Stationary Battery Monitoring by Internal Ohmic Measurements

Technical Report

Stationary Battery Monitoring by Internal Ohmic Measurements

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Interim Report, December 2001

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REPORT SUMMARY

Battery internal ohmic measurements offer a viable method of performance monitoring for stationary batteries. These measurements have demonstrated the ability to identify degraded cells and to baseline the general health of a battery. This interim report presents the in-progress results of a research effort to correlate battery capacity to internal ohmic measurements.

Background

Various routine inspections and checks offer a general indication of a battery's health and its state of charge. However, none of these routine checks provide definitive information about a battery's actual capacity. Consequently, capacity discharge tests have been, and remain, the traditional means to confirm battery capacity and therefore satisfactory performance. Although technically prudent, the time and expense associated with capacity discharge testing is increasingly at odds with pressures to reduce operating budgets. These pressures, in combination with new battery types that cannot be inspected by conventional means, encouraged development efforts for more cost-effective battery test techniques. Resulting advancements in battery monitoring equipment have produced new methods for evaluating battery health and reliability. Internal ohmic measurements, which are relatively simple and inexpensive to obtain, represent a new and cost-effective means of assessing battery capability.

Objectives

- To determine the extent to which internal ohmic measurements can identify low capacity or degraded cells
- To evaluate the correlation between battery capacity and internal ohmic measurements
- To provide guidelines to assist users with the implementation of internal ohmic measurements in a battery maintenance program

Approach

Researchers developed a test program involving a substantial quantity and wide variety of stationary batteries. The project team and project contributors recorded internal ohmic measurements for individual cells prior to conducting a capacity discharge test of each battery. The discharge test results were evaluated with respect to the internal ohmic measurements to determine the degree of correlation between capacity and internal ohmic measurements. As part of acquiring the test data, guidelines have been developed to assist users with the implementation of this technology and will be presented in the final report.

Results

Internal ohmic measurements proved an effective indicator of the general health of a stationary battery and its individual cells. These measurements reliably predicted degraded battery cells. With few exceptions, cells with a poor internal ohmic measurement value had low capacity when checked by a discharge capacity test. Furthermore, a high degree of correlation was demonstrated between the three types of internal ohmic measurements (conductance, impedance, and resistance); all three measurement-technologies were effective. The results of this project readily demonstrate that internal ohmic measurements can be a valuable part of a battery maintenance program. This interim report provides a current summary of the results. The final report will provide detailed guidelines regarding the application of internal ohmic technology for stationary batteries.

EPRI Perspective

Project results readily demonstrate that low capacity cells can be identified by internal ohmic measurements. By using this technology, utilities can implement more cost-effective battery test methods and gain a more reliable stationary battery installation. Prior EPRI reports provide additional information regarding stationary batteries and the application of internal ohmic measurements. EPRI TR-106826, *Battery Performance Monitoring by Internal Ohmic Measurements, Emergency Lighting Unit Batteries*, applies this technology to smaller emergency lighting batteries. EPRI TR-108826, *Battery Performance Monitoring by Internal Ohmic Measurements, Application Guidelines for Batteries*, provides the results of a smaller-scope evaluation of internal ohmic measurements for stationary batteries. EPRI TR-100248-R1, *Stationary Battery Guide—Design, Application, and Maintenance*, provides additional information regarding stationary batteries.

Keywords

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PROJECT OVERVIEW AND SUMMARY

1.1 Background Information

All power plants, substations, and other important utility facilities have battery-backed systems to operate critical equipment when a loss of ac power occurs. Critical equipment typically includes that equipment required to safely shut down a power plant, to ensure personnel safety, or to protect property. The battery functions as the heart of a dc system and often is the only source of uninterruptible electrical energy upon a loss of normal ac power. A battery might sit for years without ever having to provide emergency power; however, when called to use, it is expected to meet the system demands immediately and for the required duration.

The various routine inspections and checks typically performed on a battery provide a general indication of a battery's health and its state of charge; however, they do not alone provide definitive information regarding its available capacity. In particular, specific gravity and voltage measurements are good indicators of a cell's state of charge, but do not confirm adequate capacity. Other factors affecting capacity, such as aging or degradation effects, are not detectable from voltage and specific gravity measurements alone. An additional consideration for valve-regulated lead acid (VRLA) batteries is that the cell design precludes a visual inspection of the internal components. A detailed internal visual inspection has long been accepted as an important inspection for detecting age-related degradation and other abnormal cell conditions in stationary batteries. Yet, this inspection can not be accomplished for VRLA cells.

A capacity test is the industry-accepted method for determining actual battery capacity. Battery capacity tests require expensive test equipment, are time consuming to perform, and often can be conducted only under special system or plant conditions. Nonetheless, because of the critical role most batteries play in assuring backup power for system readiness and reliability, capacity tests are recommended by industry standards at regular intervals to ensure each battery is capable of performing as designed.

As a cell ages and loses capacity, its internal components (plates, grids, and connection straps) undergo unavoidable degradation. This natural degradation causes an increase in the resistance of the cell's internal conduction path. Test techniques have been developed to monitor this change in resistance. Several internal ohmic measurement techniques are currently available, including resistance, impedance, and conductance testing. A measured increase in resistance or impedance (or decrease in conductance) indicates some form of degradation in the cell's internal conduction path.

Battery internal ohmic measurements represent a fairly new battery maintenance technology; however, the technology has already gained acceptance in other parts of the world and in other industries, including the automotive and telecommunications industries. The Institute of Electrical and Electronics Engineers (IEEE) has issued a series of recommended practices for VRLA batteries. These guidance documents endorse the use of internal ohmic measurements for VRLA batteries. IEEE standards for vented lead-acid cells endorse internal ohmic measurements as an optional maintenance practice.

Despite the current use of internal ohmic measurements, the stationary battery industry does not completely agree on the level of correlation between internal ohmic measurements and cell capacity. Although many papers have been published on the subject, there is still a need for practical guidance regarding the application and interpretation of the technology.

Internal ohmic measurements are relatively easy and inexpensive to perform, particularly when compared to capacity testing. Furthermore, the measurements can be taken on-line without affecting the operational status of the battery. However, initial experience with this new test technology has yielded mixed results, indicating the need for additional research and testing to:

- Understand more fully the relationship between internal ohmic measurements and cell capacity
- Refine field test techniques to optimize measurement accuracy and repeatability.
- Assess the extent to which internal ohmic measurements can replace or reduce the frequency of more expensive capacity discharge tests

EPRI initiated this project to investigate internal ohmic measurements and resolve the uncertainty surrounding the use of this new test technology

1.2 Project Scope and Research Statement

This project assessed 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 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 would establish a successful basis for internal ohmic measurements. Given the above goal, the following associated conclusions are necessary:

- A battery without low capacity cells has acceptable capacity
- The *high degree of confidence* can be statistically established

- A method of evaluating internal ohmic measurements can be defined that routinely identifies the low capacity cells

The hypothesis in this case is that internal ohmic measurements can be used as a relative indicator of capacity. Also, the following statement influenced the project approach:

> A theory is a good theory if it satisfies two requirements. It must accurately describe a large class of observations on the basis of a model that contains only a few arbitrary measurements, and it must make definitive predictions about the results of future observations. – Stephen Hawking, A Brief History of Time

The stated research goal is important to consider, because it potentially excludes certain claims. Potential limitations of this research approach include:

- Successful demonstration of the stated goal does not simultaneously require demonstration of a high degree of correlation between a cell's capacity and its internal ohmic measurement throughout the entire range of possible capacity (0% through > 100%). But, it does require some degree of demonstrated correlation for low capacities, such as < 70%. In other words, data scatter is acceptable for cells with high capacity, but is less likely to be acceptable for low capacity cells.
- Battery capacity cannot easily be predicted based on cell internal ohmic measurements. The measurements are taken on individual cells rather than on the entire battery. The reasonable assumption here is that the battery capacity is acceptable if all cells are considered acceptable.
- The cause of a cell's low capacity is not established by this research project. Although an internal ohmic measurement might indicate a low capacity cell, the measurement does not usually offer any clues regarding the cause of the higher-than-normal resistance. The following statement applies here:

  > To be accepted as a paradigm, a theory must seem better than its competitors, but it need not, and in fact never does, explain all the facts with which it can be confronted. – Thomas S. Kuhn, The Structure of Scientific Revolutions

- Certain cell types or sizes might not support the stated goal and could require exclusion from the final methodology. Simply stated, the technology might not work on all cell types or sizes.

As part of the data acquisition and analysis, guidelines were developed to assist users with the implementation of the technology. These guidelines were tested on project data to confirm their ability to identify low capacity cells.

1.3 Project Results

This project successfully demonstrated that internal ohmic measurements can detect low capacity cells. Throughout the project, internal ohmic measurements reliably identified low capacity cells. Furthermore, all evaluated measurement technologies—conductance, impedance, and resistance measurements—were shown to be effective. This report is intended to assist users with the implementation of internal ohmic measurements by providing:

- Test results that show the degree to which a relationship was observed between internal ohmic measurements and cell capacity
- Detailed explanations of what is measured by internal ohmic measurements and how the measurements correlate to the cell aging and degradation processes
- Guidelines for the use of the equipment to ensure the best possible measurement consistency and interpretation of results
- Recommendations for the use of the test equipment as part of an integrated battery maintenance program

1.4 Related Research

In 1996, EPRI sponsored a similar project for evaluating emergency lighting unit batteries using internal ohmic measurements. The results of this project were encouraging and resulted in a recommendation to replace periodic 8-hour discharge tests with internal ohmic measurements for certain battery types commonly used in nuclear power plants. For more information on this project, refer to EPRI TR-106826, *Battery Performance Monitoring by Internal Ohmic Measurements, Emergency Lighting Unit Batteries*.

In 1997, EPRI sponsored a modest evaluation of internal ohmic measurements for stationary batteries and the results were published in EPRI TR-108826, *Battery Performance Monitoring by Internal Ohmic Measurements, Application Guidelines for Stationary Batteries*. The successful research in the 1997 project led to this more detailed review of internal ohmic measurement technology.

2
STATIONARY BATTERY AND INTERNAL OHMIC MEASUREMENTS OVERVIEW

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 cell's internal resistance using any one of the three related methods—resistance, impedance, or conductance.

Section 2 provides a detailed explanation of the cell aging process and describes how internal ohmic measurements can indicate different types of degradation. The cell model is discussed in terms of what is measured by internal ohmic test equipment. The effect of various factors on model parameters and internal ohmic measurements is explained. The discussion applies to vented lead-acid and valve-regulated lead acid (VRLA) batteries unless noted otherwise.

Section 2 discusses the theory of internal ohmic measurements without discussing the available test equipment. Section 3 provides information regarding the test equipment used by this project. If needed, refer to Appendix B.4 for unit conversions.

2.1 Vented Lead-Acid Batteries

The vented batteries evaluated by this project were high quality stationary batteries of the type commonly used in power plant and substation applications. Figure 2-1 shows a typical vented cell.

Figure 2-1
Typical Vented Lead-Acid Cell

Section 2.3 describes the aging and degradation mechanisms applicable to vented lead-acid batteries. The following aging and degradation mechanisms affect internal ohmic measurements:

- Grid corrosion
- Grid swelling and expansion
- Loss of active material
- Sulfation
- Conduction path failures

Other problems are readily detectable by a detailed visual inspection of a vented cell. By adding internal ohmic measurements to the traditional vented lead-acid battery periodic inspections, a better understanding of the expected battery capability can be gained.

2.2 Valve-Regulated Lead Acid Batteries

Valve-regulated lead acid (VRLA) batteries were also evaluated by this project. The evaluated VRLA batteries are commonly used in power plant and substation applications. A typical VRLA cell is shown in Figure 2-2.

Figure 2-2
Typical VRLA Cell Showing Internal Absorbent Glass Mat (AGM) and Plate Structure

Internal ohmic measurements have shown to be well suited for monitoring VRLA batteries. Actually, internal ohmic measurements seem to be one of the only effective means of periodically monitoring VRLA batteries. The following VRLA battery aging and degradation mechanisms affect internal ohmic measurements:

- Grid corrosion
- Grid swelling and expansion
- Loss of active material
- Sulfation
- Conduction path failures
- Dryout
- Loss of compression in absorbed glass mat cells
- Negative plate discharge
- Negative strap corrosion

2.2.1 VRLA Battery Overview

Despite industry problems with reliability and premature failures, the VRLA battery is used in many applications, including substations, and non-safety-related applications in power plants. It is effectively sealed such that the user cannot gain access to the electrolyte. And, the electrolyte is immobilized so that it is not a free liquid as in a vented cell. Electrolyte immobilization provides a cell that will leak little or no electrolyte if damaged. The VRLA battery market has quickly grown to fill the demand for a battery with the following characteristics:

- Immobilized electrolyte to prevent or minimize the potential for electrolyte leakage. This allows users to avoid the imposition of some environmental regulations regarding sulfuric acid spill contingencies in most states. Also, this allows users to install batteries in commercial buildings and other locations in which vented batteries are undesirable because of the large amount of free electrolyte.
- Smaller installation footprints than vented equivalents. By immobilizing the electrolyte, the battery can be installed in different configurations. A typical installation has the VRLA cells oriented on their side rather than upright so that they can be stacked vertically. This allows for less cabinet or floor space for the installation.
- No electrolyte maintenance. Because the cell is sealed and the electrolyte is inaccessible, water cannot be added to a VRLA cell. This feature was referred to as *maintenance-free* in early literature; however, this misleading term is not commonly used today because other types of maintenance are still necessary.
- Higher power density for high-rate discharge UPS applications. Manufacturers have developed new designs and higher electrolyte concentrations to boost the high-rate capability.

VRLA batteries have been called *sealed* batteries because they are completely sealed except for a pressure relief valve that opens as needed to vent excess internal pressure. Also, they have been called *maintenance-free* batteries because periodic water addition is not allowed by the design. However, VRLA batteries are neither truly sealed nor maintenance free. The term *starved electrolyte* has also been used to describe one VRLA cell design, referring to a lack of excess electrolyte. As the term starved electrolyte implies, the capacity of a VRLA cell can be limited by its electrolyte quantity. The term *valve-regulated* has become the standard name for this type of battery.

When they were first introduced, VRLA batteries were intended for “install and forget” truly maintenance-free applications in which battery failure would be an inconvenience, not a catastrophe. Because of some of their desirable design features, VRLA batteries are increasingly used in stationary battery applications to the point that they are now used in some very critical applications. Nuclear plants might have VRLA batteries installed in certain non-safety-related applications such as UPS systems, but VRLA batteries have not been qualified for nuclear plant safety-related use in the United States. Some utilities have used VRLA batteries extensively in substations. USA government agencies, such as the Federal Aviation Administration and the military, use VRLA batteries for critical UPS applications. In addition, the telecommunications industry widely uses VRLA batteries.

All VRLA batteries are sealed in opaque containers. As a result, the following routine inspections and maintenance that would normally be performed on a standard vented cell cannot be performed:

- Electrolyte level checks: An actual electrolyte level does not exist in a VRLA cell; the electrolyte is suspended in microporous mats or a gel surrounding the plates. Access to the electrolyte is not allowed.
- Water addition: Water cannot normally be added to a VRLA cell as a routine maintenance activity. The access port is sealed by a pressure relief valve. Furthermore, the cells are often installed on their side which would complicate water addition even if access was allowed. *Note: Some manufacturers have developed special procedures for water addition, but this is still not a common practice.*
- Visual internal inspection: The opaque container of a VRLA cell does not allow for a check of the sediment space, verification of adequate electrolyte, or color and condition of the plates.

2.2.2 VRLA Battery Aging and Degradation

Industry experience to date indicates that VRLA batteries are more sensitive to their installed environment and operating conditions than are conventional vented lead-acid batteries. VRLA battery technology has come a long way in the last 15 years; however, the technology is still developing and the degradation mechanisms are, even now, not fully understood. What is known so far is that these batteries will fail before vented batteries when exposed to similar service conditions and environments.

The lead-acid battery aging and degradation mechanisms described in Section 2.3 apply to VRLA batteries; however, these batteries usually have a smaller operating window than their vented counterparts, making them more prone to degradation. VRLA batteries are less tolerant of the following conditions:

- High temperature
- Overcharge
- Float-voltage variations
- Discharge

VRLA batteries have exhibited new failure modes rarely seen in vented batteries. The following sections describe some of the failure modes unique to VRLA batteries and explain how these failure modes affect internal resistance. For more information regarding VRLA battery aging, degradation, and failure, refer to EPRI TR-100248R1, *Stationary Battery Guide—Design, Application, and Maintenance*.

2.2.2.1 Dryout

Loss of water from a VRLA cell is irreversible in most designs. As a VRLA cell loses water, it can experience loss of capacity because of dryout. These batteries have been referred to as *starved electrolyte*, meaning that the discharge capacity can be limited by the electrolyte. In this case, any loss of electrolyte can adversely affect capacity. A vented battery is expected to require periodic watering to restore lost water; however, any water loss from a VRLA battery is irreversible because water cannot normally be added to the cell. One study determined that a 10% water loss can correlate to a 20% loss of capacity. Dryout is a recognized failure mode of a VRLA cell.

The recombination process tends to be somewhat self-regulating in that recombination efficiency improves as water is lost. In theory, a VRLA cell would lose water until it reached optimal recombination efficiency, with little water loss thereafter. However, there are other effects that occur during normal and abnormal operation that result in water loss:

- <u>Overcharging</u>: This results in gassing that exceeds the recombination ability of the cell. Thus, gases are vented from the cell through the pressure relief valve and the volume of the electrolyte solution declines over time. Small amounts of gas are vented during normal float operation. Larger quantities of gas are vented during higher charging rates, such as an equalize charge. In addition, battery charger setpoint drift or failure that causes an increased float voltage can cause more frequent gas venting.
- <u>Corrosion Process</u>: The grid corrosion process that occurs during normal aging of a lead-acid battery consumes part of the water in the electrolyte throughout the cell's operational life. Part of the oxygen generated at the positive plate by the recombination process is consumed by the corrosion process. One study showed that this normal aging process alone can consume enough of the electrolyte water to impact capacity.
- <u>High Temperature</u>: The gassing rate increases with temperature. At higher temperatures, some gases are vented rather than recombined inside the cell.
- <u>Failure of the pressure relief valve</u>: A failure of the valve to fully shut causes the cell to operate like a vented cell, that is, it continuously vents. Charge gases are then allowed to escape and the recombination process is ineffective.
- <u>Water vapor diffusion through the container</u>: As the temperature increases, the water vapor diffusion rate through the cell container also increases. The diffusion rate varies with the type and thickness of container materials, operating temperature, and relative humidity around the cell. Most manufacturers have selected container materials that minimize water vapor diffusion.
- <u>Leakage</u>: A cracked cell case or failed terminal post seal is similar to failure of the pressure relief valve; the cell will continuously vent.

As a cell experiences dryout, the internal resistance will increase. Internal ohmic measurements have shown to be capable of detecting dryout in a VRLA cell.

2.2.2.2 Absorbed Glass Mat Compression Effects

VRLA batteries of the absorbed glass mat (AGM) design can experience changes in the mat position over time, resulting in loss of compression between the mat and the plates. Compression between the absorbed glass mat and the plates is necessary to ensure that the plates are in constant contact with the electrolyte. Over time, small voids can develop between the mat and the plates, increasing the internal resistance and decreasing the available capacity. This effect is referred to as *loss of compression* and causes a permanent loss of capacity in an AGM cell. This loss of compression can be caused by manufacturing errors, improper design, excessive manufacturing tolerances, and dryout. In particular, the design and manufacturing process have been important contributors to loss of compression because battery manufacturers did not originally appreciate the importance of compression on the performance of a cell. Dryout is an inevitable aging effect that changes the level of compression over a cell's service life.

The absorbed glass mat performs a critical function in the AGM cell; it is not a simple separator and sponge holding the electrolyte. The microglass fibers must be able to hold the mat in position, maintain the necessary compression against the plates, and keep the electrolyte suspended equally throughout the mat, while also allowing oxygen to migrate through it to the negative plates. In early designs, battery manufacturers were still learning how their product performed and aged in service; compression of the mat against the plates was not recognized as a critical design feature. Early tolerances for mat thickness, volume, and mass were as high as 20%, which was too high to ensure adequate compression once the mat was assembled in the cell with electrolyte added to the mat. Many factors influence the compression as a cell is manufactured, placed in service, and allowed to sit on float charge throughout its life. Factors influencing the compression include:

- Mat thickness between the plates
- Allowed tolerance for the glass mat
- Variation of plate surface and thickness
- Initial compression
- Mat saturation
- Density and surface area of the microglass fibers
- Container material
- Uniformity of compression between plates

Loss of compression should cause an internal resistance increase, detectable by internal ohmic measurements.

2.2.2.3 Negative Plate Discharge

Although the principle of the recombination process that occurs inside a VRLA cell is relatively simple in concept, the actual implementation is quite complex. A delicate balance is maintained at the negative plates between oxygen recombination, hydrogen evolution, and plate sulfation.

This complexity places stricter constraints on the design, manufacture, application, and use of these cells compared to an equivalent vented cell. VRLA batteries are more sensitive to float voltage variations. The proper float voltage is necessary to maintain each cell within the proper operating range. If the float voltage is too low, the negative plates might be undercharged, leading to capacity loss. If the float voltage is too high, the aging process will be accelerated and the rate of dryout will increase.

Figure 2-3 shows the typical polarization voltage of a VRLA cell. As can be seen, very little polarization voltage is applied to the negative plates under normal conditions. The charging current must be abnormally high before significant negative plate polarization occurs. This low level of polarization means that the negative plates can experience a loss of capacity over time by partially discharging if the level of polarization is inadequate to prevent self-discharge.

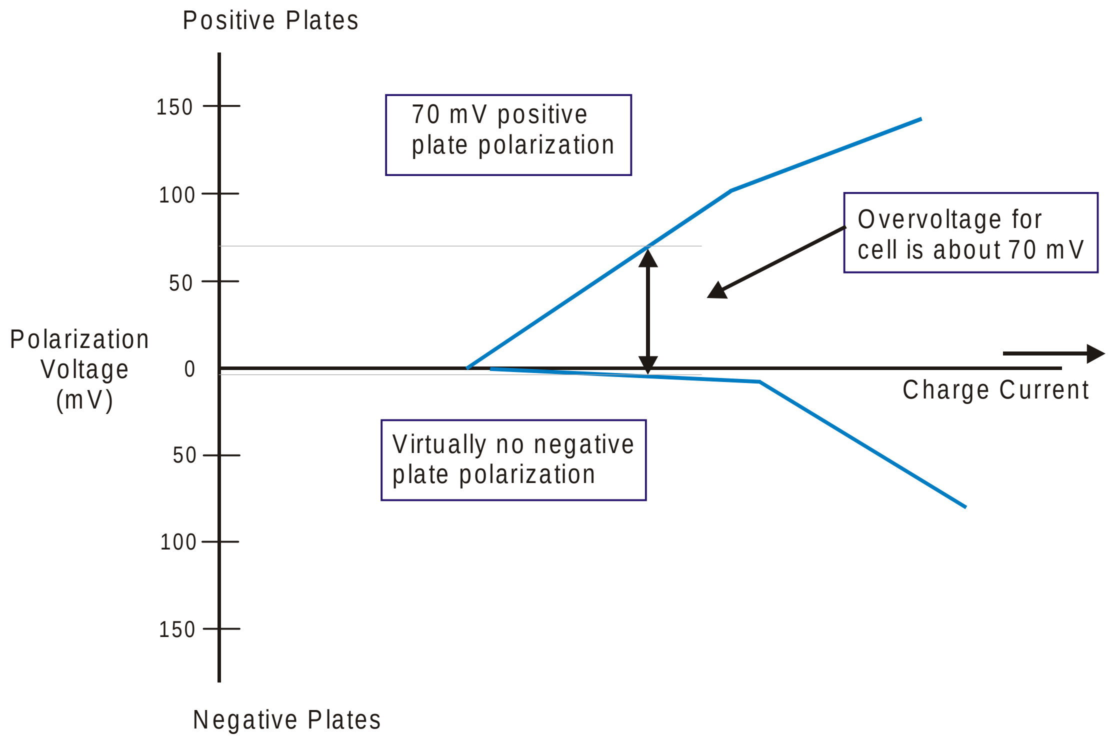

Figure 2-3
Polarization Voltage Inside a VRLA Cell

Discharged negative plates will cause an internal resistance increase that is detectable by internal ohmic measurements.

2.2.2.4 Negative Strap Corrosion

Some VRLA batteries have shown a tendency for the negative plate straps to corrode and fail prematurely. In an AGM VRLA cell, the negative strap is not immersed in the electrolyte; instead, it is exposed to a nearly pure hydrogen environment in the void space above the plates. With the negative strap exposed and the negative plates normally depolarized by the recombination process, the negative strap can experience sulfation that ultimately leads to its fracture and failure.

Some manufacturers have redesigned their batteries to be more resistant to negative strap corrosion. Design changes have included wrapping the negative strap with absorbed glass mat material to help keep it wetted or more carefully matching the grid, strap, and post alloys.

Negative strap corrosion should cause an increase in the cell's internal resistance that is detectable by internal ohmic measurements.

2.3 The Lead-Acid Battery Natural Aging Process

If properly designed, built, and maintained, a lead-acid battery can provide many years of reliable service. The ideal profile of capacity during a lead-acid battery's operational life is shown in Figure 2-4. A new battery might not initially provide 100% capacity. The capacity typically improves over the first few years of service, is fairly stable for many years thereafter, and then declines as the battery reaches its end of life. A reduction to 80% of the rated capacity is usually defined as the end of life for a lead-acid battery. Once the capacity falls below 80%, the rate of battery deterioration accelerates, and it is more prone to sudden failure resulting from a high discharge rate or from a mechanical shock (such as a seismic event). It is important to understand that this aging process is unavoidable and a lead-acid battery will eventually wear out, even under ideal conditions.

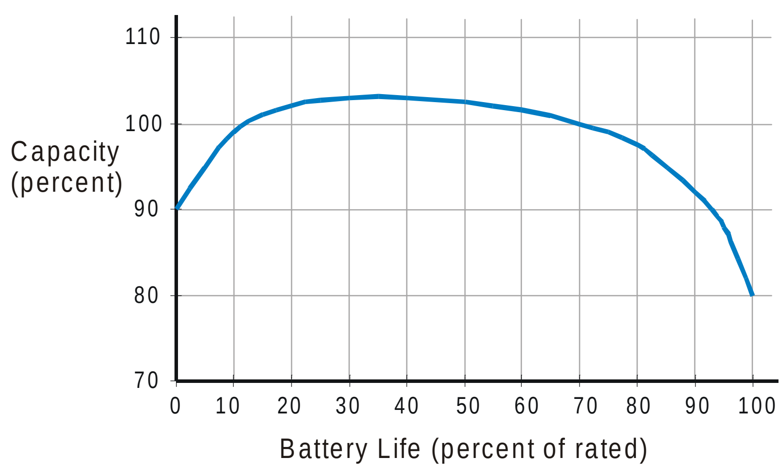

Figure 2-4
Lead-Acid Battery Typical Life Curve

Figure 2-4 applies to the most common types of stationary lead-acid batteries—lead-calcium, lead-antimony, or lead-selenium designs with pasted flat plates. But, the ideal expected life curve shown in Figure 2-4 might not be obtained; aging and degradation factors can combine so that the battery never attains 100% capacity. The effects can be dramatic; for instance, a battery with an expected service life of 20 years can fail in less than 4 years in a harsh environment without proper maintenance or as a result of a manufacturing defect. Figure 2-5 shows how the actual life can vary from the ideal case.

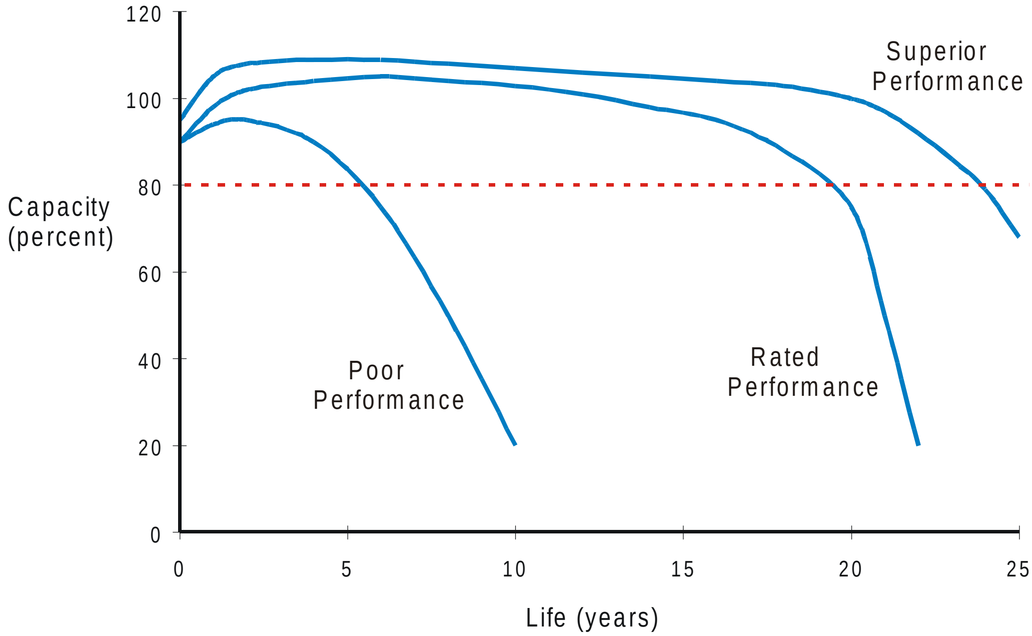

Figure 2-5
Possible Variations From the Ideal Life Cycle

The plates (grid and active material) and connection straps are the most age-sensitive components in the cell. Even under ideal conditions, the plates degrade over time because of unavoidable aging mechanisms. The positive plates are affected by aging to a greater degree than the negative plates.

The age-related degradation of the positive plates is generically referred to as corrosion of the plates, which is actually oxidation of the positive plate grid structure. In a sulfuric acid solution, the lead of the grid structure oxidizes to various corrosion products, including lead dioxide, lead peroxide, and lead sulfate. Oxidation of the positive grid causes the following adverse effects:

- Expansion of the positive grid: The lead compounds formed during oxidation have a larger volume than the original material, so the grids continue to swell and distort over the life of the cell. Grid growth places stress on the internal components and the container. These stresses can cause cracks in the jar and cover, and cause post seal failures.
- Embrittlement and weakening of the grid and strap: The lead compounds formed during oxidation are more brittle and less rugged than the original grid material.
- Increased internal resistance: As the grid structure oxidizes, the cross-sectional area of the grid wires is reduced. A decrease in the cross-sectional area of the grid reduces the size of the conductors that carry current away from the plates. Also, the corrosion products are less conductive than the original materials. The increased internal resistance reduces available capacity, particularly at high discharge rates.

- Separation of active material from the grid: As the grids grow and distort, the active material separates from the grid. This separation decreases the conductivity between the grid and active material and reduces the capacity. The cell eventually fails once electrical contact between the grid and active material degrades beyond a certain point. Battery designers generally account for a 5%–6% grid growth at end of life (80% rated capacity).

The active materials of the plates also undergo age-related degradation. Over time, fine particles of active material are shed from the plates. These particles show up as sediment at the bottom of the battery or as mossing at the top of the plates. As is the case for corrosion, the positive plates are affected to a greater degree. The shedding of active material reduces the amount of material available to constructively participate in the chemical reaction during discharge, and therefore the capacity is reduced.

High ambient temperature, overcharging, excessive cycling, and some manufacturing defects accelerate corrosion and shedding. Degradation of the positive plates, as described above, is the expected failure mode for a lead-acid battery operated under ideal conditions.

Section 2 has been provided primarily to introduce the subject of lead-acid battery aging, degradation, and failure; additional failure modes do exist. For a more detailed discussion of this topic, refer to TR-100248-R1, *Stationary Battery Guide—Design, Application, and Maintenance*.

The following sections describe the relationship between the lead-acid battery aging process and internal ohmic measurements.

2.4 Cell Model

Defining the battery model is an important part of understanding what is measured by an internal ohmic measurement. A lead-acid cell can be modeled electrically by a series-parallel combination of resistance, capacitance, and inductance. The most straightforward cell model is represented by a series resistance with some series inductance and parallel capacitance (refer to Figure 2-6). This simple model is adequate for explaining internal ohmic measurement theory.

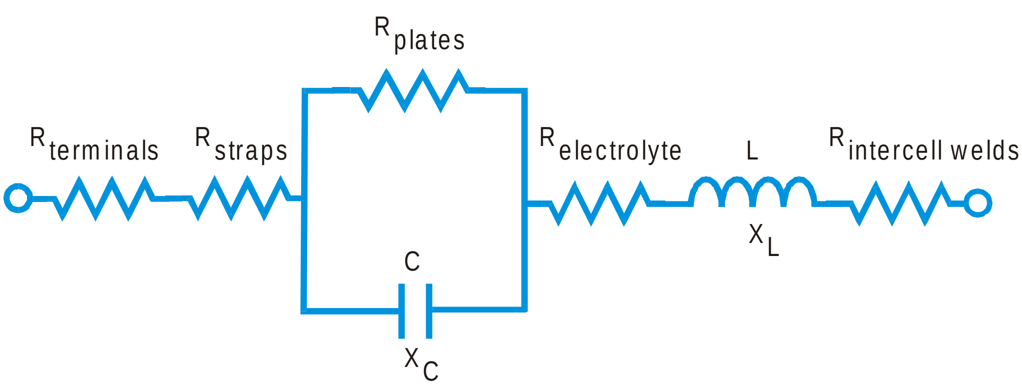

Figure 2-6
Typical Lead-Acid Cell Model

The inductance is typically very small, ranging from 0.05 to 0.15 microhenries for common cell sizes. The capacitance tends to be substantially larger, ranging from 1.5 to 2.0 farads per 100 ampere-hours of rated capacity. The internal resistance varies from less than a milliohm for a large cell to greater than 2 milliohms as the cell size decreases to less than 100 ampere-hours.

The resistance of the terminals or posts, straps, plate-to-strap welds, and intercellular welds is often referred to as the *metallic resistance* and represents the resistance of the internal conduction paths. Typically, changes in this resistance do not occur during the discharge and recharge cycle. However, the conduction path resistance can change over time as the cell ages. The cell inductance is normally associated with internal conduction path elements.

The resistance of the plates, separators, and electrolyte is referred to as the *electrochemical resistance*. Unlike the metallic resistance, the electrochemical resistance does change during the discharge and recharge cycle.

The electrochemical resistance is related to the ability of the plates to perform the electrochemical reaction. The metallic resistance is only associated with the conduction path from the plates out to the cell terminals. Accordingly, changes in either the electrochemical resistance or the metallic resistance have a different effect on the cell performance during discharge.

Figure 2-7 shows a typical simplified voltage profile during discharge of a normal cell. As will be shown in subsequent sections, the electrochemical resistance of a cell increases as it is discharged. Under ideal conditions, all changes in internal resistance would be attributed to the electrochemical resistance and the metallic resistance would remain constant. Unfortunately, conduction path problems can occur and, when they do, can have a measurable effect on the total cell resistance. Figure 2-8 shows the typical effect of a conduction path problem on the discharge voltage profile. A larger conduction path resistance has an immediate effect on the cell voltage during discharge, but this effect does not change further during a constant current discharge because the resistance is effectively constant. Compare this to Figure 2-9 in which the plates have experienced significant aging. In this case, the electrochemical resistance limits the cell capacity; the discharge profile can initially appear normal until a certain point at which the voltage falls quickly.

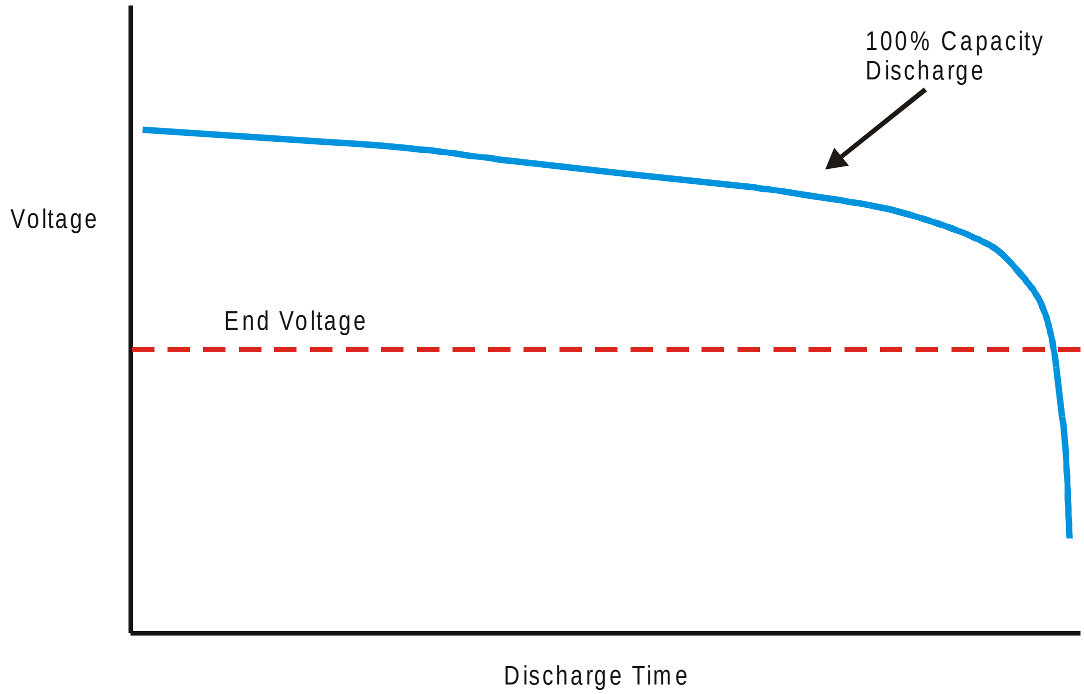

Figure 2-7
Typical Discharge Profile of 100% Capacity Battery

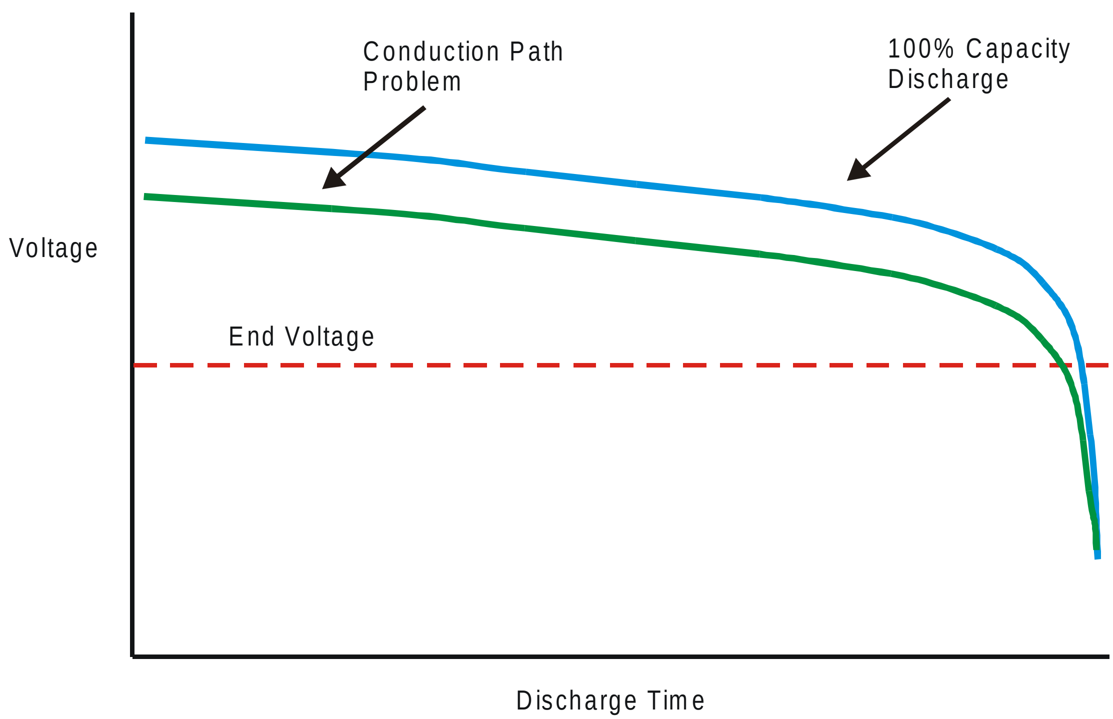

Figure 2-8
Effect of Metallic Resistance Problem on Discharge Profile

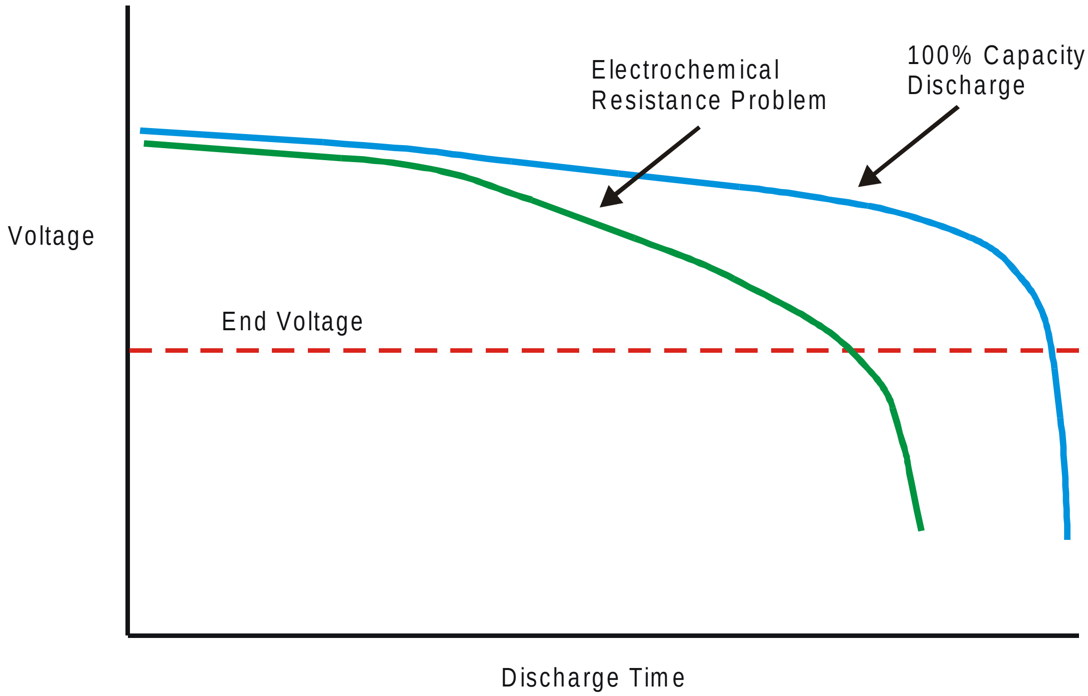

Figure 2-9
Effect of Electrochemical Resistance Problem on Discharge Profile

A discussion of electrochemical and metallic resistance is useful to introduce the concept of internal resistance inside the cell, including the concept of how different changes in internal resistance can affect cell capacity in different ways. The following sections continue this discussion.

2.5 Factors Affecting Internal Resistance

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 2-1 shows the effect of various factors on cell internal resistance and cell capacity.

Table 2-1
Effect of Various Factors on Cell Capacity and Internal Resistance

Factor	Internal Resistance	Effect on Capacity	Comments
Grid corrosion	Increase	Decrease	Natural aging process.
Grid swelling and expansion	Increase	Decrease	Includes loss of contact between active material and grid.
Loss of active material	Increase	Decrease	
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 because of mossing or sediment buildup can cause resistance to decrease, but the subsequent low voltage, self discharge, and sulfation will lead to a higher resistance
Temperature decrease	Increase	Decrease	
Temperature increase	Decrease	Increase	
Rated cell capacity	Decrease	Increase	Resistance tends to decrease as cell size (cell capacity) 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, largely corrected in newer VRLA designs.
Loss of compression	Increase	Decrease	VRLA cell failure mode in absorbed glass mat cells.

As shown in Table 2-1, virtually all factors that increase internal resistance tend to decrease capacity. Perhaps less intuitive is that the percent change in resistance might not always correlate to a similar percent change in capacity. In other words, we might expect a capacity decrease as the internal resistance increases, but we may not know the magnitude of the capacity change. The following sections discuss the most important internal resistance effects in more detail.

2.5.1 Aging Effects on Internal Resistance

A lead-acid cell exhibits an increase in its internal resistance with age. A typical graph of internal resistance and capacity as a function of age is provided in Figure 2-10.

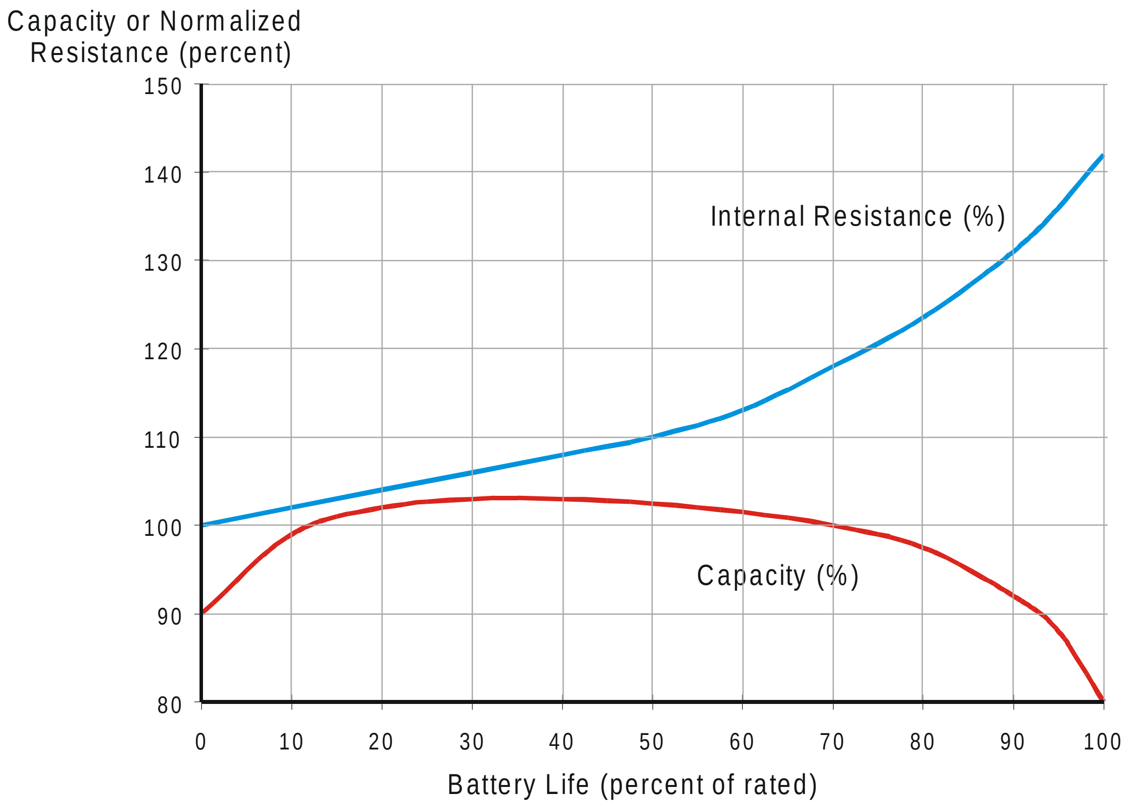

Figure 2-10
Lead-Acid Cell Internal Resistance as a Function of Age

Both the metallic resistance and the electrochemical resistance contribute to the increase in internal resistance. The metallic resistance increase is mainly attributed to corrosion of the conduction path components, or poor welds in the intercell and plate-to-strap connections. Age-related changes in the electrochemical resistance occur primarily because of aging of the plate and grid materials. This includes all effects attributable to aging, including grid corrosion, shedding of active material, and loss of contact between active material and the grid structure.

The separator is designed to minimize the possibility of internal shorts between the positive and negative plates while remaining porous enough to still allow the uninhibited passage of ions between plates. The separator resistance is not expected to change significantly with age in a vented cell unless contaminants or other effects cause the separator pores to close (sometimes referred to as separator clogging).

The electrolyte resistance of a vented cell is not expected to change with age provided that the electrolyte level is properly maintained and the electrolyte remains contaminant-free. The electrolyte resistance can change significantly in a VRLA cell if 1) some level of dryout has occurred or 2) the required compression between the plates and the absorbed glass mat is not adequately maintained.

The expected increase in the metallic and electrochemical resistance as a result of the aging process forms the underlying theory behind internal ohmic measurement technology. As shown in Figure 2-10, the aging mechanisms responsible for increasing the cell's internal resistance also have an effect on capacity. The key to internal ohmic measurement technology is to establish a correlation between this resistance increase and a corresponding capacity decrease.

2.5.2 State of Charge Effect on Internal Resistance

A lead-acid cell exhibits an increase in internal resistance as it is discharged, primarily because of changes in the electrochemical resistance. The discharge process causes the electrochemical resistance to increase because 1) the electrolyte specific gravity drops, resulting in a decrease in electrolyte conductivity, and 2) the active material on the plates converts by the electrochemical reaction from lead (Pb, negative plate) and lead dioxide (PbO_2, positive plate) to lead sulfate ($PbSO_4$), which occurs on both plates and which has a higher resistance.

Testing performed during this project revealed that the change in internal resistance is not necessarily linear as a battery is discharged (see to Figure 2-11). As shown, very little internal resistance change occurs for a substantial portion of the discharge time. The internal resistance increases quickly near the end of a discharge once the lead sulfate ($PbSO_4$) has formed to such an extent that many pores in the plates are closed, severely restricting electrolyte access deep into the plates where the active material (Pb or PbO_2) is still available. Also, notice from Figure 2-11 that voltage and internal resistance have a clear inverse relationship as would be expected from the battery model.

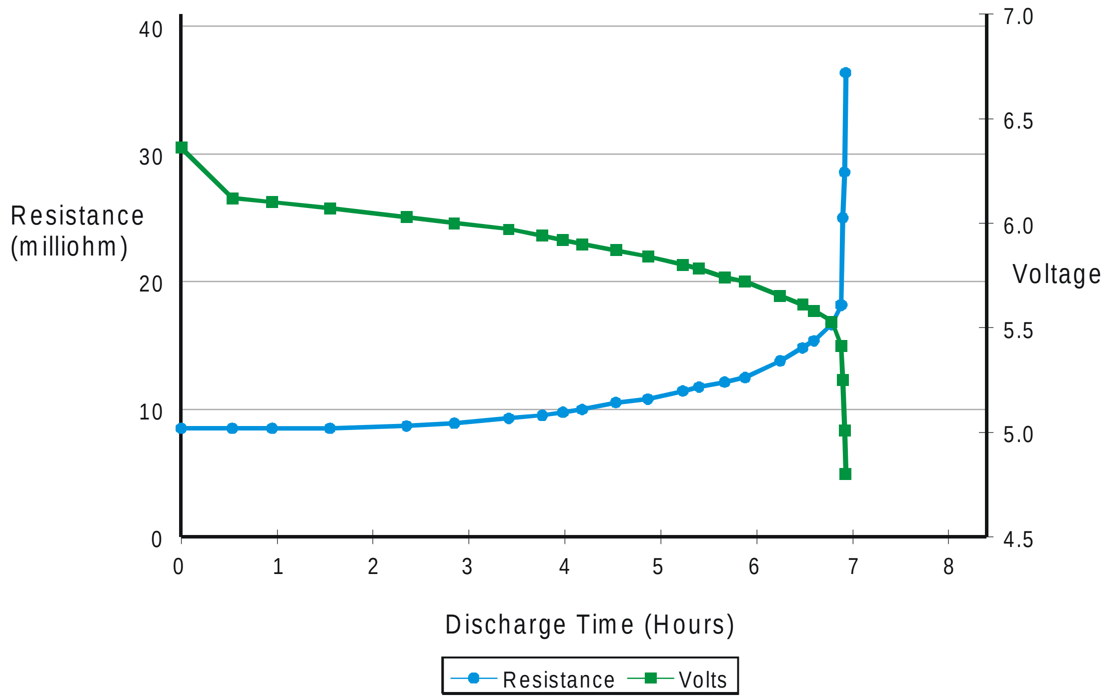

Figure 2-11
Internal Resistance During Discharge

Because there is a relatively flat relationship between resistance and state-of-charge over a good portion of a discharge, internal ohmic measurements are not a particularly good indicator of state of charge except for completely discharged cells. In general, internal ohmic measurements should only be taken on fully charged cells.

2.5.3 Temperature Effect on Internal Resistance

A lead-acid cell exhibits an increase in internal resistance as its temperature decreases. This variation with temperature tends to follow the temperature-resistivity relationship of the electrolyte and is not linear. Near 77°F, only a very moderate change in resistance occurs as a function of temperature. As temperature falls below 50°F, the rate of resistance change increases.

The temperature effect varies with electrolyte specific gravity, type of cell, and the internal design. One battery manufacturer provides the temperature-resistance relationship shown in Figure 2-12 for their VRLA cells.

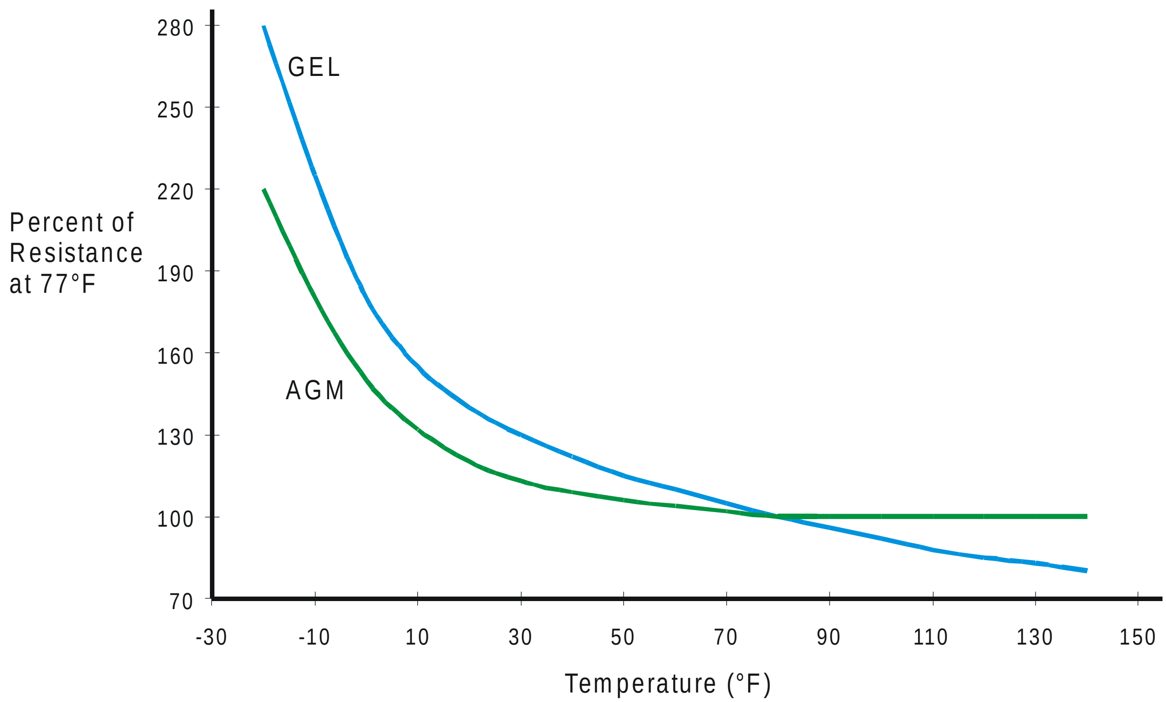

Figure 2-12
Temperature-Resistance Relationship

One test equipment manufacturer has provided the following temperature correction factors for cell <u>conductance</u> measurements:

- VRLA AGM: 0.5% per °F
- Vented and VRLA Gel: 0.75% per °F

Given that internal resistance changes with temperature, the purpose of the above correction factors is to reference all measurements to a common temperature of 77°F. Measurements taken above 77°F would be corrected down in accordance with the above correction factors and measurements taken below 77°F would be corrected up in accordance with the above correction factors.

Another test that an equipment manufacturer has provided is the following temperature correction factor for impedance values of vented lead-acid cells:

$$Z_b\ @77°\ F\ =\ \frac{0.088\ x\ Z_m}{(T + 30)^{-0.52}}$$

where,

Z_b = impedance corrected to 77°F

Z_m = measured impedance

T = electrolyte temperature in °F

In another study of vented and VRLA cells, little change in impedance was noted as temperature was varied from 77°F to 167°F, conflicting with the direction provided above by some test equipment and battery manufacturers. This study did not evaluate temperatures below 77°F.

As can be seen, different suppliers provide different recommendations regarding the temperature effect on internal resistance. However, the sources generally agree that the temperature effect varies with the type of battery. Regardless of the actual resistance change with temperature, the important point to remember is that resistance measurements taken at a temperature significantly lower than 77°F should indicate a higher value than a measurement taken with the same battery at 77°F. Similarly, a resistance measurement taken at a temperature significantly higher than 77°F can indicate a lower value than the same measurement taken with the battery at 77°F.

During this project, measurements were typically taken with the battery temperature between 60°F and 90°F. Within this temperature range, a correlation between internal ohmic values and capacity could still be developed. For this reason, temperature correction within this range is not considered necessary to obtain usable results.

2.5.4 Electrolyte Effect on Internal Resistance

Evaporation and gassing from a vented cell can cause electrolyte level to drop. Normally, only water is normally lost by these two processes, meaning that as level drops the electrolyte specific gravity increases, its conductivity increases, and the electrolyte portion of the internal resistance decreases slightly. If electrolyte level falls below the top of the plates, the increased resistance of the exposed plates offsets the increase in electrolyte conductivity. If water level is maintained within the manufacturer's recommended range, little or no change is expected for normal level variations in a vented cell.

Dryout of a VRLA cell can cause inadequate electrolyte between plates, resulting in greater internal resistance. Loss of compression between the plates and glass mat material can cause an internal resistance increase. Both dryout and loss of compression are recognized as causing a loss of capacity in a VRLA cell.

2.5.5 Internal Resistance as a Function of Rated Capacity

A cell design usually increases capacity by the addition of more positive and negative plates. For example, a particular battery model can be available in sizes ranging from 1 positive plate to over 16 positive plates per cell. With the addition of each parallel positive plate, the cell's internal resistance decreases (analogous to a decrease in resistance when resistors are connected in parallel). Figure 2-13 shows the trend in measured resistance as the cell size increases. Specific values of resistance have been intentionally left off because they are measurement dependent, varying with the test equipment and its test frequency.

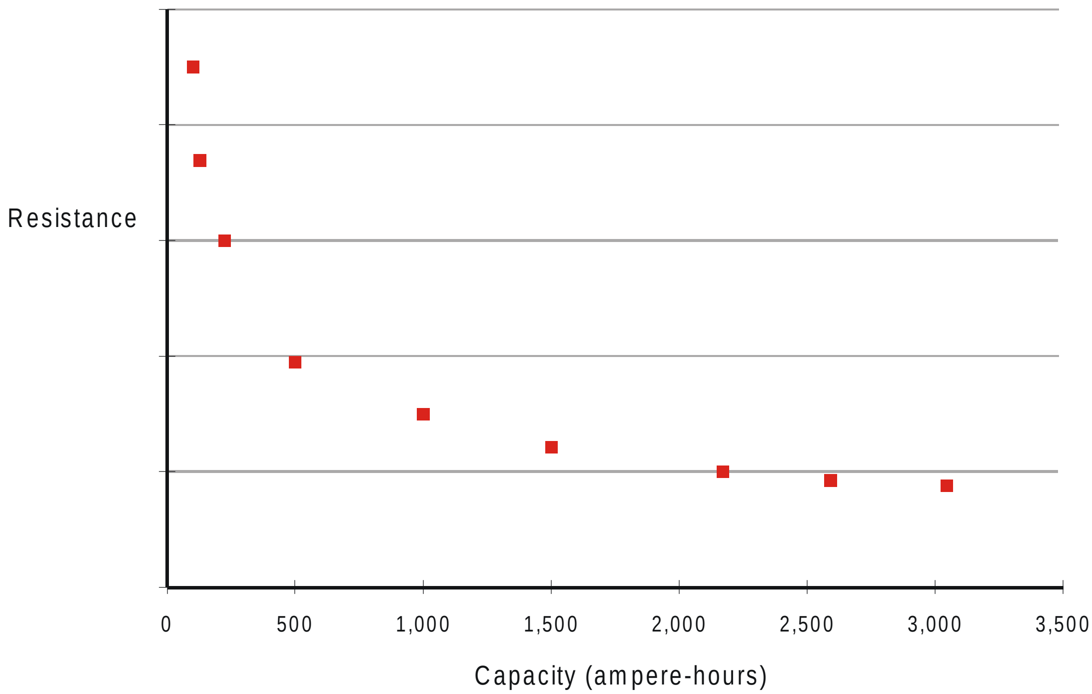

Figure 2-13
Internal Resistance as a Function of Cell Capacity

The decrease in internal resistance as the cell capacity increases is not linear. With the addition of each parallel plate, the cell's internal capacitance increases, which influences the internal resistance measurement, depending on the method of measurement and the test frequency. Within a given family of cell sizes for a particular model, the smooth curve shown in Figure 2-13 might not always apply. For example, larger cells can have multiple posts or copper inserts in the posts, causing a step-change reduction in the internal resistance.

The tendency for measured internal resistance to decrease with rated capacity applies to multicell monobloc batteries as well. A 50 ampere-hour 6 V monobloc battery will have a larger internal resistance than an equivalent design 200 ampere-hour monobloc battery.

2.5.6 Internal Resistance and Discharge Rate

Battery capacity as a function of discharge rate is reasonably well understood. As the discharge rate (current or power) increases, the amount of energy that can be removed from the battery decreases for a given end voltage. As a cell ages, its capacity might change even more as a function of its discharge rate. For example, as a cell ages, the plate grids can corrode and degrade such that they are incapable of supporting a high-rate discharge. However, a lower-rate discharge might still be quite possible because the lower current does not as severely stress the current-carrying members of the grid structure. Explained another away, a cell might be capable of 100% capacity at the 8-hour rate, yet fail very quickly at the 15-minute rate. Figure 2-14 illustrates this difference as a function of discharge rate.

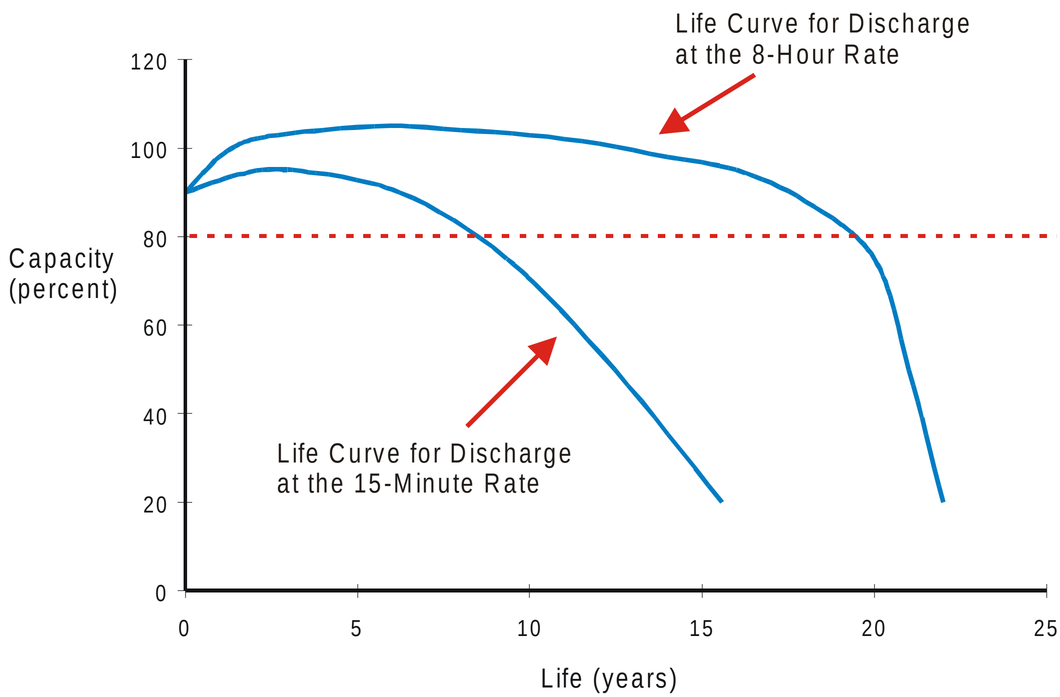

Figure 2-14
Cell Capacity/Life as a Function of Discharge Rate

Regardless of the cell's application (low-rate or high-rate discharge), it will have the same measured internal resistance prior to the discharge. The test equipment does not *know* the battery's required duty cycle or intended discharge rate. The net result might be that a measured internal resistance correlates to an acceptable battery capacity at a low discharge rate and an unacceptable capacity at a higher discharge rate.

Internal resistance changes are likely to be more significant for high-rate discharge applications. This phenomenon is not unlike that observed for capacity discharge testing; the available capacity at one discharge rate is not necessarily indicative of capacity at a different rate. Most of the battery capacity tests in this project were performed at the 1-hour to 2-hour rate. The results are expected to bound longer discharge rates, but might not be entirely indicative of performance for high-rate applications.

2.6 Ohmic Relationships and the Effect of Test Equipment Frequency

2.6.1 Effect of Test Equipment Frequency

As shown in Section 2.4, a lead-acid cell can be modeled electrically by a series-parallel combination of resistance, capacitance, and inductance. The cell inductance is normally very small, ranging from 0.05 to 0.15 microhenries for typical cell sizes. The capacitance tends to be substantially larger, ranging from 1.5 to 2.0 farads per 100 ampere-hours of capacity. The internal resistance varies from less than a milliohm for a large cell to greater than 2 milliohms as the cell size decreases to less than 100 ampere-hours.

Internal ohmic measurement test instruments typically operate at a set frequency. Depending on the method of measurement, the cell inductance and capacitance can influence the measured value of resistance. The inductive reactance, X_L, is defined by:

$$X_L = 2\pi f L$$

where,

X_L = Inductive reactance

L = Inductance

f = Frequency

• = 3.1415

The capacitive reactance, X_C, is defined by:

$$X_c = \frac{1}{2\pi f C}$$

where,

X_C = Capacitive reactance

C = Capacitance

f = Frequency

• = 3.1415

The units of inductive and capacitive reactance are ohms and, as can be seen above, reactance is frequency dependent. At low frequencies, inductive reactance becomes very small, having little effect on the operation of a circuit, but inductive reactance dominates the overall impedance at high frequencies. As the frequency becomes very low, capacitive reactance becomes very large, or the capacitor appears to be an open circuit. At a measurement test frequency of 60 Hz or less, the capacitive reactance can affect the measured impedance but the inductive reactance tends to be negligible.

The internal impedance, Z, is obtained by combining the resistance, inductive reactance, and capacitive reactance, and is generally given by:

$$Z = \sqrt{R^2 + (X_L + X_C)^2}$$

where,

Z = Impedance in ohms

R = Resistance

X_L = Inductive reactance

X_C = Capacitive reactance

As can be seen, impedance is affected by frequency whenever inductive and capacitive elements are included. Test equipment operating at 60 Hz will measure different impedance than test equipment operating at 1,000 Hz.

The expression for impedance often combines the inductive and capacitive reactances into a single term, X, that is 90 degrees out of phase with the resistance (*j* is an imaginary number), or

$$Z = R + jX$$

Impedance can be measured in a cell by applying Ohm's Law to a known current and voltage. Injecting a specified ac current into a cell and measuring the resultant ac voltage developed across the terminals can calculate the magnitude of the impedance. Ohm's Law is given by

$$V = IZ, \quad or \ Z = \frac{V}{I}$$

Admittance is the reciprocal of impedance or

$$Y = \frac{1}{Z} = G + jB$$

where,

Y = Admittance

Z = Impedance

G = Conductance

B = Susceptance

Conductance is the real portion of admittance and is typically measured by capacitively coupling an ac voltage to a battery and measuring the resultant ac current that flows. The admittance is calculated as the inverse of the impedance using Ohm's Law and the conductance is the real portion of the admittance. Conductance can be calculated by the following expression:

$$G = \frac{R}{R^2 + X^2}$$

The above relationships are important to an understanding of what is measured by the test equipment. Figure 2-15 shows how impedance can vary with frequency (the axes are unlabeled because this graph is for illustrative purposes only). Lead-acid batteries are predominantly inductive at high frequencies, predominantly capacitive at low frequencies, and resistive in mid-range. Commercially available test equipment used by this project is generally operating in the resistive region; however, different instruments do operate at different frequencies, thereby possibly complicating any attempt to directly compare instrument measurements.

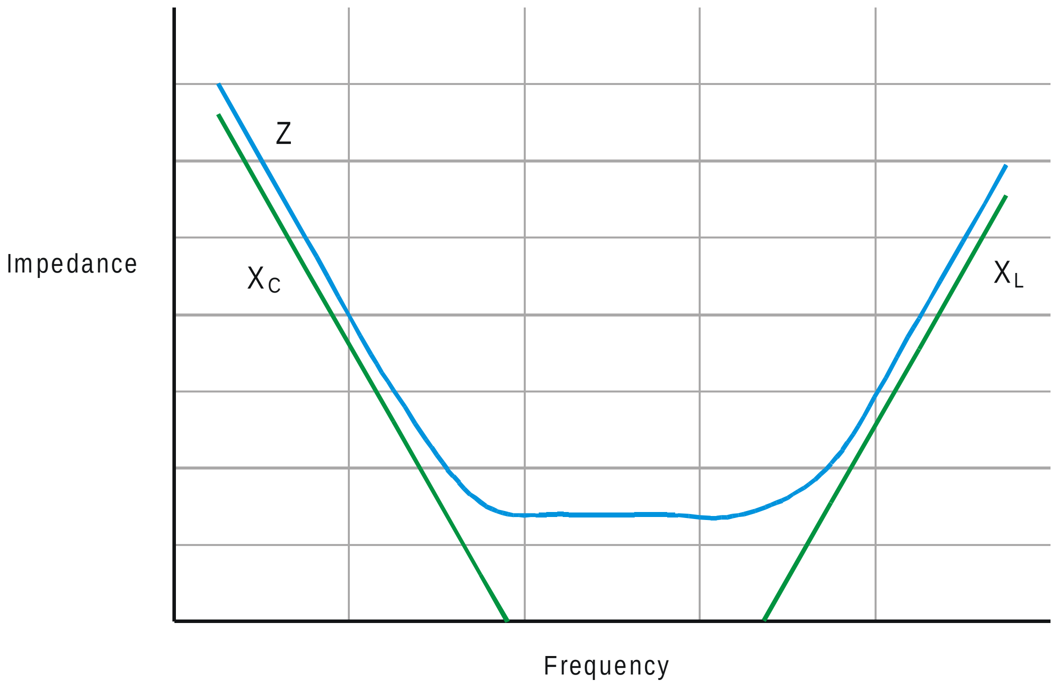

Figure 2-15
Relationship Between Impedance and Frequency

Studies have shown that the inductive reactance is similar regardless of the battery size, supporting the assumption that inductance is principally associated with the metallic components in the conduction path. However, capacitance varies significantly with battery size and does influence the measured impedance as a function of frequency. Batteries appear resistive within a certain frequency range, but this range varies with cell type and size. The practical implication of this observation is that internal ohmic measurement test equipment operating at a single frequency might be more suitable for use with certain cells, and less suitable for other sizes or types.

Internal ohmic test equipment is under development that will be capable of measurements based on a frequency scan. This measurement approach will allow direct measurement of inductance, capacitance, and resistance, which might offer insight into any causes for a capacity change.

2.6.2 Internal Ohmic Relationships

A primary goal of this project was to assess the degree of correlation between a cell's capacity and its internal ohmic measurement of resistance, impedance, or conductance. The ideal result would occur if all three internal parameters could be correlated to capacity as a straight-line, linear relationship. However, remember that impedance and resistance are related to the inverse of conductance, and the inverse of a first-order, linear function is not linear. Figure 2-16 shows an ideal first-order linear function; note that its inverse is nonlinear. Therefore, the mathematics of the relationships preclude the possibility that a first-order, linear correlation simultaneously exists for all three parameters.

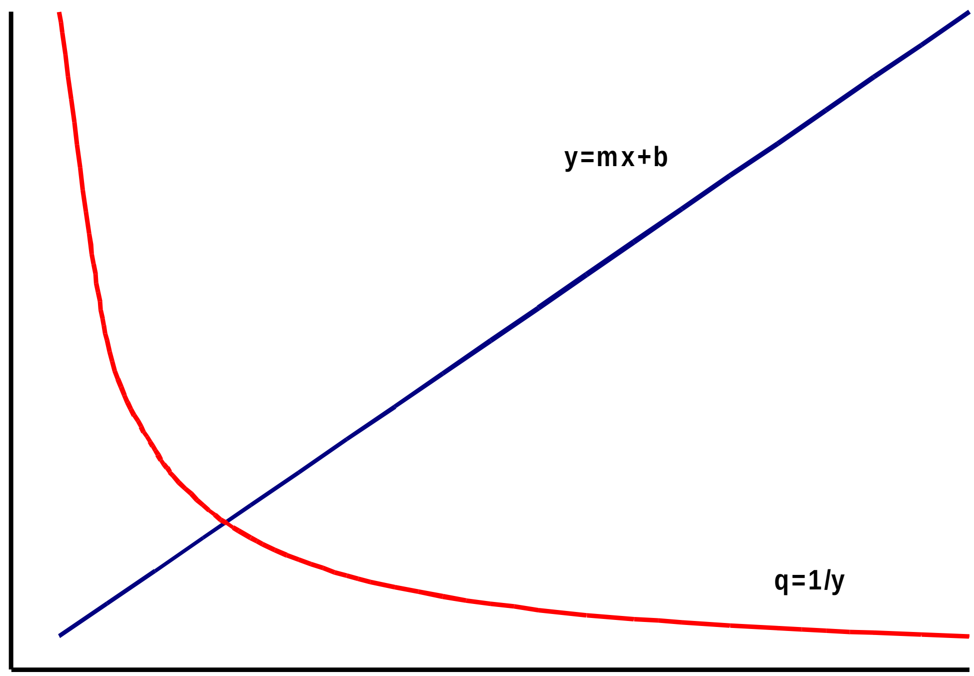

Figure 2-16
A Linear Function and Its Inverse

Notice in Figure 2-16 that data following the y = mx + b line is easy to scale and interpret because there is a linear correlation between x and y. However, consider the effect if data instead follows the q = 1/y line; the data tends to be compressed within a narrow range above 50% of scale and is harder to interpret in this range.

Testing performed as part of this project indicates that a linear relationship appears to be observed most often between conductance and capacity (in some cases, there was enough data scatter that all three methods appeared to simultaneously have an approximately linear relationship). The practical implication of this observation is that an inverse relationship should exist between impedance or resistance and capacity. Test results confirm this inverse relationship, but it must be noted that the degree of correlation varied between battery types. Nonetheless, the general relationships were quite evident and were consistent with the mathematical relationship between internal ohmic parameters.

2.7 The Meaning of an Internal Resistance Increase

An increase in internal resistance is expected to correlate with a decrease in a cell's capacity. An internal ohmic measurement can be taken with different types of test equipment (refer to Sections 3.1–3.3). Each type of internal ohmic test equipment will respond to an internal resistance increase as follows:

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

As will be shown in later sections, a relationship was observed between internal ohmic measurements and capacity. This is valuable information for stationary battery reliability. However, the measurements can not tell us everything regarding a battery. Some points to consider in the following sections 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.
- An increase in internal resistance indicates that something inside a cell is changing. However, there is no way of knowing what particular aging, degradation, or failure mode is at work inside the cell; it is only known that something is changing. For example, there is not a way to distinguish between dryout or negative plate discharge inside a VRLA cell. Although the two degradation mechanisms might have a similar effect on an internal resistance change, they may have a somewhat different effect on cell capacity – a cell with dryout might discharge for some period of time before failure, but a cell with negative plate discharge might fail immediately. The practical implication of this 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 it might be limited to identifying *good* or *bad* cells rather than making claims that a certain internal resistance indicates a particular cell capacity, accurate to 2 decimal places.

Users are typically concerned with the capacity of the *battery*. 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 predict the overall battery capacity.

3 TEST EQUIPMENT DESCRIPTION AND MEASUREMENT UNCERTAINTY

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

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

Although the method of internal ohmic measurement varies, each type of test equipment monitors a similar internal property—some form of internal resistance. Conductance is the real portion of the admittance (the inverse of impedance) and resistance is the real portion of impedance (refer to Section 2.4 for a detailed description of these relationships). The following sections describe the equipment used in this project and the factors that contribute to measurement uncertainty.

3.1 Conductance Test Equipment

Conductance describes the ability of a circuit to facilitate current flow. In a typical conductance test, an ac voltage of known frequency and amplitude is applied across a cell or battery, and the ac current that flows in response to the applied voltage is observed. The measured conductance is the ratio of current to voltage, where the current is the component in-phase with the ac voltage. The measured conductance value varies with battery manufacturer, type, and size.

Typical conductance testers are shown in Figures 3-1 through Figures 3-3. Two probes are used to connect the tester to the positive and negative posts of a cell. The Celltron Plus provides a measurement in kmho (conductance), the Micro Celltron provides a measurement in siemens (conductance), and the Midtron 3200 provides a measurement in mhos (conductance). In addition, cell voltage is displayed.

Figure 3-1
Celltron Plus Model CTP5000 Conductance Tester

Figure 3-2
Micro Celltron Conductance Tester

Figure 3-3
Midtron 3200 Conductance Tester

3.2 Impedance Test Equipment

An impedance tester capacitively couples a low-frequency current to the battery and measures the small ac voltage drop across the cell terminals. To calculate the cell's impedance, the voltage measurement is divided by the ac current passing through the battery. Consisting basically of a transmitter and receiver, an impedance tester applies an ac current to the battery. The ac test current is applied via a series capacitor (capacitive couple) to block the dc voltage of the battery. The receiver is clamped around a battery terminal and probes are used to measure the ac voltage across the cell. The instrument circuitry measures the root-mean-square (rms) current and voltage, then computes and displays these values as impedance (milliohm). Figure 3-4 shows the Miniature Battery Impedance Test Equipment (MBITE) test system and Figure 3-5 shows the Enhanced Battery Impedance Test Equipment (EBITE). Each instrument provides a measurement in terms of milliohms.

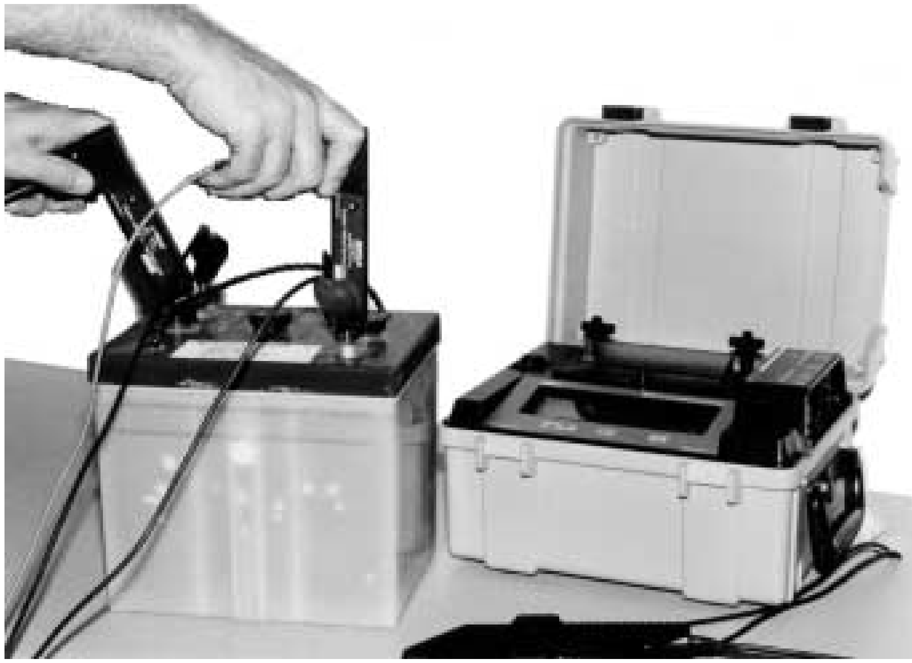

Figure 3-4
MBITE Battery Impedance Tester

Figure 3-5
EBITE Battery Impedance Tester

3.3 Resistance Test Equipment

A cell resistance measurement is taken by monitoring the instantaneous change in voltage when it is discharged by a specific amount. When a load is applied to a cell, an instantaneous voltage drop occurs and, when the load is removed, an instantaneous voltage recovery subsequently occurs. By monitoring the current and cell voltage just prior to removal of the load and the recovered cell voltage, the internal cell resistance can be calculated by:

$$R_{internal} = \frac{\Delta V}{I}$$

where,

$R_{internal}$ = Internal resistance

ΔV = Voltage change

I = Test discharge current

A typical resistance tester is shown in Figure 3-6. This tester provides a resistance measurement in terms of micro-ohms.

Figure 3-6
Cellcorder Resistance Tester

3.4 Battery Internal Ohmic Measurement Uncertainty Considerations

Although internal ohmic measurements can provide valuable insight into the potential presence of internal degradation, these measurements alone do not necessarily provide *absolute* verification of a battery's capacity; only a battery capacity test can determine the total battery capacity. As discussed in the Section 2, a number of parameters can influence the internal resistance. Consequently, some level of uncertainty in the interpretation of an internal ohmic measurement is unavoidable. The following sections discuss various contributors to uncertainty.

3.4.1 Battery Variables That Contribute to Measurement Uncertainty

Section 2 provides a discussion of the battery model and describes the effect of different parameters on a cell's internal resistance. Not all influences on a cell's internal resistance necessarily affect the capacity in a consistent manner. Some of these influences can be limited or eliminated by the user; others are outside the user's control. The following summarizes the most important contributors to measurement uncertainty.

- Battery Model: As discussed in Section 2.4, a cell can be modeled as a series-parallel combination of resistance, capacitance, and inductance. Although the various elements in the model each can influence the capacity, one should not expect that they do so in a linear manner. The practical implications of this might be that internal ohmic measurements work well when identifying very good or very bad cells, but might have mixed results with cells in between. A number of minor factors can contribute to internal resistance changes without significantly affecting capacity (or vice-versa).

- State of Charge: A partially discharged (or not fully charged) cell will not have an internal resistance fully indicative of its capacity (refer to Section 2.5.2). This variable is within the user's control; internal ohmic measurements should be taken on fully charged batteries to obtain consistent results.
- Temperature: Temperature affects the internal resistance (refer to Section 2.5.3). Internal resistance appears to have the greatest variability below 60°F. Lesser effect has been noted above 77°F. Battery manufacturers and test equipment manufacturers have provided correction factors to apply to internal ohmic measurements so that each measurement can be referenced to 77°F; however, the correction factors are not consistent among manufacturers, indicating that they might not fully understand this effect. Because of the variation noted among manufacturers, some uncertainty will be present regardless of which temperature correction method is used.
- Manufacturing Variations: Variations in the battery manufacturing process can affect the observed relationship between internal ohmic measurements and capacity. Improper curing of the active material lead paste can affect capacity, possibly without affecting internal resistance to the same degree. Cells from a given manufacturing lot can have small differences in capacity; cells from different lots might vary even more. Also, battery manufacturers produce batteries capable of meeting the stated cell performance specifications; however, a target internal resistance is not a typical manufacturing criterion. There could be lot-to-lot variations, resulting in greater uncertainty in the actual cell internal resistance reference value.
- New Battery: In accordance with IEEE standards and manufacturers' literature, a new (and acceptable) battery might have as low as 90% capacity on delivery. The reason for this is that the manufacturing process does not always complete the plate formation process. With many batteries, the formation process completes over several months after the battery is placed in service and battery capacity typically improves throughout this period. This is normal and expected behavior, but it affects the internal ohmic measurements. Depending on the extent of plate formation upon delivery, the internal resistance can easily vary by over 10% as the plates complete the formation process. This effect was confirmed by testing during this project.
- Aging Effects: A cell can age, degrade, and ultimately fail in different ways. For example, a cell in a benign environment might survive its entire rated life with its end-of-life occurring in the classical manner—corrosion of the positive plates. Another cell might experience overcharging throughout its life, accelerating the aging process of its plates and prematurely damaging the plate grid structure. Another cell might fail prematurely because of a manufacturing defect. A valve-regulated lead-acid cell might experience dryout or localized loss of compression between the plates and the absorbed glass mat. In each case above, the amount of change in internal resistance can differ in response to the particular aging or degradation mechanism.

- Cell Capacity Calculation: The purpose of this project was to evaluate the correlation between cell capacity and internal ohmic measurements. Section 4.1.4 discusses the uncertainty associated with determining cell capacity.

3.4.2 Test Equipment Variables That Contribute to Measurement Uncertainty

No measurement is free of error. Even if the test technique performed is not fully understood, the measurement process itself adds to the uncertainty. The following summarizes test equipment measurement uncertainty:

- Test Equipment Accuracy: Given a perfect connection, the test equipment has a rated measurement error. Depending on the test equipment, the rated accuracy typically varies from ±1.5% to ±5%. The elements of uncertainty contained within this accuracy rating are generally not discussed in manufacturers' literature.
- Test Equipment Calibration: The test equipment operating manuals usually provide little information regarding calibration requirements. Users of this test equipment should qualitatively assess instrument calibration with each use by verifying that the measurements are consistent for the cell size and type.
- Test Probes: Some test equipment is provided with more than one type of test leads. Differences in the resistance of the test leads can affect the measurement repeatability. In general, the same test leads should be used on all measurements to avoid these potential differences.
- Quality and Location of Test Connection: With some cell designs, access to the terminal post can be difficult, causing the internal ohmic measurement to include the effect of terminal connection hardware. Furthermore, the method of test probe connection varies among test equipment types. In some cases, a poor reading can be obtained without the user recognizing any deficiency in the test connection. Each measurement should be taken by the same test probe in the same location. A measurement can vary by changing the probe location around the terminal post.
- Analog Reading Accuracy: Some older test equipment is configured with an analog display scale. In this case, the minimum uncertainty in the reading is one-half of the minimum graduation. Depending of the battery under test, this can contribute up to 2% to the measurement uncertainty.
- Reading Stability: Depending on the battery, a measurement reading might take some period of time to stabilize. The user should wait until the reading fully stabilizes before recording the measurement.
- Float Versus Open Circuit Measurement: Different readings can be obtained between a float charge mode of operation versus open circuit. The results presented in this report are based on taking internal ohmic measurements with the cells on a float charge.
- Training: The information provided by this test equipment is not intuitive; additional background knowledge is needed to obtain a clear understanding of the measurements. Training on the use of this test equipment is a critical element for successful implementation of internal ohmic measurements.

3.4.3 Ripple Current Effects

Ripple current is the ac current that is superimposed onto the dc current applied to the battery. An unregulated battery charger is a common source of ripple current and voltage. Battery chargers normally have output capacitors to filter the rectified output current. As the capacitors age and eventually fail, the battery charger tends to produce larger levels of output ripple.

The impedance and conductance testers evaluated by this project make their measurements by applying an ac signal to the battery. If the ripple current is too large, it will interfere with the internal ohmic measurement. Ripple currents in excess of 30 amperes have been reported on large UPS systems, whereas the evaluated conductance and impedance testers generate a smaller signal.

Despite the potential problems caused by ripple currents, consistent measurements were obtained throughout the project. The conductance and impedance measurements correlated well with the Alber Cellcorder resistance measurements; the Cellcorder design is considered more resistant to ripple effects.

The applications evaluated by this project include electric utility generating stations, substations, and communications facilities. The test equipment evaluated by this project appears to be suitable for these applications.

4
ANALYSIS METHODS

Section 4 provides information regarding the types of analyses performed on internal ohmic measurements acquired for this project. In general, two types of analyses were performed:

- Direct comparisons of the internal ohmic measurements to calculated cell capacities—these analyses evaluated the level of observed correlation between internal ohmic measurements and capacity.
- Analysis techniques to identify low capacity cells— application of these methods when capacity data is available provides an opportunity to evaluate how well low capacity cells are identified.

The purpose of Section 4 is to describe the types of analyses performed. Subsequent sections provide specific results for different cell types.

4.1 Direct Comparison to Cell Capacity

A principal goal of this project was to evaluate the level of correlation between cell internal ohmic measurements and cell capacity. Although internal ohmic measurements were taken directly by test equipment, cell capacities were calculated based on the results of a capacity test. Therefore, the method by which cell capacity was determined is important to document for this project. This section describes the procedure used for calculating cell capacity and explains how the capacity was compared to internal ohmic measurements.

4.1.1 Calculating Battery Capacity

The battery capacity tests monitored by this project were typically constant current or constant power performance tests conducted at the 1-hour to 2-hour rate. Some nuclear plant tests were performed at the 4-hour rate. For a performance test, the battery capacity is calculated in accordance with IEEE standards by dividing the total test discharge time by the manufacturer's rated discharge time for a specified discharge current or power, as follows:

$$Percent\ Capacity\ at\ 77^{\circ}\,F = \frac{T_a}{T_s} \times 100$$

where,

T_a = Actual discharge time

T_s = Rated discharge time for the specified end voltage

Example 4-1

If a test at the 2-hour discharge rate continues for 2 hours and 15 minutes before the test termination criteria are reached, the calculated battery capacity is:

$$\frac{135\ minutes}{120\ minutes} \times 100 = 112.5\%$$

Example 4-2

If a test at the 2-hour discharge rate continues for only 1 hour and 30 minutes before the test termination criteria are reached, the calculated battery capacity is:

$$\frac{90\ minutes}{120\ minutes} \times 100 = 75.0\%$$

4.1.2 Calculating Cell Capacity

Internal ohmic measurements are taken on each cell in the battery rather than on the entire battery. For this reason, it is the individual cell capacity that is of interest when evaluating the correlation between internal ohmic measurements and capacity.

Calculating cell capacity can be straightforward if the cell voltage falls to the specified end voltage during the test. In this case, cell capacity is calculated in a manner similar to battery capacity. For example, if the test end voltage is 1.75 volts per cell, the cell capacity is calculated as the test discharge time divided by the manufacturer's rated discharge time for a specified discharge current or power, as follows:

$$Percent\ Capacity\ at\ 77^\circ F = \frac{T_a}{T_s} \times 100$$

where,

T_a = Actual discharge time until the cell reached its specified end voltage

T_s = Rated discharge time for the specified end voltage

This method works well for any cells that have their voltage fall below the specified end voltage during the test. However, for any battery capacity test, the battery will usually have a large proportion of the cells with a final voltage still well above the specified end voltage. If a cell's final voltage was 1.81 volts, but the specified end voltage was 1.75 volts, what is the cell capacity in this case?

Table 4-1 shows an example of actual capacity test data for a 24-cell battery. For this test at the 2-hour constant current rate, the specified end voltage was 1.75 volts and the test was terminated at 40 minutes because the battery overall voltage had fallen below an average of 1.75 volts per cell. Some cells have their voltage fall below 1.75 volts only a few minutes into the test. But, most cells maintain a voltage above 1.75 volts for the entire 40-minute test period.

Table 4-1
Typical Cell Voltages at the End of a Capacity Test

Cell Number	End Voltage	Cell Number	End Voltage	Cell Number	End Voltage
1	**1.60**	9	1.95	17	**0.87**
2	**1.48**	10	1.97	18	**1.70**
3	1.85	11	1.89	19	1.89
4	1.83	12	1.91	20	1.91
5	1.93	13	1.92	21	1.96
6	1.76	14	**1.51**	22	1.88
7	1.98	15	1.93	23	**1.14**
8	**1.42**	16	**1.69**	24	**1.64**

Table 4-1 illustrates the potential difficulties with the calculation of cell capacity:

- The battery capacity test might end well before the rated time because of a few low capacity cells.
- Cells with voltages higher than 1.75 volts do not necessarily have high capacity. Given that the test only lasted 40 minutes at the 2-hour rate, what voltage should we have expected for any high capacity cells?

Calculating capacity for cells with a final voltage above the specified end voltage involves the following steps:

1. Using the battery manufacturer's cell performance specifications, calculate how long the cell is expected to maintain the actual test discharge rate to a range of higher end voltages.

2. For the actual discharge test time, compare each cell final voltage at the end of the test to the expected time it should take to reach that voltage.

Table 4-2 provides an example of the manufacturer's cell performance specifications for the tested battery. In this case, the capacity test was performed at the 2-hour rate to an end voltage of 1.75 volts, corresponding to a rate of 109 amperes as shown on Table 4-2.

Table 4-2
Cell Performance Specifications for the Tested Battery

Discharge Time (minutes)	Discharge Rate to Specified End Voltage (amperes)				
	1.75	**1.80**	**1.84**	**1.88**	**1.95**
10	307	265	227	189	116
15	286	250	216	181	113
20	267	236	206	174	110
30	233	210	186	159	105
60	167	155	142	125	90
120	109	103	97	87	66

The specifications provided in Table 4-2 are plotted in Figure 4-1. The discharge rate was 109 amperes and Figure 4-2 shows the cell performance specifications with the y-axis scale zoomed to the area of interest.

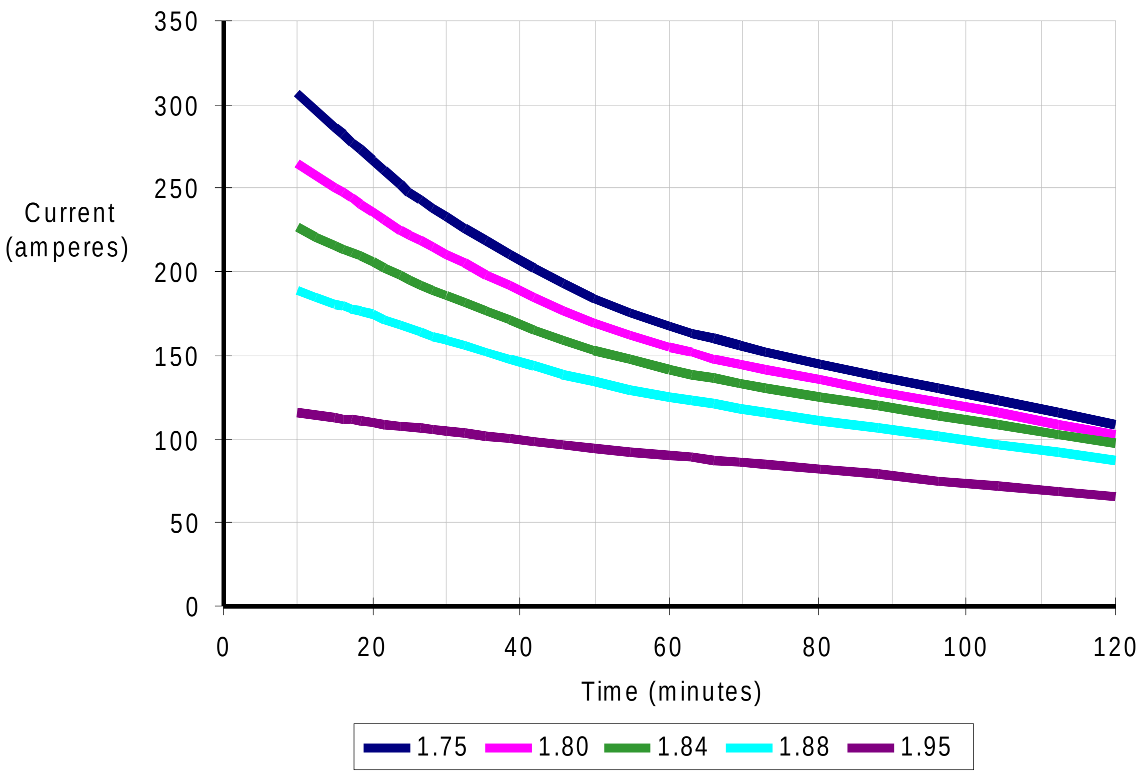

Figure 4-1
Cell Performance Specifications Plotted

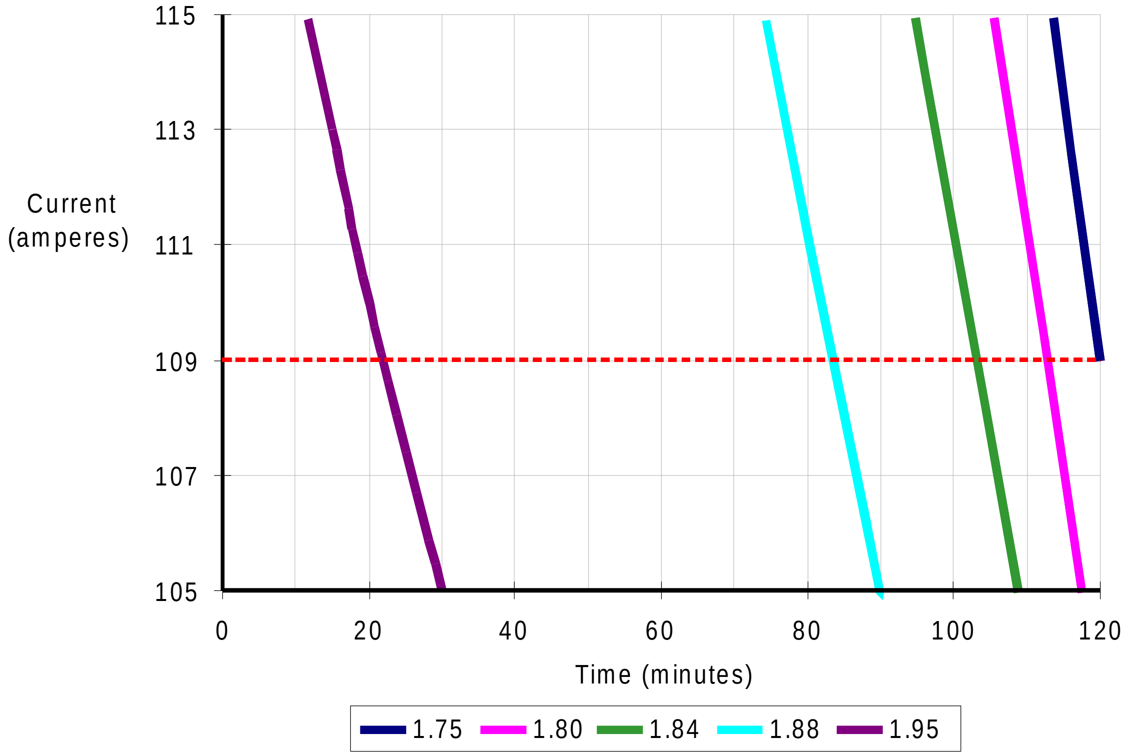

Figure 4-2
Cell Performance Specifications With Scale Zoomed

Figure 4-2 provides the information needed to calculate individual cell capacities at higher end voltages. For a discharge rate of 109 amperes, the rated discharge time to higher end voltages can be read directly from the graph. Table 4-3 provides these values. Finally, Figure 4-3 shows this information plotted so that the rated discharge time to intermediate voltages can be interpolated.

Table 4-3
Rated Discharge Time to Higher End Voltages at a Discharge Rate of 109 Amperes

End Voltage	Rated Discharge Time at 109 Amperes (minutes)
1.95	22
1.88	84
1.84	103
1.80	113
1.75	120

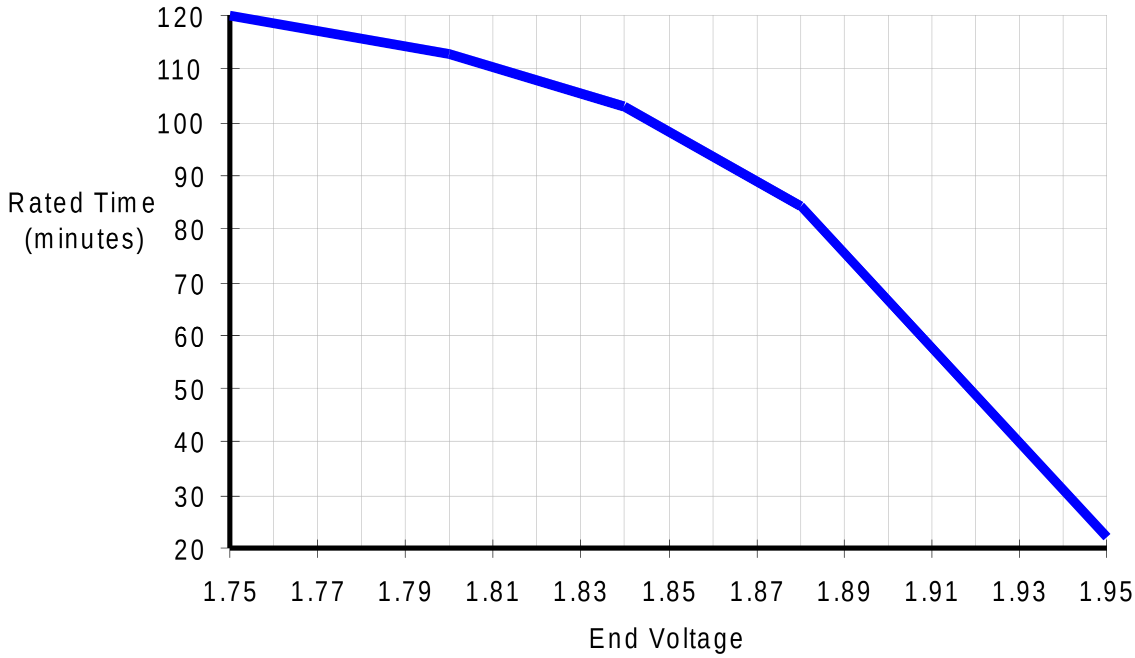

Figure 4-3
Rated Time to End Voltage at a Discharge Rate of 109 Amperes

Figure 4-3 is important in that it takes the battery manufacturer's cell performance specifications and determines an expected discharge time to a specified end voltage *at a particular discharge rate*. Notice that an entirely different graph would be derived if the discharge rate varied from the 109 amperes applied in this example. Also, a different graph would be needed for different cell sizes or cell types. In other words, the graph developed in Figure 4-3 is unique to the cell size, cell type, and discharge rate.

Using the information from Figure 4-3, a chart of rated discharge time for the entire range of end voltages of interest can be created. Table 4-4 depicts such results. Referring to Table 4-4, at a discharge rate of 109 amperes, the rated time for cell voltage to fall to 1.75 volts is 120 minutes, to 1.80 volts is 113 minutes, and to 1.89 volts is 75 minutes.

Table 4-4
Rated Time to End Voltage at a Discharge Rate of 109 Amperes

End Voltage	Rated Discharge Time (minutes)	End Voltage	Rated Discharge Time (minutes)
1.75	120.0	1.86	93.5
1.76	118.5	1.87	89.0
1.77	117.0	1.88	84.0
1.78	116.0	1.89	75.0
1.79	114.5	1.90	66.5
1.80	113.0	1.91	57.5
1.81	110.5	1.92	48.5
1.82	108.0	1.93	40.0
1.83	105.5	1.94	31.0
1.84	103.0	1.95	22.0
1.85	98.5		

With the information provided in Table 4-4, individual cell capacities can be calculated. Table 4-1 provides the capacity test results; this particular test lasted only 40 minutes before overall battery voltage fell to an average of 1.75 volts per cell. If the cell voltage at the end of 40 minutes was 1.85 volts, the cell capacity is calculated as follows:

$$Percent\ \ Capacity = \frac{T_a}{T_s} \times 100 = \frac{40.0}{98.5} \times 100 = 40.6\%$$

Notice that the cell capacity is still quite low, even though the end voltage was relatively high. Given that this particular capacity test lasted only 40 minutes, Table 4-4 shows that the expected end voltage for 100% capacity is 1.93 volts. The capacity is calculated for the evaluated range of final voltages and tabulated as shown in Table 4-5. This table provides the data needed for a correlation analysis. For this particular test, Table 4-5 shows the equivalent capacity for each final voltage.

Table 4-5
Calculated Capacity at a Discharge Rate of 109 Amperes for 40 Minutes

End Voltage	Capacity (percent)	End Voltage	Capacity (percent)
1.75	33.3	1.86	42.8
1.76	33.8	1.87	44.9
1.77	34.2	1.88	47.6
1.78	34.5	1.89	53.3
1.79	34.9	1.90	60.2
1.80	35.4	1.91	69.6
1.81	36.2	1.92	82.5
1.82	37.0	1.93	100.0
1.83	37.9	1.94	129.0
1.84	38.8	1.95	181.8
1.85	40.6		

The final step is to compare the internal ohmic measurements taken before the capacity test to the individual cell capacities. Table 4-6 shows the results. Figure 4-4 shows the correlation between impedance and capacity for this test. Figure 4-5 shows the correlation between conductance and capacity for this test.

Table 4-6
Internal Ohmic Measurements Taken Before the Capacity Test

Cell Number	Impedance (milliohm)	Conductance (kmho)	Capacity (percent)	Cell Number	Impedance (milliohm)	Conductance (kmho)	Capacity (percent)
1	1.020	0.908	7.5	13	1.890	0.465	82.5
2	1.030	0.946	1.3	14	1.090	0.851	6.7
3	1.510	0.601	40.6	15	1.980	0.450	100.0
4	1.550	0.589	37.9	16	1.190	0.802	15.0
5	1.970	0.455	100.0	17	0.611	1.620	0.4
6	1.350	0.682	33.8	18	1.150	0.801	15.0
7	2.280	0.377	135.0	19	1.590	0.558	53.3
8	0.970	0.992	2.5	20	1.800	0.492	69.6
9	2.050	0.430	130.0	21	2.030	0.415	132.0
10	2.090	0.421	134.0	22	1.690	0.524	47.6
11	1.650	0.551	53.3	23	0.777	1.240	0.4
12	1.860	0.484	69.6	24	1.130	0.782	17.5

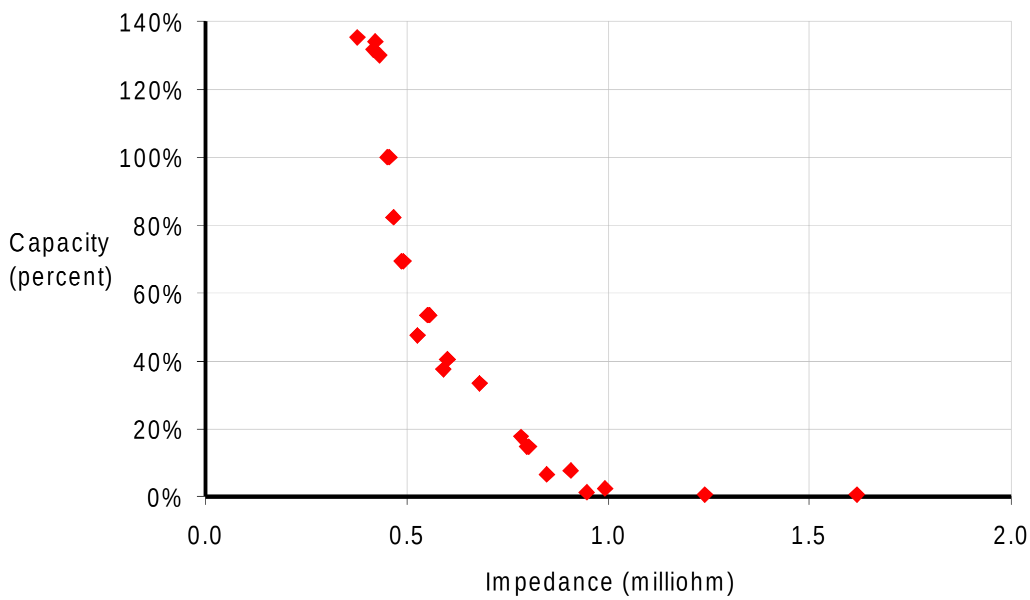

Figure 4-4
Graph of Cell Capacity Versus Impedance Measurements

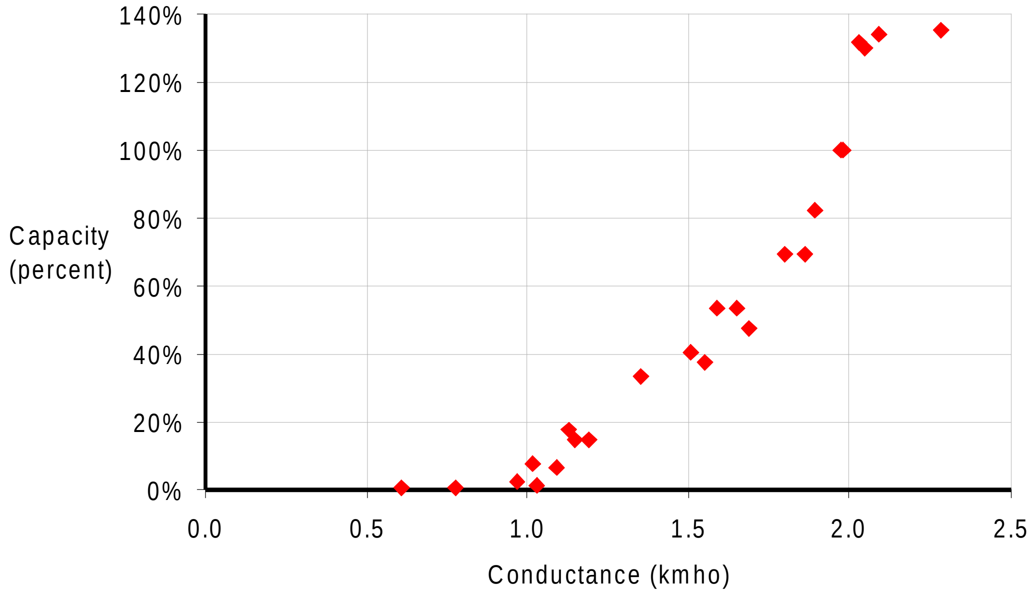

Figure 4-5
Graph of Cell Capacity Versus Conductance Measurements

The above process evaluated the test data for each capacity test in this project. Unfortunately, there is no straightforward method of automating the above analysis. Each set of calculated capacities is unique to the evaluated cell type, cell size, and discharge time. The evaluation process is the same regardless of whether the test ends before the rated discharge time (battery has less than 100 percent capacity) or after the rated discharge time (battery has greater than 100 percent capacity). The other types of analyses performed by this project relied on the individual cell capacities calculated here.

4.1.3 Effect of Temperature Variations

The capacity tests performed as part of this project usually had the test discharge rate corrected for temperature in accordance with the applicable IEEE standards. Given that the test discharge rate was adjusted for the actual battery temperature, no further adjustment is needed for the cell capacity calculation. In this case, the cell capacity calculation is based on the intended discharge rate before any adjustment for temperature.

4.1.4 Uncertainty of Cell Capacity Calculation

Section 3.4 describes measurement uncertainty considerations related to internal ohmic measurements. No measurement is free of error and internal ohmic measurements have several sources of error that contribute to measurement variability.

Test results provided in this report routinely exhibit data scatter. The sources of measurement uncertainty described in Section 3.4 certainly contribute to the data scatter when evaluating the correlation between cell resistance and cell capacity. The method by which cell capacity is calculated also contributes to the data scatter. Examples of uncertainty in the calculated cell capacity include:

- The battery manufacturer's cell performance specifications are assumed to be entirely accurate. Errors in manufacturer's specifications are occasionally identified. In some cases, the manufacturer has interpolated the data between tested cell sizes. Often, the performance is assumed to be completely linear as a function of number of positive plates, which can cause errors on the order of a few percent. Sometimes, the cell performance specifications are very conservative, which then leads to high calculated cell capacities.
- Some battery manufacturer's cell performance specifications have not been updated for over 20 years and the degree to which the specifications match current product performance is not known.
- Cells that have voltage fall below the specified end voltage during a test have their capacity calculated as the time at which cell voltage fell to the end voltage divided by the rated time. This approach is reasonable as long as voltage slowly and consistently declines during discharge, eventually reaching the end voltage. But, not all cells behave the same during discharge. For example, some VRLA cells have their voltage fall almost immediately below 1.75 volts during a capacity test, but then voltage occasionally stabilizes at some lower value for the duration of the test. What is the capacity of a cell that has its voltage fall to 1.75 volts immediately into a test, but stabilizes at 1.50 volts for the next hour of the test?
- Data is interpolated between points provided by the manufacturer. A review of manufacturer's data will usually show a *break point*, beyond which the data has a completely different slope. Interpolations in this region likely have error.
- High final voltages create unrealistically high capacities. Table 4-5 clearly illustrates this effect. Notice that a final voltage of 1.90 yielded 60.2 percent, 1.93 yielded 100.0 percent, and 1.95 yielded 181.8 percent. Once the final voltages are above the break point mentioned above, the manufacturer's cell performance specifications produce very large changes in capacity for small changes in final voltage. In some cases, this can produce calculated capacities of well over 250 percent, which is unlikely to be true. This particular feature in the cell performance specifications causes considerable data scatter for the high capacity cells. This problem was usually encountered in tests in which the battery failed early in the test because of a few low capacity cells, but the remaining cells still had high final voltages. For this project, cell capacities were artificially assumed to approach 135 to 140 percent capacity at very high final voltages.

Section 1.2 provides the statement of this project's research goal:

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

Despite the above contributions to error and uncertainty, a correlation could usually be identified despite the potential sources of data scatter described earlier. The *low capacity* cells were always identified by the internal ohmic measurements, supporting a successful completion of the stated research goal.

4.2 Percent Change from Nominal Value

4.2.1 Internal Resistance Variation as a Function of Cell Size

The *nominal value* is the typical internal ohmic value of a cell with 100% (or better) capacity. The nominal value is sometimes called the reference value. The nominal value varies with the cell size and type, and can vary significantly as shown below:

- Less than 0.2 milliohms for a large cell
- Over 1.0 milliohms for a smaller cell
- Over 2.0 milliohms for a 6-V to 12-V module

The variation in internal ohmic values is distinctly different than the variation observed in other cell parameters such as voltage or specific gravity. For a fully charged cell, voltage and specific gravity will typically exhibit little variation, regardless of the cell size. However, the internal ohmic value will be significantly different for each cell size. For this reason, users of internal ohmic test equipment should have some understanding of the cell's expected (or nominal) internal ohmic value before taking a measurement.

The nominal value varies with cell size (ampere-hour rating and type) as well as with manufacturer-specific design features. For this reason, there is not a single internal ohmic value that applies to all cells of a particular size. For example, there is not a single internal ohmic value that can be used for all 100 ampere-hour lead-acid cells, regardless of manufacturer or model. There tends to be variation between cell models, even when they have the same capacity rating. But, different model cells of a particular size typically fall within a certain range. Figure 4-6 shows the typical impedance variation as a function of ampere-hour rating in smaller lead-acid cells; this information is based on measurements taken with the AVO MBITE. Referring to Figure 4-6, it is expected that a general purpose 200 ampere-hour cell to have nominal impedance within the range of 0.6 milliohms to 1.0 milliohms. Although, there is variation between cell models, it is not generally expect that a 200 ampere-hour cell to have a nominal impedance of either 0.2 milliohms or 2.5 milliohms; both values are outside the typical range.

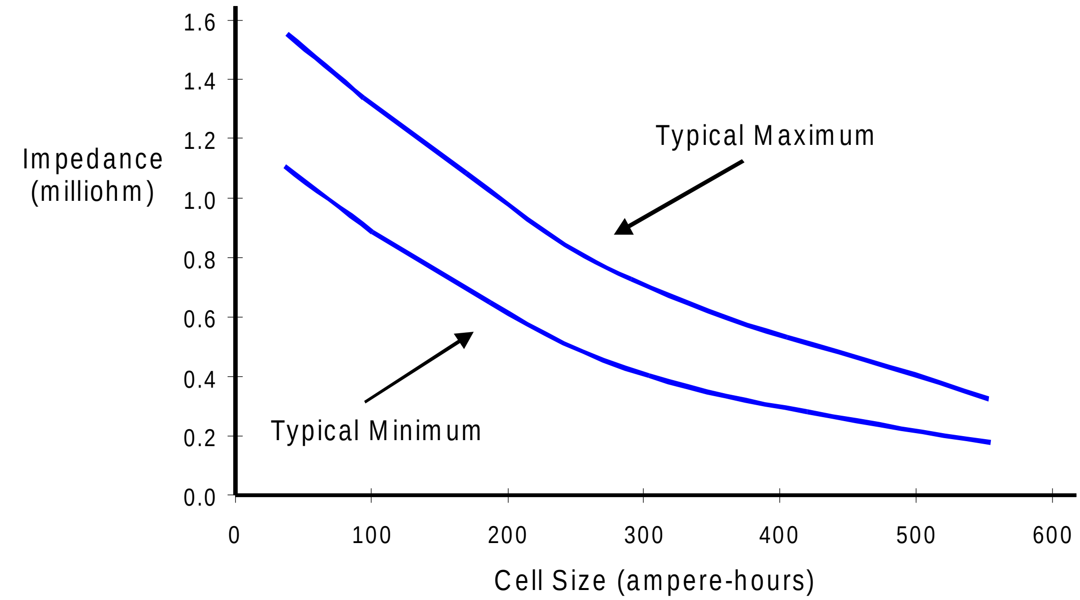

Figure 4-6
Typical Nominal Impedance Variation in Lead-Acid Cells

The typical variation in nominal resistance measurements is shown in Figure 4-7; this information is based on measurements taken with the Alber Cellcorder. As expected, the shape of the curves follows the shape of the nominal impedance curves.

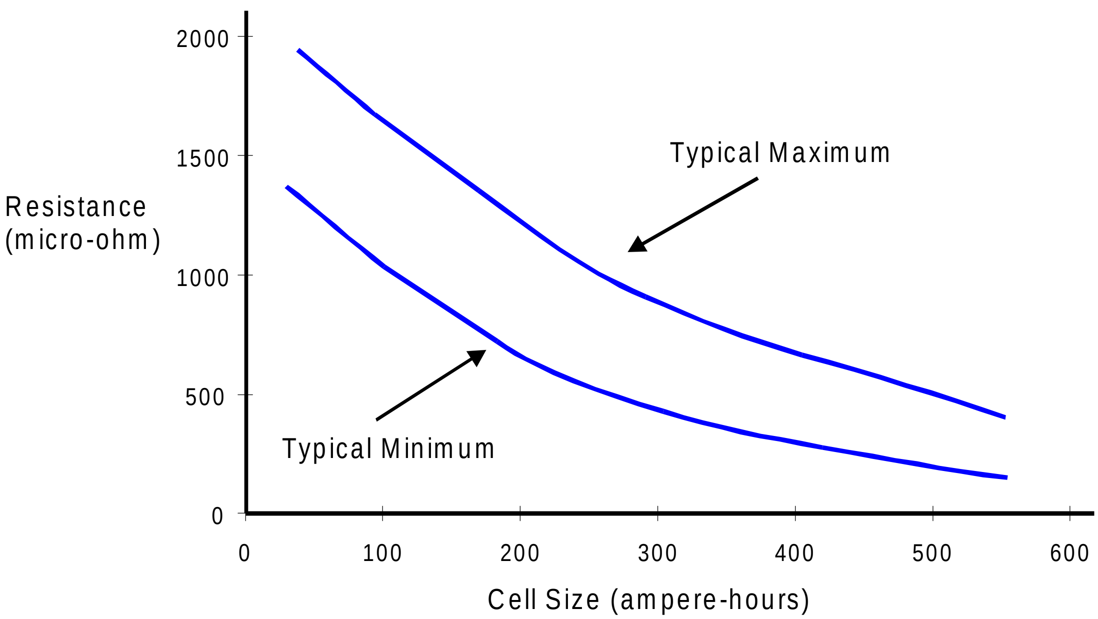

Figure 4-7
Typical Nominal Resistance Variation in Lead-Acid Cells

Figure 4-8 shows the typical variation in the nominal conductance; this information is based on measurements taken with the Midtronics Celltron Plus.

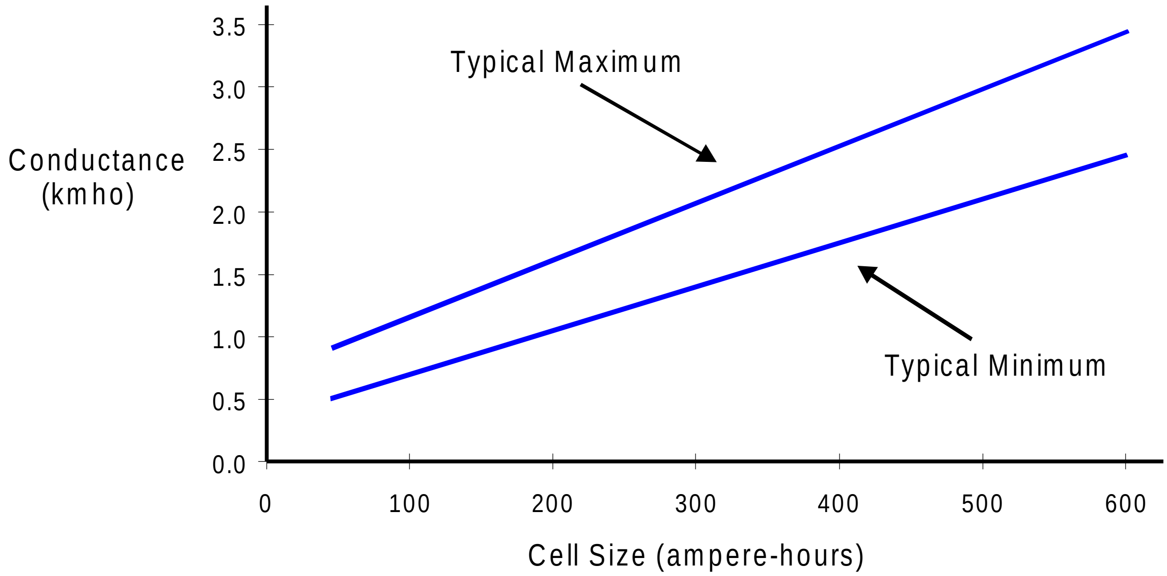

Figure 4-8
Typical Nominal Conductance Variation in Lead-Acid Cells

The typical values shown in Figures 4-6 through 4-8 provide some insight into how internal ohmic values vary as a function of cell size for the general purpose batteries typically used in electric utility applications. However, exceptions to the ranges shown in Figures 4-6 through 4-8 do exist. For example, cells designed specifically for high-rate applications likely have a much lower nominal resistance for a given ampere-hour rating.

4.2.2 Calculating the Nominal Value

For this project, nominal values were estimated based on the results of a capacity test. Individual cell capacities were calculated as described in Section 4.1. The internal ohmic measurements for that battery were plotted versus the cell capacities as shown in Figure 4-9. The best estimate of the nominal value was then determined from the graph.

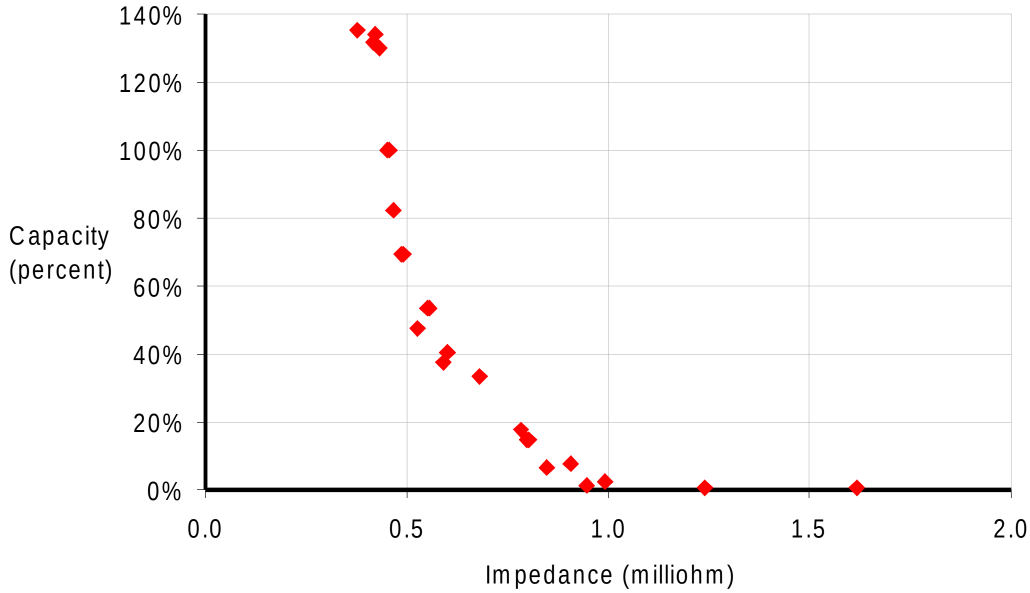

Figure 4-9
Graph of Cell Capacity Versus Impedance Measurements

Referring to Figure 4-9, the following observations can be made regarding this particular battery:

- A clear correlation between cell capacity and cell impedance is shown, particularly for the low capacity cells.
- All cells with an impedance greater than 0.9 milliohms had a negligible capacity.
- All cells with an impedance greater than 0.5 milliohms had low capacity.
- The nominal impedance appears to be about 0.42 milliohms.

The best estimate of nominal impedance based on this particular test is 0.42 milliohms. But, additional test data is necessary in this instance before this nominal impedance is used. The following contributes to our uncertainty:

- The battery had a low capacity and there are only a few high capacity cells.
- Trying to estimate cell capacity for high final voltages likely includes considerable error if the battery fails early into a capacity test (refer to Section 4.1.4).
- The slope of the capacity/impedance curve is very steep between 0.4 milliohms to 0.5 milliohms.
- This battery was 5 years old at the time of the test.

In this case, additional data would be needed to confirm the nominal impedance. Notice that the uncertainty in the nominal impedance does not rule out claims regarding the low capacity cells – all cells with an impedance greater than 0.5 milliohms had low capacity. Similar results were obtained for resistance measurements. Figure 4-10 shows the conductance measurements plotted versus the individual cell capacities.

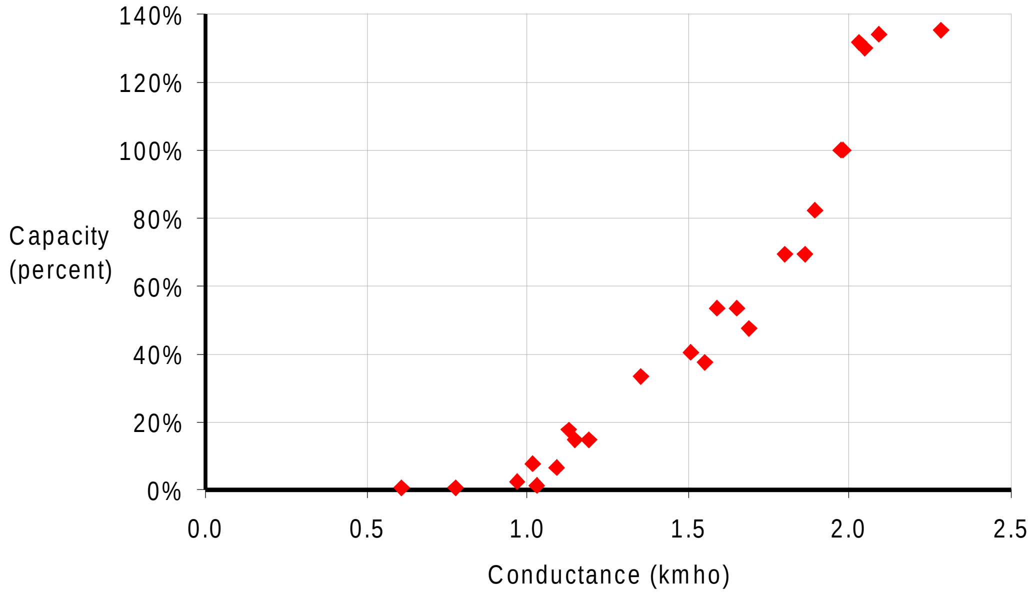

Figure 4-10
Graph of Cell Capacity Versus Conductance Measurements

Referring to Figure 4-10, the following observations can be made regarding this particular battery:

- A clear correlation between cell capacity and cell conductance is shown, particularly for the low capacity cells.
- All cells with a conductance less than 1.3 kmho had a negligible capacity.
- All cells with a conductance less than 1.8 kmho had low capacity.
- The nominal conductance appears to be about 2.1 kmho.

A nominal conductance of 2.1 kmho is our best estimate based on this particular test. But, additional test data is necessary in this instance before one could use this nominal conductance with confidence.

Section 4.2.2 illustrates the process by which nominal internal ohmic values were obtained based on actual test data.

4.2.3 Possible Changes in the Nominal Value of New Cells

Understanding the internal ohmic behavior of a new cell first requires a short discussion of the plate manufacturing process for lead-acid cells. The *pasted flat plate* is the most common design for lead-acid cells. When a pasted flat plate is assembled, lead oxide (PbO) paste is applied to a lead-alloy grid structure, and then allowed to dry in place. The lead oxide paste is called the active material and a grid structure containing the active material is a plate. Figure 4-11 shows typical pasted flat plates with the active material in place.

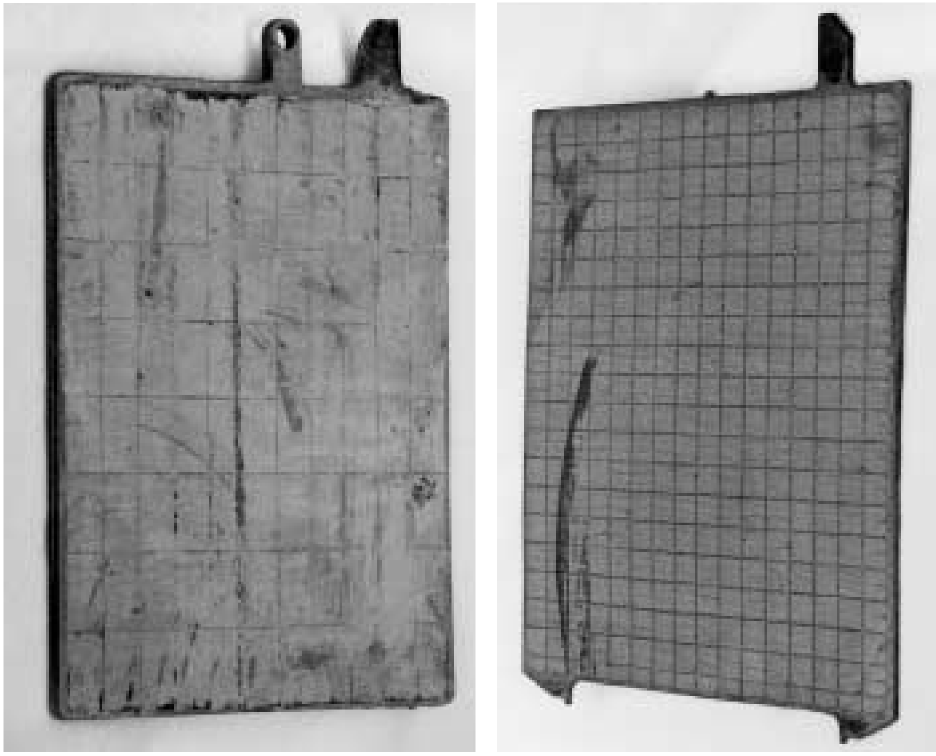

Figure 4-11
Typical Pasted Flat Plates

After the lead oxide paste has dried, the plates are immersed in a dilute sulfuric acid solution and current is passed through them, with opposite polarities for the positive and negative plates. Figure 4-12 shows an example of a cell about to receive its formation charge at the factory. The lead oxide (PbO) is converted to lead dioxide (PbO_2) in the positive plates and to lead (Pb) in the negative plates. This process is referred to as plate *formation* and is a critical part of the manufacturing process. Because of the time and expense involved with the formation process, the plates are not normally fully formed on delivery. Instead, the manufacturer forms the plates well enough so that the battery is usually capable of meeting 90% or better of its rated capacity. The formation process actually finishes after the battery is installed and placed on a float charge. Typically, several months of float charge or a few charge/discharge cycles are needed to complete the formation process.

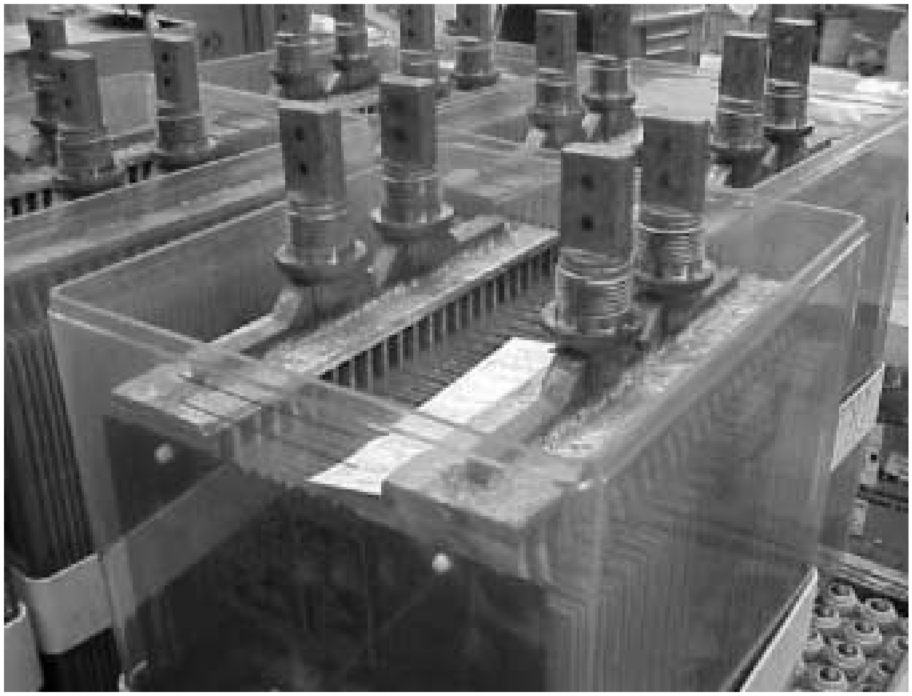

Figure 4-12
Formation Process at Factory

The plate formation process described above does have an impact on internal ohmic measurements. Because the plates are not fully formed upon initial installation, internal ohmic measurements taken at this time might not be representative of the battery after its first year of service; the internal ohmic measurements might improve. For example, Table 4-7 shows the improvement measured on an Alcad SD-11 lead-selenium battery after installation. As can be seen, the conductance and impedance both improved significantly after installation. In this particular case, the battery was on continuous float charge and was discharged twice by capacity tests.

Table 4-7
Example Internal Ohmic Value Change on a New Battery

Type of Measurement	Average Value on Installation	Average Value After 2 Months	Average Value After 1 Year
Conductance (kmho)	2.16	2.30	2.60
Impedance (milliohm)	0.46	Not Recorded	0.40

Table 4-7 illustrates the changes that might be observed on a new battery. Users should recognize that internal ohmic measurements can improve as the cells complete their formation process under float charge. The *nominal value* (the typical internal ohmic value of a cell with 100% capacity, or better) should be adjusted as these improvements are noted.

4.2.4 Evaluating Changes from the Nominal Value

Users of internal ohmic test equipment will often take periodic measurements without the benefit of corresponding capacity test results. The analyses performed in support of this project anticipated this type of application by considering the following:

- Internal ohmic measurements were compared directly to capacity test results as part of the correlation analysis.
- Using the test results, internal ohmic nominal values were determined for each cell model.
- The percentage change in the internal ohmic measurements was considered in relation to the percentage change in capacity.
- Using the above information, general assessments of the meaning of the change in internal ohmic measurements were completed.

Subsequent sections describe the results for the evaluated cell types.

4.3 Slope Analysis Method

4.3.1 Basis for the Method

The slope analysis method was developed by Pete Langan of AVO International for the evaluation of impedance data. The purpose of this method is to identify the presence of low capacity cells by evaluating only the impedance measurements taken on the battery's cells. The approach is equally applicable to resistance or conductance data.

The slope analysis method is performed as follows:

1. Take internal ohmic measurements on all cells in the battery.
2. Arrange the data in order of ascending impedance or resistance (decreasing conductance).
3. Plot the data as a line graph. A significant slope in the plotted data or a substantial change in the slope likely indicates the presence of low capacity cells. The cells with the highest impedance or resistance (lowest conductance) probably have the lowest capacity.

To illustrate the method, typical data for an acceptable capacity battery and for a low capacity battery will be shown. Figure 4-13 shows typical impedance data for a good battery; the graph was developed by the method described in Section 4.1. As shown, all cells have a capacity near 100 percent. Figure 4-14 shows the impedance data plotted in ascending order (for convenience, the capacity data is also plotted). Notice that the impedance data exhibits little change. This seems to be typical for a battery with high capacity cells.

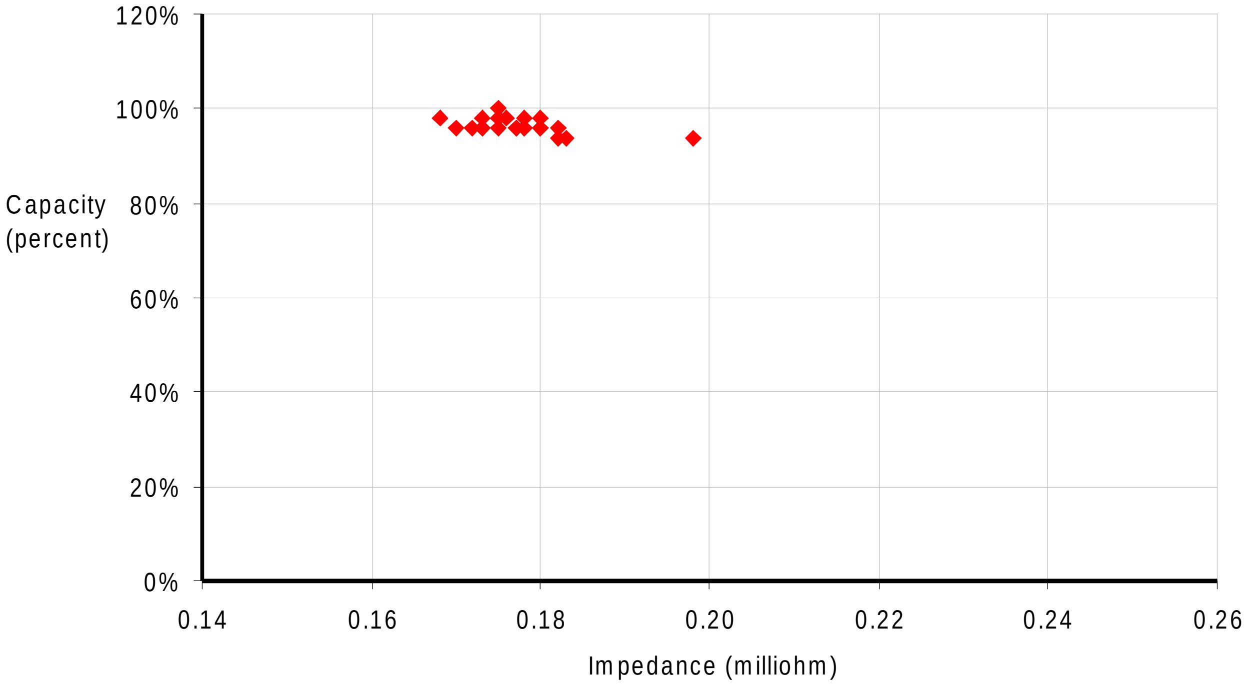

Figure 4-13
Typical Capacity Test Results for an Acceptable Capacity Battery

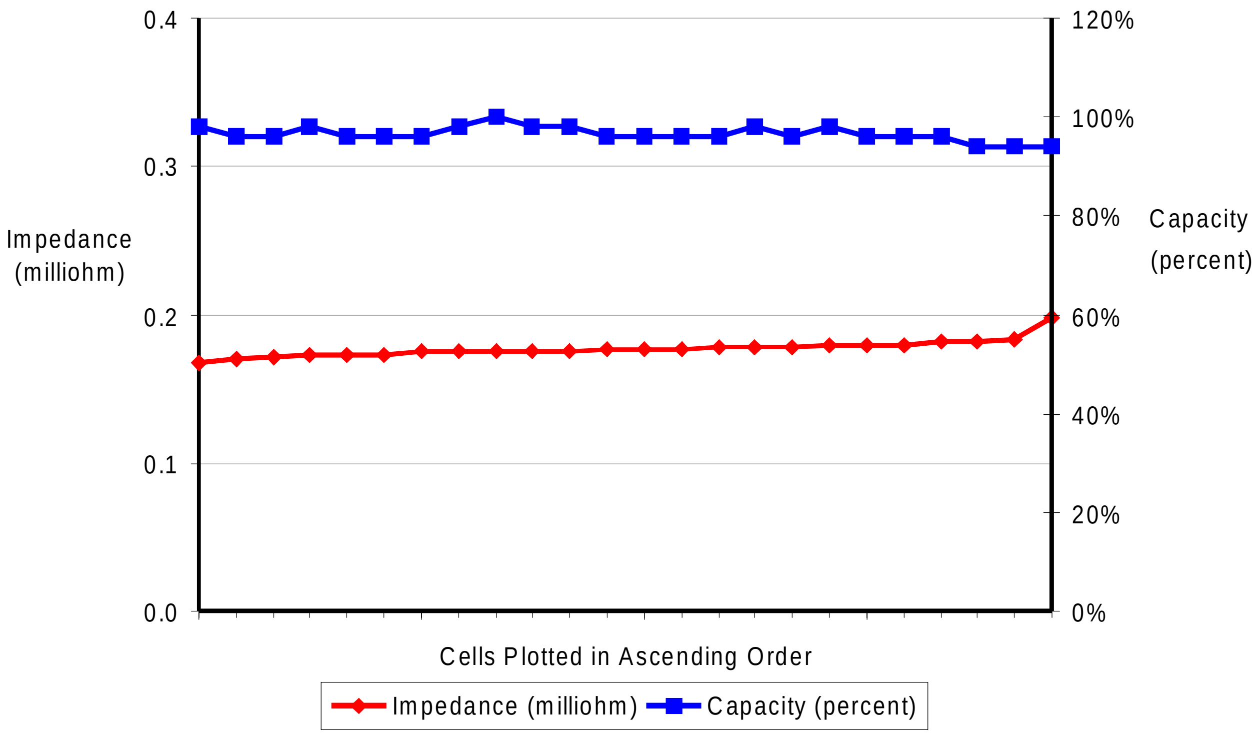

Figure 4-14
Impedance Data Slope Analysis Graph for an Acceptable Capacity Battery

Figure 4-15 shows the typical impedance data for a low capacity battery. Notice that many cells have less than 20 percent capacity and only a few cells have a high capacity. Figure 4-16 depicts the impedance data plotted in ascending order. As can be seen, the data has an obvious positive slope, with a substantial change in impedance. Figures 4-17 and 4-18 show equivalent results for resistance and conductance measurements, respectively.

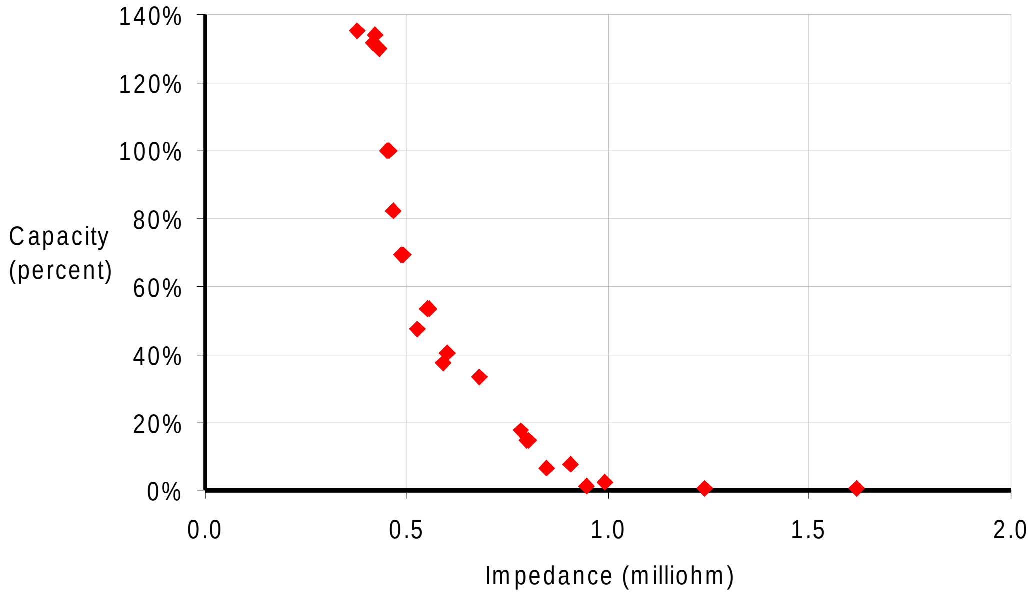

Figure 4-15
Typical Capacity Test Results for a Low Capacity Battery

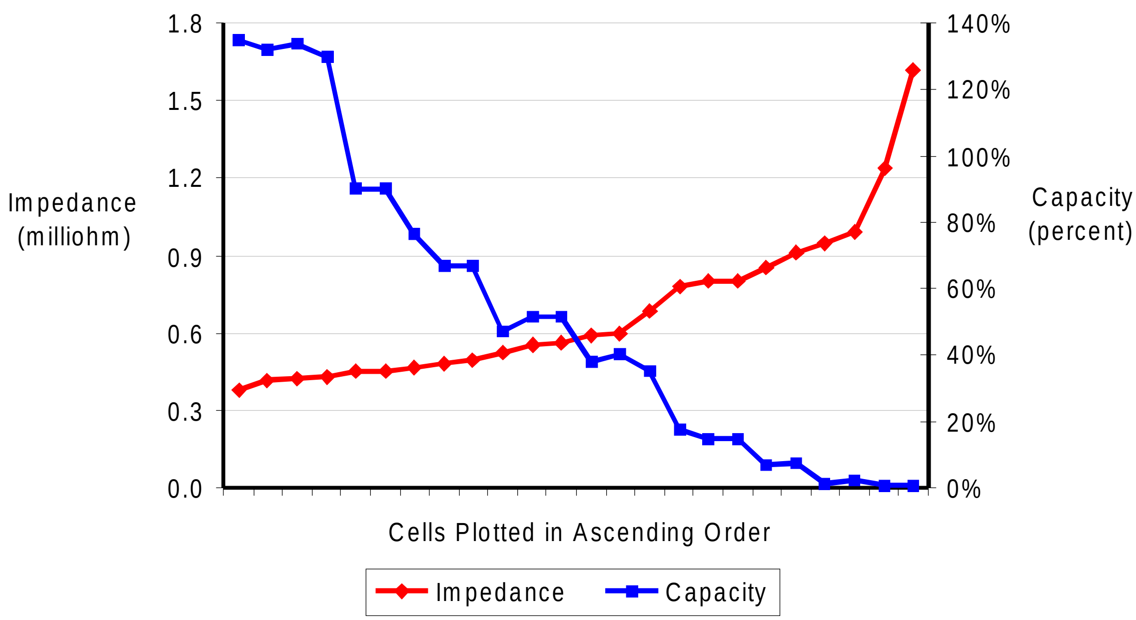

Figure 4-16
Impedance Data Slope Analysis Graph for a Low Capacity Battery

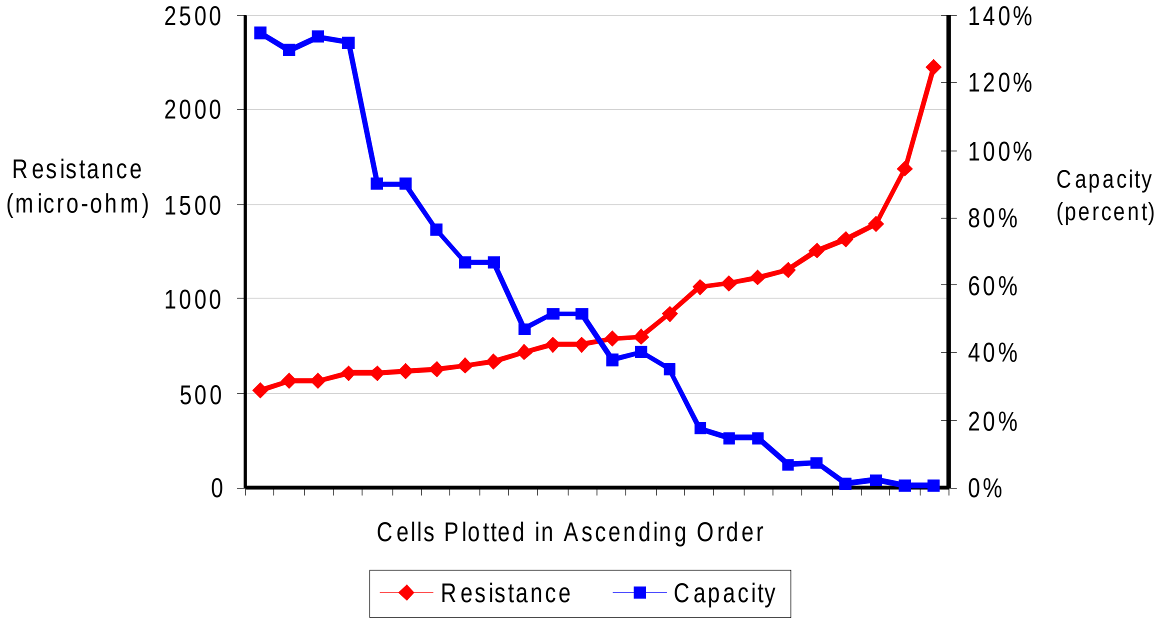

Figure 4-17
Resistance Data Slope Analysis Graph for a Low Capacity Battery

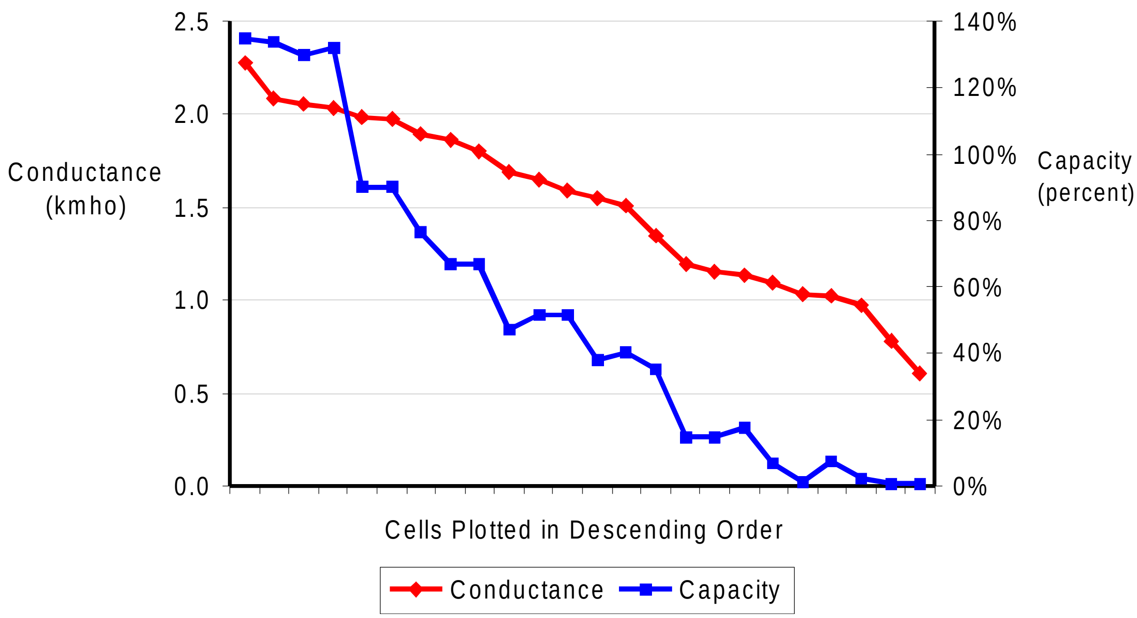

Figure 4-18
Conductance Data Slope Analysis Graph for a Low Capacity Battery

This simple graphical approach could be translated in tabular form, but the trend tends to be more apparent when shown graphically. The analysis method is easily adapted into a template form in which all data is pasted into a spreadsheet, and all calculations and graphs are automatically generated. The above figures show the corresponding capacity data, which would not be available if a capacity test was not performed. Instead, changes in the slope of the data would be taken as an indication of the potential presence of low capacity cells.

4.3.2 Application to Project Data

For the capacity test data obtained in support of this project, the internal ohmic measurements were plotted to determine if the slope analysis method generally identified low capacity cells. In order to be successful, the slope analysis method relies on variability in the measurements as an indicator of low capacity. If it is possible to have a low capacity battery, yet have very consistent internal ohmic measurements, the slope analysis method would not be effective for these cases. For this reason, the project test data were evaluated by the slope analysis method to determine if these types of cases were common. The final report will discuss the results for each type of battery.

4.4 Simple Statistical Analysis

Usually, internal ohmic measurements will be recorded and saved in a spreadsheet program, such as Microsoft Excel. Simple statistics can be calculated for the data and can provide insight into the overall likelihood of low capacity cells. The following statistics were obtained in this project:

- Mean
- Median
- Standard deviation
- Minimum
- Maximum

Similar to the slope analysis method, these simple statistics consider the overall variability in the data as an indicator of the presence of low capacity cells. The final report will provide the results for each battery type in terms of how the statistics tended to vary between high capacity batteries and low capacity batteries.

5
TEST RESULTS FOR VRLA CELLS

Section 5 provides a summary of the project test results for VRLA cells. The project results are presented from different perspectives so that users can understand the relationship between internal ohmic measurements and cell capacity under various conditions.

5.1 Evaluated Batteries

Internal ohmic measurements were obtained on over 6,000 VRLA cells. In most cases, capacity data was 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.

Figure 5-1 shows the proportion of evaluated VRLA cells sorted by manufacturer. Table 5-1 lists the specific battery models included in this test program.

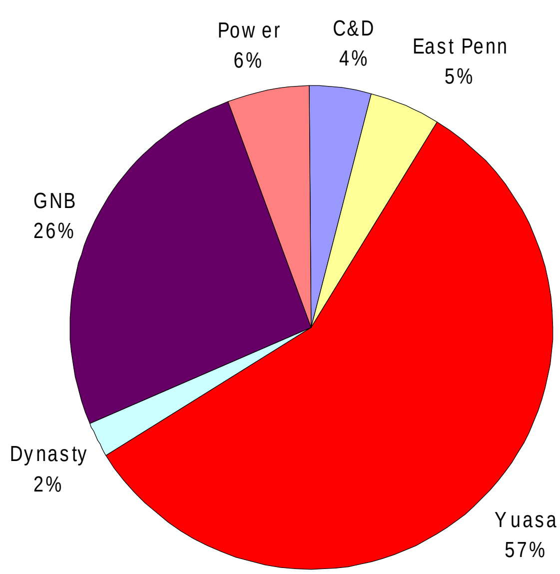

Figure 5-1
Proportion of VRLA Cells by Manufacturer

Table 5-1
VRLA Cell Models Included in Test Program

C&D	Yuasa	GNB		Dynasty	Power	East Penn
2LSX17	2SD-35	45A05	75A15	UPS12-270	PRC1235	3AVR85
LS12-25	DC60-9	45A07	75A17	UPS12-310	PRC12150	
LS12-55	DD85-33	50A07	75A23	UPS12-370	TC1280X	
LS12-100	DM80	50A09	75A27			
LS6-200	NPX-150R	50A13	90A07			
HDL-300		75A05	90A13			
HDL-440		75A07	90A21			
		75A11	100A23			
		75A13	100A29			
			100A33			

5.2 Test Equipment Correlation

Representative test instrument were used for each type of ohmic measurement. Section 3 discusses the test equipment used by this project. The test instruments used were:

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

The results presented here are based on measurements taken by the test instruments. As discussed in the previous sections, these instruments measure some form of a cell's internal resistance. However, the method of measurement and the circuit design varies in each case. It is important to understand that the evaluated instruments do not provide *exactly* the same measurement of a cell's internal resistance; each instrument produces a different measurement value because of differences in the instrument's circuit design, the test frequency, and the level of signal filtering. Despite these design differences, typically a strong correlation was observed between the conductance, impedance, and resistance measurements.

Even though the instruments do not produce the same reading on a cell, the measurements between instruments could be linearly correlated. Figures 5-2 through 5-4 show the typical correlation observed between the instruments. Remember that conductance is related to the inverse of impedance and resistance. By plotting the conductance data versus the inverse of impedance or resistance, generally a linear correlation was observed for the batteries evaluated by this project. The graph of impedance versus resistance consistently showed a linear correlation. Figures 5-5 through 5-7 show the correlation observed when data scatter was present. Even in these cases, a clear correlation between instruments can be determined.

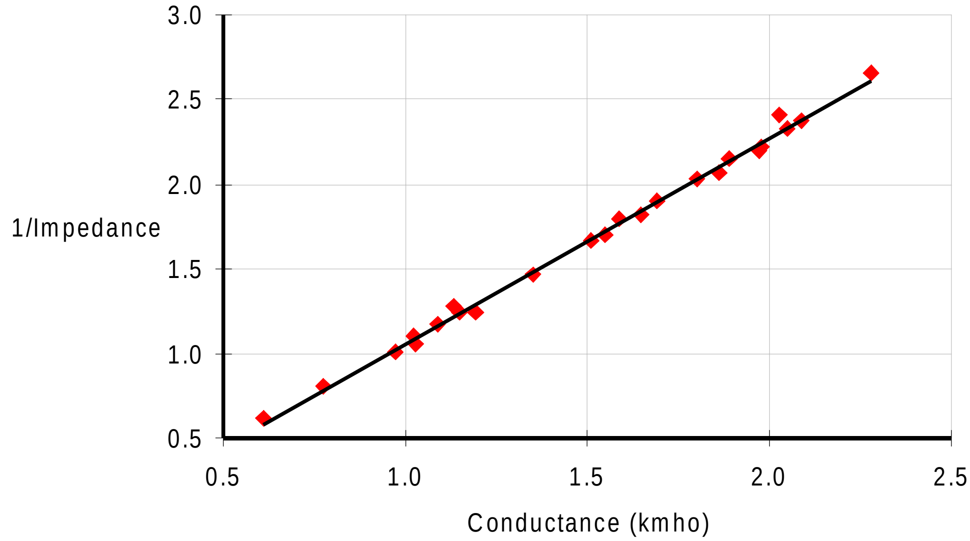

Figure 5-2
Typical Correlation of Conductance to Impedance

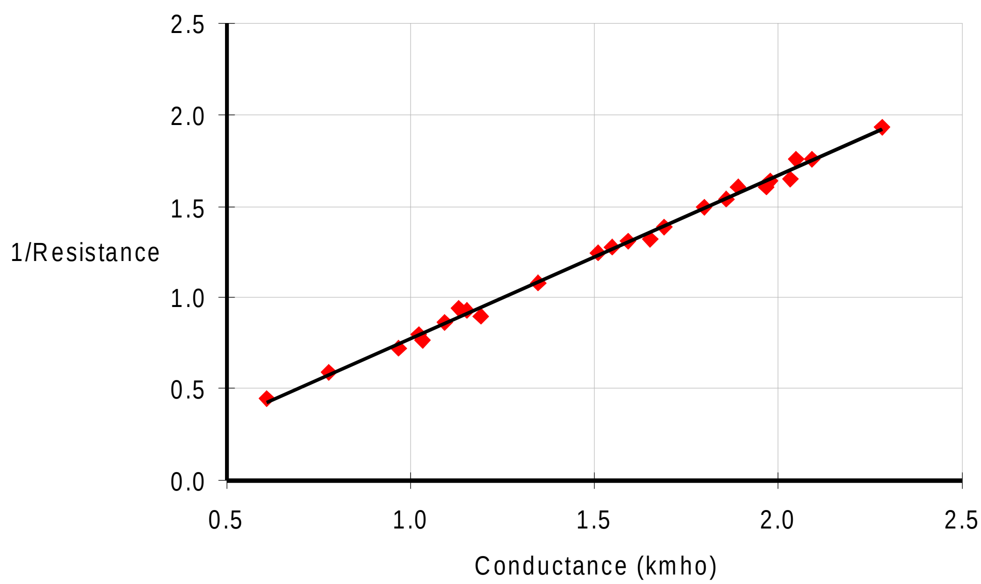

Figure 5-3
Typical Correlation of Conductance to Resistance

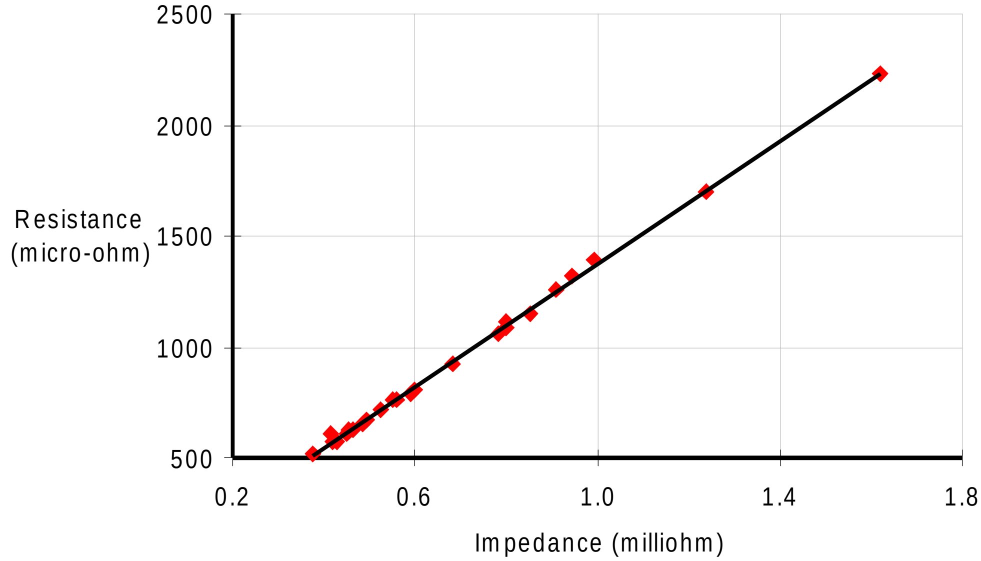

Figure 5-4
Typical Correlation of Impedance to Resistance

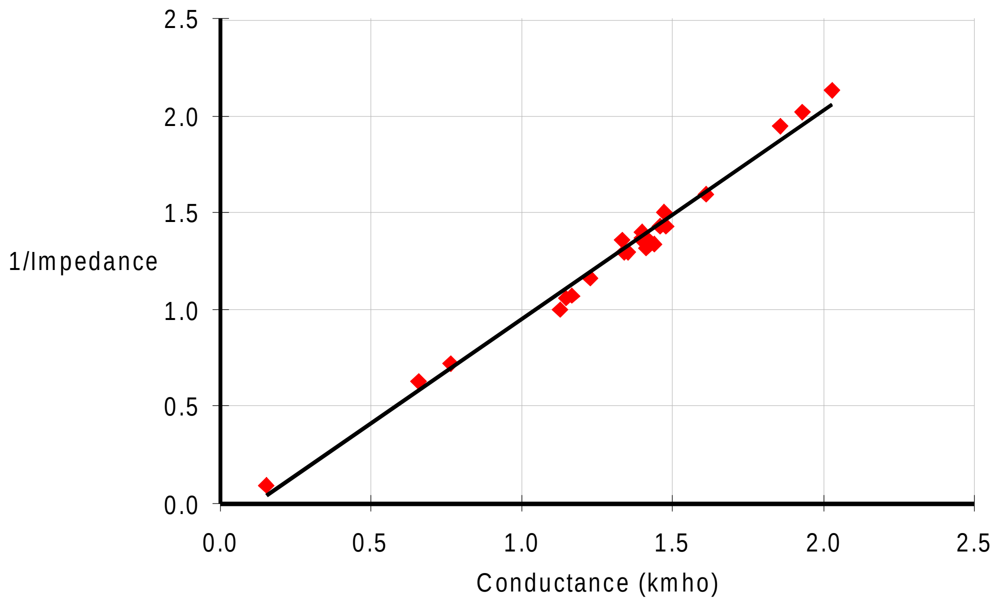

Figure 5-5
Typical Correlation of Conductance to Impedance—More Data Scatter

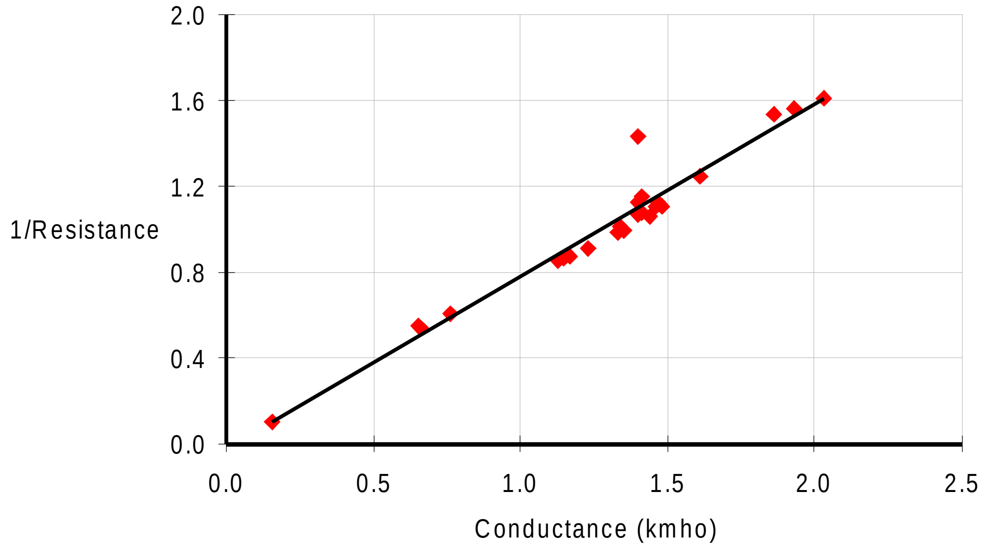

Figure 5-6
Typical Correlation of Conductance to Resistance—More Data Scatter

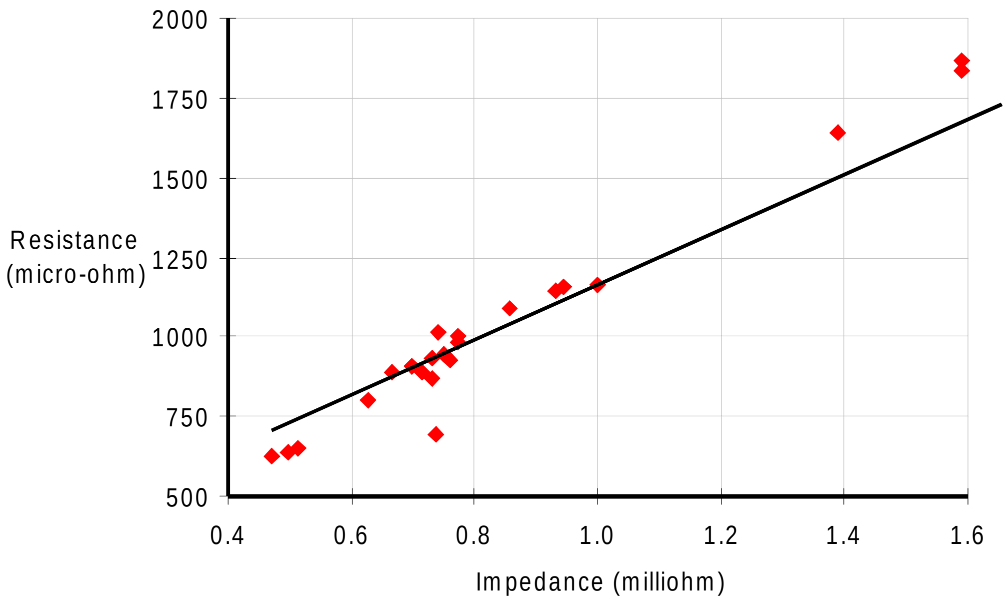

Figure 5-7
Typical Correlation of Impedance to Resistance—More Data Scatter

All three types of instruments used during this project provided equivalent results. The test results support a conclusion that any of the three parameters (conductance, impedance, or resistance) can be monitored with equal effectiveness.

5.3 Correlation to Capacity When a Battery Has Low-Capacity Cells

Internal ohmic measurements were normally taken before a battery capacity test. The capacity of each cell was calculated based on its final voltage at the end of the capacity test. Then, internal ohmic measurements were compared to the individual cell capacities to determine the trend in performance. Internal ohmic measurements show a correlation to capacity and readily identify low capacity cells in a VRLA battery string.

5.3.1 Typical Correlation When Most or All Cells Have Low Capacity

Figures 5-8 through 5-10 show the test results of a C&D HDL-300 battery that had 33% capacity (capacity test lasted 40 minutes at the 2-hour rate). Most cells had a low capacity and there is a wide variation in individual cell capacity. As can be seen with each type of internal ohmic measurement, a clear trend with respect to capacity is evident. This type of result was commonly observed when a battery had a combination of good and bad cells; in cases such as this, there were usually a wide variation in the internal ohmic measurements.

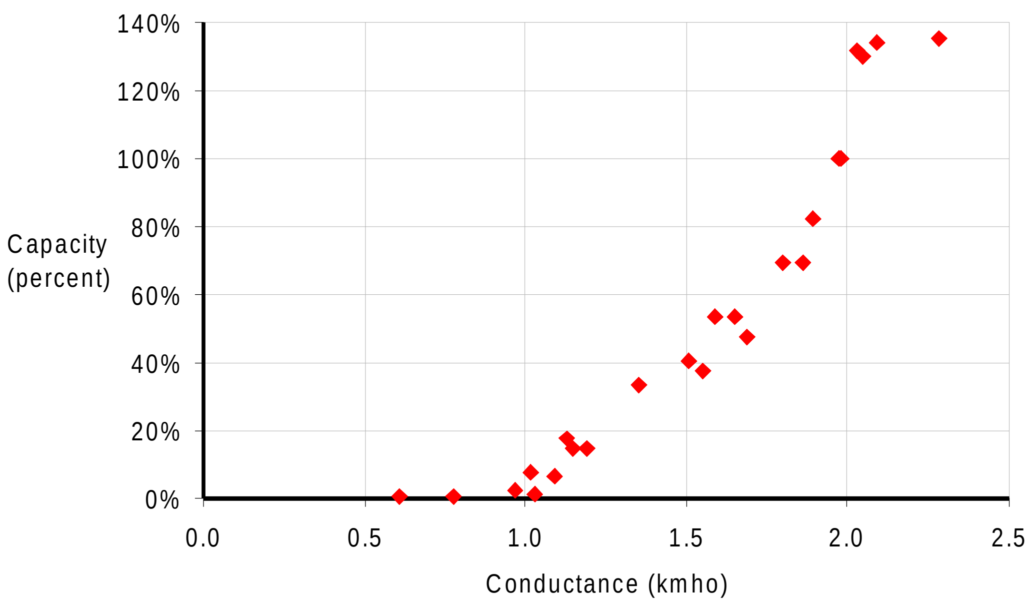

Figure 5-8
Correlation of Conductance to Cell Capacity—Most Cells With Low Capacity

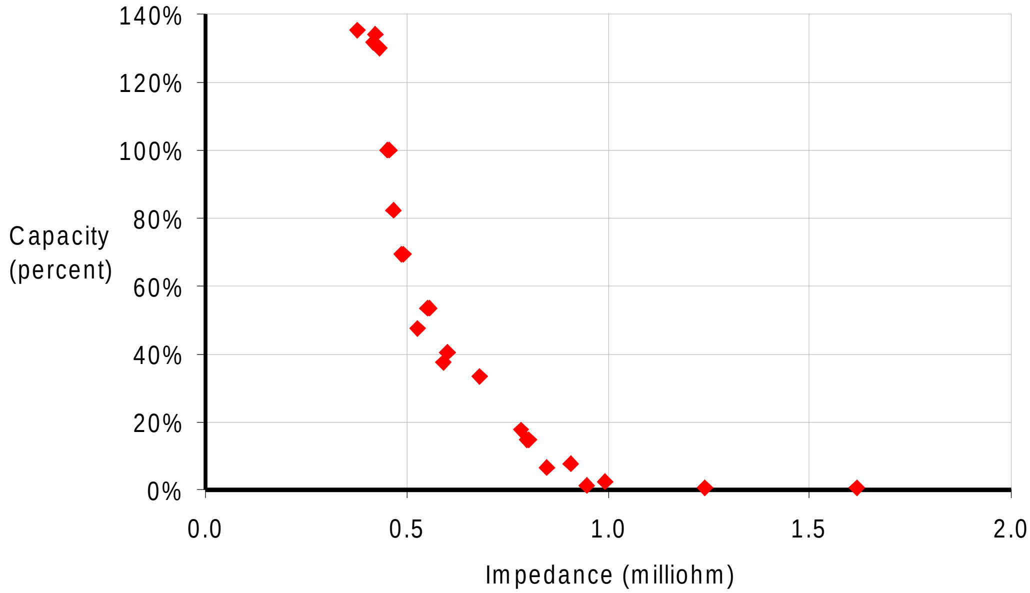

Figure 5-9
Correlation of Impedance to Cell Capacity—Most Cells With Low Capacity

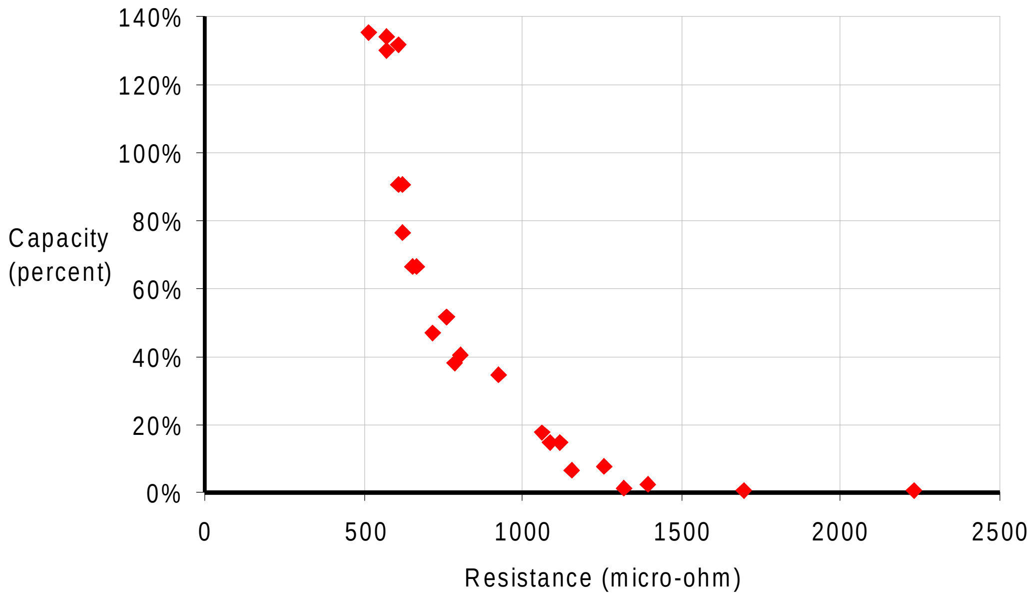

Figure 5-10
Correlation of Resistance to Cell Capacity—Most Cells With Low Capacity

Figures 5-11 and 5-12 show the test results of a GNB 75A07 battery that had 58% capacity (capacity test lasted 70 minutes at the 2-hour rate). Most cells had a low capacity and the pattern is clear.

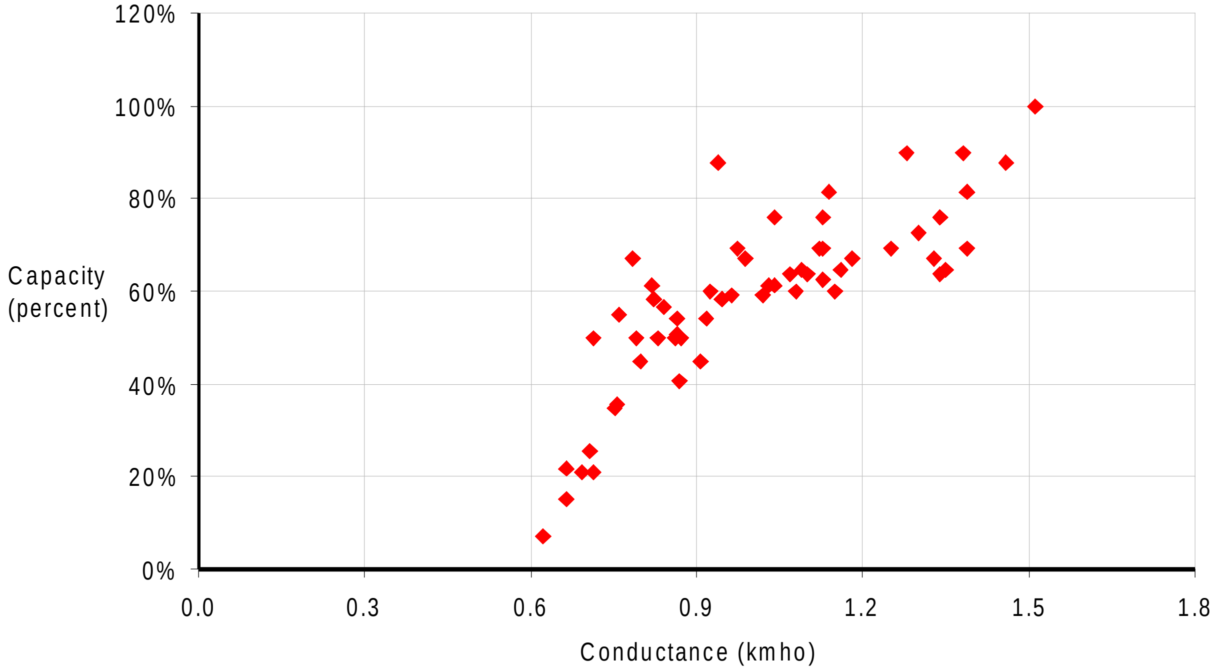

Figure 5-11
Correlation of Conductance to Cell Capacity—Low Capacity But Not Dead

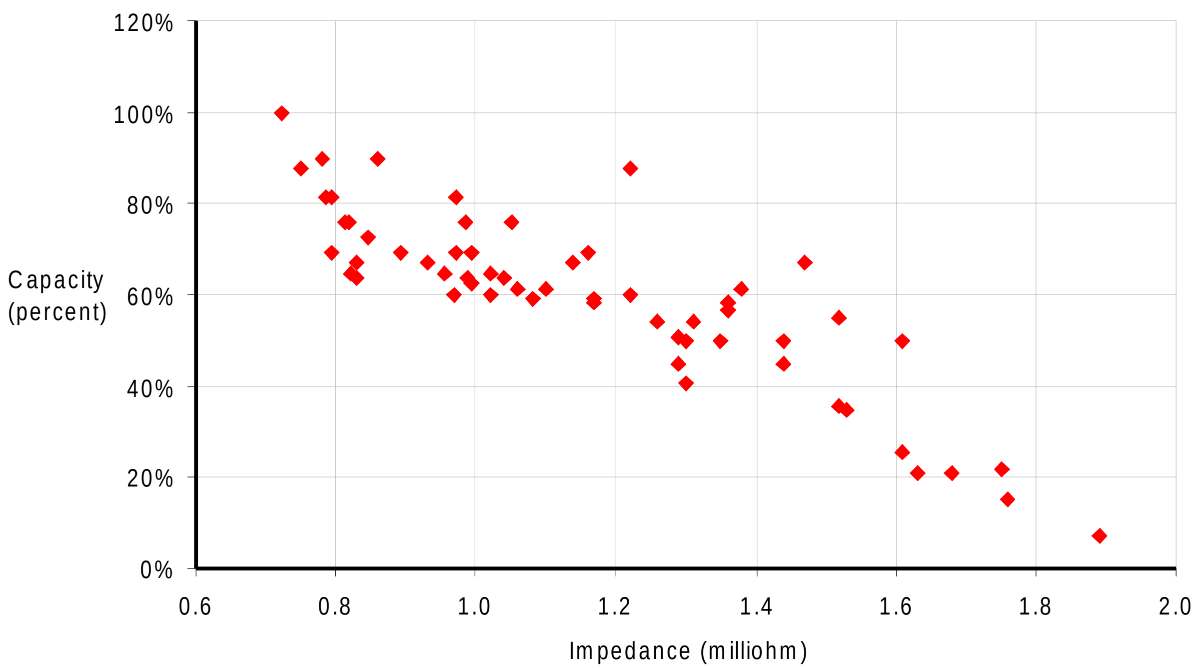

Figure 5-12
Correlation of Impedance to Cell Capacity—Low Capacity But Not Dead

Figures 5-13 and 5-14 show the test results of a GNB 75A27 battery that had about 2% capacity (capacity test lasted 5 minutes at the 5-hour rate). All cells had a low capacity and most cells are effectively dead (quickly went into reversal).

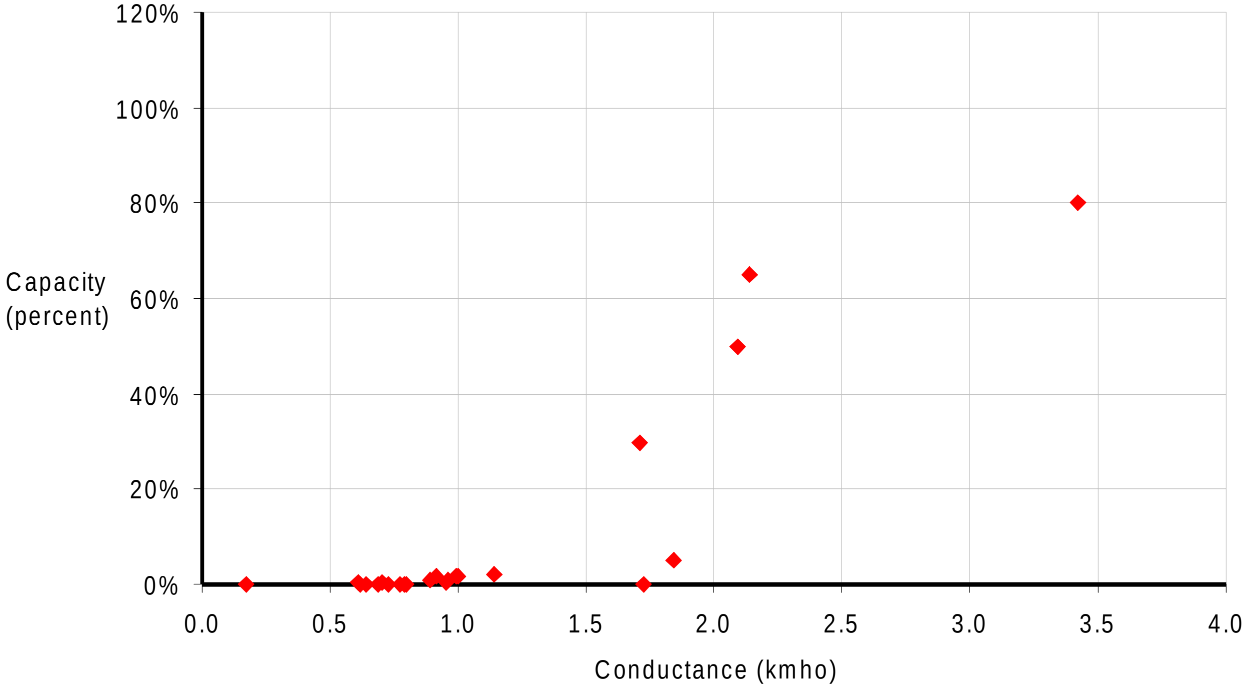

Figure 5-13
Correlation of Conductance to Cell Capacity—Most Cells Dead

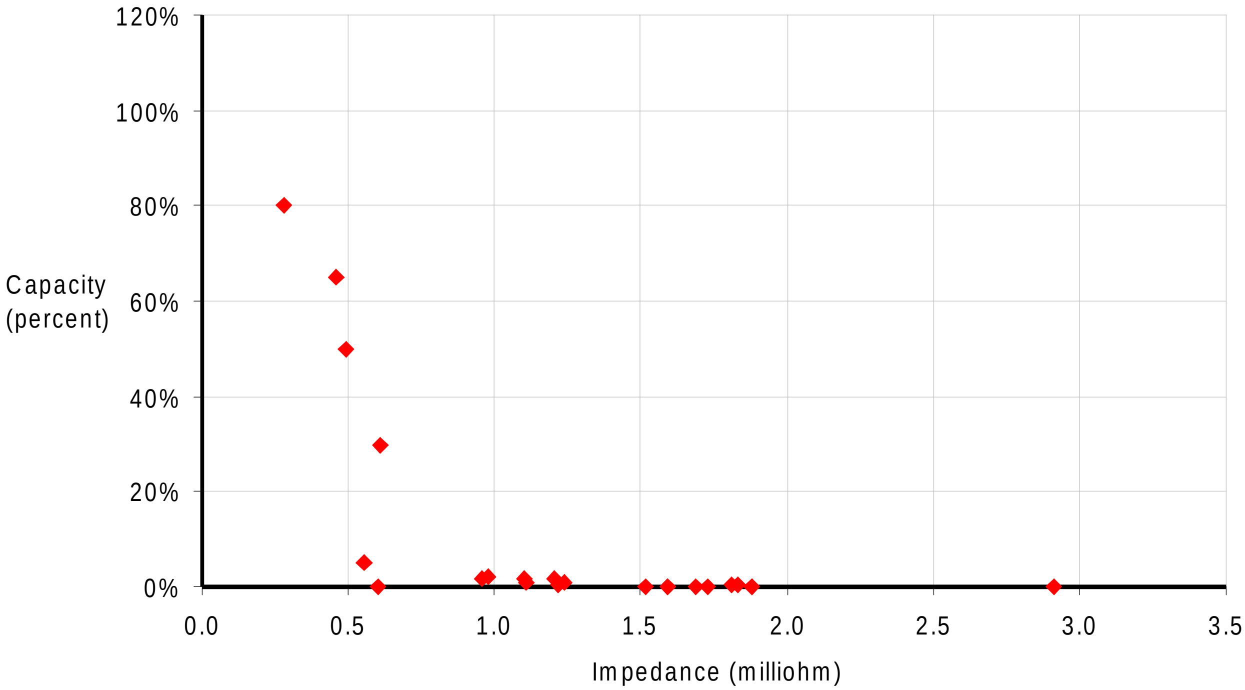

Figure 5-14
Correlation of Impedance to Cell Capacity—Most Cells Dead

5.3.2 Typical Correlation When Only a Few Cells Have Low Capacity

Figures 5-15 and 5-16 show the test results of a GNB 50A07 battery that had just over 80% capacity. Most cells have a capacity above 80%; a trend with respect to capacity can still be seen.

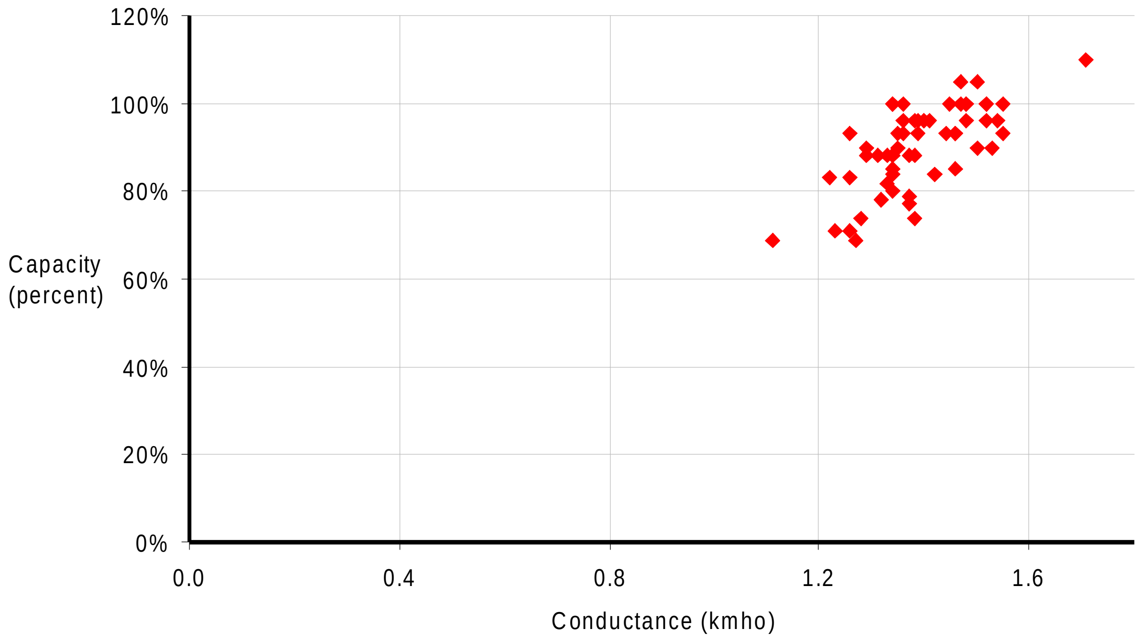

Figure 5-15
Correlation of Conductance to Cell Capacity—Most Cells Above 80% Capacity

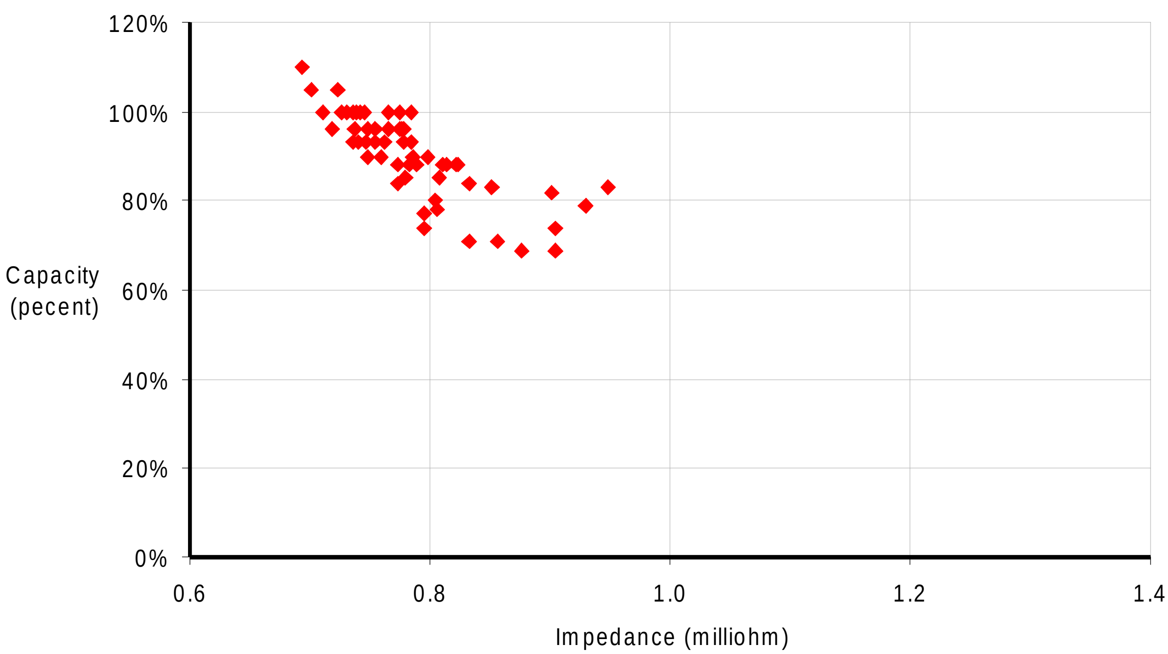

Figure 5-16
Correlation of Impedance to Cell Capacity—Most Cells Above 80% Capacity

Figures 5-17 through 5-19 show the test results of a GNB 45A07 battery that had about 96% capacity. Most cells have a capacity above 100%; a trend with respect to capacity can still be seen.

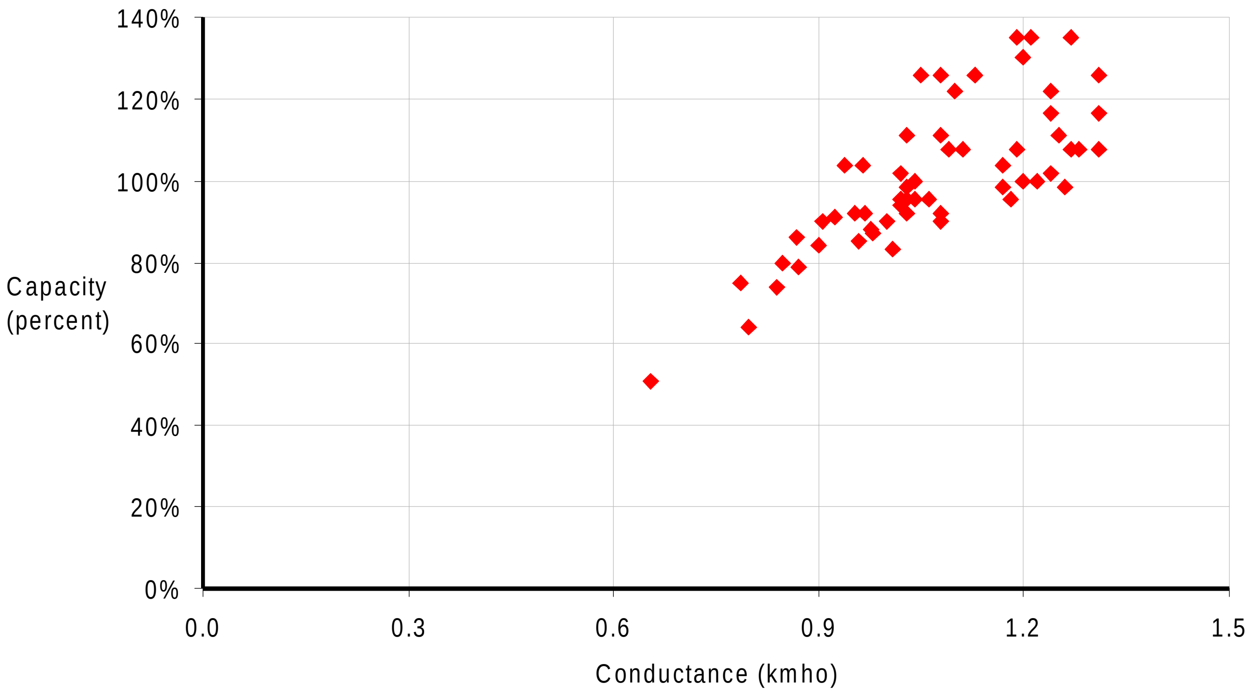

Figure 5-17
Correlation of Conductance to Cell Capacity—Most Cells Above 100% Capacity

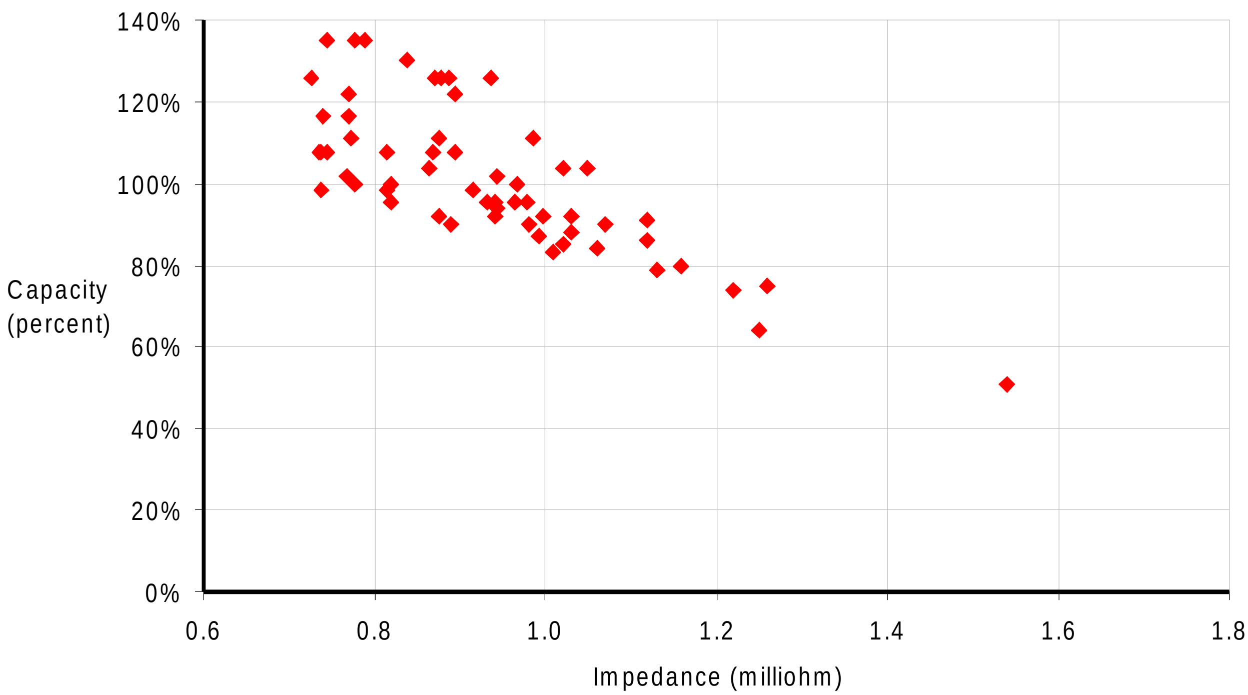

Figure 5-18
Correlation of Impedance to Cell Capacity—Most Cells Above 100% Capacity

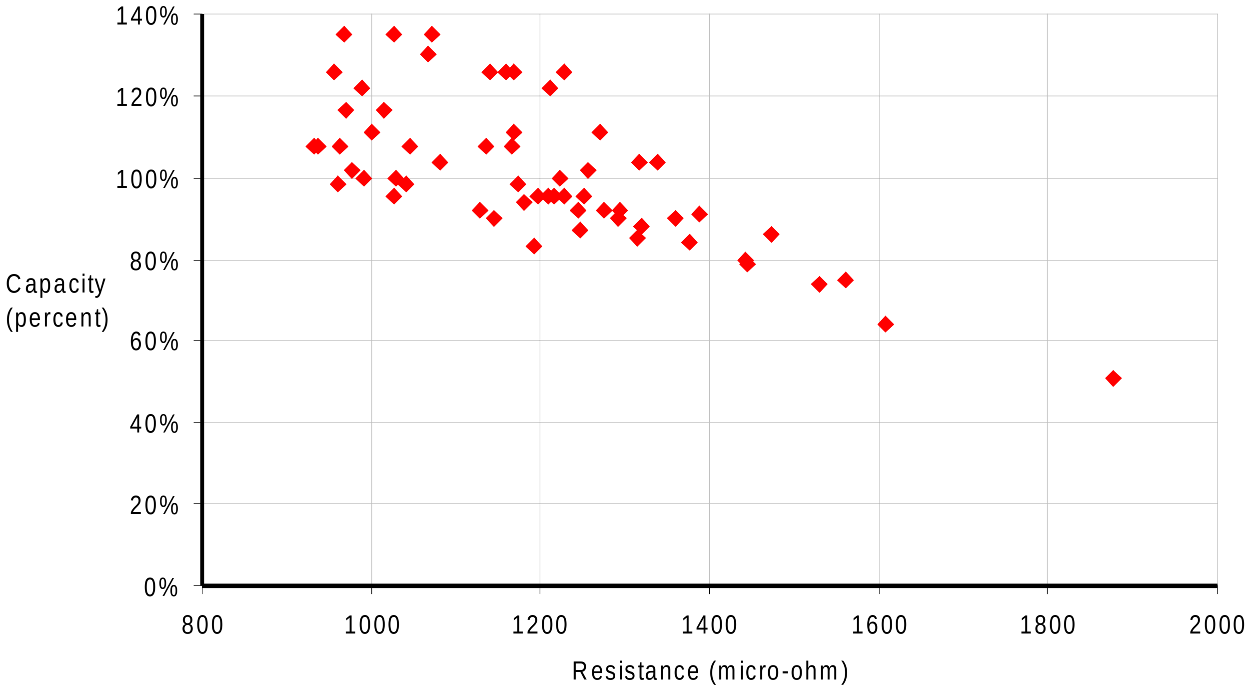

Figure 5-19
Correlation of Resistance to Cell Capacity—Most Cells Above 100% Capacity

5.4 Correlation to Capacity When a Battery Has All Good Cells

5.4.1 Correlation to Capacity for New Batteries With All Good Cells

New VRLA batteries evaluated by this project tended to have the internal ohmic measurements for most cells clumped within a relatively small range, but the measurements varied more than was observed for vented lead-acid batteries. Figures 5-20 and 5-21 show the typical results for impedance and resistance on a new Yuasa DC60-9 cell type.

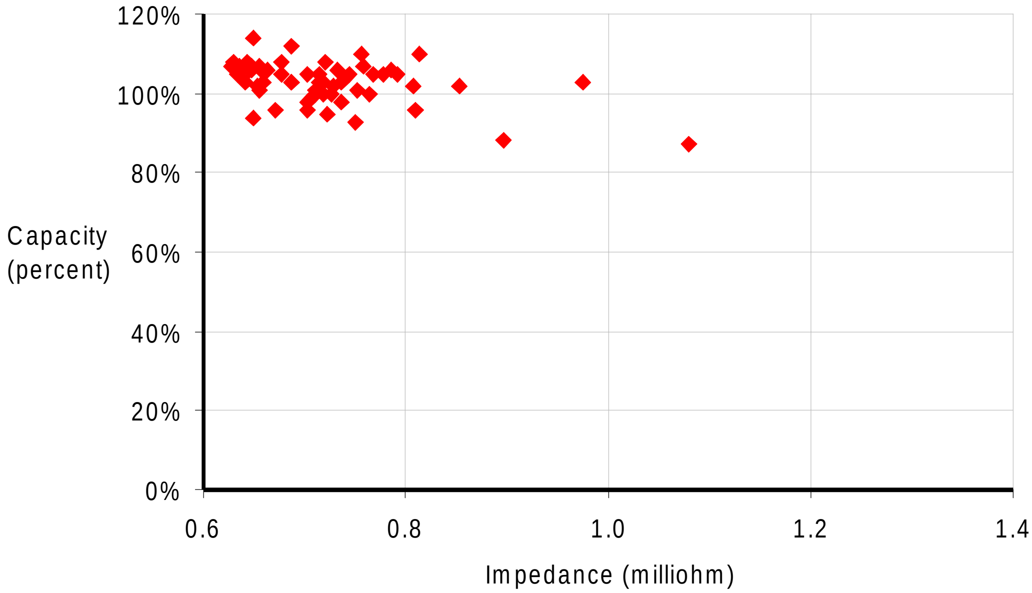

Figure 5-20
Correlation of Impedance to Cell Capacity—New Battery

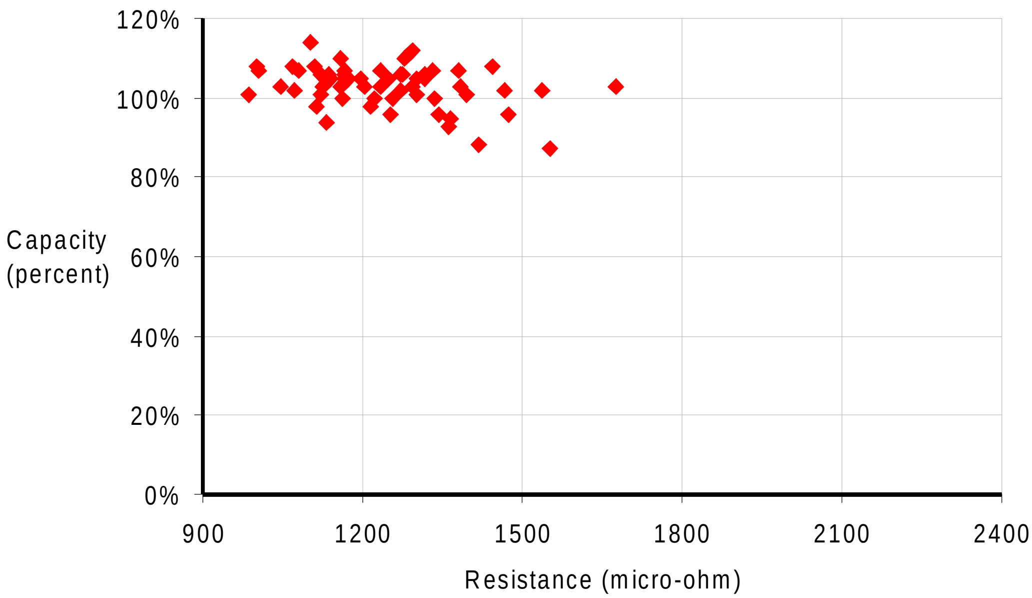

Figure 5-21
Correlation of Resistance to Cell Capacity—New Battery

5.4.2 Correlation to Capacity for Older Batteries With All Good Cells

Figures 5-22 through 5-24 show the test results of a GNB 45A07 battery that still had over 100% capacity after 5 years of service. All cells have a capacity above 100%; a trend with respect to capacity can still be seen.

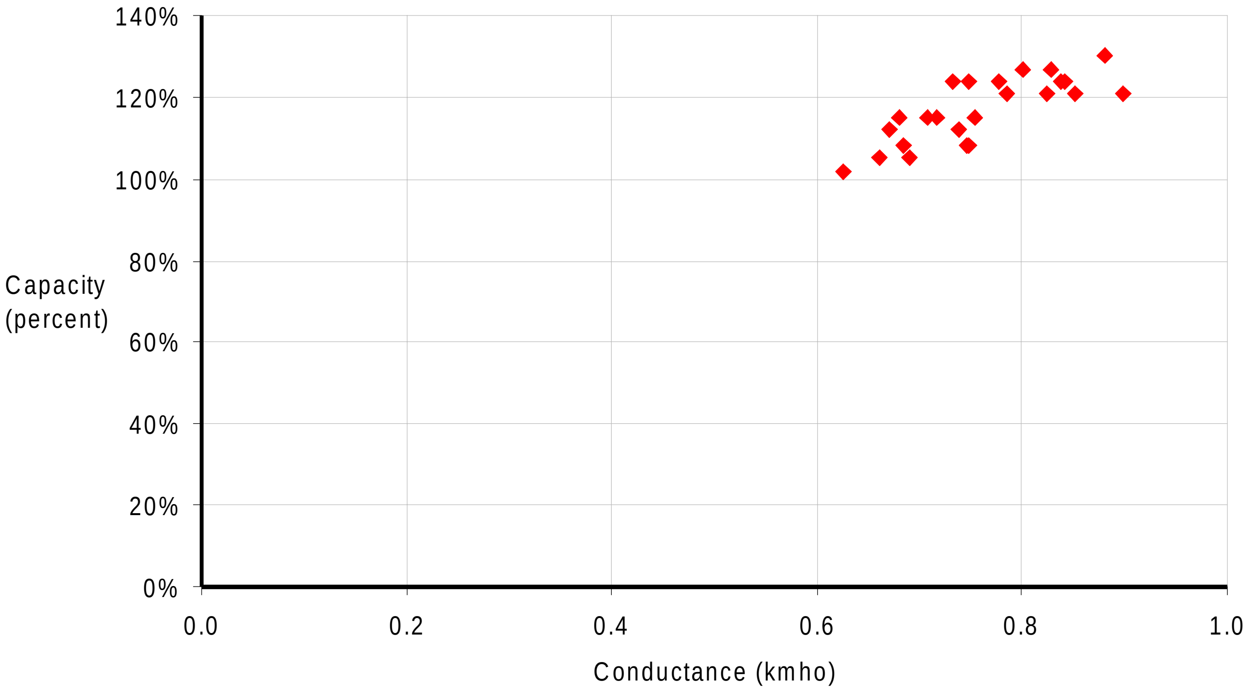

Figure 5-22
Correlation of Conductance to Cell Capacity—All Cells Above 100% Capacity

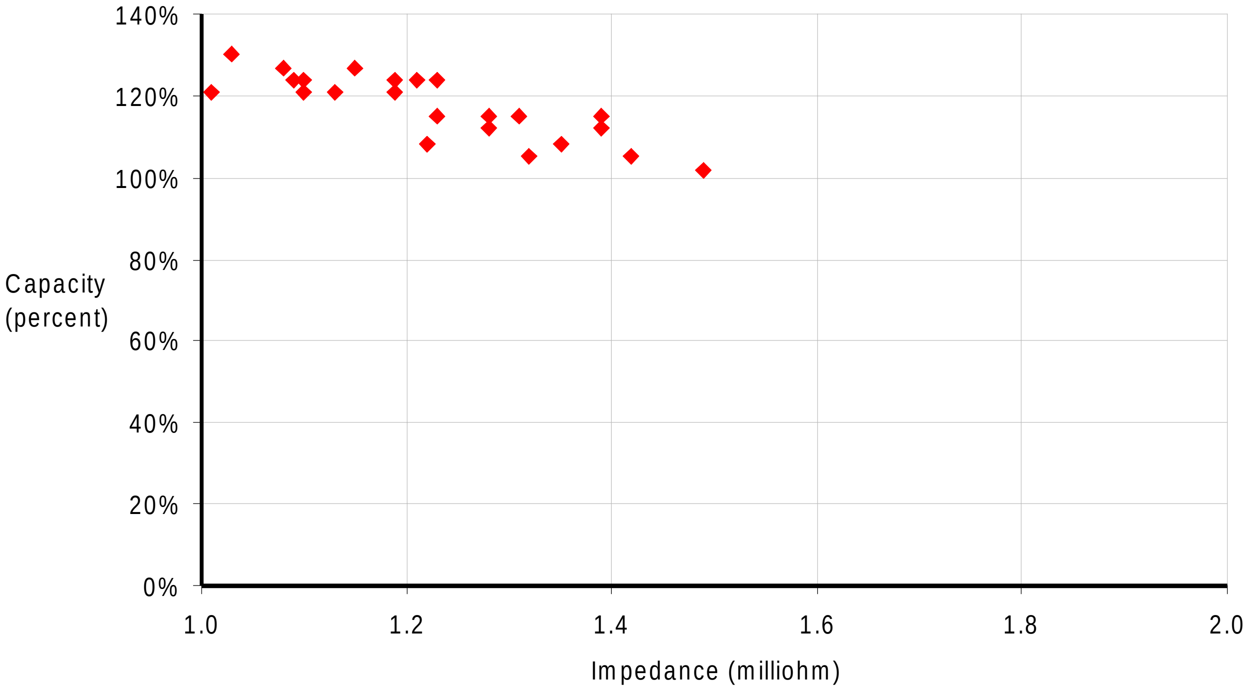

Figure 5-23
Correlation of Impedance to Cell Capacity—All Cells Above 100% Capacity

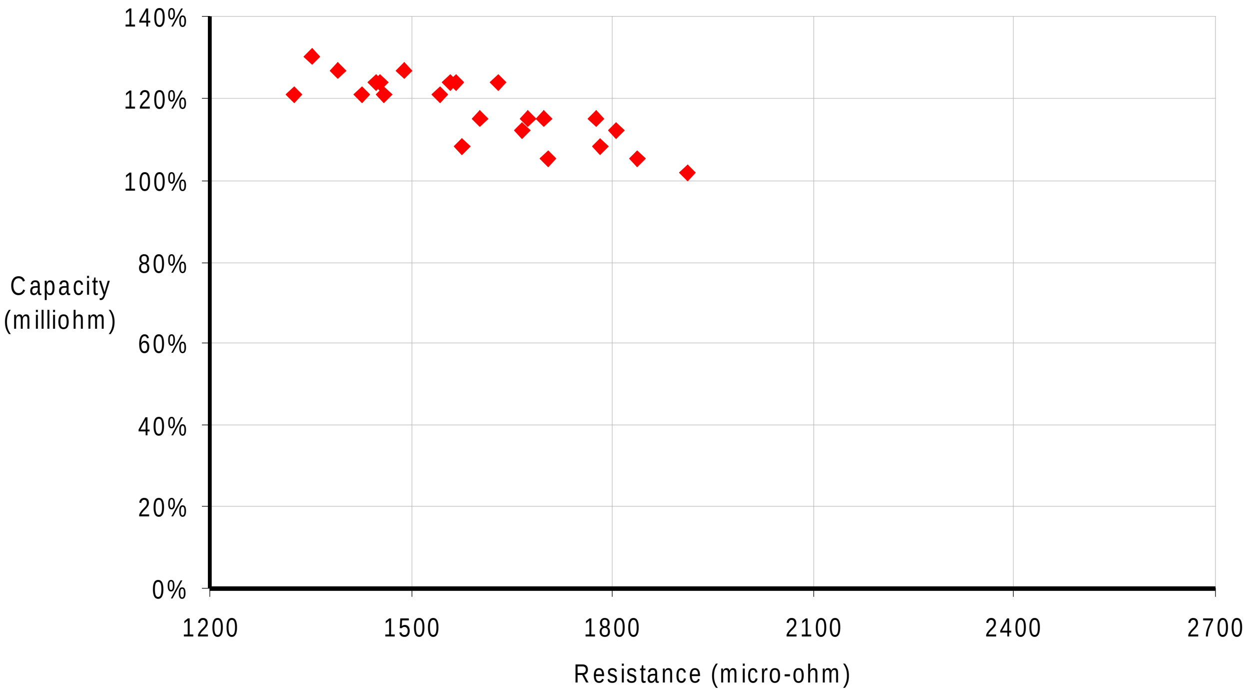

Figure 5-24
Correlation of Resistance to Cell Capacity—All Cells Above 100% Capacity

5.5 Correlation to Capacity When a Battery Has Bad Cells Replaced

One consequence of evaluating batteries by the application of internal ohmic measurements is that bad cells will be identified and replaced. Over time with such replacements, a battery might be composed of cells with differing ages. Figures 5-25 through 5-27 show examples of one facility that periodically checks all cells and automatically replaces cells with an internal resistance above 300 micro-ohms (each figure shows data for 192 cells). This practice of automatic cell replacement was started after the simultaneous failure of several battery strings. The capacity test of these batteries resulted in an acceptable capacity for each battery, although there were a few low-capacity cells. Clearly, the cell replacement approach taken here has been effective.

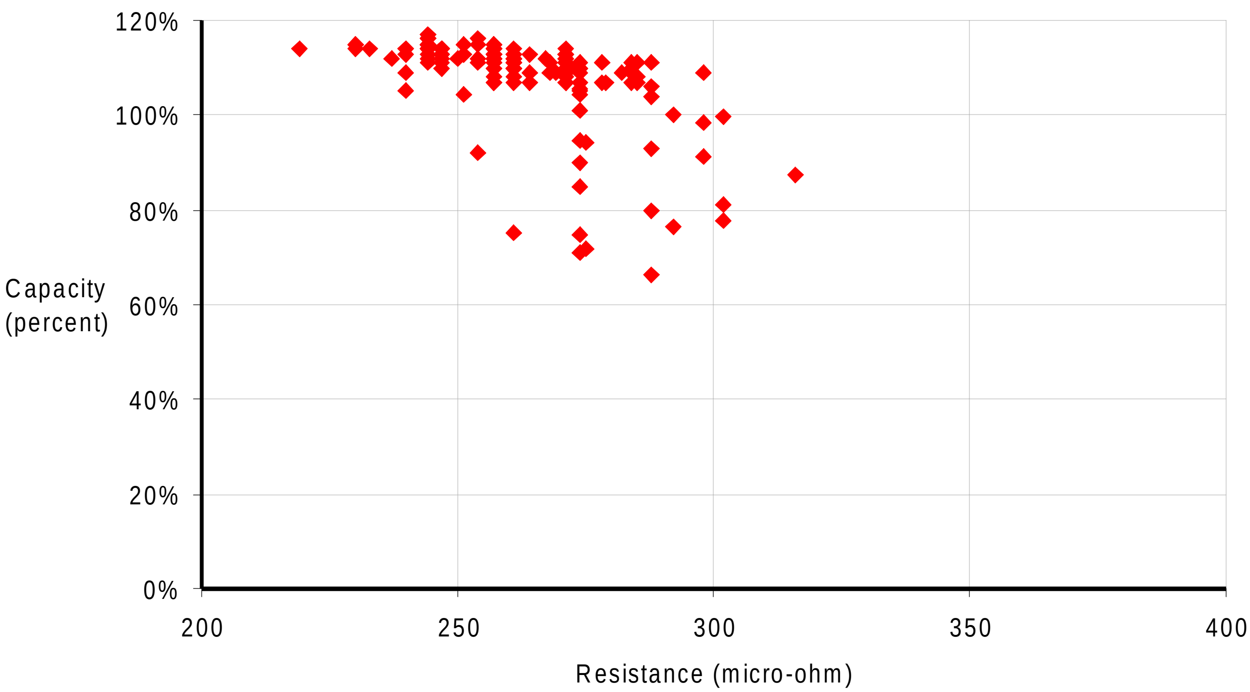

Figure 5-25
Automatic Replacement of High Resistance Cells—Example 1

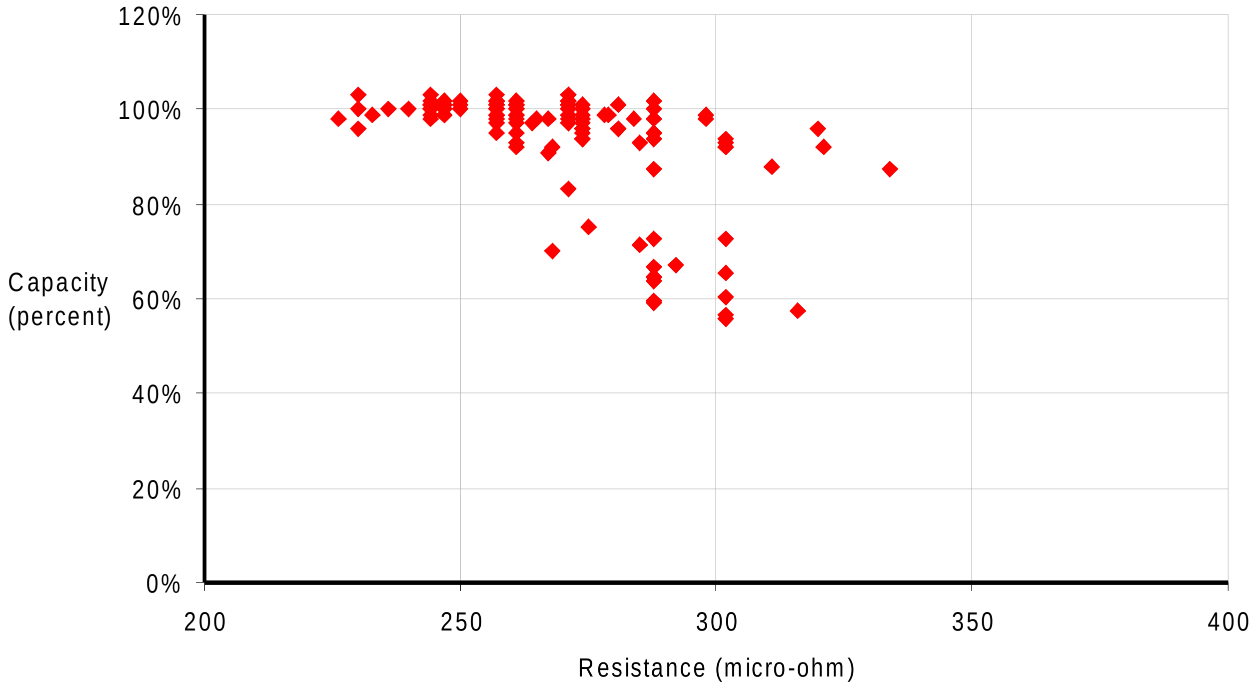

Figure 5-26
Automatic Replacement of High Resistance Cells—Example 2

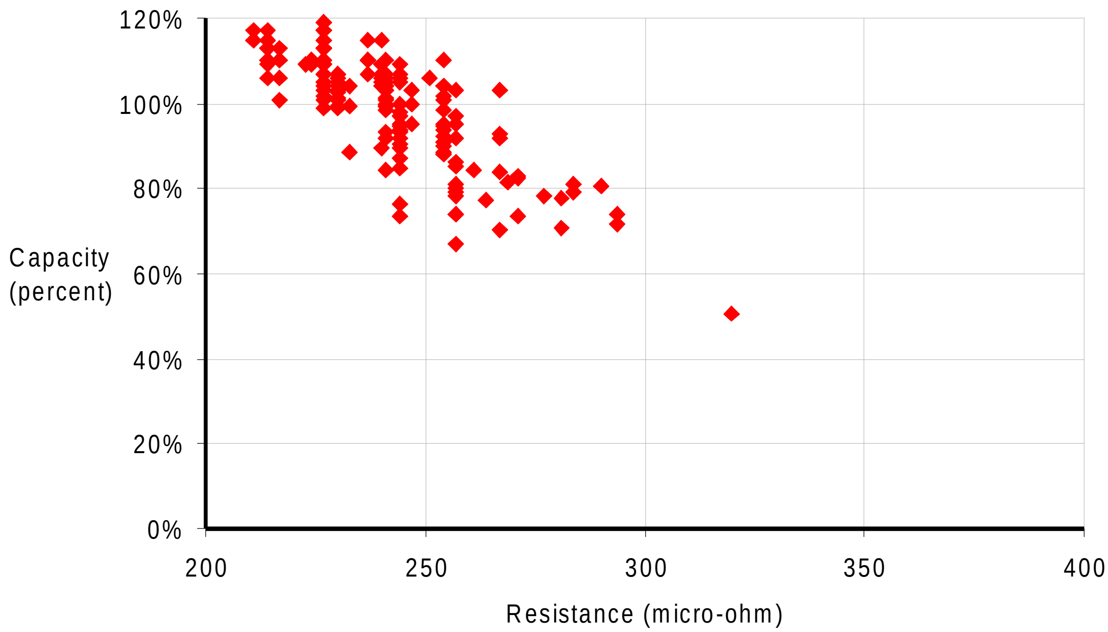

Figure 5-27
Automatic Replacement of High Resistance Cells—Example 3

5.6 Correlation of Combined Data

5.6.1 Correlation Compared to Average Values

VRLA batteries evaluated by 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 or all cells with low capacity. Table 5-2 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 for a 100% capacity cell. 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 5-2
Capacity as a Function of Internal Ohmic Measurements

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 internal ohmic measurement data provided in Table 5-2 has been graphed in Figures 5-28 and 5-29 to further illustrate the observed loss of capacity as a function of the nominal internal ohmic value.

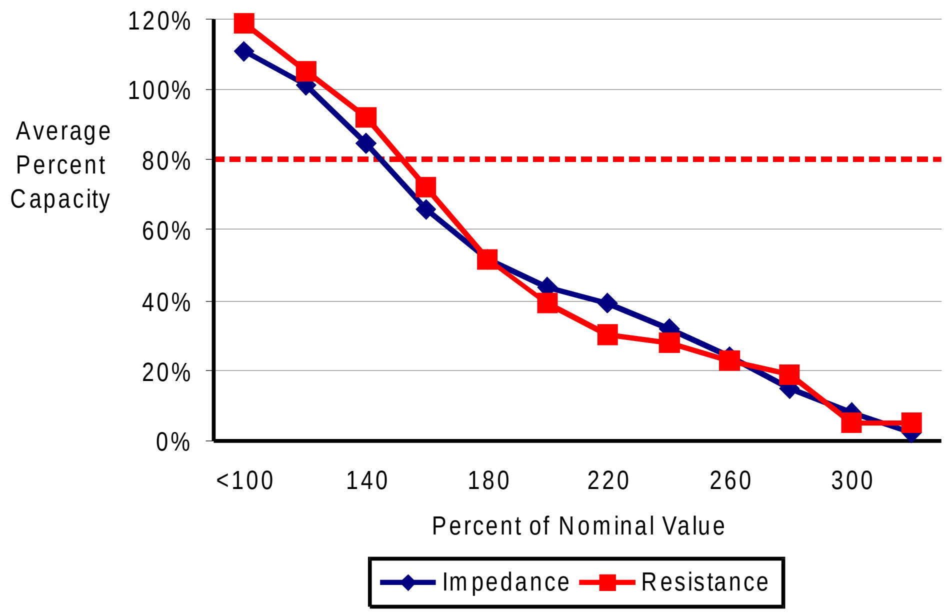

Figure 5-28
Average Capacity Decrease as Impedance or Resistance Increased

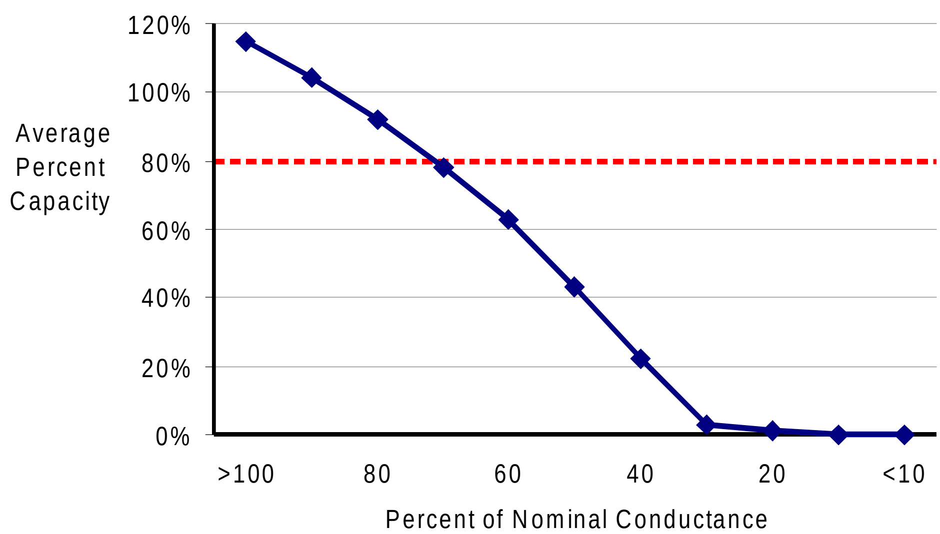

Figure 5-29
Average Capacity Decrease as Conductance Decreased

Capacity clearly decreased with increasing impedance, increasing resistance, or decreasing conductance, as shown above. However, graphs of the average values do not address the observed data scatter. Although definitive statements can be made regarding capacity as a function of the average internal ohmic values, the amount of data scatter means that not all cells behaved as indicated above. The following section discusses data scatter in the measurements and provides a summary of the conclusions that can be reached despite data scatter.

5.6.2 Correlation When Data Scatter Is Considered

A statistically significant correlation between internal ohmic measurements and capacity was observed throughout this project. However, data scatter was always present; the correlation is not perfect. Section 2 provides a detailed discussion of the various factors that can affect internal resistance and capacity. Remember that many factors can affect both internal resistance and capacity, but we do not expect that each factor affects capacity and internal resistance to the same degree. Although a large change in internal resistance correlates quite well with a decrease in capacity, smaller changes in internal resistance do not necessarily indicate a change in capacity. Section 3.4 provides additional information regarding measurement uncertainty in this respect. Even the ability to calculate cell capacity from a battery capacity test involves some level of uncertainty as discussed in Section 4.1.4.

Although there are exceptions, cells with greater than 100% capacity tend to have internal ohmic measurements clustered together with mainly small variations. And, cells with capacities below 70% tend to be readily identified by internal ohmic measurements. The range of 70% to 100% cell capacity appears to be a region within which the internal ohmic measurement data scatter has the greatest impact on our ability to interpret the results.

Figures 5-30 and 5-31 show a typical example of data scatter. In this case, the cells with greater than 100% capacity tend to be clustered around a conductance of about 1.0 kmho (resistance of about 1,200 micro-ohms). Even though a clear trend can be observed, note that cells with a conductance of 0.6 kmho (2,000 micro-ohms) have capacities ranging from 65% to 100%.

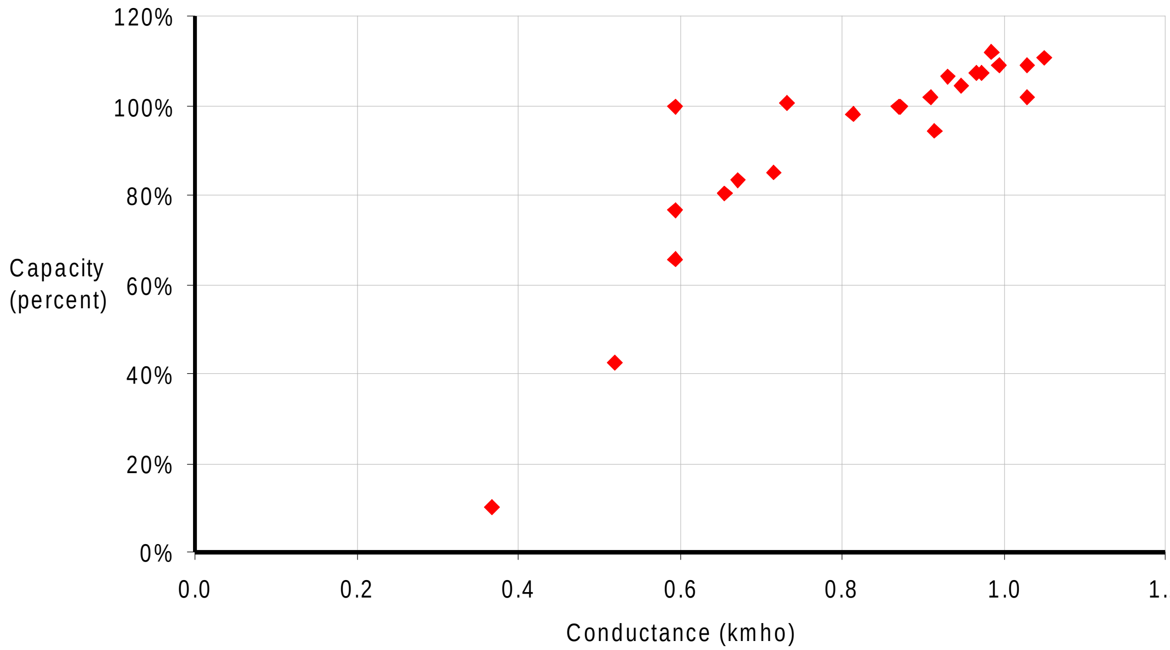

Figure 5-30
Typical Example of Data Scatter—Conductance Measurements

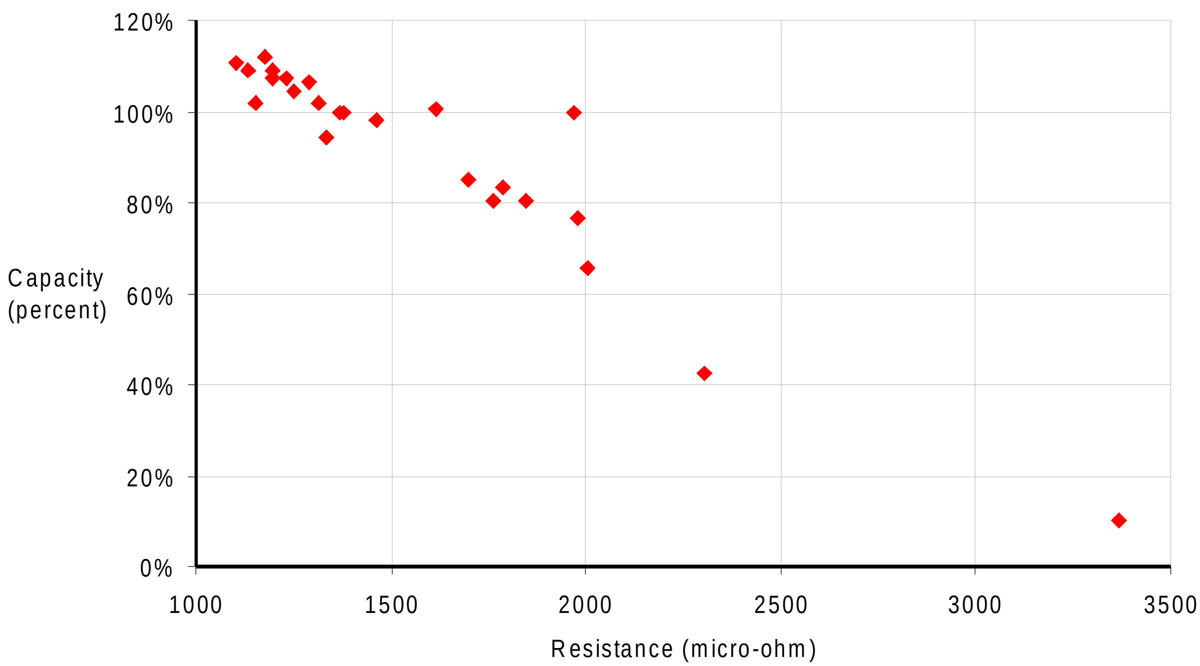

Figure 5-31
Typical Example of Data Scatter—Resistance Measurements

Figure 5-32 shows another example of the observed data scatter. Once again, a clear trend is observable, but the data scatter for a given impedance has cell capacities varying by ±15% in some cases. Notice in this case that there is significant data scatter even above 100% capacity.

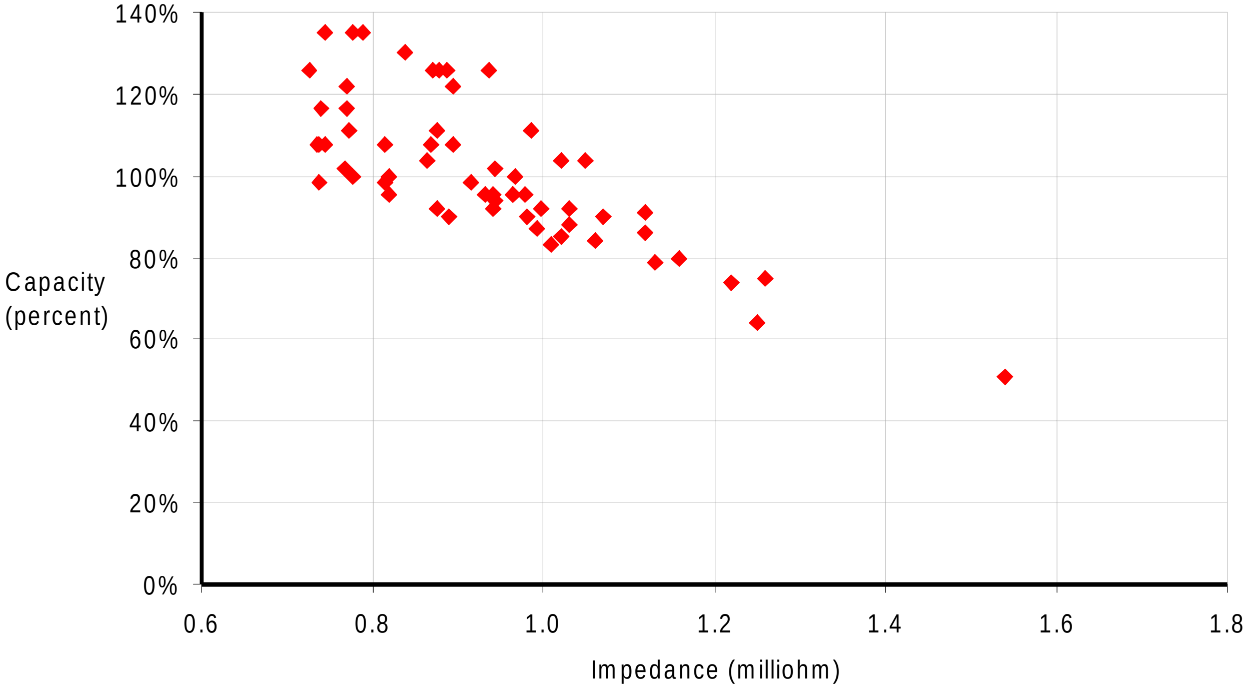

Figure 5-32
Data Scatter Above 80% Cell Capacity

The data scatter represents a valid concern in the interpretation of internal ohmic measurements. For this reason, the nominal value for each cell type was estimated in accordance with the process described in Section 4.2. This allows all measurements to be described as a percent of their nominal value, similar to per unit expressions in power system analysis. This approach enables all measurements to be combined for purposes of analysis, thereby allowing generic claims to be made regarding the effectiveness of a set of internal ohmic measurements.

Figure 5-33 shows the impedance data for VRLA cells, with the impedance data expressed in terms of percent of the nominal value. This graph includes all data, regardless of observed data scatter.

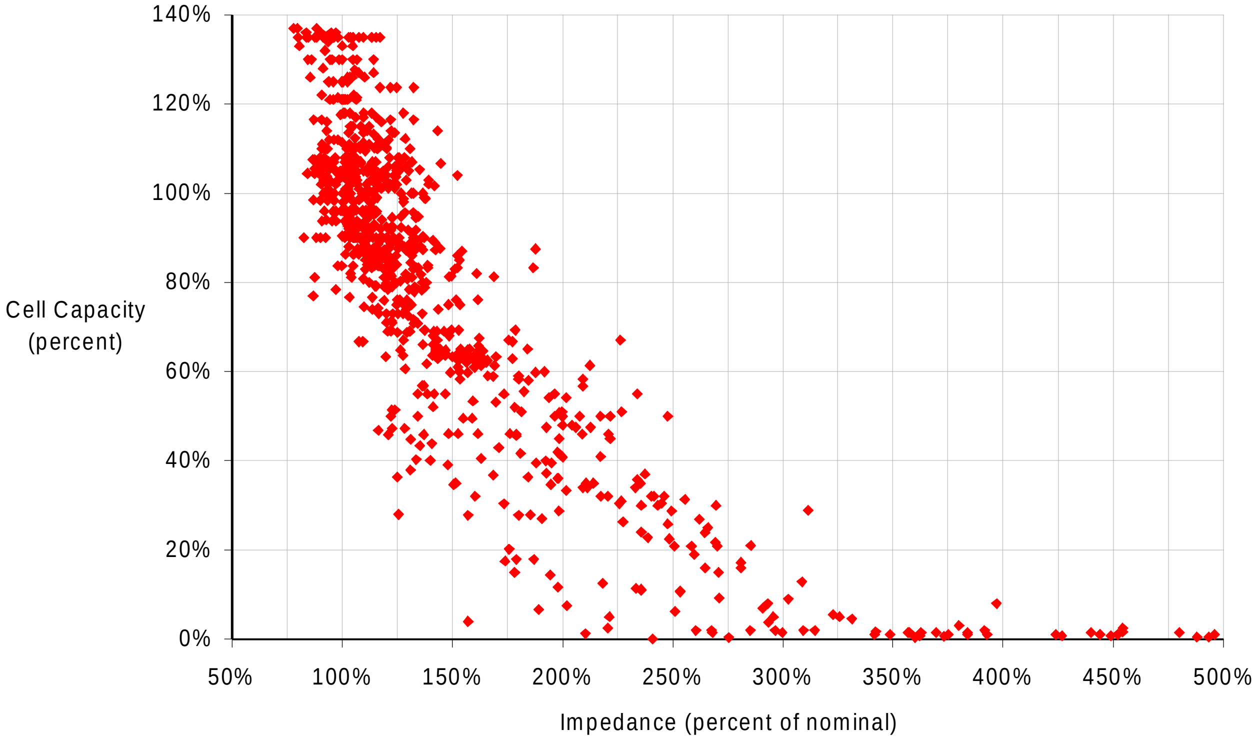

Figure 5-33
Combined Impedance Data for All VRLA Cells

Although there is data scatter, the following observations can be made regarding the impedance measurements:

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

Figure 5-34 shows the resistance data for VRLA cells, with the resistance data expressed in terms of percent of the nominal value. This graph includes all data, regardless of observed data scatter.

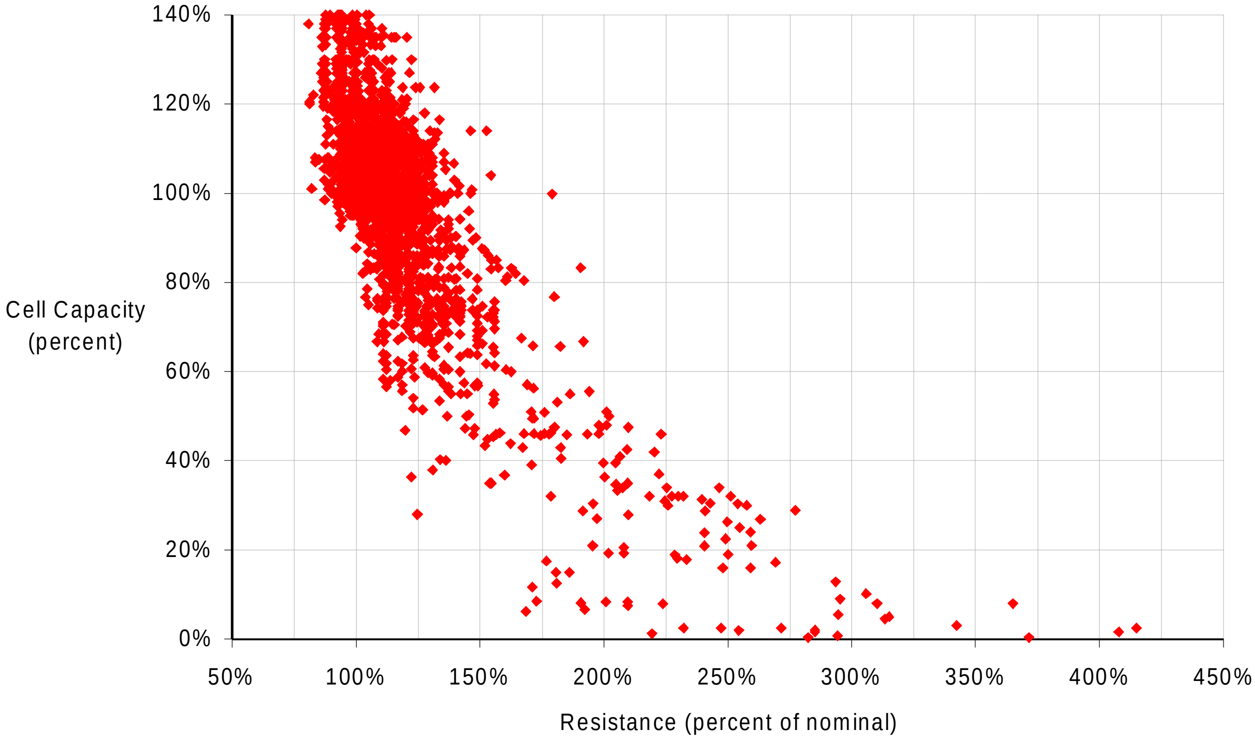

Figure 5-34
Combined Resistance Data for All VRLA Cells

Although there is data scatter, the following observations can be made regarding the resistance measurements (similar to the impedance measurements):

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

Figure 5-35 shows the conductance data for VRLA cells, with the conductance data expressed in terms of percent of the nominal value. This graph includes all data, regardless of observed data scatter.

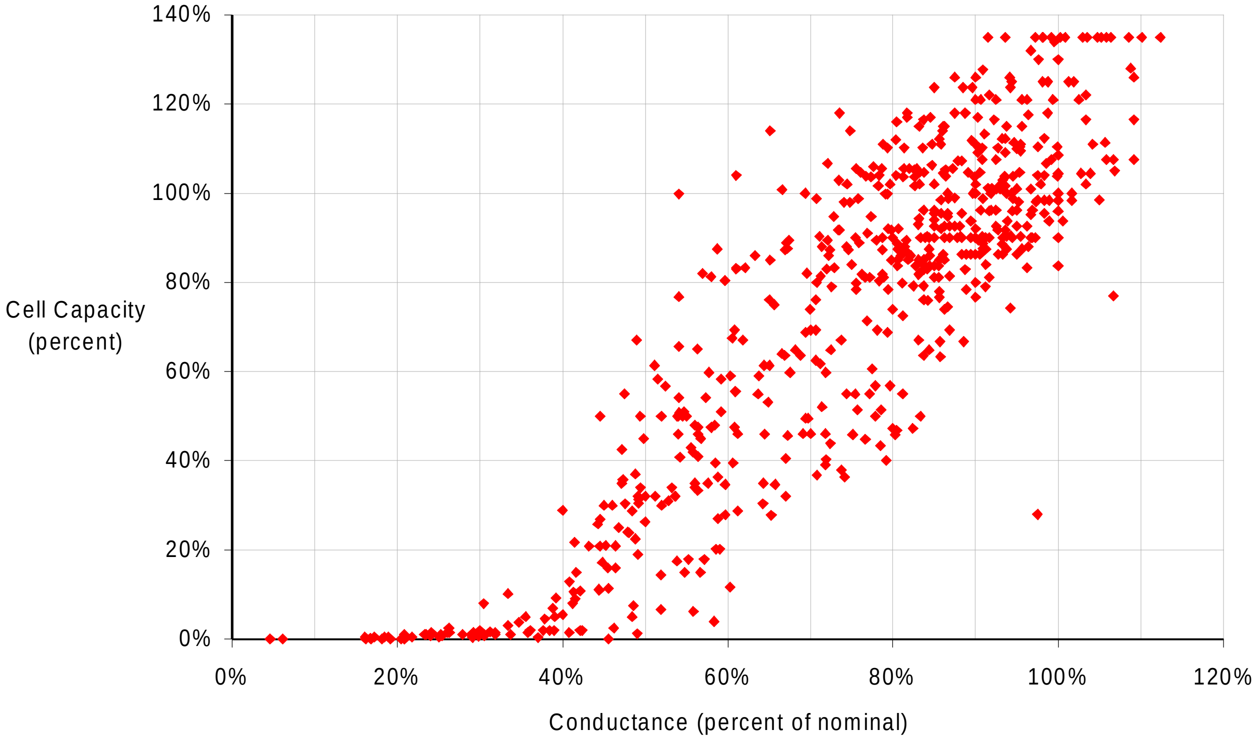

Figure 5-35
Combined Conductance Data for All VRLA Cells

Although there is data scatter, the following observations can be made regarding the conductance measurements:

- Most cells had less than 80% capacity when conductance decreased to 70% of the nominal conductance.
- Most cells had less than 60% capacity when conductance decreased to 60% of the nominal conductance. Only a few cells had an acceptable capacity (above 80%).
- Most cells had less than 40% capacity when conductance decreased to 50% of the nominal conductance. No cells had above 80% capacity.
- All cells were effectively dead when conductance decreased to 40% of the nominal conductance.

The data scatter limits our ability to assign a predicted value of capacity to a given cell. But, low capacity cells are still identifiable. When a cell's internal resistance increases beyond a certain amount, the cell virtually always has a low capacity. For this reason, the technology appears to have real value, despite the data scatter.

5.7 Battery Capacity and Internal Ohmic Measurement Variations

Batteries with little variation in the cell internal ohmic measurements were normally good batteries with no bad cells. Batteries with a large variation in the internal ohmic measurements tended to have several (or many) bad cells. This is an important observation because it means that the user should be able to qualitatively assess a battery even without performing a detailed analysis. The final report will provide detailed information regarding this assessment.

6
TEST RESULTS FOR VENTED LEAD-ACID CELLS

This section provides a summary of the project test results for vented cells. The project results are presented from different perspectives so that users can understand the relationship between internal ohmic measurements and cell capacity under various conditions.

6.1 Evaluated Batteries

Internal ohmic measurements were obtained on over 15,000 vented lead-acid cells. In many cases, capacity data was 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.

Figure 6-1 shows the proportion of evaluated vented cells sorted by manufacturer. Table 6-1 lists the specific battery models included in this test program.

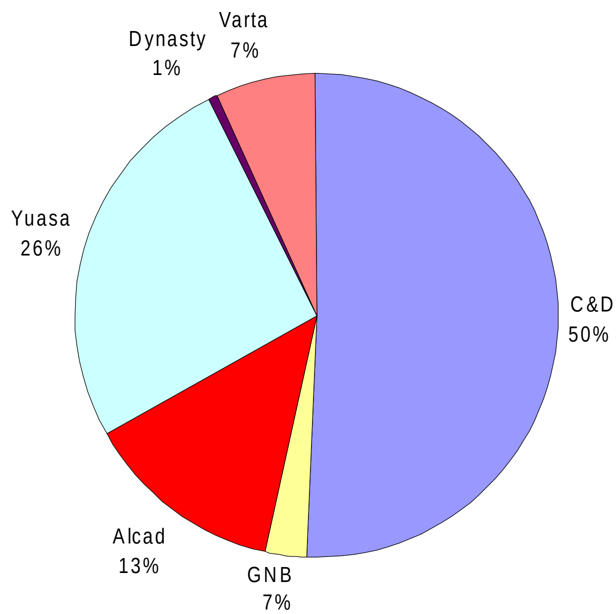

Figure 6-1
Proportion of Vented Lead-Acid Cells by Manufacturer

Table 6-1
Vented Lead-Acid Cell Models Included in Test Program

C&D		Yuasa		Alcad	GNB	Varta	Johnson Controls
KCR-07	LCR-17	3CA-05	ES-11	SD-05	NCX-31	OpzS-4	3GQA-07
KCR-09	LCR-21	3CA-07	ES-37	SD-07	NCN-31	OpzS-5	3GQA-11
KCR-15	LCR-25	3CA-09	EMP-07	SD-11		OpzS-6	3CQA-07
KCR-17	LCR-29	3CC-05	EMP-09	SD-13		GLS-12	
KCR-19	DU-09	3CC-07	DOP-07	SD-15			
XT2L-23	DCU-07	3CC-09		SD-17			
3LCW-23	DCU-09	DME-11C		SD-21			
	DCU-11			SGL-09			
				SGL-15			

6.2 Test Equipment Correlation

Representative test instrument were used for each type of ohmic measurement. Section 3 discusses the test equipment used by this project. The test instruments used were:

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

The results presented here are based on measurements taken by the above instruments. As discussed in the previous sections, these instruments all measure some form of a cell's internal resistance. However, the method of measurement and the circuit design varies in each case. It is important to understand that the evaluated instruments do not provide *exactly* the same measurement of a cell's internal resistance; each instrument produces a different measurement value because of differences in the instrument's circuit design, the test frequency, and the level of signal filtering. Despite these design differences, a strong correlation was usually observed between the conductance, impedance, and resistance measurements.

Even though the instruments do not produce the same reading on a cell, the measurements between instruments could be linearly correlated. Figures 6-2 through 6-4 show the typical correlation observed between the instruments. Remember that conductance is related to the inverse of impedance and resistance. By plotting the conductance data versus the inverse of impedance or resistance, usually a linear correlation was observed for the batteries evaluated by this project. The graph of impedance versus resistance consistently showed a linear correlation.

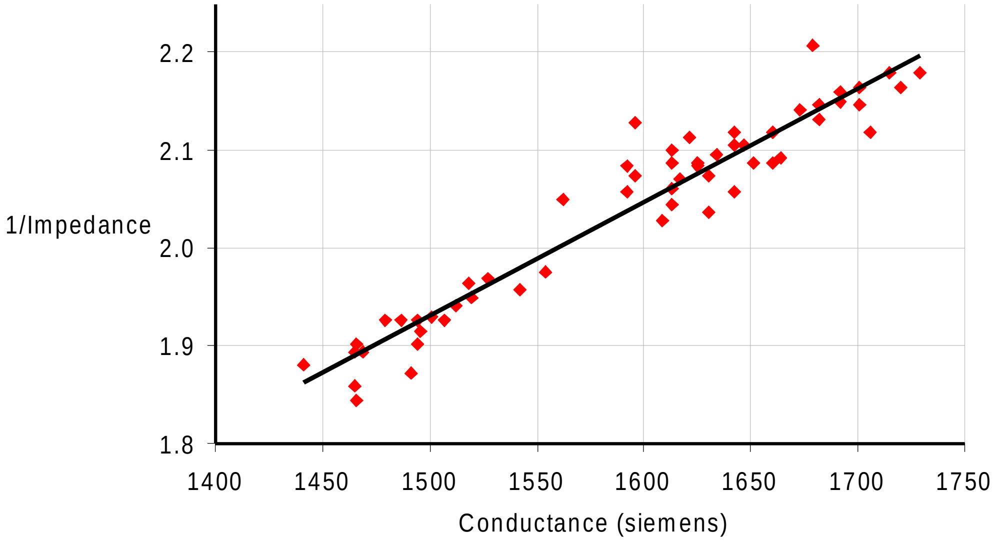

Figure 6-2
Typical Correlation of Conductance to Impedance

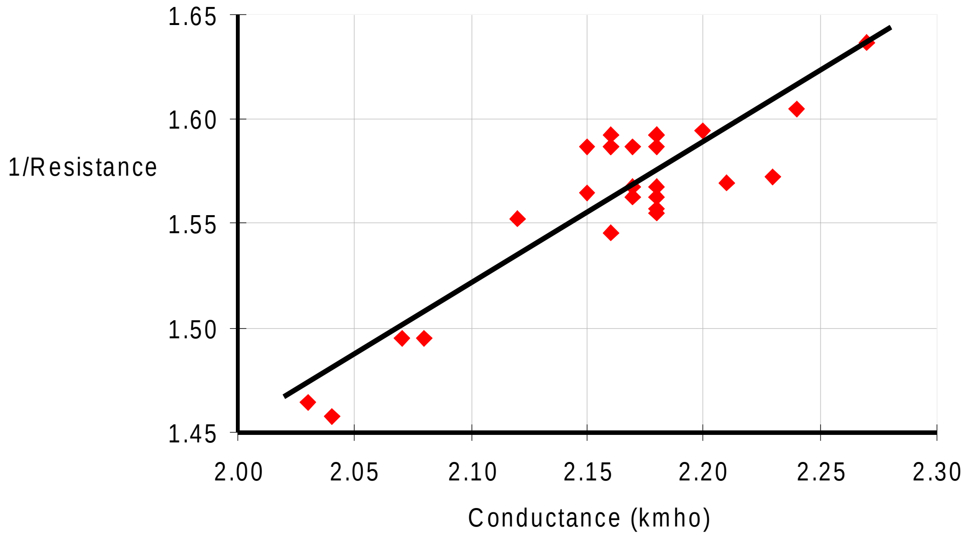

Figure 6-3
Typical Correlation of Conductance to Resistance

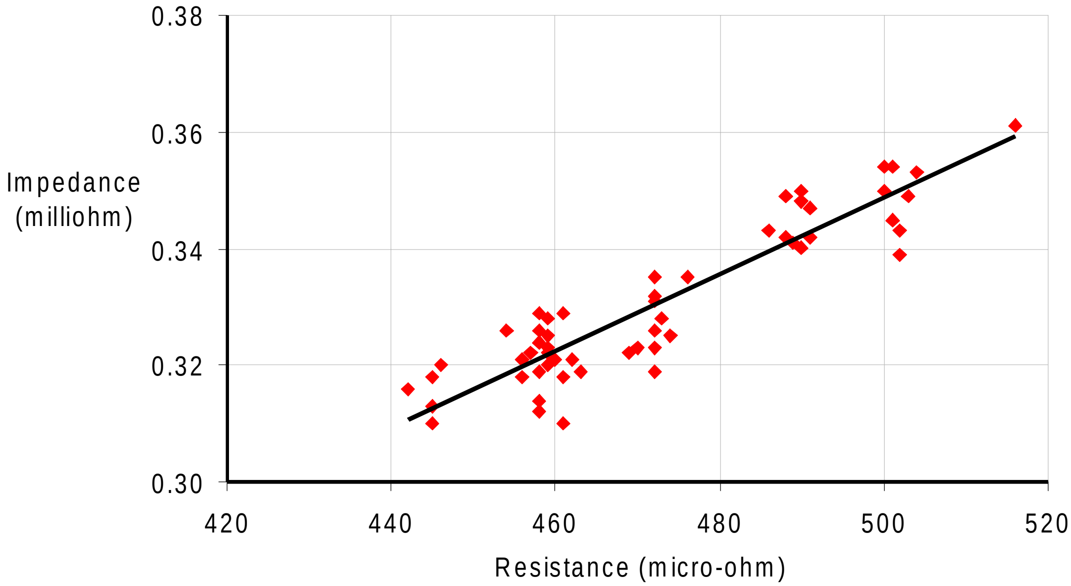

Figure 6-4
Typical Correlation of Impedance to Resistance

6.3 Correlation to Capacity When a Battery Has All Good Cells

Internal ohmic measurements were normally taken before a battery capacity test. The capacity of each cell was calculated based on its final voltage at the end of the capacity test. Then, internal ohmic measurements were compared to the individual cell capacities to determine the trend in performance. Most evaluated vented lead-acid batteries had acceptable capacity with consistent performance among the cells. In addition, this consistency is evident from the internal ohmic measurements.

6.3.1 Correlation to Capacity for New Batteries With All Good Cells

New vented lead-acid batteries evaluated by this project tended to have the internal ohmic measurements for most cells clumped within a relatively small range. Figures 6-5 and 6-6 show the typical results for conductance and impedance resistance on a new battery. Sometimes there was more data scatter as shown in Figure 6-7 for a different new battery, but this was less common.

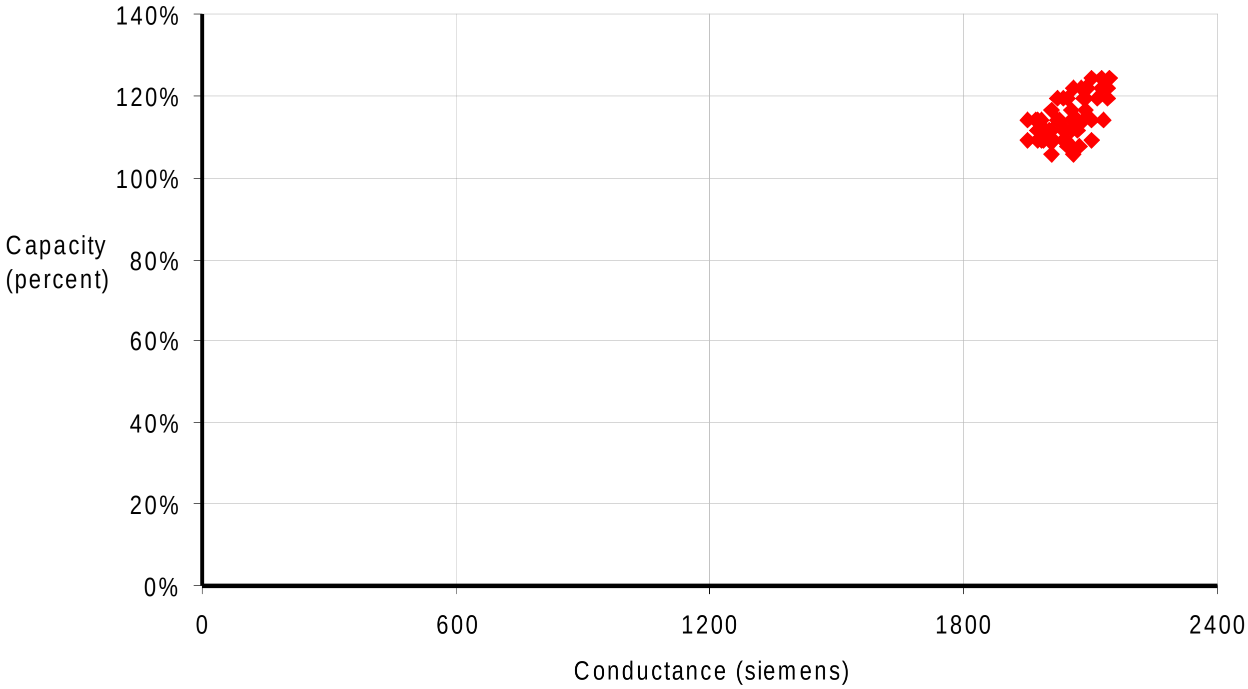

Figure 6-5
Correlation of Conductance to Capacity—New High Capacity Cells

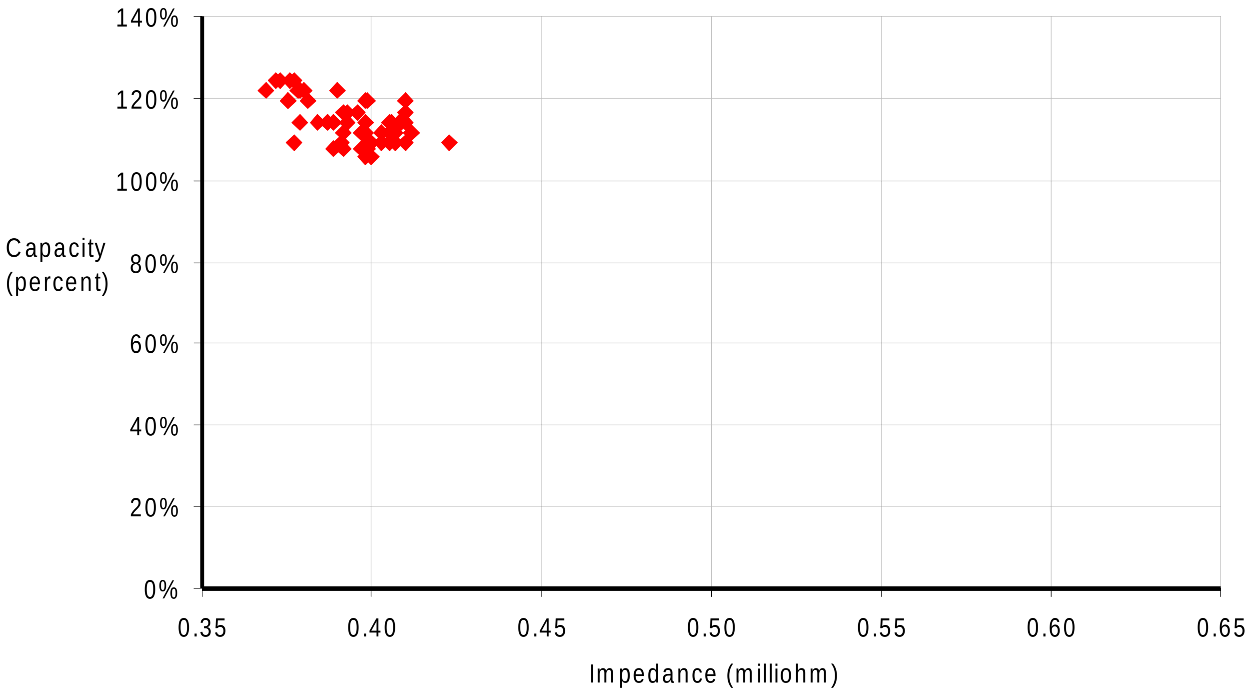

Figure 6-6
Correlation of Impedance to Capacity—New High Capacity Cells

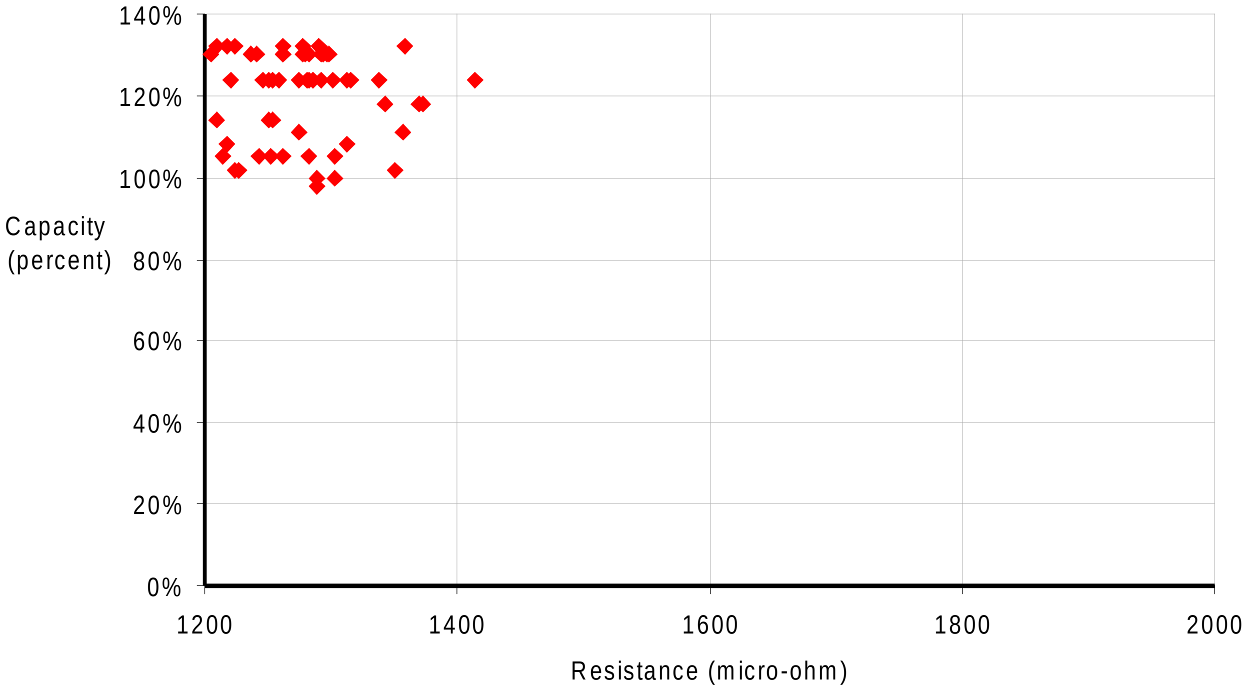

Figure 6-7
Correlation of Resistance to Capacity—New High Capacity Cells

6.3.2 Correlation to Capacity for Older Batteries With All Good Cells

Older batteries with good cells tended to appear very similar to new batteries in that the internal ohmic measurements tended to be clustered together with little variation. Figure 6-8 shows a typical battery (13 years old) with all good cells and the impedance measurements are within a 10% range. Figure 6-9 shows another battery (14 years old) with all good cells and the impedance measurements are within a 15% range. This behavior appears to be common for older vented lead-acid batteries that still have high capacity.

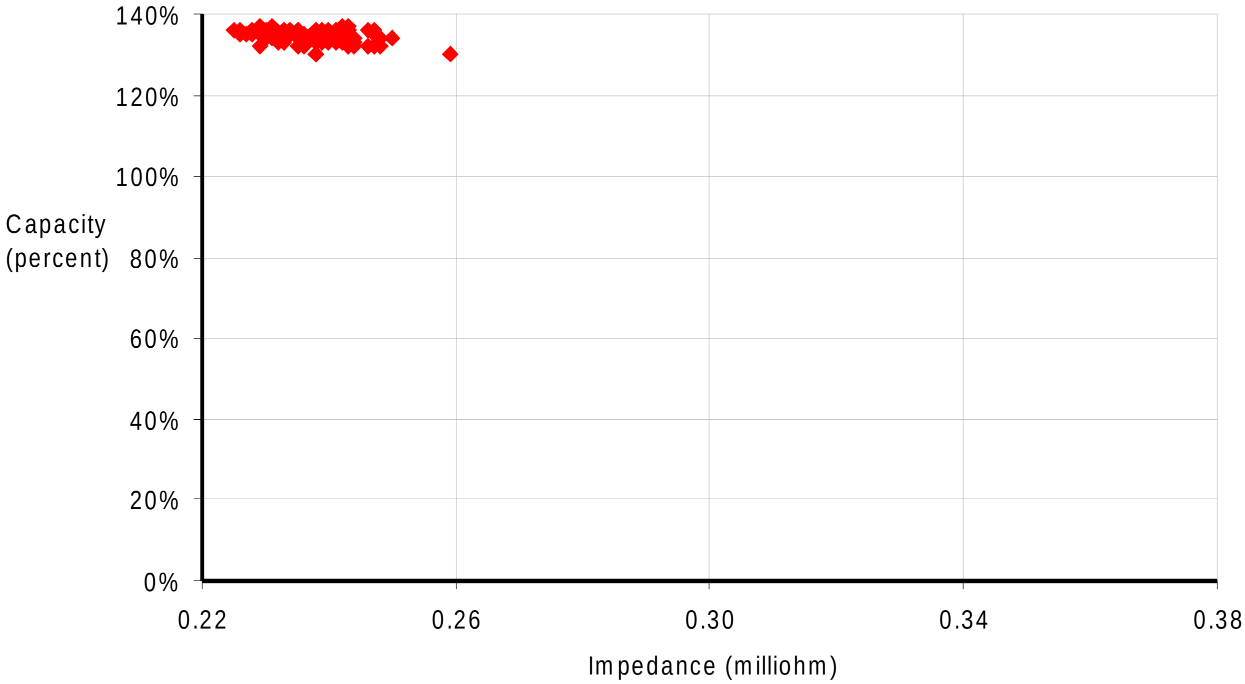

Figure 6-8
Correlation of Impedance to Capacity—13-Year-Old Vented Battery

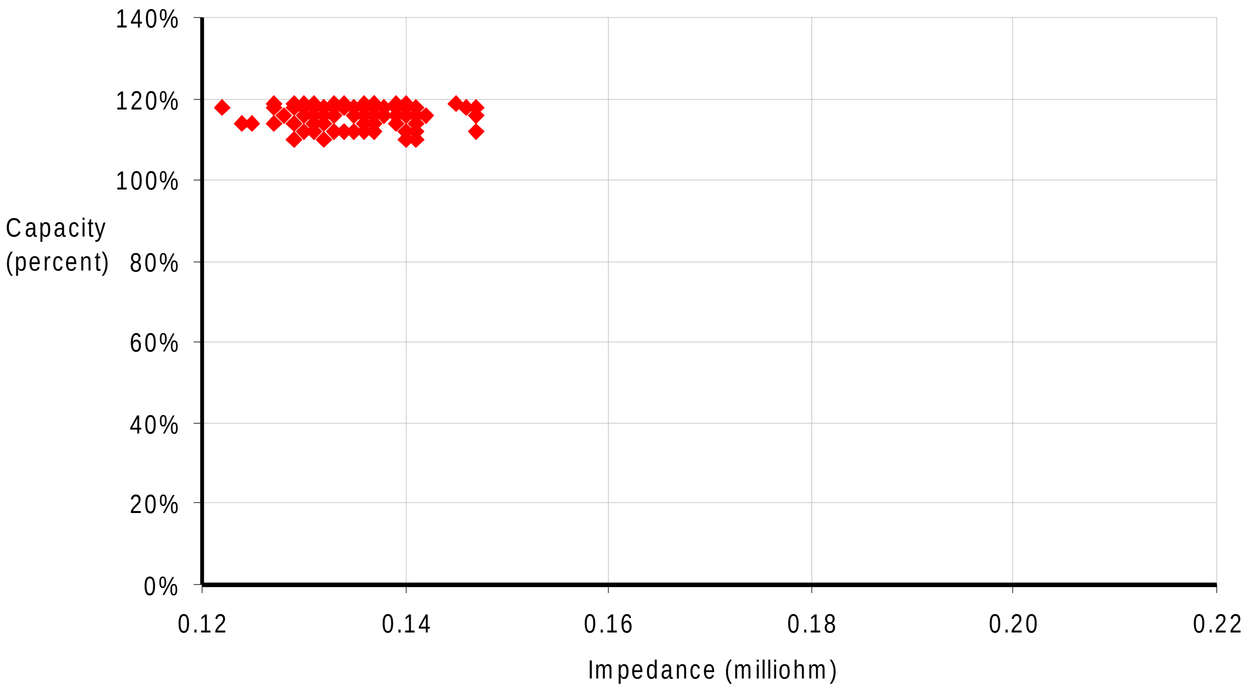

Figure 6-9
Correlation of Impedance to Capacity—14-Year-Old Vented Battery

6.4 Correlation to Capacity When a Battery Has Low-Capacity Cells

Virtually all vented lead-acid batteries evaluated so far in this project had an acceptable capacity. Whereas, the VRLA cells evaluated by this project routinely had a low capacity, the vented lead-acid cells routinely had a high capacity. But, when low-capacity cells were present, internal ohmic measurements were usually able to identify these cells. Figures 6-10 and 6-11 provide impedance and resistance measurements taken on a new battery. As denoted, the low-capacity cells do have a higher than average resistance.

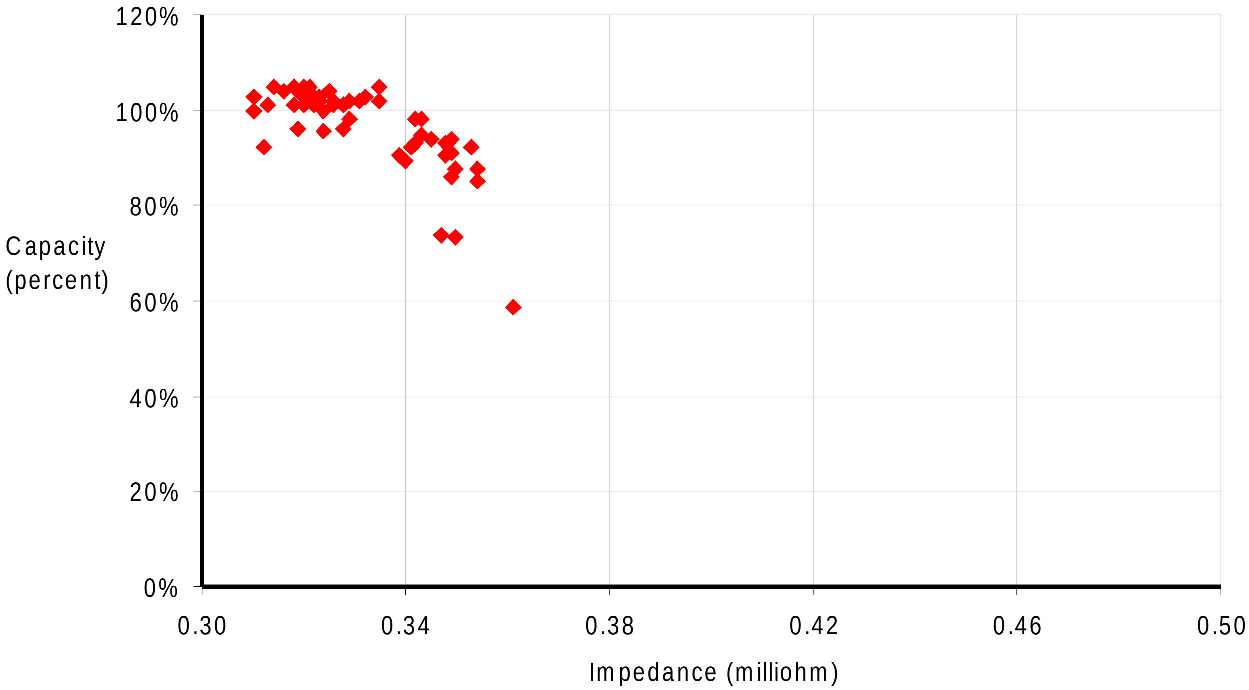

Figure 6-10
Correlation of Impedance to Capacity—Several Lower Capacity Cells

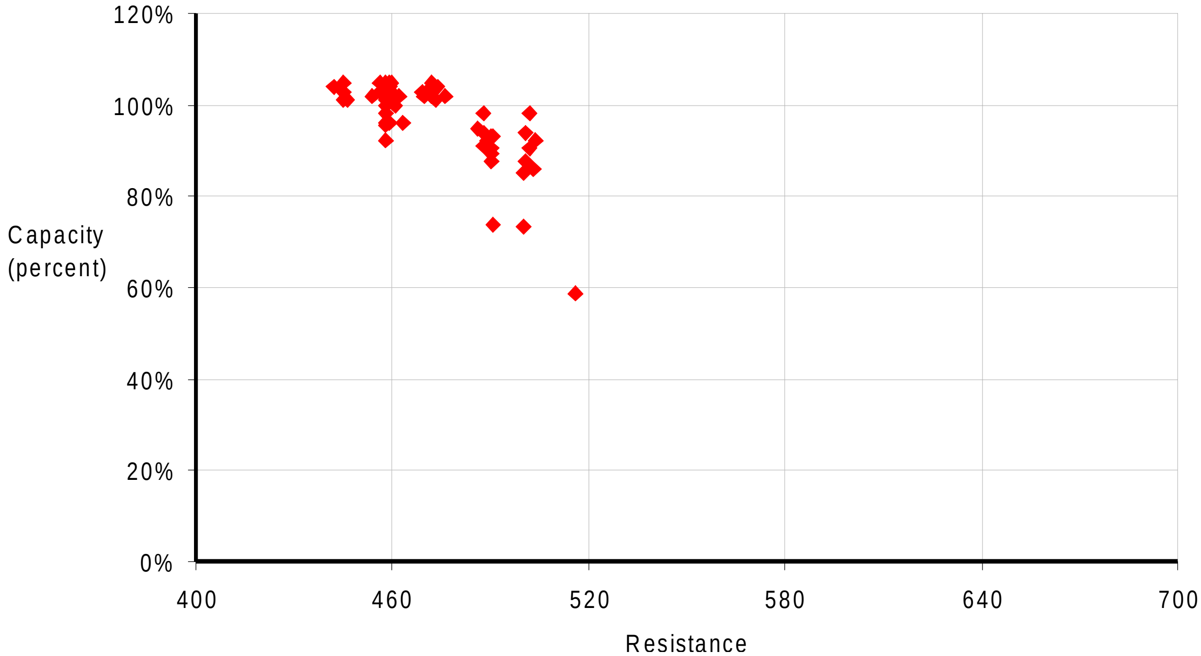

Figure 6-11
Correlation of Resistance to Capacity—Several Lower Capacity Cells

In some cases, only a few cells in the battery had a low capacity. Figures 6-12 through 6-14 show conductance and impedance measurements. Four cells have about 90% capacity and these cells clearly stand out. The lowest capacity cells have changed by about 20% from the average of the higher capacity cells.

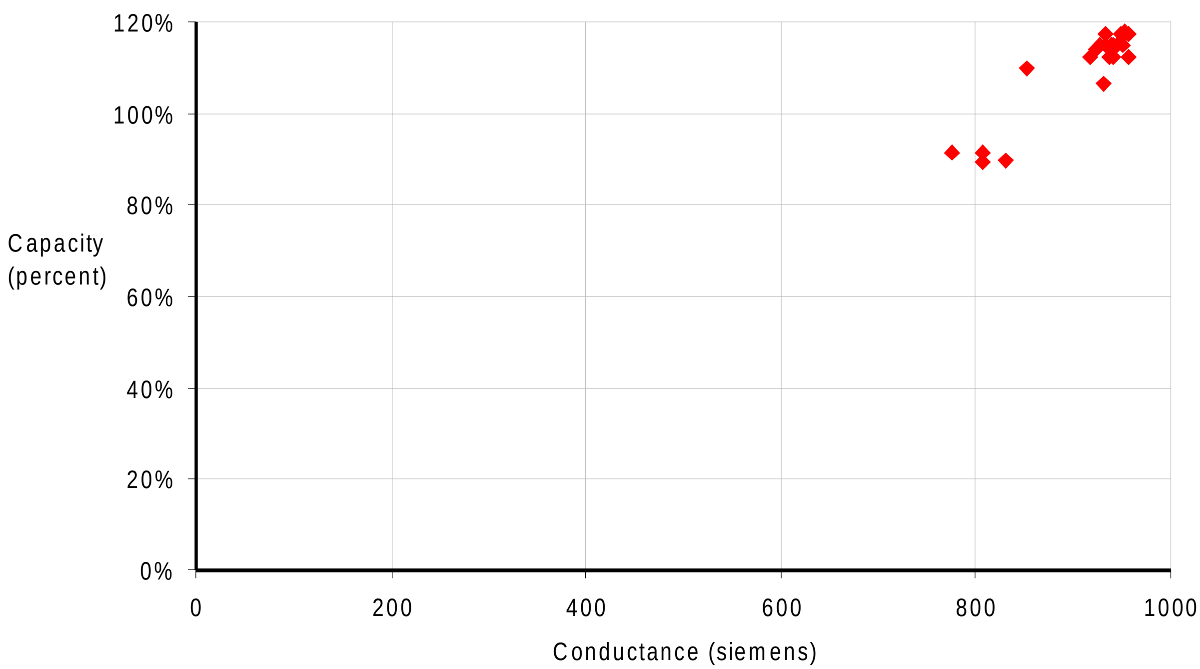

Figure 6-12
Correlation of Conductance (Micro Celltron) to Capacity—A Few Lower Capacity Cells

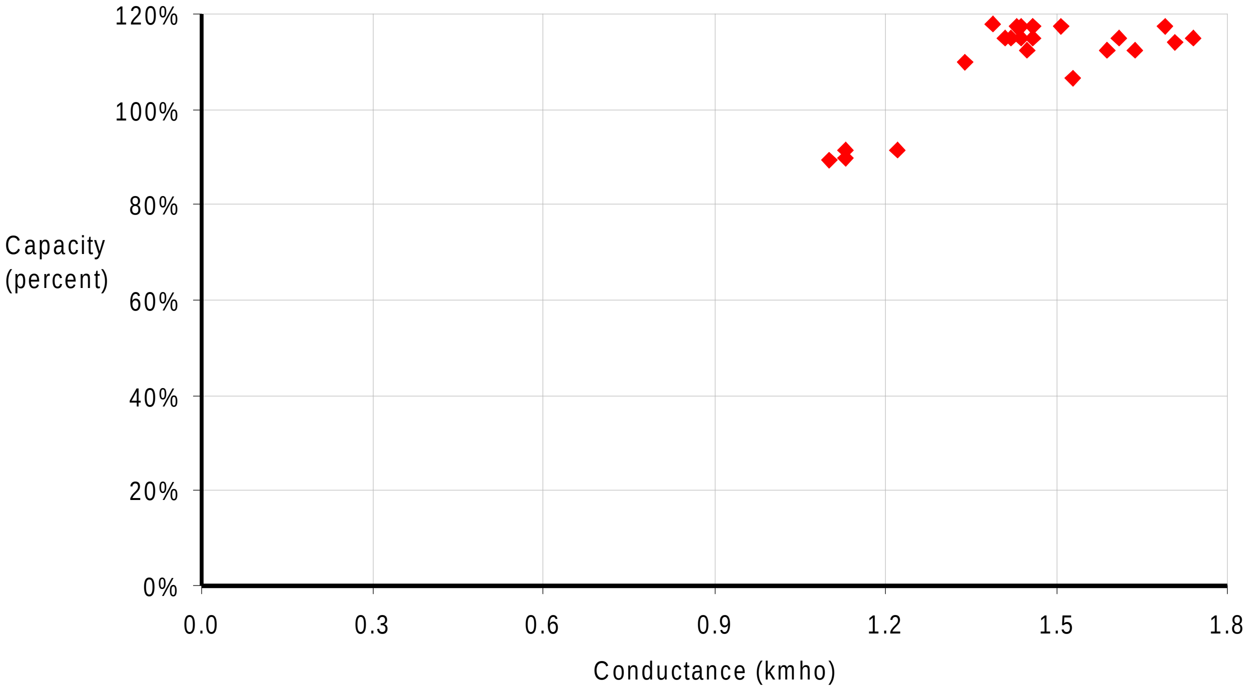

Figure 6-13
Correlation of Conductance (Celltron Plus) to Capacity—A Few Lower Capacity Cells

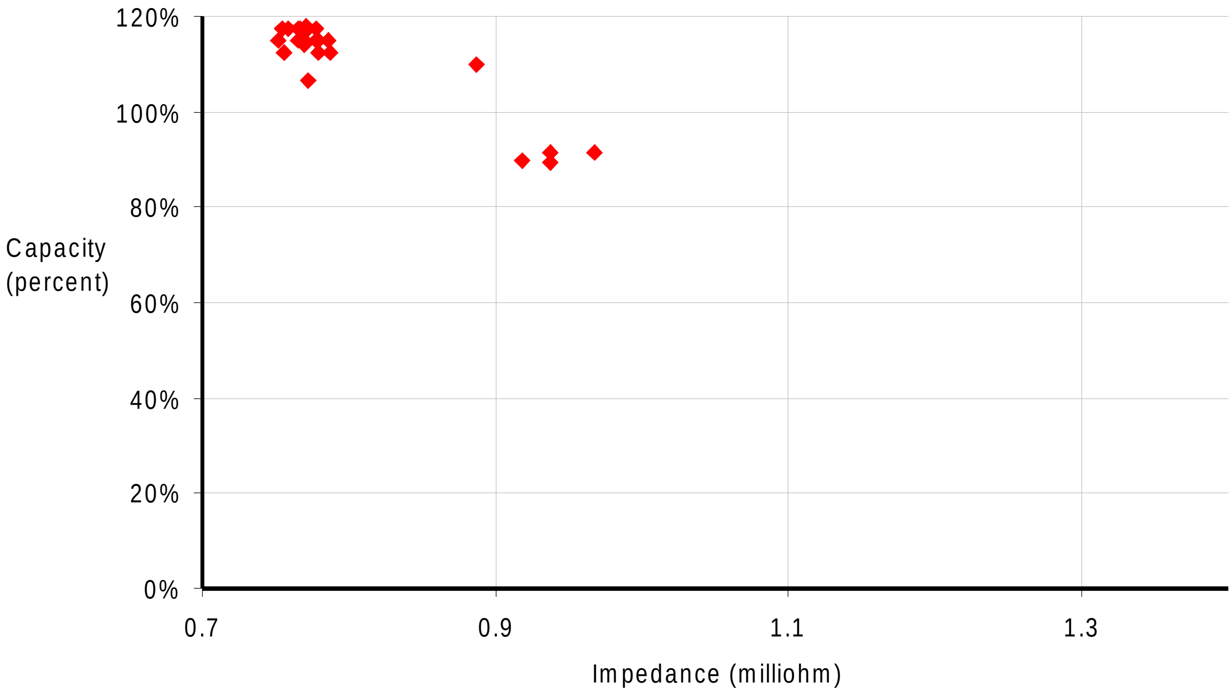

Figure 6-14
Correlation of Impedance to Capacity—A Few Lower Capacity Cells

Figures 6-15 and 6-16 show conductance and impedance measurements for a new battery with low capacity on delivery. The battery capacity was about 70% and the cells' internal ohmic measurements are consistently lower than expected for this cell size. The problem with this battery is believed to be incomplete plate formation. This particular battery highlights that the user should know the expected nominal value of a 100% capacity cell. In this case, there is not sufficient variation in the measurements to indicate a possible problem.

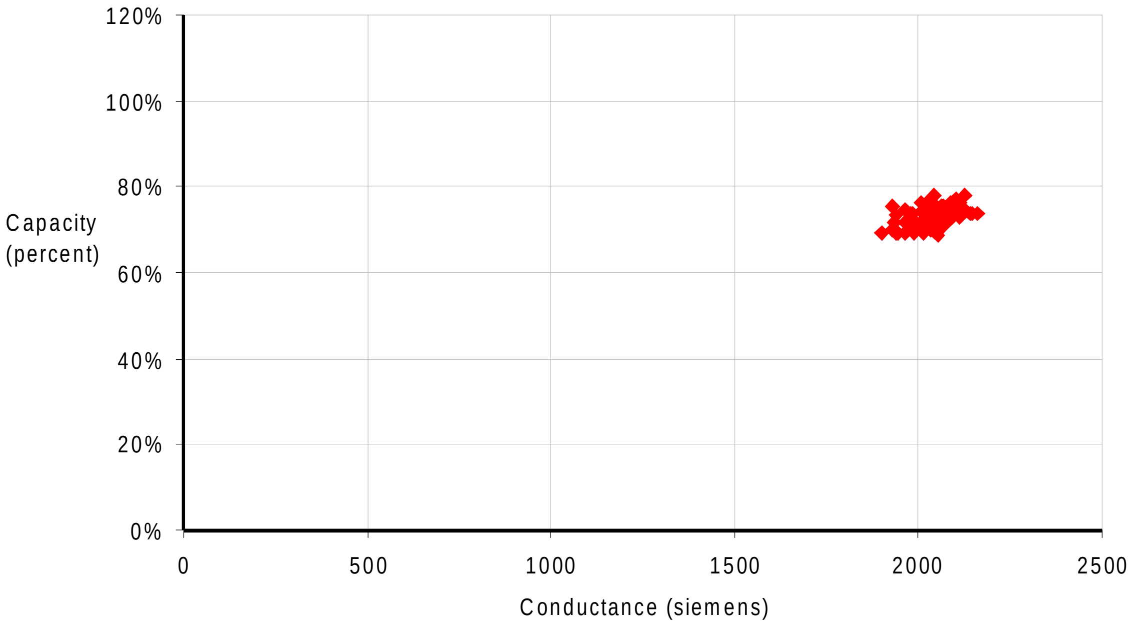

Figure 6-15
Correlation of Conductance to Capacity—All New Cells With Low Capacity

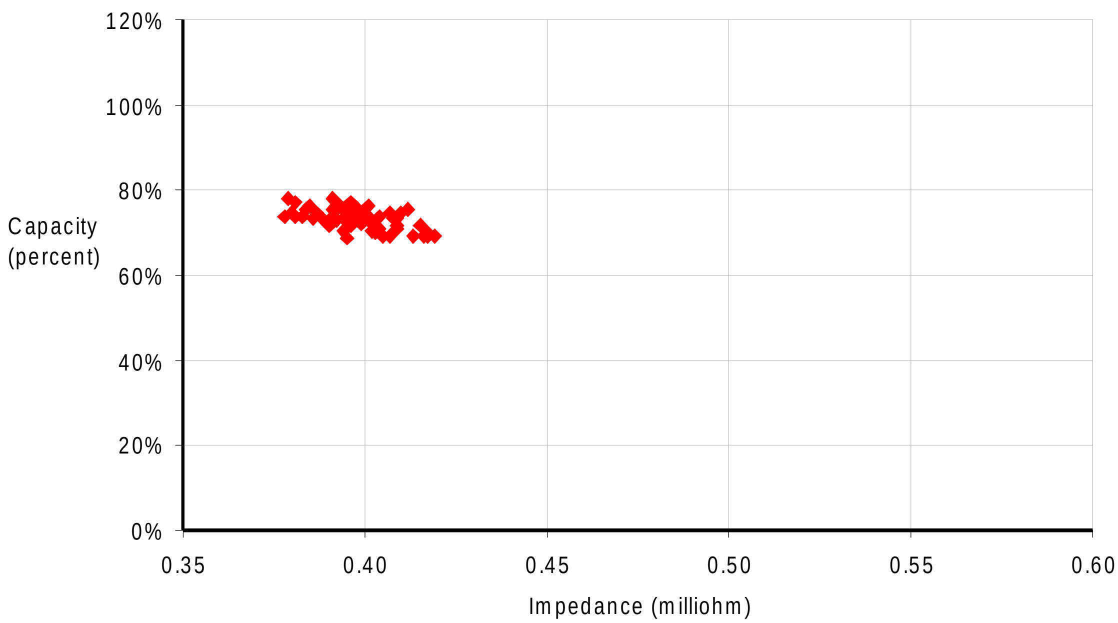

Figure 6-16
Correlation of Impedance to Capacity – All New Cells With Low Capacity

Large changes in the internal ohmic measurements consistently indicate the presence of low-capacity cells. Figure 6-17 shows an example in which one cell immediately went into reversal upon discharge and a second cell was quickly dropping in voltage. Both of these cells had extremely high internal resistances. Figure 6-18 shows another example in which the highest resistance cell has the lowest capacity.

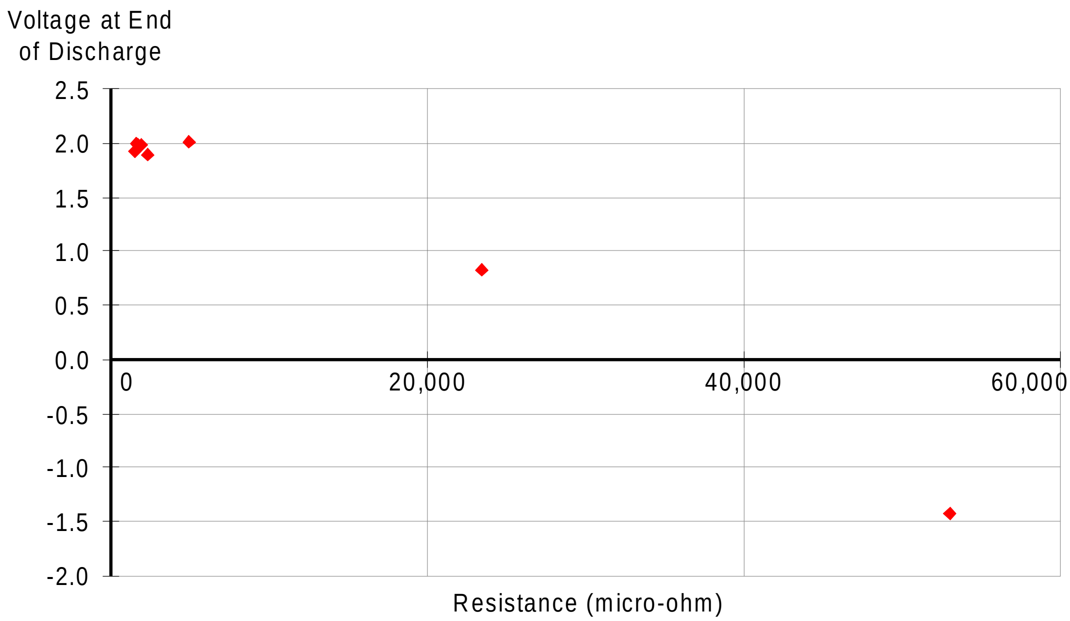

Figure 6-17
Correlation of Resistance to Capacity—Extremely High Resistance Cells

Figure 6-18
Correlation of Impedance to Capacity—Some Cells With Low Capacity

6.5 Correlation to Capacity for Different Cell Models

This section provides two examples of the correlation to capacity for different manufacturer's cell types. All available data for a given product line are combined in this section to show the consistency in measurements.

The Alcad SD series is a lead-selenium battery, available in cell sizes from 80 ampere-hours to 440 ampere-hours. All test data for the SD batteries in this project was combined for analysis. The capacity of each cell was calculated by the method described in Section 4.1.2 and the nominal value for each cell size was estimated by the method described in Section 4.2.2. All data can then be combined into a single graph in which percent cell capacity is plotted with respect to the percent of nominal internal ohmic value.

Figure 6-19 shows the conductance results for 420 cells. A relationship between conductance and capacity is evident.

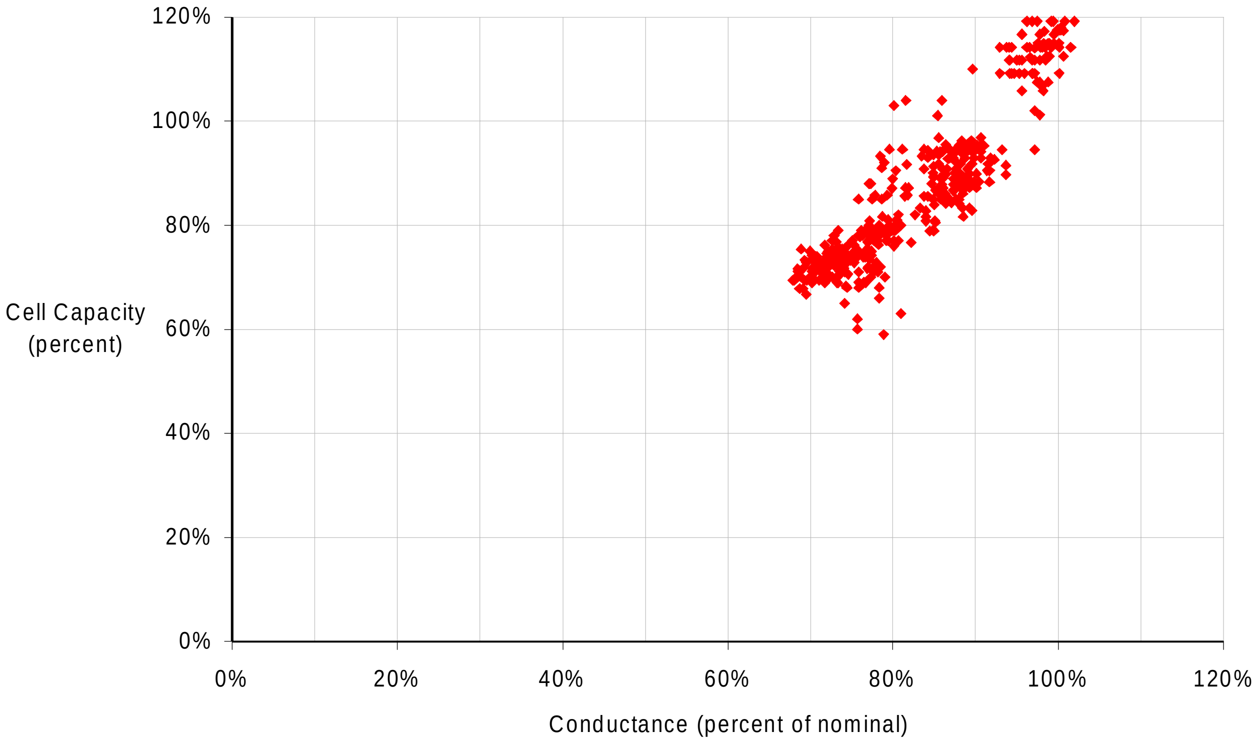

Figure 6-19
Alcad SD Cells—Conductance

Figure 6-20 shows the impedance results for 744 cells. A relationship between impedance and capacity is evident.

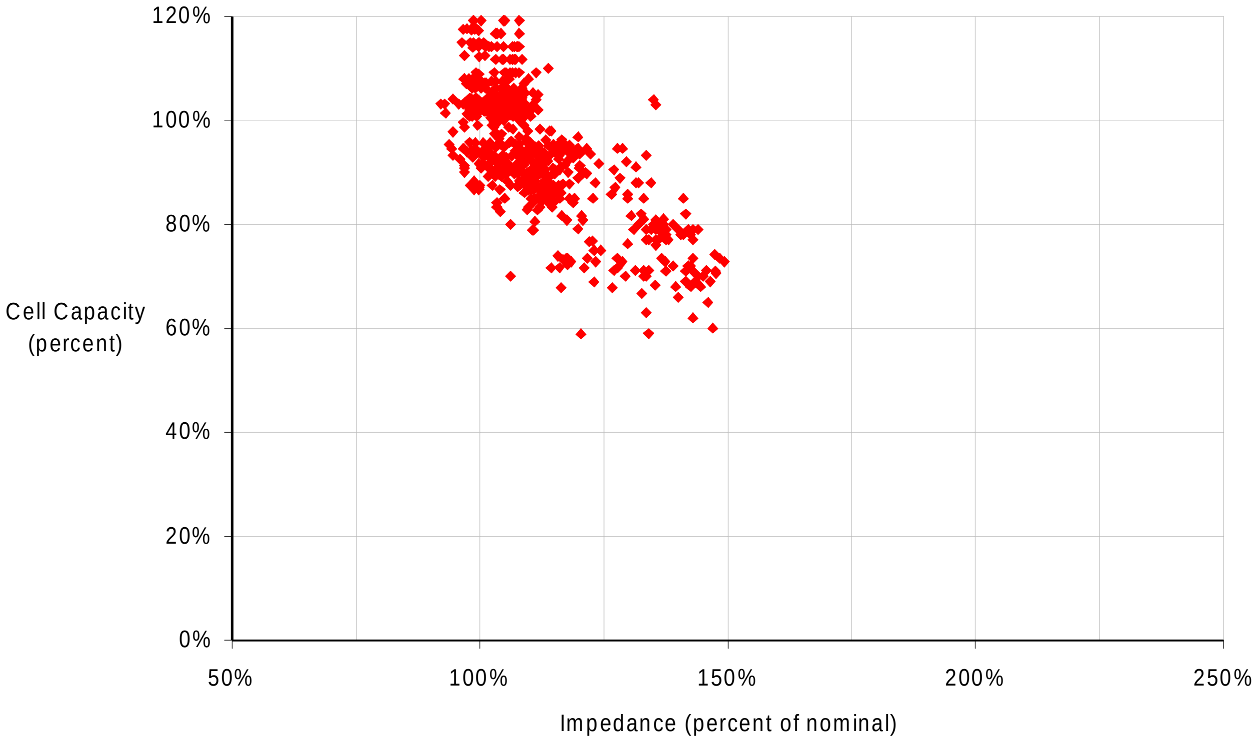

Figure 6-20
Alcad SD Cells—Impedance

Figure 6-21 shows the resistance results for 300 cells. A relationship between resistance and capacity is evident.

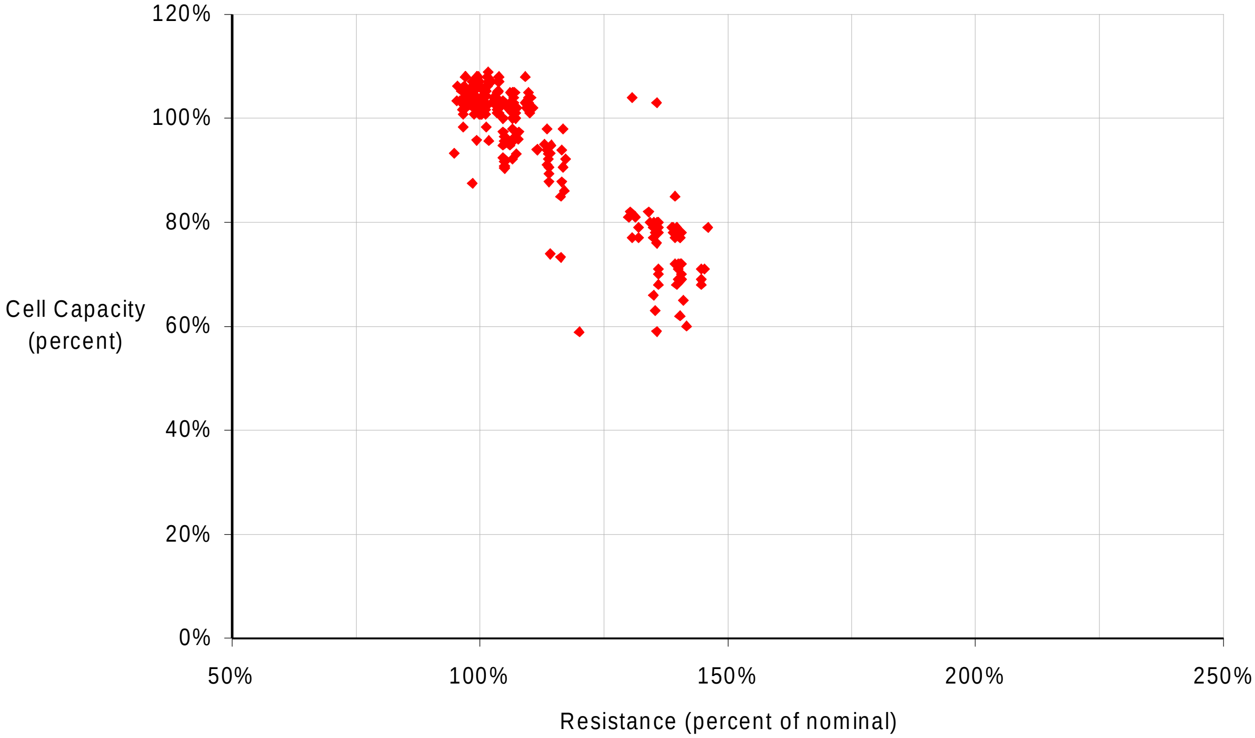

Figure 6-21
Alcad SD Cells—Resistance

The C&D KCR series is a lead-calcium battery, available in cell sizes from 180 ampere-hours to 825 ampere-hours. All test data for the KCR batteries in this project was combined for analysis. The capacity of each cell was calculated by the method described in Section 4.1.2 and the nominal value for each cell size was estimated by the method described in Section 4.2.2. All data can be combined into a single graph in which percent cell capacity is plotted with respect to the percent of nominal internal ohmic value.

Figure 6-22 shows the impedance results for 500 cells. A relationship between impedance and capacity is not obviously evident, mainly because all cells have very high capacity. 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%. The consistency of the data is encouraging, because large variations in internal ohmic values are not expected with such high cell capacities.

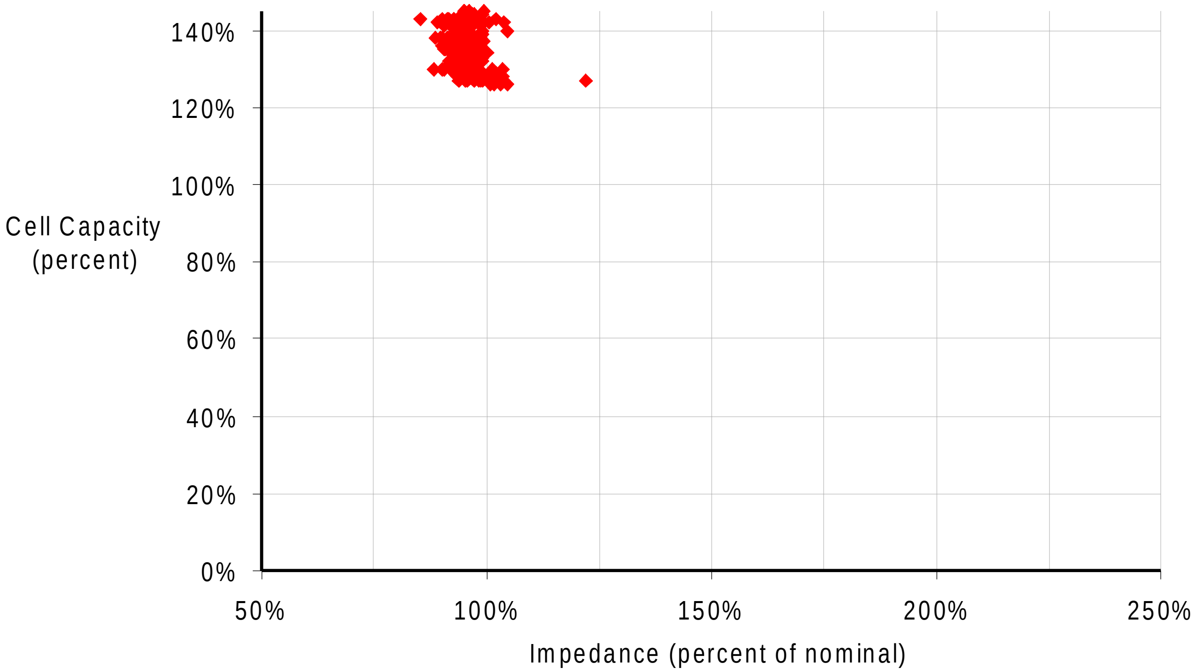

Figure 6-22
C&D KCR Cells—Impedance

6.6 Battery Capacity and Internal Ohmic Measurement Variations

Batteries with little variation in the cell internal ohmic measurements were normally good batteries with no bad cells. Batteries with a large variation in the internal ohmic measurements tended to have several (or many) bad cells. This is an important observation because it means that the user should be able to qualitatively assess a battery even without performing a detailed analysis. The final report will provide detailed information regarding this assessment.

7 CONCLUSIONS

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. Then, the measurements are 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.

This interim report provides a summary of current data and project findings.. The project participants are providing additional data on a continual basis. The project is scheduled to finish in late 2002, and this interim report will be updated with a complete report of the project results. The final report will provide specific guidance for the application of internal ohmic measurements and will address the following topics:

- The 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.
- A new section will be added to present test data for nickel-cadmium batteries.
- A *Guidelines* section will be included to provide detailed guidance regarding the application of internal ohmic measurements.
- An *Examples* section will be included providing 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.
- An *Observations* section will be included that discusses other observations or comments based on the project data.
- The *Conclusions* section will be updated to discuss the project's accomplishments.

8
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8.3.3 Battery Model

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A
GLOSSARY

The definitions provided in this appendix were obtained from the references listed in the report or were created during the course of the project. Abbreviations used in the body of the report are included in the glossary. Not all terms included in the glossary are used in the report, but are included for completeness.

A

AC – Alternating Current.

Acceptance Criteria – Specified limits placed on the characteristics or performance of an item, process, or service as defined in codes, standards, or other requirement documents.

Ambient Temperature – see Temperature, Ambient.

Ampere-Hour Capacity – The number of ampere-hours that can be delivered under specified conditions, including temperature, rate of discharge, and final voltage.

Available Capacity – The total capacity, in ampere-hours or watt-hours that will be obtained from a cell or battery at a defined discharge rate under specified operating conditions.

B

Bad Cell – In terms of capacity, a cell with less than 80% capacity.

Battery – Two or more cells connected to form one unit for producing electric energy at the required voltage and current levels.

Battery Duty Cycle – The group of load currents a battery is expected to supply over a specified discharge period.

BITE –Battery Impedance Test Equipment.

C

Cable Connector – A length of insulated cable terminating at each end in a casting or a lug and used to connect one cell to another.

Capacity – Ampere-hours available from a fully charged cell or battery.

Capacity Test – A discharge of a battery at a constant current or power to a designated terminal voltage.

Cell – An electrochemical device, composed of positive and negative plates, separator, and electrolyte, that is capable of storing electrical energy; when encased in a container and fitted with terminals, it is the basic component of a battery.

Cell Connector – An electric conductor used for carrying current between adjacent storage cells.

Cell Size – The rated capacity of a cell or the number of plates in the cell.

Charge – The conversion of electrical energy into chemical energy within the cell or battery. This restoration of the active materials is accomplished by maintaining a unidirectional current in the cell or battery in the opposite direction to that during discharge. A cell or battery thatis said to be charged is understood to be fully charged.

Charging Rate – The current expressed in amperes at which a battery is charged.

Conductance – A measure of the ability to facilitate current flow. Conductance is the inverse of resistance.

Contaminant – Undesirable element, usually in the electrolyte, that reduces the capacity of the cell.

Corrosion – The oxidation of a metal electrode.

Cover – The lid of an enclosed cell or jar.

Cycle – A battery discharge followed by a complete recharge. A deep, or full, cycle is described as the removal and replacement of 80% or more of the cell's design capacity.

Cycle Life – The number of cycles the battery can experience before its capacity falls to a point considered a failure.

Cycling – The repeated charge/discharge cycle of a storage battery. Some batteries are rated by their ability to withstand repeated, deep discharge cycles.

D

DC – Direct current.

Dead Cell – In terms of capacity, a cell whose voltage rapidly falls to zero upon application of an external load.

Deep Discharge – Withdrawal of at least 80% of the rated capacity of a cell or battery.

Depth of Discharge – The ratio of the quantity of capacity (usually in ampere-hours) removed from a cell or battery on discharge to its rated capacity.

Discharge – The conversion of the chemical energy of the battery into electrical energy.

Discharge Rate – The rate, usually expressed in amperes, at which electrical current is taken from the cell or battery.

Discharging – The withdrawing of electrical energy from a battery or cell.

E

EBITE – Enhanced Battery Impedance Test Equipment.

Electrolyte – The conducting medium in which the flow of electric current takes place by the migration of ions. For example, the electrolyte for a lead-acid cell is an aqueous solution of sulfuric acid.

Energy Density – The ratio of the energy available from a cell or battery to its volume (watt-hour/liter) or weight (watt-hour/kilogram).

F

Failure – Termination of the ability of an item to perform its required function.

Failure Mechanism – The physical, chemical, or other process that results in failure.

Failure Mode – The effect by which a failure is observed.

Failure Rate – The expected number of failures of a given type, per item, in a given time interval or a given number of operating cycles.

Float Charge – The method of maintaining a cell or battery in a charged condition by continuous, long-term constant-voltage charging at a level to balance self-discharge.

Float Service Applications – Storage batteries applied for reserve use and maintained at a "float" voltage point selected to just exceed the batteries' internal losses.

Float Voltage – The voltage applied to a battery to maintain the proper voltage for each cell of the battery during normal operation.

Flooded Cell – see Vented Cell.

Full Float Operation – Operation of a dc system with the battery, battery charger, and load all connected in parallel, and with the battery charger supplying the normal dc load plus any self-discharge or charging current, or both, required by the battery. The battery will deliver current only when the load exceeds the charger output.

G

Gassing – The evolution of gases from one or more of the electrodes during electrolysis.

Good Cell – In terms of capacity, a cell with greater than 80% capacity.

Grid – A framework employed in a storage cell for supporting the active material and conducting the electric current.

Group – An assembly, in a storage cell, of plates of the same polarity connected in parallel.

I

IEEE – Institute of Electrical and Electronics Engineers, Inc.

Impedance – The opposition or resistance of a cell or battery to an alternating current of a particular frequency.

Initial Test Temperature – The average temperature of the electrolyte in the battery cells at the beginning of discharge.

Initial Voltage – The closed-circuit voltage at the beginning of a discharge. It is usually taken after the current has been flowing for a sufficient period of time for the rate of change of voltage to become practically constant.

Inspection – Examination or measurement to verify whether an item or activity conforms to specified requirements.

Installed Life – The interval from installation to removal, during which the equipment or component thereof might be subject to design service conditions and system demands.

INTELEC – International Telecommunications Energy Conference.

Intercell Connector – A conductor used to connect adjacent cells.

Internal Ohmic Measurement – A general term to describe the measurement of a cell's conductance, impedance, or resistance.

Internal Ohmic Value – A general term to describe a cell's measured value of conductance, impedance, or resistance.

J

Jar – The container that holds the cell, or group of cells, and electrolyte.

L

Life – The duration of satisfactory performance, measured as usage in years or as the number of charge/discharge cycles.

M

Maintainability – The ease with which equipment can be maintained, including the ease with which maintenance can be performed in accordance with prescribed requirements.

Maintenance – The combination of all technical and corresponding administrative actions intended to retain an item in, or restore it to, a state in which it can perform its required function.

Maintenance-Free Battery – see Valve-Regulated Lead Acid (VRLA) Cell. An inappropriate term sometimes used to describe a VRLA battery.

Maintenance Interval – The period, defined in terms of real time, operating time, number of operating cycles, or a combination of these, during which satisfactory performance is required without maintenance or adjustments.

Mandatory Maintenance – Periodic maintenance required by insurance, operating license, vendor warranty, government regulations, or other safety regulations.

MBITE – Miniature Battery Impedance Test Equipment.

Module – A container of two or more cells. Modules are commonly produced in 3-cell (6 V) and 6-cell (12 V) containers.

N

Negative Plate – Consists of the grid and active material to which current flows from the external circuit when the battery is discharging.

Negative Terminal – The terminal toward which positive electric charge flows in the external circuit from the positive terminal when the cell discharges.

Nominal Gravity – The specific gravity of the electrolyte selected for the determination of the rated capacity of the storage battery when it is fully charged and correctly leveled.

Nominal Value – The expected internal ohmic value of a cell with 100% capacity, or better.

Nominal Voltage – The characteristic operating voltage or rated voltage of a cell or battery.

Normal Float – A constant-potential charge application to a battery to maintain it in a charged condition.

O

Open Circuit Voltage – The voltage at a cell or battery terminals when no appreciable current is flowing.

Operable – For a given point in time, a device or equipment that has been demonstrated by testing at that time to have met a set of functional performance requirements under specified test conditions.

Overcharging – Continuing charge after the battery has accepted its maximum amount of charge. In a vented cell, a result will be decomposition of water in the electrolyte into hydrogen and oxygen gases. In a VRLA cell, a result will be increased cell temperature and venting of gases through the pressure relief valve.

Oxidation – The release of electrons, by the cell's active material, to the external circuit. During discharge, active material at the negative electrode is oxidized.

Oxygen Recombination – The electrochemical process in which oxygen generated at the positive plate during overcharge is reacted (reduced) with water at the negative plate at the same time, thereby producing heat.

P

Pasted (Fauré) Plate – A plate consisting of a grid filled with active material applied as a paste.

Performance Test – A constant current or constant power capacity test made on a battery after being in service to detect any change in the capacity.

Periodic Test – A test performed at scheduled intervals to detect failures and verify operability.

Plate – An assembly of active material on a supporting framework grid, frame, or support strip.

PM – Periodic maintenance.

Point (of Specific Gravity) – 0.001 of specific gravity. A 0.010 change in specific gravity would be referred to as a "10-point" change.

Polarity – An electrical condition determining the direction in which current tends to flow on discharge. By common usage, the discharge current is said to flow from the positive electrode through the external circuit.

Polarization – The change in voltage at the terminals of the cell or battery when a specified current is flowing; it is equal to the difference between the actual and the equilibrium (constant open-circuit condition) potentials of the plates, exclusive of the internal resistance drop.

Positive Plate Limited – The operating characteristics (performance) of the cell are limited by the positive plate.

Positive Plate – The grid and active material from which current flows to the external circuit when the battery is discharging.

Positive Terminal – The terminal from which the positive electric charge flows through the external circuit to the negative terminal when the cell discharges.

Preventive Maintenance – Regularly scheduled inspections, tests, servicing, repairs, and replacements intended to reduce the frequency and impact of equipment failures.

Q

Qualified Life – The period of time for which satisfactory performance can be demonstrated for a specific set of service conditions.

R

Rated Capacity – The ampere-hour capacity assigned to a storage cell by its manufacturer for a given discharge time, at a specified electrolyte temperature and specific gravity, to a given end-of-discharge voltage.

Rating – The designated limit for a given parameter for the operating characteristic of the device.

Recharge – Return of electrical energy to a battery.

Recombinant Cell – A cell designed so that generated oxygen and hydrogen are recombined to form water rather than being vented from the cell [see Valve-Regulated Lead Acid (VRLA) Cell].

Recombination – The chemical reaction of gases at the electrodes to form a nongaseous product.

Reduction – The gain of electrons. In a cell, it refers to the inward flow of electrons to the active material.

Reliability – The characteristic of an item expressed by the probability that it will perform a required function under stated conditions for a stated period of time or operating cycles.

Resistance – The opposition or resistance to electrical current flow within a cell or battery. Its value is dependent upon battery design, state of charge, temperature, and age.

Retainer – Any material that is used to prevent the loss of active material from the positive plate.

Reversible Reaction – A chemical change that takes place in either direction, as in the reversible reaction for charging or discharging a secondary battery.

Ripple Current – The ac component of the dc output current.

Ripple Voltage – The ac component of the dc output voltage.

S

Sealed Cell – A cell that is free from some routine maintenance and can be operated without regard to position. All reactants are retained within the container.

Sealing Compound – Sealing compound is any material that is used to seal a storage cell cover to the jar.

Secondary Battery – A system which is capable of repeated use through chemical reactions that are reversible; that is, the discharged energy can be restored by supplying electrical current to recharge the cell.

Sediment – The active material that separates from the battery plates and falls to the bottom of the jar.

Self-Discharge – The spontaneous decomposition of battery materials from a charged to a discharged state.

Separator – A spacer employed to prevent metallic contact between plates of opposite polarity within the cell.

Service Conditions – The conditions under which the equipment is to be applied.

Service Life Capacity – Minimum battery capacity needed to meet design requirements, including temperature correction, but excluding margin.

Specific Gravity of Electrolyte – The specific gravity of an electrolyte is the ratio of the weight of a given volume of electrolyte to the weight of an equal volume of water at a specified temperature.

Standby Battery – A battery designed for emergency use in the event of a main power failure.

Starved Electrolyte – A term occasionally applied to a VRLA cell, meaning that the cell contains little or no free electrolyte.

State of Charge – Residual capacity of a cell expressed in terms of fully charged capacity.

Stationary Battery – A storage battery designed for service in a permanent location.

Storage Battery – A battery consisting of one or more cells electrically connected for producing electric energy.

Sulfate – Lead sulfate ($PbSO_4$) that forms on the positive or negative plates.

Sulfation – A state in which a lead-acid battery has developed an abnormal amount of sulfate and its capacity is impaired.

T

Temperature, Ambient – The average temperature of the battery's surroundings.

Temperature, Cell – The average temperature of the battery's components.

Terminal Connection Detail – Connections made between rows of cells or at the positive and negative terminals of the battery, which can include terminal plates, cables with lugs, and connectors.

Terminal Connector – An electrical conductor for carrying current from the battery to the external circuit.

Terminals – The parts of a storage battery to which the external circuit is connected.

Thermal Runaway – A condition whereby a battery on constant-potential charge at elevated temperature will destroy itself through internal heat generation by high internal currents.

Trickle Charge – A continuous charge at a low rate approximately equal to the internal losses and suitable to maintain the battery in a fully charged condition.

U

Undercharging – Applying less than the amount of current required to recharge a battery.

UPS – Uninterruptible Power System.

V

Valve-Regulated Lead Acid (VRLA) Cell – A lead-acid cell that is sealed with the exception of a valve that opens to the atmosphere when the internal gas pressure in the cell exceeds the atmospheric pressure by a pre-selected amount. VRLA cells provide a means of recombination of internally generated oxygen and the suppression of hydrogen gas evolution to limit water consumption.

VDC – Volts direct current

Vent – A normally sealed mechanism which allows the controlled escape of gases from within a cell.

Vented Cell – A lead-acid cell in which the gaseous products of electrolysis and evaporation are allowed to escape to the atmosphere as they are generated. A vented cell is also referred to as a flooded cell.

VPC – Volts per cell.

VRLA – Valve-regulated lead acid.

B
INDUSTRY STANDARDS

The Institute of Electrical and Electronic Engineers (IEEE) provides comprehensive guidance for stationary batteries. IEEE has addressed the issue of internal ohmic measurements in recently issued recommended practices. Each recommended practice is described in the following sections.

B.1 IEEE 1187-1996

IEEE 1187-1996, IEEE Recommended Practice for Installation Design and Installation of Valve-Regulated Lead Acid Storage Batteries for Stationary Applications, provides recommendations for the design and initial installation of a VRLA battery. The following topics are addressed by this recommended practice:

- Safety precautions and procedures
- Battery location
- Receiving and storage
- Cell mounting and connections
- Freshening/initial charge
- Initial measurements and testing
- Suggested records

As part of the installation process, IEEE 1187 sets the starting point for future maintenance by recommending that the following data be recorded at the time of installation:

- Receiving inspection data and condition of charge
- Initial resistance values of the intercell connections
- Individual cell or unit voltage values at the completion of the initial charge
- Acceptance test results
- Initial ripple current
- Individual cell or module internal ohmic values

Internal ohmic measurements are recommended in IEEE 1887 to identify defective cells and to establish a baseline against which to compare future measurements.

B.2 IEEE 1188-1996

IEEE 1188, Recommended Practice for Maintenance, Testing, and Replacement of Valve-Regulated Lead Acid Batteries for Stationary Applications, provides detailed periodic maintenance, inspection, and test recommendations for VRLA batteries. This recommended practice represents an important contribution to the industry by providing specific maintenance recommendations for VRLA batteries. The following topics are discussed in this recommended practice:

- Safety precautions
- Monthly general inspections:
  - Overall float voltage check
  - Charger output current and voltage check
  - Ambient temperature and condition of the ventilation and monitoring equipment
  - Visual inspection
- Quarterly inspections:
- Monthly inspection as described above
  - Internal ohmic value measurement
  - Temperature measurement of each negative terminal
  - Intercell connection resistance measurements for applications with a discharge rate of one hour or less
- Semi-annual inspections:
  - Quarterly inspection as described above
  - Voltage of each cell or unit
- Annual inspections:
  - Semi-annual inspection as described above
  - Intercell connection resistance measurement of all connections
  - AC ripple current measurement

In several instances, the above recommendations represent a significant departure from traditional maintenance for vented batteries as well as from the recommended maintenance contained in some battery manufacturers' operating manuals. In particular, the scope and frequency of inspections and tests have been increased.

Internal ohmic measurements are recommended to be taken on a quarterly basis on VRLA batteries. IEEE 1188 recommends internal ohmic measurements for VRLA batteries for the following reasons:

- VRLA batteries cannot be visually inspected internally; in vented batteries, the visual inspection often provides early indication of potential battery problems.

- Cell voltage measurements do not indicate internal problems until significant cell damage or degradation has occurred.
- Dryout is one of the most common failure mechanisms for VRLA batteries. Traditional inspections are unable to detect this condition.
- VRLA batteries have shown a tendency to be more susceptible to sudden death (that is, an unexpected failure when a load is placed on the battery) than vented lead-acid batteries. Yet, the VRLA cell design does not allow monitoring of this failure mode by conventional means.
- VRLA batteries are more sensitive to high temperature, overcharge, and over-discharge than vented lead-acid batteries. Therefore, a method of monitoring the internal rate of degradation is needed.
- Other conventional battery inspections do not necessarily provide a true indication of battery health. For example, specific gravity or cell voltage measurements do not indicate the available capacity. Either of these measurements offers general information regarding the quality of the electrolyte and the adequacy of the float voltage; however, neither provides conclusive information regarding the adequacy of internal cell conduction paths. In any event, specific gravity measurements are not possible for VRLA batteries. The primary failure mode of a lead-acid cell under ideal conditions is corrosion and degradation of the positive grid and plate, which is not assessed by either a specific gravity or a cell voltage measurement.
- Finally, there is no other measurement technique that offers the user any ability to “see” inside the cell. Some type of internal monitoring method is needed.

B.3 IEEE 484-1996

IEEE 484-1996, *IEEE Recommended Practice for Installation Design and Installation of Vented Lead-Acid Batteries for Stationary Applications,* provides installation design and installation recommendations for vented lead-acid batteries. Internal ohmic measurements have not been recommended by IEEE for vented lead-acid batteries because, unlike the VRLA battery, there are other possible methods of assessing the battery’s health. For example, a vented lead-acid battery can have its electrolyte checked and a detailed visual inspection can be performed. Nonetheless, IEEE 484 endorses internal ohmic measurements as an optional practice for those users who desire additional baseline data.

B.4 Unit Definitions

If needed, use the following terms to convert to the required units:

Ampere (Unit of current: A) = Fundamental unit of electrical current = 1
Ampere Hour (A h) = 3600.0 coulomb (C) = 3600.0 sec A
Celsius (C) to Fahrenheit = (C · 9/5) + 32
Coulomb (Unit of charge: C) = Ampere second
Energy [kilowatt hour (kW·h)] = 3.6E+6 = 3600000.0 m^2·kg/sec^2 (Joule) = 3.6E+13 cm^2·g/sec^2 (energy)
Farad (Unit of capacitance) = Coulomb $Volt^{-1}$ = Joule $Volt^{-2}$
Fahrenheit (F) to Celsius = (F - 32) · 5/9
Henry (Unit of inductance: H) = 1.0E-9 = m^2·kg/$sec^2 A^2$ = 1.0 abhenry
Joule (Unit of energy: J) = Newton meter = m^2·kg/sec^2
Ohm (Unit of resistance: ohm) = Volt $Ampere^{-1}$ (V/A) = $Volt^2$ $Joule^{-1}$ $second^{-1}$ (V^2/J·sec)
Power = U.S. horsepower (CV) = 745.7 m^2·kg/sec^3 (Watt) = 7.457E+9 cm^2·g/sec^3
Siemens (Unit of electric conductance: S) = $s^3 \cdot A^2/m^2$ kg
Volt (Unit of potential) = Joule $coulomb^{-1}$ (J/C)
Watt (Unit of power) = Ampere Volt = Joule $second^{-1}$ (J/sec)

Target:

Nuclear Power

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