INITIAL TEST RESULTS ON PROPOSED 80% SERVICE TEST ONE TEST COVERS DUTY CYCLE AND TRENDS CAPACITY

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INTRODUCTION

A new type of battery discharge test named the 80% Service Test was proposed in our Battcon 2010 paper[1]. Initial conceptual testing results look promising with more testing underway.

Currently within the electric power industry and especially at nuclear plants, performance discharge tests are used for condition monitoring and service tests are used to verify a battery meets its design duty cycle. These types of battery discharge tests are described in detail in IEEE 450[2]. With some modifications to the service test duty cycle and to the condition monitoring methodology, this paper proposes that some of these discharge tests can be replaced by the proposed 80% Service Test.

The proof-of-concept testing proposed in the earlier paper consisted of 4-hour and 72-hour discharge tests on nominal 12 volt strings of vented lead acid batteries representing existing and future nuclear plant applications. End voltages in the 1.75 to 1.90 volts per cell range were used. Conventional performance tests were done to provide percent capacity results for comparison. Automatic battery discharge test equipment was used to control the discharge currents comprised of two rates, 80% of the one minute rate for the first minute followed by 80% of the 4-hour (72-hour) rate for the remainder of the test duration.

This paper presents results on the tests completed thus far and offers some perspective on possible applications of the 80% Service Test as well as 72-hour discharge testing in general.

The initial testing was done by Nuclear Logistics, Inc. and Exide/GNB personnel at the Fort Smith, Arkansas facilities.

TEST SETUP AND SEQUENCE

The battery used for the 4-hour and 72-hour testing consisted of a nominal 12 volt string using six GNB NCN-27 cells connected in series. The discharge test equipment used for the 4-hour testing was a 2000A water-cooled unit. The discharge test equipment used for the 72-hour testing was a 2000A Bitrode unit. A Fluke Model 51 thermometer was used for measuring cell temperature. Fluke Model 87 Multimeters were used for battery and cell voltages. An Agilent Model 34401A Multimeter was used for reading the discharge current through an Empro 1200Amp, 100 millivolt calibrated shunt.

The test sequence used was as follows:

A. Initial 4-hour Performance Test to 1.75 volts per cell (VPC) end voltage.
B. Four (4) hour 80% Service Test/Rate-Adjusted Performance Tests (1.75 to 1.90 VPC)
C. Special 4-hour Service Test/Performance Test to 1.75 VPC without the first minute peak.
D. Initial 8-hour Performance Test to 1.75 VPC (Base capacity for first two 72-hour tests)
E. First two 72-hour 80% Service Tests (1.90 & 1.85 VPC)
F. Intermediate 8-hour Performance Test to 1.75 VPC (Base capacity for last two 72-hour tests)
G. Last two 72-hour 80% Service Tests 1.80 & 1.75 VPC)
H. Final 8-hour Performance Test to 1.75 VPC (Extra test for evaluation purposes)

TEST PROCEDURES USED

The test procedures described in section 7 of IEEE 450[2] were used as written for the 4 and 8 hour performance tests. These test procedures were used with some adjustments for the 80% Service Tests. The adjustments were as follows. The initial conditions in section 7.1 were followed, except the electrolyte temperature of every cell was measured since there were only 6 cells and the voltage of every cell was measured. In addition the minimum voltage during the coup de fouet and time of occurrence were recorded during the first minute. As a minimum the battery and cell voltages were recorded at 30, 60, 120, 180, 210, 240 and every 30 minutes thereafter. The battery was fully charged after each test using a stabilized float current for 3 consecutive hours as the criteria as described in Annex A.2[2] and left on float charge for at least 3 days before the next test sequence was initiated.

In the original 2010 Battcon paper[1] the capacity calculation method proposed was the one used for the Type 3 modified performance test from Annex I3[2]. The results using this method were reported in an EPRI report[3]. However, after further consideration it was determined that the rate-adjusted methodology may be more appropriate for this test, especially with the diversity in discharge rates used. Therefore, the original test data was used to calculate capacity using the rated adjusted method described in section 7.3.2[2]. The rate-adjusted capacity determination was made using formula 7.3.2.2 below with the temperature correction factors taken from Table 2[2]:

$$\%Capacity = \frac{X_a \times K_C}{X_t} \times 100$$ ***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).*

To address the two different rates one calculation is done for the first minute discharge and the second calculation is done for the remainder of the discharge. These two values are then weighted according to the relative ampere-hours associated with each discharge and combined to derive the total percent capacity for the full 80% Service Test. In this way the aging effects on the short and long duration discharges trended over time can be evaluated separately. This decision will be reviewed and discussed with industry experts before making a final decision on the best calculation methodologies. Fortunately sufficient data was collected in the initial testing to support these changes in the actual capacity calculation used.

INITIAL CELL SELECTION AND PERFORMANCE TESTING

Fourteen NCN-27 cells manufactured in the first quarter of 2010 were fully charged and performance tested at the 4-hour rate in accordance with the time-adjusted method in section 7.3.1[2]. The average electrolyte temperature of all the cells was 25.56°C and the 4-hour discharge rate used was 412A. The six cells having the highest capacity were selected for the remaining testing. The average benchmark capacity of the selected cells was 100.6%.

FOUR HOUR TESTING

Each of the 4-hour test sequences consisted of an 80% Service Test running for four hours and continuing at 80% of the 4-hour rate until the rated end voltage is reached. The first minute rate was 80% of the one minute rating of the battery. The test profile for the end voltage of 1.75 VPC is shown in Figure 1 below.

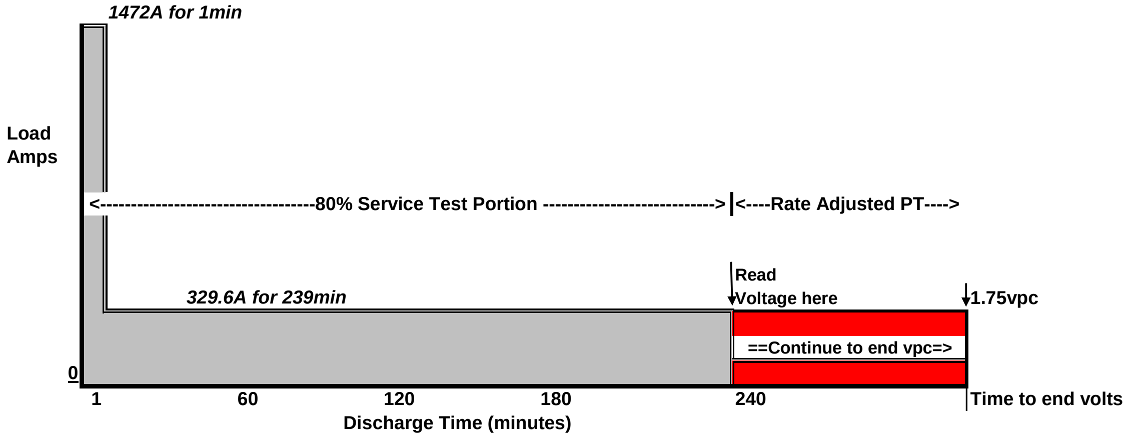

Figure 1. 4-hour Test Profile to 1.75 VPC

A review of the test sequence may be helpful here. As shown in Figure 1 above the normal 80% Service Test is completed at 240 minutes. For the 4-hour proof testing only, the same rate was continued until the specified end voltage is reached. The specified end voltages selected were 1.75, 1.81, 1.86 and 1.90 VPC. In addition to the normal 80% Service Test sequences a special test without the first minute peak was also run. The second part of the test sequences provided another capacity value for comparison purposes for the 4-hour testing only.

The critical data measured and recorded during the testing were the initial electrolyte temperatures, the discharge rates, the voltage at the end of the service test (240 minutes) and the time to rated end voltage. This data is shown in Table 1 below.

Table 1. Measured Data for 4-hour Tests

Parameter	1.75 VPC	1.81 VPC	1.86 VPC	1.90 VPC	Special 1.75VPC
Initial Temperature (°C)	24.82	24.89	23.89	25.37	23.78
First minute discharge rate in amps (X_{a1})	1477.53	1045.01	728.62	499.30	330.24
Minimum VPC during Coup de fouet (1^{st} min)	1.793	1.840	1.882	1.917	NA
Remaining discharge rate in amps (X_{a2})	329.89	306.89	273.20	234.63	330.24
Measured average end voltage at 240 min.	1.872	1.893	1.915	1.940	1.868
Time to end volts of extended discharge (t)	312	322	333	339	309

Note: The discharge rates shown above are slightly higher than 80% of the actual ratings for conservatism.

This measured data was converted to the values for use in the capacity calculations using the following process. The initial electrolyte temperature in degrees C was used to look up the temperature correction factors in Table 2[2]. The first minute and 240^{th} minute ratings associated with the minimum voltages (VPC) in Table 1 were read from the published discharge characteristic curve representing average performance for the NCN line. Linear interpolation was used to determine the discharge rates when the associated end voltages fell between plotted voltage lines on the curve. This technique is described in Annex F of IEEE 485-2010[4]. The discharge rates for the extended discharge were read from the curve by first constructing an intermediate time line corresponding to the time to end voltage given in Table 1 and then reading the Amps per Positive value at the intersection of the end voltage line and the time line just drawn. This technique is also described in Annex F[4].

The Amps per Positive values described above were then multiplied by 13 positive plates to get the rated discharge amperes shown in Table 2 for the first minute calculation and Table 3 for the remaining 239 minute calculation. The capacity calculations used the rated adjusted formula 7.3.2.2 given above.

Table 2. First Minute Capacity (C1) Calculation Data and Results

Parameter	1.75 VPC	1.81 VPC	1.86 VPC	1.90 VPC
Temperature Correction Factor (K_C)	1.002	1.001	1.011	0.996
First minute discharge rate in amps (X_{a1})	1477.53	1045.01	728.62	499.30
Rated Amps for first minute discharge (X_{t1})	1425.2	1027	729.3	535.6
Calc. %Capacity for first minute (%C1)	**103.9%**	**101.9%**	**101.0%**	**92.8%**

Table 3. Remaining 239 Minute Capacity (C2) Calculation and Results

Parameter	1.75 VPC	1.81 VPC	1.86 VPC	1.90 VPC
Temperature Correction Factor (K_C)	1.002	1.001	1.011	0.996
Remaining discharge rate in amps (X_{a2})	329.89	306.89	273.20	234.63
4-hr rated amps to end VPC at 240 min. (X_{t2})	329.8	303.8	273.3	234.0
Calc. %Capacity – Rmng 239m (%C2)	**100.2%**	**101.1%**	**101.1%**	**99.9%**
%Difference – %C2 - Initial PT	-0.4%	0.5%	0.5%	-0.7%

The remaining 239 minute capacity results in Table 3 compare favorably with the 100.6% capacity results from the initial four-hour performance test; however, the first minute results must be considered to get the total capacity for the 80% Service Test.

Due to the dramatic difference in discharge rates and battery efficiencies between the first minute and the remaining 239 minutes, some proportioning process was needed. The comparison of time and rate-adjusted performance test methods in Annex K[2] was helpful here. The process used was to calculate the ratio of the first minute discharge ampere-hours to the remaining 4-hour ampere-hours and then use this ratio to combine the two percent capacity values from Tables 2 and 3 above. This is illustrated below using the data for the 1.75 VPC test sequence.

$$\%1m = \frac{1477.53A \times 1m}{1477.53Am + 329.89A \times 239m} \times 100 = 1.84\%$$

$$\%239m = 100 - 1.84\% = 98.16\%$$

$$Total\%Cap = (103.9 \times 0.0184 + 100.2 \times 0.9816) \times 100 = 100.3\%$$

Using this process on the percent capacity results from Tables 2 and 3 above, the total capacity results are shown in Table 4 below. This is a trial process at this time and may need modification in the future.

Table 4. Total Percent Capacity for 4-hour 80% Service Tests

Parameter	1.75 VPC	1.81 VPC	1.86 VPC	1.90 VPC	Special 1.75VPC
Calc. %Capacity for first minute (%C1)	103.9%	101.9%	101.0%	92.8%	NA
Calc. %Capacity – Rmng 4h ST (%C2)	100.2%	101.1%	101.1%	99.9%	NA
Total % Capacity for 80% Service Test (%CT)	**100.3%**	**101.1%**	**101.1%**	**99.8%**	**100.2%**
% Capacity from Initial Performance Test (%PT)	100.6%	100.6%	100.6%	100.6%	100.6%
%Difference - %CT - %PT	**-0.3%**	**0.5%**	**0.5%**	**-0.8%**	**-0.4%**

The total percent capacity values for all the normal 80% Service Tests are within 0.8% of the percent capacity of the initial performance test. This confirms that the 80% Service Test can deliver accurate percent capacity values for use in condition monitoring at the four hour rate. The four hour testing was designed to simulate duty cycles for the existing nuclear plants.

Referring to Table 1 it can be seen that batteries in the 100% capacity range can have end voltages in the 1.86 to 1.94 volts per cell range. Batteries using the 80% Service Test will normally be discharged at 80% of their rating and these higher voltages are expected for most of the service life of the batteries. Therefore it is very important that we have accurate ratings in these higher voltage ranges.

TRANSITION FROM 4-HOUR TO 72-HOUR TESTING

At the conclusion of the 4 hour testing sequences it was decided to move directly into the 72-hour testing sequences. This is a change of 18 times the 4 hour duration! One has to stop and think about the implications for a moment to appreciate the differences. The question of what type of test and duration to be used for the benchmark capacity had to be answered. Extending the discharge to end voltage as was done on the four-hour tests causes test durations in the 90 hour range. Due to the limited amount of discharge data available even at 72 hours, it was clear that extending the duration to get another percent capacity value for comparison would not be possible. Based on these considerations it was determined that a series of eight hour performance tests would be used for comparison purposes. Historically, the eight hour rating has been the industry standard for capacity testing.

EIGHT HOUR TESTING

Three 8-hour time-adjusted performance tests were performed to establish benchmark capacity values for comparison with the 72-hour tests. These were run in accordance with IEEE 450 time-adjusted performance test procedures. The test sequences are identified as D, F and H in the test sequence list. As noted in the test sequence section there were three performance tests done, one before the start of the 72-hour testing, one after the first two 72-hour tests were completed and a final performance test for evaluation purposes. The test data and results are summarized in Table 5 below.

Table 5. Eight Hour Performance Test Results

Parameter/Result	First Test	Second Test	Third Test
Average electrolyte temperature (°C) before Start of Test	21.72	23.98	25.35
Temperature correction factor (K_T)	0.963	0.986	1.002
Actual time (t_A) of test to 1.75 VPC, in minutes	468	478	482
Rated time (t_S) to 1.75 VPC, in minutes	480	480	480
Calculated percent (%) Capacity	**101.2%**	**101.0%**	**100.2%**

SEVENTY-TWO HOUR TESTING

A total of four 72-hour 80% Service Tests were conducted. End voltages of 1.90, 1.85, 1.81 and 1.75 volts per cell were selected since the discharge data was available for these rates. These tests were stopped at 72 hours, which is the end of the 80% Service Test. This is a departure from the normal rate-adjusted method, which runs to end voltage.

The critical data measured and recorded during the testing were the initial electrolyte temperatures, the discharge rates and the average end voltage at 72 hours (4320 minutes). The measured data for the 72-hour testing is given in Table 6 below.

Table 6. Measured Data for 72-hour Tests

Parameter	1.90 VPC	1.85 VPC	1.81 VPC	1.75 VPC
Initial Temperature (°C)	22.78	23.44	23.91	24.00
First minute discharge rate in amps (X_{a1})	499.00	756.20	1036.52	1459.58
Minimum VPC during Coup de fouet (1^{st} min)	1.915	1.891	1.857	1.810
Remaining discharge rate in amps (X_{a2})	22.135	25.928	26.960	27.953
Average end voltage at 72 hours (4320 minutes)	1.950	1.929	1.922	1.913

This measured data was converted to values for use in the capacity calculations. These values along with other pertinent data and results are summarized in Table 7 below for the first minute calculation and Table 8 for the 72-hour discharge calculations. The conversion process used was similar to the one used for the 4-hour testing.

The first minute and 4320th minute ratings associated with the minimum voltages (VPC) from Table 6 were read from extended discharge data for the NCN line. Linear interpolation was used to determine the discharge rates when the associated end voltages fell between the available data. This technique is described in Annex F[4].

Table 7. 72-hour ST First Minute Capacity Calculation Data and Results

Parameter	1.90 VPC	1.85 VPC	1.81 VPC	1.75 VPC
Temperature Correction Factor (K_C)	1.023	1.016	1.011	1.010
First minute discharge rate in amps (X_{a1})	499.00	756.19	1036.52	1459.58
Rated Amps for first minute discharge (X_{t1})	546	682.5	911.4	1287
Calc. %Capacity for first minute (%C1)	93.5%	112.6%	115.0%	114.5%

Table 8. Remaining 72-hour ST Capacity Calculation Data and Results

Parameter	1.90 VPC	1.85 VPC	1.81 VPC	1.75 VPC
Temperature Correction Factor (K_C)	1.023	1.016	1.011	1.010
Remaining discharge rate in amps (X_{a2})	22.135	25.928	26.960	27.953
72-hr rated amps to end VPC (X_{t2}) *	22.30	25.59	26.69	27.32
Calc. %Capacity – Rmng 72h ST (%C2)	101.5%	102.9%	102.1%	103.4%

* Interpolated ratings with limited amount of data points.

The two series of percent capacity values from Tables 7 and 8 were then combined using the weighted approach described for the four hour tests above. These results are summarized in Table 9.

Table 9. Total Percent Capacity for 72-hour 80% Service Tests

Parameter	1.90 VPC	1.85 VPC	1.81 VPC	1.75 VPC
Calc. %Capacity for first minute (%C1)	93.5%	112.6%	115.0%	114.5%
Calc. %Capacity – Rmng 4h ST (%C2)	101.5%	102.9%	102.1%	103.4%
Total % Capacity for 80% Service Test (%CT)	**101.5%**	**103.0%**	**102.2%**	**103.5%**
%Capacity on Previous Performance Test (%PT)	101.1%	101.1%	101.0%	101.0%
%Difference - %CT - %PT	**0.4%**	**1.9%**	**1.2%**	**2.5%**

The percent differences between capacities for the 80% Service Test and the previous performance tests are somewhat greater than expected. However, this is a comparison between a time-adjusted performance test and a rate-adjusted performance test stopped on time, not end voltage. Overall the average percent difference is 1.5%, which is reasonable. The additional 72-hour tests will provide further evidence for analysis.

SUMMARY AND OBSERVATIONS

The four hour results in particular provide percent capacity data with reasonable resolution that could be used for condition monitoring in non safety related applications. Some less critical applications that could be used as test beds for the 80% Service Test would be very helpful going forward. Additional 72-hour testing is needed to improve the resolution on the capacity results and to gather additional extended data points at 72 hours and beyond for the higher end voltages.

One observation concerning the 80% Service Test approach to condition monitoring may be of interest. Each successful test verifies that the battery meets its design function and also proves the battery delivers at least 80% of rated capacity as required for continued operation. This is a definite addition to the normal service test results.

Currently the voltages at the end of each step in the duty cycle (test profile) should be recorded. With today's technology one can set up a predictive monitoring tool to plot the expected test results under normal conditions and then capture and trend the actual test results at the conclusion of the test.

Using the separate capacity results from the 80% Service Test, one can evaluate the high rate and low rate performance as well as the overall composite percent capacity. This allows one to identify any variation in aging effects between the two rates. With some experience evaluating the first minute capacity this could be a definite improvement to capacity trending processes.

The 72-hour test sequences required very close control of the discharge current and accurate integration across the full test duration to determine the actual discharge rate for use in the capacity calculation. Current readings were recorded every 10 seconds for this purpose.

Specific gravity readings of each cell were taken at the end of the last two 72-hour test sequences. The average specific gravity readings were 1.082 and 1.076 for the 3rd and 4th tests, respectively. Further discussion on this observation will be entertained at the meeting.

The battery recharged fully after the last 72 hour test and delivered 100.2% capacity on the final performance test.

FUTURE TESTING

At least two additional 4-hour and 72-hour test sequences are planned for 2012. We are working within the IEEE Stationary Battery Committee to gain the insights and support of the battery specialists and users there. We welcome your candid feedback and questions on this paper!

REFERENCES

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