Battery Testing and Replacement Criteria

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INTRODUCTION

Over the past twenty-five plus years, battery testing and replacement of batteries has changed. In addition, testing equipment has changed dramatically. Testing equipment in the 1960's and 1970's typically consisted of manually switched light bulbs with analog voltmeters to measure voltage across a shunt and overall terminal voltage. Today, resistor banks are typically used instead of light bulbs. Digital multi-meters and chart recorders have replaced analog voltmeters. And we have been computerized as some systems can automatically hold constant current as the voltage drops and vary the load to meet a service test as well as record the discharge rate and voltage. Testing frequency has changed, definitions of degradation have changed and inclusion of the modified performance test has changed the amount of testing at nuclear facilities. This paper will discuss the current requirements and provide some examples of applying these requirements to actual design duty cycles.

BRIEF OVERVIEW AND HISTORY OF IEEE 450 AS IT RELATES TO TESTING AND REPLACEMENT

Around 1970, with a significant amount of nuclear generation coming online, the IEEE saw a need to standardize the treatment of batteries. As a result of this need, a working Group on batteries was formed under the Station Design Subcommittee of the IEEE Power Generation Committee of the Power Engineering Society. IEEE-450 was initially issued in 1972[1]. Subsequently, IEEE Std 450 was revised in 1975[2], 1980[3], 1987[4] and 1995[5]. Some of the key differences between the various versions related to testing and replacement are listed in Table 1.

APPLICATION OF THE SERVICE TEST WITH A SAMPLE OF A PROFILE AND ACCEPTANCE CRITERIA

A service test is a test of the battery in its "as found" condition. The test should simulate as close as possible the actual worst case duty cycle the battery is expected to support. The acceptance criteria for the test is that the battery can supply the demand of the duty cycle, within the limits of the testing equipment, without the terminal voltage dropping below minimum design voltage. When setting up the test the amount of time that the battery is open circuited prior to starting the test should be minimized. The voltage and current should be continuously monitored.

Automatic testing equipment has limitations. Typically for large step increases the equipment may take up to 15 seconds to get to the set point. There are various ways to address large step increases. One can extend the peak periods by 10-15 seconds, or one can evaluate the test results such that the duration of the peak is longer than the actual duty cycle and that the energy discharged during the one minute period is larger than that actually experienced in an actual duty cycle. Another limitation is that the system can hunt around a set point and have the current fall below the set point by 1-2 amperes. This can be remedied by adding 2-5 amperes to each period. Manual control can be used with some equipment to bring the current back to the actual duty cycle. In addition, if there is margin in the sizing calculation, then a few additional amperes can be added to each period to account for future load growth.

In this first example, the battery contains 58 lead calcium cells, type XYZ-23. The minimum design voltage is 105 volts. Therefore the minimum average cell voltage is 1.81 volts per cell (vpc).

The 4 hour duty cycle from the sizing calculation using the IEEE std 485-1997 methodology and the testing amperes is as follows:

Period	Amperes	Duration in Minutes	Suggested Minimum Testing Current
1	753	1	755
2	351	14	355
3	151	15	155
4	136	30	140
5	95	179	100
6	110	1	115

In this first example only the first and sixth periods have increases in current. Testing experience has shown that with automatic load control equipment, only the first period has several seconds until the set point current has been reached. The increase associated with the last period is not significant and has been found to not require any adjustment.

In the second example, the battery contains 120 lead calcium cells, type XYZ-21. The minimum design voltage is 210 volts. Therefore the minimum average cell voltage is 1.75 vpc.

The 4 hour duty cycle from the sizing calculation using the IEEE Std 485-1997(5) methodology and the testing amperes is as follows:

Period	Amperes	Duration in Minutes	Suggested Minimum Testing Current
1	264.7	1	265
2	147.7	9	150
3	918.5	1	920
4	189.0	1	190
5	147.7	4	150
6	181.8	1	185
7	155.7	1	160
8	147.7	12	150
9	143.7	90	150
10	114.7	119	115
11	174.5	1	175

In this second example, a review of the sizing calculation indicates that the first, third, sixth and eleventh periods have a significant portion of the total current associated with momentary current. In addition the third period is the controlling period by a significant amount. Experience with this duty cycle has shown that the first and third period have taken several seconds to reach the set point current.

For both examples, either adding time (10-15 seconds) to the large step increases or gathering data to show that the actual duty cycle has been enveloped and that the energy discharged for the one minute period is greater than the actual duty cycle can be used to demonstrate successful completion of the service test.

APPLICATION OF THE PERFORMANCE TEST WITH A SAMPLE OF PROFILE AND EXPECTED RESULTS

From Example 1, the duty cycle is 4 hours. The 4 hour discharge rate to 1.75 vpc is 317 amperes. Therefore, the test should be run at a nominal 317 amperes for 4 hours. The rate will be adjusted based on the average of the temperature of at least 10% of the cells (typically 1-2 cells per step on each rack for a typical two step or two tier installation.

If the battery was sized in accordance with IEEE Std 485-1997(6) using an aging factor of 1.25, the minimum acceptance criteria would be that the battery would have at least 80% of rated capacity before dropping below the minimum design voltage. In this case, 80% of 240 minutes is 192 minutes. If a smaller aging factor was used, the acceptance criteria should be adjusted accordingly.

NRC REGULATORY GUIDE 1.129 ENDORSEMENT OF IEEE STD. 450

Regulatory guide 1.129 Revision 1 dated February 1978(7) endorses IEEE Std. 450-1975, dated May 29, 1975. This endorsement was subject to the following:

> "The battery service test discussed in subsection 4.3 "Service Test" and described in subsection 5.6, 'Service Test Description', should be performed in addition to the battery performance test.

INTERVALS OF TESTING PER IEEE450 AND NRC

The definitions of the Service Test and Performance Test in IEEE std. 450-1975 are as follows:

a) Service Test (Lead Storage Batteries). A special capacity test to demonstrate the capability of the battery to meet the design requirements of the system to which it is connected.

b) Performance Test (Lead Storage Batteries). A capacity test made on the battery, as found, after being in service to detect any change in capacity determined by the acceptance test.

In normal operations, the service test is performed at refueling intervals (e.g., 18 months) and the performance test is performed every five years, both normally performed during plant shutdown. To avoid performing two tests at the five year interval, the latest version of IEEE Std. 450 issued in 1995(5) introduced the concept of the Modified Performance Test. The Modified Performance Test is defined as "a test in the 'as found' condition, of a battery's capacity and its ability to provide a high-rate, short duration load (usually the highest rate of the duty cycle) that will confirm the battery's ability to meet the critical period of the load duty cycle, in addition to determining its capacity."

In several Technical Specifications (TS): a) the surveillance requirement states that the battery capacity is at least 80% of the manufacturer's rating when subjected to a performance discharge test. This test to be performed at least once per 60 months during shutdown, and b) once per the 60 months interval, the performance test may be performed in lieu of the service test. This statement is only correct if the discharge current (amperes) envelops the duty cycle of the service test. Most nuclear units have a high dircharge (amperes) demand in the first minute of the duty cycle that exceeds the discharge rate required for the performance test discharge. If the performance test is performed in lieu of the service test, as allowed by the above TS, the result is that a battery will not have a service test performed for 3 years or 4 years in nuclear plants with 18 month and 24 month refueling cycles respectively.

DEVELOPMENT OF MODIFIED PERFORMANCE TEST AND ITS USE

The modified performance test is a test that can be used to replace both the service test and the performance test if the test's discharge rates envelops the duty cycle of the service test. It typically consists of a one minute high rate that envelops the first minute peak of the duty cycle followed by a constant current at the manufacturer's rating. The constant current at the manufacturer's rating must also envelop the duty cycle for the duration of the test. The additional ampere hours removed from the battery due to the peak current should be less than 1-3% of the ampere-hour rating for the duration and voltage selected.

The peak current is not adjusted for temperature which follows the service test requirement, the long duration currents are adjusted for temperature in accordance with the performance test requirement. The long duration current when adjusted should not be less than any corresponding portion of the duty cycle. There can be a limitation on battery room temperature when the modified performance test is performed.

When satisfying the service test aspect of the modified performance test, it is advisable to envelop the duration of the test even when the battery does not have 100% capacity. A goal would be to have the modified performance test envelop the service test when the battery has a rated capacity equal to the design minimum capacity or 80%. This precludes any questions about the modified performance test not totally enveloping the service test duty cycle.

In IEEE Std. 450-1995, section 5.4, Modified Performance Test, the following is recommended: "The system designer and the battery manufacturer should review the design load requirements to determine if the modified performance test is applicable and to determine the test procedure". To illustrate a variation of not having the peak at the beginning of the cycle, we analyzed example 2.

The duty cycle is 4 hours long. Therefore it is desirable to have a 5 hour discharge. The rating of the battery at the 5 hour rate to 1.75 vpc is 270 amperes. This rate corresponds to 1350-ampere hours. The 270-ampere discharge rate is above all of the periods in the duty cycle except for the third period, which has a rate of 918.507 for 1 minute.

The additional ampere-hours discharges during a modified performance test at a rate of 270 amperes with a one minute peak of 918.507 is (918.507-270)/60=10.81 ampere-hours which is less than 1% of the batteries 5 hour rating.

Since the peak is at the 11th minute, ensure that the peak will not result in a terminal voltage less than 210. This is seen from a battery sizing sheet using three periods. (270 amperes for 10 minutes, 920 amperes for 1 minutes, and 270 amperes for 289 minutes).

Section	Period	Load (Amperes)	Change in Load	Duration	Time to end of Section	Capacity at t rate amps/pos (R_t)	Required section size
1	1	270	270	10	10	131.157	2.0586
						Total	**2.0586**
2	1	270	270	10	11	130.18	2.0741
	2	920	650	1	1	139.95	4.6445
						Total	**6.7186**
3	1	270	270	10	300	27.0	10
	2	920	650	1	290	27.781	23.3973
	3	270	-650	289	289	27.858	-23.3326
						Total	**10.0647**

The sizing sheet demonstrates that the peak load needs significantly less than the 10 positive plates of the final period. Therefore, the peak at the 11th minute is acceptable.

The first minute of the design duty cycle has a discharge rate of 264.717 amperes. The modified performance standard discharge rate at 77°F is 270 amperes. The correction factor for temperature cannot have a k factor greater than 1.02 (270/264.717). The k factor for 73°F is 1.017 per IEEE-450-1995[(5)]. Therefore, the minimum acceptable temperature for the test is 73°F.

The duty cycle shall be 270 amperes for 10 minutes followed by 920 amperes for 1 minute, followed by 270 amperes for 289 minutes. The 270 ampere rate should be corrected for temperature. The minimum electrolyte temperature for the test is 73 °F. The terminal voltage should be above 210 volts until the end of the duty cycle. No capacity correction is made for the peak current. In conclusion, a modified performance test can be used to replace both the performance test and the service test.

BATTERY DEGRADATION DEFINITION CHANGES

There has been a key change to the definition of degradation. Prior to the 1987 revision to IEEE Std. 450, degradation was defined as "degradation is indicated when the battery capacity drops more than 10% for the <u>average of the previous</u> performance tests. Starting with the 1987 revision of IEEE std. 450, degradation is defined as "degradation is indicated when battery capacity drops more than 10% of rated capacity from its capacity of the previous performance test". Based on the earlier definition, situations where the battery capacity dropped more than 10% from a previous test but was above 90% of the manufacturer's rating and less than 10% drop of rated capacity from its average on previous performance tests. Based on the earlier definition of "degradation" the testing interval in the example would remain at 60 months. A 10% drop in the capacity of the battery indicates that something is happening with the cells that warrant close monitoring of the health of the battery and a performance test performed after 12 months.

ACCELERATED TESTING

Accelerated testing is generally accepted as that required by IEEE Std. 450-1987 or IEEE Std. 450-1995. Annual performance testing is required when the battery demonstrates less than 90% of the manufacturer's rating or a 10% drop in capacity from the previous performance test. This requirement is more stringent than the earlier versions of the standard. Accelerated testing is also required when the battery has reached 85% of the expected service life, typically 17 years out of an expected 20 year life. Prior to the issuance of IEEE std. 450-1995, upon reaching 85% of expected life, performance testing was required annually. With the issuance of IEEE std. 450-1995, accelerated testing due to age is annual if the capacity is less than 100% and every two years if the capacity is 100% or greater.

BATTERY REPLACEMENT CRITERIA

Battery replacement criteria for flooded lead acid cells when sized in accordance with IEEE Std. 485-1997 is when the battery reached 80% of rated capacity or when replacement becomes more economical than testing. If a reduced aging factor is used then replacement is required corresponding to the reduced aging factor.

CONCLUSIONS

This paper reviews the testing and replacement requirements for vented cells. The service test can present some obstacles when using automatic test equipment that can be addressed either by adding time to periods with large step increases or by analysis. The modified performance test can be a very useful test to minimize the number of tests while gathering information to demonstrate compliance with the service test and performance test requirements. This paper proposes a method of applying the modified performance test that allows a battery to have less than 100% of rated capacity and still meet the service test requirements and a method to addressing initial high rate peaks at other than the first minute.

REFERENCES

1. IEEE Std. 450-1972, IEEE Recommended Practice for Maintenance, Testing, and Replacement of Large Stationary Type Power Plant and Substation Lead Storage Batteries
2. IEEE Std. 450-1975, IEEE Recommended Practice for Maintenance, Testing, and Replacement of Large Lead Storage Batteries for Generating Stations and Substations
3. IEEE Std. 450-1980, IEEE Recommended Practice for Maintenance, Testing, and Replacement of Large Lead Storage Batteries for Generating Stations and Substations
4. IEEE Std. 450-1987, IEEE Recommended Practice for Maintenance, Testing, and Replacement of Large Lead Storage Batteries for Generating Stations and Substations
5. IEEE Std. 450-1995, IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented lead-Acid Batteries for Stationary Applications
6. IEEE Std. 485-1997, IEEE recommended Practice for Sizing Lead Acid Batteries for Stationary Applications
7. Nuclear Regulatory Commission Regulatory Guide 1.129, Maintenance, Testing, and Replacement of Large Lead Storage Batteries for Nuclear Power Plants

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ACKNOWLEDGMENT

The authors would like to acknowledge the IEEE SCC 29 for the development of the modified performance test concept and in particular, Mr. Tim Bolgeo, formerly of TVA, whose questioning attitude of how to practically apply the modified performance test had a significant impact on the application described herein.

TABLE 1

Item	Version of IEEE Std. 450				
	1972	1975	1980	1987	1995
PERFORMANCE TEST					
Perform a Performance test within the first 2 years and then every 5 years until degradation is identified.	X	X	X	X	X
Perform a performance test every three years for nuclear class 1E batteries	X				
Performance Test normally omits equalizing and action for connection resistance prior to the test.	X	X	X	X	
Performance test allows equalizing if a service test is being performed on a regular basis				X	
Performance Test includes equalizing and checking resistance with no action unless unsafe.					X
Different process for determining capacity for tests under 1 hour	X	X			
Time is adjusted to address temperature effects	X	X			
Discharge rate is adjusted to address temperature effects			X	X	X
Jumper weak cell approaching 1V	X	X	X	X	
Stops Test for up to 10% of the test duration to maximum of 6 Min. to remove Weak cell. Only allowed once.					X
Test length should be approximately the same as the duty cycle.	X	X	X	X	X
DEGRADATION					
Indicated by a drop of 10% form the **average** of previous performance tests or below 90% of its rating. Annual testing	X	X	X		
Indicated by a drop of 10% form the **previous** performance tests or below 90% of its rating. Annual testing				X	X
When the battery has reached 85% of its service life. Annual testing		X	X	X	
When the battery has reached 85% of its service life. Capacity less than 100% - annual testing					X
When the battery has reached 85% of its service life. Capacity equal to or greater than 100% - 24 month testing					X
SERVICE TEST					
A test of the battery to deliver the design duty cycle in its "as found" condition without dropping below the design minimum voltage.	X	X	X	X	X
Identified as a test of nuclear Class 1E batteries to meet the requirements of IEEE Std.308-1974.		X			
Identified as a test of nuclear Class 1E batteries to meet the requirements of IEEE Std.308-1980. Identifies that if design parameters change, the test may need to be changed.			X	X	
MODIFIED PERFORMANCE TEST					
Performed on the battery in the "as found" condition					X
Envelops both the service test and performance test discharge rates					X
REPLACEMENT CRITERIA					
Recommends replacement of the battery within one year of reaching 80% of the manufacturer's rating	X	X	X	X	X
Identifies that if the aging factor used in sizing is less than 1.25 (80%), then replacement will be at a higher capacity to ensure that the load can be served.					X
Replacement timing is a function of sizing criteria, capacity margin available compared to load requirements.		X	X	X	X
Replacement cells should be compatible with existing cells and tested prior to installation.	X	X	X	X	X
Replacement cell not recommended as battery nears end of life.	X	X	X	X	X