Interpreting Battery Ratings and Discharge Tests – How the Same Numbers can be Interpreted in Different Ways

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ABSTRACT

All batteries have ratings, but not all ratings are equivalent. This paper will discuss the different ways that are used by battery manufacturers to develop their ratings. These methods can result in ratings that appear equivalent, but can have very different meanings. It is important that these differences be understood to allow meaningful comparisons to be done, and to allow proper conclusions to be made during any acceptance or discharge testing.

Additionally, this paper will discuss the types of performance variations that are often observed in a typical discharge test. Cell-to-cell variations, string vs. cell variations, and the different voltage variations vs. time will be discussed. These variations are often the subject of disputes between the manufacturer and the end-user. The basis for these different interpretations is discussed as well as their implications on the health of the battery.

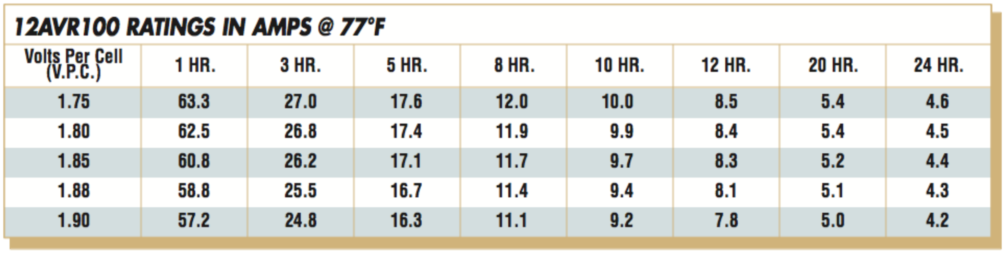
With the information presented in this paper, the end-user will be better able to compare and select an appropriate battery from its ratings tables. They will also be able to better interpret test results to determine whether a cell has actually performed to its rating.

INTRODUCTION

A battery capacity test is often described as the ultimate test of a battery, one that provides indisputable indications of a battery's health. Unfortunately, the conclusions from these voltage vs. time test results are often far from indisputable. A cell or battery that is thought to have failed a test by an end-user can be deemed acceptable by the battery manufacturer. Confusion and arguments can arise as warranty claims are denied and suppliers refuse to react to a battery thought to be underperforming by the end-user. This paper will discuss some of the common ratings issues that can arise as a battery is tested and how these results can be interpreted in different ways.

RATINGS

A typical industrial ratings table is shown below. This appears clear and simple. Unfortunately, one must know how the manufacture arrived at the displayed values to be able to use the data properly.



12AVR100 RATINGS IN AMPS @ 77°F

Volts Per Cell (V.P.C.)	1 HR.	3 HR.	5 HR.	8 HR.	10 HR.	12 HR.	20 HR.	24 HR.
1.75	63.3	27.0	17.6	12.0	10.0	8.5	5.4	4.6
1.80	62.5	26.8	17.4	11.9	9.9	8.4	5.4	4.5
1.85	60.8	26.2	17.1	11.7	9.7	8.3	5.2	4.4
1.88	58.8	25.5	16.7	11.4	9.4	8.1	5.1	4.3
1.90	57.2	24.8	16.3	11.1	9.2	7.8	5.0	4.2

Although a single value is provided for any given condition, this value can represent very different levels of performance of the given cell. For instance, if we take the 10 hour rating to 1.75 volts-per-cell (vpc), the table lists the rating at 10.0 amps. These 10 amps can represent very different things:

- Cell average – When all the cells are tested, this will be the arithmetic average of all of the cells. Cells will range above and below this value. No indication of an acceptable range is given. All cells in these three figures (Figure 1) could be listed with the same 10 amp rating, and none would be considered failures by the manufacturer.

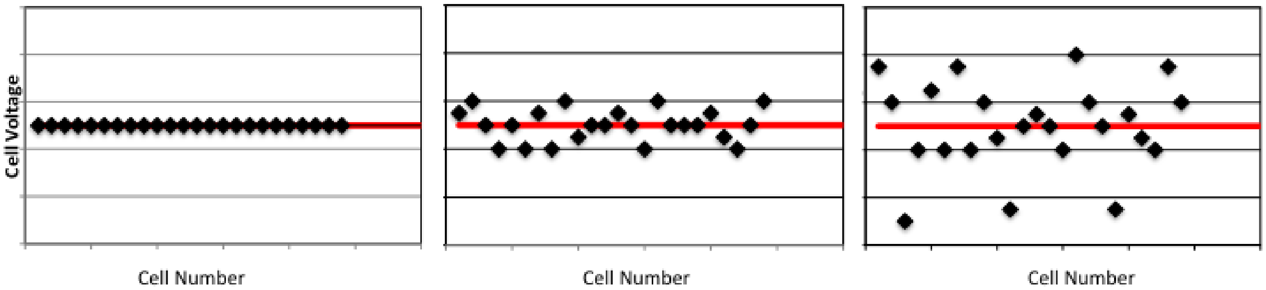


Figure 1. Ratings based on Cell Averages

- String average – when a string of cells are tested, this will be the average of the string. Strings will average above and below this value, and on top of this; the cells will range above and below the string average. See Figure 2. This can result in a much larger spread of possible individual cell voltages. Again, none of these cells would be considered a failure by the manufacturer.

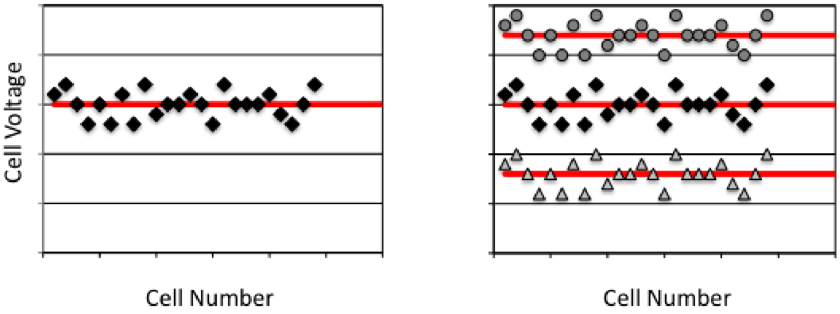


Figure 2. Ratings based on String Averages

- Cell minimum (average – 3 std. deviations) – Statistically, +/- 3 standard deviations will capture 99.73% of all expected results. If the ratings are based on the average minus 3 std. deviations, then 99.73% of all cells will be greater than the ratings value. Cells that perform below this level are statistical outliers. They should be considered a failure, and they should be replaced. This is the most conservative and clear-cut ratings definition used. See Figure 3.

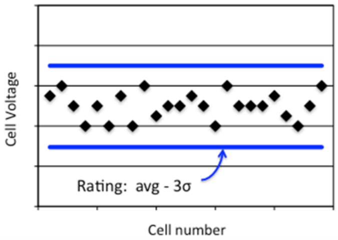


Figure 3. Ratings based on 3 std. deviations

Cell minimum (average – 2 std. deviations) A less conservative method is to calculate the rating as the average minus 2 std. deviations. In this case, 97.7% of the cells will perform greater than this value. By simple math, 2.3% of all cells are to be expected to fall below this limit. The ambiguity with this method is that the cells that perform below the rating may or may not be considered a failure, either statistically or by the manufacturer. See Figure 4.

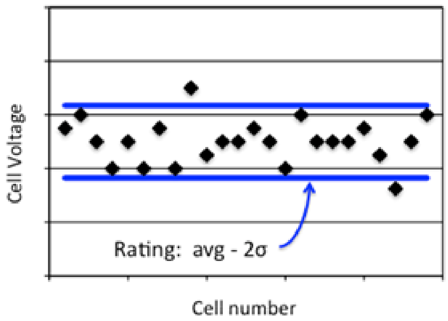


Figure 4. Ratings based on 2 std. deviations

- Connector Drop - Some manufacturers will calculate ratings which will include the expected voltage drop associated with the common connectors that will be used. If the rating does not include the connector drop, the cell voltages must be collected at the terminals of each cell and not at the connector midpoints. The string voltage is thus the summation of the individual cell voltages. Note that the string voltage as measured at the positive and negative leads to the entire battery cannot be used for determination of meeting a capacity test, unless the individual connector voltage drops are added back into the overall string voltage. See Figure 5.

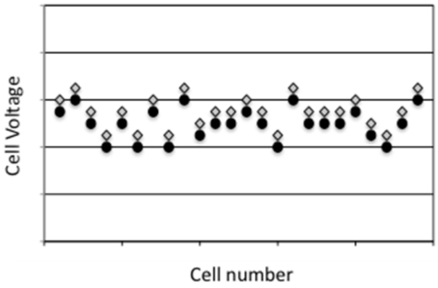


Figure 5. Cell voltage adjustment due to Connector resistances

- As Delivered - Some ratings are for batteries 'out-of-the-box', other ratings presume the battery to have been installed and operated for a fixed time. Although this appears misleading, this is a legitimate position, as some industries have historically provided a period of time after installation for the cells to develop in the field. If this is the case, any warranty claim is difficult to pursue until the expected time has passed for the battery's capacity to fully develop. This period of time must be defined by the manufacturer prior to an on-site capacity test.

DISCHARGE TEST INTERPRETATIONS

In addition to the interpretation of the ratings themselves, the cell voltage variations seen during a discharge test can also be interpreted in different ways. Figure 6 shows a grouping of individual cell voltage vs. time curves that could be typically seen during a discharge test. Most of the cells track very similarly, but there is a lot of variability seen in different areas of this data. Each of the major observations of variability is discussed, and the importance of each is reviewed.

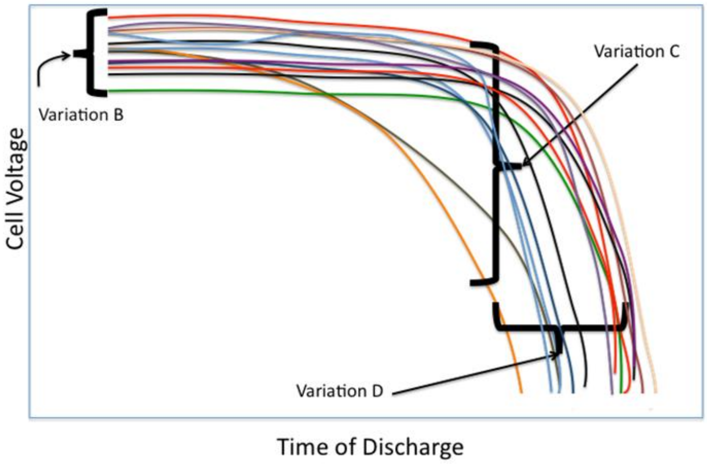


Figure 6. Individual Cell Voltage Curves during a Discharge Test

In addition to the cell voltage variations seen when a cell is charged on float, there are three additional major areas of variation in the individual cell voltages curves as indicated in Figure 6.

A. Cell voltage variations prior to discharge – on float
B. Initial cell voltage variation during the 'bulk' phase of the test
C. Voltage variation at end of discharge time
D. Run-time variation at end-of-discharge voltage

A. Cell voltage variations prior to discharge

Prior to applying a load, the cells will typically be floating at a constant string voltage with a nominal cell-to-cell voltage variation. Depending on the cell type and the number of cells in a string, this may be in the range of 100 mV or it may be slightly higher. The float voltage variation has been shown to be primarily driven by the voltage contribution of the negative plate. Since the positive plate is the limiting factor in the energy provided during a discharge, the float voltage variation is generally not a good indicator of the cell capacity or health, unless it is significantly out of range. This expected range can be obtained from the battery manufacturer. The relative level of the float voltage will change when the load is applied during the discharge test. The relative level and range under this load is much more important, as it will be driven from the positive plate, and will include any unintended current restrictions that occurred during manufacturing, such as a poor lug-to-strap weld. This is discussed in the next section.

B. Initial cell voltages

As the discharge test begins and progresses, the cells will begin to show variability in voltages. This voltage is typically relatively small and can indicate several benign situations.

- Difference in resistance of components
  As a normal part of the manufacturing process, there will be some variation in the electrical resistance of the internal components of the cell. Additionally, there will be electro-chemical variations in the plate, due to variations in its porosity, the acid diffusion and the additives in the active material. This type of variation is seen as parallel voltage readings during the onset of a discharge test. Parallel tracking is not generally an issue, but if one or more cells are tracking at a different slope, then the variation is due to other factors and may be a more severe issue.

- Difference in specific gravity of electrolyte – In both vented and valve-regulated type cells, a difference in the electrolyte strength or temperature can contribute to this variation. In a valve-regulated cell, the electrolyte amount and strength is typically not adjusted in the field and therefore this variation is not adjustable. In a vented cell, the level of the electrolyte and its strength is measured and adjusted as required over the service life of the battery. The electrolyte in a string of vented cells should be uniform in level, strength and temperature to obtain the closest cell voltages possible during a discharge.

- Very little or no reaction should be taken to the cell variation at this point of the discharge. Experience tells us that the voltage level at the onset of discharge, prior to approaching the 'knee', is not indicative of the capacity that the cell will be able to deliver. However, there is concern for cells that drop in voltage at a faster rate than others in its string. This is discussed in the next section.

C. This paper will specifically not discuss the capacity determination for long vs. short discharges (time vs. rate). Those wishing to explore these test methods in more detail are referred to the appropriate IEEE testing documents. This paper will explore the voltage variations observed as a cell reached the termination point.

There are two common termination points for a discharge test – by time (variation C, Figure 6) and by voltage (variation D, Figure 6). Both are similar for this analysis and the following discussion can be applied to both. In our earlier example, the battery was rated to deliver 10 amps for 10 hours to 1.75 volts per cell. One test method is simply to load the string with 10 amps, and measure the cell voltages. At the end of 10 hours, a reading and a capacity determination is made.

There are two possible outcomes for a capacity determination.

- All the cells are above 1.75 volts. In this case, there should be no dispute as the whether all the cells are good in terms of capacity.
- Some cells are below 1.75 volts. The string may or may not be above (1.75 volts) x (number of cells). In this case, the method the manufacturer used to rate the cells must be determined as discussed in the earlier sections of this paper. It is best to know this before the test is run to prevent any confusion and arguments afterwards.

In addition to the capacity, there will some degree of voltage variation, which can be interpreted in different ways. These are not typically used by the manufacturer as a warranty determination, but can be very valuable to the end-user in evaluating the health of their battery system. In the next section, we will examine some cell voltage curves of a discharge test and will discuss possible interpretations of these curves. See Figure 7.

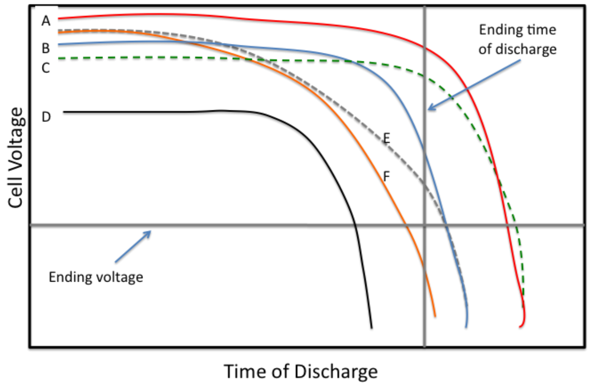


Figure 7. Common Cell Voltage vs. Time Profile Curves

Cell D certainly appears to be the problem child, but it should be screened to verify it is not easily correctable before it is simply replaced. It has a lower voltage at the onset of the applied load, and remains low throughout the test, and eventually fails early. This cell shows signs of a higher internal resistance than its neighbors. One should verify the electrolyte is at the proper concentration if it is vented, and should verify that the connectors do not have improper resistance or corrosion. This type of discharge curve can also be caused by a high resistance lug-to-strap weld, a dropped plate or a portion of the top lead that is cracked or broken. If a thermal imaging camera is available, this is a good way to examine the cell during the discharge event. A defect that is large enough to affect the cell performance is usually large enough to create a hot spot that can be seen by a sensitive thermal camera. It is unlikely, but this cell may be at a colder ambient temperature than the other cells, perhaps due to a local HVAC vent. Even more unlikely, but possible, is that this cell is smaller in capacity than the others in the string and was installed in error. Mix ups like this have occurred and can be easy to miss if the same size outer container is used for multiple internal elements. If none of these checks correct the performance problem, this cell should be replaced promptly.

Cell F started out with strong voltages and then dropped early and did not make the ending voltage. This indicates that the initial acid concentration was proper, and that the welds and components do not have major defects. This could indicate it simply ran out of fuel early, either acid or active material. A valve-regulated cell is typically acid limited by design, and this type of performance drop off is common and is not a reason in and of it’s self to replace a cell. Vented cells can be either acid limited or active material limited, so a low level of electrolyte can cause premature drop in performance like this. Check the electrolyte level is proper if vented. Another possible cause of early drop in voltage is an increase in internal resistance during the course of the discharge. This can be caused by a weak weld getting hot from the electrical current of the discharge. A thermal imaging camera is a good check to ensure a component is not heating up improperly half way through the discharge, creating a high-resistance path as it gets hot. Any severe issue is very unreliable and warrants immediate action.

Cell C has a slightly higher internal resistance, but is an otherwise strong performer. The cell voltages are steady and level in the bulk phase of the discharge, indicating that there are no growing hot spots or defects. The connector resistance and electrolyte concentration for cell C should be verified to be proper, but no other reaction to this cell is necessary. Although it is lower than Cell A and slightly lower than B, it does not appear defective in any way and just indicates the normal manufacturing variation possible with these cells. It has sufficient quantities of fuel, indicating the electrolyte volume is proper and the active material quantities are proper.

Cell B has higher voltages than C for most of the discharge, but is actually a weaker performer. It has a lower internal resistance, which allows the cell voltage to start out relatively high and remains high for most of the bulk phase. However, it drops off quickly nearing the termination time. It has run out of fuel and will quickly hit its termination voltage. Sharp ‘knees’ or voltage drops are indicative of acid limitation, and is common in valve-regulated cell designs and in ‘full box’ vented designs. Vented containers are often used for a range of element sizes. A ‘full box’ is the maximum number of plates that are put in a container. Although ‘full boxes’ provide the smallest footprint, they also provide the smallest acid-to-active material ratio and are most likely to be acid limited. This is not a problem per se, but will result in sharper ‘knees’ and hence greater voltage variations at the end of discharges. Cell designs with very thick plates, or cells running out of active material will show a less sharp ‘knee’ at the end of a discharge.

SUMMARY

In terms of good cells vs. bad cells, and the interpretation of the cell discharge voltage profiles, we can make a few general statements.

The first step is to find out from the manufacturer how the rating was determined. This will reveal whether cell F officially failed the discharge test, even though it performed below the published rating. If the rating is based on cell averages, or is a string average, or is based on average minus two standard deviations, cell F may not be branded a failed cell by the manufacturer.

Regardless of the rating definition, cell D is definitely a bad cell and should be replaced. It is not of the same population as the rest of the string, indicating it has some abnormality. It has a high internal resistance which could be a weak point and a possible future failure point. If it was not jumped out of the circuit during the discharge test, it most likely went into reversal at the end of the test, which is usually cause for automatic replacement.

Cells E and F are cells that do not need to be immediately replaced, but they should be watched in the future. They have a sharper sloping voltage profile that indicates they are not just running out of fuel in the same way as the rest of the string. It is possible this is nothing more serious than they have multiple design limitations, such as acid and positive active material. If this is the case their performance will simply degrade normally as they age and at a rate similar to the rest of the string. Their performance also indicates that they could possibly have internal defects that could cause early failures. There is no reason to replace them at this time, but their future performance trends should be watched in subsequent discharges.

Cells A, B and C are performing as would be expected by the manufacturer. They show normal variation in their voltage profiles and variations.

CONCLUSIONS

This exercise was intended to provide some insight into battery ratings and also how to interpret cell voltage profiles during a discharge test. Clearly there are many different ways to interpret a battery rating and additional ways to interpret the information from a discharge test curve. It is hoped that this knowledge will introduce the end-user to the art and science of interpreting the data points that are collected from tests of their battery systems.