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An analysis of float service life test data of VRLA batteries

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Abstract

This paper describes a statistical method for analyzing data from float service life tests of VRLA batteries. The purpose of this work was to develop a model with the following characteristics. First, it would allow test data from different batteries and test conditions to be pooled, as long as they were from the same design. Secondly, it would provide estimates at discharge rates other than the ones actually used in the test. Finally, it was desired for the model to be able to predict the time to various capacities of interest to a better resolution than the typical 3–5 years to 80% (of rated) capacity given by the battery manufacturers. The batteries in this analysis are valve regulated lead acid (VRLA) types, ranging in capacity from 4 Ah to 17 Ah, from two manufacturers. The float service life of a battery will be divided into two distinct time periods. The first being that time, from the beginning of the test, when the capacity of the battery is relatively constant. The second period is defined as that when the battery capacity begins to decrease much more rapidly until end of life is reached. © 1998 Elsevier Science S.A. All rights reserved.

Keywords: VRLA battery; Lead acid battery; Float service life

1. Introduction

Almost all uninterruptible power supplies (UPS) now use VRLA batteries to provide backup power to the load during utility outages. In low to medium power UPS ($\leq$ 18 kVA) the batteries used are typically in the 4 Ah to 17 Ah range which are the ones evaluated here. Because of the relatively low cost of the UPS and battery in this power range, it is usually not economical to purchase and install a battery monitoring system of the type and capability now available for very large battery installations. Without the monitoring, a UPS user is more likely to unconditionally replace the battery after a specified time period. One factor, then, in selecting a battery is the actual float service life (as opposed to prorated warranty life) and the consistency of this life. With this information more realistic projections of the useful life of a battery can be made which in turn may result in longer replacement periods. The method described here has some important applications in support of this effort. Some of these are evaluating warranty policies, optimal replacement times/stocking of spares for large users, and comparison of batteries from different manufacturers.

There are two different lifetimes associated with VRLA batteries, cycle life and float service life. The application of the battery determines which of these two will predominate and ultimately determine the useful life of a battery. Examples where cycle life would define the battery life are portable power tools and video cameras with VRLA batteries. In all but the most extreme UPS applications, float service life is the one which determines the usable life of the battery. Here the battery is (usually) being continuously charged (i.e., on float) and discharges are typically infrequent and usually not too long in duration. That is, the battery rarely experiences a discharge of 50% to 100% of its rated capacity. Data taken at Exide Electronics over a 3-month period indicate a power outage, of sufficient length to cause the UPS to switch to battery operation, occurred on the average of every 100 h. However, nearly all of the outages were under 5 s.

A good definition of float service life is that length of time, while on continuous float charge, until the battery capacity decreases to some specified percent of its rated capacity. Some factors associated with the battery (as opposed to those associated with the application) which effect or control float service life are grid design and alloys used, case material and thickness, arrangement of the cells in the case and specific gravity of the electrolyte. For completeness, plate thickness is probably not a major

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life determining factor in this evaluation since the batteries are first, not the long life telecommunications type and second, the discharge rates are usually > 1 C. Note that it is not the intent of this paper to discuss which, if any of these, are more significant or not in determining the float service life of the battery. This is better left to the chemists and materials scientists. Only observations and analyses made from actual float service life test data will be addressed here.

As reported by the manufacturers of these batteries, grid corrosion and dryout or loss of electrolyte are the two main mechanisms which govern float service life. Although there is some loss of electrolyte as a result of the corrosion process, according to Ref. [1] this should not significantly contribute to the end of life. Both failure mechanisms cause an increase in internal resistance of the battery which results in progressively shorter and shorter discharge times, hence lower capacity. One final factor which determines the float service life of a battery is the discharge rate used in the test or in the actual application. In general, the higher the discharge rate, the shorter the lifetime. Discharge rate will be used as a variable in this analysis.

2. Origin and description of test data

The float service life test data was obtained from two battery manufacturers plus another UPS manufacturer who had performed life tests on the same families of batteries. [1] All of the tests were conducted at either 40°C or 50°C. The times on test were normalized to 25°C using the Arrhenius relationship,

$$t_{25} = t_T \left(2^{\frac{T-25}{10}} \right) \qquad (1)$$

where: t_{25} = time at 25°C; t_T = time at temperature T; T = test temperature in °C.

In order to combine the test data from several batteries of different ampere hour ratings, the discharge capacities were normalized. The number of batteries used in each test varied between two and five. At each discharge the capacities obtained were averaged and this average was divided by the largest capacity obtained, by a single battery, at any time during the test. This average relative capacity can be expressed in the following form

$$\mathrm{rel\,cap}_{\mathrm{avg}} = \kappa_i = \left[\left(\Sigma_{j=1,n} C_{ij} \right) / n \right] / \max\{C_{ij}\} \qquad (2)$$

where n is the number of batteries on test, C_{ij} is the capacity of the of the jth battery from the ith discharge and $0 < \kappa_i < 1$.

Table 1
Rating (Ah), discharge rate, and test temperature, by manufacturer of batteries used in test

Manufacturer	Ah rating	Discharge rate	Test temperature (°c)
A	4	0.25 C	40
A	4	2.5 C	50
A	4	3 C	40
A	6.5	0.25 C	40
A	6.5	3 C	40
A	17	0.25 C	40
B	4	2.5 C	50
B	7	1 C	50
B	7	2 C	40
B	7	2.5 C	50

The batteries for which float service life test data was available are shown in Table 1, together with the manufacturer identification, discharge rate, and test temperature. The manufacturer is identified by the letters A or B. Specific life tests will be denoted in the text by, for example, A4-0.25C-40. Both manufacturers indicated their respective batteries in this table were all of the same design concept (or rules), materials and chemistry. Therefore, it would seem certain characteristics of their float service life behavior would be similar and hence, some general comparisons between the two manufacturers batteries could be made. This is the assumption on which this analysis is based.

3. Float service life model

The float service life of a battery can be characterized by two distinct time periods as shown in Fig. 1. The first is that period from the beginning when the capacity remains relatively constant. During this time whichever failure mode, loss of electrolyte or grid corrosion, will eventually dominate has yet to significantly effect the battery performance. Battery failures which occur during this period are generally due to defects in the manufacture of the battery as will be seen in some of the data. The second period begins when the capacity starts to decrease and continues until the battery reaches the end of its useable life.

There are some interesting questions which arise from studying the battery behavior during the second period of the battery life, when the capacity is decreasing. These are:

1. Do batteries from the same design or family lose capacity at the same rate?
2. Is there a significant difference in the rate of capacity loss between batteries from different manufacturers?
3. Is the rate of capacity loss related to a particular failure mechanism?

These questions will be addressed first.

Graphs of the time on float vs. relative capacity for the batteries in this study are shown in Fig. 2 for manufacturer

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[1] K. Virtanen, Battery Life Comparative Test, Unpublished report from FPS, 1995.

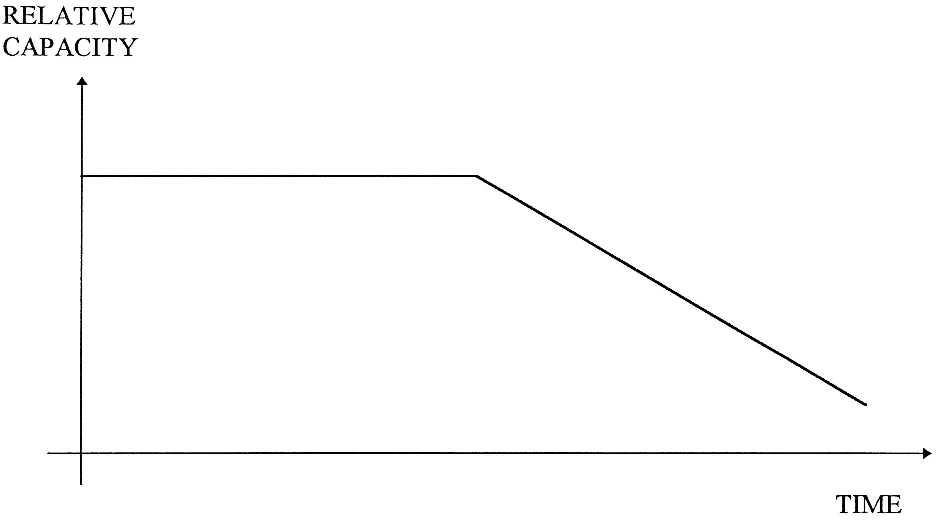


Fig. 1. Relative capacity over time of VRLA battery in float service.

A and B. Looking first at the graphs in Fig. 2a and b for the batteries from manufacturer A, it appears that in four of the six tests (3 different ampere hour batteries and 3 different discharge rates) the rate of capacity loss is similar. The two in Fig. 2b are also similar but distinctly different than the previous four even though the ampere hour ratings of the batteries and the discharge rates used are the same. The same observation of the similarity of the rate of capacity loss amongst batteries can be made for the float service life tests, in Fig. 2c, of the batteries from manufacturer B. Here also there are two different ampere hour rated batteries and two different discharge rates used. One supposition that can be made from these observations is that the rate of loss of capacity is independent of the discharge rate chosen or used for the float service life test. These observations are the basis for questions 1 and 2 above.

An attempt will be made now to quantify these observations in order to answer the questions raised above. As is evident from the graphs, the rate of capacity loss is not constant with time. Therefore, a first step in studying the second period of battery life is to find a setting where some representation of capacity is linear with the variable time. If the time on test, t, can be thought of as a random variable, then perhaps there is some distribution which will adequately describe, in some sense, the relationship between the normalized capacity and the time on test. Since the normalized capacity is decreasing with increasing time on test this idea can be expressed as

$$\mathrm{rel\,cap}_{\mathrm{avg}} = \kappa_i = \Pr\{t \le t_i\} = 1 - \Pr\{t > t_i\} \tag{3}$$

where t_i is the time on test and κ_i, $0 < \kappa_i < 1$ is the normalized relative capacity at the ith discharge. Or in other words, the normalized relative capacity at the ith discharge equals the probability that the time on test, t, is greater than t_i.

A good choice to represent the relationship given in Eq. (3) above is the extreme value distribution [2]. The probability density function (pdf) is given by

$$f(x) = (1/b)\exp\{((x-u)/b) - \exp\{(x-u)/b\}\}. \tag{4}$$

Integrating Eq. (4) with respect to x gives the survivor function,

$$S(x) = \exp\{-\exp((x-u)/b)\}. \tag{5}$$

Now the cumulative distribution function (cdf) can be obtained from the survivor function by

$$F(x) = 1 - S(x) = 1 - \exp\{-\exp((x-u)/b)\}. \tag{6}$$

Rearranging Eq. (6) and taking the natural log of both sides twice yields

$$\ln[-\ln(1-F(x))] = (x-u)/b. \tag{7}$$

Define the inverse distribution function, $F^{-1}(p)$, as

$$F^{-1}(p) = \ln[-\ln(1-F(x))] = \ln[-\ln(1-p)]. \tag{8}$$

Solve Eq. (7) for x and making the substitution indicated in Eq. (8), a linear equation for x in terms of the variable $F^{-1}(p)$ is obtained and is given by

$$x = u + bF^{-1}(p). \tag{9}$$

Before proceeding, recall from Fig. 1 the battery capacity does not necessarily start decreasing from the beginning of the test. This is the first period of the battery float service life. To accommodate this it is necessary to introduce a parameter, t_0, which represents the length of time of this period. This parameter can be thought of as a threshold or guarantee time. That is, prior to time t_0, the extreme value distribution is not defined. Continuing on define$C$: normalized relative capacity, $0 < C < 1$ and let

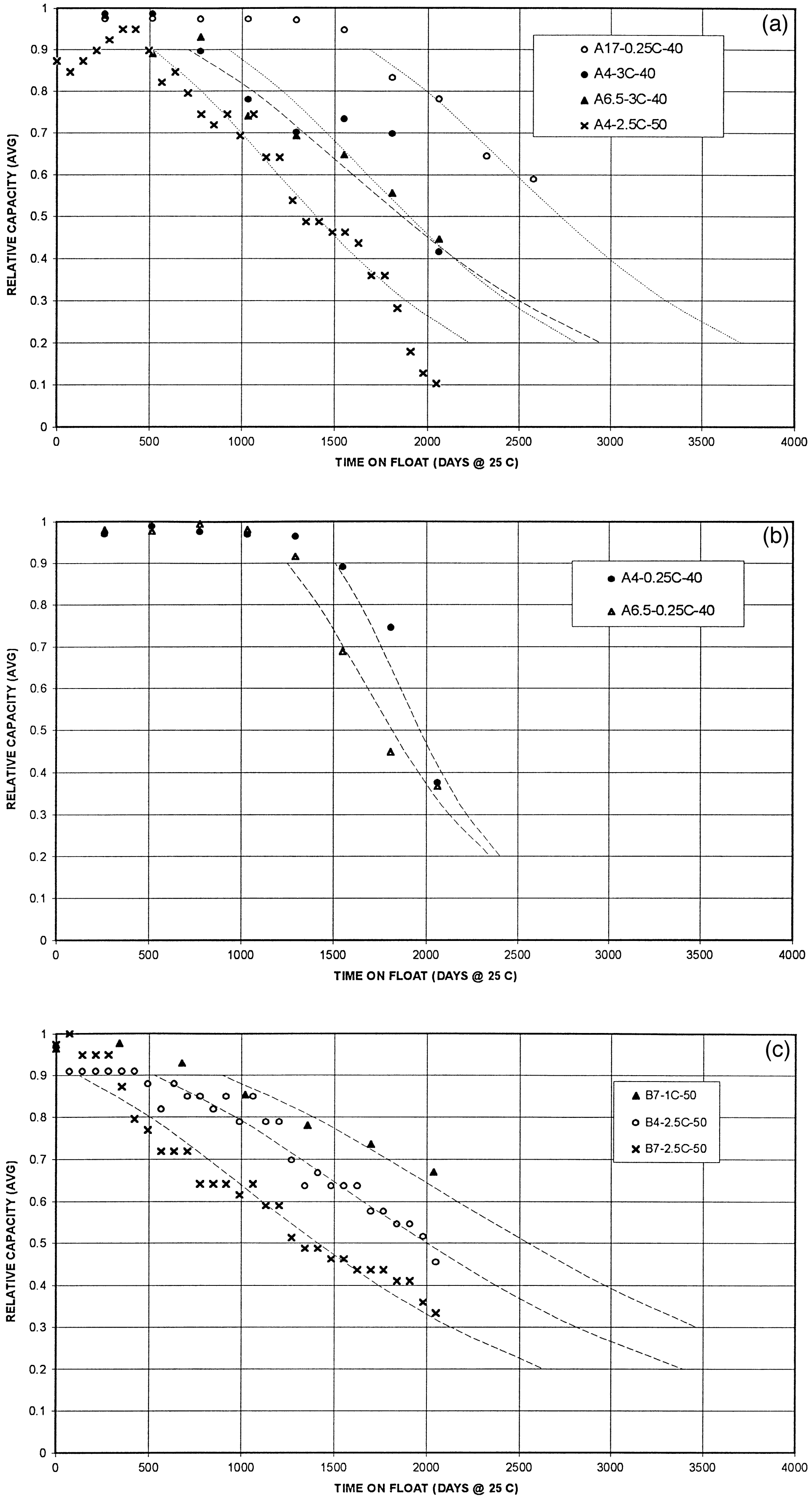


Fig. 2. Float service life test data from manufacturer A and B.

$x = t - t_0$, x, $t_0 \geq 0$ where t is the cumulative time on test. Finally substituting for x in Eq. (9) gives

$$t - t_0 = u + bF^{-1}(C). \tag{10}$$

Eq. (10) can be used to test the assumption that the second period of the battery float service life can be represented by the extreme value distribution. This can be accomplished by plotting $F^{-1}(C)$ vs. $t - t_0$ on linear graph paper and then finding the least squares fit of the data to the straight line in Eq. (10). If the fit is good (i.e., the data approximately follows a straight line) then it can be reasonably assumed the extreme value distribution is a good choice. Values of normalized capacity obtained from the model are plotted, versus time, in Fig. 2 as dashed lines. One measure of how well the data fits the straight line defined by Eq. (10) is the square of the correlation coefficient, r^2. Values greater than 0.93 seem to be sufficient to discriminate between one distribution or another. The parameter t_0 was estimated iteratively by maximizing the value of r^2 for each data set. The Kolmogorov–Smirnov one-sample test [3] was also performed on each data set to check the goodness-of-fit of the data to the extreme value distribution. The correlation coefficient and level of significance obtained from the Kolmogorov–Smirnov test are shown in Table 2.

Some additional comments need to be made concerning the graphs in Fig. 2 for manufacturer A and B. First, for the A4-2.5C-50 battery in Fig. 2a, note that there was a distinct change in the rate of capacity loss at the end of the test. This is because 2 of the 3 batteries in the test experienced catastrophic failures (i.e., discharge times went to 0). These last 3 data points were omitted from the analysis. The data set for A4-3C-40 displayed some erratic behavior in that the capacity increased for one discharge after a consistent decrease in capacity had been established. This could explain the low value (< 0.93) obtained for r^2.

Table 2
Correlation from least squares and level of significance of Kolmogorov–Smirnov test

Battery ID	r^2	Level of significance
A4-0.25C-40	0.9424	0.05
A4-2.5C-50	0.9683	0.02[a]
A4-3C-40	0.8558	0.05
A6.5-0.25C-40	0.9796	0.05
A6.5-3C-40	0.9492	0.05
A17-0.25C-40	0.9791	0.02[a]
B4-2.5C-50	0.9415	< 0.02[a]
B7-1C-50	0.9692	< 0.02[a]
B7-2C-40	0.9945	< 0.02[a]
B7-2.5C-50	0.9322	< 0.02[a]

[a] Life tests were terminated near the 50th percentile in these data sets. If the $|F_n(Y_{i-1}) - F_0(Y_i)|$ term is omitted for the last point in the data set, the level of significance would have been 0.05 or better for every data set.

Table 3
Slope from least squares fit to data and confidence interval

Battery ID	Slope (b)	95% Confidence interval	
		Upper limit	Lower limit
A17-0.25C-40	−869.9	−693.3	−1046.5
A4-3C-40	−809.4	−427.3	−1191.5
A4-2.5C-50	−732.6	−670.7	−794.4
A6.5-3C-40	−957.9	−720.9	−1194.9
A4-0.25C-40	−384.1	−4.7	−572.9
A6.5-0.25C-40	−473.0	−378.3	−567.6
B7-1C-50	−1376.7	−1036.0	−1717.4
B7-2.5C-50	−1076.6	−954.3	−1199.0
B4-2.5C-50	−1226.4	−1094.6	−1358.2

With the manufacturer B batteries, there were also some inconsistencies in the performance. First, note the sudden loss of capacity after approximately 300 days of battery B7-2.5C-50. The rate of loss of capacity then changed to one more consistent with the other batteries. One possible explanation for this behavior, suggested by the manufacturer, was that the active material density may have been lower than normal. Finally, one battery failed during the B7-2C-40 test. Since the failure was not catastrophic but lower than normal capacity, the battery was not excluded from the data set but will not be used in the analysis of the second period of the float service life.

Continuing on, now that the adequacy of the model has been established, the slope, b, obtained from the least squares fit of the data to Eq. (10) can be studied. The significance of the slope is it represents the rate of capacity loss during this period of battery life. Referring back to Eq. (6) it is seen that b is a scaling parameter of the extreme value distribution. That is, the larger the value of b, the less rapid the capacity will decrease as time increases.

The value of the slope obtained from each float service life test is shown in Table 3. The upper and lower limit of a 95% confidence interval on the estimate of the slope is also shown. Looking first at the confidence interval of the four batteries from manufacturer A it can be seen there is a range of values that is common to all four intervals. Hence, it might be expected that a single estimate of the slope, for all four tests, can be found. A hypothesis test was used to determine whether there was any evidence to reject the assumption that all four slopes were equal to a particular value. The value found which satisfies this test, at the 0.05 level of significance, is −793. Repeating this process for the float service life test data for the batteries from manufacturer B yields a common estimate for the slope of −1100.

Some discussion is in order now to explain the connection between these results and the float service life of the batteries in this analysis. Recall the earlier observation, from the graphs in Fig. 2, of the similarity of the rate of capacity loss during the second period of float service life.

From the results of the hypothesis test it is fair to say that the rates of capacity loss of the batteries in Fig. 2a are equal (i.e., there was no evidence to reject this). Similarly the same can be said for the batteries in Fig. 2b and c. So for the batteries from manufacturer A two statements can be made. One is for the batteries in Fig. 2a the rate of capacity loss during the second period of float service life is independent of the discharge rate used in the test. On the other hand, two of these same batteries display distinctly different (but equal to each other) rates of capacity loss for the same discharge rate used in one of the tests in Fig. 2a. Hence, there must be an additional factor(s) which contribute to the rate of loss of capacity.

One possibility is the prevailing failure mechanism, which governs the end of life of a particular battery, controls or determines the rate of loss of capacity (question 3). In turn, the design of a battery influences which failure mechanism will predominate. Failure analysis results were not available for all of the batteries from manufacturer A. However, the ones which are available tend to lend some support to the above mentioned possibility. It was reported by manufacturer A that one battery in the set of four in Fig. 2a reached end of life due to grid corrosion. It was also reported that loss of electrolyte was the mechanism for both batteries in Fig. 2b. Now assuming that based on the failure analyses supplied, that the predominant failure mechanism contributes to the rate of loss of capacity, it is most likely that the batteries from manufacturer A are not as similar in design and manufacture as was initially stated. Therefore, it does not appear possible to pool the float service life data from these batteries from manufacturer A.

The batteries from manufacturer B (Fig. 2c) included two different ampere hour ratings and two discharge rates. For these it can also be said that the rate of loss of capacity is equal for all three sets. Unlike those from manufacturer A the predominant life ending mechanism reported by the manufacturer for these batteries is grid corrosion.

4. First period of float service life

The first period of float service life, as defined earlier, is that time from when the battery is placed on test until the capacity loss begins to increase. This time period was referred to as a guarantee time or threshold time and identified as t_0 in Eq. (10) above. The analysis of this portion of the float service life of a battery is not quite so straightforward. The main problem, as will be seen, is the guarantee time is strongly effected by the discharge rate chosen for the test. Since for the available data only five unique discharge rates were used, by both manufacturers combined, it was not possible to obtain a satisfactory relationship between discharge rate and guarantee time. Although from the graph in Fig. 3 it is suspected some relationship may exist. An attempt was made to relate the guarantee time to either the frequency of discharges performed or time between discharges during the guarantee time. There did not seem to be any correlation between the guarantee time and either of these variables.

One observation which can be made from this data is there is a significant difference in the effect discharge rate has on guarantee time between the two manufacturers, A and B. Note the relatively small change in guarantee time as the discharge rate varies from 1 C to 2.5 C for manufacturer B. Whereas for manufacturer A the change in guarantee time is much greater with only a slightly larger range of discharge rates, 0.25 C to 3 C. One possible conclusion from this observation is the batteries from manufacturer B will have a more uniform float service life, regardless of the discharge rate (i.e., application). On the other hand, for

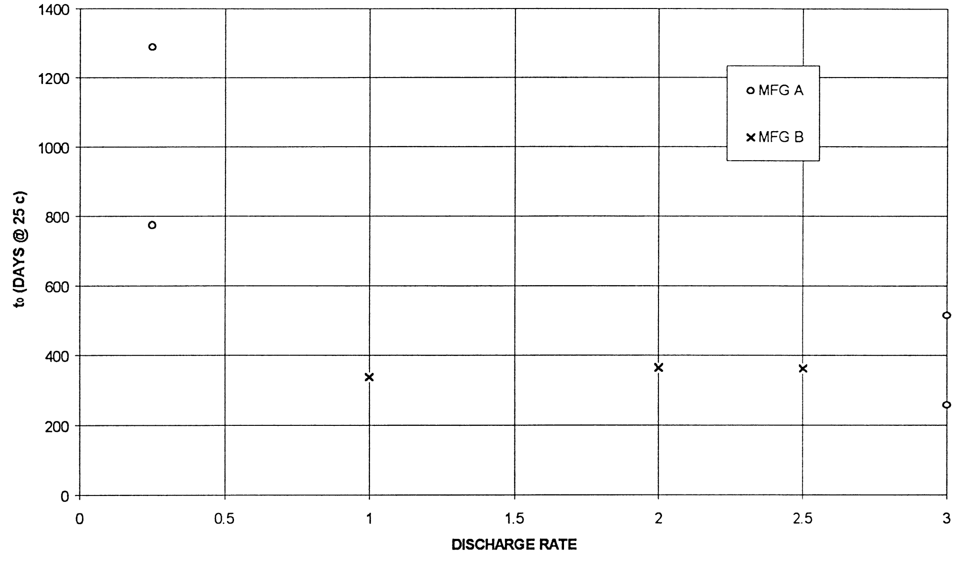


Fig. 3. Guarantee time period of float service life for batteries from manufacturer A and B.

specific applications such as low discharge rates, the batteries from manufacturer A may exhibit a longer float service life, depending on the rate of loss of capacity during the second phase of the battery life.

5. Summary

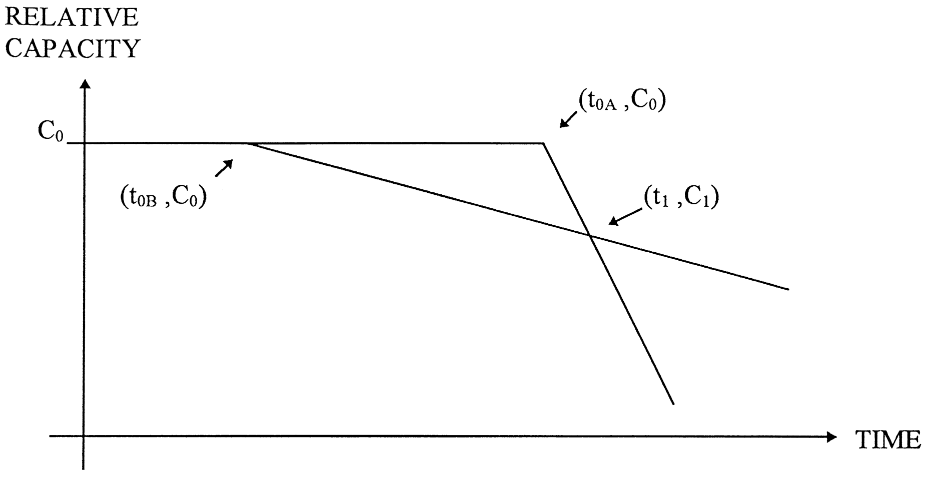
The float service life of a battery has been divided into two distinct phases, the first of which begins when the battery is placed on float and ends when the capacity begins to rapidly decrease. This period is referred to as the guarantee time and is characterized by only slight changes in capacity with time. In Section 4, the relative effect of discharge rate on the length of the guarantee time was shown although no quantitative relationship could be developed. Perhaps with more testing at different discharge rates enough data could be obtained to establish such a relationship (or the lack of one). This is an area for further work. It was also evident from Fig. 3 of Section 4 that discharge rate had a greater effect on the guarantee time for manufacturer A than for manufacturer B.

The second phase of float service life is characterized by a rapid decrease in capacity, relative to the first period. The data, from this phase, was fit to an extreme value distribution. Next, a linear model was developed and estimates made of the slope. In this model the reciprocal of the slope represents the rate of capacity loss during the second period of float service life. It was shown that there was no reason to reject the hypothesis of equal slopes for each of the three groups (Fig. 2a–c) of batteries. This implies that the batteries in each group respectively, lost capacity at the same rate regardless of the discharge rate used in the float service life test.

For the batteries from manufacturer A it appears, based on the data provided, that the rate of loss of capacity during the second period of float service life is controlled or influenced by the predominant failure mechanism which determines end of life. Information provided by manufacturer A indicates the predominant failure mechanism is influenced by certain design parameters of the battery. As such it is most likely that the group of batteries from manufacturer A is not sufficiently similar to allow pooling of the float service life test data. The batteries from manufacturer B are more uniform in design and only one failure mechanism, grid corrosion, was reported. The float service life test data can be pooled for these batteries.

One application of this model was to determine which of the two manufacturers' batteries would provide a longer float service life at various discharge rates of interest even if no float service life testing had been performed using that rate. This was not possible, as mentioned previously, because no quantitative relationship could be developed between the guarantee time and discharge rate. This was complicated further due to the batteries from manufacturer A not being similar enough in design to allow pooling of the data. However by choosing a common discharge rate the model can be used.

On comparing the float service life of the two manufacturers' batteries, it is apparent that the characteristics of the batteries are quite different. For most discharge rates, the guarantee time of the manufacturer A batteries is longer. Whereas the rate of loss of capacity during the second phase of float service life is less for manufacturer B batteries. A diagram highlighting these differences is contained in Fig. 4. Note that at some capacity the two curves will intersect. This point is a function of both the guarantee time (i.e., discharge rate) and the rate of capacity loss.



C_0, C_1 : Relative capacity
t_{0A}, t_{0B} : Guarantee times, manufacturer A & B
t_1 : Time until relative capacity of manufacturer A and B batteries equals C_1

Fig. 4. Comparison of float service life between batteries of manufacturer A and B.

Therefore, there can be no general conclusion that the float service life of one of the two manufacturers' batteries is longer than the other. The discharge rate of the intended application must be specified first.

One question which should be considered, given the distinct characteristics of the float service life of the two manufacturers' batteries, is which life is better for an intended application. This may be considered a quality of life question. That is, assume the two curves intersect at some end of life capacity of interest (i.e., time to end-of-life is equal). One measure of the quality of life might be the average (normalized) capacity of the battery over the life time. This could be obtained by (numerically) integrating the area under the float service life curve and dividing by the time until the two curves intersect. The larger the number obtained the 'better' the life. Some adjustment would have to be made to the normalized capacity if the batteries did not have the same ampere hour rating. In contrast to this measure, though, in a more practical sense one should consider the following: Is it better, from the point of view of the user, to have a battery which provides a relatively constant capacity for a long period and then degrades rapidly or is one which starts losing capacity earlier but at a much slower rate preferable? This may be a more important factor in terms of detecting impending end of life early enough to take some action. In a UPS application for example, where long discharges are infrequent, a slower degradation of capacity could be of some value.

Acknowledgements

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