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THE EFFECT OF CELL DESIGN AND TEST CRITERIA ON THE SERIES/PARALLEL PERFORMANCE OF NICKEL CADMIUM CELLS AND BATTERIES

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THE EFFECT OF CELL DESIGN AND TEST CRITERIA ON THE SERIES/PARALLEL PERFORMANCE OF NICKEL CADMIUM CELLS AND BATTERIES

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THE EFFECT OF CELL DESIGN AND TEST CRITERIA ON THE SERIES/PARALLEL PERFORMANCE OF NICKEL CADMIUM CELLS AND BATTERIES

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ABSTRACT

Nickel Cadmium batteries have been the workhorse of the satellite power subsystem for many years. In most cases, each battery in the subsystem has its own charge control device to maintain and assure full state of charge for reliable long term operation. In the January 1980 launch of the Solar Maximum Mission (SMM) spacecraft and continuing with the July 1982 launch of the Landsat-D spacecraft which utilized the Modular Power Subsystem (MPS), three batteries were operated in parallel from a common bus during charge and discharge. SMM utilized NASA Standard 20AH cells and batteries, and Landsat-D NASA 50AH cells and batteries of a similar design. Each battery consisted of 22 series connected cells providing the nominal 28V bus. The three batteries were charged in parallel using the voltage limit/current taper mode wherein the voltage limit was temperature compensated. Discharge occurred on the demand of the spacecraft instruments and electronics. Both flights were planned for three to five year missions.

The series/parallel configuration of cells and batteries for the 3-5 yr mission required a well controlled product with built-in reliability and uniformity. The Quality Control starts at the cell component level, namely the plate, electrolyte and separator. The NASA Standard 20AH cell and 50AH cell is manufactured to an agreed-upon manufacturing control process spelled out in the General Electric Manufacturing Control Document (MCD) 232A2222AA-84. The battery is produced to the McDonnell-Douglas Battery MCD-BMCD 70A232003 for 20's and BMCD 70A237005 for 50's.

In this paper, examples of how component, cell and battery selection methods affect the unformity of the series/parallel operation of the batteries both in ground testing and in flight are given.

Among the considerations for reliability and uniformity in a parallel battery operation are the voltage characteristics. These, in turn depend on the cell electrochemical characteristics; namely, the polarization over a range of current densities, impedance, conductivity, utilization of the active materials and ampere-hour efficiency. Except for impedance factors in the lead wires, all of these are related to how reproducible the cell components are. The methods for selection and control of components are described in the MCD.

THE EFFECT OF CELL DESIGN AND TEST CRITERIA ON THE SERIES/PARALLEL PERFORMANCE OF NICKEL CADMIUM CELLS AND BATTERIES

Introduction

The concept that an electrochemical cell is treated as a part, i.e. resistor, capacitor, etc. has been expressed by those unfamiliar with electrochemical technology. Those of us in the electrochemical cell and battery community are well aware that the performance of a battery is based on the complex electrochemistry and physical chemistries involved in cell and battery operation. The complexities must be taken into consideration in the design and use of nickel cadmium batteries for long term reliable use in an aerospace application. This paper will cover the parameters and evaluation data utilized in the evaluation and selection process for a flight applications and results (to date) of operating 20 and 50 ampere hour (ah) cells in a series/parallel combination in orbit.

These results refer to NASA Standard 20 ah cells and batteries in the Solar Max Mission (SMM) Spacecraft and 50 ah cells and batteries in the Landsat D Spacecraft. The requirements, selection and performance of several lots of plate materials and the cells and batteries from which they are made will be described together with in-orbit data relating to the degree of uniformity maintained for more than 2½ years.

The results achieved in this effort have been made possible by the following:

(a) Knowing something about the relationship between the manufacturing variables and the final cell/battery characteristics,

(b) Control of the materials and process of manufacture despite the complexity involved with manufacturing and

(c) A good working relationship between cell manufacturer (General Electric), battery manufacturer (McDonnell Douglas Astronautics), user (General Electric and Fairchild) and the government technical representatives.

The cells described are manufactured by General Electric to specifically documented manufacturing Control Documents. The 20 ah cells are designated 42B024AB06 (07 for signal electrode cell). The 50 ah cells are designated 42B050AB20 (21 for signal electrode cell). Both types are assembled according to Manufacturing Control Document (MCD) No. 232A2222-AA-84. The plate materials are essentially those from their commercial operation with some additional quality steps to optimize uniformity. The plate materials as well as the other cell components – separator, case, covers, etc. are eventially incorporated into the sealed cell in the G.E. Aerospace Facility. It is in this operation where the material testing and selection and cell assembly takes place. The cells, prior to delivery, are subjected to a number of tests culminating in 4 cycles at 3 temperatures-required for NASA acceptance.

The cells are then delivered to McDonnell Douglas to be selected, installed and tested in a battery for satellite power system use. The standard 20 ah battery is designated 70A237003 and the 50 ah battery 70A237005. They are assembled and tested according to BMCD 70A237003 and BMCD 70A237005 respectively.

There are several improved design features and unique procedures utilized in the production of the cells and batteries which were implemented to improve their uniformity and operational life. These are given in Table I and II.

Table I
Cell Design Features

NASA Standard Cell
lighter loaded plates (10-15%)
additional electrolyte (20%)
Material buyoff review
flooded plate stability tests
Burn-in test requirement
Standard cell NASA/GSFC Acceptance test – no rework
Capacity of 24 ± 2 ah and 60 ± 5 ah at 24°C (No optimization of energy density)

Table II
Battery Design Features

Battery Manufacturing Control Document (BMCD)
Selection of cells from GE data only
Normalization of manufacturer data
22 cells for battery selected from 25 cell lot
Standard Battery Flight Qualification & Acceptance Tests

A complete description of the battery design is provided in the Standard 20 AH Battery Manual (1) and 50 AH Battery Manual (2).

Mission Application

The mission applications of these cells and batteries are described in figure 1. The important feature is that the three batteries in each case were tied to the same bus – charged and discharged in parallel. The second important feature is the charge control method – voltage limit (temperature compensated)/current taper which our experience tells us optimizes life of nickel cadmium cells and batteries.

The in-orbit cell and battery parameters that effect operation and life are given in figure 2. All are functions of the cell design which determine cell characteristics.

Cell Design and Uniformity

The material buyoff review was instituted with the development of The Standard Cells. In addition to plate loading and dimensional characteristics, the parameters described in figure 3 were reviewed. Continuation of the cell assembly operations was dependent on the results of this review. Three lots of material have been rejected at this point in the process. Specific data for acceptable flight lots will be discussed in the following figures.

The cell design limits are given in figure 4. The plate physical characteristics including loading levels are given in Table III.

	SOLAR MAX MISSION	LANDSAT-D
BATTERIES	3	3
CELLS/BATTERY	22	22
CELL/TYPE	20AH NASA STANDARD	50AH NASA STANDARD
OPERATION	BATTERIES IN PARALLEL	BATTERIES IN PARALLEL
BUS.	COMMON BUS/NO DIODES	COMMON BUS/NO DIODES
CHARGE CONTROL	V LIMIT/I TAPER	V LIMIT/I TAPER
LAUNCHED	FEBRUARY 1980	AUGUST 1982

Figure 1. The SMM and Landsat D applications.

CELL VOLTAGE UNIFORMITY

CURRENT SHARING OF BATTERIES

EFFECT OF TEMPERATURE

CHARGE/DISCHARGE RATIO

ALL STRONGLY DEPENDENT ON CELL CHARACTERISTICS

Figure 2. In-orbit battery performance concerns.

PLATE INSPECTION (2)

PLATE WEIGHT SCREENING

FLOODED PLATE STABILITY TEST

FLOODED PACK TEST

SEPARATOR EVALUATION

Figure 3. Material buyoff review.

LOADING -- ±0.6g/dm^2

PLATE WEIGHT – ±3 1/2%

PLATE THICKNESS – ±.001

FLOODED PACK CAPACITY – ±5%

PACK WEIGHT AND THICKNESS

NASA CAP, V AND T LIMITS AT 3 TEMP.

Figure 4. Cell Design Limits.

Table III
Plate Characteristics

	20AH Cell		50AH Cell	
	+	-	+	-
No. of plates	10	11	15	16
Loading g/dm²	11.60	15.25	12.50	16.06
Loading g/cc void	1.8	2.5	2.3	2.8
Porosity %*	89	89	89	86
Plate thickness(mil)	27	31	27	31

*without substrate

The loading given in g/dm² were the manufacturer limits and the g/cc void values were determined analytically. The capacity measurements were made at 24°C, 0°C, 35°C and then again at 24°C. Each had appropriate voltage and measurement requirements given in the cell specifications. (3)

The values for loading, measured pack electrochmical test capacity and utilization are given in figures 5 and 6. The uniformity is quite good for the three parameters of the cell plate lots given. The 8A and 8B plate lot in figure 5 appears to be lower than the average loading (within the acceptable range) but had a higher than average utilization. The capacity of the lot 9 positives was high and reflected the maximum loading level and a high utilization. The negatives had utilizations as high as 88%.

The results of the plate stability test are given in figures 7 and 8. Five samples of positive plates from the entire lot are charged in the flooded condition at C/5 for 8 hours and discharged at C/2 to 0.0V for 5 consecutive orbits. Five negative plates are charged in the flooded condition at C/2 for 5 hours and discharged at C/2 to 0.0V for 20 cycles. There is a requirement that the 20th cycle capacity be within 75% of the second cycle capacity. There is an initial conditioning cycle for each plate. The results are quite consistent except for the lot 8A and 8B plates. The unusual behavior of the 8A and 8B plates in the 50AH cell plates (see figure 7) when compared with the others led to the conclusion that these plates may have been subjected to an unusual step or steps during manufacture and were rejected.

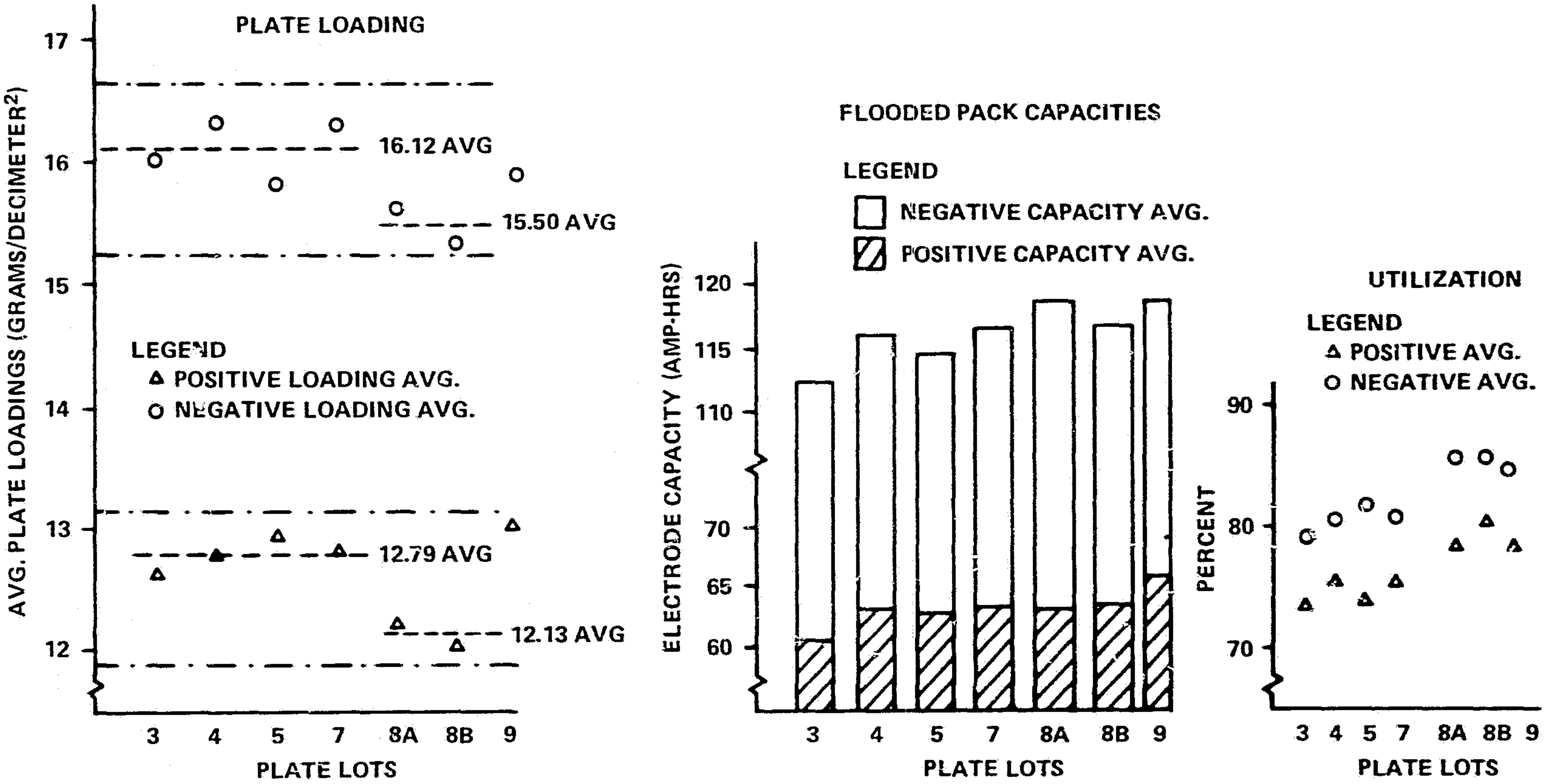

Figure 5. 50AH Summary Plate and Pack Data.

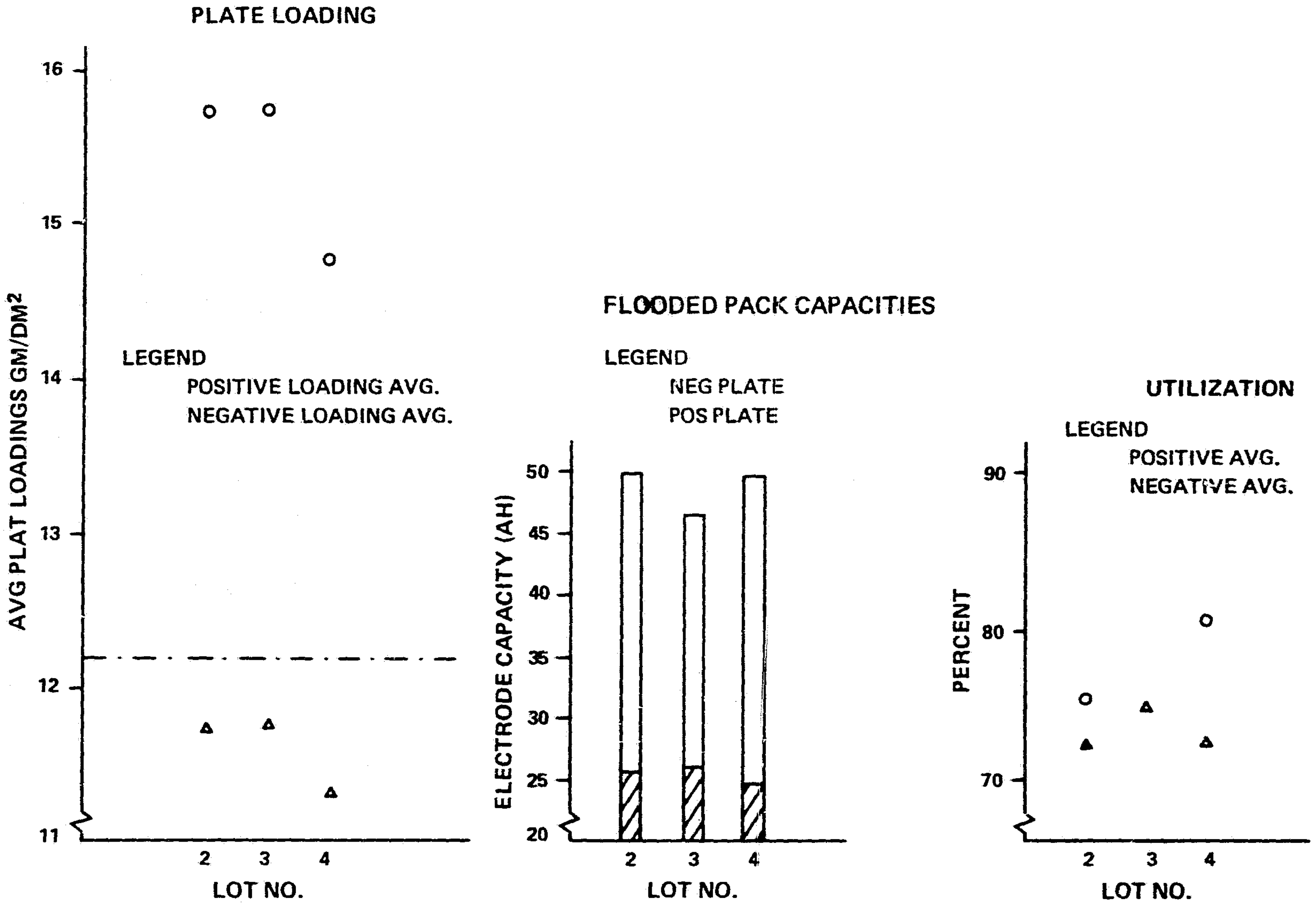

Figure 6. 20AH summary plate and pack data.

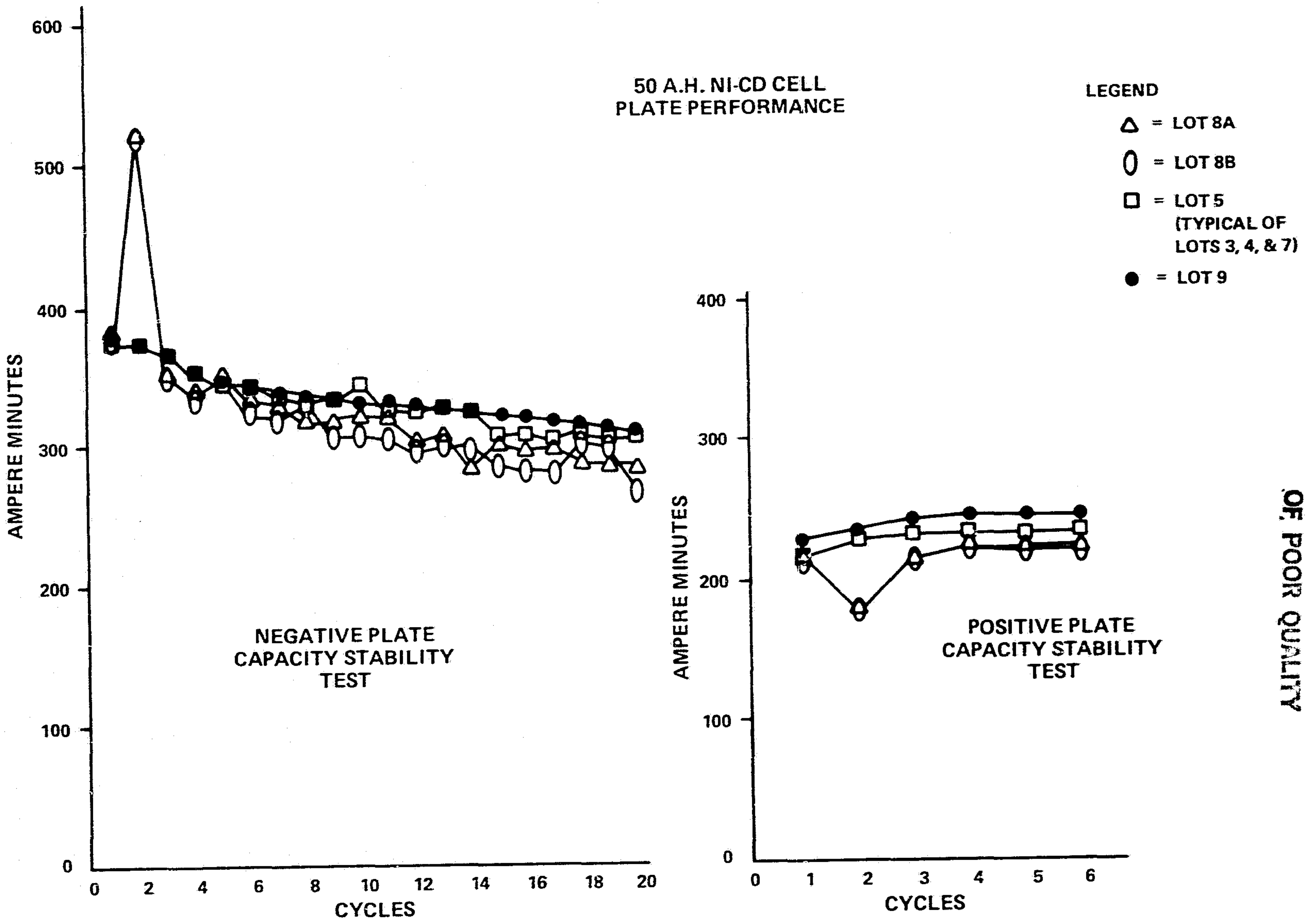

Figure 7. Plate stability test results (50AH).

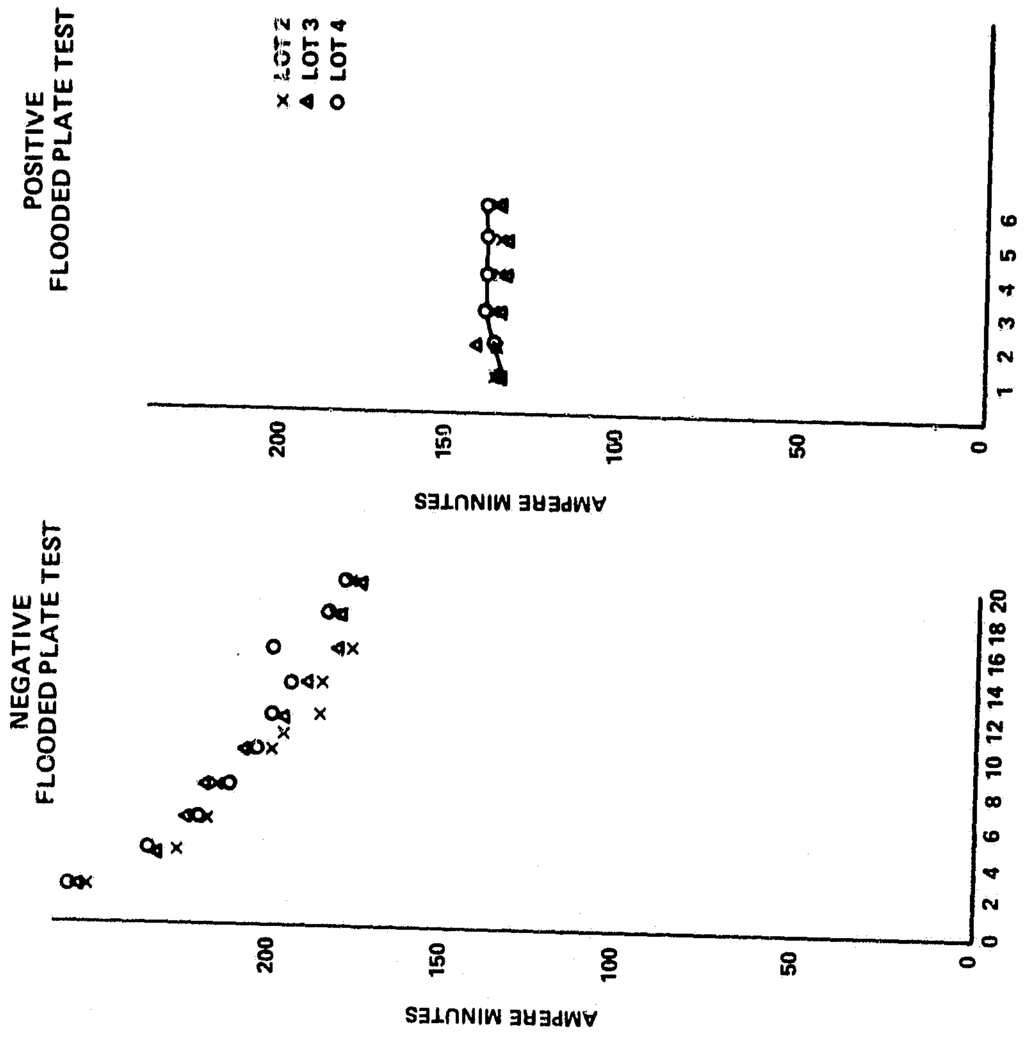

Figure 8. Plate stability test results (20AH).

The plate weight screening results are given in figure 9. The average weight of each 20AH and 50AH plate lot are given as is the ±3½% range of weight acceptable for use. This go/no go test is done by utilizing two balances, one set for the upper and the other for the lower weight. The number of total plates rejected for high and low weight are, with one exception, significantly less than 5% of the total screened. The importance of this quality screening test is based on the relationship between plate weight and plate capacity described previously.(4)

The 50AH pack capacities, theoretical and flooded, are compared in figure 10. The uniformity again is obvious. The pack capacities performed to a specific requirement in the MCD are determined by discharging through a load bank which will have an apparent effect on uniformity. The 1.8 negative to positive plate ratio is quite consistent.

Battery Design and Uniformity

The limitations and requirements on battery manufacture are given in figure 11. There are twenty-two series connected cells (see figure 12) including one with a signal electrode used to monitor relative internal oxygen pressure. The design of the battery is described in detail in refs(1) and (2). The design requirements are given in figure 11 and include also those features given in Table IV.

Table IV
Battery Evaluation Tests

(a) Selection of cells based on cell manufacturer data
(b) Selected at ±3% of capacity at 24°C and 0°C
(c) Cell voltage range ± 8mv at 24°C and 0°C
(d) Battery Capacity 90% of average manufacturer cell capacity at 20°C
    Battery Capacity 85% of average manufacturer cell capacity at 10°C
    Battery Capacity 80% of average manufacturer cell capacity at 0°C
(e) Capacity ±5% between batteries
(f) Peak load 3C for 5 minutes at 50% discharged
(g) Normalization of cell manufacturer data for seelection
(h) Selection of 22 cells from 25 cell lot

PLATE WEIGHT SCREENING

NASA STANDARD 20AH CELLS

	POSITIVE PLATES			NEGATIVE PLATES		
LOT	AVG. WEIGHT (G)	±3-1/2% WEIGHT (G)	% REJECTED HIGH/LOW	AVG. WEIGHT (G)	±3-1/2% WEIGHT (G)	% REJECTED HIGH/LOW
1	23.14	0.81	0/1.7	28.50	1.00	/0
2	23.34	0.83	6.2/3.1	29.83	1.05	0/0.3
3	22.95	0.80	6.3/4.4	28.86	1.02	0.2/2.0
4	22.95	0.80	4.4/3.0	28.85	1.01	0.2/9.0
			NASA 50AH CELLS			
1	35.65	1.25	3.2/6.7	45.51	1.60	0.8/1.4
3	35.81	1.26	2.2/0.3	46.02	1.62	0/4.5
4	35.82	1.25	5.6/3.5	45.96	1.61	.1/0
5	36.88	1.29	1.7/0	45.60	1.60	0/0
7	36.59	1.29	0/2.3	46.18	1.61	0/2.4
9	37.96	1.32	3.1/0	45.44	1.59	0.2/0.7

Figure 9. Plate weight screening.

PLATE LOT	MAX THEORETICAL CAP.* POSITIVE	MAX THEORETICAL CAP.* NEGATIVE	FLOODED CELL AVG. CAP. POS/% THEO.	FLOODED CELL AVG. CAP. NEG/% THEO.	SEALED AVG. CAP. TO IV/CELL	SEALED AVG. CAP. % FLOODED	NEG TO POS RATIO
1	83.43 AH	143.39 AH	64.30/77.0	118.69/82.7	62.76 AH	97.6	1.84
2	82.38 AH	143.22 AH	64.80/78.6	120.58/84.2	59.80 AH	92.3	1.86
3	83.03 AH	141.72 AH	60.76/73.2	112.08/79.1	60.14 AH	99.0	1.85
4	83.95 AH	144.46 AH	63.20/75.3	116.37/80.5	60.28 AH	95.4	1.84
5	85.21 AH	139.94 AH	62.78/73.7	114.47/81.8	55.54 AH	88.5	1.82
7	84.15 AH	144.19 AH	63.40/75.3	116.63/80.8	61.07 AH	96.3	1.84

* BASED ON AVG PLATE LOADING.

Figure 10. 50AH Cell Active Material Utilization Summary.

SELECT CELLS ON CELL MFG. RESULTS

CAPACITIES – ±3%

CELL VOLTAGE – ±.008V

BATTERY MATCHING – ±5%

MAX VOLTAGE AT 0°C AND 24°C

PEAK LOAD 3C FOR 5 MINUTES – 50% DOD

THERMAL GRADIENT

- **±1.5°C PARALLEL TO COVER**
- **5°C ABOVE BASEPLATE**

Figure 11. Limits On Battery Manufacturers.

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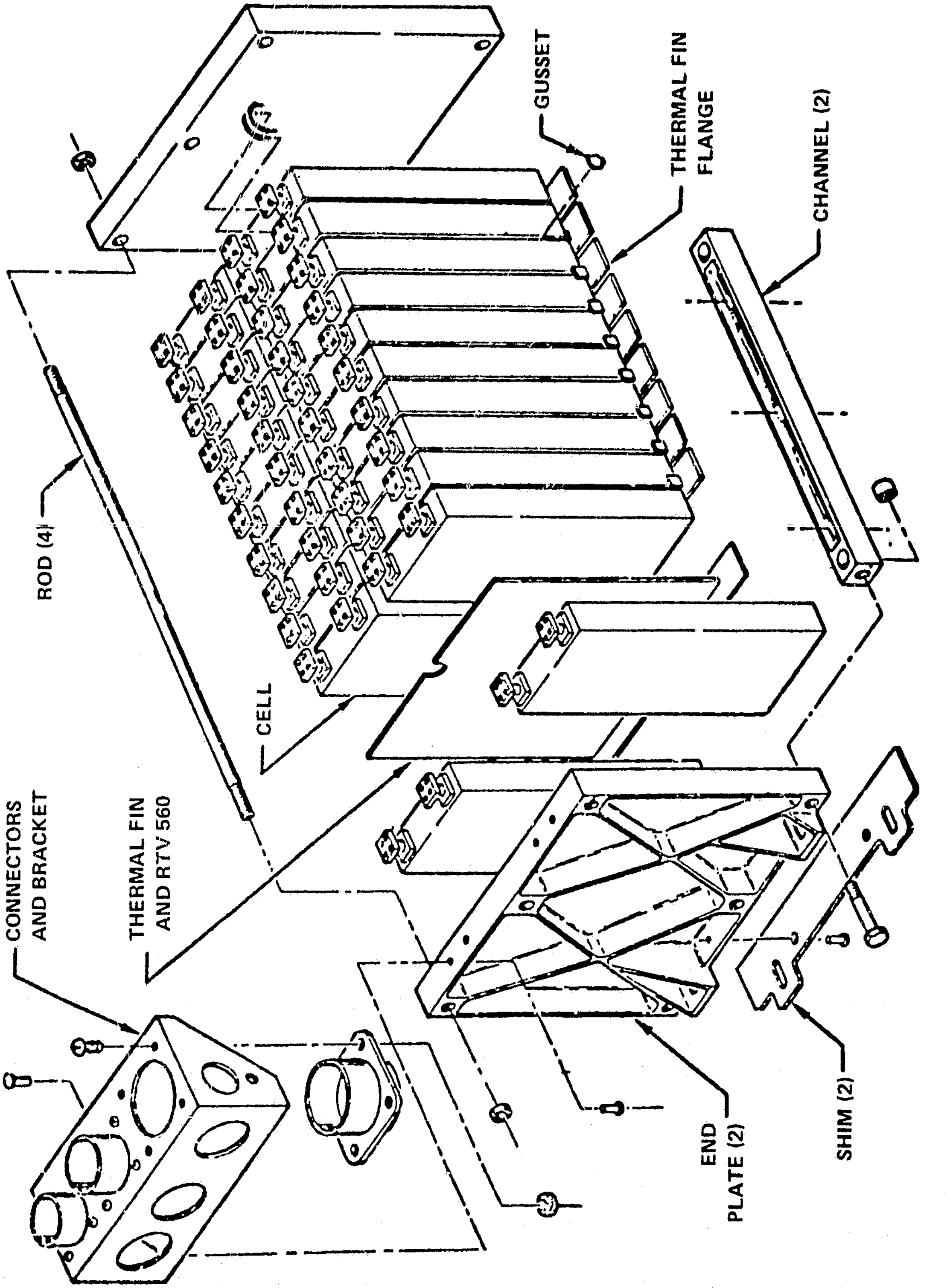

Figure 12. Battery Mechanical/Structural Design.

After normalizing the cell manufacturers capacity and voltage data for each lot the average high and low difference are determined. These are given in figure 13. The capacities are all within the required range as is the voltage at 0°C and 24°C.

Battery testing includes 25% depth of discharge operation at 0°C, 10°C and 20°C in the voltage limit/current, taper mode. Comparison of eight 50AH batteries tested individually at different time periods is given in figure 14. The maximum difference in end of discharge voltage (EODV) between all 8 batteries was 0.1 volts at 0°C. The maximum difference in end of charge voltage (EOCV) fixed by the power supplies is given to provide a measure of the variation in test conditions and equipment. The end of charge current values are also given. Here differences in temperature and charge voltage add to the effect of differences in cell material properties and internal impedence. Differences in battery voltage measured at the end of the 3C-5 minute pulse are also given.

The results of the capacity tests and the EOCV, after 1 hour of discharge at C/2 are given for the 24°C, 0°C and 10°C capacity tests on the 8 batteries in figure 15. The uniformity is quite apparent as is that given for similar cycling and capacity tests on the 20 AH batteries given in figures 16 and 17.

Landsat D Results

The evidence of operational uniformity on orbit 1251 of the Landsat D spacecraft launched in July 1982 are given in the next several figures. Figures 18 and 19 are an indication of spacecraft operating parameters exhibiting the load voltage and current. Figure 20 provides data from the high current sensors (± 50 amp) and figure 21 the low current sensors (0–3 amp) for each battery. The current sharings by the three batteries is a measure of the uniformity of operation of the cells and the batteries in parallel. Differences in cell properties will affect the battery current sharing and can result in cell and battery divergence seriously affecting life. The difference in current on orbit 1251 between the three batteries is less than 0.1 amp. The uniformity exists despite the difference

BTRY NO.	24°C CAPACITY HI-AVG	24°C CAPACITY LO-AVG	24°C VOLTAGE HI-AVG	24°C VOLTAGE LO-AVG	0°C CAPACITY HI-AVG	0°C CAPACITY LO-AVG	0°C VOLTAGE HI-AVG	0°C VOLTAGE LO-AVG
1	+1.7%	-2.8%	+5.2 MV	-2.8 MV	+3.6%	-3.1%	+5.9 MV	-4.0 MV
2	+2.9%	-1.9%	+6.1 MV	-9 MV	+2.4%	-2.2%	+6.7 MV	-5.3 MV
3	+1.6%	-1.3%	+4.2 MV	-7.9 MV	+1.3%	-1.1%	+5.1 MV	-3.8 MV
4	+2.8%	-3.0%	+4.8 MV	5.3 MV	+3.0%	-5.8%	+6.8 MV	-7.2 MV
5	+1.8%	-1.6%	+4.8 MV	-4 MV	+1.3%	-1.4%	+5.3 MV	-3.5 MV
6	+1.2%	-1.2%	+3.8 MV	-5.2 MV	+4.9%	-2.3%	+6.4 MV	-5.6 MV
7	+1.7%	-2.7%	+4.3 MV	-4.7 MV	+2.4%	-2.3%	+4.5 MV	-3.6 MV
8	+1.0%	-3.4%	+3.9 MV	-5.1 MV	+2.9%	-2.8%	+3.9 MV	-6.1 MV
9	+1.8%	-1.8%	+6.4 MV	-5.6 MV	+2.7%	-2.6%	+5.3 MV	-6.7 MV
10	+2.1%	-2.3%	+4.7 MV	-6.3 MV	+3.1%	-2.7%	+6.1 MV	-10.2 MV
11	+2.0%	-2.0%	+3.1 MV	-2.9 MV	+2.7%	-2.6%	+3.5 MV	-7.5 MV
12	+3.0%	-2.9%	+6.7 MV	-3.3 MV	+2.2%	-2.5%	+7.2 MV	-4.5 MV
13	+1.6%	-1.2%	+3.6 MV	-4.6 MV	+2.2%	-1.7	+4.6 MV	-6.5 MV
14	+2.0%	-1.3%	+2.0 MV	-3.0 MV	+1.4%	-1.4%	+3.8 MV	-4.7 MV

Figure 13. Normalized 50AH Cell Matching Summary.

CYCLING TESTS

0°C CYCLING, 25% DOD, 5TH CYCLE

	EODV	EOCV	EOCI
MAX	27.957	32.618	2.045
MIN	26.057	32.553	1.516
Δ	0.100	.065	0.529

10°C CYCLING, 25% DOD, 5TH CYCLE

	EODV	EOCV	EOCI
MAX	27.100	32.088	2.092
MIN	27.021	32.046	1.786
Δ	0.079	0.042	0.306

20°C CYCLING, 25% DOD, 5TH CYCLE

	EODV	EOCV	EOCI
MAX	27.078	31.542	2.980
MIN	27.006	31.521	2.589
Δ	0.072	0.021	0.391

3C PULSE (AFTER 1 HR DISCH.)

MAX	23.448
MIN	23.306
Δ	0.142

Figure 14. Max/Min Variations – 8-50AH Batteries Flight Acceptance.

MDAC FLIGHT ACCEPTANCE TESTS

CAPACITY TESTS

24°C CAPACITY

	EOCV	1HR C/2 DISCH V	CAPACITY
MAX	32.525	27.132	61.283
MIN	32.445	27.072	58.126
Δ	0.080	0.060	3.257

0°C CAPACITY

	EOCV*	1HR C/2 DISCH V	CAPACITY
MAX	32.243	27.012	57.53
MIN	33.036	26.808	49.11
Δ	0.207	0.204	8.42

10°C CAPACITY

	EOCV*	1HR C/2 DISCH V	CAPACITY
MAX	32.627	27.098	58.63
MIN	32.495	27.001	51.16
Δ	0.032	.097	7.47

*CONTROLLED BY POWER SUPPLY

Figure 15. Max/Min Variations – 50AH Batteries Capacity Tests.

20AH BATTERIES – MDAC FLIGHT ACCEPTANCE

CYCLING TESTS

0°C CYCLING, 25% DOD, 5TH CYCLE

	EOD	EOCV	EOCI
MAX	27.246	32.594	.700
MIN	27.205	32.588	.690
Δ	.041	.006	.010

10°C CYCLING, 25% DOD, 5TH CYCLE

	EODV	EOCV	EOCI
MAX	27.286	32.080	.831
MIN	27.263	32.064	.800
Δ	.023	0.016	.031

20°C CYCLING, 25% DOD, 5TH CYCLE

	EODV	EOCV	EOCI
MAX	27.238	32.553	1.233
MIN	27.218	31.544	1.133
Δ	.020	.009	0.100

Figure 16. Max/Min Variations – 3 flight batteries SMM.

MDAC FLIGHT ACCEPTANCE TESTS
CAPACITY TESTS

24° CAPACITY

	EOCV	1HR DISCH V	CAPACITY
MAX	32.292	27.409	24.194
MIN	32.147	27.338	23.332
Δ	0.145	0.071	0.862

0°C CAPACITY

	EOCV	1HR DISCH V	CAPACITY
MAX	33.019	27.324	22.097
MIN	32.997	27.109	21.119
Δ	0.022	0.225	0.978

10°C CAPACITY

	EOCV	1HR DISCH V	CAPACITY
MAX	32.445	27.306	22.435
MIN	32.388	27.280	21.962
Δ	0.057	0.026	0.473

3C PULSE (AFTER 1 HR DISCH.)

MAX	24.517
MIN	23.795
Δ	0.722

Figure 17. Max/min variations – 20AH batteries capacity tests.

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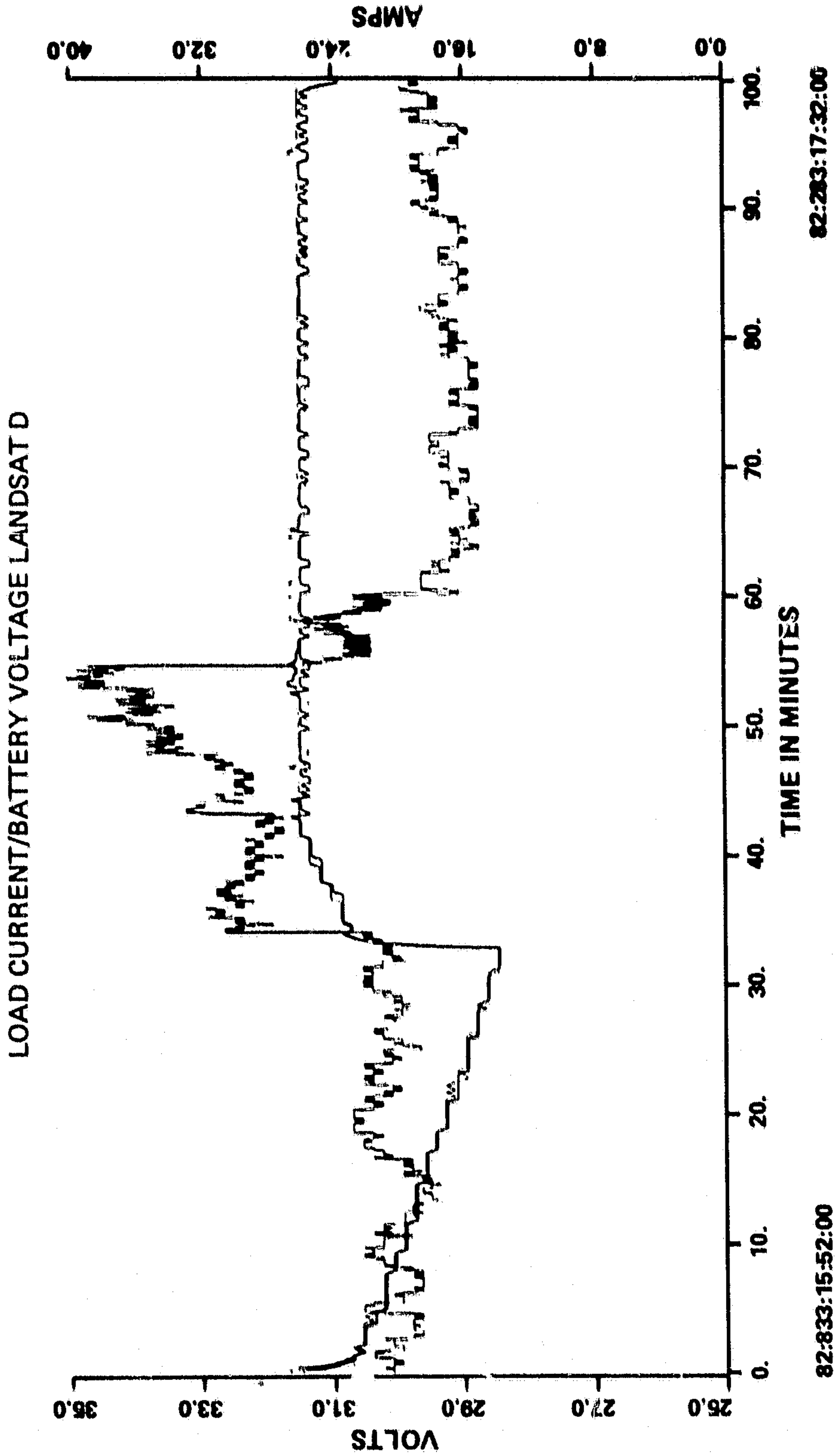

Figure 18. Load Current/Battery Voltage – Landsat D.

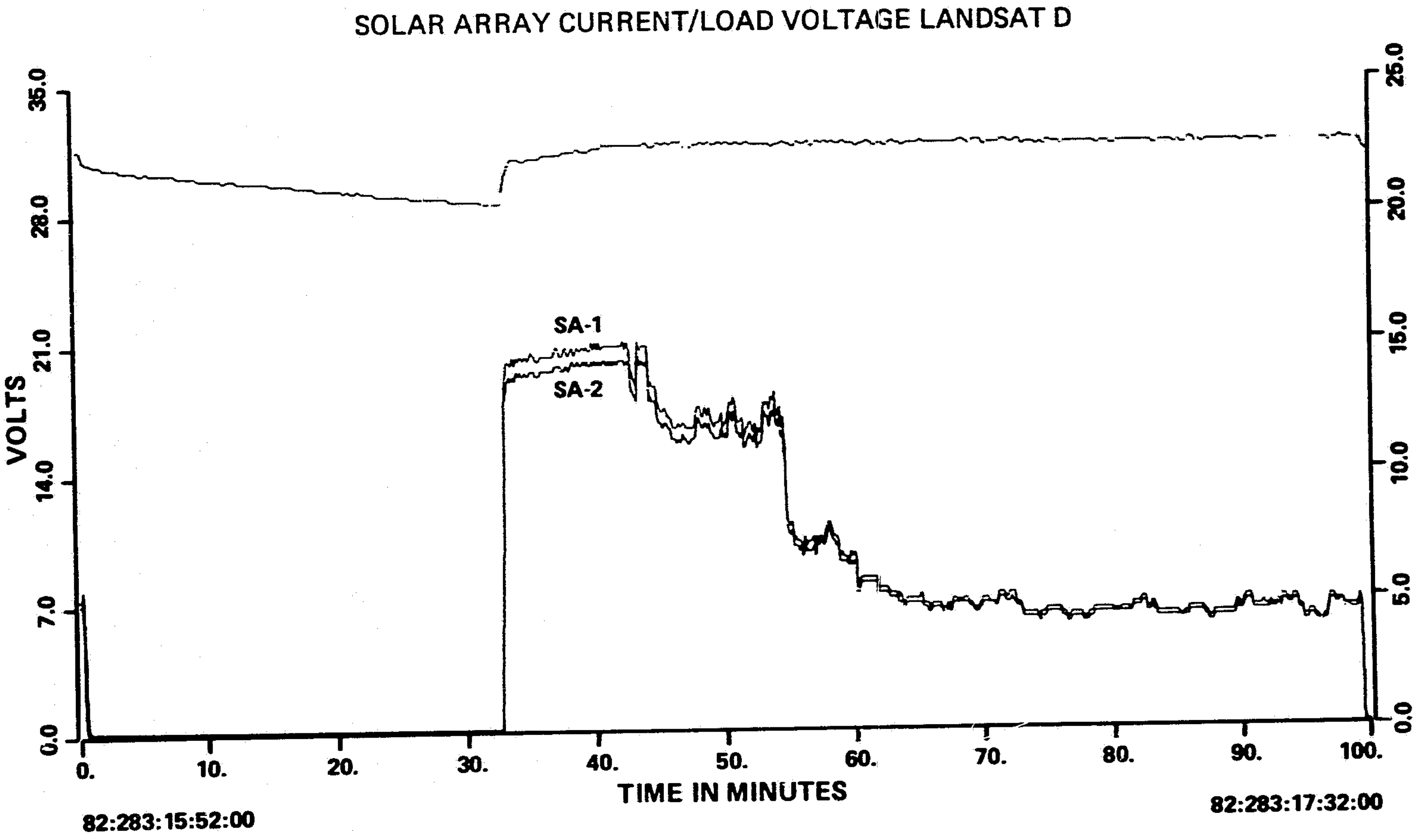

Figure 19. Solar Array Current/Load Voltage – Landsat D.

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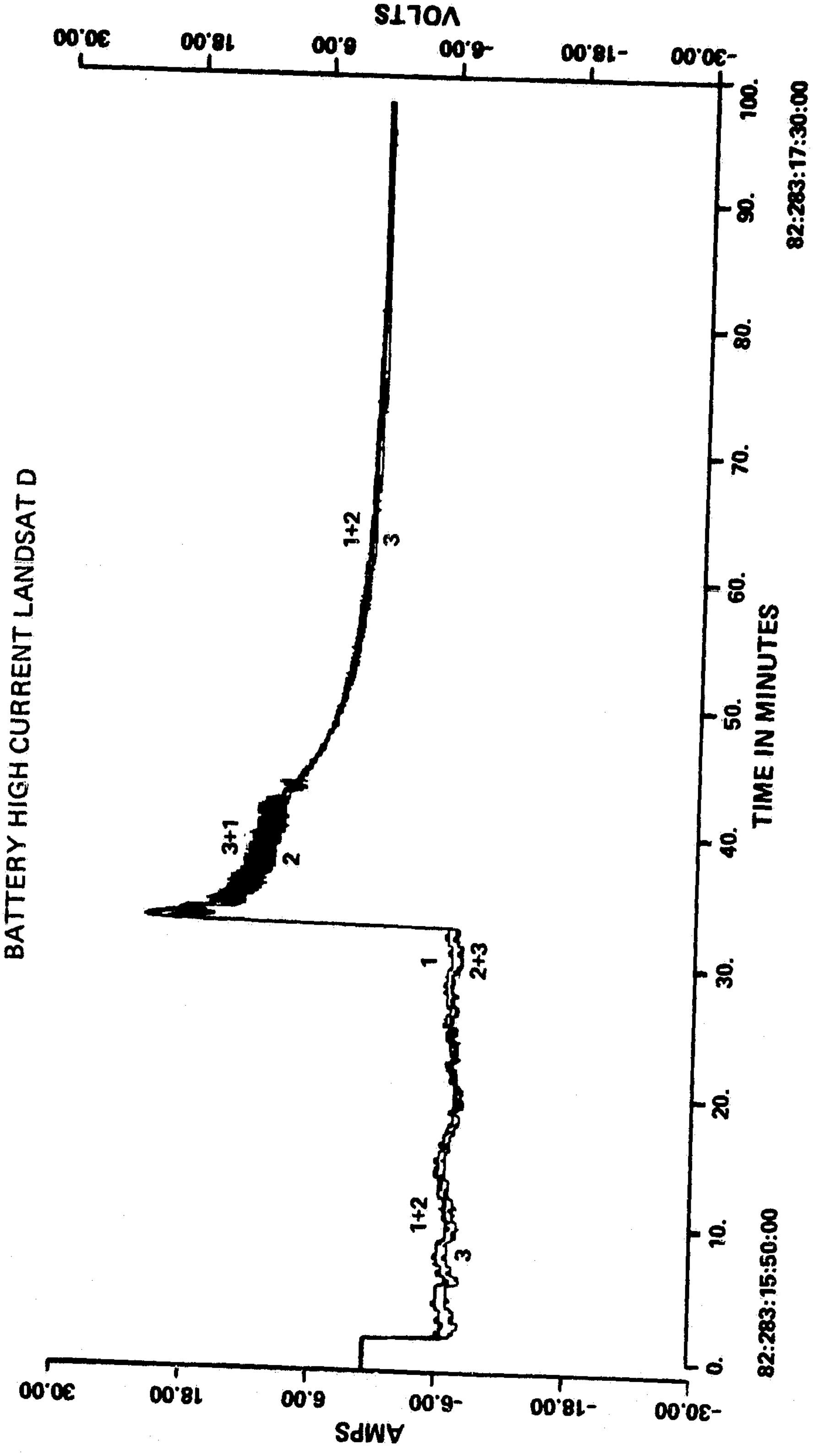

Figure 20. Battery High Current Sensor – Landsat D.

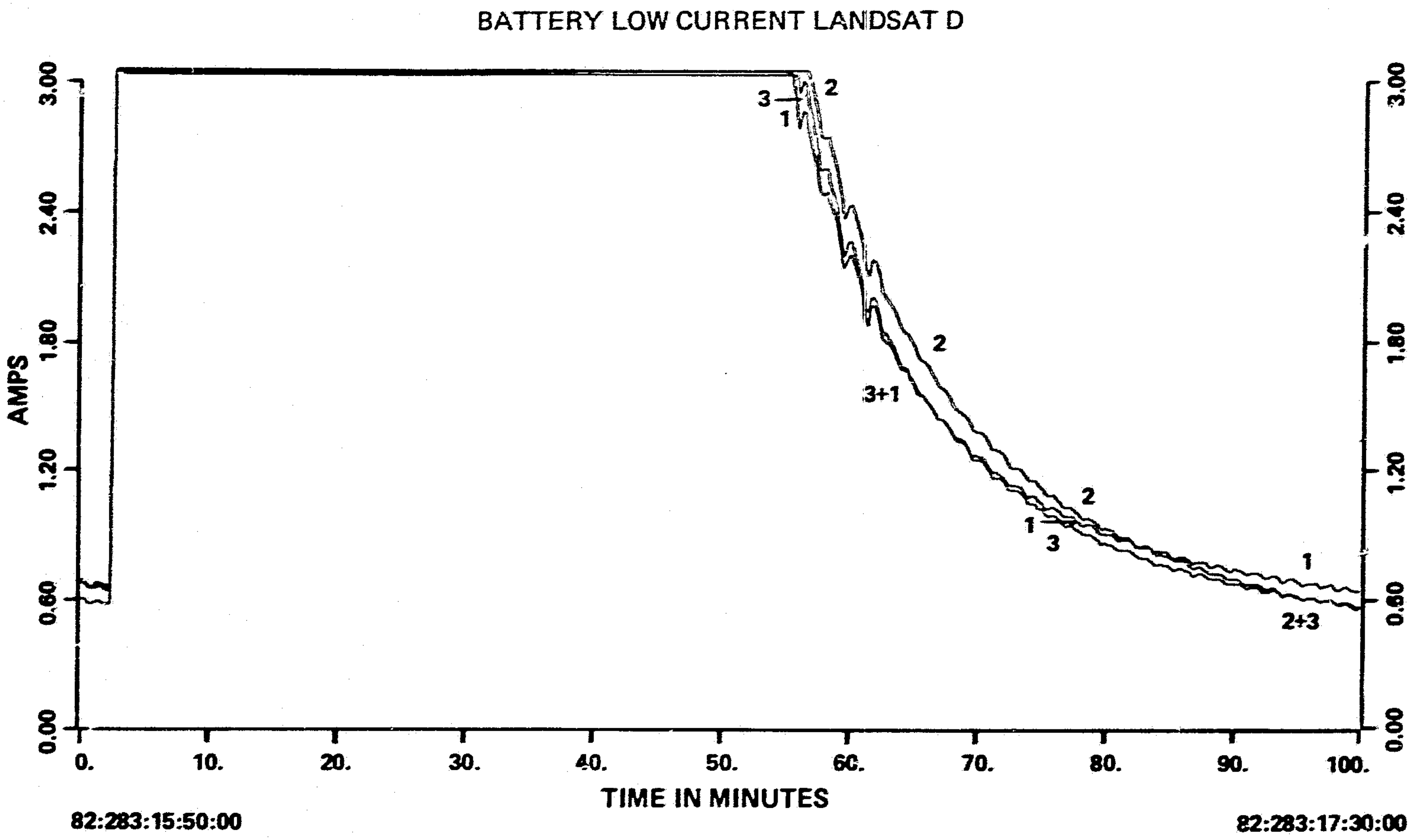

Figure 21. Battery Low Current Sensor — Landsat D.

in operating temperatures between the three batteries given in figure 22 of slightly above the maximum 5°C difference requirement. The temperature differences are due to the position of the MPS affecting the orientation of the batteries in the spacecraft – one facing earth (battery no. 1), one facing deep space (battery no. 2) and the third in-between (battery no. 3).

Battery differential voltage (figure 23) is a measure of the difference in voltage of cells 1-11 and cells 12-22 in each battery. It provides an indication of cell voltage uniformity with a battery. The original purpose was to preclude cell reversal during very deep discharges. The values for battery 1, 2 and 3 indicate a maximum ΔV of 20 mv during the orbit except at the beginning of the day period when the maximum charge current of approximately 22 amps per battery (~C/2.5) is utilized to charge the battery. Small differences in impedence can be seen with the maximum ΔV being at 30 MV when the three battery currents are *identical*. (The discontinuity in the data is due to telemetry readability of 3 mv).

<u>Solar Max Mission Results</u>

SMM has been operating in space since February 1980. It uses three 20AH batteries in the Modular Power Subsystem (MPS) instead of the three 50's of Landsat D. The 22 ampere peak current at the start of the daylight period is the same for Landsat D but for 20AH cells is greater than the C rate. Despite this high rate the batteries have operated uniformly for almost three years. The current sharing of the three batteries on orbit 14646 is given in figure 24. Some changes have taken place in the battery characteristics over the near three years of operation. One such example is that on orbit 13702 the differential battery voltage increased to approximately 60 mv (see figure 25). The charge voltage limit was at NASA V_T Level 4(5,6) (1.435V/cell at 5°C) for the past 10 months because of a relatively low (14%) depth of discharge and the need to avoid overcharge (overheating) by minimizing the ratio of ampere hours in to ampere hours out. The unusual ΔV was evident at the end of discharge and beginning of charge only on battery no. 3, the hottest of the three in the SMM modular power Subsystems (MPS). Increasing the V_T level to 5(1.455 V/cell at 5°C) eliminated the high ΔV and it returned to the 20mv maximum seen earlier (figure 26). This is consistent with the view that

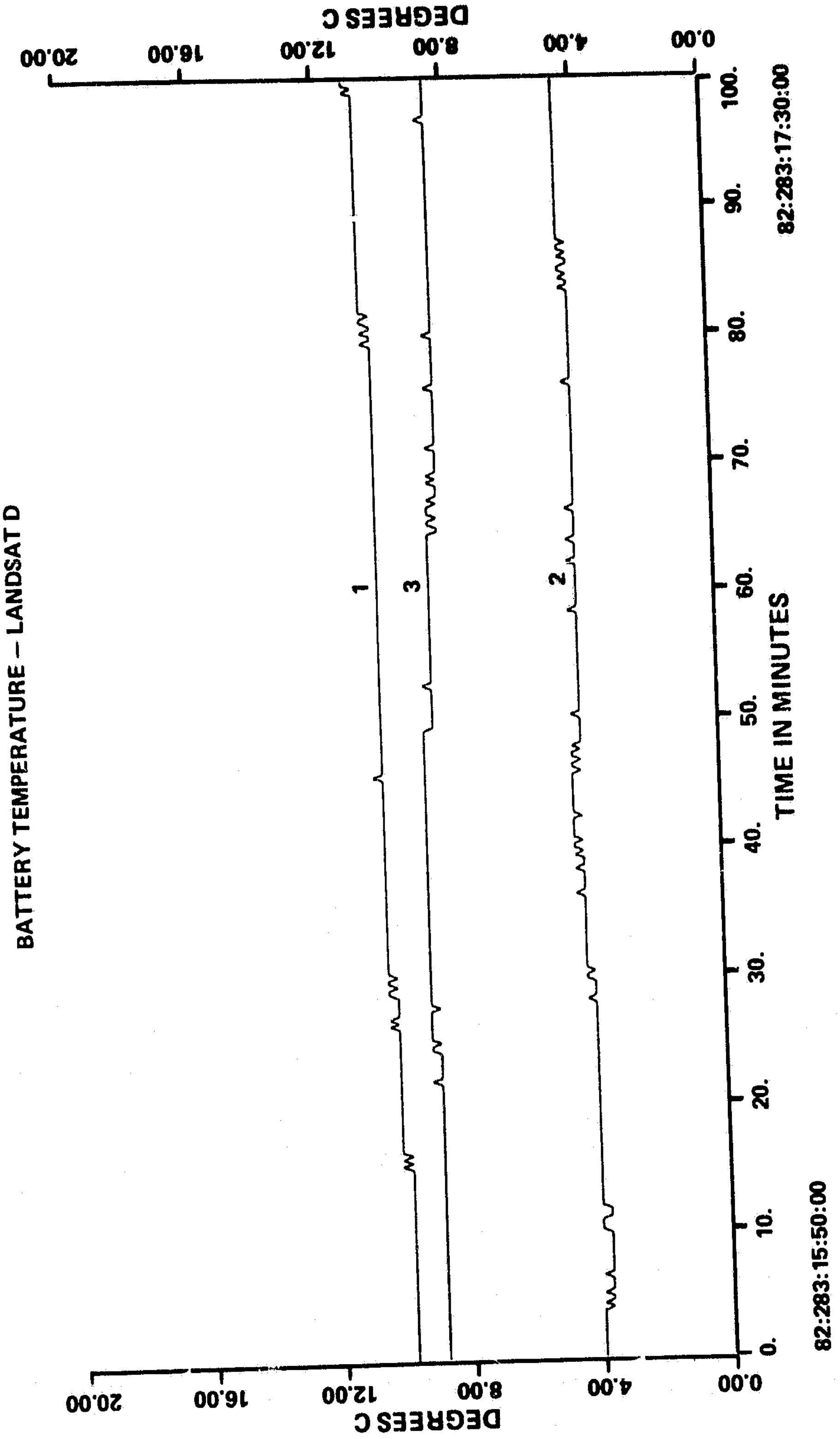

Figure 22. Battery Temperature — Landsat D.

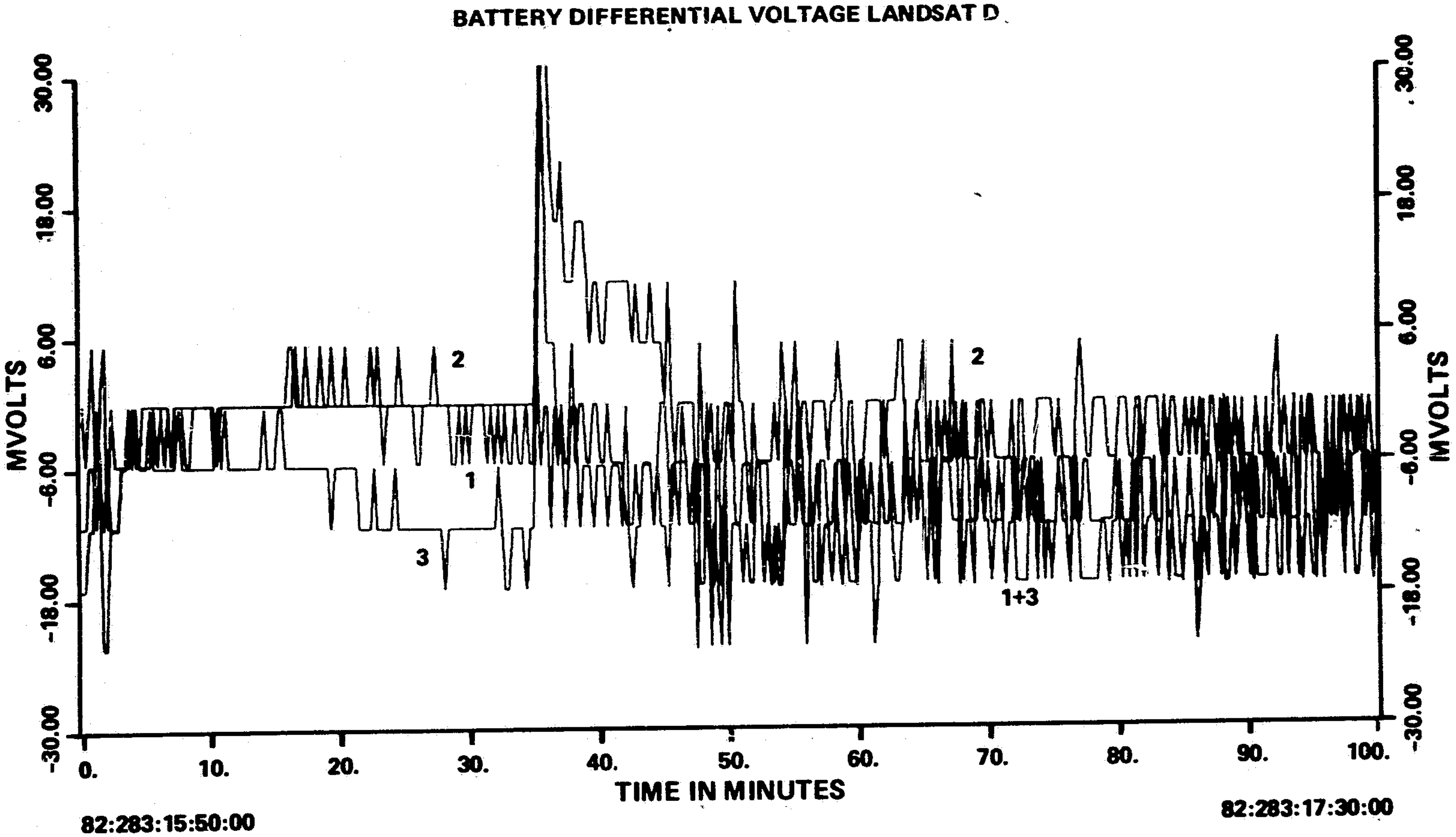

Figure 23. Battery Differential Voltage – Landsat D.

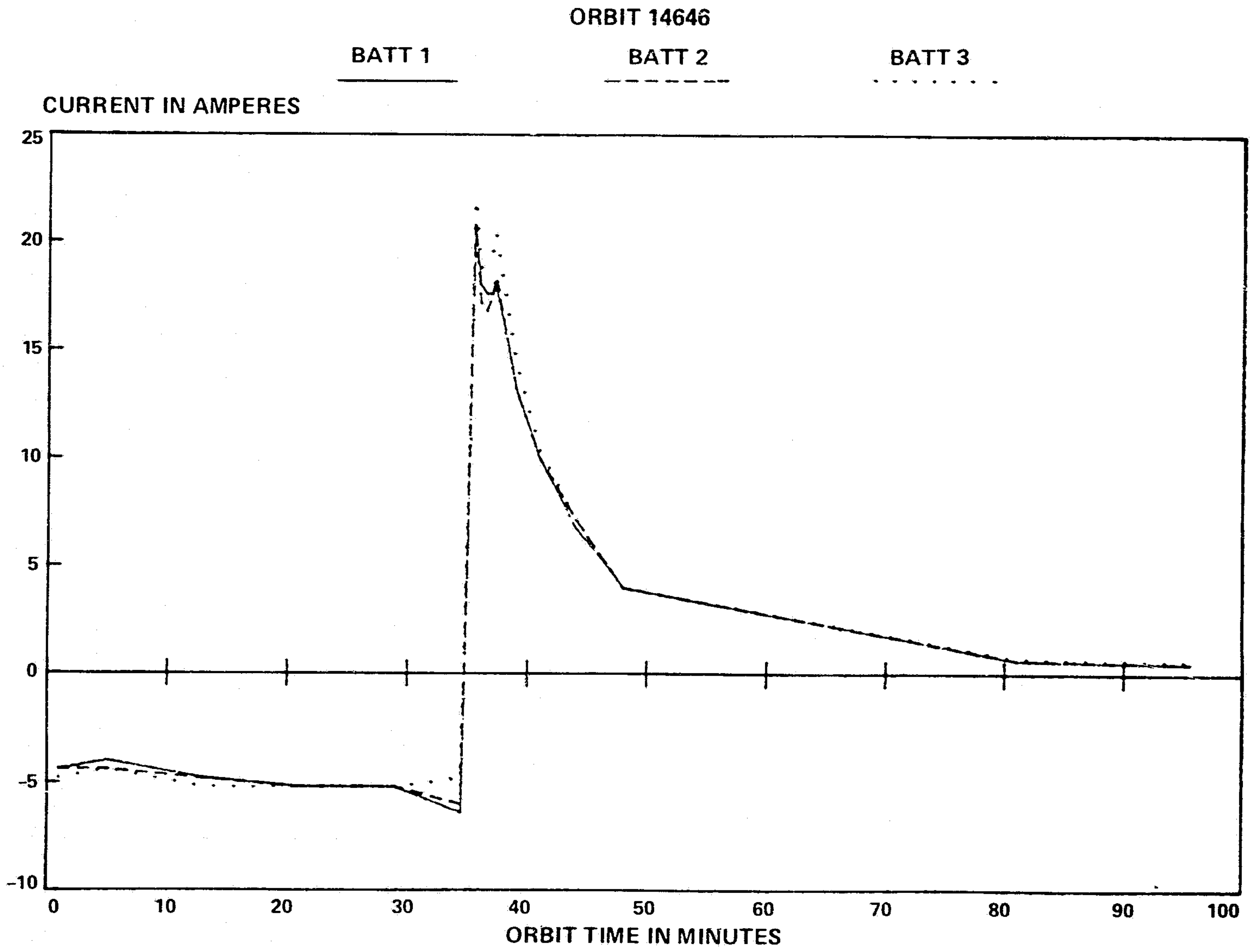

Figure 24. SMM Battery Current Sharing Characteristics.

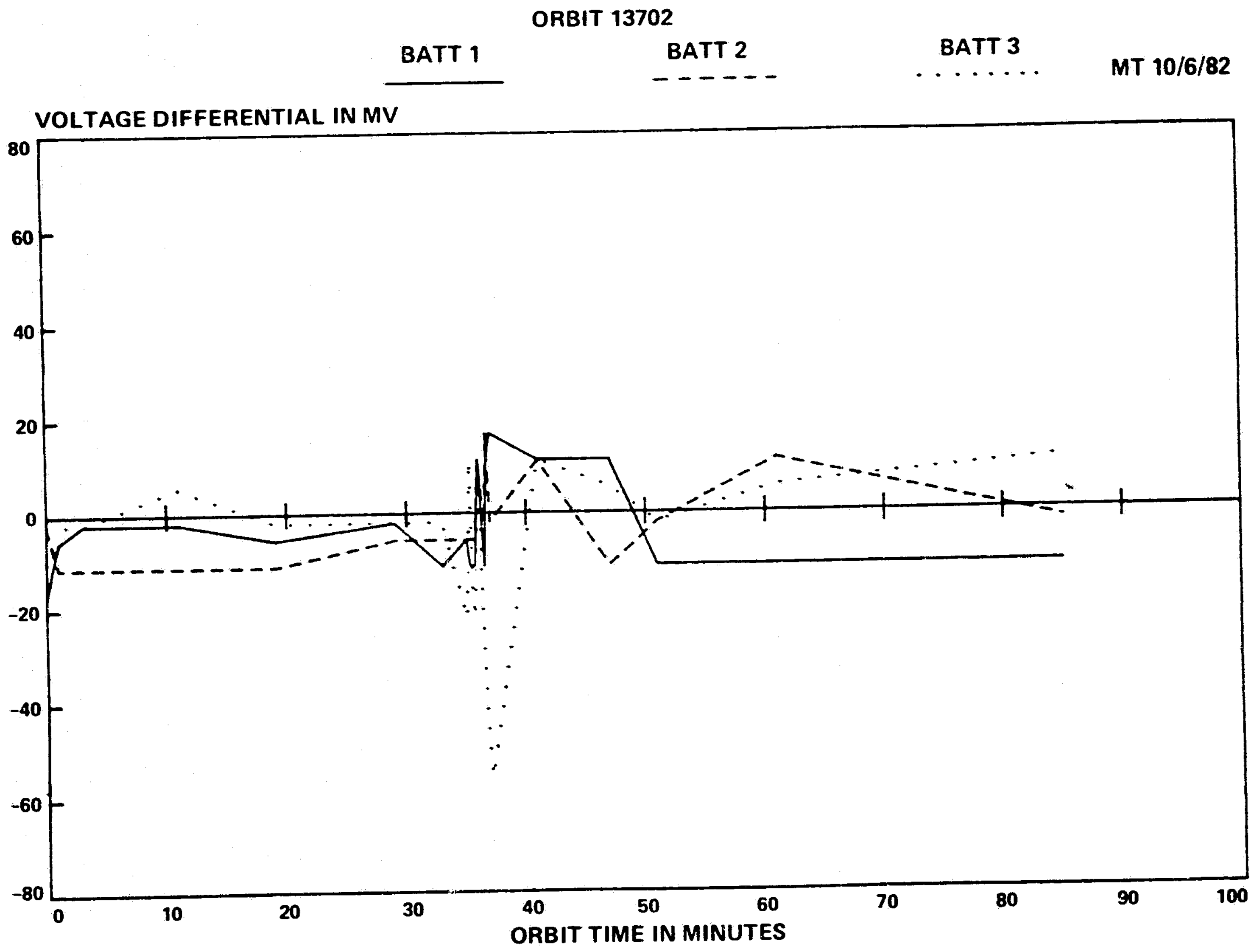

Figure 25. SMM battery differential characteristics orbit 13702.

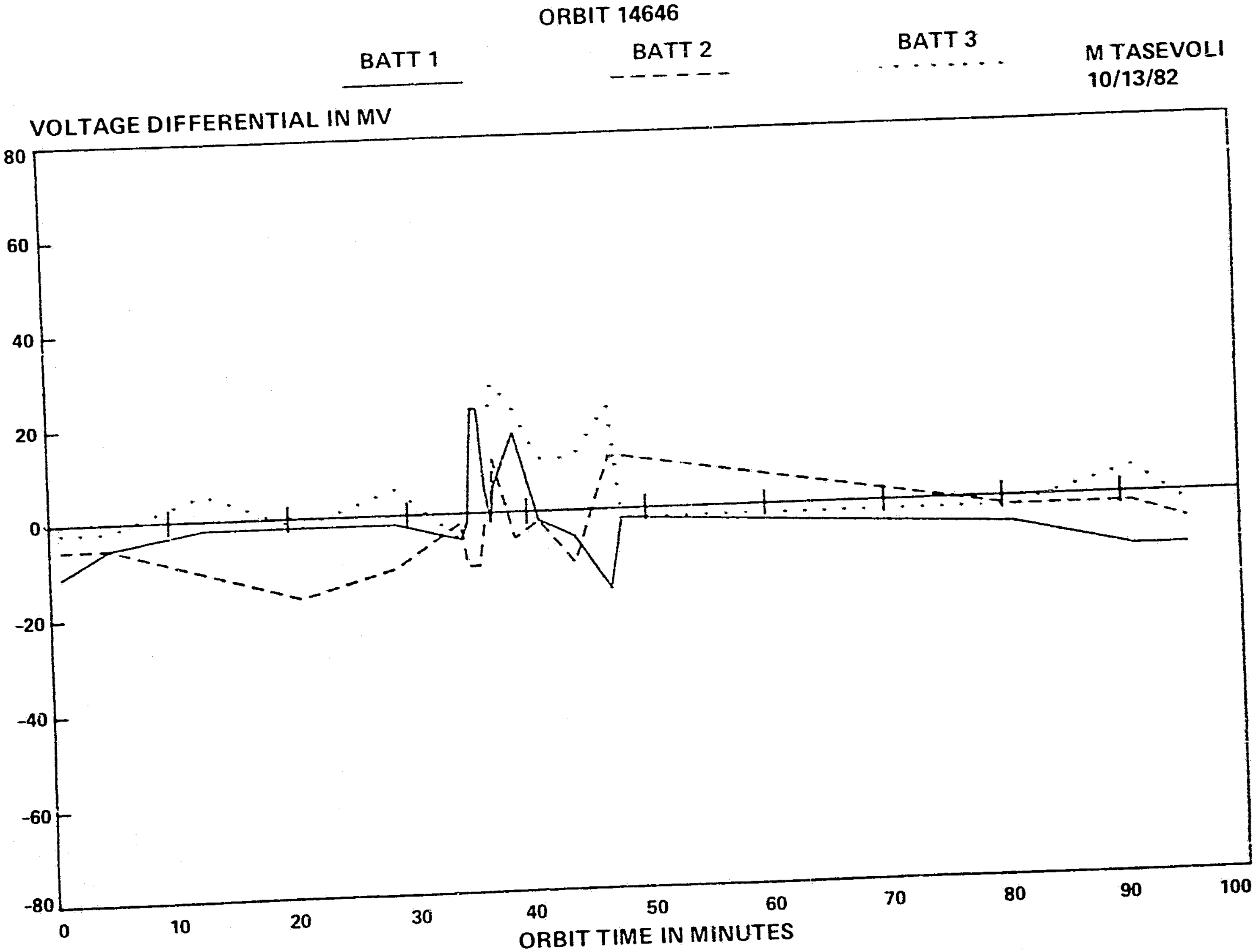

Figure 26. SMM battery differential characteristics orbit 14646.

a cell/battery is a voltage device and must be charged to a high enough voltage to maintain full charge. The higher V_T resulted in placing the cells and batteries in more uniform charged condition, thus a more uniform discharge.

Conclusions

The information presented here provides evidence that the NASA Standard cell design which emphasizes uniformity throughout the manufacturing, test and battery assembly phase can operate uniformly for extended periods of time in orbit. This is based on current sharing, ΔV, and voltage data for SMM and Landsat D over the past three years. Further, the three batteries with uniform operating characteristics can be connected in parallel on the same bus for both charge and discharge and perform almost identically for extended period with little or no adjustment in orbit. A final factor for consideration is that with the uniform cell characteristics only 25 cells were available to select 22 cells for each battery. Even more amazing is the fact that the 22 cells were selected from cell manufacturer data alone, which is a process that could only be instituted with confidence when the cells have uniform properties as those with the NASA Standard cell design assembled into batteries of the NASA Standard Battery Design.

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