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Accelerated life cycle testing and analysis for early failure prediction using two types of lead/acid batteries

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Abstract

A sample of 12 small, single cell, lead/acid batteries from each of two manufacturers was subjected to continuous charge–discharge cycling at 50 °C. Reduction of battery capacity to 60% of the manufacturer's rating was the failure criterion. Cycles-to-failure data followed a Weibull distribution, indicating wearout as the failure mode. A Weibull characteristic life of 93 and 580 cycles was found for the cylindrical and flat plate batteries tested, respectively. An early way to detect an inferior battery from among batteries of the same type is suggested. It was found, using an early cycle, that a cell with a comparatively low voltage at end-of-discharge is relatively likely to fail earlier than other batteries of the same type.

Introduction

Information is generally available from manufacturers concerning the expected life, under specified conditions, for batteries of a specific make and model. Battery users, under some circumstances, also find it useful to know which batteries, from among batteries of the same model, are likely to fail first. This study was undertaken to try to find, early in a battery's life, a simple indicator of its potential for early failure, relative to other batteries of the same make and model.

Only the small, sealed, recombinant lead/acid batteries that are gaining acceptance as uninterruptable power supplies, particularly for electronic equipment, were investigated. Two specific models of single-cell batteries were selected and subjected to accelerated cycle life tests. The first was a 'D' size single cell battery with a cylindrically wound plate and a manufacturer's rating of 2.5 A h. The second was a flat plate single cell battery rated at 3.2 A h by the manufacturer.

The cycle life of the batteries was determined by continuous charge–discharge cycling at elevated temperature until cell capacity was reduced to the arbitrary failure criterion.

Experimental

The test program was designed to determine the characteristic cycle lives of the selected batteries in a short time using a limited number of sample batteries. A group

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of 12 batteries from each manufacturer was used. A continuous series of charge–discharge cycles was performed at elevated temperature to accelerate the testing.

The batteries with the cylindrical plate were tested first and will be referred to as battery D henceforth. The details of the testing procedure and the results of these tests have been reported [1]. Briefly however, the batteries were electrically connected so that their current and voltage during charge and discharge could be controlled and monitored. The time duration of charge and discharge was controlled using an IBM PCXT computer and Keithly System 570 software. The batteries were tested in a temperature controlled cabinet which was maintained at 50 ± 0.3 °C. This temperature was selected because of the strong acceleration effect of testing at 50 °C. A cycle life acceleration factor of from 2.1 [2] to 2.6 [3] has been found for lead/acid batteries at this temperature. Charging was for 8 h. The constant voltage charger was manually adjusted so that the voltage at the battery terminals at the end of the charging process exceeded 2.32 V to assure a full charge to the batteries. No difficulty was experienced using a constant voltage charge and no gassing was detected.

After the charge phase, the batteries were placed on open circuit for 24 min and were then switched to the discharge phase. Discharge was through adjustable resistors which were manually set at the fixed resistance to provide the desired average current during the discharge phase. The discharge current was adjusted so that the D batteries delivered 1.08 A h during the 1 h discharge period. This is 60% of the manufacturer's nominal rating of 1.8 A h capacity at the 1 h discharge rate [4]. The discharge current for the flat plate batteries, henceforth to be denoted as the S batteries, was set so that they delivered 1.30 A h during the 1 h discharge period. This is 60% of the manufacturer's maximum nominal rating of about 2.1 to 2.2 A h for a nominal 3.2 A h rated battery [5]. Whenever the output of any battery dropped below 1.9 V for several cycles, the cycle at which the battery voltage first dropped to 1.9 V was recorded and the battery was removed from testing. The batteries were placed on open circuit for 3 min at the end of the 1 h discharge period and were then returned to charge to continue the charge–discharge cycling.

Data were collected at 6 min intervals during charge and at 30 s intervals during discharge. These data, which include current and voltage at each interval, were collected for each cycle for each battery and stored in digitized form on diskettes.

Results and discussion

Each set of 12 batteries was subjected to continuous cycling. It was found that the voltage at the end of discharge increased for the first few cycles. This was probably due to the known increased effective surface area which occurs during cycling in very early battery life [6]. When, during cycling, the output of any battery fell below 1.9 V at the end of the discharge process, the testing was terminated for that battery within a few cycles and the cycle at which the battery fell below the 1.9 V limit was recorded as the cycle of failure. This is the condition at which the battery can no longer deliver 60% of its 1 h rated capacity with at least 1.9 V output. Use of this voltage criterion for battery failure was arbitrary and is more restrictive than that used by the battery manufacturers in their ratings. However, batteries have little additional capacity to the lower discharge voltage limits used by the manufacturers. Selection of the high value for the cutoff voltage at discharge was made to leave the batteries in relatively good condition for subsequent testing.

Some of the batteries tested had such a gradual loss in capacity that they were never cycled to failure and were performing with little decrease in capacity at the end of testing. This is illustrated for one of the S batteries in Fig. 1. In this Figure, the 4th charge–discharge cycle is shown superimposed on the 581st charge–discharge cycle for this battery. During the charging phase, data was taken every 6 min for 8 h for a total of 80 data points. During discharge, data was taken every 30 s for 1 h for a total of 120 data points. The voltage increase shown during charging is due to a solid state switch in the charging circuit that has sufficiently high resistance that it slightly reduces the battery voltage at high charge currents. The battery charge voltage is seen to increase and level off as the battery approaches the fully charged state and the charge current approaches zero. The intermediate voltages shown between the charge and discharge processes indicate open circuit.

The charge–discharge cycling was continued until 11 of the 12 D batteries and 8 of the 12 S batteries met the previously discussed failure criterion. Each failure was converted into percent failed and the cumulative number of failures for each type of battery is plotted against the number of cycles to failure in Fig. 2. The scales selected for Fig. 2 allow Weibull statistical analysis of the experimental results to be obtained directly from the graph [7]. The Weibull distribution is an empirical, flexible distribution widely used in reliability analysis. Readers not acquainted with this distribution may consult any of a number of reliability treatises, among them Nelson [8], Martz and Waller [9] and the above cited ref. 7. Its use in analysis of battery test results was suggested in studies published by the Electric Power Research Institute [10]. A straight line was drawn passing closely through the first 9 failure points for the D batteries and another straight line was drawn passing closely through the last 7 failure points for the S batteries. The fit of the above points to the straight lines indicates that these failures closely follow a Weibull distribution. The points not lying on these lines will be discussed later. These lines intersect the 63.2% failed line at 93 cycles for the D batteries and 580 cycles for the S batteries, indicating a Weibull characteristic life of 93 cycles for the D batteries and 580 cycles for the S batteries. The steep slope of the lines indicates a high value for the Weibull shape parameter β. Both batteries

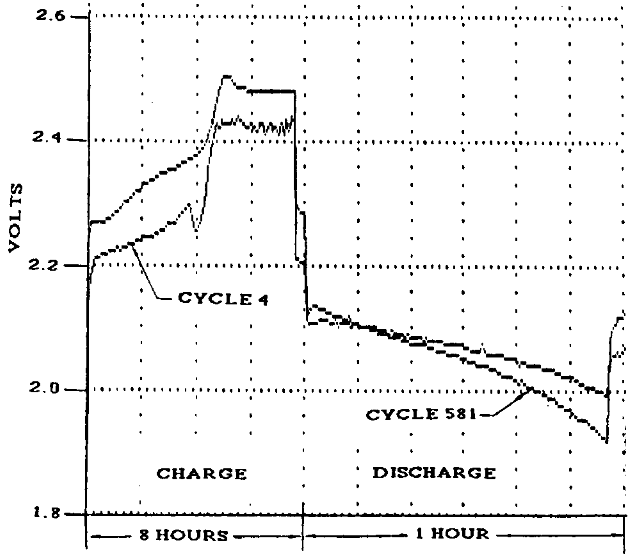

Fig. 1. Comparison of the 4th and 581st charge–discharge cycle for a well-performing S battery.

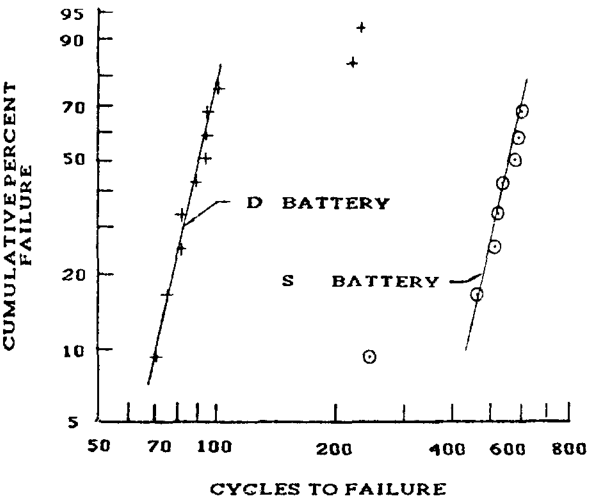

Fig. 2. Weibull plot of cycles to failure for D and S batteries.

are seen to have approximately the same shape parameter. The steep slope indicates that wearout is the probable failure mode and that wearout typically occurs in a narrow range. The calculated standard deviation in cycles to failure was 8.4 for the D batteries and 10.4 for the S batteries.

The point of failure of the first S battery to fail fell well below the straight line that fits the subsequent points well. This suggests that this battery does not meet the quality standards of the population of this type battery.

We were interested in seeing if any connection existed between low end-of-discharge voltage in early cycles and subsequent failure during cycle testing. Two questions arose regarding a connection between the voltage data and the life data. First, do the voltage data follow a well-behaved statistical distribution, such as the normal (or Gaussian) distribution, and if so, do outliers from the distribution exhibit unusually long or short cycle lives? Second, within the context of a well-behaved statistical distribution, is there any correlation between the early cycle voltage and cycle life? The fourth cycle was selected as the basis for early cycle data. The voltage of each battery at the end of the fourth cycle discharge was listed and scaled using the relationship $(V-1.990)\times 1000$ for the D batteries and $(V-1.996)\times 1000$ for the S batteries, where V is the end-of-discharge voltage. The selection of the values 1.990 and 1.996 was arbitrary and was made purely for convenience in interpreting the resulting plot. These scaled voltages are plotted on the vertical axis versus normal probability coordinates on the horizontal axis of Fig. 3. The choice of plotting points on the probability coordinates follows the recommendation of Kimball [11], as reported by Martz and Waller [9]. If the battery voltages are ranked in ascending order, the plotting point for the 'ith' battery out of a total of N samples is:

$$P=1-\frac{N-i+0.625}{N+0.25} \qquad (1)$$

Here the total sample size is 12.

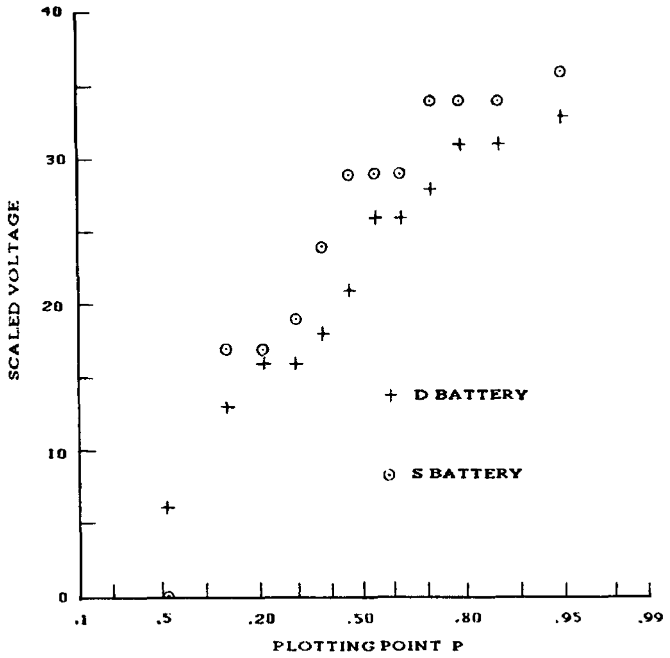

Fig. 3. Distribution of scaled fourth cycle voltages for D and S batteries.

Analysis of the data using Liliefor's adaptation of the Kolmogorov–Smirnov test [12] shows the normal distribution is a reasonable model for the voltage data. The maximum difference between the calculated value of the cumulative normal distribution, using the sample means and standard deviations as the normal distribution parameters, and the empirical distribution drawn from the data is 0.105 for the D batteries and 0.150 for the S batteries. At the 0.1 level of significance, the maximum expected difference is 0.223 between the calculated cumulative normal distribution and the empirical distribution for a sample size of 12, suggesting the normal distribution is a reasonable model of the data. However, the lowest S battery voltage does appear to be an outlier from the rest of the sample. An analysis for detecting outliers from a normal distribution results in a value, at the 0.1 level of significance, of 0.49 for Dixon's critical parameter [13]. The lowest S battery voltage produces a value of the critical parameter of 0.50, supporting the view that the lowest S battery voltage is an outlier. The battery having a voltage lower than the normal distribution on the fourth cycle was also the first battery in its group that failed. The failure of this battery occurred earlier than expected and was outside the range of prediction of the Weibull distribution of failures of the rest of the S batteries.

In addition to the failure described above, other correlations to early failure and low voltage at the end of the fourth cycle discharge were observed. The S battery with the second lowest voltage at the end of the fourth cycle discharge was the second S battery to fail and the D battery with the lowest voltage at the fourth cycle was the first D battery to fail. The two remarkably long-lived D batteries had fourth cycle end-of-discharge voltages that were in the normal distribution but were not the highest.

Conclusions

Twelve samples each of one model sealed lead/acid battery from each of two manufacturers was subjected to life cycle testing at 50 °C. The characteristic Weibull cycle life at this temperature was found to be 93 cycles in the case of the cylindrical or D batteries and 580 cycles for the flat plate or S batteries. Different values for cycle life would be expected at other temperatures. Low voltage at the end of discharge in the fourth cycle was found to be indicative of early battery failure. In particular, an 'outlier' voltage at the end of the fourth cycle may indicate that a battery will fail unusually earlier than others from the same group.

Users may find this information valuable for doing relatively quick quality sampling inspections of a battery population, considering a battery to have failed inspection if it has a low outlying fourth cycle voltage. Users looking for consistently reliable batteries might want to cycle a number of samples from several suppliers and choose those suppliers whose products showed the most tightly distributed fourth-cycle voltages and had minimal outliers.

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