MODELING NICKEL-CADMIUM PERFORMANCE: PLANNED ALTERATIONS TO THE GODDARD BATTERY MODEL

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Summary

The Goddard Space Flight Center (GSFC) currently has a preliminary computer model to simulate nickel-cadmium (Ni-Cd) performance. The basic methodology of the model was described in the paper entitled "Fundamental Algorithms of the Goddard Battery Model" submitted to the 1984 GSFC Battery Workshop At present, the model is undergoing alterations to increase its efficiency, accuracy, and generality. This paper will give a review of the present battery model, and describe the planned changes to the model

Introduction

Nickel-cadmium batteries have been, are, and will be the energy storage devices for the vast majority of photovoltaic-based spacecraft power systems. As the complexity, size, and cost of these spacecraft increase, however, it becomes less desirable (or even possible) to test and verify the performance of the power system by actual land-based testing. Therefore, another method of power system "testing" must be made available to the power system engineer. The method that has arisen is computer modeling and simulation.

By creating an accurate computer model of the system, the engineer can simulate various situations and scenarios that the system may encounter. As long as the model is accurate, and the simulation meaningful, the engineer can be confident of the results.

Nickel-cadmium batteries have long been difficult components to model This is due, in part, to their being electro-chemical devices, and not purely electrical Various approaches have been used to model Ni-Cd cells including the Equivalent Electrical Circuit approach [2], the Chemical Reaction approach [3], the Parametric Fit approach [4], and the Data Base Manipulation approach [1, 5]. The Goddard Battery Model is of the latter type.

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The present battery model

The data base

The data base for the present battery model is a family of charge and discharge matrices for various temperatures, voltage–temperature (V/T) charge limits, and depths of discharge (DODs) A typical charge/discharge matrix is shown in Table 1.

As can be seen, the matrix itself relates cell voltage with cell current and a variable called Instantaneous Proportional Capacity (IPCAP) IPCAP is a variable which keeps track of the throughput capacity of the cell. For example, consider a 50 A h cell. If 20 A h were discharged from the cell, the value of IPCAP would be 0.60. If 30 A h were returned to the cell, the value of IPCAP would increase to 1 20 The actual formula for IPCAP is given in eqn (1)

$$\text{IPCAP}_{T+t} = \text{IPCAP}_T + \frac{\text{A h to/from battery}}{\text{Cell rated capacity}} \quad (1)$$

The value of A h to/from battery is positive if the cell is being charged, and negative if being discharged Therefore, discharging the cell results in a decrease in the value of IPCAP, while charging results in an increase As can be seen from eqn (1), IPCAP is very similar to cell State Of Charge (SOC) and can be thought of as a "tracking" SOC variable (In many charts and graphs, the variables SOC and IPCAP are used interchangeably)

Using these matrices, it is possible to generate two battery performance curves voltage *versus* current with IPCAP as the third variable or voltage *versus* IPCAP with current as the third variable (Of course, cell temperature, DOD and V/T limit are also variables, but do not vary within the matrices themselves, but from one matrix to the other)

Methodology

The approach currently used by the model is to have the data from the corresponding DOD, temperature, and V/T limit matrix represented as two families of curves relating cell voltage to current with IPCAP as the third variable One family of curves represents the charge data, while the other characterises the discharge data. The curves themselves are stored as polynomial equations with cell voltage being the dependent variable and current being the independent variable. Each different curve (or equation) corresponds to a different IPCAP Figure 1 shows a typical family of curves

The model has two major modes or functions The first is known as the Normal Mode and is used to determine the cell voltage when the charge/discharge current is known The second mode is called the Taper Mode and is used to predict the current needed to maintain a constant cell voltage This mode is used whenever a V/T-type charge control is used

Normal mode operation

In calculating cell voltage, the values of normalized cell current (charge or discharge) and the IPCAP of the cell are known The model proceeds to

TABLE 1

LEO test data at beginning of life (cycle 12)

20 A h GE* 20 °C LEO 25% DOD

Discharge/charge current	IPCAP								
	0 60	0 65	0 70	0 75	0 80	0 85	0 90	0 95	1 00
−40 0				1 186	1 194	1 211	1 235	1 264	1 294
−20 0				1 228	1 237	1 252	1 278	1 305	1 335
−16 0				1 238	1 247	1 262	1 286	1 314	1 344
−10 0				1 252	1 262	1 275	1 298	1 330	1 360
− 4 0				1 273	1 283	1 300	1 325	1 350	1 380
− 2 0				1 278	1 286	1 303	1 328	1 355	1 385
− 1 0				1 281	1 289	1 306	1 331	1 358	1 388
− 0 5				1 284	1 292	1 309	1 334	1 361	1 391
0 0				1 289	1 302	1 323	1 349	1 374	1 401
0 5				1 294	1 311	1 338	1 364	1 387	1 412
1 0				1 297	1 314	1 342	1 369	1 393	1 416
2 0				1 303	1 320	1 349	1 376	1 400	1 423
4 0				1 310	1 327	1 357	1 385	1 410	1 434
10 0				1 332	1 350	1 379	1 407	1 433	1 458
16 0				1 349	1 368	1 398	1 427	1 453	1 478
20 0				1 361	1 380	1 411	1 440	1 467	1 492
40 0				1 407	1 426	1 458	1 487	1 513	1 538

*NASA standard General Electric (GE) manufactured cells

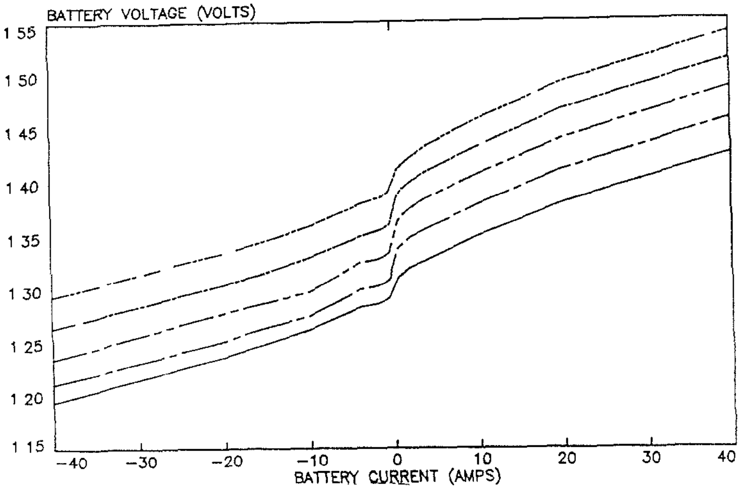

Fig 1 Battery current *vs* voltage with State Of Charge (SOC) as third variable ——, SOC 80, — — —, SOC 85, — — — —, SOC 90, —— , SOC 95, —— —— , SOC 100

find the closest upper and lower bounding curves relative to the cell's actual IPCAP For example, if the data base has curves for the IPCAP's of 100, 97, 90, 85 and 80% and the cell IPCAP is 95%, the model determines that the 97% curve is the closest upper bounding curve, whereas the 90% curve is the closest lower bounding curve This process is accomplished by using a standard binary search algorithm The model then calculates the cell voltage relating to the (known) cell current for the upper and lower IPCAP curves. This, in essence, provides the model with two cell voltages at a particular cell current one voltage refers to a cell slightly more fully charged than the simulated cell, the other voltage refers to a cell slightly less charged The cell voltage for the simulated cell is then determined through a linear interpolation of the two bounding voltages The linear interpolation introduces little error if the number of IPCAP curves is large

Figure 2 is a graph comparing the model predicted voltage curve with actual cycling data The cell temperature was 20 °C, 40% DOD, 20 A h rated capacity, 16 A discharge (30 min), 16 A charge (60 min), with a GSFG V/T limit of 7 As can be seen, the discharge voltage correlates very highly. The charge voltage also correlates, but not as well It should be noted that the cycling data being compared were not the data used to generate the data base Also, it should be noted on Fig 2 that the actual cycling data do not hit a hard voltage clamp, but "creep" up to it This makes the model appear to be more in error than it actually is

Taper mode operation

This mode of operation calculates the amount of charge current needed to maintain a cell at a constant voltage. Since, as is the case in voltage clamping charge control schemes, the current exhibits an exponential-like downward taper as the voltage remains clamped and the IPCAP increases,

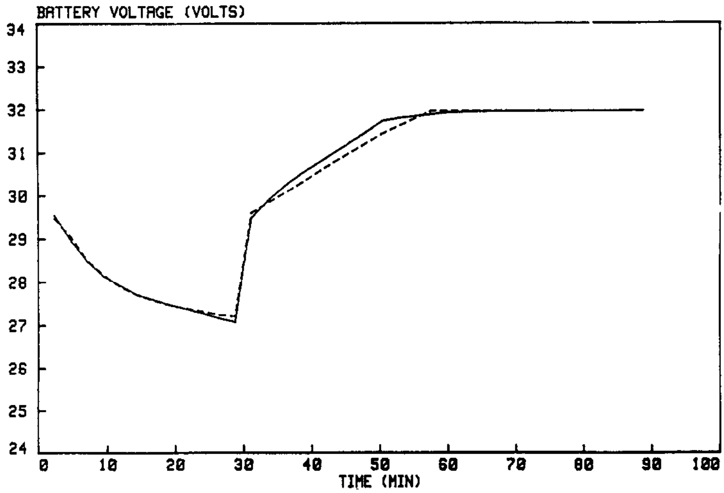

Fig 2 Modelling study using Pack 12 H Cycle 15, temp 20 °C, 40% DOD, 16 A charge, 16 A discharge ——, Real voltage, — — — —, calculated voltage

this charge current is generally known as the Taper Charge Current The approach used by this method is somewhat different from the previous mode, although, as will be seen, it actually uses the methodology of the Normal Mode Operation.

In calculating cell current, the cell voltage is known, as is the cell IPCAP The structure of the data base curves, however, does not directly allow the model to calculate cell current. To circumvent this problem, the model uses a search approach to determine the taper charge current. The search approach is based on the Binary Search Algorithm.

The model begins by setting up two bounds for the taper charge current. These bounds represent the upper and lower limits of the possible values for the current. Since these values are initially unknown, they are set to reflect a wide range. (At present, the lower bound is set at 0 A, the upper at 60 A) In essence, this means that the model assumes that the value for taper charge current needed to maintain the voltage clamp falls between these two bounds. The model then proceeds to calculate the median value between the two bounds. This median value is the Taper Charge Estimate (TCE) Using this value, the model, using the exact same method as the Normal Operation Mode, calculates the cell voltage corresponding to the TCE and compares this with the voltage clamp. If the calculated voltage is greater than the voltage clamp, the TCE was too high In this case the model resets the upper bound to the TCE, since it is now known that the actual taper charge current must be less than the TCE and does not fall between the TCE and upper bound (the taper current is no greater than TCE) Conversely, if the calculated voltage is less than the voltage clamp, the TCE was too small (the current was insufficient to maintain the cell at the voltage clamp). In this case the model resets the lower bound to the TCE, since it is now known that the actual taper charge current must be greater than the TCE The process then continues by calculating a new TCE with the adjusted bounds. In this way, as the bounds are constantly being adjusted, the model "zeroes in" on the actual taper charge current Figure 3 compares actual cycling data and model predicted data for the taper charge current Once again it should be noted that the cycling data depicted are not the data used in the data base

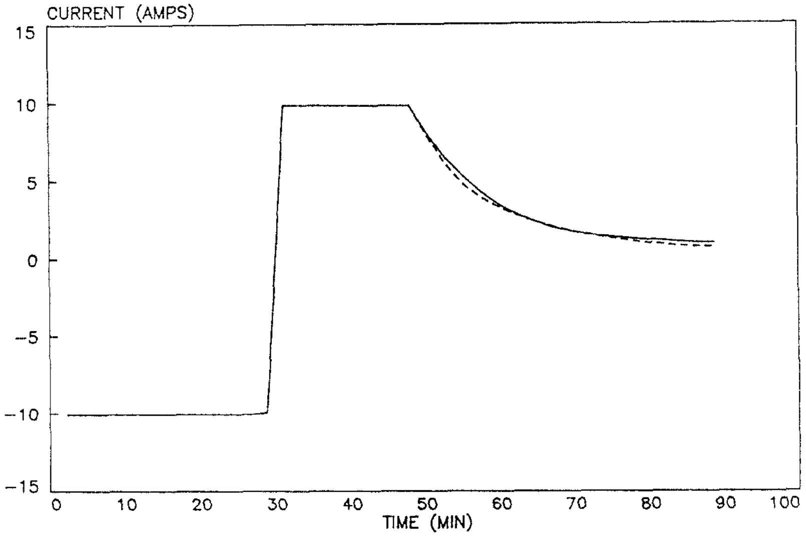

Fig 3 Modelling study using Pack 12G Comparison of real and calculated current data ——, Real data, — — —, calculated data

The planned modifications to the battery model

As mentioned in ref. 1, the data base used in the battery model is of questionable accuracy. Also, the data form itself is non-standard It was determined that the majority of cell performance data is in the form of cycling tests In standard LEO cycling *V/T* limited tests, the data do not result in the same type as depicted in Table 1 This is due to the fact that the present data base extrapolates data beyond the *V/T* clamp, and it is this extrapolation which results in the suspected inaccuracy of the data The model, however, at present requires data in this format It was therefore determined that the model be altered to accept data in the standard cycling format This will result in not only a model modification, but also an alteration in the way the data are used, as will be seen below

The new data base

The new data base was generated by cycling 5 NASA standard 50 A h cells under various *V/T* limits, DODs, temperatures, and charge/discharge rates as defined below

Data base voltage–temperature (V/T) limits (GSFC):	3, 5, 7
Cell operating temperatures (°C).	0, 10, 20
Charge rates (A).	10, 25, 30, 40
Discharge rates (A)	5, 10, 25, 40
Discharge time (min).	30
Charge time (min):	60

Since the discharge time is 30 min, the discharge rates of 5, 10, 25 and 40 A corresponds to a DOD of 5, 10, 25 and 40%, respectively. Additionally, cases where the cell would not be recharged after a cycle (for example, a discharge rate of 40 A for 30 min and a charge rate of 10 A for 60 min) were not run Therefore, the data base has

5 A discharge rate		36 test cases
V/T	3, 5, 7	(3)
Temp.	0, 10, 20	(3)
Charge	10, 25, 30, 40	(4)
10 A discharge rate		36 test cases
V/T	3, 5, 7	(3)
Temp.	0, 10, 20	(3)
Charge	10, 25, 30, 40	(4)
25 A discharge rate		27 test cases
V/T	3, 5, 7	(3)
Temp.	0, 10, 20	(3)
Charge	25, 30, 40	(3)
40 A discharge rate		18 test cases
V/T	3, 5, 7	(3)
Temp	0, 10, 20	(3)
Charge	30, 40	(2)

The data curves

As was mentioned above, the present model uses a family of curves in which cell voltage is related to current with IPCAP as a third variable. For the new model, the data will be in the form of a family of curves relating cell power to IPCAP, with the cell power being defined as the charge/discharge current multiplied by the cell voltage measured at the same instant in time. In this technique, each curve represents a different cycling scheme To make it easier for the model to differentiate between curves, an identifying code is used for each curve The code used is defined as

TTVCD

where "TT" is the temperature of the cell in °C, "V" is the GSFC V/T limit, "C" is the charge C-rate of the cell multiplied by 10, and "D" is the discharge C-rate of the cell multiplied by 10 Therefore, an identity code of "10356" distinguishes a data curve taken from cell data run at 10 °C, at V/T 3, with a 0.5 C charge rate and a 0.6 C discharge rate. Figure 4(A) - (F) shows typical data curve plots

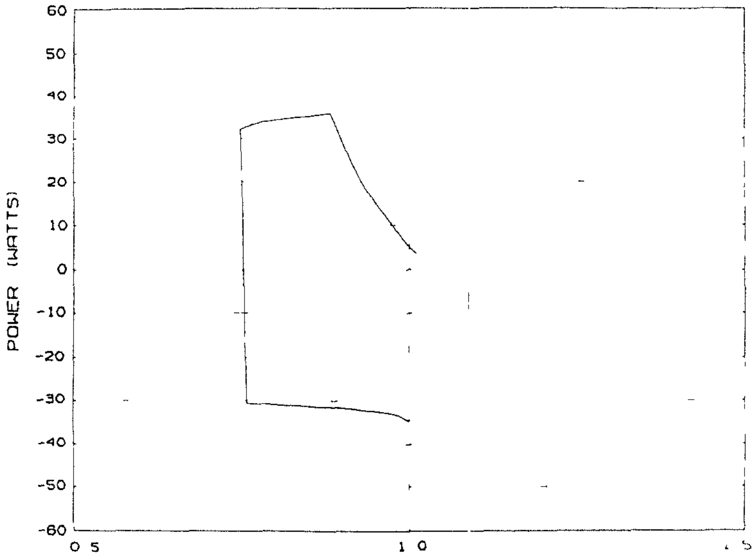

Fig 4 (A) Typical data curve plot Cell temperature 10 °C, V/T 5, charge rate 0 5 C, discharge rate 0 5 C

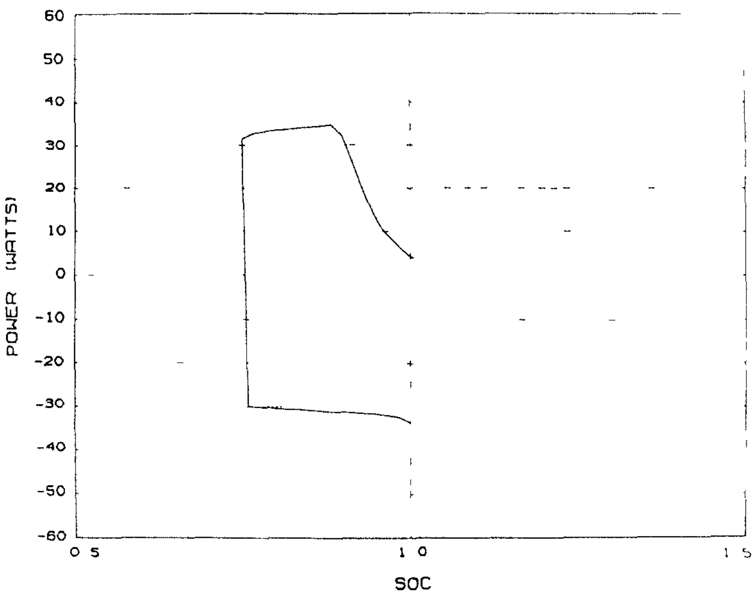

Fig 4 (B) Typical data curve plot Cell temperature 10 °C, V/T 3, charge rate 0 5 C, discharge rate 0 5 C

Data curve relationships

Upon investigating the data curves, a few interesting relationships were uncovered These relationships describe how the curve shapes alter with

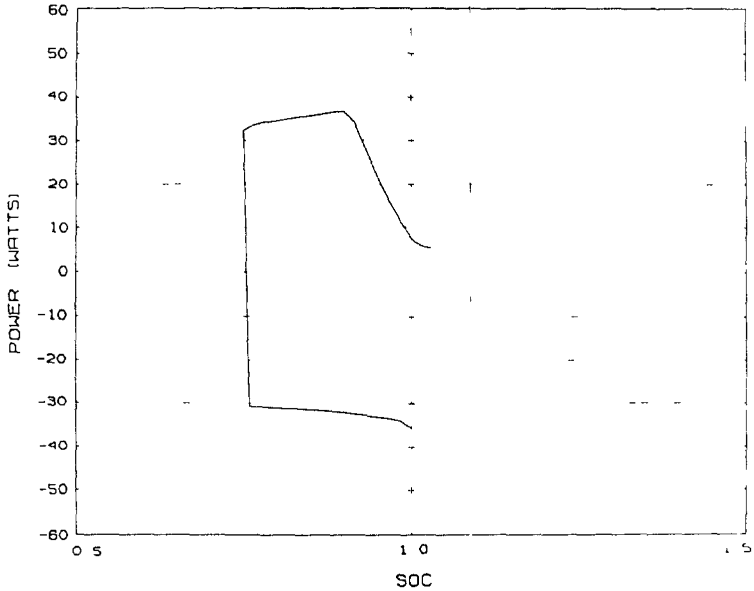

Fig 4 (C) Typical data curve plot Cell temperature 10 °C, V/T 7, charge rate 0 5 C, discharge rate 0 5 C.

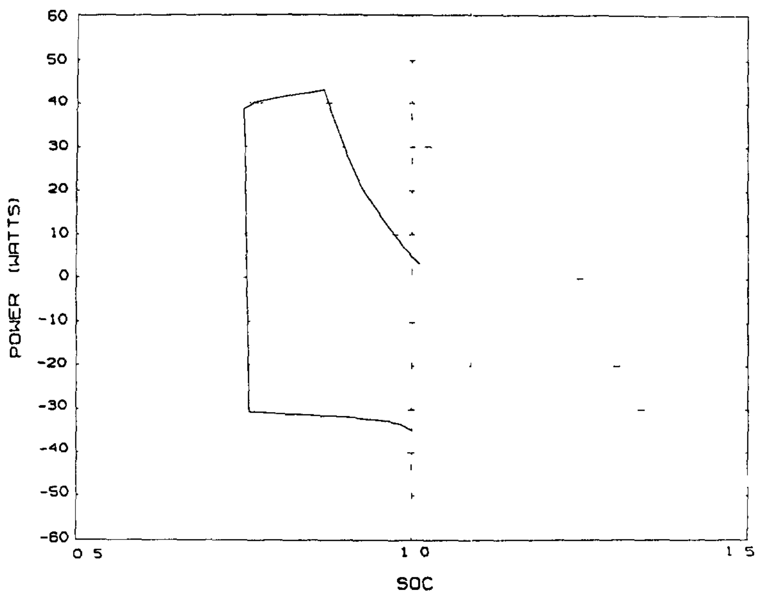

Fig 4 (D) Typical data curve plot Cell temperature 10 °C, V/T 5, charge rate 0 6 C, discharge rate 0 5 C.

varying cycling parameters. In all cases, only one parameter was allowed to vary while the rest were held constant The actual relationships will be described below.

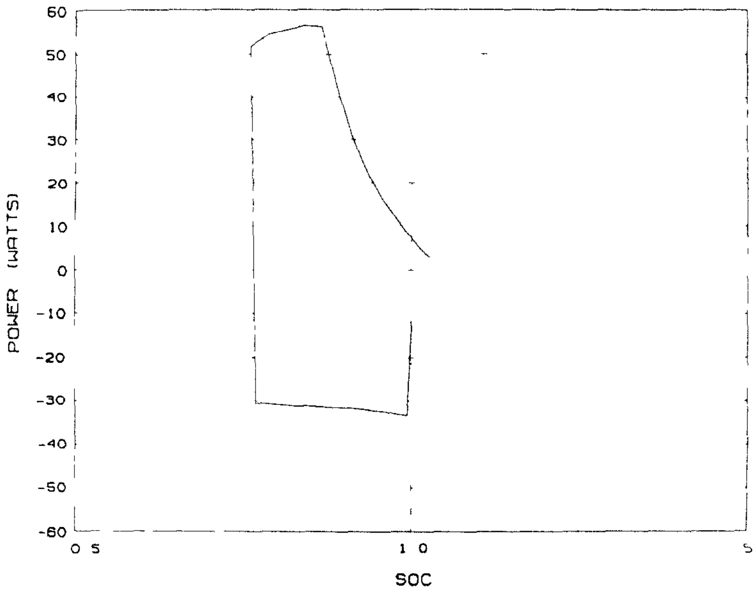

Fig 4 (E) Typical data curve plot Cell temperature 10 °C, V/T 5, charge rate 0 8 C, discharge rate 0 5 C.

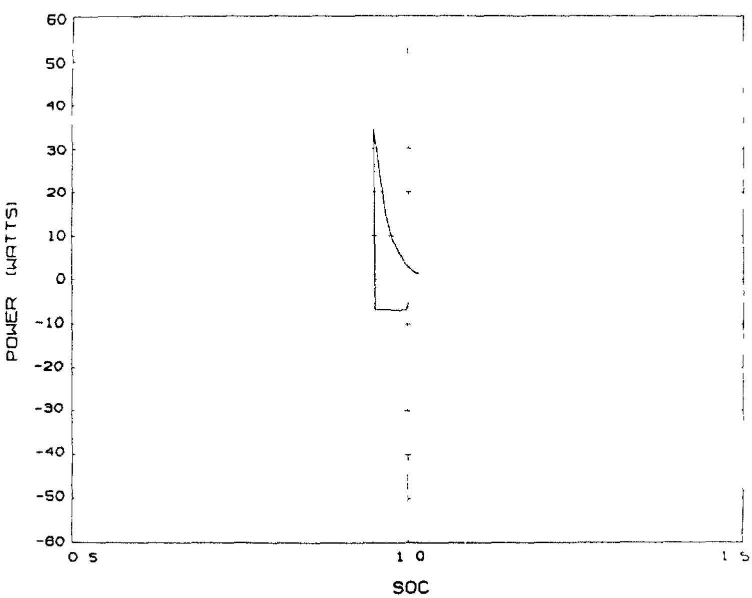

Fig 4 (F) Typical data curve plot Cell temperature 10 °C, V/T 5, charge rate 0 5 C, discharge rate 0 1 C

Varying V/T limit

When varying V/T limits, the curves alter in two aspects The first is in the discharge portion of the curve It appears that discharge power varies linearly with V/T limit. A higher V/T limit results in a higher (or larger) power output from the battery. The second change is in the taper charge portion of the curve. Again, it appears that taper power varies linearly with V/T limit The higher the V/T limit, the higher the power input during taper. A higher V/T limit also extends the taper power curve, although the actual relationship is not known at this time.

Varying charge current

As shown in Fig. 5, varying charge current seems to affect only the charge power portion of the curve. The taper and discharge curves seem totally unaffected. It should be noted that the upper curve in the Figure is skewed towards the y-axis due to an error in the data acquisition system. If the curve is readjusted to superimpose the charge/discharge continuities of all three curves, it will be seen that only the charge curves are changed. Again, the relationship appears linear since the curves are for 0.5 C, 0.6 C and 0.8 C charge rates.

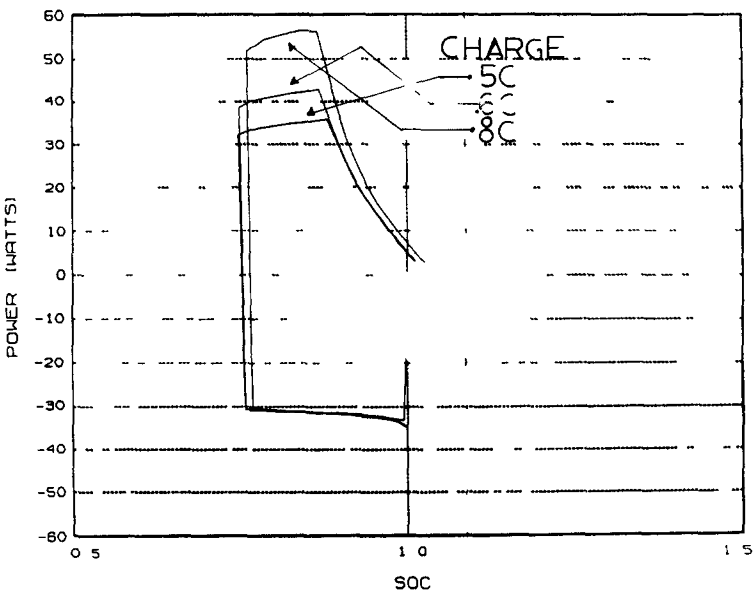

Fig 5 Effect of varying charge current on power Temperature 10 °C, V/T 5, charge rates 0 5 C, 0 6 C, 0 8 C, discharge rate 0 5 C

Varying other parameters

The effects of varying the other cycling parameters have not been investigated.

Future work

The effects of varying the remaining cycling parameters will be investigated in the near future At present it is planned that the model will use the entire data base and not take into account the relationships found between the cycling parameters and the power curves Later versions of the model will incorporate the relationships to reduce the data base size, however.

Conclusions

The GSFC Battery Model is currently being modified. Its modifcation will greatly enhance its accuracy and generality The data base generated for the model has been investigated as well as a new data format The data format relates battery power to the tracking variable IPCAP. Various relationships have been discovered linking cycling parameters to the data curves, and initial investigations reveal the relationships to be linear. Further work is underway to complete the battery model modification and to analyse more thoroughly the data curve relationships.

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