PREDICTION OF BATTERY LIFE AND BEHAVIOR

FROM ANALYSIS OF VOLTAGE DATA

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Introduction

The object of this analysis is to develop a method for simulating charge and discharge characteristics of secondary batteries. The analysis utilizes a non-linear regression technique where empirical data is computer fitted with a five-coefficient non-linear equation. The equations for charge and discharge voltage are identical except for a change of sign before the second and third terms.

$$\text{Discharge Voltage} = A - \frac{B}{C - x} + De^{-Ex}$$

$$\text{Charge Voltage} = A + \frac{B}{C - x} - De^{-Ex}$$

Figures 1 and 2 show typical charge and discharge curves, with dots representing actual voltage data and the solid line representing the theoretical fit. The data is taken from a test of 12 amp-hr, NiCd cells cycling in a near-earth orbit regime at the Jet Propulsion Laboratory. The figures show that the theoretical fit is accurate to within 2-3 millivolts.

When coefficients A, B, C, D, and E are plotted versus cycles, certain trends are apparent. Figure 3 shows the five coefficients for cells cycling at a 50% depth of discharge and 20^{0} C. A regression analysis was performed on voltage data at 100 cycle intervals up to 3000 cycles, with the exception of the first 100 cycles for which the interval was smaller.

For coefficients A, B, C, and E there is a sharp rise during the first 100 cycles, and for coefficient D, a sharp decline. After reaching the peak at 100 cycles, there is a gradual decline for approximately 1000 to 1500 cycles for coefficients A, B, C, and E; coefficient D shows a gradual increase over the same interval. By 1500 cycles, all coefficients have reached an equilibrium at which the value of the coefficient is stable.

The rates of change of the coefficients vary with temperature. Figure 4 shows coefficient A at 20, 30, and 40^{0} C. The trends are similar at each temperature, except that the point of stability is reached at progressively earlier cycles, from 1500 cycles at 20^{0} C to 500 cycles at 40^{0} C.

We have found that coefficients A, B, and C are highly correlated. Figure 5 shows coefficient A plotted against coefficient C for the cells at 20^0 C.

Modeling the Voltage

For the remainder of this analysis, the different areas of the curves will be characterized as follows (see Figure 6):

- Phase I represents the initial sharp rise (or decline) from initial voltage I_0.
- Phase II represents the gradual decline (or rise) from the peak at II_0.
- Phase III represents the region of stability beginning at III_0.

In order to predict the charge or discharge characteristics at a given cycle, specific values for coefficients A, B, C, D, and E are substituted into the original non-linear equations where voltage is now the dependent variable. To establish specific values for the coefficients at a given cycle, the following calculations were made:

- The slopes for Phases I and II were calculated for all temperatures.
- A value for the coefficient in Phase III was calculated based on the mean over that phase.
- The values for I_0, II_0, and III_0 were estimated by intersection of the linear portions of each phase.

Figure 7 shows a generalized equation where slopes are symbolized by Δ and X represents the amp-hrs of charge removed from the cell in discharge or added to the cell in charge.

Once the slopes and initial values I_0, II_0, and III_0 are determined for a particular temperature and depth of discharge, it is a straightforward calculation to determine the charge and discharge curves for a particular cycle, whatever the range (Phase I, II or III).

Operational Significance

The spacecraft manager can be faced by a number of situations where the use of a voltage prediction model could be of use:

- Voltage prediction with sparse data
- Voltage prediction of a neighboring cycle
- Voltage prediction of a cycle later in life.

The first case prediction with sparse data is a practical necessity, due to the fact that there is often a limitation on the amount of data that can be telemetered to the ground during a spacecraft orbit. Furthermore, in managing the energy balance of a spacecraft's power system, it is often useful to track the battery's performance given specific loads and thus voltage prediction of neighboring cycles. Finally, in long-term missions, it could be very useful for the manager to be able to predict power system behavior several years later in the mission.

Candidates for Life Prediction

The purpose of life prediction is to find trends such as those established in Figures 3 and 4 which correlate well with life. It would be useful, moreover, if these trends could be established early in the life of a cell; during the first few hundred cycles, for example. In this analysis, a number of trend descriptors or signatures were investigated to see which best correlated with life. The candidates for correlation with life were as follows:

- Value of parameter during first cycles
- Value after initial rise or decline
- Slope during initial rise or decline (100 cycles)
- Slope after initial rise or decline (100-1500 cycles)
- Value of parameter after leveling off.

After considering each of these "candidates," it was determined that the most consistent results were found by correlating life with the fourth candidate, the slope after the initial rise or decline (100-1500 cycles).

Figure 8 shows the ln slope of three of the coefficients, A, B, and C, plotted against temperature for two depths of discharge, 35% and 50%. This figure suggests that as temperature increases there is a linear increase in the ln slope of these coefficients over the range under investigation. The difference between 35% and 50% depth of discharge is approximately 1.0 on the ln scale.

Correlation with Life

Figure 9 shows actual and predicted values of cycles-to-failure for three of the packs cycling at JPL, 50%/40^o C, 50%/30^o C, and 35%/40^o C. The equation used to theoretically calculate mean cycles to failure was derived several years ago and is found in previous Proceedings of the Battery Workshop. The predicted cycles to failure are within 10% to 20% of the actual mean value cycle to value which are approximately 9,000 cycles for the 50%/30^o C and 35%/40^o C cells and approximately 3400 for the 50%/40^o C cells.

In a very qualitative sense, increasing temperature and depth of discharge both lead to shorter battery life, and the rise in 10° C is roughly equivalent to a 15% increase in depth of discharge. In Figure 9, an increase in temperature from 30° C to 40° C for the 50% depth of discharge cells caused a drop in cycle life from approximately 9000 to 3400 cycles. The same sort of drop was seen in the two 40° C packs when the depth of discharge is increased from 35% to 50%.

These findings are consistent with those found in Figure 8, where the increase in ln slope over 10° C (approximately 1.0) is the same differential as was found between each of the 35% and 50% depth of discharge curves. This result demonstrates in a qualitative sense at least a 10° C increase in temperature is equivalent to a 15% increase in depth of discharge.

Summary

Figure 10 is an attempt to estimate the quality or reliability of a prediction based on the amount of data available. One star indicates a fair estimate; three stars indicates a good estimate. It is clear that accumulating data over early life (Phase I) is a less reliable basis for prediction than data accumulated in mid-life (Phase II). The best prediction for both voltage behavior and cycles to failure can be made after the test has passed point III_0 when the cell reaches its stability point after approximately 500-1500 cycles.

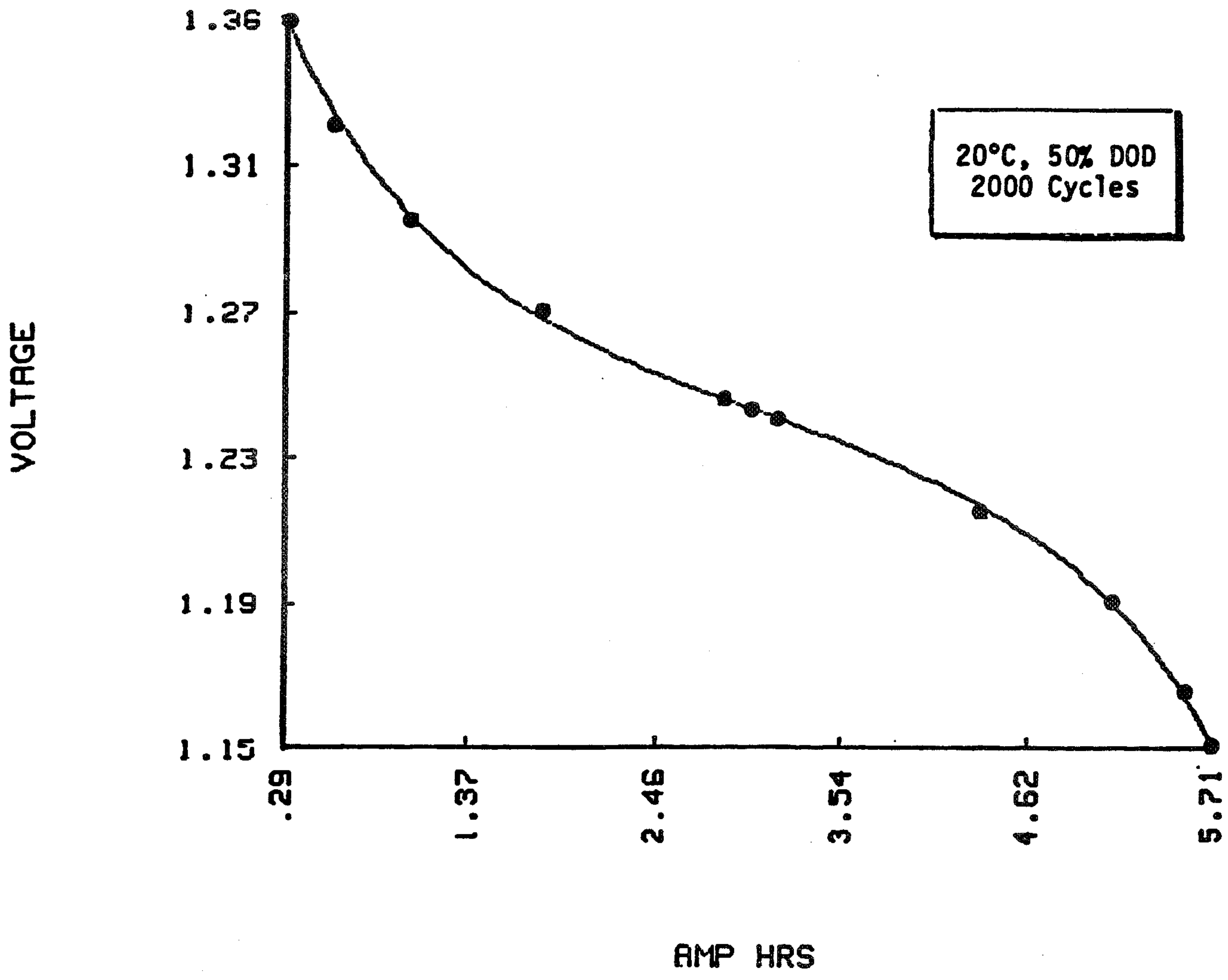

Figure 1. Five parameter discharge voltage fit.

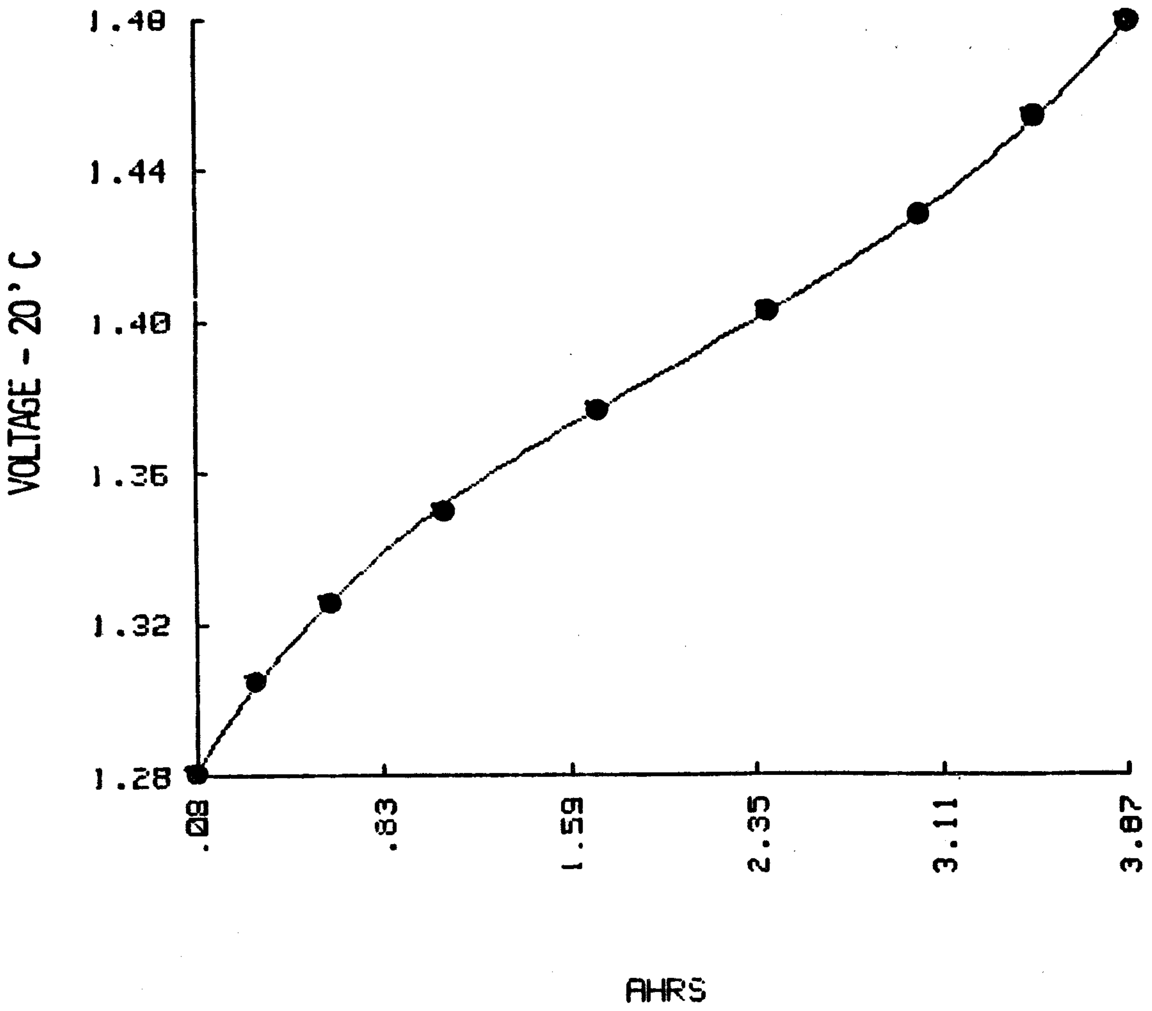

Figure 2. 5-fit charge 200 cycles 35% DOD.

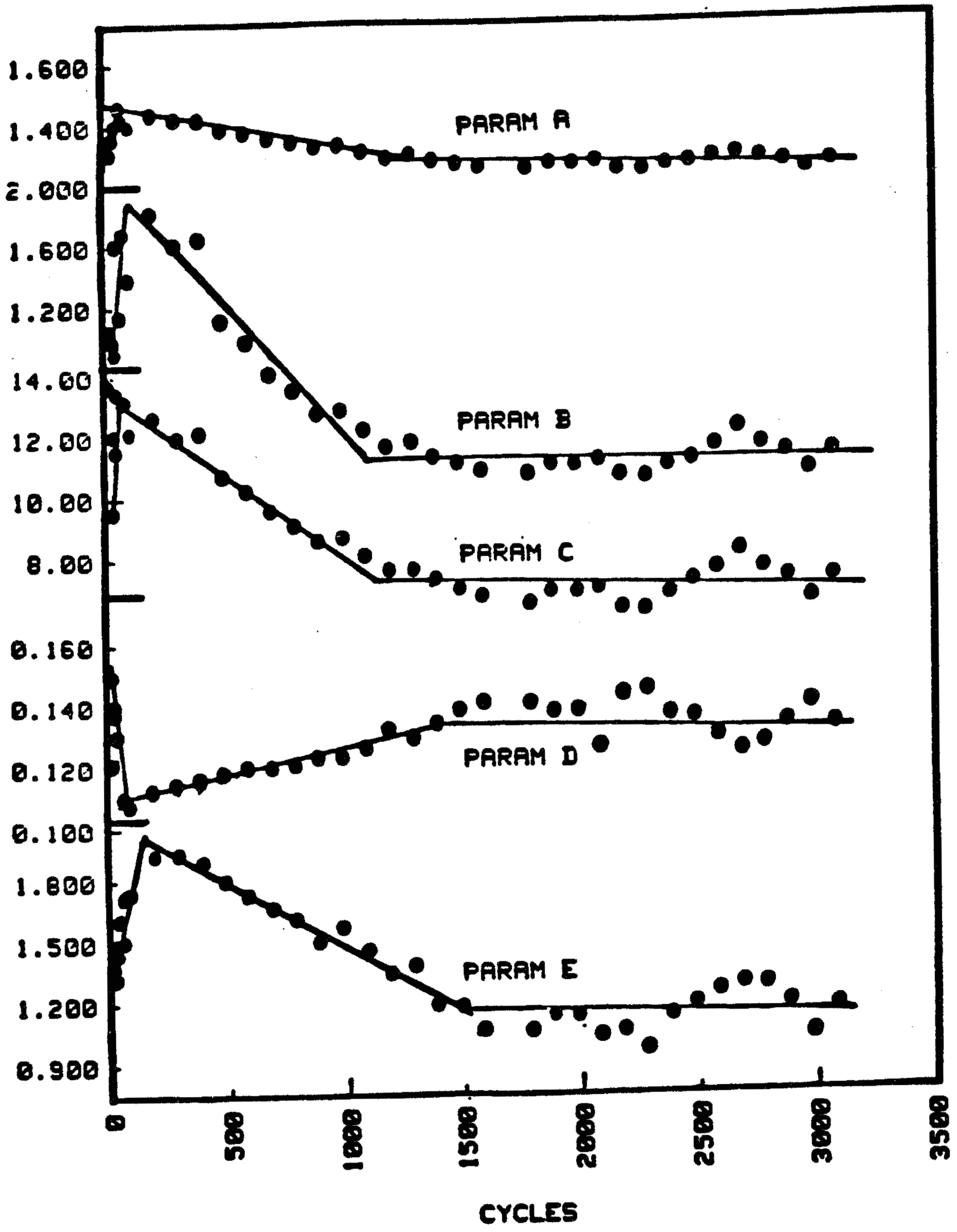

Figure 3. 5-fit discharge 50% DOD temp 20°C.

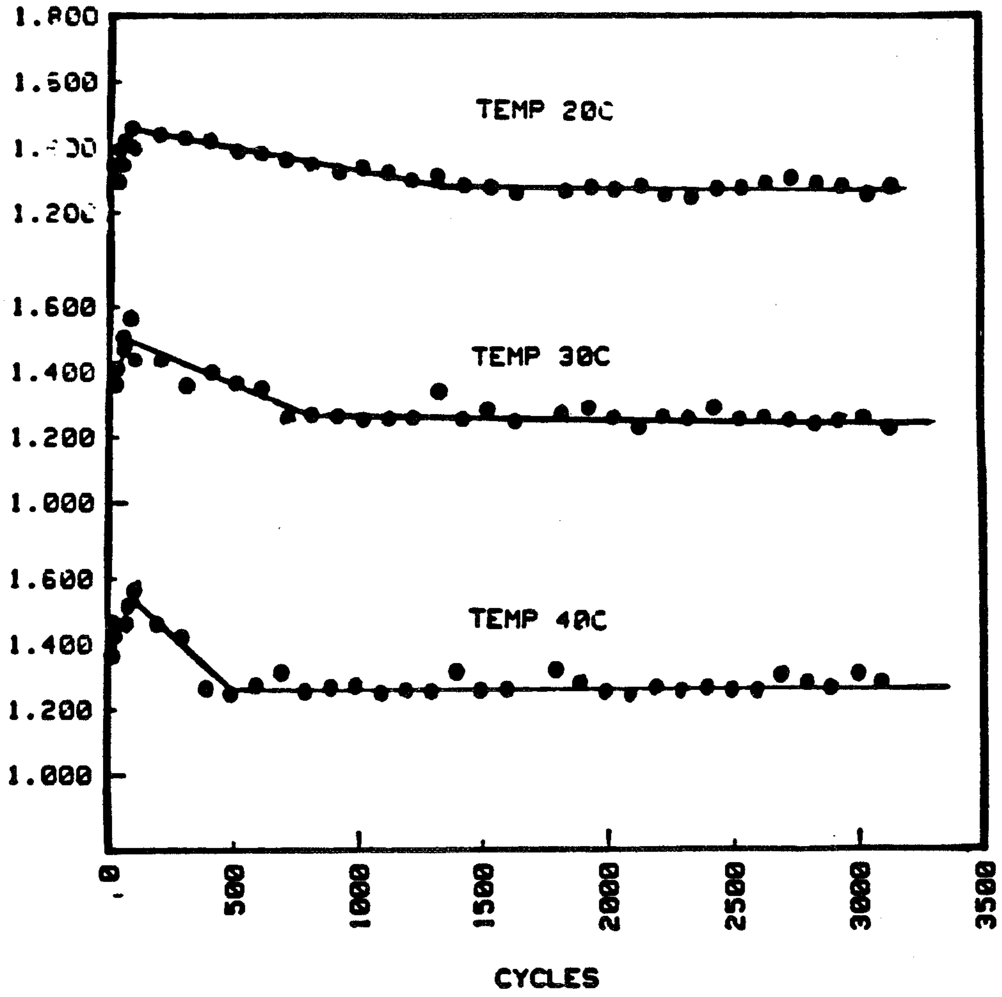

Figure 4. 5-fit discharge 50% DOD parameter A.

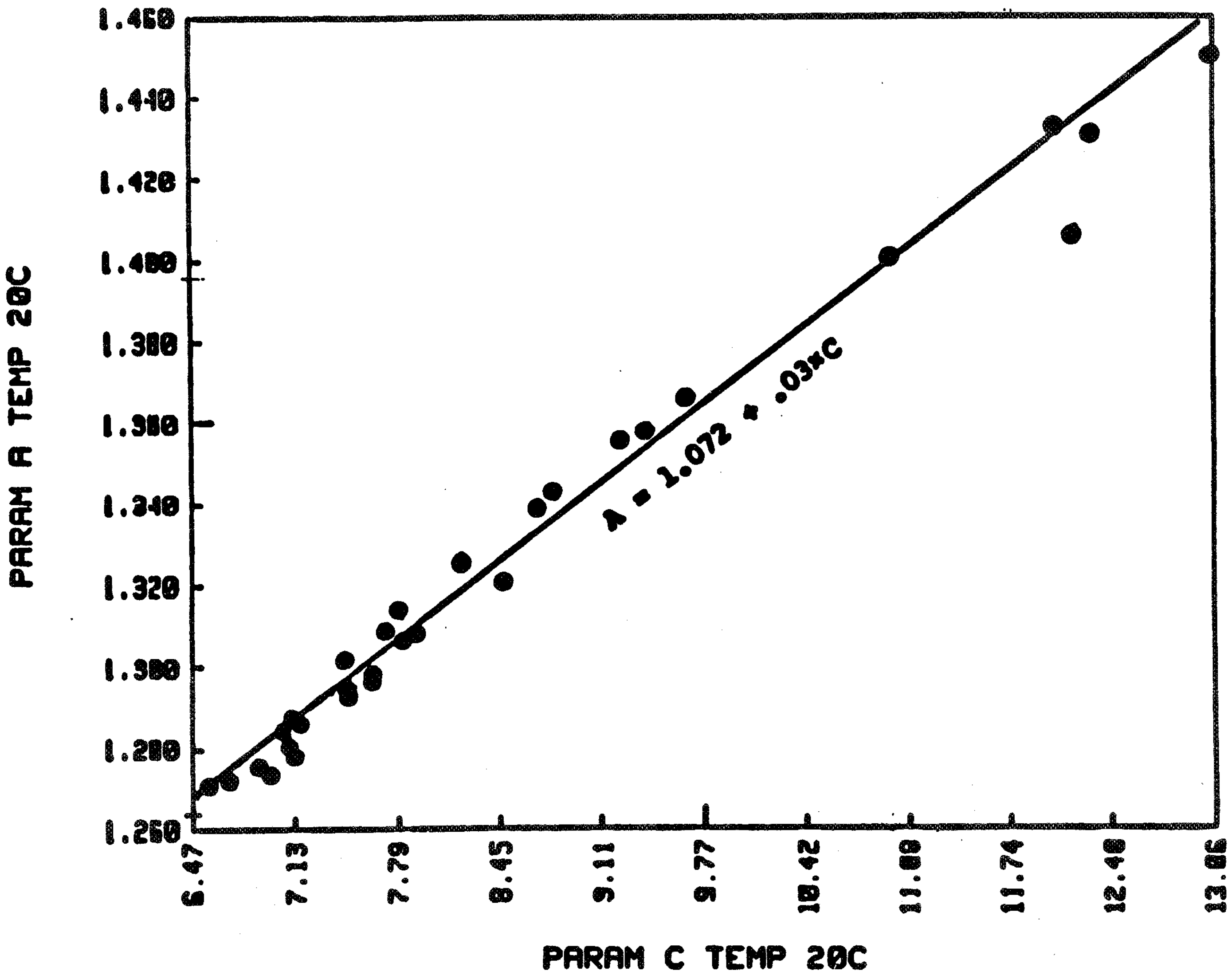

Figure 5. Correlation of coefficients A' and C.

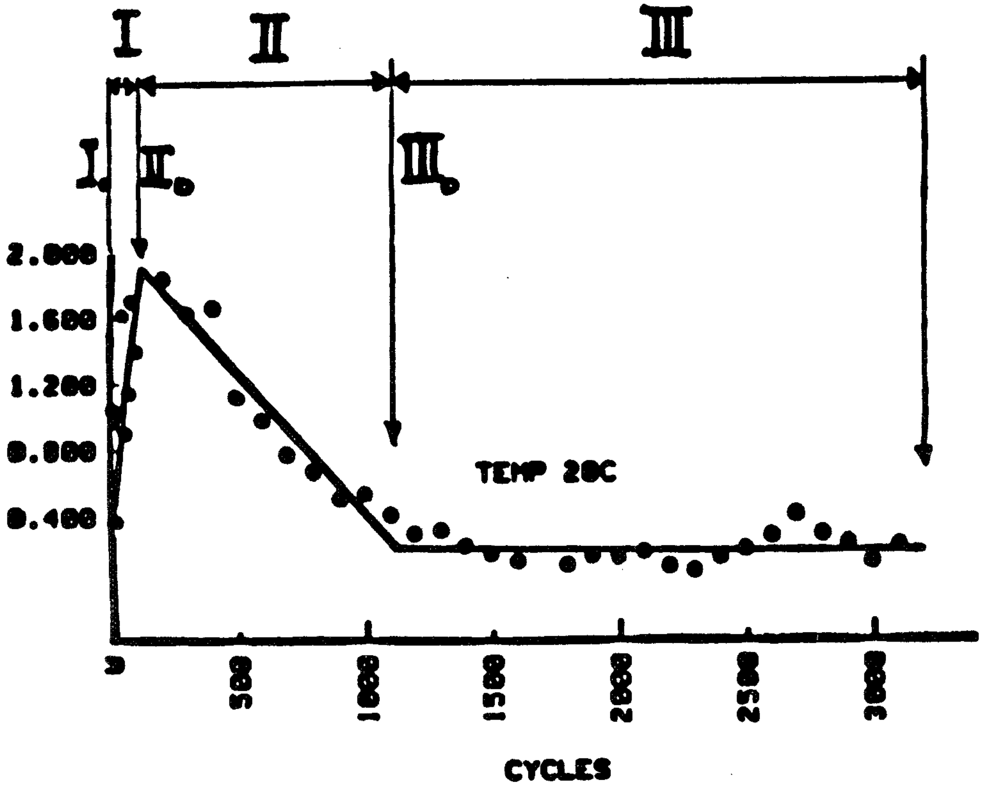

Figure 6. Discharge 50xDOD parameter B.

$$\left|\overline{\underline{\text{Voltage}}}\right| = A(I,II,III) \pm \frac{B(I,II,III)}{C(I,II,III) - X} \mp D(I,II,III)\,\exp^{-E(I,II,III)X}$$

$A(I) = A_{I\bullet} + \Delta A_I$ x Cycle No. where ΔA_I = Slope of A during Phase I cycles

$A(II) = A_{II\bullet} + \Delta A_{II}$ x Cycle no.

$A(III)$ = Average Value of A over Phase III

$B(I) = B_{I\bullet} + \Delta B_I$ x Cycle No.

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ETC. ETC. ETC. ETC.

Figure 7. Voltage prediction.

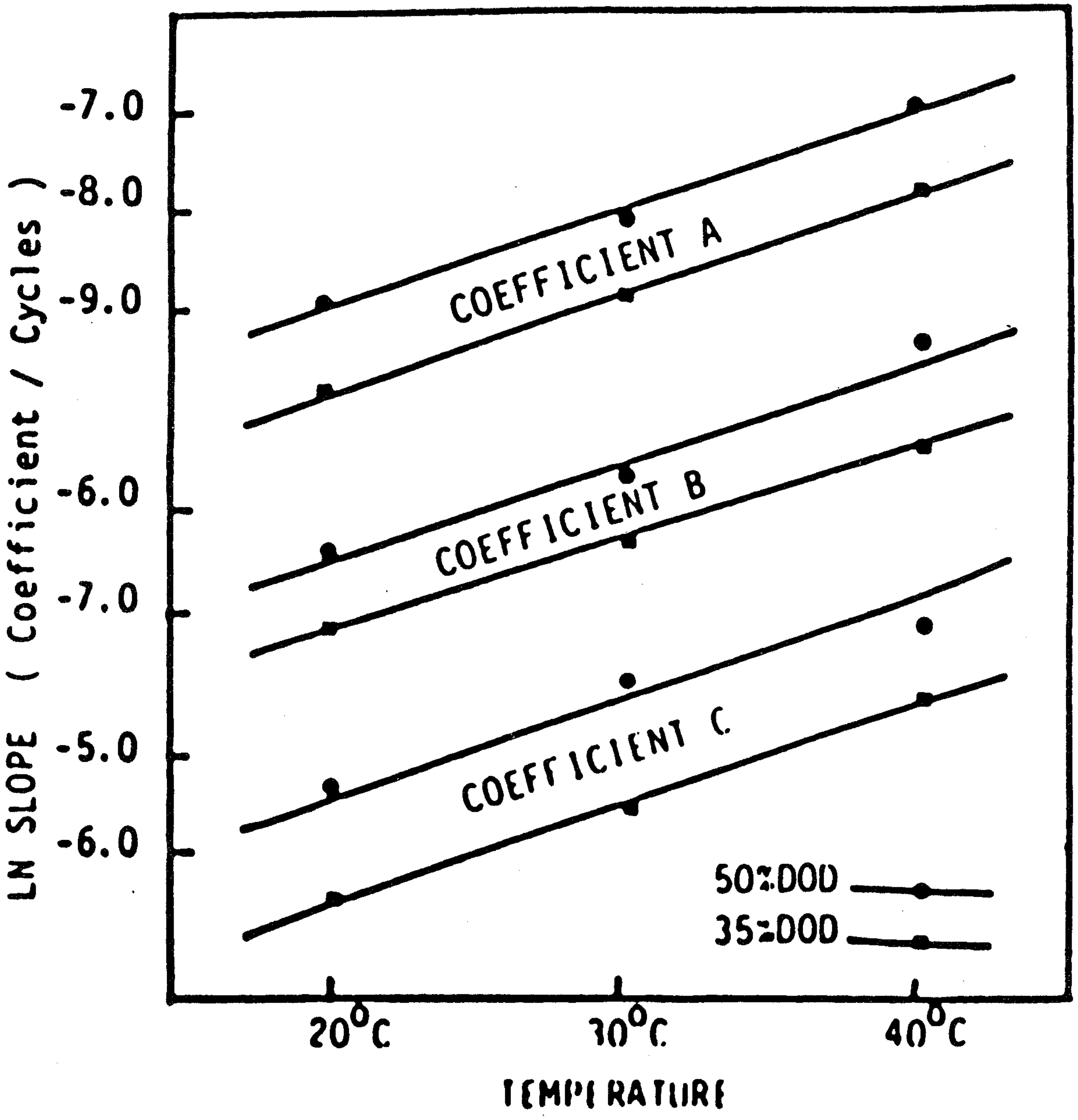

Figure 8. Ln slope vs temperature.

MEAN CYCLES = 1500(67-Temperature)$e^{-0.038(DOD)}$
TO FAILURE

DOD/TEMP	50%/40°C	50%/30°C	35%/40°C
Cycles to Failure	3351	10,367	9,042
	3441	8,600	9,042
Predicted	3800	8,300	10,700

Figure 9

	Early Life	Mid Life	Later Life
Voltage Prediction with Sparse Data	**	**	**
Voltage Prediction of Neighboring Cycle	**	***	***
Voltage Prediction of Cycle Later in Life	*	**	***
Prediction of Failure Cycle	*	**	***

Figure 10. Estimate of quality of prediction.

Q. Ellason, Lockheed: The battery with the two shorted cells - would you care to comment on the age.

A. Pickett, Hughes Aircraft: Yeah, they were at least well the in orbit life time was about seven years and you can see that from the graph when the voltage dropped off significantly. The actual age of the cells themselves were about nine years.

Q. McDermott, B&K Dynamics, Inc.: I noticed that on several of the graphs your predicted value actually changed as you were changing the loads?

A. Pickett, Hughes Aircraft: That's right.

Q. McDermott, B&K Dynamics, Inc.: So you have current density terms in there that are sort of mapping those charges?

A. Pickett, Hughes Aircraft: That's in the depth of discharge.

Q. McDermott, B&K Dynamics, Inc: How come that the last one the predicted didn't seem to change very much when the low charged quite radically?

A. Pickett, Hughes Aircraft: The reason why is that there's several cells in a number of batteries which did not have shorts. That particular battery had shorts the other cells didn't and we would have to take an average or meaning of all the other cells on the consideration and the analysis and that's why the predicted didn't follow that particular curve.

Q. Weiner, Aerospace Corporation: Did you or do you intend to include the affect of any pre-use of the battery before launch such as times and activation temperature storage burn-in cycles or acceptance test cycles and so on.

A. Pickett, Hughes Aircraft: The answer to the acceptance test cycles and burn-in cycles that's kind of hard to do since everything we do is pretty much standard. It's hard to vary that. In answer to some of the other things we plan to look at possibly the wet life is something which we should look at as well as the time the batteries have to stay in open circuit. Although I will point out that in some of these batteries that we've used for systems test as well as spacecraft test you are aware that the batteries sometimes set open circuit at high temperatures maybe as long as two or three weeks something like that.

Q. Hafen, Lockheed: Does your model predict an operating temperature?

A. Pickett, Hughes Aircraft: You could probably get that out of it by doing some analysis with it. In other words, we were able to predict an optimum charge rate using it and I think we could probably do that with temperature as long as the temperatures are within the range of the data base.

Q. Hendee, Telesat Canada: Would the battery that developed the two shorts be one that I might possibly recognize?

A. Pickett, Hughes Aircraft: No it's not an ANIK satellite.

Q. Hendee, Telesat Canada: We've had some on that as well but okay.

A. Mallory, AT&T Bell Labs: I take it from the shape of the equation that the discharge in the early stages has no affect on the prediction that the later stages but it's each individual season that you have to worry about.

Q. Pickett, Hughes Aircraft: I'm not sure I understand your question Dean.

A. Mallory, AT&T Bell Labs: In some of your curves you showed a case where the load changed drastically from one season to the next.

A. Pickett, Hughes Aircraft: Yeah I would say that yeah the depth discharge is probably more - affects the battery more later. I think if you look at the model I believe there's some cross terms in there with respect to the depth discharge in time that takes care of that.

Q. Mallory, AT&T Bell Labs: Second question. Do you plan to include anything like the reconditioning depth of discharge?

A. Pickett, Hughes Aircraft: We haven't included it here or we didn't look at it here for two reasons. It probably should be done for completeness but to give you an isolated data point one satellite which had been reconditioned to one volt average per cell showed after eight years a minimum discharge voltage of about 1.18. One that had been discharged to 54% DOD showed an average of 1.16 there may be something significant there but just on the surface I would say that it's probably not that significant.

A. Maurer, AT&T Bell Labs: I was thinking of spacecrafts D1 & 2 where it was reconditioned to 115 volts/cell for the first 3 seasons the voltage dropped off then reconditioning to one volt the voltage jumped back up again.

A. Pickett, Hughes Aircraft: Yeah we've seen that and normally what we do is the beginning of life when we recondition or what we recommend to the customers is that during the first initial seasons they go to 1.15 v/c and then as the satellite ages we go down to lower than that but we never exceed an average of one volt per cell.