A PROPOSED 80% SERVICE TEST TO SATISFY THE DUTY CYCLE AND TO TREND BATTERY CAPACITY

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INTRODUCTION

Current practice within the nuclear power industry is to use performance discharge tests for condition monitoring to determine when a battery has reached 80% of its rated capacity which is considered the end of its service life. A service test is used every refueling outage to verify that a battery can satisfy its design basis function as defined by the battery duty cycle. A modified performance test is used at intervals of one-fourth the qualified life to satisfy the requirements of both the service and performance tests. These types of battery discharge tests are described in detail in IEEE 450-2002 (Ref. 1).

As described above, the service test done every refueling outage (1.5 to 2 years) verifies the battery will satisfy its safety design function. The battery is sized in accordance with IEEE 485 (Ref. 2) thus requiring at least a 25% aging margin so the battery will still meet the design function at the end of its service life. In effect 80% of rated capacity is all that is required for the application and this is also the qualified condition for the battery according to IEEE 535 (Ref. 3) and IEEE 323 (Ref. 4). Technically the other requirement is to trend capacity to determine the onset of degradation according to IEEE 450 (Ref. 1). If both these requirements can be met with the proposed 80% Service Test done every refueling outage, then we will no longer need the varying service tests, performance tests or modified performance tests. The proposed 80% Service Test will use a discharge rate of approximately 80% of that used by the performance test to yield a percent capacity value for trending. Correction for initial electrolyte temperature will be done in the capacity calculation.

The duty cycle duration for existing nuclear plants is in the 2 to 8 hour range. Some of the new plant designs have duty cycle durations of 24 to 72 hours. Discharges at the 72 hour rate to end voltage can cause difficulties with charge acceptance at the beginning of recharge for some batteries. The proposed 80% Service Test would use a smaller discharge to yield a percent capacity value for trending and also reduce the risk of recharge issues.

This paper presents the proposed test and its possible applications at the existing and future nuclear generating stations and non-nuclear facilities as well.

POTENTIAL BENEFITS

A number of potential benefits to be gained by using the proposed test are as follows:

- Additional discharge cycles during qualification could be eliminated thus reducing the qualification period for the 24 and 72 hour batteries from 3 years to 1 year. The capacity removed by the 80% Service Test is less than or equal to that of the 8-hour rated capacity. Thus the capacity removed in the testing is bounded by existing data.
- Only one consistent test would need to be performed throughout the service life of the battery. Performance tests and modified performance tests would no longer be required.
- Capacity data would be available for trending every refueling outage. Presently this data is available every 4 to 6 years rather than every 1.5 to 2 years.
- For non-nuclear applications the proposed test could reduce the time required to test and recharge the batteries, thus saving time and money.

However, all of this is contingent on proving the concept and getting the test approved for use. These are no small tasks but we believe them to be worth the effort.

DESCRIPTION OF PROPOSED TEST

According to IEEE 450-2002 a service test is a test in the "as found condition" of the battery's capability to satisfy the battery duty cycle. In nuclear plants there may be more than one duty cycle involved for the various design scenarios. Therefore, the test duty cycle would be the most limiting duty cycle based on the magnitude and duration of the load steps as well as the minimum voltage requirements for the most critical step.

In general the capacity removed from the battery during a service test is no more than 70% of its rated capacity for the duty cycle duration and can be less than 50%. In addition the duty cycle can vary due to load changes throughout the service life. Therefore, the current type of service test is not suitable for use in providing consistent percent capacity data for use in condition monitoring. In addition a discharge rate of 80% of the published rate for a given duty cycle duration will provide consistent results for use in identifying the onset of battery degradation.

Proposed 80% Service Test Profile

The duty cycle profile for the proposed test is 80% of the published one-minute rate for the first minute followed by 80% of the published rating to the specified terminal voltage for the remaining duration of the duty cycle. Figure 1 below shows a typical 4 hour service test duty cycle with an 80% Service Test profile also shown for comparison purposes.

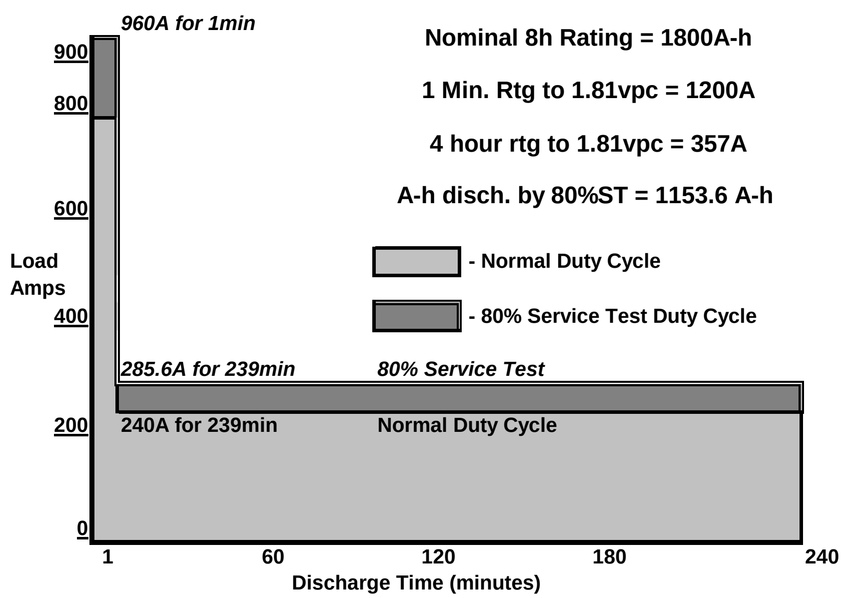

Figure 1 – 80% Service Test vs. Normal Service Test

Referring to Figure 1 the duty cycle for the 80% Service Test clearly bounds the normal service test duty cycle in both rate and time as required. This ensures that the "as found" capability of the battery to satisfy its design function is verified each refueling outage. For an "as found" test no equalizing charge is given, no temperature correction is made to the discharge rates and all battery connection resistance measurements are taken but no corrective actions taken unless there is a possibility of permanent damage to the battery. These requirements are described in more detail in IEEE 450-2002. All of these service test requirements are met by the proposed test.

Comparison of Discharge Ampere-hours (A-h)

For the normal service test shown in Figure 1, the ampere-hours discharged are calculated as follows:

$$Ahd = \frac{(1m \times 800A + 239m \times 240A)}{60m/h} = 969 Amp-hrs \qquad \textbf{\textit{Equation 1}}$$

For the 80% Service Test the ampere-hours discharged is calculated as follows:

$$Ahd = \frac{(1m \times 960A + 239m \times 285.6A)}{60} = 1153.6Amp - hrs \qquad \textbf{\textit{Equation 2}}$$

In this case the ampere-hours discharged by the 80% Service Test are 19% higher than for the normal service test. This difference accounts for the temperature correction factor and design margin.

Impact on Battery Test Procedures

To use the proposed test some changes would be required to the battery test procedures. For example a new procedure for the 80% Service Test would be required. The existing service test procedure could be retained for use in the unlikely event that an 80% Service Test failed later in the battery service life. The performance test procedures would no longer be needed, but could be retained for backup if desired.

CAPACITY DETERMINATION USING THE 80% SERVICE TEST

Can an accurate and repeatable percent capacity value be determined using the results from a service test? Not just any service test but a qualified yes if the proposed 80% Service Test is used. However, we will perform proof-of-concept testing to collect the supporting empirical data. The following discussion provides the technical justification for using the proposed 80% Service Test to determine capacity. First a comparison to modified performance tests will be made and then the actual capacity calculation methodology will be presented.

Similarities between 80% Service Test and Modified Performance Tests

Referring to Section 6.3 and 6.4 of IEEE 450-2002 describing the modified performance test the following similarities to the 80% Service Test can be identified.

- The discharge bounds the currents in the duty cycle for both tests.
- The initial conditions for both tests would be identical.
- Either test can be used in lieu of the normal service test at any time.
- Batteries sized per IEEE 485 are acceptable if tested capacity is 80% or greater.
- Jumpering (bypassing) of cells during either test is not allowed.

There are some important differences as discussed below, using the Type 1 modified performance test for the comparison.

Differences between 80% Service Test and Type 1 Modified Performance Test

The first part of the 80% Service Test is similar to a Type 1 Modified Performance Test. However, there are differences that must be considered. After the high rate discharge, the Type 1 Modified Performance Test is continued at the full rated performance test discharge to end voltage with the *ending time* being measured. The ending time and the initial electrolyte temperature are used to calculate the percent capacity using the time-adjusted method from section 7.3.1 of IEEE 450-2002. After the high rate discharge, the 80% Service Test is continued at 80% of the full rating for the duty cycle duration with *end voltage* being measured. The end voltage and the initial electrolyte temperature are used to calculate percent capacity using the rate-adjusted methodology from section 7.3.2.2. The test discharge rate is not adjusted for temperature for either type of test.

Percent Capacity Calculation for the 80% Service Test

Refer to Figure 1 above. The duty cycle will remain constant for the service life of the battery. In Figure 1, the duty cycle consists of the first minute at 960 amperes followed by the remaining 239 minutes at 285.6 amperes. Both ratings are based on the selected end voltage of 1.81 volts per cell average for this example. As calculated above, the ampere-hours discharged for the 80% Service Test in Figure 1 is 1153.6. The two other parameters needed for the capacity calculation are average end voltage and initial electrolyte temperature. The average end voltage is used to determine the rated ampere-hours for the given test duration. This data is used in the capacity equation below. (Similar to that used for the Type 3 Modified Performance Test described in Annex I.3 of IEEE 450-2002.)

$$\%Capacity = \frac{K_C \times \sum I_N \times T_N}{RtdA-h} \times 100$$ ***Equation 3***

Where: K_C = *Temperature Correction Factor from Table L.2 of IEEE 450-2002*
I_N = *Discharge current in amperes for section N*
T_N = *Duration of section N in hours*
N = Section numbers for each portion of discharge test
RtdA-h = Rated A-h to duty cycle duration for actual end voltage of test

Using the example from Figure 1 and assuming an initial electrolyte temperature of 90°F and an actual end voltage of 1.90 volts per cell (vpc) for the test, the capacity calculation is given below.

- The temperature correction factor for 90°F read from Table L.2 is 0.94.
- The rated capacity in ampere-hours at the 4-hour duration to 1.90 vpc at 77°F is read from the published data as 271A x 4h = 1084A-h.
- The ampere-hours discharged during the 80% Service Test calculated above equals 1153.6.
- The percent capacity is now calculated as follows:

$$\%Capacity = \frac{0.94 \times 1153.6}{1084} \times 100 = 100\%$$ ***Equation 3A***

This illustrates the percent capacity calculation for the 80% Service Test. With a little math, the similarity to the rated-adjusted performance test methodology can be seen. We can simplify the above equation by dividing both numerator and denominator by 4 hours which is the test duration. This results in the following equation.

$$\%Capacity = \frac{0.94 \times 288.4}{271} \times 100 = 100\%$$ ***Equation 3B***

For those of you familiar with the rate adjusted performance test, the capacity calculation formula from Clause 7.3.2.2 of IEEE 450-2002 is shown below.

$$\%Capacity = \frac{X_a \times K_C}{X_t} \times 100$$ ***Formula 7.3.2.2***

Where: X_a = *actual rate used for the test,*
X_t = *published rating for time t,*
t = time of test to specified terminal voltage,
K_C = *temperature correction factor (see Table 2, IEEE 450-2002).*

Comparing the terms between this rated adjusted formula and equation 3B above, the actual rate used for the test would be 288.4 amps. Referring to Figure 1 above, 80% of the 4 hour rating of the battery is 285.6 amps. The difference between these two values is the ampere hours removed by the first minute peak spread across the 4 hour duration. The published rating for a time of 5.93 hours to specified terminal voltage of 1.90 volts per cell is 271 amps which matches the value in equation 3B and the definition of X_t given above. Therefore, the capacity calculation method for the 80% Service Test is basically equivalent to the calculation methods used for the Type 3 Modified Performance Test and the Rate-Adjusted Performance Test. The obvious difference between the 80% Service Test and the Rated-Adjusted Performance Test is the first minute peak of 80% of the published one-minute rating.

In addition to verifying that the design basis functions are met each outage, the terminal voltage at the end of the 80% Service Test and the initial electrolyte temperature would be used to calculate an equivalent percentage of rated capacity for use in condition monitoring. This capacity trending would be used to identify the onset of degradation and to confirm that the battery meets or exceeds the qualified condition of 80% of rated capacity. In this way both functions can be fulfilled by using the 80% Service Test throughout the service life of the battery.

PROOF-OF-CONCEPT TESTING

As with any technical proposal the final proof is confirmation by actual testing. A summary of this testing is given below.

Two nominal 12 volt vented lead acid battery strings representing existing and future nuclear plant applications will be discharge tested under a variety of temperatures and end voltages. Initial electrolyte temperatures ranging from 15.6 to 35°C (60 to 95°F) and end voltages ranging from 1.75 to 1.90 volts per cell average will be used.

The discharge testing will be performed using automatic battery discharge test equipment. All tests will be fully documented with test equipment records and other documentation as required. Test procedures will be in accordance with IEEE 450 and other industry standards.

The test sequence for each voltage and temperature will consists of the following basic steps.

1. Conduct an 80% Service Test and record the end voltage, but continue discharging at the same rate using the rate-adjusted performance test methodology until the end voltage is reached. Note: No rate adjustment for temperature will be used. The temperature correction is done in the capacity calculation.

2. Calculate the percent capacity for the 80% Service Test based on the end voltage for the service test adjusted for initial temperature using Equation 3 above. This is the normal process that will be used for the 80% Service Test.

3. Calculate the percent capacity for the performance test based on the rate-adjusted equation 7.3.2.2 from IEEE 450 discussed above. This is the verification part used only for the proof of concept testing.

4. Compare the percent capacity values from 2 and 3 above. There should be a very close match between the two values for verification of the proposed test.

Using the example shown in Figure 1 above and adding the performance test portion to the end of the 80% Service Test we can see how this testing would be done. Figure 2 below shows the 80% Service Test from Figure 1 with the addition of a continued discharge at the same rate until the specified end voltage of 1.81 volts per cell average is reached. This type of combined discharge test will be used for the proof of concept testing only. The sample capacity calculations below illustrate the process that will be used for this testing.

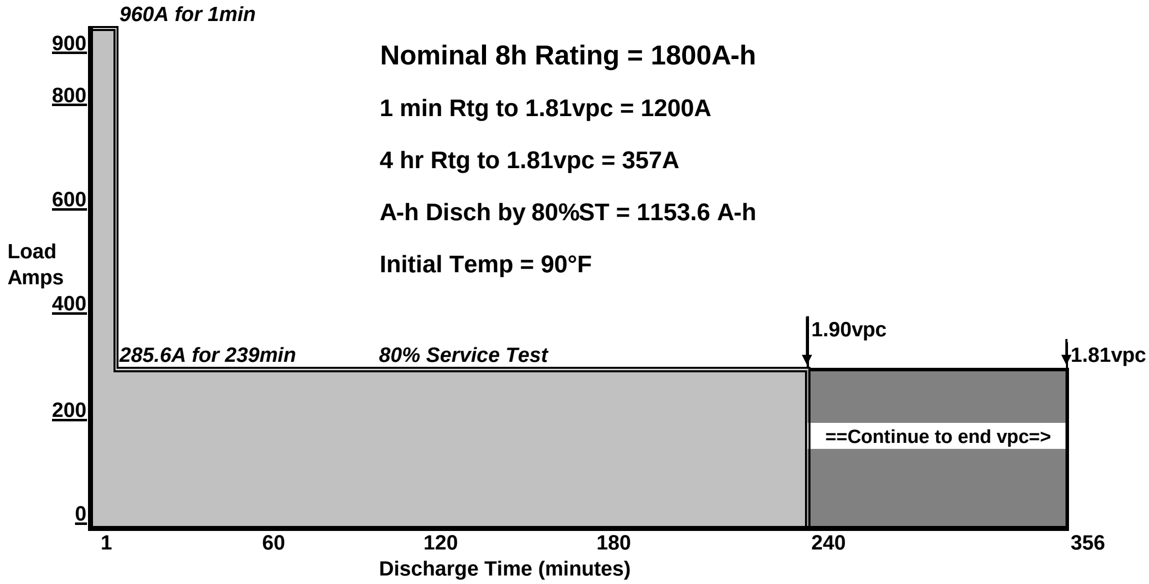

Figure 2 – Proof-of-Concept Test Example

The capacity calculation for the 80% Service Test portion in Figure 2 was already shown above with a result of 100%. It was also illustrated that a rate adjusted method of calculation would yield the same result. Now we will apply the rate adjusted calculation to the full test carried to the end voltage of 1.81 volts per cell. For illustration purposes, the end time of 356 minutes (5.93 hours) was chosen to match the 100% capacity above. Obviously, we won't know the result before we do the test! However, we can predict the expected results and then see if they are confirmed by test. The calculation is given below.

$$\%Capacity = \frac{X_a \times K_C}{X_t} \times 100 = \frac{287.5 \times 0.94}{271} \times 100 = 100\%$$

Those of you familiar with the published discharge data recognize the importance of accurate data across the range of times and end voltages involved. The availability of this kind of data will be a condition for sample selection for the testing, especially for the longer 24 and 72 hour tests.

POTENTIAL APPLICATIONS

The proposed 80% Service Test is primarily intended for use in nuclear plants and especially for those having the longer 24 and 72 hour duration duty cycles. However, now that we have the "hammer in hand" so to speak, many things look like a nail! For example many non-nuclear generating stations and substations presently use performance tests for trending of capacity. The 80% Service Test could replace the performance tests in many cases. Similar applications could be found in telecommunications facilities and data centers, depending upon the specific requirements of a given facility.

SUMMARY

- The proposed 80% Service Test has potential benefits worthy of consideration for use.
- The technical justification has shown the capability of deriving capacity data from the proposed test.
- Proof-of-concept testing is planned that will verify the capability of the proposed test.
- Changes to nuclear plant technical specifications and procedures will be required to use the test.
- Battery qualification testing would follow once the proposed test is approved for use.

REFERENCES

1. IEEE Standard 450-2002 *IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications*

2. IEEE Standard 485-1997 (R2003) *IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications*

3. IEEE Standard 535-2006 *IEEE Standard for Qualification of Class 1E Lead Storage Batteries for Nuclear Power Generating Stations*

4. IEEE Standard 323-2003 *IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations*