Testing to Evaluate Extended Battery Operation in Nuclear Power Plants

L. Ramadan
U.S. Nuclear Regulatory Commission

G. Greene, Y. Celebi, W. Gunther
Brookhaven National Laboratory
Upton, NY 11973

Introduction

The Japanese earthquake and tsunami event on March 11, 2011, illustrated how the restoration of AC power can be significantly impacted by external events and can take a longer time to recover than was previously postulated. The NRC's Office of Research sponsored testing at Brookhaven National Laboratory (BNL) to evaluate the ability of typical lead acid batteries used in U.S. Nuclear Power Plants to supply the necessary DC loads to support reactor core cooling and critical instrumentation requirements for up to 72 hours. A second part of the testing employed DC load profiles from four nuclear power plants (3 PWRs and 1 BWR) that were obtained in cooperation with the nuclear industry through the Nuclear Energy Institute (NEI).

In conducting this study, BNL used 12-cell battery strings from three nuclear grade battery suppliers and measured specific gravity, cell voltages, and recharge current while also monitoring cell and ambient temperatures. The preliminary results of how the batteries performed on these tests are discussed in this paper.

Objective

The purpose of this research project was to model and test the response of representative nuclear qualified batteries to a loss of off-site and on-site ac power known as Station Blackout (SBO) for an extended period of time beyond the current design basis for the batteries. The testing involved operating the batteries at lower loads and simulating four sample SBO load profiles provided by the NEI. As a result, this project provided information on the maximum duration available from typical nuclear station batteries to support decay heat removal and supply critical instrumentation during an extended SBO event.

Overview

The testing was comprised of two sequences. Sequence 1 verified how long the batteries could operate at reduced discharge rates. These series of tests provided a set of performance expectations for extended battery operation under lower load conditions and provided data that could be used to assess the state of health of the batteries such as specific gravity, temperature, and recharge characteristics. The battery vendors provide general specifications for their batteries at various load conditions as depicted in Table 1. For example, Enersys had data to 72 hours, C&D to 12 hours, and GNB to 8 hours. Sequence 1 testing acquired the battery data to fill in the data gaps of published data as identified by the shaded areas in Table 1, and allowed a comparison of the tested batteries against the published data for the 8-hour performance tests that BNL performed to serve as a set of baseline readings.

Table 1: Battery Vendor Data – Rated Discharge Current vs. Time for a 1.75V End Voltage

Battery/Extended Test Load (amps)	1 hour	2 hours	4 hours	**8 hours (Baseline)**	12 hours	24 hours	36 hours	48 hours	72 hours
Enersys 2GN-23	925	605	385	225	160	89	**(60)**	**(47)**	31.9
Exide/GNB NCN-21	750	515	317	187	**(132)**	**(71)**	**(50)**	**(39)**	**(27)**
C&D LCR-33	1167	799	500	290	205	**(111)**	**(77)**	**(60)**	**(42)**

In Sequence 2, extended SBO conditions were simulated by a series of load profiles and load shedding schemes to determine how long the battery can carry the actual plant loads. Each battery was tested using four different load profiles that were supplied by the Nuclear Energy Institute (NEI) and approved by NRC. The four load profiles were from 4 different Nuclear Power Plants who had analyzed the equipment they needed to achieve adequate core cooling while providing the critical instrumentation required by plant operators and decision makers.

The series of service test runs were conducted so that each battery string could be placed on a 100-hour equalize charge followed by a two-week float charge to restore the battery to a fully-charged state prior to its next test. A fully-charged battery for each test was documented by a stabilized float current below 2.0 amps and a nominal midpoint specific gravity reading of 1.215 for all cells. Battery conditions were recorded prior to the start of each cycle that included individual cell voltages, overall float current, and the specific gravity of all cells. Three measurements of specific gravity (top, midpoint, and bottom) were taken on two cells to document any electrolyte stratification prior to testing. Each battery was subjected to an 8-hour performance test prior to the start of sequence 2 and at the end of sequence 2 testing in order to assess any changes in battery capacity and capability as a result of the testing protocol.

Observations

Sequence 1 Test Results

Time versus current response

In Sequence 1, a total of 16 tests were conducted; 8-hour baseline tests on each of the three batteries, 11 tests to fill in the data gaps from the published vendor tables, and 2 tests of the Enersys battery at 72 hours, one of which was conducted with only 10 cells in the string. In each of these tests, we endeavored to start the test with the ambient temperature as close to 77°F as possible in order to minimize the amount of correction to the desired test current.

Discharge current was carefully controlled by the Alber battery test set and the test was allowed to run until the battery reached an average of 1.75V/cell (21.0 volts for our 12 cell string). From the data collected, a battery capacity could be calculated along with the amount of ampere-hours discharged. Table 2 illustrates the ampere-hours discharged for the tests. Note the increase in ampere-hours as the load was reduced to achieve the longer run times. This is indicative of the significant increase in efficiency of the battery at lower loads. The column on the right quantifies this increase in available ampere-hours between the 72 hour duration test and the 8 hour duration test.

Table 2: Ampere-Hours Discharged during extended operational tests

Battery/ Test Duration	8 hours	12 hours	24 hours	36 hours	48 hours	72 hours	% Change (72-hour to 8-hour test)
Enersys 2GN-23	1810	-	-	2178	2170	2068	**114%**
Exide/GNB NCN-21	1490	1573	1895	1933	1984	1915	**128%**
C&D LCR-33	2404	-	2919	3008	3066	3129	**130%**

By plotting the information derived from these tests along with published vendor data, one can extrapolate expected battery availability for any steady state current from one to 72 hours. This is illustrated in Figure 1.

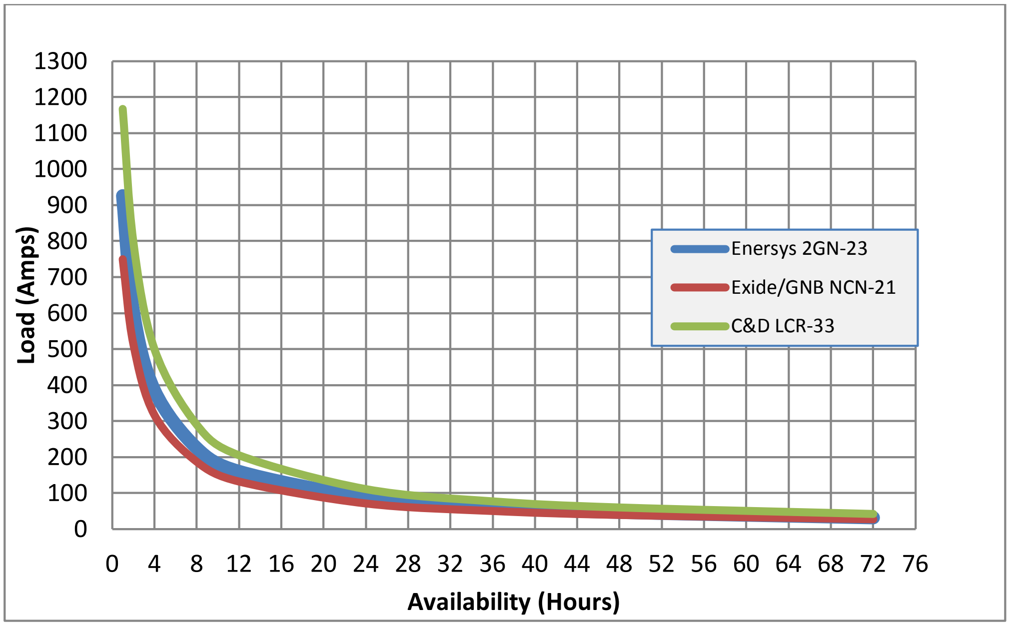

Figure 1: Battery availability versus load from 1 to 72 hours

Time versus voltage response

Figure 2 is the cell voltage response for one of the three BNL batteries that was experienced during the 72-hour performance test. The cell exhibited an initial drop from 2.25 to about 2.05 volts when the load was applied, a linear decrease over the major part of the test, and an accelerated decrease in voltage at approximately 1.85 volts to its terminal voltage of about 1.75 volts. This figure illustrates the initial drop in voltage that the battery experiences when it begins to discharge. After the voltage stabilizes from its initial drop, the voltage gradually decreases with time as the active materials and sulfuric acid are consumed in the chemical reaction. Toward the end of discharge, insufficient quantities of active material or sulfuric acid exist to sustain the chemical reaction and the voltage declines more rapidly. This response was typical for each cell in the battery string and for each of the three battery types.

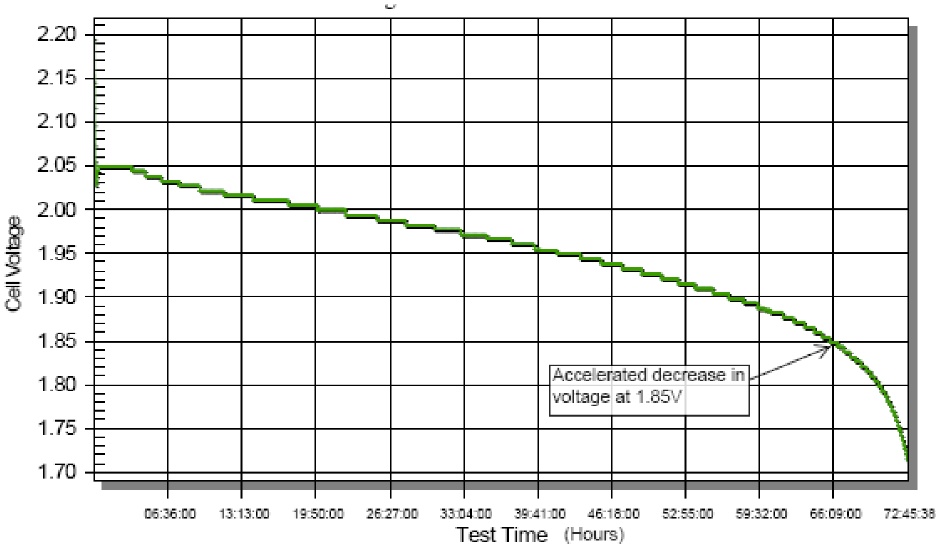

Figure 2: C&D Cell #10 response during the 72-hour test

In every case except one, the extended operational testing ended automatically when the overall battery string voltage reached 21.0 volts (1.75V/cell on average). The other mechanism to automatically stop a test was if any one cell reached a voltage of 1.3 volts. This was a conservative setting to ensure that a cell did not go into reversal which could have damaged the cell and jeopardized the test program.

Others have noted that cell variability in a discharge test is common and is not necessarily problematic; there are always weaker and stronger cells. Nispel and Shane [2] note that sharp knees in the voltage response curve are usually indicative of acid limitation. Table 3 provides an example of the end voltages for each cell in one of the battery strings. With better awareness, we might have detected that cell #2 in the Enersys battery string was consistently the lowest voltage cell. An equalizing charge may have brought it into line with the other cells resulting in better overall battery string performance.

Table 3: Enersys cell voltages at the conclusion of the extended duration tests

Cell No.	8-hour test	36-hour test	48-hour test	72-hour test
1	**1.776**	**1.758**	**1.752**	**1.786**
2	**1.655**	**1.708**	**1.675**	**1.299**
3	**1.775**	**1.746**	**1.743**	**1.784**
4	**1.755**	**1.752**	**1.752**	**1.792**
5	**1.755**	**1.744**	**1.752**	**1.795**
6	**1.730**	**1.722**	**1.723**	**1.772**
7	**1.793**	**1.784**	**1.786**	**1.821**
8	**1.781**	**1.790**	**1.804**	**1.827**
9	**1.775**	**1.779**	**1.785**	**1.816**
10	**1.766**	**1.775**	**1.777**	**1.809**
11	**1.793**	**1.791**	**1.799**	**1.824**
12	**1.763**	**1.768**	**1.775**	**1.810**
Variation (ΔV)	**0.138**	**0.083**	**0.129**	**0.528**

Time versus specific gravity

Specific gravity measurements of each cell were taken before and after each performance test, and following the recharge of the battery that was conducted at a float voltage of 2.25 V/cell. On two cells, additional specific gravity readings were taken at the top of the cell and at the bottom of the cell in order to determine the extent of electrolyte stratification.

The data that are of particular interest relate to the specific gravity readings obtained at the end of the discharge cycle, specifically the relationship of the midpoint specific gravity readings as a function of the length of the discharge test. That is, the longer the test, the lower the value of the specific gravity at the end of the test. The end point of 1.020 obtained on the 72-hour discharge tests for all three vendors is equivalent to about 3% acid; the normal acid concentration at a specific gravity of 1.215 is 29%, and the typical acid concentration at the end of an 8-hour performance test is 12%. The midpoint readings from each of cells was averaged and plotted versus the performance test duration time. The results are shown in figure 3.

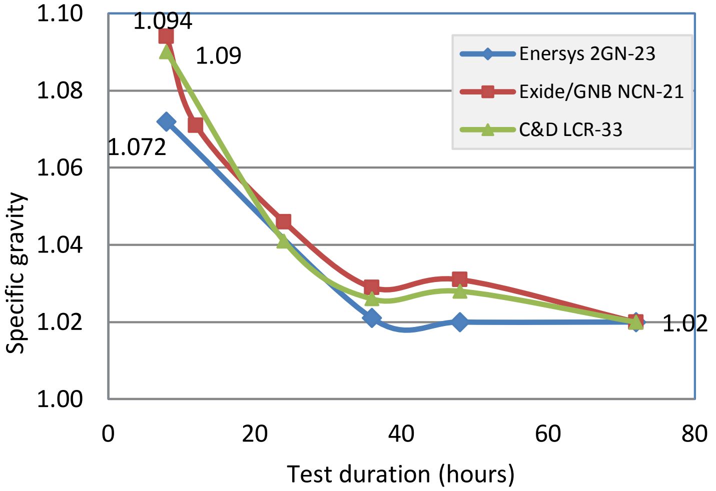

Figure 3: Average End of Test Specific Gravity - Sequence 1 Tests

The most significant aspect of this observation is that if the battery electrolyte is depleted and there is a delay in recharging the battery (ac power is not available), it may not be possible to recharge it due to the unavailability of acid in the cell.

Sequence 2 Test Results

In Sequence 2 of the test program, extended SBO conditions were simulated by a series of load profiles and load shedding schemes to determine how long the battery could carry the projected plant loads. The batteries were tested using four different load profiles that were supplied by the Nuclear Energy Institute (NEI) and approved by NRC. The four load profiles were from four different NPPs (3 PWRs and 1 BWR) who had analyzed the equipment they needed to achieve adequate core cooling while providing the critical instrumentation required by plant operators and decision makers. These profiles incorporate load shedding to extend the battery operating time during the SBO. For one of the load profiles, the assumed time for the initiation of load shedding was varied from 30 minutes to 120 minutes to understand the impact of this important parameter. For another of the profiles, five one-minute loads were applied after ten hours to simulate the effects of periodic motor-operated valve (MOV) or pump operation. And finally, one of the load profiles was tested without scaling the loads to the tested batteries in order to account for that parameter in the test results.

Table 4 summarizes the battery availability times for all four load profiles. In general it can be seen that there is a consistently close relationship between the estimated times that were predicted for battery availability versus the actual measured times from the testing of the four load profiles. The table provides columns for the estimated times using two different methods as well as the measured test time. One method used was to follow the IEEE 485-2010 process for battery sizing; the second estimate was based on an algorithm that was developed by BNL based on the Sequence 1 testing results and available vendor data. The table shows that the battery availability met or exceeded the estimates in 7 of the 12 tests. The temperature of the battery at the start of the test is also included. Recall that IEEE performance tests are based on a temperature of 77°F. Our goal was to be as close to that number as possible at the start of the test in order to minimize the need to apply any correction factors.

Table 4: Summary of Estimated To Actual Battery Availability Times (Hours)

TEST #	BATTERY	Estimate IEEE 485	Estimate BNL DATA	MEASURED	TEMP (°F)
Test Series #1					
4	C&D	27.0	25.3	**26.6**	77
5	GNB	29.2	30.4	**32.6**[1]	78
6	Enersys	29.2	28.4	**27.7**	78
Test Series #2					
7	C&D	40.6	37.7	**39.9**	77
8	GNB	20.3	21.2	**22.2**[1]	77
9	Enersys	26.3	27.2	**26.3**	77
Test Series #3					
10	C&D	30.4	28.5	**30.6**[1]	77
11	GNB	36-40	42.8	**45.2**[1]	78
12	Enersys	36-40	42.7	**41.2**	78
Test Series #4					
13	C&D	32.0	30.1	**32.2**[1]	78
14	GNB	42.0	44.9	**47.7**[1]	78
15	Enersys	43.8	45.7	**44.2**	77

[1] Measured battery availability was greater than both estimates

Employing the load shedding schemes that have been put forward by the nuclear industry through NEI, the measured durations from the batteries varied from 22 to 48 hours, much greater than the current nuclear plant coping times of 4 to 8 hours.

As noted in the extended battery testing, the voltage response of the battery during long-term constant load discharges is nearly linear until the cell voltage nears 1.85 volts at which time the voltage decrease accelerates. The other voltage response characteristic noted in the load profile testing was that as the load experiences a step decrease, the voltage slightly increases for a short time and then reverts to a near-linear decrease. This characteristic can be seen in figure 4, in which there is an immediate drop in voltage when the 1 minute load is applied; the voltage increases when that load is replaced by a lower two hour loading and then increases again after those 2 hours when a lower steady state load is maintained on the battery string until the overall voltage decreases to 21.0 volts.

A similar response was seen when five one-minute loads were applied after load shedding had occurred. A temporary voltage dip of as much as 0.5 volts was observed on the 12 cell battery strings. This would equate to a 2.5 volt dip for a 60 cell battery string application typically used in nuclear power plants. With the battery supplying various power supplies and inverters that often have low voltage protection, this voltage fluctuation could reach the setpoint resulting in the unintended loss of important instrumentation and controls. Nuclear plants whose analyses indicate a need to operate equipment intermittently during a postulated extended loss of ac power event should consider the effect of the voltage changes that result from such operations on the supplied equipment.

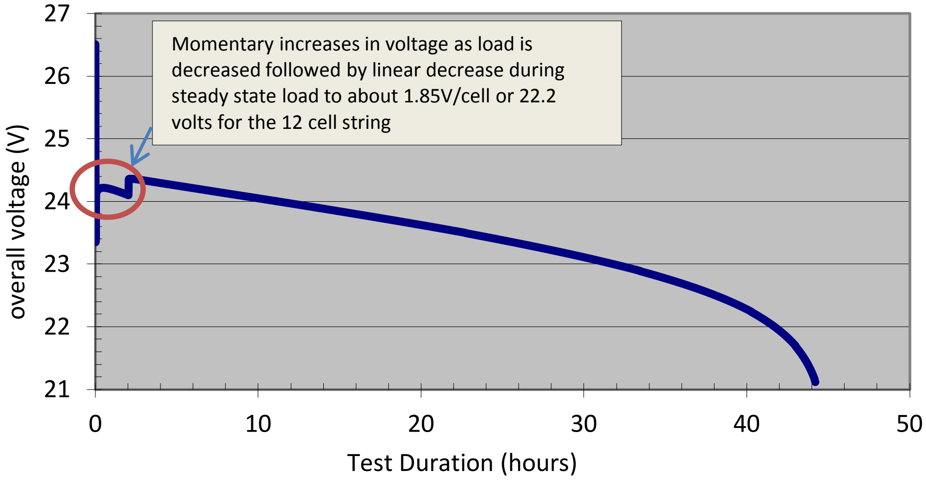

Figure 4: GNB Voltage Response to Test Series #4

Specific gravity measurements indicated that the electrolyte is quite depleted following the extended battery operations associated with each load profile. Figure 5 is a plot of the post discharge average midpoint specific gravity readings for the three battery types. Note the significant decrease in specific gravity as the test duration is increased. For instance, the 8-hour baseline performance tests had an average midpoint specific gravity that ranged from 1.08 to 1.10 for the 3 battery types, while the value decreased to between 1.02 and 1.04 when the test duration exceeded 36 hours. While this did not directly affect the battery's ability to provide load, it could impact its ability to be recharged especially if there is a delay in the time between discharge and initiation of the recharge.

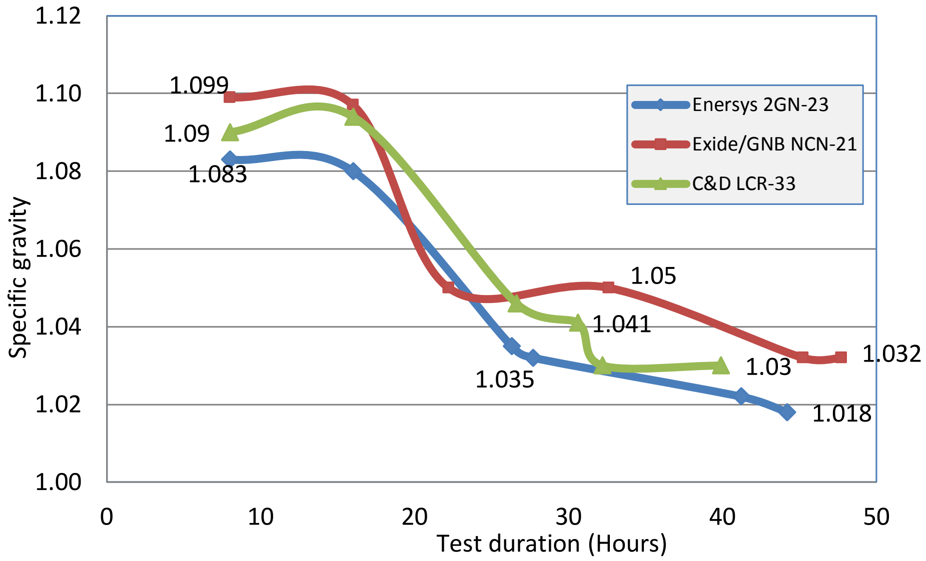

Figure 5: Average "end-of-test" midpoint specific gravity readings for Sequence 2 tests

Summary and Preliminary Conclusions

Overall the batteries tested at BNL met their performance objectives during the conduct of extended battery operation. While the number of discharge/recharge cycles that these batteries have been subjected to during the Phase 1 testing described in NUREG/CR-7148 [1] and the testing described in this report is more than what is expected to be experienced during their nominal 20 year life, there was no apparent degradation or reduction in their capacity. These batteries were neither artificially aged nor subjected to the same aging criteria that would be expected in their 20 year life in a nuclear power plant so these factors need to be evaluated to determine how the test results provided in this document are applied.

The significant observations made from this testing that are described in this paper are:

1. For the SBO-like profiles provided by industry, the measured durations from the batteries varied from 22 to 48 hours, much greater than the current plant SBO coping times of 4 to 8 hours.
2. Battery performance out to 72 hours has been demonstrated. The efficiency of the battery is increased at lower loadings, thereby increasing the available battery amp-hours.
3. The projected availability of a battery can be accurately calculated using IEEE 485 and battery vendor information. This includes the impact of the time to initiate and complete load shed actions.
4. The battery voltage response during discharge is generally linear over the discharge but decreases rapidly at about 1.85V. The temporary voltage drop that occurs when intermittent loads are applied during extended operation can impact power supplies and inverters powered by the battery if the supplied voltage is near the low voltage protection setpoint.
5. There is significant depletion of the electrolyte during long duration discharges due to the higher efficiency of the battery under lower current discharge conditions.
6. No unusual battery failure mechanisms were observed during extended operational testing; however, the significant depletion of the electrolyte during very long discharges (> 36 hours) could impact the ability to recharge the battery under some conditions (e.g., a delay between the time of battery depletion and initiation of recharge)

References

1. NUREG/CR-7148, *Confirmatory Battery Testing: The Use of Float Current Monitoring to Determine Battery State-of-Charge*, October 2012.
2. Nispel, Mike and Shane, Rod; *“Interpreting Battery Ratings and Discharge Tests – How the Same Numbers can be Interpreted in Different Ways”*, 2012 Battcon Conference.
3. *Stationary Battery Guide: Design, Application, and Maintenance*, EPRI TR-100248, Rev. 2, August 2002.

Acknowledgements

The authors greatly appreciate the open dialogue and communication of information and ideas from the nuclear industry, the battery vendors, EPRI, and the DOE. The contributions from Kyle Floyd, Rich Reister, Jan Reber, Larry Carson, Gordon Clefton, Wayne Johnson, and Ken Caraway were instrumental in completing the work that resulted in this paper.