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.

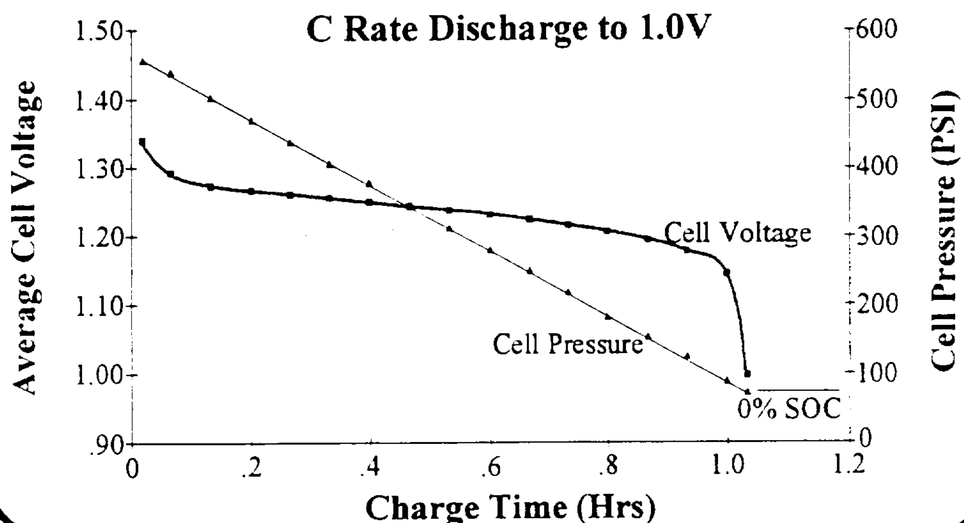
For the purposes of this test, 100% state of charge is defined as the point during a C/2 charge that the cell pressure no longer increases at a linear rate. 0% state of charge is the point during a C rate discharge that the cell voltage reaches 1.0 volts. Prior to starting life cycle, the four cells 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.

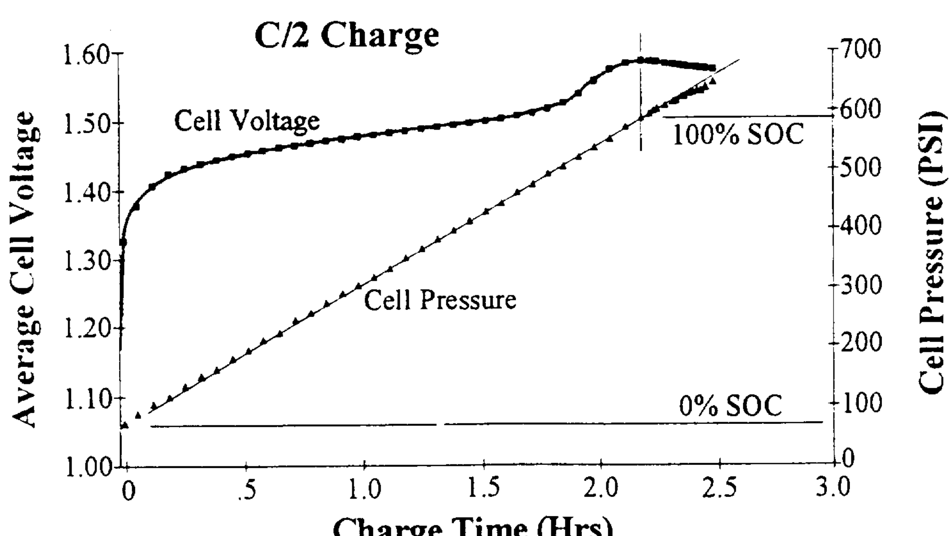
Air Force Ni-H_2 Cell Test Program

State of Charge Test



Air Force Ni-H_2 Cell Test Program

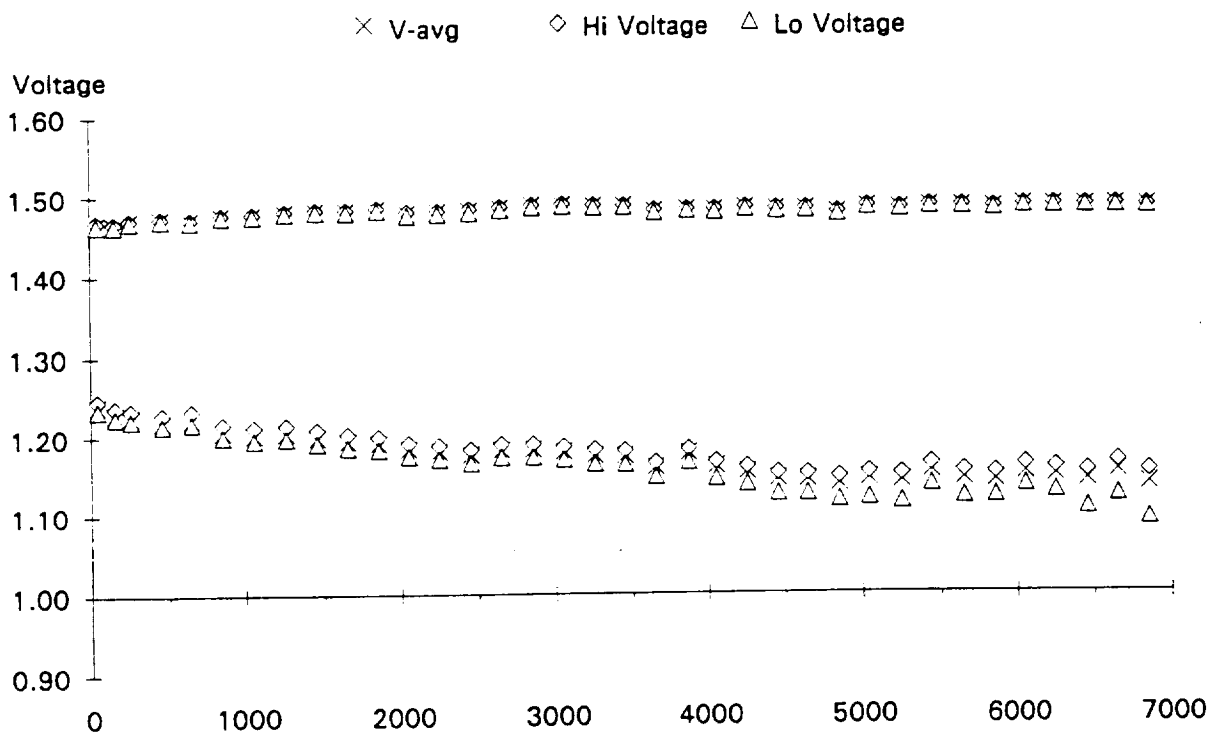
State of Charge Test

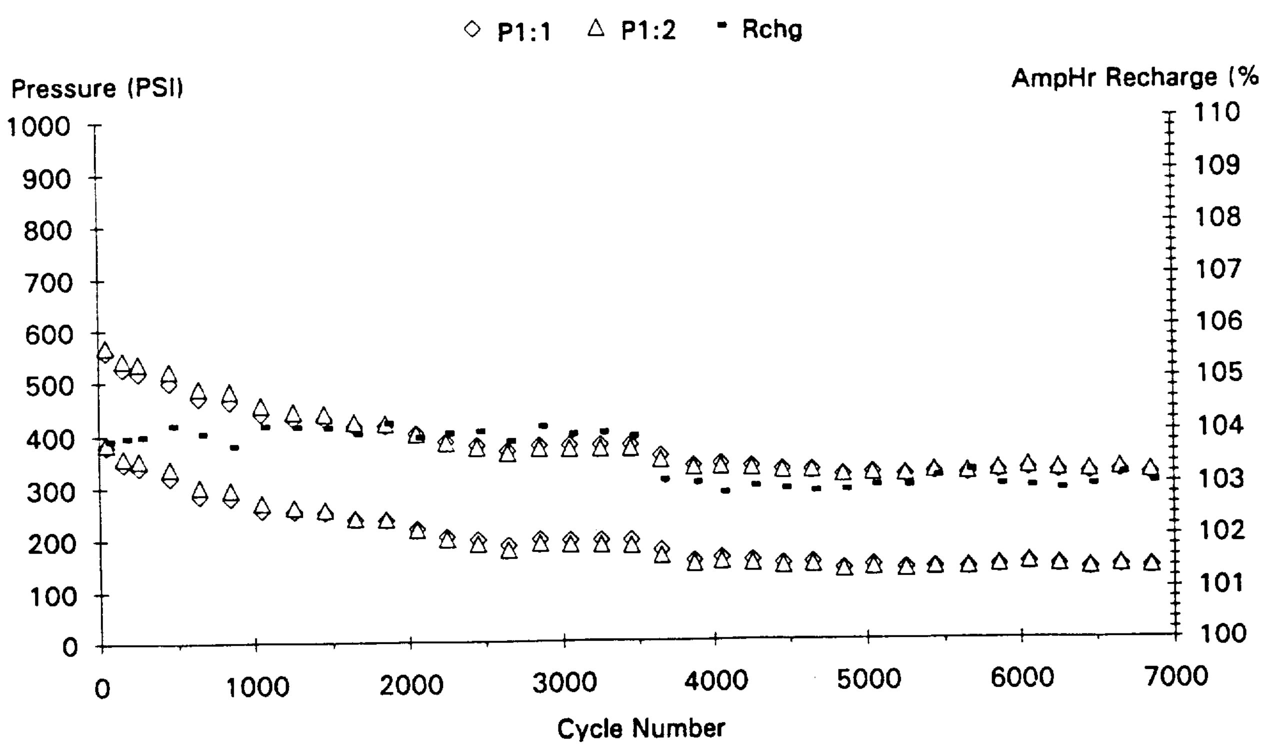


NSWC Crane **Pack ID 3214E** **10 cells**

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

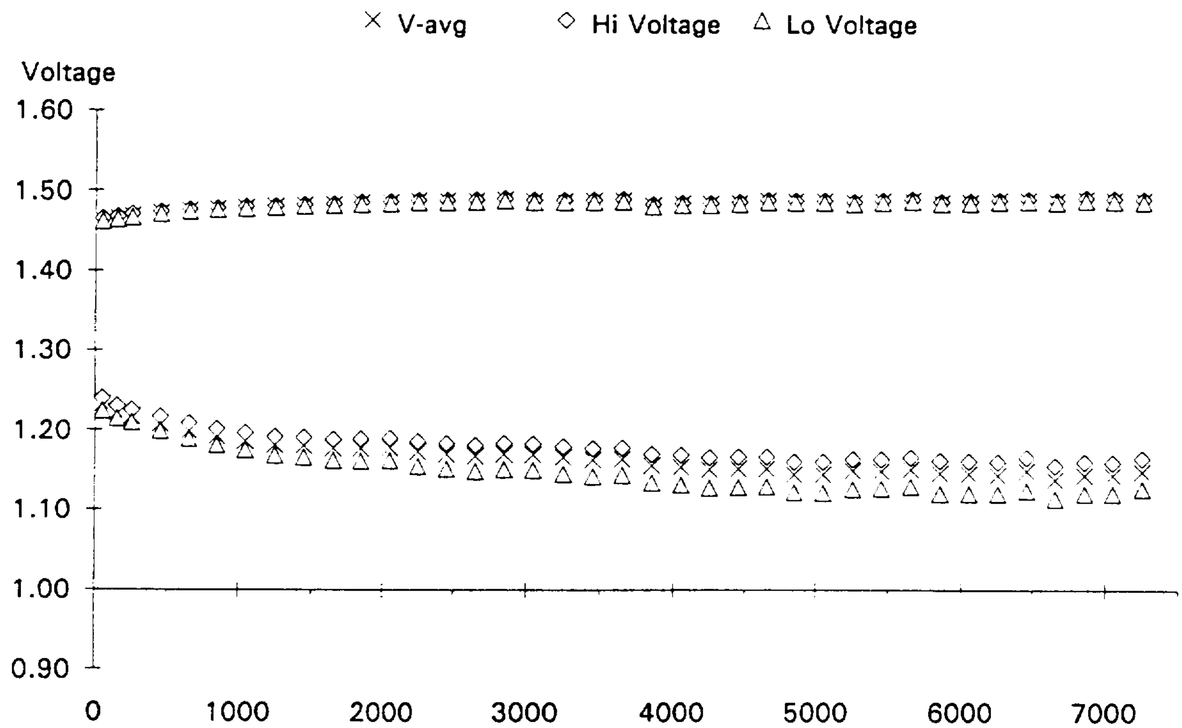


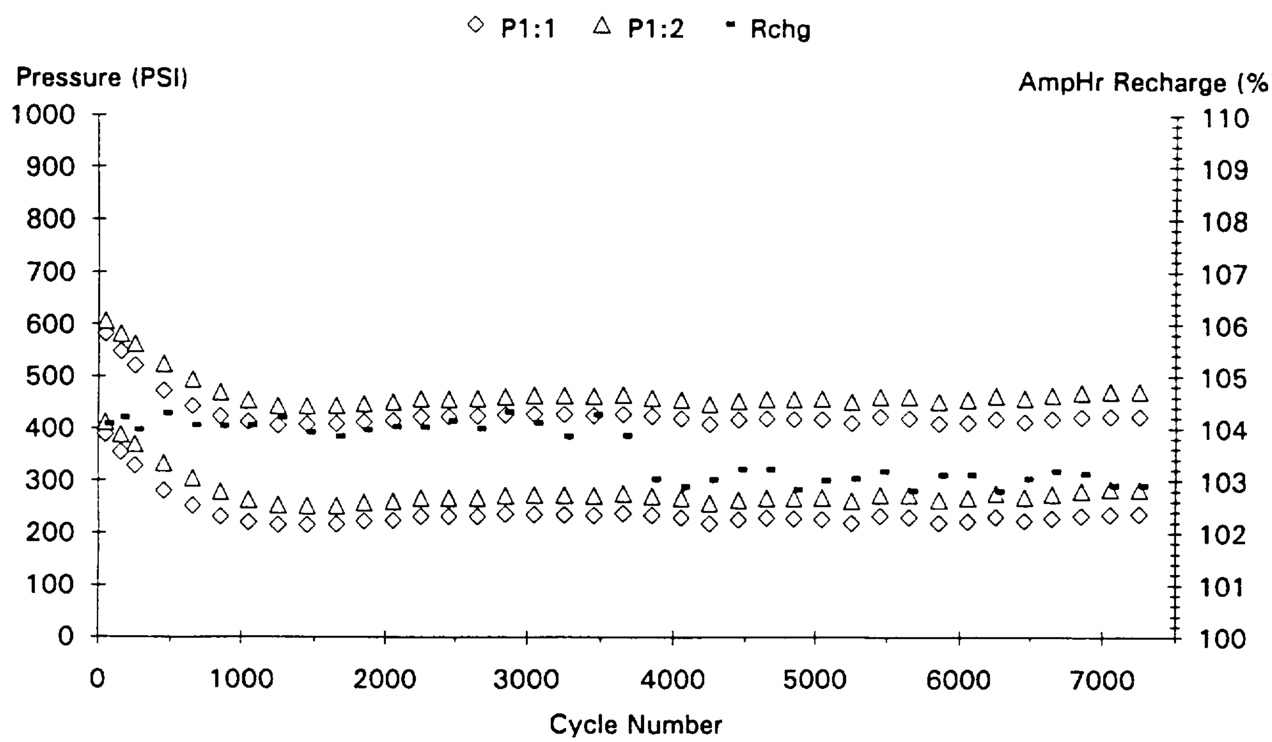


NSWC Crane   Pack ID 3314E   10 cells

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

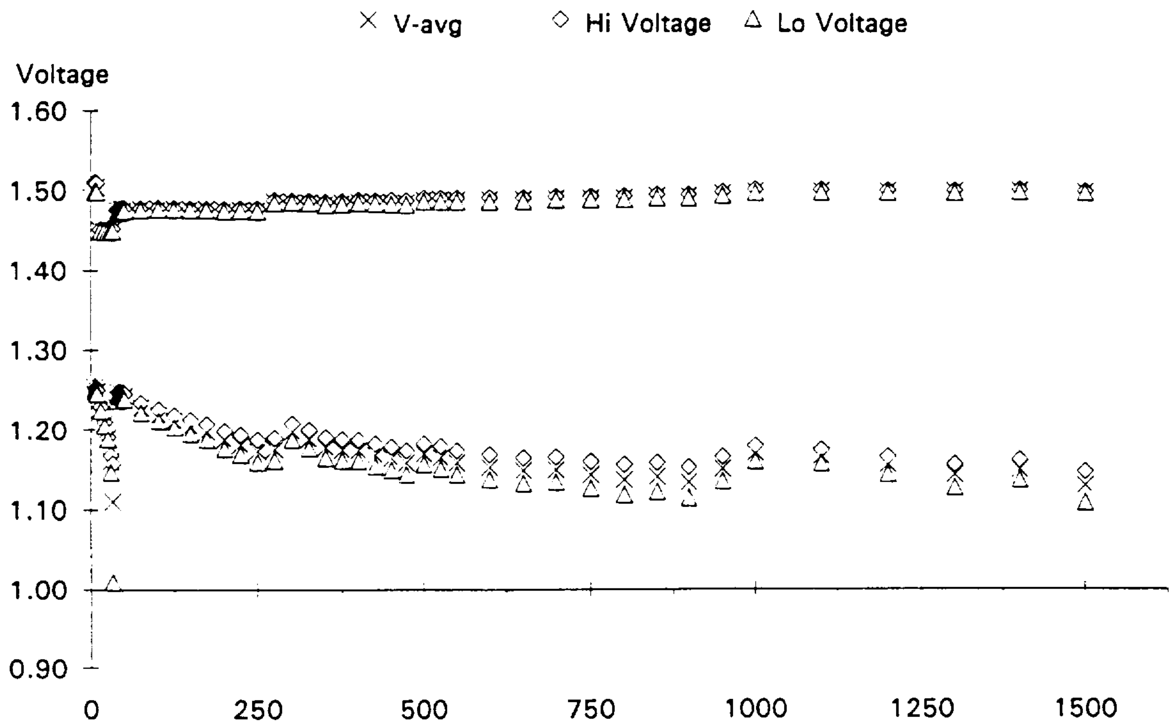


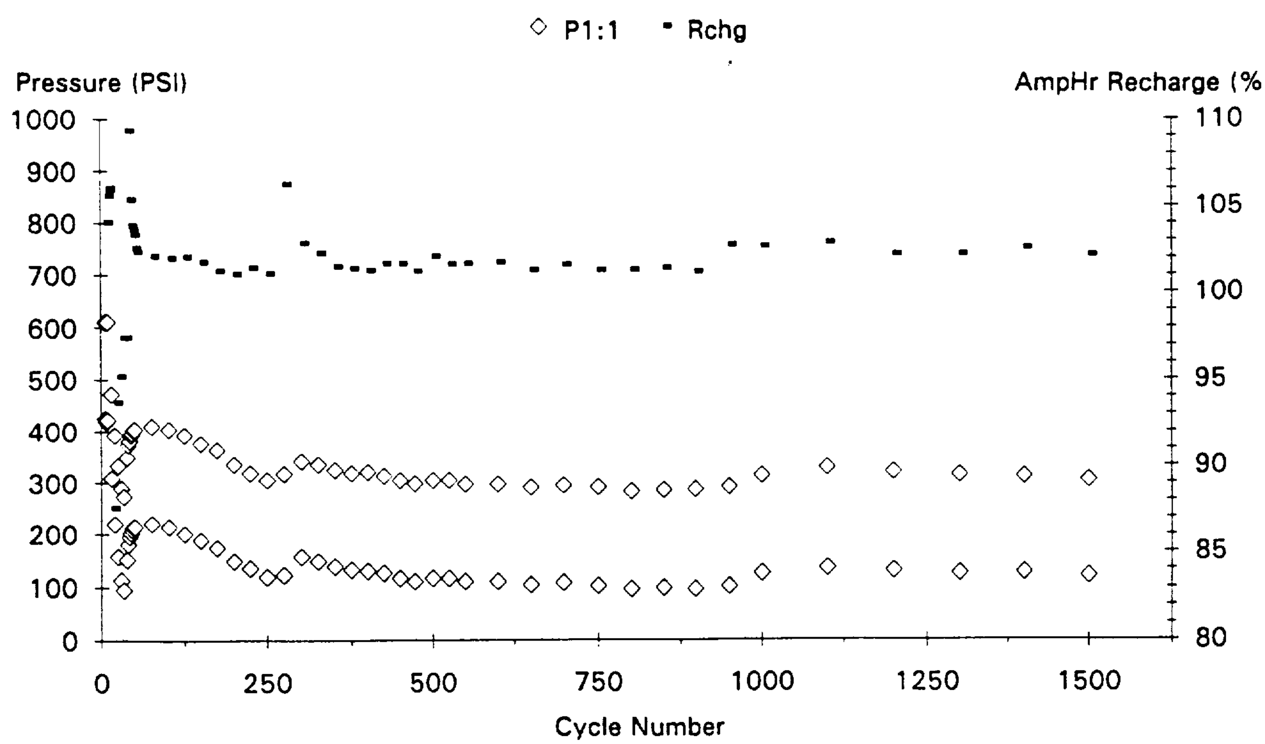


NSWC Crane   Pack ID 3001C   4 cells

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

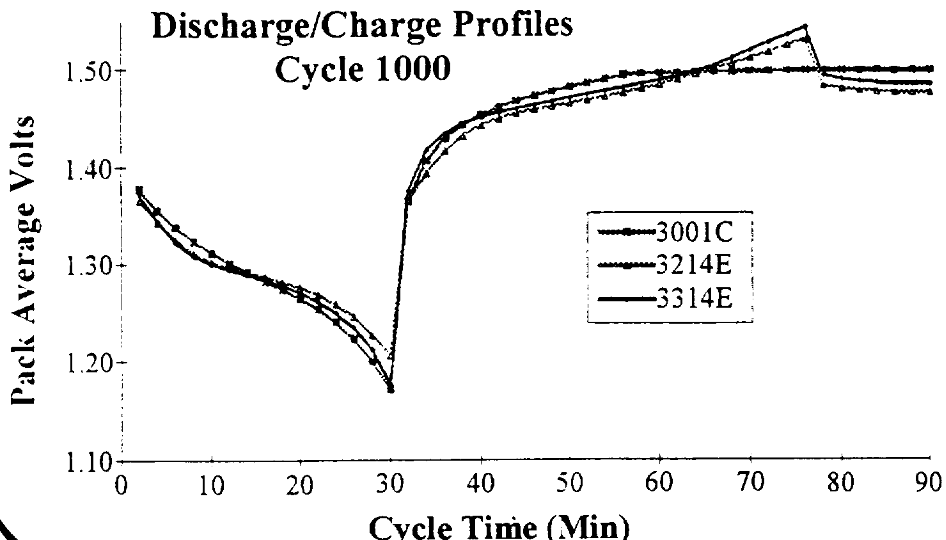
Capacities for pack 3001C were measured after 1 year standing open circuit, discharged at 5 degrees C.

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

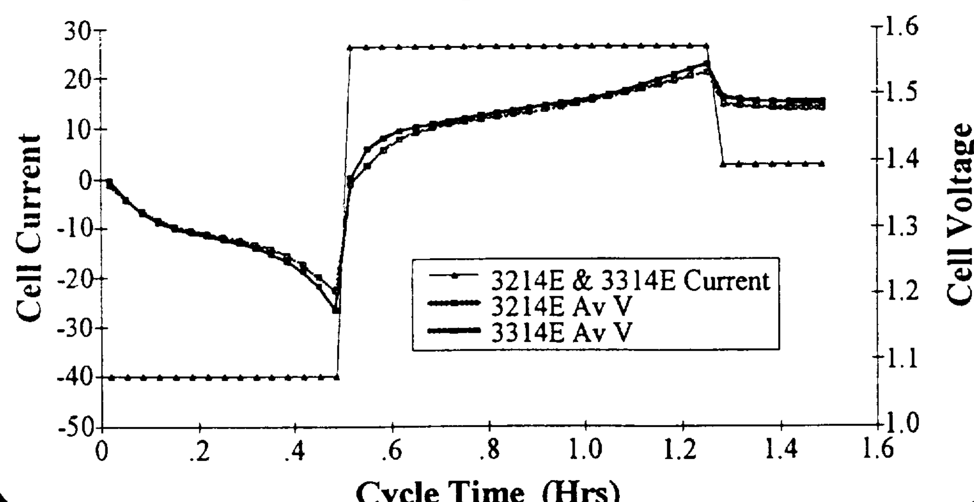
State of Charge Test



Air Force Ni-H_2 Cell Test Program

State of Charge Test

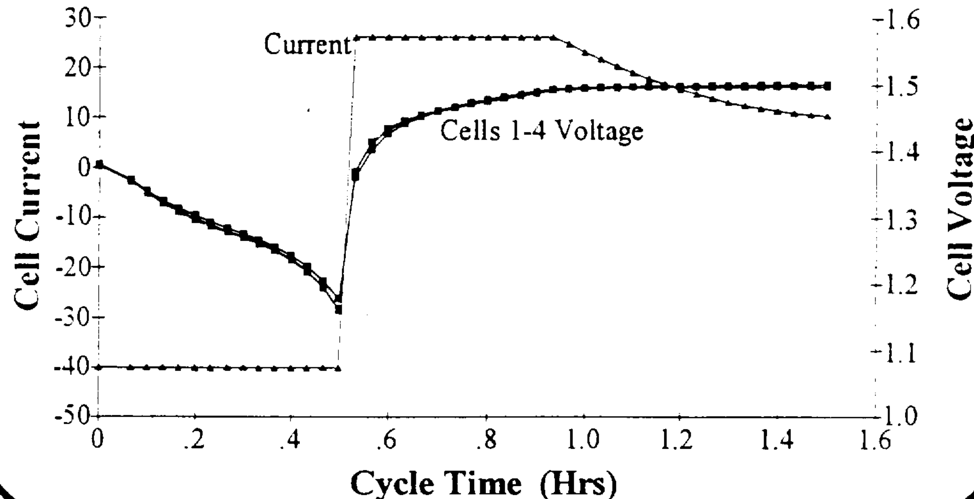
Pack 3214E and 3314E Voltage/Current Profile for Cycle 1000



Air Force Ni-H_2 Cell Test Program

State of Charge Test

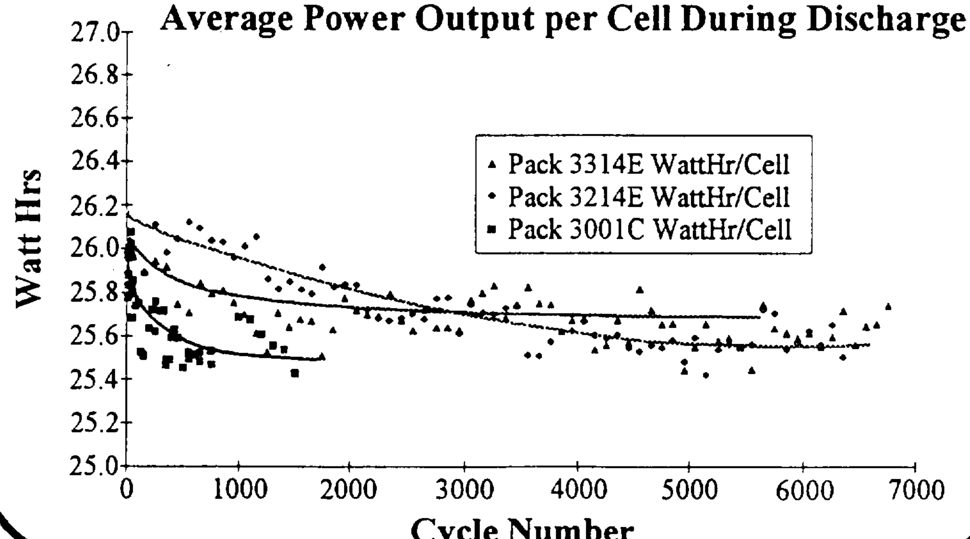
Pack 3001C Voltage/Current Profile for Cycle 1000



Air Force Ni-H_2 Cell Test Program

State of Charge Test

Average Power Output per Cell During Discharge



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)

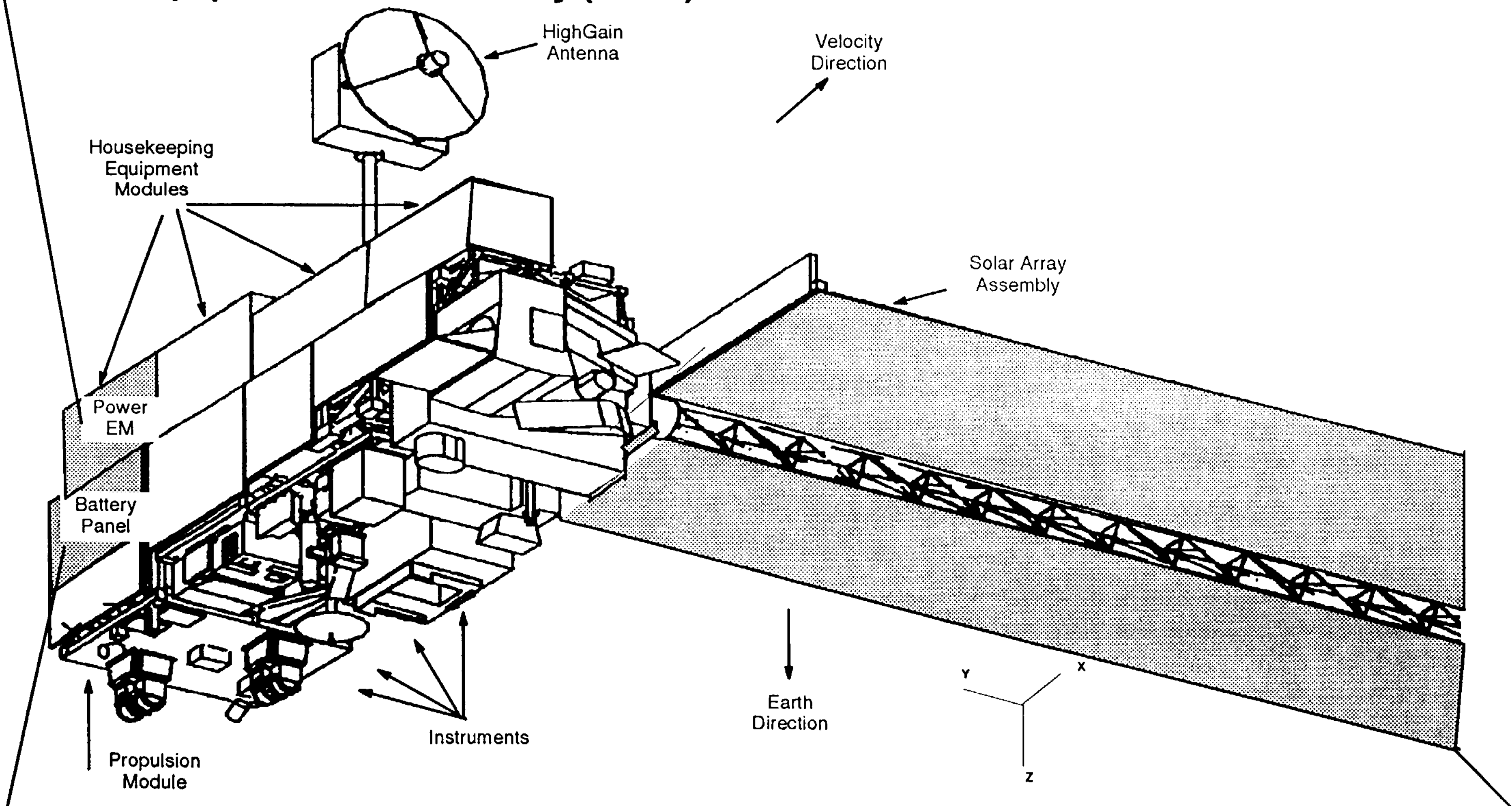
Outline

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

Battery Assembly/Spacecraft Interface

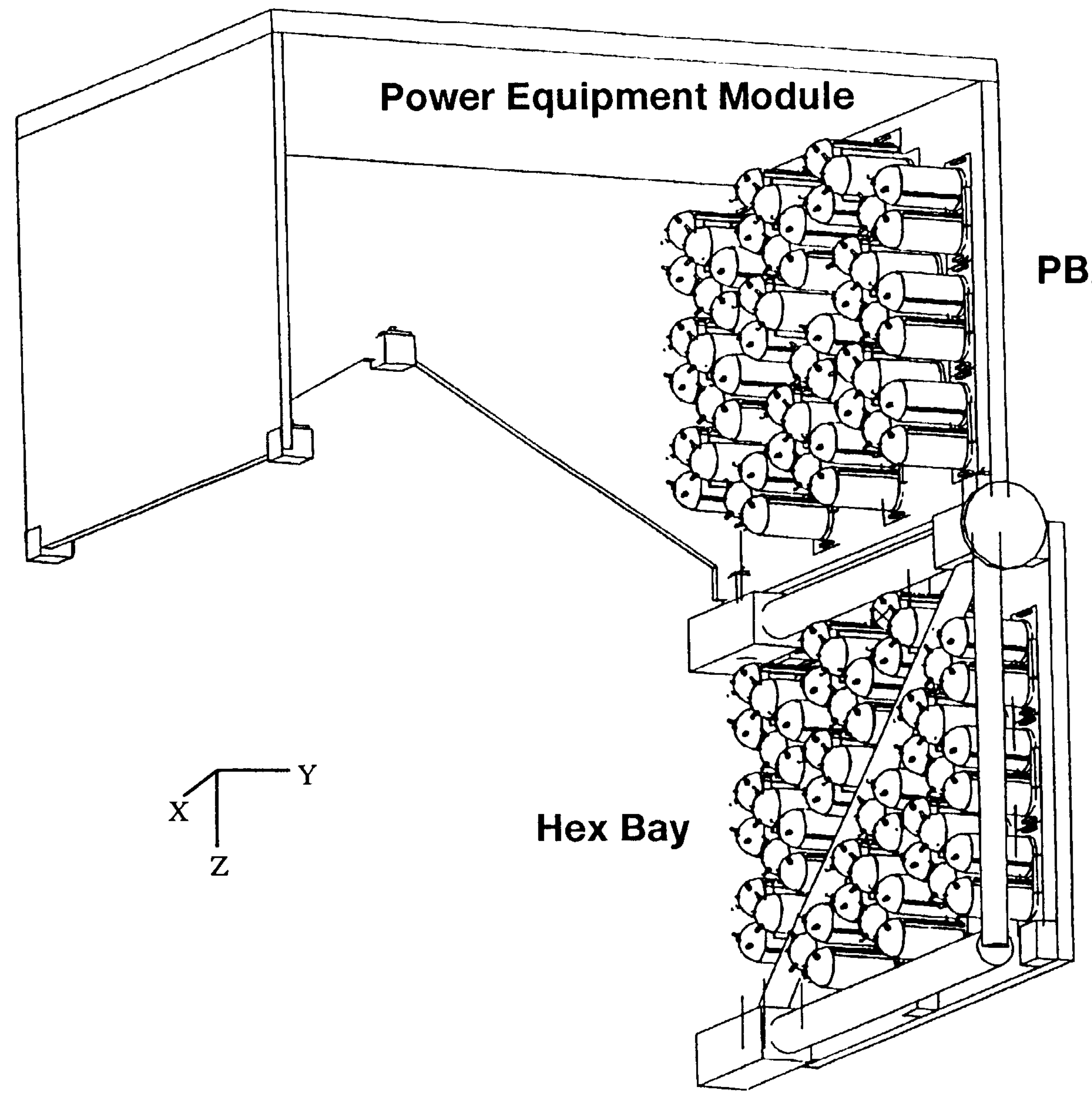
MARTIN MARIETTA
MARTIN MARIETTA ASTRO SPACE

Power Equipment Module Battery (PBAT)



Hex Bay Battery (BBAT)

Integrated Battery Assemblies



Top Level Requirements

MARTIN MARIETTA
MARTIN MARIETTA ASTRO SPACE

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

MARTIN MARIETTA
MARTIN MARIETTA ASTRO SPACE

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

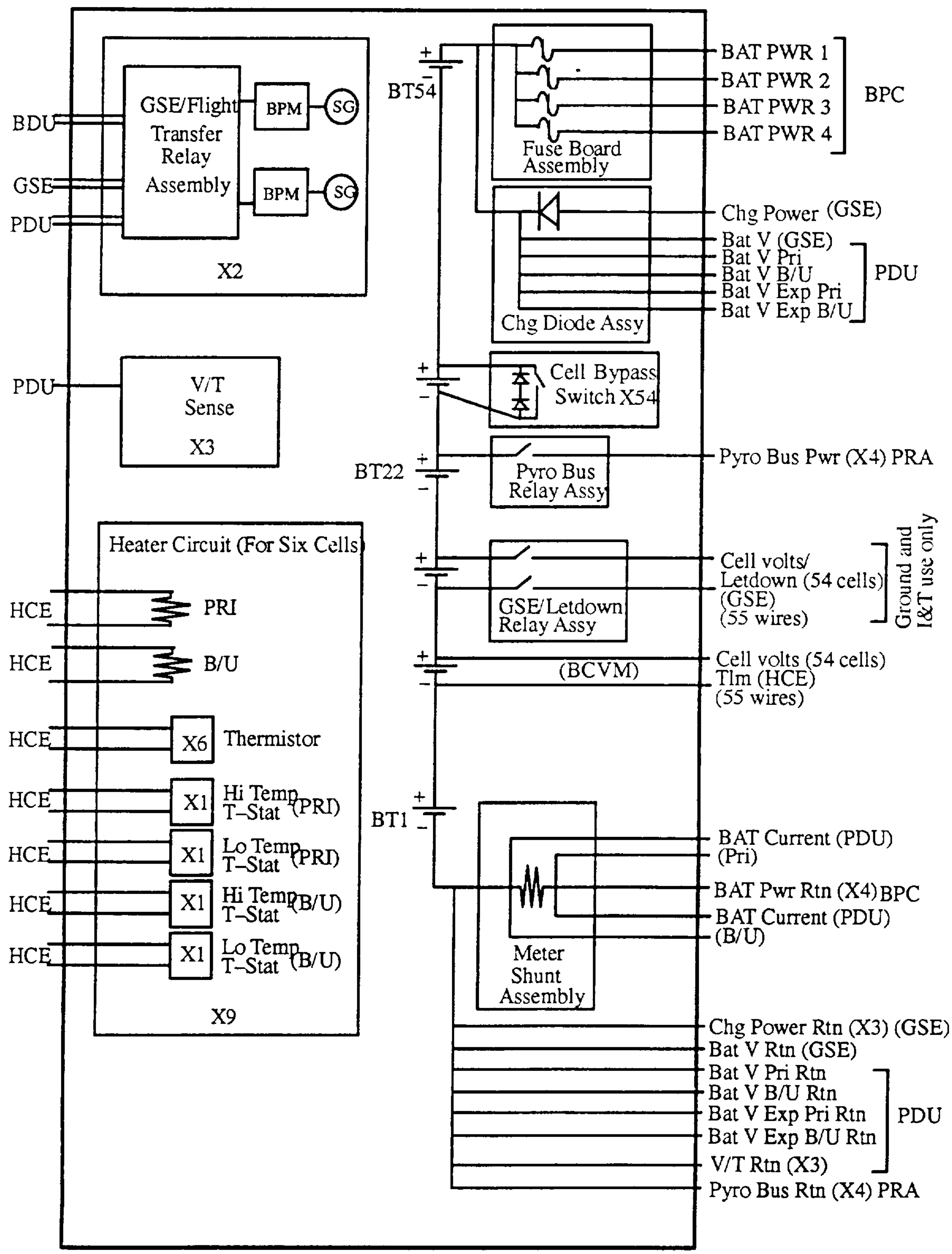
Parameter	Implementation
• Four fused outputs	Fuse Board
• Isolated pyro bus	Pyro bus relay assembly
• Conductive thermal design	Cell/sleeve assembly & baseplate
• Open cell protection	Bypass switch assembly (one per cell)
• Cell pressure telemetry	BPM (4 per BAT)
– GSE/Flight isolation	GSE/Flight transfer 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)

MARTIN MARIETTA
MARTIN MARIETTA ASTRO SPACE

Design Summary

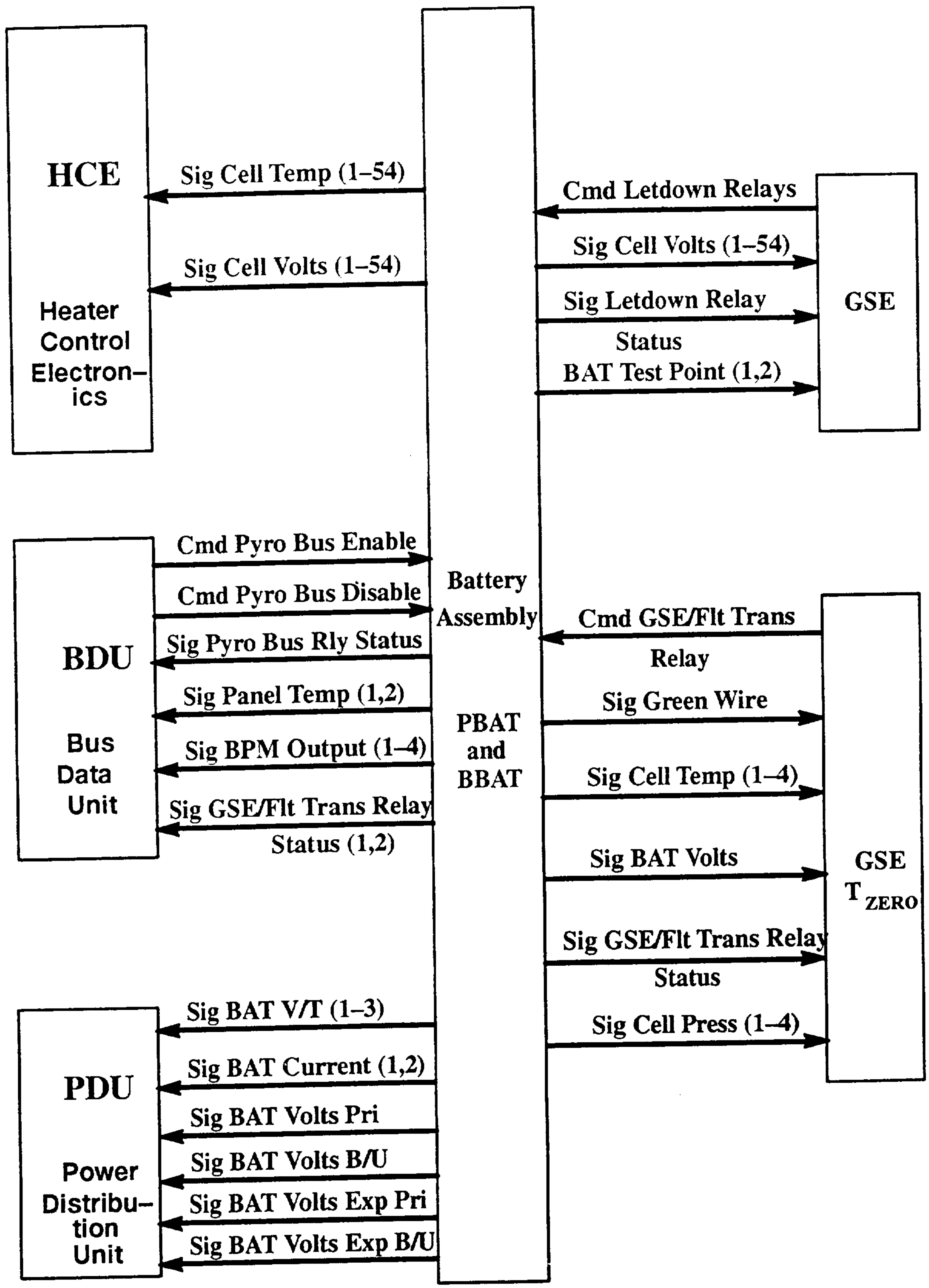
Parameter	Implementation
• Ground cell voltage monitor	GSE/letdown relay assembly
• Ground letdown function	GSE/letdown relay assembly
• Ground BPM cell temp. monitor	GSE T_{zero} umbilical
• Verifiable double insulation	TP1, TP2, TP3 via GSE T_{zero} umbilical
• Charge power connection	Charge power 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

Functional Block Diagram



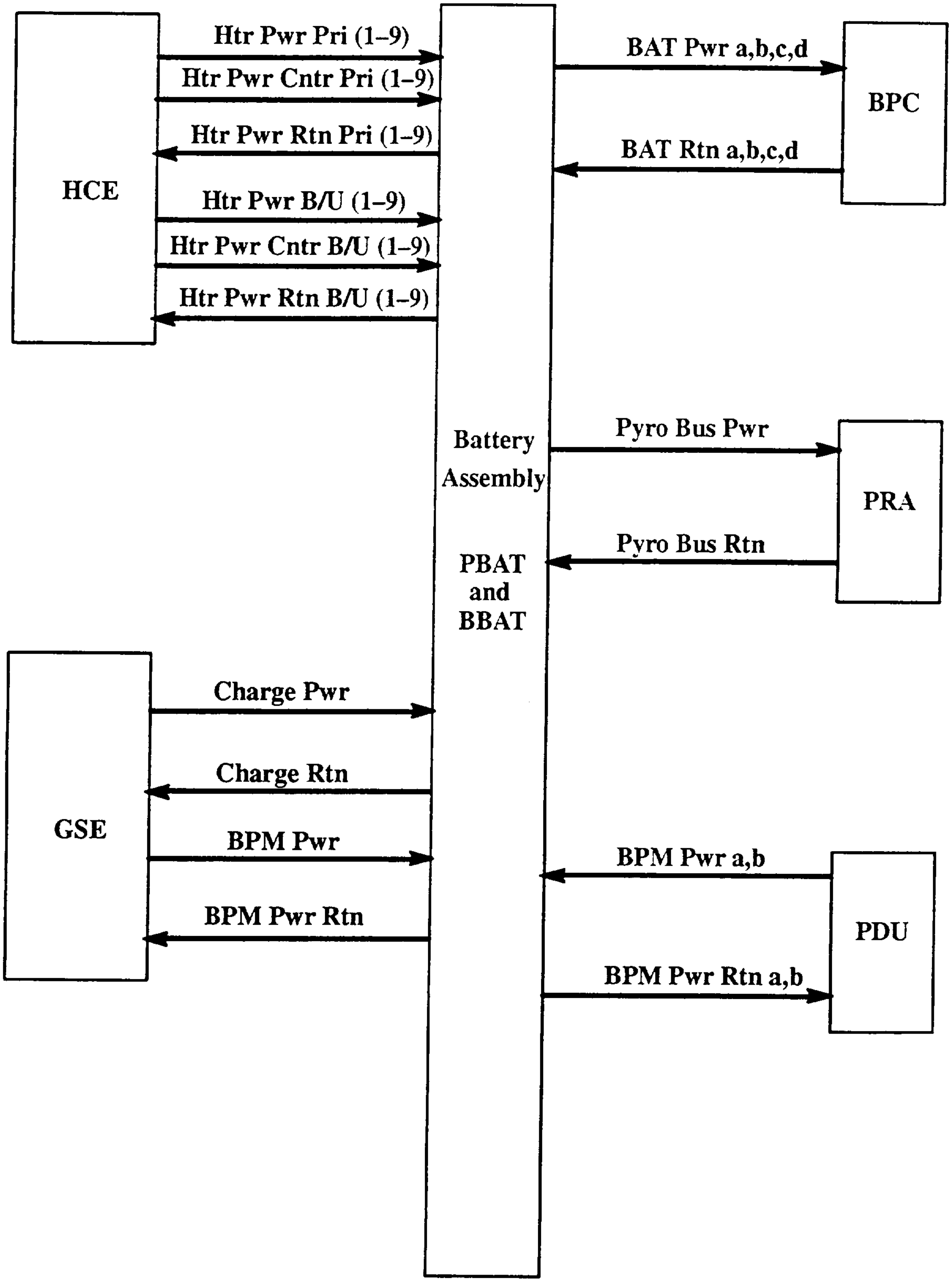
MARTIN MARIETTA
MARTIN MARIETTA ASTRO SPACE

Signal, Command and Telemetry Interfaces



Signal, Command and Telemetry Interfaces

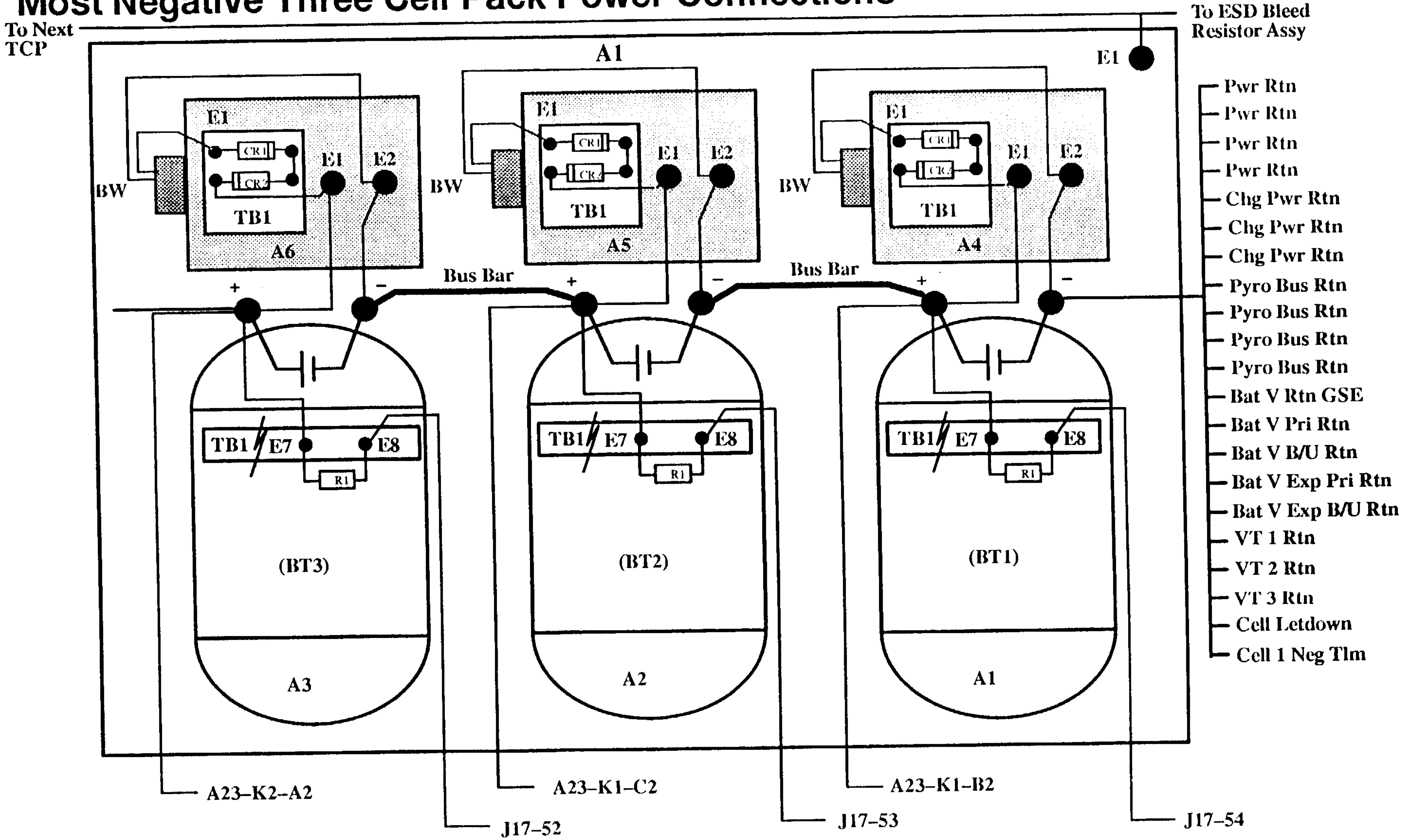
MARTIN MARIETTA
MARTIN MARIETTA ASTRO SPACE



Three Cell Pack Electrical Design

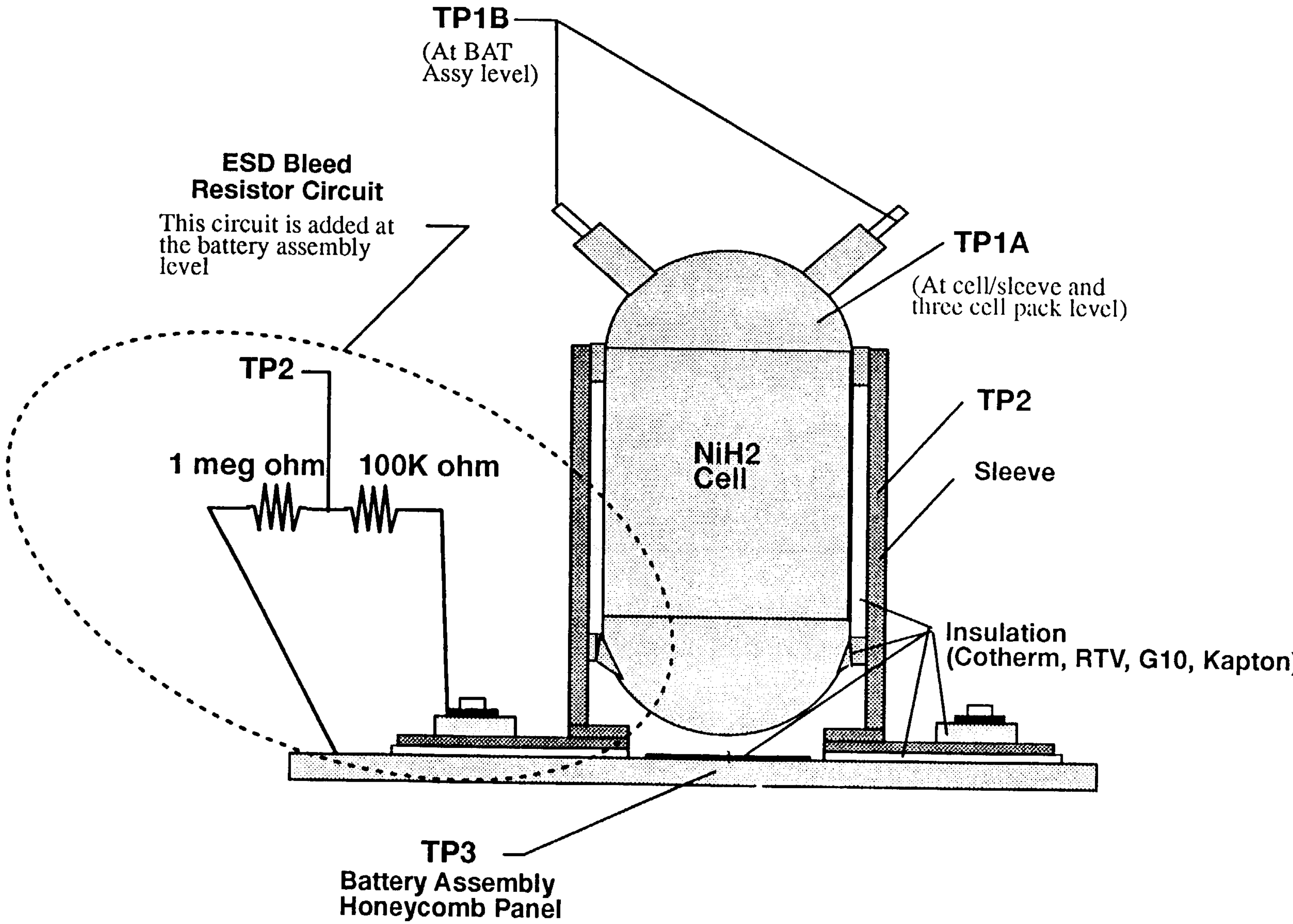
MARTIN MARIETTA
MARTIN MARIETTA ASTRO SPACE

Most Negative Three Cell Pack Power Connections



Verifiable Double Insulation

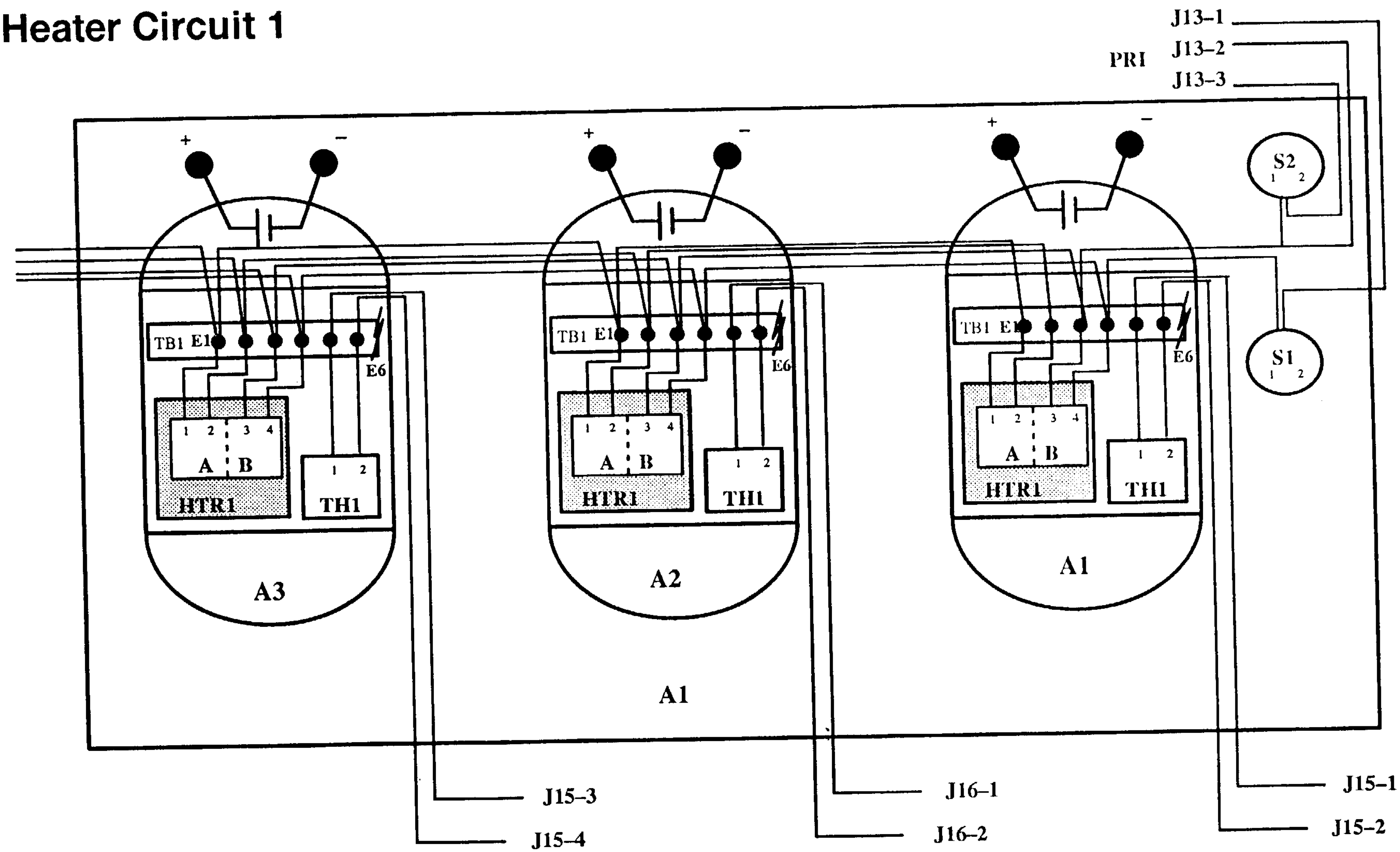
MARTIN MARIETTA
MARTIN MARIETTA ASTRO SPACE



MARTIN MARIETTA
MARTIN MARIETTA ASTRO SPACE

Three Cell Pack Heater Circuits

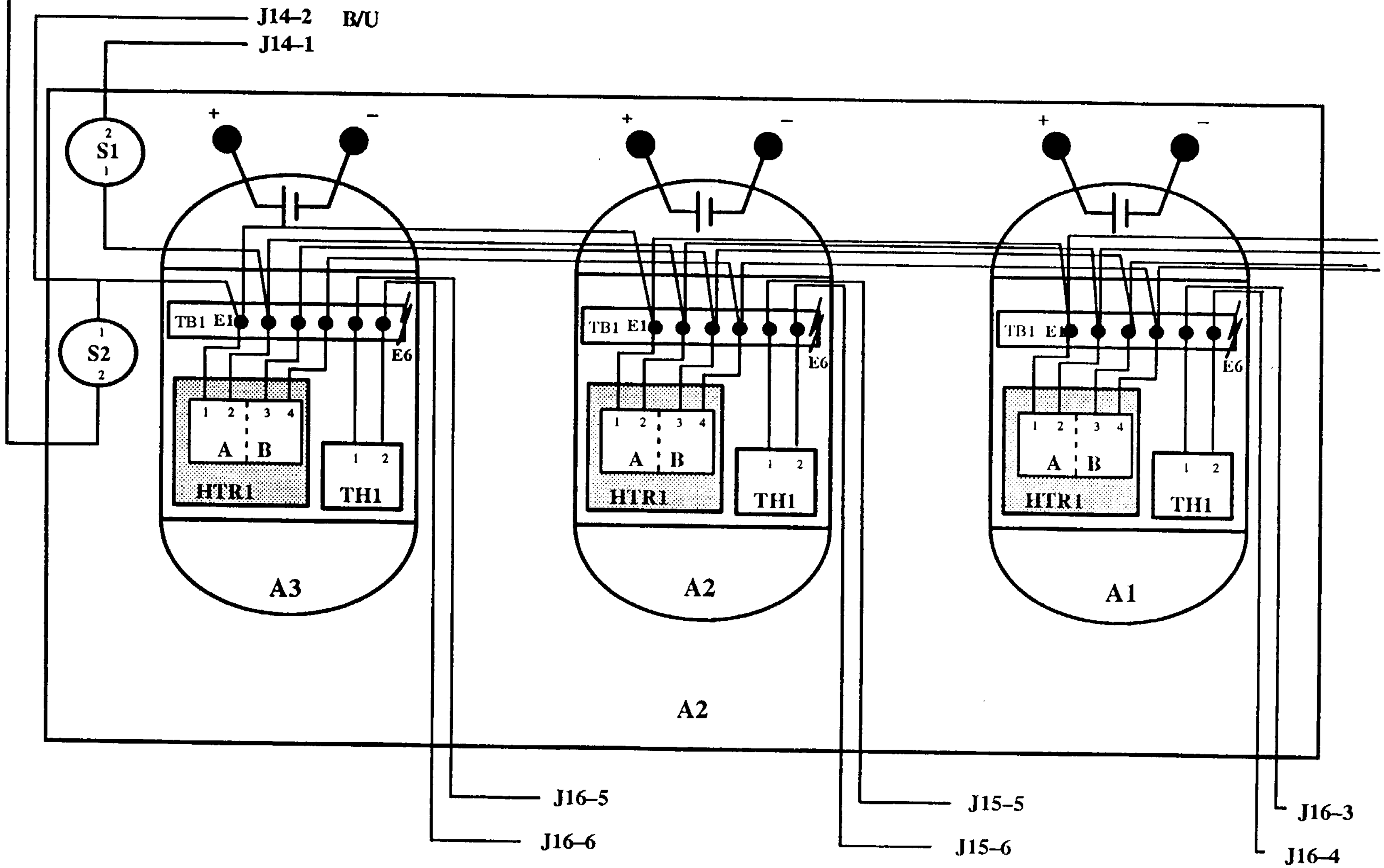
Heater Circuit 1



Three Cell Pack Heater Circuits

MARTIN MARIETTA
MARTIN MARIETTA ASTRO SPACE

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

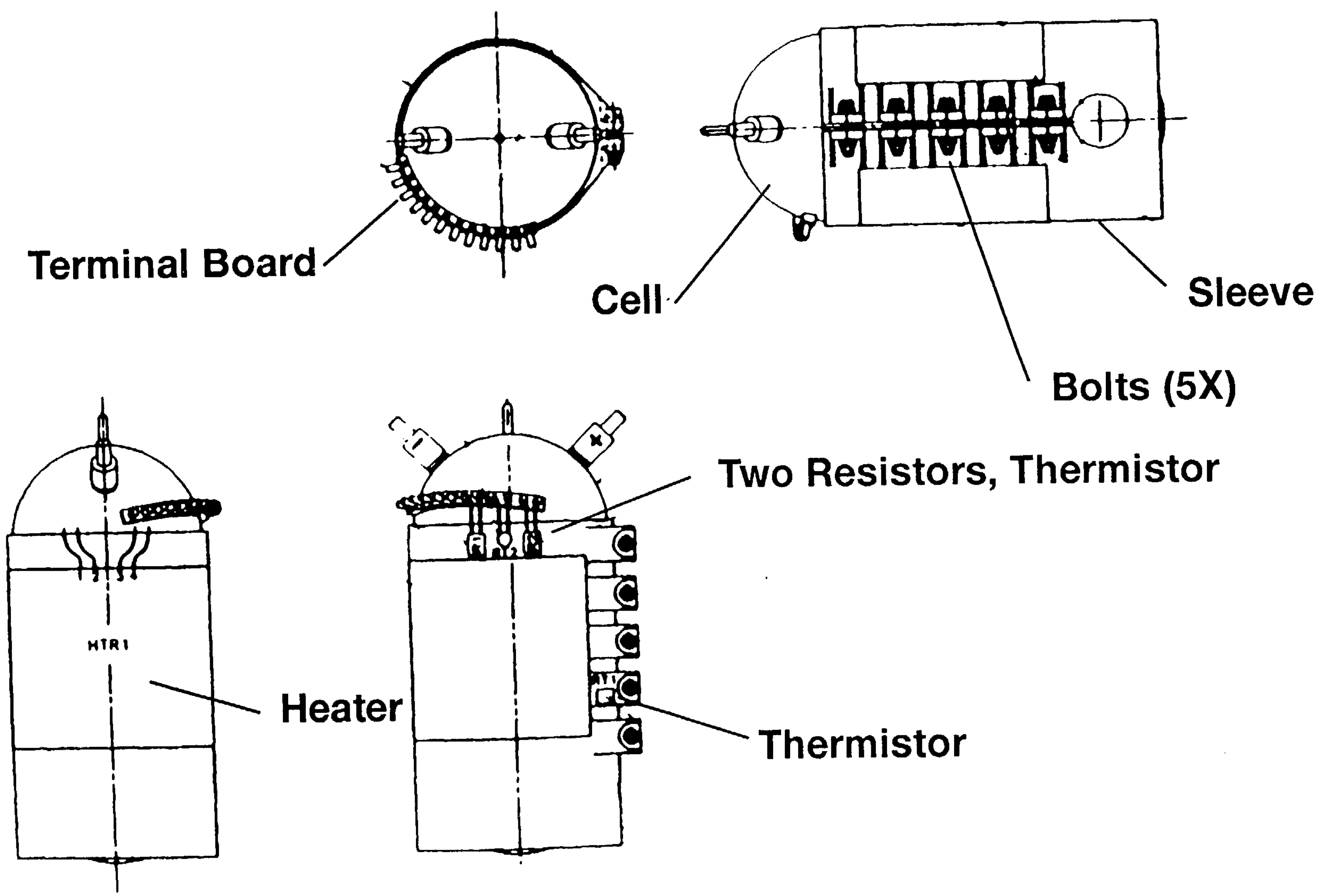
Battery Assembly Modular Design

MARTIN MARIETTA ASTRO SPACE

- 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

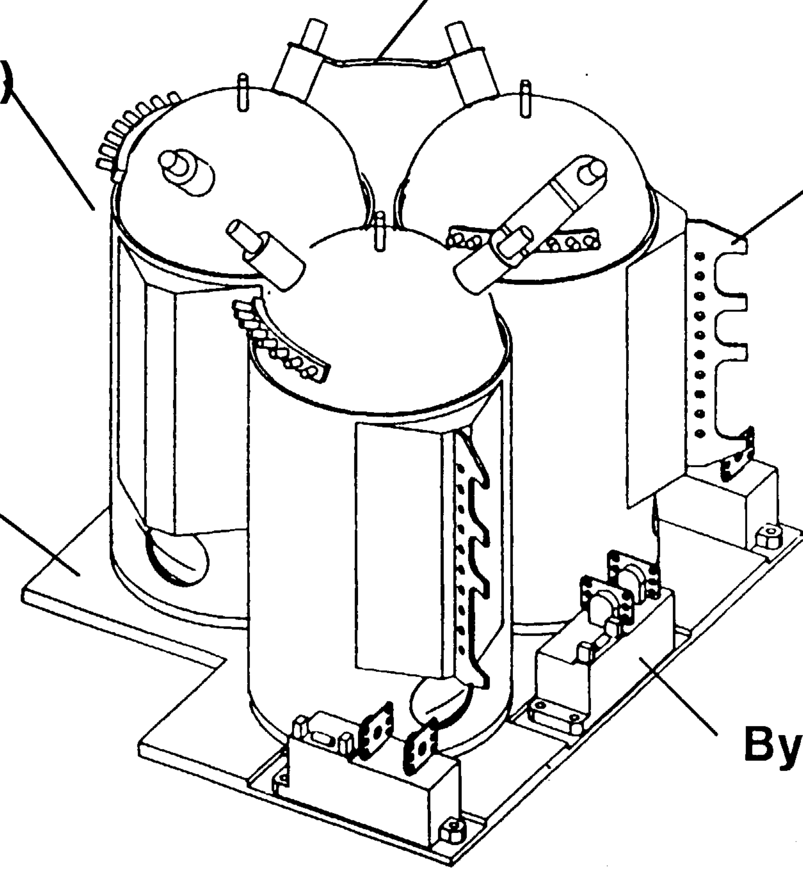
MARTIN MARIETTA
MARTIN MARIETTA ASTRO SPACE



Three Cell Pack

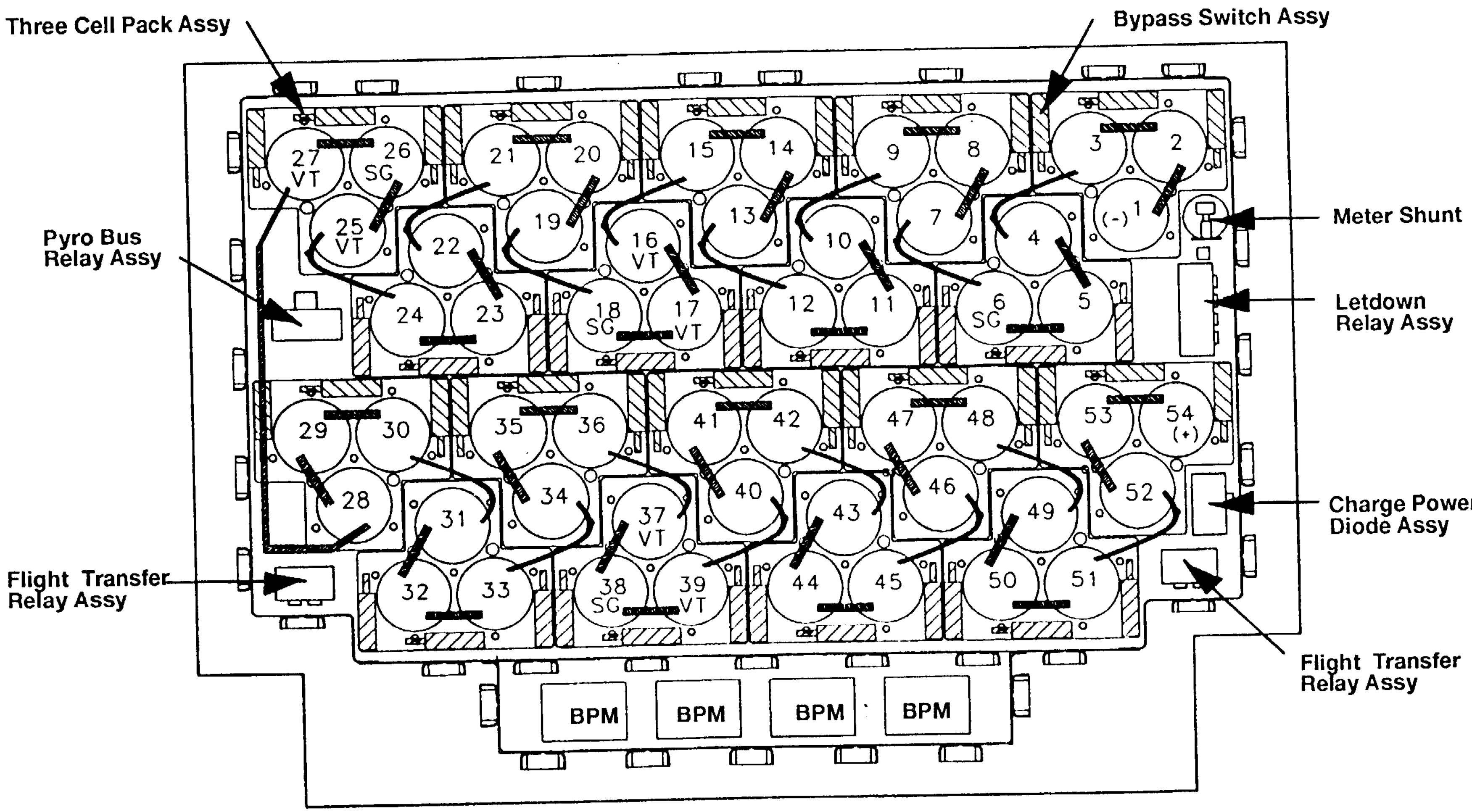
MARTIN MARIETTA

MARTIN MARIETTA ASTRO SPACE

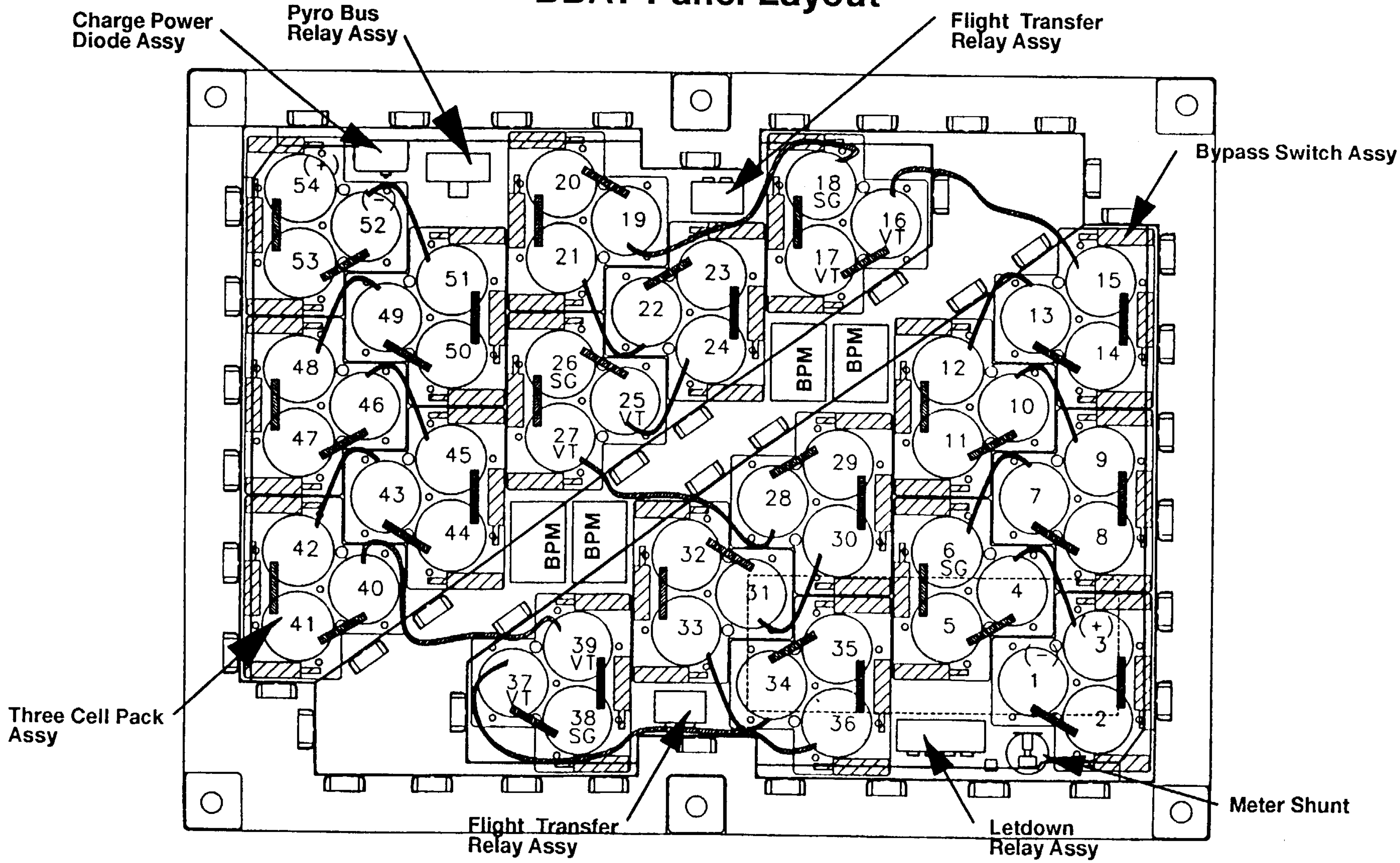


Battery Assembly

PBAT Panel Layout



BBAT Panel Layout



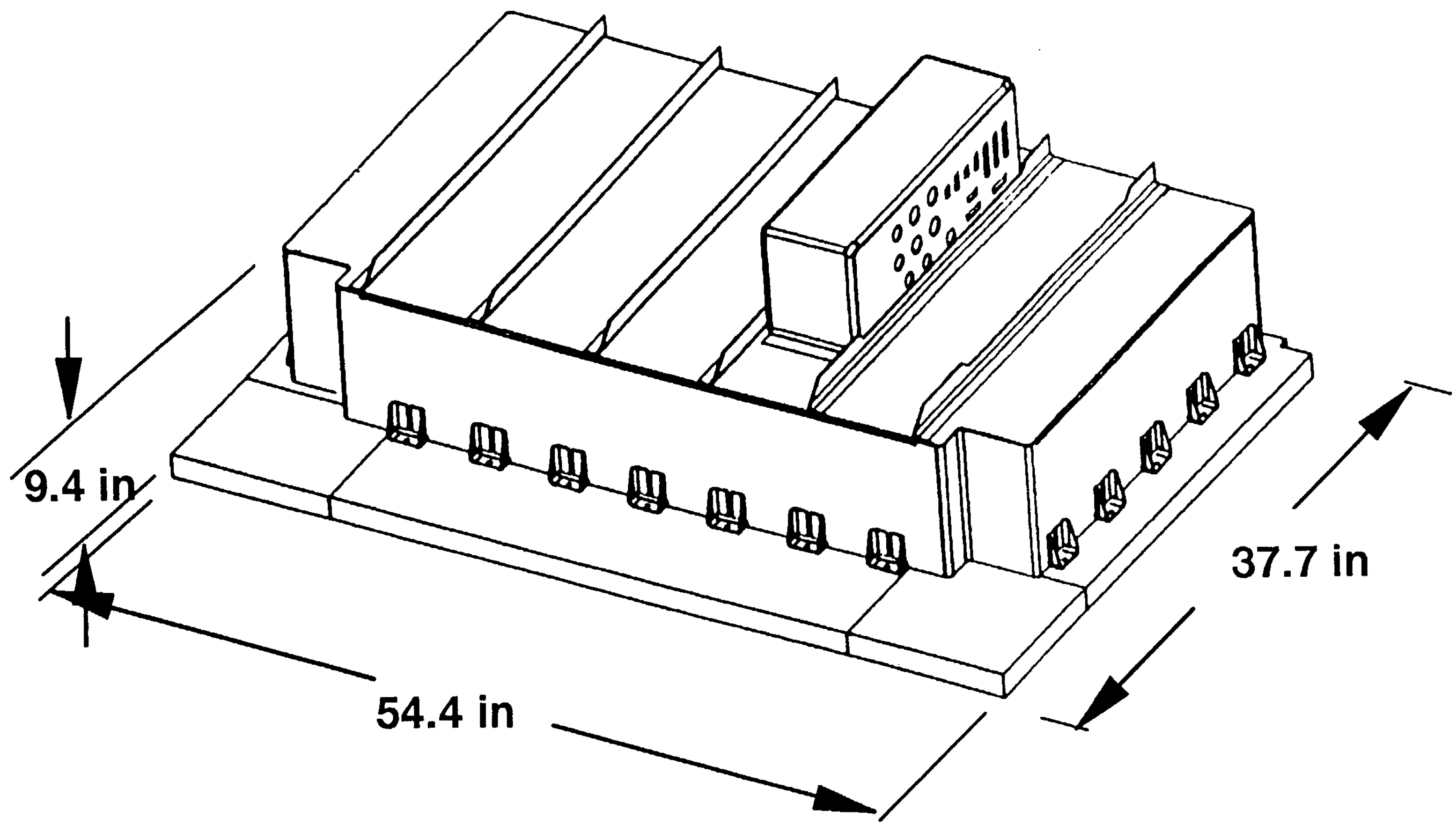
Power Module Battery Cover

MARTIN MARIETTA

MARTIN MARIETTA ASTRO SPACE

Panel and Cover

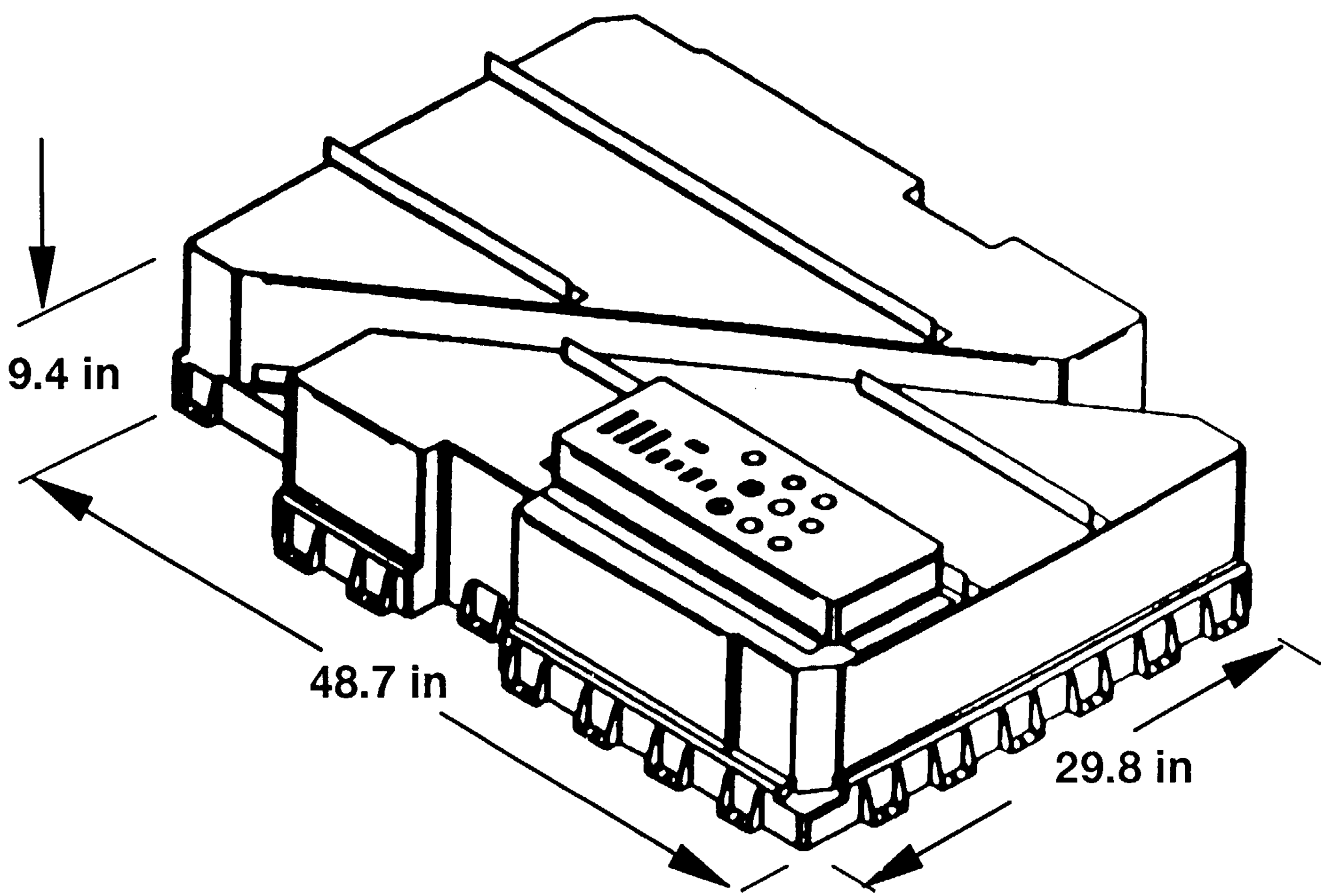
299.7 lbs



Hex Bay Battery Cover

NASA MARTIN MARIETTA
MARTIN MARIETTA ASTRO SPACE

Panel and Cover
304.7 lbs



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

esa

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

HISTORY OF USE BY ESA

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.

CLUSTER BATTERIES

esa

- ***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).

esa

BATTERY MANAGEMENT COMPARISON

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).

esa

CLUSTER BATTERY FABRICATION Problem 1

- ***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

esa

- ***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.

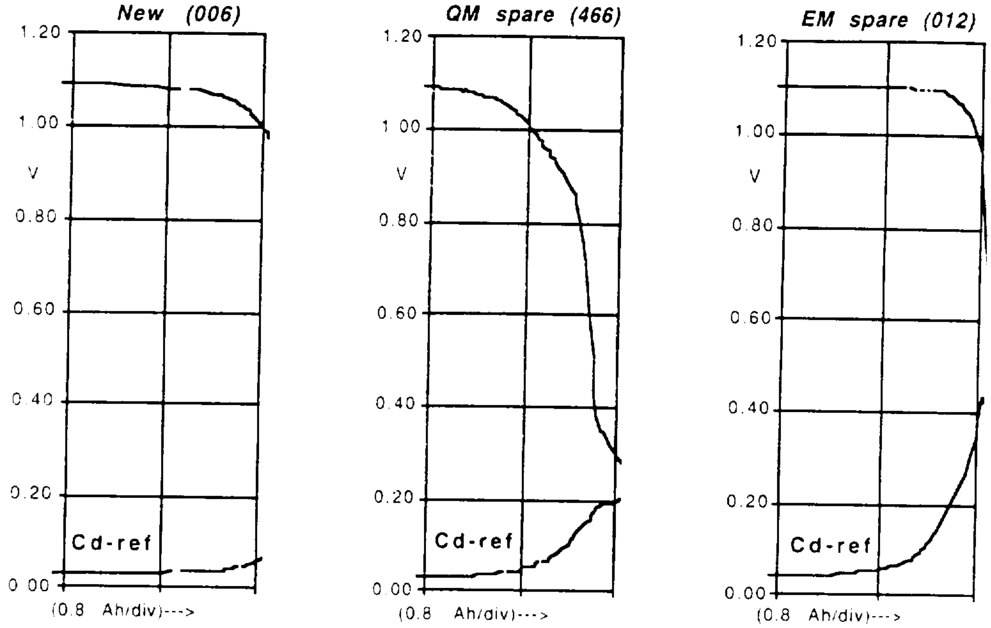
INITIAL CYCLE RESULT SUMMARY

esa

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.

esa

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

esa

- *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.

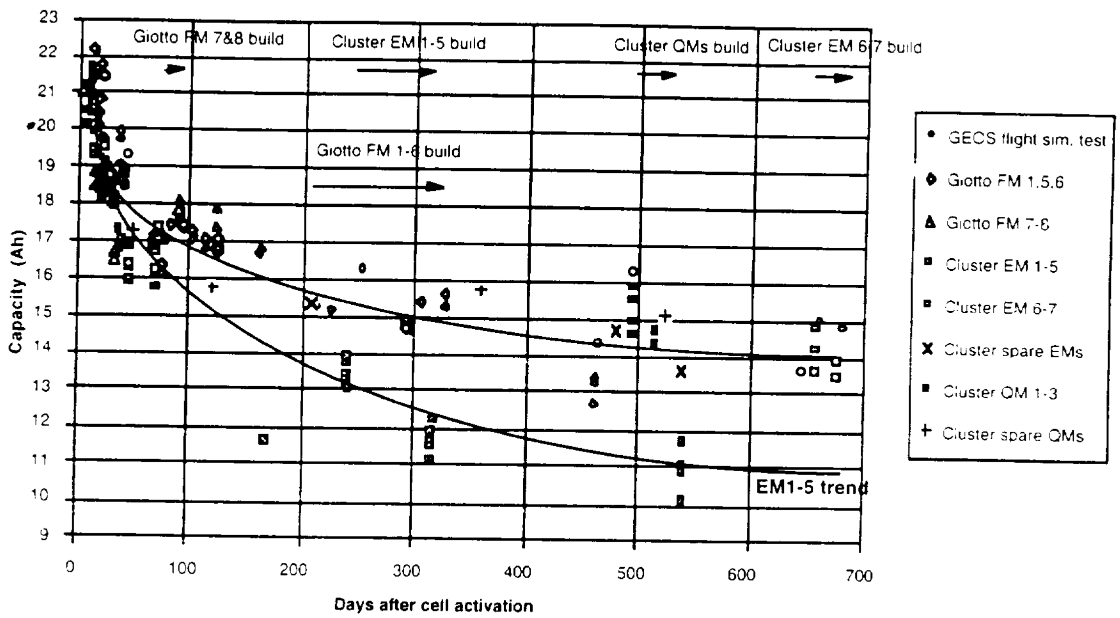
REVIEW OF EM & QM CELL FORMATION

esa

- ***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

esa

- *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*

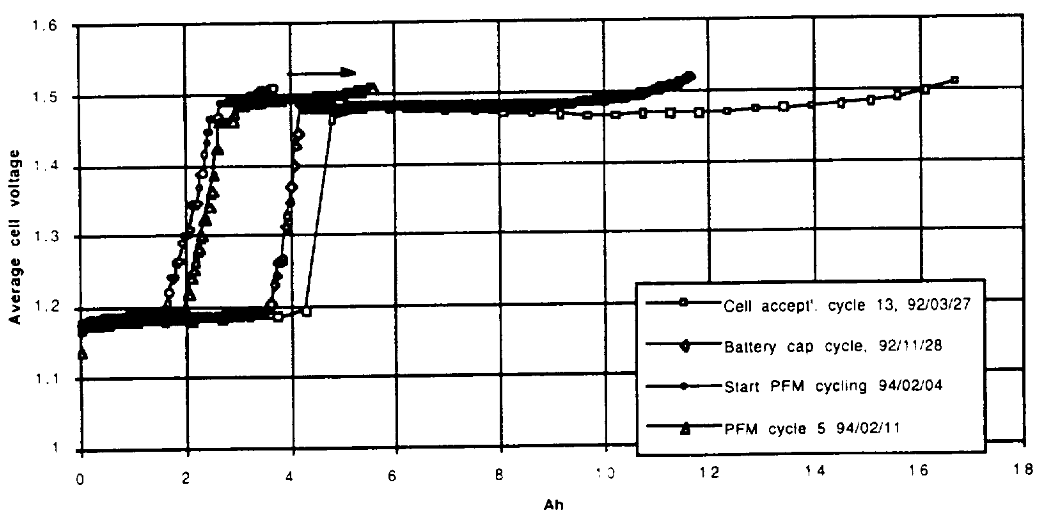
CLUSTER EM BATTERY INTEGRATION TESTS **Problem 2**

esa

- ***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***

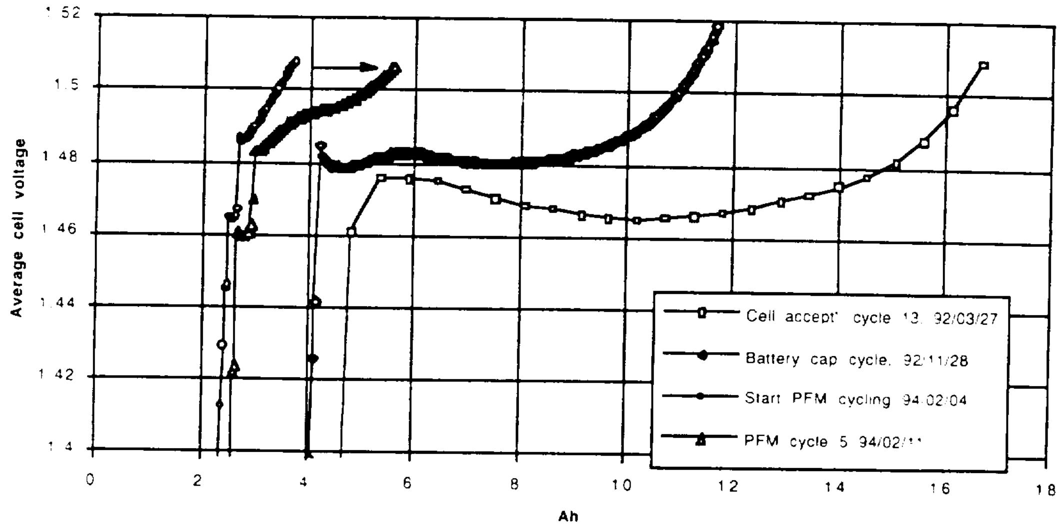
Since their construction, the EM batteries had been stored discharged at ambient temperature for 4 months before they were needed for integration testing. Before the start of these tests, a further standard capacity check was carried out and revealed a further drop in capacity of all 5 batteries. By 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



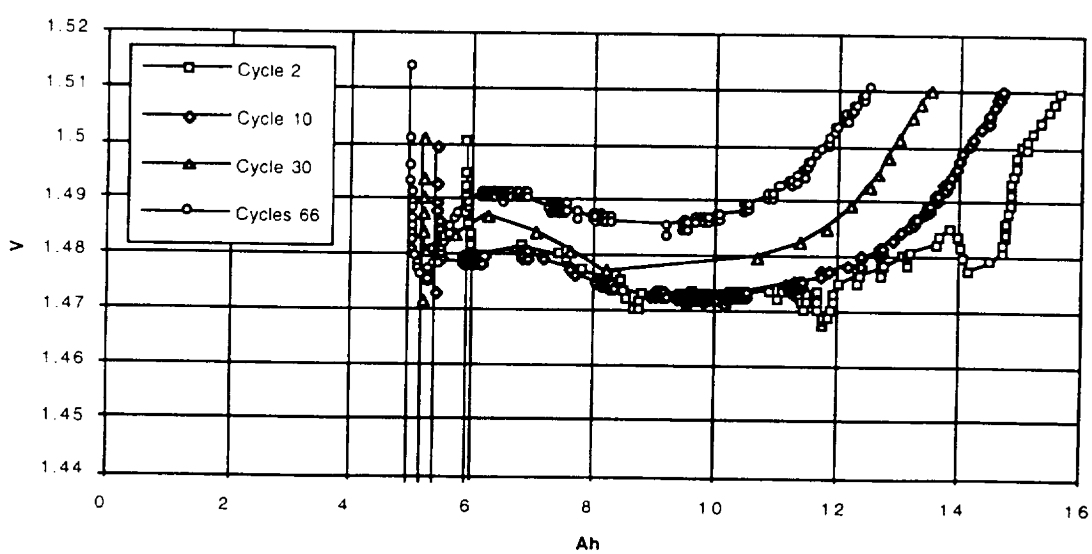
This compares the average cell voltage charge curves of the cells used to make battery EM 4 with the curves measured at battery level before the start of integration testing. The curves are dominated by the transition from the first plateau (Ag ----> Ag_2O) to the second (Ag_2O----> AgO). Although these 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)



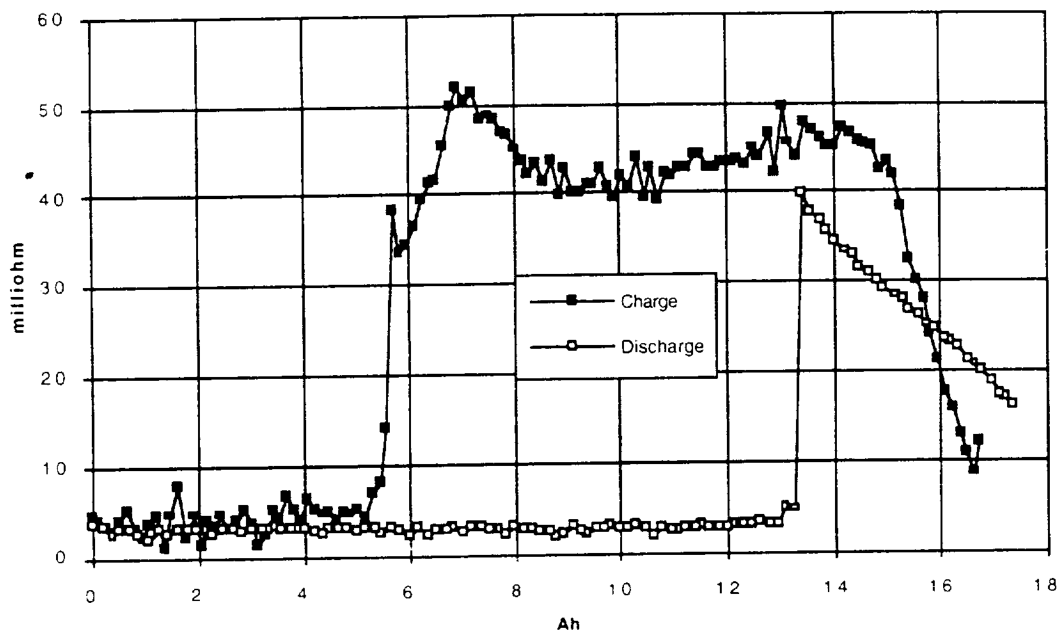
Here the same second plateau charge data is shown on an expanded scale. The change in shape of the charge voltage curves can now be seen clearly. From the reference electrode data from single cell tests we believe that these changes are due only to the silver electrode. (EM batteries are not yet available 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.

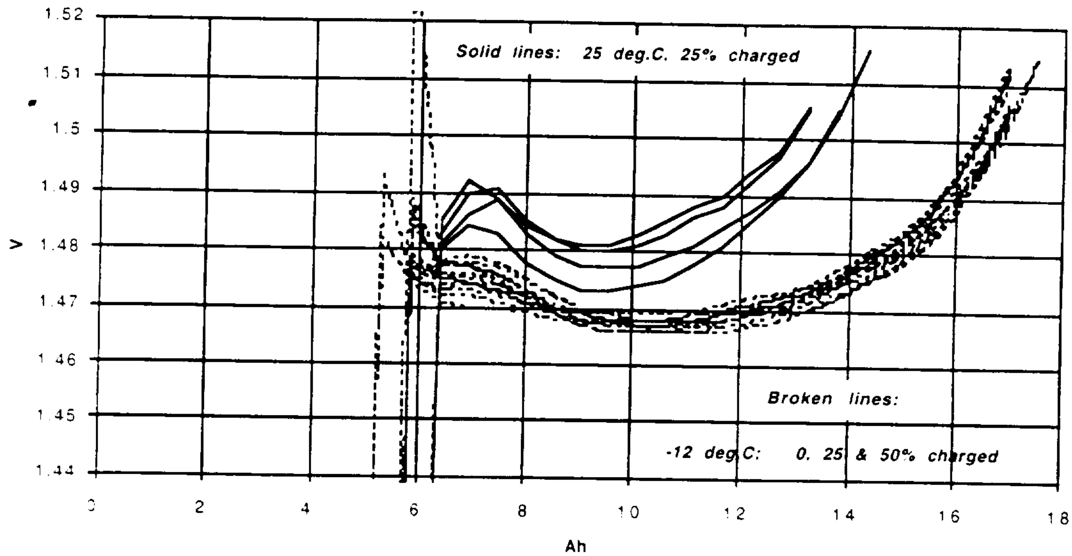
SUMMARY OF OBSERVATIONS

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.

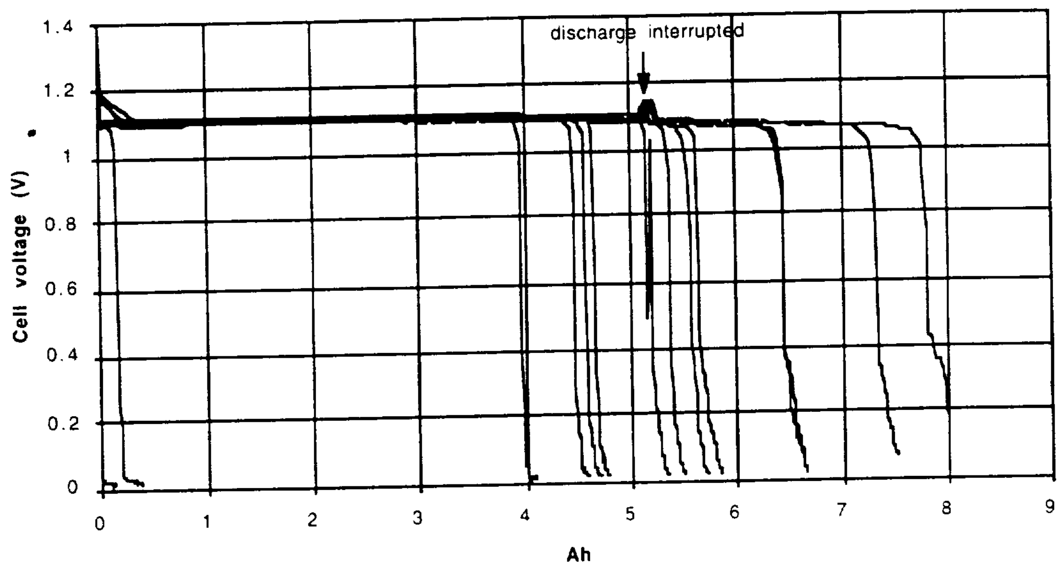
AFTER EM INTEGRATION TESTS **Problem 3**

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***

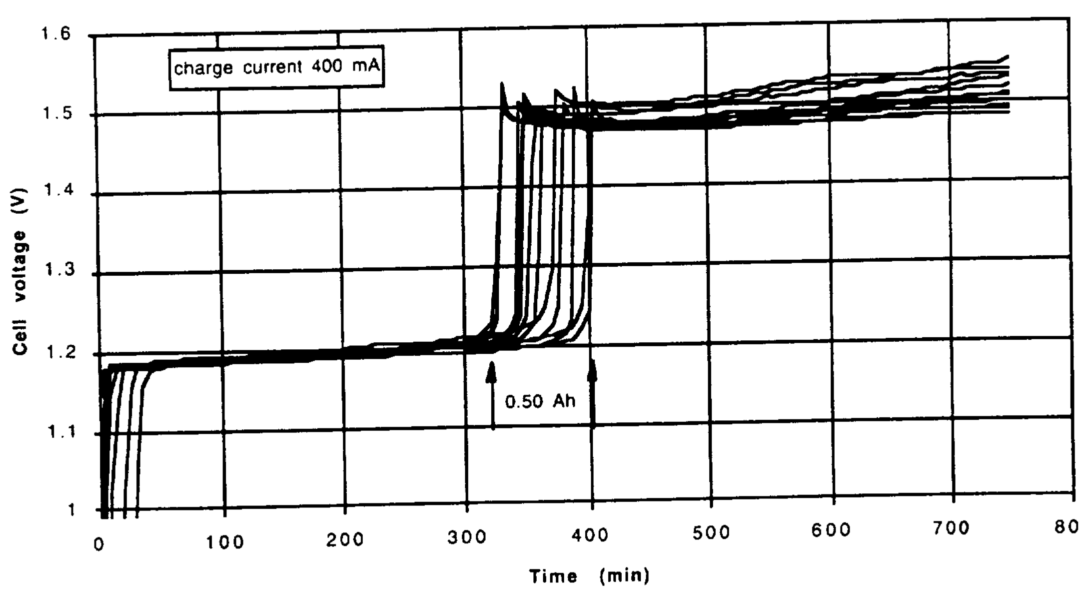
During integration tests, battery cycling was started and stopped according to the needs of the equipment under test. Consequently batteries sometimes remained for prolonged periods at intermediate states of charge. As a result individual cell's state of charge began to diverge. This in turn led the 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

esa

- ***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

esa

- ***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.

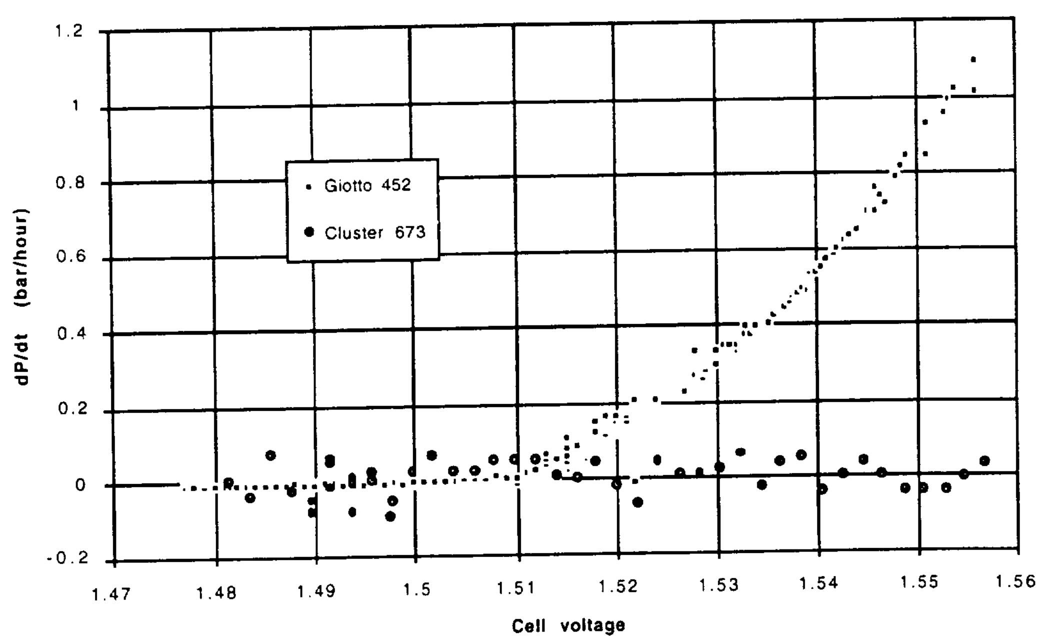
esa

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

PRECEDING PAGE BLANK NOT FILMED

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:

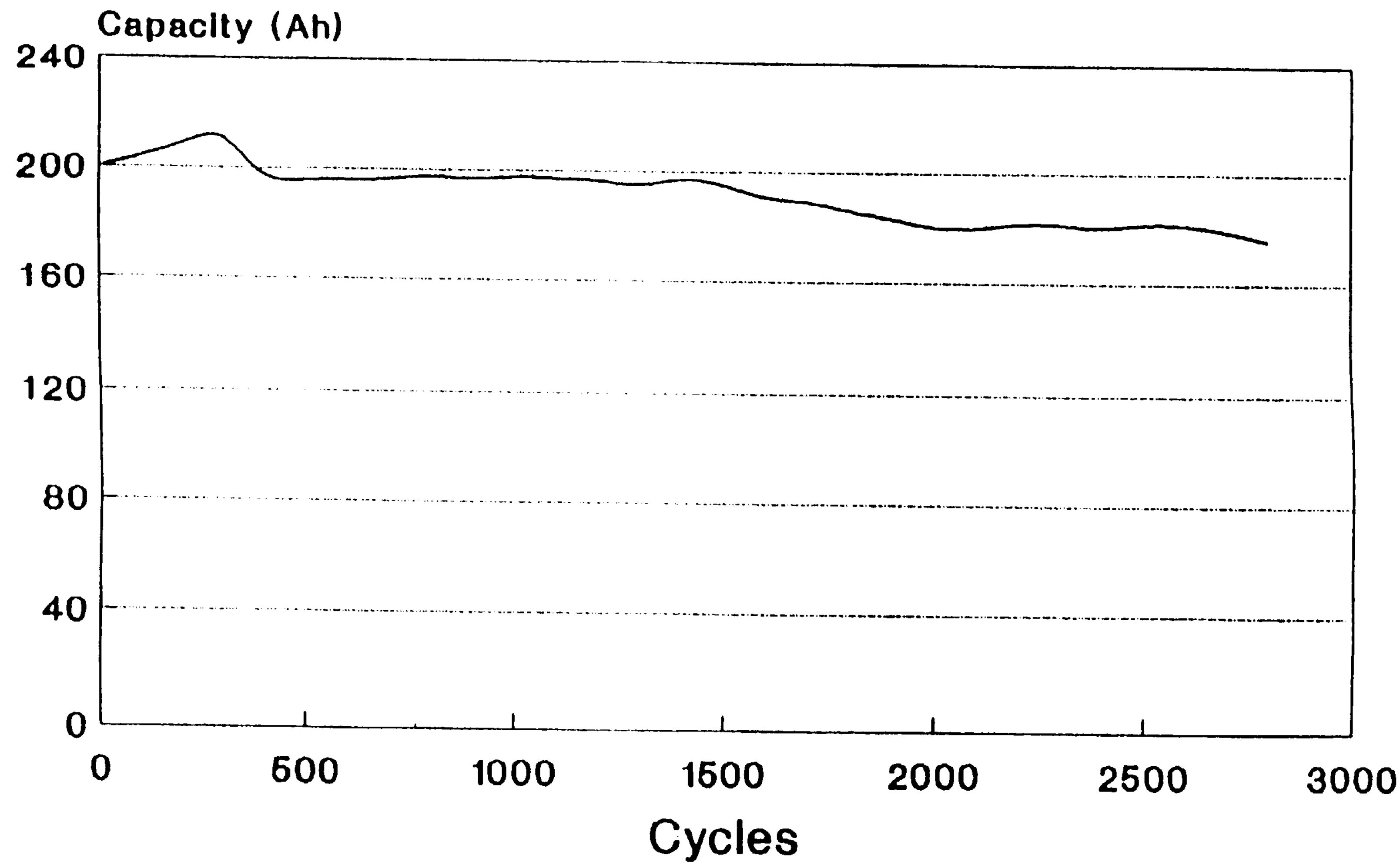
Boeing 777	Longbow Apache
MD-90	F-22

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

FNC

FNC

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



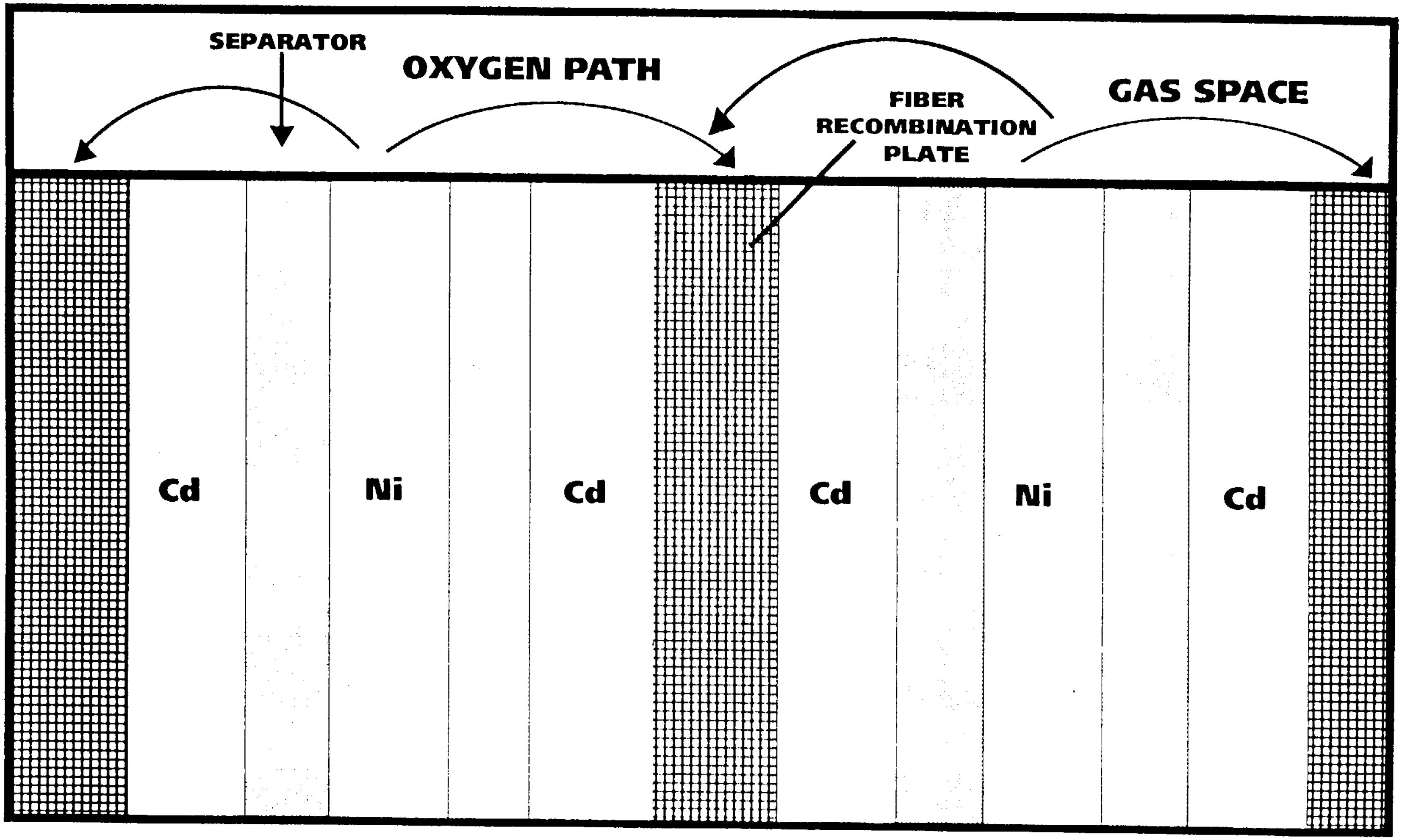
DAUG Laboratory, 1989-1990

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

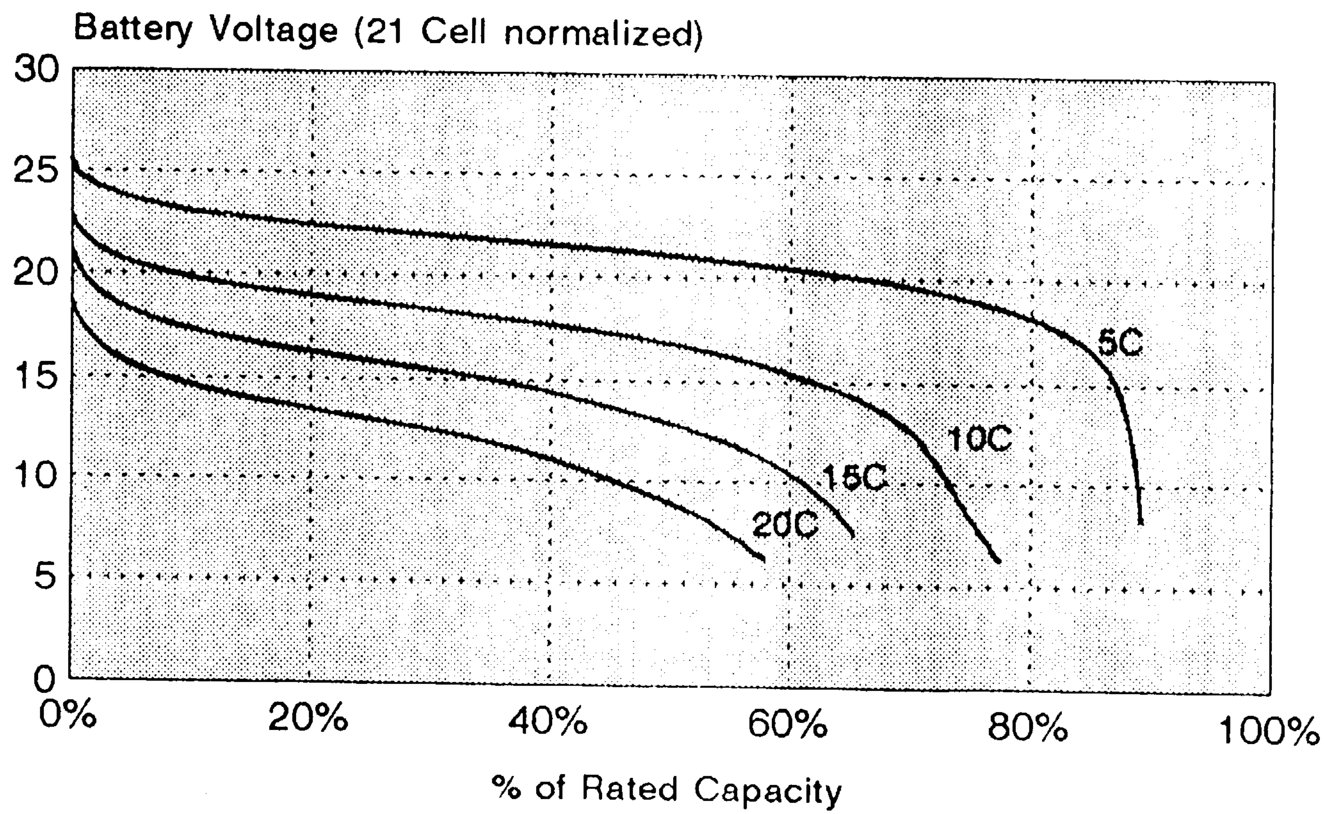
FNC

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

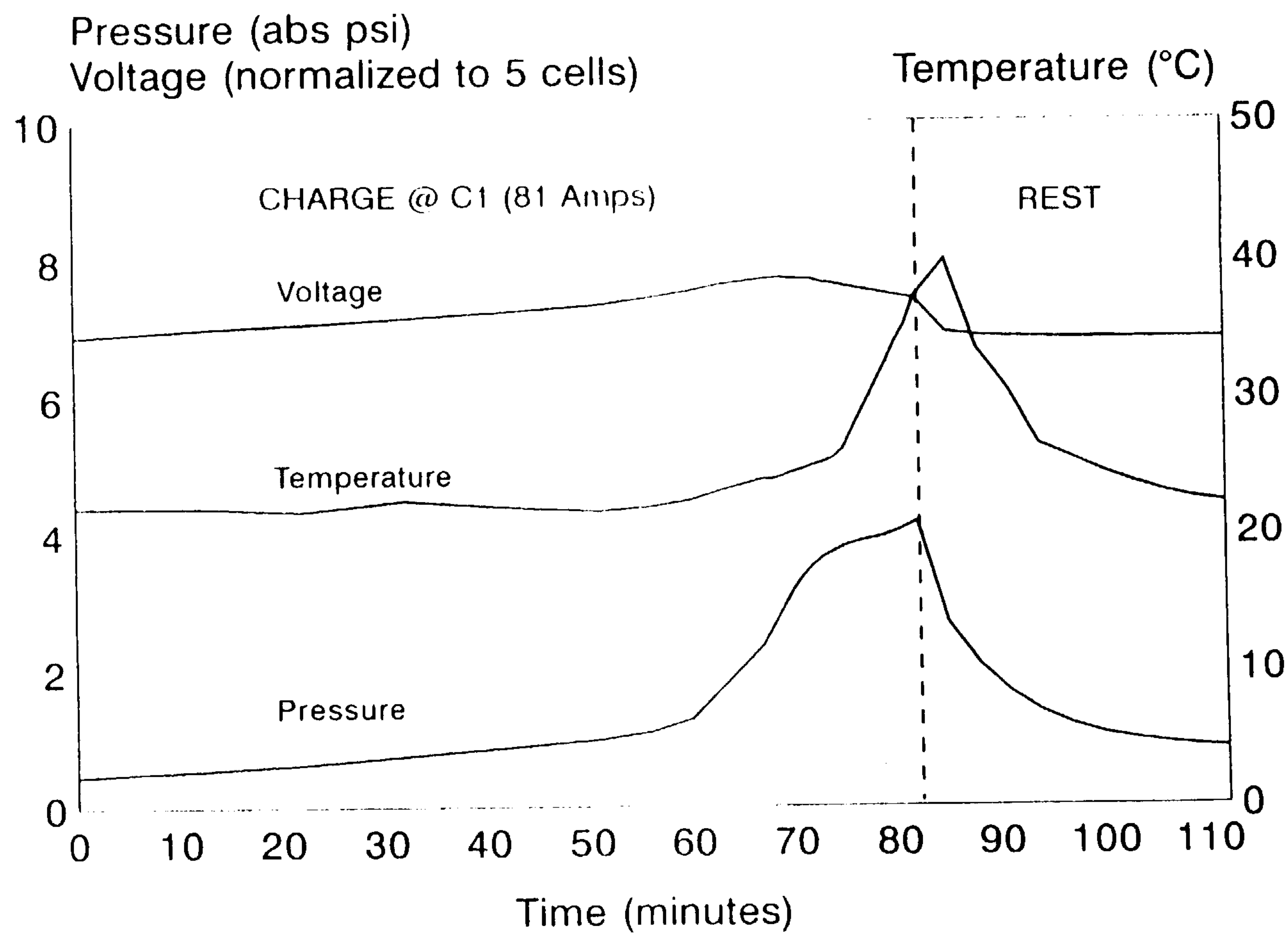
FNC

Typical Discharge Characteristics
for FNC Sealed X-type Cells



FNC

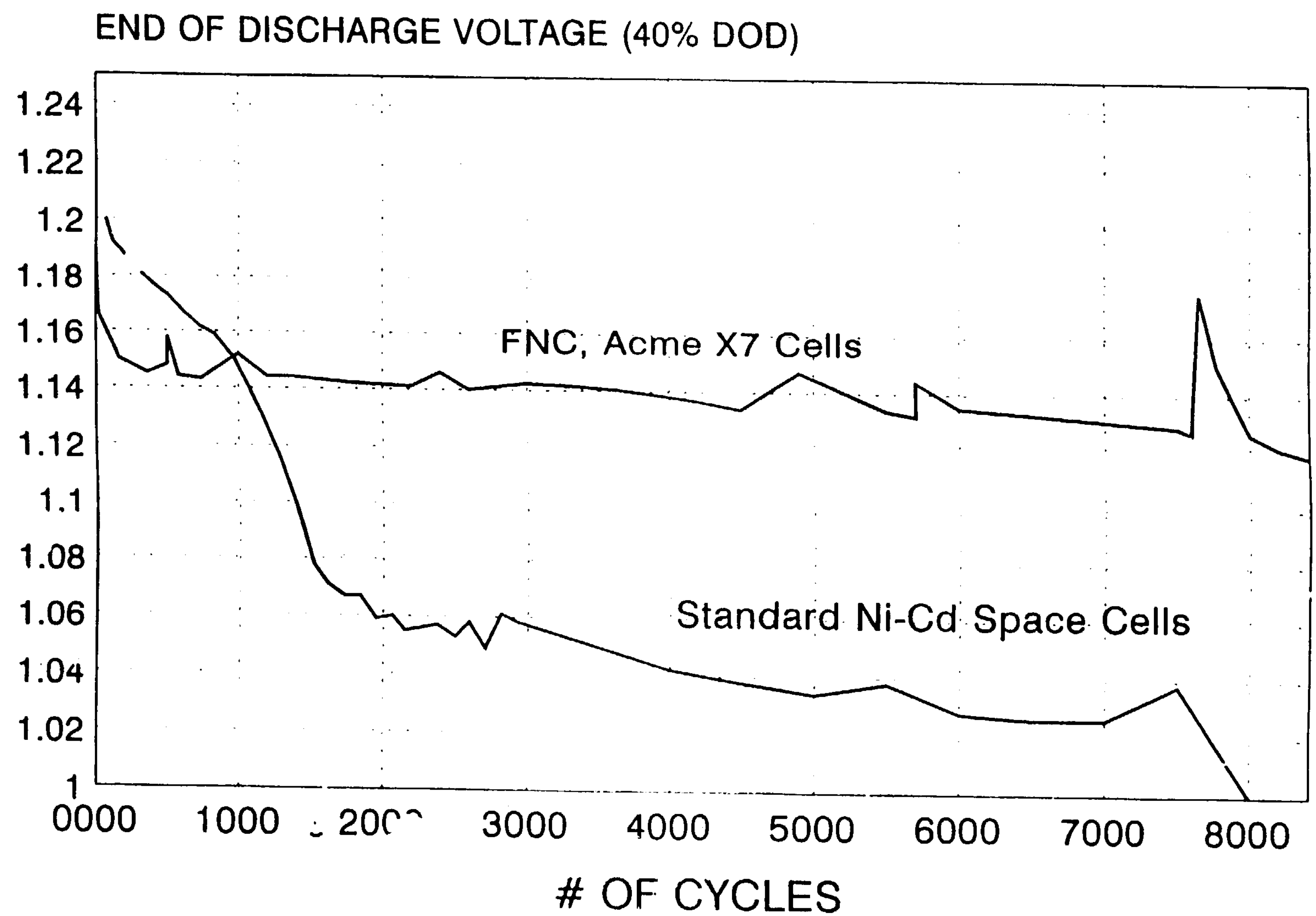
Charging Characteristics
X81 Cell, 24°C



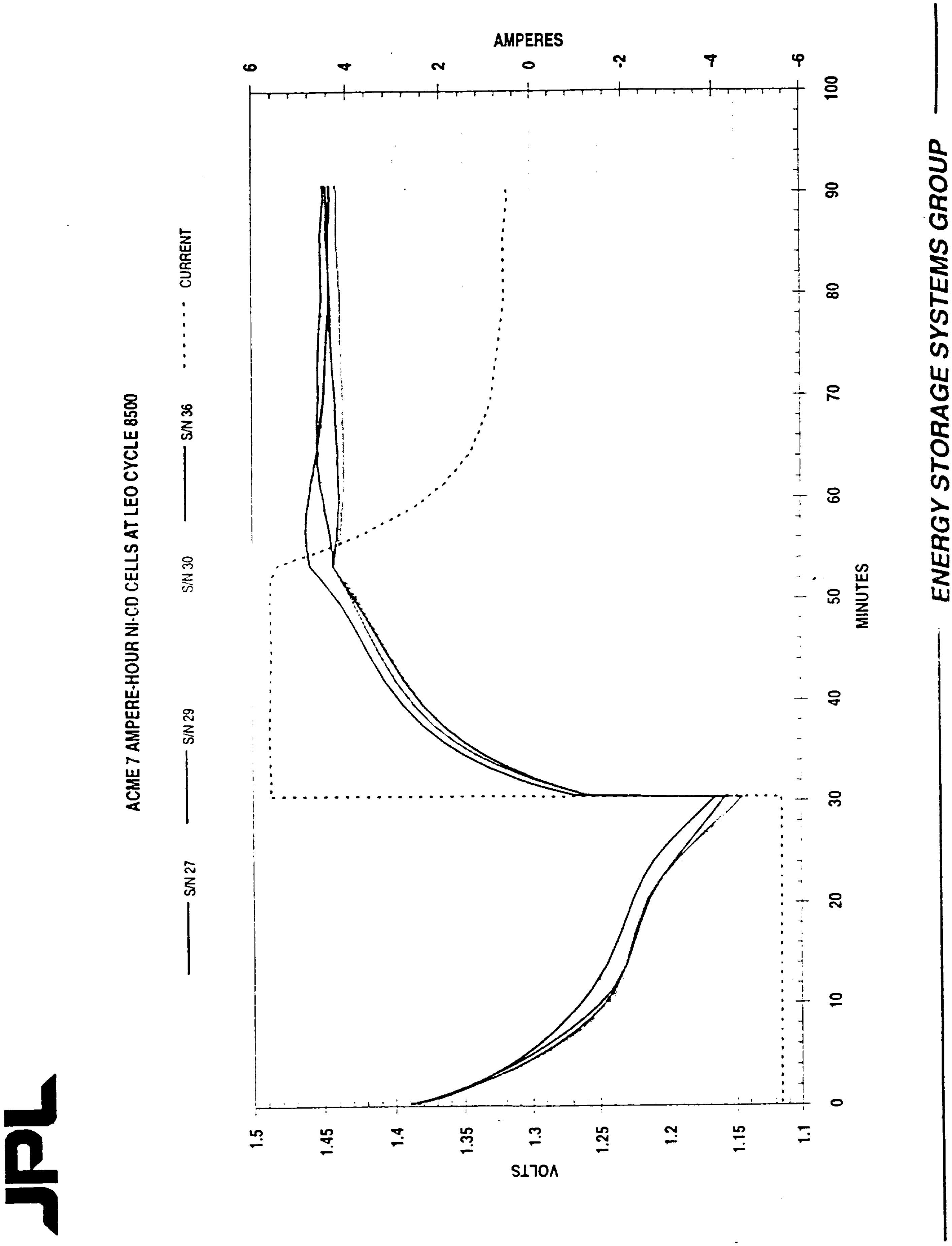
FNC

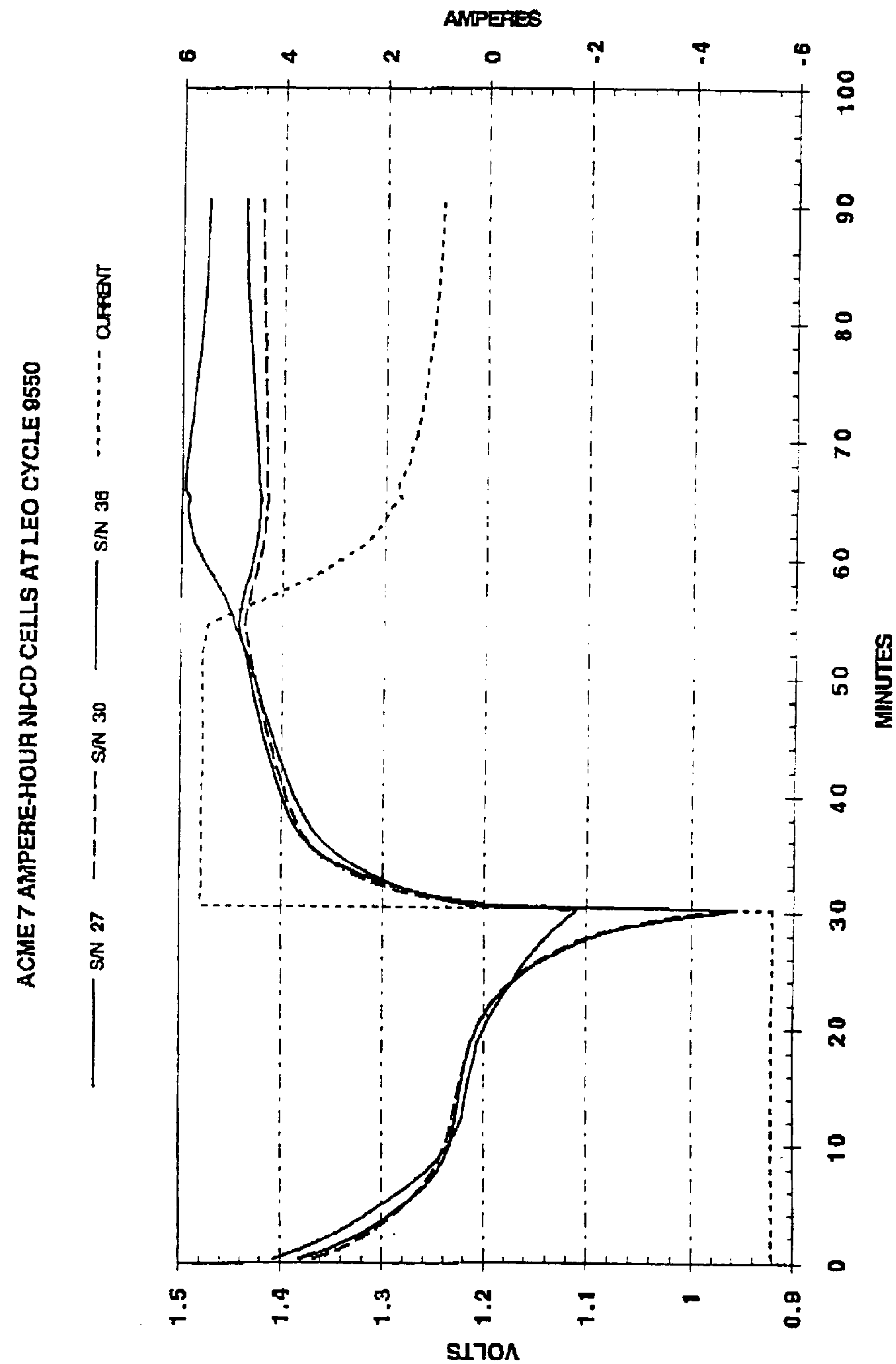
Accelerated LEO Stress Test
20°C / 40% DOD

FNC

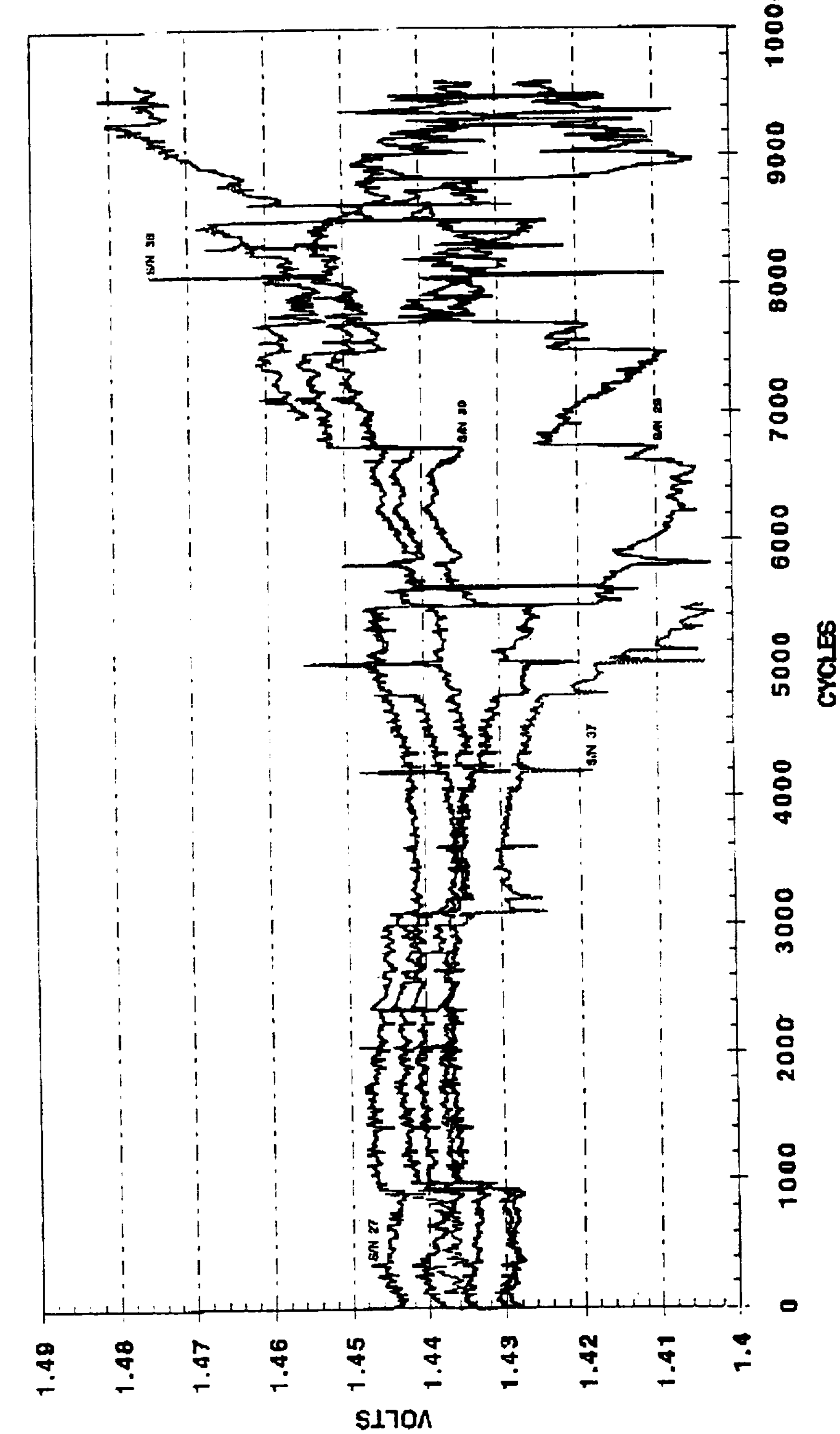


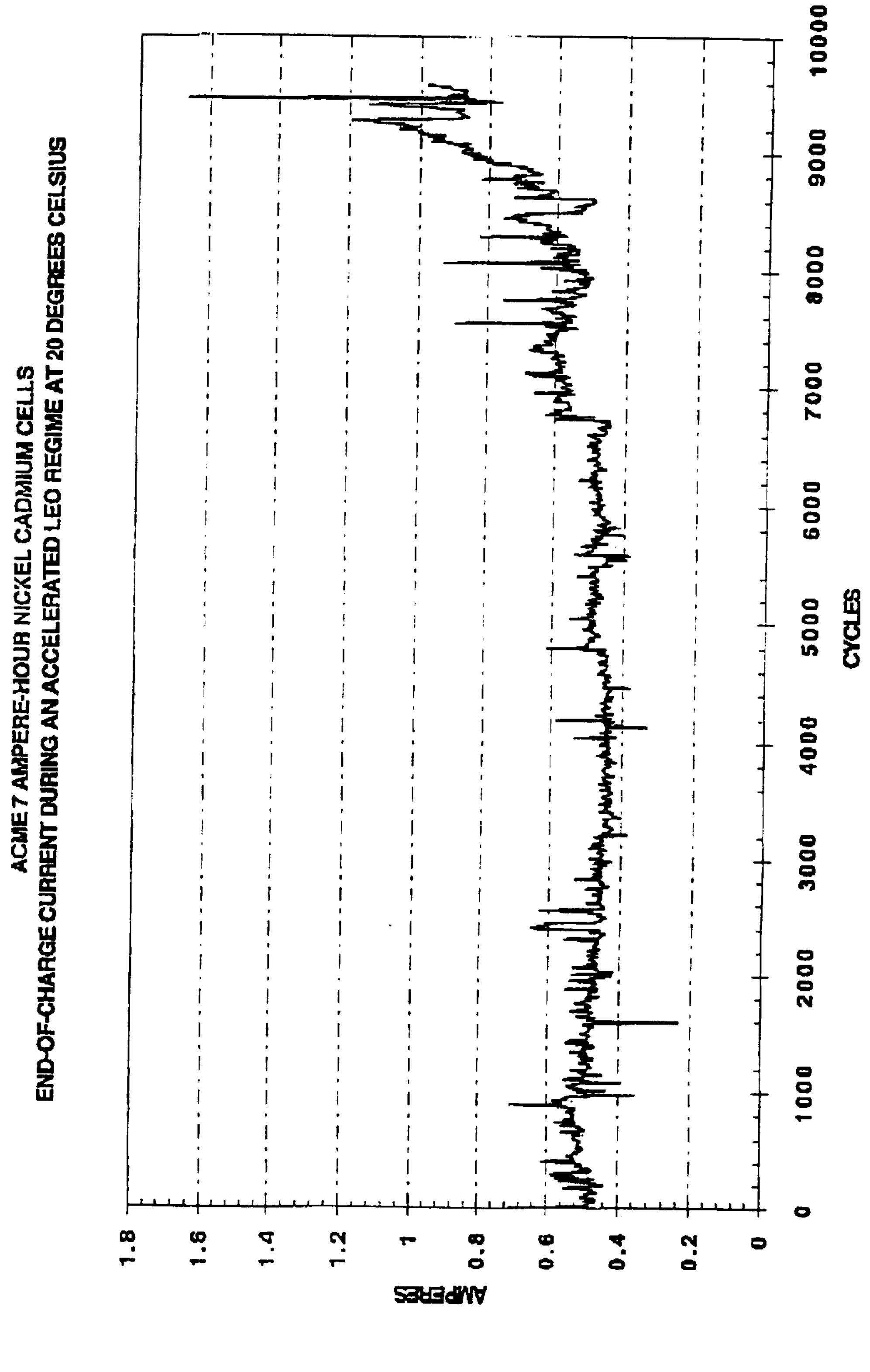
JPL Data 1991 - 1994


JPL
ACME 7 AMPERE-HOUR NI-CD CELLS AT LEO CYCLE 8500
S/N 27
S/N 29
S/N 30
S/N 36
CURRENT
AMPERES
6
4
2
0
-2
-4
-6
VOLTS
1.5
1.45
1.4
1.35
1.3
1.25
1.2
1.15
1.1
MINUTES
0
10
20
30
40
50
60
70
80
90
100
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
AMPERES
MINUTES

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

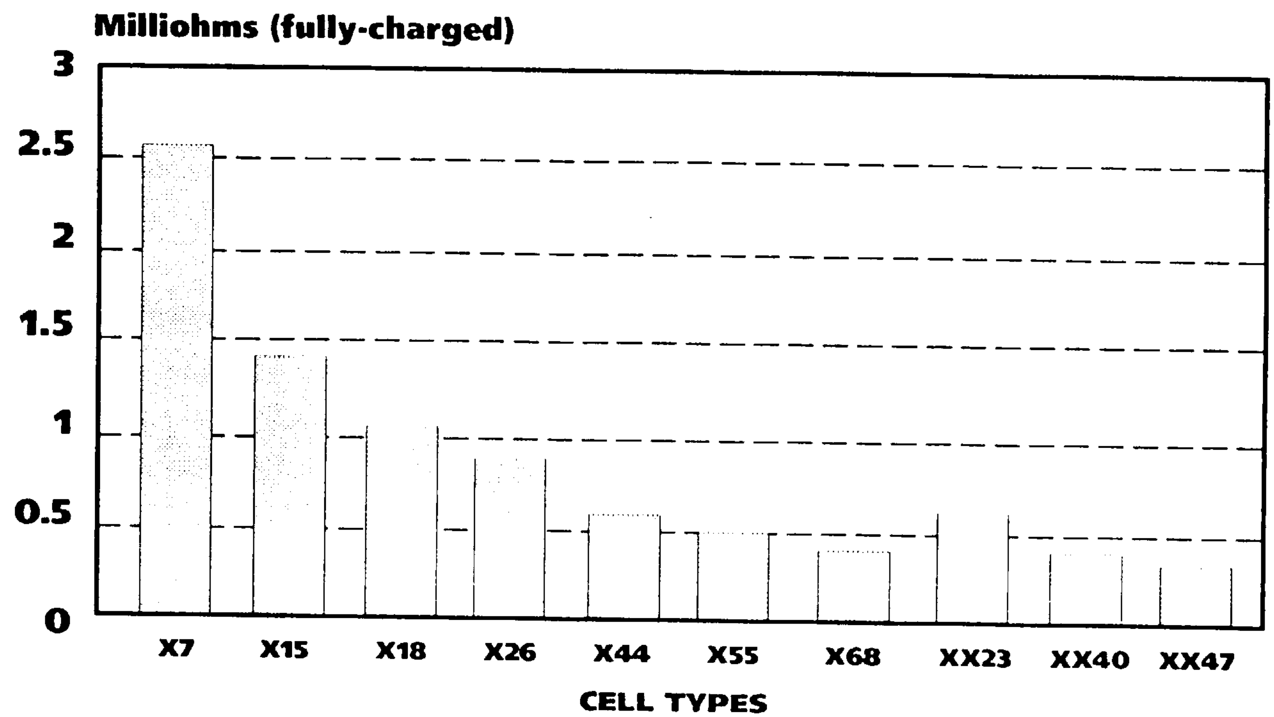



ACME 7 AMPERE-HOUR NICKEL CADMIUM CELLS
END-OF-CHARGE CURRENT DURING AN ACCELERATED LEO REGIME AT 20 DEGREES CELSIUS
AMPERES
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
CYCLES
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000

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

PRECEDING PAGE BLANK NOT FILMED

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

ENERGY STORAGE SYSTEMS GROUP

JPL

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.

ENERGY STORAGE SYSTEMS GROUP

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

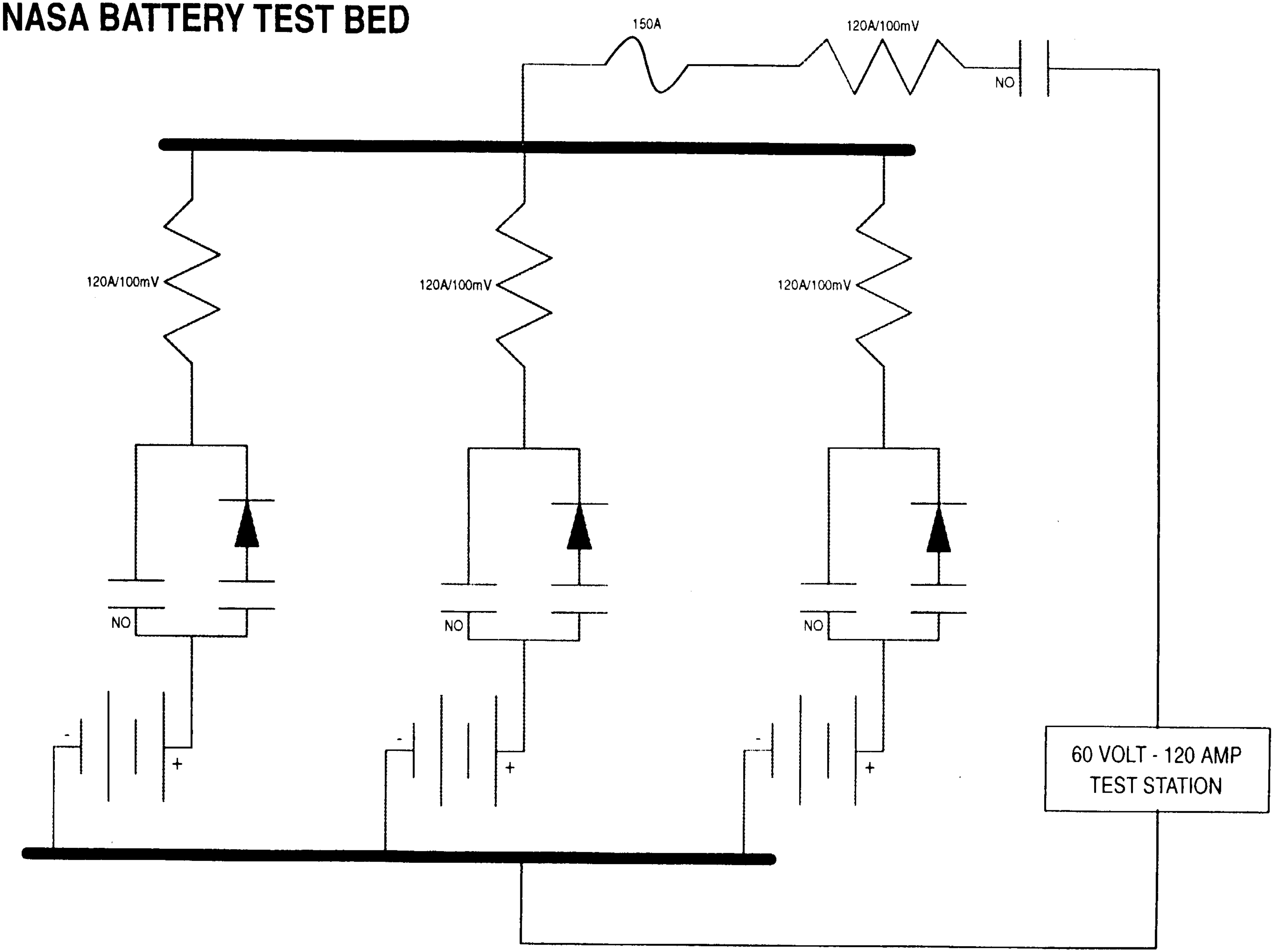
JPL

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

ENERGY STORAGE SYSTEMS GROUP

NASA BATTERY TEST BED



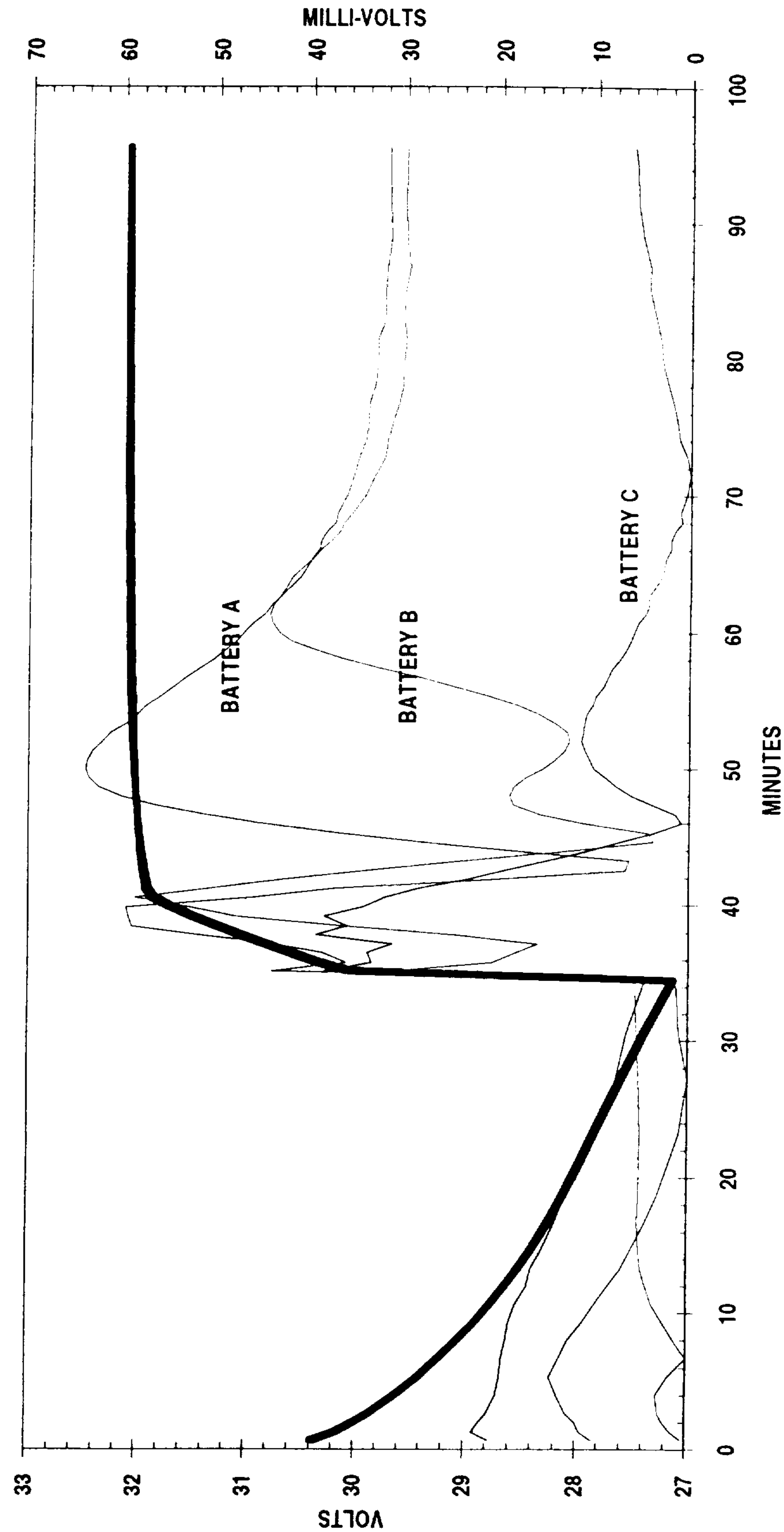
JPL

CURRENT TEST REGIME & BATTERIES

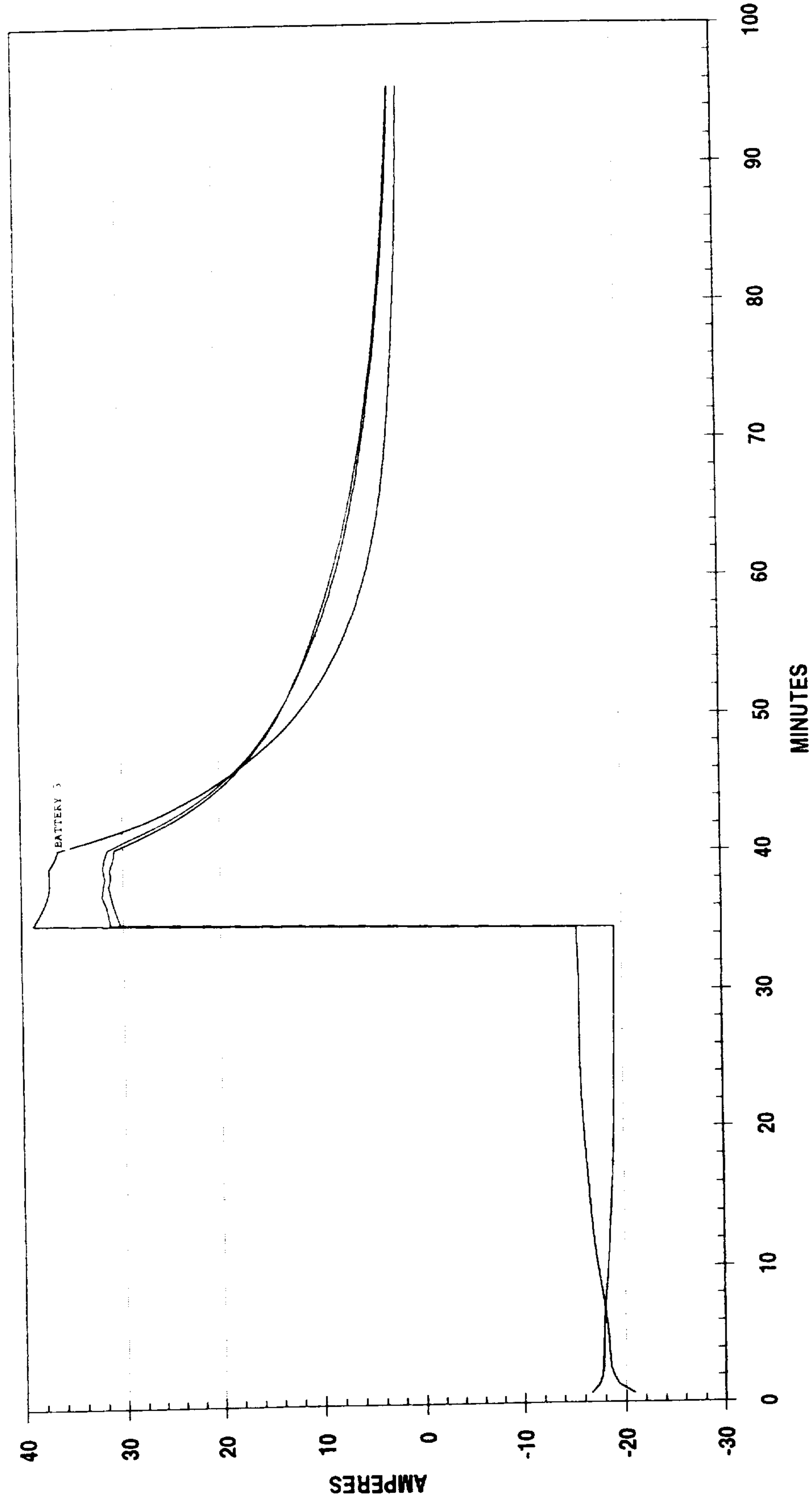
- THREE 22-CELL 50 Ah BATTERIES
  - TWO BATTERIES APPROXIMATELY 8 YEARS OLD, HAVE BEEN USED AS TEST BATTERIES ON CGRO AND TOPEX
  - ONE BATTERY WAS BUILT WITH CELLS FROM FOUR LOTS CGRO LOT, UARS LOT, EUVE FLIGHT LOT, EUVE LOT MOST CELLS WERE CYCLED FOR AT LEAST 1 YEAR
- IMPLEMENTED ONE OF THE ORIGINAL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

ENERGY STORAGE SYSTEMS GROUP

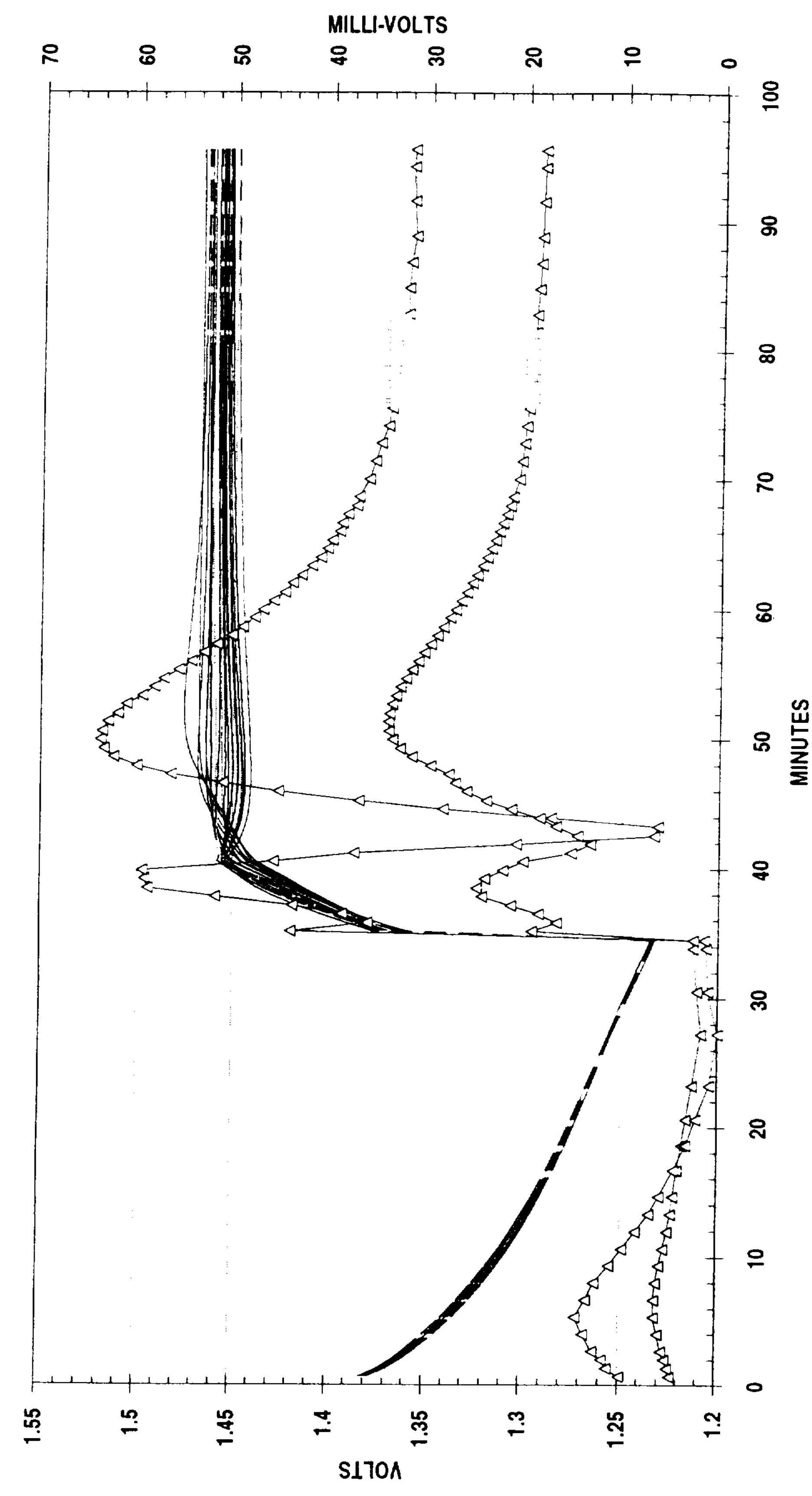
NASA BATTERY TEST BED -- BATTERY A, B & C
CYCLE 400 AT 18% DOD AT 3 DEGREES CELSIUS
BATTERY VOLTAGE & HALF BATTERY DIFFERENTIAL



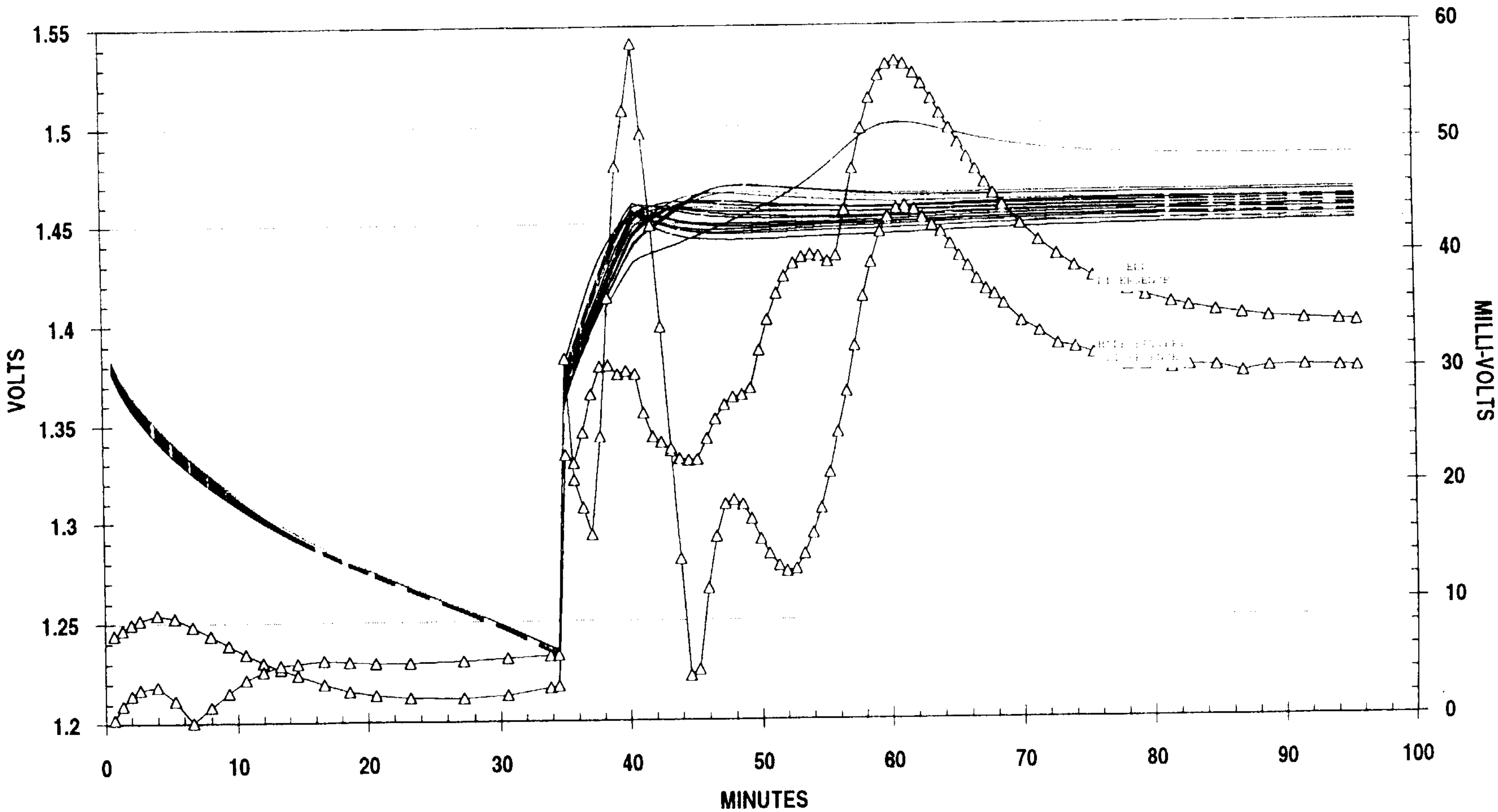
NASA BATTERY TEST BED
CYCLE 400 AT 18% DOD AT 3 DEGREES CELSIUS



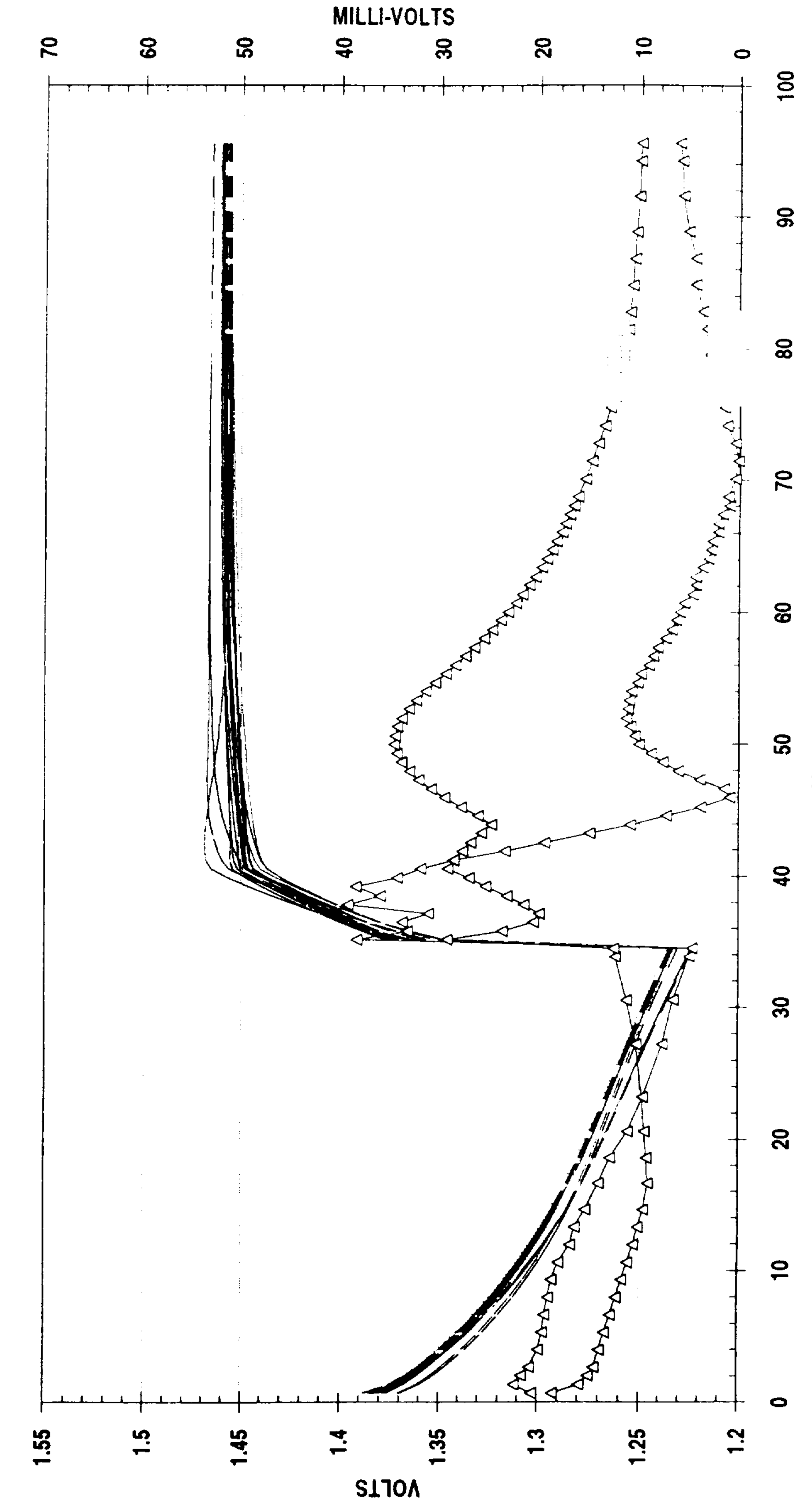
NASA BATTERY TEST BED -- BATTERY A
CYCLE 400 AT 18% DOD AT 3 DEGREES CELSIUS



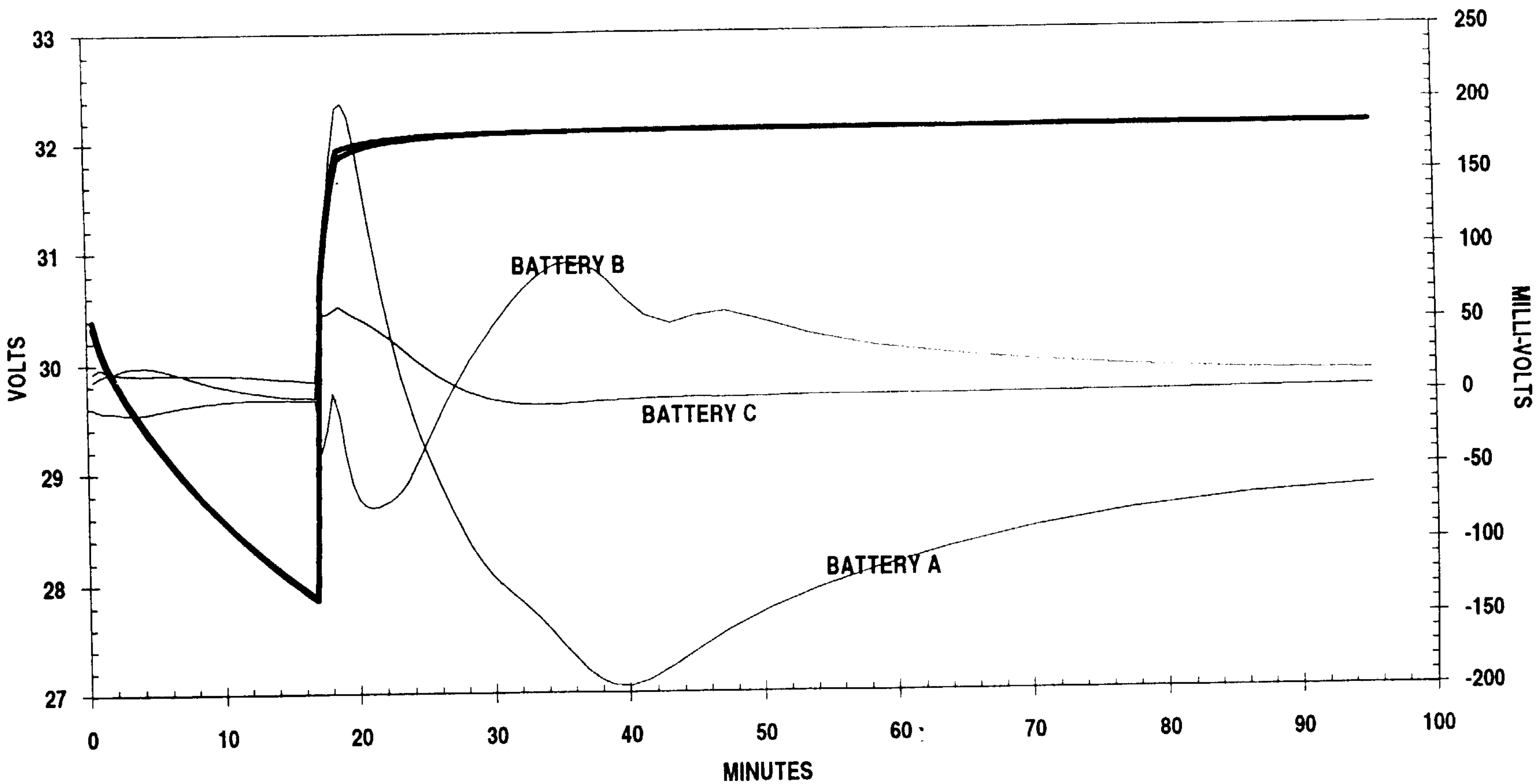
NASA BATTERY TEST BED -- BATTERY B
CYCLE 400 AT 18% DOD AT 3 DEGREES CELSIUS



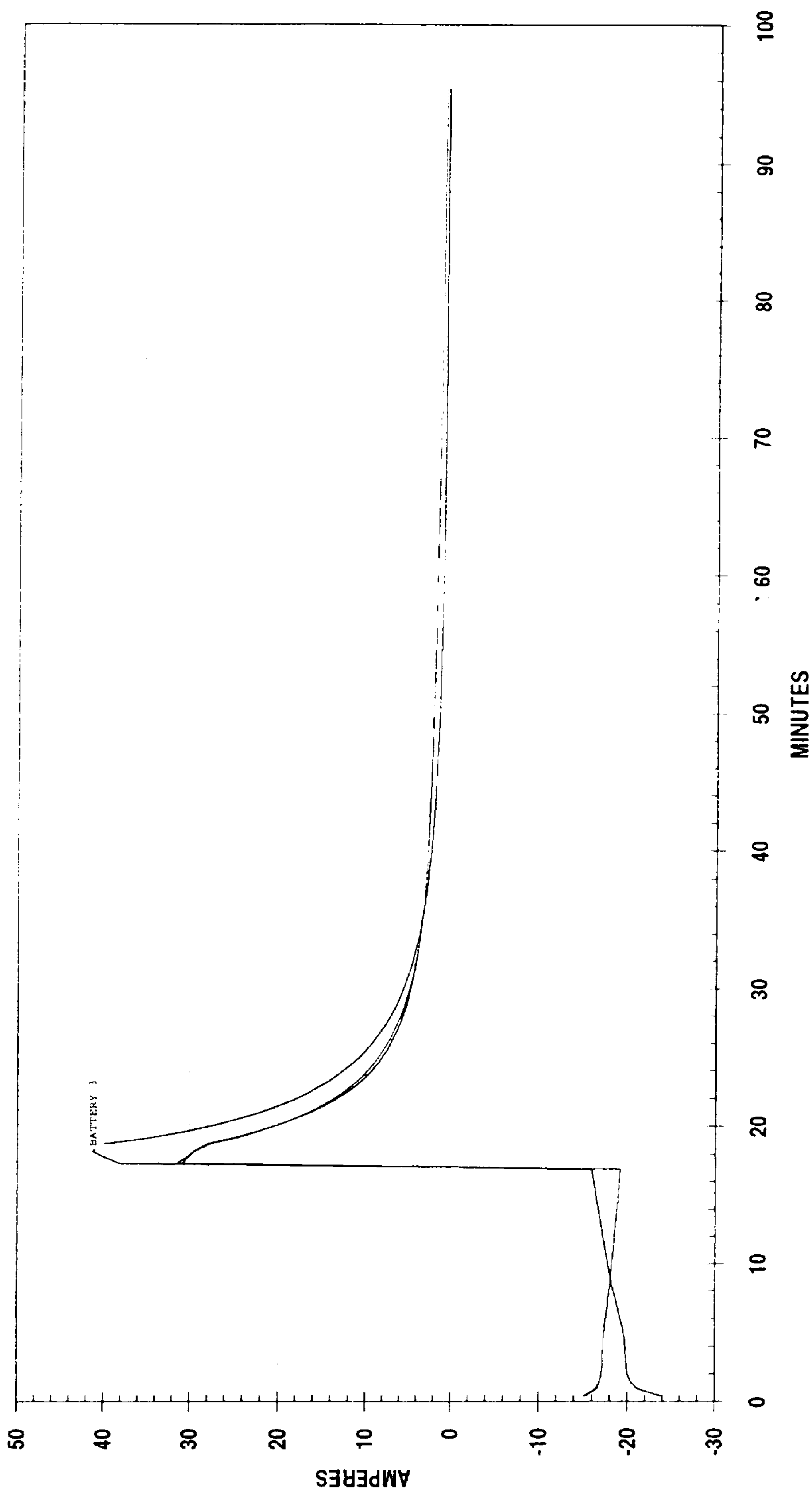
NASA BATTERY TEST BED -- BATTERY C
CYCLE 400 AT 18% DOD AT 3 DEGREES CELSIUS



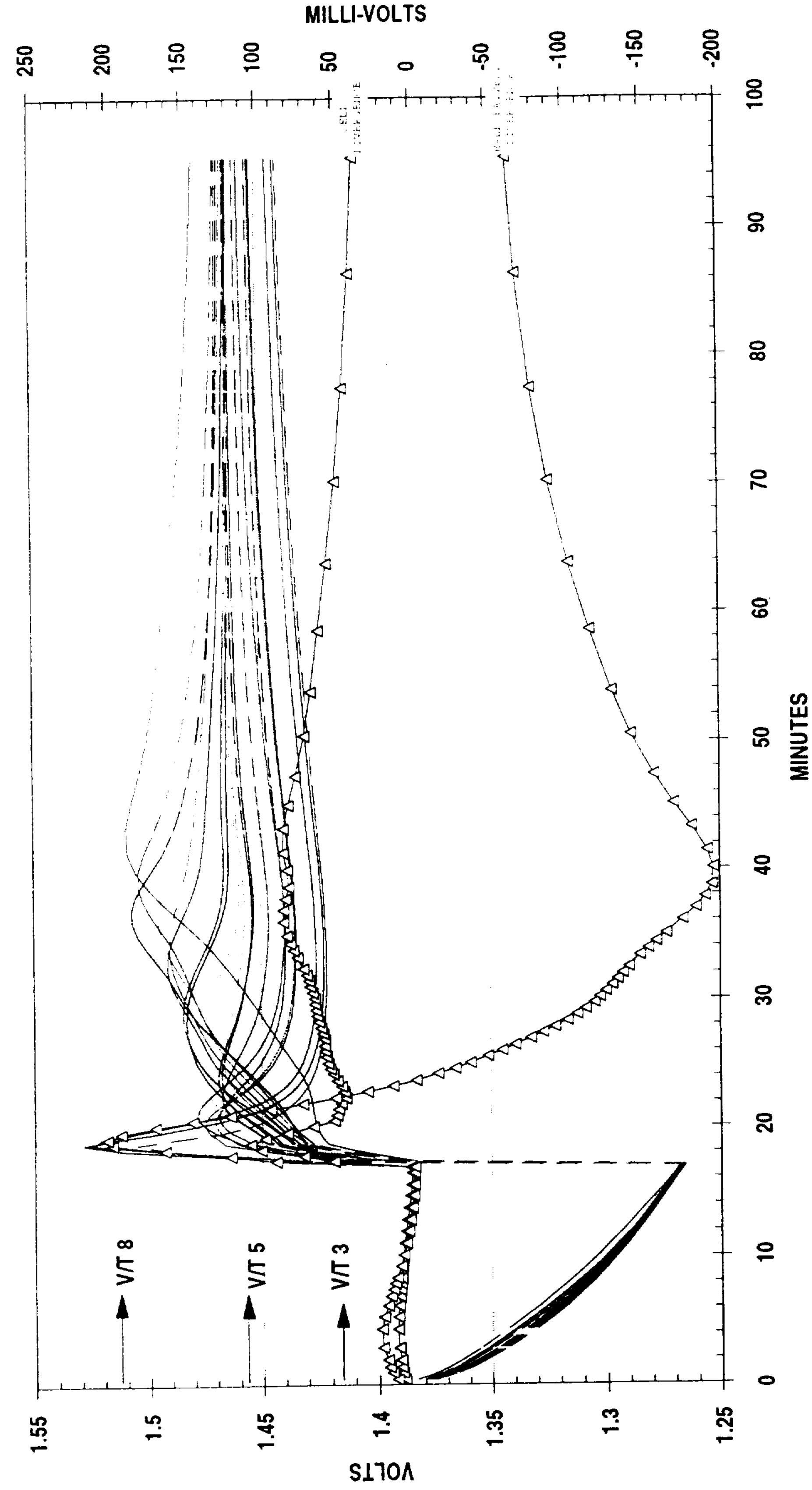
NASA BATTERY TEST BED -- BATTERY A, B & C
CYCLE 800 AT 10% DOD AT 3 DEGREES CELSIUS
BATTERY VOLTAGE & HALF BATTERY DIFFERENTIAL



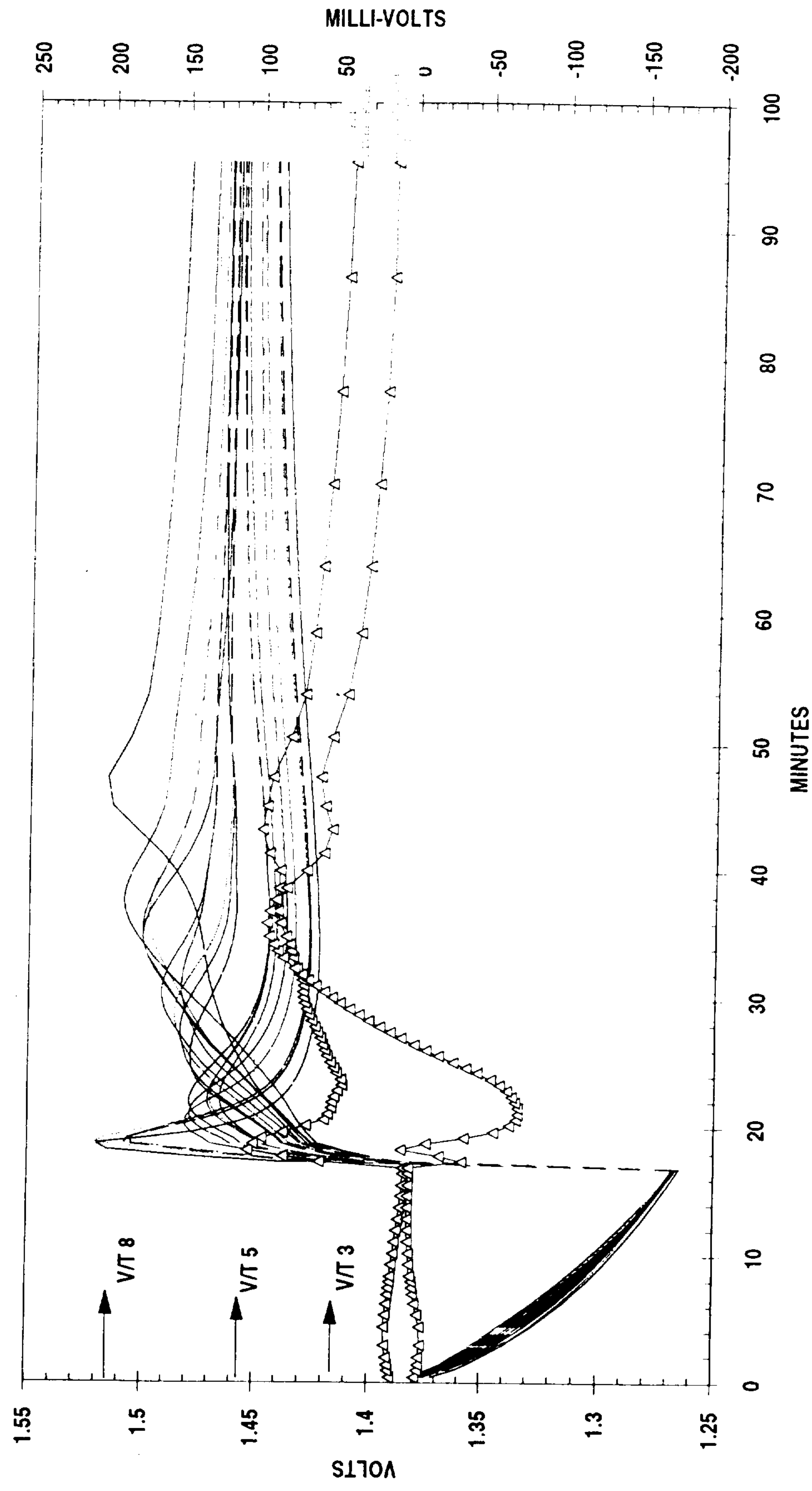
NASA BATTERY TEST BED
CYCLE 800 AT 10% DOD AT 3 DEGREES CELSIUS



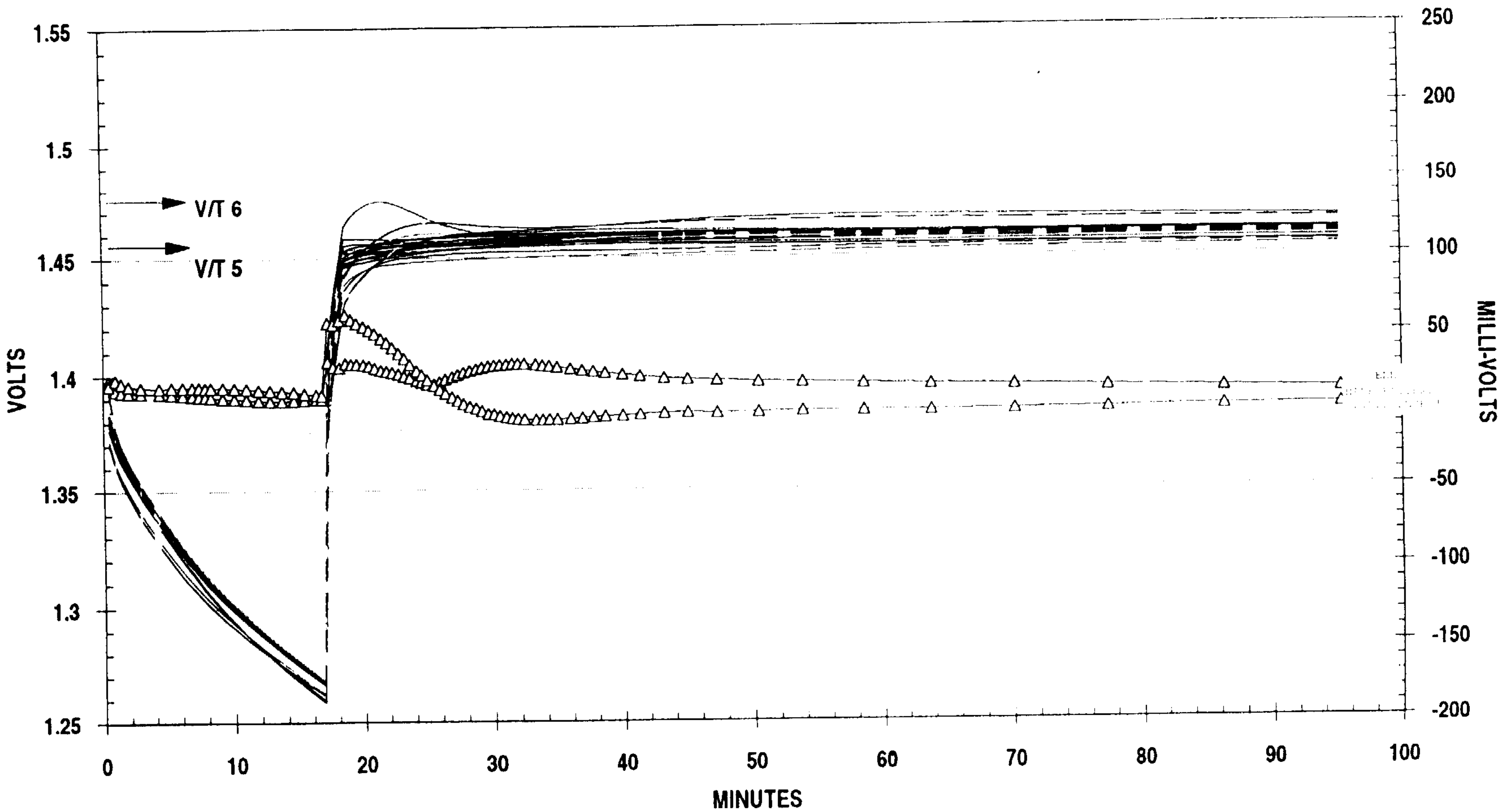
NASA BATTERY TEST BED -- BATTERY A
CYCLE 800 AT 10% DOD AT 3 DEGREES CELSIUS



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



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

JPL

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

ENERGY STORAGE SYSTEMS GROUP

JPL

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