Updated Status of Conductance / Capacity Correlation Studies to Determine the State-of-Health of Automotive SLI and Standby Lead Acid Batteries - Sept. 1993

Copy of a Paper Presented to:

Zinc and Lead Asian Service
• ZALAS
5th Asian Battery Conference
1993
Bali, Indonesia
September 1-3, 1993

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INTRODUCTION

For the past seven years, Midtronics has developed and manufactured battery conductance testers for determining the condition or "state-of-health" of automotive starting lighting and ignition (SLI) batteries. The use of conductance measurements to evaluate SLI battery performance is based upon the results first reported by Dr. Keith S. Champlin at a talk presented to the Society of Automotive Engineers (SAE) off-highway vehicle meeting in 1975[1]. Dr. Champlin reported test results which showed strong positive linear correlation between load tests and measured conductance on SLI batteries ranging from 200 to 500 CCA and of various group sizes. In this paper we will describe how the further refinement of conductance technology has been confirmed in a number of recent studies by automotive manufacturers, SLI battery manufacturers, testing by Midtronics, the test equipment manufacturer, and testing by an independent test laboratory, Atlas Testing Laboratory. This paper will describe how these studies have established the utility of using conductance technology to evaluate the condition of SLI batteries, even at very low states of charge.

In the telecommunication community, starting with the INTELEC presentation in 1986 by DeBardelaben[2], the suggestion to use impedance and more recently conductance as a means of determining the "state-of - health" of industrial stand-by reserve batteries has drawn increasing world-wide interest among both battery users and manufacturers [3,4,5]. Since the ultimate intent is to substitute conductance testing for conventional discharge capacity testing, this interest has quite naturally focused first in the area of Valve Regulated Lead Acid (VRLA) battery technology for which there are no reliable diagnostics other than the performance of a discharge capacity test. More recently, interest has expanded to include both flooded lead acid and nickel cadmium cells as well [11]. Since early 1992, the pace of work in this area has significantly accelerated with more than 8 papers presented at both national and international technical meetings [6,7,8,9,10,11,12,13]. in various industries, showing the applicability of the technique in the railroad, electric power utility, and stand-by power, as well as the telecommunications industry. While the predominant objective of these efforts was to demonstrate the validity of conductance testing as an accurate predictor of battery capacity, these studies have resulted in several significant additional benefits:

1. For the first time actual discharge tests of Valve Regulated Lead Acid (VRLA) cells have resulted in the accumulation and publication of large quantities of actual VRLA individual cell and battery ampere-hour capacity data in order to serve as a standard against which conductance results could be compared.

2. Results of these capacity tests have shown both unusually wide-spread capacity variation and significant numbers of premature capacity failures in valve regulated cells over a wide range of applications in telecommunications, U.P.S., photo-voltaic, and railroad signaling usages. These failures have appeared to occur without regard to specific manufacturer, design, application, or specific use environment.

3. In addition, over the last several years, both users and manufacturers have generally become more knowledgeable of performance characteristics, aging mechanisms and failure modes of VRLA cells, so that it is now clearly recognized that the number of serious failure modes of VRLA cells significantly exceeds those of conventional flooded cells. It has also been recognized that in almost every case, these same failure modes also affect the conductance of VRLA cells, thus strengthening the logic for the use of conductance as a suitable diagnostic technique.

In this paper we will present an overview of conductance/capacity test results obtained and reported in the last two years, augmented by significant new previously unpublished results, as well as significant new developments in both the instrumentation and application of conductance testing to determine the "state-of-health" of batteries ranging from small 12 volt SLI automotive designs, to stationary designs as large as 1000 ampere-hours used in battery strings with voltages as high 380 volts.

CONDUCTANCE TESTING OF AUTOMOTIVE BATTERIES

Test equipment and procedures, specific to the testing of automotive SLI batteries will be discussed in the sections which follow:

SLI Background

Discussions with the Big 3 U.S. automobile manufacturers, various European and Japanese automobile manufacturers, and automotive battery manufacturers have revealed the need to reduce battery warranty costs and improve customer satisfaction by providing a safe, accurate and quick diagnostic test while minimizing the need or time necessary to recharge the battery before testing. Traditionally the 1/2 cold crank amp test has been the most widely used test technique in the field in the United States. This test provides for the battery to be discharged at 1/2 its rated Cold Crank Amps (CCA) for 15 seconds to a cut-off voltage of 9.6 volts at 77°F (25°C). The actual Cold Crank Amp test is documented by the Society of Automotive Engineers (SAE), and is primarily used in the United States, and also with variations utilized in Europe (the DIN standard, and the IEC standard), and the JIS standard in Japan. However any load test has serious limitations in its ability to test partially discharged batteries in order to make an accurate judgement of the battery's high rate or starting capability. In addition, the 1/2 CCA test has the effect of discharging the customer's battery, and in some instances, it may create dangerous arcing and potential explosions during the test.

The evolution and usage of sophisticated automobile electronic control/systems with a variety of parasitic loads have changed the load profile and expectations of SLI battery performance characteristics. These changes now require that the battery not only have good high rate starting performance and adequate high rate starting reserve but also low current/reserve performance and good charge acceptance characteristics from low current drain deep discharge conditions. However as might be expected, the results of the 1/2 CCA test generally do not accurately show the deterioration of reserve capacity performance over SLI battery life.

Likewise the introduction of new SLI battery types has further emphasized the need for more sophisticated diagnostic techniques. For example, the "maintenance free" battery, for which individual cells can no longer be accessed, are designed to minimize water loss. The "maintenance free" automotive SLI battery design is generally accomplished by adaptation of Valve Regulated Lead Acid - Absorbed Glass Mat (AGM), or gelled electrolyte (GEL) lead acid designs, or is accomplished with low gassing rate grid alloys and increased electrolyte volume. In either case the use of a hydrometer as a diagnostic tool is no longer possible and more sophisticated techniques are now required.

SLI Conductance Tester Design Criteria

The adaptation of the conductance test for testing automotive SLI batteries to meet these new requirements and characteristics is based on the application of the following criteria:

1. The need to be able to make a meaningful test before a battery is re-charged.

2. Identification of defective cells prior to recharging, to prevent the potentially dangerous attempt to recharge a battery with a shorted cell.

3. Where necessary, the need to make equally meaningful test evaluation of battery condition after recharge.

4. Accurate diagnosis under all conditions, with particular emphasis on not identifying bad batteries as good batteries.

5. Using the technique to determine the acceptance of charge, and appropriateness of returning the battery to service.

6. Making the test method quick and user friendly.

The following list shows the types of tests developed for characterization of SLI battery conductance behavior in order to achieve these requirements. These tests were run on large samples of several manufacturers batteries of varying design, gravity, grid alloys, group sizes and acid to plate ratios.

1. State of charge effects on conductance at various test frequencies.

2. Temperature effect on conductance at various test frequencies.

3. Effect on conductance of cell failures as determined by either tear down or 1/2 CCA test.

4. Conductance recovery from deep discharge/stand.

5. Conductance reference characterization of SLI batteries.

The results of these tests were applied to the conductance tester to achieve the desired operational/diagnostic criteria as listed above. Some of the results/characteristics were electronically adapted to the tester, applied to the test sequence/order of diagnostic operation and finally used to provide the necessary calibration points.

SLI Experimental Procedure

In the majority of tests, SLI batteries were subjected to a comprehensive test sequence which included: visual inspection of case, electrolyte levels, pressure tests to reveal partition leaks, measurements of open circuit voltage, specific gravities, conductance, 1/2 CCA 15 second discharge voltage, charge acceptance, reserve capacity, 3 day stand loss, 600 amp high rate and ultimately tear down analysis. Each battery was independently tested in the as-received condition and was also subjected to one hour and then two hours of charge (constant current 35 amps). After each recharge, the individual battery conductance and 1/2 CCA tests were performed again. The batteries were then placed on charge under long term constant current recharge conditions and then subjected to reserve capacity tests. The batteries were then recharged and left on three day open circuit stand. Each battery was also subjected to a 600 amp constant current, five second discharge. Finally, each battery was recharged in preparation for the tear down process.

SLI Pass/Fail Criteria For Electrical and Teardown Analysis

1. The fail criterion for the 1/2 CCA test was a 15 second voltage less than 9.6 volts and the pass criterion was a voltage greater then 9.6 volts @77°F (25°C).

2. The fail criterion for the reserve capacity test (25 amps constant current discharge to 10.5 volts) was less than 75% of temperature corrected minutes vs actual rating, and pass if temperature corrected minutes (as per BCI) were greater than 80% of the rated minutes.

3. The fail criterion for the 600 amp high rate test was dependant on battery type and size with 5 second test failure voltages below 9.9, 9.5, 9.1, and 8.7 volts for the specific battery type.

4. The pass/fail criteria during tear down analysis were based on the cooperative consensus of the battery manufacturer, automotive manufacture and independent test laboratory (Atlas Testing Laboratory). **The results of these diagnostics were used as the ultimate judgement for diagnosing battery condition.**

Test Equipment Utilized

The conductance tests of SLI batteries were performed using the Midtronics **PowerSensor PLUS** tester. This device utilizes the conductance measurement technique which has been used in Midtronics automotive battery test equipment for many years, now enhanced with a new proprietary technique for testing batteries in very low states of charge. The new technique effectively separates the battery's condition or "state-of-health" from the state-of- charge and temperature effects. This tester uses a test frequency which causes the conductance readings to reflect SLI performance, and is different from the frequencies utilized in testing of stand-by batteries.

In one of the tester's functions (Test B), the conductance of an SLI battery is utilized to compare to the conductance of a battery with a particular Cold Crank Amp rating at a specific voltage. This test is possible since a battery's cold cranking capability is directly related to its conductance. This direct linear relationship is demonstrated in **Figure 1** (R^2=0.98). which shows the results of a test comparison between batteries' conductance (Cranking Power) vs. a standard SAE or Battery Council International (BCI) cold cranking test (Amps available for 30 seconds to a voltage of 1.2 Volts per cell (7.2 Volts per battery) at 0°F. (-18°C.)) These tests were performed at the laboratory of a U.S. battery manufacturer. A similar correlation has been established between the Cranking Power reading on the tester, and various other standards, including the DIN, IEC, and JIS standards. This tester also provides a "Cranking Power" reading as an indication of a good battery's state-of-charge (Test D).

SLI Conductance Tester Diagnostic Process

The following diagnostic procedure follows the four step process as specified on the tester:

1. Test A: Bad Cell Test: The first test the conductance tester performs is to test for a single bad cell on a 6 cell (12 Volt) battery. When the Light Emitting Diode (LED) is on, the tester has identified a bad cell and no further testing is necessary. If the red LED is off, the user is instructed to proceed to test B. This test prevents the user from proceeding to recharge batteries with defective cells, thus preventing dangerous mishaps in the event that charging results in arcing which may ignite the hydrogen gas.

2. Test B: Battery Condition: In this test, the overall condition of the battery is tested regardless of the battery state-of-charge. A green LED is used to tell the user that a valid test of battery condition can be performed. If the green LED is on, the user is instructed to dial in the battery's rated CCA value and the conductance measurement is performed. The test result is observed by a needle deflection on the analog meter. If the meter needle deflection is in the red area, the battery has been found to be bad and no further testing is required. If the needle deflection is in the green area, the battery is good and the operator is instructed to proceed to test C. If the green LED is off, the battery potential is below the testable range for this test and the user is instructed to recharge the battery before testing. The testable range can be calibrated and is generally dependant on the user's application requirements.

Measured Conductance "Cranking Power" vs. BCI Test Rating.
SLI-12 Volt Automotive Batteries.

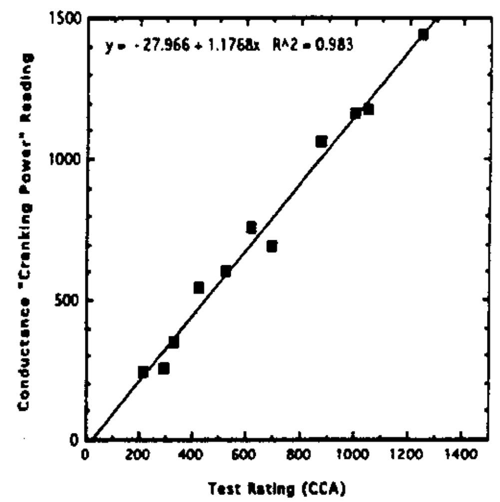


Figure 1

As Received Results, Batteries With Voltage > 10.0 Volts

Conductance Test Outcome

Tear Down Test Outcome	Bad	Good
Good	3	8
Bad	37	1

Correct Assessment Good plus Bad: $\frac{45}{49}$ = 92%

Correct Assessment Of Failures: $\frac{37}{38}$ = 97%

Total 49,12 Volt
SLI Batteries

Note: 31 additional batteries were below 10.0 volts as received and were recharged before test.

Figure 2

3. Test C: Voltage Test: If the battery passes both Test A and Test B, the user is instructed to proceed to Test C. If the battery potential is greater than 12.3 volts, the battery needs no further charging. If the battery potential is at or below 12.3 volts, the user is instructed to recharge the battery before returning it to service.

4. Test D: Cranking Power: This test is used to determine if the battery has been returned to an adequate state-of-charge. Our test results show that when

a battery's cranking power, as measured with the conductance test, meets or exceeds the battery's rated CCA after charging, the battery has regained sufficient energy to be immediately placed back into service.

5. Battery temperature at the time of test is also an important parameter to be considered for determination of overall battery condition. Analysis of temperature test results has allowed for the application of temperature compensation to be applied to the conductance tester. The user is instructed to press a momentary button if the battery temperature is below 32° F (0°C), in order to activate temperature compensation in Test B battery condition test mode.

Discussion/Results - SLI Battery Tests Automobile Manufacturer Independent Test Data

In testing conducted at the Atlas Testing Laboratory under the direction of a large U.S. automobile manufacturer, extensive tests were performed on more than 400 field return batteries. One representative sample of eighty field return batteries will be discussed in this section. The results of the balance of the data will be presented at an appropriate SAE meeting. All of the SLI batteries tested are from a random field sample of warranty return batteries from various Detroit area automobile dealers, and are not representative of a specific age, group size, manufacturer or failure mode.

In the majority of the sample groups tested, a large proportion of the batteries returned for warranty were generally below 12.4 volts as received. Because the 1/2 CCA test is most accurate when testing batteries above 12.4 volts, it is not surprising that this test was limited in its ability to test the majority of batteries as-received. In the population of batteries discussed in this section only 15/80 or 19% of the batteries could be tested as-received with the 1/2 CCA test. By marked contrast, the conductance test with state-of-charge compensation was capable of testing a significantly larger percentage of batteries (49/80 or 61%) below 12.4 volts resulting in a 42% increase in testable batteries as-received. **Figure 2** shows the as-received "Box-score" results for the conductance test and shows accurate judgements of battery condition were made in 92% of the good plus bad batteries and 97% in identification of bad batteries. The remaining 31 batteries of this sample group were under 10.0 volts and were recharged. **Figure 3** shows the "Box-score" results from the 31 batteries whose voltage had been below 10 volts, after the two hour charge (35 amps constant current) and shows the conductance test to be 84% accurate in detecting good plus bad batteries and 100% accurate in identifying bad batteries. Finally, **Figure 4** shows the composite "Box-score" test results for as-received and after charge batteries. The conductance test made accurate decisions in 89% of the good plus bad batteries and 98% in identifying bad batteries when compared to the tear down pass/fail decision. Some of the failure modes properly diagnosed with the conductance test included: positive grid corrosion/oxidation, hydration shorts from excess stand discharge, positive active material shed, broken lug, broken weld etc... Additionally, the bad cell diagnostic test A, showed 12 batteries as having bad

Results After 2 hour Charge

Conductance Test Outcome

TearDown Test Outcome	Bad	Good	
Good	5	5	$\frac{26}{31}$ = 84%
Bad	21	0	$\frac{21}{21}$ = 100%

Total 31,12 Volt SLI Batteries

Figure 3

Composite Results

Conductance Test Outcome

TearDown Test Outcome	Bad	Good
Good	8	13
Bad	58	1

Correct Assessment Good plus Bad: $\frac{71}{80}$ = 89%

Correct Assessment Of Failures: $\frac{58}{59}$ = 98%

Total 80,12 Volt SLI Batteries

Figure 4

cells. Subsequent tear down analysis also confirmed these results. The bad cell failures were of assorted variety and included: cell shorts caused from separator shift, lead run down, mossing, grid wire, spitter shorts, paste lump through separator and acid migration thru the case partition resulting in cell discharge.

These results demonstrate the capability of the conductance test to:

1. Perform accurate diagnosis on a larger proportion of batteries (as-received) before recharging,

2. Make accurate judgments of overall battery condition, most accurately on defective batteries,

3. Identify a bad cell failure regardless of the specific failure mode.

Internal Testing

In January of 1993, a sample of 31 field return batteries, gathered from a local battery distribution facility were sent to Midtronics laboratory for diagnostic testing. Batteries that had obvious mechanical failures (leaks, broken welds, post, jar cover or wall cracks/breaks) were omitted from the test sample. The test procedure included conductance measurements as-received and conductance, 1/2 CCA and reserve capacity tests after charge. In this sample of field return batteries 16/31 or 52% were below 12.4 volts as-received. Because the majority of batteries were below 12.4 volts as-received, the 1/2 CCA test could not be used to accurately determine the condition of these batteries. However all batteries were capable of being tested as-received with the conductance tester. The same pass/fail criteria for 1/2 CCA and reserve capacity tests as described above were utilized. **Figure 5** shows the "Box-score" results of the conductance test as received vs reserve capacity tests. These results again show the conductance test making 93% accurate judgments in identification of good plus bad batteries and 100% accurate in identification of bad batteries in the as-received condition.

Internal Test Results

Conductance Test Outcome

Reserve Capacity Test Outcome	Bad	Good
Good	2	13
Bad	16	0

Total 31,12 Volt SLI Batteries

Correct Assessment Good plus Bad: $\frac{29}{31} = 94\%$

Correct Assessment Of Failures: $\frac{16}{16} = 100\%$

Figure 5

Battery Manufacturer Composite Results

Conductance Test Outcome

TearDown Test Outcome	Bad	Good
Good	3	113
Bad	67	5

Total 188,12 Volt SLI Batteries

Correct Assessment Good plus Bad: $\frac{180}{188} = 96\%$

Correct Assessment Of Failures: $\frac{67}{72} = 93\%$

Figure 6

Independent Testing at a Large U.S. Battery Manufacturer

With the cooperation of the Exide Corporation and several other large U.S. automotive battery manufacturers, extensive studies have been carried out in order to further substantiate the ability of the conductance tester to accurately assess SLI battery condition. One battery manufacturer (Exide Corporation) utilized a similar test plan to that of the automotive manufacturer as discussed above. The battery manufacturer also used the tear down analysis as the ultimate judgement of overall battery condition. This manufacturer performed tests on 188 field returned SLI batteries, which represent no particular manufacturer, failure mode, age, group size or geographic area. Their findings are summarized in **Figure 6** and show the "Box-score" composite results from conductance tests performed on batteries as-received and after charge and compare these findings with the results of tear down analysis. These results again, clearly show the conductance test accuracy of 96% in diagnosing both good plus bad batteries and 93% in identification of bad batteries. Analysis of the data also shows the conductance tester as being effective in identification of bad cells. The manufacturer also verified the bad cell diagnosis with the results of tear down analysis. Similar to the results obtained above, the predominant failure mode observed during tear down was found to be due to cell shorts.

CONDUCTANCE TESTING OF STAND-BY BATTERIES

Experimental Procedures, Stand-by Batteries

Previous papers by the authors have described the theory of conductance testing, details and special features of the test equipment (Midtronics Celltron and Midtron products), and techniques for their use in obtaining individual cell conductance data for cells in stationary reserve applications [7]. Briefly, conductance is defined as the real part of the complex admittance and is measured in the Systems International (SI) unit of Mhos, or the international unit: Siemens. The AC conductance test is performed by applying a low frequency AC voltage signal of known frequency and amplitude across a cell/battery and observing the AC current that flows in response to it. The AC conductance is the ratio of the AC current component that is in-phase with the AC voltage, to the amplitude of the AC voltage producing it. Since only the in-phase current component is considered, the effects of spurious capacitance and inductance, which predominantly influence the out-of-phase component are minimized. The Celltron product is used to measure the actual conductance of an individual cell, or to dial in a reference standard, and test the condition of a cell based on that standard. The Midtron product provides similar information on 6 volt and 12 volt monoblocs. Both testers are passive, instantaneous measuring instruments. More specific product information will not be repeated here except to note all conductance data previously reported were obtained with the battery disconnected from the load and the cells allowed to stand on open circuit from periods ranging from 30 minutes to several days. Later in this paper a new technique will be described which allows "on-line" conductance measurements to be taken with both battery charger and loads connected to their operating system. Likewise, previous papers dealing with batteries in stationary reserve applications have fully described the specific experimental procedures involving open circuit cell individual conductance measurements followed by full string capacity discharge testing at rates ranging from the one hour to the five hour rate. Discharge tests have been performed to end of discharge voltages ranging from 1.95 to 1.75 volts per cell depending on the requirements of the specific application being tested. In every case individual cell voltage/time characteristics were measured.

Results of Tests on Batteries in Stationary Reserve Applications

In telecommunication reserve applications, significant numbers of tests have been performed to provide a clear indication of performance of large VRLA cells and batteries in standby float service. **Figure 7** shows capacity distribution of a single string from a large telecommunication transmission office containing 15 parallel 48 volt strings made up of 1000 ampere-hour Valve Regulated Lead Acid - Absorbed Glass Mat (VRLA/AGM) cells made by Manufacturer A. Although these cells had been in service for only 25% of their expected design life, capacities ranging from 11% to 100% were observed within a single string. This behavior was repeated for each of the strings tested in this office. **Figure 8** shows the capacity/conductance correlation plot for this 24 cell string and indicates a correlation coefficient of $R^2=0.897$. For each of the 14

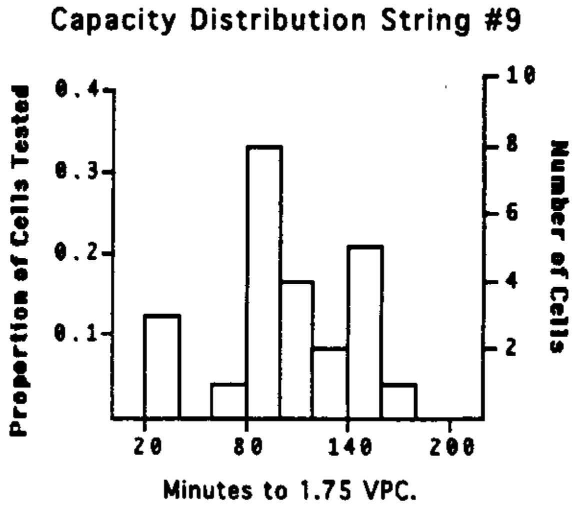


Figure 7

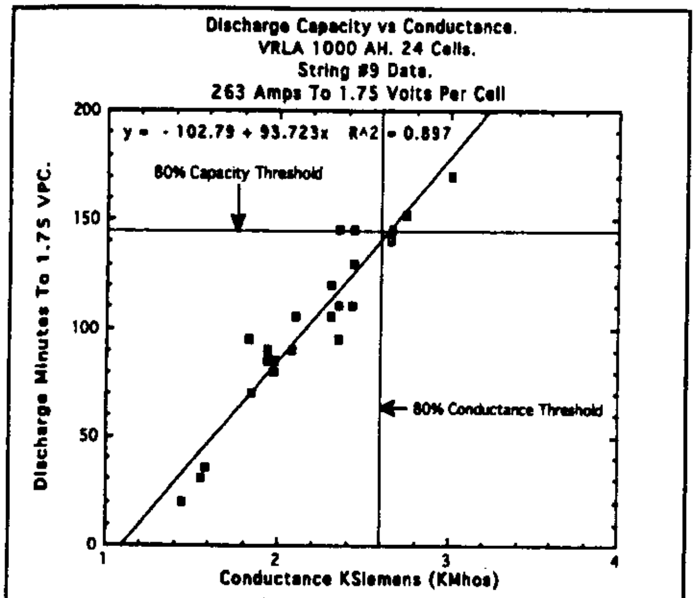


Figure 8

Conductance Test Outcome

Capacity Test Outcome	Bad	Good
Good	2	3
Bad	18	1

Correct Assessment Overall: $\frac{21}{24} = 88\%$

Correct Assessment of Failures: $\frac{18}{19} = 98\%$

Analysis of String #9
24 Cells.

Figure 9

strings tested, capacity/conductance correlations (R^2) range from 0.83 to 0.97 in this office. **Figure 9** shows a "Box-score" presentation designed to quantify the accuracy of conductance measurements in predicting cell performance. Using a typical 80% capacity criterion indicative of cell capacity failure, overall conductance correctly identified 21 of 24 good plus bad cells (88%) and correctly identified 18 of 19 bad cells for a 95% accuracy rating. **Figure 10** shows capacity distribution for all 336 cells tested in this plant to an end of discharge voltage of 1.80 volts per cells. Again note the wide-spread capacity distribution, ranging from zero to 100% throughout the entire plant. **Figure 11** shows the capacity/conductance correlation plot for these 336 cells with a correlation coefficient $R^2 = 0.855$. **Figure 12** shows the "Box-score" taken from the correlation

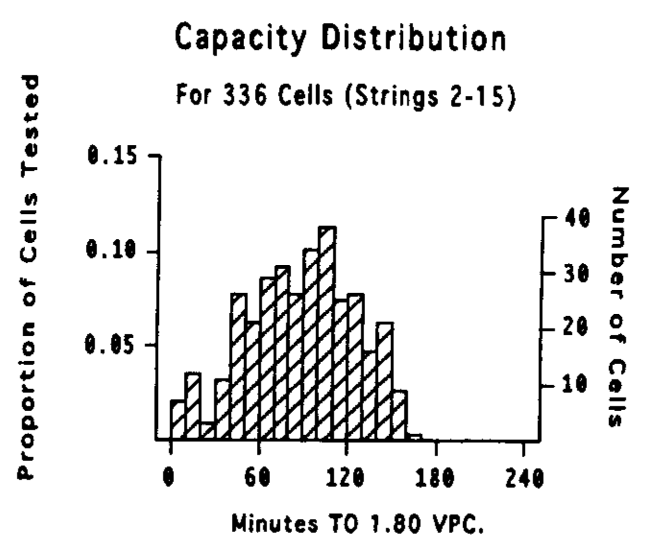


Figure 10

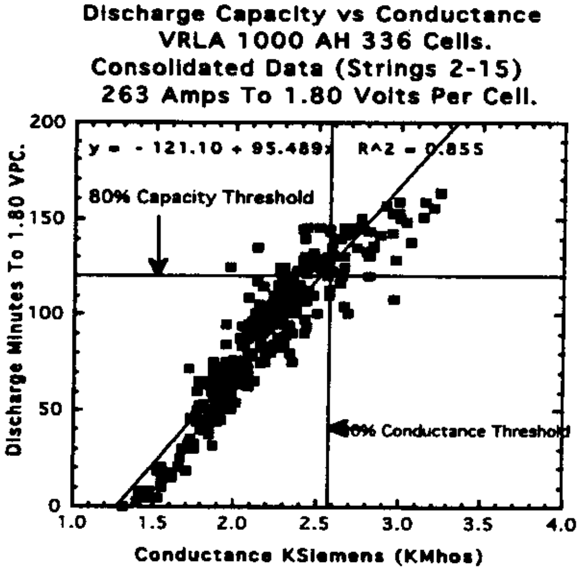


Figure 11

Conductance Test Outcome

Capacity Test Outcome	Bad	Good
Good	37	34
Bad	259	6

Correct Assessment Overall: $\frac{293}{336} = 88\%$

Correct Assessment of Failures: $\frac{259}{265} = 98\%$

Analysis of Strings
(2-15) 336 Cells.

Figure 12

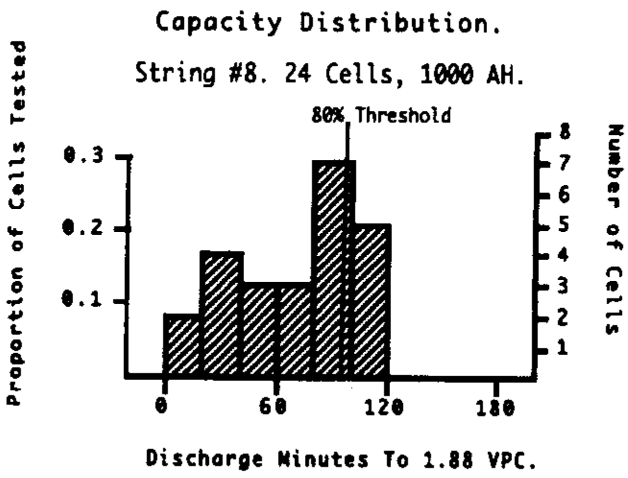


Figure 13

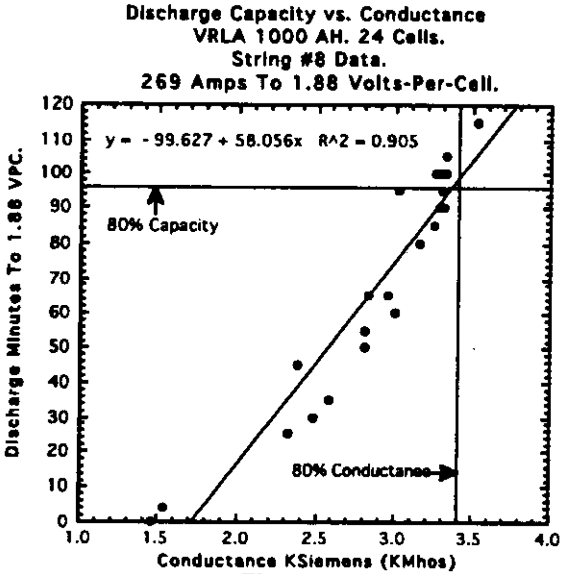


Figure 14

Conductance Test Outcome

Capacity Test Outcome	Bad	Good
Good	4	1
Bad	19	0

Correct Assessment Overall: $\frac{20}{24} = 83\%$

Correct Assessment of Failures: $\frac{19}{19} = 100\%$

Total 24 Cells
String #8

Figure 15

plot indicating 88% overall accuracy of conductance in predicting good plus bad cells and 98% accuracy in detecting failed cells.

In a second telephone transmission office, using similar 1000 ampere-hour cells also made by Manufacturer A, but of a newer design, similar results were obtained. This office contained 10 parallel 48 volt strings. Typical single string capacity distribution results are shown in **Figure 13** for string #8. Even for this newer design, capacities ranged from zero to 100%. **Figure 14** shows the excellent capacity/conductance correlation of $R^2 = 0.905$. "Box-score" analysis for this string shown in **Figure 15** indicates that conductance accurately predicted of 20 out of 24 good plus bad cells or 83%, with 19 of 19 failed cells correctly predicted for 100% accuracy. Overall capacity behavior for 8 of the 9

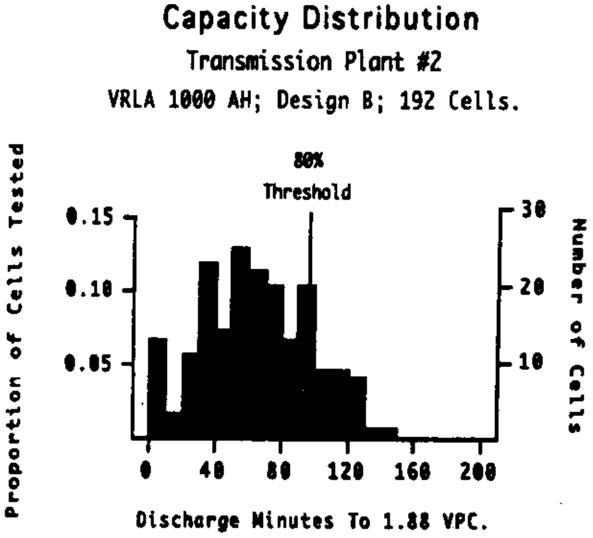


Figure 16

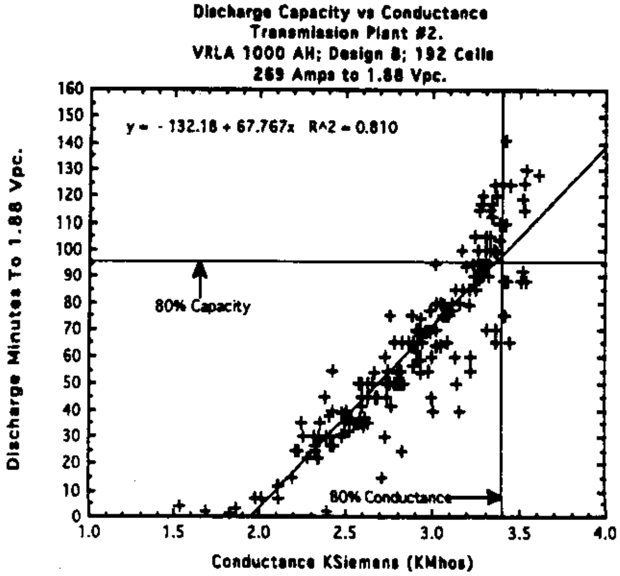


Figure 17

Conductance Test Outcome

Capacity Test Outcome	Bad	Good
Good	16	10
Bad	160	6

Correct Assessment Overall: $\frac{170}{192} = 89\%$

Correct Assessment of Failures: $\frac{160}{166} = 96\%$

Total 192 Cells

Figure 18

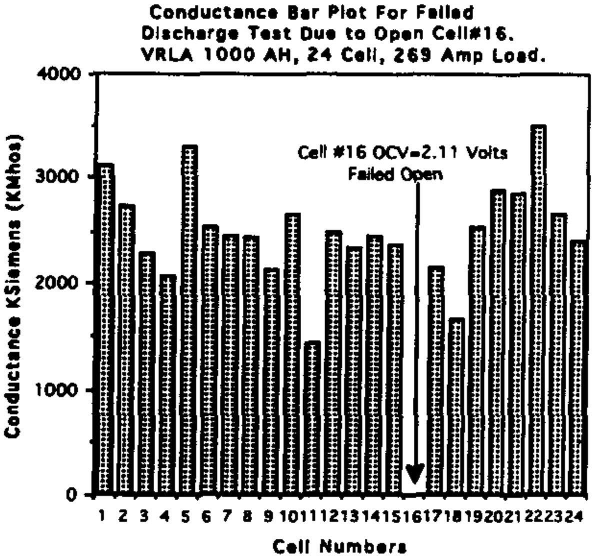


Figure 19

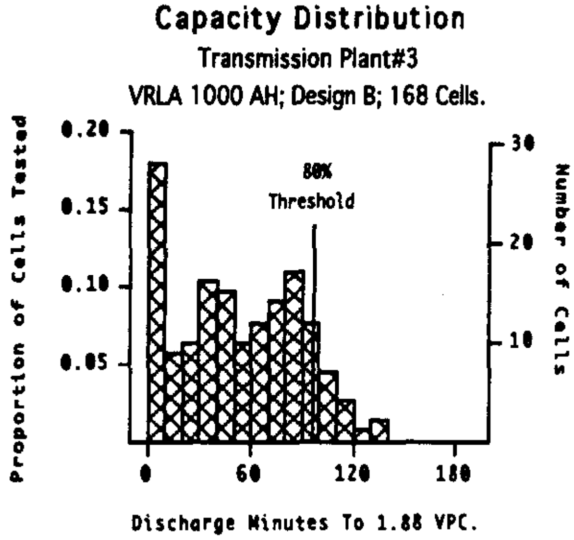


Figure 20

strings tested is shown in **Figure 16**. Here again we see capacity distribution from 0 to 115% for the 192 cells tested after a service period of only 25% of their design life. Capacity/conductance correlation results for all 192 cells shown in **Figure 17** again indicate good correlation $R^2=0.81$. **Figure 18** shows the "Box-score" with an overall conductance predictive accuracy of 170 of 192, or 89% and most significantly, an accuracy of 160 of 166 or 96% in detecting cells with less than 80% capacity. A ninth string was also tested in this office. Individual cell conductance values for this string are shown in the bar chart in **Figure 19**. Cell 16 showed zero conductance indicating an internal open. The subsequent discharge failed instantly confirming the conductance reading. It should be noted that neither float voltage nor open circuit voltage measurements on cell 16 had indicated a catastrophic internal condition.

In a third telephone transmission office similar results were obtained. This office contained seven parallel 48 volt strings of 1000 ampere cells of Manufacturer A's newer design (identical in size and design and of similar age as those in office #2). Capacity distribution results are shown in **Figure 20**. Again capacities ranged over the full spectrum of 0 to 115% for cells in service for only 25% of their design life. The capacity/conductance correlation plot shown in **Figure 21** again indicates good correlation of $R^2 = 0.81$. **Figure 22** shows the "Box-score" with an overall predictive accuracy for conductance of 92% and 100% predictive accuracy for failed cells.

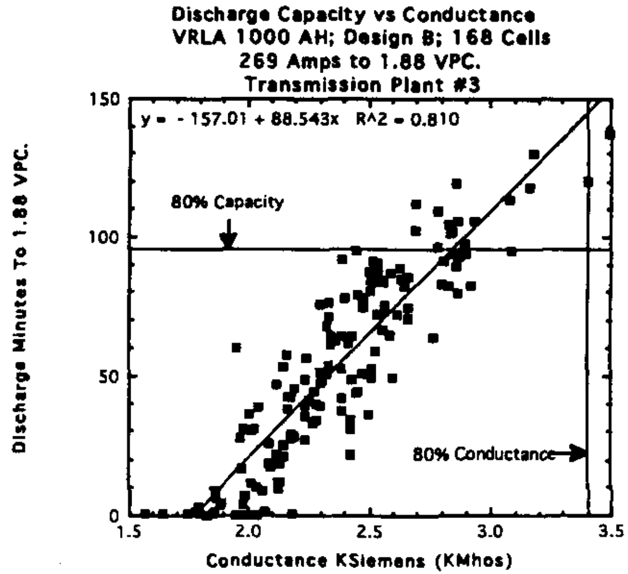


Figure 21

Conductance Test Outcome

Capacity Test Outcome	Bad	Good
Good	13	2
Bad	153	0

Total 168 Cells
Transmission Site #3

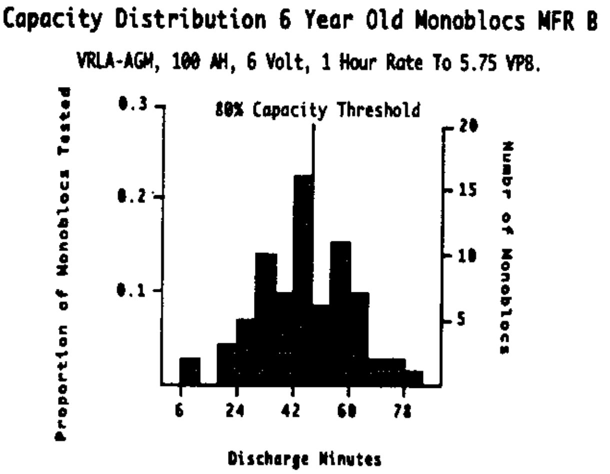
Correct Assessment Overall:

$\frac{155}{168} = 92.3\%$

Correct Assessment of Failures

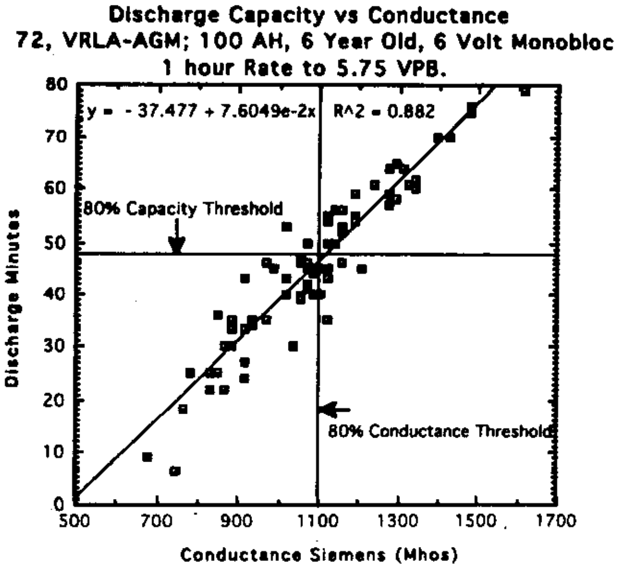
$\frac{153}{153} = 100\%$

Figure 22



Capacity Distribution 6 Year Old Monoblocs MFR B
VRLA-AGM, 100 AH, 6 Volt, 1 Hour Rate To 5.75 VPB.

Figure 23



Discharge Capacity vs Conductance
72, VRLA-AGM; 100 AH, 6 Year Old, 6 Volt Monobloc
1 hour Rate to 5.75 VPB.

Figure 24

sion stationary stand-by service, data on approximately 700 cells indicates 584 actually failed to meet their 80% capacity requirement. Conductance testing correctly predicted 572 or 98% of these capacity failures.

Additional capacity/conductance data on VRLA-AGM cells in telecommunication stand-by service are provided by a recent paper presented by Mr. Bill Jones from British Telecom[12]. Because of its relevance, data has been abstracted from that paper and has been reformatted so it could be presented in the same format as the US telecommunications data previously presented. In this case, the batteries made by Manufacturer B consist of eight 3 cell VRLA/AGM monoblocs, series connected as a 48 volt battery. The typical United Kingdom telecommunication office contained 3 parallel 48 volt strings. Each 3 cell monobloc was rated at 100 ampere-hours at the 1 hour rate (50 amps) and was designed to provided capacity to 1.917 end of discharge voltage per cell (or 5.75 volts per monobloc). Data were presented on 168 six volt monoblocs (504 cells) ranging in age from one to nine years. Both capacity and conductance data were presented. Data on one year old monoblocs indicated 133% of rated capacity. Capacity distribution, capacity/conductance correlation plots and "Box-scores" are shown according to time in service and then as an overall combined population. Figure 23 shows capacity distribution for nine 48 volt batteries, 6 years old, taken from 4 different telephone offices. For Manufacturer B and under U.K. float conditions, capacities ranged from 5 minutes (8%) to 80 minutes (133%) of rating at approximately 60% of

Conductance Test Outcome

Capacity Test Outcome	Bad	Good
Good	2	27
Bad	36	7

Total 72 Six Year
Old Monoblocs

Correct Assessment Overall:

$\frac{63}{72} = 88\%$

Correct Assessment Of Failures:

$\frac{36}{43} = 84\%$

Figure 25

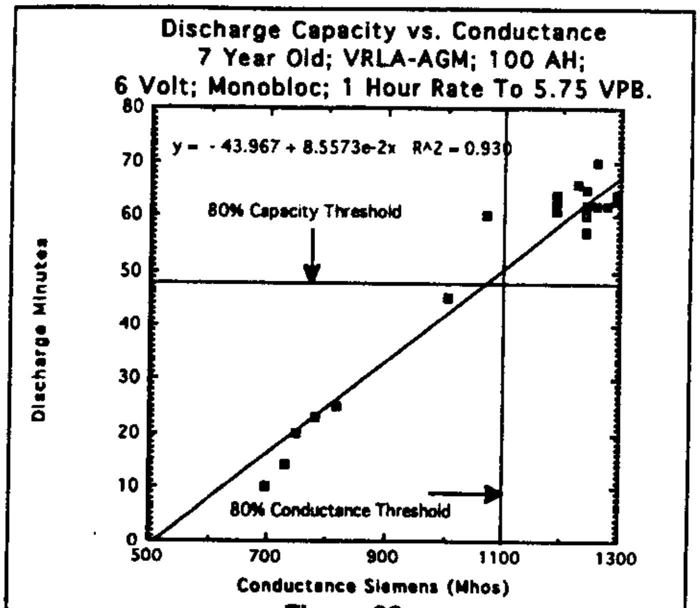


Figure 26

Conductance Test Outcome

Capacity Test Outcome

	Bad	Good
Good	1	17
Bad	6	0

Correct Assessment Overall: 23/24 = 96%

Correct Assessment Of Failures: 6/6 = 100%

Total 24, Seven Year Old Monoblocs

Figure 27

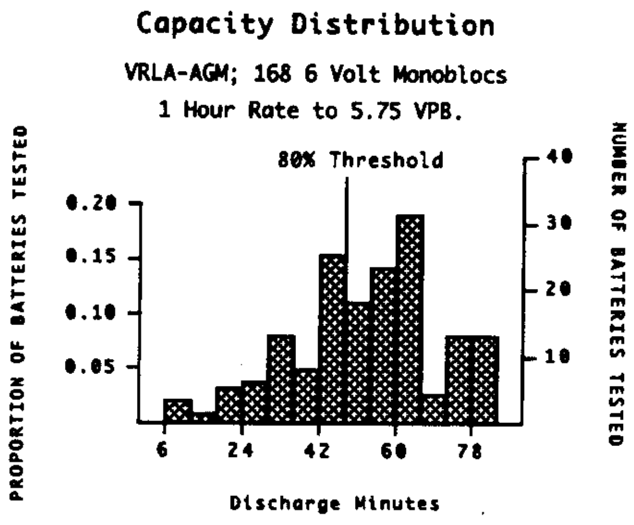


Figure 28

monoblocs failing to meet the 80% capacity requirement. The nine 6 year old strings have been combined into a single capacity/conductance correlation plot, shown in **Figure 24** with a combined correlation coefficient of R^2=0.88. **Figure 25** shows the combined group "Box-score" indicating an overall conductance predictive accuracy of 88% and an accuracy of 84% in detecting 6 year old monblocs which had failed the 80% criterion.

While 60% of the 6 year old monoblocs failed the 80% capacity requirement, only 1 of the 24 five year old monoblocs and none of the 1 year old monoblocs failed. Six of 24 (25%) of the seven year old monoblocs failed while 12 of 20 (60%) of the nine year old monoblocs failed. A typical capacity/conductance correlation plot for the seven year monoblocs is shown in **Figure 26** with a correlation coefficient of R^2=0.93. The "Box-score" shown in **Figure 27** shows 96% overall accuracy and 100% (6 of 6) accuracy in detecting failed monoblocs. **Figure 28** shows capacity distribution for the entire 168 monobloc group and indicates 61 of 168 = 36% overall failures, primarily in the six year and older age group. **Figure 29** shows capacity/conductance overall correlation plot for the entire population with a very good correlation coefficient R^2=0.89. An overall "Box-score" is shown in **Figure 30** indicating 90% overall predictive accuracy for conductance and 83% accuracy in detecting failed cells.

Additional data on 6 volt monoblocs were obtained from two U.P.S. installations. The first contained 60

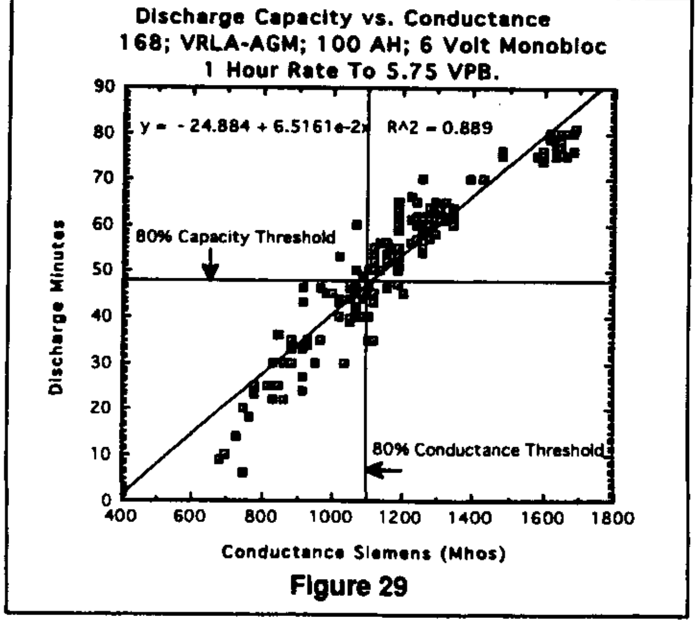


Figure 29

Conductance Test Outcome

Capacity Test Outcome	Bad	Good
Good	5	98
Bad	54	11

Correct Assessment Overall: $\frac{152}{168}$ = 90%

Correct Assessment Of Failures: $\frac{54}{65}$ = 83%

Total 168, Six Volt Monoblocs

Figure 30

Capacity Distribution

20; VRLA-AGM; 200 AH; 6 Volt Monobloc's

100 Amps To 5.85 VPB

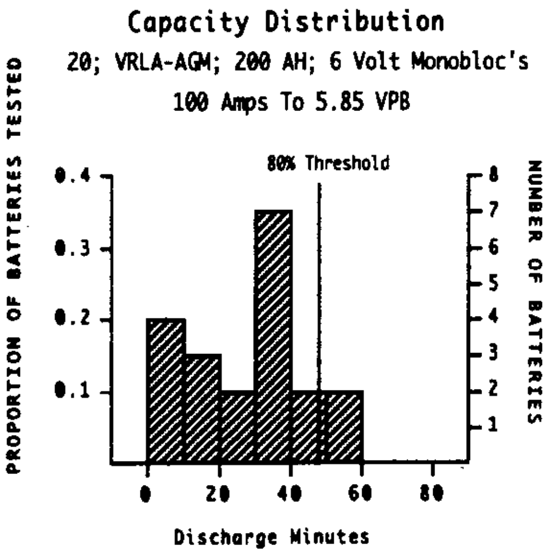


Figure 31

Discharge Capacity vs Conductance.
VRLA 6 Volt, 200 AH. 20 Batteries.
100 Amps To 5.85 Volts Per Battery.

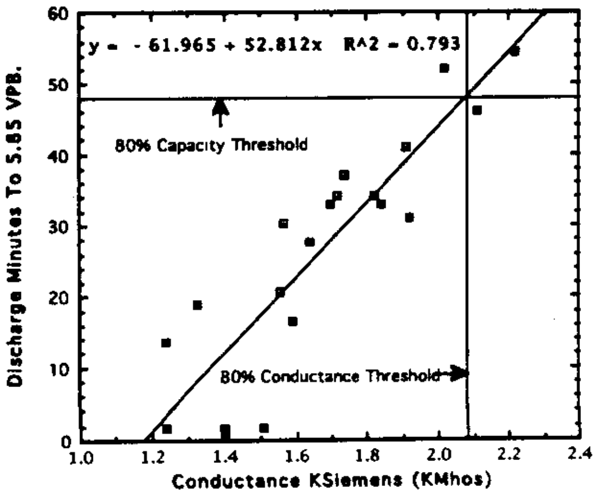


Figure 32

six year old 6 volt, 200 ampere-hour monoblocs made by Manufacturer C and arranged in three parallel strings of 20 monoblocs each. One of the three parallel strings (20 monoblocs) was conductance tested and then capacity tested at the one hour rate to 5.85 volts per monobloc (1.95 volts per cell). Capacity distribution results are shown **Figure 31** and range from 2 minutes (3%) to 55 minutes (92%) with an overall failure rate of 18/20 or 90%. Correlation of capacity vs. conductance is shown in **Figure 32** and indicates a correlation coefficient of R^2=0.79. "Box-score" analysis shown in **Figure 33** indicates 90% overall predictive accuracy for conductance and 94% accuracy in predicting failed monoblocs.

Conductance Test Outcome

Capacity Test Outcome	Bad	Good
Good	1	1
Bad	17	1

Correct Assessment Overall: $\frac{18}{20}$ = 90%

Correct Assessment Of Failures: $\frac{17}{18}$ = 94%

Total 20, 200 AH Monoblocs

Figure 33

Capacity Distribution

MFR D, VRLA 200 AH, 6 Volt Monoblocs

1 Hour Rate To 5.64 VPB

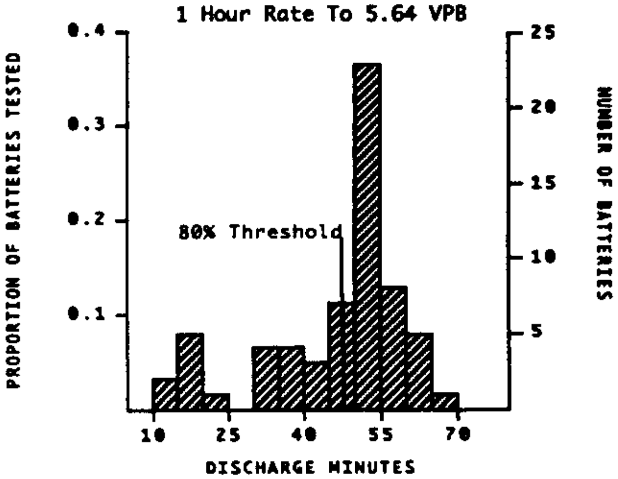


Figure 34

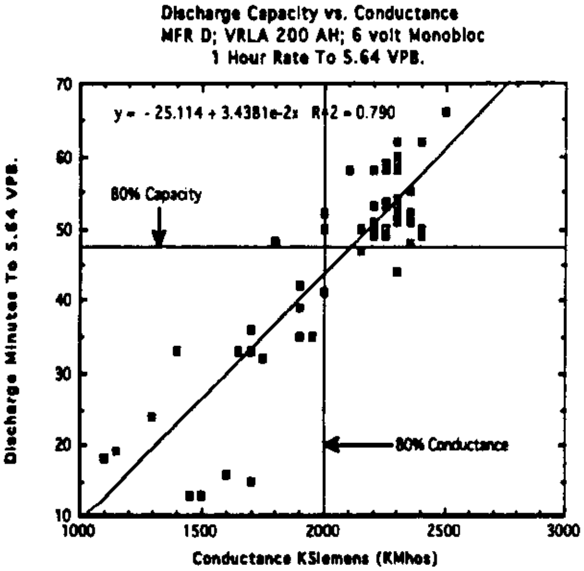
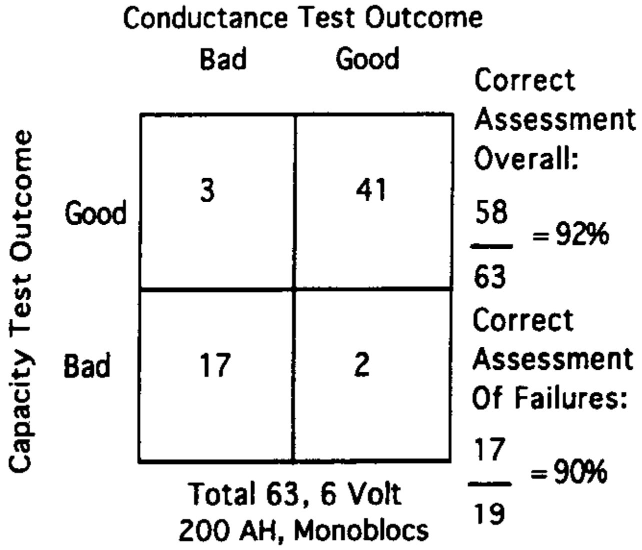


Figure 35



Conductance Test Outcome

Capacity Test Outcome	Bad	Good
Good	3	41
Bad	17	2

Total 63, 6 Volt
200 AH, Monoblocs

Correct Assessment Overall:

$\frac{58}{63} = 92\%$

Correct Assessment Of Failures:

$\frac{17}{19} = 90\%$

Figure 36

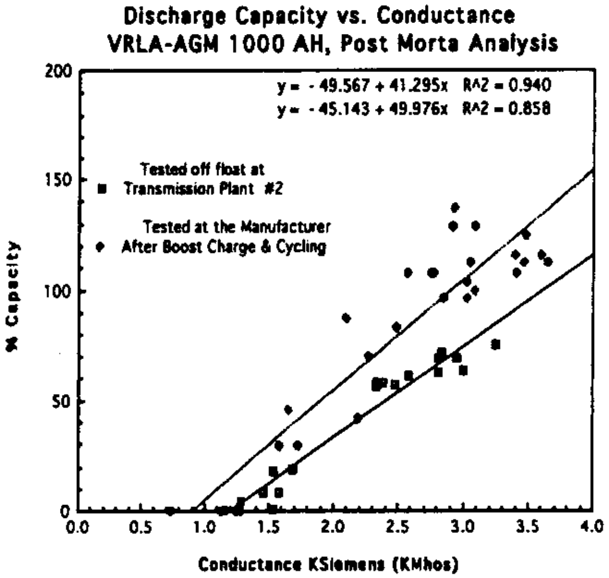


Figure 37

A second U.P.S. installation consisted of three year old 6 volt, 200 ampere-hour monoblocs made by Manufacturer D arranged in three parallel strings of 63 monoblocs each. One of the three parallel strings (63 monoblocs or 189 cells) was conductance tested and then capacity tested at the one hour rate to 5.64 volts per monobloc (1.88 volts per cell). Capacity distribution results are shown in **Figure 34** and again indicate capacities ranging from 12 minutes (20%) to 65 minutes (108%), with a failure rate of 19/63 or 30% after only three years service. Correlation of capacity with conductance is shown in **Figure 35** and indicates a correlation coefficient of R^2=0.79. The "Box-score" in **Figure 36** indicates 92% overall predictive accuracy for conductance and 90% accuracy in detecting failed monoblocs.

For 6 volt monobloc designs made by three different manufacturers, capacity data indicate premature failure rates ranging for 30% to 90% from monoblocs only three to six years old. In all cases, conductance correlated well with capacity and detected failed monoblocs with an accuracy ranging from 82% to 94%. Since each monobloc consists of three cells, with each cell probably differing in both capacity and conductance, this consistency of conductance/capacity correlation and predictive accuracy of conductance for these three cell monoblocs is, at the least, remarkable.

Post-Morta Results

In the past year capacity and conductance data have been supplemented on a limited basis by post morta tear downs and diagnostics by the manufacturer. Capacity and conductance results of 225 ampere-hour railroad signaling cells was described in last years Journal of Power Sources [6]. Results of post morta on the same cells has been reported in a recent issue of Journal of Power Sources [13]. Tear down diagnostics indicated varying degrees of positive plate growth, and/or dry out but did not provide clearly defined or quantitative failure modes which would accurately account for the order of magnitude range in capacities or the four to one range in conductance which has been previously reported for these cells.

More recently, additional tests and post morta have been performed on thirty 1000 ampere-hour cells from

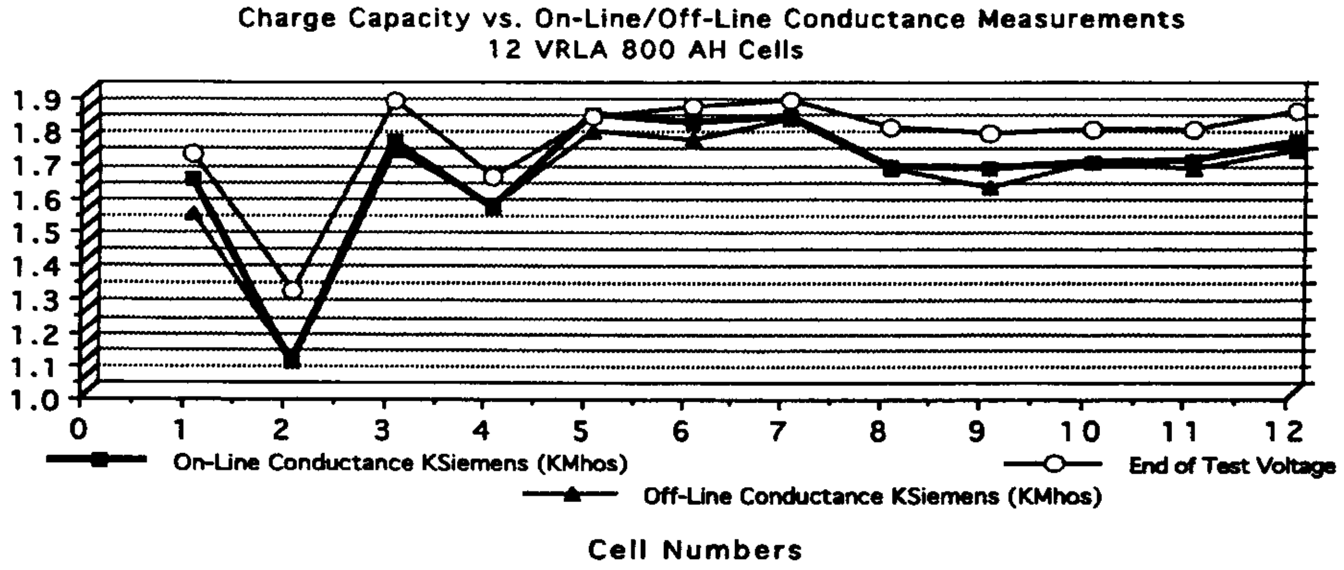


Figure 38

the telephone transmission office which has previously been discussed as office #2. Cells were returned to the manufacturer, recharged at both constant voltage and constant current and then discharged for three repetitive charge/discharge cycles. Conductance was then measured and cells discharged at the same rate originally used at the telephone office. Of the 24 cells from one string, 20 which had originally tested from 56% to 92% capacity, recovered to 83% to 137% after the conditioning cycles. The remaining four cells of this string still failed after conditioning as did the six additional cells from other strings, which had originally tested from 0 to 19%. **Figure 37** compares capacity/conductance results after conditioning by the manufacturer to capacity/conductance results obtained at the telephone office. After cycling and boost charging, although many capacities improved (on average 25% - 30%) the conductance still correlated well with the improved capacities (R^2=0.86) compared to the original correlation of R^2=0.94 as tested at the telephone office. Failure modes were determined for the 8 cells which were torn down. Failures included: 1.) Partial or complete negative strap corrosion failure; 2.) Positive grid corrosion, growth and grid frame fracture; 3.) Dry-out; 4.) Very low stack compression. All but one of the cells showing very low capacity had evidence of internal iron contamination. The one high capacity cell showed no significant defects upon tear down.

Flooded Stationary Battery Results and Discussion

As reported in recent publications [10,13]. Field tests were performed at several electric utility substation locations on flooded stationary batteries of various age and manufacture. Measurements of specific gravity, float voltage, conductance and discharge tests were performed. Two of the authors reported results showing the conductance test as being more sensitive to actual cell performance than traditional measurements of cell specific gravity or float voltage. Results reported in one of the studies [13] showed 0 % accuracy of either float voltage or specific gravities in finding low capacity cells (<80%). By contrast, the conductance test accuracy was shown to be greater than 84% in finding the low capacity cells (<80%). These results, as well as, results reported [6,7,11] again confirm the inability of either float voltage or specific gravity to identify capacity degradation while conductance measurements show greater accuracy in finding cells which have degraded just below the normally recommended 80% failure criteria.

Experimental On-Line Measurements

All conductance measurements reported to date have been performed with the cells on open circuit and the battery strings disconnected from both their power source and the load which they support. On-line measurements made without disconnecting the charging system or the load are possible when "noise" current is minimal, and have successfully been performed. However in the majority of practical applications AC noise will interfere with conductance measurements. Development of a new auxiliary circuit "noise elimina-

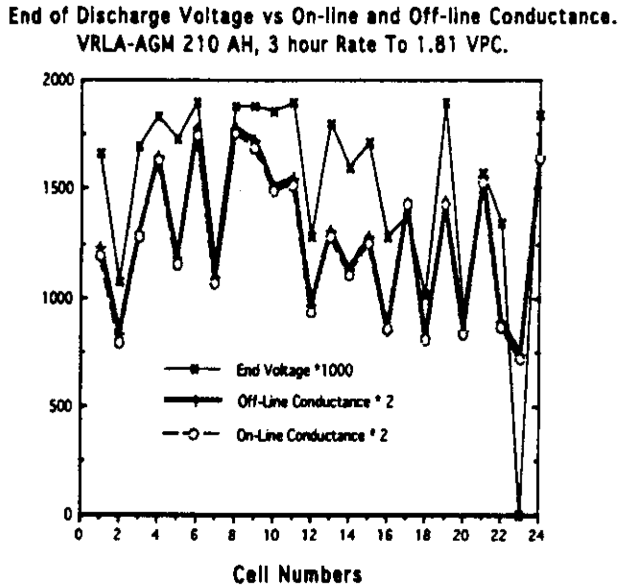


Figure 39

tor" device has allowed direct on-line measurements to be made. Results of one test of both on-line and off-line testing as well as discharge test results are shown in **Figure 38**. This test involved twelve 800 ampere-hour cells used to provide stand-by reserve power for a cellular telephone site. AC noise currents of 2 amperes, peak to peak, were measured. The trend plot of **Figure 38** shows the conductance results on cell by cell basis for off-line versus on-line measurements obtained with the noise eliminator. The differences observed from the on-line/off-line conductance measurements are generally negligible, less than 5%. More importantly the capacity/conductance correlation is shown to be unaffected when measurements are performed on-line with the noise eliminator.

Results of a second test of 24, 210 ampere-hour batteries arranged in a 48 volt office are shown in **Figure 39**. Again off-line conductance is compared to on-line conductance measurements obtained with the noise eliminator. In this case circuit noise was measured as 2.5 amperes peak to peak. Again discharge tests results are shown on the same trend plot. As before, on-line measurement using the noise eliminator correlates very well with off-line measurements and both correlate well with capacity discharge results. The development of this noise eliminator, by allowing on-line measurements, should significantly increase the use of conductance testing, resulting initially in a substantial increase in the amount of both conductance and capacity data and further enhancing the capacity/conductance correlation data base.

CONCLUSIONS - Automotive SLI Batteries

1. Conductance testing of SLI batteries, even in very low states of charge, is now possible, and will allow automobile dealers and battery distributors to accurately evaluate the condition of returned batteries, often before charging, thus improving customer service, and saving warranty cost.

2. The use of conductance testing on SLI batteries has been determined to be a highly accurate method of determining the condition of batteries in various states of charge, and at various temperatures.

3. Conductance testing of SLI batteries overcomes the disadvantages of the standard 1/2 CCA load test, in that it is instantaneous, does not discharge the tested battery, as well as evaluating batteries in very low states of charge.

CONCLUSIONS - Stand-by Batteries

1. Conductance testing of Stand-by batteries in telecommunications, electric power utilities, railroads, and uninterruptable power systems, has been shown to be an effective method of determining battery condition.

2. Given the increasing use of VRLA batteries which cannot be hydrometer tested, and the limited availability of manpower to perform more time-consuming tests, conductance testing provides an effective substitute for timed discharge testing.

3. Conductance testing is highly accurate in detecting defective cells as well as monoblocs.

4. The conductance test method has effectively determined the condition of batteries made by various manufacturers, including VRLA, flooded lead acid, as well as Nickle Cadmium.

5. With the newly developed noise eliminator device, tests can be effectively made either off line, or on line, with similar accuracy.

ACKNOWLEDGEMENTS

The Authors would like to acknowledge the significant contribution of conductance and capacity test data provided by: Thomas G. Croda (Sprint), Don Ogden

(Ogden Power, Inc.), Bill Jones (British Telecommunications) and Carl Anderson & Fred Feres (Exide Corporation).

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