

ANALYTICAL MODELING OF BATTERY CYCLE LIFE

SIDNEY GROSS

Boeing Aerospace Company, M S 8W-08, P O. Box 3999, Seattle, WA 98124 (U S A)

Summary

An analytical model has been developed for battery life relating wear-out processes, depth of discharge, and cycle life. The model has been tested against existing nickel-cadmium cycle life data and gives good correlation over the range 20 - 50% depth of discharge. Insufficient test data are available to evaluate the model at very low and very high depths of discharge.

Introduction

Considerable emphasis has been applied in recent years to the use of statistical approaches to the correlation of battery cycle life data [1 - 16]. That approach can be useful, but it has some important limitations. Statistical approaches operate on the premise that nothing is known about the causes of failure, and so the equations that are developed may have little relationship to the physical and chemical processes affecting battery wearout.

In this study, a physical model has been hypothesized for battery wearout and failure. An analytical model has been developed relating wear-out processes, depth of discharge, and cycle life, and the model has been tested against existing cycle life data. Good correlation has been obtained, giving credence to the developed model.

The major assumption made is that battery cells in a cycling regime gradually lose capacity until the remaining capacity is insufficient to support the required discharge. For those cells which fail more abruptly, it is assumed that processes which are severe in degrading cell capacity are equally severe in accelerating abrupt failures such as shorts, therefore making this approach useful for most cell failure modes. Further, it is assumed that battery wearout consists of time-dependent chemical degradation, plus physical damage caused by cycling.

Results and discussion

The following nomenclature is used in this analysis:

D = depth of discharge as a fraction of total initial capacity. Note that

actual initial capacity, typically, is approximately fifteen percent higher than rated capacity.

N = number of cycles to failure, typically defined as failure to sustain a voltage minimum, e.g., 1.0 V for Ni/Cd, but it also includes other failure criteria. (Note that time could also be used as the dependent variable instead of cycles.)

a = Coefficient of chemical degradation, capacity fraction loss per cycle.

b = Coefficient of cycling degradation, capacity fraction loss per unit of cycling capacity.

Assuming a cell of unit capacity, the capacity required to maintain cycling is D . The remaining, unused capacity is $1 - D$, and the battery cycle life will be reached when the amount of capacity degradation reaches $1 - D$. The capacity loss by chemical degradation will be aN . The capacity loss by cycling damage will be bND . Thus, total capacity loss is

$$1 - D = aN + bND \quad (1)$$

The coefficient b may be considered to be a function of D . Thus, the general expression may be given as

$$1 - D = aN + bND^m \quad (2)$$

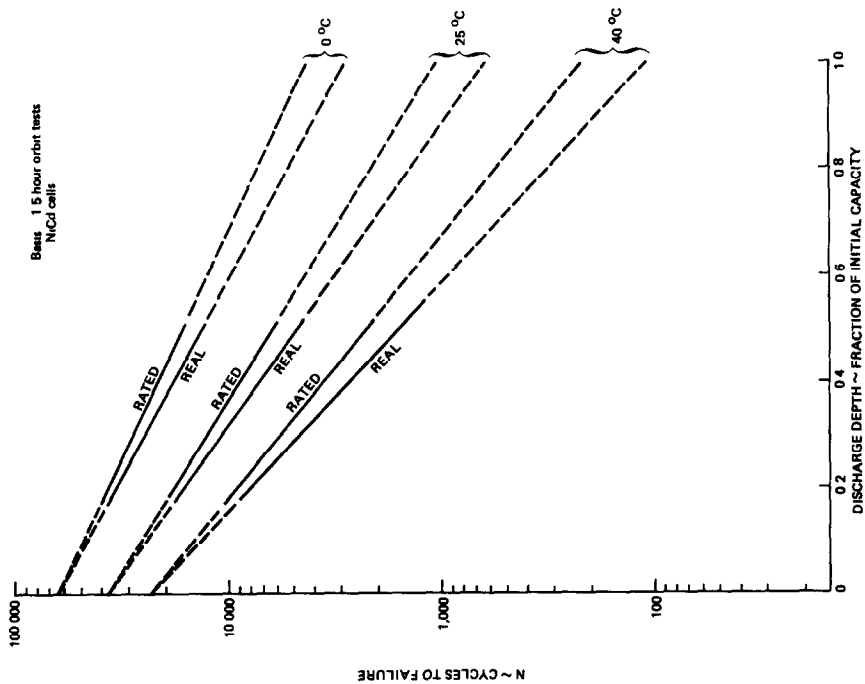
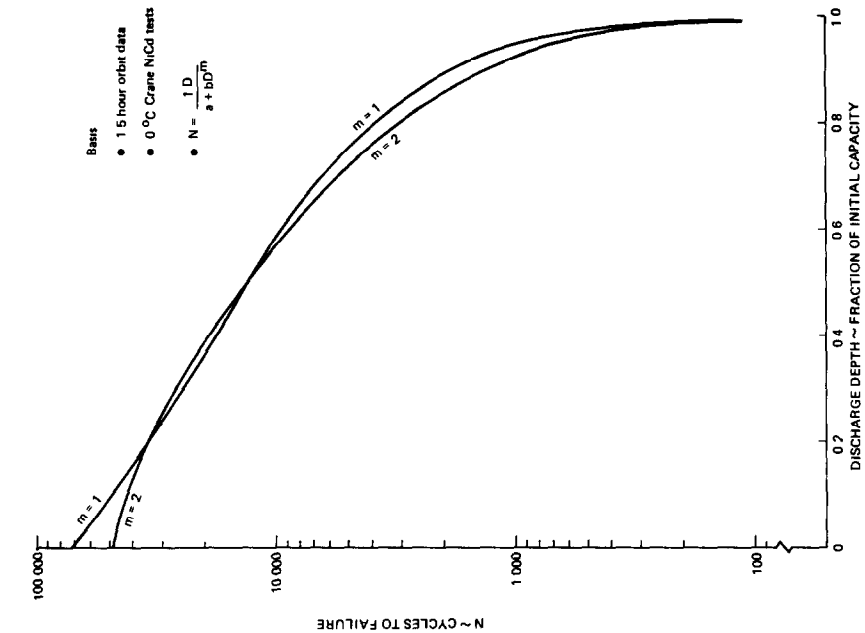
With b independent of D , then $m = 1$, with b proportional to D , then $m = 2$, other relationships may also be considered. This equation then reduces to

$$N = \frac{1 - D}{a + bD^m} \quad (3)$$

This analytical model was applied to cycle life data obtained from NAD Crane tests [2]. The cycle life data are shown in Fig. 1. Depth of discharge data reported for the Crane tests were based on the rated capacity of the cells. However, this analytical model is based on real capacity values, thus requiring a correction. It has been assumed that the real capacity initially was fifteen percent greater than the rated capacity in the Crane tests. This adjustment has been made to the cycle life/capacity data, and is shown in Fig. 1.

The effects of the exponent m are shown in Fig. 2 for the 0 °C test data. Cycle life is greater at very low and very deep depths of discharge for $m = 1$ than for $m = 2$. In the mid-discharge region, from $D = 0.2 - 0.5$, where all the test data are obtained, the data can be fitted with either exponent. For subsequent analyses, m was taken to be 2. These correlations are given in Fig. 3 for the data of 0, 25 and 40 °C. Good fits of the data are obtained over the range of the test results. Lack of data at very small and very large depths of discharge limits the precision to which the analytical model can be defined.

In attempting to analyze for the effect of temperature, it was found that the effect of elevated temperature was complex. Cross plotting in Fig. 4 some of the Fig. 1 data shows that high temperature (40 °C) has a greater



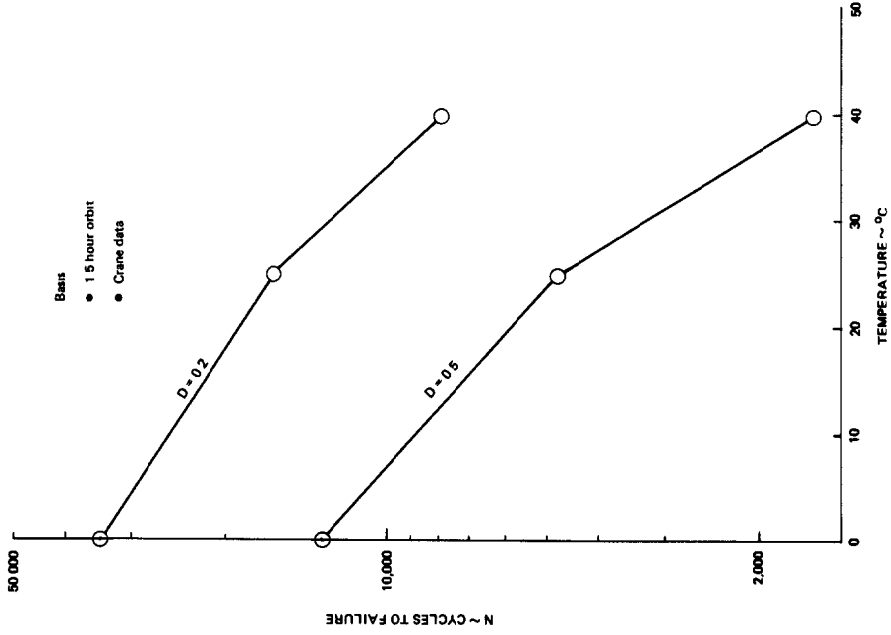


Fig 4 Effect of temperature on Ni-Cd cycle life

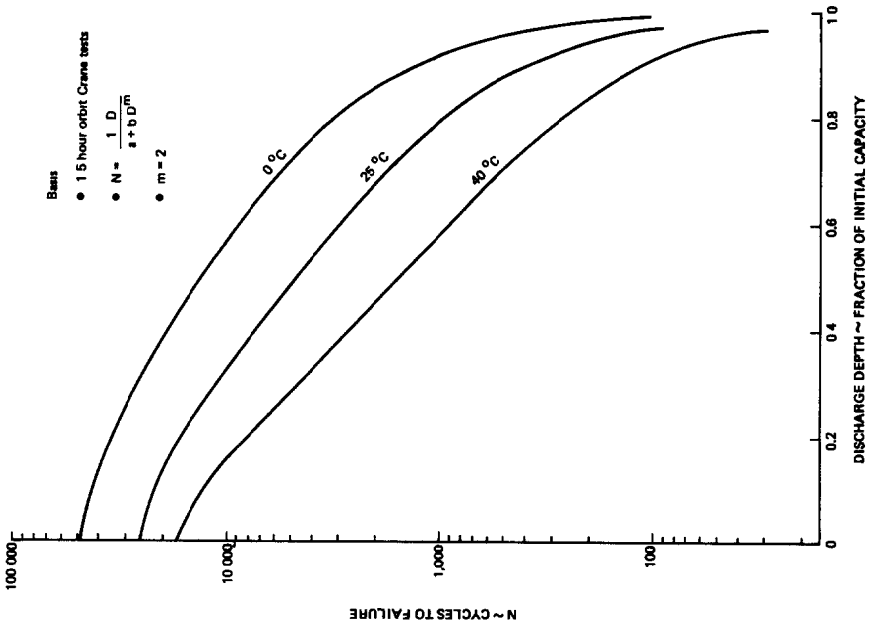


Fig 3 Ni-Cd cycle life analysis.

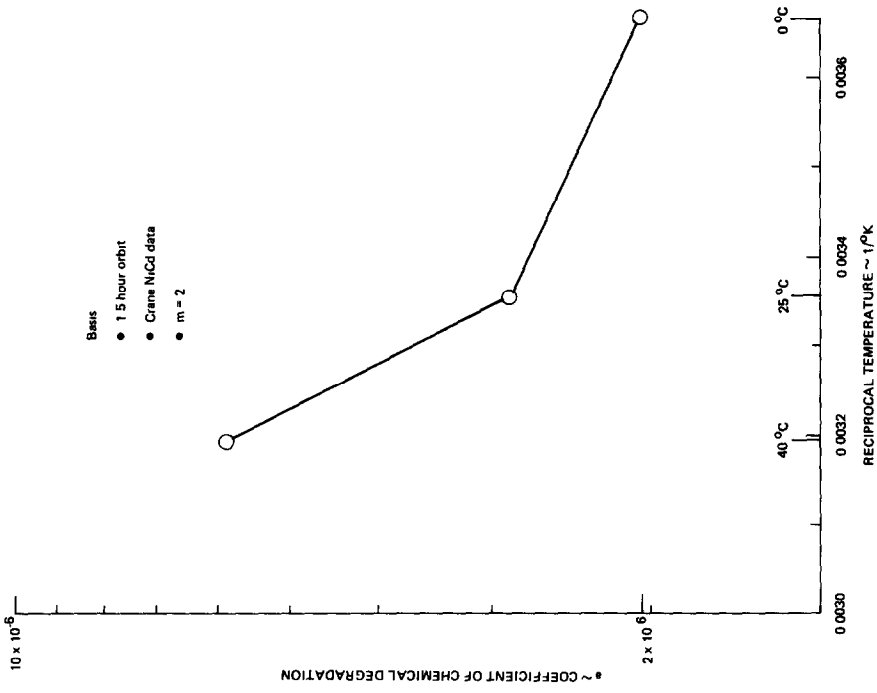


Fig 5 Calculated coefficient of chemical degradation

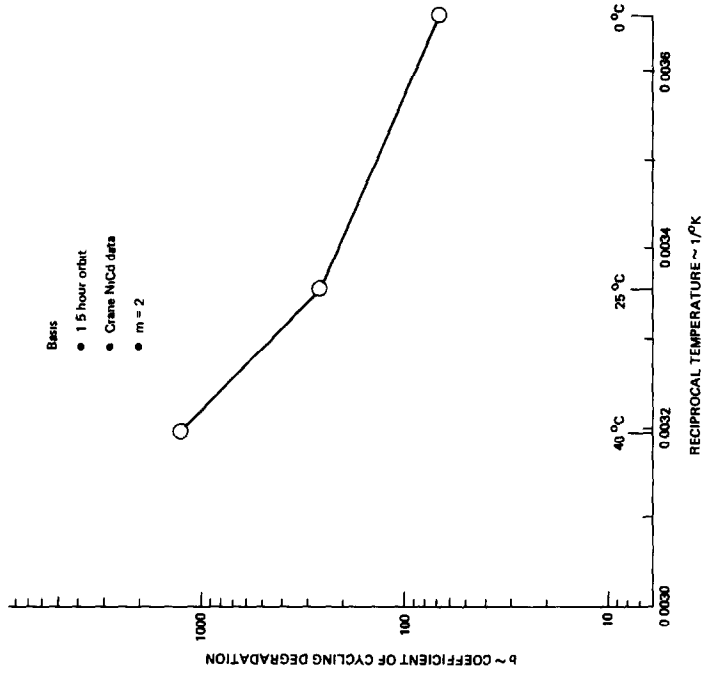


Fig 6 Calculated coefficient of cycling degradation

effect at $D = 0.5$ than at $D = 0.2$. Different slopes are also observed at low temperature from those at high temperature, suggesting that the set of degradation reactions at high temperature differs from the set at low temperature. This is also shown in the Arrhenius-type plots of Fig. 5 for the coefficient of chemical degradation, a , and in Fig. 6 for the coefficient of cycling degradation, b . Barring the possibility that the experimental data are in error, it is apparent that different degradation processes are operating at high temperature from those at low temperature. This places important limitations on the use of elevated temperature for the acceleration of battery cycle life. Any use of high temperature for accelerated testing should take these changing processes into account.

Because cycle life can be correlated with depth of discharge, the assumption is customarily made that discharge is the event that brings about failure. Since each discharge is followed by a charge and an overcharge, it is quite possible that the charge and overcharge are significant contributors to cell wearout and failure [17]. It is known that charging exerts an important influence on battery life, but actual data are quite limited.

Analytical relationships can be developed similar to those of eqns (1) - (3), based on the assumption that the wearout and failure are due to charge rather than to discharge. If the assumption is made that the degradation rate is related to the amount of active material charged, then the results will be similar to those given here for degradation caused by discharge. Degradation related to charge rate, overcharge rate, and overcharge amount will require different analytical representation, but can be developed along the lines given in this paper.

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