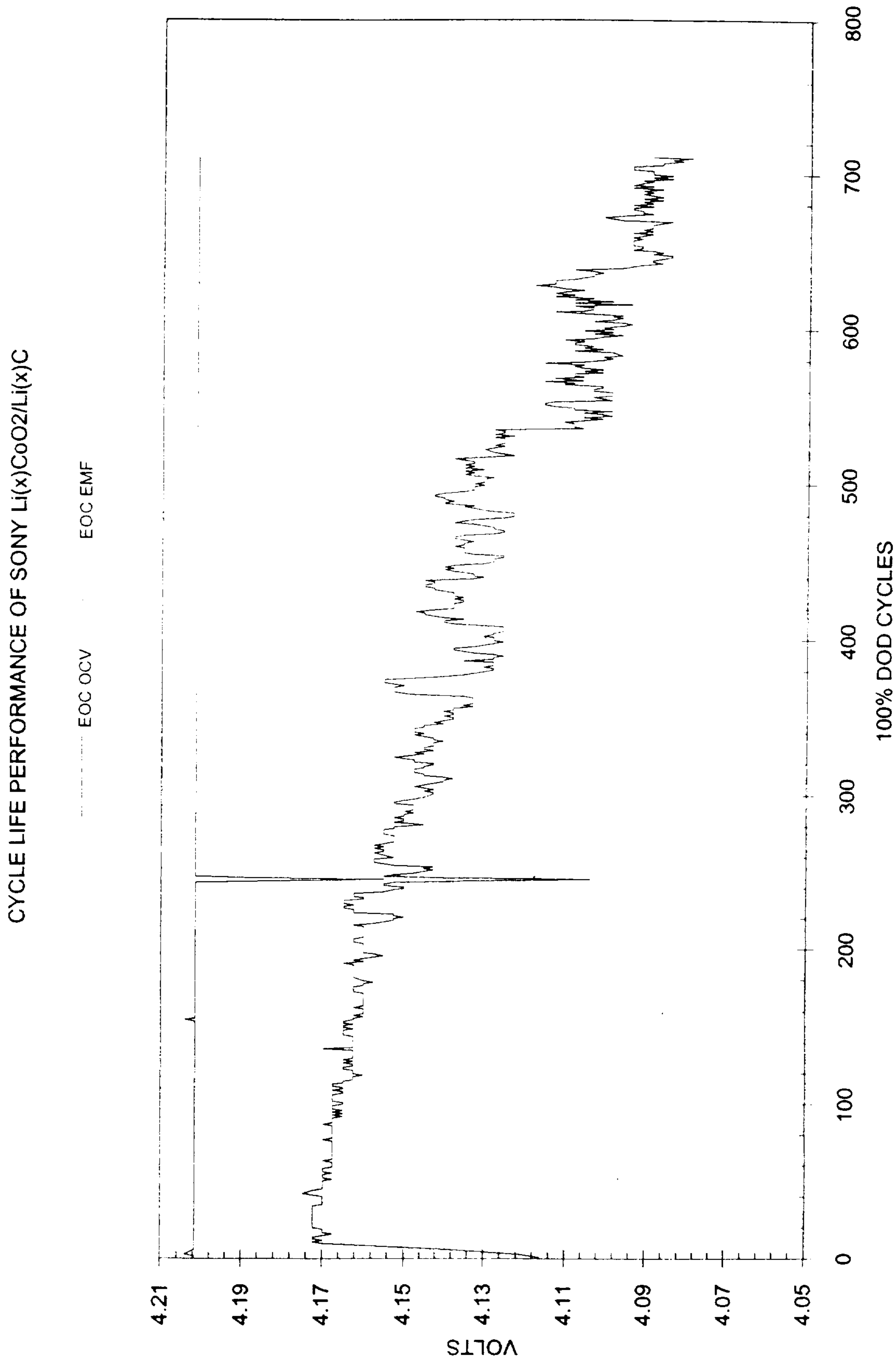


SONY Li-ION CELL - DISCHARGE PERFORMANCE AT VARIOUS CURRENTS AT 25 DEGREES CELSIUS
0.25 AMPERES
0.5 AMPERES
0.75 AMPERES
0.83 AMPERES
VOLTS
4.3
4.1
3.9
3.7
3.5
3.3
3.1
2.9
AMPERE-HOURS
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

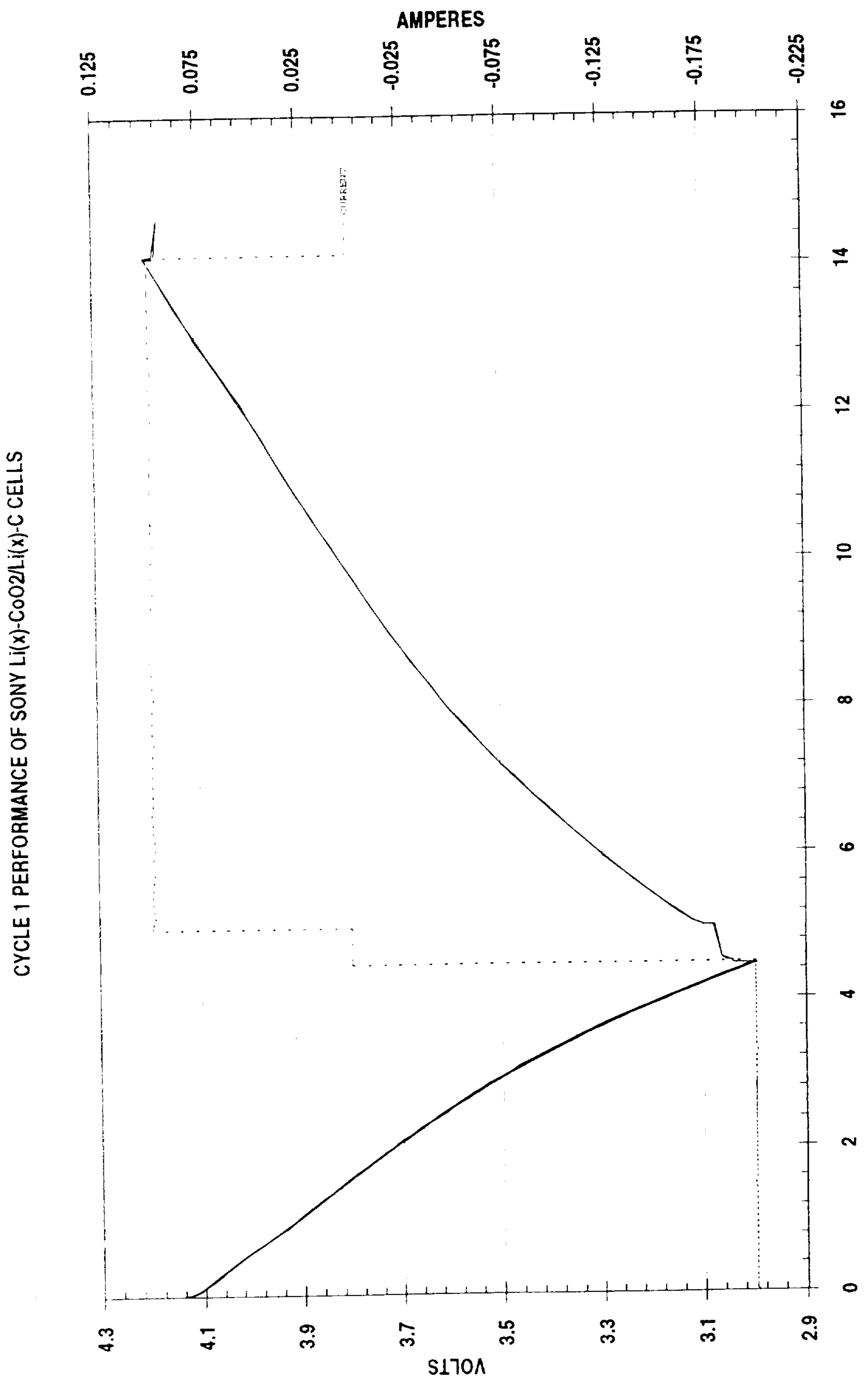
100% DOD CYCLE LIFE PERFORMANCE OF SONY SAMPLE 03022-50
0.2 AMPERES DISCHARGE TO 3.0 VOLTS AND 0.1 AMPERES CHARGE TO 4.2 VOLTS



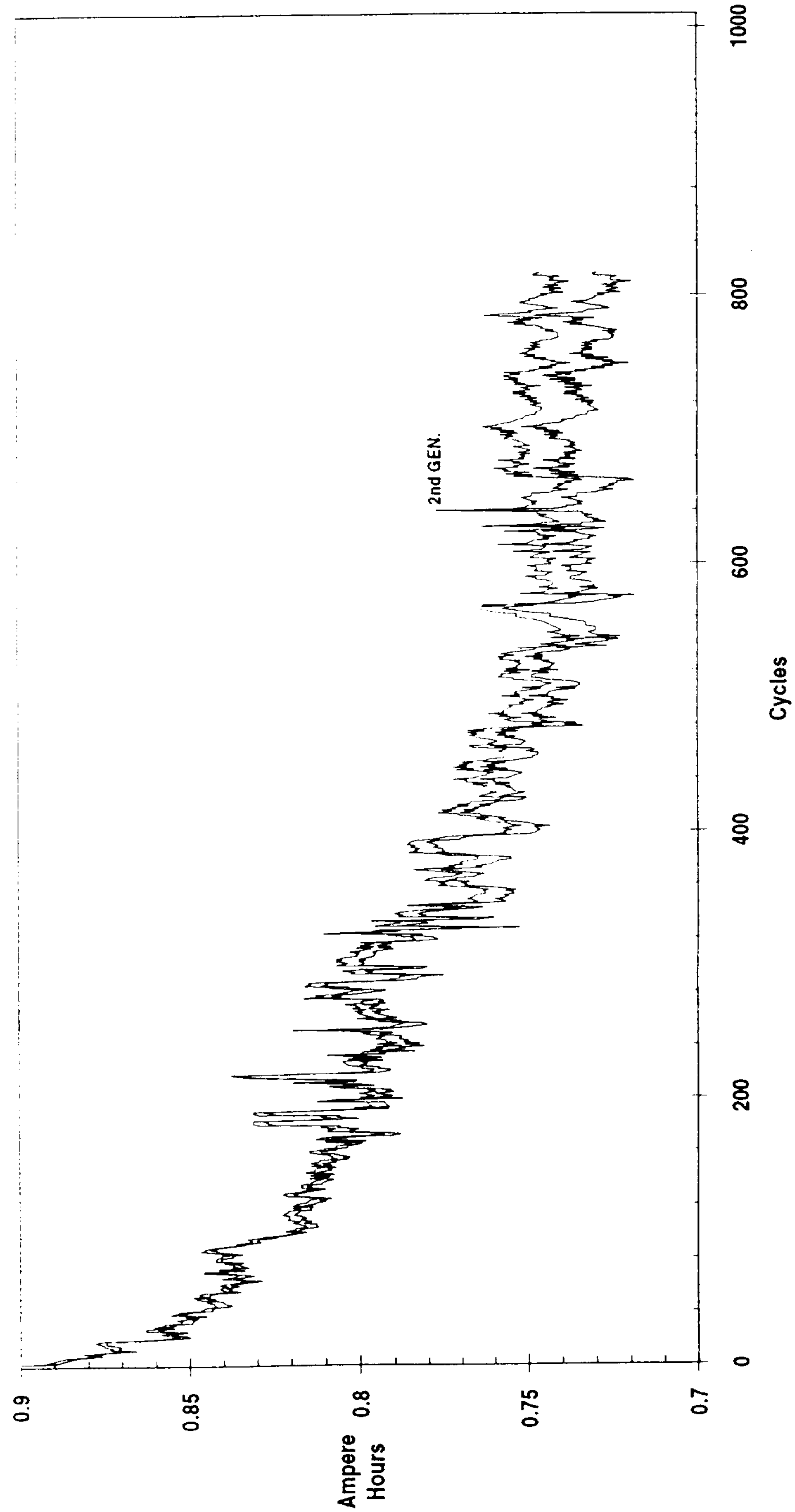

CYCLE LIFE PERFORMANCE OF SONY Li(x)CoO2/Li(x)C
EOD EMF
EOD OCV
VOLTS
3.45
3.4
3.35
3.3
3.25
3.2
3.15
3.1
3.05
3
2.95
0
100
200
300
400
500
600
700
800
100% DOD CYCLES



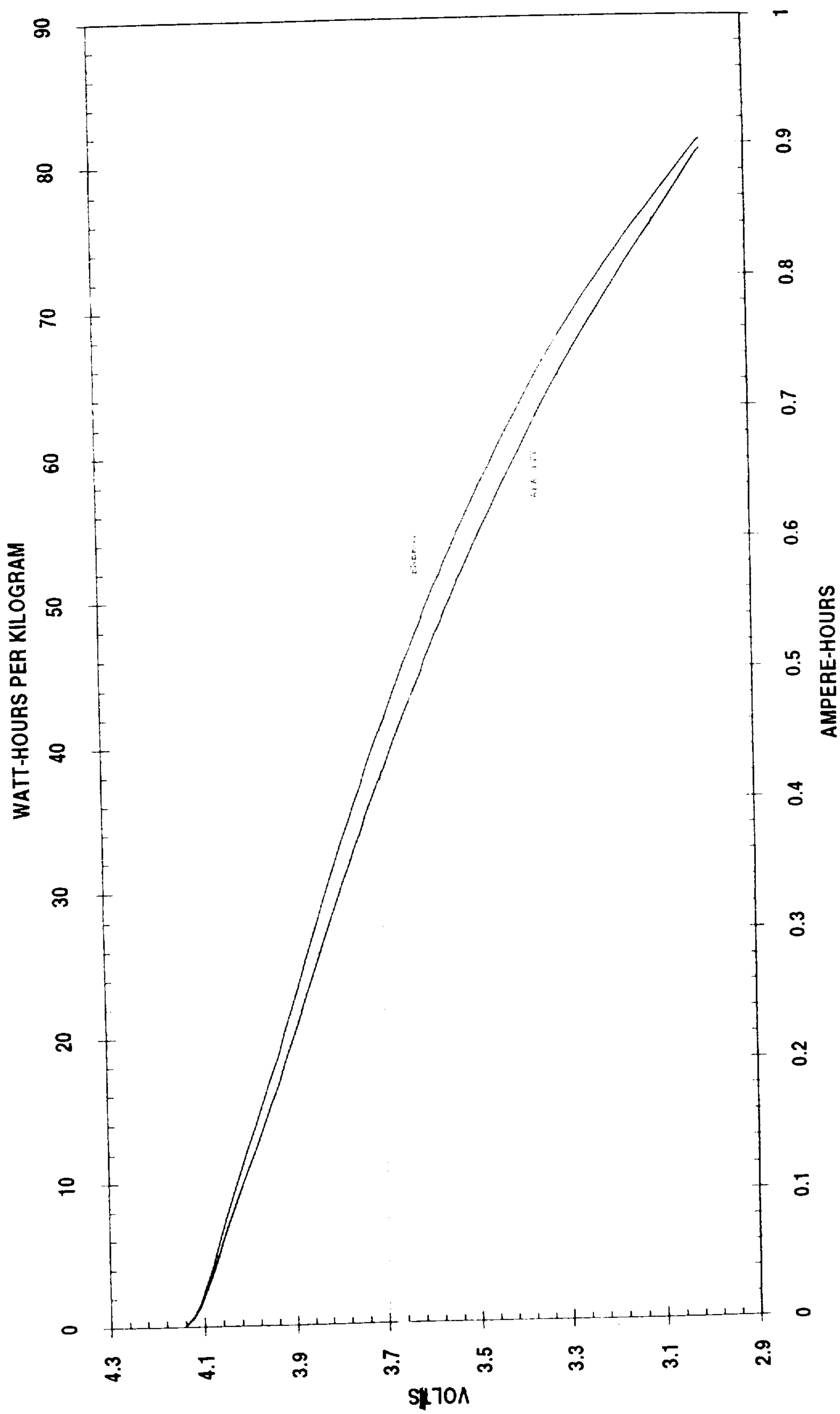
CYCLE LIFE PERFORMANCE OF SONY Li(x)CoO2/Li(x)C
EOC OCV
EOC EMF
VOLTS
4.21
4.19
4.17
4.15
4.13
4.11
4.09
4.07
4.05
100% DOD CYCLES
0
100
200
300
400
500
600
700
800


CYCLE 1 PERFORMANCE OF SONY Li(x)-CoO2/Li(x)-C CELLS
AMPERES
0.125
0.075
0.025
-0.025
-0.075
-0.125
-0.175
-0.225
VOLTS
4.3
4.1
3.9
3.7
3.5
3.3
3.1
2.9
HOURS
0
2
4
6
8
10
12
14
16

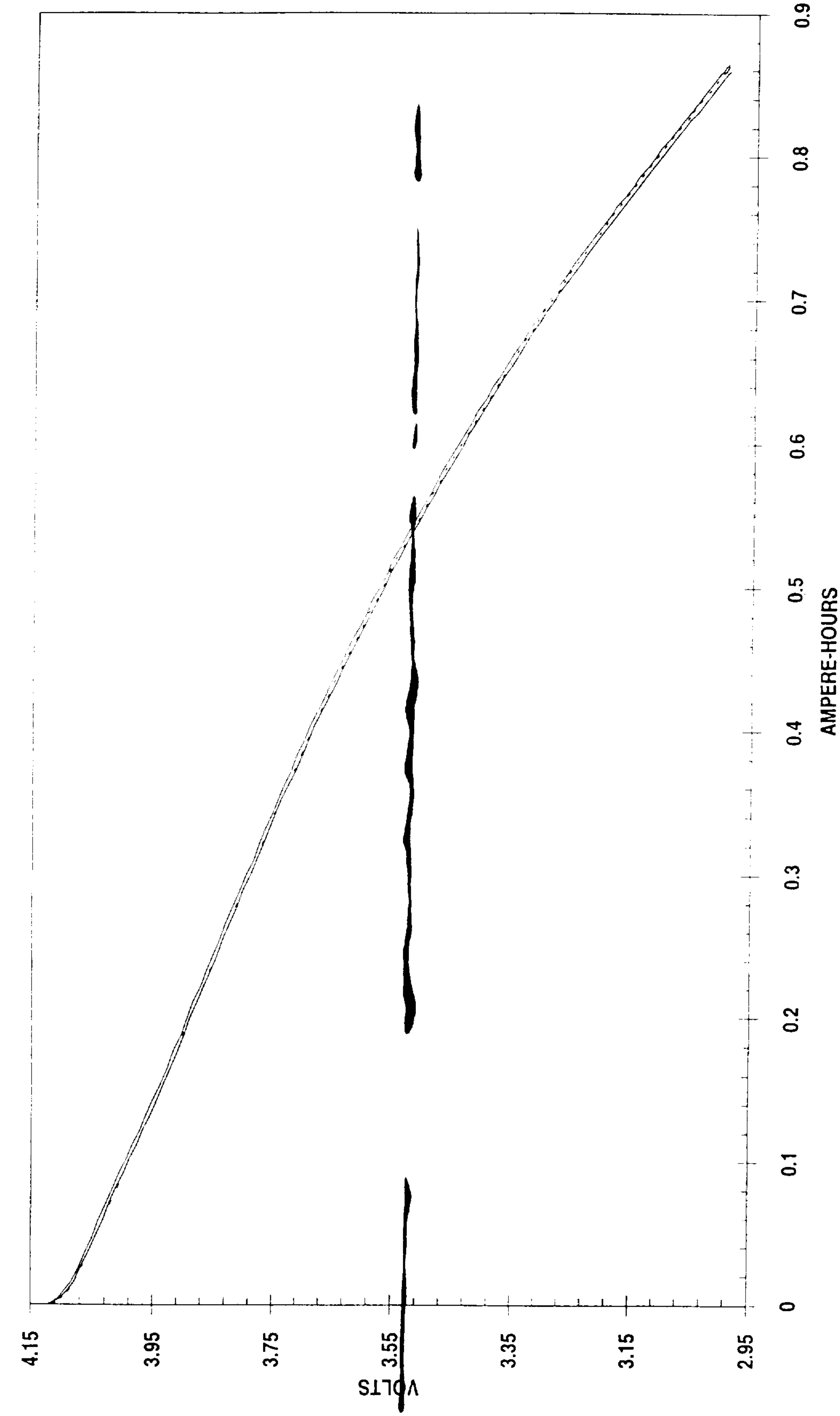
COMPARISON OF PERFORMANCES IN
FIRST AND SECOND GENERATION "LITHIUM-ION" CELLS
CYCLES VS. DISCHARGE AMPERE-HOURS AT 23 DEGREES CELSIUS

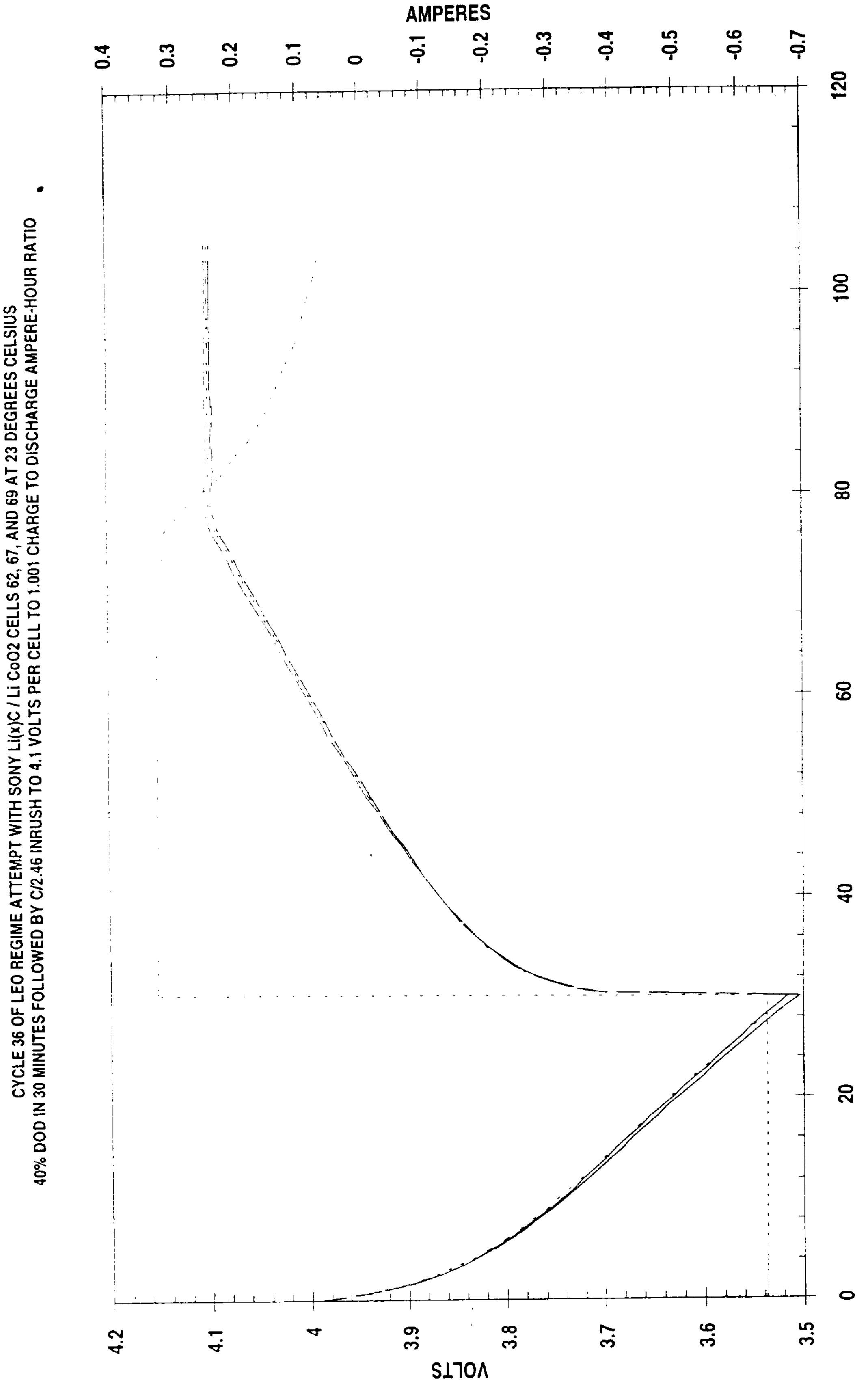


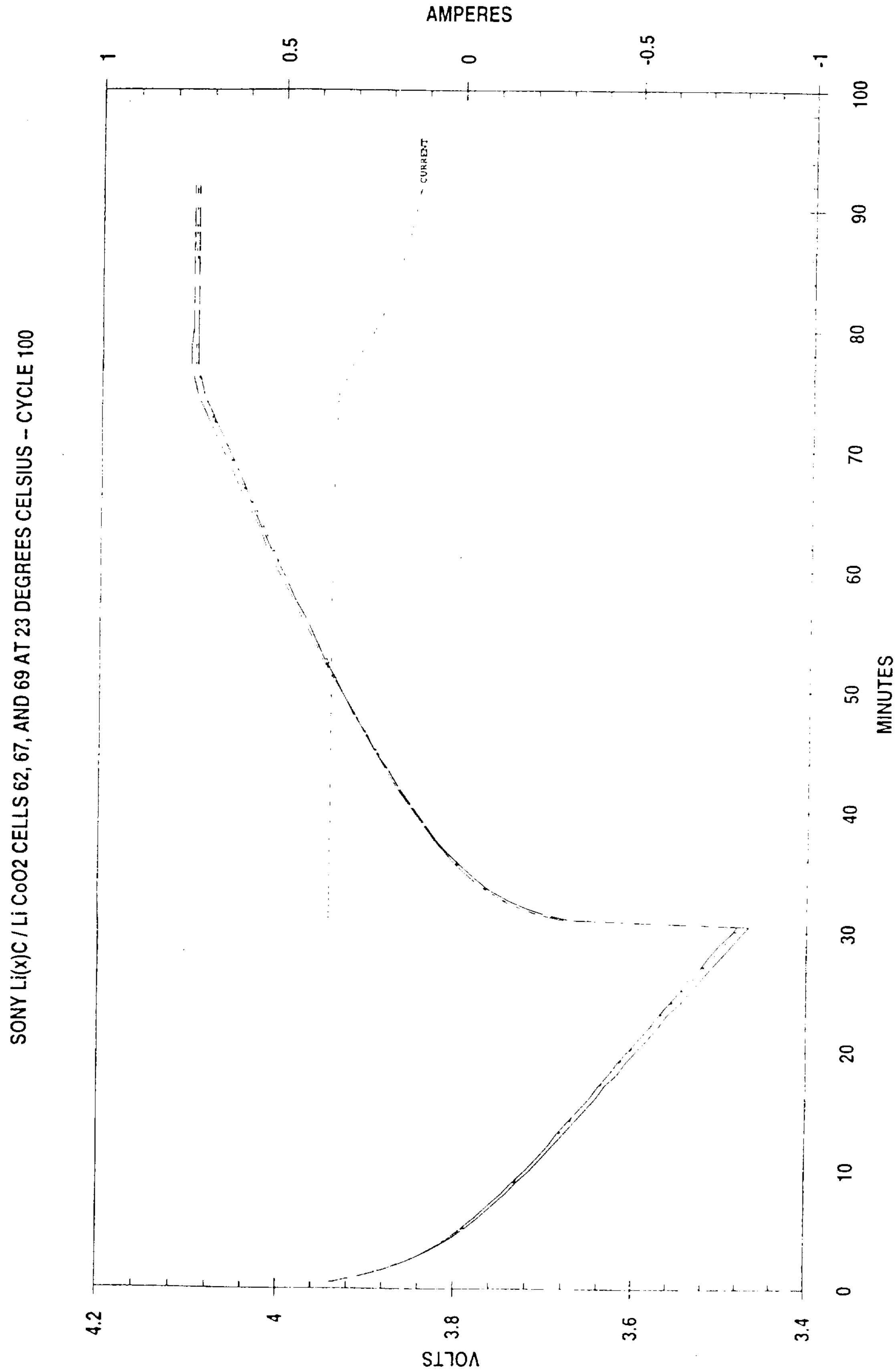
SONY Li(x)-CoO2/Li(x)-C SAMPLE CELL #88
CYCLE 1 C/5 DISCHARGE PERFORMANCE



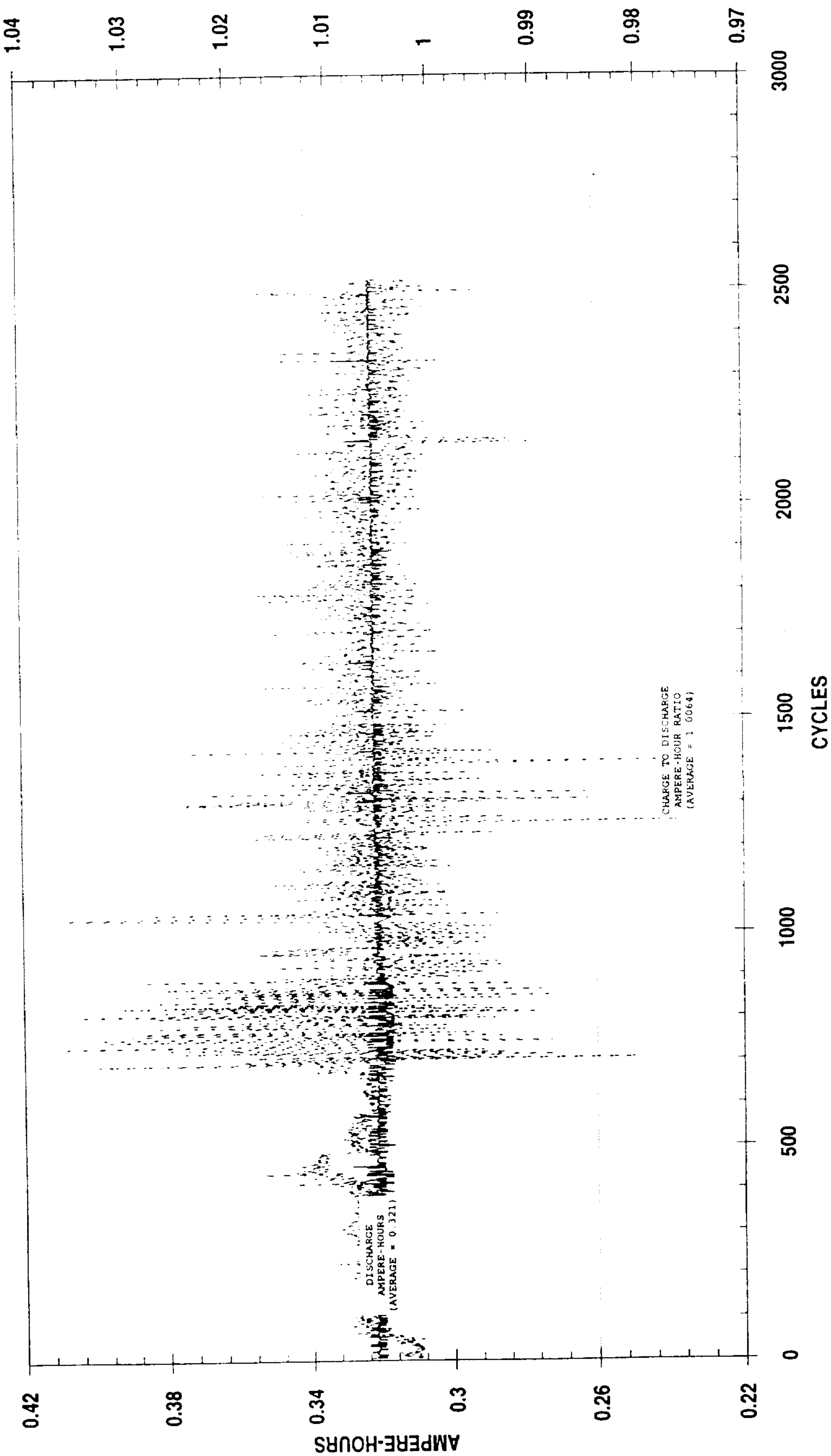
SONY Li(x)C / Li CoO2/ CELLS 62, 67, AND 69
DISCHARGE 1 AT 0.2 AMPERES TO 3.0 VOLTS PER CELL AT 23 DEGREES CELSIUS



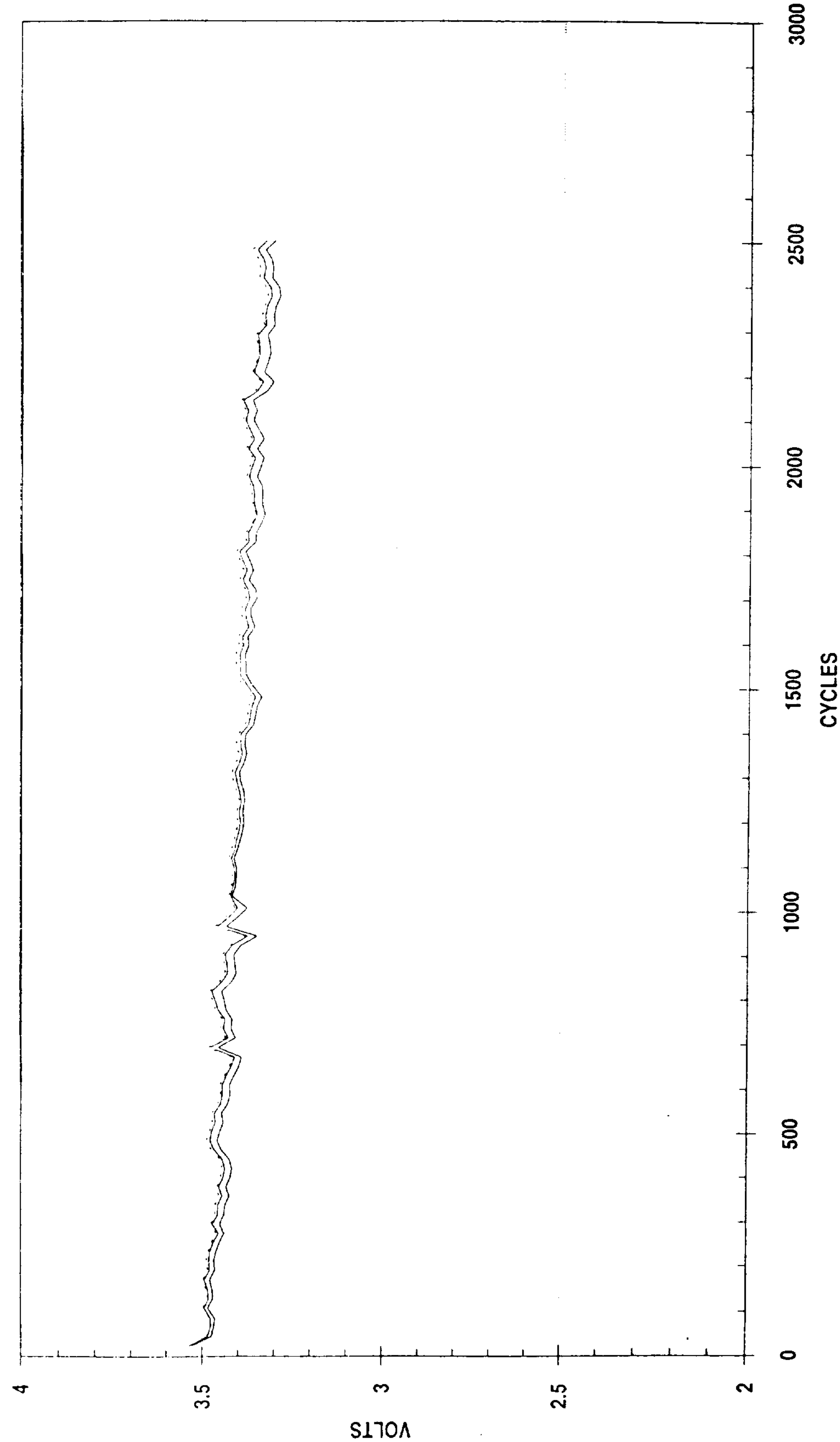

CYCLE 36 OF LEO REGIME ATTEMPT WITH SONY Li(x)C / Li CoO2 CELLS 62, 67, AND 69 AT 23 DEGREES CELSIUS
40% DOD IN 30 MINUTES FOLLOWED BY C/2.46 INRUSH TO 4.1 VOLTS PER CELL TO 1.001 CHARGE TO DISCHARGE AMPERE-HOUR RATIO
AMPERES
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
VOLTS
4.2
4.1
4
3.9
3.8
3.7
3.6
3.5
MINUTES
0
20
40
60
80
100
120


SONY Li(x)C / Li CoO2 CELLS 62, 67, AND 69 AT 23 DEGREES CELSIUS -- CYCLE 100
AMPERES
1
0.5
0
-0.5
-1
VOLTS
4.2
4
3.8
3.6
3.4
MINUTES
0
10
20
30
40
50
60
70
80
90
100
CURRENT

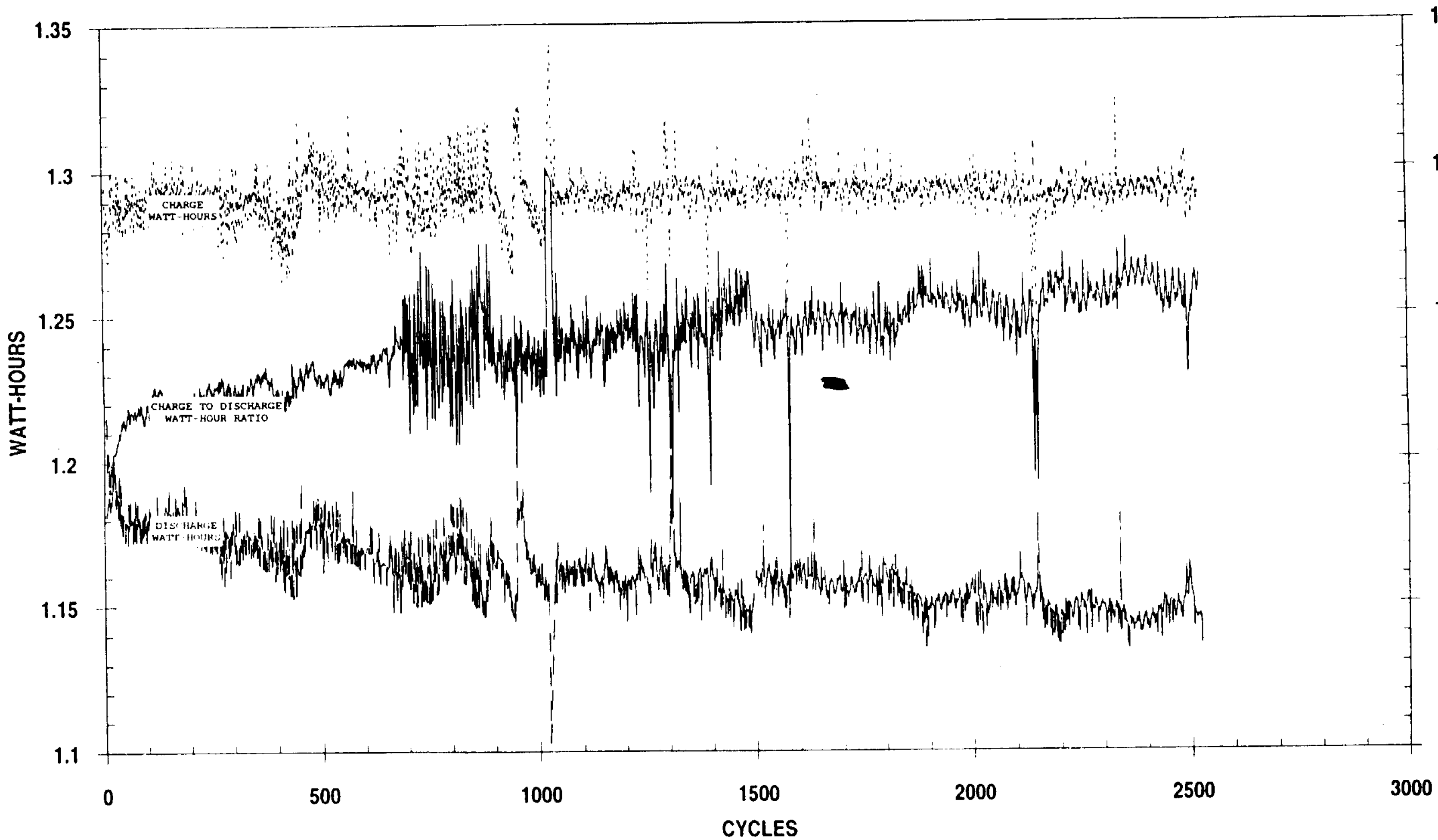
SONY Li(x)C / Li CoO2 CELL SAMPLE NUMBER 28012-62, 67, AND 69
CYCLES VS. DISCHARGE AMPERE-HOURS DURING AN ACCELERATED LEO REGIME AT 23 DEGREES CELSIUS



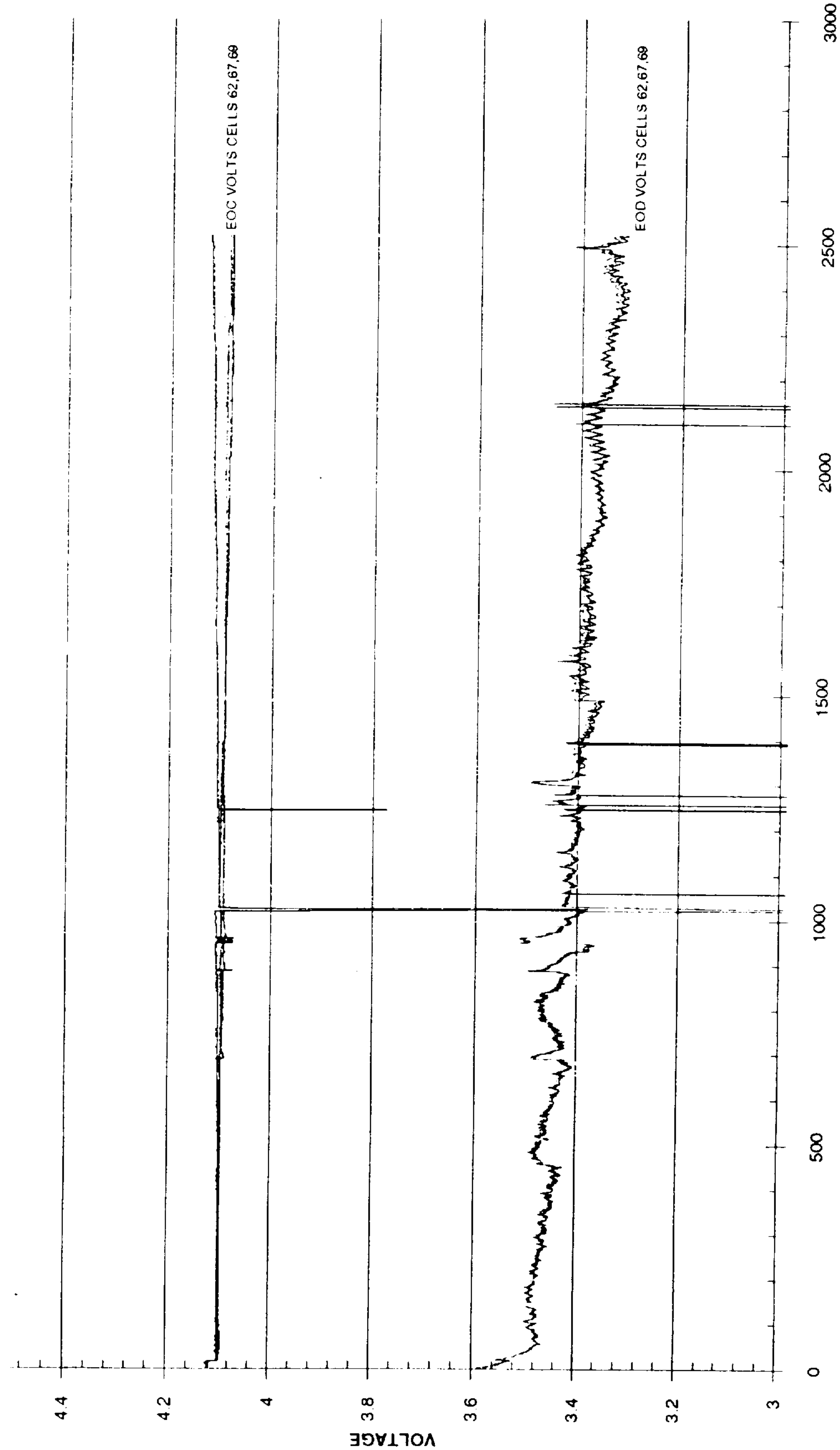
SONY Li(x)C / Li CoO2 CELL SAMPLE NUMBER 28012-62, 67, AND 69 AT 23 DEGREES CELSIUS
CYCLES VS. END OF DISCHARGE CELL VOLTAGES DURING AN ACCELERATED LEO REGIME

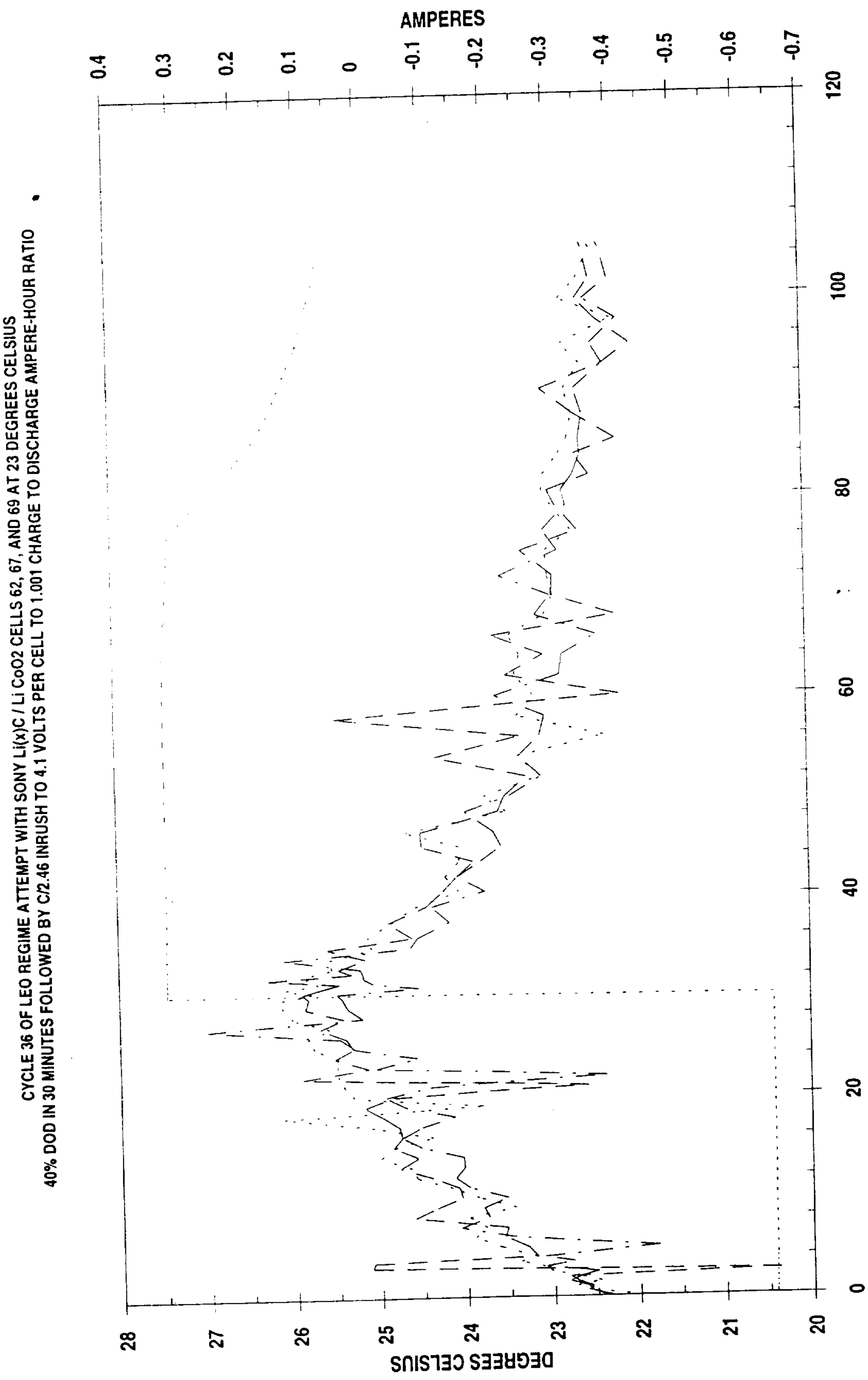


SONY Li(x)C / Li CoO2 CELL SAMPLE NUMBER 28012-62, 67, AND 69
CYCLES VS. AVERAGE WATT-HOURS DURING AN ACCELERATED LEO REGIME AT 23 DEGREES CELSIUS

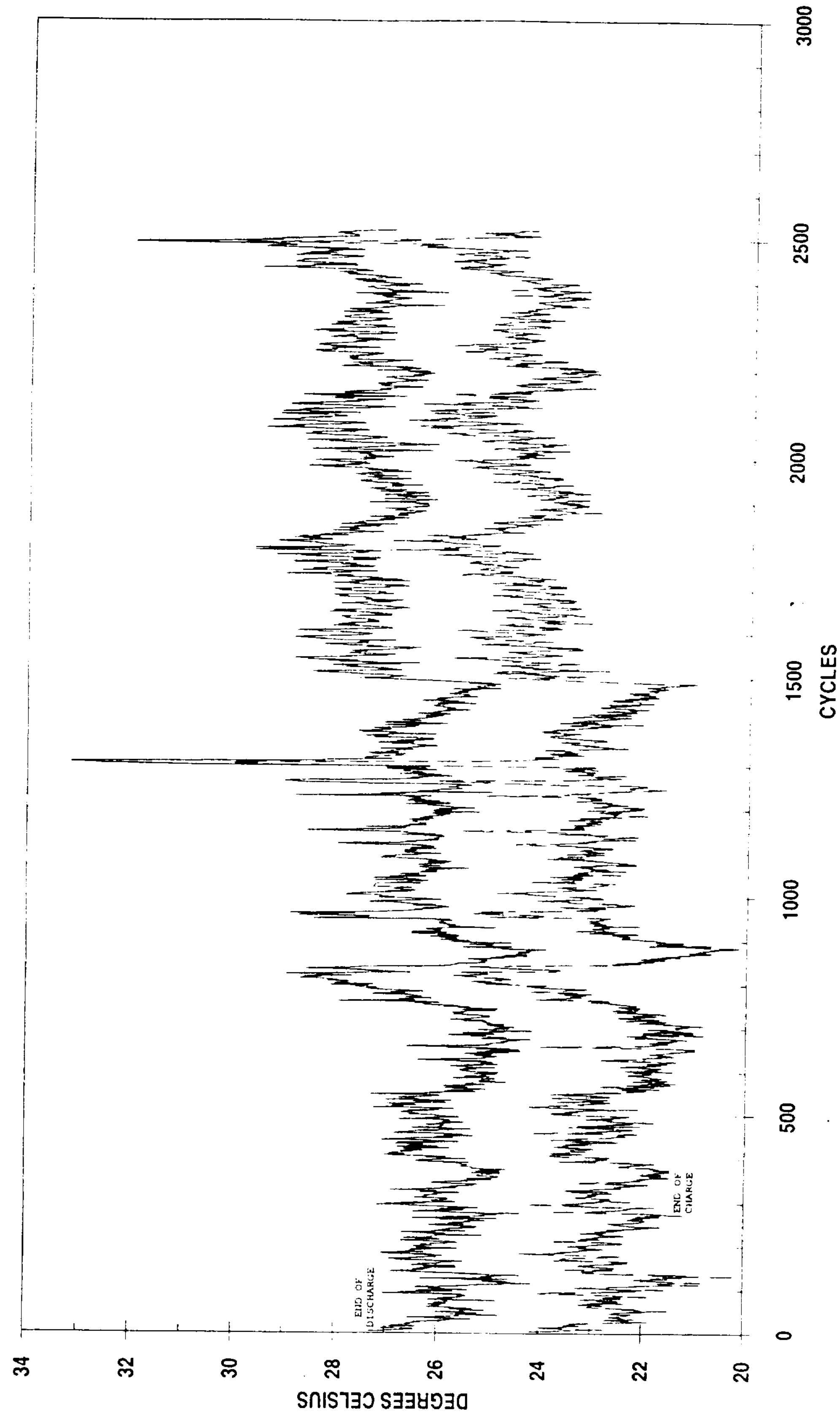


SONY LI-ION END OF CHARGE/END OF DISCHARGE VOLTS VS CYCLES

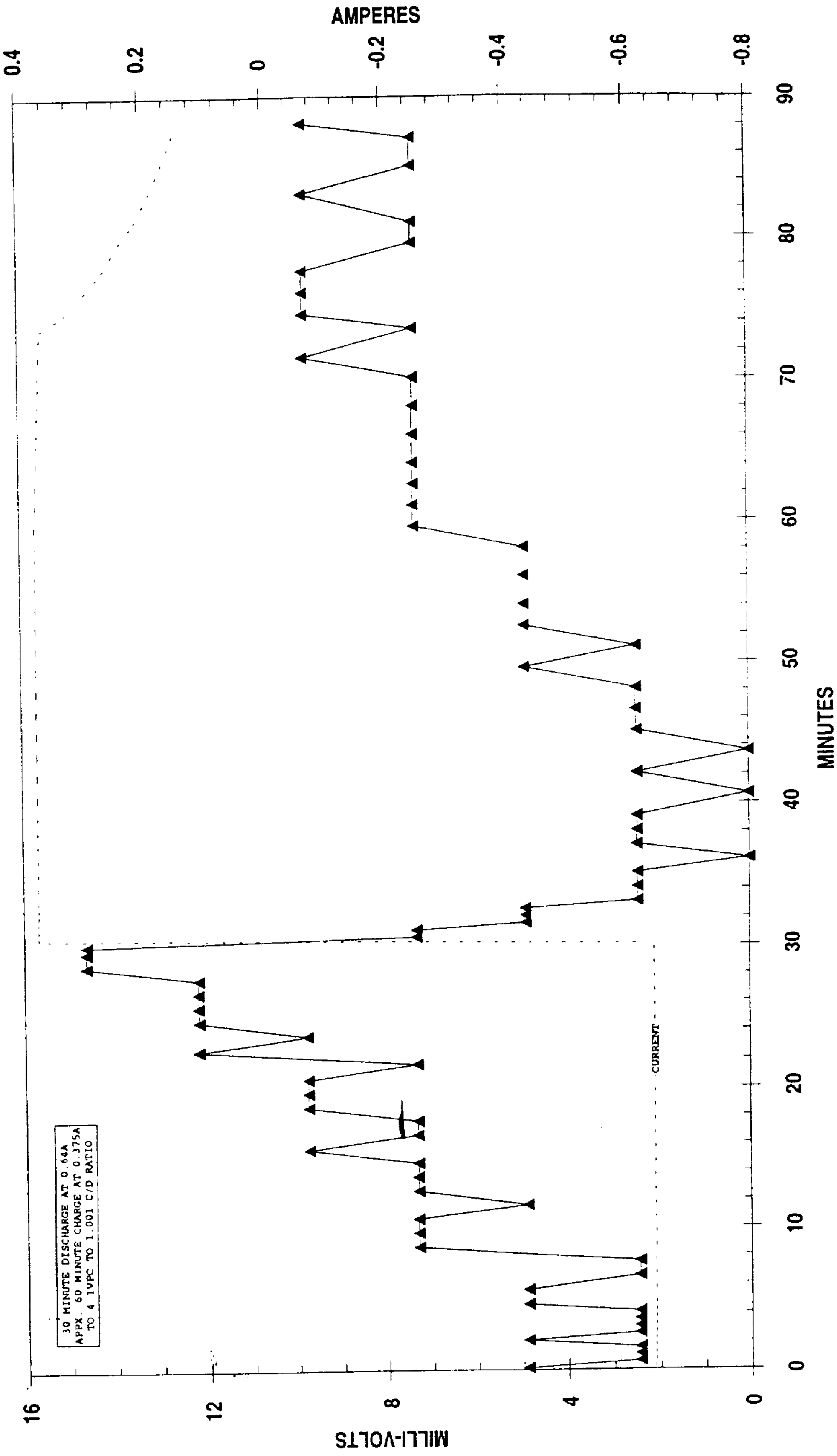



CYCLE 36 OF LEO REGIME ATTEMPT WITH SONY Li(x)C / Li CoO2 CELLS 62, 67, AND 69 AT 23 DEGREES CELSIUS
40% DOD IN 30 MINUTES FOLLOWED BY C/2.46 INRUSH TO 4.1 VOLTS PER CELL TO 1.001 CHARGE TO DISCHARGE AMPERE-HOUR RATIO
AMPERES
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
DEGREES CELSIUS
28
27
26
25
24
23
22
21
20
MINUTES
0
20
40
60
80
100
120

SONY Li(x)C / Li CoO2 CELL SAMPLE NUMBER 28012-62, 67, AND 69
AVERAGE CELL TEMPERATURES MEASURED ON CASE DURING AN ACCELERATED LEO REGIME AT 23 DEGREES CELSIUS



SONY Li(x)C / Li CoO2 CELL SAMPLE NUMBER 28012-62, 67, AND 69 AT 23 DEGREES CELSIUS
CELL DIVERGENCE = 1000 x (MAXEMF(1:3)) - (MINEMF1:3))



JPL

Summary

1) First Generation Cell yielded 780 mAh capacity, second generation cell delivered 860 mAh capacity.

2) Cycle life performance of the second generation cell appears to exceed the first.

3) Accelerated “LEO” testing has already demonstrated 2500 cycles at 40% DOD, and continues to cycle.

4) Energy density per volume is larger with the second generation cells.

5) Cell performance is consistent which demonstrates good fabrication techniques.

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ENERGY STORAGE SYSTEMS GROUP

Round Table Discussion of Advanced Technology for Space Applications
Gerald Halpert, Jet Propulsion Laboratory

NASA BATTERY WORKSHOP
MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA
November 1994

OPEN DISCUSSION
On the Subject of

WHAT WILL IT TAKE TO GET ADVANCED BATTERY TECHNOLOGY INTO SPACE APPLICATIONS?

Chairman: Gerald Halpert
Jet Propulsion Laboratory
Notes by Michelle Manzo, NASA LeRC

OPENING REMARKS - G. Halpert
New battery technologies have been improving over the last several years. It took almost 20 years for NASA to use a Ni-H2 battery. Even then it was used on Hubble Space Telescope as a replacement for a Ni-Cd battery in which life limiting concerns had been raised. What do we have to do to use Ni-MH or Li-ion batteries in space? How do we qualify cells and batteries for space missions?

If you ask the spacecraft Manager or project manager, he or she will ask where has it been used previously and what is the experience with the device? Even though there may be significant test data, and the mass and volume is lower or the mission capability can be increased, the project manager will generally opt for a previously used battery system. The philosophy is "Not on my spacecraft."

The subject is open for discussion to all attendees. I hope you will participate. The first speaker is Dave Pickett from Hughes.

ATTENDEE PARTICIPATION
Pickett - It took 8 years to fly modern Ni-Cd and 11 years to for Ni-H2. A compelling reason is needed for implementation of new technology, whether it be economics, or other. It takes time, and someone willing to take the risk. Usually, commercial needs lead the way.

The new technologies are Ni-MH, Li-ion, and CPV Ni-H2. Larger IPV are being considered as well as CPV. Predictions for spaceflight of Ni-MH , 5 years, and Li Ion 8-10 years. This is the time it takes from cell test to battery integration.

E. Darcy - Safety issues with Li make Ni-MH more of a near term option.

J. Firmin - Safety tests have been conducted. Requirements need to be defined and tech must meet the requirements.

G. Methlie - Agreement with safety issue. Ni-MH intermediate term is needed. Difficult to accelerate verification.

M. Klein - Ni-MH is the battery of choice for next 10-15 years. Aerospace should leverage off commercial.

C. Lurie - High cost for qualification of Ni-Cd to Ni-MH. Not clear that it offers significant advantages at battery level. Li-Ion will probably ultimately replace Ni-MH. Probably cannot justify costs.

G. Dudley - Wh efficiency less for Ni-MH than Ni-Cd.

C. Lurie - Ni-MH advantage is improved round trip efficiency, thus, smaller array.

W. Tracinski - Possible use for all technologies to optimize for all applications.

G. Methlie - Project forward by looking backward. If end up with one system, you better be right. Also need multiple vendors.

D. Maurer - Need all technologies. Li-Ion a long way off. Need several technologies going at once. The mechanism for demo in space will be in small s/c.

A. Dunnett - Cheaper and faster, not better. No new battery systems seen without compelling reason. Ni-MH will not be qualified with Ni-Cd and Ni-MH available. Li-Ion is the next step.

G. Halpert - What is the necessary incentive to go Li-Ion? Does your company support R&D on Li-Ion?

A. Dunnett - Lower battery weight, more propellant, increase in payload. My organization does not support Li-Ion or other R & D.

E. Darcy - The time line is long without terrestrial applications. Ni-MH make sense in todays environment.

C. Lurie - Small satellites are new visions for aerospace. They become the platform for new technology.

M. Anderman - Ni-MH advantages depend on DOD capability and life as a function of DOD.

V. Kennedy -Responding to a question on Na-S, acceptance and abuse tests are being worked.

Johnson -Go on to far term technologies. Let other Intermediates develop in commercial technology. Sponsor research in space for space applications.

G. Methlie - Commercial base does not guarantee success in space.

J.Firmin - Same battery as EV commercial? Need to begin improvement at early stages to influence development.

P. O'Donnell - Need dual-use drivers. Can't take terrestrial alone. Need to work on parallel paths.

J. Firman - Limit documentation for qualification of new technologies for space. Documentation is costly.

C. Lurie - Dual answer. Small satellites, Yes, DOD/NASA, no.

C. Lurie - On the capacity fade issue - It still exists but we have an understanding. TRW prefers to deal with Ni precharge issues.

G. Halpert - Managers want low cost but also want guarantees that product will work. Thus, costs will remain high. However, we are careful. Not always battery failures, e.g., Magellan - failure was arrays not battery.

S. House - Phillips Lab will not support development of Ni-Mh. Lithium-ion possible substitution to Na-S and Ni-H2. 7 year test is required.

M. Toft - To get new technology into orbit, which product has been shown to be best understood. Elimination of documentation and visibility is the wrong way to go. Vendor data is valuable. It holds clues to success. If you show understanding, customers will be willing to pay.

C. Bennett - There is a large database for Ni-H2. Varied parameters, no consistent production. Need to use a model.

G. Halpert - Why do we have all these variations in product? (No response)

J. Armantrout - Historically we have used database for decisions. Develop a standard for a 5Kw satellite. Need more standardized designs.

J. Wheeler - The process is: The manufacturer recommends to the customer, then customer has strong preferences including plate and cell designs. The manufacturer is at the customer's mercy. There are multiple paths to success. Let the customer make the selection.

C. Garner - Cooperative efforts work well.

G. Methlie - Commercial look at products.

S. Surampudi - Technology is driven by customer. Customer was leader. Leader disappeared replaced by managers. They want the best products without supporting costs.

G. Halpert - Are there any planned Ni-Mh flights?

B. Bragg - Shuttle orbiter GFE. Ni-MH flown in IBM think pad. To be flown in helmet light. NASA/JSC approves specific designs and specific applications - no blanket chemistry approval. OSHA and EPA have environmental concerns. Japanese Ni-MH flight in 1998 will follow European's and Amercians.

A. Dunnett - The delta performance improvement does not warrant development of Ni-Mh over Ni-Cd.

G. Halpert - Are there any planned Li-Ion flights?

S. Surampudi - JPL use in 1997. Small spacecraft 5-10 Ah cells. 45 new technologies evaluated for new spacecraft. Li-Ion was selected. Looking at Li-Ion instead of Ni-MH because no apparent payoff over Ni-H2. The fallback is Ni-Cd compelling reason is size.

Session adjourned

Many thanks to Michelle Manzo for taking these notes

Nickel-Hydrogen / Nickel-Cadmium Data Session

N95- 26794

Hubble Space Telescope Nickel-Hydrogen Battery Testing An Update

Marshall Space Flight Center
Huntsville, Al 35812

EB72 / Thomas H. Whitt
EB74 / Jeffrey C. Brewer

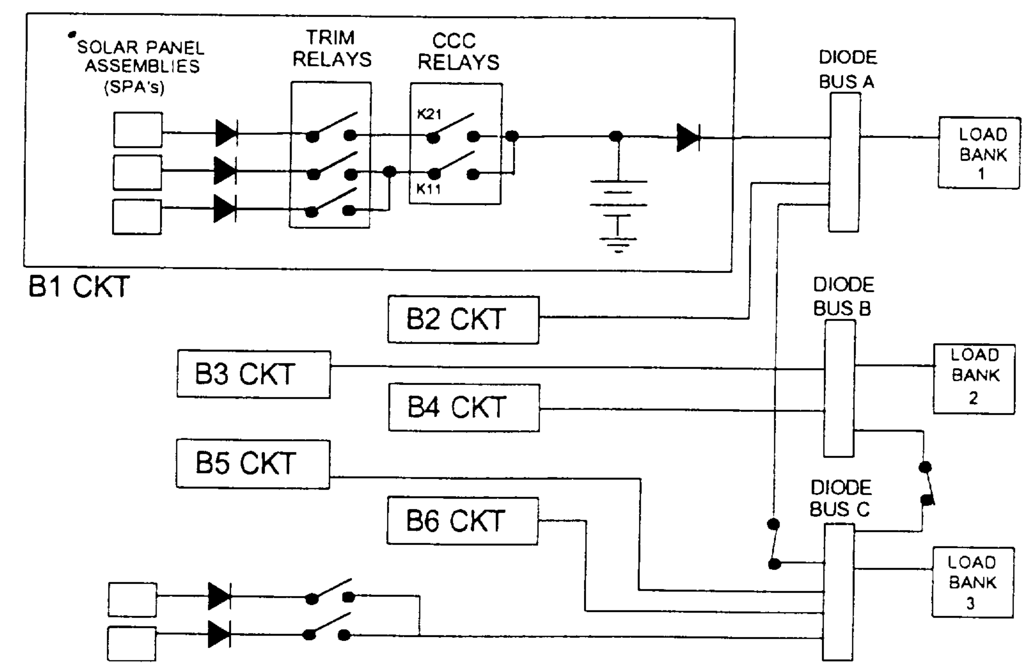
The Marshall Space Flight Center (MSFC) began testing the HST Ni-H2 Six Battery Test and the Flight Spare Battery Test approximately one year before the launch of the HST. These tests are operated and reported on by MSFC, but are managed and funded by Goddard Space Flight Center in direct support of the HST program.

The HST Batteries
Eagle Picher RNH-90-3

- High rate charge => 10 - 13 amps (C/8)
- Charge scheme => V/T limit
- Discharge => 9 - 11 amps (C/9)
- Depth of discharge (DOD) => 6 to 9%
- Operating temp => 0 to 3 degrees C
- Sun/eclipse periods => 60/36 to 70/26

The HST Ni-H2 Batteries are built from Eagle Picher RNH-90-3 cells. The bullet chart above describes the typical operating conditions of the batteries in the HST EPS.

SIMPLIFIED BLOCK DIAGRAM OF THE HST EPS



The figure above is simplified block diagram of the HST electrical power system (EPS). The HST EPS is direct energy transfer power system. The solar array is divided into 20 solar panel assemblies (SPAs) with 3 SPA sections going to each battery channel and 2 going directly to the load bus. The trim and charge current control (CCC) relays are the battery charge control relays that are located in the power control unit (PCU). The 3 load busses are normally tied together to act as a common load bus.

HST Battery Tests at MSFC

- HST Six Battery Test
  - Breadboard of the HST EPS
  - 6 batteries of test module cells
  - Packaged in flight type modules
- "Flight Spare Battery"
  - Simulation - 1 of 6 battery channels
  - Cells from flight spare lot

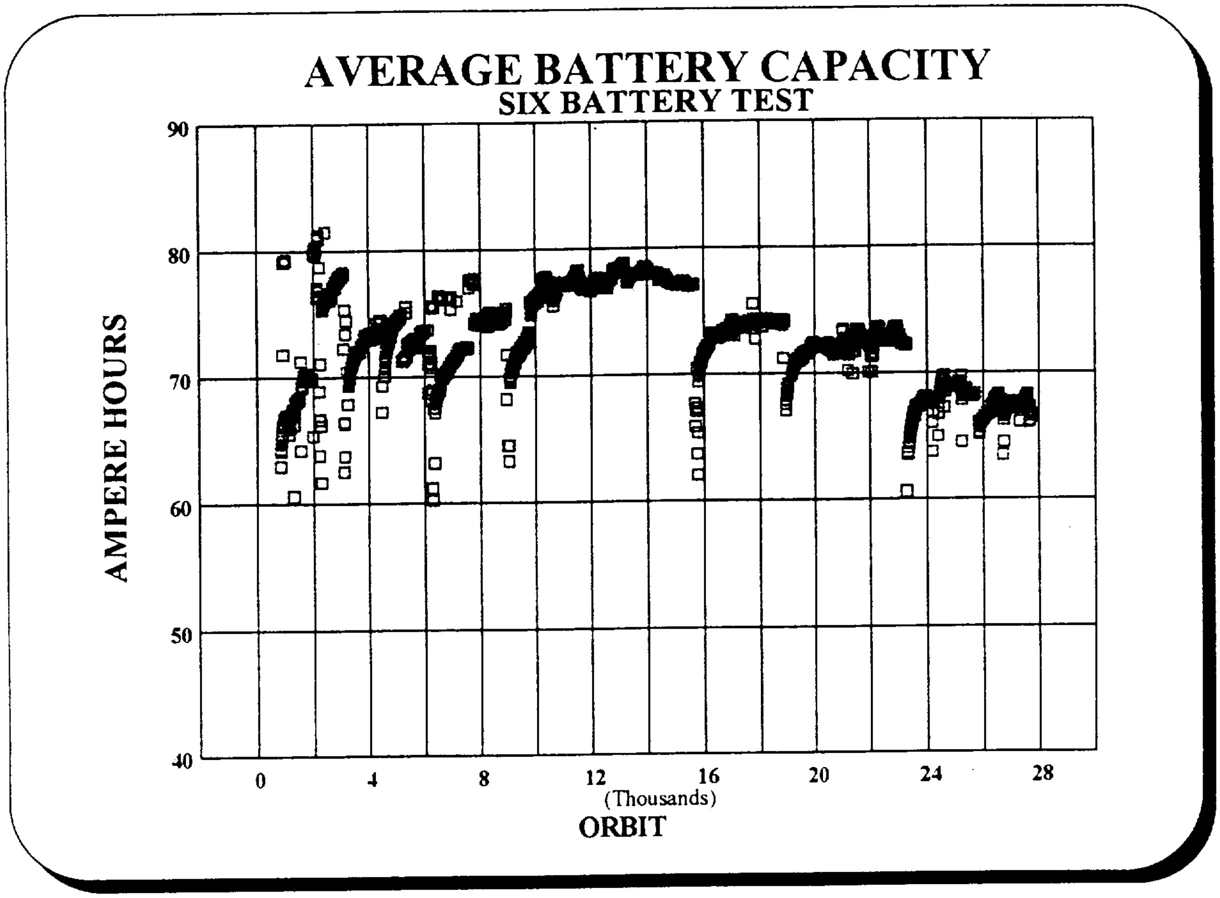
The HST Ni-H2 Six Battery Test is a breadboard of the HST EPS. The batteries in the test are composed of test module cells and packaged into 3 battery modules identical to the flight modules. This test is the HST EPS Testbed.

The "Flight Spare Battery" Test is a simulation of 1 of the 6 battery channels on the HST. The cells in the test are from the flight spare lot of cells, which are the same lot of cells that 3 of the 6 HST flight batteries are made from. This test is the battery life test for the HST program.

Test Objectives

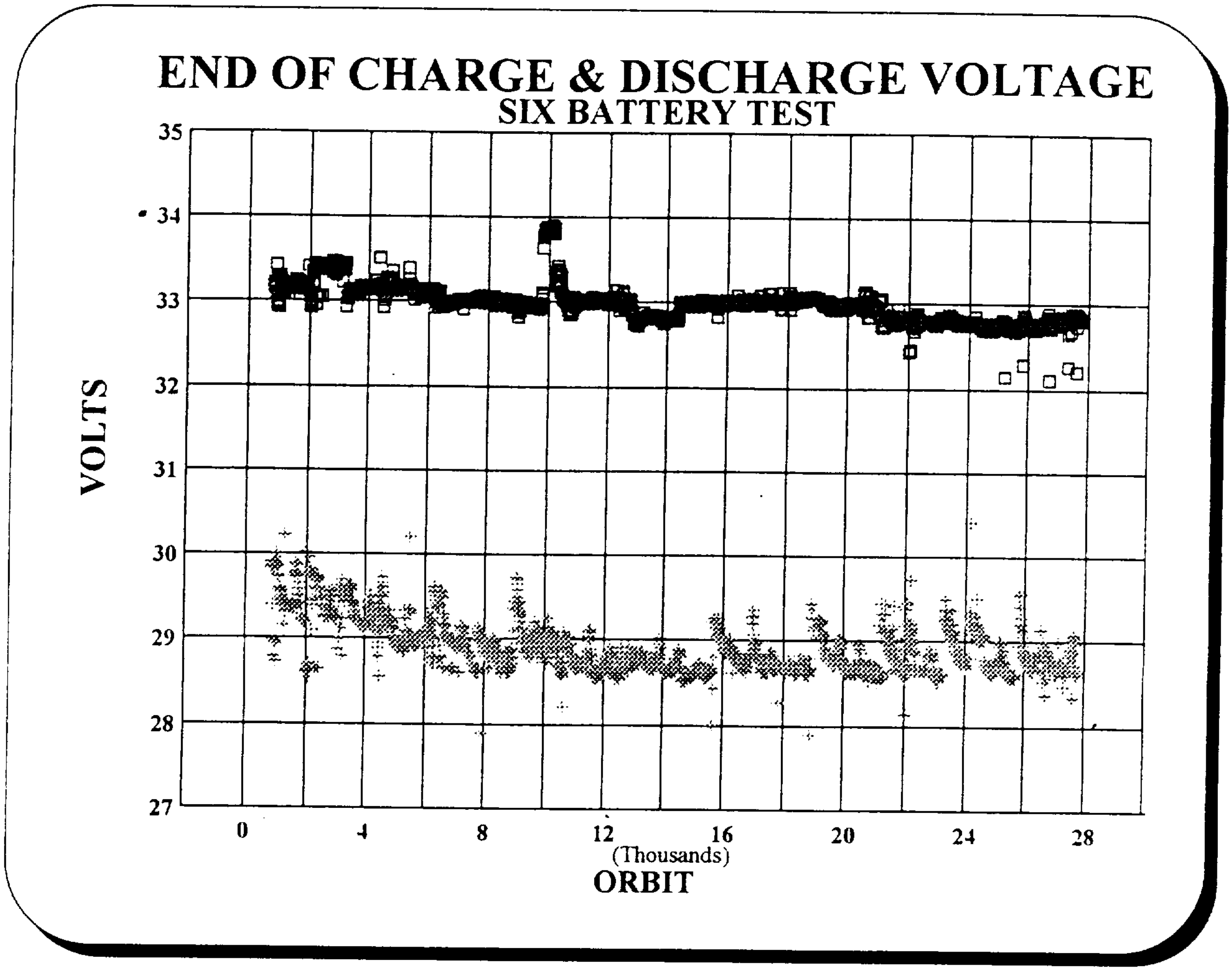
- **Determine operating characteristics of the batteries**
- Investigate on-orbit anomalies
- Test proposed variations prior to implementation on orbit

The first of the test objectives is to determine the operating characteristics of the batteries. The test batteries began cycling one year before the launch of HST and have now been cycling under the HST Flight conditions for over 5.5 years. The graphs on the following 3 pages show the average battery capacity, the end of charge & discharge voltages, and the battery watt-hour efficiency over the life of the test.

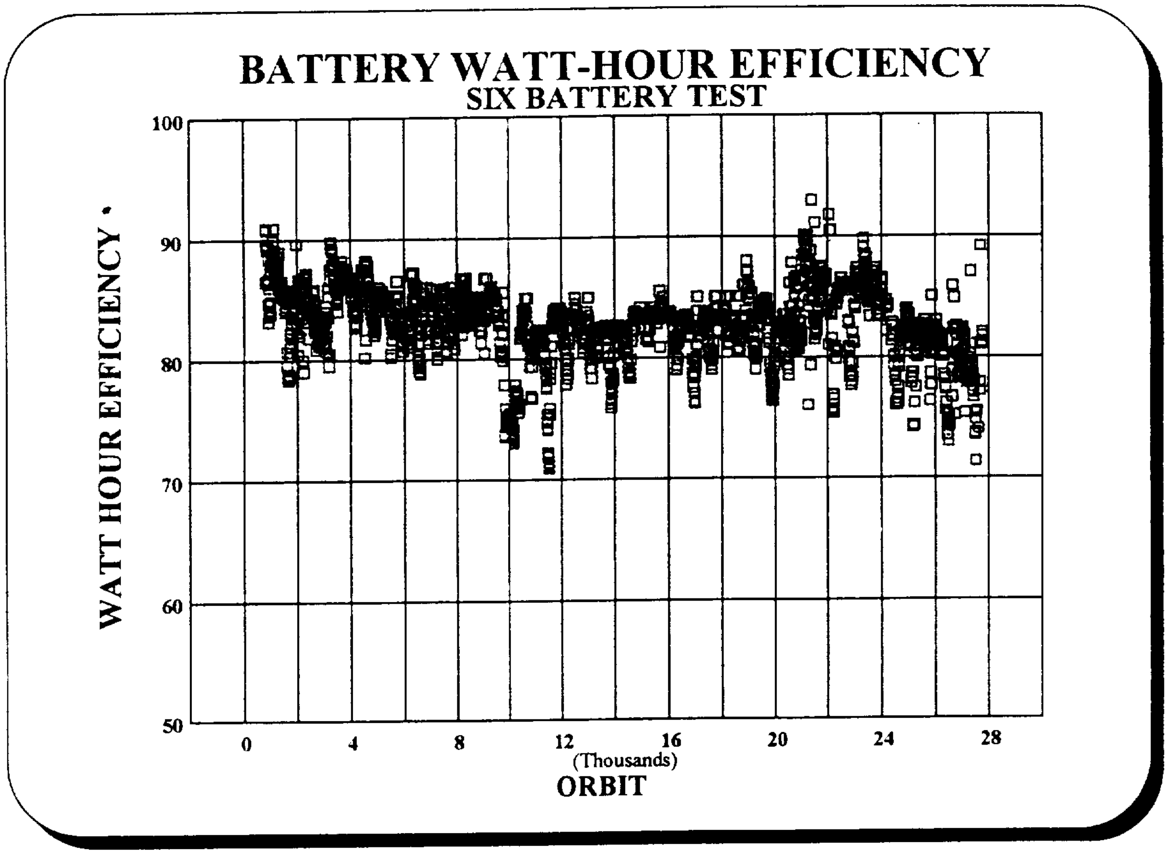


This plot is of the average battery capacity of the HST Ni-H2 Six Battery Test over the life of the test. The fluctuations in the capacity are a result of the numerous capacity tests run on the batteries (approximately 9). Over the first 4 years of the test the average battery capacity was between 70 and 77 ampere-hours (AH). During this time the batteries were being charged to 1.5 v/cell with a step to trickle charge scheme. At orbit 20,000, the charge voltage was dropped to 1.49 v/cell as a result of some charge control relays failing and the thermal situation of the batteries. The thermal situation of the HST batteries is the reason the batteries have not been charged to higher charge voltages from the beginning.

Since launch the flight batteries have always had 10 to 15 AH more than the test batteries. The flight batteries underwent an almost ideal launch scenario and within a couple of months on flight were cycling with 90 to 95 AH. To date the HST flight batteries have cycled for almost 4.5 years and have underwent or will soon have underwent 2 capacity checks per battery. The present average capacity of the flight batteries is 78 to 80 AH. It is felt that most of the operating capacity lost is a result of the low charge level (1.49 v/cell) that the batteries are being charged to. Thermal changes to the HST battery bays are being considered for the next servicing mission to allow for charging the batteries to a higher voltage.



This plot shows the end of charge and end of discharge voltages over the life of the Six Battery Test. The end of charge voltage tracks the different charge levels that have been used and the end of discharge voltages track the general state of health of the batteries. Even though the end of discharge voltages have essentially stabilized, a gradual decline over the life of the batteries is to be expected.



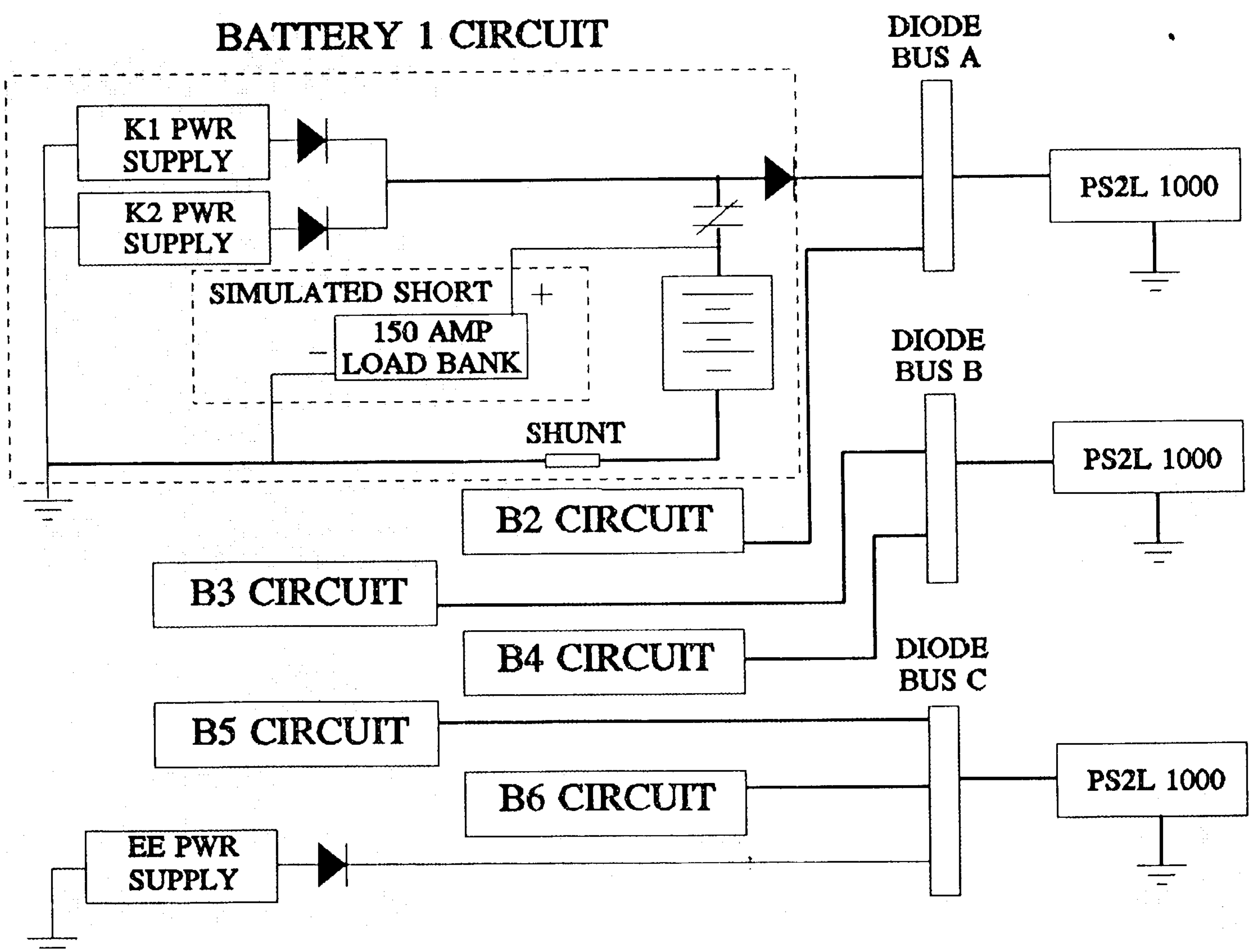
This plot shows the average battery watt-hour efficiency over the life of the HST Ni-H2 Six Battery test. The batteries cycled with a step to trickle charge scheme and charged to 1.5 v/cell for the first 20k orbits. After orbit 20k the charge scheme was changed to hardware control (essentially a taper charge) and the charge voltage was lowered to 1.49 v/cell. The watt-hout efficiency of the HST Ni-H2 cells has varied from about 77 to 85%.

Test Objectives

- Determine operating characteristics of the batteries
- **Investigate on-orbit anomalies**
- Test proposed variations prior to implementation on orbit

As a result of an electrical fault that occurred on the Hubble Space Telescope (HST) in September, 1991, the HST Electrical Power System (EPS) Operations group at GSFC requested a series of tests on the HST batteries on test at MSFC. In October '91 tests were run on the HST Six Battery Test with 3 second discharges as high as 70 amperes. From 12/23/91 to 1/3/92 additional tests were run on a 4 cell pack of HST Flight Spare Module cells on test at MSFC where the cells were discharged at rates up to 250 amps. The Six Battery Test results revealed that a fault as low as 70 amperes could have caused the EPS anomalies observed during the fault. Further test to 250 amperes indicated that: (1) no damage should have occurred to the HST batteries as a result of the fault and (2) that the HST test batteries impedances were constant over the entire tested range at 1.2 to 1.3 milliohms per cell. On the following page is a block diagram showing how the fault was simulated on the Six Battery Test.

Block Diagram of Battery Anomaly Simulation



Test Objectives

- Determine operating characteristics of the batteries
- Investigate on-orbit anomalies
- **Test proposed variations prior to implementation on orbit**

The Six Battery Test has been used extensively for testing proposed variations in operating mode. The test was used for launch scenario testing, investigating possible methods to boost up operating capacity, and investigating possible EPS configurations during the first servicing mission. Prior to the servicing mission, the HST Six Battery Test underwent numerous test in support of the servicing mission. In the simulations the test batteries were put through conditions the flight batteries would experience during the servicing mission. The simulations determined the battery capacity and the optimum configuration for the battery circuits for the mission.

Power Control Unit (PCU)

Relay Minimization Test

- Background
  - 2 PCU relays have failed
  - Failures have potential to damage DIU
  - PCU is not an orbital replacement unit
- Purpose - minimize cycling on the PCU relays
- Plan - develop a battery charge control algorithm that will minimize PCU relay cycling w/out sacrificing battery capacity

The most recent use of this test as a means for testing proposed variations in operating mode is the investigation of a proposed "PCU Relay Minimization Scheme". Since launch, the HST electrical power system (EPS) has had two solar array trim relays fail. The relays were being used as battery charge control relays when the failures occurred. The relays are located on the power contol unit (PCU), which was not designed as an orbital replacememnt unit (ORU). To reduce the cycling on the PCU relays, GSFC is investigating operating the EPS with a reduced solar array by opening a number of solar array trim relays. A set of conditions, based on the batteries state of charge (SOC) and the number or orbits since the batteries were fully charged, will determine the number of trim relays to open or close. A reduced solar array will reduce battery charge current, and require less charge control relays to cycle. The algorithm that determines the number of trim relays to open or close is being referred to as the "PCU Relay Minimization Charge Scheme". Phase I of this sheme was tested on the HST NiH2 Six Battery Test from 6/28/94 to 8/24/94.

PCU Relay Minimization Phase I

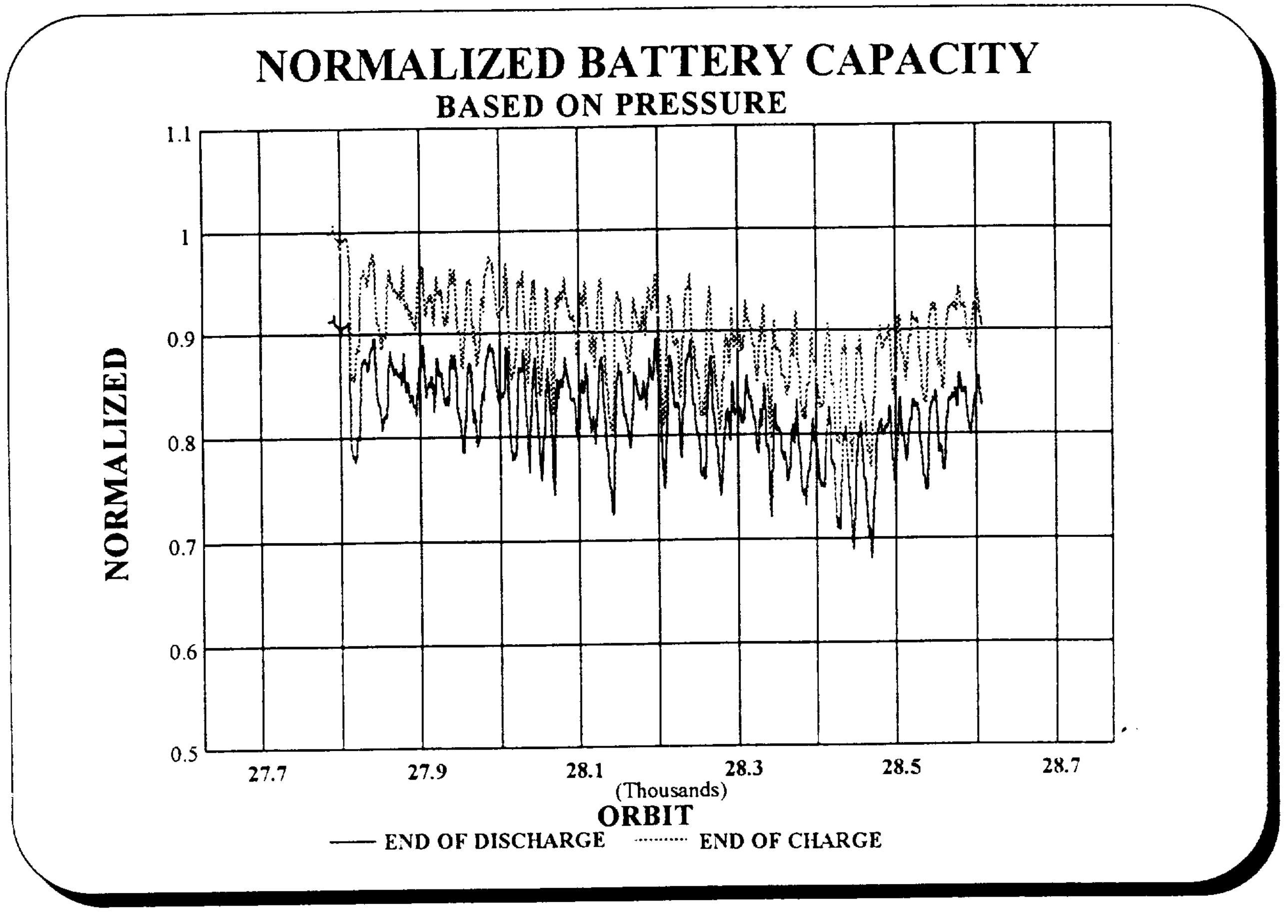
- Remove SPAs until batteries are unable to charge to V-T charge level (STARVATION MODE)
- When SOC gets below 85% or 15 orbits since last full charge, put 1 SPA back on line (this is the transition to FULL CHARGE MODE)
- When 2 batteries reach V-T limit for 2 consecutive orbits, remove 1 SPA (transition back to starvation mode)

The above chart describes the basic conditions of the Phase I of the PCU relay minimization charge scheme. The charge scheme consisted of two modes of operation:

1) STARVATION MODE - remove enough SPAs so the batteries do **not** reach the V-T limit. Stay in this configuration for 15 orbits or until the batteries SOC at the end of discharge goes below 80 or 85%. Then put one SPA back on line and transition to:

2) FULL CHARGE MODE - in this mode the batteries capacity will be increasing. The system will stay in this configuration until 2 or 3 of the batteries have charged up and reached their V-T limit. Then one spa will be removed and the system will return to the starvation mode.

Phase I was implemented on the Six Battery Test for 60 days and reduced PCU relay switching by 90%.



This graph shows the normalized battery capacity during Phase I of the PCU relay minimization test. Even though 2 of the batteries were reaching the V-T limit during the full charge mode, the capacity was gradually going down. At orbit 28450, when it was decided to require 3 batteries to reach the V-T limit before returning to the starvation mode, the capacity began to slowly increase. But, during this testing GSFC ran a capacity check on one of the HST flight batteries, and the battery had less capacity than was being predicted. With the flight batteries having less capacity than predicted and this charge mode showing another possible reduction in capacity, GSFC began considering changes to the algorithm to optimize the trade off between relay cycling and battery capacity. The changes to the algorithm are Phase II of the PCU Relay Minimization Charge Scheme.

PCU Relay Minimization Phase II

- Instead of putting 1 SPA on line to transition to full charge mode, return entire solar array.
- Return to starvation mode after 4 or 5 batteries reach the V-T level.
- Phase II should reduce PCU relay cycling by 75%

In Phase II of the PCU Relay Minimization test, during the FULL CHARGE mode the entire solar array will be put back on line instead of just one additional SPA. This will give the batteries a higher rate full charge and and this charge mode will continue until 4 or 5 of the batteries reach the V-T limit. This phase of the test has just begun and it is too early to predict exactly how this change will effect the capacity. A HST EPS model predicts this charge scheme will reduce PCU relay cycling by 75%. This test will be completed by February '95.

SUMMARY

- Batteries have cycled for over 5 years and performance continues to be nominal
- Testbed continues to be a very beneficial tool for testing proposed operating configurations and investigating flight anomalies

N95- 26795

ADIABATIC CHARGING OF NICKEL-HYDROGEN BATTERIES

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REDONDO BEACH, CALIFORNIA

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THE 1994 NASA AEROSPACE BATTERY WORKSHOP
THE HUNTSVILLE MARRIOT, 5 TRANQUILITY BASE
HUNTSVILLE, ALABAMA
NOVEMBER 15 - 17, 1994

BACKGROUND

- ACTIVE BATTERY COOLING, DURING PRE-LAUNCH ACTIVITIES, IS DIFFICULT AND EXPENSIVE
- NICKEL-HYDROGEN BATTERY CHARGING, IN THE ABSENCE OF ACTIVE COOLING, WAS INVESTIGATED FOR APPLICATION DURING AXAF-I PRE-LAUNCH ACTIVITIES.
- TESTING WAS CONDUCTED TO
  - DEMONSTRATE THE FEASIBILITY OF THE "ADIABATIC CHARGING" APPROACH
  - PROVIDE A PARAMETRIC DATA BASE

Battery management during prelaunch activities has always required special attention and careful planning. The transition from nickel-cadmium to nickel-hydrogen batteries, with their higher self discharge rate and lower charge efficiency, as well as longer prelaunch scenarios, has made this aspect of spacecraft battery management even more challenging.

The AXAF-I Program requires high battery state of charge at launch. The use of active cooling, to ensure efficient charging, was considered and proved to be difficult and expensive. Alternative approaches were evaluated. Optimized charging, in the absence of cooling, appeared promising and was investigated. Initial testing was conducted to demonstrate the feasibility of the "Adiabatic Charging" approach. Feasibility was demonstrated and additional testing performed to provide a quantitative, parametric data base.

ADIABATIC CHARGING
DEFINITION

- ADIABATIC CHARGING IS CHARGING IN THE ABSENCE OF COOLING
- HEAT DISSIPATED BY THE CHEMICAL PROCESSES IN THE CELLS, AS WELL AS I^2R HEATING, STAY IN THE BATTERY AND ITS TEMPERATURE INCREASES
- THE BATTERY HAS A LARGE THERMAL MASS
- THE ADIABATIC CHARGE METHODOLOGY INVESTIGATED FOR AXAF-I CONSISTS OF
  - CHARGING THE BATTERY, IN THE ABSENCE OF COOLING
  - MONITORING BATTERY TEMPERATURE,
  - TERMINATING CHARGE WHEN BATTERY TEMPERATURE REACHES 85° F

The assumption that the battery is in an adiabatic environment during prelaunch charging is a conservative approximation because the battery will transfer some heat to its surroundings by convective air cooling. The amount is small compared to the heat dissipated during battery overcharge. Because the battery has a large thermal mass, substantial overcharge can occur before the cells get too hot to charge efficiently.

The testing presented here simulates a true adiabatic environment. Accordingly the data base may be slightly conservative.

The adiabatic charge methodology used in this investigation begins with stabilizing the cell at a given starting temperature. The cell is then fully insulated on all sides. Battery temperature is carefully monitored and the charge terminated when the cell temperature reaches 85° F. Charging has been evaluated with starting temperatures from 55° F to 75° F.

SCOPE

- TESTING INCLUDED INVESTIGATION OF
  - ADIABATIC CHARGING
  - ADIABATIC TOP OFF CHARGING
  - VERY LOW RATE TRICKLE CHARGING

- TODAY'S PRESENTATION WILL COVER, PRIMARILY, ADIABATIC CHARGING TEST RESULTS

- DETAILS OF OTHER TEST RESULTS WILL BE REPORTED IN THE FUTURE.

The overall AXAF-I battery test program, which is continuing, addresses several aspects of prelaunch battery management including charging, top off charging, open circuit stand, and low rate trickle charging; all in an environment in which there is little or no cooling. Parametric testing in the adiabatic charge mode has been completed and is reported in this presentation. Other results will be reported in the future.

TEST PLAN

- PROOF OF CONCEPT: DEMONSTRATE ADIABATIC CHARGE CAPABILITY
  - CHARGE RATE: C/5, C/10, C/15, C/20
  - INITIAL TEMPERATURE: 55° F, 65° F, 75° F
  - RUN WITH RNH 65-5 CELLS (ON LOAN FROM EPI) WHICH ARE SIMILAR IN DESIGN TO THE AXAF-I BASELINE CELL
- PARAMETRIC TEST: CONFIRMATION AND DATA BASE DEVELOPMENT
  - CHARGE RATE: C/5, C/8, C/10, C/15
  - INITIAL TEMPERATURE: 60° F, 65° F, 70° F, 75° F
  - RUN WITH FLIGHT CONFIGURATION RNH 30-9 CELLS

Adiabatic charging was addressed in a series of three tests.

A proof of concept test was run to demonstrate the feasibility of the approach. The test was run on RNH 65-5 cells which were loaned to us by Eagle Picher Industries. During the test, the thermal environment (e.g., adiabatic), the cell design, and the final charge temperature were fixed. Therefore the major test variables impacting charge acceptance were charge rate and initial charge temperature. Charge rate was varied over the range C/5 to C/20 which includes the lowest and highest rates deemed practicable during prelaunch activities. The initial-temperature range was constrained, at the low end by dew point considerations in the prelaunch environment, and at the high end by the fixed final charge temperature.

A parametric test was next run to validate the results of the proof of concept test and to provide a quantitative parametric data base. Test articles were flight configuration RNH 30-9 cells. The charge rate and initial charge temperature variable ranges were based on analysis of the proof of concept test results.

TEST PLAN CONT'D

- MISSION SIMULATION TEST
  - PRE-POST LAUNCH SCENARIO SIMULATION TESTING WAS PERFORMED AS PART OF A TOTAL MISSION SIMULATION TEST AT MSFC
  - THE POSTULATED SEQUENCE INCLUDED
    - = ADIABATIC CHARGING
    - = OPEN CIRCUIT STAND
    - = ADIABATIC TOP OFF
    - = C/500 RATE TRICKLE CHARGE
    - = DISCHARGE

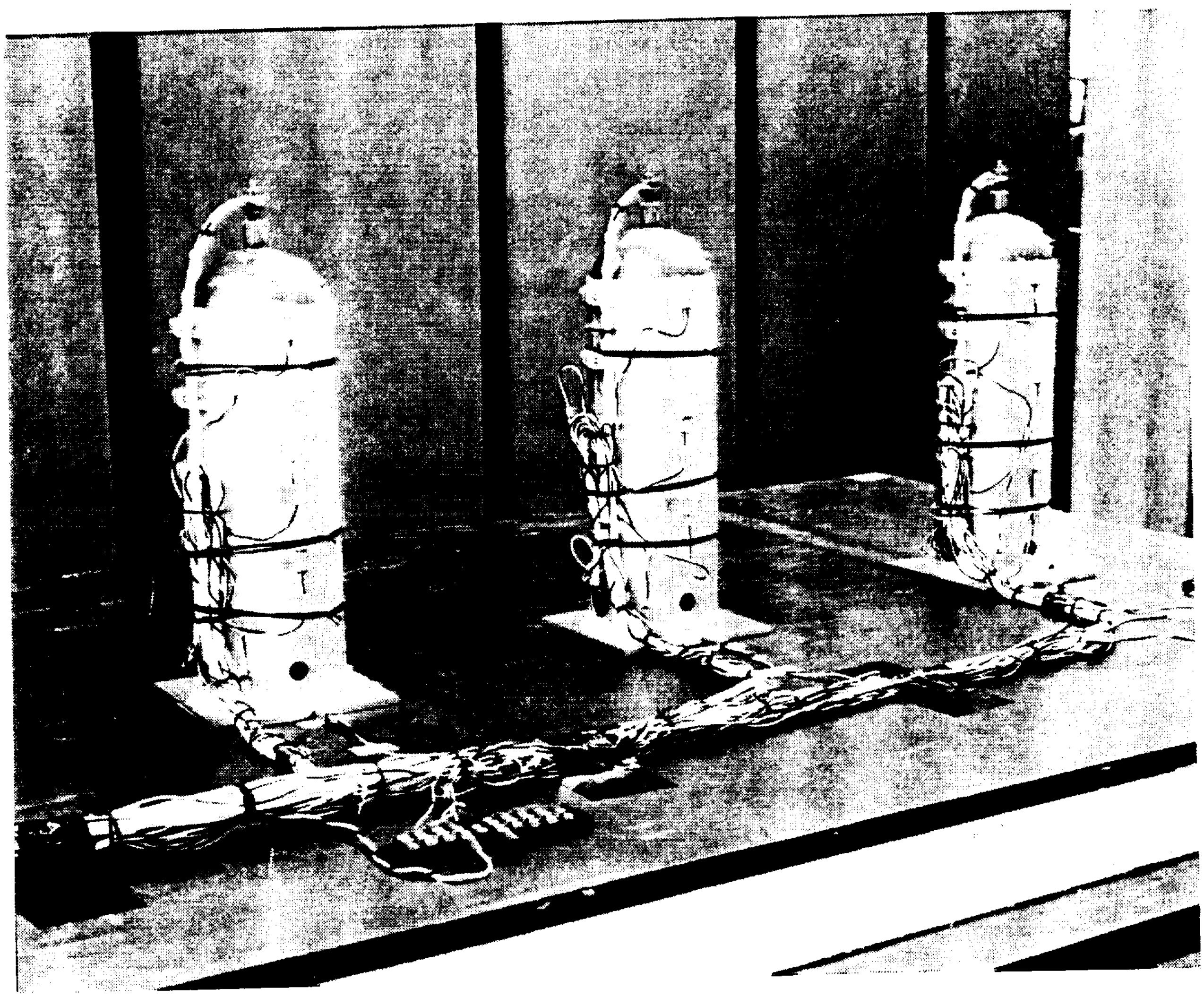
An AXAF-I mission simulation test is being run at MSFC. The test includes battery operation in a postulated pre-post launch scenario, as well as operation simulating on orbit cycling. Results obtained during operation in the simulated pre-post launch scenario are reported in this presentation.

TEST ARTICLES

CELL PART NUMBER	RNH 65-5	RNH 30-9
RATED CAPACITY (Ah)	65	30
STACK CONFIGURATION	BACK-TO-BACK	BACK-TO-BACK
POSITIVE ELECTRODE	0.030", SLURRY	0.030", SLURRY
SEPARATOR	ZIRCAR, 2 LAYERS	ZIRCAR, 2 LAYERS
ELECTROLYTE (%, FINAL)	31	31
OPERATING PRESSURE (psi)	800	475
STRAIN GAUGE	YES	YES
TERMINAL CONFIGURATION	AXIAL	AXIAL
WEIGHT (gms)	1815	1010
PRECHARGE	POSITIVE	POSITIVE

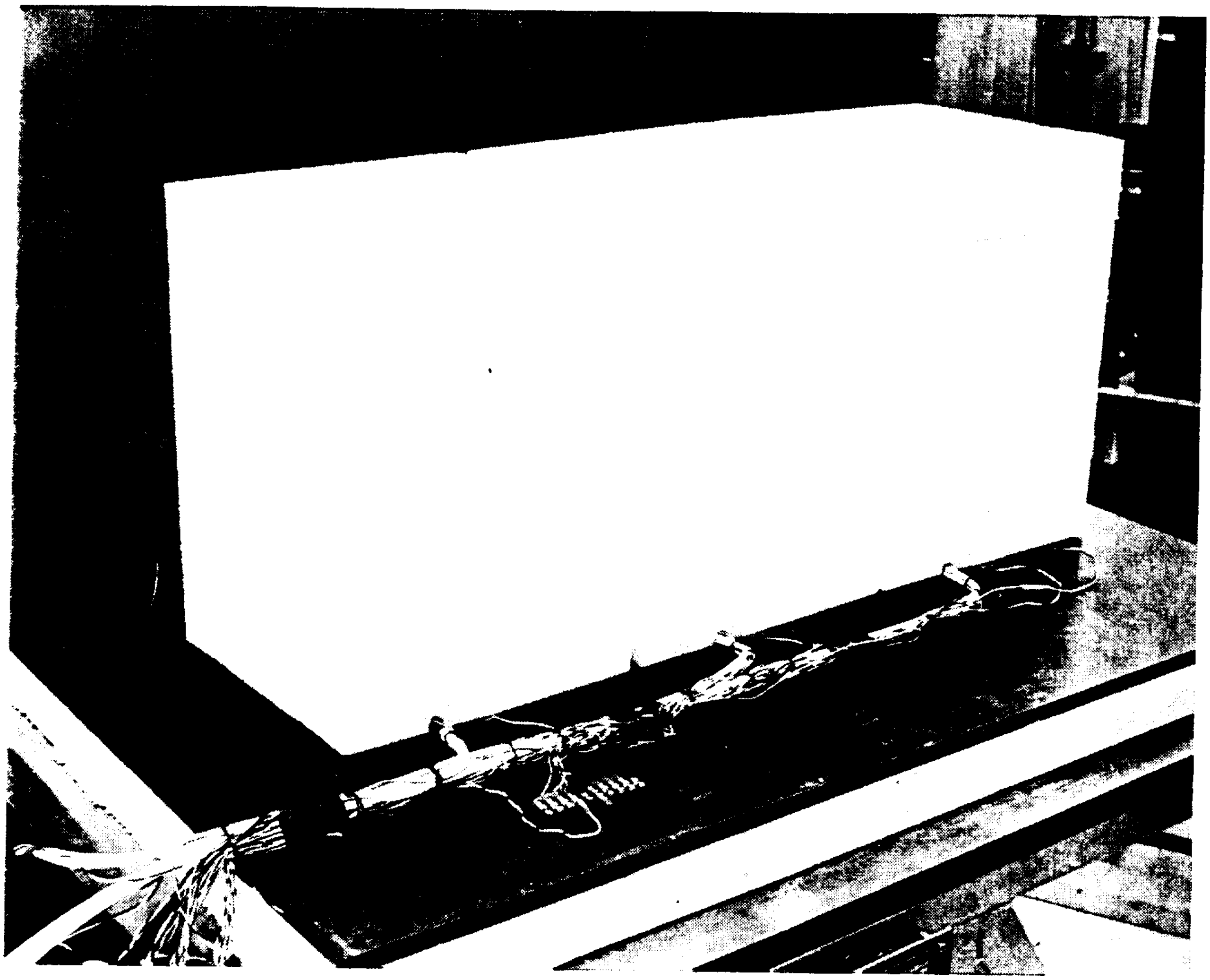
The 30 Ah and 65 Ah cell designs differ only in capacity, weight/dimensions, and pressure. Electrode stack components, configuration, and electrolyte are identical.

TEST CELLS
ON COLD PLATE



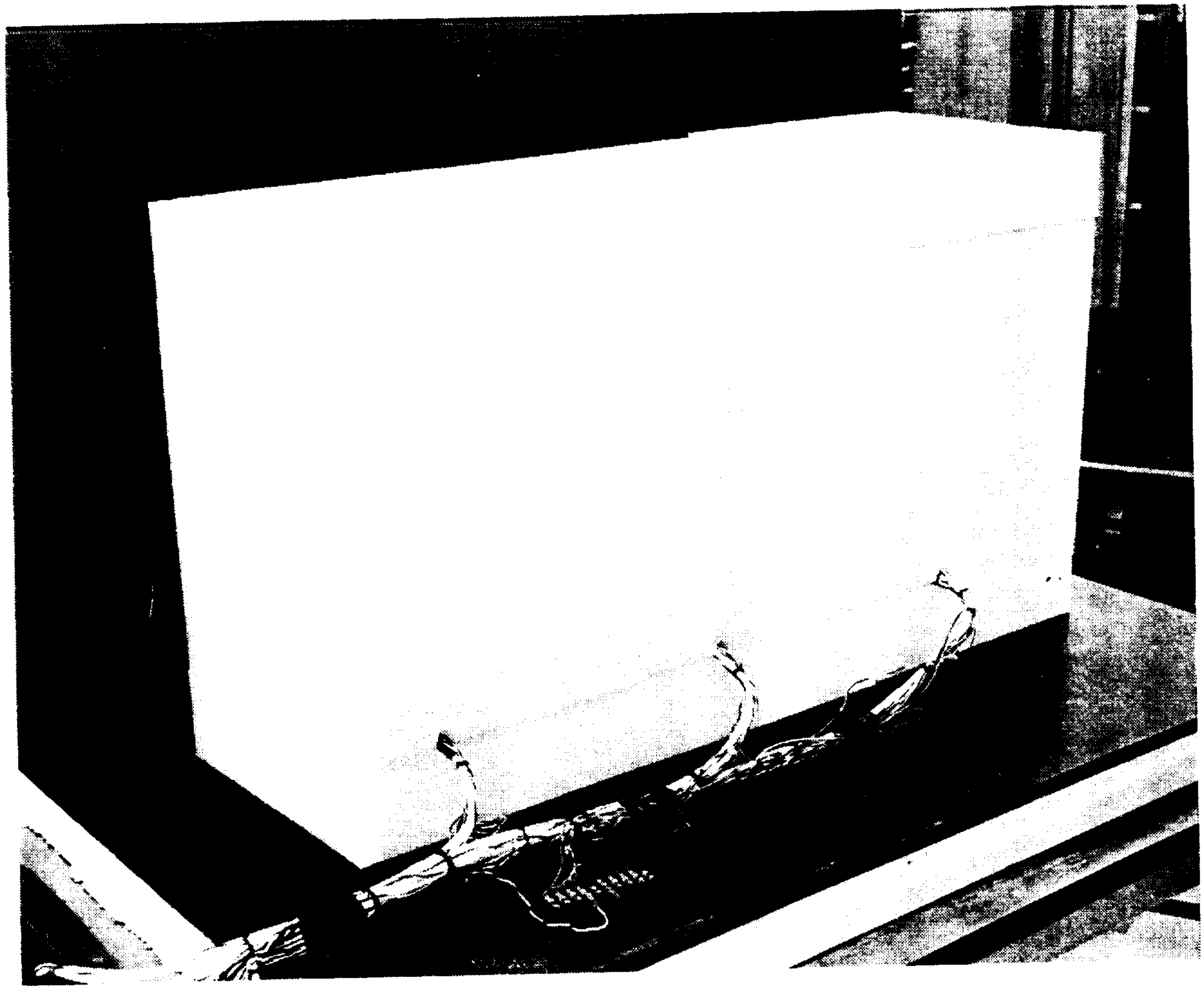
Individual cell instrumentation includes strain gauges for pressure measurement and thermistors at five locations from the top of the thermal sleeve to the sleeve base. In the configuration shown the sleeves are mounted directly to a thermally controlled cold plate. Ambient air and cold plate temperatures are also measured. Cell voltage, current, and pressure, as well as all temperatures are logged automatically. Data logging frequency is controlled by a slope sensing algorithm that increases the data logging frequency as the voltage and/or temperature rates of change increase.

INSULATED TEST CELLS
HEAT REJECTION TO COLD PLATE



In the configuration shown the cell sleeve base remains in contact with the cold plate and the remainder the cell-thermal sleeve assembly is insulated with three inch thick Ethafoam insulation. This configuration was used for all discharges.

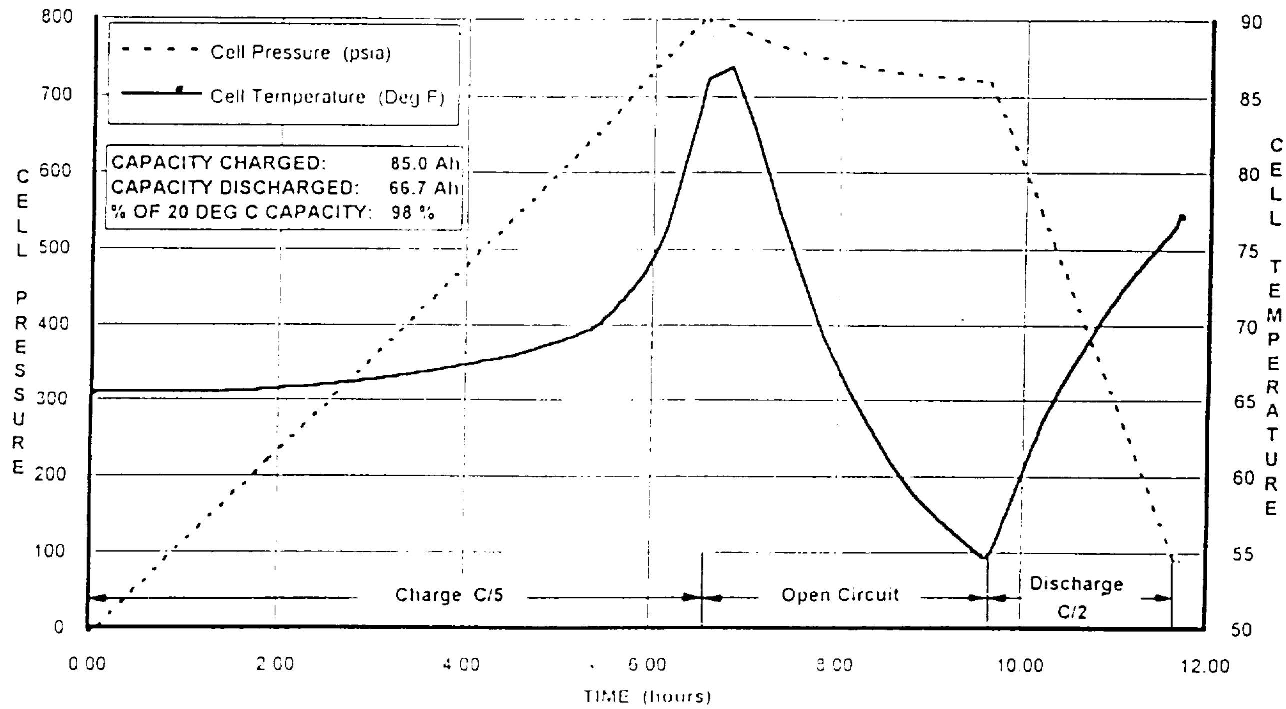
INSULATED TEST CELLS
ADIABATIC OPERATION



This configuration is similar to the previous one except that Ethafoam insulation is added between the sleeve base and the cold plate. The cell is thermally isolated. This configuration was used for all adiabatic operations.

TYPICAL ADIABATIC CHARGE

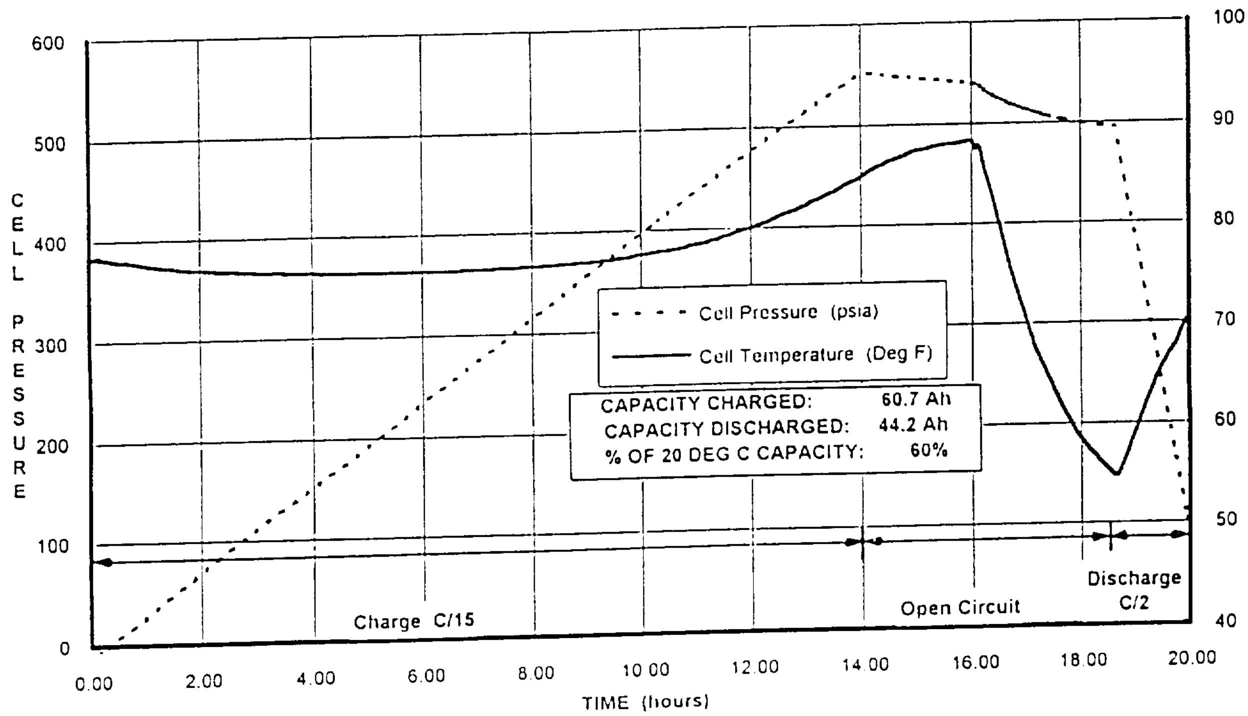
65° F, C/5 CHARGE RATE



This chart shows typical data logged during an adiabatic charge. Charge acceptance is tracked using cell pressure. The final discharge capacity is in excellent agreement with the capacity derived from pressure data. Charging was terminated at 85° F and overshoot took it to 87° F. The test configuration was changed from the fully-insulated cell to the configuration in which the baseplate is in contact with the cold plate. The cell was then cooled to 55° F and a standard C/2 discharge to 1.0 volt performed. The capacity discharged, 66.7 Ah, is 98% of the capacity recovered during a 68° F standard capacity cycle (16 hour C/10 charge at 68 ± 5° F, C/2 discharge to 1.0 volt.) The recharge ratio, calculated as capacity charged divided by capacity discharged, is 1.27, which is acceptable for the small number of cycles occurring during prelaunch activities.

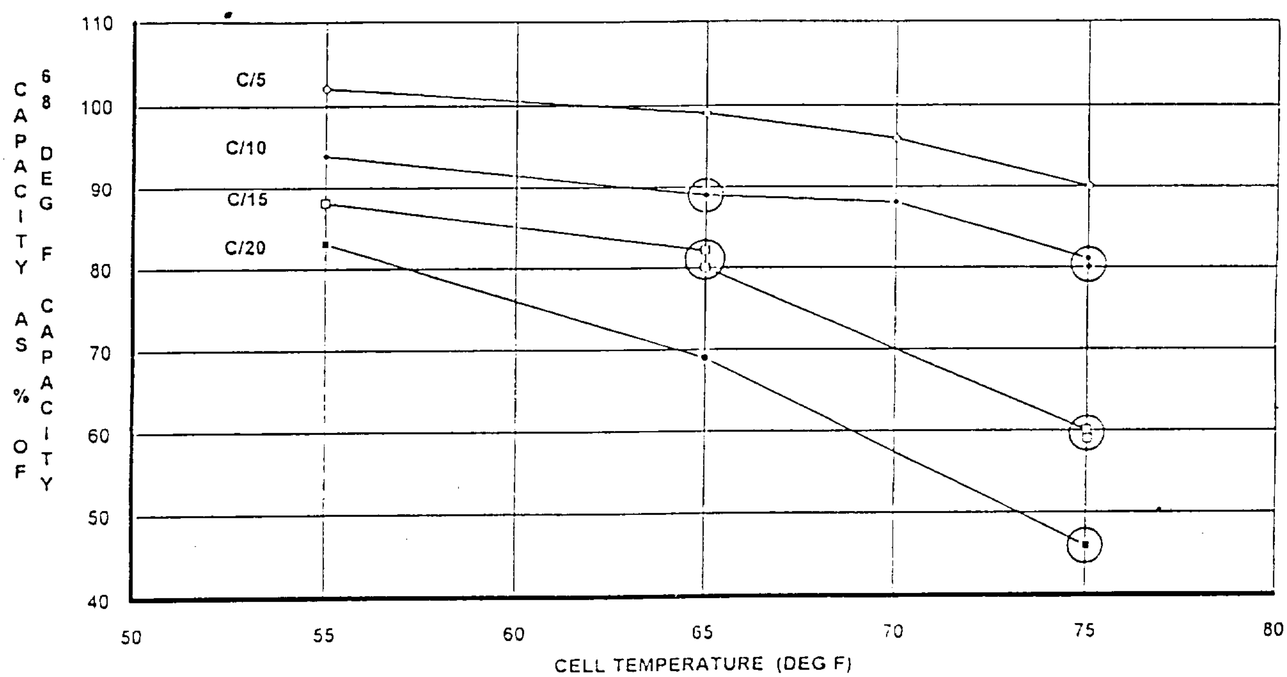
TYPICAL ADIABATIC CHARGE

75° F, C/15 CHARGE RATE



The cycle shown on this chart is similar to the previous cycle except that the adiabatic charge was performed at 75° F and a C/15 charge rate. These are less efficient conditions and the capacity discharged, 44.2 Ah, is significantly lower than the 66.7 Ah recovered at the more efficient charge conditions of 65° F and a C/5 charge rate shown on the previous chart. Charge insertion was 60.7 Ah and the recharge ratio 1.37. Comparison with the previous chart indicates that, at 75° F and a charge rate of C/15, less charge is inserted and utilization of that charge is less efficient.

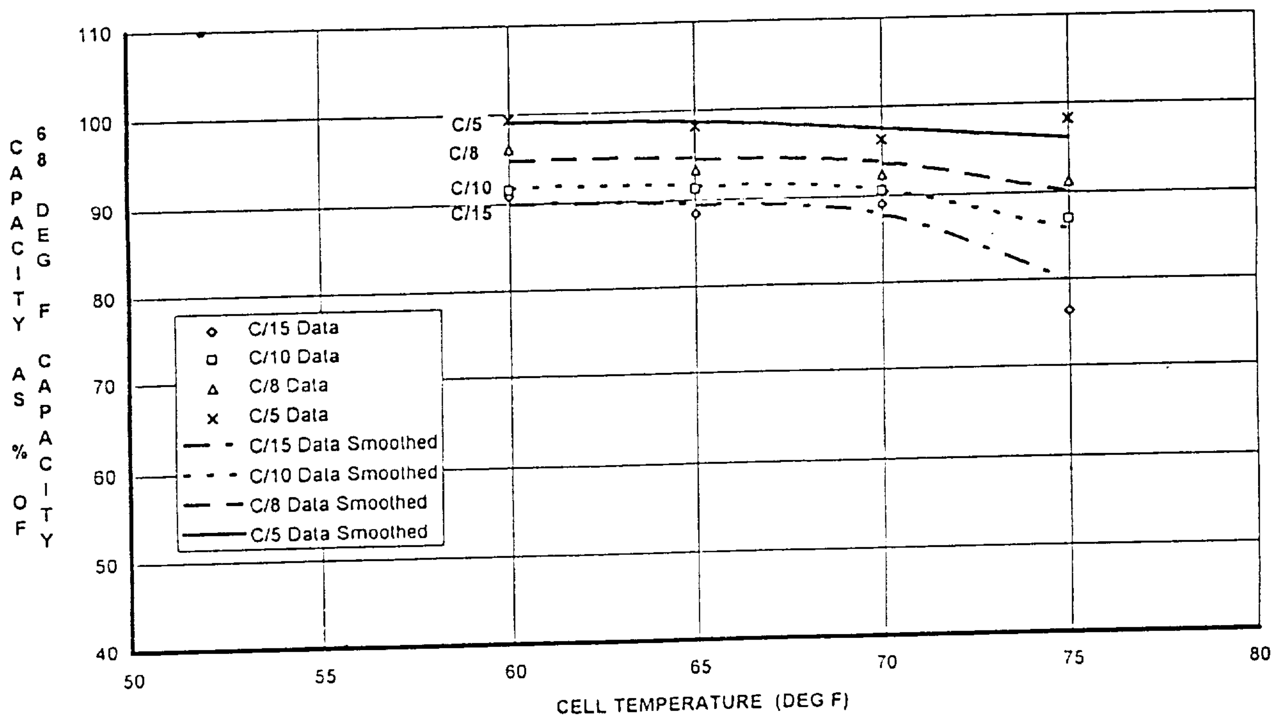
CAPACITY EXPRESSED AS % OF 68 DEG F STANDARD CAPACITY 65 AH CELLS



Adiabatic charge results obtained with the 65 Ah cells are summarized as a family of curves showing the relationship between capacity, initial cell temperature, and charge rate. Capacity is expressed as per cent of standard 68° F capacity to allow comparison of cell lots with differing actual capacities. The circles indicate replicated data points.

These curves demonstrate that good charge acceptance is achieved, during adiabatic charging, provided charge parameters are maintained in efficient ranges.

CAPACITY EXPRESSED AS % OF 68 DEG F STANDARD CAPACITY 30 AH CELLS



The adiabatic charge results obtained with the 30 Ah cells are summarized similarly and may be compared with the 65 Ah cell results. At conditions providing efficient charging, e.g., low initial cell temperature and high charge rate, the two sets of results are similar. However, when charge efficiency is lower, e.g., at higher initial temperatures and lower charge rates, the 30 Ah cells provide significantly higher relative capacities than the 65 Ah cells when both are charged adiabatically at the same conditions. The difference is attributed to the lower specific energy of the 30 Ah cell.

ADIABATIC CHARGE
EFFECT OF THERMAL MASS

- THE ADIABATIC CHARGE APPROACH WORKS BECAUSE THE BATTERY ABSORBS THE HEAT DISSIPATED AS THE CELLS GO INTO OVERCHARGE

- FOR A GIVEN DISSIPATION RATE: THE GREATER THE CELL MASS THE GREATER THE TOTAL CHARGE BEFORE THE CELL GETS TOO HOT TO CHARGE EFFICIENTLY

- THE DIFFERENCES IN ADIABATIC CHARGE ACCEPTANCE, BETWEEN THE 65 Ah and 30 Ah CELLS, CAN BE EXPLAINED BY THE RELATIONSHIP BETWEEN CELL WEIGHT AND CAPACITY, FOR THE 65 Ah AND 30 Ah CELLS

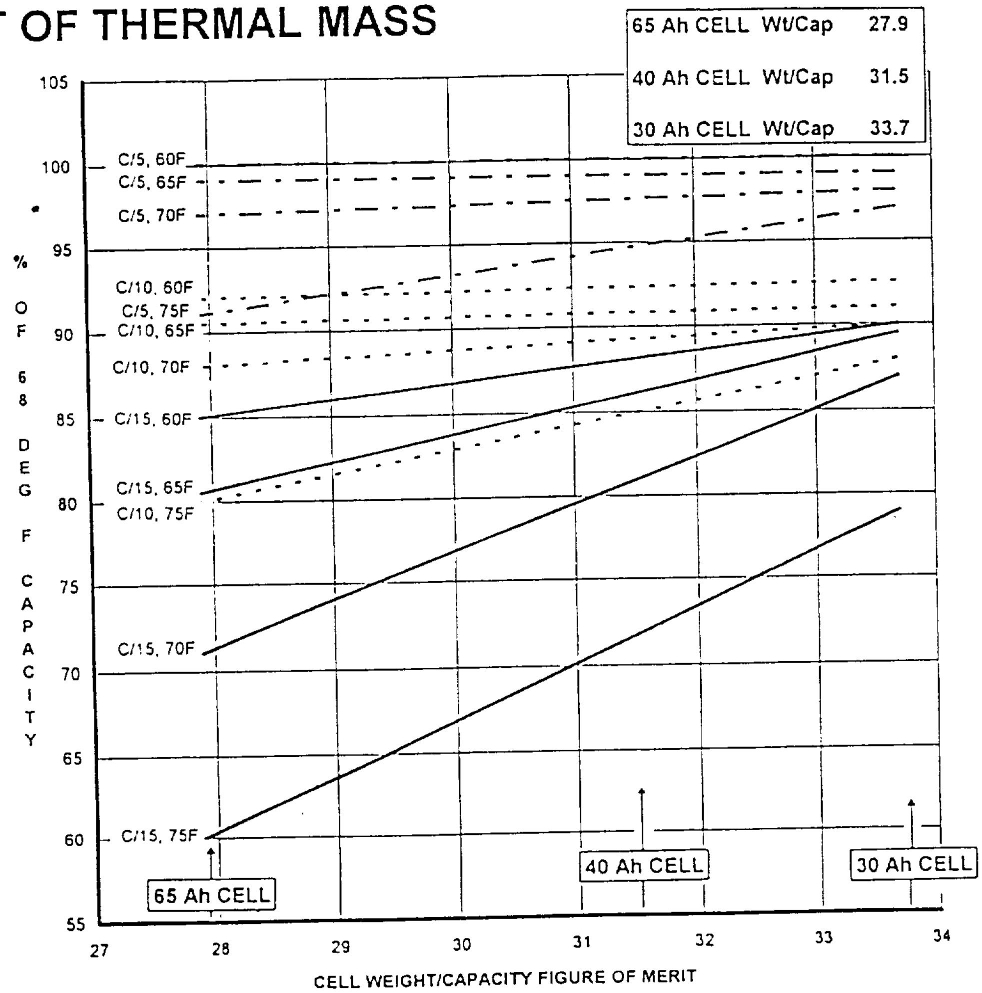
- CELL WEIGHT DIVIDED BY CAPACITY IS A CONVENIENT FIGURE OF MERIT TO COMPARE ADIABATIC CHARGE ACCEPTANCE RESULTS

$$\text{FIGURE OF MERIT} = \frac{\text{CELL WEIGHT}}{\text{CAPACITY}} \quad \frac{\text{gms}}{\text{Ah}}$$

Because of its small size the 30 Ah cell is packaged less efficiently than the 65 Ah cell. The low operating pressure, 475 psi, is the maximum practical with this size and design. Another consequence of the difference in packaging efficiency is the difference in specific energy; 36 Wh/Kg for the 30 Ah cell and 43 Wh/Kg for the 65 Ah cell.

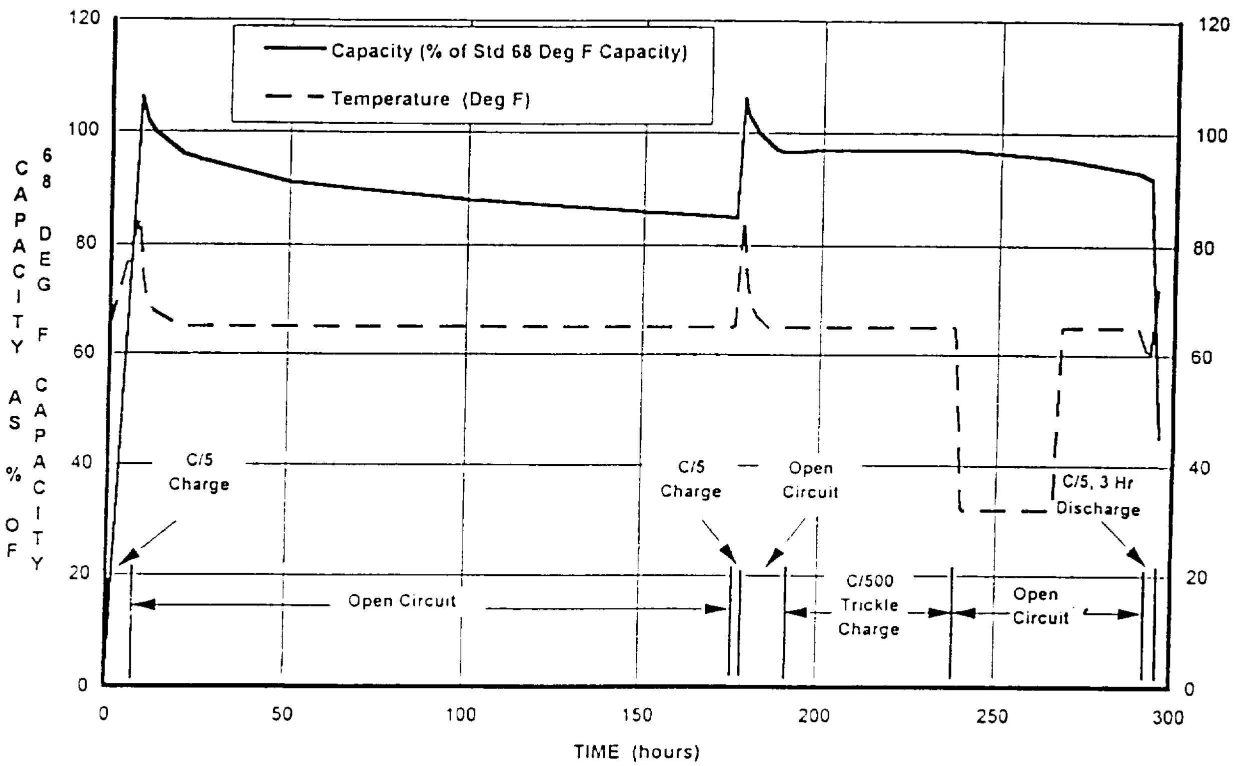
For a specific cell capacity and a given set of adiabatic charge conditions: the larger the cell mass the more charge accepted before reaching the charge termination temperature.

ADIABATIC CHARGE
EFFECT OF THERMAL MASS



Capacity, expressed as per cent of standard 68° F capacity, is plotted against the cell weight/cell capacity figure of merit for initial charge temperatures of 60° F, 65° F, 70° F, and 75° F, and charge rates of C/5, C/10, and C/15. The data is displayed as three sets of curves, one set for each charge rate. Each of the sets of curves consists of four individual curves, one for each initial charge temperature. Inspection of these curves indicates that the impact of the cell weight/cell capacity figure of merit on charge acceptance, in the adiabatic charge mode, is significant at conditions of low charge efficiency, and very small at conditions of high charge efficiency.

PRE-POST LAUNCH SCENARIO SIMULATION



Adiabatic charging was integrated into a pre-post launch simulation to validate the approach in a mission related scenario. The test cells were charged, from a fully discharged condition, at the C/5 charge rate, with an initial charge temperature of 65° F. Following a one-week open circuit stand at 65° F, the cells were topped off adiabatically at the C/5 charge rate with an initial charge temperature of 65° F. The initial and post top off cell pressures are equal and, after correction for temperature and stored oxygen, the indicated capacities are in good agreement with parametric data base predictions. Following top off the cells were maintained on C/500 rate trickle charge until the simulated launch. The temperature was then decreased to 32° F and held at that temperature for one day. Cell temperature was increased to 65° F and decreased to 59° F as part of the launch simulation. The cells were then discharged at the C/5 rate. Observed capacities are in good agreement with pressure data.

CONCLUSION

NICKEL-HYDROGEN BATTERIES CAN ACHIEVE HIGH STATES OF CHARGE, IN THE ABSENCE OF COOLING, WHEN CHARGED USING THE "ADIABATIC CHARGING" APPROACH DESCRIBED.

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Alternate Charging Profiles for the Onboard Nickel Cadmium Batteries of the Explorer Platform/ Extreme Ultraviolet Explorer

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ABSTRACT

The Explorer Platform/ Extreme Ultraviolet Explorer (EP/EUVE) spacecraft power is provided by the Modular Power Subsystem (MPS) which contains three 50 ampere-hour Nickel Cadmium (NiCd) batteries. The batteries were fabricated by McDonnell Douglas Electronics Systems Company, with the cells fabricated by Gates Aerospace Batteries (GAB), Gainesville, Florida.

Shortly following launch, the battery performance characteristics showed similar signatures as the anomalous performance observed on both the Upper Atmosphere Research Satellite (UARS) and the Compton Gamma Ray Observatory (CGRO). This prompted the development and implementation of alternate charging profiles to optimize the spacecraft battery performance. The Flight Operations Team (FOT), under the direction of Goddard Space Flight Center's (GSFC) EP/EUVE Project and Space Power Applications Branch have monitored and managed battery performance through control of the battery Charge to Discharge (C/D) ratio and implementation of a Solar Array (SA) offset. This paper provides a brief overview of the EP/EUVE mission, the MPS, the FOT's battery management for achieving the alternate charging profile, and the observed spacecraft battery performance.

INTRODUCTION

The EP/EUVE spacecraft was designed, built, and managed by NASA, GSFC. EP/EUVE is operated by NASA and Loral AeroSys with the primary payload, the Extreme Ultraviolet Explorer (EUVE), operated by the University of California at Berkeley. The Explorer Platform (EP) spacecraft design was based on the Multimission Modular Spacecraft (MMS). The platform can support a variety of remote sensing, Low-Earth-Orbit (LEO) missions requiring solar, stellar, or earth pointing missions. The EP provides a space based platform from which the explorer class instruments and equipment can be remotely exchanged during Space Shuttle-based servicing missions. The MMS structure supports the Platform Equipment Deck (PED), which serves as the EP interface to the payload. The payload module, currently EUVE, is mounted on the PED and the

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mission-unique equipment has been placed within removable PED modules. When EP was integrated with its payload module, EUVE, it became the mission-unique EP/EUVE satellite.

The EP/EUVE spacecraft was launched on a Delta II Expendable Launch Vehicle (ELV) from Cape Canaveral Air Force Station, Florida on June 7, 1992 into a circular orbit 528 km in altitude with an inclination of 28 degrees. The EUVE is a LEO astronomical survey mission that has produced the first definitive sky map and catalog in the portion of the electromagnetic spectrum that extends from approximately 100 to 1000 angstroms. Scientifically, the mission includes three objectives, all-sky survey, deep survey and spectroscopy. The all-sky survey and deep surveys were performed concurrently during the first 6 months of the mission and completed in January, 1993 with gap filling completed in July, 1993. The balance of the EUVE mission is being used for additional spectroscopy experiments.

During the two spacecraft modes of operation, the spacecraft orientation is defined as follows. In survey mode, the spacecraft maintains a constant rotation of 0.18914 +/- .00005 degrees per second. In spectroscopy mode the spacecraft will be inertially fixed such that the spacecraft is pointed within the design constraints of 0 to 110 degrees with respect to the $-X_{acs}$ axis and +/- 33 degrees with respect to the Command and Data Handling (C&DH) roll axis.

MODULAR POWER SUBSYSTEM

The EP/EUVE MPS is comprised of all the power control, distribution, regulation, provision, and other power-related hardware. This includes the McDonnell Douglas MPS and the two Solarex solar arrays. Figure 1 illustrates the subsystem interfaces.

The functions of the EP/EUVE major power subsystem components are presented in Table 1.

Table 1: EP/EUVE Major Power Subsystem Components

Power Subsystem Component	Function
Bus Protection Assembly (BPA)	Fusing of internal MPS loads
50 Ampere Hour Batteries (3)	Energy storage
Power Control Unit (PCU)	Power distribution
Remote Interface Unit (RIU) (2)	Command & Data Handling interface
Signal Conditioning Assembly (SCA)	Command and telemetry conditioning
Solar Arrays (2)	Energy conversion
Solar Array Drives (2)	Maintains solar array position as determined by the Solar Array Drive (SAD) flight software and commanded by the Solar Array Drive Electronics (SADE)
Solar Array Drive Electronics (2)	Monitors and commands the SAD movement as determined by the SAD flight software or ground issued commands
Standard Power Regulator Unit (SPRU)	Battery charge control
Thermal Control Subsystem	Battery system thermal regulation

The batteries onboard the EP/EUVE spacecraft are three 50 amp-hour conventional NiCd batteries in parallel configuration. Each battery contains 22 serially connected cells. The plates were fabricated at GAB during the 1/85 to 5/85 time period. The cells were activated in March 1988.

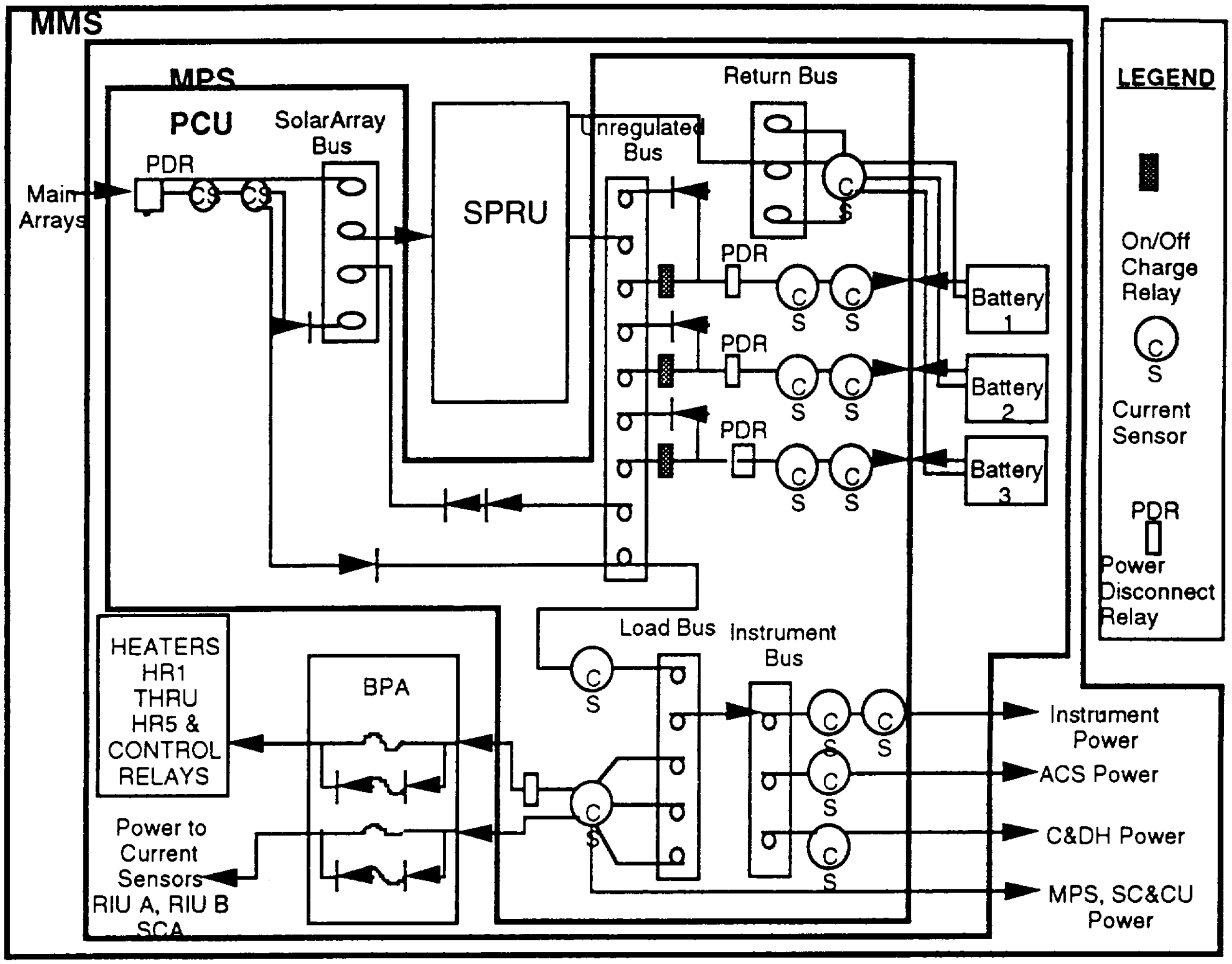

Figure 1: EP/EUVE Power Block Diagram

POWER SUBSYSTEM OPERATIONS

The MPS operations have evolved on-orbit to rely heavily on various SPRU modes of operation. The modes of SPRU operation are discussed in Table 2.

EARLY MISSION OPERATIONS

At launch, the Voltage Limit Mode of SPRU was set at V/T level 5; however, the level was commanded to V/T level 4 on launch day based on the observed high average C/D ratio values (1.286, 1.241 and 1.224 for batteries 1, 2 and 3, respectively). The level was later lowered to V/T level 3 on May 5, 1993 to further reduce the C/D ratio.

Thermostat control was also implemented during early mission operations. MPS battery temperature regulation was implemented to maintain a specific battery temperature operating range greater than the thermistor set points for the battery heater controls. This can be performed on the EP spacecraft because the MPS configuration includes an externally mounted heat pipe implementation that maintains a stable thermal environment between all three batteries. Current operation maintains a battery baseplate temperature of greater than 5 degrees C and less than 8 degrees C. This temperature range is maintained through Onboard Computer (OBC) Telemetry Monitor (TMON) control. The original operational implementation was introduced on September

8, 1992 based on a temperature goal of 2 degrees C. This goal was changed, in steps, to the current operational temperature range on October 23, 1992. The battery temperature trends for the length of the mission is presented in Figure 2. This thermostat control showed no appreciable impact on the battery charge profile.

Table 2: SPRU Modes of Operation

SPRU Modes of Operation	
Standby Mode	The MPS power is supplied by the batteries due to no available solar array power. The SPRU is able to receive commands and retains a memory of its last commanded state in this mode.
Peak Power Tracking Mode	The maximum SA output power point will be maintained to provide all available power to the spacecraft load and recharging the batteries until the Voltage-Temperature (V/T) set point is reached or the constant current mode is enabled.
Voltage Limit Mode	The battery voltage limit is determined by one of the eight commandable NASA standard V/T limits. When the battery terminal voltage rises to the limit, the battery current is reduced to a taper profile.
Current Limit Mode	The current limit is an externally commanded mode which limits the total battery charge current to one of the three selectable levels, 0.75 amps, 1.5 amps or 3.0 amps.
Safe Mode	In the event of three consecutive pulses being missed to the MPS Computer Status Monitor (CSM), the SPRU will be commanded to the appropriate V/T level based on the selected V/T level (currently V/T level 1). No external commanding will be allowed to the SPRU until the CSM has been disabled.

CURRENT POWER OPERATIONS

The C/D ratio and the net overcharge of all three batteries remained higher than recommended for the batteries. This is due in part to the small loading requirements of the spacecraft and the large size of the SAs. Because the arrays were designed to support a 10-year Platform mission life integrated with EUVE and a variety of follow-on Explorer class Instruments, the available power to the payload was budgeted at 300 watts for an orbital average with peaks of 1000 watts. On-orbit EUVE payload power needs, however, have been an orbital average of 200 watts with peaks of 300 watts during both spectroscopy and survey modes.

The FOT currently utilizes three of the SPRU modes - the constant current mode, the peak power track mode and the voltage limited mode, on an orbital basis for nominal battery operations. These standard operational procedures for a single EP/EUVE orbit are presented in Figure 3.

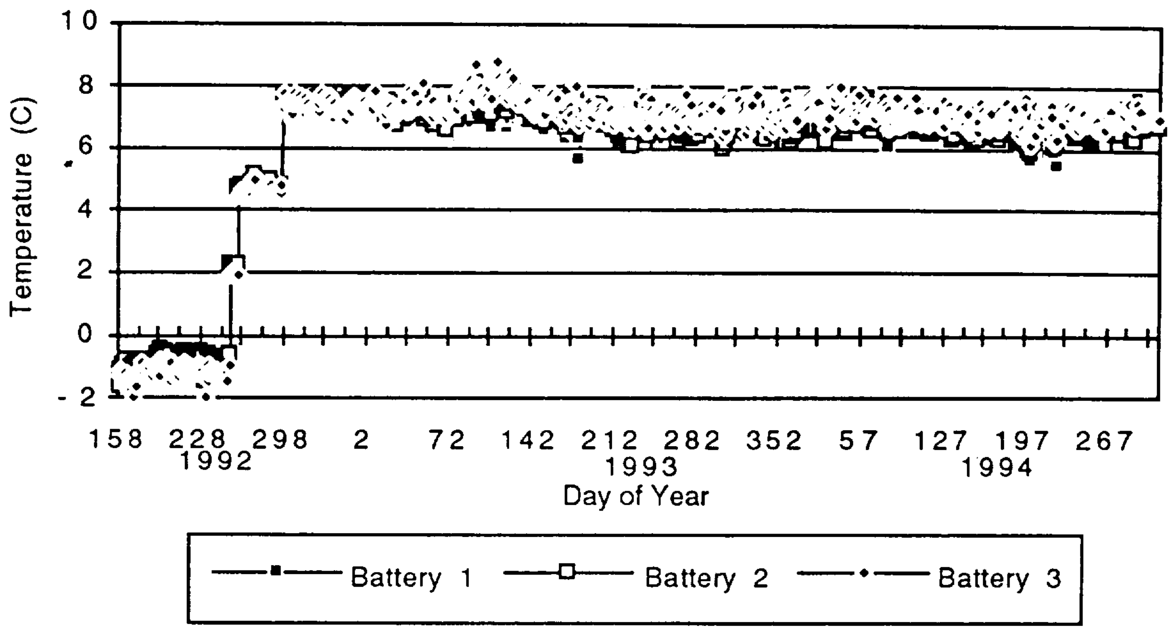

Figure 2: Mean Battery Temperatures for the Mission Life

Constant Current Mode at Orbital Sunrise

Constant Current Mode (CCM) at Orbital Sunrise (OS) was implemented to regulate the high battery charge current from the SAs when the arrays are cold. The operational goal has been about 20 amps. The onboard implementation uses the OBC Orbital Time Processor (OTP) flag 6 to trip when the spacecraft to sun vector cosine is -0.5 corresponding to an angle of 120 degrees. This equates to approximately 2 minutes prior to spacecraft day. The flag executes a Relative Time Sequence (RTS) that commands the SPRU to 3.0 amp CCM at orbital sunrise then returning the SPRU to V/T control approximately 10 minutes into day.

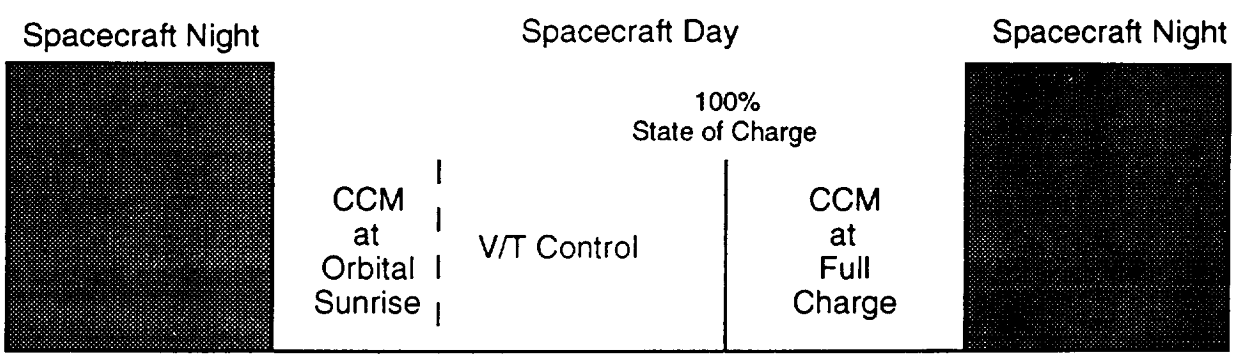

Figure 3: Standard EP/EUVE Orbital Battery Management

Constant Current Mode at Full Charge

CCM at full charge was implemented to minimize the batteries overcharge. Proactive steps have been taken to maintain a ground minus CCM calculated C/D ratio goal range of 1.02 to 1.07 and hence minimize the batteries overcharge. In this implementation, the SPRU commands 0.75 amp

CCM to maintain a trickle charge on the batteries while still in spacecraft day after the C/D ratio goal has been reached as determined through TMON sampling of the battery state of charge. The C/D Ratio goal is based on the assumption that when the battery reaches 100 percent state of charge at a specified 0.98 Power Monitor (PMON) processor battery charge efficiency, the C/D ratios approximate 1.02.

PMON battery efficiency changes

The PMON battery efficiency changes were implemented to stabilize the End-of-Night Load Bus Voltage (ENLBV), which was decreasing during extended maximum eclipse period. The PMON battery efficiency is decreased by 0.01 during the maximum eclipse period to allow additional charge on to the batteries while marginally increasing the C/D ratio by 1 percent. The CCM at full charge target C/D ratio may be changed by changing the Battery 1, 2, and 3 charge efficiencies in the PMON processor via OBC system table load. This is routinely being performed by changing the target C/D ratio. The efficiency is set to 0.97 for spacecraft eclipse periods of greater than 34.5 minutes and set to 0.98 for eclipse periods less than 34.5 minutes. The PMON efficiency changes are presented with the length of spacecraft day in Figure 4.

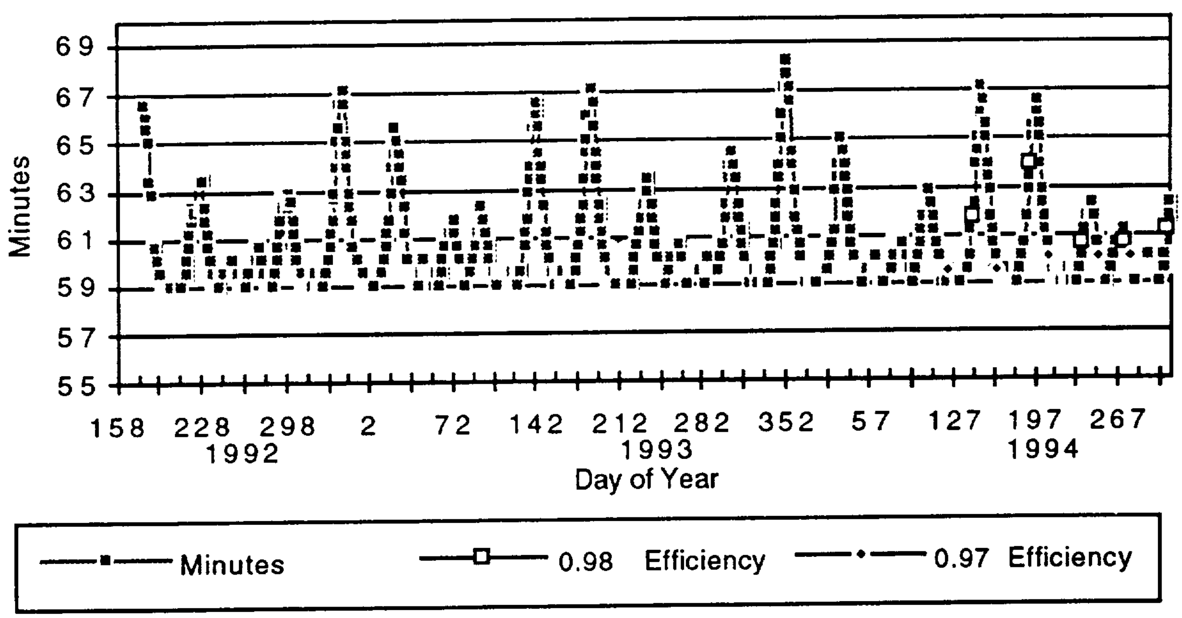

Figure 4: Length of Spacecraft Day for the Mission Life

Solar Array Offset

The SADs remained powered off during the first 13 months of the EP/EUVE mission, In-Orbit Checkout (IOC), survey, and 6 months of inertial point mode. Then, following the completion of the gap fill-in portion of the all sky survey in July 1993, the SADs were validated during a mini-IOC. Two SA hardware limitations, specular reflection and an Extra Vehicular Activity (EVA) handrail, were identified during the validation. The spacecraft body, specifically the Signal Conditioning and Control Unit (SC&CU), reflects sunlight onto the solar array panel 1. This causes heating of the panel in the vicinity of thermistor 3 to the solar panel red high temperature qualification limit, 114 degrees C. Additionally, an EVA handle prevents the movement of solar array 2 past 83 degrees -X_{acs} limiting the range of possible SA motion. A flight software change has been implemented which will maintain the solar arrays at a table-defined offset. This flight software implementation repositions the SAs to the offset position, currently 40 degrees to avoid specular reflection, taking into account the EVA handrail limitations, when the spacecraft slews to a new target. The change in the spacecraft attitude may be seen in the effective solar array offset (figure 5)..

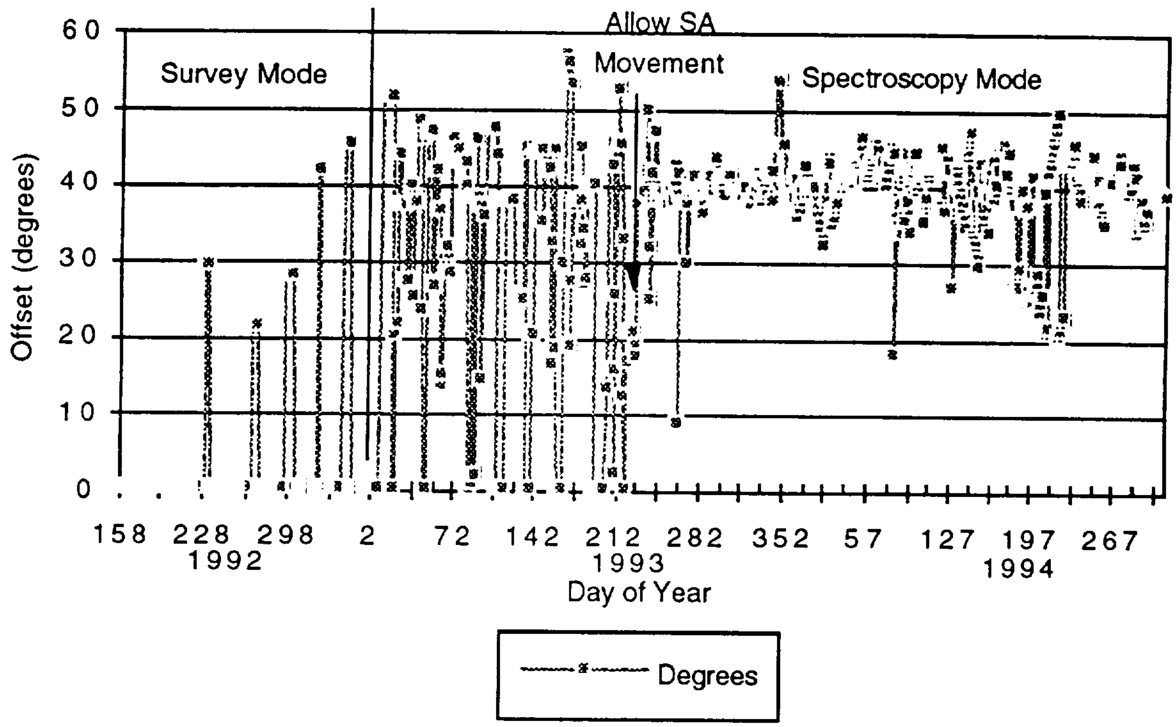

Figure 5: Effective Solar Array Offset for the Mission Life

DATA

With the implementation of CCM and SA offset management, the charge-to-discharge ratios have decreased for the length of the mission (figure 6). The average IOC C/D ratios (including CCM) of 1.08 to 1.09 in comparison with the current values of 1.06 to 1.07 showing an improvement of 2 percent for batteries 1 and 2 and of 1.5 percent for battery 3. The battery C/D ratios show stable in-family trending of high numbers during the survey portion of the mission with the SA position constantly normal to the sun. The C/D ratios diverged in January 1994 with the spacecraft transition to inertial point mode and the introduction of CCM at OS. During this mission phase, the SADs remained fixed, while the spacecraft changed pointing positions throughout the sky on a daily and sometimes orbital basis. This varied the effective SA offset to the sun from 0 to 55 degrees, and thus varied the available solar array current to the batteries. Two operational events, a deep discharge of the batteries (24.5%) on June 17, 1993 (DOY 168) and the implementation of a constant 40 degree SAD offset on August 6, 1994 (DOY 218), have contributed to the stable and lower C/D ratio values seen since June of 1993.

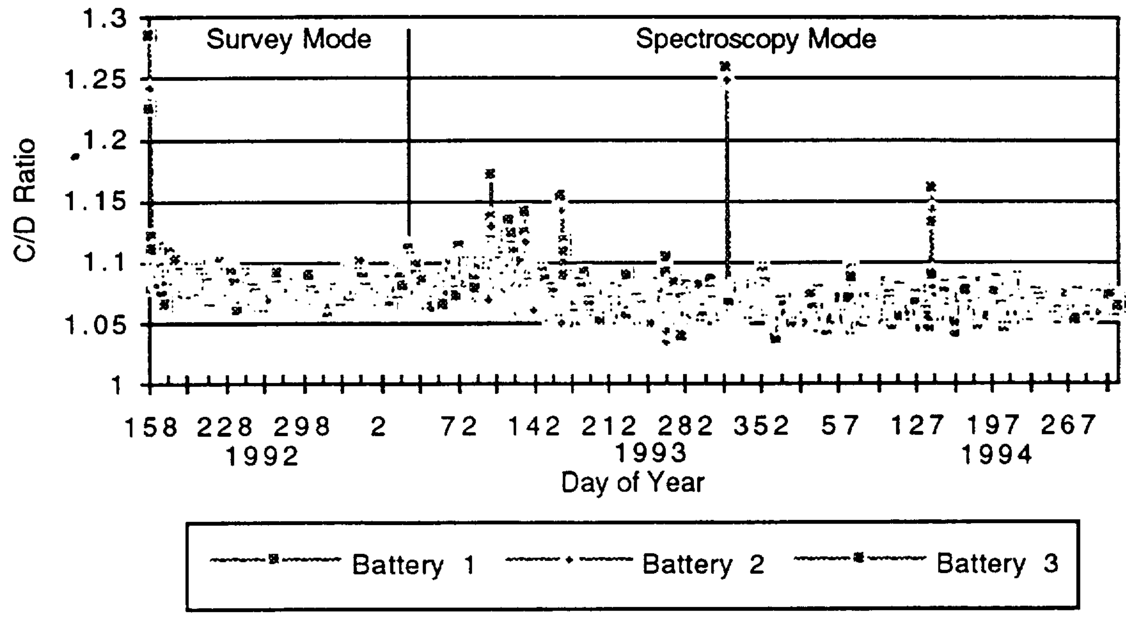

Figure 6: C/D Ratio for the Mission Life

Half battery differential voltages for batteries 1, 2, and 3 are presented in Figure 7. The battery differential voltages showed similar degraded features with all three batteries crossing zero as the spacecraft to inertial point mode. An improvement is evident in all three half battery differential voltages. The half battery differential voltages for battery 1 continues to near zero, while batteries 2 and 3 are approaching toward zero.

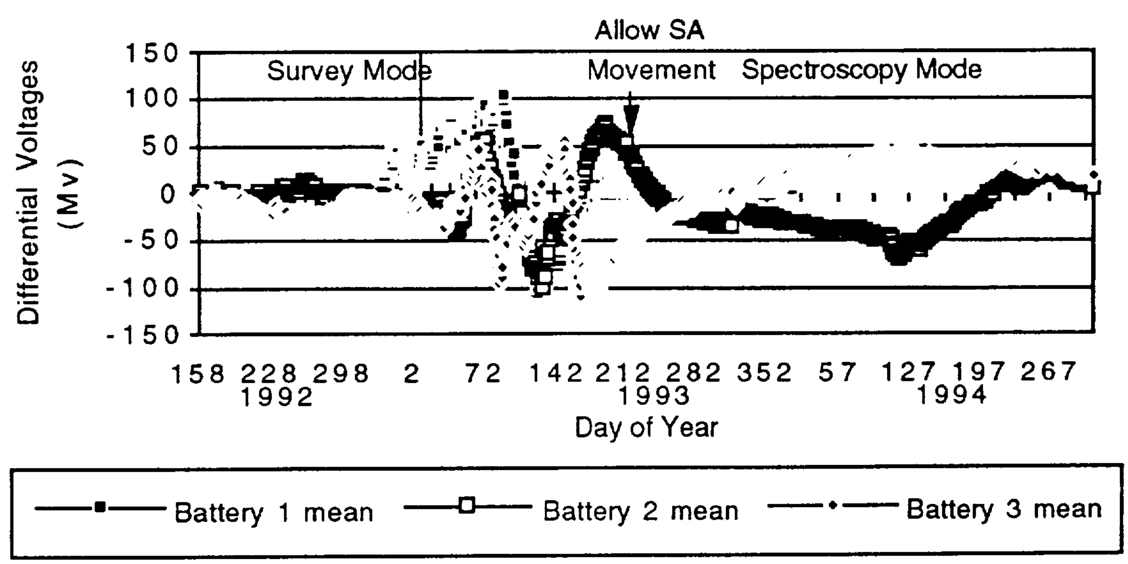

Figure 7: Half Battery Differential Voltages for the Mission Life

A significant improvement in the end-of night load bus voltage is apparent from Figure 8 for the last six months. The end-of-night load bus voltage has been approximately 26.88 volts for this period.

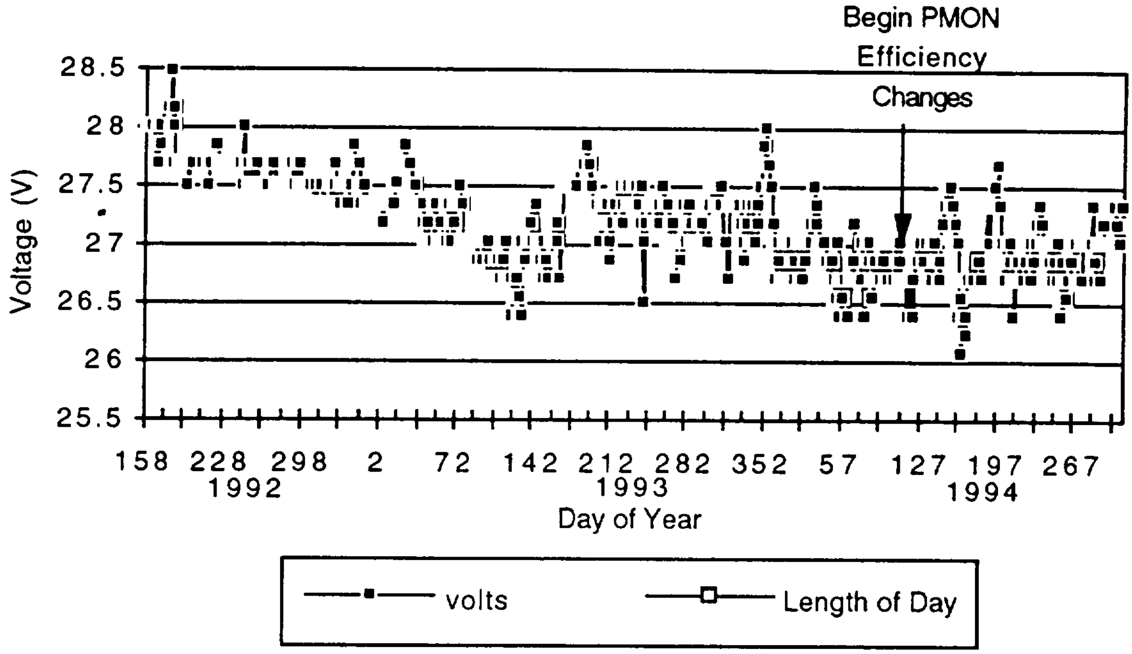

Figure 8: End-of-Night Load Bus Voltage for the Mission Life

CONCLUSIONS

The constant current mode implementation successfully limits the C/D ratio to a specified goal. This has been enhanced by the use of the battery efficiency change which allow the end of night load bus voltage to stabilize about 26.88 volts during periods of maximum eclipse. The 40 degree solar array offset maintains a battery current input between 13 amps and 20 amps. The implementation of the CCM charge control, PMON efficiency change, and the SA offset have optimized battery operation for the EP/EUVE spacecraft.

DATABASE FOR MANAGEMENT OF THE UPPER ATMOSPHERE RESEARCH SATELLITE'S BATTERIES

Presented to

1994 NASA AEROSPACE BATTERY WORKSHOP

By

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and

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November 15 - 17, 1994

BACKGROUND

- UPPER ATMOSPHERE RESEARCH SATELLITE (UARS) launched on space shuttle discovery on September 12, 1991 for a nominal 36-month mission
- 96-minute LEO orbit inclined 57 degrees to the equator (results in at least two full-sun periods per year)
- Spacecraft built by General Electric (now Martin Marietta) and incorporates Multimission Modular Spacecraft (MMS)

BACKGROUND - continued

- Maximum spacecraft load was projected as 1600 watts
- The MMS design utilizes the Modular Power Subsystem (MPS) built by McDonnell Douglas
- The MPS contains three NASA Standard 50 Ah Nickel Cadmium batteries in a parallel configuration
  - batteries contain 22 series-connected cells
  - battery instrumented to measure the voltage difference between the first 11 cells in series and the second 11 cells in series (differential voltage)
- The MPS also contains a NASA Standard Power Regulator Unit (SPRU) that employs NASA Standard VT levels and constant current modes for the charging of batteries

CHRONOLOGY

- 9/91. Power system configuration - VT 6 to 1.11 C/D ratio, then trip to VT 5
- 12/91: First full-sun period
- 1/92: Differential voltage on all three batteries becomes non-zero, exceeding 50 mV; switch to full-time use of VT 5
- 3/92: Differential voltages exceed 150 mV; switch to VT 4
- 4/92: Differential voltages exceed 300 mV

Raising VT level from 4 to 5 causes differential voltages to exceed 400 mV and temperature spread between battery 1 (inboard - facing earth) and battery 2 (outboard - facing space) diverged from nominal value of 3 °C to almost 8 °C

CHRONOLOGY - continued

- 4/92 (cont.) Return to VT 4 reduced spread in temperature; Battery heater thermostats bypassed to raise nominal battery temperatures ~4 °C, to a nominal value of 5 °C
- 5/92: Solar array drive anomalies caused Solar array to be parked at "spacecraft noon"; load partially shed as battery charging (and spacecraft operation) is temporarily altered to a cosine power curve
- 7/92: Solar array drive restarted; median value of battery differential voltages now different by as much as 500 mV from two months before

CHRONOLOGY - continued

- 8/92: Incorporation of Solar Array offset to limit charge currents at spacecraft sunrise below 25 amps per battery
- 12/92: Introduction of a deep conditioning discharge on batteries during full-sun periods - average DOD this first time was 31%; first use of VT 3 for shallow DOD periods
- 3/93: Introduction of the use of a constant current charge mode at the end of spacecraft day to control C/D ratio

CHRONOLOGY - continued

- **6/93: Second full-sun deep conditioning discharge**
  - Deep discharges were conducted on two consecutive days and approached 40% DOD on the second day
  - Artificial eclipses between 10% and 20% DOD were also accomplished on the days before and after the deep discharges
- **12/93: Third full-sun deep conditioning discharge**
  - Deep discharges were conducted on two consecutive days and approached 36% DOD on the second day
- **6/94: Fourth full-sun deep conditioning discharge**
  - Deep discharges were conducted on two consecutive days and approached 32% DOD on the second day

DATABASE

- Data accumulation began in April 1992 and continues to this day
- Data presented in this paper is limited to 1994
- The database consists of 27 ground-processed telemetry values and focuses on daily averages and/or daily ranges:
  1. Daily average Beta Angle (degrees)
  2. Daily average battery Net Charge (Amp-minutes) (3)
  3. Daily average battery discharge (Amp-minutes) (3)
  4. Daily maximum battery discharge (Amp-minutes) (3)
  5. Daily average C/D ratio (3)
  6. Daily maximum discharge current (Amps) (3)

DATABASE - continued

- Telemetry values (continued):
  7. Daily average end-of-night load bus voltage (V)
  8. Minimum battery differential voltage (mV) (3)
  9. Maximum battery differential voltage (mV) (3)
  10. Daily average battery temperature (°C) (3)
  11. Daily average maximum charge current (Amps)
- There are also 11 trend values derived from the ground-processed telemetry:
  12. Load-sharing differential between battery 1 and battery 2 (Amp-minutes - from daily average load and daily maximum load) (2)

DATABASE - continued

- Trend values (continued):
  13. Average battery depth of discharge (Amp-minutes - from daily average and daily maximum) (2)
  14. Median battery differential voltage (mV - average of daily max and daily min) (3)
  15. Differential voltage span (mV - difference between daily max and daily min) (3)
  16. Temperature spread between battery 1 & 2 (°C)
- All of the data is entered into an Excel© spread-sheet along with Day of year, Mission Day #, the VT level, the C/D ratio goal (if Constant Current Mode is being used) and operational "Notes"

Sample of UARS Flight Battery Database

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	MISSION DAY	YEAR	DOY	BETA	NET1	NET2	NET3	DISCHG1	DISCHG2	DISCHG3	D1-D2	AVGDOD	CD1
150	963	1994	121	29.9	19.2	5.2	14	517	476	484	41	16.4%	1.037
151	964	1994	122	32.3	17.5	3.2	12	510	469	477	41	16.2%	1.034
152	965	1994	123	34.5	13.8	0.9	9.4	513	462	476	51	16.1%	1.027
153	966	1994	124	36.3	24.2	11.4	19.6	500	453	466	47	15.8%	1.048
154	967	1994	125	37.8	26.4	10.4	19.3	482	455	459	27	15.5%	1.055
155	968	1994	126	38.9	27.2	10	19	478	451	456	27	15.4%	1.057
156	969	1994	127	39.5	27.6	9.9	18.8	475	448	453	27	15.3%	1.058
157	970	1994	128	39.8	27.3	8.9	17.9	477	448	453	29	15.3%	1.057
158	971	1994	129	39.5	25.5	7.3	16.2	496	457	468	39	15.8%	1.051
159	972	1994	130	38.9	27.7	8.5	17.9	520	479	491	41	16.6%	1.053
160	973	1994	131	37.8	29.7	9.5	19	519	482	492	37	16.6%	1.057
161	974	1994	132	36.3	30.3	9.7	19.2	522	485	495	37	16.7%	1.058
162	975	1994	133	34.4	30.5	9.7	19.3	529	493	502	36	16.9%	1.058
163	976	1994	134	32.2	31	9.9	19.4	533	497	506	36	17.1%	1.058
164	977	1994	135	29.7	30.1	9.1	18.7	544	507	517	37	17.4%	1.055
165	978	1994	136	27	29.8	9	18.6	554	516	527	38	17.7%	1.054
166	979	1994	137	24	28.4	7.4	17.1	564	525	536	39	18.1%	1.050
167	980	1994	138	20.9	37.5	13.1	22.8	570	526	539	44	18.2%	1.066
168	981	1994	139	17.5	30.6	6	15.9	545	513	518	32	17.5%	1.056
169	982	1994	140	14	31	8.5	18.1	541	508	514	33	17.4%	1.057
170	983	1994	141	10.4	30.4	7.7	17.8	549	514	522	35	17.6%	1.055
171	984	1994	142	6.7	31.4	8.7	18.6	555	520	527	35	17.8%	1.057
172	985	1994	143	2.4	32.7	11	20.6	550	514	521	36	17.6%	1.059
173	986	1994	144	1	34.1	9.7	19.2	525	495	498	30	16.9%	1.065
174	987	1994	145	5	33.2	9.4	19.2	552	518	524	34	17.7%	1.060
175	988	1994	146	9	32.3	8.1	18	547	513	520	34	17.6%	1.059
176	989	1994	147	13.1	31.9	8	18	544	509	516	35	17.4%	1.059
177	990	1994	148	17.2	33.9	8.8	18.5	538	503	510	35	17.2%	1.063
178	991	1994	149	21.4	34	8.4	17.8	534	498	505	36	17.1%	1.064
179	992	1994	150	25.6	35.5	9	18.4	524	490	496	34	16.8%	1.068
180	993	1994	151	29.2	30.9	3.4	12.7	508	475	480	33	16.3%	1.061
181	994	1994	152	34.1	29.2	7.5	15.2	479	440	450	39	15.2%	1.061
182	995	1994	153	38.3	29.5	8	15	470	430	440	40	14.9%	1.063
183	996	1994	154	42.6	30.2	8	15.4	451	416	424	35	14.3%	1.067

Sample of UARS Flight Battery Database

	C	N	O	P	Q	R	S	T	U	V	W	X	Y
1	DOY	CD2	CD3	MAXD1	MAXD2	MAXD3	MAXD1-D2	AVGMAXDOD	I1	I2	I3	EONLBV	DV1MIN
150	121	1.011	1.029	532	491	499	41	16.9%	18.1	15.4	16.2	25.56	-97
151	122	1.007	1.025	521	480	489	41	16.6%	17.6	15.3	16	25.58	-59
152	123	1.002	1.020	525	476	489	49	16.6%	17.9	15.5	16.4	25.20	-53
153	124	1.025	1.042	514	460	477	54	16.1%	18.2	15.2	16.4	25.63	-18
154	125	1.023	1.042	494	466	470	28	15.9%	17.4	15.5	15.9	26.49	-22
155	126	1.022	1.042	492	464	468	28	15.8%	17	15.4	15.8	26.38	-36
156	127	1.022	1.042	482	455	460	27	15.5%	17	15.3	15.9	26.33	-55
157	128	1.020	1.040	484	454	461	30	15.5%	17.4	15.6	16.1	26.30	-60
158	129	1.016	1.035	528	484	497	44	16.8%	19.1	16.2	17.6	25.83	-67
159	130	1.018	1.036	573	529	540	44	18.2%	19.5	17.3	18	25.68	-66
160	131	1.020	1.039	528	489	500	39	16.9%	19.1	16.5	17.6	25.69	-95
161	132	1.020	1.039	527	491	501	36	16.9%	19.2	16.6	17.6	25.59	-112
162	133	1.020	1.039	533	497	507	36	17.1%	19.1	16.4	17.6	25.42	-101
163	134	1.020	1.037	541	505	515	36	17.3%	19	16.4	17.7	25.37	-66
164	135	1.018	1.036	557	517	528	40	17.8%	19.2	16.7	18.1	25.25	-94
165	136	1.017	1.032	567	528	539	39	18.2%	19.1	16.6	18.2	25.10	-109
166	137	1.014	1.043	571	532	543	39	18.3%	19.1	16.6	18.4	24.96	-111
167	138	1.025	1.029	583	537	550	46	18.6%	19.1	16.9	18	25.20	-122
168	139	1.012	1.035	573	543	548	30	18.5%	18	17.1	17.3	25.85	-169
169	140	1.017	1.035	547	514	520	33	17.6%	17.6	15.9	16.4	25.28	-171
170	141	1.015	1.036	558	522	530	36	17.9%	18.1	16	17.3	25.04	-178
171	142	1.017	1.039	566	528	538	38	18.1%	17.7	16	16.9	24.98	-165
172	143	1.021	1.037	576	537	546	39	18.4%	18.1	16.1	17.1	25.03	-146
173	144	1.020	1.039	553	520	525	33	17.8%	18.2	16	17.3	25.38	-130
174	145	1.018	1.034	562	528	535	34	18.1%	17.6	16.2	16.9	25.03	-83
175	146	1.016	1.035	547	522	529	25	17.8%	17.7	16	17	25.03	-62
176	147	1.016	1.036	544	517	524	27	17.6%	17.8	16	16.9	25.05	-42
177	148	1.017	1.035	538	515	523	23	17.5%	17.7	16	16.5	25.21	-38
178	149	1.017	1.036	544	511	519	33	17.5%	18	16	16.8	25.24	-42
179	150	1.018	1.026	524	501	507	23	17.0%	17.8	16.2	16.3	25.31	-52
180	151	1.007	1.032	508	493	499	15	16.7%	17.6	15.9	16.1	25.56	-76
181	152	1.017	1.033	490	449	460	41	15.5%	17.4	14.9	15.8	25.02	-87
182	153	1.019	1.035	487	444	455	43	15.4%	17.2	14.8	15.7	25.09	-55
183	154	1.019	1.033	470	430	440	40	14.9%	17.1	14.9	15.4	25.46	-25

Sample of UARS Flight Battery Database

	C	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL
1	DOY	DV1MAX	DV1MED	DV1MAG	DV2MIN	DV2MAX	DV2MED	DV2MAG	DV3MIN	DV3MAX	DV3MED	DV3MAG	T1	T2
150	121	59	-19	156	-17	13	-2	30	-22	22	0	44	5.2	2.25
151	122	64	2.5	123	-15	13	-1	28	-20	22	1	42	5.16	2.14
152	123	78	12.5	131	-11	25	7	36	-22	22	0	44	5.02	1.92
153	124	90	36	108	-15	25	5	40	-20	36	8	56	4.81	1.79
154	125	90	34	112	-17	18	0.5	35	-7	35	14	42	4.62	1.74
155	126	81	22.5	117	-17	15	-1	32	-10	32	11	42	4.64	1.7
156	127	78	11.5	133	-15	15	0	30	-8	35	13.5	43	4.68	1.65
157	128	78	9	138	-17	17	0	34	-7	36	14.5	43	4.84	1.65
158	129	81	7	148	-15	14	-0.5	29	-13	34	10.5	47	5.16	1.8
159	130	87	10.5	153	-22	13	-4.5	35	-22	28	3	50	5.58	2.07
160	131	80	-7.5	175	-22	13	-4.5	35	-21	29	4	50	5.78	2.28
161	132	64	-24	176	-22	11	-5.5	33	-25	25	0	50	6.77	3.31
162	133	80	-10.5	181	-22	11	-5.5	33	-34	22	-6	56	7.44	3.83
163	134	77	5.5	143	-22	11	-5.5	33	-34	22	-6	56	7.64	4.18
164	135	70	-12	164	-22	11	-5.5	33	-34	22	-6	56	7.81	4.37
165	136	59	-25	168	-22	13	-4.5	35	-35	22	-6.5	57	8.05	4.49
166	137	52	-29.5	163	-22	18	-2	40	-35	21	-7	56	8.26	4.88
167	138	60	-31	182	-18	20	1	38	-34	22	-6	56	8.56	4.88
168	139	56	-56.5	225	-21	11	-5	32	-31	22	-4.5	53	8.45	4.58
169	140	25	-73	196	-21	11	-5	32	-34	22	-6	56	7.98	4.36
170	141	21	-78.5	199	-17	21	2	38	-34	22	-6	56	8.18	4.44
171	142	22	-71.5	187	-13	24	5.5	37	-34	24	-5	58	8.27	4.75
172	143	31	-57.5	177	-14	32	9	46	-34	22	-6	56	8.24	4.84
173	144	38	-46	168	-20	17	-1.5	37	-34	22	-6	56	8.04	4.44
174	145	50	-16.5	133	-17	25	4	42	-35	21	-7	56	8.69	4.98
175	146	49	-6.5	111	-17	29	6	46	-36	20	-8	56	8.46	4.73
176	147	56	7	98	-14	29	7.5	43	-36	21	-7.5	57	8.06	4.35
177	148	56	9	94	-13	24	5.5	37	-34	20	-7	54	8.01	4.16
178	149	56	7	98	-17	22	2.5	39	-34	18	-8	52	7.95	3.89
179	150	56	2	108	-21	15	-3	36	-34	15	-9.5	49	7.69	3.58
180	151	49	-13.5	125	-22	13	-4.5	35	-34	22	-6	56	7.67	3.35
181	152	29	-29	116	-20	28	4	48	-34	22	-6	56	5.99	2.12
182	153	39	-8	94	-11	31	10	42	-32	22	-5	54	5.33	1.56
183	154	55	15	80	-11	25	7	36	-29	22	-3.5	51	6.06	2.59

Sample of UARS Flight Battery Database

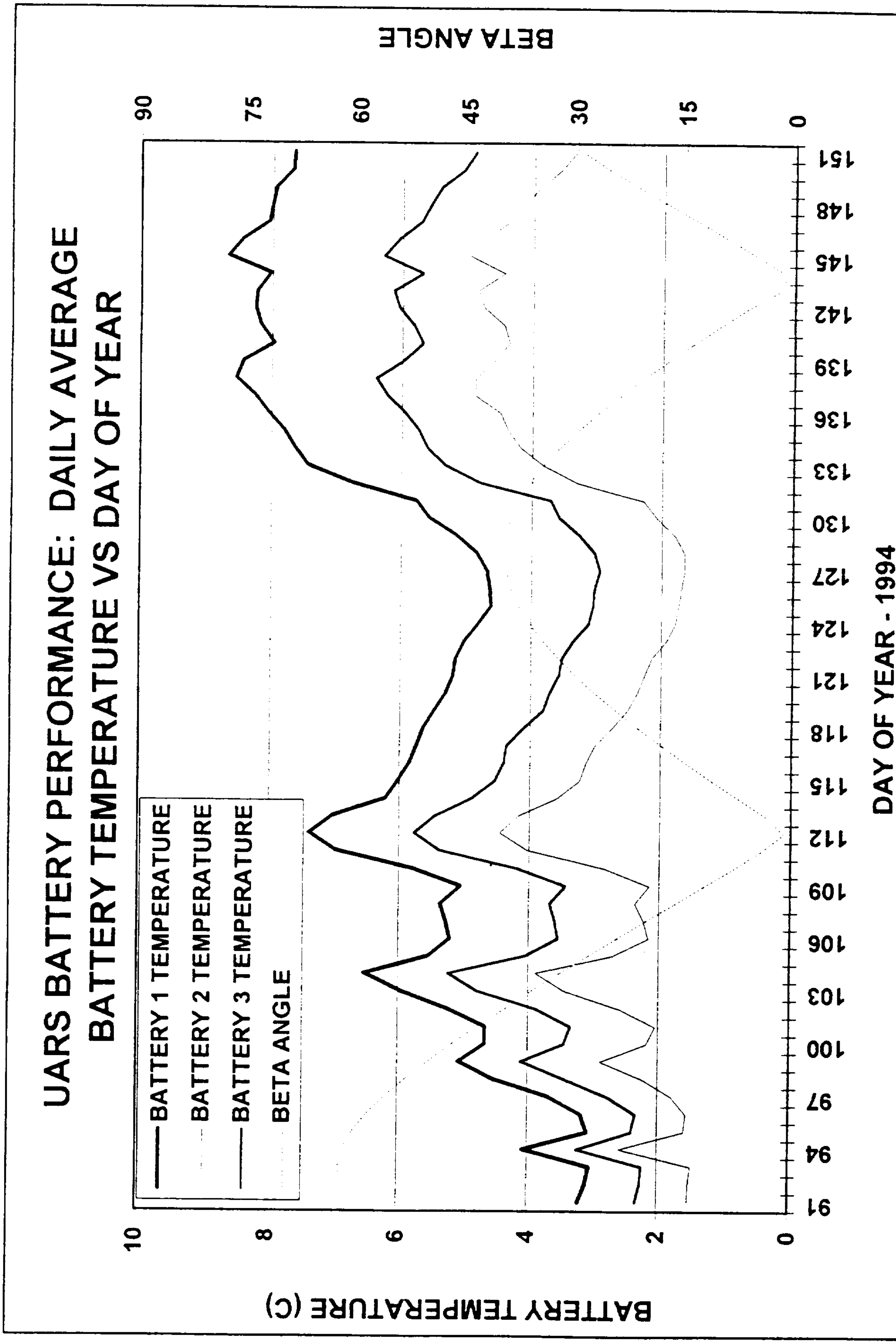
	C	AM	AN	AO	AP	AQ
1	DOY	T3	T1-T2	AVGPEAKI	VT	EFF. C/D GOAL
150	121	3.57	2.95	18.2	4	1.035
151	122	3.52	3.02	18.3	4	1.025
152	123	3.35	3.1	18.3	4	1.025
153	124	3.12	3.02	18.5	4	2
154	125	3.05	2.88	17.3	4	2
155	126	3.03	2.94	17.1	4	2
156	127	2.95	3.03	17.1	4	2
157	128	3.03	3.19	16.9	4	1.05
158	129	3.27	3.36	17.2	4	2
159	130	3.58	3.51	17.6	4	2
160	131	3.71	3.5	17.7	4	2
161	132	4.8	3.46	17.7	4	2
162	133	5.34	3.61	18.3	4	2
163	134	5.61	3.46	18.4	4	2
164	135	5.74	3.44	18.2	4	2
165	136	5.95	3.56	17.6	4	2
166	137	6.23	3.38	17.6	5	1.04
167	138	6.4	3.68	17.6	5	2
168	139	5.99	3.87	17.9	4	2
169	140	5.69	3.62	17.6	4	2
170	141	5.83	3.74	16.9	4	2
171	142	6.05	3.52	17.2	4	2
172	143	6.14	3.4	16.9	4	2
173	144	5.7	3.6	17.8	4	2
174	145	6.29	3.71	19	4	2
175	146	6.06	3.73	18.1	4	2
176	147	5.72	3.71	17.1	4	2
177	148	5.58	3.85	17.1	4	2
178	149	5.42	4.06	17.3	4	2
179	150	5.07	4.11	16.8	4	2
180	151	4.89	4.32	18	3	2
181	152	3.61	3.87	17.7	3	2
182	153	3	3.77	16.7	3	2
183	154	3.99	3.47	16	3	2

Sample of UARS Flight Battery Database

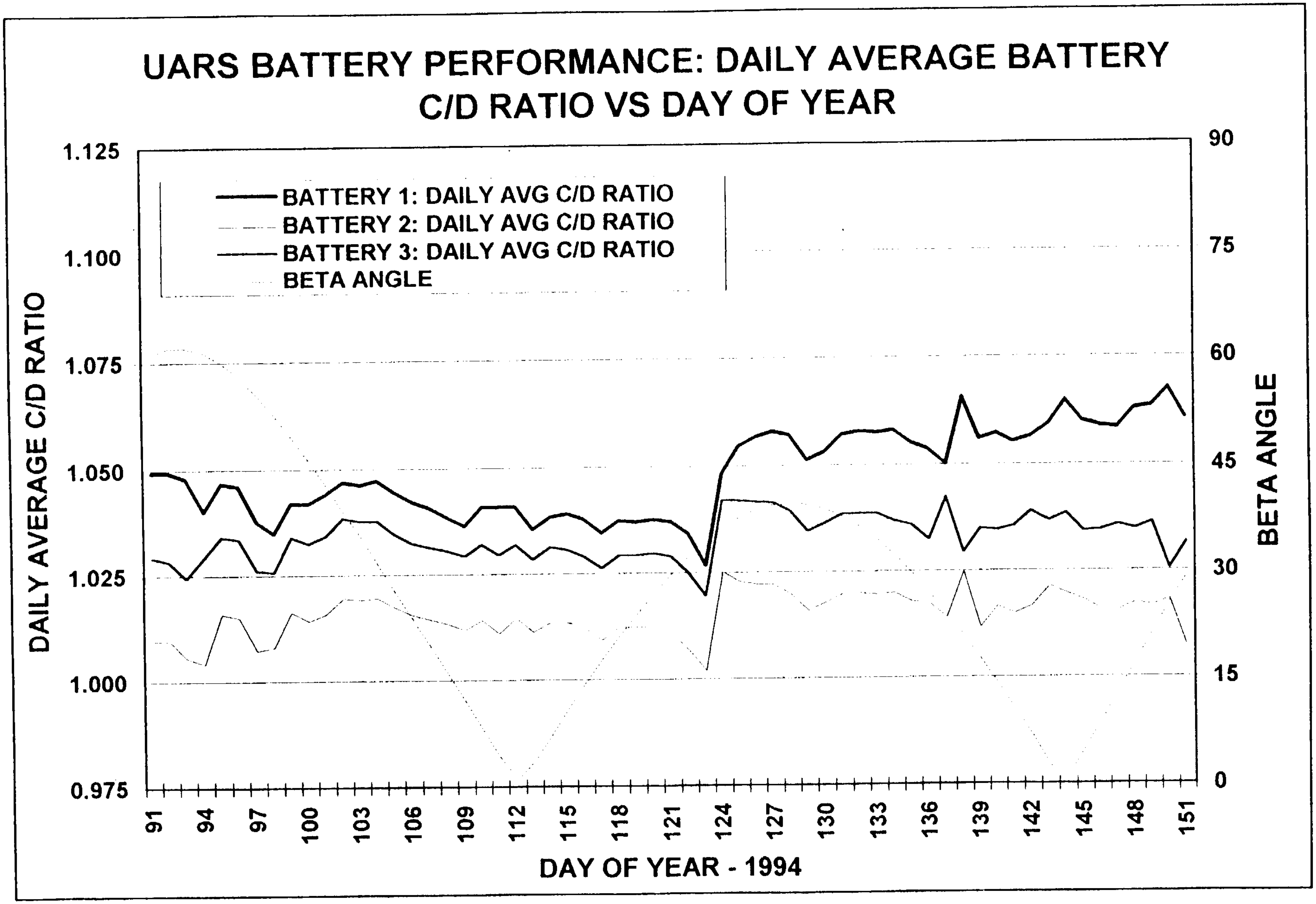
	C	AR
1	DOY	NOTES
150	121	
151	122	
152	123	
153	124	STRAIGHT VT4;
154	125	
155	126	
156	127	
157	128	
158	129	ISAMS TO HIGH POWER; STRAIGHT VT4;
159	130	STRAIGHT VT4; SOLAR ECLIPSE;
160	131	STRAIGHT VT4;
161	132	STRAIGHT VT4;
162	133	STRAIGHT VT4;
163	134	STRAIGHT VT4;
164	135	STRAIGHT VT4;
165	136	STRAIGHT VT4;
166	137	
167	138	1.05 C/D GOAL, THEN STRAIGHT VT5;
168	139	ISAMS TO LOW POWER; STRAIGHT VT4;
169	140	STRAIGHT VT4;
170	141	STRAIGHT VT4;
171	142	STRAIGHT VT4;
172	143	STRAIGHT VT4; ISAMS OFF; YAW-AROUND;
173	144	STRAIGHT VT4; ISAMS TO LOW POWER;
174	145	STRAIGHT VT4;
175	146	STRAIGHT VT4;
176	147	STRAIGHT VT4;
177	148	STRAIGHT VT4;
178	149	STRAIGHT VT4;
179	150	STRAIGHT VT4;
180	151	STRAIGHT VT3; ISAMS OFF;
181	152	STRAIGHT VT3;
182	153	STRAIGHT VT3;
183	154	STRAIGHT VT3;

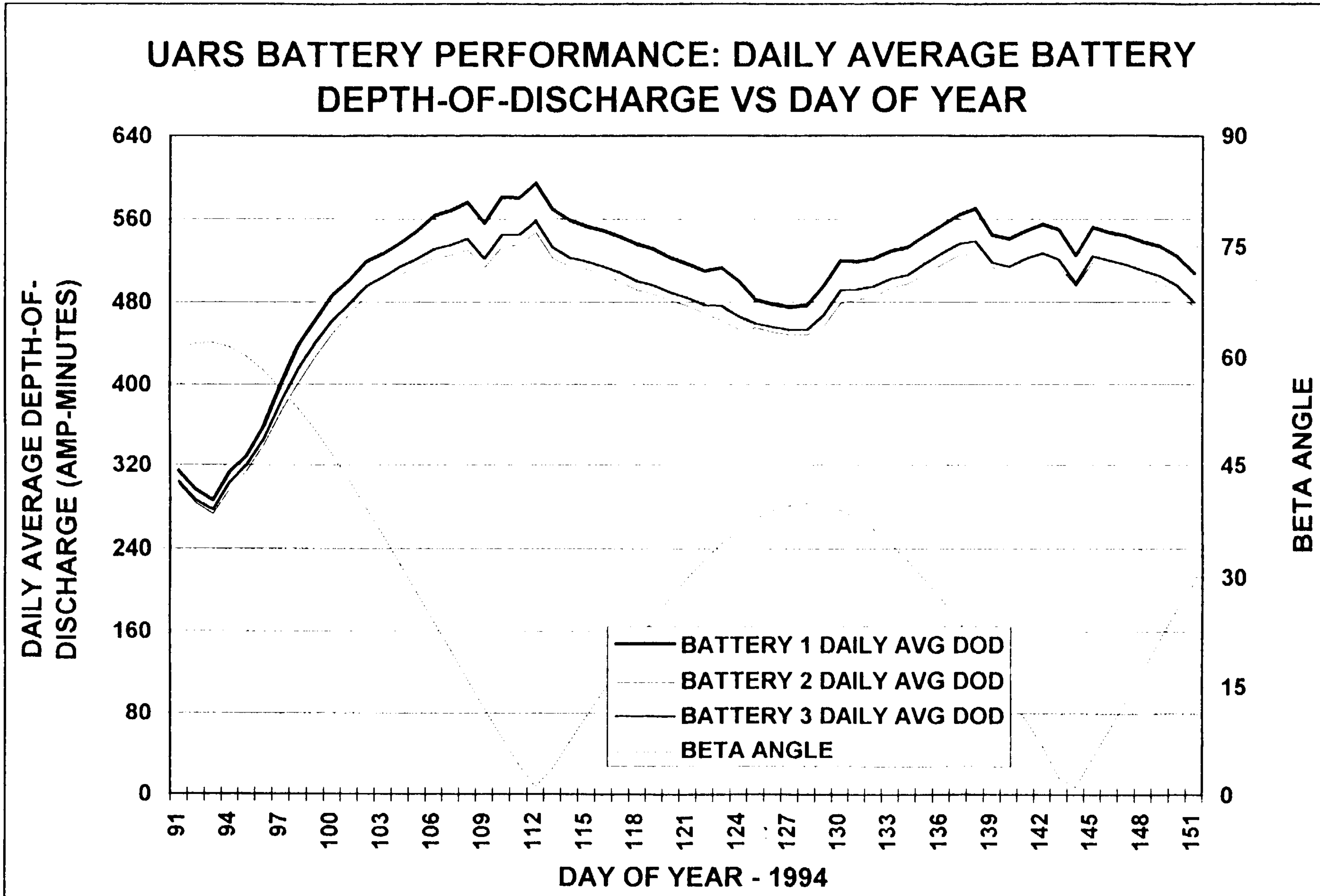
DATABASE FIGURES

- Each of these 16 parameters (except #2 and #4) are plotted versus Day of Year
- The Beta Angle is on each figure as a reference
- Some figures cover the entire year on a single page while others are confined to 60-day intervals for greater utility

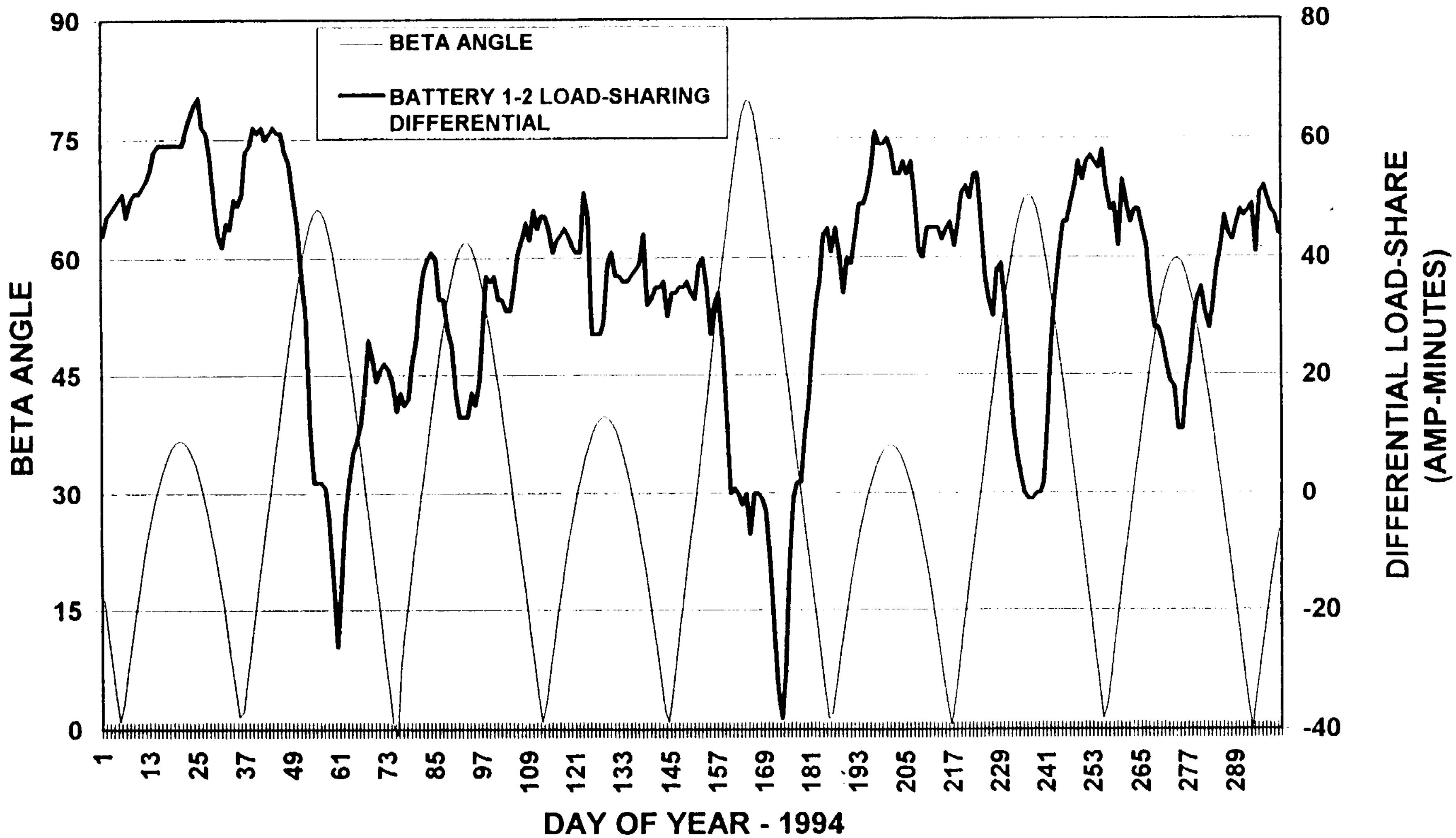


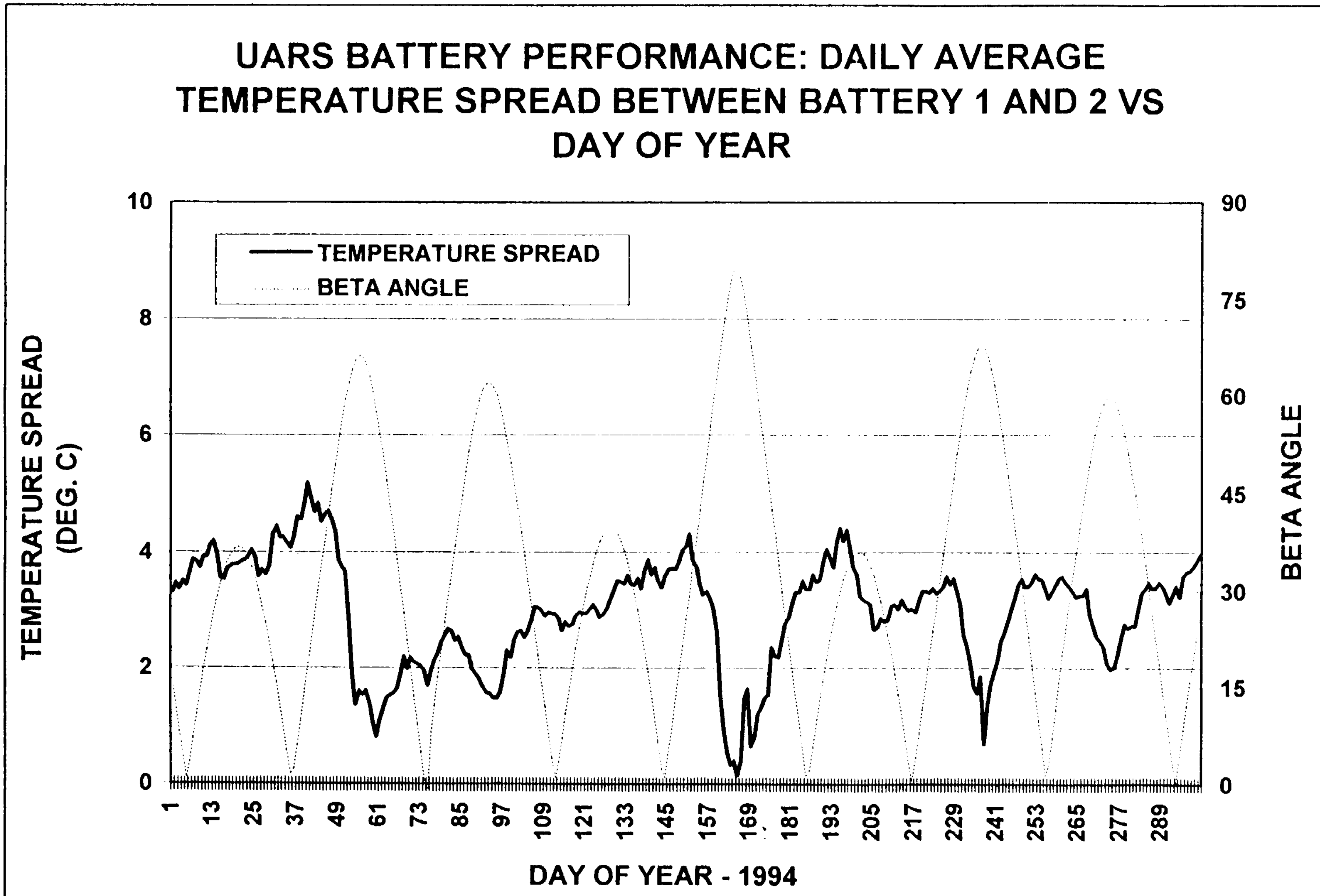
UARS BATTERY PERFORMANCE: DAILY AVERAGE
BATTERY TEMPERATURE VS DAY OF YEAR
BATTERY 1 TEMPERATURE
BATTERY 2 TEMPERATURE
BATTERY 3 TEMPERATURE
BETA ANGLE
BATTERY TEMPERATURE (C)
0
2
4
6
8
10
BETA ANGLE
0
15
30
45
60
75
90
DAY OF YEAR - 1994
91
94
97
100
103
106
109
112
115
118
121
124
127
130
133
136
139
142
145
148
151


UARS BATTERY PERFORMANCE: DAILY AVERAGE BATTERY C/D RATIO VS DAY OF YEAR
BATTERY 1: DAILY AVG C/D RATIO
BATTERY 2: DAILY AVG C/D RATIO
BATTERY 3: DAILY AVG C/D RATIO
BETA ANGLE
DAILY AVERAGE C/D RATIO
1.125
1.100
1.075
1.050
1.025
1.000
0.975
BETA ANGLE
90
75
60
45
30
15
0
91
94
97
100
103
106
109
112
115
118
121
124
127
130
133
136
139
142
145
148
151
DAY OF YEAR - 1994

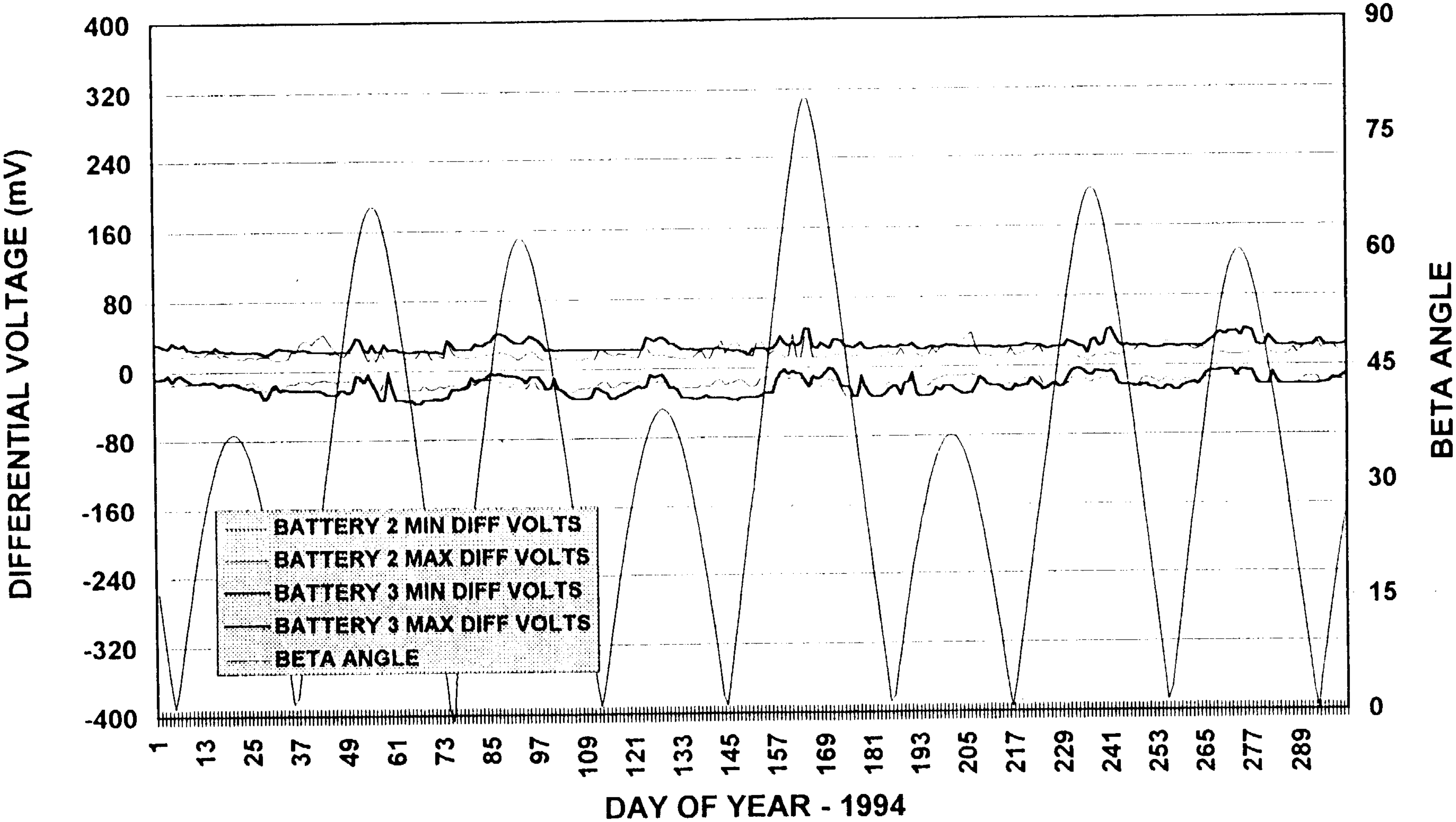

UARS BATTERY PERFORMANCE: DAILY AVERAGE BATTERY DEPTH-OF-DISCHARGE VS DAY OF YEAR
DAILY AVERAGE DEPTH-OF-DISCHARGE (AMP-MINUTES)
0
80
160
240
320
400
480
560
640
BETA ANGLE
0
15
30
45
60
75
90
DAY OF YEAR - 1994
91
94
97
100
103
106
109
112
115
118
121
124
127
130
133
136
139
142
145
148
151
BATTERY 1 DAILY AVG DOD
BATTERY 2 DAILY AVG DOD
BATTERY 3 DAILY AVG DOD
BETA ANGLE

UARS BATTERY PERFORMANCE: DAILY LOAD SHARE DIFFERENTIAL BETWEEN BATTERY 1 & 2 VS DAY OF YEAR




UARS BATTERY PERFORMANCE: DAILY AVERAGE TEMPERATURE SPREAD BETWEEN BATTERY 1 AND 2 VS DAY OF YEAR
TEMPERATURE SPREAD
BETA ANGLE
TEMPERATURE SPREAD (DEG. C)
BETA ANGLE
DAY OF YEAR - 1994
0
2
4
6
8
10
0
15
30
45
60
75
90
1
13
25
37
49
61
73
85
97
109
121
133
145
157
169
181
193
205
217
229
241
253
265
277
289

UARS BATTERY PERFORMANCE: DAILY BATTERY DIFFERENTIAL VOLTAGE VS DAY OF YEAR



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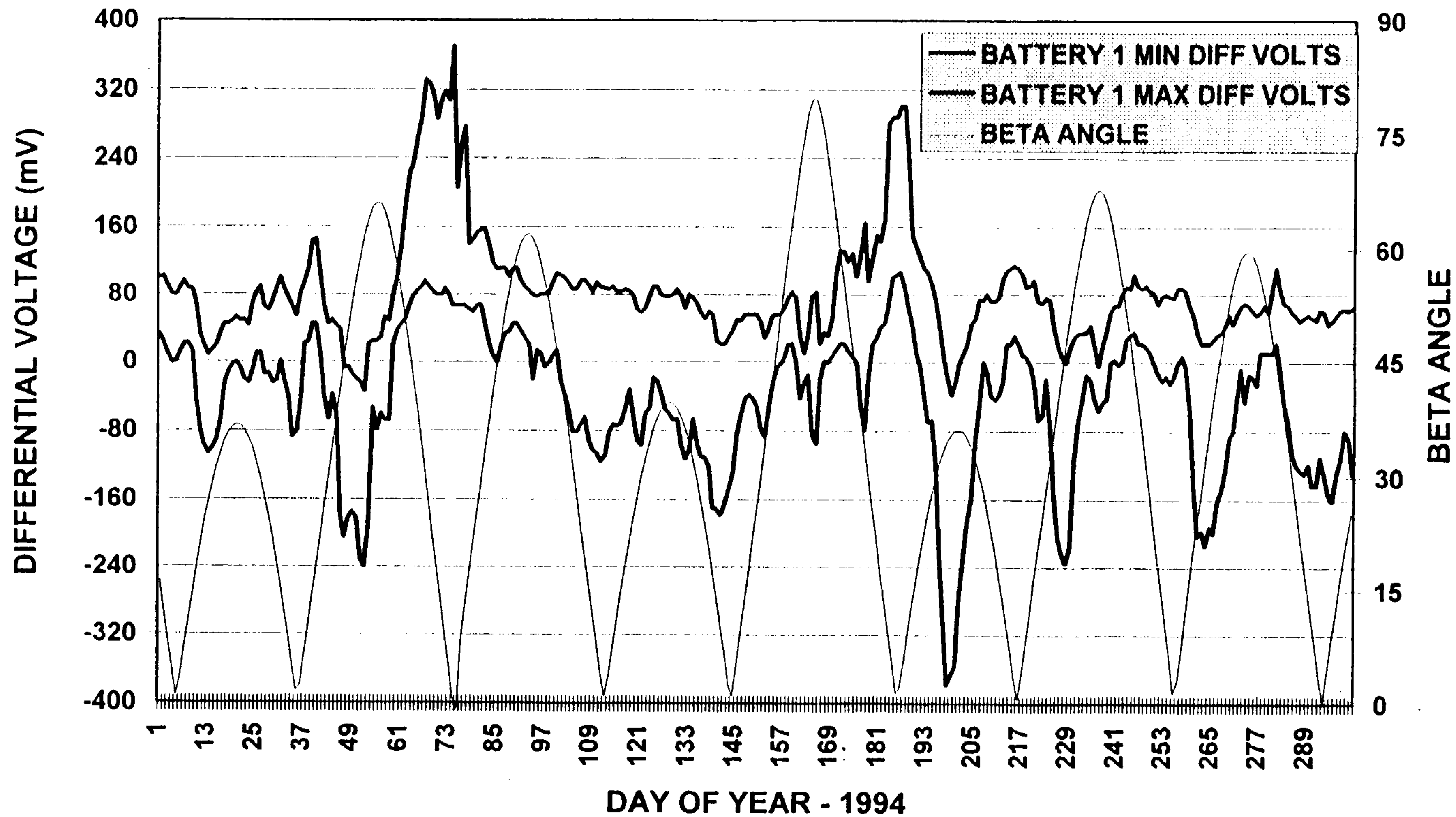
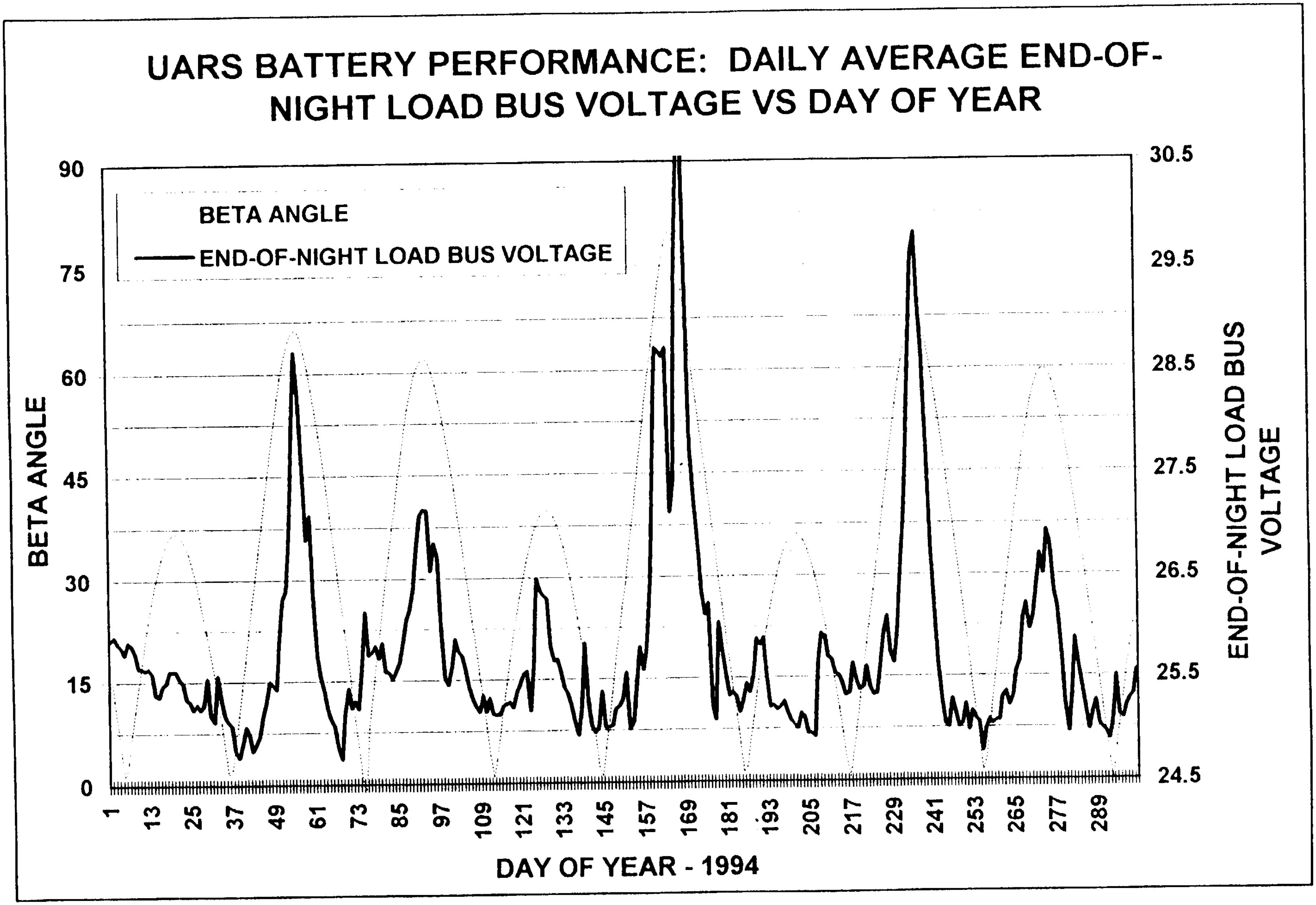
UARS BATTERY PERFORMANCE: DAILY BATTERY DIFFERENTIAL VOLTAGE VS DAY OF YEAR

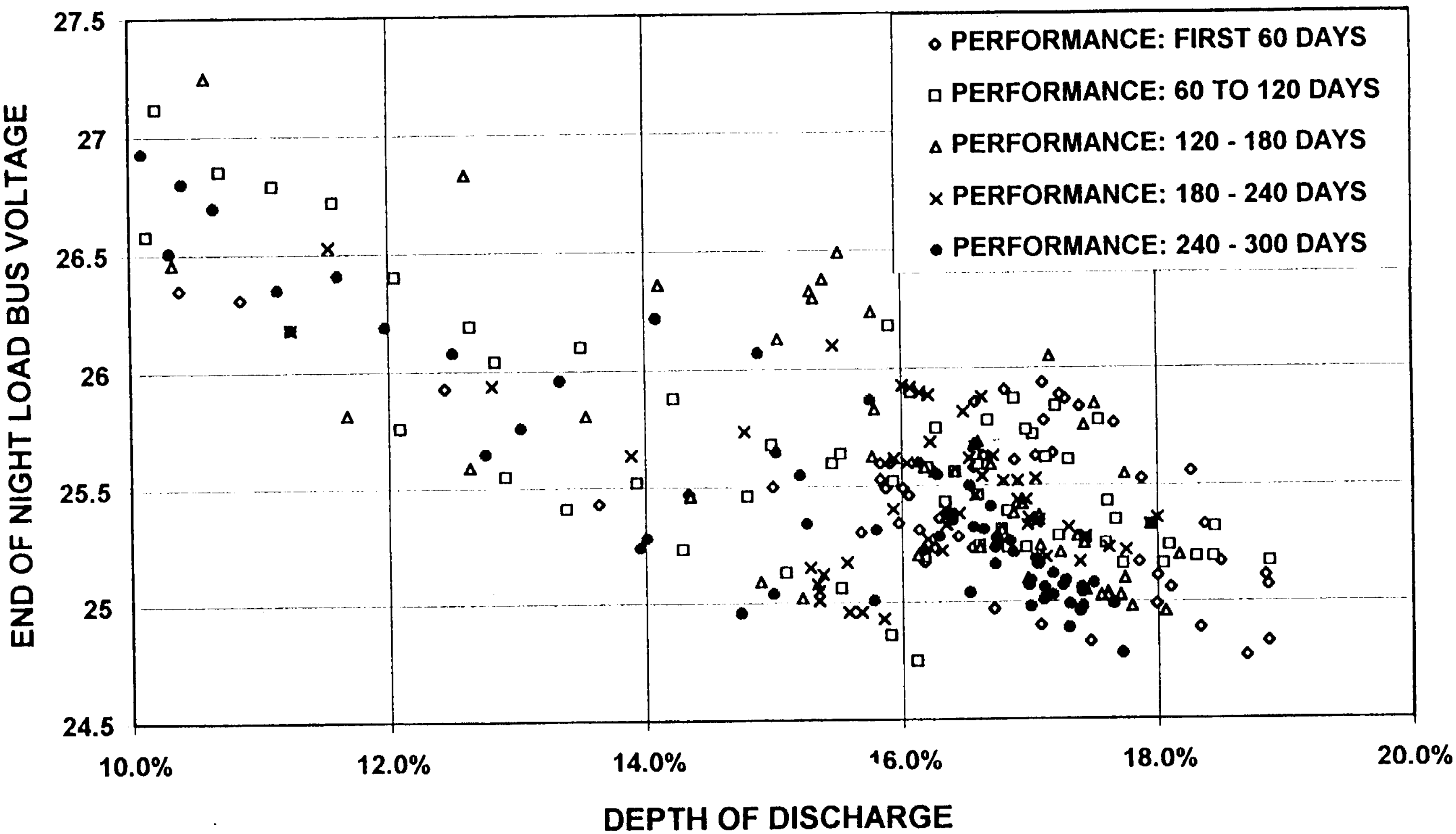



UARS BATTERY PERFORMANCE: DAILY AVERAGE END-OF-NIGHT LOAD BUS VOLTAGE VS DAY OF YEAR
BETA ANGLE
END-OF-NIGHT LOAD BUS VOLTAGE
BETA ANGLE
0
15
30
45
60
75
90
END-OF-NIGHT LOAD BUS VOLTAGE
24.5
25.5
26.5
27.5
28.5
29.5
30.5
DAY OF YEAR - 1994
1 13 25 37 49 61 73 85 97 109 121 133 145 157 169 181 193 205 217 229 241 253 265 277 289

DATABASE FIGURES - continued

- Daily Average End of Night Load Bus Voltage could be a misleading indicator of battery health and state-of-charge and should be correlated to Daily Average Battery Depth-of-Discharge.
- An additional figure examines this relationship. The figure covers the first 300 days of 1994, and is broken out into discrete 60-day periods. It suggests that battery voltage performance has not significantly degraded over the last 300 days.

UARS BATTERY PERFORMANCE: DAILY AVERAGE DEPTH OF DISCHARGE vs DAILY AVERAGE END OF NIGHT LOAD BUS VOLTAGE FOR SPECIFIC PERFORMANCE PERIODS



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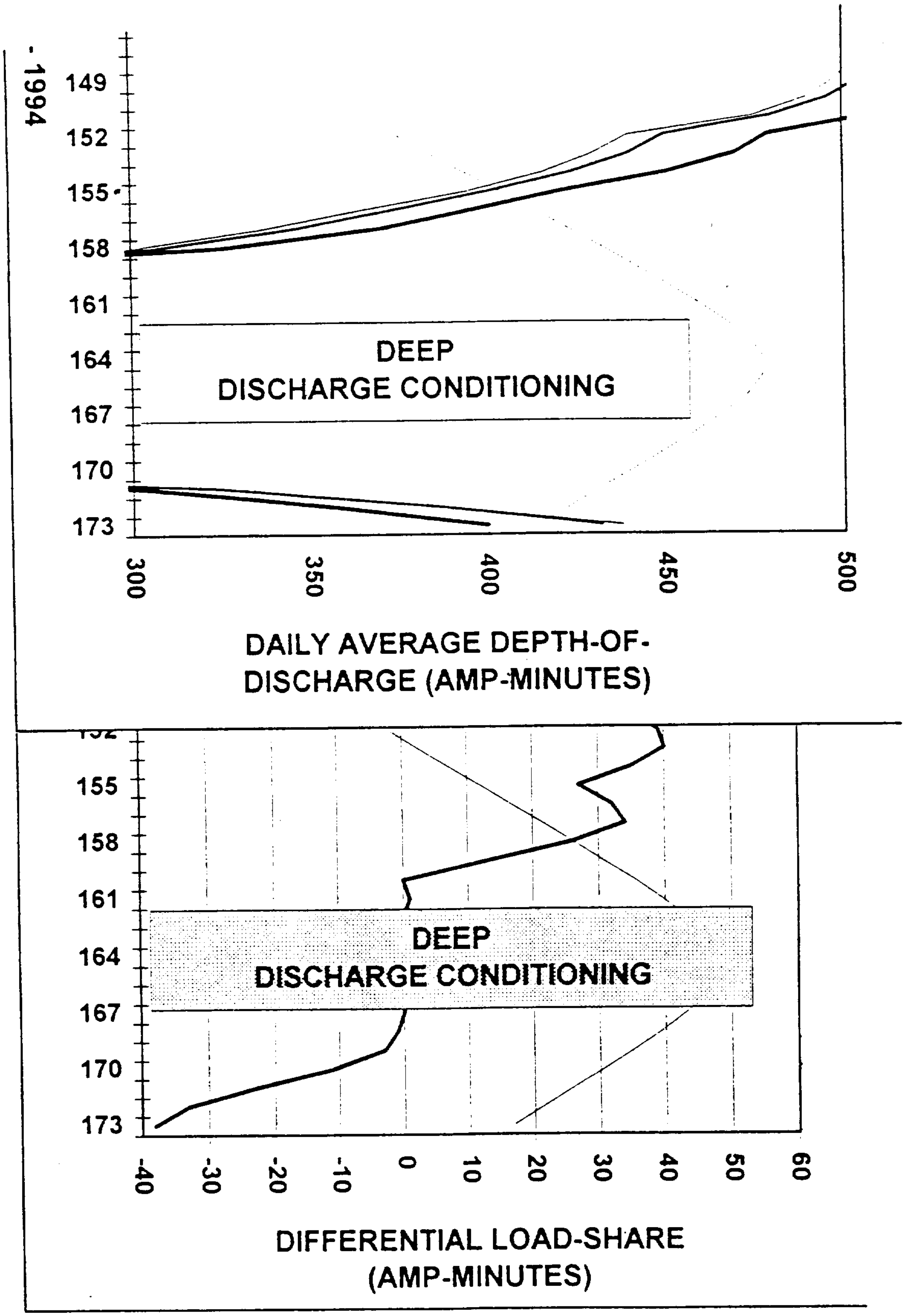
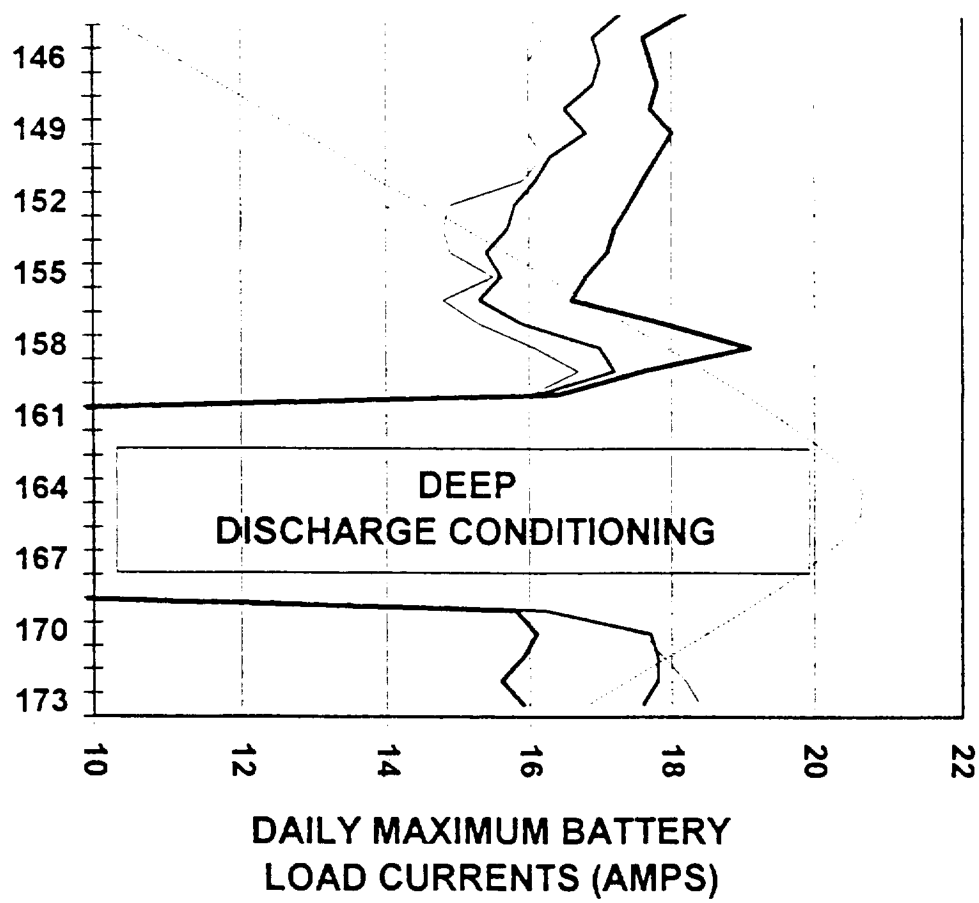
APPLICATION OF THE DATABASE

- To illustrate the usefulness of the database and its applicability for future battery operations and management, let us examine three of the many operational modes employed in 1994:

  1. Deep discharge conditioning on DOY 164 and 165
  2. Control C/D ratio by switching from "straight" VT 3 to a combination of VT 4 and Constant Current Mode for a C/D ratio goal of 1.04 on DOY 174
  3. Use of straight VT 4 from DOY 188 to 192



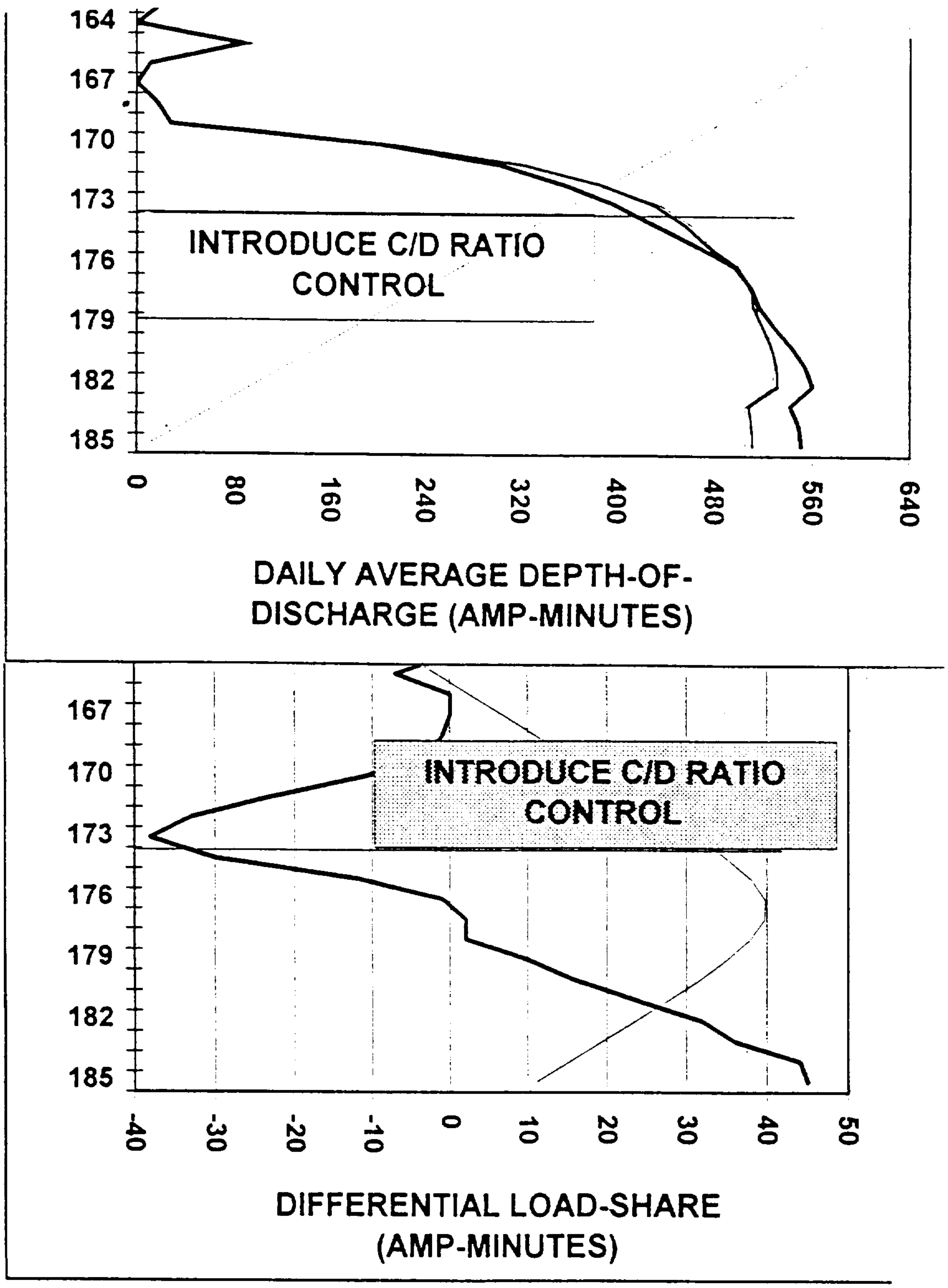
Example 1: Effects of Deep Discharge Conditioning



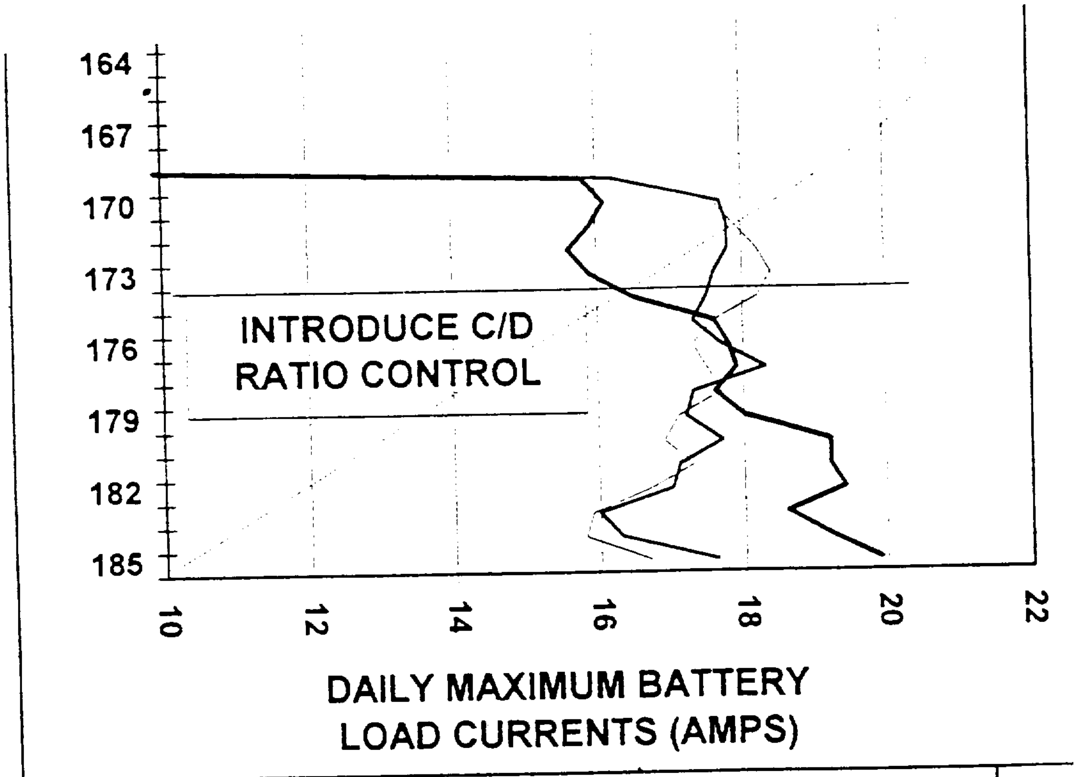
Example 1: Effects of Deep Discharge Conditioning
(continued)

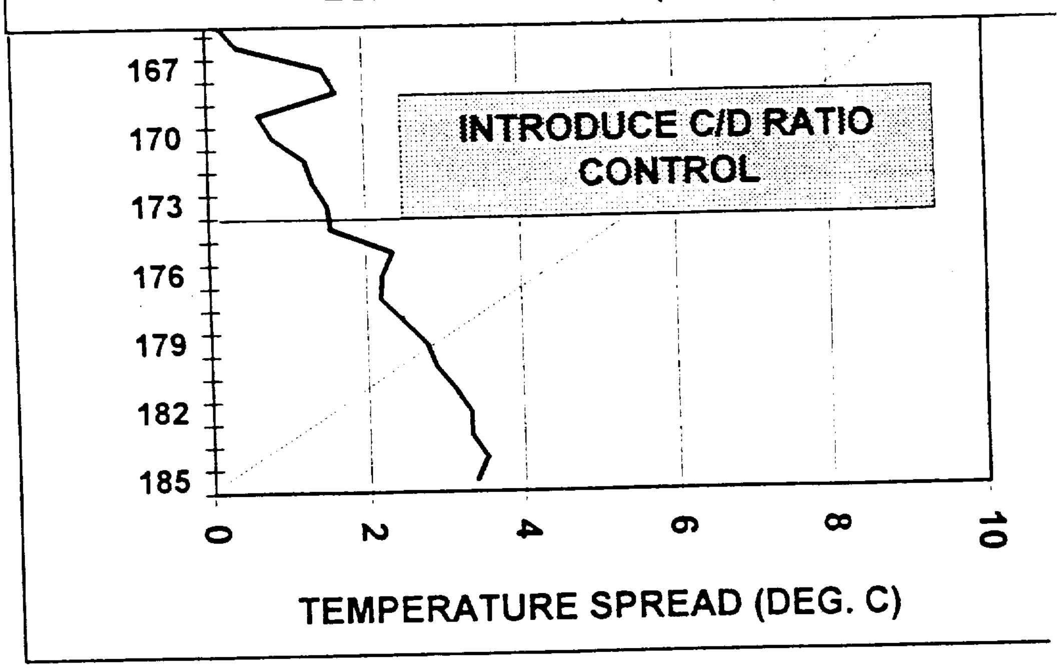
CONCLUSIONS FROM EXAMPLE 1

- Deep discharge conditioning temporarily improves battery performance
- Improved battery performance also probably arises from the convergence of battery temperatures during full-sun periods



Example 2: Effect of C/D Ratio Control

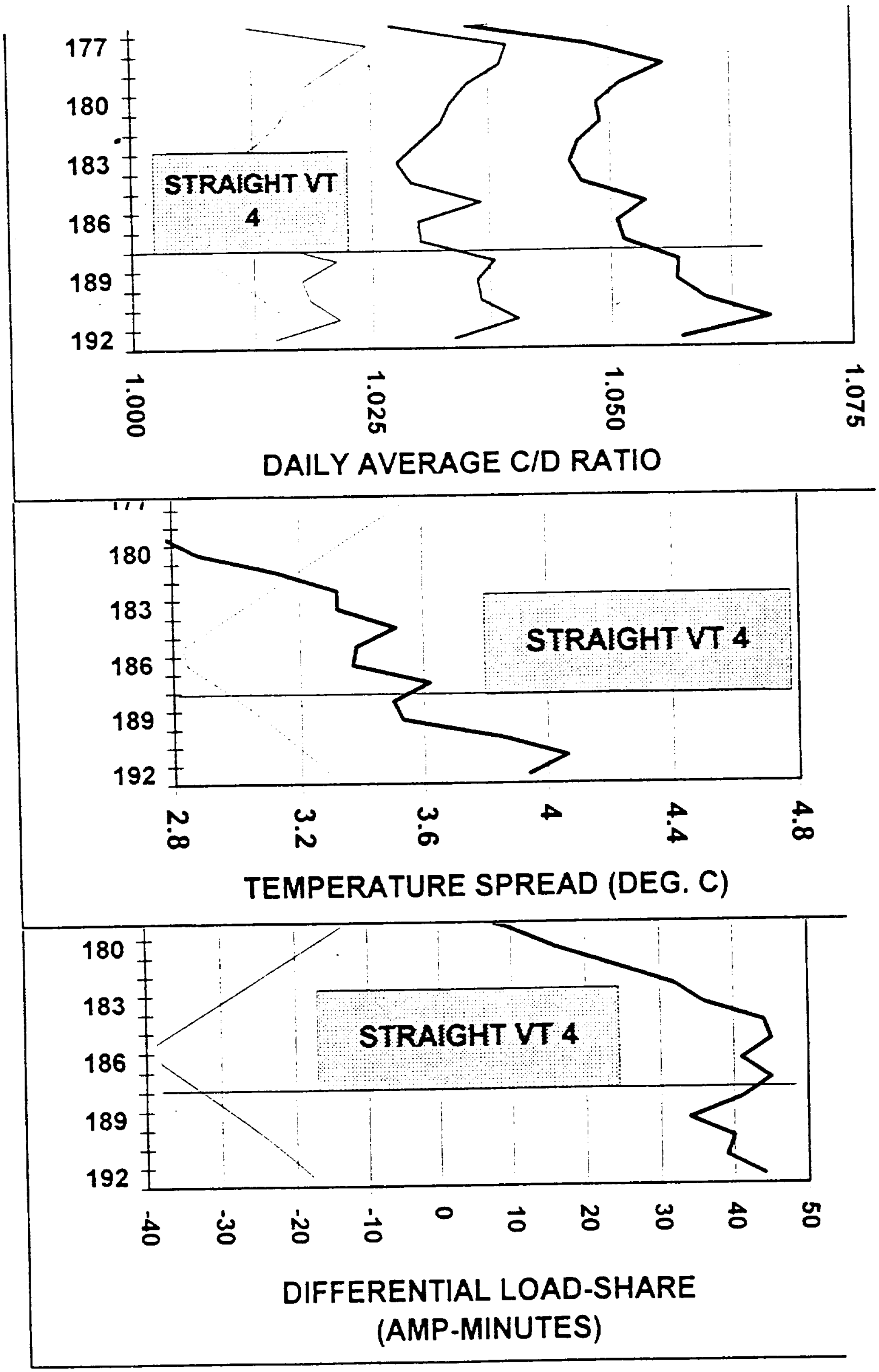




Example 2: Effect of C/D Ratio Control
(continued)

CONCLUSIONS FROM EXAMPLE 2

- Performance improvements realized from deep discharge conditioning appear to be temporary
- Minimizing overcharge on the warmest battery can result in undercharging of colder batteries and a state-of-charge imbalance among the three batteries
- Divergence of some battery performance parameters is probably due to state-of-charge divergence
- Presently, for UARS, the use of Constant Current Mode to control C/D ratio is not preferred when the Beta angle is decreasing (eclipse duration increasing / length of S/C day decreasing)



Example 3: Effect of Straight VT 4

CONCLUSIONS FROM EXAMPLE 3

- Straight VT charging yields better load-sharing in the short run, but leads to divergence in the long run
- Ensuring an adequate level of overcharge on the coldest battery by this method can be detrimental to the warmest battery (generates waste heat at end of charge, increases the C/D ratio). Divergence in states-of-charge is a likely result
- For the present, on UARS, use of straight VT charging is not preferred when the Beta angle is increasing (eclipse duration decreasing / length of S/C day increasing)

PRESENT OPERATIONAL STRATEGIES

- Hold sunrise battery charge currents below 20 amps via Solar Array offset
- Use VT 3 unless DOD exceeds 15% or end-of-night Load Bus Voltage drops to 24.8 V; then use VT 4
- Use Constant Current Charge Modes only as necessary to maintain C/D ratios below 1.06
- Use Constant Current Charge Mode to control C/D ratios only when the Beta angle is increasing
- Use straight VT charging only when the Beta angle is decreasing

PRESENT OPERATIONAL STRATEGIES - continued

- Execute deep conditioning discharges and/or artificial eclipsing during every full-sun period
- Maintain temperature spread between battery 1 and battery 2 below 4 °C
- Monitor battery differential voltages to detect unusual signatures:
  - "spikes" during charge, of 50mV or more
  - rapid changes at the end of discharge exceeding 300 mV
  - an absolute value exceeding 350 mV at any time in an orbit

SUMMARY

- Anomalous performance of the UARS batteries has necessitated intensive battery management characterized by frequent changes in operational modes and close monitoring of trends
- Establishment and use of a battery performance database has aided in this management effort:
  - Identified the operational strategies that have led to poor performance
  - Identifies the operational strategies that are yielding acceptable performance
  - Suggests operational strategies that may lead to optimum performance

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