TESTING TO EVALUATE STATE OF CHARGE OF NUCLEAR GRADE LEAD-ACID BATTERIES

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INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) is responsible for regulating the Nation's civilian use of byproduct, source, and special nuclear materials to ensure adequate protection of public health and safety, to promote the common defense and security, and to protect the environment. NRC's regulatory mission covers three main areas: (1) commercial reactors for generating electric power and research and test reactors used for research, testing, and training; (2) uses of nuclear materials in medical, industrial, and academic settings and facilities that produce nuclear fuel; and (3) transportation, storage, and disposal of nuclear materials and waste and decommissioning of nuclear facilities from service.

Each nuclear power plant (NPP) in the United States is licensed to operate within specified operational limits set forth in the Technical Specifications to address safety limits, limiting conditions for operation, and surveillance requirements to ensure safe operation. The initial Technical Specifications for NPP batteries required the measurement of specific gravity to determine the state of charge of the batteries.

NRC has since established Improved Standard Technical Specifications (ISTS) (NUREG 1430-34) that are better aligned and more appropriately reflect the intent of regulatory requirements. The ISTS are voluntary and may be adopted by NPPs. NRC is currently in the process of revising the ISTS to include a rewrite of the Technical Specifications for direct current power systems. This rewrite has been coordinated with industry stakeholders and is titled Technical Specification Task Force (TSTF)-500, “DC Electrical Rewrite – Update to TSTF-360.” If approved by NRC, TSTF-500 will improve the ISTS by focusing on operability concerns versus routine maintenance inspections. One particular improvement to the ISTS would allow the use of float current monitoring in lieu of specific gravity monitoring as the indicator of state of charge for nuclear-grade vented lead-acid batteries. This allowance would be consistent with the recommendations provided in the latest versions of the Institute of Electrical and Electronics Engineers (IEEE) Standard (Std.) 450, “IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications.” The nuclear industry is eager to adopt float current monitoring as the Technical Specification requirement for determining state-of-charge because it offers the apparent benefit of providing an earlier indication that a battery has the required capacity to perform its safety function as specified in each NPP’s design bases document.

The focus of this paper is to discuss research activities that NRC has begun in conjunction with the Brookhaven National Laboratory (BNL) to determine whether charging current is a suitable indicator of a fully-charged condition for nuclear-grade vented lead-acid batteries as required by NPP Technical Specifications. The purpose of this research project is to verify the adequacy of recommendations provided in industry standards. In conducting this study, BNL has cycled battery strings from three commonly used nuclear-grade battery suppliers and measured both specific gravity and charging current over time while also monitoring battery capacity and cell temperatures.

OBJECTIVE

The Office of Nuclear Reactor Regulation (NRR) and the Office of Nuclear Regulatory Research (RES) jointly developed a research plan to verify whether float current monitoring is a suitable method for determining a nuclear-grade vented lead-acid battery’s state-of-charge. NRR is responsible for rulemaking, licensing, oversight, and incident response for commercial NPPs and test and research reactors to protect the public health, safety, and the environment. RES is responsible for research programs and processes to achieve enhanced safety and efficiency.

Based on the research plan, RES contracted BNL to perform research and testing to determine whether float current monitoring can be used as a suitable indicator for determining the state-of-charge for a nuclear-grade vented lead-acid battery. The research project began in December 2009 and is expected to last about 2 years. The objective of this paper is to provide the preliminary data and observations from the testing that has been completed to date. This paper does not establish a regulatory position nor does it create any new regulations or changes in regulatory policy.

OVERVIEW

NRR, RES, and BNL collaborated to develop a detailed test program to determine whether charging current is a suitable indicator of state-of-charge for nuclear-grade vented lead-acid batteries. This research program required the purchase of equipment to model typical NPP battery system installations. The test plan specified the testing of nuclear-grade vented lead-acid batteries from the three commonly-used nuclear battery vendors, hereafter referenced as Battery X, Y, and Z. Each test arrangement included a 12-cell battery, a battery charger, a load bank, and the necessary equipment to record and monitor performance parameters. Batteries X, Y, and Z were all nuclear-grade vented lead-calcium type batteries with rated capacities of 1,800 ampere-hours (Ah), 1495 Ah, and 2320 Ah, respectively. Two sizes of battery chargers were used for this project, one rated at 200 amperes and the other at 100 amperes. The 200-amperes battery charger was used for testing (i.e., recharging the batteries after deep-cycle discharging) while the 100-amperes battery charger was used to maintain the batteries on a float charge between tests. All 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.

In accordance with the test plan, BNL adhered to the IEEE Standards related to the installation, testing, and qualification of nuclear-grade vented lead-acid batteries, including IEEE Stds. 450-1975 and 2002, IEEE Stds. 484-1996 and 2002, “IEEE Recommended Practice for Installation Design and Installation of Vented Lead-Acid Batteries for Stationary Applications;” IEEE Std. 485-1997, “IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications;” and IEEE Std. 535-1986, “IEEE Standard for Qualification of Class 1E Lead Storage Batteries for Nuclear Power Generating Stations.” These revisions of the IEEE Standards are endorsed either in whole or in part by NRC in guidance documents known as regulatory guides (RGs). RGs describe methods that NRC considers acceptable for use in complying with the agency’s regulations.

The test plan required BNL to perform a series of 10 performance discharge tests on each battery, subsequently recharging each battery to the fully-charged state after each discharge. For the purpose of the project, each battery discharge and recharge was considered a single cycle. BNL subjected each battery to 4-hour performance discharge tests at constant current and applied the appropriate temperature correction factors. A capacity test set was used to control and monitor each performance test. It provided data on the discharge current, individual cell voltages, and a real-time calculation of battery capacity. Within 1 hour of completion of the discharge test, the battery was recharged at a maximum initial current of 180 amperes to restore the discharged capacity. Throughout the testing, BNL frequently consulted with each battery manufacturer to ensure proper recharge voltage, temperature, and the expected duration of recharge. Following each cycle, BNL allowed the battery to remain on float charge for at least 4 days to ensure that the battery was fully charged prior to commencing further testing. This resulted in completing one discharge-recharge cycle per week.

OBSERVATIONS

Prior to the start of each discharge test, BNL took baseline readings of specific gravity, cell temperature, and conductance.

The 4-hour performance test was conducted at the start of each cycle. The capacity test set was set to automatically stop the test when the overall battery string reached 21.0 volts (i.e., 12 battery cells times 1.75 volts).

During each cycle, BNL monitored and recorded the float current, specific gravity, cell voltage, cell conductance, and cell temperature. BNL used a temperature data acquisition system to monitor cell temperatures over the entire cycle. During each recharge, BNL continuously monitored float current using two methods. One method uses a device that is a state-of-the art float current monitor and the second is a calibrated 200 ampere/50 millivolt shunt. The shunt provides a redundant reading for the float current monitor measurement and was used to verify the accuracy of the float current monitor measurements. Each of these devices measure the float current being supplied by the battery charger to the battery. The float current monitor was used exclusively on the first battery string (Battery X); both the float current monitor and the shunt were used in the measuring of float current on the second and third battery strings (i.e., Battery Y and Battery Z). The two float current monitoring devices were connected to data acquisition systems that provided continuous monitoring of the float current. The float current monitor had an accuracy of 1.00 percent while the calibrated shunt had an accuracy of 0.33 percent.

Both devices provided virtually the same curve for float current; however, it was noted during the testing of battery string Y that the float current monitor was reading about 10 percent higher than the calibrated shunt. Upon further investigation and correlation between the two methods, BNL calculated a constant correction factor of 0.92 that needed to be applied to the float current monitor readings to match the calibrated shunt over the entire range of recharge current.

In addition to the float current measurements, BNL periodically took manual readings of specific gravity using a digital hydrometer during the discharge-recharge cycle. 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.

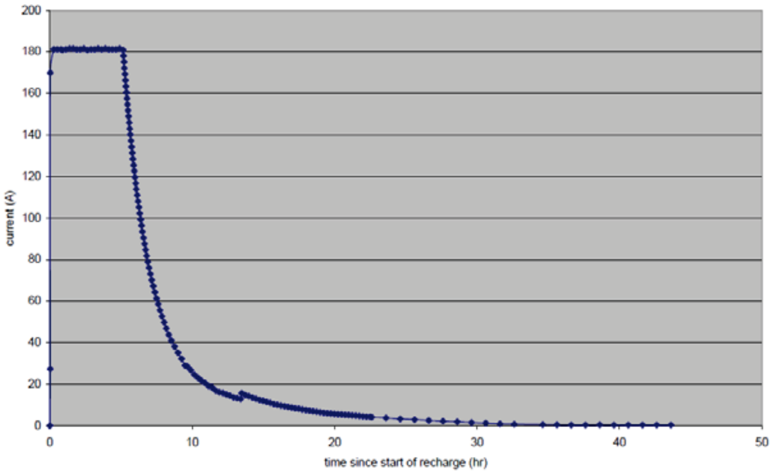
At the end of each cycle, BNL recorded the battery capacity and prepared a detailed test report that both summarized and documented the measured data.

The following graphs show the charging characteristics for both float current and specific gravity for each set of batteries.

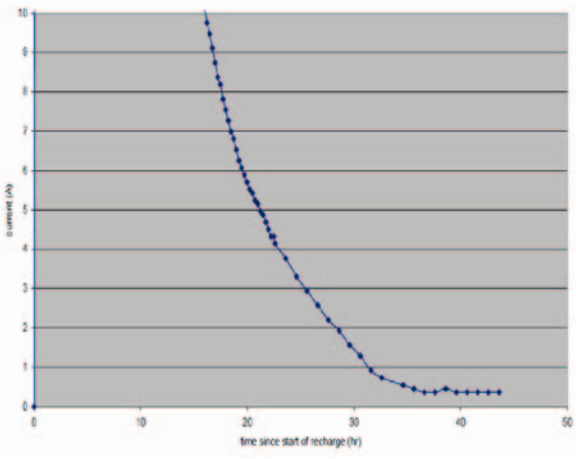
<u>Battery X Summary</u>

BNL has completed all 10 cycles for Battery X.

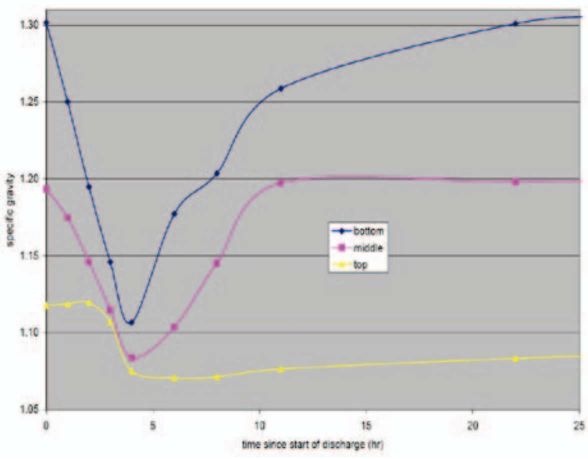
The capacity test set was used to record the cell voltages for the first 24 hours following initiation of recharge at a float voltage of 27.0 volts. With the exception of a capacity test set failure on one cycle, all equipment operated properly and the tests were conducted in accordance with the test plan. The following graphs represent data measured for a cycle (Cycle 10).


Complete Recharge Cycle

Late Cycle Recharge



Specific Gravity vs. Time



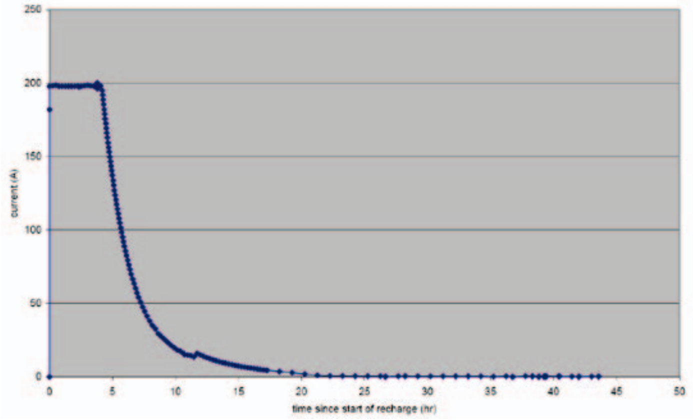
BNL calculated the return of Ah, the time at current limit, and the time to stable float current (2.0 amperes). The late-cycle recharge graph above represents data collected from the float current monitor and shows that 100 percent of the discharged Ah have been returned to the battery at time equals 17.2 hours following recharge for Battery X. This condition has not been verified to be representative of a fully-charged condition. The specific gravity versus time graph shows that Battery X reaches rated specific gravity (1.215) (normalized specific gravity at the midpoint) 8 hours following recharge (i.e., recharge commenced at 4 hours, Battery X reaches 1.215 specific gravity at 12 hours, subtracting 4 hours from 12 hours indicates that it has taken 8 hours for Battery X to reach rated specific gravity). Note the significant stratification between the top and bottom specific gravity readings. Battery X reached a stable float current at 26.3 hours after initiation of recharge. When the float current gets to about 2.0 amperes, the curve is becoming asymptotic and. therefore. the amount of Ah being returned to the battery is very small. This condition has not been verified to be representative of a fully-charged condition.

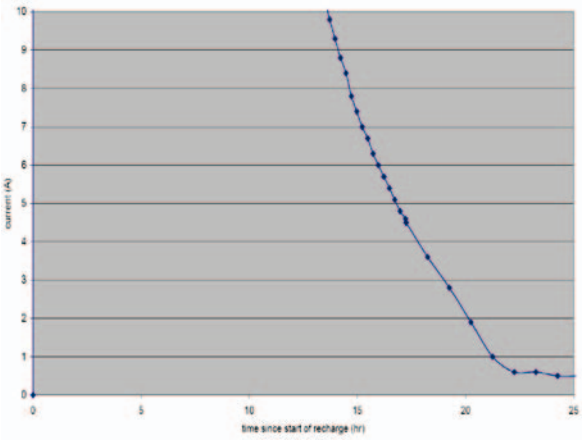
<u>Battery Y Summary</u>

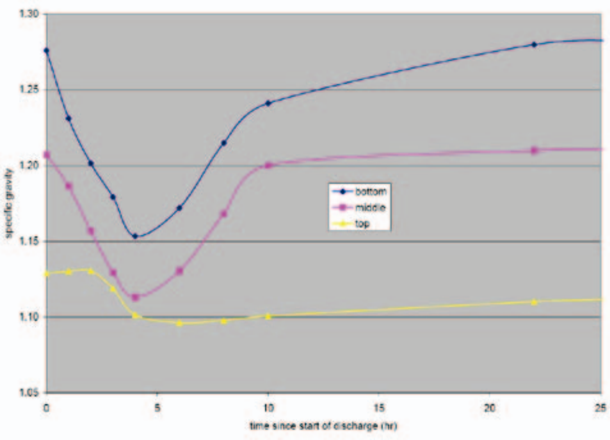
BNL has completed all 10 cycles for Battery Y.

The capacity test set was used to record the cell voltages for the first 24 hours following initiation of recharge at a float voltage of 27.0 volts. With the exception of a capacity test set failure and the finding of the float current monitor offset issue, all equipment operated properly and the tests were conducted in accordance with the test plan. The following graphs represent data measured for a cycle (Cycle 8).

Complete Recharge Cycle




Late Cycle Recharge

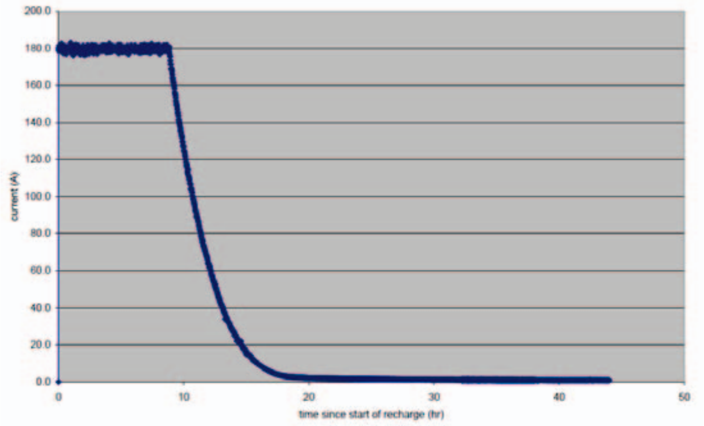

Specific Gravity vs. Time

BNL calculated the return of Ah, the time at current limit, and the time to stable float current (2.0 amperes). The late-cycle recharge graph above represents data collected from the float current monitor and shows that 100 percent of the discharged Ah have been returned to the battery at time equals 14.6 hours following recharge for Battery Y. This condition has not been verified to be representative of a fully-charged condition. The specific gravity versus time graph shows that Battery Y reaches rated specific gravity (1.215) (normalized specific gravity at the midpoint) about 7 hours following recharge (i.e., recharge commenced at 4 hours, Battery Y reaches 1.215 specific gravity at about 11 hours, subtracting 4 hours from 11 hours indicates that it has taken about 7 hours for Battery Y to reach rated specific gravity). Note the significant stratification between the top and bottom specific gravity readings. Battery Y reached a stable float current at 19.7 hours after initiation of recharge. When the float current gets to about 2.0 amperes, the curve is becoming asymptotic and therefore the amount of Ah being returned to the battery is very small. This condition has not been verified to be representative of a fully-charged condition.

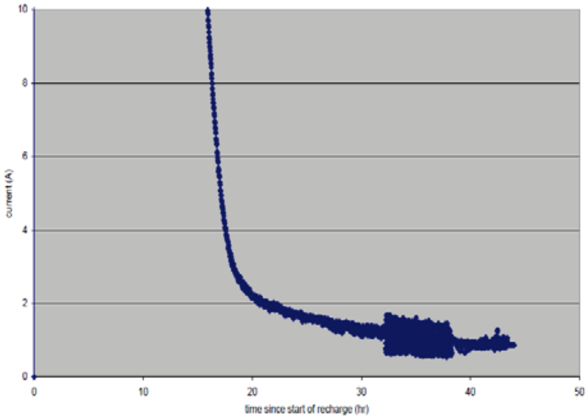
Battery Z Summary

BNL has completed 1 cycle for Battery Z.

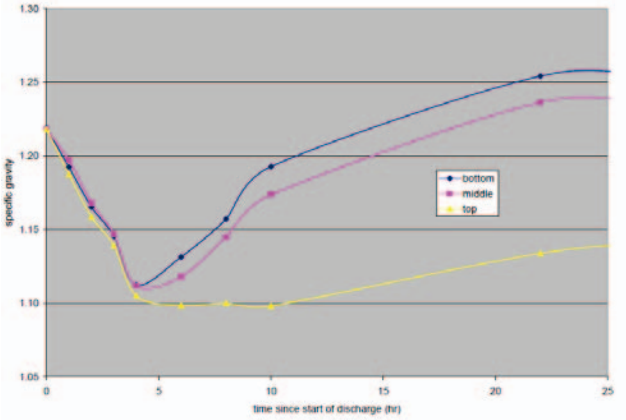
The capacity test set was used to record the cell voltages for the first 24 hours following initiation of recharge at a float voltage of 27.0 volts. All equipment operated properly, and the test was conducted in accordance with the test plan. The following graphs represent data measured for the first cycle.


Complete Recharge Cycle

Late Cycle Recharge



Specific Gravity vs. Time



BNL calculated the return of Ah, the time at current limit, and the time to stable float current (2.0 amperes). The late-cycle recharge graph above represents data collected from the calibrated shunt and shows that 100 percent of the discharged Ah has been returned to the battery at time equals 14.6 hours following recharge for Battery Z. This condition has not been verified to be representative of a fully-charged condition. The calibrated shunt data are used in this example because of the unavailability of the float current monitor data at the time of preparing this paper. The specific gravity versus time graph shows that Battery Z reaches rated specific gravity (1.215) (normalized specific gravity at the midpoint) about 12 hours following recharge (i.e., recharge commenced at 4 hours, Battery Z reaches 1.215 specific gravity at about 16 hours, subtracting 4 hours from 16 hours indicates that it has taken about 12 hours for Battery Z to reach rated specific gravity). Note the significant stratification between the top and bottom specific gravity readings. Battery Z reached a stable float current at 21 hours after initiation of recharge. When the float current gets to about 2.0 amperes, the curve is becoming asymptotic and therefore the amount of Ah being returned to the battery is very small. This condition has not been verified to be representative of a fully-charged condition.

Battery X, Y, Z Summary

Based on our preliminary review of the data provided above, the results appear to be consistent among all three battery strings. BNL needs to complete its testing of Battery Z (nine additional cycles) prior to evaluating the results further and drawing any formal conclusions.

SUMMARY

The following preliminary observations were noted when comparing the various measurement data collected to date:

- Results appear consistent among all three battery strings.
- Float current appears to stabilize when float current drops below 2.0 amperes.
- Midpoint and bottom specific gravity readings respond on recharge to predischarge values within 8-10 hours.
- Within 24 hours of start of recharge, indicators such as specific gravity (midpoint and bottom) and float current return to predischarge levels.
- Significant stratification exists and progresses with cycling reducing the “midpoint” specific gravity readings.
- BNL needs to complete its testing of Battery Z (nine additional cycles) prior to evaluating the results further and drawing any formal conclusions.

Upon completion of this research project, NRC will issue a NUREG-CR report that documents the final findings and observations. The NUREG report is expected to be complete by the end of 2011.

REFERENCES

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

2. IEEE Stds. 450-1975 and 2002, *IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications.*

3. Regulatory Guide 1.128, *Installation Design and Installation of Vented Lead-Acid Storage Batteries for Nuclear Power Plants.*

4. IEEE Stds. 484-1996 and 2002, *IEEE Recommended Practice for Installation Design and Installation of Vented Lead-Acid Batteries for Stationary Applications*.

5. Regulatory Guide 1.212, *Sizing of Large Lead-Acid Storage Batteries.*

6. IEEE Std. 485-1997, *IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications.*

7. Regulatory Guide 1.158, *Qualification of Safety-Related Lead Storage Batteries for Nuclear Power Plants.*

8. IEEE Std. 535-1986, *IEEE Standard for Qualification of Class 1E Lead Storage Batteries for Nuclear Power Generating Stations.*

9. NUREG 1430-1434, *Standard Technical Specifications.*

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