

RATE ADJUSTED BATTERY CAPACITY TESTING AND CALCULATIONS, INCLUDING WHAT TO DO WHEN SOMEONE SAYS OOPS!

**M. S. (Steve) Clark
Battery and DC System Engineer
South Texas Project Nuclear Operating Company
Wadsworth, Texas**

ABSTRACT

The subject of battery capacity testing is one of the most discussed at any meeting of battery users. The subject of this paper is not to address all aspects of capacity testing. Rather it is to look at the less commonly used method of capacity testing known as “Rate Adjusted Testing” and how the principles of this method can be applied if things go wrong during a traditional time adjusted capacity test.

While it is not unusual for me to be asked questions about test methods or results by other users, the last 12 months have been different because I have been asked to evaluate test results from tests gone wrong not once but twice. In both instances the users did not follow the traditional time adjusted test methodology as described in IEEE 450-2002 [1]. As a result of these errors, the users were unable to accurately determine the capacity of the battery and the change in capacity between tests.

What makes these two examples unusual is that they do not fit the common test problems which typically involve test equipment failure or human performance errors. Rather they occurred because the test procedure or program was improperly prepared. In this paper we will use these events as examples of how the principles of rate adjusted testing can be used to resolve problems when a traditional time adjusted capacity test goes wrong without having to re-perform the test. Before we can do that, we have to look at the principles of battery capacity testing and specifically rate adjusted testing.

TIME ADJUSTED COMPARED TO RATE ADJUSTED CAPACITY TESTING

As the secretary of IEEE450-2002 [1] I can clearly state that one of the most acrimonious parts of preparing the document was the inclusion of rate adjusted testing. For many members of the IEEE 450 Working Group, this method flew in the face of traditional time adjusted capacity testing and was difficult to accept (including the author, I might add!). However, rate adjusted testing is a very valuable tool and deserves to be better understood and used especially when performing short duration high rate discharge tests. As we will see later, there is really no difference between the two methods. After all, capacity is capacity.

To determine the capacity of a battery requires the same set of data no matter which method is employed:

- The duration of the discharge.
- The battery voltage at the end of the discharge.
- The load current during the discharge (which can vary)
- The temperature of the battery at the start of the discharge

In an ideal world, when performing a rate adjusted test as described in IEEE 450-2002[1], the test preparer would also have the design end of life capacity.

No matter which test method is used, calculated battery capacity is the ampere-hours delivered during the test divided by the manufacturer’s rated ampere-hours corrected for temperature. In doing a time adjusted test, the rate is held constant so the rate cancels out and we are left with time over time. When performing a rate adjusted capacity test, the time is held constant so the resulting capacity calculation is simply rate over rate.

In the time adjusted method, a battery is tested based on the manufacturer’s published data. In this method the test current is the published rate for the desired test duration. In most previous versions of IEEE 450 the temperature correction factor was applied to the test current at the start of the test. However, in IEEE 450-2002 [1] we have reverted to the 1975 version where the temperature correction factor is applied to the test results after the test is completed or:

$$\% \text{ Capacity} = \frac{\text{Test Duration (minutes)}}{\text{Rated Duration (minutes)} \times \text{Temperature Correction Factor}} \times 100$$

While the reason for doing this was to support the modified performance test, it also eliminates one of the most common human performance errors we see in capacity testing.

The rate adjusted method works in essentially the same manner with one important difference. The difference is that when we perform a rated adjusted test, we **typically** adjust the current for the aging factor used in battery sizing. As an example, if a 25% aging factor is used in sizing then the design battery end of life is 80%. If we have a battery rated for 100 amps for 15 minutes, then per IEEE450-2002[1] the battery would be tested at:

$$\text{Manufacturer's Rate} \times \text{design end of life capacity} = 100 \text{ amps} \times 80\% \text{ or } 80 \text{ amps}$$

As in all capacity testing, the test is conducted until the specified end voltage is reached. We then compare the test rate to the manufacturer's rate for the actual test duration. The difficulty in using this method is to determine what the rated current is for the actual test duration, since this rate is often not in the manufacturer's published data. This means we have to interpolate the manufacturer's published data or go to the battery Fan or S-Curve to find the rate that matches the actual test duration. Our other option is to contact the manufacturer to obtain the rate. After we have our manufacturer's rate, then per IEEE 450-2002 [1] capacity is calculated as:

$$\% \text{ Capacity} = \frac{\text{Test Rate (amps)} \times \text{Temperature Correction Factor}}{\text{Rated Current (amps) for the actual Test Duration}} \times 100$$

For a lead-acid battery the end of life point by the time adjusted test is reached when the battery provides 80% of rated time when tested at 100% of rated current. With the rate adjusted method that point is reached when the battery provides 100% of rated time when tested at 80% of rated current. Both calculations yield an answer of 80% but the rate adjustment method is closer to the assumptions of the sizing calculation. The critical difference is that when testing high rate short duration system designs, the rate adjusted method more accurately reflects the ability of the battery to meet the design load. This is because of the impact of efficiency on the battery as the load current is increased.

The two methods yield the same results for batteries that perform at exactly 100% of their ratings. The time adjusted method is much simpler to perform but tends to overstate capacity deviations above and below the 100% mark. For longer test durations, particularly using an end voltage of 1.75 V/cell, the differences between the two methods are not significant and the simpler test method is always preferred. For shorter test durations, or tests that are terminated at higher end voltages (as is often the case when things go wrong), the rate adjusted method can give more accurate results.

Once we understand the principle of interpolating manufacturer's data we can expand it to time adjusted testing. We can express a time adjusted format using interpolation in the following manner:

$$\% \text{ Capacity} = \frac{\text{Test Duration (minutes)}}{\text{Rated Duration (minutes) for the actual test current} \times \text{Temperature Correction Factor}} \times 100$$

Applying interpolation to time adjusted test results enables us to calculate battery capacity for end voltages and times that are not included in the manufacturer's published data.

COMMON CAPACITY TEST ERRORS AND PROBLEMS

Most battery capacity tests are performed correctly and the test results are easily evaluated. However, failures do occur. The most common problems I have seen or been asked to evaluate fall into two categories.

- 1) Common Types of Equipment Failure include:
 - a) Loss of power to the load test equipment (So common, we've learned to take our own backup UPS with us)
 - i) Someone unplugged the load test equipment
 - ii) The laptop battery went dead
 - iii) Someone (no joke) plugged in a floor buffer and tripped the test equipment supply breaker (then you have to find the breaker)
 - iv) Load bank failure (a good justification for doing thermography on the load bank during every test and before if possible)
 - b) Computer malfunction (make sure everything is working right before you start)
 - c) A cell reached the low voltage cutoff before the 90% mark in the test, but we didn't have the equipment available to jumper out the cell. (A good reason to plan for this in advance, otherwise you may be referring to this paper!)
- 2) Human Error –
 - a) Temperature correction factor is incorrectly applied at the start of the test (Don't know how many times I've seen this even from highly experienced technicians. Best justification in the world to apply it after the test!)
 - b) Test is terminated early by operator
 - c) Wrong current value entered into the test set
 - d) Incorrect test procedure
 - i) We changed the battery (larger or smaller) but not the procedure. (I'd like to think I'm smarter than this, but I'm not. Just don't do it yourself. It's embarrassing.)
 - ii) The procedure has the wrong values (the best laid plans of mice and men)
 - iii) Procedure values changed between tests making trending almost impossible (why did we make that change???)
 - e) Wrong end voltage entered into the test set

As we've seen, there are a many potential pitfalls in performing capacity testing. Any one of them can result in test data that at the first glance appears to be un-usable or indicates a degraded battery (per IEEE 450-2002[1] a degraded battery is indicated by greater than a 10% drop in capacity between tests). The recent cases I evaluated both involved the inability of the user to determine if the battery was degraded.

In the nuclear power industry the potential for testing errors is about to increase. New nuclear power plant designs have 24 to 72 hour battery duty cycles. Existing federal regulations require the batteries be tested for these durations to verify battery capacity and capability. Both of the examples discussed in this paper occurred at nuclear plants and involved tests with a maximum duration of 4 hours. Based on the number of testing errors we see today when of performing 3-4 hour tests, it is quite possible that capacity testing issues will increase when the industry starts performing 24 and 72 hour tests.

BATTERY MANUFACTURER FAN AND S CURVES (THE IMPORTANCE OF CORRECTION FACTORS)

Whether you use the rate adjusted method for capacity testing or to evaluate time adjusted test results, there are times it will be necessary to refer to the manufacturer discharge curves rather than the published tabular data. This is often caused by the lack of tabular data for the end voltages of the test being reviewed.

It is not the intent of this paper to explain how to read manufacturer discharge curves. Rather it is to ensure users are aware of one important point fact to remember when using curves. That is, it is very rare to find a curve that exactly matches the manufacturer's published data. While some manufacturers include correction factors on the curve itself, it is important to compare the results obtained by reading the curve at published data points to the published data and to verify the published correction factors.

By making these comparisons, the user can determine if a correction factor needs to be applied to the curve data to make it agree with the published tabular data. For users that are uncomfortable doing this, the best way to obtain data for rates and times that are not included in the published data tables is to contact the manufacturer directly.

LOGARITHMIC AND LINEAR INTERPOLATION OF MANUFACTURER'S DATA

Peukert's Law

In 1897 the German scientist W. Peukert formulated an equation that relates the capacity of a battery to the rate of discharge and the duration of the discharge. This is sometimes referred to as Peukert's Law. The basic form of the equation is available on the Smart Gauge website [2] and is:

$$I^n T = C$$

Where:

I = the discharge current in amps

t = the time in hours

C = the capacity of the battery in amp hours

n = Peukert's exponent for that particular battery type

The advantage of Peukert's equation is that it allows us to perform a logarithmic interpolation of the logarithmic battery discharge curve. This enables us to calculate the manufacturer's rated discharge current for the rated time at any point along the curve. Smart Gauge makes available a Peukert Calculator [3] on the internet in Microsoft Excel format.

In Storage Batteries [5] page 218, George W. Vinal provides a comparison of the Peukert calculation against actual test data. This shows that the Peukert method is accurate when calculating battery capacity. Additional data on Peukert's Law can be found on the Smart Gauge website [2] and [4] as well as other websites.

Linear

The other method of finding a discharge rate or time that falls between the published data points is to perform a linear interpolation of the published data. The interpolation should be made not on the published currents but on the capacities removed (published current multiplied by published time) for each data point. This can be less accurate than the Peukert method when the available data points are widely spaced as a percentage of the test time. Using a test duration of 8 minutes as an example, interpolation between data points for 1 minute and 15 minutes may not be accurate, while interpolation between data points for 5 minutes and 10 minutes would yield insignificant errors.

Comparison of Real World Data

For the first set of test data I was asked to review in 2006, I decided to perform the capacity calculations in three different ways. The user (Plant A) provided the data and had already performed the calculations using the time adjusted method in IEEE450-1995. The first calculation I did was just a seat of the pants check to see if the initial change in capacity calculation was yielding accurate results. When this calculation called into question the results of the initial calculation, I performed the calculation using both linear interpolation and the Peukert equation. In this case the Peukert calculator I used was provided by the battery manufacturer. The test being evaluated was for a nominal duration of 2 hours.

For nuclear power plants, it is very important to know the change in capacity between tests. This is because additional testing is required by federal regulations for a degraded battery. IEEE 450-2002[1] defines degradation as a greater than 10% reduction in capacity between tests or capacity less than 85% of rated capacity. In this instance there were errors in the test methodology and performance that resulted in a calculated capacity drop of 13.08% using standard time adjusted methods. For Plant A, these results would require to plant to shutdown in 12 months verses the normal 18 months for the sole purpose of performing a battery capacity test.

Since nuclear power plant down time can easily cost a \$1,000,000/day, Plant A requested assistance to evaluate the test results. I evaluated the capacity change between the two sets of capacity test results using the interpolation principles from the rate adjusted method. The advantage in this instance was that the manufacturer's published data tables provided all the information necessary to perform the analysis without referring to the discharge curve.

The following table provides a comparison of the results based on the different methods used to calculate the test results.

Table 1 Capacity Calculation Method Comparison

Capacity Calculation Method	Capacity Reduction
Time Adjusted Per IEEE 450-2002 [1]	13.08%
Peukert Equation	5.55%
Linear Method	5.57%
Seat of the Pants	8.80%

As seen in the table the calculated capacity reduction using rate adjusted methods was much less than the reduction using the standard time adjusted method. Applying rate adjusted techniques saved an estimated \$3,000,000 over having to shutdown the plant to perform a capacity test.

EVALUATING RESULTS DUE TO INCORRECT TEST VALUES

When evaluating test results, there are several things to consider. The first is what methodology to employ. The methodology selected is often based on the available information and what the question is. The question can be one of warranty compliance, regulatory compliance or simply trending battery capacity to estimate when a battery will reach the end of life. Which ever methodology is chosen there are several things to we need to know.

- 1) The actual test duration. The actual duration minutes to the nearest tenth of a minute. If you are being asked to help someone, then make sure you get a copy of the test results. Do not use a number from a phone call.
- 2) The test temperature. Same caveat, get the actual test data sheet.
- 3) The actual test discharge rate. This is often not the calculated or input number, but rather the closest the test equipment can come to that value and should be obtained from the test data sheets. Since this number often varies slightly over the duration of the test, calculate the average discharge rate based on the number of data points available.
- 4) The manufacturer’s published data. This can be in form of tables or based on a fan or S curve.
- 5) The correction factor to be applied when using a fan or S curve.

As we have seen the Peukert method illustrated in the table below yields highly accurate results. Peukert calculators are readily available and easy to use. The disadvantage is that the Peukert method is that it is iterative. The input current (2) and Input Increment may have to be adjusted several times to find the manufacturer’s current and time ratings that match the test results being evaluated.. This is why most of the available calculators have been developed in computer based spreadsheet programs. Computer based spreadsheet programs make it easy to keep making adjustments until an the correct manufacturer’s rating is found. The table below shows a sample calculation. To save space, the iterative row values have been deleted.

In the example in the following table, the time adjusted capacity calculation yielded a value of 117.1%. This is significantly greater than the actual capacity of 108.9%. Errors of this type make predicting battery end of life much more difficult because they overstate the health of the battery.

Table 2 Sample Peukert Calculation

<i>Peukert's Equation, $t = C/i^n$</i>					
		D			
	33601813.49				
	33601813.49	-0.00000002980			
n	C				
1.949259177	33601813.49	time 1	120		
		current 1	623		
		time 2	180		
		current 2	506		
current	time	(2.) Input Current	574.4		
574.58	140.4991	(3.) Input Increment	0.01		
			Test Duration	140.5	Minutes
			Discharge Rate	574.58	Manufacturer's Rated
			Mfg Rated Cap	1345.475	Ah @77F
			Test Result Cap	1464.876	Ah corrected to 77F
			Percent Cap	108.9%	
Test Results 605 amps @71° F for 116.6% capacity					
Temp Correction Factor		1.034			
The calculations performed compare the manufacturer's rated Ah capacity for the actual test duration, to the actual test capacity corrected to 77°F.					

EVALUATING RESULTS DUE TO EARLY TEST TERMINATION

One of the more common mistakes in capacity testing is early test termination. This can be caused by test director error, procedure error, equipment malfunction etc. When using computer based test systems it is often caused by entering the test duration incorrectly, i.e. a four hour test duration is set to run for four hours. This does not cause a problem if the battery is less than or equal to 100% capacity. However, when the battery has greater than 100% capacity, the test terminates before the end voltage is reached. This makes it difficult to determine the actual capacity and makes trending for predicting end of life impossible. This is a simple error correct. When a test is planned for a four hour duration, then the test set should be set for a duration of at least four and one half hours. This allows sufficient time for the test to reach the end voltage.

The following table illustrates how data from early termination can be analyzed to determine the actual capacity using rate adjusted methods. The results shown are real world data from two 4 hour tests. In this example the manufacturer only published data for end voltages of 1.75 volts/cell and 1.81 volts/cell. Since both tests terminated above 1.81 volts/cell it was necessary to consult the manufacturer’s curve to obtain data points for other voltages.

The manufacturer’s curve showed that at 4 hours there were only small differences in the amps per positive plate. For this reason a straight linear interpolation was used. However, there were differences between the curve values and the published values. Therefore, it was necessary to develop a correction factor. The average correction factor was then used to adjust the amps per positive plate values for the other voltages on the curve and a set of data points was developed. The data set was then used to determine the actual capacity for the two tests. Once again, this was a nuclear power plant, so the actual capacity difference between the two tests was critical to determine if the battery were degraded.

Table 3 Example of Capacity Calculation for Early Test Termination

Develop Table of Rated Discharge Currents	End V	Curve		Table		Cor. Fact		Curve		Table		Cor. Fact		Curve Amps Per Positive Plate		
		3 Hrs	3 Hrs	3 Hrs	4 Hrs	4 Hrs	4 Hrs	5 Hrs	5 Hrs	5 Hrs	5 Hrs	3 Hours	4 Hours	5 Hours		
Use the Curve to Find the Rated Amps per Positive Plate at each voltage on the Curve	1.96	154.4	161		134.4	143		121.6	126			19.3	16.8	15.2		
	1.92	224	234		189.6	201		170.4	177			28	23.7	21.3		
	1.88	264	276		224	238		195.2	203			33	28	24.4		
Enter the published data points that bound the area being evaluated.	1.84	296	309		248	263		214.4	223			37	31	26.8		
	1.81	324	336	1.037	268	284	1.060	230.4	240	1.042		40.5	33.5	28.8		
	1.78	340	355		276	293		240	249			42.5	34.5	30		
Compare the curve points to the published points to develop a correction factor to apply to the data points where no published points exist.	1.75	347.2	365	1.051	285.6	304	1.064	246.4	255	1.035		43.4	35.7	30.8		
	1.67	372	388		289.6	308		248	257			46.5	36.2	31		
Multiply the curve values by the correction factor.				1.044			1.062			1.038						
Test 2 Capacity																
Calculate End Voltage in VPC=105.8/58=	1.824															
Calculate Amps/Unit = (284-263)/3=	7.000															
Calculate number of units = End voltage - 1.81=	1.414															
Calculate current offset =Amps/Unit*No. Units=	9.897															
Calculate rated current = Offset + 1.81 rated =	274.1															
Calculate capacity = Actual current/rated current =	103.6%															
Adjust Capacity for Actual Current = Cap*Correct =	103.8%															
Actual Test Current Correction For Test 2																
Compute Actual Average Current	285.4	284.8	284.7	284.2	284.1	280	285	0	0							
	1	12	8	2	1	1	2	0	0	27						
	285.4	3417.6	2277.6	568.4	284.1	280	570	0	0	7683.1						
Actual Test Current =	284.6															
Comute Current Correction = (284.5593/284) =	1.002															
Capacity Reduction = Test 1 - Test2 =	4.5%															
Test 1 Capacity																
Calculate End Voltage in VPC=106.7/58=	1.84															
Calculate Amps/Unit = (284-263)/3=	7.000															
Calculate number of units = End voltage - 1.81=	2.966															
Calculate current offset =Amps/Unit*No. Units=	20.759															
Calculate rated current = Offset + 1.81 rated =	263.2															
Calculate capacity = Actual current/rated current =	107.9%															
Adjust Capacity for Actual Current = Cap*Correct =	108.3%															
Actual Test Current Correction For Test 1																
Actual Current	280.6	280.1	280.2	279.6	280.3	280	280.4	279.9	279.6							
Number of Data Points	1	15	2	1	1	1	2	1	2	26						
Data points x current	280.6	4201.5	560.4	279.6	280.3	280	560.8	279.9	559.2	7282.3						

CONCLUSIONS

Rate adjusted testing is a valid method for determining battery capacity. It is based on how the battery was sized and accounts for the change in battery efficiency as the discharge rate changes. While the rate adjusted method appears different than the time adjusted method, the principle of interpolation can be used to calculate capacity based on time as well as rate. Depending on the battery characteristics and discharge time, the linear interpolation methods provides results that are acceptable for most applications. When the most accurate results are required, a Peukert calculator should be employed to find the rated current and time point from the manufacturer’s published data. The advantage of understanding the rate adjusted test method is the ability to use interpolation to calculate battery capacity when a time adjusted test goes wrong. The advantage of not having to re-perform a test makes the ability to accurately interpolate the manufacturer’s data a true asset for anyone involved in battery capacity testing.

ACKNOWLEDGEMENTS

The author would like to acknowledge the following members of the IEEE Stationary Battery Committee for their assistance in developing this paper:

- Mr. Jim McDowall
- Mr. José Marrero

ABBREVIATIONS

- IEEE – Institute of Electrical and Electronics Engineers Inc.
- UPS – Uninterruptible Power Supply

REFERENCES

- [1] Institute of Electrical and Electronic Engineers, Inc., IEEE450-2002, IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications, April 3, 2003
- [2] Smart Gauge, A proper explanation of Peukert's Equation (Peukert's Law) <http://www.smartgauge.co.uk/peukert.html> 2-4-2007, Available at <http://www.smartgauge.co.uk/peukert.html>
- [3] Smart Gauge, Peukert's Equation Calculator, <http://www.smartgauge.co.uk/calcs/peukert.xls> 2-4-2007. Available at <http://www.smartgauge.co.uk/calcs/peukert.xls>
- [4] Smart Gauge, An in depth analysis of the maths behind Peukert's Equation (Peukert's Law) http://www.smartgauge.co.uk/peukert_depth.html 2-4-2007. Available at: http://www.smartgauge.co.uk/peukert_depth.html
- [5] Vinal, George Wood Sc. D., Storage Batteries, Pages 216 through 218, New York, John Wiley & Sons, Inc. fourth edition, 1955
- [6] Wikipedia, Peukert's Law http://en.wikipedia.org/wiki/Peukert's_Law 2-4-2007 Available at http://en.wikipedia.org/wiki/Peukert's_Law