# MODELING NI-CD PERFORMANCE

## Planned alterations to the Goddard Battery Model

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## **ABSTRACT**

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" (reference 1) 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**

Ni-Cd 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.

Ni-Cd 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 (reference 2 and others), The Chemical Reaction approach (reference 3), The Parametric Fit

approach (reference 4), and The Data Base Manipulation approach (reference 1, 5 and others). The Goddard Battery Model is of the last type.

## 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 figure 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 ampere hour cell. If 20 amp-hrs were discharged from the cell, the value of IPCAP would be 0.60. If 30 amp-hrs were returned to the cell, the value of IPCAP would increase to 1.20. The actual formula for IPCAP is given in equation 1.

$$1) \quad IPCAP_{T+t} = IPCAP_{T} + \frac{\text{Amp-Hr to/from Battery}}{\text{Cell Rated Capacity}}$$

The value of "Amp-Hr 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 the equation, 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 is 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 dependant variable and current being the independant variable. Each different curve (or equation) corresponds to a different IPCAP. Figure 2 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 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 3 is a graph comparing the model predicted voltage curve actual cycling data. The cell temperature was 20 deg C, 40% DOD, 20 ampere-hour rated capacity, 16 amp discharge (30 minutes), 16 amp charge (60 minutes), with a GSFC V/T limit of 7. As can be seen, the discharge voltage

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correlates very highly. The charge voltage also correlates but not as well. It should be noted that the cycling data being compared was not the data used to generate the data base. Also, it should be noted on figure 3 that the actual cycling data does not hit a hard voltage clamp, but "creeps" 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, this charge current is generally known as the Taper Charge Current. The approach used by this method is somewhat different than the previous mode, although, as it 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. However, the structure of the data base curves 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 amps, the upper at 60 amps.) 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 (TCH). 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 4 shows a comparision between actual cycling data and model predicted data for the taper charge current. Once again it should be noted that the cycling data depicted is not the data used in the data base.

## THE PLANNED MODIFICATIONS TO THE BATTERY MODEL

As mentioned in reference 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 does not result in the same type as depicted in figure 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. However, the model 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 is used, as will be seen below.

### The New Data Base

The new data base was generated by cycling 5 NASA standard 50 ampere-hour cells under various V/T limits, DODs, temperatures, and charge/discharge rates as defined in the following table.

| Data Base Voltage-Temperature (V/T) Limits (GSFC): | 3, 5, 7 | | |
|---|---|---|---|
| Cell Operating Temperatures (degrees C): | 0, 10, 20 | | |
| Charge Rates (Amps): | 10, 25, 30, 40 | | |
| Discharge Rates (Amps): | 5, 10, 25, 40 | | |
| Discharge Time (minutes): | 30 | | |
| Charge Time (minutes): | 60 | | |

Since the discharge time is 30 minutes, the discharge rates of 5, 10, 25, and 40 amps correspond 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 amps for 30 minutes and a charge rate of 10 amps for 60 minutes) were not run. Therefore, the data base has data according to the table below.

| 5 Amp Discharge | Rate | | 36 test cases |
|---|---|---|---|
| | V/T | 3, 5, 7 | (3) |
| | Temp | 0,10,20 | (3) |
| | Charge | 10,25,30,40 | (4) |
| 10 Amp Discharge | Rate | | 36 test cases |
| | V/T | 3, 5, 7 | (3) |
| | Temp | 0,10,20 | (3) |
| | Charge | 10,25,30,40 | (4) |
| 25 Amp Discharge | Rate | | 27 test cases |
| | V/T | 3, 5, 7 | (3) |
| | Temp | 0,10,20 | (3) |
| | Charge | 25,30,40 | (3) |
| 40 Amp 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, a identifying code is used for each curve. The code used is defined below.

TTVCD

where "TT" is the temperature of the cell in degrees 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

degrees C, at V/T 3, with a 0.5 C charge rate and a 0.6 C discharge rate. Figures 5A to 5F are typical data curve plots.

## Data Curve Relationships

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

### Varying V/T Limit

As shown in figure 6, 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 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 figure 7, 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 0.5C, 0.6C, and 0.8C charge rates.

### Varying Other Parameters

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

## 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 modification 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 more thoroughly analyse the data curve relationships.

## ENCLOSURES

A copy of the view-graphs presented at the 1985 workshop are included with this paper.

# REFERENCES

1. J. Jagielski, "Fundamental Algorithms of the Goddard Battery Model," Proc. The 1984 GSFC Battery Workshop, November 1984, p. 255-268.

2. H. Zimmerman, R. Peterson, "An Electrochemical Cell Equivalent Circuit for Storage Battery/Power System Calculations by Digital Computer," IECEC Transactions, 1970, p. 533-539.

3. M. Spritzer, "Fitting Voltage Curves with an Electrochemically Derived Equation," Proc. The 1982 GSFC Battery Workshop, November 1982, p. 164-177.

4. P. McDermott, "Prediction of Battery Life and Behavior from Analysis of Voltage Data," Proc. The 1983 GSFC Battery Workshop, November 1983, p. 245-258.

5. P. Bauer, "Battery Mathematical Computer Model," TRW/Power Subsystem Engineering Department, an unpublished work.

20 AH GE 20 DEG C LEO 25%DOD

| IFCAP --> CUR-->V | 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 |
| 0.0 | | | | 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 |

Figure 1. LEO TEST DATA AT BEGINNING OF LIFE [CYCLE 12]
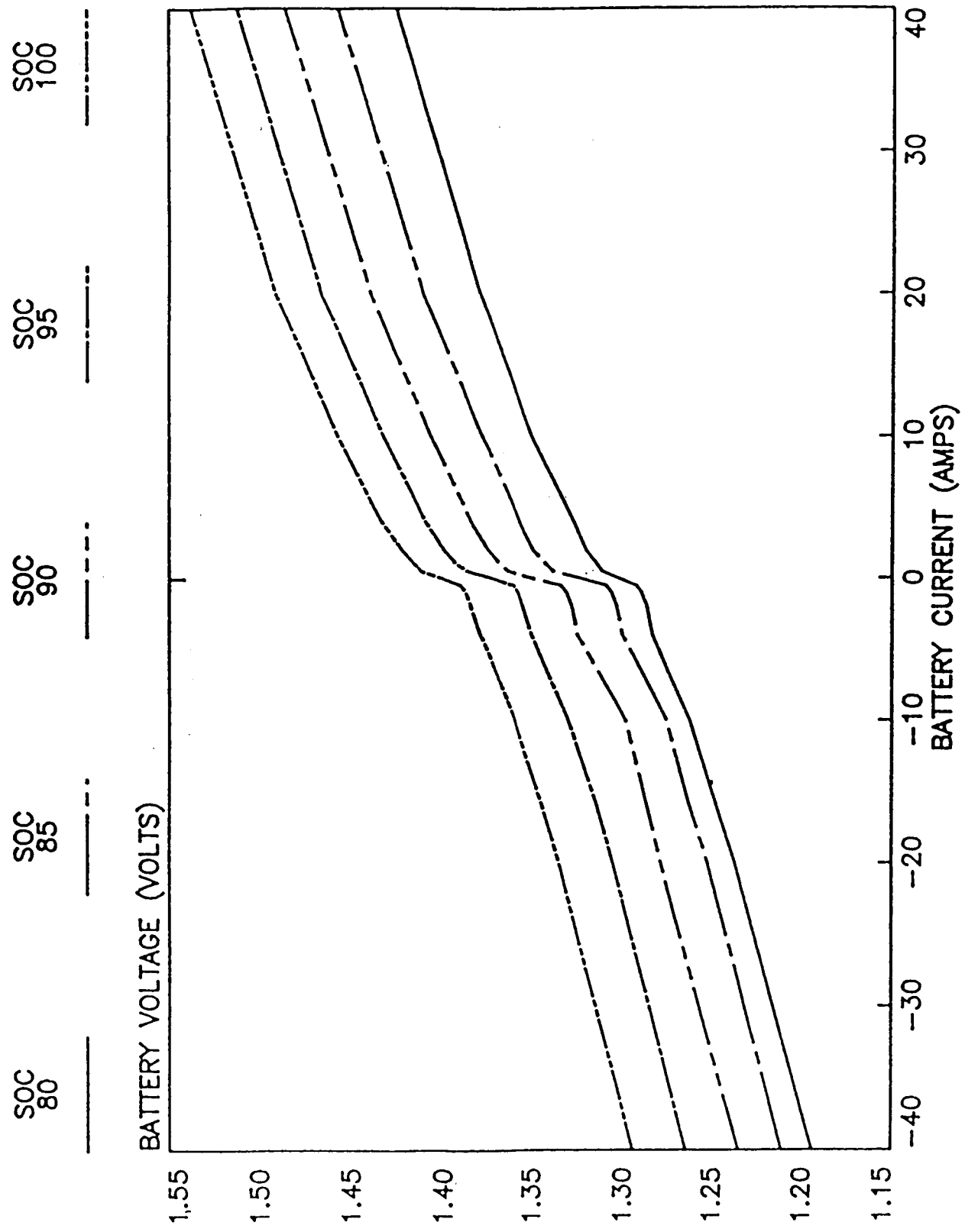
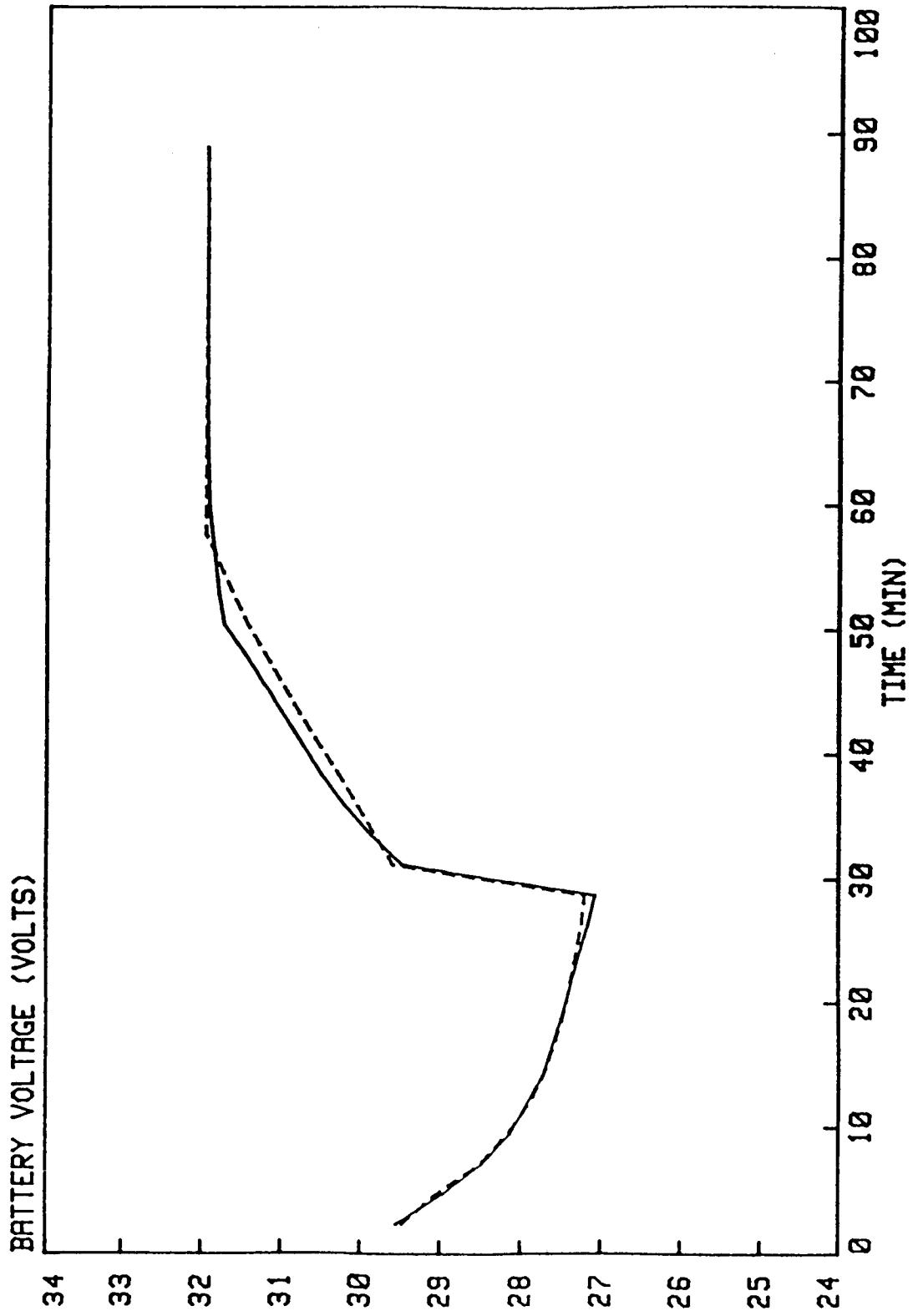Figure 2. BATTERY CURRENT VS VOLTAGE WITH SOC AS 3RD VARIABLE

Figure 3.  MODELING STUDY USING PACK 12H
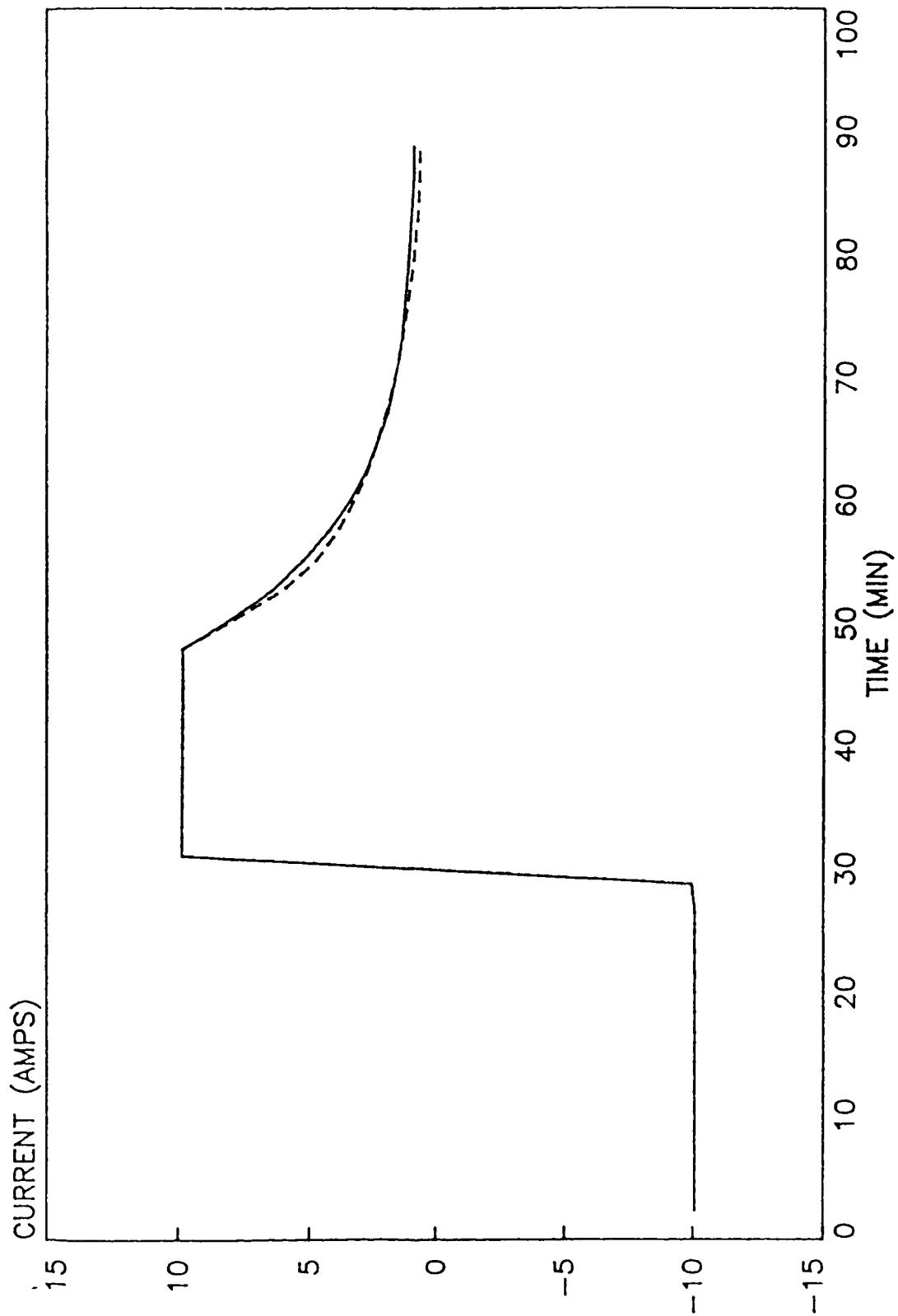CYCLE 15, 20 C, 40% DOD, 16A CHG, 16A DISCHG

Figure 4. MODELING STUDY USING PACK 12G
COMPARISON—REAL AND CALCULATED CURRENT DATA
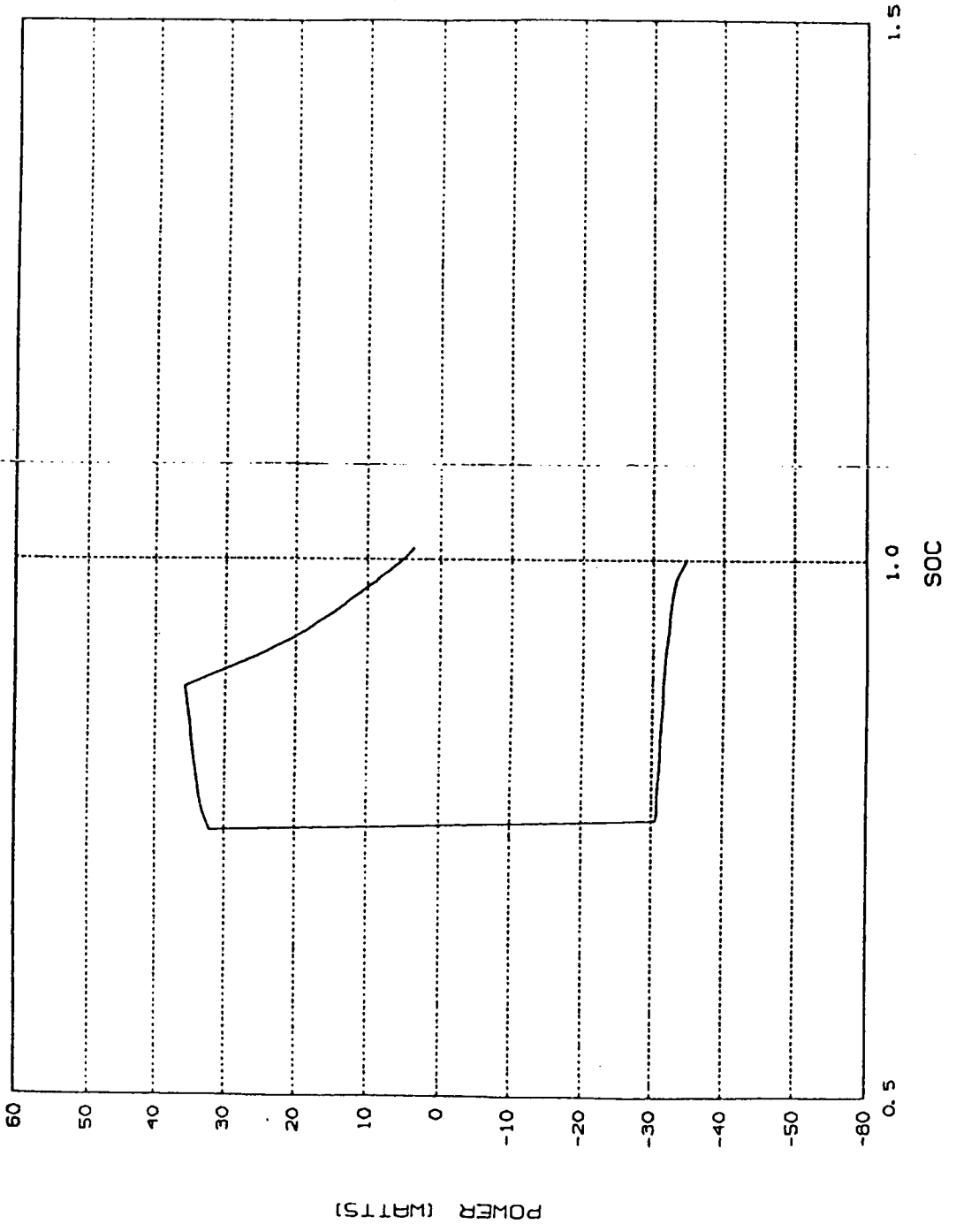
Figure 5A

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Figure 5B

POWER (WATTS)

SOC

10355
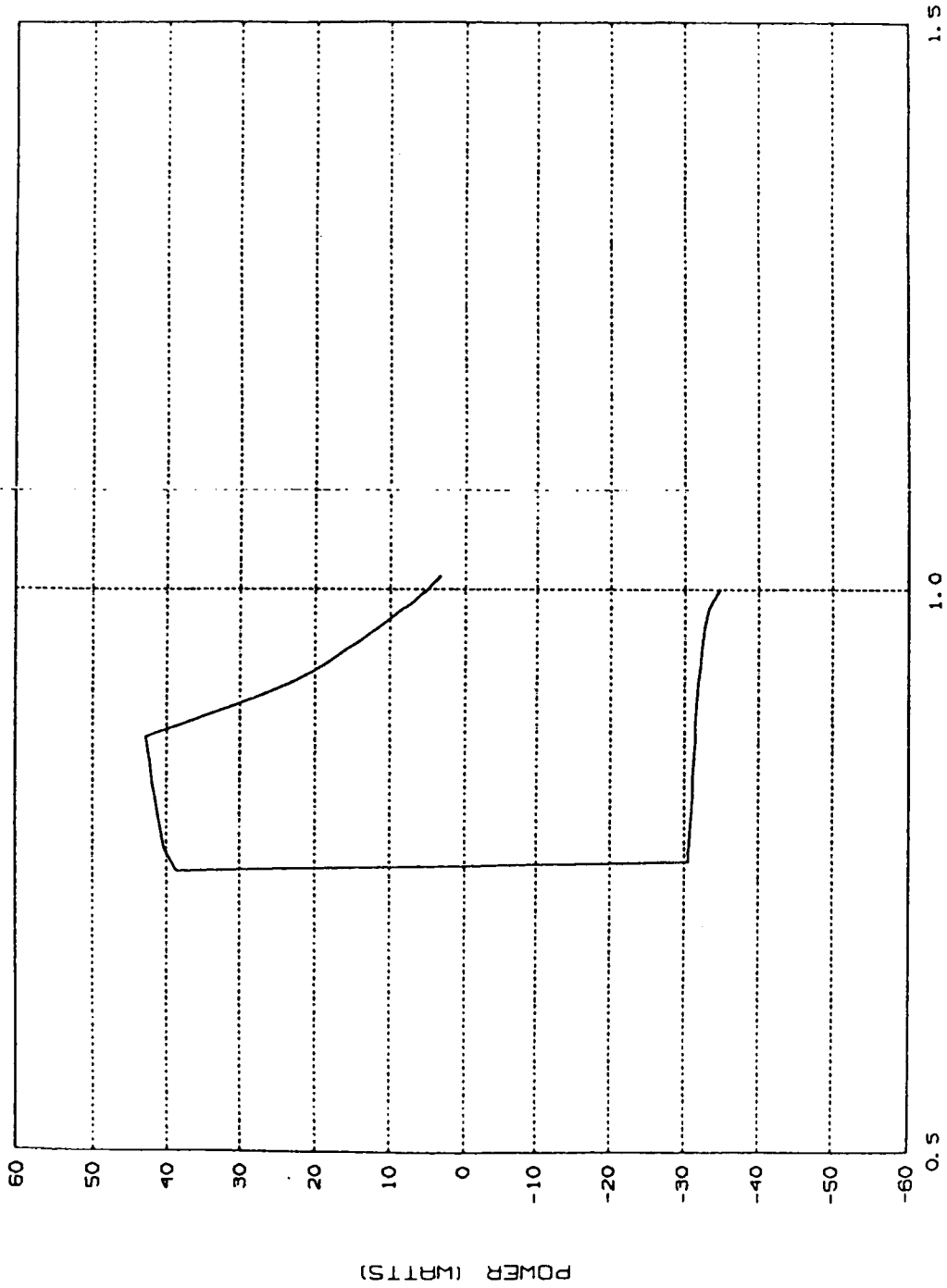
231

Figure 5C

POWER (WATTS)

SOC

10755

10565

POWER (WATTS)

SOC

Figure 5D

233

*105B5*

POWER (WATTS)

SOC

Figure 5E

234

Figure 5F

*10551*

235

Figure 6

236
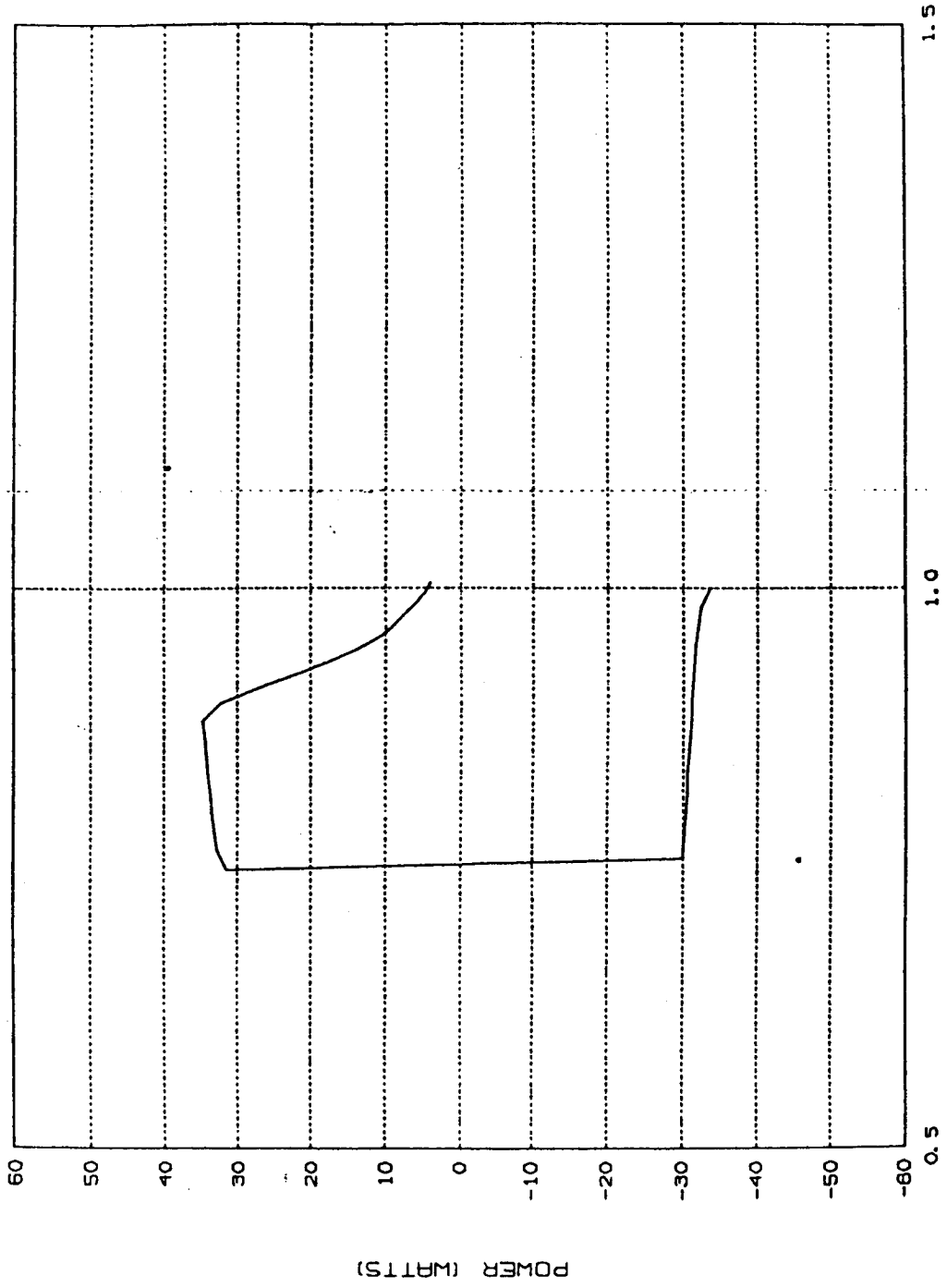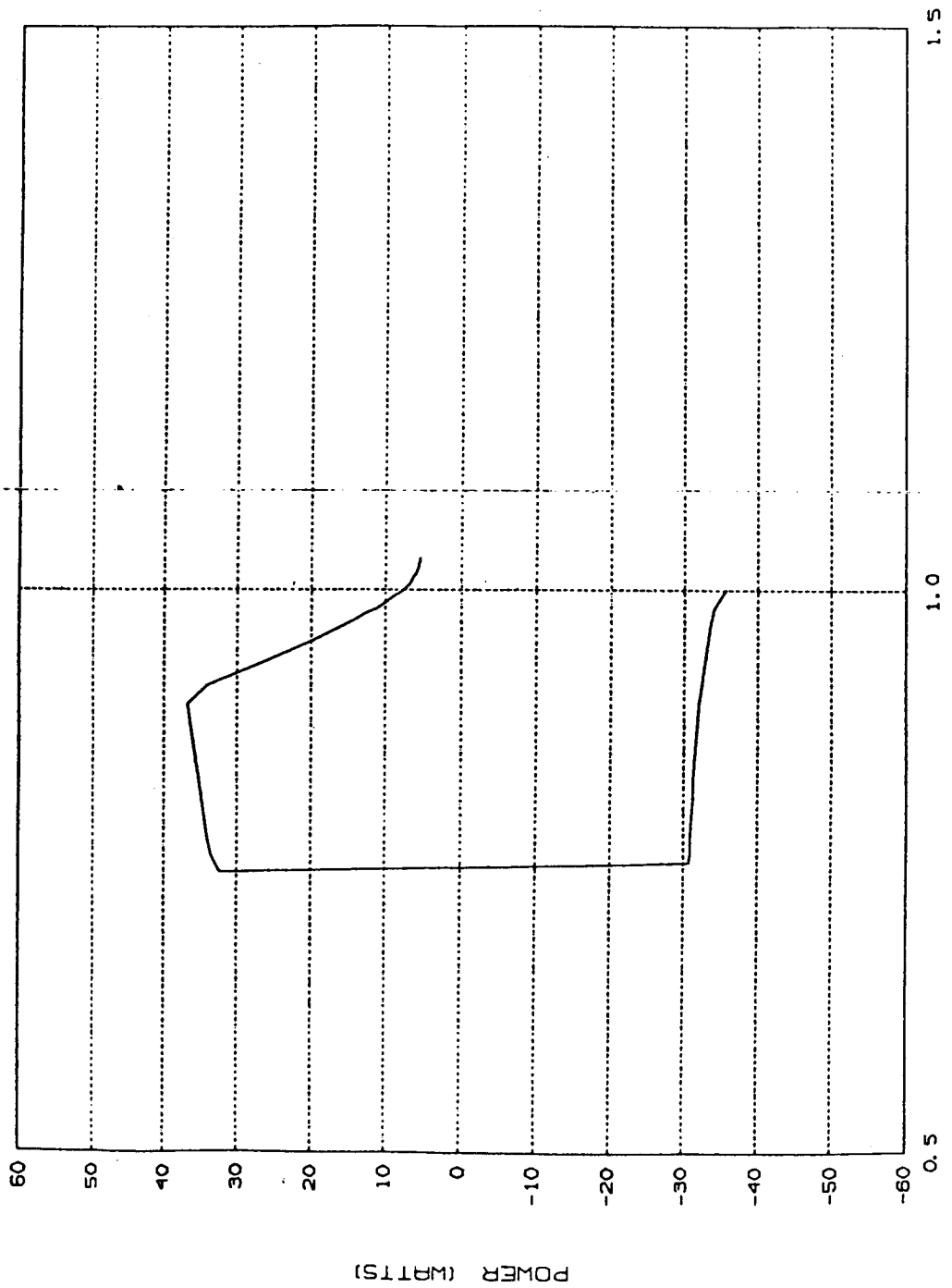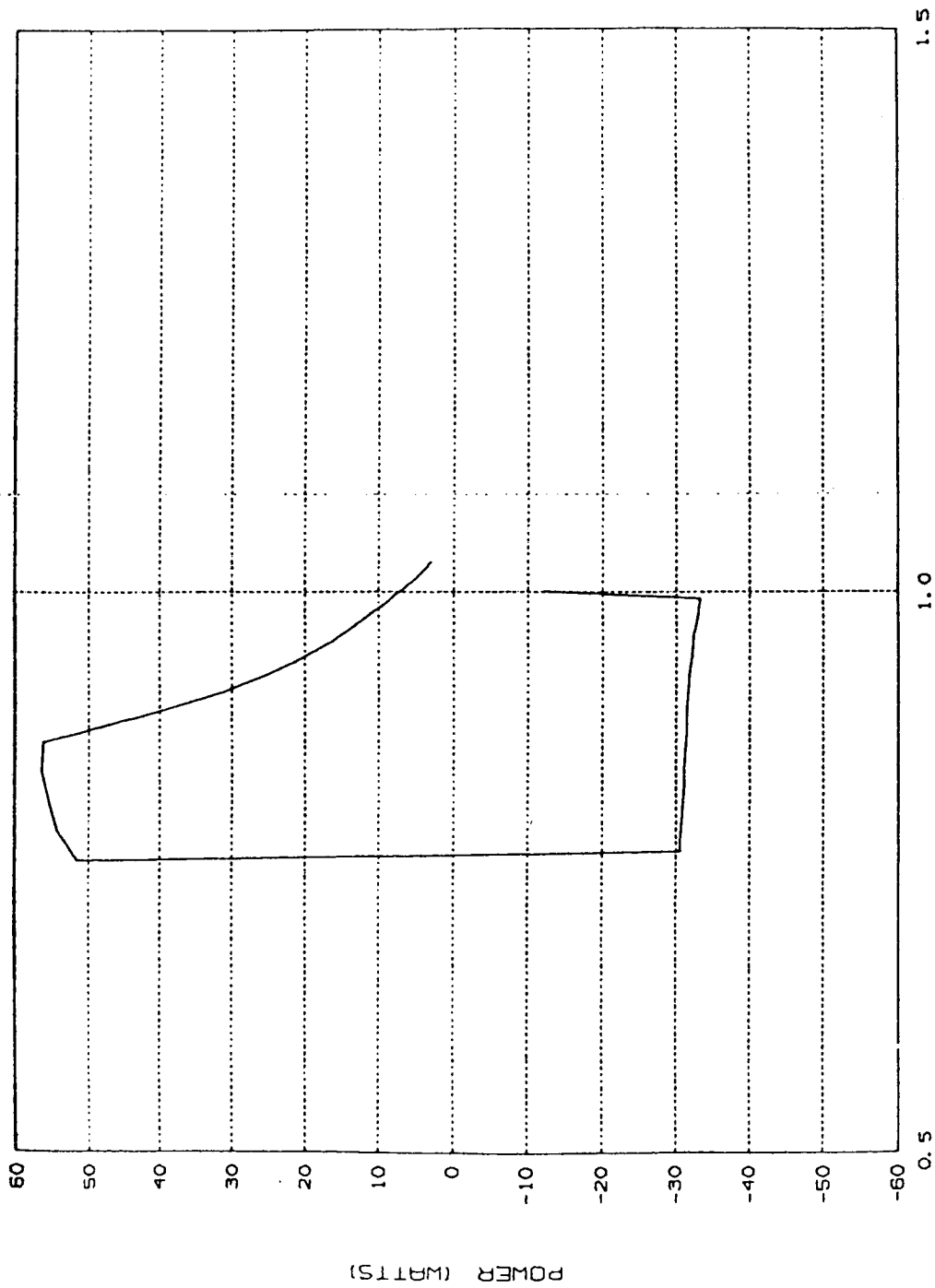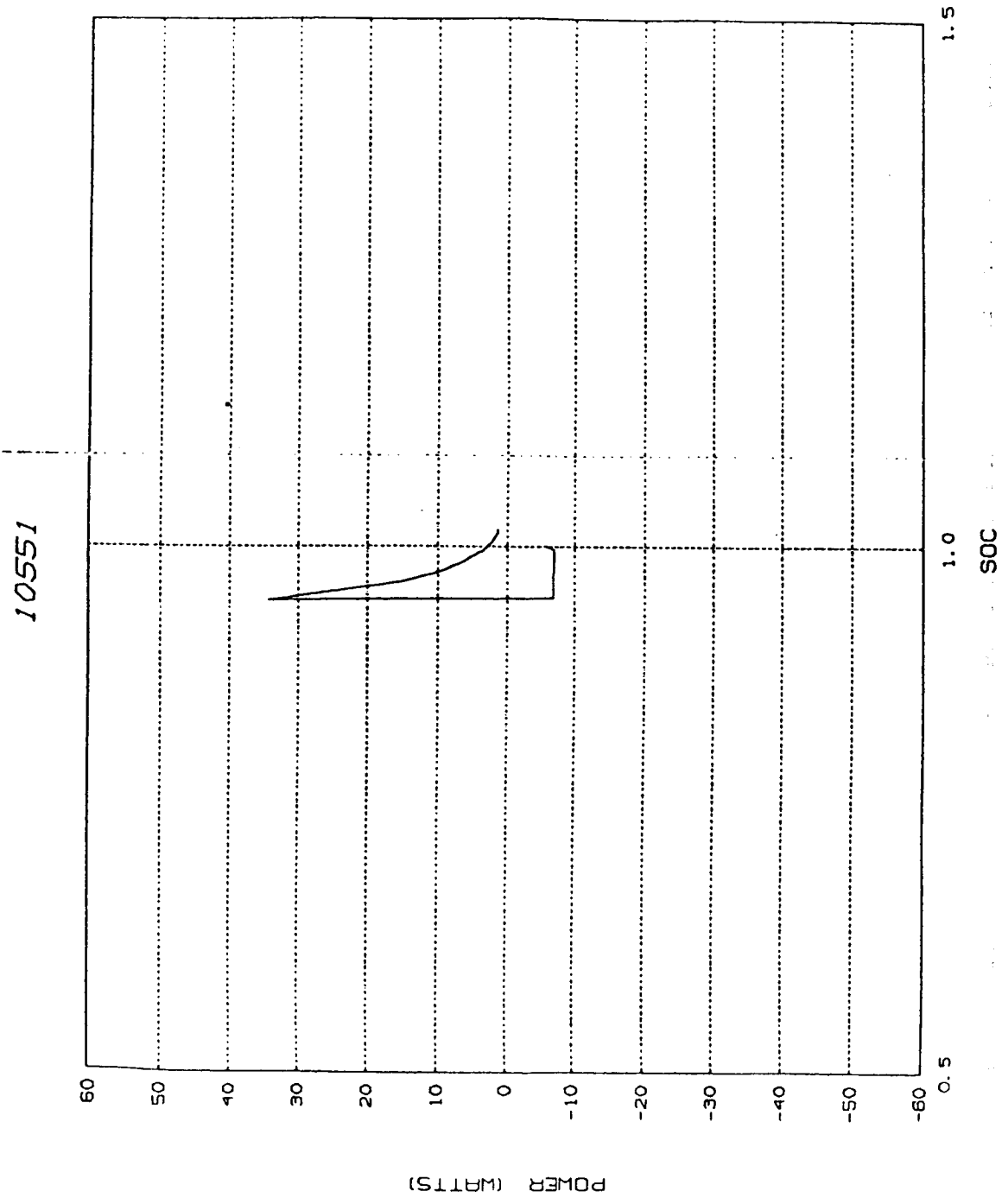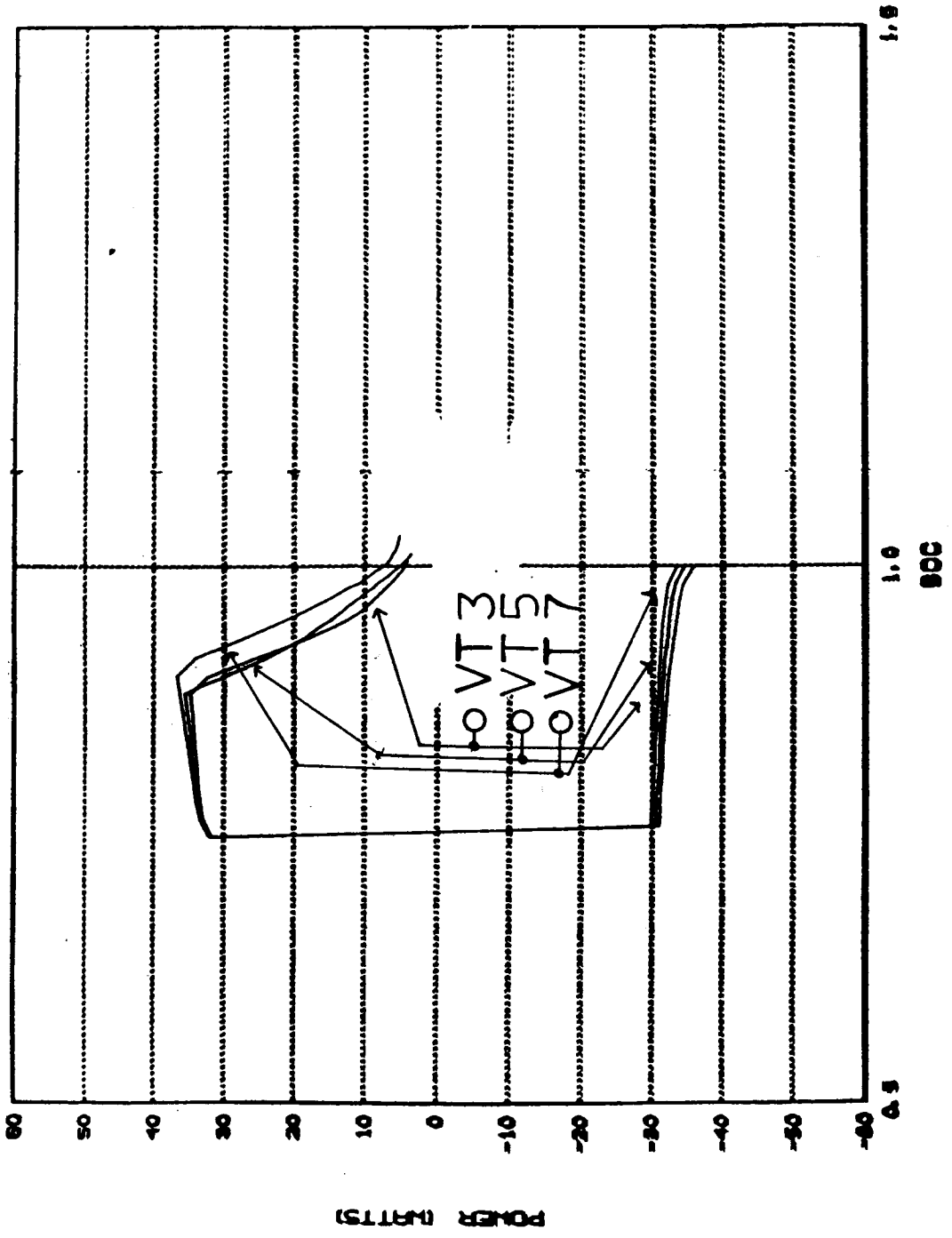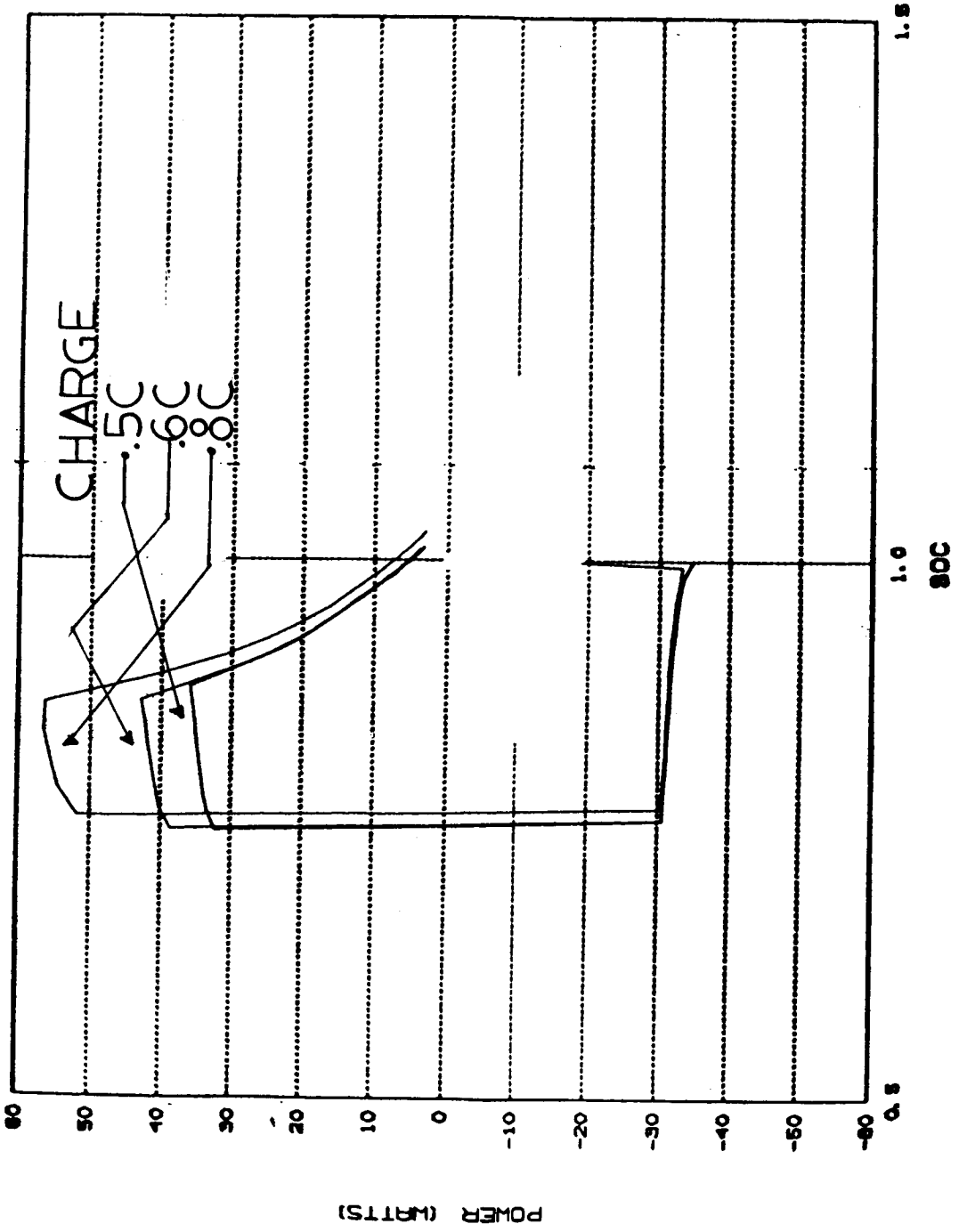
Figure 7

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# MODELING NI-CD PERFORMANCE

## Planned Alterations to the Goddard Battery Model

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The Goddard Battery Model

o The Present Model

    o The Data Base

    o Methodology

o Planned Modifications

    o The New Data Format

# The Present Battery Model

o Data curves: Vc vs. Ic with IPCAP third variable

o 2 modes: NORMAL and TAPER

BATTERY CURRENT VS VOLTAGE
WITH SOC AS 3RD VARIABLE

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# GETIBATT FLOWCHART
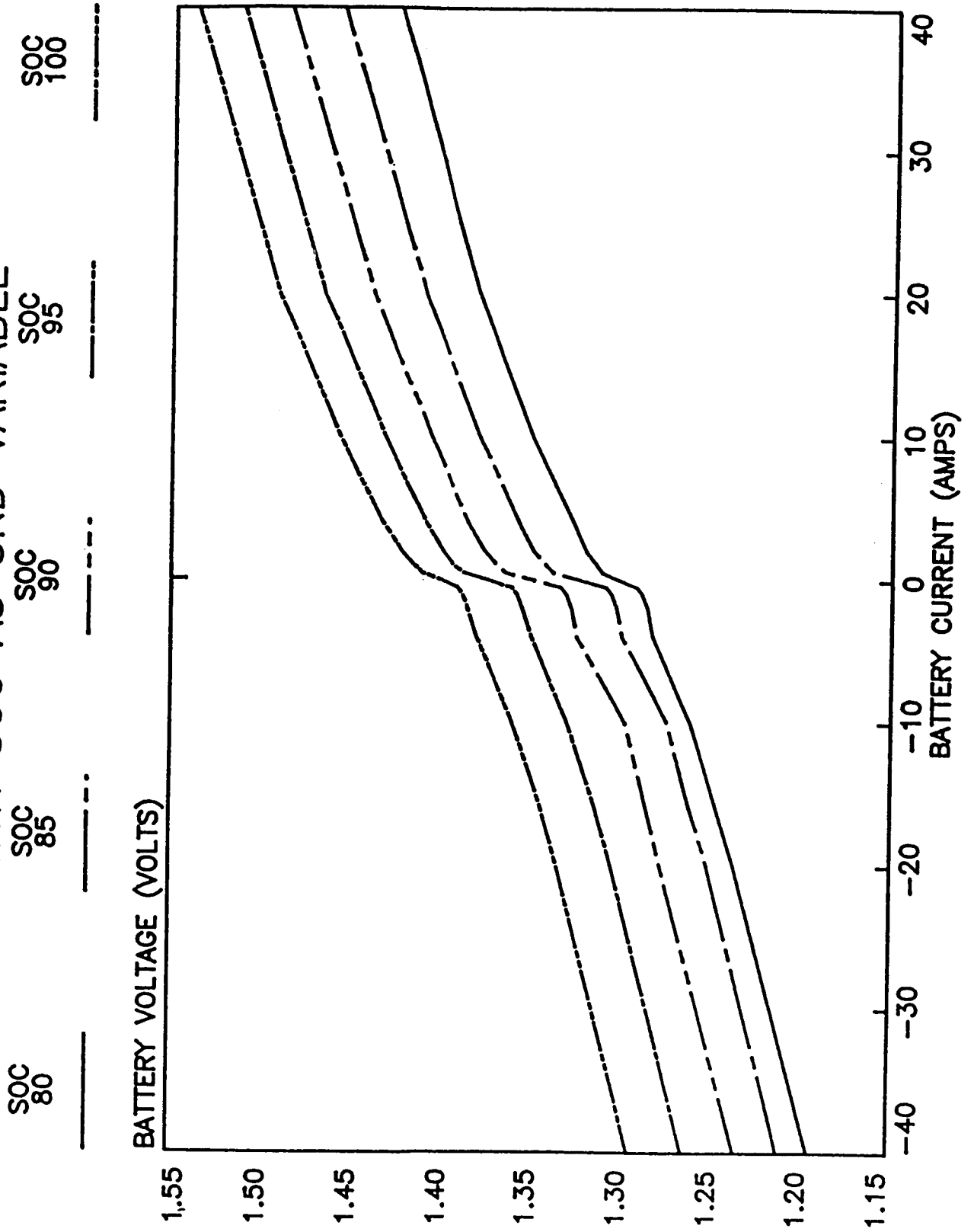## CALCULATE TAPER CURRENT

```
┌─────────────────────┐
│       ENTER         │
│     SUBROUTINE      │
└─────────────────────┘
           │
┌─────────────────────┐
│  CALCULATE RELATIVE │
│   STATE OF CHARGE   │
└─────────────────────┘
           │
┌─────────────────────┐
│ ESTIMATE NORMALIZED │
│    TAPER CHARGE     │
└─────────────────────┘
           │
┌─────────────────────┐
│     INTERPOLATE     │
│     CHARGE DATA     │
└─────────────────────┘
           │
    CALCULATED VOLTAGE
     EQUAL V/T LIMIT?     NO
           │ YES
┌─────────────────────┐
│ "UNNORMALIZE" AND RETURN │
└─────────────────────┘

    CALC > V/T LIMIT?     NO
           │ YES
┌─────────────────────┐
│  RESET UPPER BOUND  │
└─────────────────────┘

┌─────────────────────┐
│  RESET LOWER BOUND  │
└─────────────────────┘

┌─────────────────────┐
│   NEW ESTIMATE =    │
│   (UPPER+LOWER)/2   │
└─────────────────────┘
```
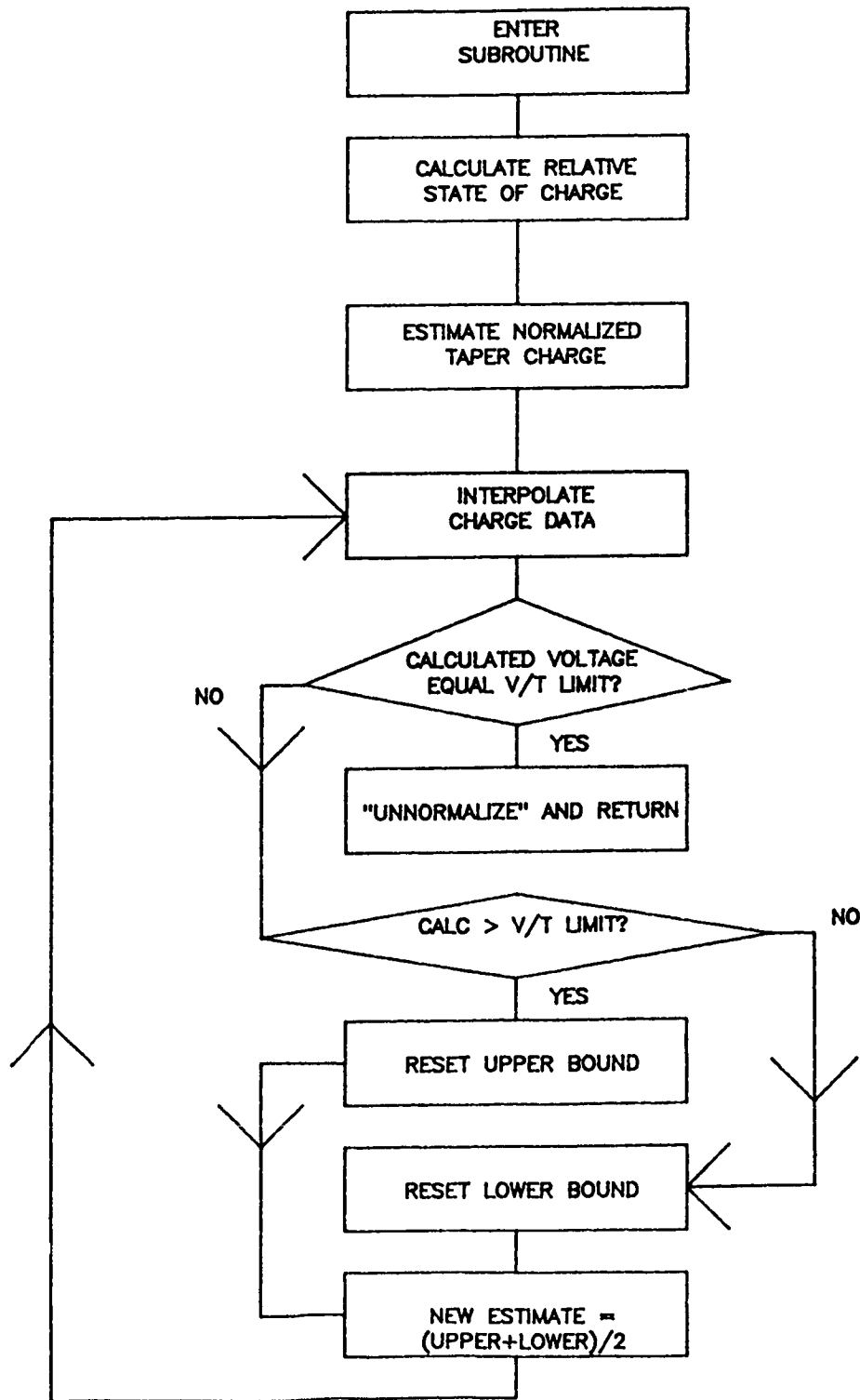
# GETVSYS FLOWCHART
## CALCULATE BATTERY VOLTAGE

```
┌─────────────────────┐
│       ENTER         │
│    SUBROUTINE       │
└─────────────────────┘
           │
┌─────────────────────┐
│  CALCULATE RELATIVE │
│   STATE OF CHARGE   │
└─────────────────────┘
           │
┌─────────────────────┐
│     NORMALIZE       │
│  BATTERY CURRENT    │
└─────────────────────┘
           │
        ◇ IS BATTERY
          DISCHARGING? ◇
       │              │
      NO             YES
       │              │
              ┌─────────────────────┐
              │    INTERPOLATE      │
              │  DISCHARGE DATA     │
              └─────────────────────┘
       │              │
┌─────────────────────┐
│    INTERPOLATE      │
│   CHARGE DATA       │
└─────────────────────┘
           │
┌─────────────────────┐
│  EXPAND CELL DATA   │
│  TO BATTERY DATA    │
└─────────────────────┘
           │
┌─────────────────────┐
│       RETURN        │
└─────────────────────┘
```
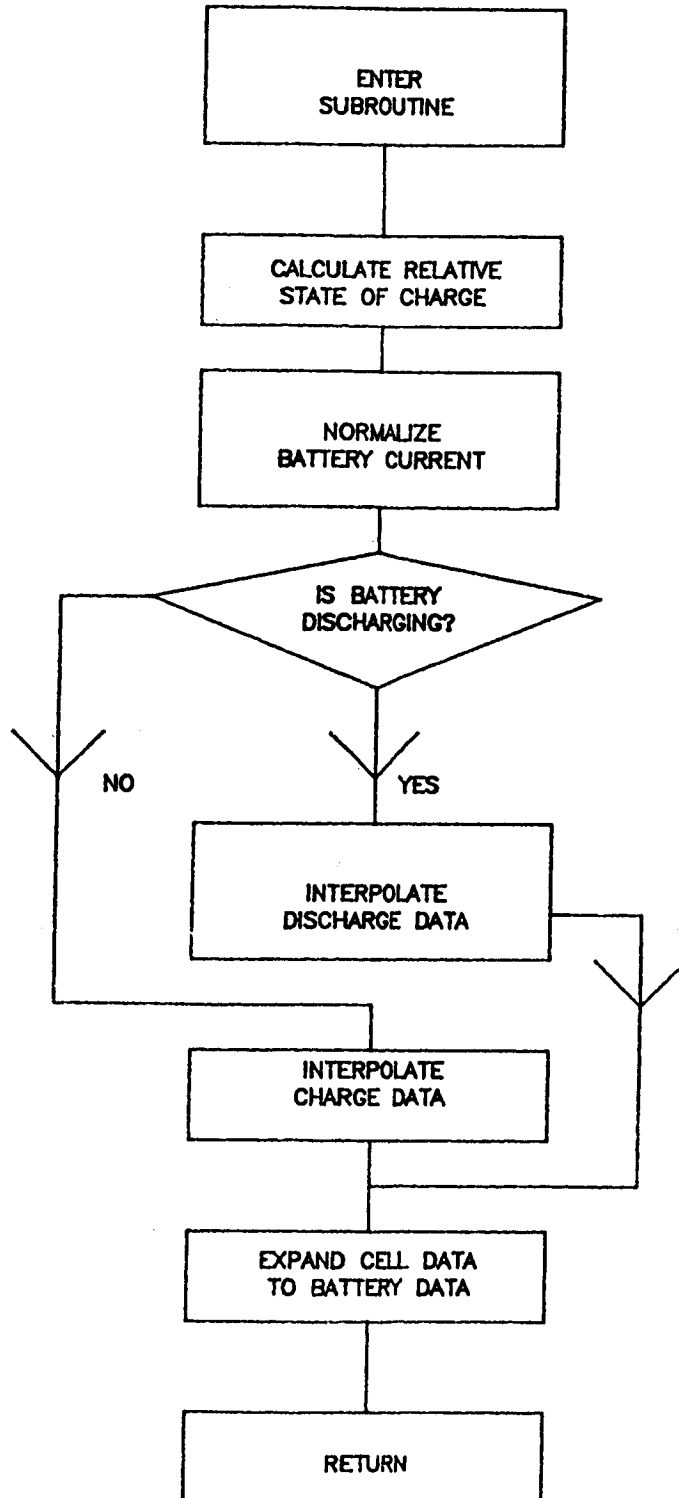
MODELING STUDY USING PACK 12H

CYCLE 15, 20 C, 40% DOD, 16A CHG, 16A DISCHG

REAL VOLTAGE

CALCULATED VOLTAGE

BATTERY VOLTAGE (VOLTS)

TIME (MIN)

244
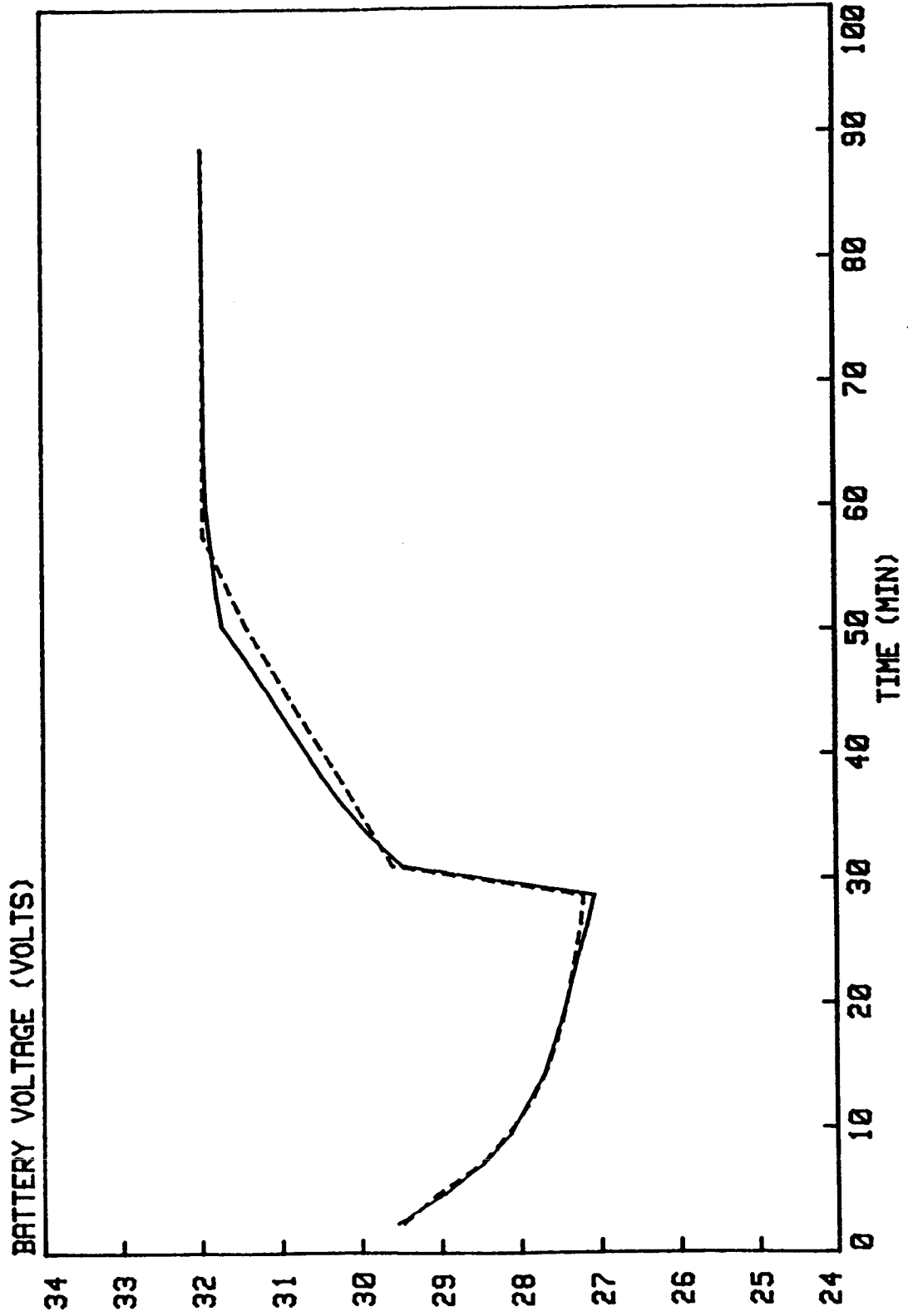
MODELING STUDY USING PACK 12G

COMPARISON – REAL AND CALCULATED CURRENT DATA

REAL
DATA
————

CALCULATED
DATA
– – – – – –

CURRENT (AMPS)

TIME (MIN)
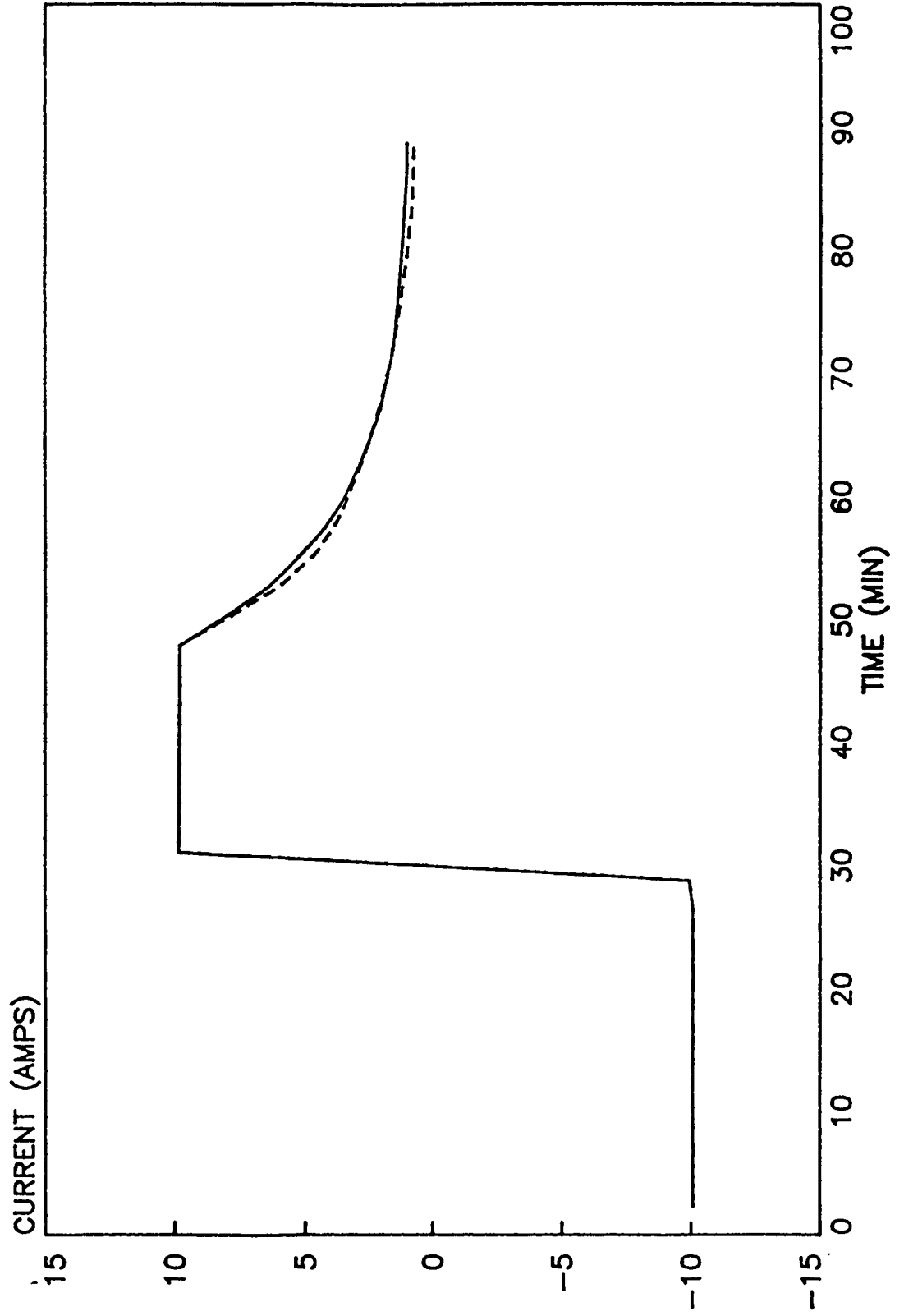
# Planned Modifications to the Model

o  **Uses new data base**

o  **Uses different data format**

o  **Methodology**

# The New Data Base

- VT limits: 3, 5, 7
- Temperatures: 0, 10, 20 (deg C)
- Charge Rates: .2C, .5C, .6C, .8C
- Discharge Rates: .1C, .2, .5C, .8C
- Tests run on 50 Amp-Hr cells

# The New Data Format

- Data curves: Cell Power vs. IPCAP
- Advantages
  - Uses all LEO cycling data
  - Battery is a "power" device
  - Allows for inclusion of other data