PREDICTION MODEL FOR THE LIFE OF NICKEL-CADMIUM BATTERIES IN GEOSYNCHRONOUS ORBIT SATELLITES

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ABSTRACT

Hughes has developed a mathematical model which predicts life of nickel-cadmium batteries designed for geosynchronous orbit satellites. A statistical analysis technique called regression was used to analyze orbital data on second-generation trickle-charged batteries.

The model gives average cell voltage as a function of design parameters, operating parameters, and time. The voltage model has the properties of providing a good fit to the data, good predictive capability, and agreement with known battery performance characteristics. Average cell voltage can almost always be predicted to within 0.02 volts for up to 8 years.

This modeling shows that these batteries will operate reliably for 10 years. Third-generation batteries, which are being used in the latest generation of Hughes satellites, are expected to operate even longer.

INTRODUCTION

Over the past 20 years there has accumulated considerable in-orbit data on batteries in geosynchronous orbit satellites designed and built by Hughes Aircraft Company. These satellites began in 1963 with Early Bird, the first geosynchronous communications satellite, and continue through the new HS 376 series. This series includes the SBS and Anik-C satellites recently launched by the Space Transportation System. Since launch of the Intelsat IV series of satellites in the early 1970's, one cell manufacturer, General Electric Company, has been used almost exclusively by Hughes for production of satellite batteries. Consequently, Hughes has an extensive data base of design and in-orbit data on General Electric battery cells.

These batteries, beginning with the Intelsat IV (ref. 1) and the Anik-A (Canada) (ref. 2) series of spacecraft, can be conveniently divided into three generations of designs. The first generation was the Intelsat IV (F2 through F7) and Anik A1 and A2 series of spacecraft batteries. The second generation was the Intelsat IV F1 and F8, Intelsat IV-A, COMSTAR, Anik-A3, WESTAR I, II, and III, Palapa-A (Indonesia) and MARISAT designs. The third generation is the

LEASAT and HS 376 design, which includes SBS (satellite business systems), Anik-C, WESTAR IV and V, Palapa-B, Telstar III (AT&T), Aussat (Australia), Brasilsat (Brazil), Galaxy (Hughes Communications), and Morelos (Mexico).

The first-generation batteries were stored open circuit and had temperatures close to 25°C, high active material loading in the positive electrode (12 to 13 g/dm^2), low levels of electrolyte (2.5 cm^3/A-hr), and low plate areas, resulting in high current densities (5.5 to 5.9 mA/cm^2). These batteries did not reach their design life of seven years at 50 to 60 percent depth of discharge (DOD). Low battery voltage dictated removal of some of the spacecraft loads after 5-1/2 years.

In order to reduce early degradation, second-generation battries were stored trickle-charged in orbit at 15° to 23°C. More electrolyte was added to the cells (3.0 cm^3/A-hr), and other improvements were made. These changes resulted in batteries which have now exceeded 7 years of in-orbit operation without load reduction at DOD levels greater than 50 percent.

Prior to design of the HS 376 batteries, several significant relationships were established and quantified, such as separator degradation as a function of time and temperature, the effect of electrolyte quantity, and the effect of positive plate swelling (ref. 3, 4). These discoveries, along with improvements in the spacecraft power electronics, have resulted in a third-generation design life of over 10 years. The complete power system designs for the HS 376 series of spacecraft have been described earlier (ref. 5, 6).

DATA BASE AND PARAMETERS

The data base used in the analysis consisted of telemetered data from batteries in operational satellites. It included data on forty batteries on twenty satellites comprising ten different programs. The longest operating time was 16 eclipse seasons, or 8 years. All batteries were trickle charged. The battery cell sizes ranged from 6 to 24 A-hr, and were all procured from General Electric. All cells were of the second-generation type.

The measure of battery performance used was average cell voltage at end of discharge during the longest eclipse each season. The end of battery life is taken to be the time when this voltage drops below some specified value.

The design and operational parameters that appear in the final model are: depth of discharge, eclipse temperature, trickle-charge rate, electrolyte loading, and time in eclipse seasons. The minimum, maximum, mean, and standard deviation for these parameters are listed in table I. In addition, we also studied the effects of solstice (non-eclipse) temperature, discharge current, density, percent recharge, high charge rate, percent electrolyte, and cumulative depth of discharge.

METHODOLOGY

We selected, evaluated, and then modified a statistical model that employs multiple regression for use in predicting the life of nickel-cadmium in geosynchronous orbit satellites. Our goal was to obtain a model which provides good fit and predictive capability, for both the group of batteries and individual batteries.

A set of parameters thought to influence battery life was identified. Relationships between these parameters were examined by looking at correlations. This information was used in later stages to help select potential variables for use in the model.

All possible regression models with the selected parameters were examined (ref. 7), and several models were selected for further investigation. This selection was based on statistics that measure the models' ability to fit and predict observed phenomena well. The meaningfulness of physical relationships implied in the model was also considered. A reduced set of potential variables of interest was identified, and the process of model evaluation and selection was repeated.

Our initial set of variables was ten battery parameters, time, time^2, and time^3. Based on the results obtained by an iteration using these variables, a set of eight main effects and all first-order iterations of these eight main effects were selected for further investigation. This process was repeated several times. Two models were selected as final candidates. These two were than compared by investigating the following relationships: voltage versus number of eclipse seasons, battery life versus depth of discharge, and R(t) (probability of surviving at least t eclipse seasons). Judging from the standpoints of overall fit, fit to individual battery performance, prediction, and agreement with known battery characteristics, we selected a model. Variables not listed did not significantly reduce the amount of unexplained variation and therefore were not included in the model. Although those variables may have a significant influence on voltage, their effect in modeling is minimal, owing to their correlation with other variables used in the model. Addition of a variable correlated with another variable already in the model does not produce a significant reduction in unexplained variability.

RESULTS AND DISCUSSION

The selected battery voltage model is as follows.

$$\text{Voltage} = 1.12 - k_1 (D) + k_2 (D)E + k_3 (TCR) - k_4 (ET)\ TCR^2$$

$$- k_5 (D)T + k_6 (T^2) - k_7 (ET)\ (T^3),$$

where:

Voltage	=	Minimum end of discharge voltage, averaged for all cells in a battery
D	=	Depth of discharge in percent
E	=	Electrolyte in CC/A-hr
TCR	=	Trickle charge rate in A/A-hr
ET	=	Eclipse temperature in °F
T	=	Time in eclipse seasons
$k_1 - k_7$	=	Statistically determined coefficients (constants)

The value of the coefficients were, of course, derived in the analysis but are omitted here because of other considerations.

Figure 1 shows voltage as a function of time for all other variables set to their means. Symmetric prediction intervals are presented at the 99, 95, and 75 percent levels for a response (voltage) at a specified set of conditions. With a given confidence, we can say that a future observation will be within the specified interval.

It is important to note the large effect that depth of discharge has on voltage and consequently on battery life. The lower the depth of discharge, the longer the battery will last. (See figure 2.) This relationship follows our expectations. Similar results have been obtained for batteries on life test. The model also indicates that we could operate our batteries at a higher depth of discharge than is currently being done. An interaction of $D^{2.3}$ with time (from results obtained by previous Hughes battery research) was considered for inclusion in the model (ref 8). However, this relationship did not provide results as good as those obtained by using the interaction of D with time.

Temperature seems to affect the batteries late in life, as might be expected. We feel it is appropriate that eclipse temperature rather than solstice temperature appears in the model, since eclipse temperature was the temperature at the time the voltage measurements were taken. Also, this is a case where two variables closely correlate and therefore only one of them needs to be in the model.

These relationships can be used, within the ranges of the parameters, to design and operate nickel-cadmium batteries that will have increased longevity. Extrapolation beyond these ranges should be avoided for several reasons. 1) Prediction error increases with distance from the mean of the data. 2) This model may be not a true representation of the underlying relationships but rather a good approximation within the range of our data. By creating a model that is sound from an engineering standpoint, we have minimized this effect.

3) Regression assumptions may no longer be valid outside the range of the data. An example of this fact is the occurrence of shorts late in life, which affects prediction error and could violate the assumption of constant variance over time. 4) Main effects and interactions omitted from the current model may be more influential outside the range of data used.

Figure 1 shows prediction intervals about the regression line. The individual prediction lines can be used to estimate reliability versus time in the following way. First, note that the lowest prediction line is such that, for any given time, the voltage will exceed that value with 0.995 probability. Thus, for a given voltage and given probability, we can find the time which corresponds to the voltage and probability. For a fixed voltage, we can then construct a plot of probability versus time. The probability of exceeding a given voltage at a given time can be used as an approximation of reliability at that time.

Reliability versus time was investigated for voltage values of 0.90 to 1.10, because required voltage may vary, depending on specific satellite requirements. The probability that voltage, as defined in the model, is above the minimum requirement of 1.00 is 1 for the number of eclipse seasons less than or equal to 23. This probability value was obtained from a relationship relating reliability to prediction intervals, as described above, when all variables except time are set to their means. At voltage = 1.05, the reliability is 1 for 20 eclipse seasons, and then drops quickly. This is illustrated in figure 3a. When voltage = 1.10, this drop in reliability occurs sooner, after 17 eclipse seasons. (See figure 3b.) These results correspond quite well to currently accepted estimates of mean battery life as being on the order of 12 years. In addition, these results agree favorably with mission duration and design lives of 7 to 10 years.

The R^2 value for this model is 0.68. Although not as high as we would have liked, it is a good value, given that the model uses actual orbital data and is not a controlled laboratory study. A designed, controlled study has certain advantages. It can highlight situations that occur late in life, by increasing the duration of the test; it can make predictions over a wider range by controlling the levels that parameters of interest take on; and it can study specific interactions. However, results obtained from controlled laboratory environments are sometimes critized for being unrealistic or inappropriate. A model based on orbital data has the advantage that the batteries have been operated in a real environment.

One use of the model is to predict the performance of the new third-generation cell designs now with limited (up to five seasons) orbital experience. The new HS 376 design improvements include increased electrolyte quantity, lower operating current density, and lower operating temperatures. This work is still in progress.

The most prudent conclusion that can be drawn thus far from these results is that the HS 376 batteries can easily meet their design goal of 10 years at 50 percent DOD, since they are an improvement over those analyzed here.

For a prediction at the 65 percent DOD extreme of the data base, a different statistical approach should probably be used.

The data base includes data on two batteries on two different satellites, having two shorted cells each. All four shorts occurred late in life and caused complete loss of voltage in the four cells. The remaining cells are functioning as expected, in view of the additional loads being imposed on them. The fact that the data base included shorts which occurred late in life had a strong effect on the model, making the $time^3$ term more significant. (Note, however, that in our earlier paper (ref. 9), the $time^3$ term was also present, and there were no shorted cells in the data base at that time.)

Because the effect of shorts is included in the voltage model, it is included in the reliability plots as well. This has important implications for reliability analysis as practiced in reliability engineering. The cell short failure mode has been treated as having a constant failure rate. However, this treatment may now be inappropriate in view of the fact that the shorts occurred late in life. Future reliability analysis should address this matter.

The model is derived from aggregate data on a large number of batteries. In such cases, the resulting model often fails to accurately predict the performance of an individual member. However, as shown in figures 4 and 5, our model does accurately predict the voltage versus time of individual batteries. (Fluctuations in voltage, both for actual and predicted values, are explained by adjustments to depth of discharge.) These plots of actual versus predicted voltage are typical of the fits which were obtained. Figure 5 shows the model's fitting of the performance of a battery experiencing two shorts at the sixteenth eclipse season. Since some batteries at this time had shorts and others did not, the model tends to overpredict voltage in the presence of shorts. When shorts occur, depth of discharge is reduced at the ground station to increase remaining life. This fact explains the increase in predicted voltage at the sixteenth eclipse season.

CONCLUSIONS

The model described in this paper has many important features. First, it fits the orbital data and provides accurate predictions. (Although the fit to the data is not as good as one typically sees with laboratory data, we feel the model is more realistic, being based on orbital data.) It is a useful tool in designing and operating batteries for longer lives. The effect of shorts has been included, making this model more complete than its predecessors. Finally, the model predicts that a typical second-generation battery will last well beyond ten years. We believe that a typical third-generation battery could last even longer. This is true even at depth of discharge levels higher than those presently used.

Hughes intends to update this analysis periodically.

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Table I
Summary of the Data Base

Variable	Unit	Minimum value	Maximum value	Mean value	Standard deviation value
Average cell voltage	volts	1.08	1.23	1.18	0.018
Time	eclipse seasons	1	16	6.6	3.8
Depth of discharge	%	24	62	43	8.0
Electrolyte	cc/A-hr	2.9	4.2	3.2	0.31
Eclipse temperature	°F	50	66	55	3.1
Trickle-charge rate	A/A-hr	C/62	C/36	C/50	-

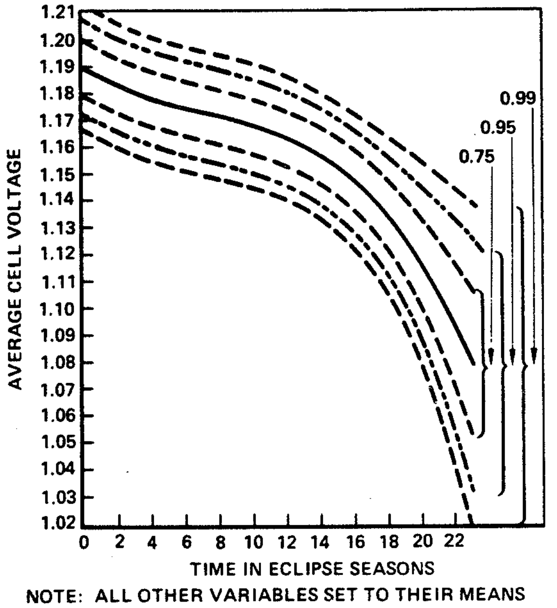

Figure 1. Voltage versus time.

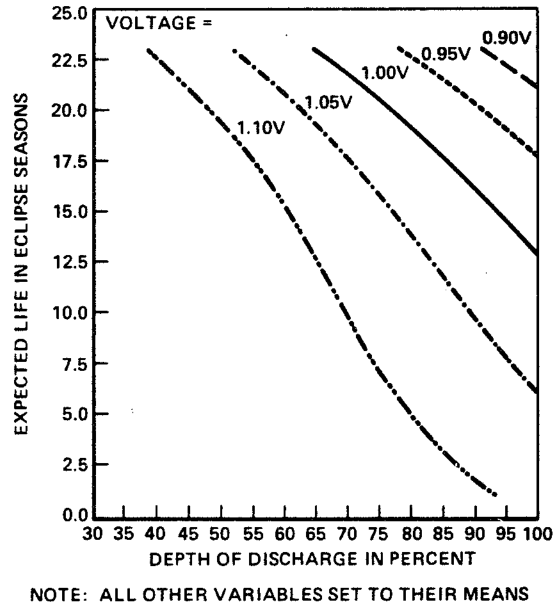

Figure 2. Expected life versus depth of discharge.

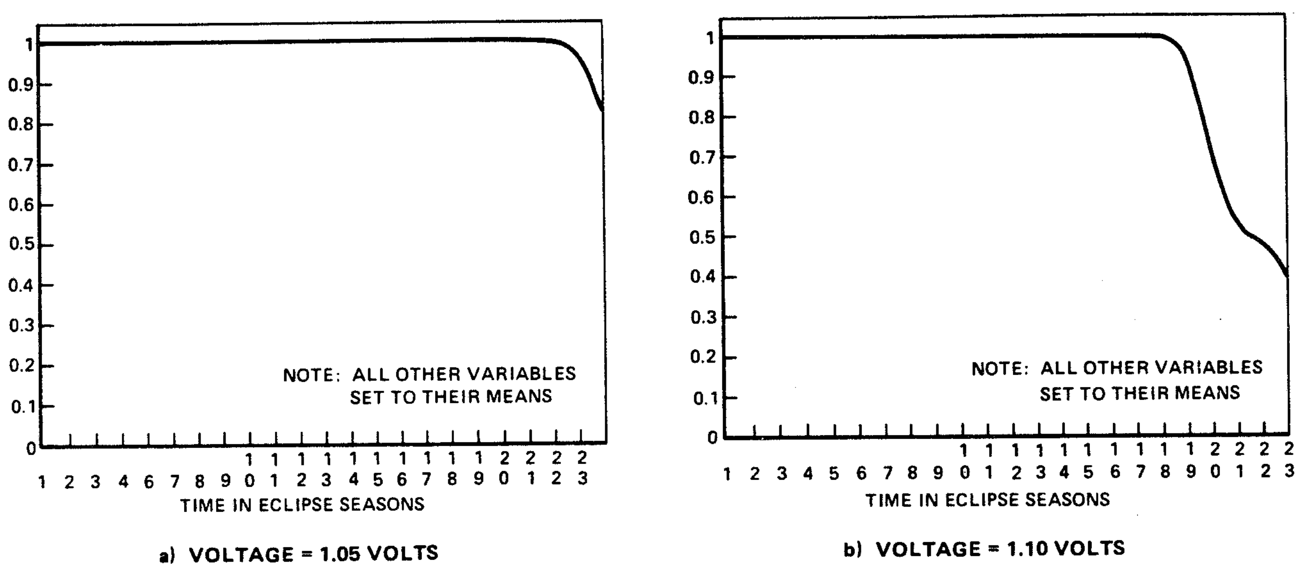

Figure 3. Reliability versus time.

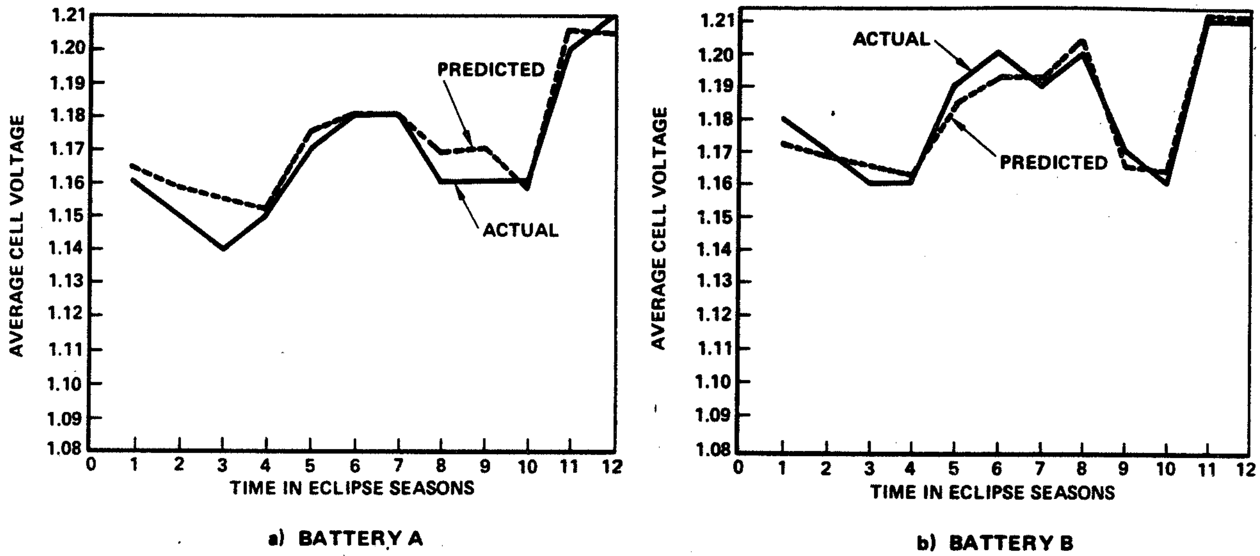

Figure 4. Voltage versus time for typical batteries.

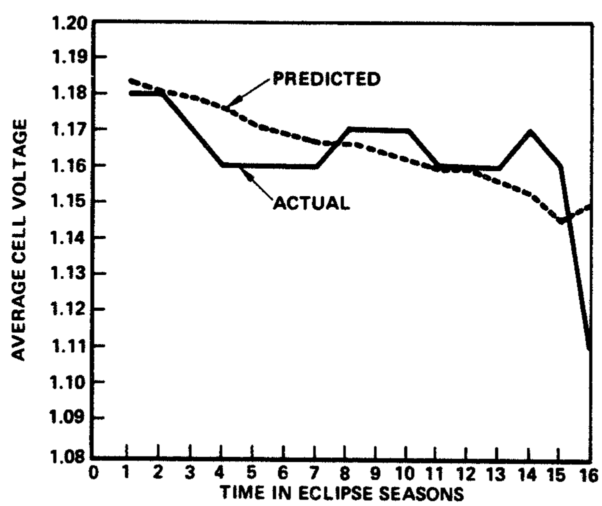

Figure 5. Voltage versus time for a battery containing two shorted cells.

Q. Unidentified: Did your survey include the launch handling of batteries at all or is this after launch life?

A. Broderick, GTE Satellite Corporation: No this was just data. I would assume that many of these test points that in orbit performance would include integration and test.

Q. Unidentified: Some of them like you mentioned TRW do not use flight batteries for integration testing?

A. Broderick, GTE Satellite Corporation: Okay, it never has been. Ford I think has presented information before that he thinks that in orbit or integration in test will age at about twice the rate of in orbit performance. So if you assume 3 months of integration and test double that then you might lose 6 months of performance on the ground.

Q. Unidentified: Did you include anything like the differences of the depth of discharge during reconditioning in orbit?

A. Broderick, GTE Satellite Corporation: What I've assumed is that all of these will be deep discharge reconditioning and that is one of the reasons why we've been able to make such improvements on life.

Q. Rogers, Hughes Aircraft: You emphasized that the newer MOS devices used have lower internal resistance have lower voltage drive than the older ones.

A. Sullivan, APL: Yes, that's right.

A. Rogers, Hughes Aircraft: That may be the particular devices but that's contrary to normal devices.

A. Sullivan, APL: Contrary to normal devices?

A. Rogers, Hughes Aircraft: In other words, for the same area or same weight device chip you'll get considerably lower resistance in a newer device and that is not what you want.

A. Sullivan, APL: Well all I was referring to is the older transistor which they had like 6/10 of a volt drop silicon devices as compared to the newer devices that we look at. I was looking at like 2/10th's of an ohm resistance in their on-stage.