FUNDAMENTAL ALGORITHMS OF THE GODDARD BATTERY MODEL

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ABSTRACT

The Goddard Space Flight Center (GSFC) is currently producing a computer model to predict Nickel Cadmium (NiCd) performance in a Low Earth Orbit (LEO) cycling regime. The model proper is currently still in developement, but the inherent, fundamental algorithms (or "methodologies") of the model are defined. At present, the model is closely dependant on emperical data and the data base currently used is of questionable accuracy. Even so, very good correlations have been determined between model predictions and actual cycling data. A more accurate and encompasing data base has been generated to serve dual functions: show the limitations of the current data base, and be inbred in the model proper for more accurate predictions. This paper will describe the fundamental algorithms of the model, describe the present data base and its limitations, and give a brief preliminary analysis of the new data base and its verification of the model's methodology.

INTRODUCTION

Nickel Cadmium cells have long been used as energy storage devices for photovoltaic-based satellite power systems. They have also long been the subject of many modelling efforts and discussions. A great many models have been produced to predict NiCd performance and all have their inherent weak and inherent strong points along with their own particular methodology of prediction. This is due to the fact that NiCd cells are simply not easy to model. To draw an analogy, a meteorologist may know that with the atmospheric conditions being a certain way, rain should result. Yet he is quite unable to really accurately predict how much rain will fall, how long the rain will last, or even if it will rain at all. Not only does the sheer number of variables complicate the prediction process, but the system itself (in this case, the atmosphere) is quite complex of itself. Thus, the meterologist speaks of "probability" or "the chance of rain". So it must be with any model. The measure of a good model is how great the probability is that the model is correct. Conversely, this could be looked at as how small the error between what the model predicts and what is seen or measured in the "real world".

THE PRESENT DATA BASE

The data utilized for modelling cell performance was obtained on the NASA 20 ampere-hour (amp-hr) standard cell, manufactured by General Electric, during the Standard Cell Simulated LEO cycling (4 packs) (30 minutes discharge and 60 minutes charge) and General Performance tests (1 pack) conducted at NWSC, Crane. The desired end result was a family of charge and discharge matrices for various temperatures, voltage-temperature (VT) charge limits, and depth of discharge (DOD).

The data used was from all four LEO packs: one pack was run at 25 percent DOD at 20oC (0.5C charge and discharge rate), the other three at 40 percent DOD at 10, 20 and 30oC (0.8C charge and discharge rate). This resulted in only a few data curves for the compilation of the matrices. In order to "fill in" the empty cells of the matrices, the data generated by the General Performance testing was analysed to reveal or discover various trends or relationships in the data. The results of the General Performance testing were used to extrapolate other data curves for matrix compilation. It is this use of the General Performance testing data and the extrapolation from it which results in this data base being of questionable accuracy. Even so, the desired end result (see above) was achieved. Figure 1 is a typical charge/discharge matrix.

As can be seen, the matrices are such that each column represents a constant State of Charge (SOC) for various currents, whereas each row represents a constant charge or discharge current as the SOC of the cell varies. From this type of matrix, it is therefore possible to generate two types of battery performance curves: Voltage versus Current with SOC as a third variable, or Voltage versus SOC with Current as a third variable. (Of course, cell temperature and DOD are also variables, but are not inherent in the matrices themselves. In other words, temperature and DOD vary from matrix to matrix, not from "inside" the matrix.)

METHODOLOGY

The approach currently used by the model is to have the data from the corresponding DOD and cell temperature matrix represented as a family of curves relating cell voltage to current with SOC as the third variable. The curves themselves are represented as polynomial equations with cell current as the independent variable and cell voltage as the dependent variable. Each different curve corresponds to a different SOC. Figure 2 shows a typical family of curves.

The model at present has two major functions. The first is to predict cell voltage when cell current is known (the model keeps track of the cell SOC, so this value also is "known"). This is the normal mode of operation. The second function or mode is to predict the cell current needed to maintain a constant cell voltage. This mode is used whenever any sort of voltage-clamping charge control is used. This is the taper-charge mode of operation.

NORMAL MODE OPERATION

In calculating cell voltage, the values of normalized cell current (charge or discharge) and the SOC of the cell are known. The model proceeds to find the closest upper and lower bounding curves relative to the cell'c actual SOC. For example, if the data base has curves for the SOC's of 100, 97, 90, 85, and 80 (percent) and the cell SOC is 95 (percent), the model determines that the 97 (percent) curve is the closest upper bounding curve whereas the 90 (percent) 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 SOC 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 SOC curves is large.

Figure 3 is a graph comparing the model predicted voltage curve actual cycling data. The cell temperature was 20oC, 40% DOD, 20 ampere-hour rated capacity, 16 amp discharge (30 minutes), 16 amp charge (60 minutes), with a GSFC VT 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 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-CHARGE 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 SOC 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 SOC. 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.

MODEL LIMITATIONS

When the cycling scheme of the data base correlates with the cycling scheme to be modeled, the model gives accurate results. As the modeled cycling scenario deviates from the data base specifications, the model becomes less accurate.

To further test model accuracy, the model was utilized in such a fashion as to predict various battery characteristic trends (such as "Charge Time to VT vs. DOD) and compare these model predicted trends to actual data trends. In all cases examined, the model predicted trends which very highly correlated to actual data trends. In many cases (such as "DOD vs. End of Charge Current", "DOD vs. Charge Time to VT", and "C/D Ratio vs. VT Limit") not only did the model exhibit the same trends, but the slopes of the model and data curves were very similar.

THE NEW DATA BASE

As stated earlier, the model is in early developement. To further enhance the model's accuracy, and to reduce its dependence on an empirical data base, another data base was generated at GSFC. Through the analysis of the new data base, it will be possible to detect, investigate, and quantify the effects of environment and history on battery performance. In this way, by concentrating on the effects rather than the results, a more comprehensive, self-contained battery model will be achieved (By knowing WHY and HOW the voltage changes, the need to know actual values of the voltage is redundant and unnecessary).

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

Data Base Voltage-Temperature (VT) 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 (percent) 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
VT	3, 5, 7	(3)
Temp	0,10,20	(3)
Charge	10,25,30,40	(4)
10 Amp Discharge Rate		36 test cases
VT	3, 5, 7	(3)
Temp	0,10,20	(3)
Charge	10,25,30,40	(4)
25 Amp Discharge Rate		27 test cases
VT	3, 5, 7	(3)
Temp	0,10,20	(3)
Charge	25,30,40	(3)
40 Amp Discharge Rate		18 test cases
VT	3, 5, 7	(3)
Temp	0,10,20	(3)
Charge	30,40	(2)

The model was tested against the new data base. There was good correlation between the taper charge current and Charge/Discharge (C/D) ratios. The model showed significant error in predicting cell voltage but this error was later determined to be caused mainly by the age of the cells in the new data base. The present data base was on new cells.

The data from the new data base was analysed in order to determine any functional relationships between data values and the cycling environment. The findings are quite interesting and will be discussed below.

PRELIMINARY ANALYSIS OF THE NEW DATA BASE

The first data matrix generated and analysed corresponded to the 10 deg C, VT 5 discharge test cases. Using the actual data, the matrix in figure 5 was constructed. As can be seen, the matrix has a few "empty" cells. In trying to determine a method to fill in these empty cells, an interesting functional relationship was exposed.

For each column in the matrix (in other words, each set of data with constant SOC), it was found that the cell voltage in linearly dependant on the cell voltage according the the formula:

$$Vcell = (Msoc * Icell) + Bsoc$$

where Msoc and Bsoc refer to the slope and y-intercept for each particular SOC, respectively. Figure 6 is a table containing the values of Msoc and Bsoc for each SOC set.

Upon further investigation, it was determined that the value for Msoc varies linearly with Bsoc according to the formula:

$$Msoc = (M1 * Bsoc) + B1$$

where M1 = 0.011576 and B1 = -0.013757. Hence, by knowing Msoc one can easily calculate Bsoc, and vice-versa. Knowing these values, one can easily calculate Vcell or Icell knowing the value of the other. The only restraining factor is a functional relationship between SOC and either Msoc or

Bsoc. The relationship is linear (correlation factor of 0.94) but this does not offer enough accuracy. Therefore a polynomial equation was used to relate SOC with Bsoc.

The result of this is that one can completely describe the discharge matrix, and therefore the discharge characteristics, by two real numbers (M1 and B1) and the coefficients of the polynomial equation relation SOC to Bsoc. This is a total of 6 numbers (assuming one uses a cubic equation having 4 coeficients) that the model must recall. This greatly reduces the storage requirements of the program. Additionally, since only two equations need be evaluated, the efficiency and speed is greatly increased.

Further analysis is underway to determine if the values of B1 and M1 are dependant on cell temperature and VT limit. Preliminary results point to a linear relationship but this has not been fully worked out. It will also be desired to relate the coefficients of the polynomial equation to temperature and VT limit. This has not been started as of yet.

CONCLUSION

The Goddard Space Flight Center is currently producing a LEO Battery Model for performance calculation. At present the model is in its early stages but already has shown very good correlation with cycling data which is close in history and environment to the model's data base. A new data base was generated to suppliment the model and upon analysis exposed some interesting and useful functional relationships concerning battery performance. Analysis is continuing in order to determine other relationships, if they exist, and determine their usefulness.

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20 AH GE 20 DEG C LEO 25%DOD [C.PALANDATI]

	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	1.479
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)

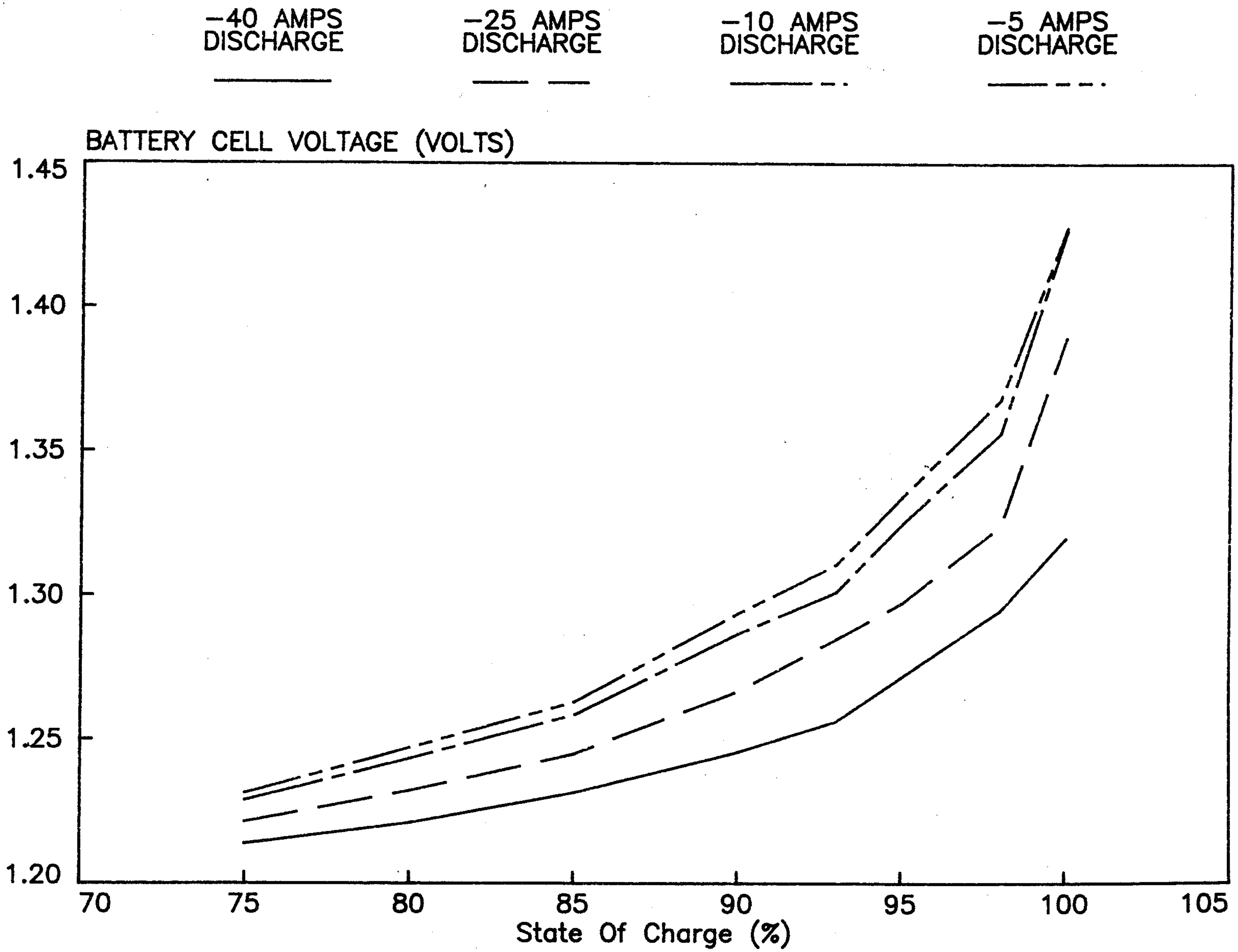

Figure 2. Discharge Curves for 10 deg C and VT 5

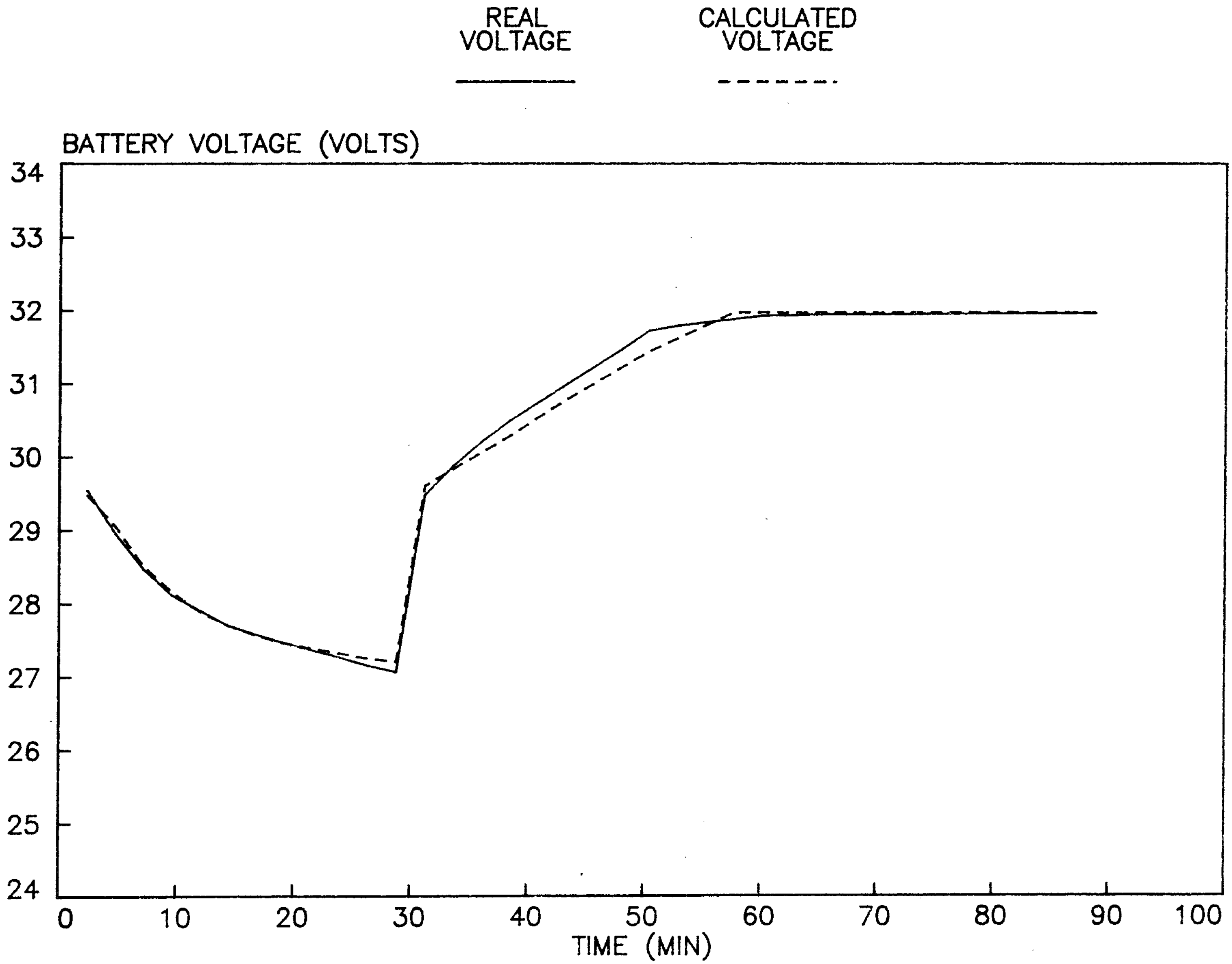

Figure 3. Modeling Study for Battery Workshop: Cycle 15, 20 C, 40% DOD, 16A Chg, 16A Disch

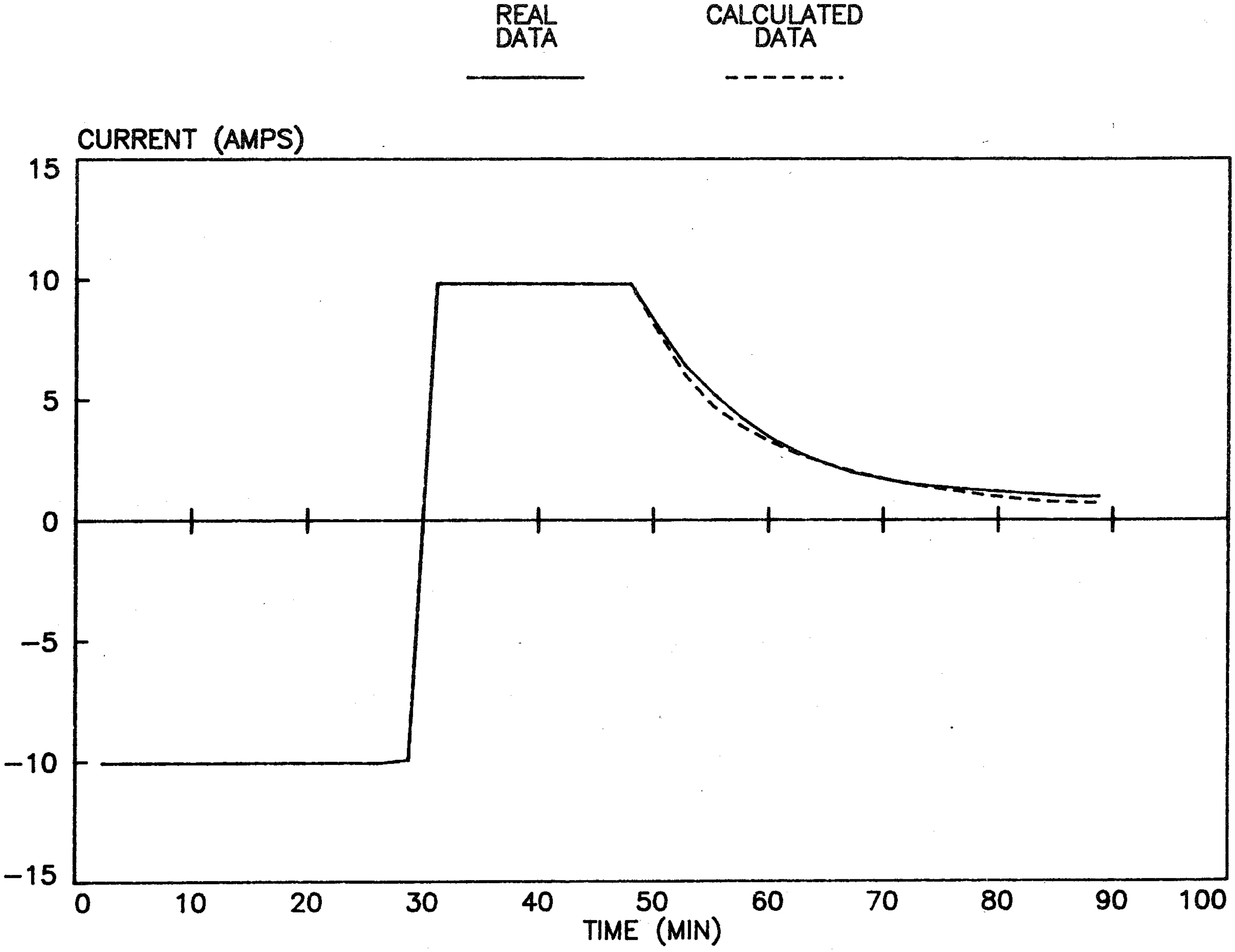

Figure 4. Modeling Study for Battery Workshop: Comparison—Real and Calculated Current Data

CURRENT AMPS	S O C							
	75	80	85	90	93	95	98	100
-40 :	1.2138	1.2209	1.2314	1.2455	1.2562	1.2717	1.2948	1.3200
-25 :	1.2213	1.2321	1.2449	1.2667	1.848	1.2974	1.3241	1.3895
-10 :				1.2866	1.3012	1.3248	1.3563	1.4266
- 5 :						1.3341	1.3679	1.4276

Figure 5. Data Matrix for 10 deg C, VT5, 50 Ahr, Leo

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 SOC
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100          Bsoc  :  1.453125
             Msoc  :  0.003110

 98          Bsoc  :  1.377508
             Msoc  :  0.002087

 95          Bsoc  :  1.342698
             Msoc  :  0.001785

 93          Bsoc  :  1.318233
             Msoc  :  0.001500

 90          Bsoc  :  1.300517
             Msoc  :  0.001370

 85          Bsoc  :  1.267400
             Msoc  :  0.000900

 80          Bsoc  :  1.250770
             Msoc  :  0.000747

 75          Bsoc  :  1.233800
             Msoc  :  0.000500
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Figure 6. Values of 'Bsoc' and 'Msoc' for Various SOCs. Data from Figure 5.