

INTERNAL OHMIC TESTING AS RELIABILITY PREDICTOR TO LARGE FORMAT VRLA LEAD-ACID BATTERIES

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Introduction

Lead-acid batteries naturally degrade as they age. One effect of this degradation is the increase in resistance of the various conductance paths of the internal cell element. The internal ohmic testing devices are generally designed to detect this internal change. The testing devices that are commercially available input an electrical signal and interpret the reflected signal in various manners, ultimately linking the signal to the internal resistance of the cell. These internal ohmic device are commonly used to test a battery when new, and then periodically at various intervals. When the baseline reading begins to deviate beyond a pre-determined level, it is presumed that the battery is deteriorating internally. The term internal ohmic testing has been used to encompass these various techniques that are used - conductance, impedance or resistance.

The internal ohmic testing usage has increased as end-users continue to seek the methods to predict the reliability of lead-acid battery systems. The main focus has been on VRLA batteries due to the inability to inspect the internals and failure to replenish lost moisture to cells. Many impedance and conductance meters are in the market today touting their ability to predict the life thus foregoing the capacity testing and other relevant maintenance items. They are marketed as a screening device to track trends and to detect any cells that deviate from other healthy cells of same model and type.

Recently, what had been a matter of testing and debate has taken on a significant economic overtones. Several large battery users have demanded that conductance measurements be used as the basis for warranty replacement, and have written this requirement into purchasing contracts. Given the cost of replacing VRLA products, and the cost of unanticipated outages for battery users, errors in setting the parameters for "good" and "bad" ohmic readings can have a significant impact on both battery producers and customers.

This paper examines the results from two types of studies. The first test (Experiment 1) was conducted to determine the value of using internal ohmic readings as a valid tool to determine the exact health of VRLA batteries by testing three types of cells and comparing the capacity degradation versus conductance values. The second test (Experiment 2) was performed to examine the relationship between the common product deviation (initial defects) and internal ohmic readings.

EXPERIMENT 1:

Three of the most popular large format VRLA cells were selected for the test program. The brands are identified as follows:

- Brand A: VRLA – 700 AH, sample size 6 cells
- Brand B: VRLA – 665 AH, sample size 6 cells
- Brand C: VRLA – 460 AH, sample size 6 cells

All cells were received into the testing facility as production quality product, shipped as ready for customer use. A standard set of characterization tests were performed on receipt. These included:

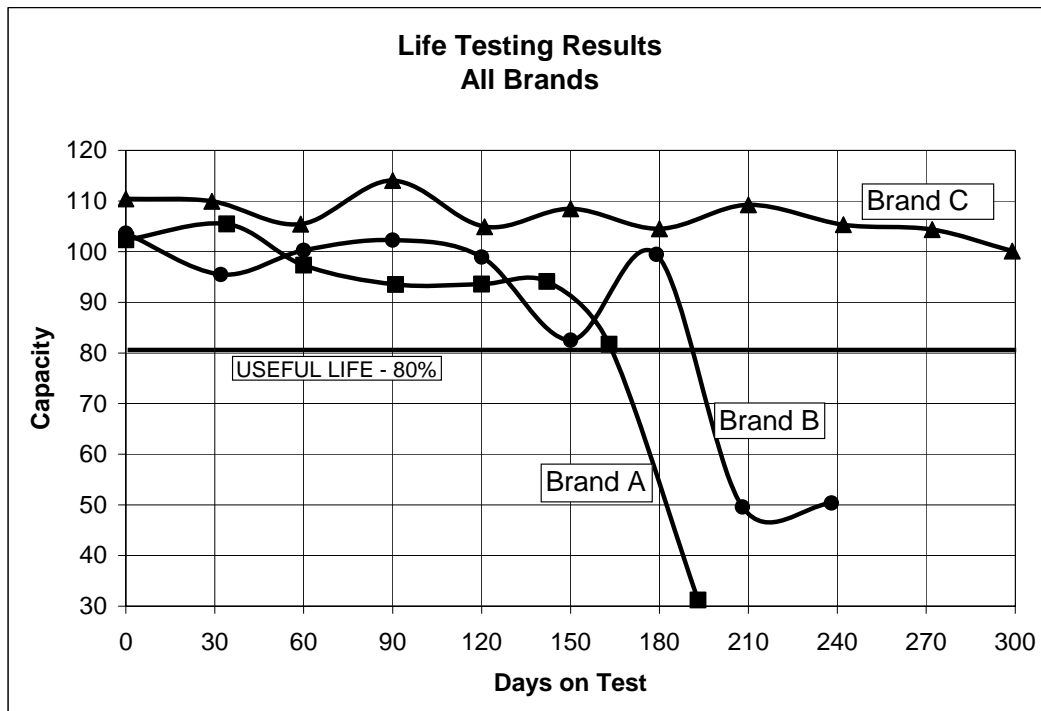
- Open Circuit Voltage
- Cell Weights
- Conductance Measurements (using a Midtronics CTM-100 meter)
- Float voltage spread and current measurement at room temperature
- Capacity at the published C/8 discharge rate to 1.75 VPC. (C rate for the Li-Ion cells)

Accelerated Testing: The testing program for the VRLA products was based on the SR-4228ⁱ protocols. The accelerated test environment was 71°C and 20% rH. The products were charged at the manufacturers recommended voltages while at temperature. Cells were removed from the environmental chambers at intervals of approximately 30 days, simulating approximately 2 years of life at 25°C for the VRLA products.

On removal from the test chamber the cells were allowed to cool to room temperature while still on constant voltage charge for a minimum of 24 hours. Float current was measured once the cells cooled and stabilized. Capacity testing was repeated at the C/8 rate, with percent capacity determined for each cell as the cell passed 1.75 VPC. Cell recharge was performed at constant voltage charge for a minimum of 72 hours. The cells were then weighed, conductance values measured using the Midtronics device, and if the capacity was > 80%, the system was reassembled and put back into the test chamber for additional aging. Teardowns were performed on any cells failing to reach 80% capacity or that were otherwise incapable of continuing the test. The teardowns recorded the gross condition of the cell, degree of corrosion in any components, paste and plate conditions, and specific gravity of the electrolyte.

Results & Discussion from Experiment 1:

The summary of the life test results is shown on Figure 1. There was a large variation in life between the different brands – from 163 days (~11 years) to 299 days (>20 years according to the Telcordia’s SR-4228 protocols). The data obtained were reviewed to determine if it was possible to use the conductance and capacity data gathered to predict cell or system failure. Following are the results and discussion for each of the different models.



Brand A: Capacity results vs. time are shown on Table 1. At the 163 day mark capacity for five cells were limited to 81% due to one cell running 68.7%. Two cells were removed from the test due to high current demand (the demand pushed the charging system into current limit). On the subsequent test the system failed catastrophically, with system voltage going to zero on application of current. Two cells were found to have open circuit response to load current, a third had less than 50% capacity, and only one cell retained useful life. Teardown of the system showed failure due to corrosion and detachment of the positive straps from the plate lugs, combined with dryout and positive plate corrosion.

Days	Cell 1		Cell 2		Cell 3		Cell 4		Cell 5		Cell 6	
	Cap	mho	Cap	mho	Cap	Mho	Cap	mho	Cap	mho	Cap	mho
0	103.2	3168	100.1	3014	103.2	3037	101.1	2917	103.2	3181	103.2	3207
34	106.6	2849	102.1	2696	106.6	2764	104.4	2688	106.6	2998	106.6	2934
60	98.1	1958	94.6	2184	99.3	2198	93.3	2070	99.3	2066	99.3	2225
91	94.7	1806	94.4	2038	96.9	1838	89.9	1774	89.2	1758	96	1873
120	96.2	1860	93.7	1879	94.4	2406	91.6	1827	89.2	1717	96.4	1902
142	96.6	1717	94.2	1738	96	1722	93.6	1789	87.5	1643	96.8	1816
163	81.7	1282	81.7	1630	81.7	1622	81.7	1565	68.7	1117	81.7	1463
193	Removed		81.3	1323	43.5	790	0	360	Removed		0	39

A chart of the average capacity and conductance values is shown on Figure 2. The useful portion of the batteries life was 163 days-before the thermal runaway effects in cells 1 and 5 swamped the charger output. Total capacity drop during the useful portion of the battery life was roughly 25%, the average conductance drop was 50%. The conductance drop occurred at two times during the test, a 35% drop between test start and 90 days, and then a 15% drop between 140 days and 163 days. The capacity also had an initial drop, plateau, and final drop. The first capacity drop between 0 and 90 days was about 11% on average. The second capacity drop was more pronounced totaling 14% between 140 and 163 days.

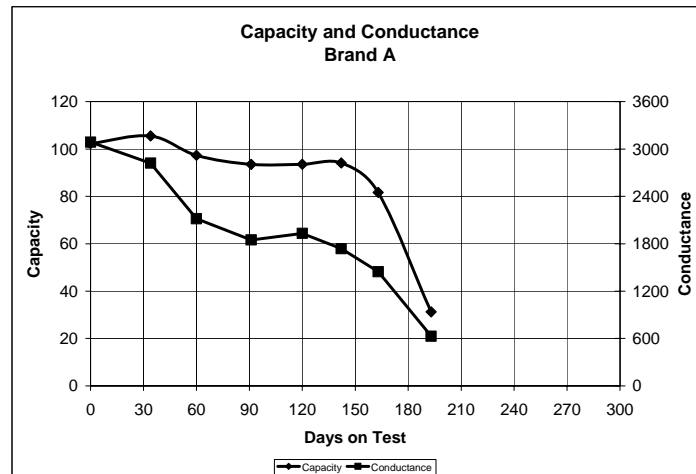


Figure 1

As noted in the introduction, some customers are replacing capacity testing with conductance readings as the basis for determining battery performance. A natural question is whether the conductance readings taken during the test could be used predict the capacity of the product.

One method is to compare the change in conductance to capacity. Table 2 shows the cell capacities for Brand A with the ratio of test conductance to as new conductance.

Days	Cell 1		Cell 2		Cell 3		Cell 4		Cell 5		Cell 6	
	Cap	Ct/Cn	Cap	Ct/Cn	Cap	Ct/Cn	Cap	Ct/Cn	Cap	Ct/Cn	Cap	Ct/Cn
0	103.2	100%	100.1	100%	103.2	100%	101.1	100%	103.2	100%	103.2	100%
34	106.6	90%	102.1	89%	106.6	91%	104.4	92%	106.6	94%	106.6	91%
60	98.1	62%	94.6	72%	99.3	72%	93.3	71%	99.3	65%	99.3	69%
91	94.7	57%	94.4	68%	96.9	61%	89.9	61%	89.2	55%	96	58%
120	96.2	59%	93.7	62%	94.4	79%	91.6	63%	89.2	54%	96.4	59%
142	96.6	54%	94.2	58%	96	57%	93.6	61%	87.5	52%	96.8	57%
163	81.7	40%	81.7	54%	81.7	53%	81.7	54%	68.7	35%	81.7	46%
193	Removed		81.3	44%	43.5	26%	0	12%	Removed		0	1%

Ct=Conductance at capacity test Cn=conductance when new

Previous studiesⁱⁱ have suggested using an 80% limit on conductance drop. This clearly would have resulted in the rejection/replacement of cells well before the end of their useful life – the average conductance reached 80% of its initial value in 45 days, barely a quarter of the useful time in the field. The same study also suggested possibly using a 50% limit – with the caveat that the customer would be exposed to additional risk. The data indicate that this approach may be more useful – the cells on average reached 50% of their initial conductance at approximately the same time (160 days) that the string capacity reached 80%. This approach would not, however, detect the high float current issue that ultimately caused the cells to be removed from the string.

In the same work regression analysis was used to determine if there was a statistically significant relationship between conductance and capacity. This could point towards a more suitable figure for use in determining good and bad cells. A capacity vs. conductance scatter plot is shown on Figure 3. The best fitting linear relationship has an R^2 of 67%, meaning that the change in conductance explains roughly 67% of the change in capacity for all of the life test cells. The best fit line predicts that the capacity will fail below 80% when the cell conductance falls below 1631 mho, about 52% of the original average conductance. As shown on the scatter plot there were six points below the conductance limit, but above the capacity limit. These would represent the risk of removing cells that are still defined as “good”. Referring back to Table 1, however, these cells would have been at the end of life.

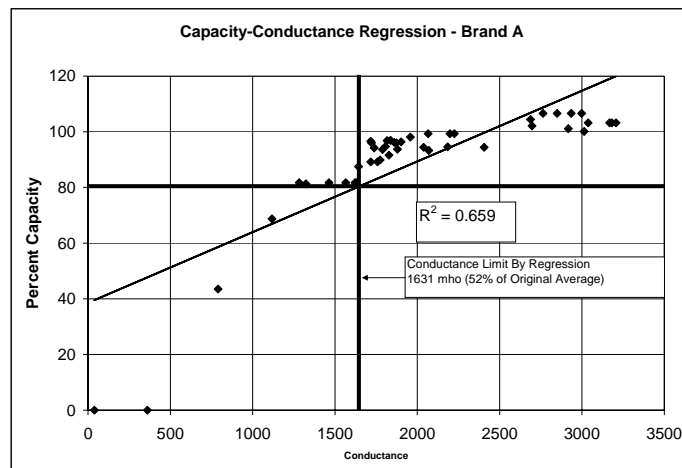


Figure 2

Brand B: The capacity and conductance readings for Brand B are shown on Table 3. This system ran 179 days with good capacity. Testing at 208 days showed a sharp drop in capacity to 49%. After returning the system to the test chamber less the failed cell, two additional cells showed failure at 238 days. Teardowns showed that cause of failure was dry out and sulfation, compounded by two dropped outside negative plates in one cell. The sulfation on the negative plate and strap probably contributed to the dropped plates. In contrast to Brand A the system never went to zero capacity – a far better result for a customer than the catastrophic failure found at 193 days in Brand A. During the course of the test there were two non-conformities. The first was a unexplained drop in capacity at 150 days, followed by a rebound at 179 days, and the second was a missed conductance reading on a failed cell at 208 days.

Days	Cell 1		Cell 2		Cell 3		Cell 4		Cell 5		Cell 6	
	Cap	mho	Cap	mho	Cap	mho	Cap	mho	Cap	mho	Cap	mho
0	104.2	3417	104.2	3331	104.2	3224	102.4	3410	102.7	3419	104.1	3369
32	96.3	3216	96.3	3287	96.3	3168	95.1	3148	93.4	3224	95.7	3233
60	101.2	3242	101.2	3216	101.2	3202	99.9	3061	97.0	3233	101.2	3331
90	103.3	3164	102.7	3126	103.3	3037	102.8	2823	98.3	3025	103.3	3369
120	100.1	3498	97.4	3325	100.1	3250	100.1	3207	96.0	3269	100.1	3400
150	82.8	3516	82.8	3181	82.8	3359	82.8	3126	81.2	2654	82.8	3429
179	102.9	3427	98.5	3379	103.1	3260	102.5	3287	87.3	2678	102.5	3379
208	49.7	3298	49.7	3250	49.7	3199	49.7	3224	49.0	N/R	49.7	3014
238	50.6	2737	49.4	2487	50.6	2749	50.6	2587	Removed		50.6	2806

The chart of average capacity and conductance is shown on Figure 4. The system had a useful life of ~200 days, about 25% longer than Brand B, and there was no sudden loss of capacity as experienced with Brand A. The conductance behavior of this model was also much different than Brand A. The profile with time was relatively flat until the end of its useful life.

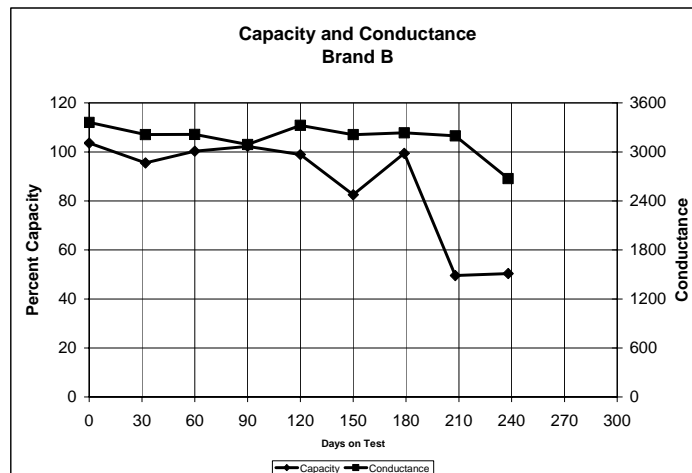


Figure 3

Table 4 shows the capacity and percent conductance drop for Brand B. The cells that limited the system capacity are shaded. There was relatively little change in conductance with capacity during the life of the product for individual cells. Cell 4 showed the greatest degree of variation in

the test, dropping to 83% of its initial conductance at 90 days, and then dropping to 76% of its original conductance at the end of the 238 day test.

TABLE 4 BRAND B CAPACITY AND CONDUCTANCE RATIO												
Days	Cell 1		Cell 2		Cell 3		Cell 4		Cell 5		Cell 6	
	Cap	Ct/Cn	Cap	Ct/Cn	Cap	Ct/Cn	Cap	Ct/Cn	Cap	Ct/Cn	Cap	Ct/Cn
0	104.2	100%	104.2	100%	104.2	100%	102.4	100%	102.7	100%	104.1	100%
32	96.3	94%	96.3	99%	96.3	98%	95.1	92%	93.4	94%	95.7	96%
60	101.2	95%	101.2	97%	101.2	99%	99.9	90%	97	95%	101.2	99%
90	103.3	93%	102.7	94%	103.3	94%	102.8	83%	98.3	88%	103.3	100%
120	100.1	102%	97.4	100%	100.1	101%	100.1	94%	96	96%	100.1	101%
150	82.8	103%	82.8	95%	82.8	104%	82.8	92%	81.2	78%	82.8	102%
179	102.9	100%	98.5	101%	103.1	101%	102.5	96%	87.3	78%	102.5	100%
208	49.7	97%	49.7	98%	49.7	99%	49.7	95%	49	NR	49.7	89%
238	50.6	80%	49.4	75%	50.6	85%	50.6	76%	Removed		50.6	83%

Setting conductance limits for this type of behavior introduces more uncertainty than even Brand A. Setting the limit to 80% of its value would catch the cells ultimately responsible for limiting the system capacity; however, it would also have removed Cell 5 at 150 days, well before the end of its useful life.

Regression analysis was also performed on Brand B, again in an attempt to get a more refined limit on conductance values. The results are shown in Figure 5. The R^2 value was very low at 0.269. The model gave a conductance limit of 2978 mho, or 89% of the original value, a higher value than any published in the literature. Using this method would have both alpha and beta type risks – good cells removed for no reason, and cells with less than 80% capacity left in the system.

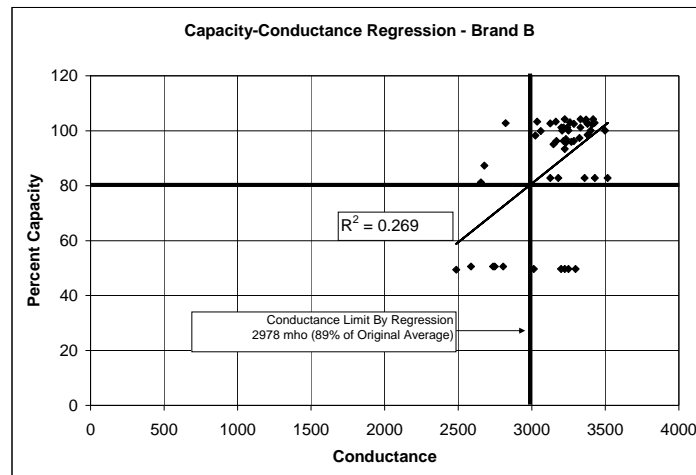


Figure 4

Brand C: The capacity and conductance behavior for Brand C are shown in Table 5. The system ran 299 days with good capacity and no cells below 95% – by far the best performance in the group. At the 299 day point the plastic on several jars, brittle due to the high test temperatures, failed when the cells were being weighed. Teardowns on the cells showed slight indications of cell dryout, positive plate sulfation, and some positive grid corrosion. These conditions were consistent with the high capacity of the cells at teardown.

Days	Cell 1		Cell 2		Cell 3		Cell 4		Cell 5		Cell 6	
	Cap	mho	Cap	mho	Cap	mho	Cap	Mho	Cap	mho	Cap	mho
0	109.9	2737	110.9	2230	111.0	2920	109.7	2547	112.4	2684	108.8	2797
29	111.0	2777	106.3	2089	112.7	2681	109.7	2666	110.1	2121	NO READING	
59	96.2	2452	108.0	2644	106.1	2353	108.2	2393	108.7	2615	105.5	2454
90	110.8	1921	117.3	2420	113.0	2414	111.3	1998	117.4	2463	114.4	2465
121	100.9	3007	108.1	2504	97.4	2775	106.9	2074	108.1	2288	108.1	2334
150	102.0	3099	111.8	2468	106.8	2106	110.2	2198	111.8	2156	108.2	2244
180	106.8	2626	106.8	2273	98.8	2269	106.8	2124	103.6	1978	104.5	2088
210	112.9	2313	109.6	2214	103.5	2066	111.0	2156	112.9	2140	105.6	2103
242	108.1	2202	104.3	2103	101.2	2080	107.2	2095	108.2	2106	102.9	2080
272	102.4	1850	102.0	1965	99.5	1958	108.1	2010	109.1	2066	105.1	2060
299	99.5	1727	96.0	1763	98.1	1674	102.9	1952	102.9	1934	101.4	1884

The average capacity and conductance for the test is shown on Figure 6. The pattern is different than either Brand A or Brand B. There was a significant drop in conductance – 31% from initial values to final, with a small drop in average capacity – 10% from the initial 110% to 100% at the end of the test. Most of the conductance drop occurred during the second half of the battery's life. At the 90 day point there was a negative correlation between capacity and conductance – a rise to 114% capacity with a drop in conductance of 8% from the previous test.

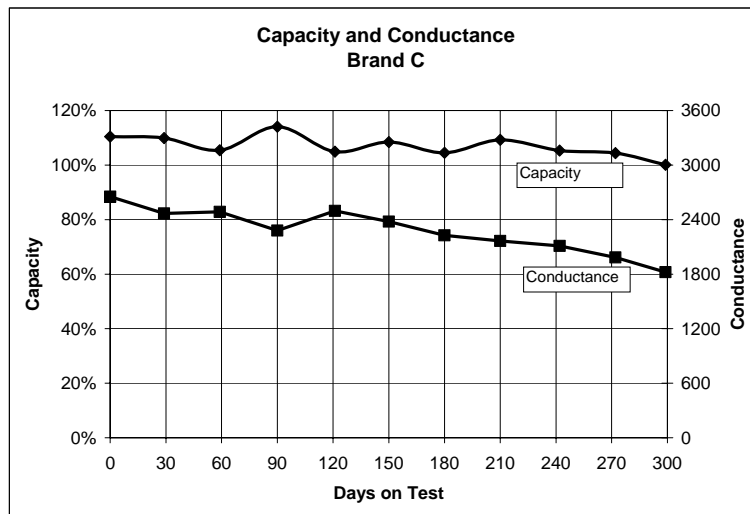


Figure 5

Table 6 shows the capacities and percent conductance drop for Brand C. Since there were no individual cell failures during the test conductance limits cannot be set. The 80% limit suggested in previous works would have caused replacement of nearly all cells while the cells still had 50% or more of their life remaining. A 50% limit would not have caused any replacements during the duration of this test.

TABLE 6 BRAND C CAPACITY AND CONDUCTANCE RATIO												
Days	Cell 1		Cell 2		Cell 3		Cell 4		Cell 5		Cell 6	
	Cap	Ct/Cn	Cap	Ct/Cn	Cap	Ct/Cn	Cap	Ct/Cn	Cap	Ct/Cn	Cap	Ct/Cn
0	109.9	100%	110.9	100%	111.0	100%	109.7	100%	112.4	100%	108.8	100%
29	111.0	101%	106.3	94%	112.7	92%	109.7	105%	110.1	79%		
59	96.2	90%	108.0	119%	106.1	81%	108.2	94%	108.7	97%	105.5	88%
90	110.8	70%	117.3	109%	113.0	83%	111.3	78%	117.4	92%	114.4	88%
121	100.9	110%	108.1	112%	97.4	95%	106.9	81%	108.1	85%	108.1	83%
150	102.0	113%	111.8	111%	106.8	72%	110.2	86%	111.8	80%	108.2	80%
180	106.8	96%	106.8	102%	98.8	78%	106.8	83%	103.6	74%	104.5	75%
210	112.9	85%	109.6	99%	103.5	71%	111.0	85%	112.9	80%	105.6	75%
242	108.1	80%	104.3	94%	101.2	71%	107.2	82%	108.2	78%	102.9	74%
272	102.4	68%	102.0	88%	99.5	67%	108.1	79%	109.1	77%	105.1	74%
299	99.5	63%	96.0	79%	98.1	57%	102.9	77%	102.9	72%	101.4	67%

Obtaining a limiting conductance value by regression (Figure 7) returned a meaningless result when the regression line was extrapolated to 80%. In addition, the correlation was worse than Brand A or B ($R^2 = 0.097$) suggesting that prediction even within the data set would be risky.

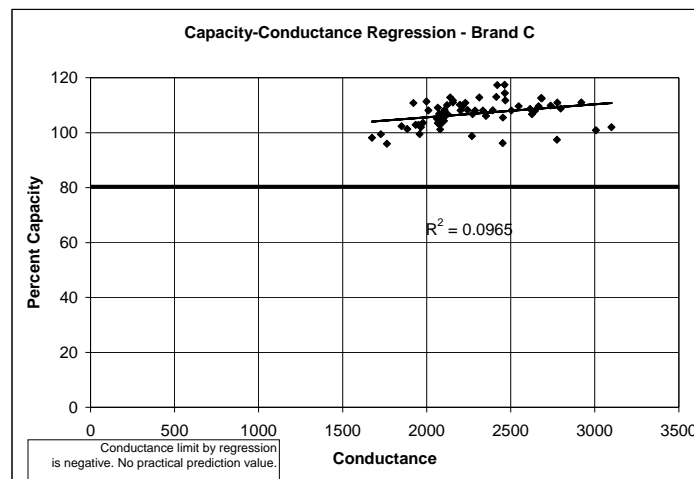


Figure 6

Experiment 1 Conclusion:

Three general conclusions can be made from the analysis of the data generated by this study

1. Product life (at least as measured using SR-4228 methods) exceeded 10 years for all brands and reached 20 years for one brand. This behavior is quite different than previous experience with large format VRLA products, and points towards improvements in the design and construction of the products. There are still wide variations in product performance (~50% difference in useful life) and end of life performance (catastrophic capacity loss vs. benign capacity drop). These attributes need to be considered by the battery users when selecting products.
2. There were wide variations in the relationship between capacity and conductance between the different brands. The behavior ranged from a roughly linear response, to no change in conductance with wide changes in capacity, to wide changes in conductance with small changes in capacity. This shows, at a minimum, that results from one brand of

battery cannot be generalized to other manufacturer's products. Using Brand B's conductance "rules" for Brand A or C would have caused significant replacements of good products, while using A's rules for B would have exposed the battery users to significant risk of battery failure.

3. The correlation between capacity and conductance within brand types was poor enough to place significant doubt on the practice of replacing capacity testing with conductance testing. The data simply do not show the R^2 values of 90 or 95% required to make economic decisions using regression data.

The above comments are not implying that ohmic measurements do not have value in monitoring VRLA products. These devices are used effectively both in a laboratory and field environment. The data indicate, however, that these readings should not be used alone as an absolute judge of product performance, especially when there are no custom models developed for the type of battery being tested. Users and manufacturers need to use judgment and experience to analyze the data, and then supplement the data with additional measurements – including capacity testing - when deciding whether to replace products in the field.

EXPERIMENT 2:

The second experiment again utilized a standard, commercially available 20-year, 2-volt, stackable VRLA cell. The model selected was one that is currently being sold into the industrial battery market, primarily the unregulated, telecommunications industry. The general features of this battery are consistent with the other major brands that compete in this same space. It is offered that the results of this study are applicable to other batteries of this same general design concept. The basis of this study was the assembly of cells with known defects. Four major defect criteria were selected and are discussed below. All other aspects of the test cells were identical. Assembly was conducted within one single lot size, with the same operators in the same time-frame.

1. Reduction in Positive Active Material (PAM):

This defect was implemented by removal of pellet sections from the pasted plate. Amounts that were removed were 0%, 1%, 4% and 10% of the total pasted amount. A few of the actual defects that were simulated by this method include; underweight pasting of the plate during manufacture, improper curing of the plates during manufacture, damage to the plate prior to assembly and broken or corroded grid wires in the plate.

2. Reduction in absorbed glass mat (AGM) separator:

This defect was implemented by removal of sections of the AGM between one plate pair in the cell. The design of this cell has two layers of AGM between each plate pair. For this study, 0%, 10% and 20% of the AGM was removed from between the plates. The removal was done with only one of the two layers, as one layer was required as a minimum, to prevent a direct electrical short between the positive and negative plates. This defect simulated a torn separator that may occur during the cell manufacturing process.

3. Improper acid level:

For this defect, cells were intentionally underfilled and overfilled with electrolyte. This defect would not only cover errors during the manufacturing process, but processing errors as well. Improper initial charging of the cells could cause excessive electrolysis and gas release, resulting in an 'underfilled' condition of the cell. For this study, cells were filled with 90%, 95%, 100% and 105% of the design goal of the cell.

4. Paste lump:

Because of the fragile, non-woven nature of the AGM separator material, plate lumps can pierce the separator material and cause an electrical short over time. Deep cycling can

accelerate this development. This defect was created by placing a paste lump on top of the plate, of the same thickness of the pasted plate. This defect would almost certainly pierce the separator over a short period of time and cause a hard, electrical short.

Once the standard processing was complete for these test cells, they were then tested using three different, commercially-available internal ohmic testers of various vintages. Units include AVO Biddle meter, the Midtronics Conductance meter and the Alber Cellcorder. All units were purchased independently by C&D, and there has been no collaboration or cooperation with any of the manufacturers of these test units for any portion of this study.

As a final point of comparison, all of the test cells were capacity discharged. All cells were floated within the same string and then discharged together. A temperature-corrected, constant-current discharge at the 8-hour rate to 1.75 ending voltage was conducted.

Results and discussion from Experiment 2:

Overall Trends:

Once manufactured, every test cell was discharged. The entire group was discharged within one single string to ensure there were no variations in discharge current, environmental conditions or procedures. The measured capacity discharge performance of each test group is shown in Figure 7, from lowest to highest capacity. The discharge test performed was a constant current discharge, at the 8-hour rate to 1.75 ending voltage. Each test group represents 3-5 individual cells. The control test lot was made to be as identical as possible to the test groups. Identical material lots, operators and manufacturing processes were used. For ease in comparisons, the capacity of the control lot was normalized to 100 percent. This data manipulation allows for simple percentage determinations of the comparison lots as compared to the control group.

As seen in this table, there are distinct variations in performance between the different test groups. The significance of each individual test group is discussed below.

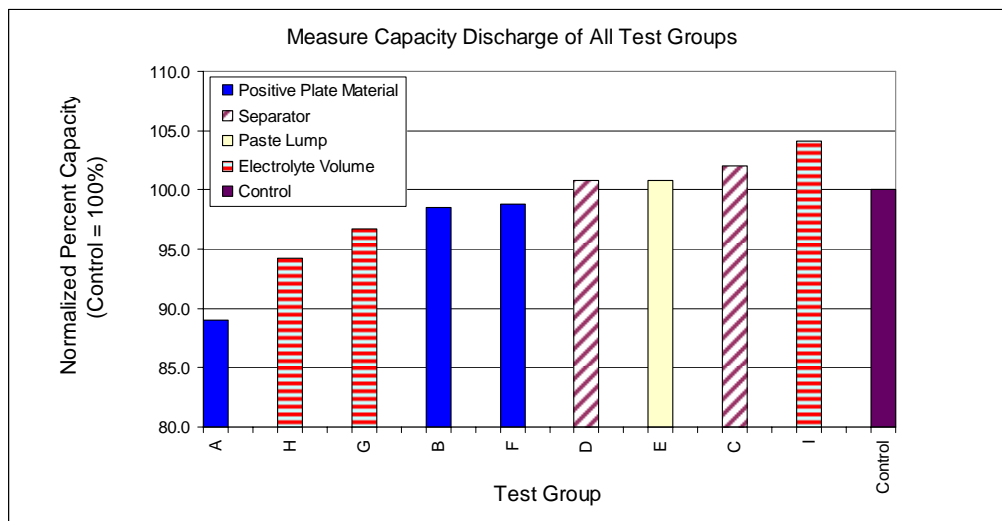


Figure 7. Measured Capacity of all Test Groups

All cell lots were tested with all three internal ohmic testing units. The comparisons of the readings from these three units are shown in Figure 8. The readings for each unit were normalized such that the readings for the control cells were set to a value of 1. In this manner, the percentage shift from the control value is easily determined. Additionally, because the units of one of the test unit is based on conductance, and the other two are based on resistance, the inverse of the conductance readings were used so that the directional change in values would be consistent within all three test units.

Although several test groups (Groups B, F and D) had essentially the same reading values as the control, there were others (Groups H and G) with significant shifts. This figure indicates significant deviations of 5.4% lower and 21.8% higher than the control group. A further analysis of these test groups in regards to the type and degree of internal defect can be found below.

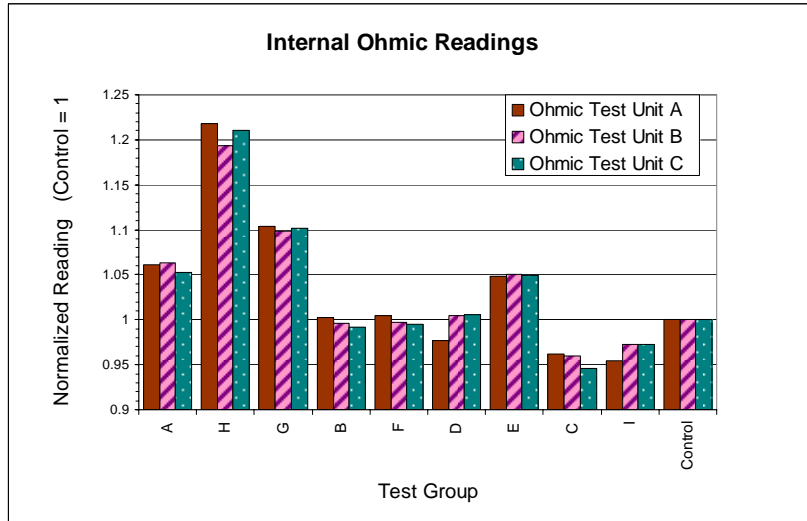


Figure 8. Internal Ohmic Readings of all Test Groups

Figure 9. provides one final analysis of the combined test groups. This figure shows the correlation between ohmic readings for all three testing devices versus the measured capacity of each test group. All three testing devices show close agreement for all test groups, when looked at in a normalized perspective. For this figure, the ohmic readings for the control cells for each testing device was mathematically set to be 1.0. Other test values were then plotted as a fraction of this normalized value. A greater than 98% correlation coefficient was found between the normalized ohmic values of the three testing devices. However, the correlation coefficient of each of the ohmic data ranges with the discharge capacity values was only in the range of 60.3 to 64.9. The further analysis of the capacity correlation will not be discussed here, and is left to the reader for final interpretation.

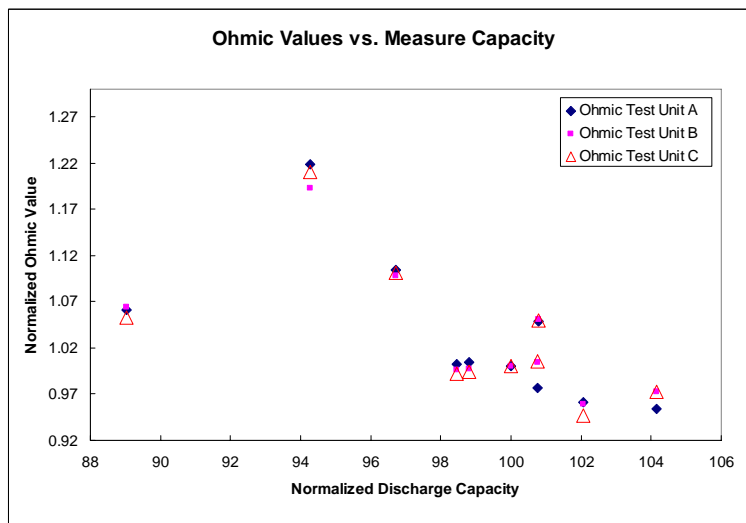


Figure 9. Ohmic Values vs. Measured Capacity of all Test Groups

Analysis of Defect Conditions:

The basis of this study was to determine the accuracy of detecting internal cell defects with commercially available internal ohmic testing devices. The individual analysis of each defect follow.

Positive Active Material (PAM)

By design, the limiting reagent in the chemical reaction occurring during discharge in a VRLA cells is the sulfuric acid in the electrolyte. With a design excess of plate active material, a reduction in PAM would not be expected to affect discharge capacity until it fell below the amount to chemically balance the sulfuric quantity.

For this test, cells were built with reduced PAM in the amounts of 1%, 4% and 10% less than nominal. The ohmic test readings for these groups, as well as their discharge performances are shown in Figure 10. This data shows that there was no significant shift in the readings from any of three ohmic testers associated with the loss of 4% of PAM or less. However, at 10% loss of PAM, there was a significant shift of 5.3-6.5% of the baseline (control) reading. The discharge performance of each test group is shown as well in Figure 10, and shows a trend in performance loss as the active material is decreased. Table below summarizes the findings of this test group. This test indicates that ohmic readings did not accurately detect minor active material losses of 4% or less, even though with this amount of PAM loss, there was a slight decrease in the discharge performance.

Test Group	Discharge Capacity	Ohmic Values (average of all three test units)
100% PAM	100	1.000
99% PAM	98.8	0.999
96% PAM	98.5	0.997
90% PAM	89.0	1.060

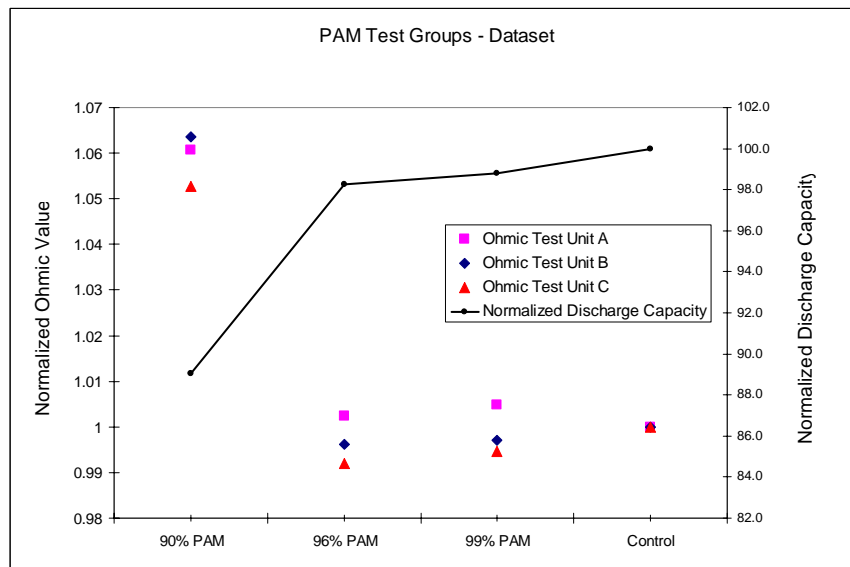


Figure 10. Ohmic Values and Discharge Capacity for PAM Test groups

Absorbed Glass Mat (AGM) Separator

Cells were built with two full sheets of AGM separator between each plate pair as the standard control. The separator material is a non-woven glass, with limited strength to resist tearing and

damage during handling. Ten percent and twenty percent of one sheet was removed to simulate damage and tears to the separators that may occur during cell assembly and processing. Because of the high compression of the plates used in VRLA batteries, it is unlikely that tears and gaps in the separator will occur after cell assembly.

Figure 11 shows the ohmic readings obtained for the three AGM test groups. There was a small drop in ohmic readings at 10% missing AGM, with the ohmic reading essentially returning to the control baseline at 20% missing AGM. The cause of the shift at 10% has not been identified, although it does not appear to be random test variability. This unknown cause of ohmic variation should be noted well, as it is unsupported by known physical or chemical reasons.

Although the data is not conclusive, the preliminary assertion is that gaps in the separator of the extent introduced in this test cannot be detected by the ohmic testing units. Although the initial performance capacities of the cells were not compromised, this defect is important to detect early. Severely damaged or torn separators can result in electric shorts immediately upon cell assembly. It is believed that less severe damage provides a path of reduced resistance to 'soft' or dendritic shorts in the future. High cycling and deep discharge regimes increase the chances of these types of shorts developing in weakened separator sections. It is also believed that two thin sheets of separator versus one thick sheet will increase the resistance to dendritic shorts by interrupting the porous pathways through the glass.

It is asserted that the cells with missing AGM sections would fail early in their lives, and would not have been detected by the internal ohmic testers.

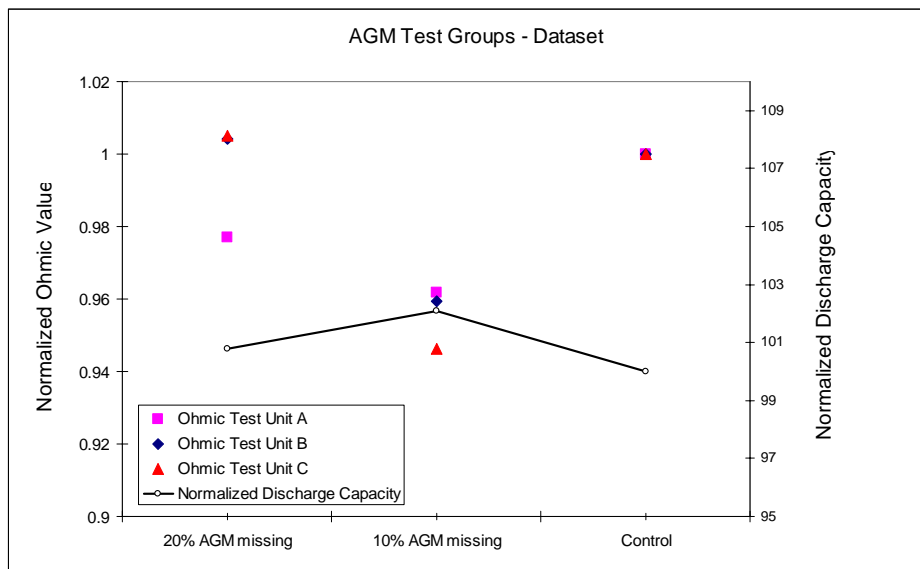


Figure 11. Ohmic Values and Discharge Capacity for AGM Test Groups

Electrolyte Level

By design, VRLA cells are physically undersaturated by a specific design amount, typically 3-8%. This is required to properly allow the recombination reaction to occur. With the sulfuric acid as the limiting reagent in the chemical discharge reaction, it would be anticipated that variations in acid quantity would directly and strongly affect the cell's discharge performance. This was shown to be so, as can be seen in Figure 12.

Cells were filled with 90%, 95% 100% and 105% of the design quantity of electrolyte. The same electrolyte batch and specific gravity was used in all cells. Cells were all filled at the same time to negate any temperature effects.

The ohmic values of these cells are shown in Figure 12. There was strong agreement by all three testing devices with each test group. Additionally, the percentage shifts in the ohmic values for each of the three testing devices was almost identical. Clearly, all devices were shown to be successful in quantifiably detecting electrolyte quantity within these test groups. By nature of the strong design dependence of performance capacity on electrolyte quantity, all three testing devices appear able to determine performance capacity due to electrolyte quantity.

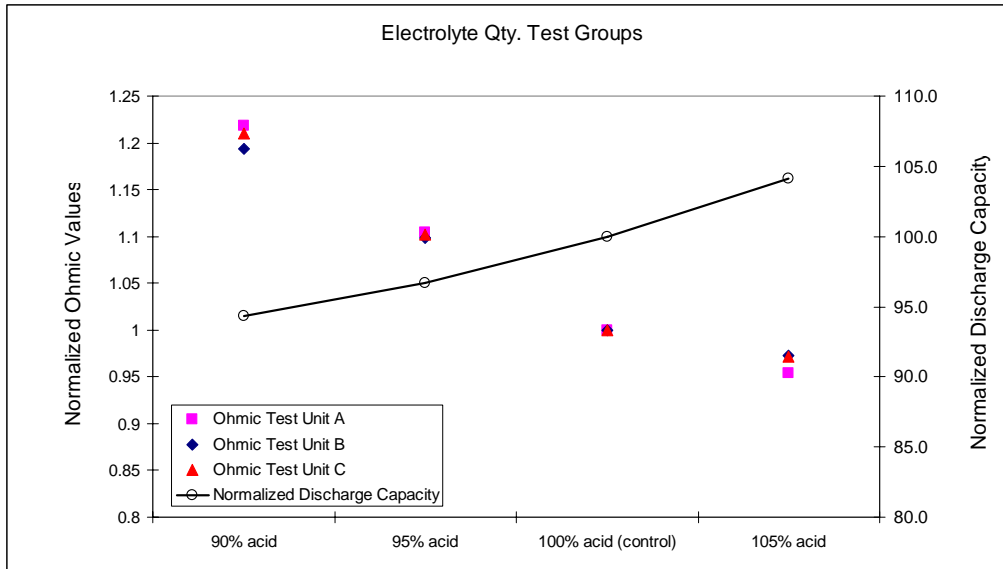


Figure 12. Ohmic Values and Discharge Capacity for Electrolyte Qty. Test Groups

Paste Lump

This last variable is generally accepted by VRLA battery manufacturers to be an important factor in production of reliable and long-lasting cells. Because of the high compression of the VRLA cells, and the soft, non-woven nature of the AGM separator, foreign matter between the plate pairs can easily lead to electrical shorts. Most battery manufacturers expend significant energies in ensuring smooth, lump-free plate surfaces.

This test was to determine whether the ohmic testing devices could detect a significant lump on the plate surface. Although the actual duty cycle and environmental conditions would greatly affect the development of a short, the lump was large enough that it would almost certainly have caused failure of the cell within its first year or few years of life. During the cell assembly process, it was determined that the AGM separator was strongly compressed at the lump, but was not pierced or torn during assembly.

The discharge performance of the test group with paste lumps is shown in Figure 13, in comparison to the control cells. No drop in performance was seen indicating that the paste lump had not yet pierced the separator or grown into an electrical short. Interestingly, the ohmic readings from all three testing devices increased approximately 5% in a very consistent manner.

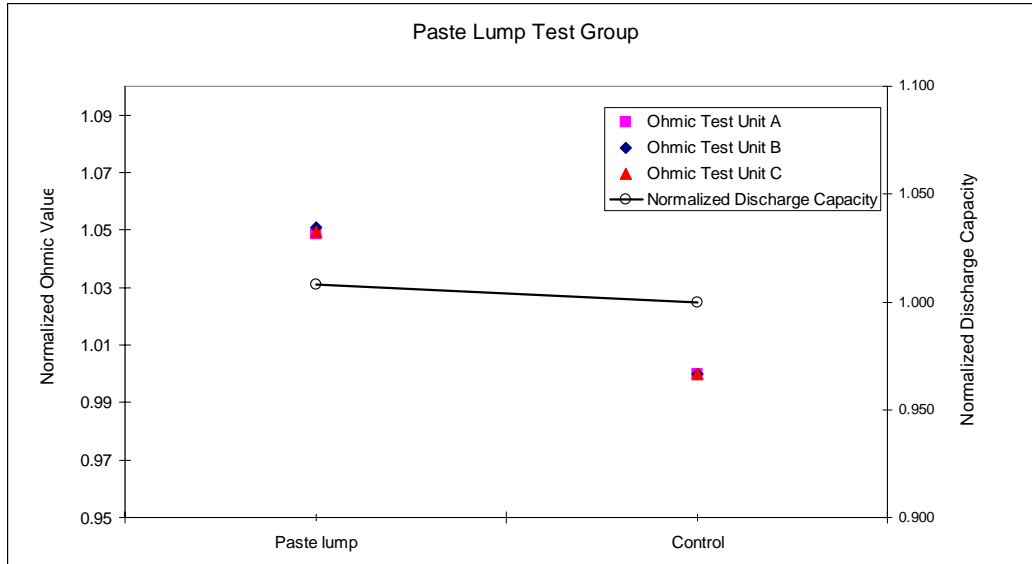


Figure 13. Ohmic Values and Discharge Capacity for Paste Lump Test Groups

Conclusions from Experiment 2:

This study intended to determine the ability of commercially available internal ohmic devices to detect and quantify internal cell defects. Analyzing the data in a normalized manner allowed direct comparisons of the different testing devices. It was found that there was greater than 98% correlation between the three ohmic testers. Specifically, the three testing devices provided percentage deviations from baseline that were extremely similar to each other. Therefore, for the conditions of this test and the specific test groups within this study, the three different testing devices performed similarly within each defect lot.

This study revealed that the ohmic testing devices were able to quantifiably detect variations in electrolyte levels. This is not totally unexpected, as the electrolyte is a major contributor to the internal resistance of the cell. This is a very valuable detection for most VRLA batteries. Since VRLA batteries are typically electrolyte-limited in their design, the discharge capacity is often directly related to the electrolyte level. And so, the changes in ohmic reading that are due to electrolyte levels can be directly correlated to the discharge performance of the cell.

This study also showed that the internal ohmic devices appear able to detect a sizable paste lump prior to it developing into a short. This is an important item and is worthy of the topic for further studies to verify that these results are repeatable and accurate.

This study came up with the limitations inherent in these testing devices. Other internal cell defects that can cause loss of capacity were not able to be picked up by these devices. Specifically, these devices failed to detect small, but substantial changes in the positive plate active material content. This indicates that the increase in electrical resistance of the cell was not changed significantly by the loss of the PAM pellets. Since the material in the positive plate is clearly required for the discharge reaction, the implication is that the cell discharge performance could be compromised without detection by the ohmic testing devices. Only when the plate material defect was very large (approaching the loss of an entire plate within a cell) were the testing devices able to detect a significant deviation from baseline.

The ohmic testing devices also failed to detect substantial defects in the AGM separator. This defect would be expected to eventually develop into an internal electrical short, causing infant mortality of the cell. In this case, the cell would appear to be perfectly healthy by all

measurement methods (including a capacity discharge), yet would be expected to fail prematurely.

A summary of the results, are shown in the Table below.

Defect type	Preliminary Conclusions
Positive Active Material	<ul style="list-style-type: none">• Cannot detect small defect level (<4%)• Could detect large defect level (10%)
AGM Separator	<ul style="list-style-type: none">• Could not detect AGM defects up to 20% of one layer
Electrolyte level	<ul style="list-style-type: none">• Could detect varying electrolyte levels (90% to 105%)
Paste lump	<ul style="list-style-type: none">• Could detect plate surface lump prior to becoming electrical short

In summary, commercially-available internal ohmic testing devices appear to have important but limited usefulness and accuracy in detecting internal defects

OVERALL CONCLUSIONS FROM EXPERIMENTS 1 & 2:

1. There is no substitute for capacity testing to absolutely define product performance.
2. Ohmic readings remain a valid guideline when properly trended, but should not be written into warranty specifications.

ⁱ Telcordia Technologies **SR-4228**, *VRLA Battery String Certification Levels Based on Requirements for Safety and Performance, Issue 1*, 1996

ⁱⁱ D. Feder, M Hlavac, “*Analysis and Interpretation of Conductance Measurements used to Assess the State of Health of Valve Regulated Lead Acid Batteries – Part III: Analytical Techniques*” Intelec, 1994