NE Utilities Battery Conference

September 20, 1994 | Albany, New York

ARE INTERNAL CELL PARAMETER MEASUREMENTS A SUBSTITUTE OR SUPPLEMENT TO CAPACITY TESTING?

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INTRODUCTION

Impedance, conductance, or better yet, resistance testing of battery cells or modules has been one of the hottest topics in the battery industry for the past few years. Witness the fact that it has been on this conference's program for at least three or more years in a row.

Does it really warrant this kind of attention, or is it all sales talk? Certainly if you read today's advertising literature you'll get excited. There are companies out there promising you black magic. Their ads tell you that you can throw away your capacity test sets, because with an impedance or conductance meter you can accurately measure cell capacity and remaining battery life. One has to wonder if their engineering department had anything to do with producing these ads.

This presentation, however, is not intended to discourage or discredit internal cell measurements, but rather explain a little of the theory involved, how they are performed and what can be learned from them.

The questions that this presentation would like to answer are:

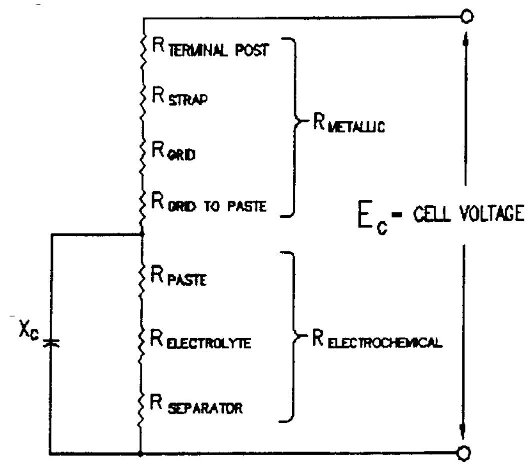
- ***Is there any validity to Internal Parameter Testing?***
- ***How do the readings relate to capacity?***
- ***What cell problems can be identified?***
- ***Are these tests a supplement or a substitute for capacity testing?***

The answer to whether or not there is any validity to Internal Parameter Testing is yes, and it should be part of the regular maintenance program. It is important, though, that the user understand what these readings will and will not tell him. The rest of the questions will be answered in the following sections.

INTERNAL BATTERY PARAMETERS

The total conductance path through the cell includes the metallic or ohmic path as well as the path that is involved electrochemically as illustrated in Figure 1. Ohmic path includes the resistance of the terminal posts, the strap, the grid structure, and the grid to paste connection. The electrochemical path includes the paste, electrolyte and the separators. The capacitor Cp is the result of all the parallel plates with a dielectric between them. Capacitor value is a substantial 1.3 to 1.7 farad per 100 ampere hours of battery rating depending on battery design. The inductance of the battery has been ignored since its effect is negligible for the frequency range used by today's battery impedance instruments.

Looking closer at the equivalent circuit, it is obvious that the capacitive reactance (X_C) effectively shunts R_E (the electrochemical part of the path), masking the changes that may take place in this part of the path. This part of the path includes the paste and electrolyte resistances which are the most important parameters in determining the capacity of the battery. Since the capacity of a battery is related to the quality of the conductance path, it means that what is really needed is to measure the internal resistance rather than impedance. A generally accepted equivalent of a lead-acid battery is illustrated below in Figure 1.



Simplified Model of a Lead-Acid Cell
Figure 1

HOW INTERNAL MEASUREMENTS ARE MADE

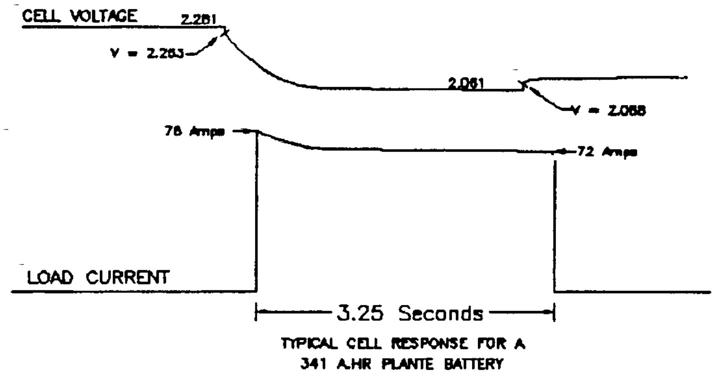
Instruments presently available use either an AC current injection method or a momentary load test (DC measurement). AC injection instruments (better known as impedance or conductance meters) apply a test signal through the battery and then measure the resulting AC voltage and current. The impedance reading V/I varies with the frequency or the value of capacitive reactance X_C which in turn lowers electrochemical resistance R_E.

The consensus of the technical papers presented since 1959, is that the cell resistance rather than impedance is what is important to analyze. For that reason, the lower the test current frequency the better, since the impedance approaches the internal resistance as frequency approaches either zero or DC.

The problem with AC measurements is that they are susceptible to charger ripple currents and other noise sources. Some instruments cannot be used while the battery is on-line (i.e. connected to the charger and load in a normal full float operation). A particularly bad choice of test current frequency is 60 Hz in the US and 50 Hz in the majority of the rest of the world, since this is the primary charger ripple and noise source frequency. It is not uncommon to have rms ripple currents in excess of 30A flowing through large UPS batteries.

The DC load test instruments, which measure resistance, subjects the battery to a momentary load current and then measures the instantaneous change in battery terminal voltage. Figure 2 shows what happens when a battery is subjected to a load for a few seconds. The instantaneous drop when the load is applied or the instantaneous voltage recovery when the load is removed is due to the internal resistance.

A resistance meter (such as the Albercorp CellCorder) reads the current and cell voltage just prior to removal of load and then measures the recovered cell voltage. The resultant resistance is simply $R_{cell} = \Delta V/I$. Present day A/D converters can effectively measure the DC values while totally ignoring any AC signals flowing through the battery at the same time. Thus, this type of instrument is capable of operating on-line, even in high noise environments.



$$R_{internal} = \frac{\Delta V}{I} = 375 \text{ Microhms}$$

Typical Load Test Response of a 340Ah Plante Cell
Figure 2

HOW INTERNAL CELL RESISTANCE RELATES TO CELL CAPACITY

The capacity of a battery is a measure of how much energy it can store. The amount of energy it can store is a function of active material and acid available.

The amount of energy a battery can deliver to a given load is a function of how fast the energy is withdrawn and to what end voltage the battery is discharged. A typical substation battery is rated 200 Ah and when in good condition can deliver the full 200 Ah if discharged at the eight hour rate to an end voltage of 1.75 volts per cell (25 amps constant current for eight hours). That same battery if discharged at 100 amps to a 1.75 volts per cell end voltage will only last one hour for an effective capacity of 100 Ah.

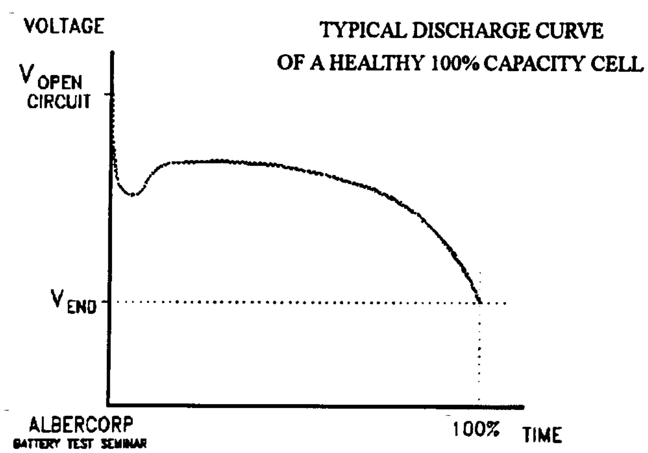


Figure 3

The typical discharge curve of a battery is shown in Figure 3 above. Note that there is an instantaneous voltage drop due to the internal resistance of the battery followed by an exponential voltage decay and subsequent recovery known as the 'coup de fouet' phenomena before the voltage stabilizes. Once the voltage stabilizes, it is sustained by the electrochemical reaction which as mentioned above is fueled by the available active material and acid.

Figure 4 shows the same battery, tested at the same rate, but with a higher internal metallic resistance path (assume a bad lead burn between strap and grids or bad internal connection between two adjacent cells in a six volt module). This figure clearly shows the loss of capacity due to a high internal metallic resistance. The higher the discharge current the higher the internal voltage drop and the lower the capacity.

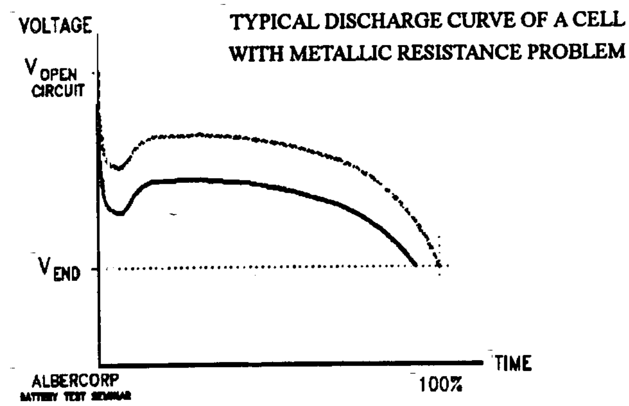


Figure 4

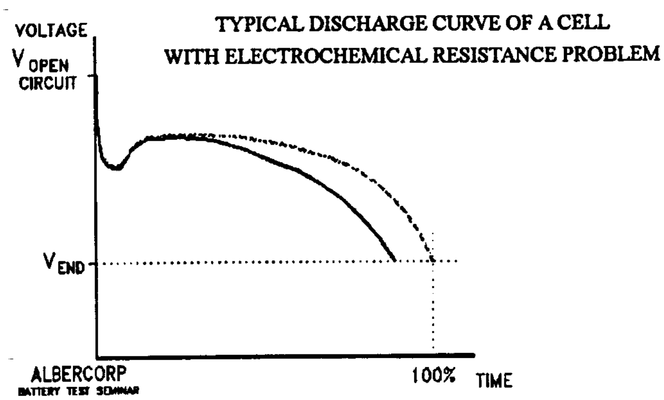


Figure 5

Figure 5 shows the same battery as Figure 3, but with a problem in the electrochemical path (paste, electrolyte or separator problems). This figure also shows a loss of capacity, since the fuel supply has been affected. Note however, that there is no initial voltage depression due to this problem.

What does all this mean ?

It means that capacity is affected by internal resistance and that there is some correlation between the two. However, there is not a linear relationship between capacity and resistance, impedance, conductance or whatever anyone wants to call it.

The impact on capacity differs for a metallic resistance problem and that of a electrochemical resistance problem. The electrochemical part of the resistance path appears to represents a small part of the total cell resistance. For that reason, it takes a major change in this part of the path before it has an impact on the overall resistance.

To prove this theory, Albercorp conducted the following experiment on two large flooded cells, the experiment was performed twice on one of the cells with the same result each time:

The cells were first equalized for a minimum of four days; then floated for a minimum of 24 hours; then left on open circuit for 3 to 7 days and then discharged in 2 to 4% increments at a very low discharge rate. Following each of the above events an internal resistance reading was taken and the results are tabulated below (Note: Data points shown in 4% increments):

STATE OF CHARGE (% Energy removed)	RES. (uohms) CELL # 7	RES. (uohms) CELL # 9
0 open	110	111
4 "	111	111
8 "	112	112
12 "	112	112
16 "	112	113
20 "	113	113
24 "	113	113
28 "	113	113
32 "	113	113
36 "	113	120
40 "	114	128

Table 1

The deliberate discharge of energy from the cells only influenced the paste and electrolyte resistance. The fact that the overall resistance did not change appreciably with up to 40% of the cells energy removed, clearly demonstrates that there is not a linear relationship between a cell's capacity and it's internal resistance. It also proves that the paste/electrolyte resistance is a small percentage of the total.

To illustrate the point that a metallic resistance increase influences the capacity differently than the electrochemical resistance the following example is presented below:

- Assume that in cell 9 above, that the same 18 microhm resistance which caused a 40% change in capacity was introduced in the metallic path instead.

- This resistance increase, causes an additional voltage drop of 10 millivolts in the cells terminal voltage if the cell is subjected to a three hour discharge to an end voltage of 1.75 volts (580 amps x .000018 ohms).

- The actual run-time of the three hour cell capacity test would be shortened by less than 5 minutes. This means that capacity is reduced by less than 3 percent.

- If the capacity test was conducted at the eight hour rate the 18 microhm increase would influence the capacity by less than 1%.

Following the 40% low rate test, the two cells were single cell capacity tested at the three hour rate (580 amps) to an end voltage of 1.75v. Cell # 7 lasted 1 hour and 58 minutes, which equates to 66% capacity. Cell # 9 lasted 1 hour and 24 minutes for a capacity of 47%. During the three hour rate test, the test was halted twice for less than two minutes and the cell resistances were measured.

Figure 6 shows the increase in cell resistance as the total cell energy was removed by the combination of the two different tests mentioned above. (Note: Resistance is plotted as number of microhms increase.)

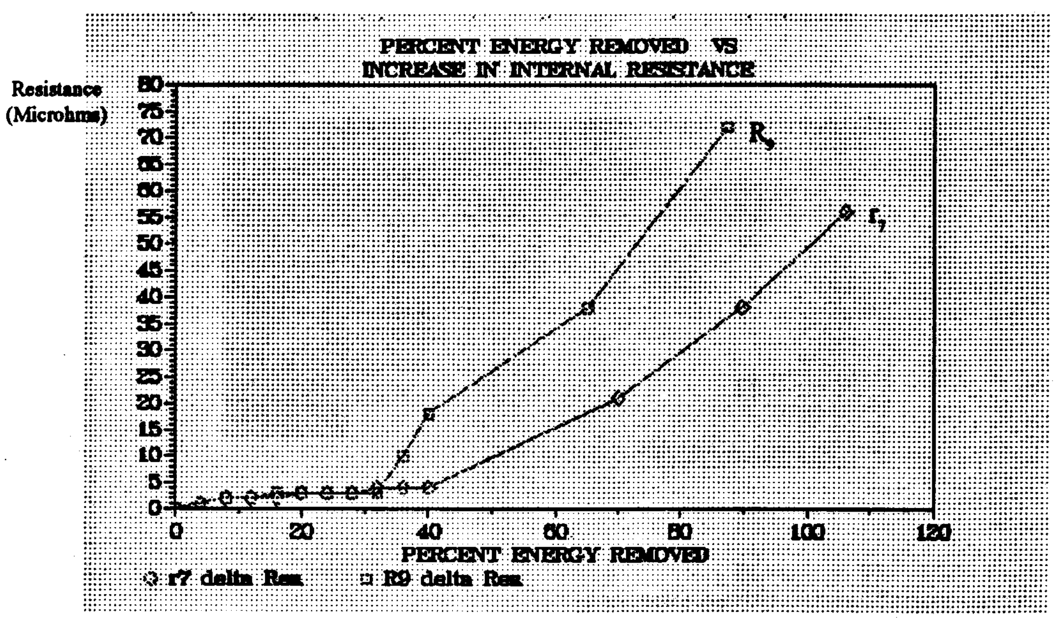


Figure 6

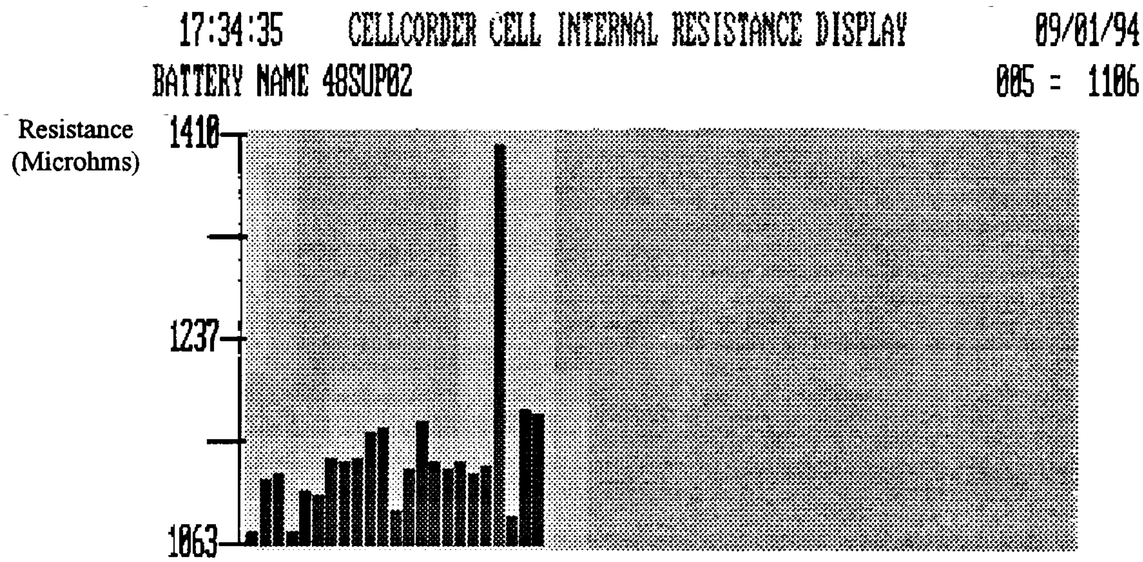
Temperature Testing

Following the state of charge versus resistance test, the two cells were recharged and then subjected to a temperature test. The test consisted of heating the batteries to a temperature of 106°F and then letting them cool down to ambient 78°F temperature. Resistance readings were then taken at 106°F, 96°F, 85°F and 78°F.

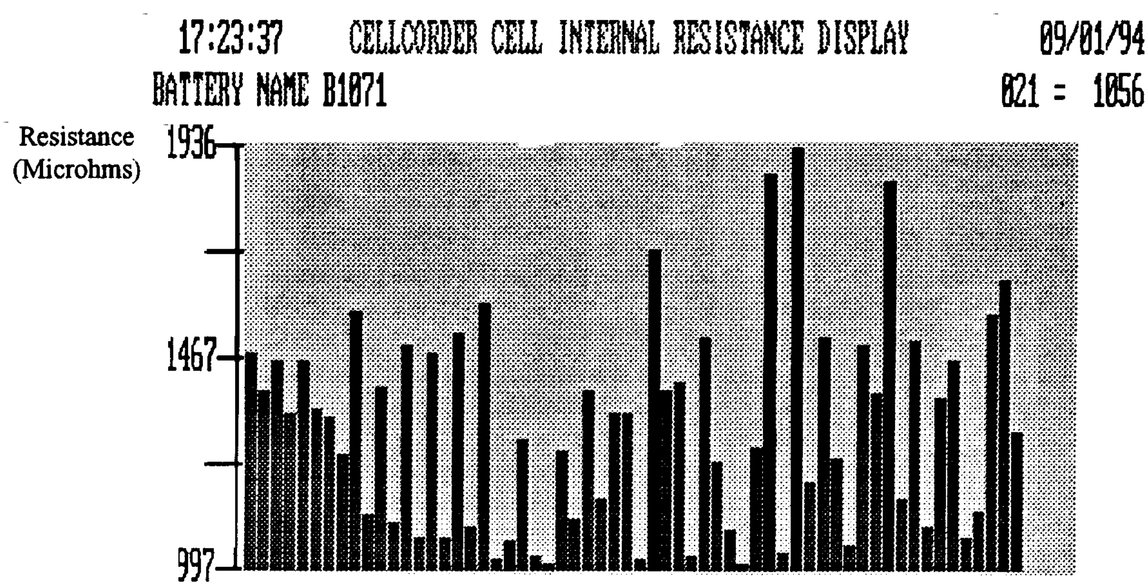
The result showed no change in resistance over the temperature range, the resistance remained a constant 109 microhms for both cells. This result confirms the short circuit test that Albercorp performed for a group of nuclear power plants a few years ago. Short circuit testing was performed on several cells at both 77°F and 102°F without any traceable difference in the current.

Comparison of Flooded & VRLA Cells

Field test results of both Flooded and VRLA cells seem to track very closely with the performance history of these cells. The internal resistance of flooded cells is quite uniform throughout a given string, even for strings that are showing signs of aging. VRLA cell resistances, on the other hand are uniform only for brand new healthy cells. After two or three years of service these cells show a significant variation from cell to cell. Figures 7 & 8 show typical readings.



23 Cell Flooded Substation Battery - Installed 1987
Figure 7



60 Cell VRLA Substation Battery - Installed 1990
Figure 8

The flooded string has one questionable cell, but the readings of the remaining cells are very closely matched (Low Cell = 1073, High Cell = 1174). A follow-up performance test, verified that cell 20 in the flooded string only had 67% capacity while all other cells were between 100 and 102 percent.

Note the wide variation in readings for the VRLA string, this battery as expected did not pass a capacity test and the entire string has been recommended for replacement. The common failure modes of today's VRLA cells are not the same as the flooded cells. Most VRLA cell last six years or less and most of these premature failures are attributed to the following:

- Drying out (Loss of fuel supply)
- Sulphation (Loss of fuel supply)
- Corrosion of negative strap assembly (metallic resistance increase)

The above mentioned failures do not occur in all cells and do not occur at the same rate in all cells. Therefore a big variation in internal resistance. Well maintained flooded batteries, on the other hand, normally fail from positive plate corrosion and shedding of active material. This is a gradual decay that is fairly uniform throughout a cell group.

Many other field tests, have confirmed that cells which have a resistance of 25% or more above the known good baseline value for that type of cell, will typically fail a capacity test. A cell resistance that is 100% or greater than baseline will normally fail in minutes.

So the answer to the question ***"How does a cell's resistance compare to its capacity"*** is:

As cell resistance increases, capacity decreases. The relationship is not linear, it depends on whether the resistance problem is electrochemical or metallic in nature. For metallic resistance problems it also depends on how high the discharge rate is. For example, a 1 milliohm increase does not affect capacity if the discharge current is 10 amps, but it definitely has an impact if the discharge current is 100 amps.

WHAT INTERNAL PROBLEMS CAN BE DETECTED

All metallic resistance problems can be detected, as a matter of fact they show up dramatically as seen below.

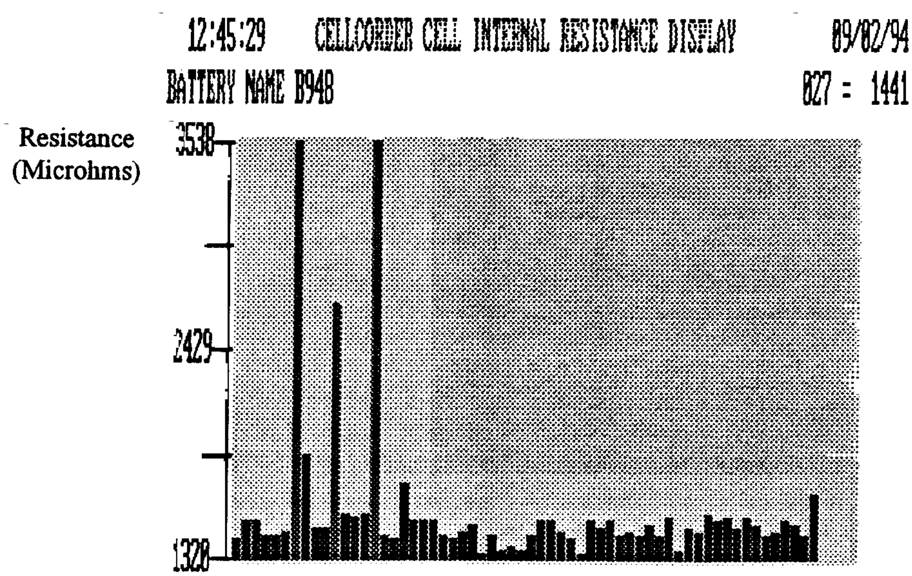


Figure 9

This type of problem can stem from manufacturing problems or from corrosion and plate growth. After 12 to 15 years of service, flooded batteries experience significant plate growth. This causes the paste to break away from the grid structure leading to high contact resistance problems between the paste and the grid. At high current rates metallic resistance problems become very significant and could even lead to an explosion.

Electrochemical resistance problems can be detected if severe enough. However by the time this problem shows up the cell is already below 80% of rated capacity. The only good news about this type of problem is, that the battery will not fail instantaneously nor does it represent an explosion hazard. It will just not be able to support the DC system for the rated period of time.

SUMMARY

Resistance of the cell is what is important, not the Impedance.

- A high test current is important in order to get decent measurement resolution.

Only the DC load test approach can be used on-line, even in high noise environments.

- There is a definite relationship between a cell's resistance and its capacity, but it is not linear and cannot be used to accurately predict capacity or remaining life.

The most dangerous and troublesome resistance problems (metallic resistance problems) are the easiest to identify.

- State of charge and temperature have negligible effects on overall cell resistance.
- To perform any meaningful analysis on cell readings, it is necessary to know the baseline value of known good cells. This data originates from capacity testing.

CONCLUSIONS

- Internal cell resistance measurements are very valuable in determining whether a battery string is going to perform its intended mission. However these measurements should be used as a supplement to capacity testing. The new IEEE std 1188 "Maintenance Practices for VRLA batteries" agrees with this position and calls for quarterly measurements. If measurements indicate a problem then capacity testing is recommended.
- A battery discharge test completely simulates the operating environment and therefore conclusively proves if the battery can perform during an emergency.
- Resistance measurements will probably detect 80% or more of all cell problems. The results of these tests will help set the priority for capacity testing and as the user becomes more familiar with his batteries, may help him extend his capacity test intervals.

Today's modern instruments with data storage capability will reduce maintenance man-hours and provide meaningful test reports complete with data analysis.