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Ni-H_2 Cell Characterization for INTELSAT Programs

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ABSTRACT

Various Ni/H_2 cell designs manufactured for INTELSAT Programs during the past decade have been characterized electrically as a function of temperature. The resulting data for these INTELSAT V, VI, VII and VIIA cells are assembled in a manner which allows ready comparison of performance. Also included is a detailed description of each design.

INTRODUCTION

As part of a coordinated program to extend the operational lives of its spacecraft, INTELSAT characterizes the performance of each type of battery cell flown.

INTELSAT is operating batteries using 30 Ah cells made by Eagle-Picher, Industries, 48 Ah cells from Hughes Aircraft Company, and 85 Ah cells made by Gates Aerospace Batteries. In the near future we will be operating 120 Ah Gates cells also.

Life testing, performance characterization, and associated analytical work is done at COMSAT Corporation Laboratory, Clarksburg, Md.

This paper reports on the results of the performance characterization, with temperature, of the four types of Ni/H_2 cells in or about to be in operation with the INTELSAT fleet of geostationary communications satellites.

BACKGROUND

One reason why INTELSAT is successful in achieving long life for its operational fleet of spacecraft is the care taken in the operation of the spacecraft batteries. In support of the orbital operation, batteries of each type flown are placed into real time life test. These tests, performed at COMSAT Laboratories, simulate the operation in orbit as closely as possible. A test is normally started three seasons before the first use of the batteries in orbit. Individual cells are operated in the same test with the battery and are periodically removed from the test for destructive physical analysis (DPA). These tests are not intended to validate the design of the batteries; rather they are to address problems on the ground before they are encountered in orbit. Solutions can be devised and tested to ensure continued operation in orbit.

In addition to the life testing, COMSAT also performed a series of parametric performance tests, at the cell level, to characterize the response of the batteries under a variety of thermal and charge conditions.

Since 1983 INTELSAT spacecraft have all had Ni/H_2 batteries. These batteries have used cells from the three main Ni/H_2 cell manufacturers in the USA. Sixteen batteries using 30 Ah Eagle-Picher Industries (EPI) cells are in operation on the later INTELSAT V spacecraft, ten batteries using 44 Ah Hughes Aircraft Company cells are in operation on the INTELSAT VI spacecraft, and two batteries using 85 Ah Gates Aerospace Batteries have recently been launched on the first INTELSAT VII. This is the first of at least six similar spacecraft which will be joined by three INTELSAT VIIA spacecraft equipped with batteries using 120 Ah Gates cells. These are the four types of cell reported upon.

Details of the cells are given in Table 1. Figures 1 to 4 show cross-sectional drawings of each cell. While Table 2 gives details of each battery, INTELSAT has always flown two batteries per spacecraft. Figures 5 to 7 are pictures of each type of battery. As yet no pictures are available of an INTELSAT VIIA battery.

PARAMETRIC TESTING

In each of the four cases, a minimum of four cells of each type were subjected to charge/discharge cycles at 10°C intervals from +30 to -20°C except for the I-5 cells which, because of their design, operate successfully down to -30°C. In addition, self discharge performance data was generated at 10, 20, and 30°C for durations of 144 hours. The testing sequence is presented in Table 3. Pressure, temperature, cell voltage, charge, and discharge current are carefully monitored.

Figure 8 displays a typical series of charge/discharge voltage and temperature profiles. From this type of data, cell end-of-charge voltage, mid-discharge voltage and capacity are determined as a function of cell temperature. This is a modification to the data which was previously presented using chamber set point temperature for the abscissa [1]. Two cells of each group were instrumented with strain-gauges. A typical series of charge/discharge pressure profiles are displayed in Figure 9. When this data is normalized to 0°C using the gas law and cell temperature data, the resulting profiles indicate the degree to which the gauges are temperature compensated. The charging pressure profiles can be used to generate plots of instantaneous charge efficiency by taking their derivative with respect to time. Finally, pressure profiles for 144 hours of self-discharge were determined at 10, 20, and 30°C. These pressure profiles were converted to capacity remaining profiles by considering the pressure range for capacity measurements. The results for each case are displayed in Figures 10 to 13. Plotted are capacity, end-of-charge voltage and mid-discharge voltage as a function of cell temperature; charge efficiency versus charge in and percent capacity remaining as a function of open-circuit time at temperature.

The self-discharge data can be further developed assuming first order kinetics and Arrhenius behavior [2]. The resulting self-discharge characteristics and Arrhenius plots are displayed in Figure 14. The activation energy associated with the rate constant for each case is included in Table 4.

[1] J. D. Dunlop, et. al., "NASA Handbook for Nickel-Hydrogen Batteries," NASA Reference Publication 1314, 1993, Chapter 5.

[2] J. F. Stockel, "Self-Discharge Performance and Effects of Electrolyte Concentration on Capacity of Nickel-Hydrogen (Ni/H_2) Cells," 20th Intersociety Energy Conversion Engineering Conference, Miami Beach, Florida, August 1985, Vol. 1, pp. 1.171-1.174.

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TABLE 1. SUMMARY OF INTELSAT NI-H_2 CELL DESIGNS

	IV	IVI	IVII	IVII-A
Manufacturer	EPI	HAC/EPI	GAB	GAB
Cell Dimensions (cm)				
Diameter	8.9	8.7	8.7	11.8
Total Length	21.2	28.0	29.3	20.2
Cell Mass (g)	890	1460	1840	2640
Capacity @ 10°C to 1.0V (Ah)	34	56	90	122
Stack Design				
Component Shape	Truncated Disk	Pineapple Slice	Pineapple Slice	Pineapple Slice
Configuration	Single	Single	Single	Single
Arrangement	Back to Back	Recirculating	Back to Back	Back to Back
Terminal Design	Ziegler/Axial	Teflon/Axial	Ceramic/Axial	Ceramic/Rabbit Ear
Positive Electrode				
Plaque Type	Wet Slurry	Dry Powder	Dry Powder	Dry Powder
Impregnation Type	Aqueous EC	Alcohol EC	Aqueous EC	Aqueous EC
$Ni(OH)_2$ Loading (g/cc)	1.42	1.29	1.49	1.52
$Co(OH)_2$ Loading (g/cc)	0.12	0.16	0.13	0.12
Plate Thickness (mm)	0.775	0.880	0.920	0.920
No. of Plates	24	40	48	38
Mass Fraction (%)	37.3	34.4	37.3	35.2
Separator Type	Asbestos	2 Layer Zircar	2 Layer Zircar	2 Layer Zircar
Thickness (mm)	0.25	0.60	0.60	0.60
Mass Fraction	2.0	5.9	6.1	5.3
Electrolyte				
Discharged State (w/o)	38	31	31	31
Mass Fraction (%)	10.7	15.9	15.0	13.7
Negative Electrode				
No. of Plates	34	41	48	38
Thickness (mm)	0.137	0.148	0.116	0.116
Pt Loading (g/cm^2)	8.10	7.52	3.20	2.80
Mass Fraction (%)	4.2	4.4	4.2	4.0

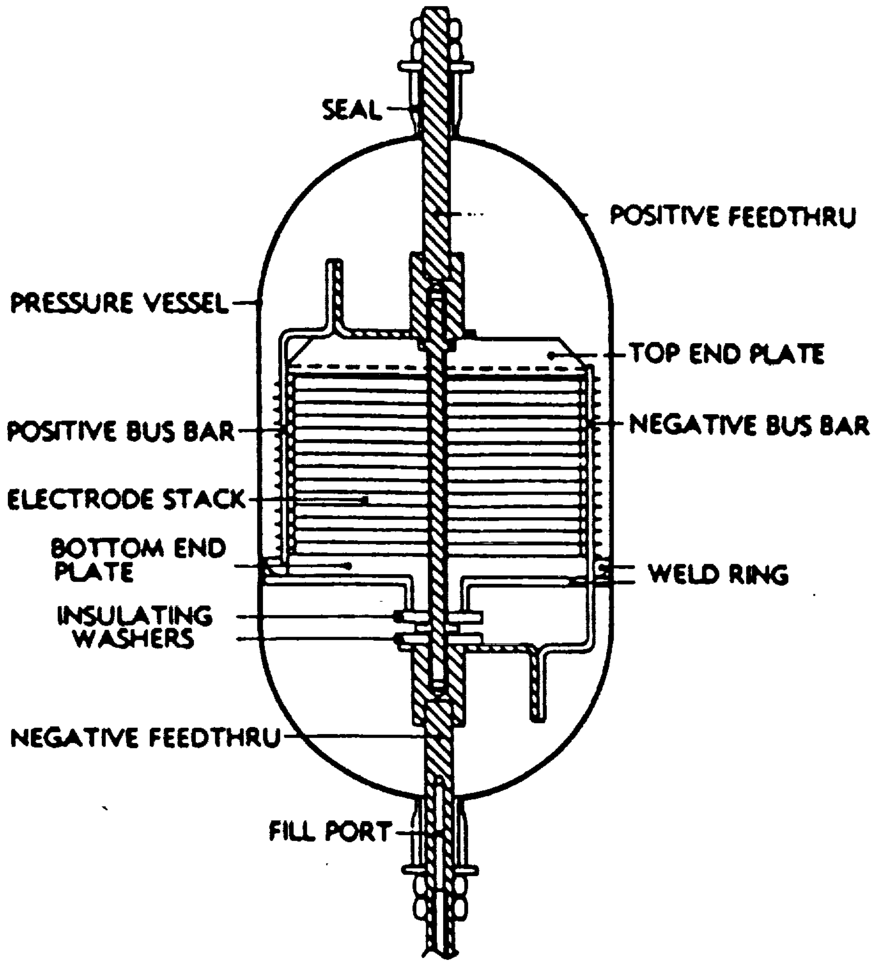

Figure 1. Cross-sectional view of an INTELSAT V NiH2 Cell

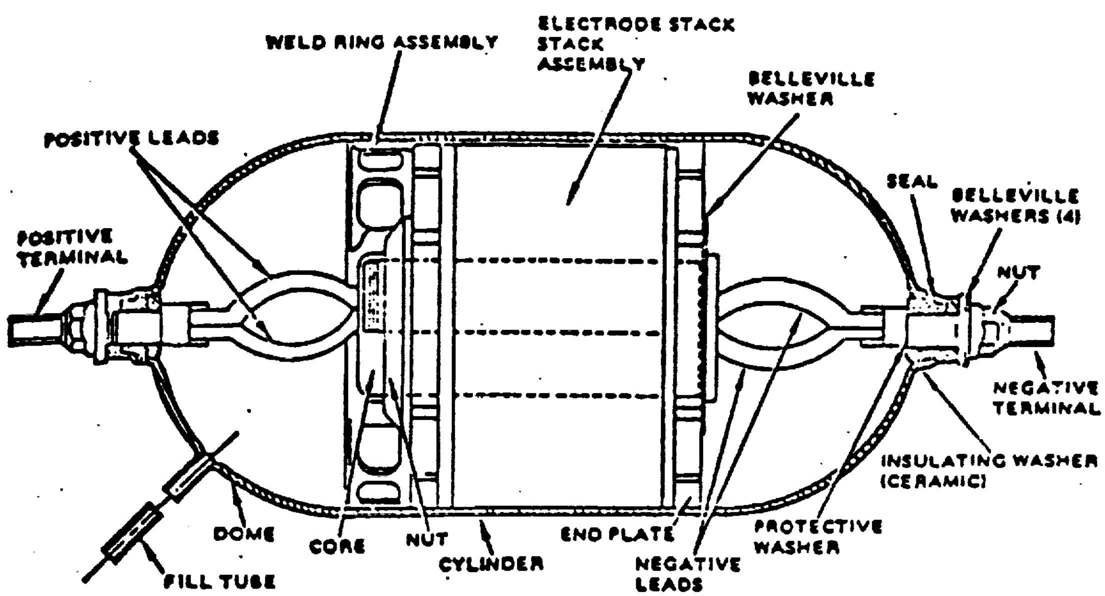

Figure 2. Cross-sectional view of an INTELSAT VI NiH2 Cell

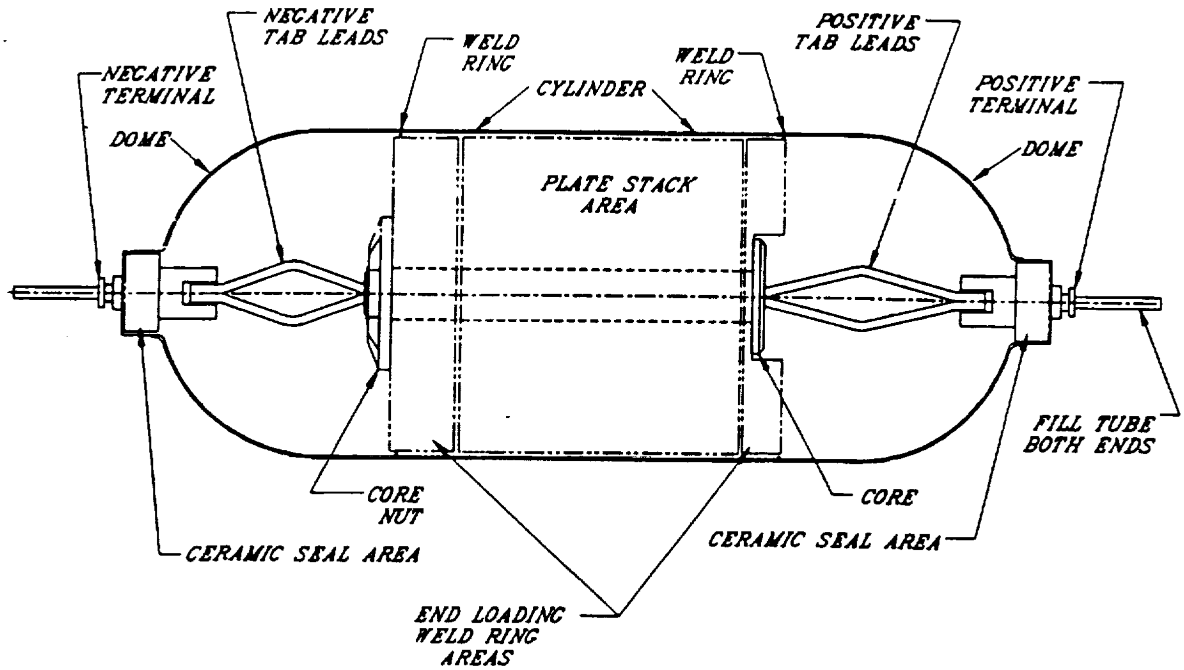

Figure 3. Cross-sectional view of an INTELSAT VII NiH2 Cell

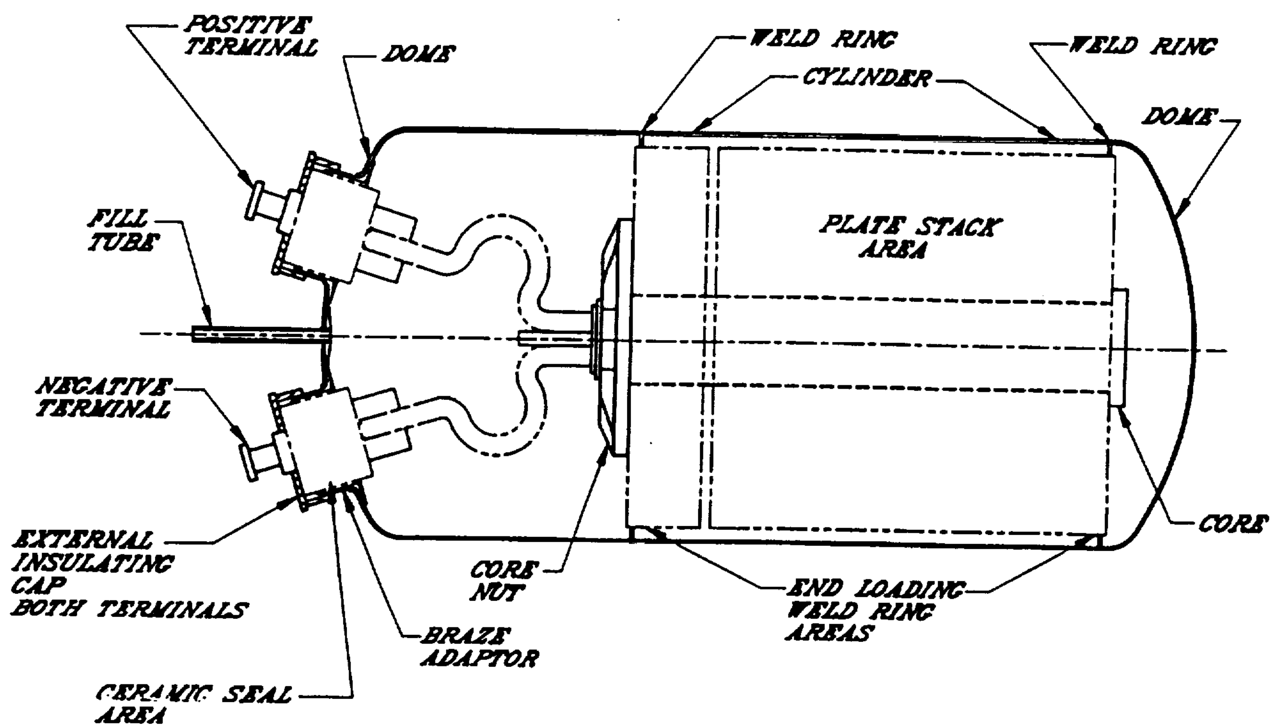

Figure 4. Cross-sectional view of an INTELSAT VIIA NiH2 Cell

Gates Energy Products
Gates Aerospace Batteries

TABLE 2. SUMMARY OF INTELSAT BATTERY DESIGNS

	I-V	I-VI	I-VII		I-VII-A	
Manufacturer	Ford Aerospace	HAC	SS/Loral		SS/Loral	
No. Batteries/SC	2	2	2		2	
No. Packs/Battery	1	2	2		2	
No. Cells/Battery	27	32	27		27	
Battery Dimenions (cm)		2 Quadrants	Pack 1	Pack 2	Pack 1	Pack 2
Length	51.8		51.0	51.0	50.8	50.8
Width	52.1		51.0	37.8	52.8	39.5
Height	22.2	28	30.4	30.4	23.5	23.5
Radius		80				
Battery Mass (Kg)	30.12	63.9	66.8		81.45	
Rated Capacity (Ah)	30	44	85.5		120	
Reconditioning (Ω)						
Load A	50	43.2	23.5		16.2	
Load B		86.4				
Diode Bypass	✓	✓	✓		✓	

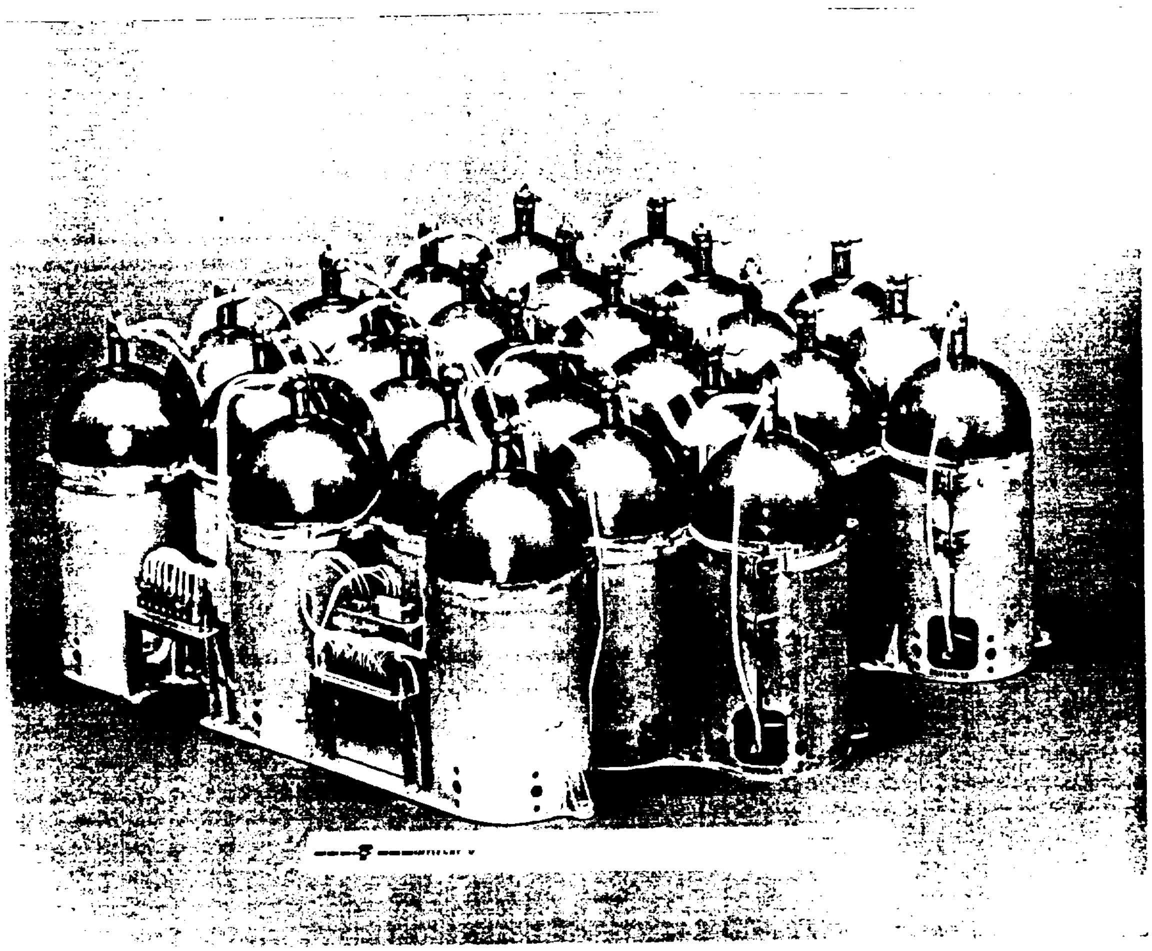

Figure 5. INTELSAT V NiH2 Battery

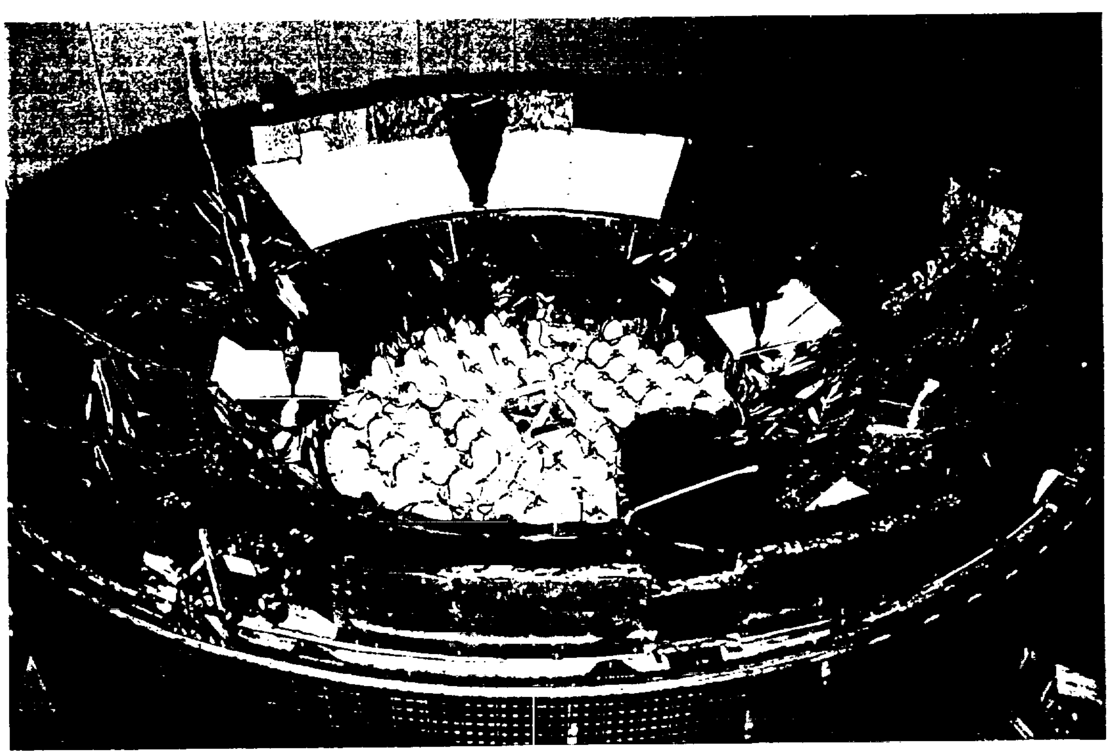

Figure 6. Two INTELSAT VI NiH2 Batteries on the Flt. 1 S/C

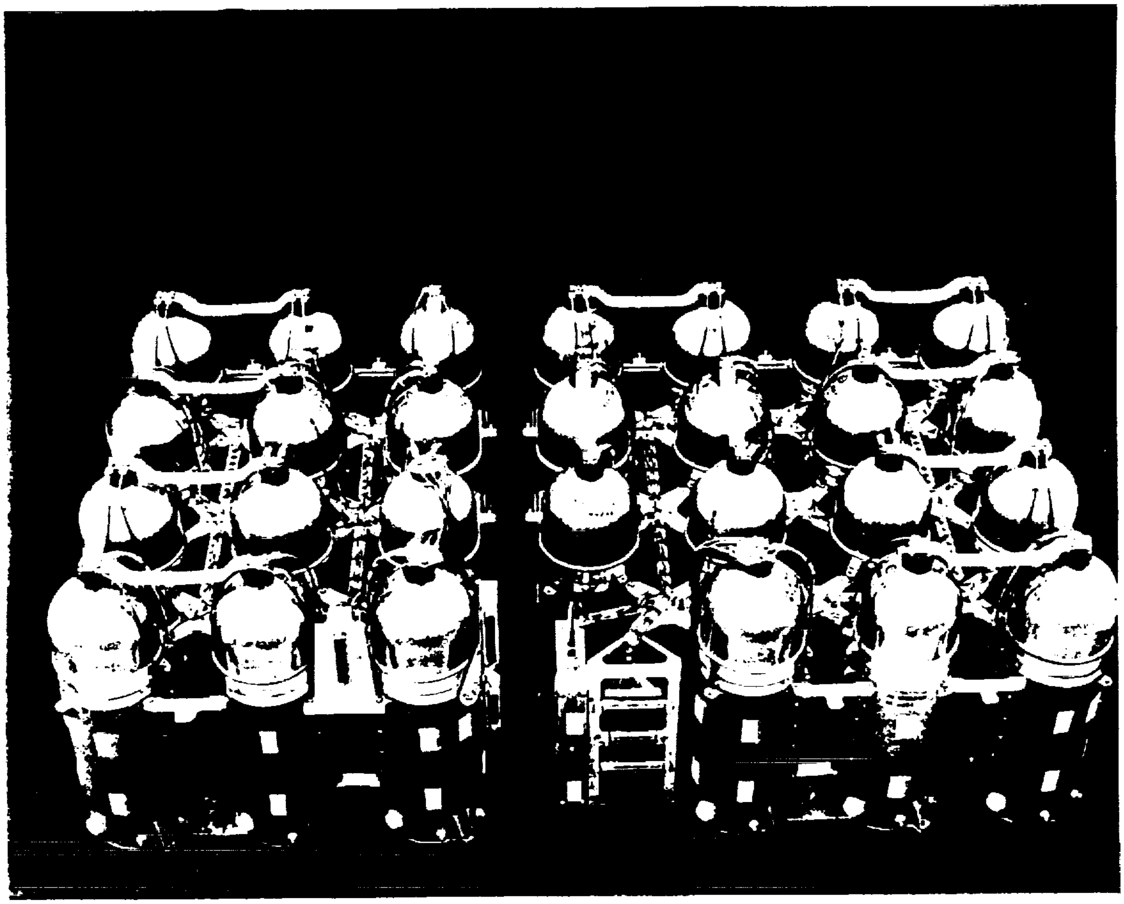

Figure 7. INTELSAT VII NiH2 Battery

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TABLE 3 - INTELSAT CHARACTERIZATION TEST REGIME

Sequences	Temp.	Measurements	Charge/Discharge	I-V	I-VI	I-VII	I-VIIA	Remarks
1	10° C	Reconditioning	C/20 , C/2	x	x	x	x	
2	10° C	Capacity	C/10 , C/2	x	x	x	x	
3	10° C	Capacity	C/10 , C/2	x	x	x		
4	0° C	Capacity	C/10 , C/2	x	x	x	x	
5	0° C	Capacity	C/10 , C/2	x	x	x	x	
6	-10° C	Capacity	C/10 , C/2	x	x	x	x	
7	-10° C	Capacity	C/10 , C/2	x	x	x	x	
8	-20° C	Capacity	C/10 , C/2	x	x	x	x	
9	-20° C	Capacity	C/10 , C/2	x	x	x	x	
10	-30° C	Capacity	C/10 , C/2	x			x	
11	-30° C	Capacity	C/10 , C/2	x			x	
12	10° C	Capacity	C/10 , C/2	x	x	x	x	
13	10° C	Capacity	C/10 , C/2	x	x	x	x	
14	20° C	Capacity	C/10 , C/2	x	x	x	x	
15	20° C	Capacity	C/10 , C/2	x	x	x	x	
16	30° C	Capacity	C/10 , C/2	x	x		x	
17	30° C	Capacity	C/10 , C/2	x	x		x	
18	10° C	Capacity	C/10 , C/2	x	x	x	x	
19	10° C	Charge Stand	C/10 , C/2	x	x	x	x	1
20	20° C	Charge Stand	C/10 , C/2	x	x	x	x	2
21	30° C	Charge Stand	C/10 , C/2	x	x	x	x	3
				C=30Ah	C=48Ah	C=86Ah	C=120Ah	
			CELLS #	L4-04 L4-84 L4-90 * L4-107*	L003* L012* L013 L014	L1-001* L1-022* L2-023 L2-060	L1-002* L1-004* L1-016 L1-018 L1-022 L1-032	

(1) Charge for 16 hours @ 10°C, Open circuit for 144 hours @ 10°C, Discharge to 0.1V @ 10°C
(2) Charge for 16 hours @ 10°C, Open circuit for 144 hours @ 20°C, Discharge to 0.1V @ 20°C
(3) Charge for 16 hours @ 10°C, Open circuit for 144 hours @ 30°C, Discharge to 0.1V @ 30°C

* Cells with Strain Gauge

		(TO 0.1V)	(TO 0.1V)	(TO 0.1V)	(TO 1.0V)	(TO 1.0V)	(TO 1.0V)
	0°C	1.241	138.60	171.13	1.242	137.10	170.05
	-10°C	1.230	149.30	182.60	1.232	147.00	180.81
	-20°C	1.211	154.15	185.25	1.214	149.32	181.27
	10°C	1.248	123.22	151.96	1.249	120.33	149.81
	20°C	1.261	109.34	135.54	1.262	106.51	133.46
	30°C	1.263	87.40	108.13	1.265	84.30	105.85

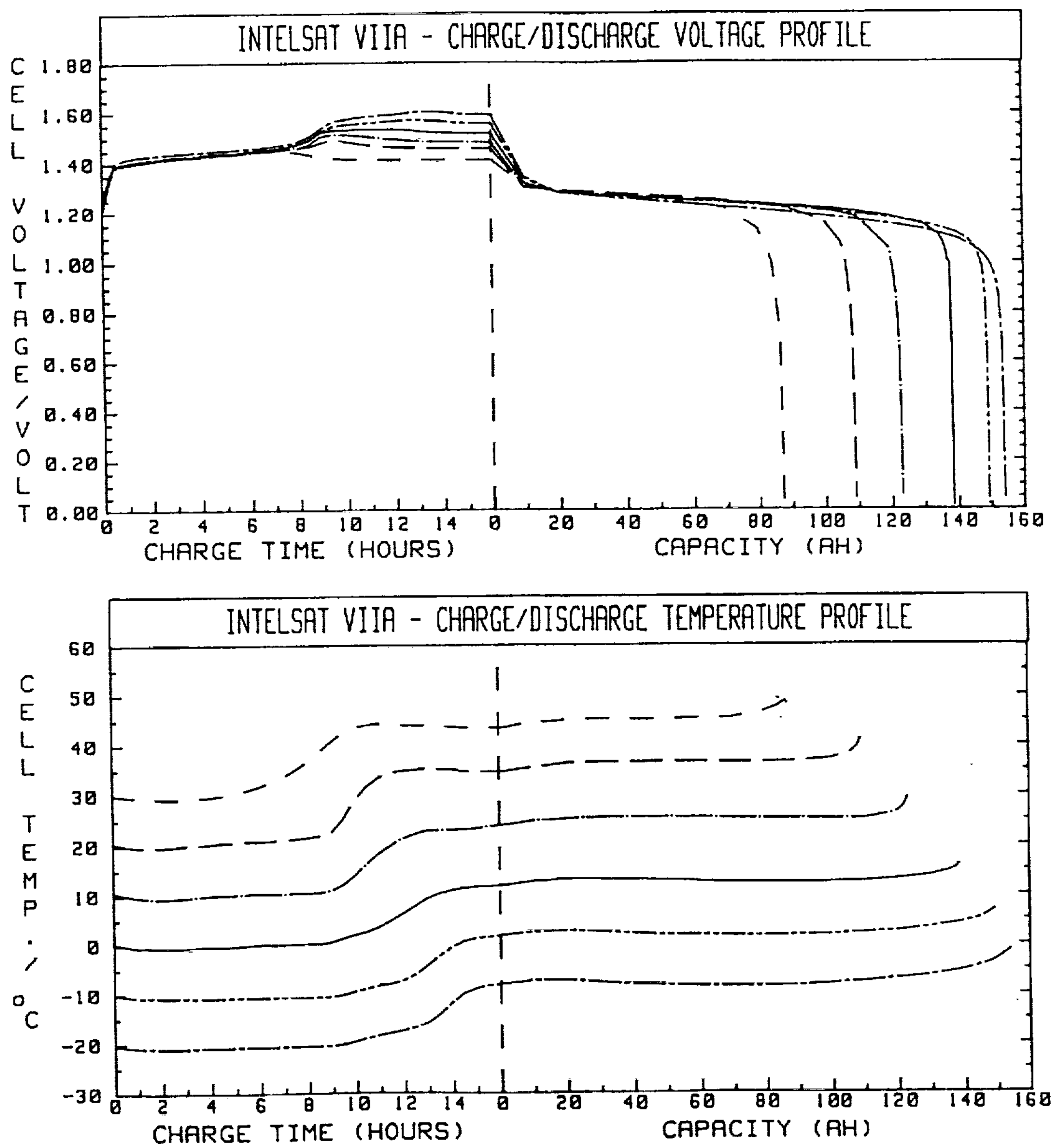
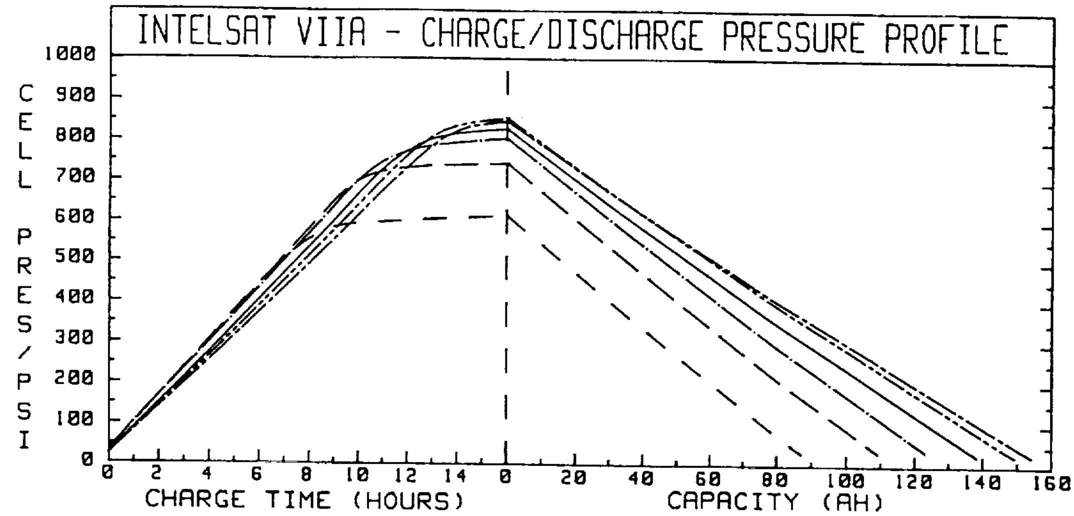


FIGURE 8

		CHARGE		DISCHARGE	
	Temp.	Slope	Intercept	Slope	Intercept
——	0°C	64.05	18	-5.716	815
—··—	-10°C	61.2	20	-5.48	841
—·—	-20°C	58.77	19	-5.251	833
——	10°C	66.79	31	-6.161	794
— —	20°C	68.95	27	-6.438	734
— —	30°C	69.93	26	-6.656	608



		CHARGE		DISCHARGE	
	Temp.	Slope	Intercept	Slope	Intercept
——	0°C	63.53	19	-5.467	779
—··—	-10°C	63.28	21	-5.443	835
—·—	-20°C	63.04	21	-5.415	858
——	10°C	63.91	31	-5.65	727
— —	20°C	63.84	26	-5.698	649
— —	30°C	63.29	26	-5.734	523

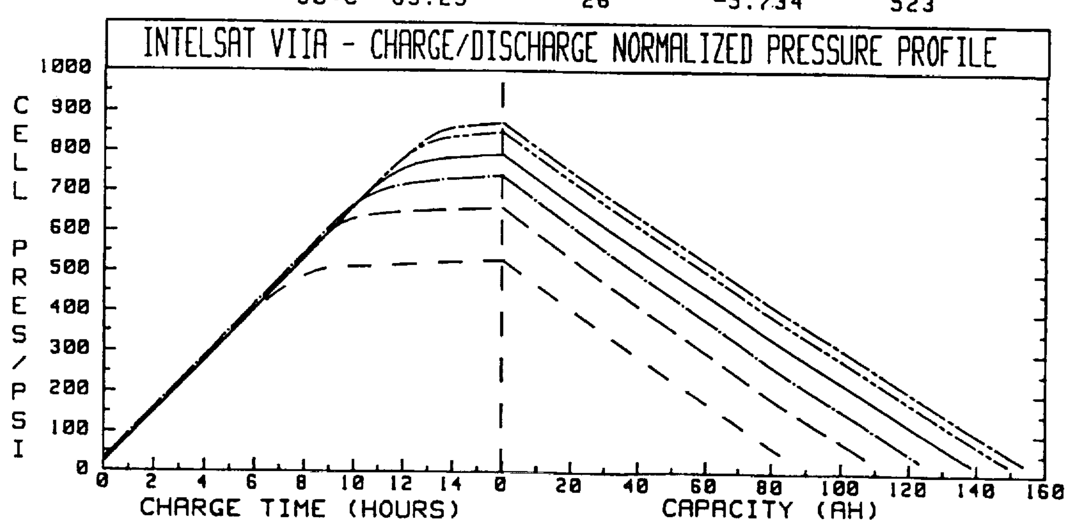


FIGURE 9

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INTELSAT V

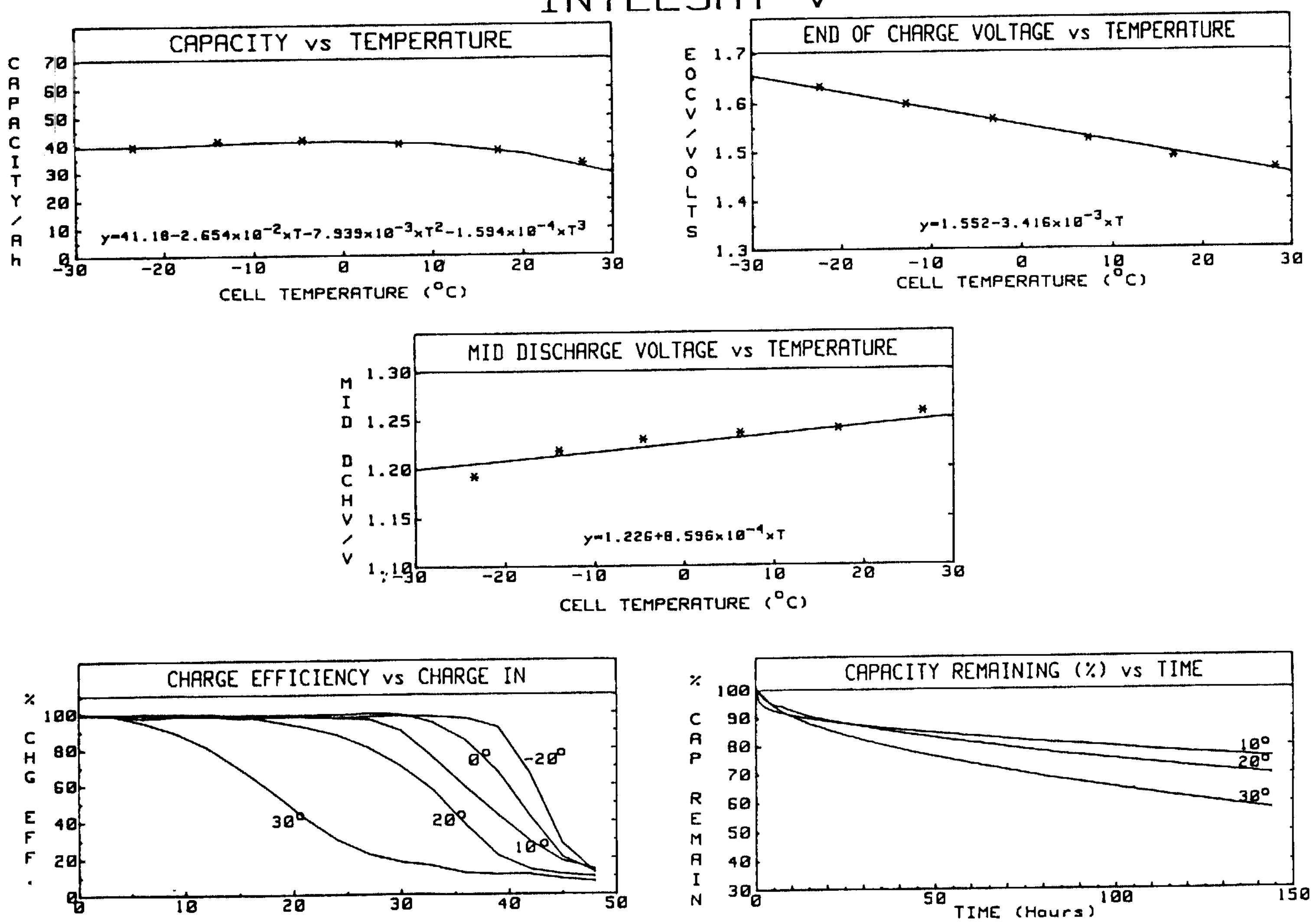

FIGURE 10

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INTELSAT VI

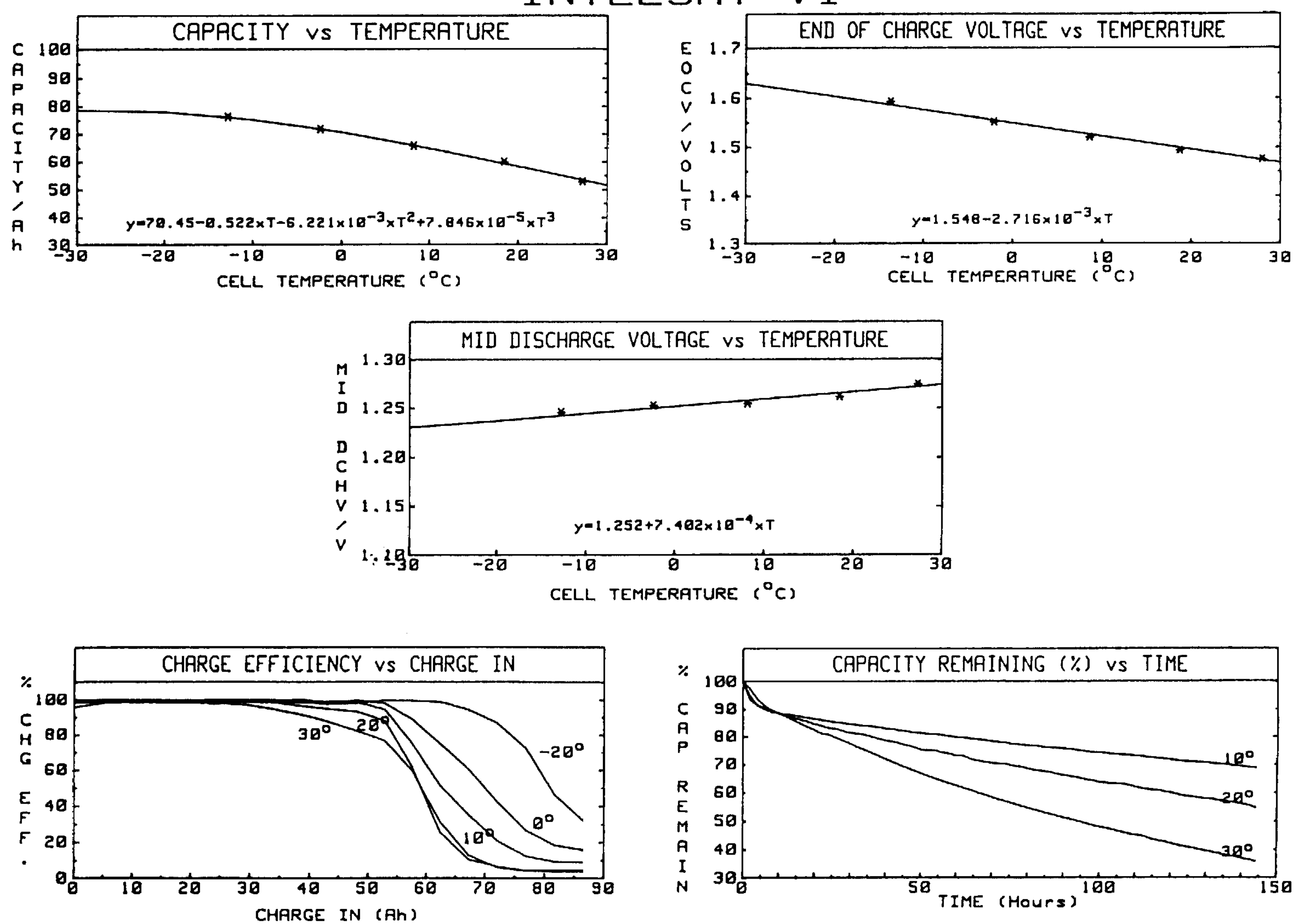

FIGURE 11

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INTELSAT VII

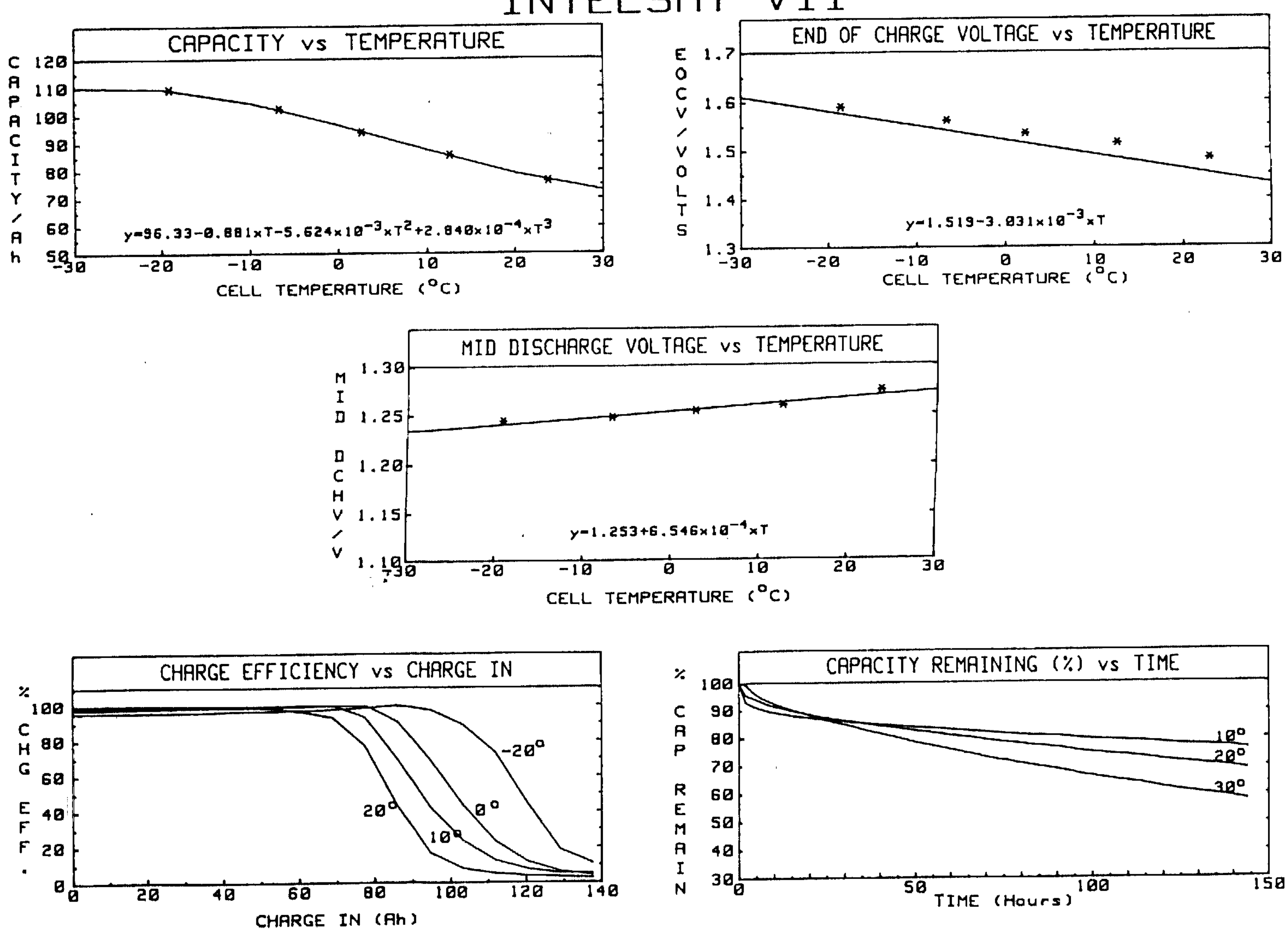

FIGURE 12

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INTELSAT VIIA

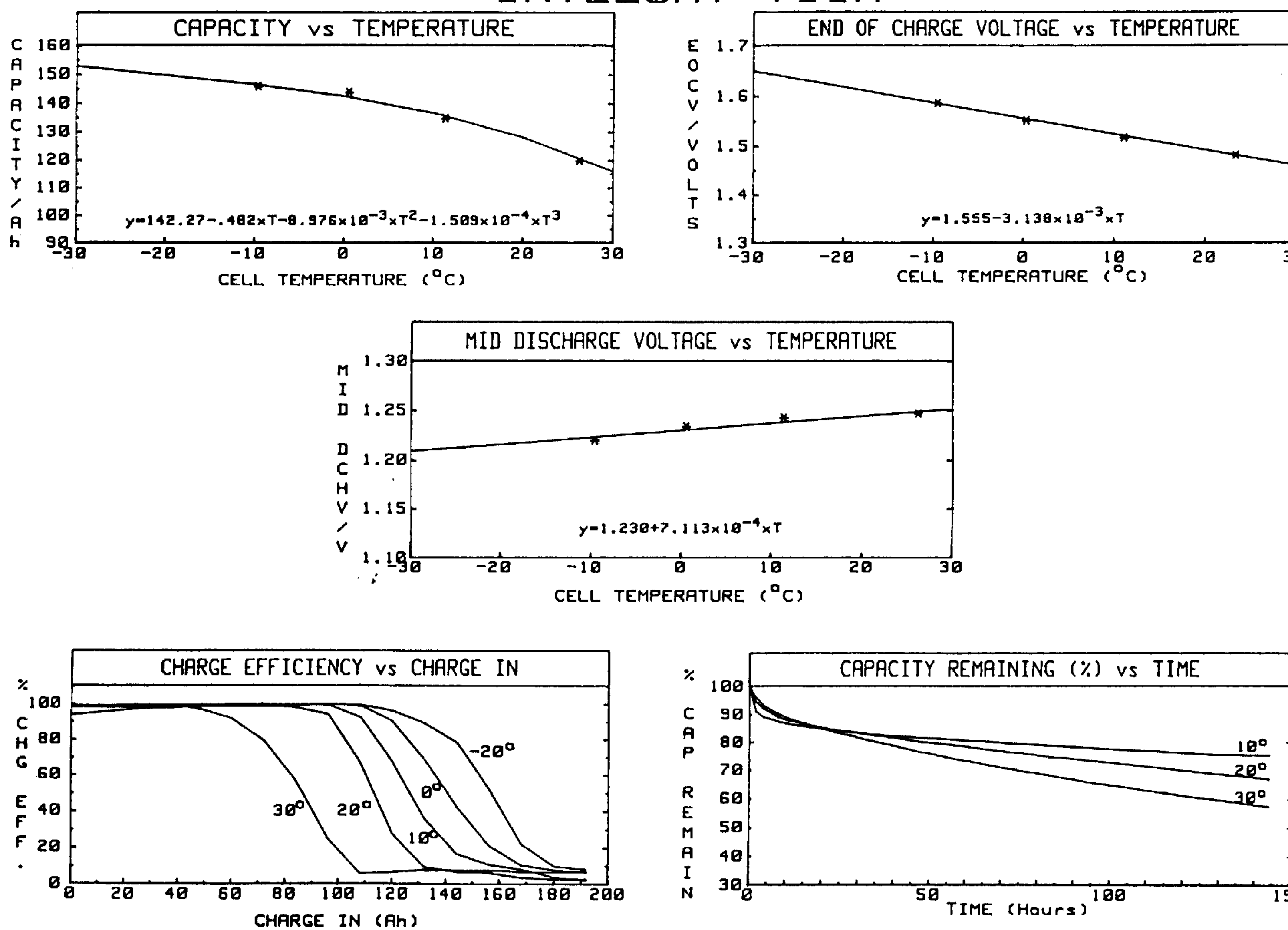

FIGURE 13

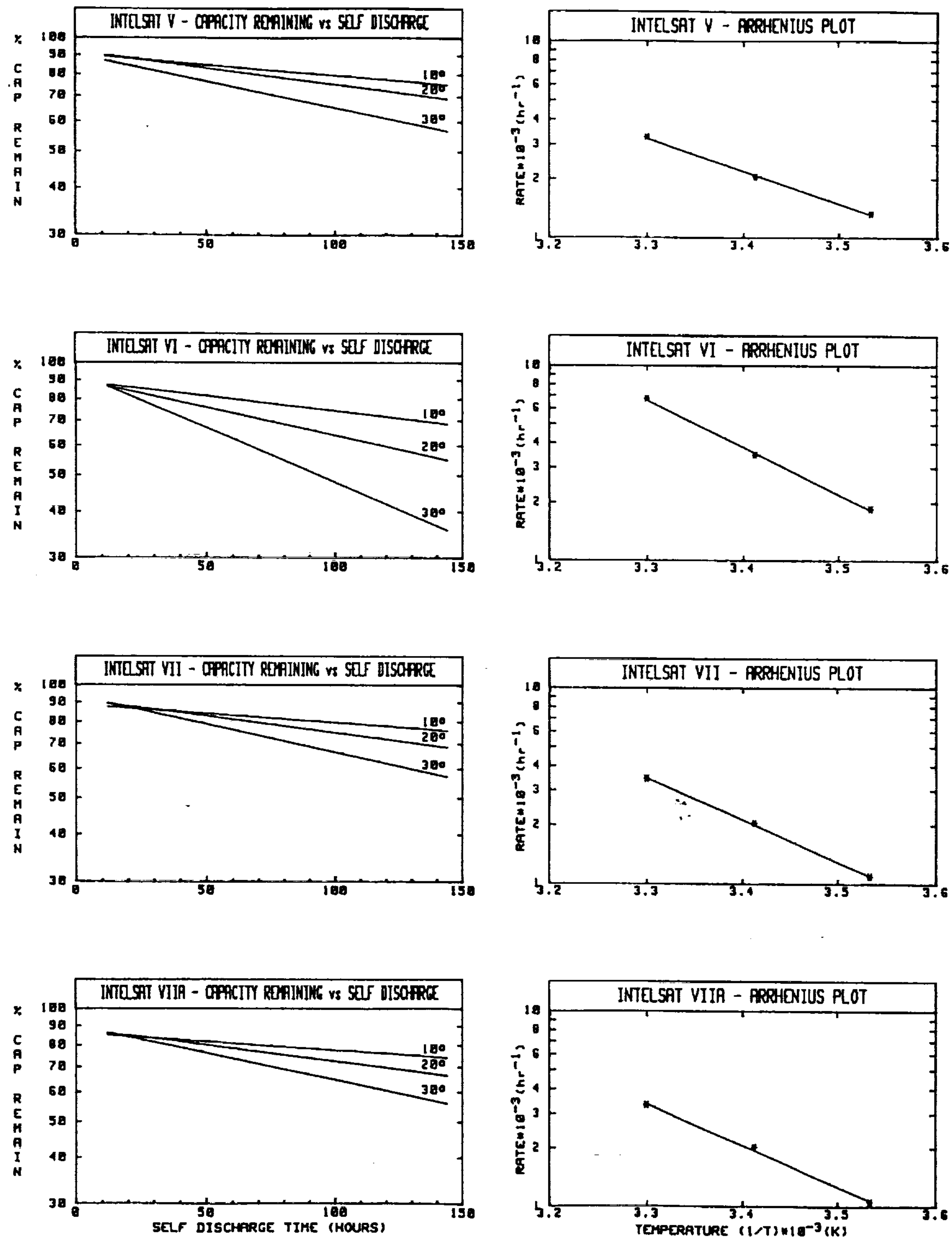
INTELSAT V - CAPACITY REMAINING vs SELF DISCHARGE
INTELSAT V - ARRHENIUS PLOT
INTELSAT VI - CAPACITY REMAINING vs SELF DISCHARGE
INTELSAT VI - ARRHENIUS PLOT
INTELSAT VII - CAPACITY REMAINING vs SELF DISCHARGE
INTELSAT VII - ARRHENIUS PLOT
INTELSAT VIIA - CAPACITY REMAINING vs SELF DISCHARGE
INTELSAT VIIA - ARRHENIUS PLOT
% CAP REMAIN
RATE*10^-3 (hr^-1)
10°
20°
30°
SELF DISCHARGE TIME (HOURS)
TEMPERATURE (1/T)*10^-3 (K)

FIGURE 14

TABLE 4. SELF-DISCHARGE ANALYSIS

	Intercept				Slope			Ratex10^{-3}		
	10°C	20°C	30°C	Ave.	10°C	20°C	30°C	10°C	20°C	30°C
INTELSAT V	90.51	92.05	90.16	90.91	-.00132	-.00203	-.00324	1.32	2.03	3.24
INTELSAT VI	89.11	90.09	93.64	90.95	-.00184	-.00346	-.00671	1.84	3.46	6.71
INTELSAT VII	88.52	91.44	93.36	91.11	-.00109	-.00203	-.00343	1.09	2.03	3.43
INTELSAT VIIA	85.93	88.36	89.78	88.02	-.00105	-.00201	-.00331	1.05	2.01	3.31

THE SELF-DISCHARGE CHARACTERISTICS (Self-Discharge Time, t>10 hours)

	10°C	20°C	30°C
INTELSAT V	ln(PR)=ln(90.51)-.00132xt	ln(PR)=ln(92.05)-.00203xt	ln(PR)=ln(90.16)-.00324xt
INTELSAT VI	ln(PR)=ln(89.11)-.00184xt	ln(PR)=ln(90.09)-.00346xt	ln(PR)=ln(93.64)-.00671xt
INTELSAT VII	ln(PR)=ln(88.52)-.00109xt	ln(PR)=ln(91.44)-.00203xt	ln(PR)=ln(93.36)-.00343xt
INTELSAT VIIA	ln(PR)=ln(85.93)-.00105xt	ln(PR)=ln(88.36)-.00201xt	ln(PR)=ln(89.78)-.00331xt

THE EQUATIONS THAT BEST FIT THE ARRHENIUS PLOT

INTELSAT V	$\ln(Rate)=\ln(11.100*10^{2})-3864.3/Temperature(K)$
INTELSAT VI	$\ln(Rate)=\ln(57.462*10^{4})-5538.4/Temperature(K)$
INTELSAT VII	$\ln(Rate)=\ln(38.126*10^{3})-4912.9/Temperature(K)$
INTELSAT VIIA	$\ln(Rate)=\ln(36.958*10^{3})-4911.5/Temperature(K)$

PERCENT CAPACITY REMAINING FOR ANY OPEN-CIRCUIT TIME AND AT ANY TEMPERATURE

INTELSAT V	$PR=90.91/e^{yt}$ (where $y=11.100\times10^{2}/e^{3864.3/Temp.(K)}$, time>10 hrs)
INTELSAT VI	$PR=90.95/e^{yt}$ (where $y=57.462\times10^{4}/e^{5538.4/Temp.(K)}$, time>10 hrs)
INTELSAT VII	$PR=91.11/e^{yt}$ (where $y=38.126\times10^{3}/e^{4912.9/Temp.(K)}$, time>10 hrs)
INTELSAT VIIA	$PR=88.02/e^{yt}$ (where $y=36.958\times10^{3}/e^{4911.5/Temp.(K)}$, time>10 hrs)

ACTIVATION ENERGY (kcal/mole)

INTELSAT V	INTELSAT VI	INTELSAT VII	INTELSAT VIIA
7.729	11.077	9.826	9.823