# Updated status of conductance/capacity correlation studies to determine the state-of-health of automotive and stand-by lead/acid batteries

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**Abstract**

For the past seven years, Midtronics has developed and manufactured battery conductance testers for determining the condition of automotive batteries. This paper presents a further refinement of the technology. Studies by automobile manufacturers, automotive battery manufacturers, as well as testing by Midtronics and an independent test laboratory have established the utility of conductance technology in evaluating the condition of automotive batteries, even at very low states-of-charge. The use of conductance to determine the state-of-health of stand-by batteries has attracted increasing worldwide interest among both battery manufacturers and users. Attention has focused first on the area of valve-regulated lead/acid batteries (VRBs) for which there are no reliable diagnostics other than a cumbersome discharge test. Several recent studies have demonstrated the validity of conductance testing as an accurate predictor of battery capacity in railroad, electric power utility, stand-by power and telecommunications applications. Other benefits includes:

(i) for the first time, tests have resulted in the accumulation and publication of large quantities of actual capacity data for individual valve-regulated cells and batteries that will serve as a standard against which conductance results can be compared;

(ii) 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, UPS, photovoltaic and railroad signaling systems; these failures have appeared to occur without regard to specific manufacturers, design, application or use environment;

(iii) in addition, both users and manufacturers have generally become more knowledgeable of performance characteristics, ageing mechanisms and failure modes of valve-regulated cells, so that it is now clearly recognized that the number of serious failure modes significantly exceeds those of conventional flooded cells; it has also been recognized that, in almost every case, these same failure modes also affect the cell conductance, this strengthens the logic for the use of conductance as a suitable diagnostic technique.

An overview is given of conductance/capacity test results obtained and reported in the last two years, augmented by significant new results, as well as significant new developments in both the instrumentation and application of conductance testing to determine the 'state-of-health' of batteries that range from small 12-V automotive designs to stationary designs as large as 1000 Ah in strings with voltages as high 380 V.

## Introduction

The use of conductance measurements to evaluate automotive battery performance is based upon the results first reported in 1975 by Champlin [1]. The data demonstrated


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a strong positive linear correlation between load tests and measured conductance for automotive batteries that ranged from 200 to 500 cold-cranking amps (CCA) and comprised various group sizes. In this paper, a description is given of the further refinement of conductance technology that has been achieved through a number of recent studies by automotive manufacturers, automotive battery manufacturers, Midtronics (the test equipment manufacturer) and an independent test laboratory (Atlas Testing Laboratory). It is shown that these investigations have established the utility of using conductance technology to evaluate the condition of automotive batteries, even at very low states-of-charge.

Within the telecommunications 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 worldwide interest among both battery users and manufacturers [3–5]. 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 battery (VRB) technology for which there are no reliable diagnostic other than the performance of a discharge capacity test. More recently, interest has expanded to include both flooded-electrolyte lead/acid and nickel/cadmium cells as well [6]. Since early 1992, the pace of work in this area has accelerated significantly. For example, more than eight papers have been presented at both national and international technical meetings [6–13] in various industries. These have demonstrated the applicability of the technique in the railroad, electric power utility, stand-by power, and telecommunications industries. While the predominant objective of these efforts was to demonstrate the validity of conductance testing as an accurate predictor of battery capacity, the studies have resulted in the following significant additional benefits:

(i) For the first time, discharge tests of valve-regulated cells have resulted in the accumulation and publication of large quantities of actual individual cell and battery Ah capacity data in order to serve as a standard against which conductance results can be compared.

(ii) Results of the above capacity tests have shown both unusually widespread capacity variation and significant numbers of premature capacity failures in valve-regulated cells over a wide range of applications in telecommunications, uninterruptible power supply (UPS), photovoltaic and railroad signaling usages. It appears that these failures have occurred without regard to specific manufacturer, design, application, or use environment.

(iii) In addition, over the last several years, both users and manufacturers have generally become more knowledgeable of performance characteristics, ageing mechanisms and failure modes of valve-regulated cells. As a consequence, it is now clearly recognized that the number of serious failure modes significantly exceeds that of conventional flooded cells. It has also been recognized that in almost every case, these same failure modes also affect the conductance of such cells. This observation strengthens the logic for the use of conductance as a suitable diagnostic technique.

In this paper, an overview is presented of the results of conductance/capacity tests that have been obtained and reported in the last two years. These data are augmented by significant new previously unpublished results, as well as by significant new developments in both the instrumentation and application of conductance testing to determine the 'state-of-health' of batteries that range from small 12-V automotive designs, to stationary designs as large as 1000 Ah used in battery strings with voltages as high as 380 V.

**Conductance testing of automotive batteries**

*Background*

Discussions with the 'Big Three' US 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 to recharge the battery before testing. Traditionally, the 1/2 CCA test has been the most widely used technique in the USA. This test provides for the battery to be discharged at 1/2 its rated CCA for 15 s to a cutoff voltage of 9.6 V at 77 °F (25 °C). The actual CCA is documented by the Society of Automotive Engineers (SAE), and is primarily used in the USA. With variations, it is also utilized in Europe (the DIN standard and IEC standard), and in Japan (the JIS standard). Nevertheless, 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, dangerous arcing and potential explosions may be created 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 automotive-battery performance characteristics. These changes now require that the battery not only has good high-rate starting performance and adequate high-rate starting reserve, but also has low-current/reserve performance and good charge-acceptance characteristics from low current-drain, deep-discharge conditions. As might be expected, however, the results of the 1/2 CCA test generally do not show accurately the deterioration of reserve capacity performance over battery life.

The introduction of new automotive 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 battery design is generally accomplished by adaptation of absorbed glass-mat (AGM) or gelled-electrolyte (GEL) VRB designs, or is accomplished with low gassing-rate grid alloys and increased electrolyte volume. In either case, the use of hydrometer as a diagnostic tool is no longer possible and more sophisticated techniques are now required.

*Conductance tester design criteria*

The adaptation of the conductance test to allow automotive batteries to meet the new requirements and characteristics discussed above is based on the application of the following criteria:

(i) the need to be able to make a meaningful test before a battery is recharged;

(ii) identification of defective cells prior to recharging, to prevent the potentially dangerous attempt to recharge a battery with a shorted cell;

(iii) where necessary, the need to make equally meaningful evaluation of the battery condition after recharge;

(iv) accurate diagnosis under all conditions, with particular emphasis on not identifying bad batteries as good batteries;

(v) using the technique to determine the acceptance of charge, and appropriateness of returning the battery to service, and

(iv) making the test method fast and user friendly.

The following list shows the type of tests developed for characterization of automotive battery conductance behaviour in order to achieve the requirements listed above. These tests were run on large samples of batteries from several manufacturers. The batteries were of varying design, gravity, grid alloys, group sizes and acid-to-plate ratios:

(i) state-of-charge effects on conductance at various test frequencies;

(ii) temperature effect on conductance at various test frequencies;

(iii) effect on conductance of cell failures as determined by either tear down or 1/2 CCA test;

(iv) conductance recovery from deep-discharge/stand, and

(v) conductance reference characterization of automotive 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.

*Experimental procedure*

In the majority of tests, automotive batteries were subjected to a comprehensive test sequence that included: visual inspection of the case and electrolyte levels, pressure tests to reveal partition leaks, measurements of open-circuit voltage, specific gravities, conductance, 1/2 CCA 15-s discharge voltage, charge acceptance, reserve capacity, 3-day stand loss, 600 A high rate, and, ultimately, tear-down analysis. Each battery was independently tested in the as-received condition and was also subjected to 1 h, and then 2 h, of charge (constant current: 35 A). After each recharge, the individual battery conductance and 1/2 CCA tests were repeated. The batteries were than 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 3-day open-circuit stand. Each battery was also subjected to a 600 A constant current, 5-s discharge. Finally, each battery was recharged in preparation for the tear-down process.

*Pass/fail criteria for electrical and tear-down analysis*

1. The fail criterion for the 1/2 CCA test was as 15-s voltage of less than 9.6 V. The pass criterion was a voltage greater than 9.6 V at 77 °F (25 °C).

2. The fail criterion for the reserve capacity test (25 A constant-current discharge to 10.5 V) was less than 75% of temperature-corrected minutes versus actual rating. The battery was passed if the temperature-corrected minutes (as per Battery Council International (BCI)) were greater than 80% of the rated minutes.

3. 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 evaluating battery condition.

*Test equipment*

The conductance tests of automotive batteries were performed using the Midtronics Power Sensor Plus tester. This device utilizes the conductance measurement technique that has been employed by Midtronics for many years, now enhanced with a new proprietary method 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 frequency that causes the conductance readings to reflect battery performance, and is different from the frequencies adopted in the testing of stand-by batteries.

In one of the tester's functions (test B), the conductance of an automotive battery is compared with that of a battery with a particular CCA rating at a specific voltage. This test is possible since a battery's cold-cracking capability is directly related to its conductance. The direct linear relationship is demonstrated in Fig. 1 ($R^2$=0.98). The data are the results of a test comparison between batteries's conductance (cranking power) versus a standard SAE or Battery Council International (BCI) cold-cranking test (amperes available for 30 s to a voltage of 1.2 V/cell (7.2 V/battery) at 0 °F (−18 °C). These tests were performed in the laboratory of a US 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 procedures. This tester also provides a 'cranking power' reading as an indication of a good battery's state-of-charge (Test D).

*Conductance tester diagnostic process*

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

(*i*) *Test A*: *bad cell test*. The first procedure the conductance tester performs is to search for a single bad cell on a 6-cell (12-V) battery. When the light emitting diode (LED) is on, the equipment 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, and thus prevents dangerous mishaps, e.g. arcing that may ignite the hydrogen gas.

(*ii*) *Test B*: *battery condition*. In this test, the overall condition of the battery is evaluated regardless of the battery state-of-charge. A green LED is used to inform

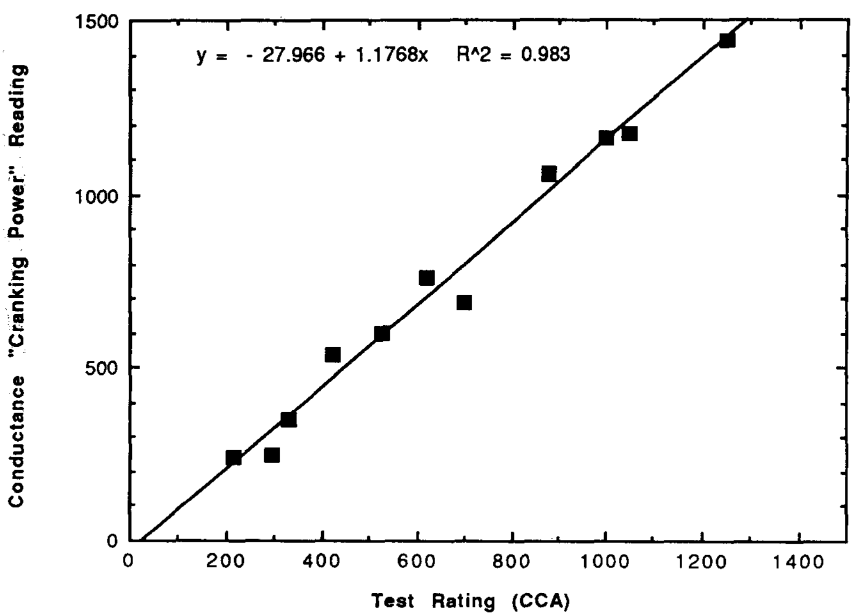


Fig. 1. Measured conductance 'cranking power' vs. BCI test rating (12-V automotive batteries).

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 measurable range for this test and the user is instructed to recharge the battery before testing. The range can be calibrated and is generally dependent on the user's application requirements.

(*iii*) *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 V, the battery needs no further charging. If the battery potential is at or below 12.3 V, the user is instructed to recharge the battery before returning it to service.

(*iv*) *Test D*: *cranking power*. This test is used to determine if the battery has been returned to an adequate state-of-charge. Test results have shown that when a battery's cranking power, as measured with the conductance test, meets or exceeds the battery's rate CCA after charging, the battery has regained sufficient energy to be placed back immediately into service.

(*v*) *Battery temperature* at the time of test is also important parameter to be considered for determination of overall battery condition. Analysis of temperature data 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 the test B procedure.

*Testing by an independent laboratory*

In testing conducted at the Atlas Testing Laboratory under the direction of a large US automobile manufacturer, extensive tests were performed on more than 400 field-return automotive batteries. One representative sample of 80 of these 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 batteries are from a random sample of warranty-return batteries from various automobile dealers in the Detroit area. The batteries are not representative of a specific age, group size, manufacturer, or failure mode.

| Tear Down Test Outcome | Conductance Test Outcome: Bad | Conductance Test Outcome: Good |
|---|---|---|
| Good | 3 | 8 |
| Bad | 37 | 1 |

Total 49, 12-Volt SLI Batteries

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

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

Fig. 2. As-received results; batteries with voltage > 10.0 V. Note: 31 additional batteries were below 10.0 V as-received and were recharged before test.

In the majority of the sample groups, a large proportion of the return batteries were generally below 12.4 V. Because 1/2 CCA test is most accurate when testing batteries above 12.4 V, it is not surprising that this procedure was limited in its ability to evaluate the majority of batteries as-received. In the population of batteries discussed in this section only 15 (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 (viz., 49 or 61%) below 12.4 V. This resulted in a 42% increase in testable batteries as-received. Figure 2 shows the 'box-score' results for the conductance test. 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 were under 10.0 V and were recharged. Figure 3 gives the 'box-score' for these 31 batteries after a 2-h charge (35 A, constant current). It can be seen that the conductance test is 84% accurate in detecting good-plus-bad batteries and 100% accurate in identifying bad batteries. Finally, Fig. 4 presents the composite box-score results for as-received and after-charge batteries. Accurate decisions were made for 89% of the good-plus-bad batteries and for 98% of the bad batteries, when compared with 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 in

Conductance Test Outcome

| TearDown Test Outcome | Bad | Good |
|---|---|---|
| Good | 5 | 5 |
| Bad | 21 | 0 |

Total 31,12-Volt SLI Batteries

Correct Assessment Good plus Bad: $\frac{26}{31}$ = 84%.

Correct Assessment Of Failures: $\frac{21}{21}$ = 100%

Fig. 3. Results after 2-h charge.

Conductance Test Outcome

| TearDown Test Outcome | Bad | Good |
|---|---|---|
| Good | 8 | 13 |
| Bad | 58 | 1 |

Total 80,12-Volt SLI Batteries

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

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

Fig. 4. Composite results for as-received and after-charge batteries.

a discharged state, positive active-material shedding, broken lug, broken weld, etc. Additionally, the bad-cell diagnostic test A, indicated that 12 batteries had bad cells. Subsequent tear-down analysis also confirmed these results. The bad-cell failures were various and included: cell shorts caused from separator shift, lead run-down, mossing, grid wire, spitter shorts, paste lump through separator, and acid migration through the case partition that resulted in cell discharge.

These studies have shown conductance testing can: (i) perform accurate diagnosis on a larger proportion of batteries (as-received) before recharging; (ii) make accurate judgements of overall battery condition, most accurately on defective batteries and (iii) identify a bad-cell failure regardless of the specific failure mode.

*Testing at Midtronics*

In January 1993, a sample of 31 field-return batteries, gathered from a local battery-distribution facility were sent to the Midtronics laboratory for diagnostic testing. Batteries that had obvious mechanical failures (i.e., leaks, broken welds, post, jar cover or wall cracks/breaks) were omitted from the sample. The test procedure included conductance measurements as-received, as well as conductance, 1/2 CCA and reserve-capacity tests after charge. Results showed that 16 (or 52%) of the batteries were below 12.4 V as-received. Because this constituted the majority of the batteries, the 1/2 CCA test could not be used to determine accurately the condition of the batteries. All batteries were capable, however, 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 versus reserve-capacity tests. The conductance test made 94% accurate judgments in the identification of good-plus-bad batteries, and 100% accurate assessments in the identification of bad batteries in the as-received condition.

*Independent testing at a large US battery manufacturer*

With the cooperation of the Exide Corporation and several other large US automotive battery manufacturers, extensive studies have been carried out in order to further substantiate the ability of the conductance tester to evaluate accurately the condition of automotive batteries. One battery manufacturer (Exide Corporation) utilized a similar test plan to that of the automotive manufacturer discussed above. The battery manufacturer also used tear-down analysis as the ultimate judgement of overall battery condition. This manufacturer performed tests on 188 field-returned batteries. The latter represented no particular manufacturer, failure mode, age, group

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: $\frac{16}{16} = 100\%$

Fig. 5. Test results performed at Midtronics laboratory.

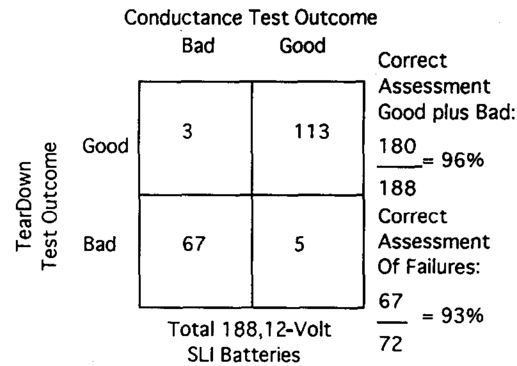


Fig. 6. Composite results from a battery manufacturer.

size or geographic area. The findings are summarized in Fig. 6. The conductance-test accuracy was 96% in diagnosing both good-plus-bad batteries, and 93% in identifying bad batteries. Analysis of the data also shows the conductance tester as being effective in the identification of bad cells. The manufacturer also verified the bad-cell diagnosis from the results of tear-down analyses. Similar to the results obtained above, the predominant failure mode was found to be cell shorts.

## Conductance testing of stand-by batteries

*Experimental procedures*

The theory of conductance testing, details and special features of the test equipment (Midtronics Celltron and Midtron products), and techniques for its use in obtaining conductance data for individual cells in stationary reserve applications have been discussed previously [7]. Briefly, conductance is defined as the real part of the complex admittance and is measured in the Système International (SI) unit of mhos, or the international unit siemens. The a.c. conductance test is performed by applying a low-frequency a.c. voltage signal (of known frequency and amplitude) across a cell/battery and observing the a.c. current that flows in response to it. The a.c. conductance is the ratio of the a.c. current component that is in-phase with the a.c. voltage, to the amplitude of the a.c. voltage that produces it. Since only the in-phase current component is considered, the effects of spurious capacitance and inductance, that 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- and 12-V monoblocs. Both testers are passive, instantaneous measuring instruments. More specific product information will not be repeated here, except to note that all conductance data previously reported were obtained with the battery disconnected from the load and the cells allowed to stand at open circuit for periods ranging from 30 min to several days. Later in this paper, a new technique will be described that allow '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 that involve conductance measurements on individual cells at open circuit, followed by full string capacity discharge testing at rates that range from the 1-h to the 5-h rate. Discharge tests have been performed to end-of-discharge voltages between 1.95 and 1.75 V/cells, as determined by the requirements of the specific application under test. In all cases, individual cell voltage–time characteristics have been measured.

*Results for 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 valve-regulated cells and batteries in stand-by float service. Figure 7 shows the capacity distribution of a single string from a large telecommunication transmission office containing 15 parallel 48-V strings made up of 1000 Ah, valve-regulated, absorbed glass mat (AGM) cells made by manufacturer A. Although these cells had been in service for only 25% of their expected design life, the capacities ranged from 11 to 100% within a single string. This behaviour was common for each of the strings tested in this office. Figure 8 shows the capacity/conductance correlation plot for the 24-cell string. A correlation coefficient of $R^2 = 0.897$ is observed. For each of the 14 strings tested, capacity/conductance correlations ($R^2$) ranged from 0.83 to 0.97. Figure 9 gives a box-score presentation that is designed to quantify the accuracy of conductance measurements in predicting cell performance. Using an 80% capacity criterion to be indicative of cell capacity failure, overall conductance correctly identified 21 of 24 good-plus-bad cells (88%) and correctly identified 18 of the 19 bad cells (95% accuracy). The capacity distribution for all 336 cells tested in this plant to an end-of-discharge voltage of 1.80 V/cell is presented in Fig. 10. Again, note the widespread capacity distribution; it ranges from zero to 100% throughout the entire plant. The capacity/conductance correlation plot for these 336 cells gave a correlation coefficient $R^2 = 0.855$ (Fig. 11). The box-score taken from the correlation plot indicates an 88% overall accuracy of conductance in predicting good-plus-bad cells, and 98% accuracy in detecting failed cells (Fig. 12).

Similar results were obtained in a second telephone transmission office that used similar 1000-Ah cells made by manufacturer A, but of a newer design. This office contained 10 parallel, 48-V strings. The typical capacity distribution in a single string is shown in Fig. 13 for string #8. Even for this newer design, the capacities ranged from zero to 100%. Figure 14 shows an excellent capacity/conductance correlation of $R^2 = 0.905$. The corresponding box-score analysis is given in Fig. 15 and indicates that

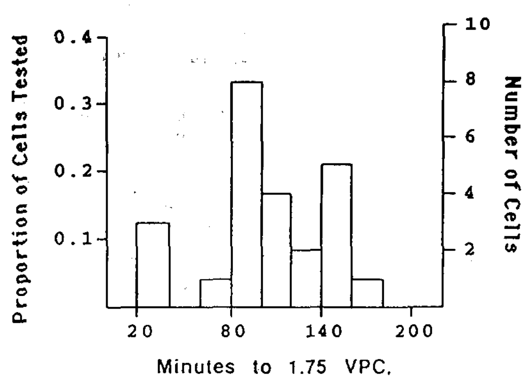


Fig. 7. Capacity distribution in string #9 of AGM valve-regulated stand-by cells, office No. 1; VPC = volts per cell.

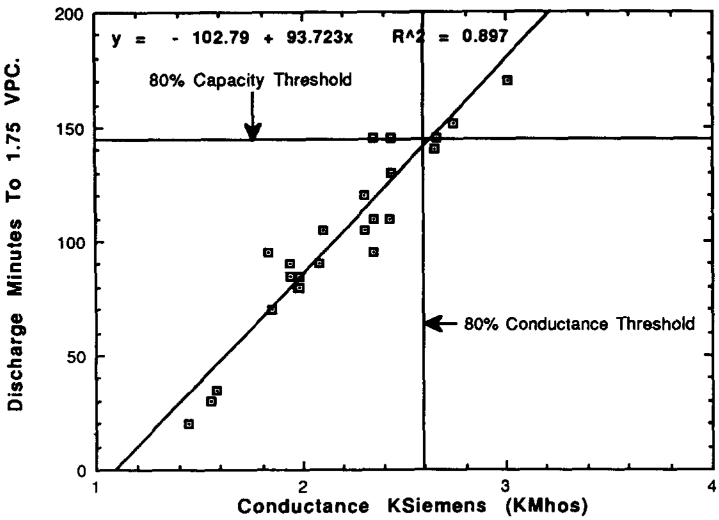


Fig. 8. Discharge capacity vs. conductance for cells in string #9, office No. 1. (Discharge: 263 A to 1.73 V/cell.)

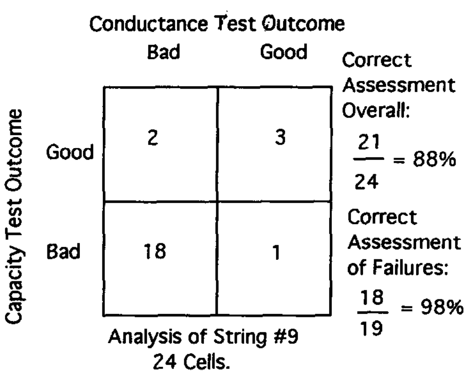


Fig. 9. Results for cells in string #9, office No. 1.

conductance accurately predicted of 20 out of 24 good-plus-bad cells (or 83%), with 19 of 19 failed cells correctly predicted (100% accuracy). The overall capacity behaviour for 8 of the 9 strings tested is presented in Fig. 16. Again, the capacity distribution varies widely (i.e., from 0 to 115%) after a service period of only 25% of the cell design life. Capacity/conductance correlation results for all 192 cells (Fig. 17) indicate a good correlation of $R^2 = 0.81$. The box-score gave an overall conductance predictive accuracy of 170 of 192 (or 89%) and, most significantly, an accuracy of 160 of 166 (or 96%) in the detection of cells with less than 80% capacity (Fig. 18). A ninth string was also tested in this office. The corresponding individual cell conductance values are presented as a bar chart in Fig. 19. Cell #16 showed zero conductance and this indicated an internal open circuit. The subsequent discharge failed instantly and thus confirmed the conductance reading. It should be noted that neither float voltage no open-circuit voltage measurements on cell #16 had indicated a catastrophic internal condition.

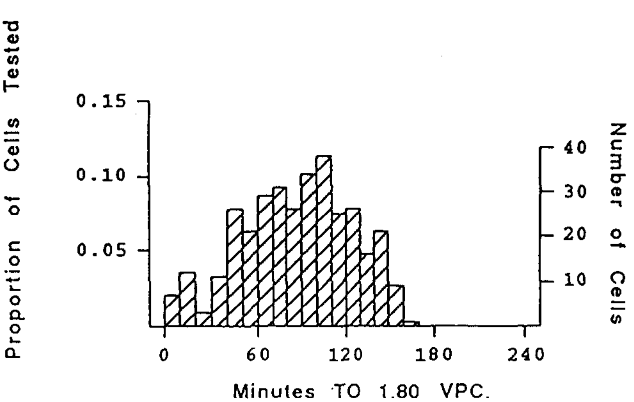


Fig. 10. Capacity distribution for strings #2 to 15 (336 cells), office No 1; VPC=volts per cell.

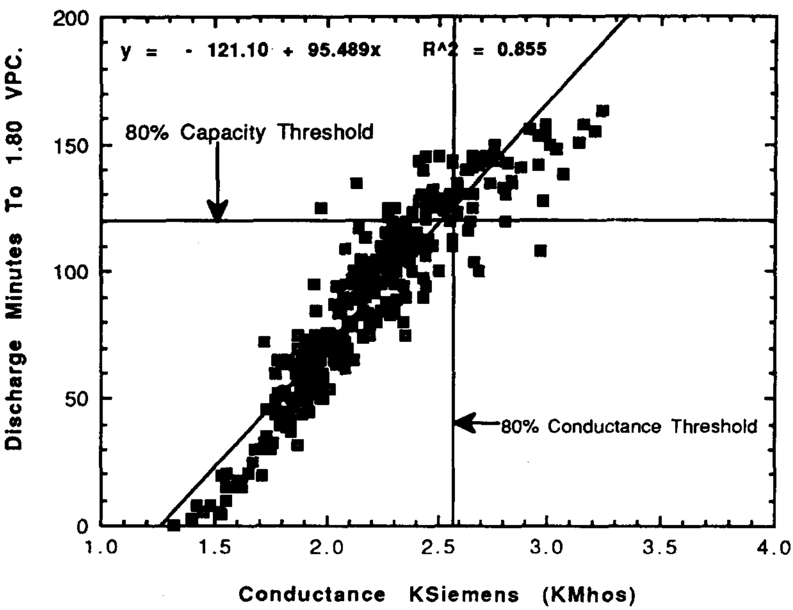


Fig. 11. Discharge capacity vs. conductance for 336 in strings #2 to 15, office No. 1. (Discharge: 263 A to 1.8 V/cell.)

Again, the same observations were made in a third telephone transmission office. This office contained seven parallel 48-V strings of 1000 Ah cells of the newer design from manufacturer A (identical in size and design and of similar age as those in the second office above). Capacity distribution results are shown in Fig. 20. As before, the 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 (Fig. 21) indicates a good correlation of $R^2=0.81$. The box-score gave an overall predictive accuracy for conductance of 92% for good-plus-bad cells, and 100% predictive accuracy for failed cells (Fig. 22).

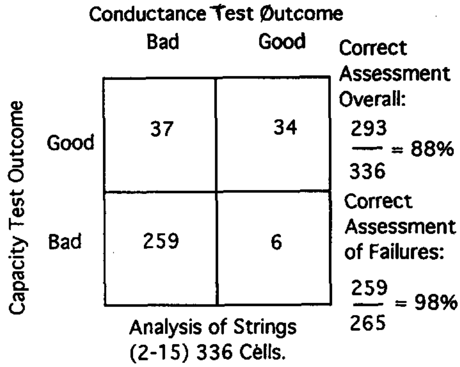


Fig. 12. Results for cells in strings #2 to 15, office No. 1.

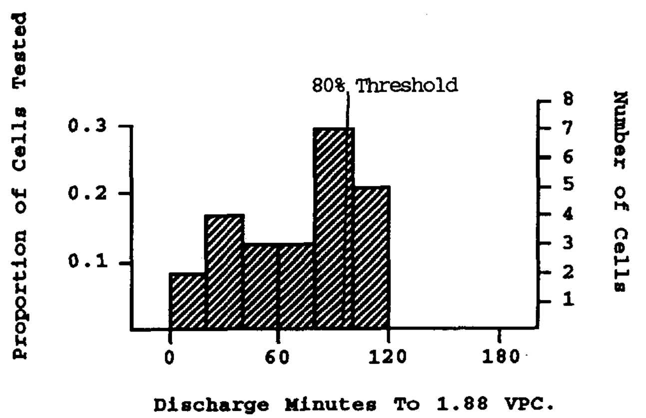


Fig. 13. Capacity distribution in string #8, office No. 2; VPC=volts per cell.

In summary, for this type of cell in telephone transmission stand-by service, data on approximately 700 cells indicate that 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 AGM cells in telecommunication stand-by service have been provided recently by a recent paper presented by Jones (British Telecom) [12]. Because of its relevance, data have been abstracted from this paper and have been reformatted to be compatible with the US telecommunications data presented above. In this case, the batteries (made by manufacturer B) consist of eight 3-cell AGM monoblocs that are series-connected as a 48-V battery. Each monobloc is rated at 100 Ah at the 1-h rate (50 A) and is designed to provide capacity to an end-of-discharge voltage of 1.917 V/cell (or 5.75 V/monobloc). Data were presented for 168 6-V monoblocs (504 cells) that varied in age from one to nine years. Both capacity and conductance data were presented. Results for the one-year-old monoblocs indicated 133% of rated capacity. Capacity distribution, capacity/conductance correlation plots and box-scores are derived in accordance with the time in service and then as an overall combined population. Figure 23 gives the capacity distribution for nine batteries, six years old, taken from four different telephone offices. Under UK float

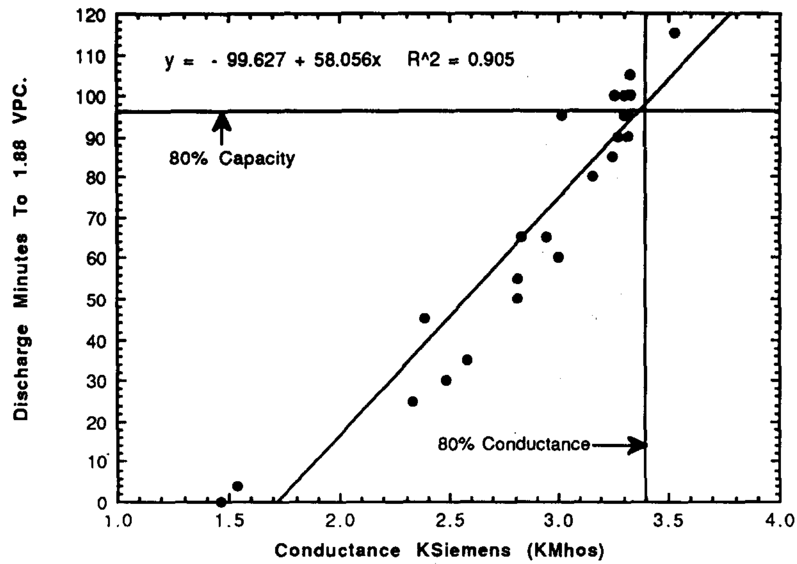


Fig. 14. Discharge capacity vs. conductance for 14 cells in string #8, office No. 2. (Discharge: 269 A to 1.88 V/cell.)

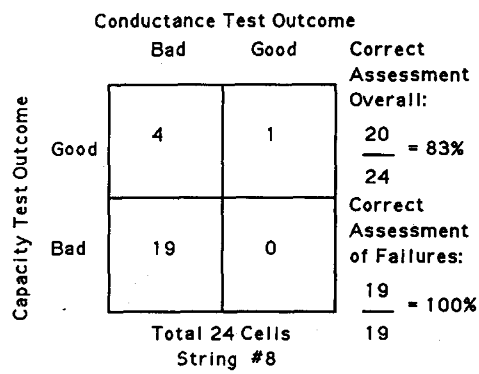


Fig. 15. Results for cells in string #8, office No. 2.

conditions, the capacities ranged from 5 min (8%) to 80 min (133%) of rating at approximately 60% of the rated design life. Further, 43 out of 72 (60%) monoblocs failed to meet the 80% capacity requirement. The nine strings have been combined into a single capacity/conductance correlation plot given in Fig. 24; the combined correlation coefficient is $R^2=0.88$. The combined group box-score yielded an overall conductance predictive accuracy of 88%, and an accuracy of 84% in detecting 6-year-old monoblocs that had failed the 80% capacity criterion (Fig. 25).

While 60% of the 6-year-old monoblocs failed the 80% capacity requirement, only 1 of the 24 5-year-old monoblocs, and none of the 1-year-old monoblocs failed. Six out of 24 (25%) of the 7-year-old monoblocs failed, while 12 out of 20 (60%) of the 9-year-old monoblocs failed. A typical capacity/conductance correlation plot for the 7-year-old monoblocs is shown in Fig. 26. The correlation coefficient is $R^2=0.93$. The

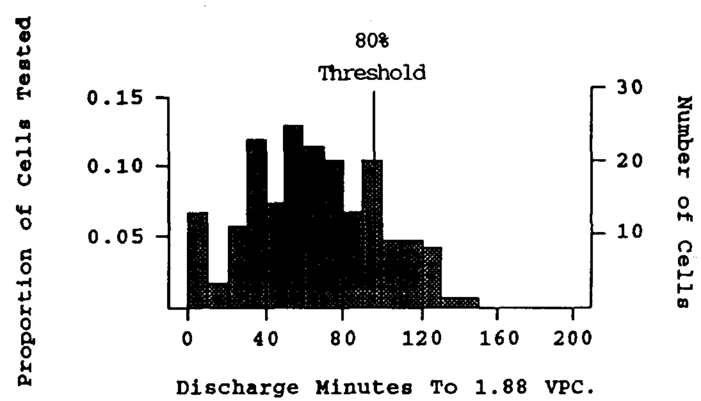


Fig. 16. Capacity distribution for 192 cells, office No. 2.; VPC=volts per cell.

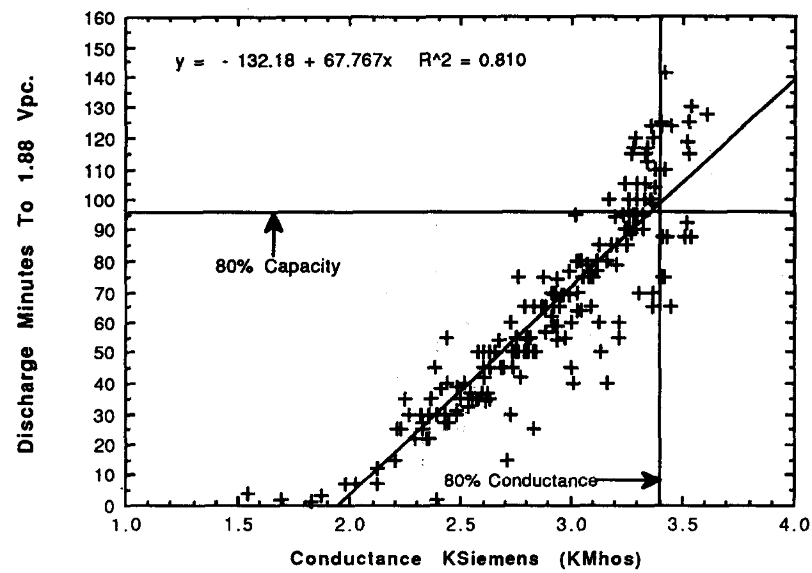


Fig. 17. Discharge capacity vs. conductance for 192 cells, office No. 2. (Discharge: 269 A to 1.88 V/cell.)

box-score (Fig. 27) gives 96% overall accuracy, and 100% accuracy in detecting failed monoblocs. From the capacity distribution for the entire 168 monoblocs group (Fig. 28), it can be seen that that there are 61 (36%) failures, primarily in the six-year and older age group. The capacity/conductance overall correlation plot for the entire population has a very good correlation coefficient of $R^2=0.89$ (Fig. 29). An overall box-score is shown in Fig. 30 and demonstrates a 90% overall predictive accuracy for conductance, and 83% accuracy in detecting failed cells.

Additional data on 6-V monoblocs were obtained from two UPS installations. The first contained 60 6-year-old, 6 200-Ah monoblocs made by manufacturer C and arranged in three parallel strings of 20 monobloc each. One of the strings was conductance tested and then capacity tested at the 1-h rate to 5.85 V/monoblocs. The

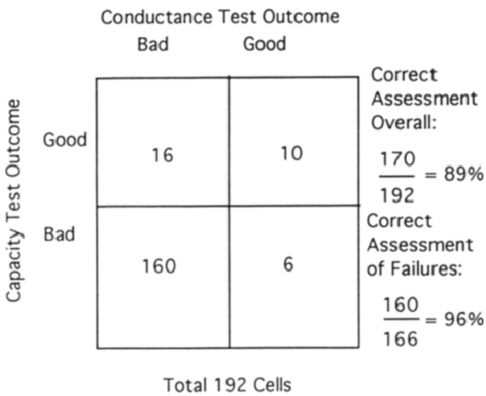


Fig. 18. Results for 192 cells, office No. 2.

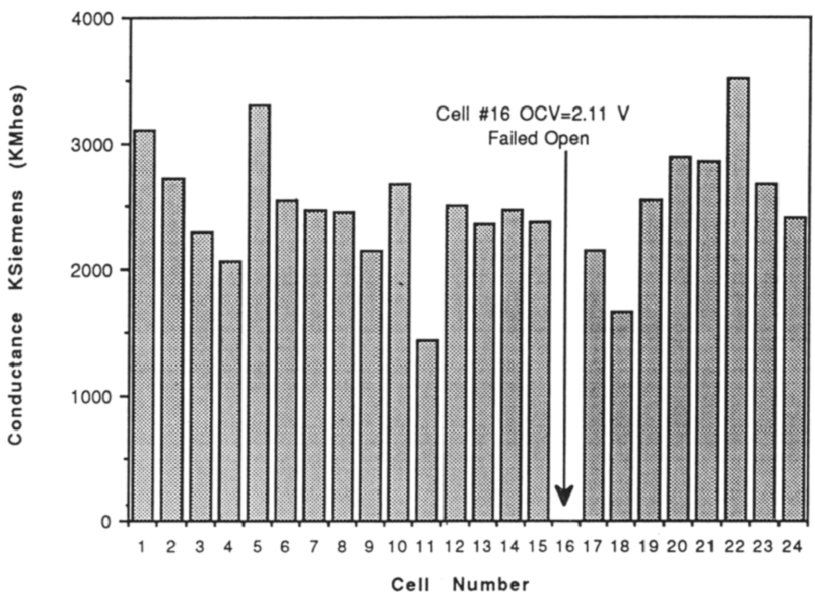


Fig. 19. Conductance bar plot for cells in string #9, office No. 2. (Discharge: 269 A.)

capacity distribution results are given in Fig. 31 and range from 2 min (3%) to 55 min (92%), with an overall failure rate of 18/20 (or 90%). The correlation of capacity with conductance is shown in Fig. 32 and indicates a correlation coefficient of $R^2 = 0.79$. Box-score analysis (Fig. 33) indicates 90% overall predictive accuracy for conductance and 94% accuracy in predicting failed monoblocs.

A second UPS installation consisted of 3-year-old, 6-V, 200-Ah monoblocs made by manufacturer D and arranged in three parallel strings of 63 monoblocs each. One of the strings was conductance tested and then capacity tested at the 1-h rate to 5.64 V/monobloc. The capacity-distribution results are shown in Fig. 34 and show values that ranged from 12 min (20%) to 65 min (108%), with a failure rate of 30%. Correlation of capacity with conductance is given in Fig. 35 and indicates a correlation

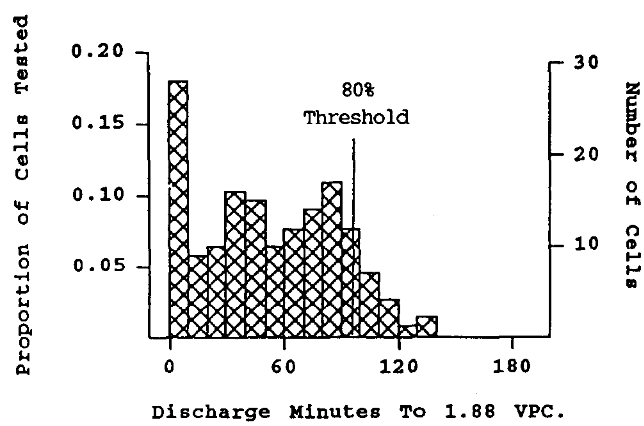


Fig. 20. Capacity distribution of 168 cells, office No. 3; VPC = volts per cell.

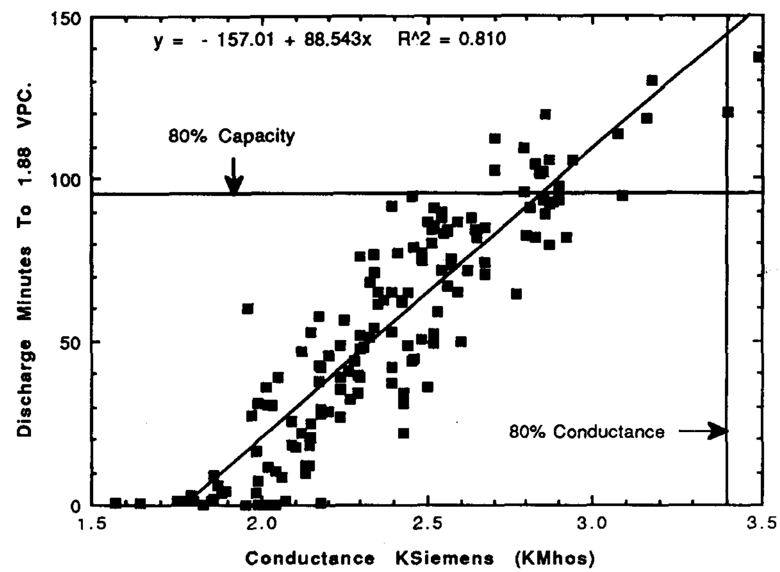


Fig. 21. Discharge capacity vs. conductance for 168 cells, office No. 3. (Discharge: 269 A to 1.88 V/cell.)

coefficient of $R^2 = 0.79$. The box score (Fig. 36) indicates 92% overall predictive accuracy for conductance, and 90% accuracy in the detection of failed monoblocs.

For 6-V monobloc designs made by three different manufacturers, capacity data indicate premature failure rates that range from 30 to 90% for monoblocs only 3- to 6-years old. In all cases, conductance correlated well with capacity and detected failed monoblocs with an accuracy of 82 to 94%. Since each monobloc consists of three cells, with each cell probably differing in both capacity and conductance, this consistence of conductance/capacity correlation and predictive accuracy of conductance is, at the least, remarkable.

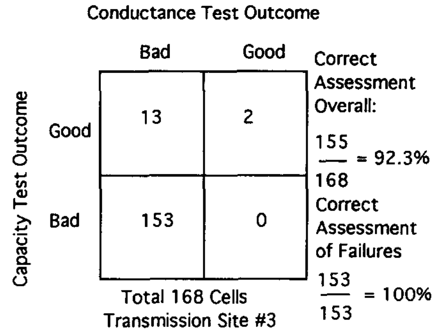


Fig. 22. Results for 168 cells, office No. 3.

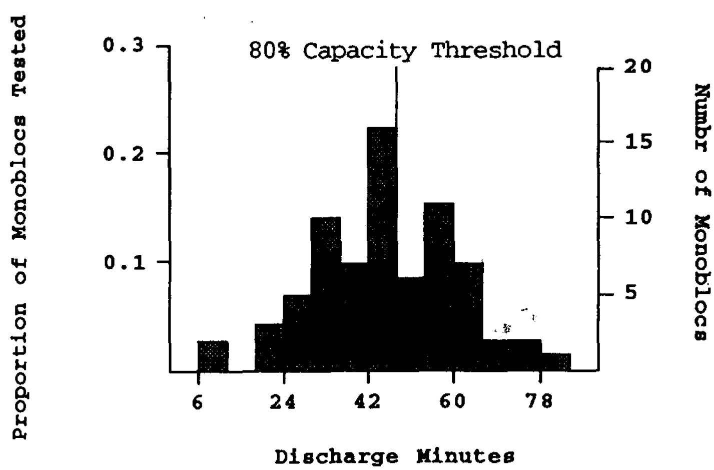


Fig. 23. Capacity distribution in 6-year-old AGM monoblocs (UK data).

*Results from postmortem analyses*

In the past year, capacity and conductance data have been supplemented in a limited basis by tear-downs and diagnostics by the manufacturer. Capacity and conductance results of 225-Ah railroad signaling cells have been reported previously [7]. Postmortem results on the same cells have been published in ref. 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 that would account accurately for the order of magnitude range in capacities, or for the four-to-one range in conductance that has been previously reported for these cells.

More recently, additional tests and tear-down studies have been performed on thirty, 1000-Ah cells from the telephone transmission office that has been discussed above as second office. 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 that was originally used at the telephone office. Of the 24 cells from one string, 20 which had originally tested from 56 to 92% capacity, recovered from 83 to 137% after the conditioning cycles. The remaining four cells still failed after conditioning,

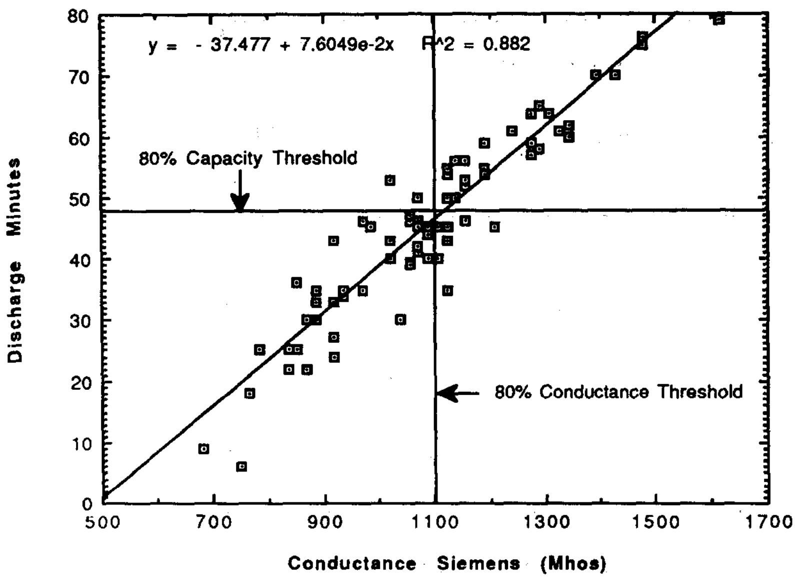


Fig. 24. Discharge capacity vs. conductance for 6-year-old AGM monoblocs (UK data).

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

Fig. 25. Results for 6-year-old AGM monoblocs (UK data).

as did six additional cells from other strings, that had originally tested from 0 to 19%. Figure 37 compares capacity/conductance results, after conditioning by the manufacturer, with capacity/conductance results obtained at the telephone office. Although many capacities improved (on average 25 to 30%) after cycling and boost charging the conductance still correlated well with the improved capacities ($R^2 = 0.86$) compared with the original correlation of $R^2 = 0.94$ as tested at the telephone office. Failure modes were determined for eight cells. These included: (i) partial or complete negative-strap corrosion failure; (ii) positive-grid corrosion, growth and grid-frame fracture; (iii) dry-out and (iv) very low stack compression. All but one of the cells that showed very low capacity had evidence of internal iron contamination. The one high-capacity cell revealed no significant defects upon tear down.

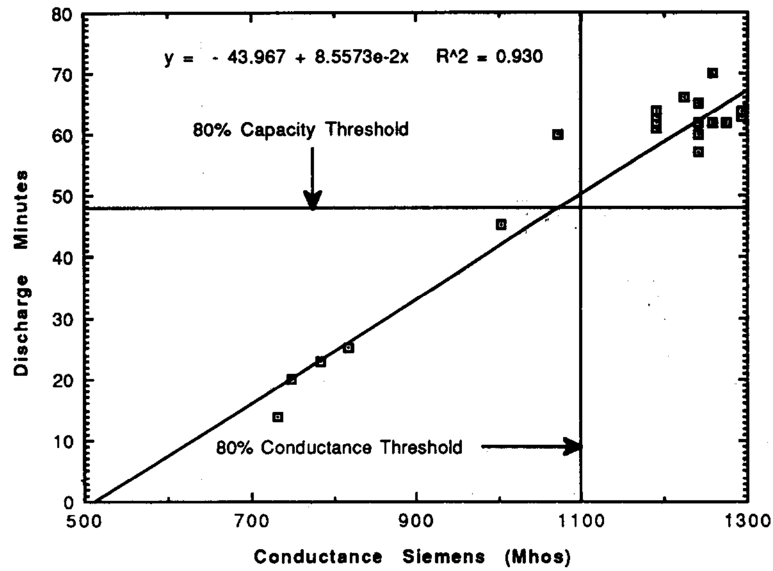


Fig. 26. Discharge capacity vs. conductance for 7-year-old AGM monoblocs (UK data).

Conductance Test Outcome

| Capacity Test Outcome | Bad | Good |
|---|---|---|
| Good | 1 | 17 |
| Bad | 6 | 0 |

Total 24, Seven-Year-Old Monoblocs

Correct Assessment Overall: $\frac{23}{24} = 96\%$

Correct Assessment Of Failures: $\frac{6}{6} = 100\%$

Fig. 27. Results for 7-year-old AGM monoblocs (UK data).

*Results on flooded stationary batteries*

As reported in recent publications [11, 12], 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. The conductance test was more sensitive to actual cell performance than traditional measurements of cell specific gravity of float voltage. Results [13] showed % accuracy of either float voltage or specific gravities in finding low-capacity cells (<80%). By contrast, the conductance-test accuracy was greater than 84% in detecting the low-capacity cells (<80%). These results, together with others [6–8] again confirm the inability of either float voltage or specific gravity to identify capacity

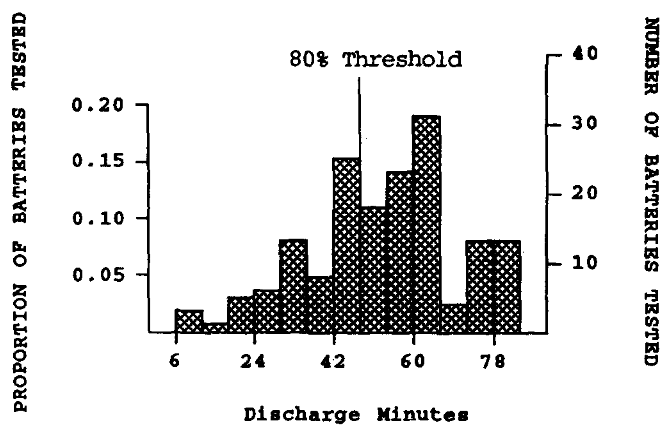


Fig. 28. Capacity distribution for 168 6-V AGM monoblocs (UK data).

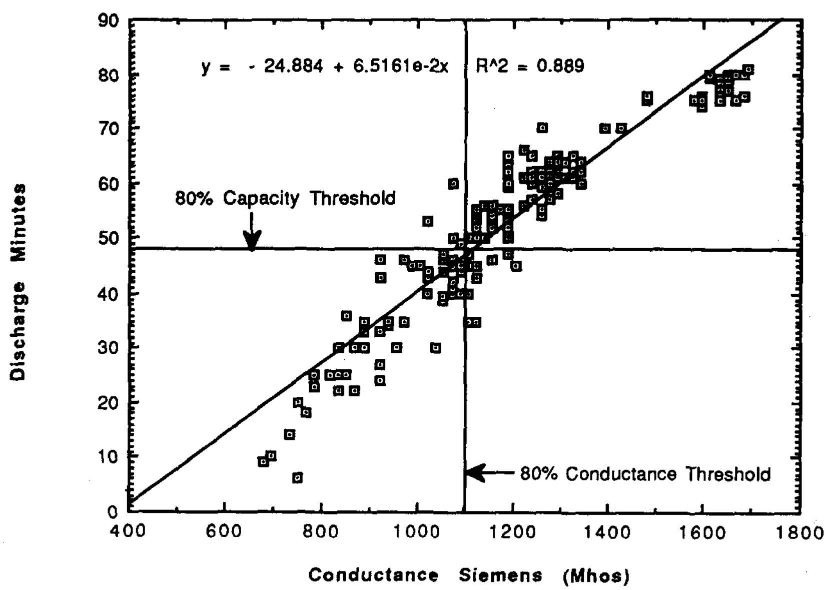


Fig. 29. Discharge capacity vs. conductance for 168 AGM monoblocs (UK data).

degradation, in contrast to conductance measurements that show greater accuracy in finding cells that have degraded just below the normally recommended failure criterion of 80% capacity.

*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 the 'noise' current is minimal, and have successfully been performed. In the majority of practical applications, however, a.c. noise will interfere with conductance measurements. Development of a new auxiliary

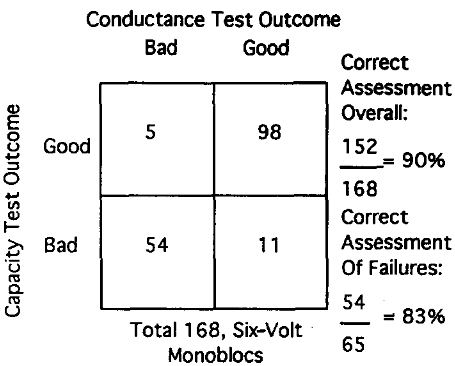


Fig. 30. Results for 168 AGM monoblocs (UK data).

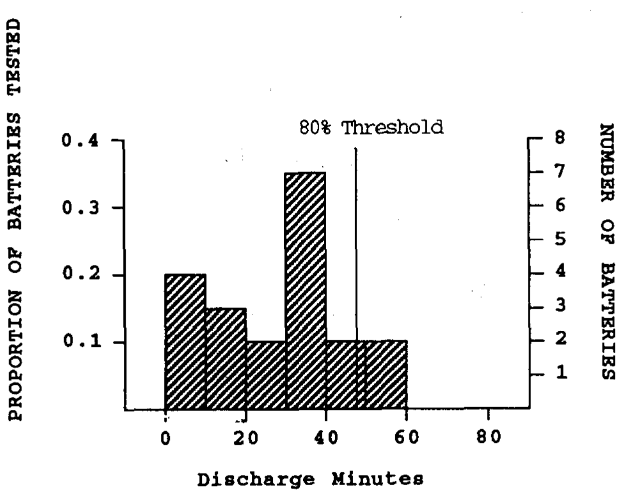


Fig. 31. Capacity distribution of 6-V AGM monoblocs (UPS installation, manufacturer C).

circuit 'noise eliminator' device has allowed direct on-line measurements to be made. Data from one test of both on-line and off-line testing, as well as discharge-test results, are given in Fig. 38. This test involved twelve 800-Ah cells used to provide stand-by reserve power for a cellular telephone site. The a.c. noise currents were 2 A peak to peak. The trend plot of Fig. 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, i.e. <5%. More importantly, the capacity/conductance correlation is shown to be unaffected when measurements are performed on-line with the noise eliminator.

Results of second test of twenty-four 210-Ah batteries, arranged in a 48-V office are given in Fig. 39. Again, off-line conductance is compared with on-line conductance measurements obtained with the noise eliminator. In this case, the circuit noise was measured as 2.5 A peak to peak. Again, discharge-test 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

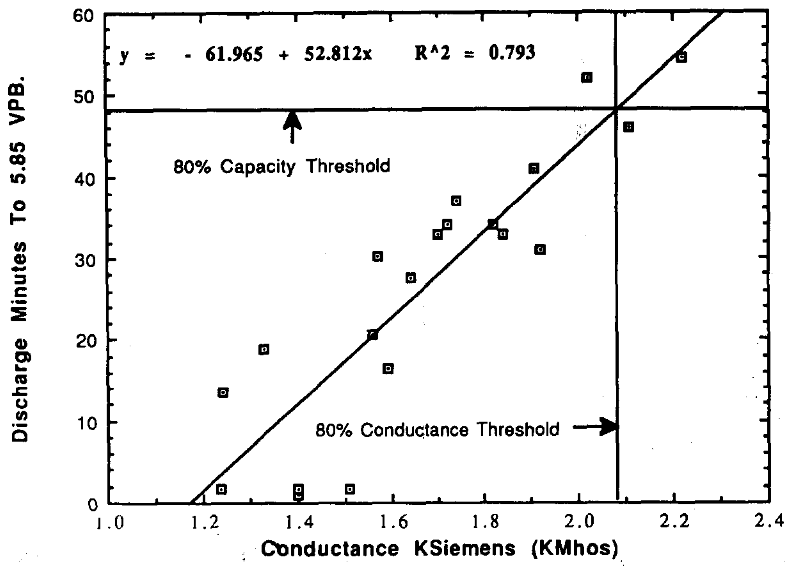


Fig. 32. Discharge capacity vs. conductance for 20, 6-V AGM monoblocs (UPS installation, manufacturer C); VPB = volts per battery.

| Capacity Test Outcome | Conductance Test Outcome: Bad | Conductance Test Outcome: Good |
| --- | --- | --- |
| Good | 1 | 1 |
| Bad | 17 | 1 |

Total 20, 200-AH Monoblocs

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

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

Fig. 33. Results for 20, 6-V AGM monoblocs (UPS installation, manufacturer C).

significantly increase the use of conductance testing. This, in turn, will result in a substantial increase in the amount of both conductance and capacity data and will further enhance the capacity/conductance correlation database.

## Conclusions

### *Automotive batteries*

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

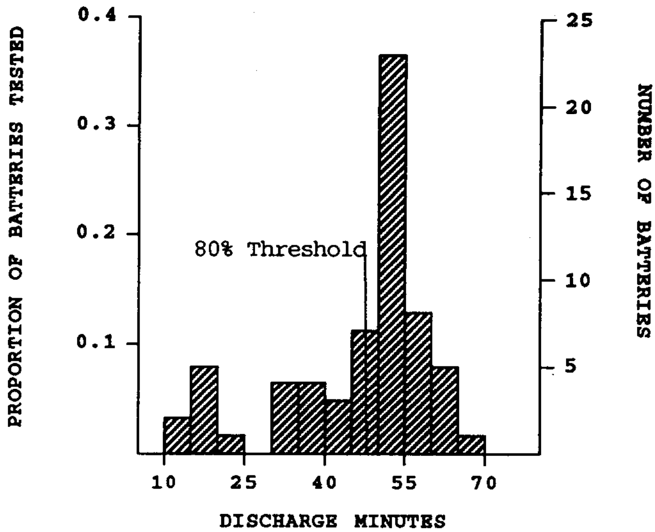


Fig. 34. Capacity distribution of 3-year-old, 6-V AGM monoblocs (UPS installation, manufacturer D).

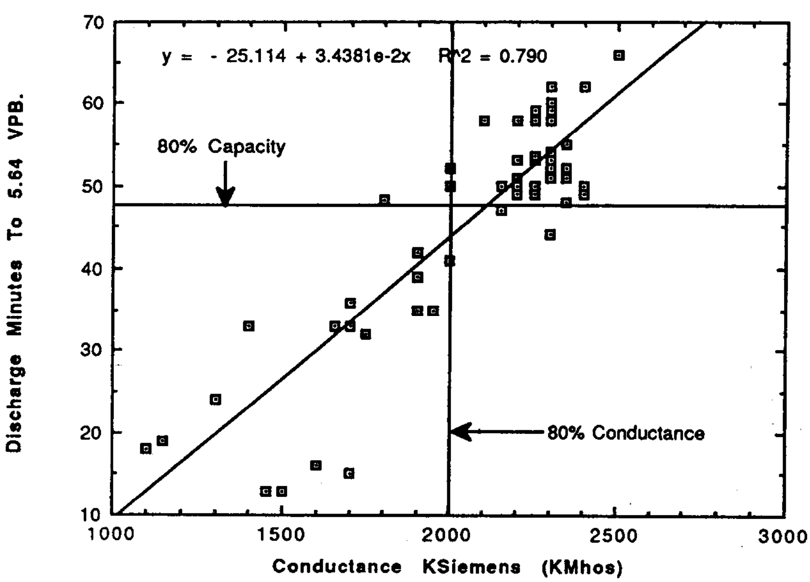


Fig. 35. Discharge capacity vs. conductance for 3-year-old 6-V monoblocs (UPS installation, manufacturer D), VPB = volts per battery.

2. The use of conductance testing is a highly accurate method of determining the condition of batteries in various states-of-charge, and at various temperatures.

3. Conductance testing overcomes the disadvantages of the standard 1/2 CCA load test, in that it is instantaneous, does not discharge the tested battery, and evaluated batteries at very low states-of-charge.

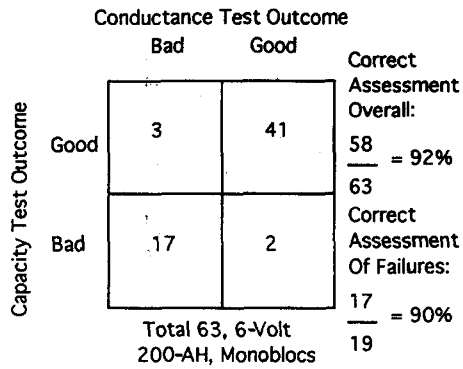


Fig. 36. Results for 63, 3-year-old, 6-V AGM monoblocs (UPS installation, manufacturer D).

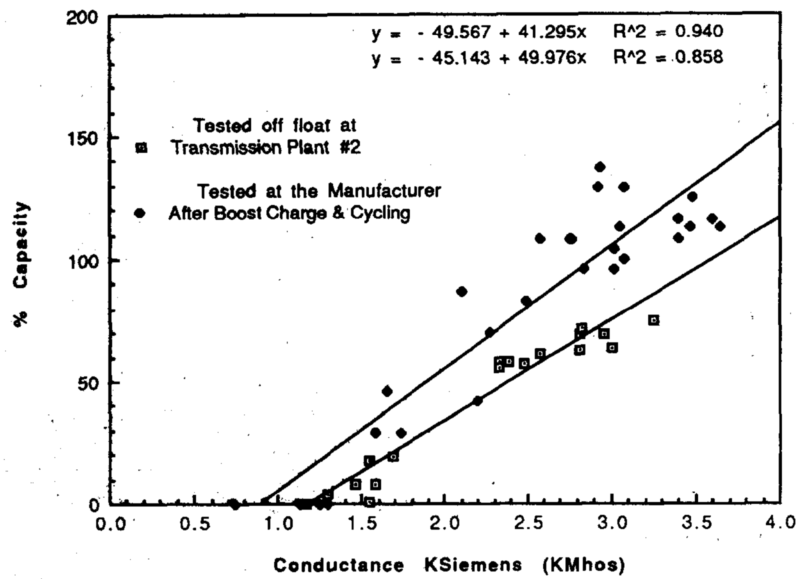


Fig. 37. Discharge capacity vs. conductance (office No. 2).

*Stand-by batteries*

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

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

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

4. The conductance test method has determined effectively the condition of batteries made by various manufacturers, including valve-regulated and flooded-electrolyte lead/acid technologies, as well as nickel/cadmium types.

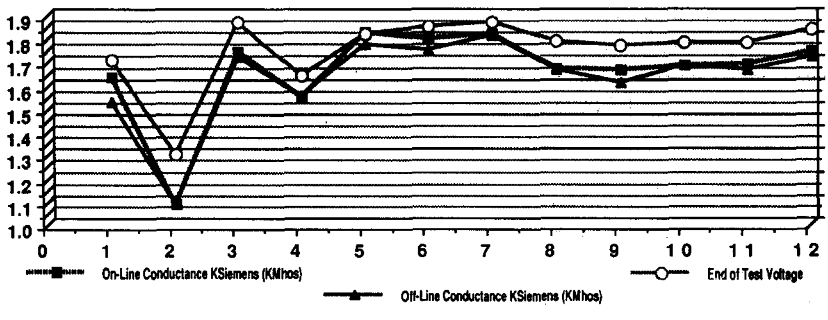


Fig. 38. Charge capacity vs. on-line/off-line conductance measurements.

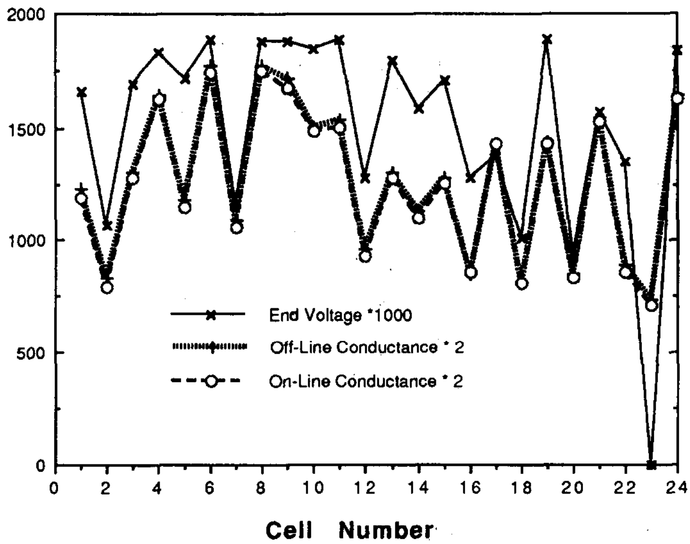


Fig. 39. End-of-discharge voltage vs. on-line/off-line conductance.

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

## Acknowledgements

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