# Conductance testing compared to traditional methods of evaluating the capacity of valve-regulated lead/acid batteries and predicting state-of-health

David O. Feder
*Electrochemical Energy Storage Systems Inc., 35 Ridgedale Ave, Madison, NJ 07940 (USA)*

Thomas G. Croda
*Sprint, Long Distance Division, 533 Airport Boulevard, Burlingame, CA 94010 (USA)*

Keith S. Champlin
*5437 Elliot Avenue South, Minneapolis, MN 55417 (USA)*

Stephen J. McShane
*Midtronics, Inc., 7101 Adams Street, Willowbrook, IL 60521 (USA)*

Mark J. Hlavac
*Midtronics, Inc., 7101 Adams Street, Willowbrook, IL 60521 (USA)*

**Abstract**

Recently, timed discharge capacity tests were performed on 336 individual valve-regulated lead/acid cells in a telecommunications power system. The results were compared with traditional methods of determining cell health (i.e., float voltage, open-circuit voltage, and calculated specific gravity.) At the same time, conductance measurements were taken, and these results were also compared to the results of the timed discharge capacity tests. Data will be presented which show that traditional methods indicate almost no correlation to timed discharge capacity testing. Conductance test data will be presented which show a very nearly linear correlation. Based on this correlation, these results indicate that conductance testing can provide users of valve-regulated lead/acid batteries with a valuable predictive tool for determining the state-of-health of individual cells.

The industry is rapidly moving toward valve-regulated lead/acid (VRLA) batteries for a number of reasons, including their size, configuration, claims of superior safety and minimal (or zero) loss of gas, freedom from acid spillage, and the claim that they are 'maintenance free'. For these reasons, VRLA batteries have rapidly achieved customer acceptance and application into a previously unimaginable variety of usages. Unfortunately for the user, this 'maintenance-free' feature creates a unique dilemma since for all practical purposes, VRLA batteries have been essentially maintenance proof.

The traditional methods of determining state-of-charge or state-of-health of flooded vented cells are not applicable to VRLA cells. Measurement of specific gravity, observation of internal plate/grid structures to ascertain extent of grid corrosion and

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growth, measurement of excessive use of water by checking water level and water addition when necessary, are all impossible by design for the VRLA system. For all practical purposes, this leaves the user with only two techniques:

(i) Measurement of individual cell voltages in the hope that voltage variation will serve as a reliable diagnostic for imminent cell failure.

(ii) Single-cell or full-string discharge testing as the only certain reliable procedure to determine a cell's state-of-health.

Furthering the problems facing the users of valve-regulated batteries are a number of applications problems which probably result from lack of appreciation, by both the battery manufacturer and the user, of the sensitivity of this VRLA technology to its usage. Among these applications-related problems are the excessive use of parallel strings, high temperatures which have the effect of lowering life expectation, and improper float voltages which can reduce the life of cells.

In this paper, we will discuss a relatively new technique for the measurement of cell conductance as a potential indicator of the state-of-health of VRLA cells and compare its reliability to individual cell voltage measurements (and calculated specific gravity from open-circuit voltage measurements) using full string discharge tests as the ultimate standard of cell condition. The new technique may provide users with a method which dramatically improves the ability to monitor and maintain these systems and therefore assure the proper performance of VRLA battery systems as the number of applications for VRLA batteries continues to grow.

First, however, let us review the variety and range of factors which can influence cell behavior and cause premature failure of VRLA cells in order to establish the complex nature of the dilemma facing the user, i.e., that there are a greater number and variety of failure modes which do not affect vented flooded cells but are unique to VRLA cells and yet the user has fewer diagnostic tools at his command.

While grid corrosion is common to both vented and VRLA cells, it is more rapid and hence more serious in VRLA cells because of higher specific gravity electrolyte and higher float currents, (and often excessive positive polarization when operating in a recombinant mode). Because the technology is newer, VRLA cells generally use newer grid alloys for which there exists more limited corrosion/growth data, further contributing to the uncertainty of its effect on the rate of cell aging and failure. Finally, and perhaps most important, the grid corrosion process itself consumes oxygen, leading ultimately to cell dry-out – a failure mode unique to VRLA cells.

Dry-out also results from a variety of other causes including excessive gas evolution, leaking post seal or jar cover seals (so prevalent in vented cell designs) and finally via water, hydrogen and oxygen diffusion through the walls and cover of the plastic container – a failure mode which is especially significant in elevated temperature usages.

Additional failure modes unique to VRLA cells can result from faulty operation of the gas relief valve. Stuck open, it can cause dry-out and also allow air to enter the cell, causing negative plate self-discharge. Stuck closed, the result is jar bulge and potential explosion.

Cooling of VRLA cells is far more critical than for vented cells. If inadequate, thermal runaway may result in immediate cell dry-out, melt-down or explosion.

A failure mode which has to date been observed with far greater frequency in VRLA cells than in their vented counterparts, involves internal corrosion and failure of the post strap or plate connecting lugs. This effect can and has occurred at either the positive or negative terminals inside the cell container and can cause immediate failure on discharge. It can also cause a cell explosion on discharge if an arc were to jump the 'open' gap. This is a real effect and has been observed and reported in a significant number of installations.

To summarize the user's dilemma, visual observation of catastrophic failure modes, cell voltage variation and capacity testing are the only currently available diagnostic methods of determining cell aging or imminent failure which result from any or all of the wide variety of failure modes unique to VRLA cells.

However, there is a newer technique: measurement of cell conductance or its reciprocal impedance as a possible diagnostic. The balance of this paper will review the use of the Midtronics conductance testing technique and present data indicative of its reliability in predicting cell performance.

In a paper presented at the 1991 Battery Council International Meeting, one of the authors [1] reviewed the status of the data then available, which could be used to correlate conductance or impedance with capacity. He noted that the cell conductance/impedance correlation with capacity could depend on a specific number of variables and might, in fact, require 'cradle to grave' correlation for individual cell installations. Cell conductance/impedance was also affected by a variety of VRLA cells operational and failure modes which could further confound the accuracy of its correlation with capacity. At that time, following an extensive survey of battery manufacturers, battery users and conductance/impedance tester manufacturers, Feder concluded that:

(i) Conductance/impedance could successfully detect catastrophic internal corrosion and imminent cell failure and also act as a useful safety aid in preventing explosions on discharge.

(ii) Significant deviations from the normal value of conductance or impedance were readily detectable but that further diagnostics were needed to catalog their possible causes.

On the issue of conductance/impedance correlation with capacity, Feder [1] concluded in April 1991 that the available data were far too limited to allow a firm conclusion to be drawn. At that time he recommended that critical diagnostics be limited to capacity testing with conductance/impedance testing recommended for safety prior to a discharge test. (This concept has subsequently been included in draft standard 1188: 'Recommended practice for maintenance, testing and replacement of VRLA batteries for stationary applications' currently undergoing final editing, following successful balloting by sub-committee SCC29 of the Institute of Electrical and Electronics Engineers (IEEE) (see Fig. 1). However, in April 1991 Feder also urged, most vigorously, that industry manufacturers, users, and conductance/impedance tester manufacturers cooperate in test programs to develop the quantity and variety of data essential to the determination of the validity of the conductance/impedance correlation with capacity.

The balance of this paper will be devoted to a discussion of an extensive series of tests of conductance versus capacity performed on cells in telephone transmission, cellular and other typical stationary reserve application usage, using Midtronics conductance testers. Other programs intended to provide data for correlation which are also underway at this time include Midtronics testing at long distance and cellular telephone sites. Biddle testing at utilities and other users, Exide-Yuasa conductance testing with telephone users and with in-plant quality control, AT&T Bell Labs laboratory and field tests, and Power Battery laboratory and field tests.

While cell specific gravity is not directly measurable in a VRLA cell, it can be determined indirectly by measurement of cell open-circuit voltage and calculated via the following formula:

$$\text{specific gravity} = \text{cell open-circuit voltage} - 0.85 \qquad (1)$$

ACTIONS TAKEN AND APPROVED BY BALLOT AT APRIL 1992 MEETING:

INDIVIDUAL CELL FLOAT VOLTAGE MEASUREMENT:
FREQUENCY CHANGED FROM QUARTERLY TO SEMI-ANNUAL.

CONTINUITY TEST REPLACED (WHERE POSSIBLE) BY:
CONDUCTANCE/IMPEDANCE TEST.

FOR SAFETY REASONS.

FOR IMPROVED DIAGNOSTIC CAPABILITY.

CONDUCTANCE/IMPEDANCE TESTING APPROVED FOR:
QUARTERLY TESTING OF INDIVIDUAL CELL/MONOBLOCS.

FOR CONDUCTANCE/IMPEDANCE CHANGES GREATER THAN 20/30%, CONTACT MANUFACTURES FOR URGENT CORRECTIVE ACTION.

FOR CONDUCTANCE/IMPEDANCE CHANGES GREATER THAN 30/50%, PERFORM CAPACITY TEST AS SOON AS FEASIBLE.

FOR SAFETY, PERFORM CONDUCTANCE/IMPEDANCE TESTS:

PRIOR TO ANY CAPACITY TESTS.

PRIOR TO ANY CONTINUITY TESTS.

Fig. 1. IEEE Par 1188-recommended practice for maintenance, testing and replacement of valve-regulated lead/acid batteries for stationary applications.

This is not normally a useful diagnostic since it requires 12 to 36 h open-circuit stand for voltage stabilization. Nevertheless, in one series of tests involving 168 cells in a working telephone transmission office (7 parallel strings of 24 cells each of approximately 1000 A h capacity per cell), open-circuit values were determined following a 36 h stand and specific gravities were subsequently calculated. Following this, discharge tests were performed sequentially on each of the 7 strings at the nominal 3 h rate (263 A) to 1.75 V per cell. Figure 2 shows the total lack of correlation between calculated specific gravity and discharge time to 1.75 V. Note especially that this lack of correlation extends over a range of discharge times from as little as 15 min to as much as 180 min (approximately 100% capacity).

The next series of tests involved attempts to correlate individual cell float voltages with capacity. Here, two separate studies were performed. The first involved 48 200 A h VRLA cells arranged in two 24-cell parallel strings in a cellular telephone site. After measurement of cell voltages on float, each string was sequentially discharged at the nominal 2 h rate to 1.75 V per cell. Figure 3 shows the total lack of correlation between float voltage and capacity. Further, it indicates discharge times ranging from 82 to 118 min for cells which are all well within the manufacturer's allowable float voltage variation limits. Prior to discharge, individual cell conductance values were also measured for these 48 cells. The correlation of discharge time versus conductance in mho (or S) is shown in Fig. 4. The correlation is a vast improvement in diagnostic sensitivity compared with float voltage.

The same sequence, float voltage versus capacity and conductance versus capacity, was performed on the 168 1000 A h cells previously tested for specific gravity versus capacity. Figure 5 shows the float voltage distribution among all 168 cells and indicates that all were within the manufacturer's allowed range of variation. Figure 6 shows the results of float voltage versus capacity to 1.75 V per cell. Just as with the

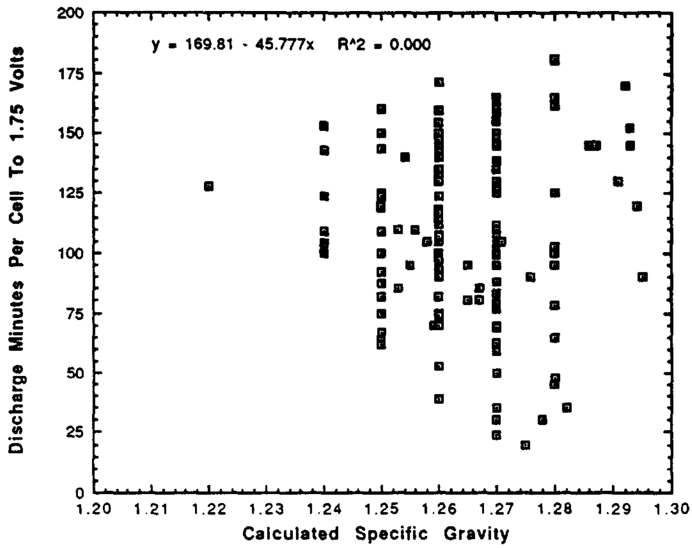


Fig. 2. Calculated specific gravity vs. discharge capacity: VRLA 1000 A h, 168 cells 263 A to 1.75 V per cell. (Calculated specific gravity = open-circuit voltage >36 h–0.85).

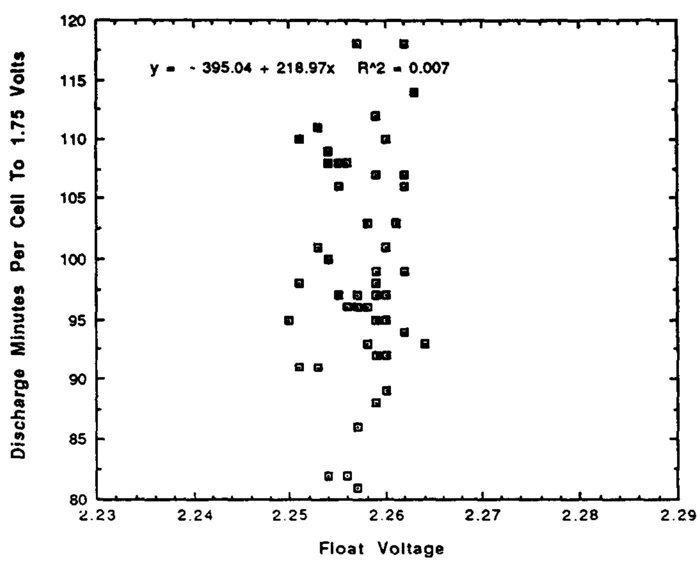


Fig. 3. Float voltage vs. discharge capacity: VRLA 200 A h, 48 cells 2 h discharge rate to 1.75 V per cell.

200 A h cells shown in Fig. 3, these data show no correlation of capacity with float voltage. Again, by contrast, Fig. 7 shows the correlation of capacity versus conductance, measured in kmho (kS), of these same 168 cells. Here the correlation coefficient is approximately 0.8 for conductance versus capacity, in marked contrast to the lack of correlation of float voltage versus capacity.

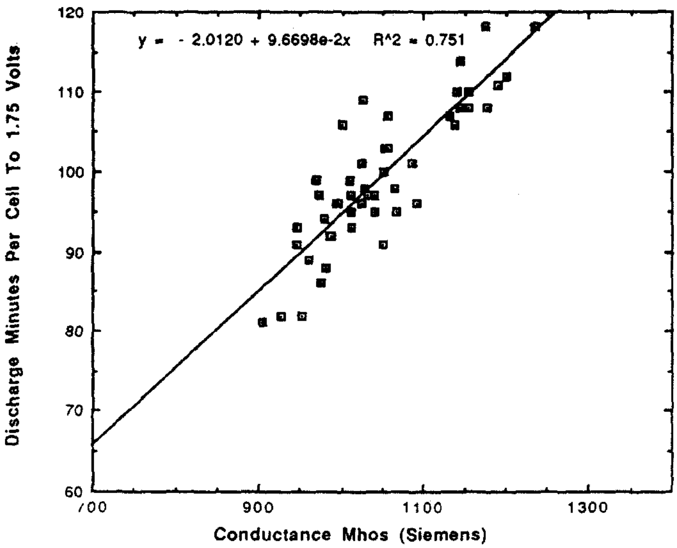


Fig. 4. Conductance vs. discharge capacity: 48 cells VRLA 200 A h, 2 h discharge rate to 1.75 V per cell.

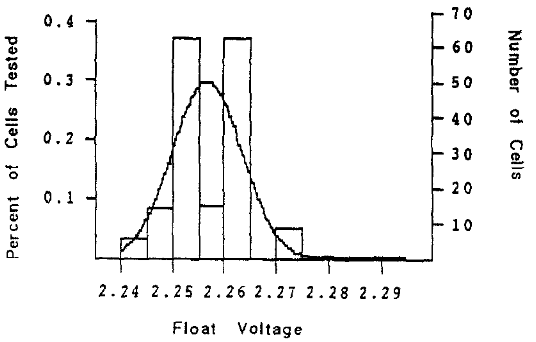


*Fig. 5. Float voltage distribution: VRLA 1000 A h, 168 cells consolidated data (strings 9–15).*

Since telephone equipment often operates to end-of-discharge voltages greater than 1.75 V per cell, conductance/capacity correlation plots were also made for capacity to 1.84 V per cell (Fig. 8) and 1.80 V per cell (Fig. 9). The correlation to 1.84 V per cell is approximately 0.88 while the correlation to 1.80 is approximately 0.83.

In this same telephone transmission office, an additional 7 parallel strings of 24 cells (1000 A h each) were tested prior to those reported in the previous Figs. 7 to 9. The correlation of capacity versus conductance in these 168 cells in strings 2–8 is shown in Fig. 10 with a correlation coefficient of 0.88. Capacities ranged from zero to 160 min at 263 A (approximately the 2.5 h rate to 1.80 V per cell). From the correlation plot for these strings — strings 2–8 — calculation of the capacity mean and standard deviation capacity values were made, calculated at 0.1 kmho (kS) intervals over the entire range of capacities. The results of these predictive correlation calculations were then overlaid onto the results of the capacity/conductance plot of the 168 cells

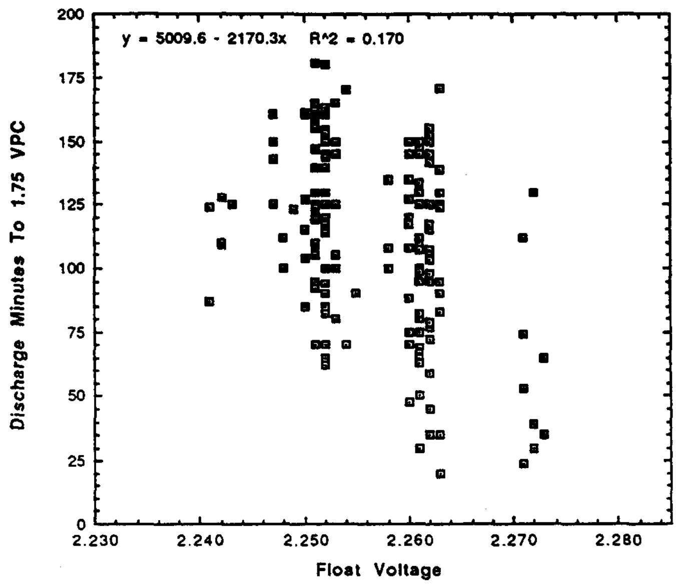


Fig. 6. Float voltage vs. discharge capacity: VRLA 1000 A h, 168 cells 263 A to 1.75 V per cell (VPC).

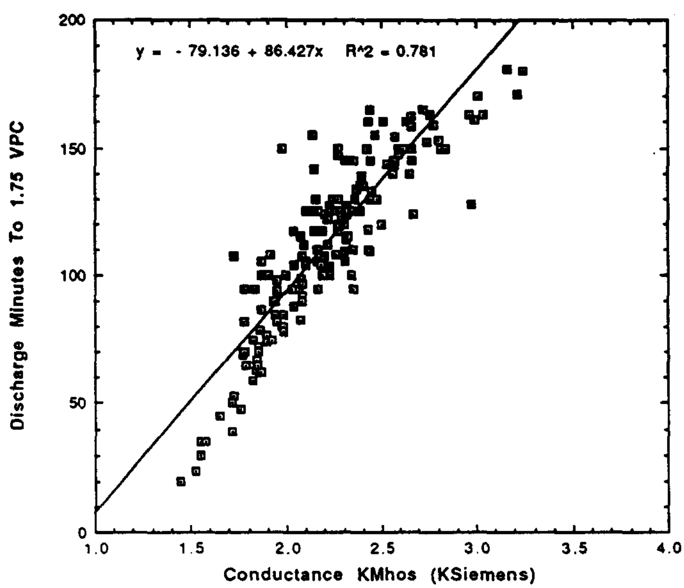


Fig. 7. Conductance vs. discharge capacity: VRLA 1000 A h, 168 cells consolidated data (strings 9–15), 263 A to 1.75 V per cell (VPC).

of strings 9–15. This is shown in Fig. 11 in which the population of strings 9–15 is shown to fall almost totally within the calculated mean plus or minus two standard deviation values calculated from the correlation plot of strings 2–8. The obvious

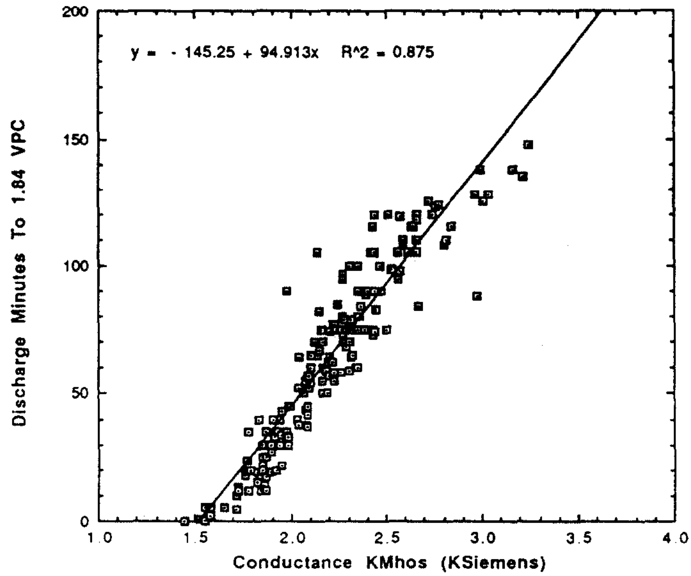


Fig. 8. Conductance vs. discharge capacity: VRLA 1000 A h, 168 cells consolidated data (strings 9–15), 263 A to 1.84 per cell (VPC).

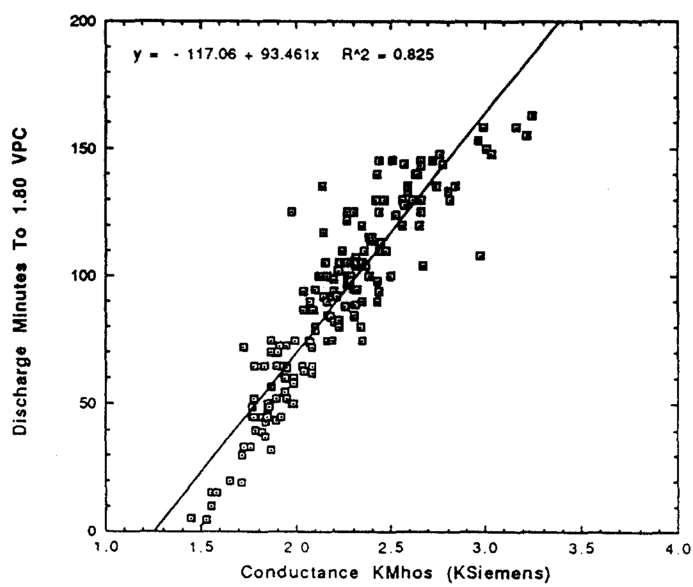


Fig. 9. Conductance vs. discharge capacity. VRLA 1000 A h, 168 cell consolidated data (strings 9–15), 263 A to 1.80 V per cell (VPC).

significance of this exercise is to demonstrate that the correlation plots of capacity versus conductance of one group of cells can be used to predict the performance of a similar group of cells being operated under the same sets of conditions.

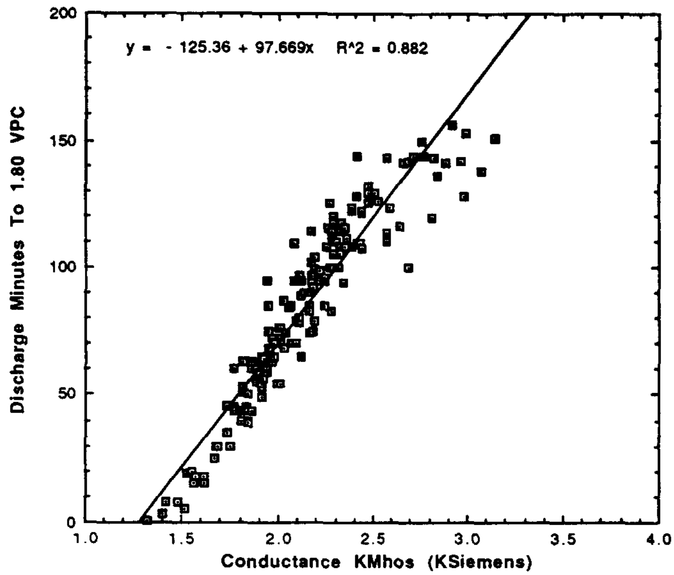


Fig. 10. Conductance vs. discharge capacity: VRLA 1000 A h, 168 cells initial consolidated data (strings 2–8), 263 A to 1.80 V per cell (VPC).

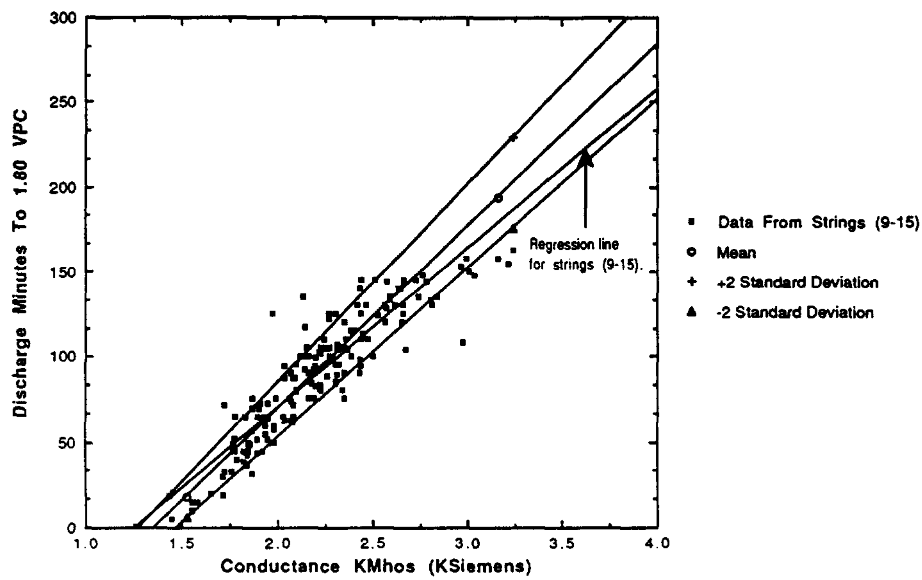


Fig. 11. Conductance vs. discharge capacity: VRLA 1000 A h, correlation plot using calculated mean and standard deviation from strings 2–8 (168 cells) to make predictions for strings 9–15 (168 cells).

One of the benefits of VRLA cells is their monobloc 6 and 12 V construction which minimizes the number of individual units that must be interconnected in order to provide a higher voltage battery string. The obvious drawback of such a monobloc is the inability to measure any individual cell parameters. Included in the series of tests reported in this paper is a series of tests performed on twenty 6 V, 200 A h monoblocs. Figure 12 shows the correlation between conductance (kmho) and discharge time to 1.95 V per cell for 6 V, 200 A h monobloc designs discharged at 100 A, the 1 h rate to 1.95 V per cell. The correlation of conductance versus capacity for the 20 monoblocs tested is excellent for discharge times capacities ranging from as little as 3 min to as much as 55 min at the 1 h rate. The calculated correlation coefficient is 0.79. The same data plotted as end-of-discharge voltage for individual monoblocs versus conductance is shown in Fig. 13. Again, the correlation is significant, despite the fact that monoblocs are being tested, rather than individual cells.

In another series of tests, six 225 A h cells were tested for conductance and were subsequently discharged at the 5 h rate to 1.75 V per cell. On the first cycle (Fig. 14) correlation of capacity versus conductance was 0.98 covering a range of capacities from 10 to 118%. After recharge, conductance was remeasured and cells discharged again at the 5 h rate to 1.75 V per cell. Figure 15 shows the correlation, with the value of 0.98.

The data obtained in this study on more than 500 cells indicate a very strong correlation of capacity with conductance. The cells include a range of sizes and capacities from 200 to 1000 A h and both single-cell and 6 V monoblocs are included. Their ages ranged from four to six years and their capacities from zero to greater than 100%; for at least one set of tests, they represent both an earlier design and its subsequent redesigned replacement. Clearly, more extensive studies, which include other designs (especially gel designs), other sizes, other applications, and single-string versus parallel-string plates are needed before final judgments can be rendered. Nevertheless, at this stage, the correlation of capacity and conductance is sufficiently

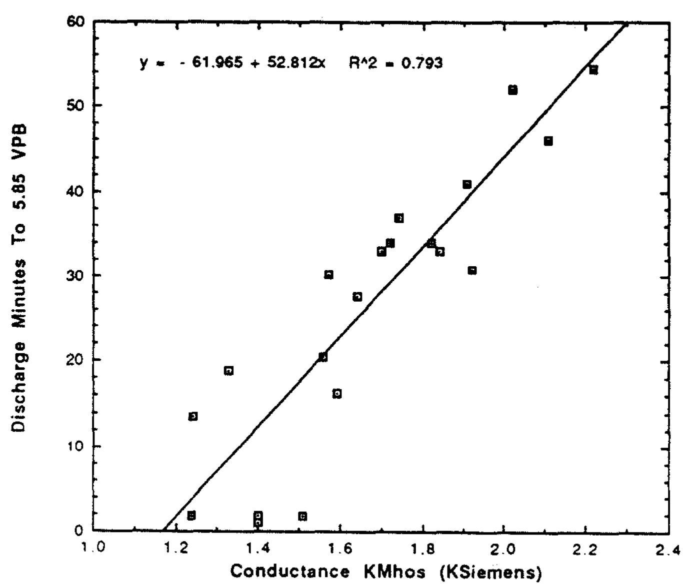


Fig. 12. Conductance vs. discharge capacity: VRLA 6 V, 200 A h, 20 batteries, 100 A to 5.85 V per battery (VPB).

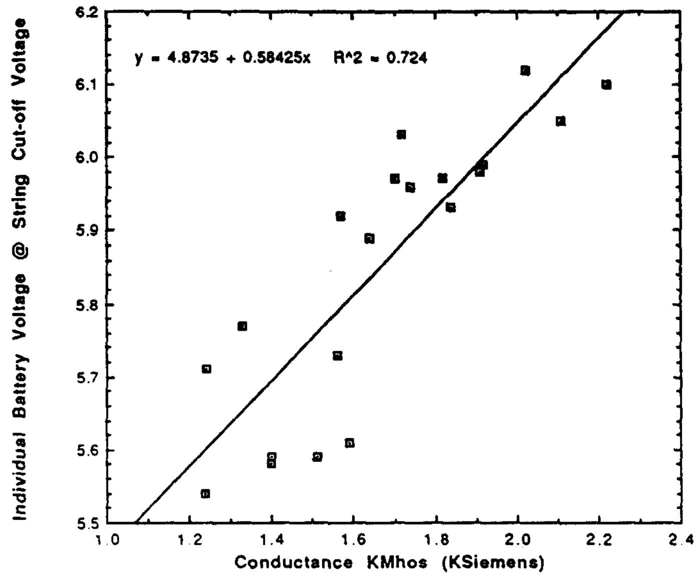


Fig. 13. Conductance vs. battery voltage at string cutoff voltage: VRLA 6 V, 200 A h, 20 batteries, 100 A to 5.85 V per battery.

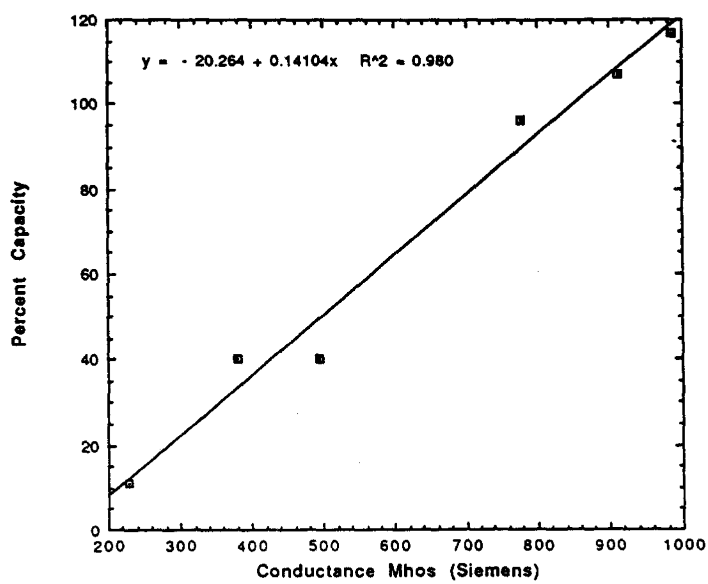


Fig. 14. Conductance vs. discharge capacity (cycle # 1): VRLA 225 A h, 6 cells 42 A to 1.75 V per cell.

strong to serve as a significant indicator of cell performance. Whether or not it can be used as a sole determinant for cell replacement is at this time a commercial, not a technical, question. The inclusion of conductance/impedance testing combined with

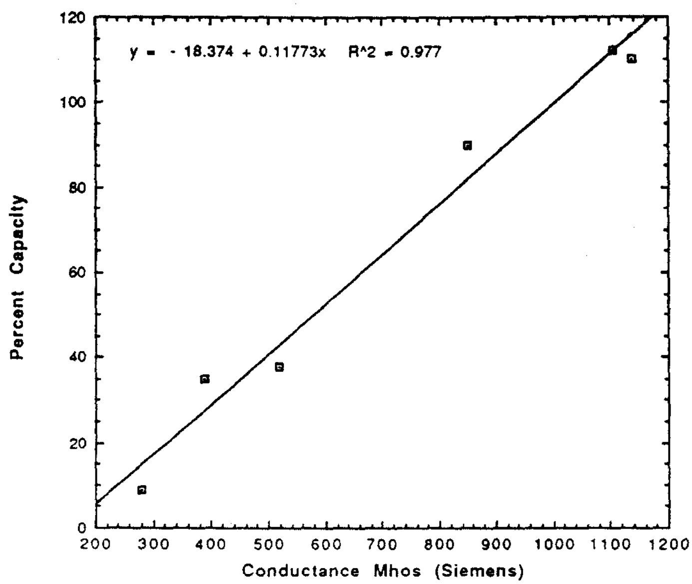


Fig. 15. Conductance vs. discharge capacity: (cycle # 2): VRLA 225 A h, 6 cells 42 A to 1.75 V per cell.

capacity testing as a requirement of the draft standard text of IEEE 1188 should quickly result in a practical resolution of this question (see Fig. 1).

Finally, as a result of the test programs described, several additional characteristics of VRLA cells have emerged which should be reported at this time.

As a result of the capacity/conductance tests previously described, several hundred discharge curves (voltage versus time) have become available. A sampling of these, shown in Figs. 16–18, raise some intriguing and disturbing questions on the performance of VRLA cells. In Figure 16, three discharge curves are shown representing three values of conductance. Discharge times ranging from 10 to 150 min to 1.75 V per cell are noted. Note that the discharge plateaus are depressed approximately in proportion to the conductance values. Note also that the poorly-performing cells appear to have full capacity, but it is only available at significantly lower cell end-of-discharge voltages, approximately 0.5 V per cell. In Fig. 17, discharge curves are shown for 5 cells ranging in conductance values from 1.56 to 2.47 kmho (kS) and from zero to 120 min to an end voltage of 1.84 V per cell. Again, discharge plateau depression is approximately proportional to conductance values but here there is no indication that all cells have retained full capacity to lower end-of-discharge voltages.

Figure 18, which represents a different (225 A h) size cell, again shows capacities in direct proportion to conductance but represent a classic example of discharge curves at increasingly higher current densities. A plot of this effect, that is, the effect of increased current density on capacity was previously shown at this ILZRO seminar in the paper presented by Maja and Spinelli [2] representing model calculations of discharge behavior. Based on Fig. 18 and Spinelli's analysis, even without a postmortem, it is clear that the performance of these particular cells is directly dependent on current density. Since the current for this group of cells is constant for all four cells, the difference in current density must be related to loss of available active material,

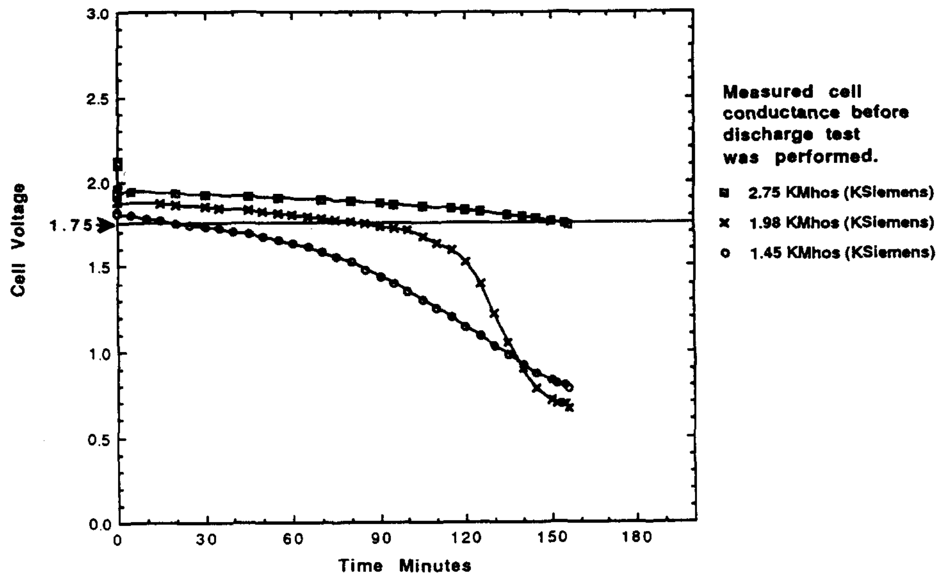


Fig. 16. Discharge curves cells with various initial conductance: VRLA 1000 A h, 263 A to 1.75 V per cell.

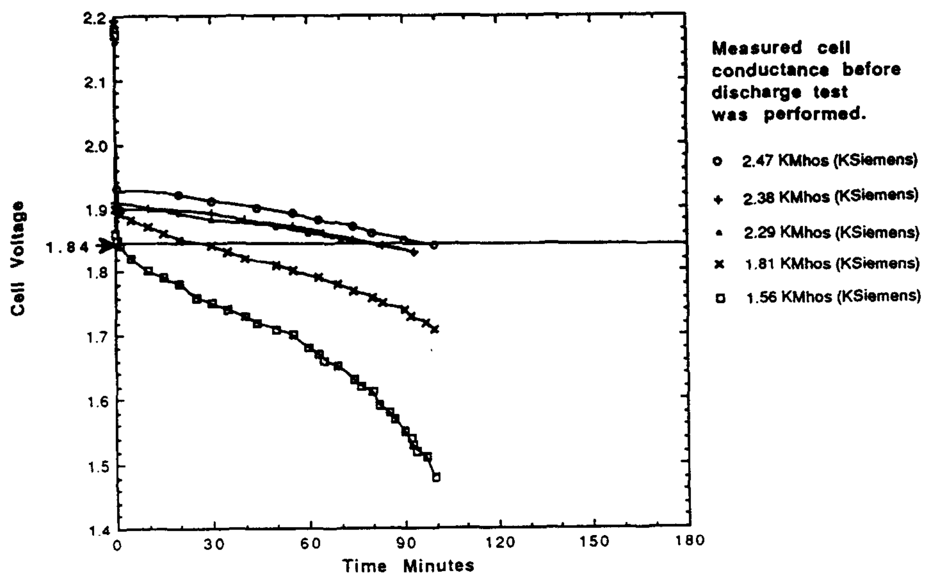


Fig. 17. Discharge curves cells with various initial conductance: VRLA 1000 A h, 263 A to 1.84 V per cell.

whether from dry-out, loss of contact due to grid corrosion, or perhaps some other failure mode.

The above examples of discharge characteristics, while only a small sampling of the more than 500 discharge curves available for analysis, emphasize the need for

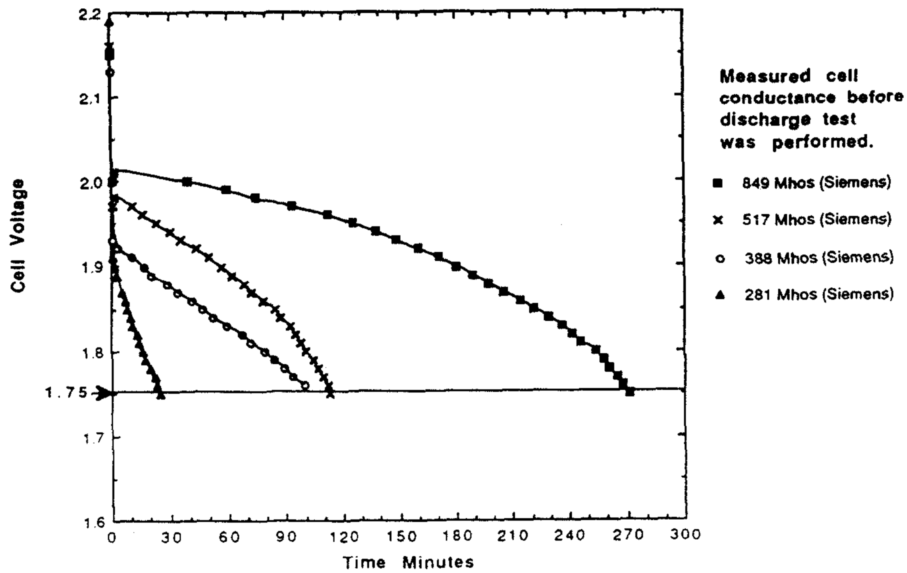


Fig. 18. Discharge curves cells with various initial conductance: VRLA 225 A h, 42 A to 1.75 V per cell.

postmortem tear-down analyses in order to pinpoint the precise failure modes for the specific shapes of the discharge curves involved.

While perhaps only indirectly related to conductance, thermal effects during discharge will be of interest to many readers. Figure 19 shows the results of temperature measurements made on the negative post during discharge of three of the 336 1000 A h telephone cells tested. It seems surprising that temperature increases during discharge are of the order of 20 to 30 °F (11 to 17 °C) when the equivalent values for vented cells of similar size and at similar rates would be approximately 5 °F (3 °C). These temperature increases are in general, but not in total agreement with the conductance values. Figure 20 shows temperature increase data during the same discharge on the same cells, except that the measurements were made on the jar wall between adjacent cells in the three cell battery assembly container. Again, temperature increases are of the order of 20 °F, much greater than with their vented counterparts.

While many more measurements of this type remain to be made, it seems clear that temperature rise on discharge must be measured and be taken into account when calculating capacity for VRLA cells and that the values obtained will be a direct function of cell size, geometry of the cell installation, type of application and discharge rate. While the problems of VRLA cells due to temperature rise on charge have generally been appreciated, the above data indicate that temperature rise on discharge must be also carefully considered.

In conclusion, as of April 1992, a significant number of conductance versus capacity test data is available, and without question, the correlation looks very promising, especially when compared with traditional methods (voltage and specific gravity). Such correlation suggests that conductance testing may be a valuable tool needed to assure that the continued use of VRLA technology is accompanied by proper maintenance and monitoring techniques. Proper maintenance and monitoring techniques, along with

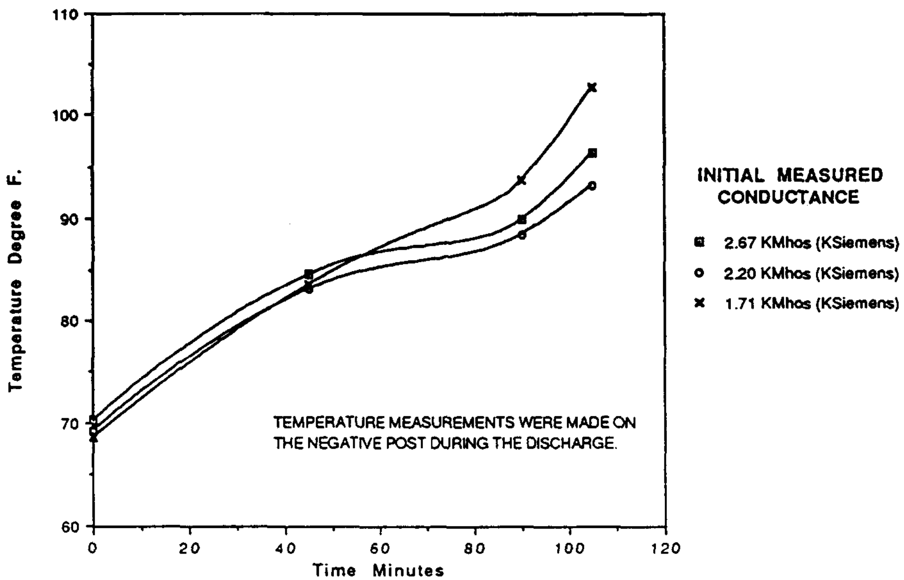


Fig. 19. Temperature rise (°F) during discharge: VRLA 1000 A h, 263 A to 1.75 V per cell.

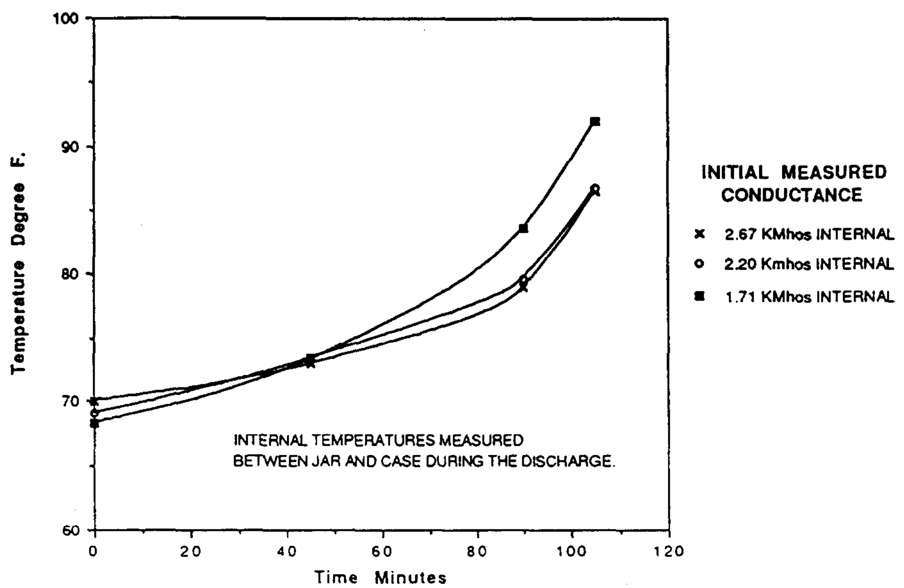


Fig. 20. Temperature rise (°F) during discharge: VRLA 1000 A h, 263 A to 1.75 V per cell.

stricter applications specifications are needed if the use of VRLA battery technology is to continue to grow. Further, when compared with the cost and potential disruption required for capacity testing, conductance testing appears very attractive, indeed.

## References

1 D. O. Feder, Diagnostic Testing of Stationary Valve Regulated Lead Acid Batteries, in *103rd Convention Battery Council International, April 1991, Washington, D.C.*
2 M. Maja and P. Spinelli, *J. Power Sources, 40* (1992) 81–91.