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Testing to Evaluate Extended Battery Operation in Nuclear Power Plants

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Testing to Evaluate Extended Battery Operation in Nuclear Power Plants

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ABSTRACT

The Japanese earthquake and tsunami event on March 11, 2011, illustrated the fact that restoration of the alternating current (AC) power supply at nuclear power plants (NPPs) can be significantly impacted by external events and can take a longer time to recover under certain scenarios. Therefore, a lesson learned from the Japanese event that may be applicable to U.S. NPPs is the need to examine the extended loss of alternating current power (ELAP) conditions and determine if the existing vented lead acid batteries can function beyond their defined design basis (or beyond-design basis if existing Station Blackout (SBO) coping analyses were utilized) duty cycles in order to support core cooling. The NRC's Office of Nuclear Regulatory Research sponsored testing to evaluate the battery's performance availability and capability to supply the necessary direct current (DC) loads to support core cooling and instrumentation requirements for extended periods of time. Plant profiles from four NPPs [3 Pressurized Water Reactors (PWRs) and 1 Boiling Water Reactor (BWR)] were obtained from the nuclear industry through the Nuclear Energy Institute (NEI) and were used for this test program. The testing provided an indication of the amount of time available (depending on the actual load profile) for batteries to continue to supply core cooling equipment beyond the original duty cycles for a representative plant. Testing also demonstrated that battery availability can be significantly extended using load shedding techniques to allow more time to recover AC power. The projected availability of a battery can be accurately calculated using the IEEE Standard 485-2010, "IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications," or using the empirical algorithm described in this report. This report provides detailed test results and analysis regarding the battery's performance availability and capability for the tested load profiles.

FOREWORD

This NUREG report documents the testing that was sponsored by the U.S. Nuclear Regulatory Commission (NRC) and conducted at Brookhaven National Laboratory (BNL) to determine the ability of the vented lead-acid batteries used in nuclear power plants (NPPs) to operate during an extended loss of alternating current power (ELAP) event which is similar to a Station Blackout (SBO) with the exception that alternate alternating current (AAC) power sources are not available and the emergency diesel generators and offsite power are assume non-recoverable.

The Japanese earthquake and tsunami event on March 11, 2011, illustrated the fact that restoration of alternating current (AC) power at NPPs can be significantly impacted by external events and can take a long time to recover under certain scenarios. Therefore, a lesson learned from the Japanese event that may be applicable to U.S. NPPs is the need to examine ELAP conditions and determine if the existing safety-related Class 1E batteries can function beyond their design basis (or beyond-design basis if existing Station Blackout (SBO) coping analyses were utilized) duty cycles to support core cooling.

The purpose of this research project was to test the batteries' response to ELAP conditions and to determine the batteries' performance capability. The testing simulated four load profiles that were longer periods of time than typical SBO coping times and, in some respects, with less severe low load profiles. As a result, this testing provided information on the maximum duration available from typical NPP batteries to support decay heat removal (natural circulation) during an ELAP event. The four typical load profiles tested were developed in cooperation with the Nuclear Energy Institute and the Electric Power Research Institute, along with voluntary participation from several nuclear power plants. The profiles were collectively derived from typical SBO loading profiles at several NPPs (three pressurized water reactors and one boiling water reactor) and modified to address the impacts of the time to initiate load shedding and the effect of intermittent loads.

BNL retained three sets of nuclear qualified batteries from a previous test arrangement. The three battery vendors were Enersys, Exide/GNB, and C&D Technologies. Each battery consisted of twelve battery cells that are the same models typically used in NPP safety-related Class 1E direct current (DC) power systems. The production and control of the batteries met requirements set forth in Appendix B of Title 10 of part 50 of the Code of Federal Regulations and Regulatory Guide 1.129 that are installed in safety-related Class 1E DC power systems at NPPs. The test setup was consistent with a typical nuclear power plant's Class 1E battery system design except for seismic supports, the number of cells in the battery strings used, and an aging factor to simulate a near-end-of life condition. The batteries used in this testing were deep cycled many times, which was equivalent to the number of deep discharges that a nuclear grade battery would typically see during its typical 20-year life. Nonetheless, the most significant uncertainty associated with the test results is that the batteries were not pre-aged to simulate an end-of-life condition. In order to account for the fewer number of cells in a battery string, a scaling factor was used in the analysis of the test results.

The testing described in this NUREG report provides an indication of the amount of time available (depending on the load profile) for batteries to continue to supply core cooling equipment and vital instrumentation during an ELAP event. This extended power supply may be helpful in managing the recovery of AC power to the battery chargers and/or AC power in general to maintain or restore core cooling during an ELAP event.

Overall, the measured battery availability varied from 22 to 48 hours. Nevertheless, several plant-specific factors can reduce the extended battery times. These factors include aging due to the length of time a battery is in service and the battery's ambient operating temperature. Conversely, testing confirmed that the batteries can be operated up to 72 hours at a constant load.

The testing also demonstrated that battery performance is consistent with manufacturer performance data. This enabled the staff to conclude that battery performance can be accurately predicted using the IEEE Standard 485-2010, "IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications" or using the empirical algorithm described in this report. All of this information can be valuable to nuclear power plant licensees in planning strategies for an ELAP event to maintain key safety functions.

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EXECUTIVE SUMMARY

The Japanese earthquake and tsunami event on March 11, 2011, illustrated the fact that restoration of AC power at nuclear power plants (NPPs) can be significantly impacted by external events and can take a long time to recover under certain scenarios. Therefore, a lesson learned from the Japanese event that may be applicable to the U.S. NPPs is the need to examine ELAP conditions and determine if the existing safety-related Class 1E batteries can function beyond their design basis (or beyond-design basis if existing Station Blackout (SBO) coping analyses were utilized) duty cycles to support core cooling. This report describes the research approach that was taken, the testing activities that were performed, and the results and conclusions drawn from this research effort.

BNL used the three sets of nuclear qualified batteries from a previous test arrangement as described in NUREG/CR-7148 [1]. Each battery string consisted of 12 cells. The production and control of the cells met 10 CFR 50 Appendix B Criteria and Regulatory Guide 1.129 that are installed as safety-related Class 1E DC power systems at nuclear plants. Test equipment was calibrated to national standards to reduce the parametric uncertainty associated with measurements of current, voltage, specific gravity, temperature and time. The batteries were tested in a manner consistent with how they would be operated in a typical nuclear power plant's safety-related Class 1E DC power system using a resistive load bank. The most significant uncertainty associated with the test results is that the batteries were not pre-aged to simulate an end-of-life condition for the batteries. Further discussion of the test assumptions and uncertainty can be found in section 1.3 of this report.

Two sets of test results are provided in this report denoted as Sequence 1 and Sequence 2. In Sequence 1, a series of tests were conducted to verify various lengths of time that the tested batteries can operate at reduced discharge rates. The battery vendors provide capacity specifications for their batteries at various load conditions. For example, Enersys has published capacity data to 72 hours, C&D to 12 hours, and GNB to 8 hours. Sequence 1 testing at BNL acquired battery capacity data to fill in the data gaps of the vendor data out to 72 hours with discharge intervals of 8, 12, 24, 36, 48, and 72 hours. BNL compared the tested batteries against the published data for the 8-hour performance test that served as the baseline readings. The tests allowed BNL to develop an algorithm to predict the expected availability for a battery at any given load. This algorithm was used along with IEEE Standard 485-2010 to predict the battery run times for the load profiles tested in sequence 2.

In Sequence 2, ELAP conditions were simulated by a series of load profiles and load shedding schemes to determine how long the battery could carry the anticipated plant loads. These tests used 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) who had analyzed the equipment needed to assure core cooling during an ELAP event while providing the critical instrumentation required by plant operators and decision makers. These load profiles were designated as EBR-2 through EBR-5 to preserve the anonymity of the NPPs who volunteered their load profile information. In each of these tests, the test terminated when the overall battery string reached 21.0 volts (an average of 1.75 volts/cell). Some NPPs have calculated higher battery end voltages due to specific load demands or the length of cable from the battery to the loads, so their expected battery availability times would be less but calculable from the test data. Four observations of relevance to understanding battery performance for extended battery duty cycles (i.e., those greater than 8 hours which is the maximum credited battery coping time to satisfy the existing SBO Rule) are summarized below:

<u>Observation 1</u>: In Sequence 1 of the test program, a series of performance tests were conducted to verify various lengths of time that the tested batteries can operate at reduced discharge rates. The battery vendors provide capacity specifications for their cell types at various load conditions as depicted in Table ES-1. For example, Enersys published data to 72 hours, C&D to 12 hours, and GNB to 8 hours. The testing at BNL acquired battery data to fill in the gaps of vendor data as identified by the shading and parentheses in Table ES-1. BNL also tested the batteries to confirm the 8 hour data point that was available from each vendor.

Table ES-1 Summary of Sequence 1- Extended Battery Operational Testing

Test Duration (amps)/Battery Type	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)**

The resulting composite information of battery availability for a given load from 1 to 72 hours is displayed in Figure ES-1. The C&D battery LCR-33 battery has an 8-hour rating of 2320 ampere-hours; the Enersys 2GN-23 battery has an 8-hour rating of 1800 ampere-hours; the Exide/GNB NCN-21 battery has an 8-hour rating of 1496 ampere-hours. The testing showed that batteries typically used in NPPs could safely operate for 72 hours when there is load reduction between (25 and 45 amps in this case), depending on the ampere-hour capacity of the battery.

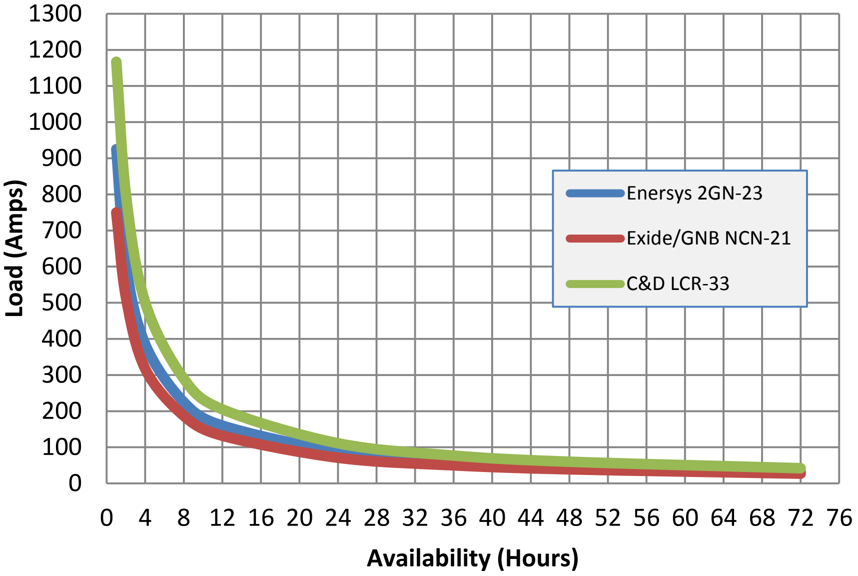

Figure ES-1 Extended Battery Availability Test Results

In Sequence 2 of the testing program, battery duration times obtained during testing were consistent with the estimates obtained using the approach provided in IEEE Standard 485-2010 [10] and an algorithm that was developed by BNL using battery vendor data supplemented by the extended operational testing results achieved in the Sequence 1 testing (see Section 1.5 for the algorithm development).

Table ES-2 contains the results of the Sequence 2 tests along with the estimates that were made of battery availability prior to the test. Load shedding was initiated at various times and the loads applied to the batteries were based on the data provided by the NEI. The table illustrates how accurately battery availability can be calculated once the loads and their duration are obtained.

Table ES-2 Summary of Test Duration Times Compared to Calculated Estimates

TEST #	BATTERY TYPE	Estimate (Hours); IEEE 485	Estimate (Hours); BNL	Test Measurement (Hours)	Temp. (°F); (start of test)
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
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
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
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 time exceeded both estimates

Observation 2: The voltage profiles for the cell and overall string voltage were linear through most of the discharge until it approached 1.85 volts where it decreased more rapidly. This non-linear response at the point where the overall battery voltage is about 111 volts (1.85V x 60 cells) has important operational implications since the ability to supply critical loads will be significantly diminished. This consistently observed response indicates the need to more carefully monitor the battery as it approaches its end voltage. An example of the voltage response is illustrated in Figure ES-2.

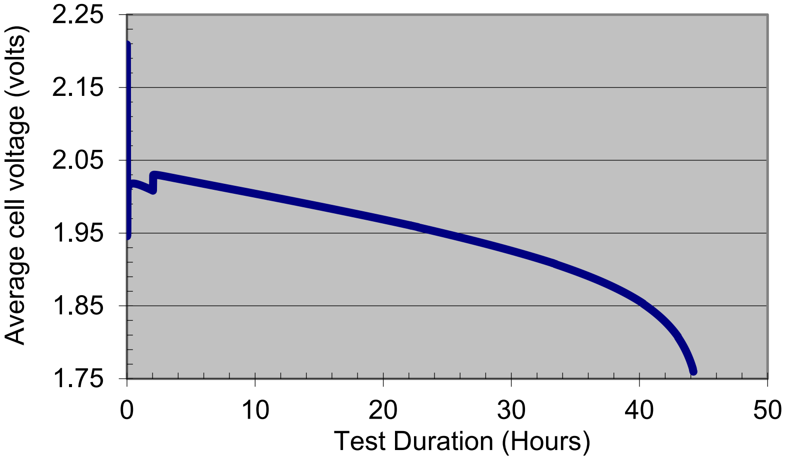

Figure ES-2 Enersys load profile EBR-2 - Average Cell Voltage

Observation 3: Specific gravity was routinely measured on all cells prior to each test, at the completion of the discharge cycle, and following the recharge of the battery. Specific gravity is a measure of a cell's state of charge. An important observation made following the longer duration test is that the specific gravity had decreased to a very low level as compared to the 4-hour and 8-hour tests that are typically used to measure battery capacity. The data that is of interest relates to the specific gravity readings obtained at the end of the discharge cycles, 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 fully charged acid concentration is 29% for a specific gravity of 1.215 and the typical acid concentration at the end of an 8-hour performance test is 12%. The average cell midpoint specific gravity measured at end of the various tests is illustrated in Figures ES-3 and ES-4 for Sequences 1 and 2, respectively.

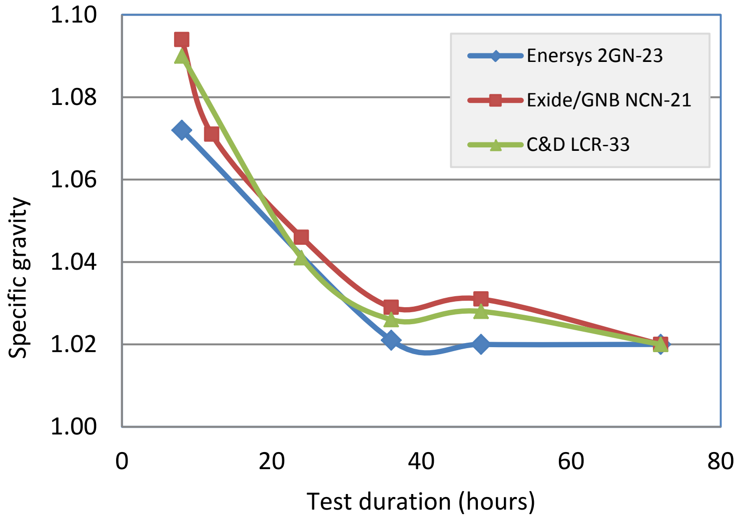

Figure ES-3 Average End of Test Specific Gravity - Sequence 1 Tests

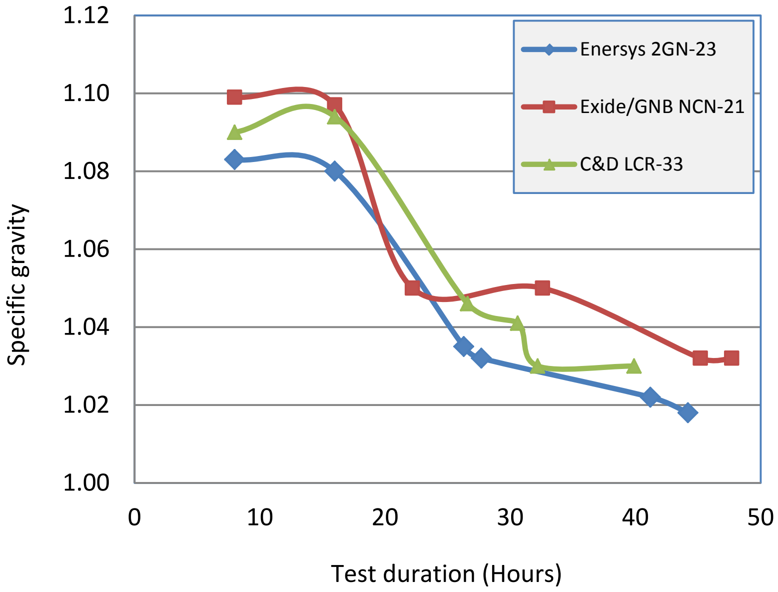

Figure ES-4 Average End of Test Specific Gravity - Sequence 2 Tests

The implication of this observation is that the ability of the battery to be recharged once ac power becomes available could be jeopardized if the specific gravity remains extremely low for several hours. One of the battery vendors noted that in low specific gravity circumstances, the sulfate on the face of the plate can dissolve and re-crystallize back onto the surface in a continuous layer, essentially forming a lead sulfate/lead hydrate surface coating over the whole plate. This, in combination with the very low specific gravity of the electrolyte between the plates, can combine to create a sufficiently high resistance to impede current flow making the battery inoperable.

Observation 4: The time to recharge the battery to a fully charged state is longer following the long duration discharge tests. Following each discharge during the Sequence 1 testing, the battery was placed on a float charge as recommended by the battery vendors (27 volts or 2.25 V/cell) and the recharge current monitored for 24 hours. Figure ES-5 illustrates the recharge current curve for each of the extended operational tests of the C&D battery. The other two battery types exhibited a similar response.

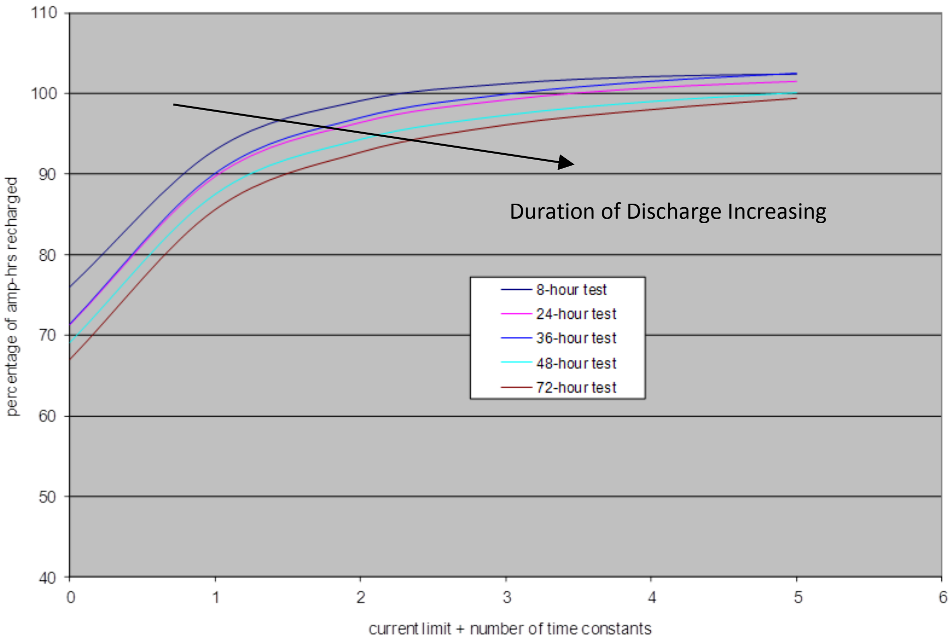

Figure ES-5 Recharge Current Curves for C&D cycles 15-19 (Sequence 1 Tests)

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ABBREVIATIONS AND ACRONYMS

BNL	Brookhaven National Laboratory
BWR	Boiling Water Reactor
EPRI	Electric Power Research Institute
ELAP	Extended Loss of AC Power
IEEE	Institute of Electrical and Electronics Engineers
LOCA	Loss of Coolant Accident
LOOP	Loss of Off-site Power
MOV	Motor Operated Valve
NEI	Nuclear Energy Institute
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
PWR	Pressurized Water Reactor
PRA	Probabilistic Risk Assessment
SBO	Station Blackout

1 INTRODUCTION

In 1991, the NRC published NUREG 1150, "Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants." In this study the NRC used new and improved Probabilistic Risk Analysis (PRA) techniques for consequence analysis. The study was a significant turning point in the use of PRA in all regulatory matters. As a result, risk informed regulation such as 10 CFR 50.63, Loss of all alternating current power [station blackout (SBO)], was implemented. The NRC also issued guidance for addressing severe accidents and PRA in the following document: "NRC Policy Statement on Severe Reactor Accidents regarding future designs and existing plants." This guidance contains four items for new and operating reactors. One of the four items was a special focus on assuring the reliability of decay heat removal systems and reliability of alternating current (AC) and direct current (DC) operated steam driven/diesel driven cooling systems. The DC-operated core cooling systems are generally relied on for SBO conditions.

The Japanese earthquake and tsunami event on March 11, 2011, illustrated the fact that restoration of AC power at nuclear power plants (NPPs) can be significantly impacted by external events and can take a longer time to recover under certain scenarios. Therefore, a lesson learned from the Japanese event that is applicable to the U.S. reactors is the need to examine extended loss of AC power (ELAP) conditions and determine if the existing safety-related Class 1E batteries can function beyond their design basis (or beyond-design basis if existing Station Blackout (SBO) coping analyses were utilized) duty cycles to support core cooling.

This Report describes the efforts undertaken and the results achieved to satisfy the objectives of this research.

1.1 Objectives

The purpose of this research project was to model and test the response of representative samples of nuclear qualified batteries to ELAP conditions to determine battery capacity and capability under these conditions. The testing involved operating the batteries at the lower loads needed to extend the availability of the battery, and simulating four sample load profiles provided by the NEI. The four load profiles were from four different NPPs who had analyzed the equipment needed to assure core cooling during an ELAP event while providing the critical instrumentation required by plant operators and decision makers. As a result, this project provided information on the durations available from typical safety-related Class 1E batteries to support decay heat removal and supply critical instrumentation during an ELAP event.

BNL used the three sets of nuclear qualified batteries from a previous test arrangement as described in NUREG/CR-7148 [1]. The three battery types are:

- Enersys type 2GN-23 cells with an 8-hour rating of 1800 Ampere-hours (A-hrs) at 225 Amperes (A),
- Exide GNB type NCN-21 cells with an 8-hour rating of 1496 A-hrs at 187 A, and
- C&D Technologies type LCR-33 cells with an 8-hour rating of 2320 A-hrs at 290 A.

Each battery string consisted of 12 battery cells. The production and control of the cells met 10 CFR 50 Appendix B Criteria and Regulatory Guide 1.129 that apply to batteries that are installed as safety-related Class 1E at NPPs. The test arrangement is consistent with a typical NPP's safety-related Class 1E battery design except for seismic supports and the fact that a battery string at a NPP typically consists of 60-cell battery strings for a 125 Volt (V) DC power system. While these batteries were not pre-aged they had each had been subjected to fifteen deep discharges (4-hour capacity tests) prior to the start of this program. This is an equivalent number of deep discharges that a nuclear grade battery would typically see during its typical twenty-year life.

1.2 Research Approach

The approach taken in this research project involved testing battery models that are typically used in commercial NPPs in the U.S. The batteries were subjected to a series of tests to simulate a range of loads that are representative of a variety of SBO conditions in which non-essential or redundant equipment is de-energized to extend the output of the battery. Actions of this nature are known as load shedding.

A terminal voltage of 1.75 volts/cell was used as the desired end state for each of the load tests. The 1.75 volts per cell is equivalent to 105 volts for a 60-cell battery string typically used in a NPP and reflects a common end state used by battery vendors and NPPs to evaluate battery functionality. Other battery parameters were monitored such as electrolyte temperature and specific gravity to further assess the changes in battery state as the various loads were applied. Float current and specific gravity were measured to determine when the battery had returned to a fully charged state following each discharge test. Following each series of tests, the data were compiled and transmitted to the NRC and industry representatives to discuss preliminary observations regarding the battery performance during extended operation and to make minor adjustments to the test plan as necessary.

1.3 Assumptions and Measures of Uncertainty

In conducting the testing to assess the extended operation of batteries beyond their typical design times, certain assumptions were made that could contribute to slight uncertainties in the final test outcome:

a. The testing was performed under relatively constant temperature and humidity laboratory conditions. In a postulated ELAP event, there is a potential for other factors such as extreme temperatures and humidity to exist in the battery room. These conditions could impact the ability of the battery to perform its function for the length of time that was achieved in the laboratory.
b. Three battery models from three battery manufacturers were used in this test program. It is assumed that other models and types of vented lead acid batteries used in NPPs would perform similarly to the batteries tested.
c. The batteries tested were not pre-aged raising the uncertainty that older batteries could perform differently. It should be noted that the NPP load profiles that were provided did apply an aging correction factor of 1.25 that effectively reduces the expected battery availability (see section 3.3).
d. A resistive load bank was used to simulate plant loads. Some DC loads in a NPP are motors which have an inrush current when started. For the load profile testing (EBR-3), the inrush current value was assumed to exist for the entire one minute of MOV operation. This higher than expected value still did not affect overall battery availability but did cause a temporary voltage dip that could affect the supplied equipment.
e. The endpoint of the tests was when the average cell voltage of the battery reached 1.75 volts (21.0 volts for the BNL 12-cell battery string). It is recognized that not all plants can tolerate an end voltage of 1.75 volts due to cable runs or specific equipment voltage

needs. Therefore, it is likely that the BNL battery availability times exceed what most plants will experience simply due to the plant-specific end voltage requirements.

1.4 Test Facility

BNL established a controlled area for this testing that achieved the needed environmental and electrical safety parameters contained in IEEE and manufacturer's standards, and meets good practices and BNL safety procedures. The battery laboratory contains temperature, humidity, and hydrogen monitoring and control, electrolyte spill control measures, and adequate air flow to prevent hydrogen accumulation. Access to the testing area is limited to those directly involved with the battery testing program. Data acquisition equipment is installed to acquire and store the measured parameters during testing.

1.4.1 Laboratory Space

Testing was performed in a high bay area located in Building 526 at BNL. The dedicated space for the battery testing is approximately 800 square feet, has a controlled heating and ventilation system and adequate electrical power sources to support the battery charging and associated test equipment. In addition, the space was upgraded in accordance with battery vendor recommendations to include a containment system to capture any spilled electrolyte from the cells and a hydrogen monitor to detect any accumulation of explosive gasses. The room temperature can be maintained or adjusted as needed to provide the same ambient conditions for all tests as closely as reasonably practical to avoid having to make temperature corrections to compare results.

1.4.2 Battery Test Setup

Battery racks are used that replicate a NPP installation with the exception that the racks are not seismically qualified. There are three racks of 12 cells each. Adequate spacing between the racks is provided to ensure that test leads can be attached and specific gravity measurements can be taken for all of the cells. The installation is shown in Figure 1-1.

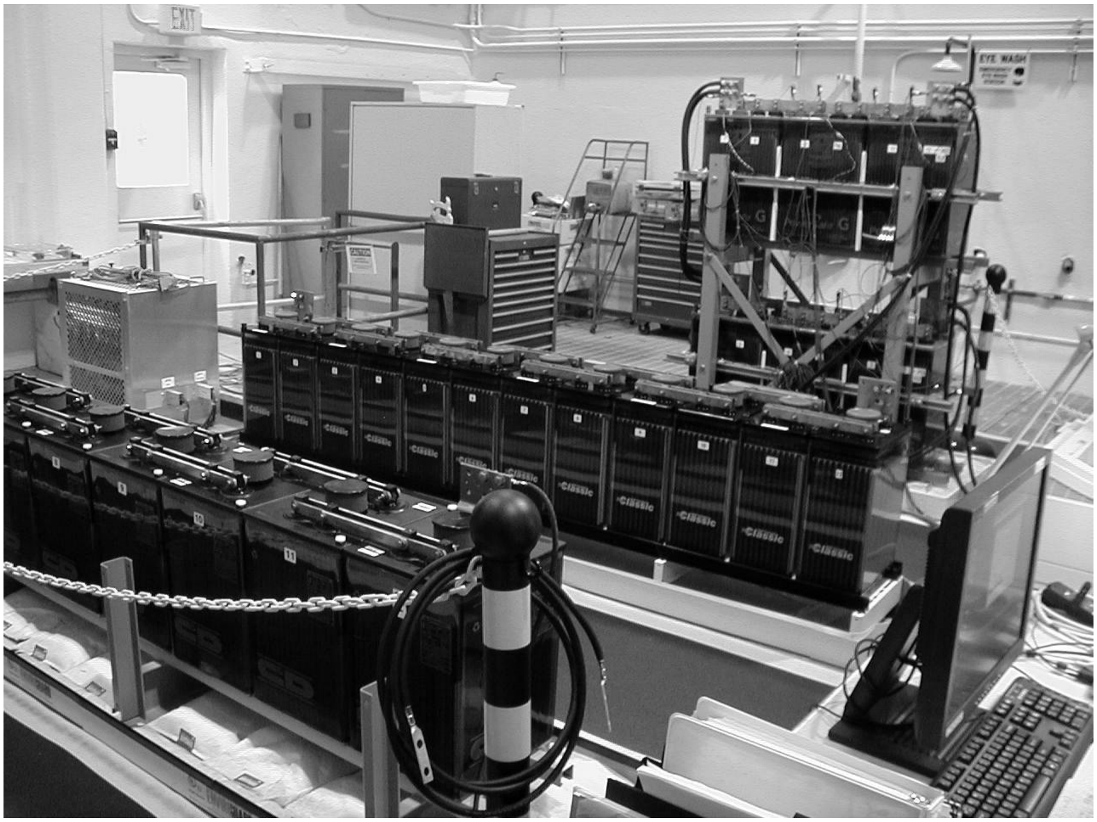

Figure 1-1 BNL Battery Facility

1.4.3 Data Acquisition Equipment

The testing employed an automated capacity test set, manufactured by the Alber Corporation (Alber), to control the load on the battery string. This test equipment monitors and displays cell voltages and was programmed to discharge the battery strings at various defined load conditions to simulate the desired operational conditions of the battery's extended duty cycle. A 600 amp (A) load bank was used in conjunction with the Alber BCT-128 capacity test set.

In addition to test equipment that acquires a continuous stream of data during testing, manual specific gravity readings were taken using a calibrated digital hydrometer (Model SBS-2500 with an accuracy of $.0001 g/cm^3$) were taken to assess battery condition [19]. Float current was monitored to verify the state-of-charge of the battery following each discharge test. The monitoring of the recharge process and recording of the float current response provided useful information about the battery string's capacity and capability.

1.5 Quality Plan

Existing BNL quality control procedures were used to ensure that the test results are reproducible and accurate. Instruments were calibrated using standards that are traceable to a national standard.

1.6 Test Plan

The testing was comprised of two sequences. Sequence 1 verified various lengths of time that the tested 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 1-1. 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 the battery manufacturer's published capacity data as identified by the shaded areas in Table 1-1, 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 1-1 Battery Vendor Data – Rated Discharge Current vs. Time for a 1.75V End Voltage

Battery/Extended Test Load (amps)	1 hr	2 hrs	4 hrs	8 hrs (Baseline)	12 hrs	24 hrs	36 hrs	48 hrs	72 hrs
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)

The beginning state for each test was a fully-charged battery. A fully-charged battery is represented by a stabilized float current below 2.0 amperes (amps) and a nominal midpoint specific gravity reading of 1.215 for all cells (the bench-mark value established by each of the three battery vendors). Previous testing of these three batteries at BNL had shown that when a stable float current below 2.0 amps is achieved, the battery can meet its design performance requirements. The end state for the discharge tests was when the overall battery string voltage reached 21.0 volts (average of 1.75 volts per cell, a common end-point value) or if any one cell reached 1.30 volts (to avoid a possible cell voltage reversal). In only one case (the 72 hour test of the Enersys battery) did the test terminate when a cell reached 1.30 volts. This test and the resulting analyses by the vendor are described in section 2.4. All other tests were terminated on the 21.0 volt criterion.

Sequence 1: Table 1-2 outlines the testing planned for Sequence 1. This series of 15 tests were intended to subject each battery to performance tests of different durations while allowing the battery to recover to a charged condition prior to the next test. These performance tests were conducted in accordance with IEEE 450-2010 and were used to fill in the data that were missing in Table 1-1 (shaded area). In addition, each of the three batteries was tested at their 8-hour rated current to provide a baseline for confirming the capacity of each battery. The Enersys battery was tested at its 72-hour rated current to provide confirmation of the vendor's published data.

The discharge current for the tests in Sequence 1 was calculated by developing an equation based upon the discharge currents and times that were published by the vendors for the three batteries to be tested.

Table 1-2 Test Plan of Loads and Estimated Test Duration (Sequence 1)

Test	Battery Type	Calculated Discharge Current (Amps)	Vendor Discharge Current (Amps)	Expected Duration (hours)
1	GNB	189	187	8
2	C&D	292	290	8
3	Enersys	227	225	8
4	GNB	132	(N/A)*	12
5	C&D	111	(N/A)*	24
6	Enersys	60	(N/A)*	36
7	GNB	71	(N/A)*	24
8	C&D	77	(N/A)*	36
9	Enersys	47	(N/A)*	48
10	GNB	50	(N/A)*	36
11	C&D	60	(N/A)*	48
12	Enersys	32.5	31.9	72
13	GNB	39	(N/A)*	48
14	C&D	42	(N/A)*	72
15	GNB	27	(N/A)*	72

*(N/A) These data were not available from the vendors at the time of the testing

The approach that was taken was to use the available performance data to develop an empirical relationship that could be used to estimate the missing data. The first step was to normalize each of the seven discharge current data that were provided by the battery vendors in Table 1-1 for 8 to 72 hours by the 8-hr rated current. This resulted in a set of normalized currents vs. time, in which the normalized current was bounded between unity and zero. Examination of the trend of the data suggested that a curve fit to the collective data from the three batteries would be best represented by a power law function of the form,

$$i^*(t) = K \bullet t^b$$

where the normalized current is $i^* = i(t)/i(t{=}8\text{ hr})$, t = time in hours, and “K” and “b” are constants derived from the curve fit to the data. The empirical relationship that was derived to interpolate the rated current data that were missing from Table 1-1 is as follows:

$$i^*(t) = 6.345 \bullet t^{-0.8842}$$

In order to solve for the rated current for one of the batteries at a specified discharge time, insert the specified time in hours into the equation above, solve for i*(t), and then multiply the value of i*(t) by the battery’s rated discharge current at 8 hours, the normalizing value. The test matrix for Sequence 1 that was developed is given in Table 1-2. Note that the calculated discharge currents listed in Table 1-2 for tests 1, 2, 3, and 12 are the rated discharge currents as published by the battery vendors. The remaining numbers are the calculated discharge currents using the algorithm previously described.

While the algorithm was developed using the data on the BNL test batteries, it turns out to be applicable to other battery types as well. To demonstrate this, the battery specifications for the battery types identified by NEI in the load profiles that were tested in Sequence 2 of this research were evaluated using the above the algorithm. Figure 1-1 illustrates how the general form of the capacity curves can be replicated using the algorithm out to 72 hours. Table 1-3 provides the data for this figure.

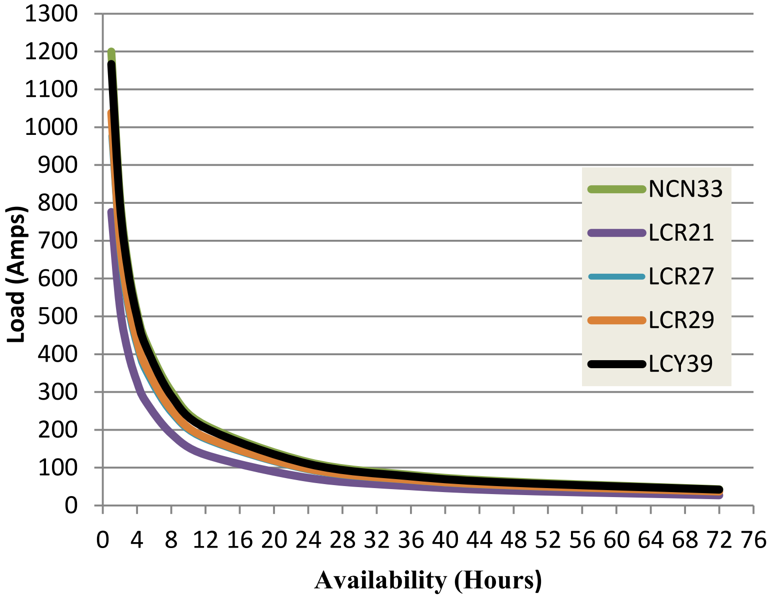

Figure 1-1 Battery availability for other battery types using algorithm

Table 1-3 Battery availability for other battery types using algorithm

Availability (Hours)→	**8**		**12**		**24**	**36**	**48**	**72**
Battery Mfg./Model	Spec amps	Calc. amps	Spec. amps	Calc. amps	Calc. amps	Calc. amps	Calc. amps	Calc. amps
Exide/GNB NCN-33	302	302	N/A	212	115	81	63	43
C&D LCR-21	190	190	134	132	73	51	39	27
C&D LCR-27	244	244	174	172	93	65	50	35
C&D LCR-29	254	254	180	180	97	68	53	37
C&D LCY-39	300	300	212	212	115	80	62	43

The results of the Sequence 1 testing are provided in Section 2 of this report.

<u>**Sequence 2**</u>: Simulation of ELAP conditions: In this series of service tests, representative load profiles with load shedding schemes were replicated to determine how long the battery could carry the specified loads. Four different load profiles that were provided by the NEI and approved by NRC were used. These load profiles represent a cross section of inputs from NPPs who have analyzed what equipment is needed to assure core cooling while providing the critical instrumentation needed by plant operators and decision makers. The test profiles factor in a response time for initiating the shedding of loads and reflect the impact of various loads on battery performance. Each of the three battery types available at BNL were used equally in this testing sequence. That is, for the eighteen test runs associated with Sequence 2, each battery was tested six times. Because the sizes of the BNL batteries are different than what was

provided by NEI with the load profiles, scaling of the load profiles was performed to relate the plant specified battery type to the different capacities of the three battery types actually being tested (based on the ratio of their amp-hour ratings). Following a series of discussions with NEI, EPRI, and NRC, load profiles were adjusted to evaluate different load shedding initiation times and assess the impacts of intermittent loads on the batteries. In addition, it was decided to conduct one series of 3 tests without scaling the loads in order to observe each of the batteries response to an identical load profile.

The series of service test runs conducted is briefly described below and summarized in Table 1-4. Note that a battery string was tested no sooner than every third week so that it 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. As noted previously, a fully-charged battery is represented 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 (test runs 1-3) and at the end of sequence 2 testing (test runs 16-18) in order to assess battery capacity and capability over the test runs.

Four load profiles were selected that represent several of the nuclear power plant DC load responses to an ELAP condition. As noted previously, variations in load shedding timing were also incorporated into the load profiles to assess the impact of this parameter on battery availability. These load profiles are summarized in Table 1-4. A brief description provided by NEI of the basis for the load profiles follows the table.

The test results from Sequence 2 are described in detail in Section 3 of this report.

Table 1-4 Summary of Load Profile Tests

TEST RUN	BATTERY TYPE	LOAD STEP 1	LOAD STEP 2	LOAD STEP 3	LOAD STEP 4
TEST SERIES #1 (Based on EBR-5); load scaling for battery type					
4	C&D	514A for 1 minute	333A for 120 minutes	118A for 120 minutes	86A to 21.0 volts
5	GNB	332A for 1 minute	214A for 30 minutes	76A for 30 minutes	55A to 21.0 volts
6	Enersys	399A for 1 minute	258A for 60 minutes	91A for 60 minutes	67A to 21.0 volts
TEST SERIES #2 (Based on EBR-4; no battery load scaling)					
7	C&D	443A for 1 minute	334A for 52 minutes	328 for 15 minutes	67A to 21.0 volts
8	GNB	443A for 1 minute	334A for 52 minutes	328 for 15 minutes	67A to 21.0 volts
9	Enersys	443A for 1 minute	334A for 52 minutes	328 for 15 minutes	67A to 21.0 volts
TEST SERIES #3 (Based on EBR-5 for C&D/60 minute load shed; EBR-3 for Enersys and GNB); includes load scaling					
10	C&D	514A for 1 minute	333A for 60 minutes	118A for 60 minutes	86A to 21.0 volts
11	GNB	160A for 90.2 minutes	39A for 10.5 hours	39A with 1 minute loads of 160A every 2 hours to 21.0 volts	
12	Enersys	192A for 90.2 minutes	47A for 10.5 hours	47A with 1 minute loads of 190A every 2 hours to 21.0 volts	
TEST SERIES #4 (Based on EBR- 5 for C&D/30 minute load shed; EBR-2 for Enersys and GNB); includes load scaling					
13	C&D	514A for 1 minute	333A for 30 minutes	118A for 30 minutes	86A to 21.0 volts
14	GNB	112A for 120 minutes	38A to 21.0 volts	No Load Step 3	No Load Step 4
15	Enersys	469A for 1 minute	135A for 120 minutes	45A to 21.0 volts	No Load Step 4

Battery Test Runs 1-3 and 16-18 (Baseline performance test for each battery type)

- Each battery was fully charged.
- An 8-hour performance test was conducted to establish a battery capacity baseline for each battery type

Battery Test Runs 4- 6 (Load Profile #1 [EBR-5] for each battery type – initiation of the load shedding sequence for the C&D battery was 120 minutes for comparison to tests 10 and 13)

EBR-5 is representative of a BWR using reactor core isolation cooling (RCIC) for decay heat removal that employed their procedures and guidance to determine the amount of non-essential loads that could be shed. This profile assumes RCIC is switched to manual mode once the procedures and guidance are activated. This removes several automatic DC Motor-Operated Valve (MOV) operations.

- Each battery was fully charged prior to the test.
- The extended load profile (EBR-5) was run with the loads scaled to each battery's rating to determine how the battery functions over time.

Battery Test Runs 7-9 (Load Profile #2 [EBR-4] for each battery type)

EBR-4 is representative of a PWR where automatic tripping of 4kVAC and 600 VAC breakers occurs during the first minute. Plant SBO procedures are assumed for the first 53 minutes until load shedding is started. These procedures were also used to identify the non-essential loads to be shed during this event.

- Each battery was fully charged prior to the test.
- The extended load profile (EBR-4) was simulated without applying any load scaling.

Battery Test Run 10 (Load Profile #1 [EBR-5] but with 60-minute load shed for C&D battery)

- The C&D battery was fully charged prior to the test.
- The EBR-5 load profile was applied to the C&D battery, but with the load shed initiation set to 60 minutes in order to check the impact that the initiation of load shedding has on battery availability.

Battery Test Runs 11 and 12 (Load Profile #3 [EBR-3] for the GNB and Enersys Batteries)

EBR-3 represents a PWR where ac loads are stripped from their respective buses. At 90.2 minutes, the operators are able to open breakers to selected panels and shed non-essential DC loads. Only critical safe shutdown loads are supplied by this battery after 90 minutes.

- Each battery was fully charged prior to the test.
- The extended load profile (EBR-3) was simulated with the loads scaled to each battery's rating to determine how the battery functions over time. In this profile, the GNB and Enersys battery test runs were used to simulate five (5) intermittent loads every 2 hours after 12 hours. The battery string was then operated at a steady load until the battery string reached 21.0 volts or any one cell reaches 1.3 volts.

Battery Test Run 13 (Load Profile #1 [EBR-5] with 30-minute load shed for C&D battery)

- The C&D battery was fully charged prior to the test.
- The EBR-5 load profile was applied to the C&D battery, but with the load shed initiation time reduced to 30 minutes in order to check the impact that the initiation of load shedding has on battery availability.

Battery Test Runs 14-15 (Load Profile #4 [EBR-2] for the GNB and Enersys Batteries)

EBR-2 is representative of a PWR in which normal SBO loading is assumed for the first two hours before load shedding is initiated. Loads shed include non-Class 1E loads and other non-essential loads in accordance with the ELAP operating procedures/guidance.

- Each battery was fully charged prior to the test.
- The extended load profile (EBR-2) was simulated with the loads scaled to each battery's rating to determine how the battery functions over time.

2 EXTENDED BATTERY OPERATION (SEQUENCE 1) TESTING RESULTS

2.1 Background

Sequence 1 was directed at establishing a bounding set of performance expectations for extended battery operation. In general, a higher discharge rate (increased load current) will result in reduced capacity (shorter time to discharge) while a low discharge rate will result in increased capacity (longer time to discharge). However, the relationship between load and capacity is not linear; reducing the load by half will not double the time to discharge. For this reason, manufacturers normally specify several discharge rates (in amperes) along with their associated discharge times (in hours).

Sequence 1 tests were conducted to verify how long the batteries could operate at specified reduced discharge rates. The battery vendors provide capacity specifications for their batteries at various load conditions as previously depicted in Table 1-1. Understanding the battery response to lower discharge current and longer duration testing was the key objective of Sequence 1 testing. In general, battery capacity varies with the discharge rate; the higher the discharge rate, the lower the cell capacity. Manufacturers' literature on the three battery types used at BNL specified several discharge rates (in amperes) along with the associated discharge time (in hours).

2.2 Test results-Time versus current response

In the Sequence 1 series of tests, a total of 16 tests were conducted; 8-hour baseline tests on each of the 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 (Enersys-19) 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.

Table 2-1 provides a summary of the specified discharge current and nominal duration and the associated ampere-hours expected to be expended by the battery during the discharge (columns 2 and 3). It also indicates the actual measured current and duration of the test and the associated ampere-hours discharged (columns 4 and 5). From these data, a battery capacity can be calculated in two ways- by comparing the measured time to the specified time or by comparing the measured ampere-hours discharged to the specified ampere-hours. As indicated in column 6 of Table 2-1, these measurements of capacity are fairly uniform, although the ratio of ampere-hours expended is generally higher than the ratio of the time. The Alber capacity test set uses the time ratio to calculate capacity, which is the more commonly used method in the nuclear industry.

Table 2-1 Summary of Sequence 1 Performance Tests

(1)	(2)	(3)	(4)	(5)	(6)		(7)
Test-Battery/Test Cycle	Specified Current/Discharge Duration	Specified Amp·hrs Discharged	Measured Current/Discharge Duration (Alber)	Measured Amp·hrs Discharged	Battery		Initial Temp (°F)
					Time[1]	Amp-hrs[2]	
GNB-15	187 A /8 hr =	1496 A·hr	187 A/7.97 hr =	1490 A·hr	99.6%	99.6%	76
C&D-15	290 A /8 hr =	2320 A·hr	291 A/8.26 hr =	2404 A·hr	103.3 %	103.6 %	77
Enersys-15	225 A /8 hr =	1800 A·hr	226 A/8.01 hr =	1810 A·hr	100.1 %	100.6 %	77
GNB-16	132 A/12 hr =	1584 A·hr	135 A/11.65 hr =	1573 A·hr	97.1%	99.3%	80
C&D-16	111 A/24 hr =	2664 A·hr	113 A/25.83 hr =	2919 A·hr	107.6 %	109.6 %	80
Enersys-16	60 A/36 hr =	2160 A·hr	62 A/35.13 hr =	2178 A·hr	97.6%	100.8 %	80
GNB-17	71 A/24 hr =	1704 A·hr	73 A/25.96 hr =	1895 A·hr	108.2 %	111.2 %	79
C&D-17	77 A/36 hr =	2772 A·hr	79 A/38.08 hr =	3008 A·hr	105.8 %	108.5 %	80
Enersys-17	47 A/48 hr =	2256 A·hr	49 A/44.28 hr =	2170 A·hr	92.3%	96.2%	78
GNB-18	50 A/36 hr =	1800 A·hr	52 A/37.17 hr =	1933 A·hr	103.3 %	107.4 %	78
C&D-18	60 A/48 hr =	2880 A·hr	61 A/50.27 hr =	3066 A·hr	104.7 %	106.4 %	77
Enersys-18	31.9 A /72 hr =	2297 A·hr	33 A/66.21 hr =	2185 A·hr	92.0%	95.1%	77
GNB-19	39 A/48 hr =	1872 A·hr	41 A/48.40 hr =	1984 A·hr	100.8 %	106.0 %	78
C&D-19	42 A/72 hr =	3024 A·hr	43 A/72.76 hr =	3129 A·hr	101.1 %	103.5 %	75
GNB-20	27 A/72 hr =	1944 A·hr	28 A/68.39 hr =	1915 A·hr	95.0%	98.5%	75
Enersys-19 (10 cells)	31.9 A/72 hr =	2297 A·hr	33 A/62.67 hr =	2068 A·hr	87.0 %	90.0 %	76

[1] Battery capacity is the ratio of measured discharge duration ÷ specified discharge duration.
[2] Battery capacity is the ratio of measured A·hr discharged ÷ specified A·hr discharged

By plotting the information derived from these tests along with published vendor data, one can extrapolate the increased efficiency of the battery at lower loads and the expected battery availability for any steady state current from one to 72 hours. These are illustrated in Table 2-2 and Figure 2-1, respectively.

Table 2-2 Actual Ampere-Hours discharged as a function of test duration

Battery/Test Duration	8 Hours	12 Hours	24 Hours	36 Hours	48 Hours	72 Hours
Enersys	1810	No Test	No Test	2178	2170	2185/2068
GNB	1490	1573	1895	1933	1984	1915
C&D	2404	No Test	2919	3008	3066	3129

Table 2-2 shows the nearly 30% increase in battery efficiency at lower loads as compared to the 8-hour rating that results in longer battery availability.

Figure 2-1 illustrates the significant decrease in loads in order to achieve longer duration availability of the batteries.

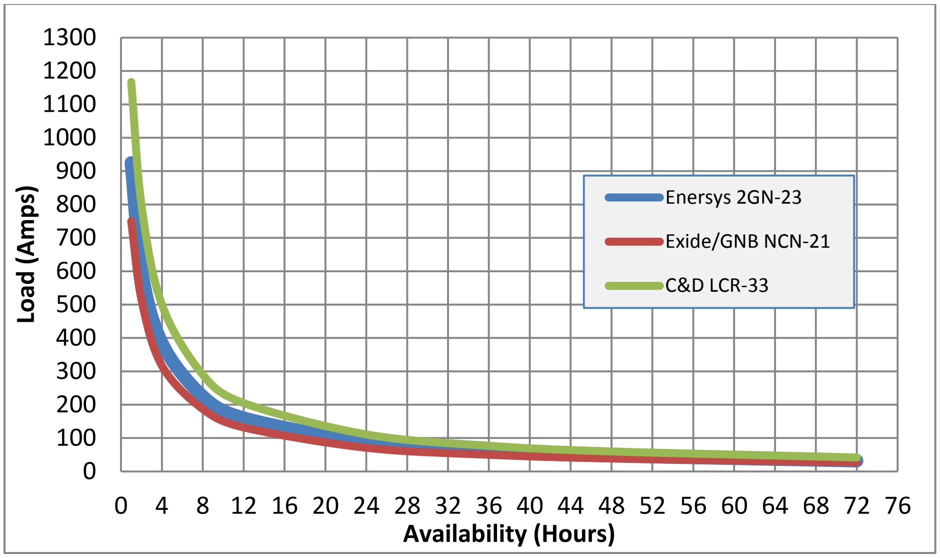

Figure 2-1 Battery availability versus load from 1 to 72 hours

2.3 Test results-Time versus voltage response

EPRI Report TR- 1006757 [20] presents the expected voltage profile for a lead-calcium cell undergoing a constant current discharge as Figure 2-2. This figure illustrates the initial drop in voltage that the cell 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. A weak cell in a battery string may exhibit a steeper decline in voltage over time. This could be detected during a performance test by monitoring the individual cell voltages. The impact of a weak cell in a battery string is discussed further in Section 2.4.

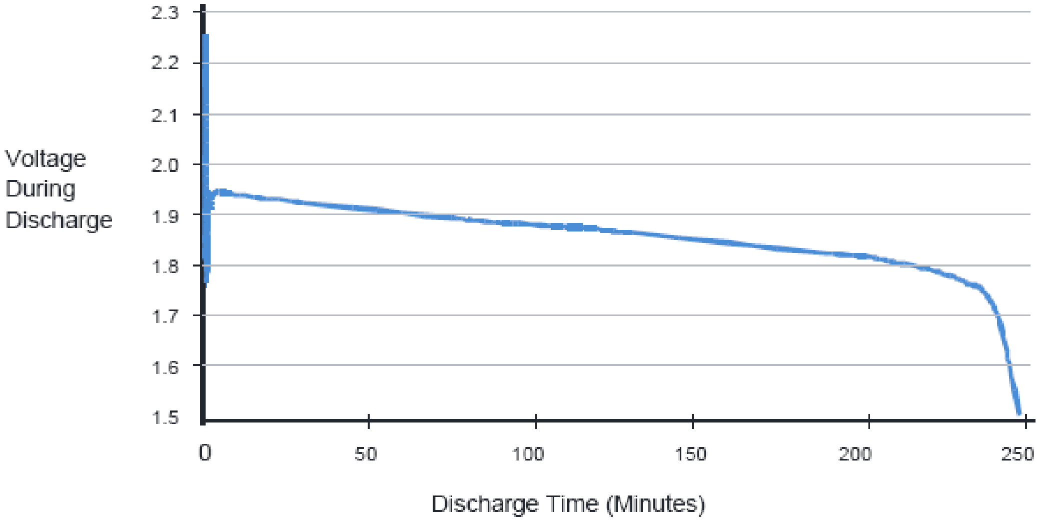

Figure 2-2 Typical Lead-Acid Battery Cell Voltage Response During Constant Current Discharge (EPRI 1006757 [20])

As noted earlier, the testing conducted at BNL used an average cell voltage of 1.75 volts at the point of test termination (21.0 volts for our 12 cell battery strings). Manufacturers and users often evaluate cell performance using 1.75 V per cell as a reference point. However, the system design could require a higher voltage (or allow a lower voltage) to meet the voltage requirements of all components. Manufacturers rarely provide discharge ratings below 1.5 V per cell; once the voltage has fallen to this level, the rate of voltage decline is very rapid and little additional energy can be removed from the battery.

Figures 2-3, 2-4, and 2-5 are the cell voltage responses for the three BNL batteries that were experienced during three 72-hour performance tests. In each case, 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.

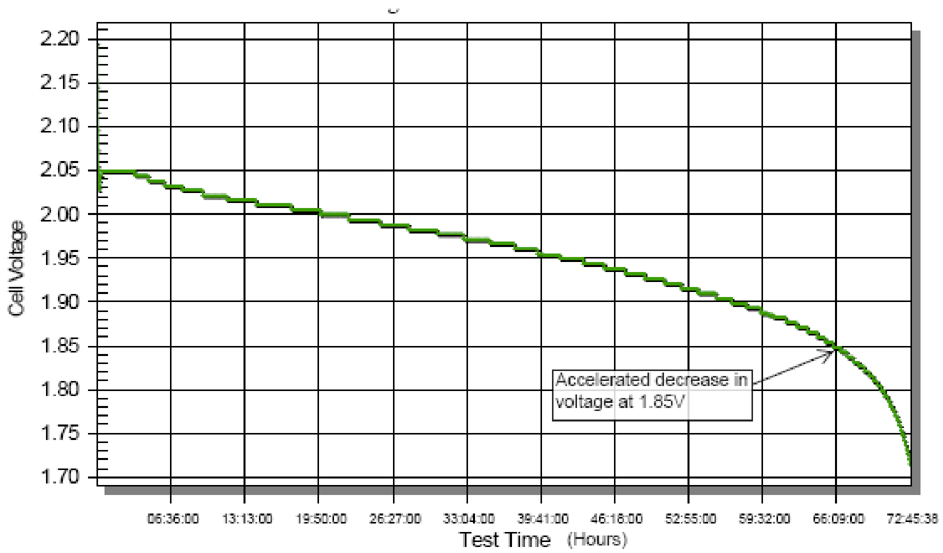

Figure 2-3 C&D Cell #10 Response during 72-hour discharge test

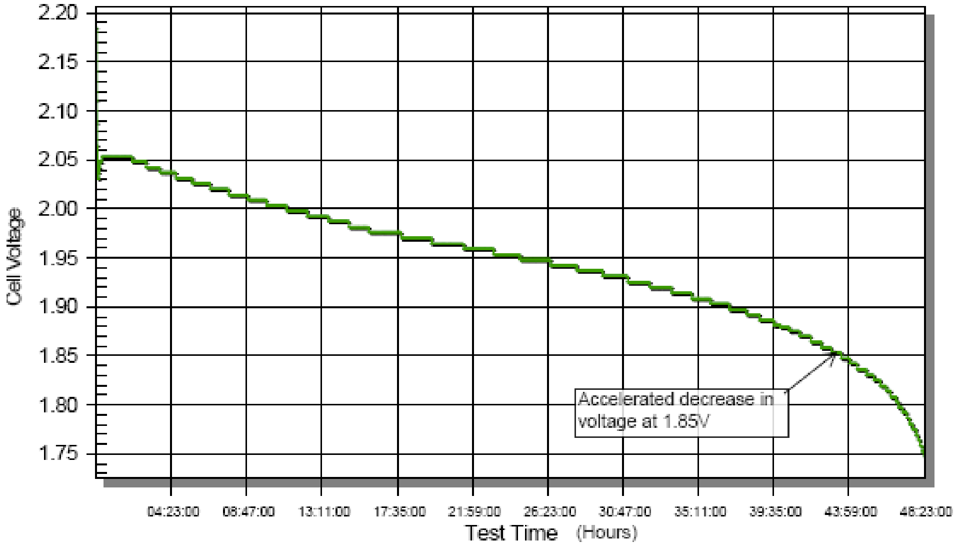

Figure 2-4 GNB Cell #4 Response during 48-hour discharge test

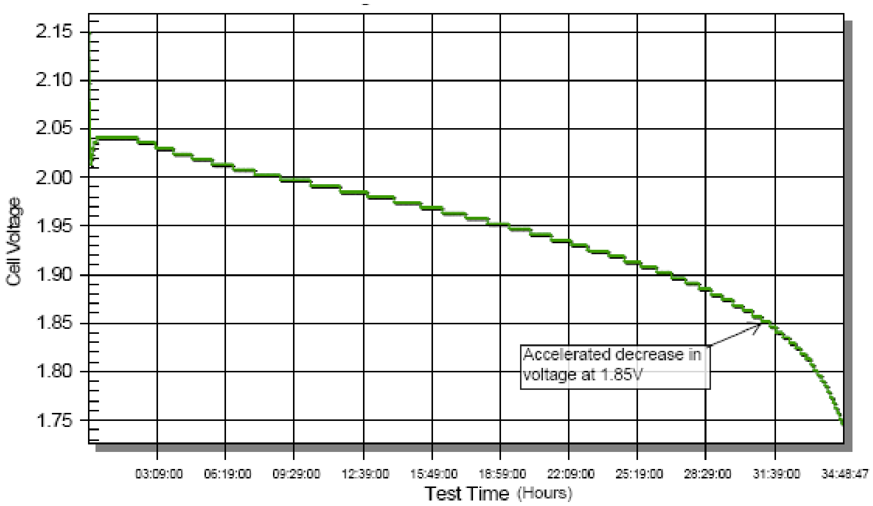

Figure 2-5 Enersys Cell #3 Response during 36-hour discharge test

In summary, the results from this extended discharge testing are consistent with the expected response of a battery during a normal discharge. These characteristics are:

- An initial prompt voltage drop (known as Coup de Fouet)
- A voltage recovery during the first few minutes of discharge
- A nearly linear voltage drop during most of the discharge period
- A rapid nonlinear voltage drop at the end of discharge (~1.85V)

2.4 Test results-Time versus voltage response-special case

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.

During the conduct of the 72 hour test of the Enersys battery, cell #2 reached 1.3 volts at about the 66 hour mark during the night when the test lab was unattended and the test was automatically stopped. The voltage versus time response is illustrated in Figure 2-6.

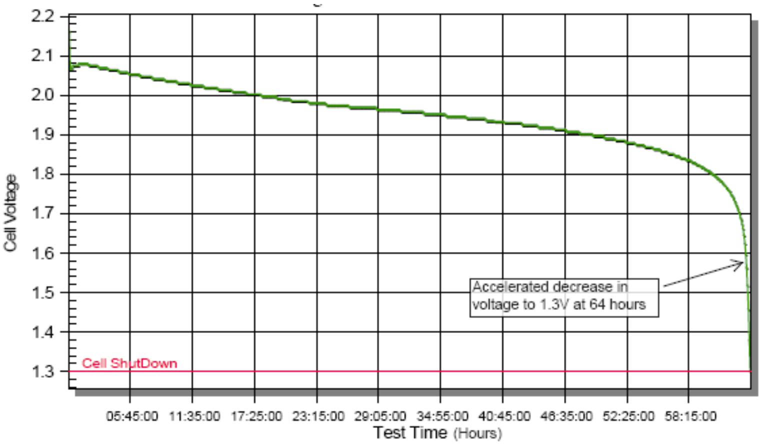

Figure 2-6 Enersys Cell #2 voltage response during 72-hour test

Approximately 10 hours after the test terminated, recharge of the battery string commenced. At about 3.5 hours into the recharge at 27.0 volts (2.25 V/cell), an abnormally high voltage and high temperature was observed on cell #2. A manual action was taken to disconnect the battery from the charger so the cause of these abnormal conditions could be evaluated and to prevent a potential thermal runaway condition that could have severely damaged the cell. Figure 2-7 illustrates the voltage response on cell #2 during the recharge and Figure 2-8 displays the corresponding temperature response.

Thermal runaway conditions can develop because of variations in cell-to-cell voltages. In that situation, the lower voltage cells are slowly discharging and building sulfate crystals on the plates, and the high voltage cells are gassing excessively, with the potential for thermal runaway. Gassing that results in more heat generation than the cell can dissipate occurs somewhere above a cell voltage of 2.33 volts when the ambient temperature is 77°F [3].

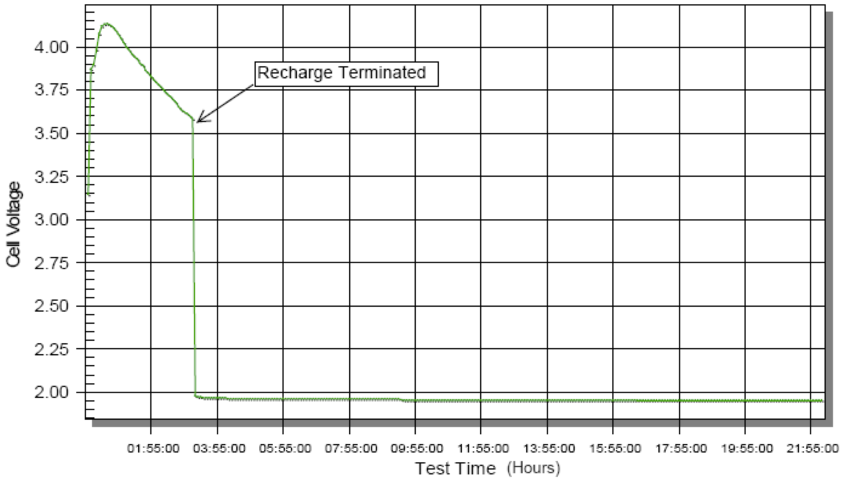

Figure 2-7 Cell #2 Voltage Response during attempted recharge

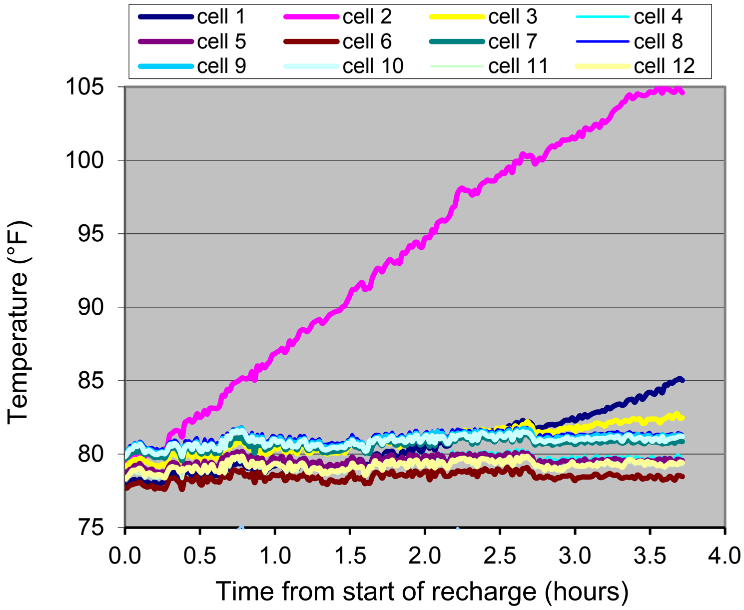

Figure 2-8 Cell #2 Temperature Response during attempted recharge

2.5 Evaluation of Test Anomaly

The jar containing cells 1 and 2 were shipped to Enersys for further analysis. Their test report provided the following description regarding the observed problem. A definitive root cause for the spike in charge voltage on cell 2 was not uncovered in the recovery efforts and testing performed at the Enersys laboratory. When the recharge was initiated at BNL, the charger came on at full power. Cell 2 could not absorb the full current, and its voltage increased until its current-voltage relationship was in line with the driving current. This was substantially higher than the other cells and generated significantly more heat due to the high resistance of the cell. It can only be speculated that the timing from the end of the discharge to the beginning of the recharge allowed a sufficient, but not excessive, highly resistive layer of lead sulfate and/or lead hydrate to develop. Cell 2 was the lowest in specific gravity based on the voltage seen in the discharge results. In low gravity circumstances, the sulfate on the face of the plate can dissolve and re-crystallize back onto the surface in a continuous layer, essentially forming a lead sulfate/ lead hydrate surface coating over the whole plate. This, in combination with the very low specific gravity of the electrolyte between the plates, combines to create a sufficiently high resistance to impede current flow. The action of removal and shipment may have redistributed sufficient acid to reduce that resistance to allow current flow when the recovery effort commenced at Enersys.

Enersys recommended that we modify our recharge process to ensure that the recharge is sufficient to bring the cells back to a fully charged condition. This is required because the frequency of the deep discharge events are sufficiently in excess of that expected in the field operation that normal field charge routines are insufficient to fully recover the battery. As a result of this incident and the vendor's recommendation, subsequent testing incorporated a 100-hour equalizing charge and at least 2 weeks on a float charge to ensure that the battery was sufficiently charged before embarking on the next extended operational test.

<u>Additional BNL Analysis</u>: Looking back over the test data, we noted that cell #2 was often the lowest voltage cell when the test was terminated. Figure 2-9 depicts the cell voltages at the conclusion of the 72 hour test. The overall cell voltage was 21.135 volts, yielding a cell average voltage of 1.761 volts.

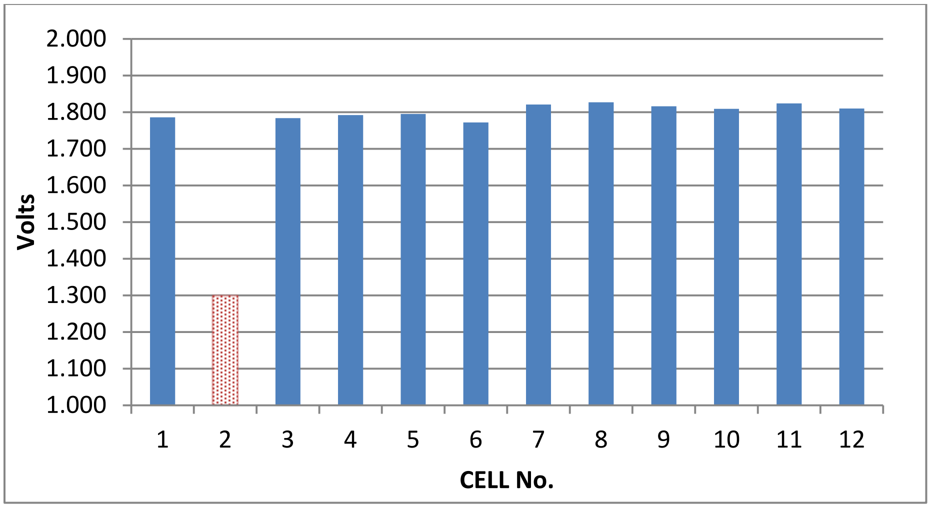

Figure 2-9 Enersys Cell Voltages at the conclusion of the 72-hour performance test

For each of the extended operation tests, cell #2 was the lowest voltage when the test was automatically terminated. This is illustrated in Table 2-3.

Table 2-3 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

Perhaps this consistent performance could have been an indication that this cell required attention prior to the very long duration tests. Battery monitoring systems and periodic capacity testing might give the nuclear plant operator warning that a cell could potentially degrade the performance of the entire battery string.

Looking back at the cell voltages at the conclusion of the extended performance tests for the other two battery strings revealed that the GNB and C&D battery strings also had a cell that affected the overall performance of the battery strings. As illustrated in Table 2-4, the GNB cell (#7) was consistently lower than the rest of the cells at the conclusion of the test. Only on the 72-hour test did its value drop below 1.7 volts.

Table 2-4 GNB cell voltages at the conclusion of the extended duration tests

Cell No	8 hour test	12 hour test	24 hour test	36 hour test	48 hour test	72 hour test
1	1.769	1.755	1.745	1.757	1.760	1.776
2	1.786	1.783	1.785	1.792	1.792	1.795
3	1.767	1.765	1.755	1.755	1.748	1.751
4	1.753	1.765	1.755	1.751	1.747	1.749
5	1.739	1.752	1.750	1.751	1.758	1.763
6	1.759	1.759	1.761	1.770	1.779	1.785
7	1.728	1.741	1.740	1.723	1.712	1.686
8	1.767	1.760	1.749	1.755	1.765	1.775
9	1.751	1.756	1.755	1.755	1.751	1.741
10	1.792	1.787	1.789	1.795	1.798	1.798
11	1.743	1.750	1.754	1.751	1.749	1.747
12	1.755	1.750	1.756	1.751	1.756	1.759

For the C&D battery, the lowest end voltages varied only slightly from test to test. This is illustrated in table 2-5. This table shows that cell #10 had the lowest voltage at the conclusion of four of the five tests, and was the second lowest cell on the fifth (72 hour test), but in no case did any cell end at a voltage less than 1.7 volts.

Table 2-5 C&D cell voltages at the conclusion of the extended duration tests

Cell No.	8 hour test	24 hour test	36 hour test	48 hour test	72 hour test
1	1.785	1.785	1.775	1.787	1.782
2	1.752	1.736	1.720	1.720	1.700
3	1.749	1.758	1.757	1.765	1.769
4	1.753	1.764	1.770	1.765	1.772
5	1.778	1.778	1.766	1.773	1.767
6	1.737	1.732	1.742	1.730	1.744
7	1.752	1.764	1.777	1.774	1.782
8	1.780	1.793	1.797	1.793	1.798
9	1.771	1.758	1.748	1.758	1.736
10	1.737	1.715	1.720	1.709	1.714
11	1.765	1.761	1.761	1.765	1.766
12	1.762	1.766	1.778	1.779	1.787

Others have noted that cell variability in a discharge test is common [13] and is not necessarily problematic; there are always weaker and stronger cells. It was also noted that sharp knees in the voltage response curve are usually indicative of acid limitation. This is likely what happened with the Enersys Cell #2 due to not being fully recharged prior to the 72-hour test. End-of-test cell voltage readings were continued during the Sequence 2 testing where it was observed that Enersys cells #2 and #10 and C&D cell #10 reached voltage levels below 1.7 volts at the time when the overall battery string reached an end-of-test voltage of 21.0 volts (average of 1.75V/cell). These readings are provided in Tables 3.4, 3.9, 3.13, and 3.19.

2.6 Test results –Time versus specific gravity

Specific gravity measurements of each cell were taken prior to each performance test, following the 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.

Tables 2.6, 2.7, and 2.8 illustrate the end-point specific gravity readings on each cell for the extended operations tests on the C&D, GNB, and Enersys batteries, respectively. Following each set of specific gravity readings, a calibration check was performed using distilled water to ensure that the digital hydrometer was operating within specifications. This is indicated in the table as H_20.

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 these tables was averaged and plotted versus the performance test duration time. The results are shown in figure 2-10 that follows the three tables.

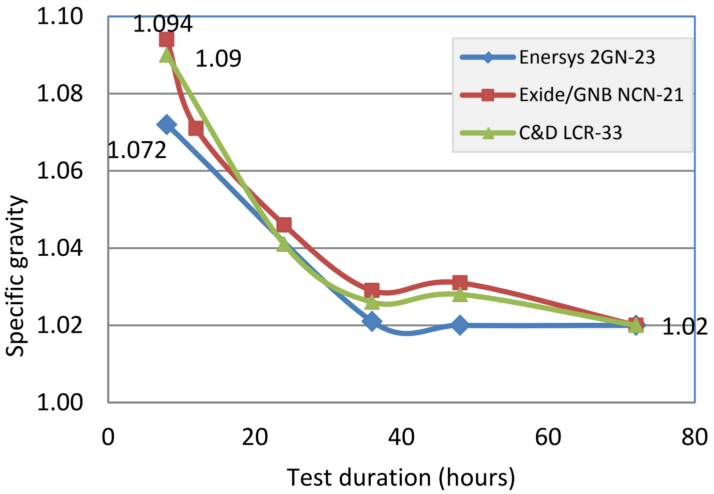

Figure 2-10 Average End of Test Specific Gravity - Sequence 1 Tests

Table 2-6 C&D cell specific gravity at the conclusion of the extended duration tests

Battery/Test	**C&D 15 (8 hour test)**	**C&D 16 (24 hour test)**	**C&D 17 (36 hour test)**	**C&D 18 (48 hour test)**	**C&D 19 (72 hour test)**
Cell/Position	Post Discharge Specific Gravity	Post Discharge Specific Gravity	Post Discharge Specific Gravity	Post Discharge Specific Gravity	Post Discharge Specific Gravity
1-Midpoint	1.09	1.04	1.03	1.03	1.02
2-Midpoint	1.09	1.04	1.02	1.02	1.01
3-Midpoint	1.09	1.04	1.03	1.03	1.02
4-Midpoint	1.09	1.04	1.03	1.03	1.02
5-Midpoint	1.09	1.04	1.03	1.03	1.02
6-Midpoint	1.09	1.04	1.02	1.03	1.02
7-Midpoint	1.09	1.04	1.03	1.03	1.02
8-Midpoint	1.09	1.04	1.03	1.03	1.02
9-Midpoint	1.09	1.04	1.02	1.03	1.02
10-Midpoint	1.09	1.04	1.02	1.02	1.02
11-Midpoint	1.09	1.04	1.03	1.03	1.02
12-Midpoint	1.09	1.04	1.03	1.03	1.02
9-Top	1.08	1.03	1.02	1.02	1.01
11-Top	1.08	1.04	1.02	1.02	1.02
9-Bottom	1.09	1.05	1.03	1.04	1.03
11-Bottom	1.09	1.05	1.03	1.04	1.03
H_2O	1.00	1.00	1.00	1.00	1.00

Table 2-7 GNB cell specific gravity at the conclusion of the extended duration tests

Battery-Test	**GNB 15 (8 hour test)**	**GNB 16 (12 hour test)**	**GNB 17 (24 hour test)**	**GNB 18 (36 hour test)**	**GNB 19 (48 hour test)**	**GNB 20 (72 hour test)**
Cell-Position	Post Discharge Specific Gravity	Post Discharge Specific Gravity	Post Discharge Specific Gravity	Post Discharge Specific Gravity	Post Discharge Specific Gravity	Post Discharge Specific Gravity
1-Midpoint	1.09	1.07	1.04	1.03	1.03	1.02
2-Midpoint	1.10	1.08	1.05	1.03	1.04	1.02
3-Midpoint	1.09	1.07	1.05	1.03	1.03	1.02
4-Midpoint	1.10	1.07	1.05	1.03	1.03	1.02
5-Midpoint	1.09	1.07	1.05	1.03	1.03	1.02
6-Midpoint	1.09	1.07	1.05	1.03	1.03	1.02
7-Midpoint	1.09	1.07	1.04	1.03	1.03	1.02
8-Midpoint	1.09	1.07	1.04	1.03	1.03	1.02
9-Midpoint	1.09	1.07	1.05	1.03	1.03	1.02
10-Midpoint	1.10	1.07	1.05	1.03	1.04	1.03
11-Midpoint	1.09	1.07	1.05	1.03	1.03	1.02
12-Midpoint	1.09	1.07	1.04	1.03	1.03	1.02
9-Top	1.09	1.06	1.04	1.03	1.02	1.02
11-Top	1.09	1.06	1.04	1.03	1.02	1.02
9-Bottom	1.10	1.08	1.06	1.05	1.05	1.09
11-Bottom	1.10	1.08	1.06	1.05	1.05	1.08
H_2O	1.00	1.00	1.00	1.00	1.00	1.00

Table 2-8 Enersys cell specific gravity at the conclusion of the extended duration tests

Battery/Test	Enersys 15 (8 hour test)	Enersys 16 (36 hour test)	Enersys 17 (48 hour test)	Enersys 18 (72 hour test)
Cell/Position	Post Discharge Specific Gravity	Post Discharge Specific Gravity	Post Discharge Specific Gravity	Post Discharge Specific Gravity
1-Midpoint	1.07	1.02	1.02	1.02
2-Midpoint	1.07	1.02	1.01	1.01
3-Midpoint	1.07	1.02	1.02	1.02
4-Midpoint	1.07	1.02	1.02	1.02
5-Midpoint	1.07	1.02	1.02	1.02
6-Midpoint	1.07	1.02	1.02	1.02
7-Midpoint	1.07	1.02	1.02	1.03
8-Midpoint	1.08	1.03	1.03	1.03
9-Midpoint	1.07	1.02	1.02	1.03
10-Midpoint	1.07	1.02	1.02	1.02
11-Midpoint	1.08	1.03	1.03	1.03
12-Midpoint	1.07	1.02	1.02	1.03
9-Top	1.07	1.02	1.02	1.02
11-Top	1.07	1.02	1.02	1.03
9-Bottom	1.08	1.03	1.04	1.07
11-Bottom	1.08	1.03	1.04	1.08
H_2O	1.00	1.00	1.00	1.00

2.7 Test results –Time versus temperature

The temperature of each of the cells was monitored continuously using surface mounted thermocouples (Fig. 2-11) whose output was transmitted to a data acquisition system [17]. This was done primarily to ensure that the capacity measurements were referenced to 77°F. For the sake of standardization, battery performance ratings are normally specified at a temperature of 77°F (25°C). This allows battery capability information provided by the vendors to be based on the same criterion.

The characteristics of a lead-acid battery vary with temperature; heat accelerates chemical activity and cold slows it down. A change in the electrolyte temperature from the reference temperature has two significant effects on lead-acid battery performance:

- Battery capacity decreases as the temperature drops below 77°F (25°C).
- Battery life decreases as the temperature rises above 77°F (25°C).

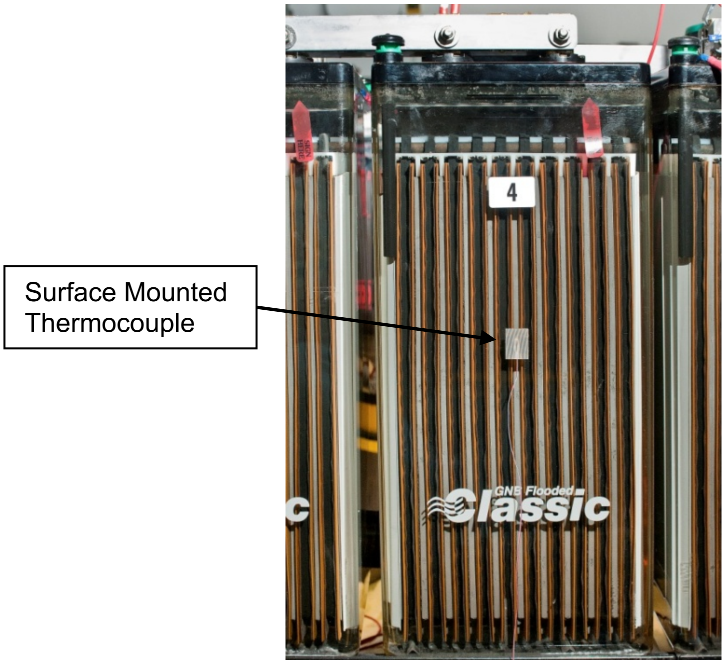

Figure 2-11 Cell Temperature Monitoring Using Surface Mounted Thermocouple

At temperatures lower than 77°F (25°C), the battery will not be able to provide its rated capacity. In general, a lower temperature increases the viscosity of the electrolyte, and thus restricts its ability to circulate into the plates. Also, the efficiency of the chemical reaction decreases as temperature decreases. Figure 2-12 provides typical battery capacity factors at temperatures other than the reference temperature of 77°F (25°C). For example, at 60°F a battery can provide only 90% of its rated capacity. The data contained in Figure 2-12 are based on a vented lead-acid battery with a specific gravity of 1.215. As previously illustrated in Table 2-1, the ambient temperature at the start of the Sequence 1 tests was maintained between 75°F and 80°F in order to minimize the correction factor that needed to be applied.

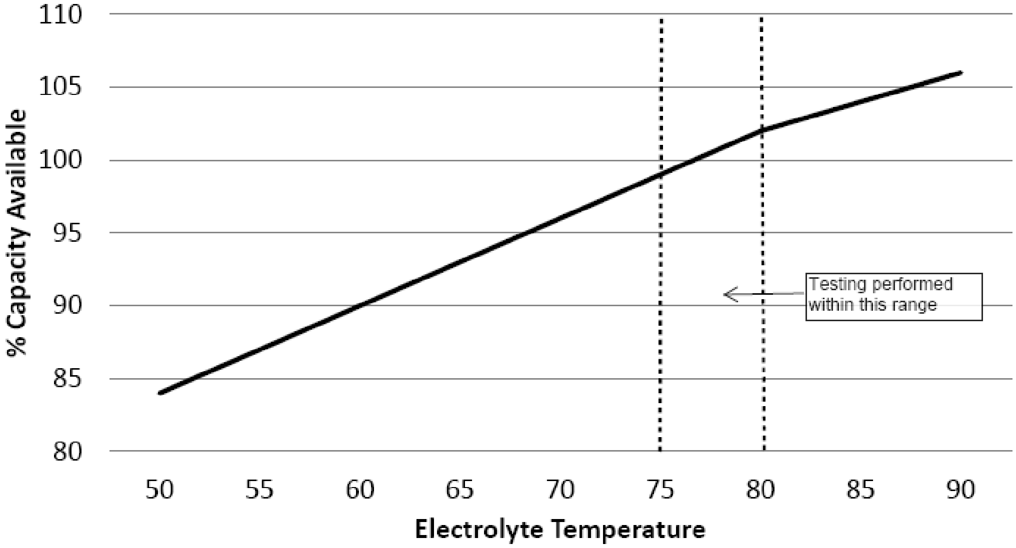

Figure 2-12 Effect of Temperature on Capacity (Adapted from IEEE Standard 485 -2010 [10])

2.8 Test Results – Battery Recharge Characteristics

In the Phase 1 test program (NUREG/CR-7148), a series of 4-hour performance tests were conducted to validate the use of float current as a means of determining battery state-of-charge. Recharge data continued to be acquired during the extended battery operational testing. During the Sequence 1 tests, recharge was conducted at a float voltage of 2.25 volts per cell or 27.0 volts for the 12 cell battery string.

As illustrated in Tables 2-9, 2-10, and 2-11, discharging the battery at lower loads for extended periods of time increases the amount of ampere-hours that can be obtained from the battery and alters the recharge characteristics with regard to the time needed to recharge the battery. Columns 3, 5, and 9 in each of the tables are based upon comparisons of the measured Ah discharged (col. 2) to the rated Ah capacity (col. 1) for a discharge performance test from 2.25 Volts/cell (V/cell) to an end voltage of 1.75 V/cell.

For example, Table 2-9 shows that the 4-hour performance test of the Enersys battery discharged 1530 Ah at a discharge rate of 385 A. The 72-hour performance test of the Enersys battery with a discharge rate of 31.9 A yielded 2068 ampere-hours, a 35% increase in its ampere-hour output. The time to fully charge the battery was 64 hours at the float voltage recharge rate.

Similarly, Table 2-10 indicates that the 4-hour performance test of the GNB battery discharged 1201Ah at a discharge rate of 317A, while a 72-hour test of the same battery at a discharge rate of 27A yielded a total of 1915Ah, a 60% increase in its Ah output. The time to reach a float current of 2A was 24 hours as compared to 15.8 hours for the 4-hour performance test.

And finally, as illustrated in Table 2-11, the 4-hour performance test of the C&D battery conducted at a discharge rate of 500A produced 2050Ah, while a 72-hour performance test conducted at 42A produced 3129Ah, an increase of 52% in the Ah output. During recharge at 2.25 V/cell, it took 68 hours to reach a float current of 2A as compared to 20.6 hours when the battery was recharged at the float voltage value following the 4-hour performance test.

Table 2-9 Enersys Extended Service Recharge Data

Cycle-Parameters	Ah Discharged	Time to 100% Recharge (hr)	Time to 2 A (hr)	% Recharged at 2 A	Time Constant, t_C (hr)	Time at Current Limit, Δt_{CL} (hr)	$\Delta t_{CL} + 5*t_C$	% Recharged at $\Delta t_{CL} + 5*t_C$
1 (385A, 4 hr)	1530 Ah	11.2	11.9	100.6%	1.98	6.50	16.4	101.3%
15 (225A, 8 hr)	1810 Ah	17.5	19.7	100.4%	3.20	7.15	23.15	100.6%
16 (60A, 36 hr)	2178 Ah	27.2	36.5	101.3%	4.06	7.95	28.25	100.2%
17 (47A, 48 hr)	2170 Ah	47.2	46.0	98.9%	4.19	7.28	28.23	97.0%
19 (31.9A, 72 hr)	2068 Ah	64.0	62.3	99.8%	4.36	5.96	27.76	93.6%

Table 2-10 GNB Extended Service Recharge Data

Cycle-Parameters	**Ah Discharged**	**Time (hr) to 100% Recharge**	**Time to 2 A (hr)**	**% Recharged at 2 A**	**Time Constant, t_C (hr)**	**Time (hr) at Current Limit, Δt_{CL}**	**Δt_{CL} + 5*t_C**	**% Recharged at Δt_{CL} + 5*t_C**
4 (317A, 4 hr)	1201 Ah	12.0	15.8	101.0%	2.51	4.25	16.8	101.0%
15 (187A, 8 hr)	1490 Ah	11.3	14.5	101.8%	2.47	6.17	18.5	102.1%
16 (132A, 12 hr)	1573 Ah	10.8	19.9	107.6%	3.23	6.27	22.4	107.9%
17 (71A, 24 hr)	1895 Ah	20.1	29.6	102.1%	3.61	7.00	25.1	101.4%
18 (50A, 36 hr)	1933 Ah	28.0	27.6	101.5%	3.85	6.57	25.8	99.5%
19 (39A, 48 hr)	1984 Ah	32.8	46.9	102.2%	3.97	6.52	26.4	98.3%
20 (27A, 72 hr)	1915 Ah	16.9	24.0	103.1%	3.28	7.57	24.0	103.1

Table 2-11 C&D Extended Service Recharge Data

Cycle-Parameters	**Ah Discharged**	**Time (hr) to 100% Recharge**	**Time to 2 A (hr)**	**% Recharged at 2 A**	**Time Constant, t_C (hr)**	**Time at Current Limit, Δt_{CL} (hr)**	**Δt_{CL} + 5*t_C**	**% Recharged at Δt_{CL} + 5*t_C**
1 (500A, 4 hr)	2050 Ah	14.6	20.6	101.9%	3.03	8.87	24.0	102.2%
15 (290A, 8 hr)	2404 Ah	18.5	25.6	102.2%	3.60	10.20	28.2	102.4%
16 (111A, 24 hr)	2919 Ah	27.6	40.3	102.1%	4.61	11.62	34.7	101.5%
17 (77A, 36 hr)	3008 Ah	27.1	>48	>103.5%	4.97	12.00	36.9	102.4%
18 (60A, 48 hr)	3066 Ah	36.3	>47.9	>101.5%	5.04	11.85	37.1	100.1%
19 (42A, 72 hr)	3129 Ah	40.9	68.0	>102.9%	5.20	11.72	37.7	99.4%

2.9 Comparison to Vendor Curves

Figure 2-13 is a set of curves for the C&D battery used in this testing program. It illustrates the capacity ratings for the LCR cell type for 8 to 72 hour reserve times with various end point cell voltages (1.75 to 2.00 volts).

The load is expressed as Amperes per Positive Plate. For example, an LCR-33 has 16 positive plates and 17 negative plates (33 total plates), so the values on the horizontal axis would be multiplied by 16 to determine the load that the LCR-33 cells can supply for a given time to a given end voltage. The output derived from this process compares very closely to the data acquired from the normalized curve fit calculation and the actual measured results described in the previous sections.

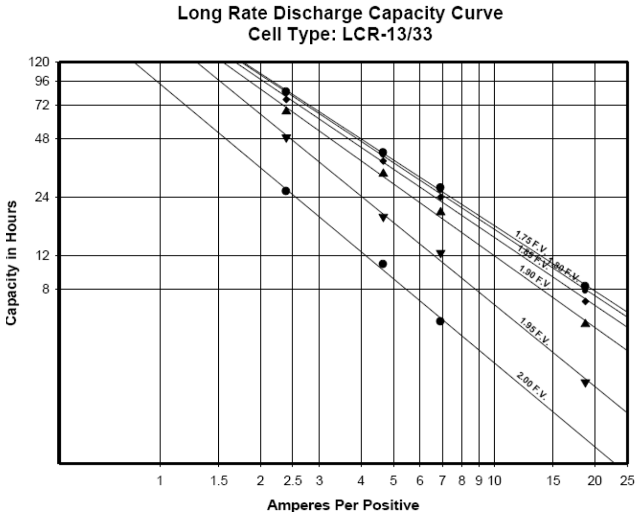

Figure 2-13 C&D Capacity Curves for the LCR-33 battery

2.10 Summary of Sequence 1 Test Results

As described in Section 2.1, Sequence 1 testing at BNL acquired battery data to fill in the data gaps of vendor data out to 72 hours. We compared the tested batteries against the published data for the 8-hour performance test that served as the baseline readings. The tests allowed BNL to develop an algorithm to predict the expected time up to 72 hours for a battery to reach 1.75V/cell at any given loading. This algorithm compared favorably to battery vendor data that was subsequently made available to the industry.

Operation of the batteries at these extended times revealed the following characteristics:

1. Batteries used in NPPs can safely operate out to 72 hours when the loading is reduced (between 25 and 45 amps in this case), depending upon the ampere-hour capacity of the battery.
2. The electrolyte depletes significantly in very long discharges. Acid concentrations as low as 3% (nominal concentration for a fully charged battery is 29%) was obtained on the long duration tests as illustrated in Figure 2-14.

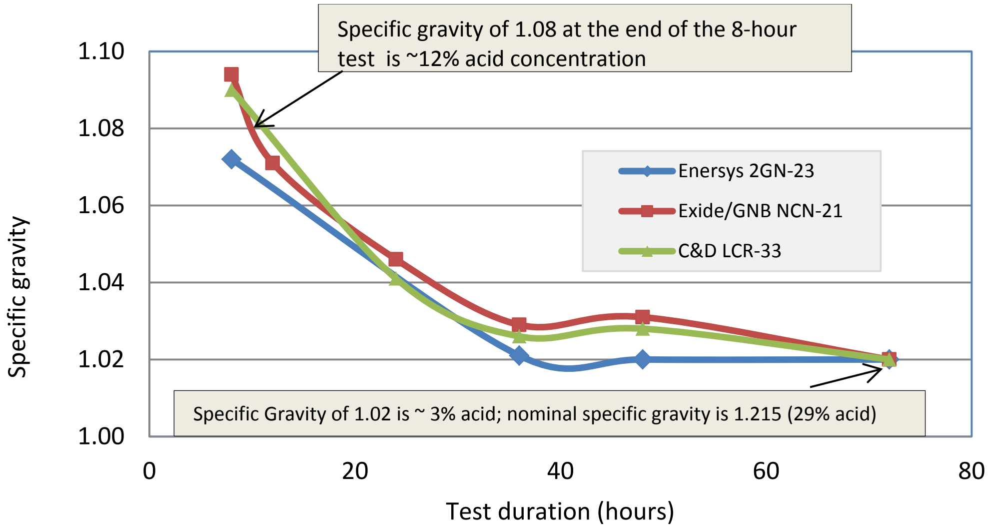

Figure 2-14 Average "end-of-test" cell midpoint specific gravity

3. The battery voltage response during the long discharge at constant current is nearly linear until the cell voltage nears 1.85 volts (111 volts for a 60-cell battery string) at which time it decreases more rapidly. Figure 2-15 is an example of this response for cell #2 of the C&D battery during its 72 hour performance test. This characteristic is important for the operator to be aware of in SBO situations where the battery is supplying power to critical plant equipment. The supplied equipment could become unavailable sooner than the operator would expect if the voltage response was entirely linear.

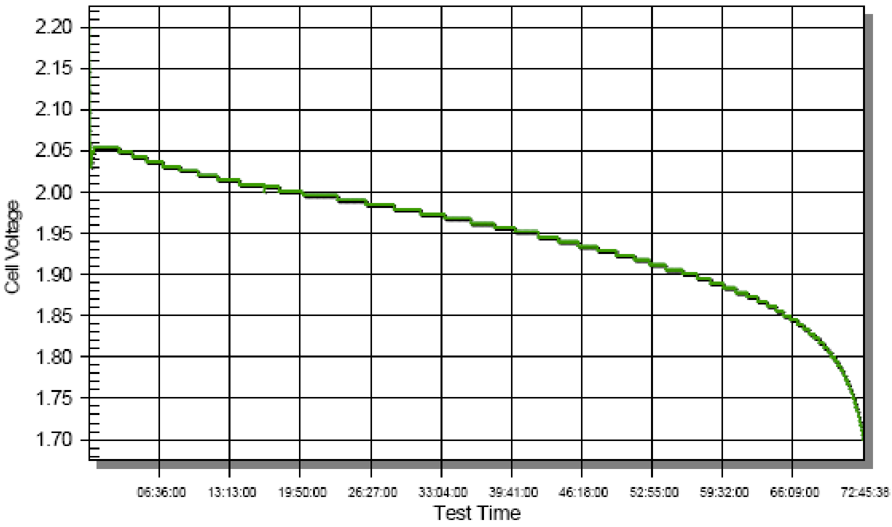

Figure 2-15 C&D Cell #2 Voltage Response during the 72-hour performance test

4. The length of time necessary to recharge a battery increases in proportion to the length of time that it has been discharged. This is reflected in the recharge current response depicted in figure 2-16 which shows that the battery is recharged to full capacity in a shorter time for the short duration tests and increases in time with the longer duration tests.

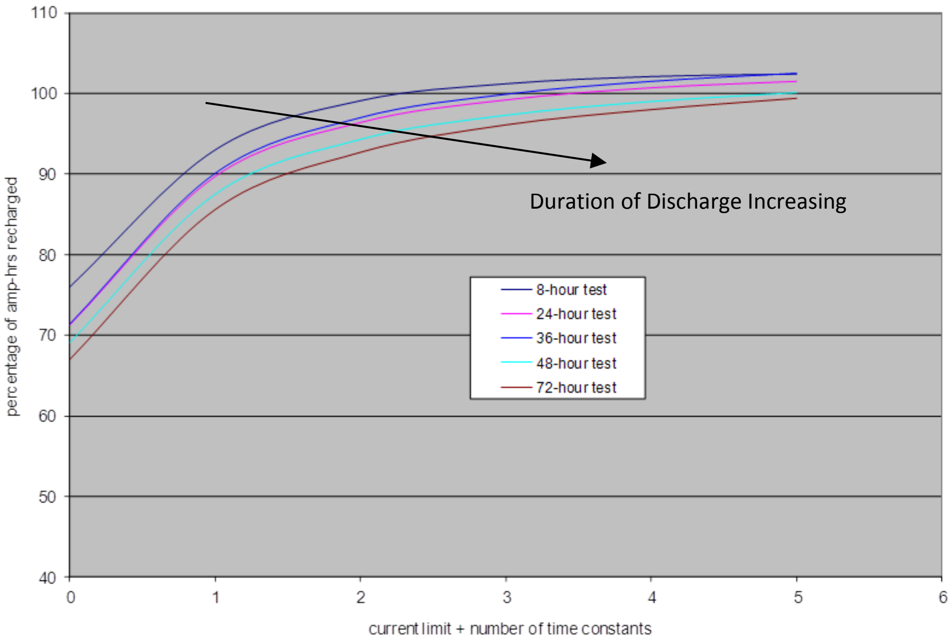

Figure 2-16 C&D recharge characteristics for tests from 8 hours to 72 hours

5. Individual cell voltage differences observed at the end of the extended performance test supports the practice of monitoring individual cell voltages during required performance testing in order to detect a weak cell or cells that could affect the overall performance of the battery string.
6. Aside from the test anomaly associated with the 72-hour test of the Enersys battery, no new battery failure mechanisms were observed during extended operational testing. However, the depletion of the electrolyte during very long battery discharges (36-72 hours) could impact the ability to recharge the battery under some conditions such as if there was a delay between the time when the battery is fully discharged and the initiation of recharge.

3 LOAD PROFILE (SEQUENCE 2) TESTING RESULTS

3.1 Introduction

In Sequence 2, ELAP 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 NEI and approved by the NRC. The four load profiles were from four different NPPs (3 PWRs and 1 BWR) who had analyzed the equipment they needed to assure 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 ELAP. 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 the time it takes the operators to initiate load shedding. 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.

3.2 Background Information – ELAP

Alternating current (AC) electric power is primarily supplied by the offsite power transmission system to which the plant is connected. In the event offsite sources of power are lost, redundant and independent emergency ac power systems (typically diesel generators), are provided to permit the functioning of equipment and systems that are essential to reactor shutdown, reactor core cooling, containment isolation, and heat removal. In addition to the emergency ac power systems, each plant also has two (or more) redundant trains of DC power that are capable of powering essential safety loads for a specified period of time. The size of the DC batteries are based on the amount of starting and running current each load draws from the battery and the length of time each load needs to be supplied from the batteries during an accident. The battery duty cycles, or accident load profiles, are created from the list of design loads by plotting the total current drawn by those loads versus time.

For a loss of offsite power (LOOP) only event, the time the batteries are needed is very short (<1 minute). In the event of an SBO, the batteries may be required to remain operable for several hours. As observed from the events at Fukushima, an ELAP caused by other external events such as flooding may prevent restoration of normal or backup AC power. The current NRC regulatory framework for SBO (10 CFR 50.63) requires each plant to demonstrate that it can cope with and recover from an SBO that lasts for a specified duration. For plants that rely solely on the use of batteries to power essential equipment, the SBO coping time is typically between 4 and 8 hours. These time frames are based on the assumption that at least one source of AC power (offsite or onsite) will be successfully restored within four hours. The common-cause damage to the emergency power supplies and electrical distribution systems that occurred at Fukushima triggered an ELAP that ultimately led to core damage in three reactors.

The earthquake and tsunami at the Fukushima Dai-ichi nuclear power plant in March 2011, highlighted the possibility that extreme natural phenomena could challenge the prevention, mitigation and emergency preparedness defense-in-depth layers already in place in nuclear power plants. At Fukushima, limitations in time and unpredictable conditions associated with the accident significantly challenged attempts by the responders to preclude core damage and containment failure. During the events in Fukushima, the challenges faced by the operators were beyond any faced previously at a commercial nuclear reactor and beyond the anticipated design-basis of the plants.

Following the events at the Fukushima Dai-ichi nuclear power plant on March 11, 2011, the NRC established a senior-level agency task force referred to as the Near-Term Task Force (NTTF). The NTTF was tasked with conducting a systematic and methodical review of the NRC regulations and processes and determining if the agency should make additional improvements to these programs in light of the events at Fukushima Dai-ichi. As a result of this review, the NTTF developed a comprehensive set of recommendations, documented in SECY-11-0093, "Near-Term Report and Recommendations for Agency Actions Following the Events in Japan," dated July 12, 2011. Following interactions with stakeholders, these recommendations were enhanced by the NRC staff and presented to the Commission.

On February 17, 2012, the NRC staff provided SECY-12-0025, "Proposed Orders and Requests for Information in Response to Lessons Learned from Japan's March 11, 2011, Great Tohoku Earthquake and Tsunami," to the Commission, including the proposed order to implement the enhanced mitigation strategies. As directed by SRM-SECY-12-0025, the NRC staff issued Order EA-12-049, "Order Modifying Licenses with Regard to Requirements for Mitigation Strategies for Beyond-Design-Basis External Events." This order directed licensees to develop, implement, and maintain guidance and strategies to maintain or restore core cooling, containment, and spent fuel pool cooling capabilities in the event of a beyond-design-basis external event (BDBEE). In particular, licensee strategies need to be capable of mitigating a simultaneous loss of all AC power and loss of normal access to the ultimate heat sink (LUHS) resulting from a BDBEE by providing the capability to maintain or restore core cooling, containment, and spent fuel pool cooling capabilities at all units on the WBNP site. Order EA-12-049 applies to all power reactor licensees and all holders of construction permits for power reactors.

Order EA-12-049 requires that operating power reactor licensees and construction permit holders use a three-phase approach for mitigating BDBEEs. The initial phase requires the use of installed equipment and resources to maintain or restore core cooling, containment and spent fuel pool cooling capabilities. The transition phase requires providing sufficient, portable, onsite equipment and consumables to maintain or restore these functions until they can be accomplished with resources brought from off site. The final phase requires obtaining sufficient offsite resources to sustain those functions indefinitely. Specific requirements of the order are listed below:

1) Licensees or construction permit (CP) holders shall develop, implement, and maintain guidance and strategies to maintain or restore core cooling, containment, and spent fuel pool capabilities following a beyond-design-basis external event.

2) These strategies must be capable of mitigating a simultaneous loss of all AC power and loss of normal access to the ultimate heat sink [UHS] and have adequate capacity to address challenges to core cooling, containment, and spent fuel pool capabilities at all units on a site subject to Order EA-12-049.

3) Licensees or CP holders must provide reasonable protection for the associated equipment from external events. Such protection must demonstrate that there is adequate capacity to address challenges to core cooling, containment, and spent fuel pool capabilities at all units on a site subject to Order EA-12-049.

4) Licensees or CP holders must be capable of implementing the strategies in all modes.

5) Full compliance shall include procedures, guidance, training, and acquisition, staging, or installing of equipment needed for the strategies.

On August 21, 2012, following several submittals and discussions in public meetings with NRC staff, the Nuclear Energy Institute (NEI) submitted document NEI 12-06, "Diverse and Flexible Coping Strategies (FLEX) Implementation Guide," Revision 0 to the NRC to provide specifications for an industry-developed methodology for the development, implementation, and maintenance of guidance and strategies in response to the Mitigation Strategies order. On August 29, 2012, the NRC staff issued its final version of JLD-ISG-2012-01, "Compliance with Order EA-12-049, Order Modifying Licenses with Regard to Requirements for Mitigation Strategies for Beyond-Design-Basis External Events," endorsing NEI 12-06, Revision 0, as an acceptable means of meeting the requirements of Order EA-12-049, and published a notice of its availability in the *Federal Register* (77 FR 55230).

While the initiating event is undefined, it results in an extended loss of ac power (ELAP) with loss of normal access to the ultimate heat sink (LUHS), which is considered a surrogate for a BDBEE. The initial conditions and assumptions for the analyses are stated in NEI 12-06, Section 3.2.1, and include the following:

1. The reactor is assumed to have safely shutdown with all rods inserted (subcritical).
2. The DC power supplied by the plant batteries is initially available, as is the ac power from inverters supplied by those batteries; however, over time the batteries may be depleted.
3. There is no core damage initially.
4. There is no assumption of any concurrent event.
5. Because the loss of AC power presupposes random failures of safety-related equipment (emergency power sources), there is no requirement to consider further random failures.

On February 28, 2013, licensees submitted their draft overall integrated plans (OIPs) that described their strategy for satisfying NRC Order EA 12-049. While these OIPs are still under staff review, the initial assessment found that all licensees are relying on their DC power system, specifically the safety-related Class 1E batteries, as part of their Phase 1 coping strategy. The duration which licensees are crediting the safety-related Class 1E batteries varies from several minutes to as many as 34 hours before transitioning to Phase 2. Therefore, a lesson learned from the Japanese event that may be applicable to the U.S. NPPs is the need to examine ELAP conditions and determine if the existing safety-related Class 1E batteries can function beyond their design basis (or beyond-design basis if existing Station Blackout (SBO) coping analyses were utilized) duty cycles to support core cooling, containment, and spent fuel pool cooling.

Battery sizing is important to ensure that the loads being supplied are adequately supported by the battery for the expected coping times. An accepted method for sizing a lead-acid battery is described in IEEE Standard 485-2010, “IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications” [10] as endorsed by Regulatory Guide 1.212, “Sizing of Large Lead-Acid Storage Batteries”.

Factors that govern the size (number of cells and rated capacity) of a battery include:

1. the maximum system voltage,
2. the minimum system voltage,
3. correction factors (Temperature, Design Margin, Aging)
4. the duty cycle.

If factors 1- 3 are equal, battery size is based on the duty cycle, which is defined as *loads a battery is expected to supply for specified time periods* (IEEE Standard 485-2010 [10]).
As indicated in IEEE Standard 485-2010, momentary loads can occur one or more times during the duty cycle but do not exceed 1 min at any occurrence. When several momentary loads occur within the same 1 min period, the load for the 1 min period should be assumed to be the sum of all momentary loads occurring within that minute. Sizing for a load lasting only a fraction of a second, based on the battery’s 1 min performance rating, results in a conservatively sized battery. Typical momentary loads are: a) Switchgear operations, b) Motor-driven valve operations (stroke time≤ 1 min), c) Motor starting currents and d) Inrush currents.

For an ELAP, the battery duty consists of various loads applied and removed during the period of time AC power is lost. Examples of such loads are:

- Switchgear and load center control, tripping, closing, and indicating devices;
- Certain automatically / remotely actuated valves (solenoid and DC MOVs)
- Inverter loads;
- Emergency turbine lube-oil pump;
- Protective relaying;
- Fire protection loads;
- Annunciators;
- Turbine-generator excitation breakers and controls;
- DC emergency lighting;
- Communications.

The application, removal, and duration of such loads produce a load current profile of the battery known as the battery duty cycle. Removing loads that are not important for preserving the integrity of the reactor core and the containment building during an ELAP can significantly extend the battery duty cycle. Since the present regulatory framework does address actions to extend the battery duty cycle beyond those considered under the SBO Rule, the amount of time batteries could remain available in an ELAP scenario has not been previously analyzed.

3.3 Sequence 2 Load Profiles

To address this issue, the NRC requested BNL to evaluate the length of time a sample of batteries could remain available when supplying representative load profiles provided by the NEI. While load profile calculations can be performed, actual testing of batteries using these loads had not been performed in the past.

In Sequence 2 of the battery testing program, ELAP conditions were simulated by a series of load profiles and load shedding schemes to determine how long the battery could carry the desired load. Four different load profiles were proposed by the NEI and approved by NRC. The four load profiles are summarized below:

EBR-2 represents the ELAP load profile for "Train B" of a PWR having an independent SBO generator (i.e., AAC power source[1]) and the SBO is assumed for the first two hours. In a station SBO, both trains of batteries are required for the first hour. Critical momentary (1 minute) loads (629 amps total or 10.5 A-hrs) are supplied by the Train A battery which has a capacity of 2532 A-hrs. The current SBO scenario assumes that the Train A will be restored via the SBO generator in 1 hour. If after 1 hour, the SBO generator is not available (ELAP condition), operators would begin the process of load shedding in accordance with ELAP operating procedures/guidance. Required operator actions are assumed to be completed by end of the second hour.

In this scenario, the Train B battery is run to depletion or to the point that some Train B power is restored. It is on this basis that the initiation of load shedding was set to 2 hours. Achieving safe shutdown during the ELAP condition requires operators to implement a set of manual actions that would bring the plant to a stable condition using secondary cooling and maintain natural circulation for core cooling. Secondary cooling is not interrupted by the loss of AC since the motive force for the cooling water (Auxiliary Feed Water) is steam driven and sources of steam (steam generators) are available as long as decay heat is available. A minimum amount of instrumentation was selected to be available to make it possible for control room operators to safely manage the plant. To maintain power to these instruments, with limited DC power availability, a set of load shedding actions is assumed to be initiated early in the event.

Other assumptions that were made in determining this load profile involved the inverter loading. For this profile, the overall inverter load is based on past field measurements and adjusted for voltage, assuming a constant power characteristic for the inverter. 50% efficiency is assumed for the inverter, resulting in a 50 A constant contribution to the long term load profile. This particular plant based its battery loading on an end voltage of 1.78 volts per cell, or 106.8V for their 60-cell string.

Using IEEE Standard 485-2010, the calculated runtime by the plant for this battery load condition was 29 hours. This is factoring in a minimum design temperature of 60°F and a 1.25 aging correction factor. One of the actual tests using this profile is illustrated in Figure 3-1. The test duration to 1.75 volts per cell was 44.2 hours.

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[1] One acceptable means of complying with the requirements in 10 CFR 50.63 involves the provision of an Alternate AC (AAC) power source (typically a diesel generator) that will be available on a sufficiently timely basis to permit operation of systems necessary to achieve and maintain a safe-shutdown condition.

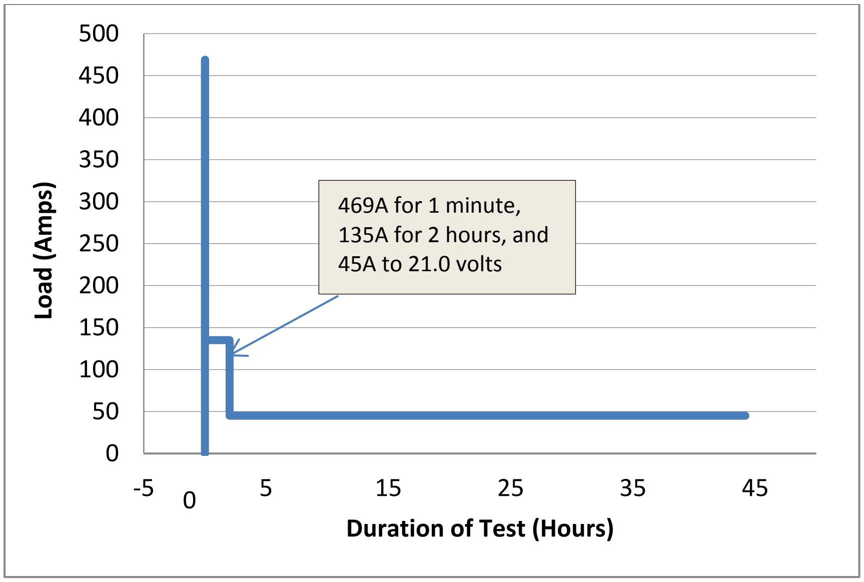


Figure 3-1 EBR-2 Load Profile Test Results for Enersys Run #15

EBR-3 represents the ELAP load profile of a "Train B" battery at a PWR. During the SBO all AC loads are stripped from their respective buses. These loads would normally be sequenced on but since there is no AC bus voltage available, the sequencer will not start. All active components powered by DC are assumed to be available for the first 90 minutes. At 90 minutes, the battery coping strategy will focus on reducing the DC loads (by operator action at distribution panels) by 194 amps, including 165 amps of inverter feeds to redundant instrumentation and controls, diesel generator sequencing, and Heating, Ventilation, and Air Conditioning (HVAC); 27 amps to control panels for the HVAC, and 22 amps to non-essential valves and actuators. Only the following loads would be supplied by the Train B battery:

- Reactor Protection (43 amps);
- 4160 and 480 volt Switchgear instrumentation (10 amps) and
- Auxiliary Relay Panels and Diesel Generator Engine Control Panel (9 amps).

Thus, after 90 minutes, only critical safe shutdown loads totaling 62 amps would be supplied by this battery. The core cooling strategy is the same as EBR-2 (Auxiliary Feedwater System and natural circulation cool down of the core). For EBR-3, the inverter demand in amps was assumed to be at the lowest input voltage of 1.86 volts per cell. It was also noted that battery voltage and amps are instrumented in the main control room and would be available to the operator to know when it was "approaching depletion". The percent capacity of the battery on the most recent performance test is another factor used in the procedure to determine battery depletion. A switch over to the other train could be initiated by the operator from the control room when this point is reached.

The plant calculated the expected runtime for this battery load condition to be 21.8 hours using a plant specific end voltage of 1.86 volts, an aging correction factor of 1.25, a minimum design temperature of 70°F, and a design margin of 10%.

One of the actual tests using this profile is illustrated in figure 3-2. Note that five MOV/pump operations were simulated every 2 hours after approximately 10.5 hours and the battery was available for 41.2 hours to an average cell voltage of 1.75 volts.

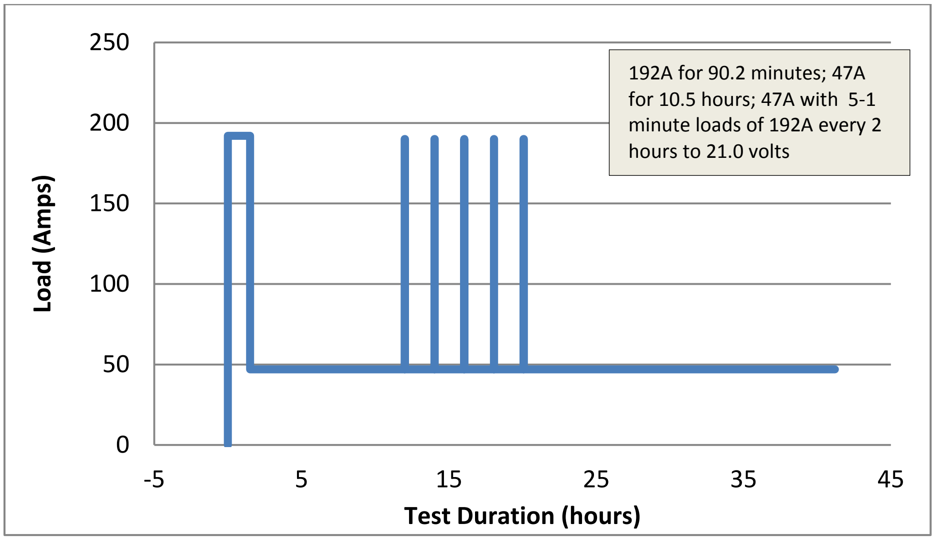


Figure 3-2 EBR-3 Load Profile Test Results for Enersys Run #12

EBR-4 represents an ELAP load profile of a "Train A" battery at a PWR. Automatic tripping of 4kV and 600 V breakers occurs during the first minute. For this load profile, normal SBO loading is assumed for the first 53 minutes until load shedding is started. All loads except critical instrumentation are shed to support ELAP.

To maximize battery runtime, the strategy employed at this site is to run the Train A battery first and minimize the load on the Train B battery initially. When the Train A battery is approaching depletion, the alternate Train B instrumentation would be re-energized from the Train B battery. This plant also used field measurements to determine the inverter loads and then assumed the ampere loading at the lowest input battery voltage, which in this case is 1.85 volts per cell (60-cell string). This plant requires a minimum battery voltage of 111 volts to ensure adequate voltage at its critical loads. They indicated that they use a special procedure to estimate the remaining battery availability that incorporates battery voltage and current measurements that are available in the control room along with battery temperature and % capacity. The plant calculated runtime for this battery load condition is 15.5 hours using an end voltage of 1.85 volts per cell, a minimum design temperature of 60°F, an aging correction factor of 1.25, and a design margin of 5%.

One of the actual tests using this profile is illustrated in Figure 3-3. The test duration to an average cell voltage of 1.75 volts was 22.2 hours.

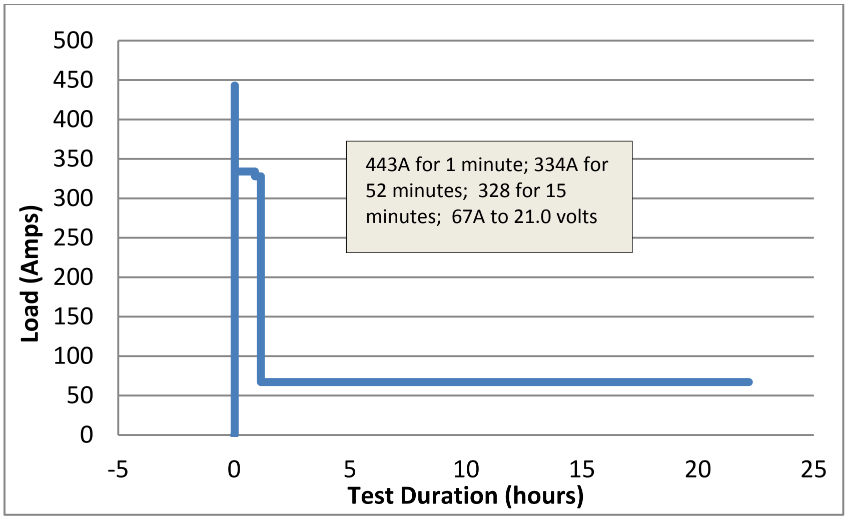


Figure 3-3 EBR-4 Load Profile Test Results for GNB Run #8

EBR-5 represents an ELAP load profile for Train A of a BWR. This profile assumes that the Reactor Core Isolation Cooling System (RCIC) is switched to manual mode once the extended ELAP procedure/guidance is activated. This removes several automatic DC MOV operations. It is assumed that the normal SBO loads are only required for the first 61 minutes. The SBO and ELAP procedures provide operator actions to bring the plant to a stable condition using the RCIC system taking suction from the Condensate Storage Tank and operating in manual mode. The procedures call for non-essential loads being shed within 30 minutes. This includes the Main Turbine Emergency Bearing Oil Pump, the 125V DC cabinet feeding non-1E loads, and the redundant Control Building Emergency Lighting Cabinet.

Critical instrumentation powered by this battery includes reactor water level and pressure. Other important instrumentation such as containment integrity parameters and spent fuel pool level are provided by other power sources

The plant calculated a runtime for this battery load condition of 21 hours based on an end voltage of 1.75 volts per cell, a minimum design temperature of 65°F, an aging factor of 1.25, and a design margin of 5%. One of the actual tests using this profile is illustrated in Figure 3-4. The test duration to an average cell voltage of 1.75 volts was 32.6 hours.

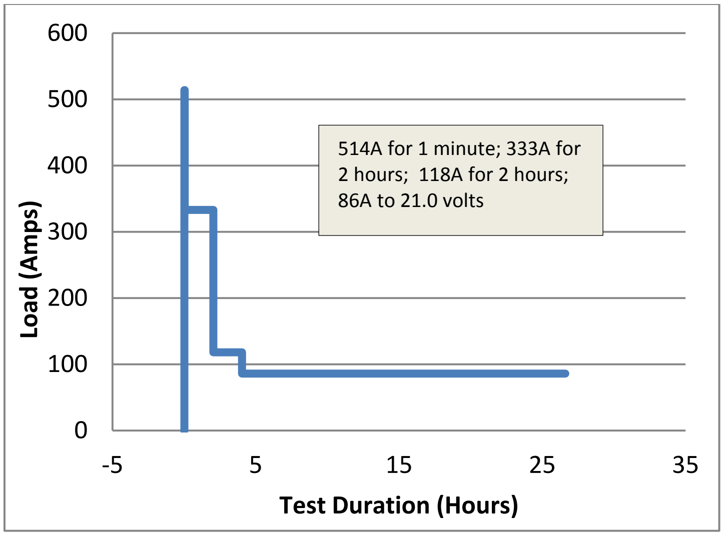


Figure 3-4 EBR-5 Load Profile Test Results for C&D Run #4

<u>Evaluation of load profiles</u>: In May 2012, when the NRC requested the NEI to assist with providing representative load profiles that could be used in this testing program, benefits to both the NRC and the nuclear industry were anticipated. Specifically, the letter stated:

"*Participation will provide the NRC staff with direct current (DC) load profiles to be modeled and tested, which should yield test results more closely representing existing station battery SBO coping capabilities. The goal is to use the insights gained through the cooperative research program to potentially develop and provide guidance to extend battery performance during a prolonged SBO event. The nuclear industry could benefit from the research data by the development of coping strategies for extended SBO events.*" [12]

The goal of obtaining realistic load profiles that could be tested using the existing battery laboratory at BNL was achieved through the cooperative effort with NEI, the Electric Power Research Institute (EPRI), and participating NPPs. NEI not only provided the load profiles that their analyses indicated were achievable, they also provided information about the genesis of the profiles, with specific information about the equipment that could be shed as well as the associated loads for the equipment that would be called upon to achieve a safe shutdown condition. Individual plant assumptions when estimating battery availability may contain other criteria such as a battery specific gravity value in accordance with the minimum allowed by their technical specifications and/or specific operator actions conducted in a certain time frame.

3.4 Sequence 2 Test Results

The results of Sequence 2 testing indicate that battery availability can be significantly extended beyond 4-8 hours when used to meet the load demands anticipated in an ELAP condition. In each of these tests, the test terminated when the overall battery string reached 21.0 volts (average of 1.75 volts/cell). A second criterion for test termination was a cell voltage of 1.3 volts but that was never experienced in the Sequence 2 testing. Since some NPPs have calculated higher battery end voltages due to specific load demands or the length of cable, the expected battery availability would be somewhat less. The battery voltage response curve (see Figure 3-5 for example) can be used to determine the battery availability based on the plant specific end voltage value.

Prior to the start of the load profile testing, an 8-hour baseline performance test was run on each of the three battery strings. These were identified as test runs 1, 2, and 3. The battery capacities obtained from these tests were:

- C&D LCR-33:	100.5%
- GNB NCN-21:	95.5%
- Enersys 2GN-23:	94.8%

These batteries had been subjected to more than 20 deep discharge cycles prior to the Sequence 2 testing. The resulting difference in capacity accounts for some of the minor differences seen in the performance of the batteries on identical load profiles.

This section will describe the results from the load profiles, highlighting five important areas:

1. The extended duration capability of the batteries,
2. The ability to predict the duration using IEEE 485 or vendor supplied information,
3. The generally linear voltage response during battery discharge until near the cell approaches 1.85 volts when the voltage decreases more rapidly,
4. The depletion of electrolyte during the longer duration tests, possibly impacting the ability of the battery to be recharged, and
5. The slight variation in the cell voltages at the end of the discharge that could be worthwhile monitoring to ensure that no thermal runaway conditions develop.

Following the load profile testing, 8-hour baseline performance tests were again conducted on each of the battery strings. The battery capacities obtained from these tests, designated as cycles 16-18 were:

- C&D LCR-33:	101.5%
- GNB NCN-21:	97.2%
- Enersys 2GN-23:	95.8%

These results show no apparent degradation of the batteries as a result of conducting the load profile testing.

3.4.1 Test Series #1: Load Profile EBR-5

Subsequent to the baseline test runs, the first load profile tested was identified by NEI as EBR-5. The nominal test parameters provided by NEI were based on a profile for a C&D model LCR-29 battery and includes four different battery loads applied over time with an assumed load shed initiation time of 30 minutes. The load profile was tested on each of the three battery strings at BNL, but was scaled linearly according to the sizes (amp-hour ratings) of the batteries as compared to the LCR-29 battery. The load shed time for the C&D battery was modified to 120 minutes and the load shed time for the Enersys battery to 60 minutes to determine the impact of the load shedding initiation times on the overall battery availability time. The ampere loading and load shed times for the test runs are summarized in table 3-1. Step 4 was voltage limited rather than time limited by using an average end voltage of 1.75 volts per cell (21.0 volts for the 12-cell battery string) as the testing endpoint.

Table 3-1 Test Series #1 Loading (Rated Current and Time)

Battery Type	Scaling Factor	Step 1 (1 minute)	Step 2 (variable)	Step 3 (variable)	Step 4 (to 21.0 Volts)
C&D LCR-29 (NEI)	----	450 amps	291 amps (30 minutes)	103 amps (30 minutes)	75 amps
C&D LCR-33 **(test #4)**	1.143	514 amps	333 amps (120 minutes)	118 amps (120 minutes)	86 amps
GNB NCN-21 **(test #5)**	0.737	332 amps	214 amps (30 minutes)	76 amps (30 minutes)	55 amps
Enersys 2GN-23 (**test #6)**	0.887	399 amps	258 amps (60 minutes)	91 amps (60 minutes)	67 amps

The Alber Battery Capacity Test Set was used to control and monitor the test. The Alber unit provided real-time data on the discharge current, battery string overall voltage, and individual cell voltages. The capacity test set automatically adjusts the load to 77°F. In test run #4, the actual temperature was 77°F so no adjustment was required. Test runs #5 and #6 were initiated with the battery at 78°F, requiring a very minor adjustment to the applied test current. The Alber test set was also used to record the cell voltages for the first 24 hours following initiation of recharge at an equalizing voltage of 28.0 volts (2.33 volts per cell).

The results of the tests are in line with the estimates that had been made based on a battery sizing calculation derived from IEEE Standard 485-2010 and one that used a curve fit calculated by BNL. This information is illustrated in Table 3-2.

Table 3-2 Test Series #1 Comparison of estimated to actual battery availability

Test Run #	Estimate 1	Estimate 2	Actual
4 (C&D)	25.3 hours	27.0 hours	**26.6 hours**
5 (GNB)	30.4 hours	29.2 hours	**32.6 hours**
6 (Enersys)	28.4 hours	29.2 hours	**27.7 hours**

Estimate 1 – Estimated test duration based on curve fit derived by BNL from battery vendor and BNL test data
Estimate 2 – Estimated test duration based on 14-step battery sizing spread sheet derived from IEEE 485

The impact of battery availability times as a function of how quickly the load shedding occurs is illustrated in table 3-3. By initiating the load shedding as soon as possible, the loading on the battery is reduced and its availability extended by several hours.

Table 3-3 Impact of load shed timing on battery availability

Test Run #	Load Shed Time	Battery Availability
5 (GNB)	30 minutes	32.6 hours
6 (Enersys)	60 minutes	27.7 hours
4 (C&D)	120 minutes	26.6 hours

Voltage Response: Figure 3-5 was developed by taking the data acquired from the Alber battery capacity test set directly to a spread sheet. This provides a smoother curve fit that is more indicative of the actual voltage change that occurred over time. It is expected that this type of curve could be used to determine the battery availability for any desired end voltage at or higher than 1.75 volts per cell. The end voltage is a plant-specific determination based on the supplied equipment voltage requirements and the lengths of the cable runs.

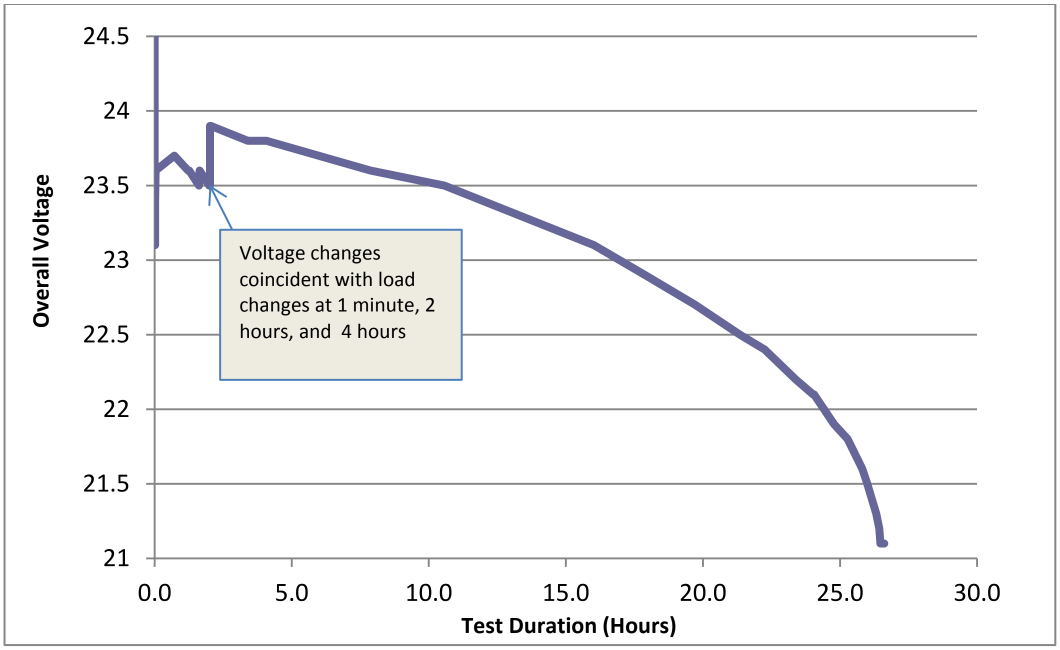


Figure 3-5 Voltage Change over Time (C&D battery test run #4)

While the end point for each of the tests is when the overall battery voltage reaches 21.0 volts, it should be noted that the individual cell voltage characteristics vary among the three battery types. Table 3-4 shows the end voltages for each of the three battery strings for this first load profile test. The high and low end cell voltages for each battery string are highlighted in the table and quantified in the right column. The span of approximately 10% of the end voltage readings for the Enersys battery string (.180/1.75V) is larger than the other two battery strings and this points out the need for NPPs to monitor cell voltages as a means to detect and mitigate weak cells.

Table 3-4 First End Voltages of Each Cell (When Overall Voltage Reached 21.0 volts)

Battery Type and Run #	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Cell 7	Cell 8	Cell 9	Cell 10	Cell 11	Cell 12	End voltage span
C&D (#4)	1.787	1.728	1.747	1.747	1.794	1.711	1.763	1.780	1.781	1.709	1.781	1.784	.085
GNB (#5)	1.749	1.781	1.773	1.772	1.750	1.752	1.741	1.743	1.746	1.792	1.768	1.767	.051
Enersys (#6)	1.771	1.701	1.749	1.746	1.742	1.635	1.801	1.804	1.796	1.790	1.815	1.789	.180

Specific Gravity Results: The specific gravity readings vary slightly as well among the three battery types. Readings taken prior to the discharging the battery, at the completion of the discharge, and following the 100-hour equalizing charge are shown in table 3-5 for each cell. For cells # 9 and 11 on each string, two additional specific gravity measurements were taken as well. These readings were at the top and bottom of the cell and provide an indication of the amount of electrolyte stratification that existed in the C&D and GNB batteries even after the 100-hour equalizing charge. Highly stratified electrolyte in the cells will impact the batteries capacity and capability. Note that after each set of readings, a calibration check of the instrument was conducted using distilled water. These data are also included in the table.

Table 3-5 Specific Gravity readings for Test Series #1

Battery	**C&D (Test Run #4)**			**GNB (Test Run #5)**			**Enersys (Test Run #6)**		
Cell/Position	Pre-Test	Post Discharge	Post Recharge	Pre-Test	Post Discharge	Post Recharge	Pre-Test	Post Discharge	Post Recharge
1-Midpoint	1.227	1.049	1.229	1.205	1.048	1.219	1.219	1.031	1.202
2-Midpoint	1.225	1.043	1.224	1.211	1.053	1.225	1.220	1.028	1.200
3-Midpoint	1.227	1.047	1.229	1.207	1.051	1.223	1.206	1.028	1.195
4-Midpoint	1.227	1.046	1.225	1.208	1.051	1.224	1.214	1.030	1.201
5-Midpoint	1.229	1.048	1.227	1.209	1.049	1.222	1.221	1.030	1.209
6-Midpoint	1.223	1.043	1.223	1.207	1.049	1.223	1.206	1.025	1.195
7-Midpoint	1.226	1.046	1.225	1.206	1.048	1.223	1.222	1.034	1.210
8-Midpoint	1.232	1.049	1.229	1.205	1.047	1.221	1.228	1.038	1.211
9-Midpoint	1.228	1.045	1.227	1.206	1.048	1.225	1.221	1.034	1.206
10-Midpoint	1.226	1.043	1.224	1.210	1.053	1.224	1.219	1.033	1.208
11-Midpoint	1.225	1.046	1.222	1.208	1.050	1.223	1.222	1.037	1.208
12-Midpoint	1.229	1.049	1.227	1.207	1.050	1.223	1.215	1.032	1.205
9-Top	1.214	1.042	1.183	1.174	1.043	1.131	1.217	1.033	1.201
11-Top	1.221	1.043	1.190	1.177	1.046	1.136	1.218	1.035	1.205
9-Bottom	1.246	1.048	1.278	1.260	1.060	1.276	1.263	1.038	1.278
11-Bottom	1.233	1.048	1.273	1.256	1.058	1.273	1.264	1.040	1.281
H_2O	1.000	1.001	1.002	1.000	1.000	1.002	1.002	1.001	1.001

3.4.2 Test Series #2 (Load Profile EBR-4)

The second load profile tested was identified by NEI as EBR-4. This load profile represents a PWR in which automatic tripping of the 4kV and 600 V breakers occur during the first minute. Normal SBO loading is assumed for the first 53 minutes until load shedding is started. “Loss of all ac power” procedures were used to determine the non-essential loads to be shed during this event. During Step 3 all loads except critical instrumentation are shed to support ELAP. Step 4 loads consist of critical instrumentation.

The nominal test parameters for EBR-4 provided by NEI were based on a profile for a C&D model LCR-27 battery and include four different battery loads applied over time. As agreed upon in the development of the test plan, this load profile was tested on each of the three battery strings at BNL without scaling for the sizes (amp-hour ratings) of the batteries being tested at BNL as compared to the LCR-27 battery. It was felt that one test series without scaling would be warranted to observe each battery’s response to the same load profile. The load shed timing for each test run was also maintained the same for each battery test. The ampere loading and load shed times for these test runs are summarized in Table 3-6.

Table 3-6 Test Series #2 Loading (Rated Current and Time)

Battery Type	Scaling Factor	Step 1 (1 minute)	Step 2 (52 minutes)	Step 3 (15 minutes)	Step 4 (to 21.0 Volts)
C&D LCR-27 (NEI)	----	443 amps	334 amps	328 amps	67 amps
C&D LCR-33 **(test #7)**	1.0	443 amps	334 amps	328 amps	67 amps
GNB NCN-21 **(test #8)**	1.0	443 amps	334 amps	328 amps	67 amps
Enersys 2GN-23 **(test #9)**	1.0	443 amps	334 amps	328 amps	67 amps

As illustrated in table 3-7, the results of the tests are in line with the estimates that had been made based on a battery sizing calculation derived from IEEE Standard 485-2010 [10]and one that used a curve fit derived from battery vendor supplied battery specifications supplemented by BNL test data.

Table 3-7 Test Series #2 Comparison of estimated to actual battery availability

Test Run #	Estimate 1	Estimate 2	Actual
7 (C&D)	37.7 hours	40.6 hours	**39.9 hours**
8 (GNB)	21.2 hours	20.3 hours	**22.2 hours**
9 (Enersys)	27.2 hours	26.3 hours	**26.3 hours**

Estimate 1 – Estimated test duration based on curve fit derived from battery vendor and BNL test curves
Estimate 2 – Estimated test duration based on 14-step battery sizing spread sheet derived from IEEE 485

Scaling factor analysis: This test series yielded the predicted response that the largest battery (C&D) would have the longest availability while the smallest battery (GNB) would have the shortest availability. Table 3.8 illustrates the ratio of the 8-hour amp-hour ratings of the batteries (normalized to the GNB battery which is the smallest) and compares it to the ratio of the test duration times normalized to the GNB battery. While the 8- hour amp-hr rating was used for scaling purposes throughout this testing program, it should be noted that this ratio is consistent with the longer duration tests completed in Sequence 1. Namely, the amp-hr ratios of the C&D battery to the GNB battery at 36 and 72 hours are1.54 and 1.56, respectively and the amp-hr ratios of the Enersys to the GNB battery are 1.2 and 1.18, respectively. There is a close correlation between these two ratios for the Enersys battery with the GNB battery, however the ratio of the C&D battery test duration exceeded the ratio of the ampere-hour ratings (1.80 to 1.55). For the purposes of this testing, the scaling factor applied to the battery loads turned out to not be a significant variable when assessing long duration capabilities of the batteries.

Table 3-8 Comparison of battery rating to its availability

Test Run #	8- hour amp-hr rating	8- hour amp-hr Ratio	Test Duration	Test Duration Ratio
7 (C&D)	2320	1.55	39.9 hours	1.80
8 (GNB)	1496	1.0	22.2 hours	1.0
9 (Enersys)	1800	1.20	26.3 hours	1.18

Voltage Response: Figure 3-6 takes the data from the Alber test set for test #9 directly to a spread sheet and provides a smoother curve fit that is more indicative of the actual voltage change that occurs over time. The actual end voltage would be a plant-specific determination based on the supplied equipment voltage requirements and the lengths of the cable runs.

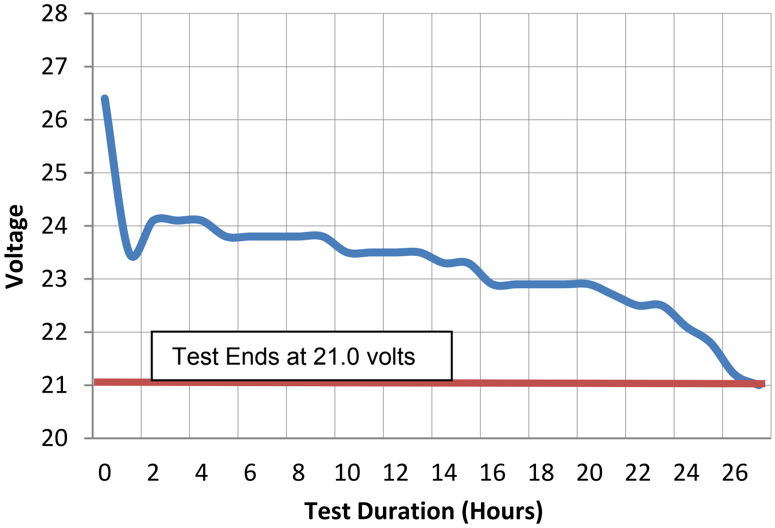


Figure 3-6 Voltage Change over Time (Enersys battery test run #9)

While the end point for each of the tests is when the overall battery voltage reaches 21.0 volts, it should be noted that the individual cell voltage characteristics vary among the three battery types. Table 3-9 shows the end voltages for each of the three battery strings. The high and low end cell voltages for each battery string are highlighted in the table and quantified in the right column.

Table 3-9 Second End Voltages of Each Cell (When Overall Voltage Reached 21.0 volts)

Battery Type and Run #	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Cell 7	Cell 8	Cell 9	Cell 10	Cell 11	Cell 12	End voltage span
C&D (#7)	1.792	1.738	1.768	1.758	1.788	1.710	1.763	1.785	1.770	1.697	1.770	1.778	0.095
GNB (#8)	1.733	1.788	1.779	1.768	1.740	1.763	1.736	1.744	1.747	1.795	1.765	1.763	0.062
Enersys (#9)	1.775	1.720	1.742	1.722	1.722	1.674	1.795	1.795	1.794	1.785	1.809	1.784	0.135

Specific Gravity Results: As previously described, the specific gravity readings were taken at the midpoint of each cell prior to the load profile discharge, following the discharge, and following the 100-hour equalizing charge. The readings for the second load profile (EBR-4) are illustrated in table 3-10. The midpoint readings are denoted as M while the top and bottom cell specific gravity readings are denoted as T and B, respectively. In this test, each of the 3 battery types exhibited some stratification of the electrolyte following the recharge, although the Enersys battery had the least (due to better mixing during recharge).

Table 3-10 Specific Gravity readings for Test Series #2

Battery	**C&D (Test Run #7)**			**GNB (Test Run #8)**			**Enersys (Test Run #9)**		
Cell/Position	Pre-Test	Post Discharge	Post Recharge	Pre-Test	Post Discharge	Post Recharge	Pre-Test	Post Discharge	Post Recharge
1-Midpoint	1.226	1.032	1.231	1.207	1.048	1.214	1.210	1.033	1.194
2-Midpoint	1.223	1.026	1.226	1.211	1.053	1.219	1.211	1.030	1.196
3-Midpoint	1.225	1.030	1.228	1.209	1.051	1.218	1.209	1.032	1.196
4-Midpoint	1.224	1.030	1.226	1.208	1.051	1.219	1.214	1.034	1.191
5-Midpoint	1.226	1.031	1.228	1.209	1.049	1.218	1.220	1.033	1.201
6-Midpoint	1.222	1.027	1.224	1.207	1.049	1.219	1.208	1.029	1.192
7-Midpoint	1.224	1.030	1.227	1.207	1.047	1.217	1.221	1.038	1.203
8-Midpoint	1.230	1.033	1.230	1.206	1.048	1.217	1.224	1.041	1.209
9-Midpoint	1.224	1.028	1.229	1.208	1.048	1.220	1.220	1.038	1.202
10-Midpoint	1.223	1.026	1.226	1.212	1.053	1.220	1.221	1.037	1.205
11-Midpoint	1.222	1.030	1.226	1.209	1.050	1.219	1.223	1.041	1.202
12-Midpoint	1.227	1.033	1.230	1.207	1.050	1.216	1.216	1.036	1.205
9-Top	1.210	1.025	1.176	1.168	1.043	1.139	1.211	1.035	1.192
11-Top	1.215	1.027	1.185	1.171	1.046	1.142	1.222	1.038	1.196
9-Bottom	1.255	1.036	1.282	1.263	1.064	1.274	1.248	1.041	1.284
11-Bottom	1.246	1.034	1.276	1.261	1.062	1.273	1.252	1.043	1.288
H_2O	1.000	1.001	1.001	1.002	0.999	1.000	1.000	0.999	1.001

3.4.3 Test Series #3 (Load Profile EBR-5 and EBR-3)

The third series of tests was a combination of two load profiles. The first run using the C&D battery modified the load profile identified by NEI as EBR-5 by initiating the load shedding at 60 minutes versus the original specified time of 30 minutes. The second and third runs using the GNB and Enersys battery strings respectively were based on the load profile designated by NEI as EBR-3. This load profile represents a PWR in which automatic tripping of the 4kV and 600 V breakers occur during the first minute. Normal SBO loading is assumed for the first 90.2 minutes until load shedding is started and only critical safe shutdown loads are supplied.

For EBR-3, the test parameters provided by NEI were based on a profile for a C&D model LCY-39 battery which has a 2400 Ah 8-hour rating. The load profile was applied to the GNB and

Enersys battery strings at BNL with scaling for the sizes (amp-hour ratings) of the batteries being tested at BNL as compared to the LCY-39 battery. The ampere loading and load shed times for these test runs are summarized in Table 3-11.

Table 3-11 Test Series #3 Loading (Rated Current and Time)

Battery Type	Scaling Factor	Step 1	Step 2	Step 3	Step 4 (to 21.0 Volts)
C&D LCR-29 (NEI) **(EBR-5)**	-----	450 amps	291 amps	103 amps	75 amps
C&D LCR-33 **(test #10)**	1.143	514 amps (1 minute)	333 amps (60 minutes)	118 amps (60 minutes)	86 amps
C&D LCY-39 (NEI) **(EBR-3)**	----	256 amps	62 amps	N/A	N/A
GNB NCN-21 **(test #11)**	0.623	160 amps (90.2 minutes)	39 amps (10.5 hours)	5-1 minute loads of 160 amps at 2 hour intervals then 39 amps to the end	
Enersys 2GN-23 **(test #12)**	0.750	192 amps (90.2 minutes)	47 amps (10.5 hours)	5-1 minute loads of 192 amps at 2 hour intervals then 47 amps to the end	

The results of the tests are in line with the estimates that had been made based on a battery sizing calculation derived from IEEE Standard 485-2010 and one that used a curve fit derived from battery vendor supplied battery specifications supplemented by BNL test data. This information is illustrated in Table 3-12.

Table 3-12 Test Series #3 Comparison of estimated to actual battery availability

Test Run #	Estimate 1	Estimate 2	Actual
10 (C&D)	28.5 hours	30.4 hours	**30.6 hours**
11 (GNB)	42.8 hours	36-40 hours	**45.2 hours**
12 (Enersys)	42.7 hours	36-40 hours	**41.2 hours**

Estimate 1 – Estimated test duration based on curve fit derived from battery vendor and BNL test curves
Estimate 2 – Estimated test duration based on 14-step battery sizing spread sheet derived from IEEE 485

The Alber capacity test set was programmed to provide the loads to the battery at the prescribed time, and to automatically shut down the test when the overall voltage reached 21.0 volts. The output from the Alber test reports is provided as figure 3-7, 3-8, and 3-9. These figures show the overall voltage on the left vertical axis and the load current on the right axis. Note that these figures skew somewhat the voltage response in the sense that it is depicted as a series of step changes rather than a relatively smooth linear decrease when steady state loads are applied as illustrated in figure 3-10.

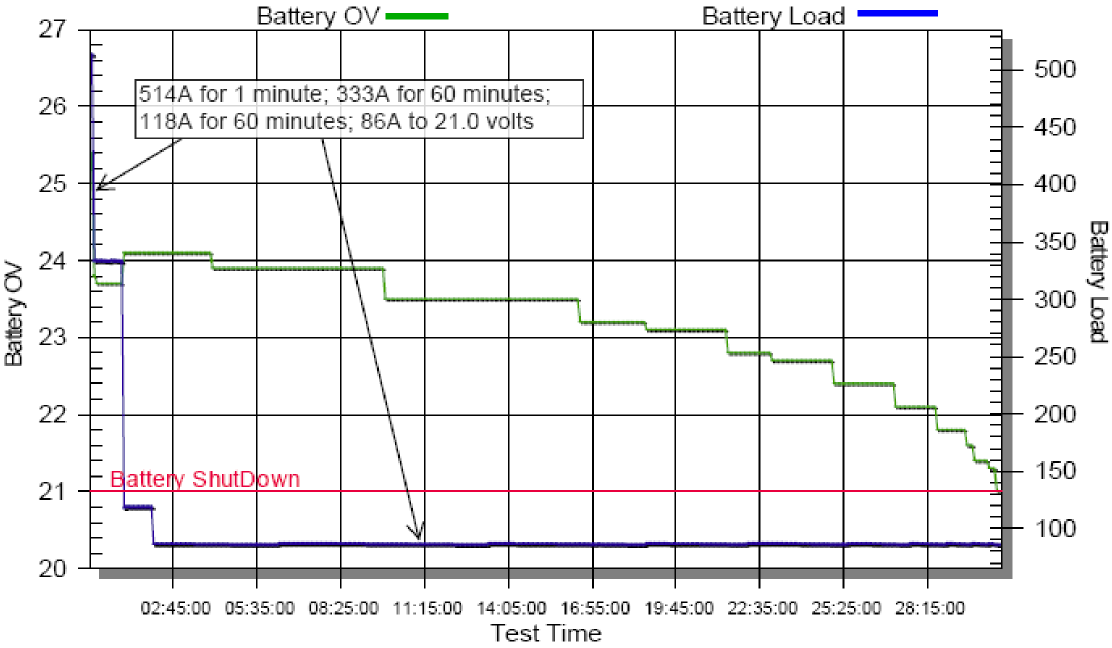


Figure 3-7 Test Run #10 (C&D LCR-33 Battery)

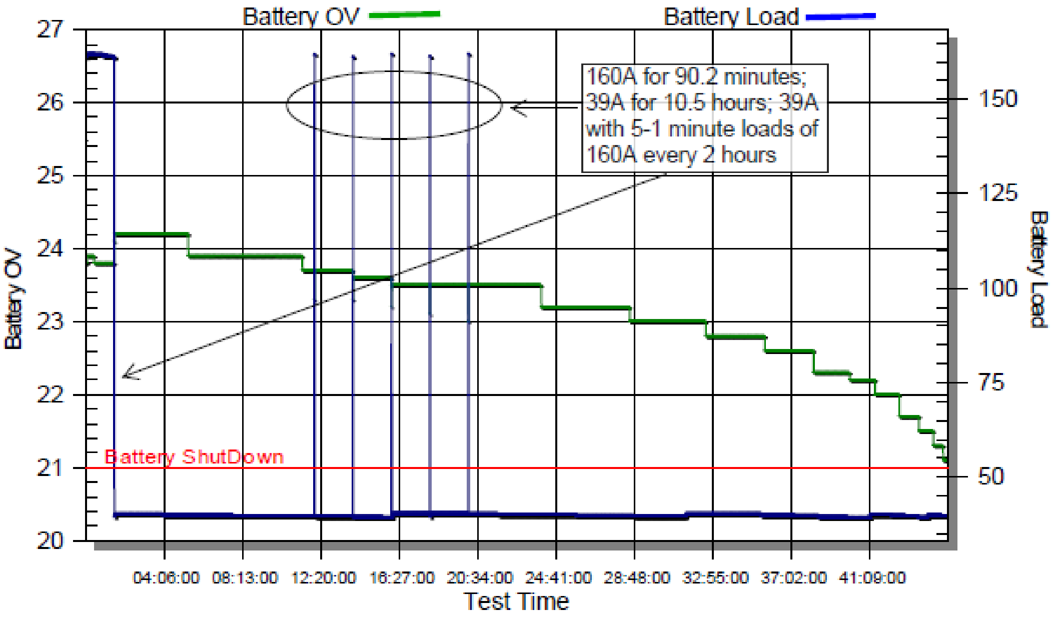


Figure 3-8 Test Run #11 (GNB NCN-21 Battery)

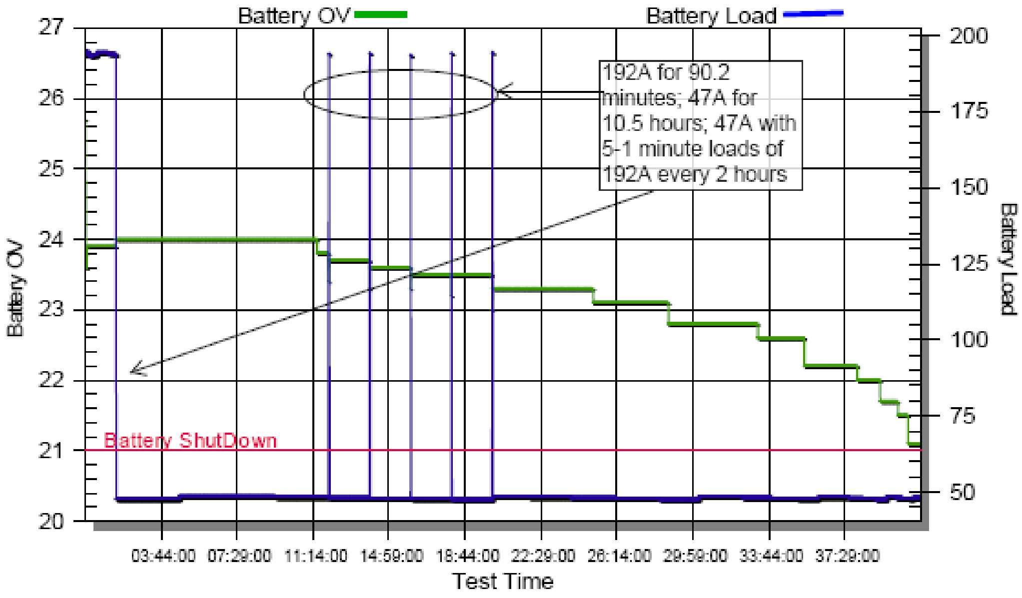


Figure 3-9 Test Run #12 (Enersys 2GN-23 Battery)

<u>Voltage Response</u>: Figure 3-10 illustrates the voltage response for Enersys cell #6 during the conduct of test run #12. This curve is representative of the response from the other cells in that the voltage decreases fairly linearly until the battery approaches ~1.85 volts where the voltage decreases more rapidly with time.

As noted in the previous tests, it is expected that this type of curve can be used to determine the battery availability for any desired end voltage at or higher than 1.75 volts per cell. The end voltage for determining battery availability is a plant-specific determination based on the supplied equipment voltage requirements and the lengths of the cable runs.

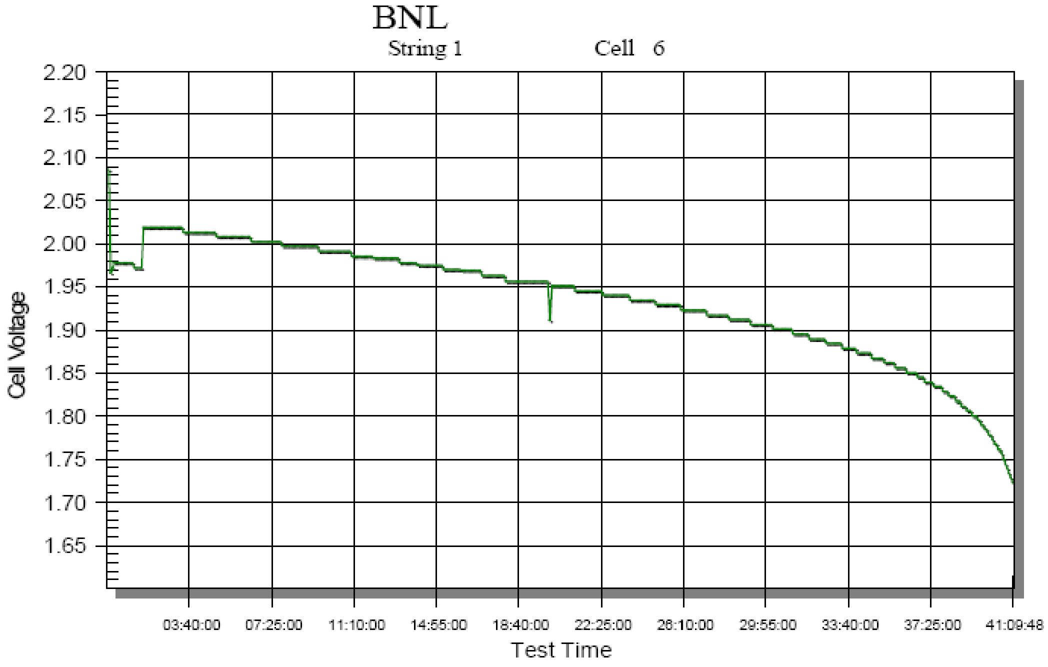


Figure 3-10 Voltage Change over Time (Enersys cell #6- test run #12)

While the end point for each of the tests is when the overall battery voltage reaches 21.0 volts, it should be noted that the individual cell voltage characteristics vary among the three battery types. Table 3-13 shows the end voltages for each of the three battery strings highlighting the highest and lowest along with the end voltage spans in the right column.

Table 3-13 Third End Voltages of Each Cell (When Overall Voltage Reached 21.0 volts)

Battery (Run #)	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Cell 7	Cell 8	Cell 9	Cell 10	Cell 11	Cell 12	End Voltage Span
C&D (#10)	1.775	1.709	1.748	1.756	1.780	1.731	1.767	1.784	1.768	1.734	1.773	1.784	.075
GNB (#11)	1.748	1.785	1.771	1.771	1.748	1.755	1.731	1.749	1.748	1.785	1.766	1.767	.054
Enersys (#12)	1.739	1.685	1.749	1.761	1.758	1.722	1.785	1.791	1.778	1.779	1.798	1.772	.113

<u>Short-term impact of intermittent loads</u>: What's not shown on figures 3-8 to 3-10 but was observed by reviewing the detailed battery string voltages over time was the brief but measurable decrease in overall string voltage when the intermittent loads were applied during test runs 11 and 12. These intermittent loads were applied to simulate valve and pump operations that may be required to achieve a cold shutdown condition. This loading will vary from plant to plant based on the size of the motors and their starting or inrush current.

For the GNB battery (test run #11), when the five-one minute loads of 160 amps were applied, the overall string voltage decreased by 0.4 to 0.5 volts and then recovered to the original voltage level within 0.1 volts when the intermittent load was removed and the load returned to a steady state value of 39 amps. For the Enersys battery (test run #12), the overall string voltage decrease was 0.3 to 0.5 volts when the five one-minute loads of 192 amps were applied. The voltage level recovered within 0.1 volt of the original level when the load returned to a steady state value of 47 amps except after the 5th applied load when the voltage was 0.2 volts less than the battery voltage before the load was applied. These data are illustrated in Table 3-14.

Table 3-14 Voltage changes with application of intermittent loads

Battery/ Intermittent Load #	Intermittent Load #1			Intermittent Load #2			Intermittent Load #3			Intermittent Load #4			Intermittent Load #5		
	Pre	Load	Post	Pre	Load	Post	Pre	Load	Post	Pre	Load	Post	Pre	Load	Post
GNB- Test Run #11	23.7	23.3	23.7	23.7	23.3	23.6	23.6	23.2	23.6	23.5	23.1	23.5	23.5	23.0	23.5
Enersys- Test Run #12	23.8	23.4	23.7	23.7	23.3	23.6	23.6	23.2	23.5	23.5	23.2	23.5	23.5	23.0	23.3

While the application of intermittent loads about midway through the run did not appear to impact the overall battery availability since not many ampere-hours are expended, the voltage dip when the load is applied could impact the power supplies and inverters that are being powered by the battery especially as the overall string voltage gets closer to its minimum value. A 0.5 volt dip on the 12 cell string employed for this test translates to a 2.5 volt dip when this is extrapolated to a 60 cell string typically used in most nuclear plant applications. This one minute change in voltage could be sufficient to trip a power supply or inverter if the voltage is close to its low voltage protection set point.

<u>Specific Gravity Results</u>: As noted earlier, specific gravity measurements were taken on each cell prior to the discharge test, following the discharge, and following the 100-hour equalizing charge. The measurements were taken at the midpoint location in a consistent manner. A summary of the specific gravity measurements are provided in table 3-15. The distilled water measurement was taken after each set of readings as a calibration check on the hydrometer.

Table 3-15 Specific Gravity Summaries for test series #3

Battery	C&D (Test Run #10)			GNB (Test Run #11)			Enersys (Test Run #12)		
Cell/Position	Pre-Test	Post Discharge	Post Recharge	Pre-Test	Post Discharge	Post Recharge	Pre-Test	Post Discharge	Post Recharge
1-Midpoint	1.225	1.043	1.228	1.207	1.030	1.211	1.211	1.019	1.195
2-Midpoint	1.222	1.037	1.225	1.211	1.036	1.217	1.211	1.017	1.191
3-Midpoint	1.224	1.041	1.227	1.210	1.032	1.216	1.207	1.019	1.189
4-Midpoint	1.226	1.042	1.224	1.209	1.033	1.217	1.214	1.021	1.185
5-Midpoint	1.226	1.043	1.227	1.209	1.031	1.217	1.219	1.019	1.201
6-Midpoint	1.223	1.039	1.223	1.208	1.032	1.219	1.210	1.017	1.192
7-Midpoint	1.225	1.042	1.225	1.208	1.029	1.216	1.220	1.024	1.200
8-Midpoint	1.230	1.045	1.228	1.207	1.030	1.215	1.223	1.026	1.204
9-Midpoint	1.223	1.040	1.227	1.210	1.030	1.219	1.219	1.024	1.200
10-Midpoint	1.223	1.038	1.224	1.212	1.035	1.219	1.221	1.023	1.202
11-Midpoint	1.223	1.041	1.222	1.209	1.032	1.216	1.221	1.027	1.200
12-Midpoint	1.227	1.044	1.226	1.207	1.032	1.213	1.218	1.024	1.205
9-Top	1.199	1.034	1.171	1.164	1.025	1.132	1.217	1.021	1.186
11-Top	1.207	1.037	1.183	1.166	1.028	1.136	1.219	1.024	1.190
9-Bottom	1.267	1.045	1.293	1.265	1.050	1.279	1.257	1.027	1.290
11-Bottom	1.258	1.044	1.280	1.263	1.049	1.279	1.261	1.031	1.294
H_2O	1.001	0.999	1.002	1.000	1.001	1.000	1.001	1.001	1.001

3.4.4 Test Series #4 (Load Profiles EBR-5 and EBR-2)

The fourth test series completed was a combination of two load profiles. The first run using the C&D battery modified the load profile identified by NEI as EBR-5 by initiating the load shedding at 30 minutes versus the previously tested load shed times of 120 and 60 minutes. The second and third runs using the GNB and Enersys battery strings respectively were based on the load profile designated by NEI as EBR-2. For this load profile, normal SBO loading is assumed for the first two hours with load shedding taking place at the end of two hours. Critical momentary (1 minute) loads are supplied by the Train A battery for this PWR unit. Loads shed include some non-1E loads and other non-essential loads in accordance with extended SBO operating procedures.

For EBR-2, the test parameters provided by NEI were based on a profile for a GNB model NCN-33 battery which has a 2416 Ah 8-hour rating. The load profile was tested on the GNB and Enersys battery strings with scaling for the sizes (amp-hour ratings) of the batteries as compared to the GNB-33 battery. Scaling the load profile to the ampere-hour rating ratio of the BNL batteries versus the NEI load profile battery allows a direct comparison of the test duration. The ampere loading and load shed times for these test runs are summarized in table 3-16. Note that a one minute loading was added to test run #15 to confirm that the impact that this demand has on the overall battery performance is small.

Table 3-16 Test Series #4 Loading (Rated Current and Time)

Battery Type	Scaling Factor	Step 1	Step 2	Step 3	Step 4 (to 21.0 Volts)
C&D LCR-29 (NEI) **(EBR-5)**	-----	450 amps	291 amps	103 amps	75 amps
C&D LCR-33 **(test #13)**	1.143	514 amps (1 minute)	333 amps (30 minutes)	118 amps (30 minutes)	86 amps
GNB NCN-33 (NEI) **(EBR-2)**	----	181 amps	61 amps	N/A	N/A
GNB NCN-21 **(test #14)**	0.623	112 amps (120 minutes)	38 amps (to 21.0 volts)	N/A	
Enersys 2GN-23 **(test #15)**	0.750	469 amps (1 minute)	135 amps (120 minutes)	45 amps (to 21.0 volts)	N/A

The results of the tests were in line with the estimates that had been made based on a battery sizing calculation derived from IEEE 485 and one that used a curve fit derived from battery vendor supplied battery specifications supplemented by BNL test data. This information is illustrated in Table 3-17.

Table 3-17 Test Series #4 Comparison of estimated to actual battery availability

Test Run #	Estimate 1[1]	Estimate 2[2]	Actual
13 (C&D)	30.1 hours	32.0 hours	**32.2 hours**
14 (GNB)	44.9 hours	42.0 hours	**47.7 hours**
15 (Enersys)	45.7 hours	43.8 hours	**44.2 hours**

[1] – Estimated test duration based on curve fit derived from battery vendor and BNL test curves

[2] – Estimated test duration based on 14-step battery sizing spread sheet derived from IEEE 485

Table 3-18 illustrates the second goal of this load profile- evaluating the impact of the load shed time on the same battery type. As noted in Table 3-18, the battery availability time was 4 hours longer when the initiation of load shedding occurred an hour earlier for each of the two load shed steps. In test run #13, the same profile was applied assuming that load shedding occurs in ½ hour for each of the two load shed steps. This increases the battery availability time by another 1.6 hours. The three tests (runs #4, #10, and #13) provide a spectrum of battery availability times based on the time to initiate load shedding on the same battery and identical load profiles.

Table 3-18 Impact of load shedding time on battery availability

Test Run #	Load Shed Time	Estimated (Avg.)	Measured
4 (C&D)	2 hours	**26.2 hours**	**26.6 hours**
10 (C&D)	1 hour	**29.5 hours**	**30.6 hours**
13 (C&D)	½ hour	**31.1 hours**	**32.2 hours**

The Alber capacity test set was programmed to provide the loads to the battery at the prescribed time, and to automatically shut down the test when the overall voltage reached 21.0 volts. The output from the Alber test reports is provided as figure 3-11, 3-12, and 3-13. These figures show the overall voltage on the left vertical axis and the load current on the right axis.

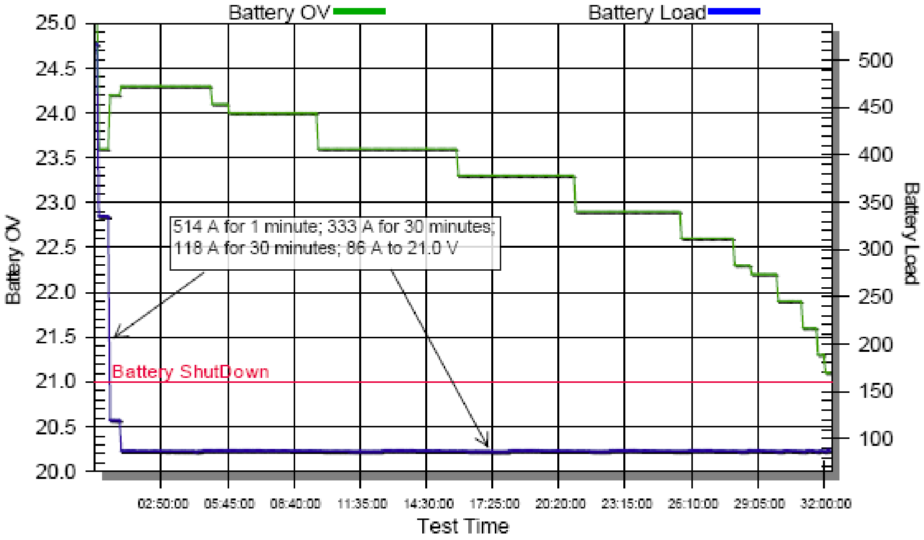

514 A for 1 minute; 333 A for 30 minutes; 118 A for 30 minutes; 86 A to 21.0 V

Figure 3-11 Test Run #13 (C&D LCR-33 Battery)

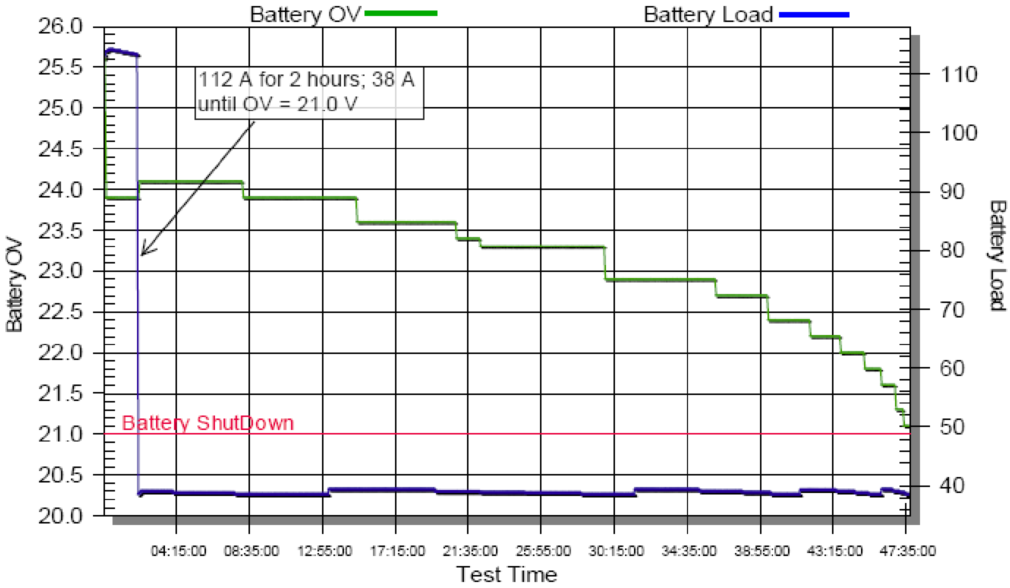
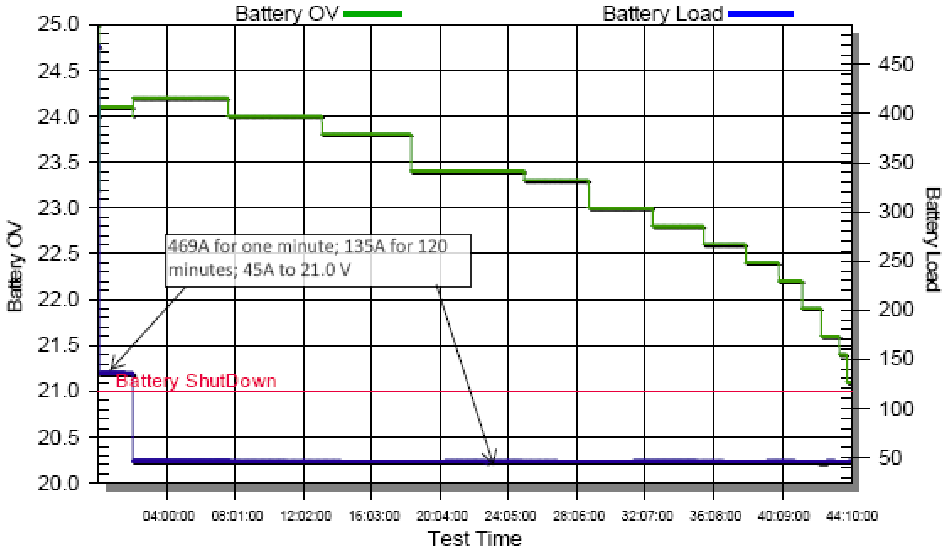

112 A for 2 hours; 38 A until OV = 21.0 V

Figure 3-12 Test Run #14 (GNB NCN-21 Battery)



469A for one minute; 135A for 120 minutes; 45A to 21.0 V

Figure 3-13 Test Run #15 (Enersys 2GN-23 Battery)

<u>Voltage Response</u>: Figure 3-14 illustrates the voltage response for C&D cell #6 during the conduct of test run #13. This curve is representative of the response from the other cells in that the voltage decreases fairly linearly until the battery approaches ~1.85 volts where the voltage decrease more rapidly with time.

As noted in the previous tests, it is expected that this type of curve can be used to determine the battery availability for any desired end voltage at or higher than 1.75 volts per cell. The end voltage for determining battery availability is a plant-specific determination based on the supplied equipment voltage requirements and the lengths of the cable runs.

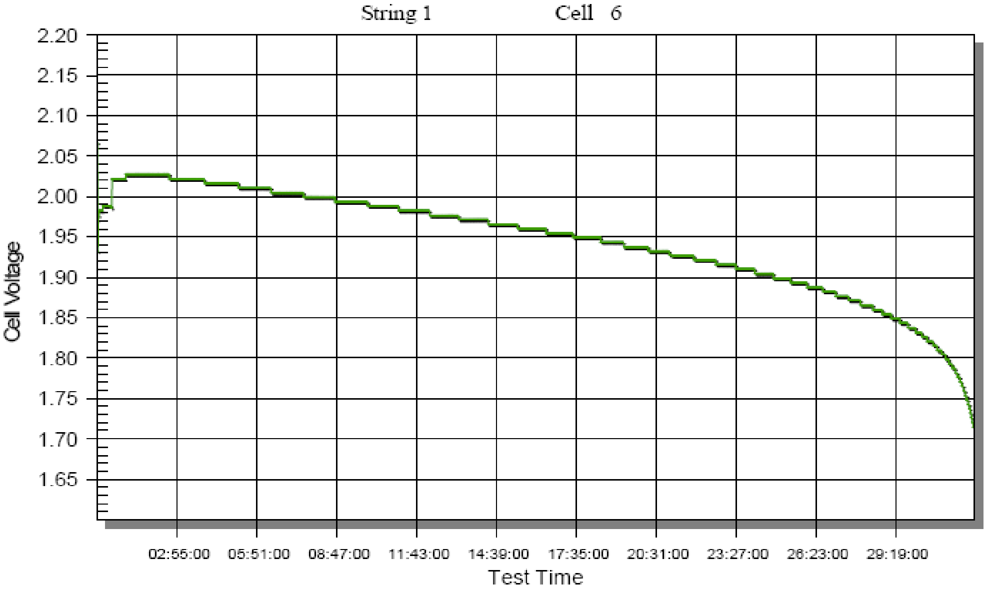


Figure 3-14 Voltage Change over Time (C&D cell #6- test run #13)

While the end point for each of the tests is when the overall battery voltage reaches 21.0 volts, the individual cell voltages were also measured during the test. A cell voltage of 1.3 volts would also terminate the test. Table 3-19 shows the cell end voltages for each of the three battery strings, highlighting the highest and lowest along with the end voltage spans in the right column.

Table 3-19 Fourth End Voltages of Each Cell (When Overall Voltage Reached 21.0 volts)

Battery (Run #)	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Cell 7	Cell 8	Cell 9	Cell 10	Cell 11	Cell 12	End Voltage Span
C&D (#13)	1.791	1.727	1.762	1.768	1.787	1.714	1.773	1.800	1.763	1.679	1.768	1.784	.121
GNB (#14)	1.753	1.791	1.772	1.767	1.749	1.761	1.728	1.748	1.738	1.786	1.766	1.765	.063
Enersys (#15)	1.748	1.683	1.746	1.759	1.743	1.720	1.785	1.792	1.785	1.780	1.804	1.778	.121

<u>Specific Gravity Results</u>: A summary of the specific gravity measurements for this fourth load sequence is illustrated in table 3-20. It shows the values prior to initiation of the discharge, following the discharge, and following the 100-hour equalizing charge. A calibration check was performed as well.

Table 3-20 Specific Gravity readings for Test Series #4

Battery	C&D (Test Run #13)			GNB (Test run #14)			Enersys (Test Run #15)		
Cell/Position	Pre-Test	Post Discharge	Post Recharge	Pre-Test	Post Discharge	Post Recharge	Pre-Test	Post Discharge	Post Recharge
1-Midpoint	1.224	1.032	1.222	1.203	1.030	1.208	1.212	1.014	1.191
2-Midpoint	1.220	1.025	1.221	1.208	1.036	1.213	1.215	1.012	1.193
3-Midpoint	1.224	1.029	1.223	1.206	1.033	1.214	1.214	1.015	1.190
4-Midpoint	1.226	1.030	1.221	1.206	1.033	1.213	1.218	1.016	1.194
5-Midpoint	1.227	1.031	1.223	1.206	1.031	1.213	1.223	1.016	1.201
6-Midpoint	1.222	1.027	1.219	1.205	1.032	1.214	1.214	1.013	1.188
7-Midpoint	1.225	1.030	1.221	1.204	1.030	1.211	1.225	1.020	1.202
8-Midpoint	1.232	1.033	1.225	1.203	1.029	1.212	1.228	1.023	1.205
9-Midpoint	1.221	1.028	1.223	1.205	1.030	1.214	1.225	1.021	1.199
10-Midpoint	1.223	1.026	1.220	1.208	1.035	1.217	1.227	1.020	1.205
11-Midpoint	1.222	1.030	1.218	1.205	1.033	1.213	1.227	1.024	1.200
12-Midpoint	1.227	1.032	1.223	1.204	1.032	1.212	1.222	1.020	1.200
9-Top	1.207	1.026	1.176	1.174	1.025	1.130	1.224	1.019	1.194
11-Top	1.216	1.029	1.186	1.177	1.028	1.136	1.227	1.022	1.197
9-Bottom	1.264	1.038	1.291	1.263	1.047	1.283	1.248	1.024	1.292
11-Bottom	1.250	1.035	1.283	1.261	1.045	1.281	1.251	1.027	1.296
H_2O	1.001	0.999	1.000	1.002	0.999	1.001	1.001	1.000	1.001

3.5 Recharge Characteristics of Load-Profile Tests

The primary difference between the Sequence 1 and Sequence 2 tests was that Sequence 1 testing was conducted at constant loads while Sequence 2 tests contained several load changes over the course of the test period, including intermittent (1-minute) loads to simulate MOV and/or pump operations. In addition, Sequence 1 testing was conducted out to 72 hours while the longest Sequence 2 test duration was 47.7 hours. The major difference between Sequence 1 and Sequence 2 associated with the recharge of the batteries was that in Sequence 1, recharge was conducted at a float voltage of 2.25 volts per cell (27 volts) while in Sequence 2, the recharge was conducted at an equalizing voltage of 2.33 volts per cell (28 volts).

This section addresses the recharge characteristics that were experienced following the load profile tests conducted in Sequence 2. As illustrated in Figure 3-15, when recharging the battery at an equalizing voltage, the percentage of ampere-hours returned to the battery is between 85 and 90% when the charger came out of a current limit mode regardless of the battery discharge time (8 hours to 44.2 hours). As an example, Figure 3-15 contains the recharge curves for the Enersys battery. For EBR-5, the test duration was 27.7 hours, for EBR-4 it was 26.3 hours, for EBR-3 it was 41.2 hours, and for EBR-2 the test duration was 44.2 hours. The pre and post 8-hour baseline test recharge curves are also included. The form of the graphs once the charger comes out of current limit mode is very similar. The time to return 100% of the ampere-hours expended during the test is also nearly identical (slightly greater than 1 time constant).

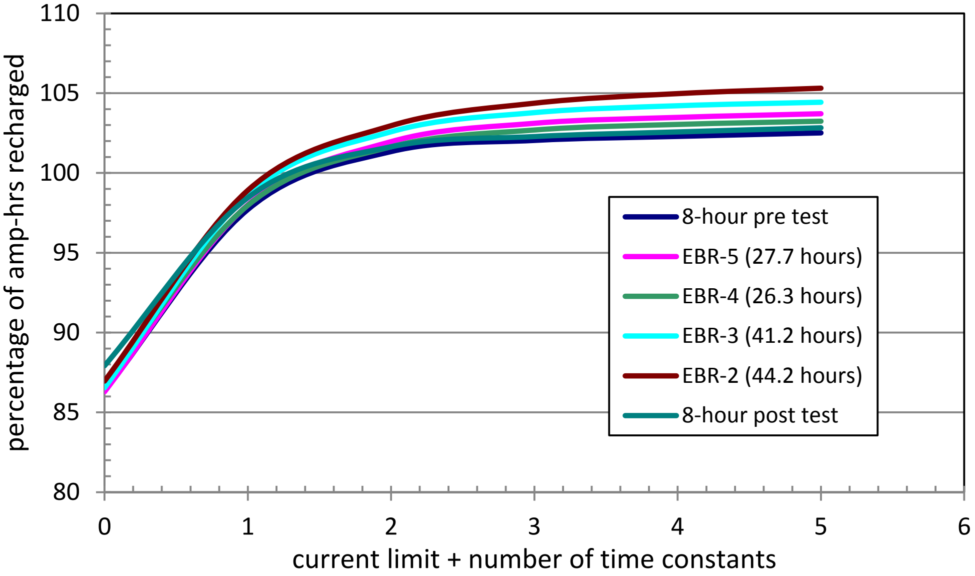


Figure 3-15 Enersys Battery Recharge Characteristics during Load Profile Testing

Table 3-21 is a compilation of the recharge data for each of the three batteries showing the total ampere-hours discharged in each test, how long the battery charger was on current limit, the calculated time constant in hours, and the percentage of ampere-hours returned to the battery in three time constants. For all three batteries, more than 100% of the ampere-hours discharged were returned to the battery within three time constants. The similarities of the data among the three batteries are reflected in the close approximation of the curves of which Figure 3-15 is an example.

Table 3-21 Recharge Characteristics Observed/Calculated During Sequence 2 Testing

ENERSYS: percent recharge vs. time constant						
Load Profile Duration (Hours)	8-hour (pre)	27.7	26.3	41.2	44.2	8-hour (post)
amp-hr discharged	1714	2080	2063	2166	2176	1716
current limit (CL, hr)	8.22	9.97	9.95	10.42	10.47	8.35
time constant (tc, hr)	1.69	2.1	1.99	2.28	2.28	1.57
percentage of amp-hr recharged						
at current limit	86.3	86.3	86.8	86.5	87.0	87.9
CL + 3 tc	102.0	103.1	102.7	103.8	104.4	102.3
GNB percent recharge vs. time constant						
Load Profile Duration (Hours)	8-hour (pre)	22.2	45.2	47.7	8-hour	
amp-hr discharged	1429	1811	2000	1963	1446	
current limit (CL, hr)	6.67	8.35	8.99	8.94	6.78	
time constant (tc, hr)	1.57	1.97	2.47	2.70	1.60	
percentage of amp-hr recharged						
at current limit	84.0	83.0	80.9	82.3	84.8	
CL + 3 tc	101.7	101.0	101.5	105.1	102.5	
C&D percent recharge vs. time constant						
Load Profile Duration (Hours)	8-hour (pre)	26.6	39.9	30.6	32.2	8-hour (post)
amp-hr discharged	2289	2854	2978	2919	2915	2339
current limit (CL, hr)	11.34	13.95	14.65	14.12	14.37	11.59
time constant (tc, hr)	2.00	2.50	2.59	2.77	2.62	1.94
percentage of amp-hr recharged						
at current limit	89.1	88.0	88.5	87.0	89.1	89.5
CL + 3 tc	103.7	103.0	103.3	103.1	104.5	103.1

3.6 Summary of the Load Profile Testing (Sequence 2)

In Sequence 2, ELAP conditions were simulated using 4 load profiles that were provided by the nuclear industry as being representative of the load shedding schemes used by NPPs to extend the battery availability while maintaining power to critical plant loads. The four load profiles were from four different NPPs (3 PWRs and 1 BWR) who had analyzed the equipment they need to assure core cooling while providing the critical instrumentation required by plant operators and decision makers.

Table 3-22 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 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. The table shows that the measured 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 capacity 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 correction factors.

Table 3-22 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 NPP specific SBO battery coping times of 4 to 8 hours.

Voltage Response: As noted in the sequence 1 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 [5]. This characteristic can be seen in figure 3-16, 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.

When intermittent higher loads of one-minute durations were applied during the load profile tests #11 and #12, it was observed that the overall battery string voltage decreased by as much as 0.5 volts while the higher load was applied. For a 60-cell battery string typically employed at NPPs, this voltage drop would be equivalent to about 2.5 volts, a fairly significant change that could impact power supplies and inverters powered from the battery. The NPP operator needs to be aware of the voltage change when performing these necessary intermittent operations.

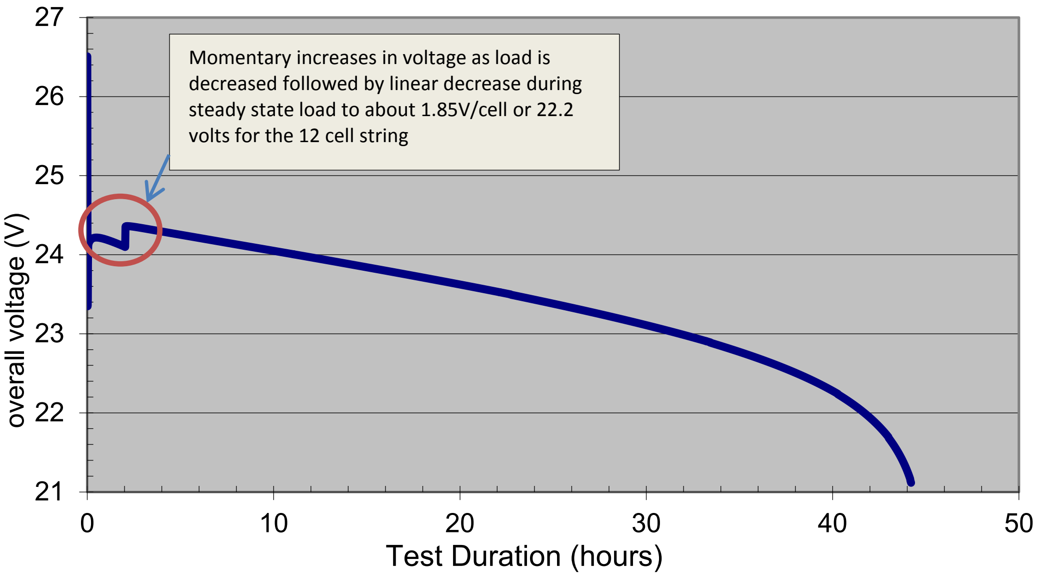


Figure 3-16 GNB Voltage Response to Load Profile #4 (EBR-2)

Specific Gravity Results: Specific gravity measurements indicated that the electrolyte is quite depleted following the extended battery operations associated with each load profile. Figure 3-17 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.

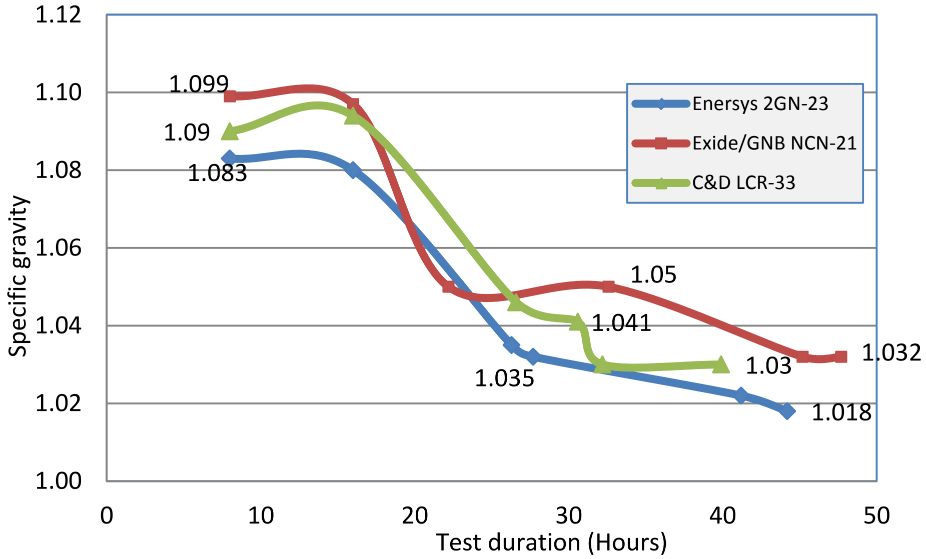


Figure 3-17 Average "end-of-test" midpoint specific gravity readings for Sequence 2 tests

4 SUMMARY AND CONCLUSIONS

The Japanese earthquake and tsunami event on March 11, 2011, illustrated the fact that restoration of AC power at NPPs can be significantly impacted by external events and can take a long time to recover under certain scenarios. Extending the availability of safety-related Class 1E batteries can be accomplished through the manual shedding of non-essential loads thereby reducing the demand on the battery. The testing described in this report showed how typical nuclear-grade batteries perform when operated for extended periods under these postulated scenarios.

BNL used the three sets of nuclear qualified batteries with each battery string consisting of 12 cells. The batteries were tested in a manner consistent with how they would be operated in a typical nuclear power station's Class 1E DC power system using a resistive load bank. Two test sequences were performed. The first applied lower loading on the battery strings to assess their operation at regular time intervals out to 72 hours. The second test sequence applied varying load conditions on the battery to simulate NPP load shedding responses to an ELAP.

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 to them or reduction in their capacity. However, these batteries were neither artificially aged nor subjected to the same aging criteria that would be expected in their 20-year life in a NPP environment. Therefore, it cannot be concluded that the batteries in operation near the end of their design life would perform in the same manner as the ones that were tested in this research program. This fact represents the largest uncertainty associated with the test results.

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

1. Battery performance at various time intervals out to 72 hours was demonstrated. The efficiency of the battery at lower loadings increases by approximately 30% thereby increasing the available battery amp-hours during the extended operation.
2. For the load 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. This increased availability of the batteries to supply critical equipment and instrumentation is accomplished through an aggressive load shedding process. Information associated with the load profiles provided by NEI is included in this report. Test results showed that the time to initiate load shedding is important, but even when that time is 2 hours (as compared to ½ hr), battery availability beyond 24 hours can still be achieved.
3. The projected availability of a battery can be accurately calculated using IEEE Standard 485-2010 and battery vendor information. This includes the impact of the time to initiate and complete load shed actions. Procedures can be put in place at the NPPs to identify the critical loads that need to be maintained as long as possible as well as the process to eliminate non-essential loads in a timely manner. Knowing the ampere requirements for these critical loads and the loads that will be shed permits the availability of the battery to be calculated using IEEE Standard 485-2010, including accepted factors to address battery aging, design margin and the plant-specific battery end-voltage.

4. The battery voltage response during discharge is generally linear over the discharge but decreases rapidly at about 1.85V. The momentary voltage drop from intermittent operation of equipment during load shedding can impact the operation of power supplies and inverters as the battery supplied voltage gets close to their low voltage protection setpoints. NPP operators should be cognizant of the battery voltage response and the critical equipment that could be adversely affected as the battery voltage decreases. The specific equipment that could be affected by a low voltage battery condition should be identified in emergency operating procedures to allow the operators to take mitigating actions before the supplied equipment is de-energized.
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. This could affect the ability to recharge the battery. Severe accident management guidance that provides information on how to slowly recharge a battery that has been depleted for more than 8 hours would allow the operators to safely return the battery to service when AC power becomes available.
6. No new battery failure mechanisms were observed during extended operational testing; however, as noted above, 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 the battery depletion and initiation of recharge)

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10. SUPPLEMENTARY NOTES
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11. ABSTRACT (200 words or less)

The Japanese earthquake and tsunami event on March 11, 2011, illustrated the fact that restoration of the alternating current (AC) power supply at nuclear power plants (NPPs) can be significantly impacted by external events and can take a longer time to recover under certain scenarios. Therefore, a lesson learned from the Japanese event that may be applicable to U.S. NPPs is the need to examine the extended loss of alternating current power conditions and determine if the existing vented lead acid batteries can function beyond their defined design basis (or beyond-design basis if existing Station Blackout coping analyses were utilized) duty cycles in order to support core cooling. The NRC's Office of Nuclear Regulatory Research sponsored testing to evaluate the battery's performance availability and capability to supply the necessary direct current (DC) loads to support core cooling and instrumentation requirements for extended periods of time. Plant profiles from four NPPs [3 Pressurized Water Reactors and 1 Boiling Water Reactor] were obtained from the nuclear industry through the Nuclear Energy Institute and were used for this test program. The testing provided an indication of the amount of time available (depending on the actual load profile) for batteries to continue to supply core cooling equipment beyond the original duty cycles for a representative plant. Testing also demonstrated that battery availability can be significantly extended using load shedding techniques to allow more time to recover AC power. The projected availability of a battery can be accurately calculated using the IEEE Standard 485-2010, "IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications," or using the empirical algorithm described in this report. This report provides detailed test results and analysis regarding the battery's performance availability and capability for the tested load profiles.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

Extended loss of alternating current power, Station blackout (SBO), Fukushima, battery, direct current (DC) power, alternating current (AC) power, battery capacity and capability, extended battery operation, battery sizing, battery duty cycle, load profiles, diverse and flexible coping strategies, battery recharge and discharge, and beyond-design basis.

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