Testing to Evaluate State-of-Charge in Nuclear Grade Lead Acid Batteries, Part 2

L. Ramadan, U.S. Nuclear Regulatory Commission; G. Greene and
W. Gunther, Brookhaven National Laboratory, Upton, NY 11973-5000

Introduction

The United States Nuclear Regulatory Commission (NRC) and Brookhaven National Laboratory (BNL) completed the research project established in 2010 to confirm that charging current is a suitable indicator of a fully-charged condition for nuclear grade vented lead-acid batteries as required by nuclear power plant Technical Specifications. The research project validated the improvement to the Technical Specifications for direct current power systems which focused on the effectiveness of float current monitoring in lieu of specific gravity monitoring as the indicator of state-of-charge for nuclear grade vented lead-acid batteries and upheld the recommendations provided in industry standards, namely the updated version of IEEE Standard 450-2010, "IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications."

In conducting this study, BNL cycled battery strings from three nuclear grade battery suppliers and measured both specific gravity and charging current over time, while also monitoring cell and ambient temperatures and other parameters. This paper summarizes the analysis of test results and observations from the testing. Complete results from the testing program are available in NUREG/CR-7148, "Confirmatory Battery Testing: The Use of Float Current Monitoring to Determine Battery State-of-Charge" published in October 2012.

Objective

The primary objective of this research project was to determine whether the float charging current can be a useful indicator for determining a vented lead-calcium battery's state-of-charge over the life of the battery. This project evaluated the acceptability of using float charging current as a means of monitoring battery state-of-charge for lead-acid calcium batteries from three vendors. A secondary objective was to evaluate the point at which a battery could be returned to service and meet its performance requirements.

Overview

The NRC and BNL teamed up to devise a detailed technical plan to execute the objectives. The research program required the procurement of equipment to model typical nuclear power plant battery system installations except for the seismic installations. The specific batteries to be tested were selected by the NRC and are representative of the batteries used in most U.S. nuclear power plants. The lead-calcium batteries procured and used were:

- Enersys 2GN-23 cells with a nominal capacity (8-hour rating) of 1800 ampere-hours,
- Exide GNB NCN-21 cells with a nominal capacity (8-hour rating) of 1496 ampere-hours, and
- C&D Technologies LCR-33 cells with a nominal capacity (8-hour rating) of 2320 ampere-hours.

The Exide GNB specimens were supplied by Nuclear Logistics Inc., the sole supplier of nuclear grade batteries for Exide. Two sizes of battery chargers were used for this project, one rated at 200 amperes and the other at 100 amperes. The 200-ampere battery charger was used for testing (i.e., recharging the batteries after deep-cycle discharging) while the 100-ampere battery charger was used to maintain the batteries on a float charge between tests. Test equipment was calibrated to specifications set forth by the National Institute of Standards and Technology. The batteries and associated equipment were installed in an environmentally-controlled and monitored area with adequate ventilation to prevent hydrogen accumulation.

The state-of-charge of a vented lead-acid storage battery has traditionally been monitored by conducting measurements of the specific gravity of the electrolyte in specified pilot cells, nominally sulfuric acid with a specific gravity of 1.215. However, measurements of the specific gravity of pilot cells during deep discharge and subsequent recharge performance testing have demonstrated that the specific gravity distribution in a battery cell can remain stratified for a long time following the recharge to the fully-charged condition. Therefore, considerable care must be taken in performing specific gravity measurements to ensure that they are always conducted at the same depth into the electrolyte cell jar of the pilot cells to ensure consistency between the measurements.

The NRC-sponsored research identified two different monitoring methods for determining a battery's state-of-charge. The first method relies on stabilized charging current to determine a fully-charged condition as recommended in IEEE Standard 450, "IEEE Recommended Practice for Sizing Lead Acid batteries for Stationary Applications."

For the evaluation of float current response as a means of determining battery state-of-charge, BNL performed a series of 10 performance discharge tests on each battery, subsequently recharging each battery to the fully-charged state after each discharge. A four-hour performance test at a temperature-compensated constant current was conducted to discharge the battery. Within one hour of completion of the discharge test, the battery was recharged at a maximum initial current of 180 amperes (referred to as the current limit) to restore the discharged capacity. Following each cycle, BNL allowed the battery to remain on a float or equalize charge for at least four days prior to commencing further testing. This resulted in completing one discharge-recharge cycle per week.

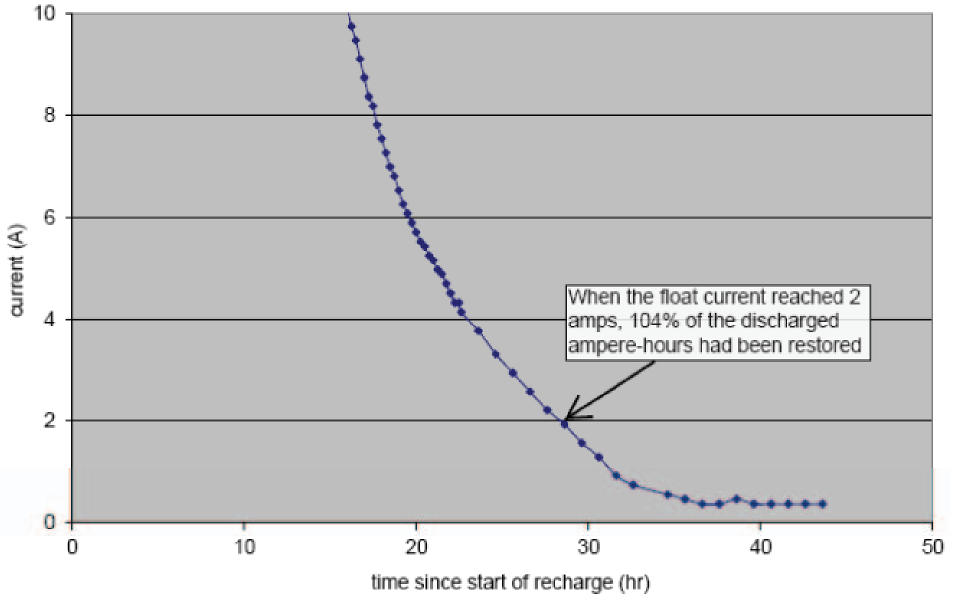
For the evaluation of the return-to-service concept, an additional three test cycles were conducted on each battery string. These series of tests evaluated the ability of the battery to be returned to service as soon as a stable float current was achieved and when the float current had obtained a value equivalent to the three time constant point on the recharge/float current curve.

Observations

During each cycle, BNL monitored and recorded the float current, cell voltage, cell conductance, and cell temperature. In addition, BNL periodically took manual readings of specific gravity using a digital hydrometer during the discharge and recharge cycles. To provide a set of profile data on two representative cells, BNL took specific gravity readings at the midpoint on all cells and on two of the cells at three points—midpoint, near the bottom of the cell, and above the top of the plates.

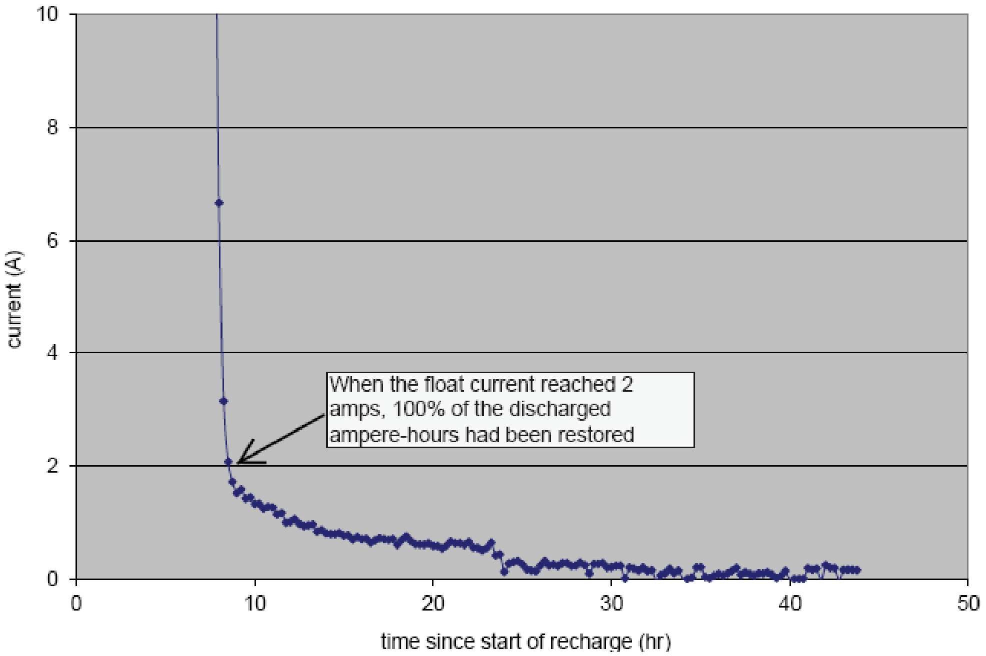
Throughout the testing program, BNL calculated the ampere-hours that are restored to the battery as it was recharged as one means to determine that the battery had been recharged. In many test cycles, the total number of ampere-hours returned to the battery exceeded the number of ampere-hours discharged <u>before</u> the float current reached a steady-state level. For the lead acid batteries that were tested, the stable float current achieved was in the 0.5 to 2.0 amp range. At that point in the current vs. time curve, only small numbers of ampere-hours are being returned to the cell.

This is illustrated in Figures 1 to 3 for representative curves from the three different battery strings. In Figure 1, the float current response below 10 amps is shown for the cycle 10 test of the Enersys battery when the recharge was conducted at 27.0 volts. Figure 2 depicts the float current response for the GNB battery when the recharge was conducted at 28.0 volts. Figure 3 illustrates the response for the C&D battery with the recharge conducted at 27.0 volts. Note that the largest of the cells, the C&D LCR-33 model, took a longer time to reach a stable float current due to the higher number of ampere-hours needed to be returned to the battery following the performance test.



When the float current reached 2 amps, 104% of the discharged ampere-hours had been restored

Figure 1 - Enersys cycle 10 float current response (recharge at 27.0 volts)



When the float current reached 2 amps, 100% of the discharged ampere-hours had been restored

Figure 2 - GNB cycle 1 float current response (recharge at 28.0 volts)

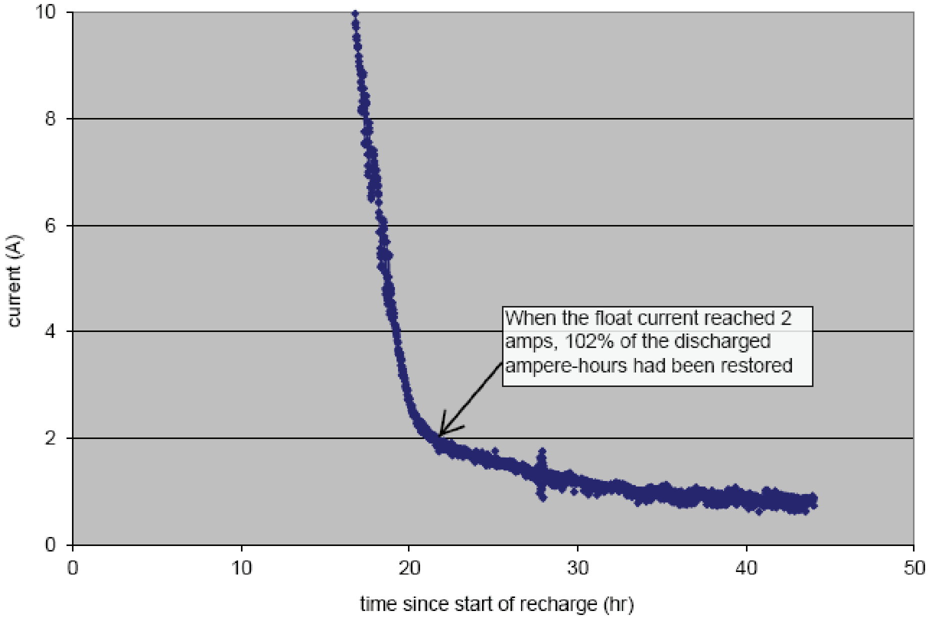


Figure 3 - C&D cycle 2 float current (recharge at 27.0 volts)

The float current responses on the three battery strings support the following conclusions:

1. The battery's state-of-charge as measured by the return of the discharged ampere-hours to the battery can be correlated to the stabilizing of the float current (generally about 0.5 to 2.0 amps). The stable current is slightly higher when the applied voltage (equalizing charge) is higher.
2. Once the float current reaches an asymptotic level, the ampere-hours being returned to the battery are minimal. This observation relates to identifying when the battery can be returned to service with assurance that it will be able to perform its design function.
3. Recharging at an equalizing voltage rather than a float level voltage results in returning ampere-hours to the battery more quickly, but does not consistently improve the time to reach a stable float current.

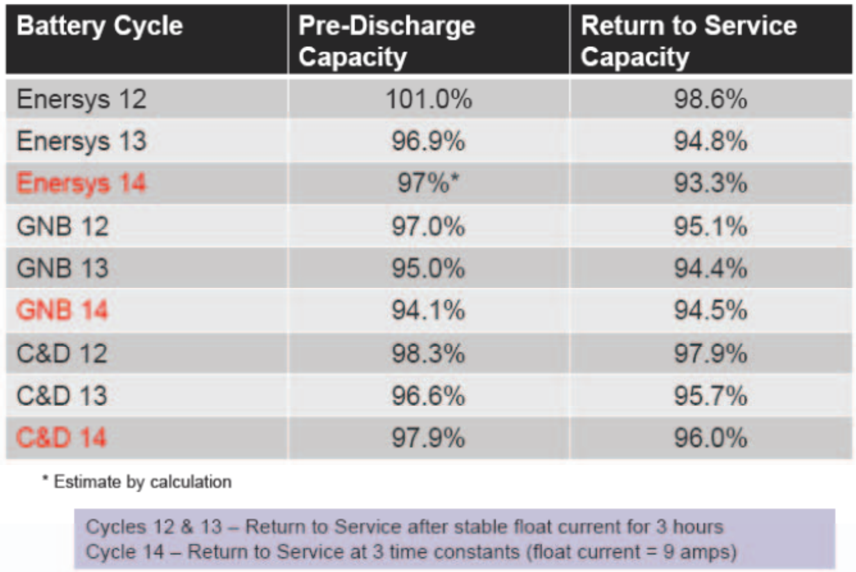
In the return-to-service testing, two return-to-service criteria were evaluated: the first was the achievement of a stable float current for a period of three consecutive hours (see Annex A.2 of [2]); the second was recharge of the battery string to the point that the exponential recharge current curve had decreased from the current limit by three time constants.

In these tests, the first step was to subject the battery to a four-hour discharge performance test. In order to investigate the first criterion, the battery was then recharged until the recharge (float) current had stabilized for three consecutive hours, generally in the range of 0.5-2.0 amps. When the battery had been recharged to that point, a second performance discharge test was conducted to determine if the battery could satisfy its design function (>80% of rated capacity). Following this second performance test, the battery string was fully recharged before the next test.

For the second criterion, the first step once again was to subject the battery to a four-hour discharge performance test. Subsequently, the battery was recharged to the point that the recharge current had come off the current limit setting and had decreased down the exponential recharge current curve by three time constants, a figure of merit that would be appropriate for a specific battery string. For the batteries that were tested by BNL, the high-capacity battery charger was set to a current limit of 180 amps. During recharge following a performance test, the recharge current would remain at 180 amps until such time that the battery demanded less current. At this point, the recharge current would decrease exponentially with time, thus exhibiting a characteristic exponential time constant. In mathematical terms, the recharge current would decrease from 180 amps to nine amps ($1/e^3$) at three time constants following departure from the current limit. At this point in the test, the recharge was terminated and a second performance discharge test was performed to determine if the battery could satisfy its design function (>80% of rated capacity). For both return-to-service criteria that were evaluated, all three battery strings were successful in delivering greater than 90% of their rated capacities.

Table 1 summarizes the results of the return-to-service capacity tests that were performed for cycles 12-14 for each battery string. The results of this testing indicate that the battery return-to-service criteria using stable float current and a float current equivalent to three time constants are both valid means to ensure that a battery can satisfy its design criterion following its full discharge.

Table 1 - Summary of return-to-service tests



Battery Cycle	Pre-Discharge Capacity	Return to Service Capacity
Enersys 12	101.0%	98.6%
Enersys 13	96.9%	94.8%
Enersys 14	97%*	93.3%
GNB 12	97.0%	95.1%
GNB 13	95.0%	94.4%
GNB 14	94.1%	94.5%
C&D 12	98.3%	97.9%
C&D 13	96.6%	95.7%
C&D 14	97.9%	96.0%

* Estimate by calculation

Cycles 12 & 13 – Return to Service after stable float current for 3 hours
Cycle 14 – Return to Service at 3 time constants (float current = 9 amps)

The utility of the recharge current time constant can be illustrated by consideration of the percentage of the battery capacity that is recharged following a deep-discharge performance test for the three batteries that were tested during this program. The following data for each battery were compiled for each test cycle: the ampere-hours discharged during the performance test, the time on current limit during recharge, and the time constant for the exponentially decreasing period of recharge for each cycle for each battery. For each of the three batteries tested, at least 60% of the battery's capacity was restored during recharge within the time the battery charger was supplying current at the current limit. In addition, the data for all the tests indicate that the batteries were recharged to more than 80% of their capacities within one time constant following the departure from current limit, and were recharged to more than 90% of their capacities within two time constants following the departure from charging at the current limit.

One can get a better perspective of the dependence of the recharge current and the recharged capacity as a function of time after the current limit period by examining the data in graphical form. For this evaluation, the combined data for the first 10 cycles for the Enersys battery are presented. In Figure 4, the normalized recharge current is presented vs. time, while Figure 5 presents the percentage of battery capacity recharged vs. time (both in units of time constants following the current limit period).

Figure 4 demonstrates that the normalized recharge current closely follows an exponential function out to five time constants beyond the time on current limit. At one time constant, the value of the normalized recharge current should be approximately 0.368 (1/e), at two time constants the normalized recharge current should be approximately 0.135 ($1/e^2$), and at three time constants the normalized recharge current should be approximately 0.050 ($1/e^3$). It is expected that the data will deviate from a true negative exponential with increasing time constants, because the current is not asymptotically approaching zero as would a pure exponential function but is approaching the lower limit of stable float current.

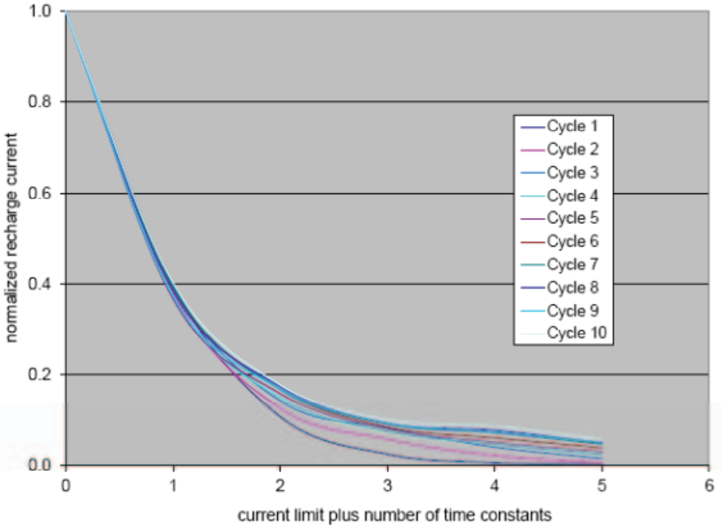


Figure 4 - Normalized recharge current following current limit vs. time constant for Enersys cycles 1-10

Figure 5 presents the data out to five time constants beyond the time the battery charger comes off of the current limit. The battery capacity rises rapidly until about two time constants beyond the current limit, after which time the rate of recharge decreases, providing little additional capacity afterwards. The recharge time constant concept can be a useful quantitative criterion in evaluating the state-of-charge and the return-to-service limits for a battery as previously discussed. Each battery has its own unique characteristics and the limits for evaluating the state-of-charge and the return-to-service limits for a battery would have to be established on a case-by-case basis that includes knowing the battery charger parameters such as its current limit setting and its recharge voltage. However, the recharge time constant provides an opportunity to reconsider the protocols whereby decisions are made concerning the operability status of batteries when returning them to service.

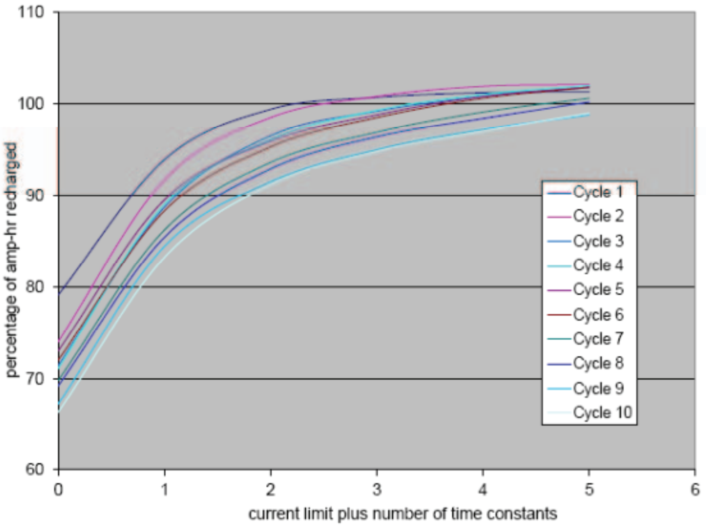


Figure 5 - Percentage of battery capacity recharged following current limit vs. time constant for Enersys cycles 1-10

Summary

From the 30 cycles of testing used to compare specific gravity and float current, the following conclusions can be made with regard to the primary objectives of this test program:

1) Both float current and specific gravity provide adequate means to determine battery state-of-charge. Float current has an advantage in that it provides an indicator of the entire battery string, while specific gravity is measured on a cell by cell basis.
2) Both float current and specific gravity have similar response times when the battery is recharged. Generally speaking, 100% of the ampere-hours discharged are returned to the battery within 24 hours of the start of the recharge cycle. Float current response will vary based on the recharge voltage applied to the battery. However, regardless of the voltage applied during recharge, the float current of a nearly fully-charged battery becomes stable at less than two amps.
3) The use of pilot cells to ascertain specific gravity is supported by the consistent response observed among all cells during both discharge and recharge.
4) The amount of electrolyte stratification is significant following a performance test and it can take several months before equilibrium is reached again within the cells. Therefore, it is critical to measure specific gravity at the correct depth from the top of the cell as suggested in the battery vendor's manual and supported by IEEE Std. 450-2002. The electrolyte stratification, by itself, does not appear to impact the ability of the battery to meet its capacity and capability requirements.

The test program also verified the point where the battery can be safely returned to service. In a series of six additional tests (two tests per battery string), the battery strings were able to meet their capacity and capability requirements at the point where the float current was stable for three hours. The time to satisfy this recharge criterion was generally in the range of 24-36 hours. Thus the criterion used in IEEE Std. 450-2002 was found to be an acceptable practice for ensuring the capacity and capability requirements of the battery were met before returning it to service.

Similarly, three cycles of tests were performed in which each battery was returned to service when the float current reached the value equivalent to three time constants on the recharge/float current curve. This occurred within about 12 hours and at a higher current than the previously described return-to-service tests. In each case, the battery was also able to meet its capacity and capability requirements. The time constant criterion developed from battery-specific recharge/float current curves from actual test data may be a more practical method for returning a battery to service due to its quantitative predictability.

References

1. Regulatory Guide 1.129, *Maintenance, Testing, and Replacement of Vented Lead-Acid Storage Batteries for Nuclear Power Plants.*

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

3. NUREG/CR-7148, *Confirmatory Battery Testing: The Use of Float Current Monitoring to Determine Battery State-of-Charge*, October 2012.

4. Clark, S., *State-of-Charge: Specific Gravity versus Battery Charging Current*, Battcon 2010 Conference Paper.

5. McConnell, M, *Testing to Evaluate State-of-Charge in Nuclear Grade Lead Acid Batteries*, Battcon 2011 Conference Paper.

6. Floyd, K., et al., *Assessment of Lead-Acid Battery State-of-Charge by Monitoring Float Charging Current*, IEEE Explore, 1994.