INTERNAL OHMIC MEASUREMENTS AND THEIR RELATIONSHIP TO BATTERY CAPACITY – EPRI'S ONGOING TECHNOLOGY EVALUATION

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INTRODUCTION

Internal ohmic measurements are used to determine the *health* of a battery by monitoring the internal resistance of its individual cells. Resistance, impedance, and conductance test equipment all measure some form of a cell's internal resistance. The term *internal ohmic measurement* is a generic term referring to a measurement of a battery cell's internal resistance, typically using any one of three available techniques — conductance, impedance, or resistance.

As a battery cell ages and loses capacity, its vital internal components (plates, grids, and connection straps) undergo unavoidable degradation. This natural degradation causes an increase in the resistance of a cell's internal conduction path. Valve-regulated lead acid (VRLA) batteries have other internal effects that also can cause loss of capacity and an associated increase in resistance. Internal ohmic measurements are intended to measure this change in resistance. A measured increase in resistance or impedance (or decrease in conductance) indicates likely degradation and a corresponding loss of capacity.

A number of factors can affect the internal resistance and capacity of a cell simultaneously. However, not all factors affect a cell's capacity to the same degree as they affect internal resistance, or vice-versa. Fortunately, there is a general correlation in which most factors that increase internal resistance do tend to decrease capacity. Table 1 shows the effect of various factors on cell internal resistance and cell capacity.

Table 1 – Factors Affecting a Cell's Internal Resistance

Factor	Internal Resistance	Effect on Capacity	Comments
Grid corrosion	Increase	Decrease	Unavoidable natural aging process.
Grid swelling and expansion	Increase	Decrease	Includes loss of contact between active material and grid.
Loss of active material	Increase	Decrease	Active material sheds from plates, forming sediment. Too much sediment can lead to internal shorts.
Discharge	Increase	Decrease	Either self-discharge or discharge into a load.
Sulfation	Increase	Decrease	Attributable to undercharging.
Internal short circuits	Possible decrease followed by an increase	Decrease	Internal short circuits can cause resistance to decrease, but the subsequent low voltage, self discharge, and sulfation will lead to a higher resistance.
Temperature decrease	Increase	Decrease	Low temperature retards the cell chemical reaction, slows the aging process, and limits available capacity.
Temperature increase	Decrease	Increase	High temperatures accelerates the cell chemical reaction, shortens the cell life, and increases the available capacity.
Rated cell capacity	Decrease	Increase	Resistance tends to decrease as cell size increases.
Dryout	Increase	Decrease	VRLA cell failure mode.
Negative plate discharge	Increase	Decrease	VRLA cell failure mode.
Negative strap corrosion	Increase	Decrease	VRLA cell failure mode, corrected in newer designs.
Loss of compression	Increase	Decrease	VRLA cell failure mode in absorbed glass mat cells.

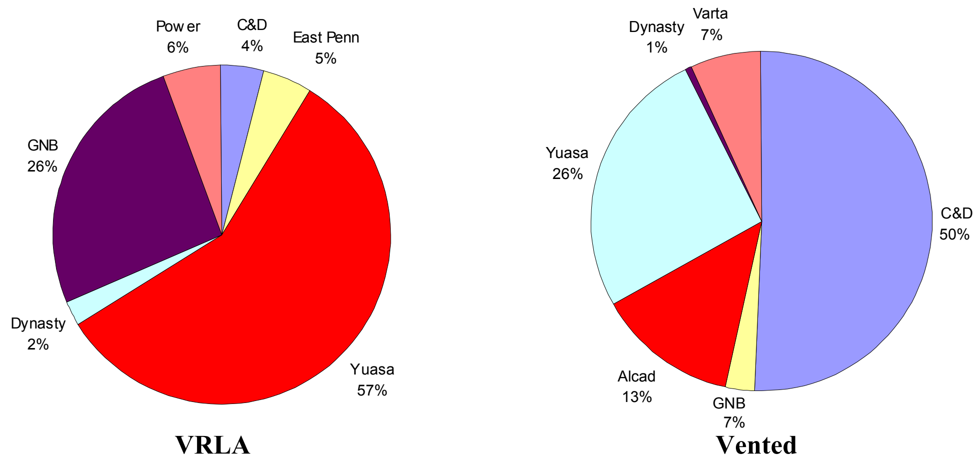
To summarize, an increase in internal resistance is expected to correlate with a decrease in a cell's capacity in most cases. Each type of internal ohmic test equipment will respond to an internal resistance increase as follows:

- Conductance tester — decrease
- Impedance tester — increase
- Resistance tester — increase

PROJECT DESCRIPTION

The Electric Power Research Institute (EPRI) has sponsored a project to evaluate the relationship between internal ohmic measurements and battery capacity. The project started in 2000 and will complete by the end of 2002. Data on over 24,000 cells have been acquired to date and data for over 40,000 cells is expected by the end of the project. Most batteries in the program are used in electric utility applications: generating plants, substations, and communication centers. Figure 1 shows the battery manufacturers represented in the battery data.

Figure 1 – Proportion of Cell Types by Manufacturer



This project is evaluating the viability of using internal ohmic measurements as an indicator of cell and battery capacity. Internal ohmic measurements were taken as part of capacity tests on stationary batteries. The measurements were then compared to the cell capacity to determine the relationship between capacity and internal ohmic measurements. The project scope was developed to validate the following research goal:

> *Properly recorded and evaluated internal ohmic measurements can identify low capacity cells with a high degree of confidence.*

Based on past research, this goal was considered achievable and can establish a successful basis for the application of internal ohmic measurements. This paper provides in-progress results of this project.

TEST EQUIPMENT

The following test equipment was used during this project to measure the internal resistance of stationary battery cells:

- Albércorp Cellcorder—resistance
- AVO Miniature Battery Impedance Test Equipment (MBITE) and Enhanced Battery Impedance Test Equipment (EBITE)—impedance
- Midtronics Celltron Plus and Micro Celltron Conductance Tester—conductance

All instrument types used during this project provided equivalent results. A correlation was always observed between the instruments, although the level of correlation varied with battery type. The test results support a conclusion that any of the three parameters — conductance, impedance, or resistance — can be monitored with equivalent effectiveness.

PROJECT RESULTS – VRLA CELLS

Internal ohmic measurements were obtained on over 6,000 VRLA cells. In most cases, capacity data was also acquired so that a comparison could be made between internal ohmic measurements and cell capacity. Most evaluated batteries were installed in electric utility generating stations, substations, communications facilities, or backup power facilities. The evaluated batteries represent a good cross-section of the battery types installed at utilities throughout the United States.

Correlation to Capacity When a VRLA Battery Has Bad Cells

Internal ohmic measurements were normally taken before a battery capacity test. After the battery capacity test was completed, the capacity of each cell was calculated based on its end voltage upon completion of the capacity test. Then, internal ohmic measurements were compared to the individual cell capacities to determine the trend in performance. Internal ohmic measurements readily identify low capacity cells in a battery string. Figures 2 through 4 show the test results of a battery in which most cells have low capacity. As can be seen with each type of internal ohmic measurement, a clear trend with respect to capacity can be seen. This type of behavior was commonly observed when a battery had a combination of good and bad cells.

Figure 2 – Correlation of Conductance to Cell Capacity – Most Cells With Low Capacity

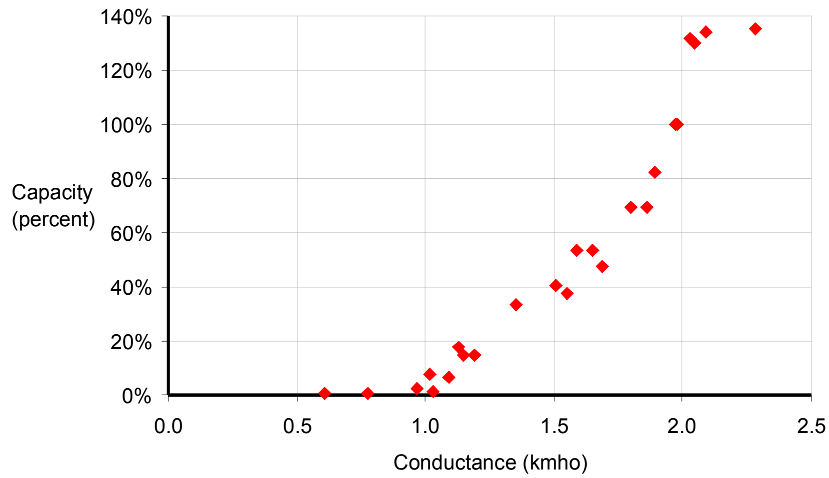


Figure 3 – Correlation of Impedance to Cell Capacity – Most Cells With Low Capacity

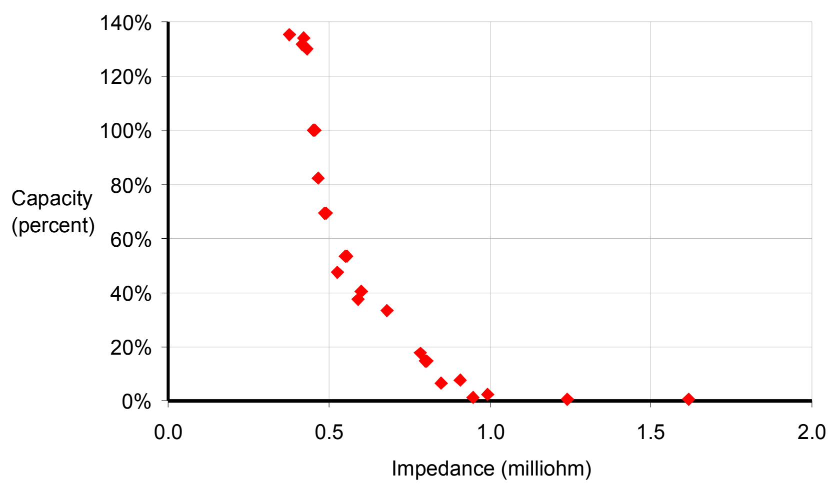
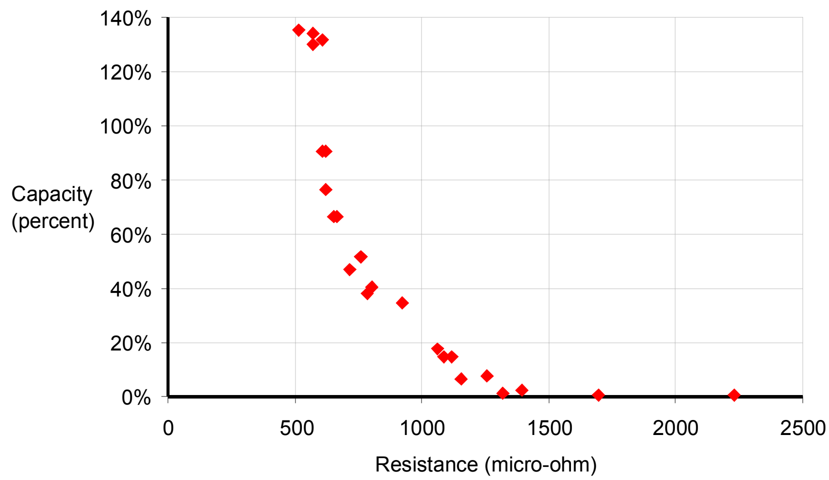


Figure 4 – Correlation of Resistance to Cell Capacity – Most Cells With Low Capacity



Figures 5 and 6 show the test results of different VRLA batteries with decreased capacity. In most cases, the cells had less than 80 percent capacity. Even so, a clear trend with respect to capacity can be observed.

Figure 5 – Correlation of Impedance to Cell Capacity – Low Capacity But Not Dead

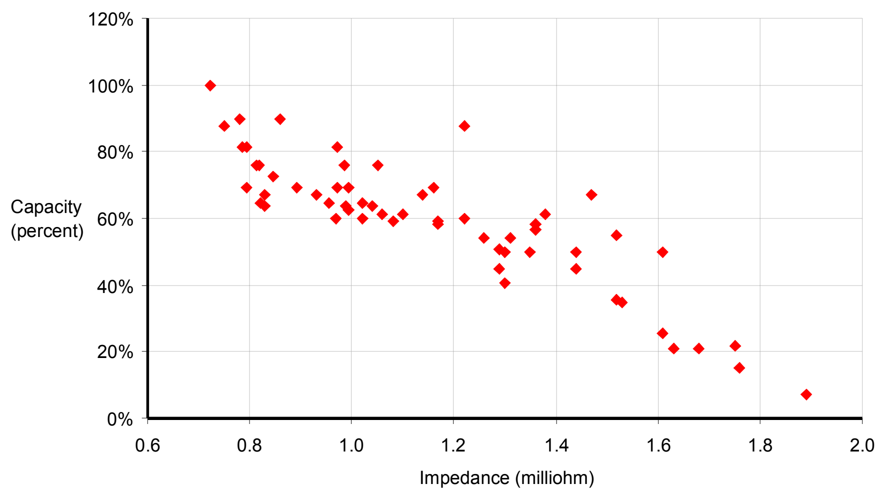
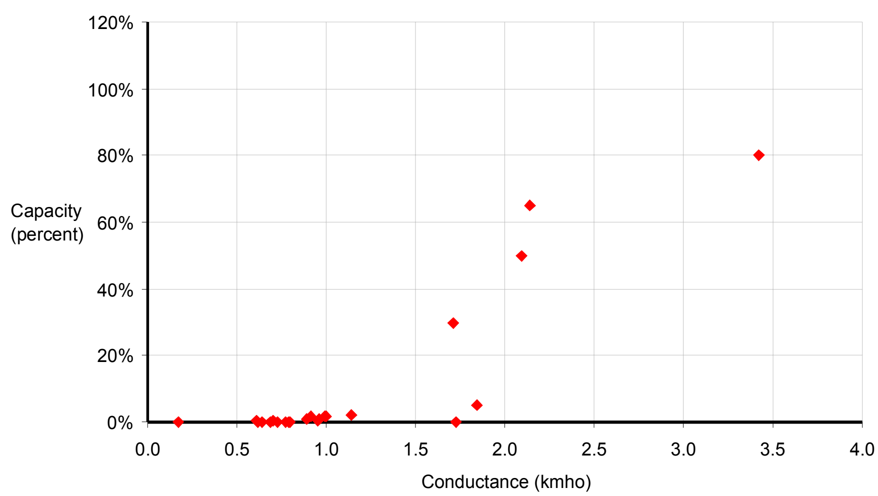


Figure 6 – Correlation of Conductance to Cell Capacity – Most Cells Dead



Correlation to Capacity When a VRLA Battery Has Only a Few Bad Cells

Many VRLA batteries have an overall acceptable capacity, but might have a few low capacity cells. In these cases, an obvious relationship between internal ohmic measurements and capacity was usually observed. Figures 7 and 8 show typical examples.

Figure 7 – Correlation of Impedance to Cell Capacity – Most Cells Above 80 Percent Capacity

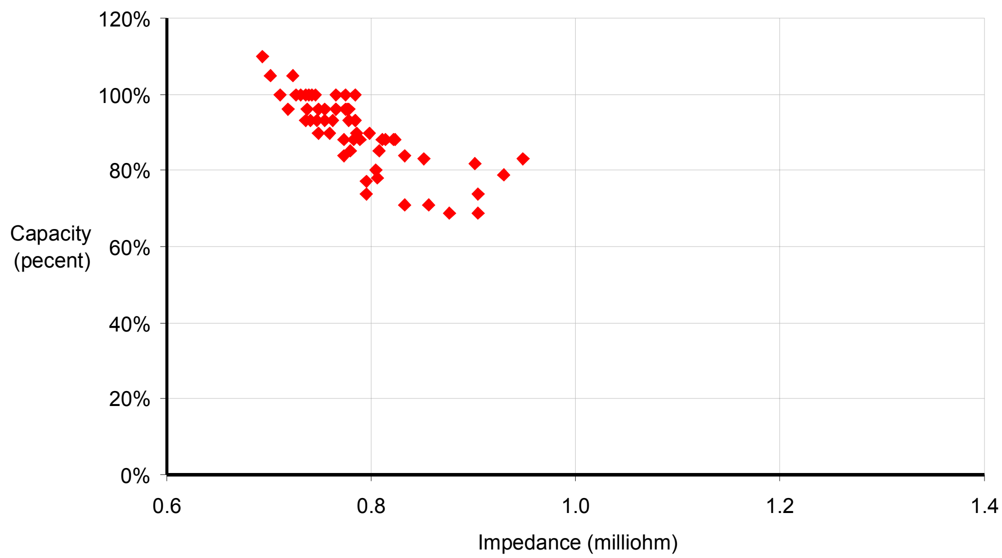
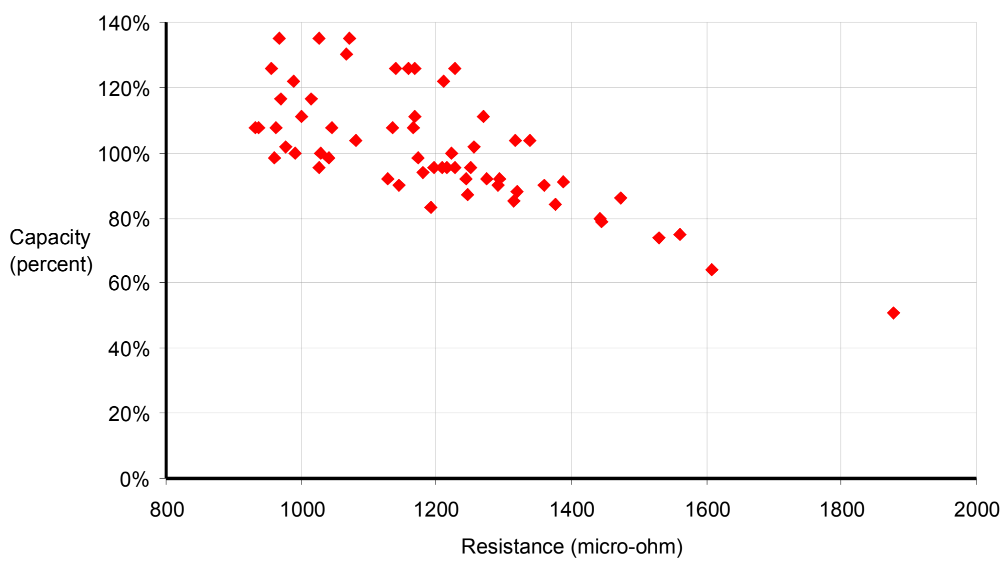


Figure 8 – Correlation of Resistance to Cell Capacity – Many Cells Above 100 Percent Capacity



VRLA Cell Capacity as a Function of the Nominal Internal Ohmic Value

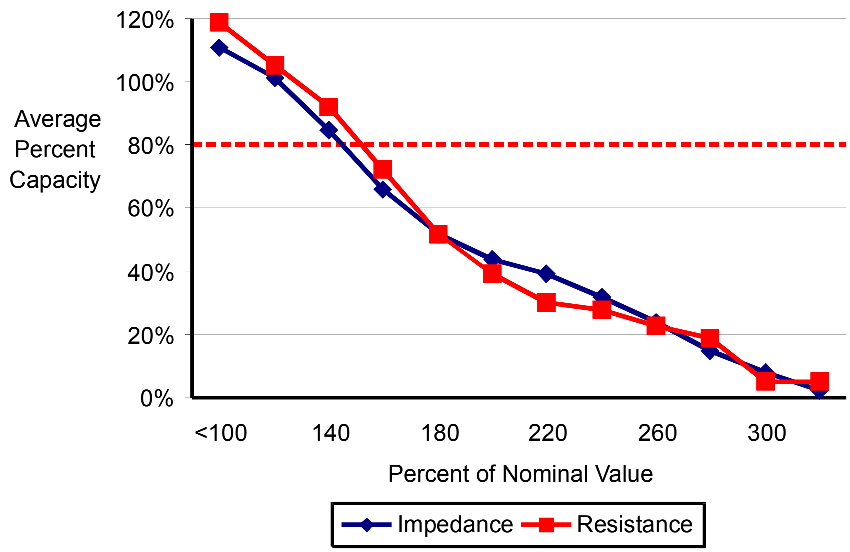
VRLA batteries evaluated during this project tended to have a wider range of capacity on a per cell basis than did vented cells, and many VRLA batteries had some cells with low capacity. Table 2 shows an evaluation of the average cell capacity as a function of internal ohmic value. For each cell, the measured internal ohmic value was converted to a percent of nominal value based on the expected internal ohmic value when the cell was new. After the discharge test, the capacity of each cell was calculated based on its end voltage compared to the expected end voltage for the discharge rate. As can be seen, capacity clearly decreased with increasing impedance, increasing resistance, or decreasing conductance.

Table 2 – Percent Cell Capacity as a Function of the Nominal Internal Ohmic Value

Percent of Nominal Conductance	Average Percent Capacity	Percent of Nominal Impedance	Average Percent Capacity	Percent of Nominal Resistance	Average Percent Capacity
>100	115	<100	111	<100	119
90 - 100	104	100 - 120	101	100 - 120	105
80 - 90	92	120 - 140	85	120 - 140	92
70 - 80	78	140 - 160	66	140 - 160	72
60 - 70	63	160 - 180	52	160 - 180	52
50 - 60	43	180 - 200	44	180 - 200	39
40 - 50	22	200 - 220	39	200 - 220	30
30 - 40	3	220 - 240	32	220 - 240	28
20 - 30	1	240 - 260	24	240 - 260	23
10 - 20	0.2	260 - 280	15	260 - 280	19
<10	0	280 - 300	8	280 - 300	5
		>300	2	>300	5

The impedance and resistance data provided above in Table 2 has been graphed in Figure 9 to further illustrate the observed loss of capacity as the internal resistance increased. A graph of conductance measurements yields similar results.

Figure 9 – Percent Cell Capacity as a Function of Nominal Impedance or Resistance



Although there is data scatter, the following observations can be made regarding the impedance test results (similar observations can be made for conductance and resistance measurements):

- Most cells had less than 80 percent capacity once impedance increased to 150 percent of the nominal impedance (a 50 percent increase). Only a few cells had an acceptable capacity.
- Most cells had less than 50 percent capacity once impedance increased to 200 percent of the nominal impedance (doubled). No cells had an acceptable capacity (above 80 percent).
- Most cells had less than 25 percent capacity once impedance increased to 250 percent of the nominal impedance (a 150 percent increase). No cells had above 40 percent capacity.
- All cells were effectively dead once impedance increased to 300 percent of the nominal impedance (tripled).

PROJECT RESULTS – VENTED LEAD ACID CELLS

Internal ohmic measurements were obtained on over 16,000 vented lead acid cells. In many cases, capacity data was also acquired so that a comparison could be made between internal ohmic measurements and cell capacity.

Correlation to Capacity When a Vented Lead Acid Battery Has Low Capacity Cells

Virtually all vented lead acid batteries evaluated in this project had an acceptable capacity. But, when low capacity cells were present, internal ohmic measurements were able to identify these cells. Figures 10 and 11 show examples of batteries with some low capacity cells.

Figure 10 – Correlation of Impedance to Capacity – Several Lower Capacity Cells

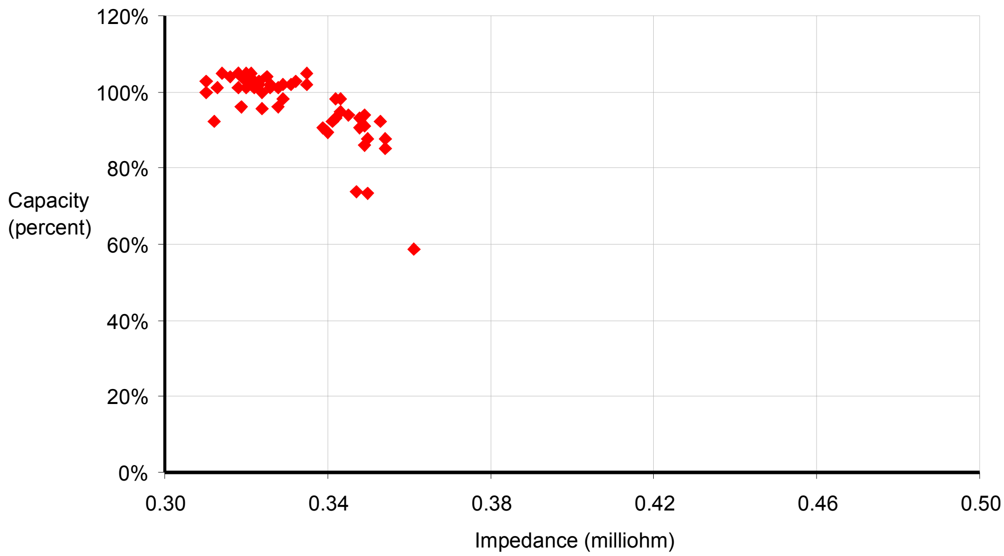


Figure 11 – Correlation of Resistance to Capacity – Several Lower Capacity Cells

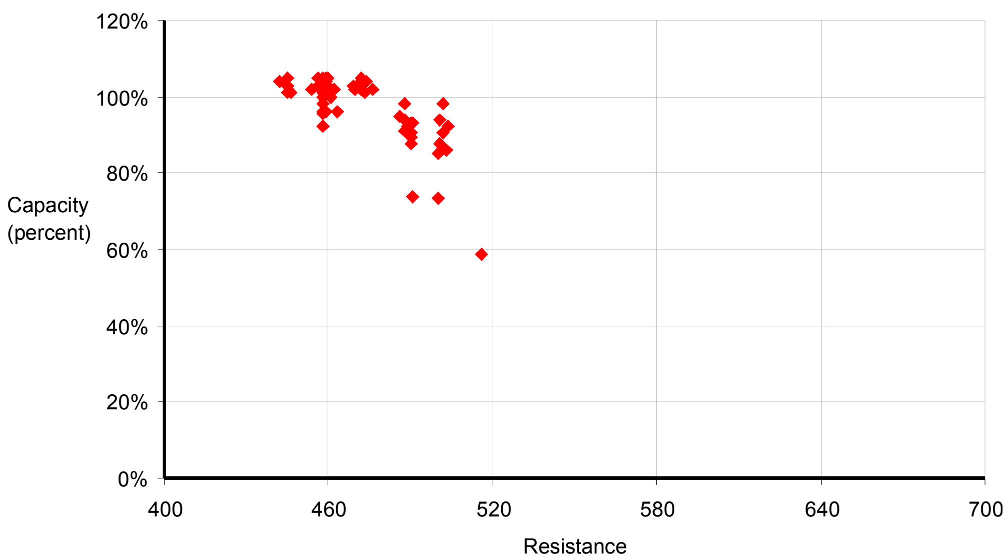


Figure 12 shows the conductance results for 420 cells of a single battery type (same model but different cell sizes). These are all new vented cells installed in several battery strings. As can be seen, many of the cells had low capacity on delivery; a relationship between conductance and capacity is evident.

Figure 12 – Conductance Results for One Cell Model

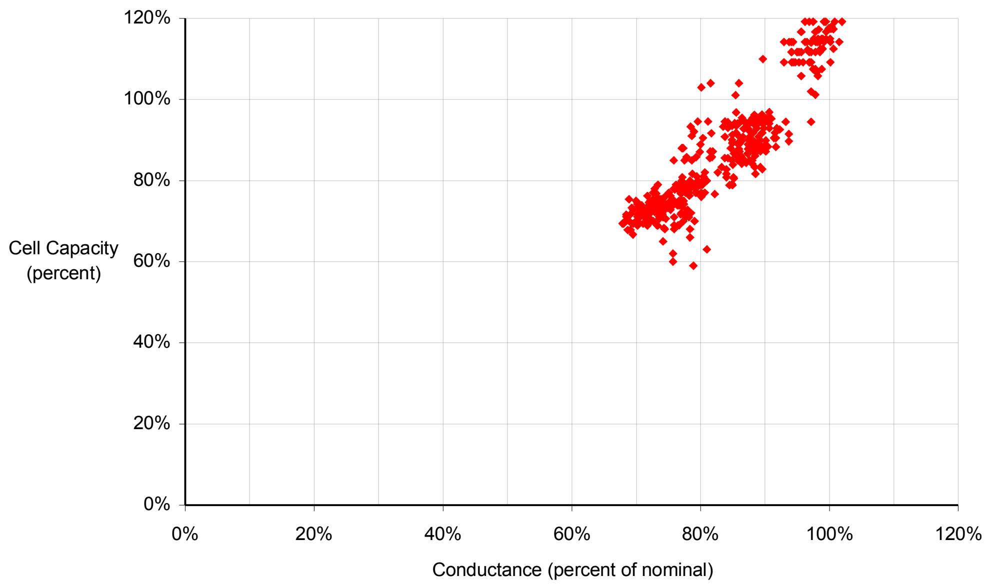
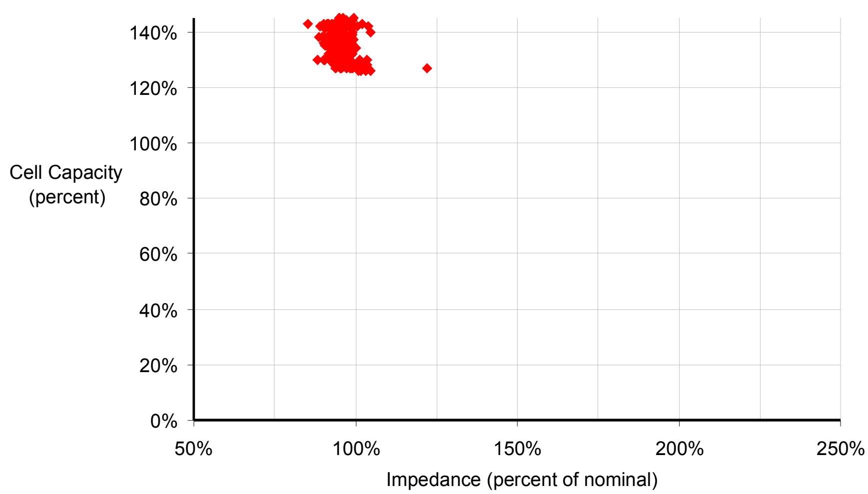


Figure 13 shows the impedance results for 500 cells of a different battery type. A relationship between impedance and capacity is not clearly evident, mainly because all cells have very high capacity with very little data scatter. Most cells were 9 to 13 years old and a small number are new. Notice that the impedance data is within a range of about 15 percent. The consistency of the data is encouraging in that large variations in internal ohmic values are not expected in vented lead acid batteries with such high cell capacities.

Figure 13 – Impedance Results for One Cell Model



EQUIPMENT GUIDELINES

The challenge when taking internal ohmic measurements is how to interpret the results so that low capacity cells can be identified. In many cases, it will be necessary to make a go/no-go decision on the battery based solely on the internal ohmic measurements. A three-step evaluation process is presented as follows:

1. First, understand what internal ohmic value is expected for the type or model of cell to be checked. This expected value is referred to as the *nominal value* and is the typical value of a 100 percent (or better) capacity cell. This nominal value does not have to be precise, but should be representative of the expected value. The nominal value varies widely with cell size (ampere-hours) and design. Battery manufacturers and test equipment suppliers can assist with this information.

2. After all cell measurements have been taken on a battery, compare each measurement to the average internal ohmic value for the battery. If there is a wide variation in the data, compare the measurements to the expected nominal value.
3. Evaluate the variation in the internal ohmic measurements. A battery with a large variation in internal ohmic values likely has bad cells. For example, if the measurements are evaluated by comparing the smallest value to the largest value, a large difference indicates a likely problem. Also, if several cells are identified as bad based on significantly poor internal ohmic values, it is possible that other low-capacity cells exist but do not readily stand out from the data set because the data for the weakest cells masks their presence.

Step 2 above is the basic method of identifying low capacity cells and appears to work well when there are only a few bad cells in an otherwise good battery. Step 1 above provides an additional measure of assurance; a battery with all bad cells can be difficult to evaluate by a simple comparison to the average value of the measurements. Step 3 provides a final check to confirm that the results make sense.

CONCLUDING REMARKS

This project continues to demonstrate that internal ohmic measurements can detect low capacity cells. Internal ohmic measurements are taken as part of capacity tests on stationary batteries and the measurements are then compared to each cell's capacity to determine the relationship between capacity and internal ohmic measurements. Throughout the project, internal ohmic measurements have reliably identified low capacity cells. Furthermore, all evaluated measurement technologies — conductance, impedance, and resistance measurements — were shown to be effective.

Internal ohmic measurements can not tell us everything regarding battery capability or condition. Some points to consider are:

- An increase in internal resistance (as measured by resistance or impedance testers) or a decrease in conductance (as measured by a conductance tester) was correlated to a reduction in cell capacity. But, there is substantial data scatter in the results. The presence of data scatter means that low capacity cells can be identified, but absolute predictions regarding cell capacity are more difficult to make. For example, it is possible to predict that a cell's capacity is probably less than 50 percent, but it is unlikely that a capacity prediction to two decimal places will be accurate. In particular, considerable data scatter was observed in VRLA cells when the capacity was between 70 percent to 100 percent..
- An increase in internal resistance indicates that something inside a cell is changing. However, we often have no way of knowing what particular aging, degradation, or failure mode is at work inside the cell; we only know that something is changing. For example, we can not readily distinguish between dryout or plate corrosion inside a VRLA cell using a single internal ohmic measurement. Although the two degradation mechanisms might have a similar effect on an internal resistance change, they may have a different effect on cell capacity. The practical implication of this observation is that there will likely be some degree of data scatter in any correlation between capacity and internal ohmic measurements. This does not really imply a shortcoming of internal ohmic measurement technology, but it does mean that we will likely be limited to identifying *good* or *bad* cells rather than making claims that a certain internal resistance indicates a *particular* cell capacity.
- The test equipment does not distinguish whether the battery is used in a low-rate or a high-rate application. A given percentage change in resistance will likely have less effect on a long, low-rate discharge compared to a short, high-rate discharge.
- Users are typically concerned with the *battery* capacity. Internal ohmic measurements are taken on individual *cells*. A single cell with low capacity does not necessarily mean that the battery has low capacity. This is a key difference between a battery capacity test and battery health as determined by internal ohmic measurements. A battery capacity test really does determine the battery's capacity. Internal ohmic measurements have the ability to identify degradation in individual cells. Although internal ohmic measurements can identify low capacity cells (which is certainly valuable), the technology does not precisely predict overall battery capacity. If you need an accurate measure of the overall battery capacity, perform a battery capacity test.

An interim report documenting the project results to date was published at the end of 2001. The EPRI project is continuing throughout 2002 and a final report will be published at the conclusion of the project. The final report will provide the following information:

- The interim report will be updated with a summary of all project data (expected to consist of data for over 40,000 cells). A companion CD will be developed with the report that provides all project data, including the available data for nickel cadmium batteries.
- Detailed guidance will be provided regarding the application and interpretation of internal ohmic measurements. Different analysis methods will be described.
- Examples will be included that provide case studies to illustrate application of the guidelines. The examples will describe how to interpret internal ohmic measurements by using actual project data.
- A limitations section will be included explaining limitations of the technology and describing battery configurations that exhibited unique problems relating to obtaining reliable internal ohmic measurements. Test equipment limitations will also be addressed.

REFERENCES

1. EPRI TR-1006522, *Stationary Battery Monitoring by Internal Ohmic Measurements*, Interim Report, November 2001.