Conductance Testing of Standby Batteries in Signaling and Communications Applications for the Purpose of Evaluating Battery State-of-Health - April 1993

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CONDUCTANCE TESTING OF STANDBY BATTERIES IN SIGNALING AND COMMUNICATIONS APPLICATIONS FOR THE PURPOSE OF EVALUATING BATTERY STATE OF HEALTH

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Abstract:

This paper introduces the use of conductance measurements as a practical technique to monitor the state of health of lead acid batteries in standby service for signaling and communications applications.

Laboratory and field test results will be presented which show the direct linearity which has been observed in the relationship between conductance testing and timed discharge capacity testing. Hundreds of batteries and cells have been evaluated, in the railroad, telecommunications, and other industries, with similar results.

Application Background:

Each Railroad may have several hundred battery systems located in signal sites, hump towers, telecommunications systems and locomotive applications. The batteries are used for gate crossings, signal communications, retarder control, CTC house control, intermediate signal relays, light signals, track circuits, uninterruptable power supply (UPS) for computer track control systems and diesel starting for locomotives. The type of batteries used in these applications vary from newer Valve Regulated Lead Acid (VRLA), Flooded Lead Acid to Nickel Cadmium (NiCad) designs. The batteries can represent several million dollars of cost and may help to protect billions of dollars in assets, not to mention public safety for commuter transit lines and avoidence of car/train accidents. In all cases the batteries are required to provide a reliable source of DC power to support these critical systems in the event of an AC power outage.

Traditionally battery maintenance practices for the Railroad industry have been designed by engineering personnel responsible for a specific area. The engineer will typically refer to the Institute of Electrical and Electronics Engineers (IEEE) standards and battery manufacturer guidelines for development of maintenance procedures. In the past, visual inspections and traditional measurements of float voltage and or specific gravities have been the primary techniques used to ascertain battery state-of-health. Because of the sheer number of battery strings each maintainer has to test, discharge testing is rarely, if ever, used to test batteries in the field.

Discussions with several signal maintainers and supervisors have revealed that because of their increased work loads and manpower cuts all they can do is to take quarterly/semi-annual float voltages or specific gravity readings. More often than not batteries are replaced based on age and appearance or when it appears that a major fault has developed in a particular battery system.

The conductance measurement is based upon the adaptation of the technology first reported by Dr. Keith S. Champlin[1]. In recent years several studies have been performed utilizing conductance technology to ascertain the relative condition of batteries, and successful attempts have been made to correlate the conductance results to timed discharge tests [2,3,4]. Other measurements of cell impedance have also been actively pursued as possible methods for evaluating cell/battery condition [5,6,7,8]. The application of conductance measurements in a maintenance practice has been shown to be superior to traditional measurements of specific gravity and or float voltage and can provide the maintainer critical information about a battery's condition and have recently been written into the IEEE draft standard (PAR 1188) on maintenance of VRLA batteries.

Conductance Technology:

Conductance is the ability to conduct current 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.

Two types of Midtronics industrial conductance testers were utilized in performing the field tests. The first type is the "Celltron" tester which is a self contained, fully portable tester designed to measure the conductance of a single cell or three cell battery over a wide range of sizes from 10 to 8000 ampere-hours. The second type of tester is the "Midtron" tester which is a self contained, fully portable tester designed to measure the conductance of three and six cell batteries over a wide range of sizes from 2 to 600 ampere-hours.

Discussion of VRLA Future in Railroad Applications

Over the last ten years, Valve-Regulated Lead Acid (VRLA) batteries have been rapidly replacing the older conventional Flooded Lead Acid and Nickle Cadmium (NiCad) designs in a majority of Railroad applications. Their attractive "Maintenance Free" feature parallels the business changes which include reduction in manpower and budget reductions that are forthcoming, not only in the Railroad industry, but in many other industries. However "Maintenance Free" should not mean "no maintenance". Since the typical VRLA design does not allow for specific gravity measurements or visual inspection of internal plate structures, the maintainer is left with fewer tools to ascertain battery condition. Therefore the conductance measurement provides the maintainer a useful tool for maintaining the newer VRLA technology in addition to quantifying the condition of older Flooded and NiCad battery plants.

The number and type of potentially serious failure modes of VRLA cells significantly exceed those of conventional flooded cells whose primary failure mode results from grid corrosion/growth and loss of contact to the active material. In VRLA cells post seal, jar-cover leakage, and valve malfunction, all cause dry-out, in addition to loss of grid/paste contact; loss of plate/separator/electrolyte compressive contact can cause capacity loss; internal corrosion and loss of contact between post/strap/

Site #1
Battery A, MFR June 1989
VRLA 225 AH Cells

Cell #	Float Voltage	Conductance KMhos (KSiemens)
1	2.24	0.725
2	2.24	0.968
3	2.25	0.844
4	2.25	0.865
5	2.24	0.969
6	2.25	0.963
7	2.24	0.741
8	2.25	0.9647

Site #1
Battery B, MFR June 1989
VRLA 225 AH Cells

Cell #	Float Voltage	Conductance KMhos (KSiemens)
1	2.27	0.449 (RFT)
2	2.26	0.479
3	2.24	0.925 (RFT)
4	2.25	0.860
5	2.25	0.931
6	2.25	0.955

NOTE: The Reference Conductance of a 100% capacity cell of this cell type is 1.0 KMhos (KSiemens). Also, cells Removed for Test are Noted by (RFT)

Figure 1

Site #2
Battery A, MFR April 1990
VRLA 225 AH Cells

Cell #	Float Voltage	Conductance KMhos (KSiemens)
1	2.27	1.226
2	2.27	1.136
3	2.27	1.190
4	2.26	0.909
5	2.28	1.087
6	2.27	1.071

Site #2
Battery B, MFR May 1987
VRLA 225 AH Cells

Cell #	Float Voltage	Conductance KMhos (KSiemens)
1	2.26	1.012 (RFT)
2	2.25	0.668
3	2.25	0.781
4	2.25	0.789
5	2.25	0.409 (RFT)
6	2.25	0.533

NOTE: The Reference Conductance of a 100% capacity cell of this cell type is 1.0 KMhos (KSiemens). Also, cells Removed for Test are noted by (RFT).

Figure 2

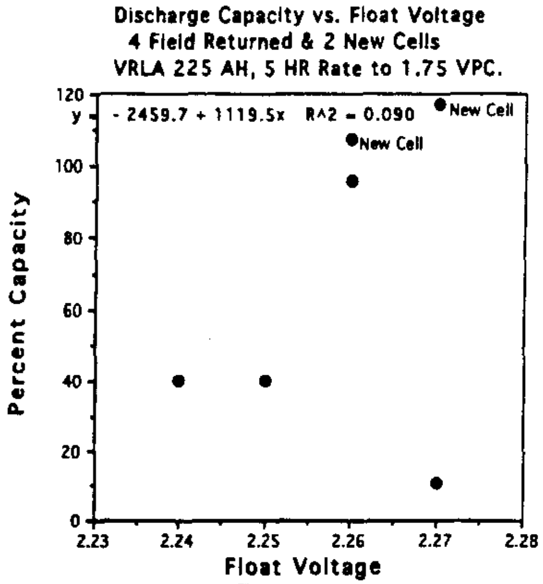


Figure 3

plate lugs all result in a decrease in capacity. Since all these factors also result in a decrease in conductance, it is clear that a conductance measurement should provide the maintainer an indication of potential cell/battery failure.

Experimental Tests Performed on VRLA Cells in Railroad Signal Sites.

In January of 1992 a field investigation was conducted with the cooperation of a major railroad. A total of eight signal sites were tested. Two sites will be discussed in detail. For the cells tested in the two sites, four cells showing low, medium and high conductance were tagged, removed from service and sent to the Midtronics laboratory for discharge capacity tests and correlation analysis.

Various other studies also show that in other locations, VRLA cells also show a wide range of conductance distribution.

Figures 1 and 2 show the site location and the conductance of each cell as found. **Figures 1 and 2** also show two cells each which were tagged Return For Test (RFT) and sent to Midtronics for discharge capacity testing and correlation analysis. The railroad also sent two new cells of the same design and manufacture so that a reference conductance could be established.

Figure 3 shows the correlation of measured float voltage and discharge capacity for the four field returned cells and two new cells. As you can see, no useful prediction of cell state-of-health can be made using the measured float voltages.

By marked contrast, **Figure 4** shows the correlation of discharge capacity and conductance for the six cells with an R^2 correlation coefficient of 0.976. **Figure 5** shows the conductance measurements obtained before the discharge test and the resultant discharge curves for the four field returned cells. Again, the individual cell discharge curves show a correlation of conductance with the decrease in time to the cut off voltage of 1.75 volts per cell.

The cells were then returned to the manufacturer for further analysis. Two subsequent charge/discharge cycles were performed at the manufacturer's facilities with no appreciable improvement in cell conductance or discharge capacity.

Finally, tear down analyses were performed on each cell. The tear down of these cells showed conductance detecting poor cell performance whether due to poor lug-to-strap burns, positive grid corrosion, poor positive active material adhesion and some degree of "dry out". Despite the fact that these failure modes were different in every case, conductance testing was able to detect the four cells. It is worth noting that these cells were in service only 25% of their "expected life". Although this represents only a small population of cells, the results clearly show a strong positive linear correlation of discharge capacity and conductance.

Conductance Tests performed on VRLA Cells in Telephone Transmission Office.

Not unlike the test results shown above **Figure 6** shows the correlation of conductance and discharge tests performed on an individual 24 cell string in a telephone transmission office which shows an R^2 correlation coefficient of 0.897. **Figure 7** shows a "Box Score" analysis for these same cells for which the conductance assessment was correct 88 percent of the time. If we look at the number of bad capacity cells the conductance was correct on 18 of 19 cells or 95 percent correct. **Figure 8** shows the correlation of discharge capacity and conductance for a large population of VRLA cells in the same transmission office with an R^2 correlation coefficient of 0.855. It is worth noting that the data presented in this paper only shows a fraction of conductance/discharge capacity data which has been collected to-date.

These results demonstrate the effectiveness of conductance in characterizing the capacity distribution among VRLA cells in a given power plant and in detecting premature capacity failure.

Experimental Flooded Battery Data:

Various field tests have been conducted in electric power industry on flooded lead acid batteries. Measurements of specific gravity, float voltage, conductance and discharge testing were performed. The results clearly reveal the conductance test as being more sensitive to actual cell performance than traditional

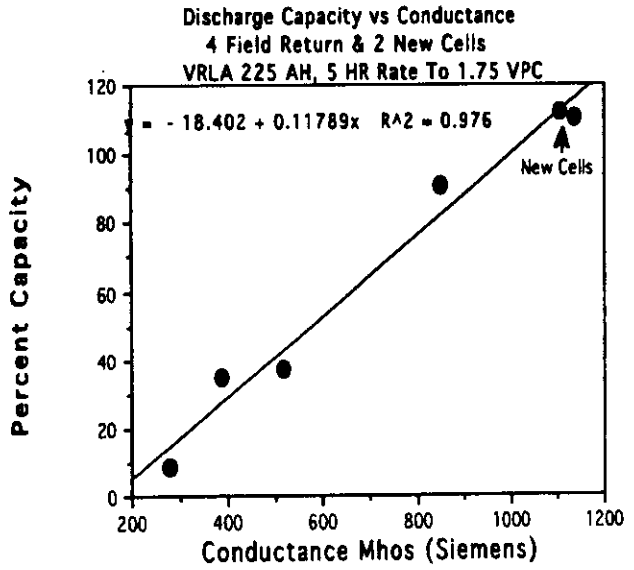


Figure 4

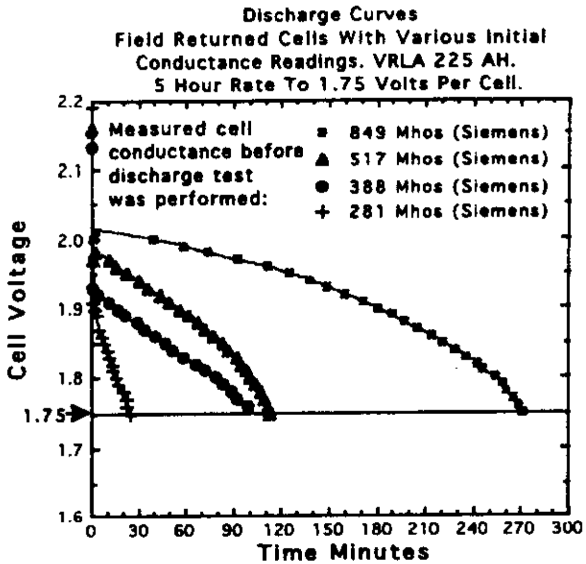


Figure 5

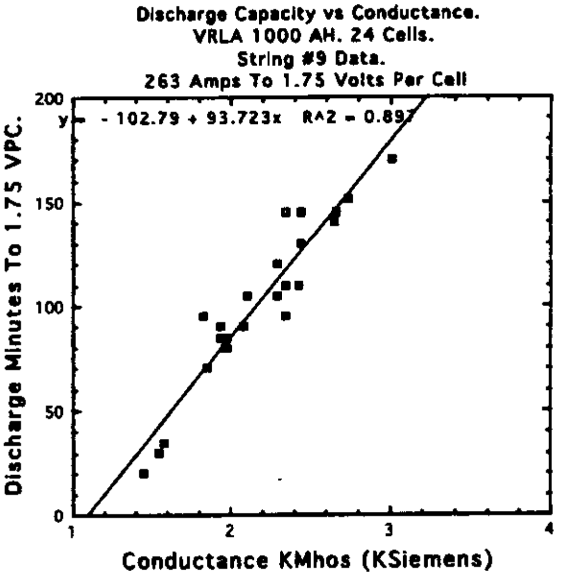


Figure 6

Conductance Test Outcome

		Good	Bad
Capacity Test Outcome	Good	3	2
	Bad	1	18

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

Analysis of String #9
24 Cells.

Figure 7

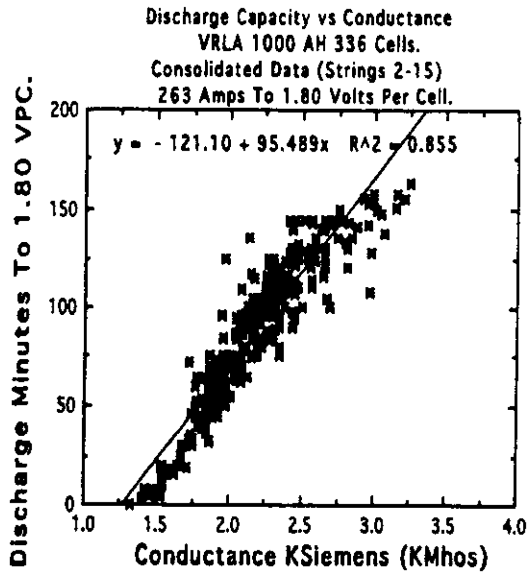


Figure 8

measurements of cell specific gravity or float voltage. The conductance measurement has been found to be a indicator of cell/battery performance, and it finds cells that vary significantly from the rest of the population in capacity.

Described below are the results of a study performed at a substation location, and only show fraction of the data we have to date.

A series of tests were performed at an electric utility substation. The battery was less than one year old, 200 Ampere hour, lead calcium design. Discharge testing was performed on the 58 cell battery at a 30 minute rate to 1.75 volts per cell. This data set reveals the results of several measurement parameters such as: specific gravity, float voltage, conductance, and timed discharge capacity and explores the relationships and sensitivities of each measurement.

In order to describe the sensitivities of specific gravity, float voltage and conductance as they relate to actual timed discharge capacity, a trend analysis plot for each technique is presented.

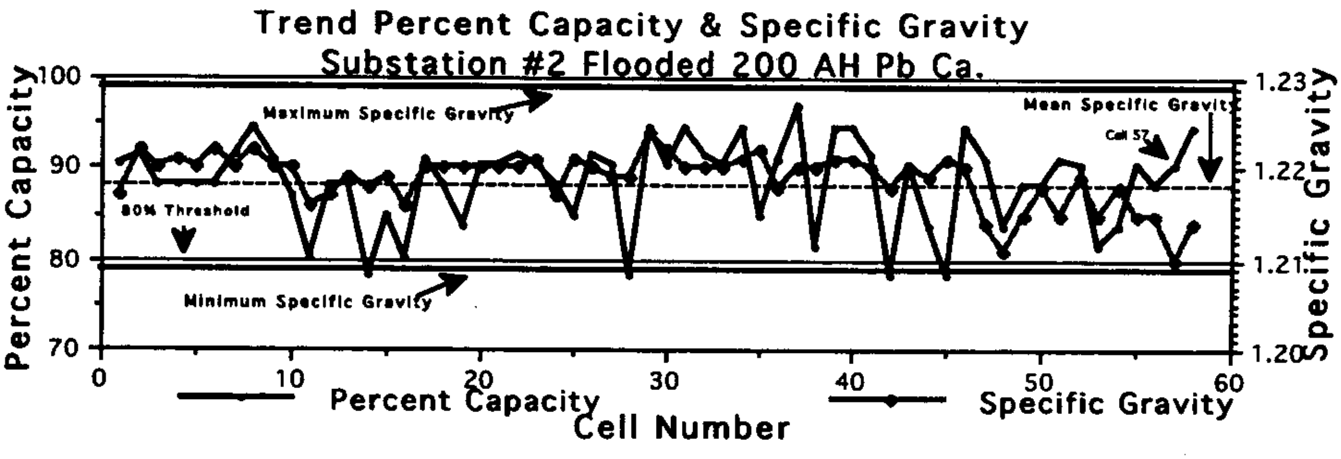


Figure 9

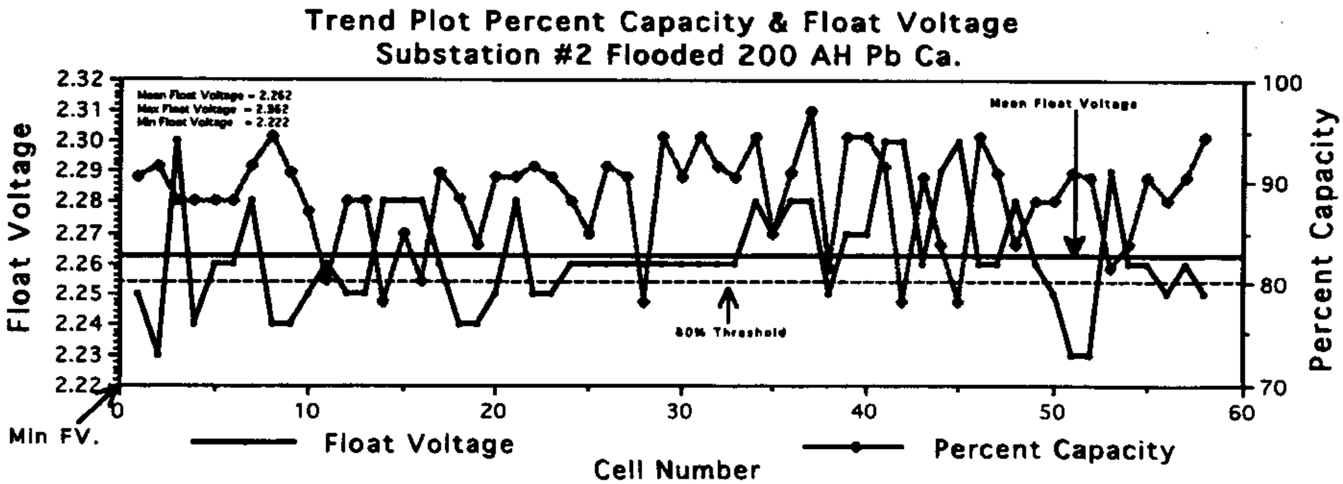


Figure 10

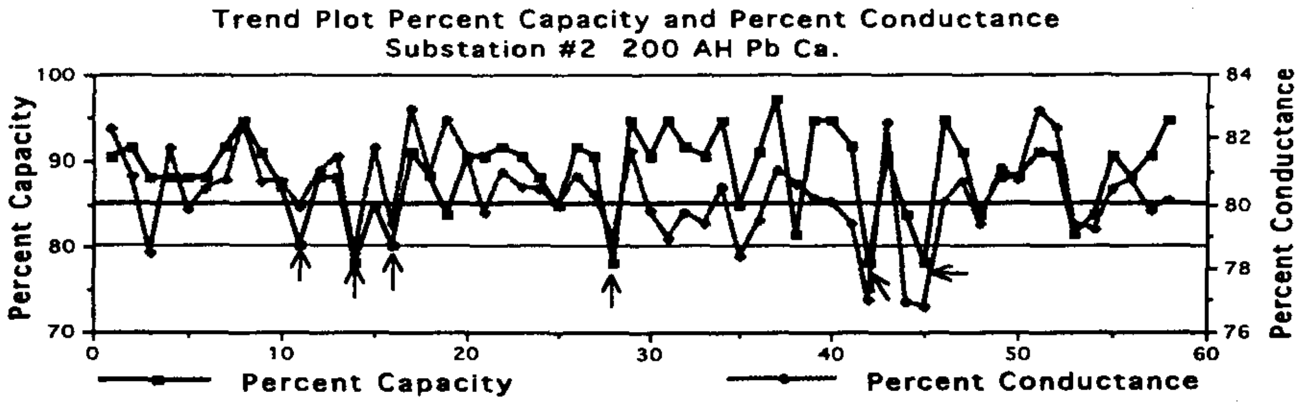


Figure 11

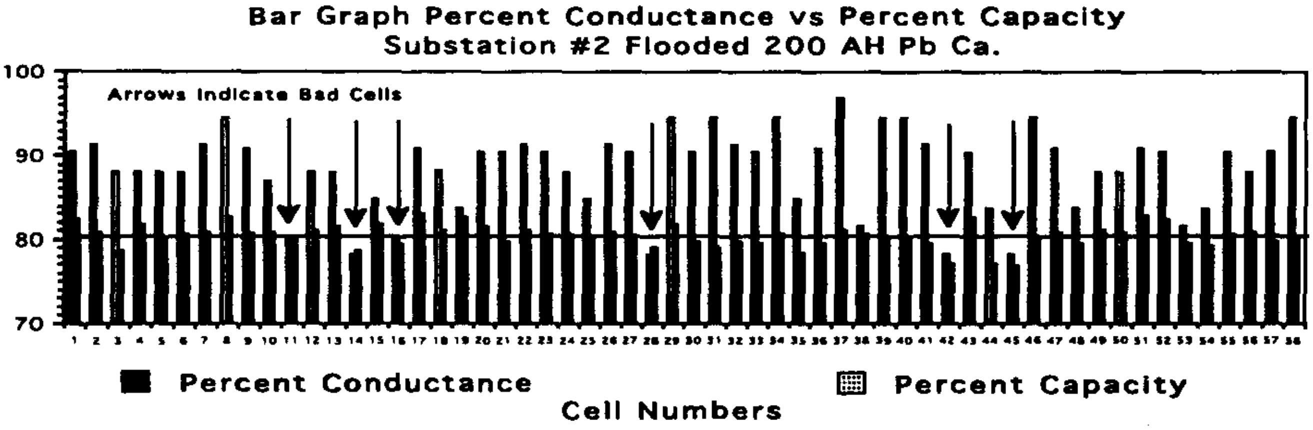


Figure 12

		Conductance Test Outcome	
		Good	Bad
Capacity Test Outcome	Good	40	12
	Bad	0	6

Correct Assessment: $\frac{46}{58} = 80\%$

Total 58 Cells
Substation #2

Figure 13

Figure 9 shows six cells at or slightly below the 80 percent capacity limit; for those 6 cells, specific gravity gives no indication of capacity loss. It is curious that the only specific gravity value at the low limit (cell #57) corresponds to a 91 percent capacity.

Figure 10 shows the same 6 cells as slightly below 80 percent capacity but their float voltages are either at the mean or well within + 40mV of the mean and therefore give no indication of low capacity cells. **Figure 11** shows the trend analysis of conductance and percent capacity. Both capacity and conductance are in agreement for the six failed cells as indicated by the arrows. While 12 cells appear to have failed conductance but did not also fail the capacity criteria, it should be noted that 8 of the 12 cells only failed conductance by 1 percent. **Figure 12** shows the same data set in a bar graph plot. The results are summarized in **figure 13** and show a conductance test accuracy of 80 percent. The conductance results represent a significant improvement in battery diagnostic sensitivity when compared to traditional measurements and would provide early warning to the user of failing cell/battery state of health.

Despite the capacity range shown above, all the float voltages and specific gravities were well within the manufacturer's allowable maximum and minimum range.

As a result of the tests described above we can assess data obtained from field tests performed with the same railroad in June of 1992. Examination of the data shows the conductance deterioration as a function of cell age during real life usage.

Figure 14 shows conductance measurements made on (crossing batteries) flooded cells of 200AH design, where the majority of cells are approximately 10 to 15 years old. You will quickly see the cell which was recently replaced. The measured conductance of the new cell has much greater conductance than the aged cells. This is a strong indication of capacity loss in the aged cells. Although we do not have specific discharge results for these cells, our experience has shown that the aged cells could be ranked and would perform in ascending discharge capacities.

Next, **Figure 15** shows similar results for another data set, this time for 80 AH flooded lead acid (track circuit) cells. Again, Site C has cells that are less than 5 years old while Site A and Site B show cells which are older (10 to 15 years old). Notice again that the conductance of several of the older cells in is only a fraction of their corresponding newer cell conductance. As an exercise, **Figure 15** shows a simplistic indication of predicted performance for each cell. Again our experience has shown that these cells would perform in ascending discharge capacities.

Experimental Nickel Cadmium Cells (NiCad) Data:

Preliminary railroad studies have also been conducted on NiCad cells. Below, we will discuss results of both field conductance measurements and laboratory discharge testing which show that conductance testing does find poor discharge performance in NiCad cells.

In June of 1992 field conductance measurements were performed on NiCad 200 Ampere hour batteries. **Figure 16** shows conductance measurements for cells as found in the field. These cells were tagged and taken to Midtronics for discharge capacity tests. Prior to performance testing the cells were charged at a constant current rate of 48 amps for eight hours, rested for 10 hours and then discharged at the manufacturer's suggested

Site A
Battery A, 200 AH
Flooded Lead Acid
Crossing Battery

Cell #	Float Voltage	Conductance KMhos (KSiemens)
1	2.21	0.808
2	2.22	1.253 *New Cell
3	2.20	0.150
4	2.20	0.375
5	2.19	0.752
6	2.20	0.830
7	2.20	0.620

Figure 14

Site A
80 AH, Flooded Lead Acid Track Battery
10 to 15 Year Old Cells

Cell #	Float Voltage	Conductance KMhos (KSiemens)
1	2.21	0.371 *Bad Cell
2	2.19	0.177 *Bad Cell
3	2.20	0.370 * Bad Cell
4	2.20	0.633 *Good

Site B
80 AH, Flooded Lead Acid Track Battery
10 to 15 Year Old Cells

Cell #	Float Voltage	Conductance KMhos (KSiemens)
1	2.20	0.409 *Bad Cell
2	2.19	0.518 *Fair
3	2.20	0.505 *Fair
4	2.20	0.244 *Bad Cell
5	2.18	0.650 *Good
6	2.18	0.125 *Bad Cell
7	2.19	0.648 *Good
8	2.17	0.653 *Good
9	2.19	0.562 *Good
10	2.18	0.285 *Bad Cell

Site C
80 AH, Flooded Lead Acid Track Battery
Less than 5 Year Old Cells

Cell #	Float Voltage	Conductance KMhos (KSiemens)
1	2.20	0.687 *Newer Cell
2	2.21	0.688 *Newer Cell
3	2.22	0.664 *Newer Cell
4	2.21	0.673 *Newer Cell

Figure 15

NiCad Measurements
10 Cells, 200 AH, Truck Crossing

Cell #	Voltage Open Circuit	Conductance KMhos (KSiemens)	Average Two Cell Discharge Minutes 1 hr Rate to 1.0 VPC
1&2	2.68	0.195	0.45
3&4	2.66	0.215	0.90
5&6	2.55	0.300	1.50
7&8	2.40	0.376	1.90
9&10	2.36	0.372	2.05

NOTE: Each conductance measurement includes two cells and one strap connection

Figure 16

New Cell NICad Measurements
4 Cells, 200 AH

Cell #	Voltage Open Circuit	Conductance KMhos (KSiemens)	Discharge Minutes 1 hr Rate to 1.0 VPC
A&B	2.73	0.762	65
C&D	2.72	0.706	63.5

NOTE: Each conductance measurement includes two cells and one strap.

Figure 17

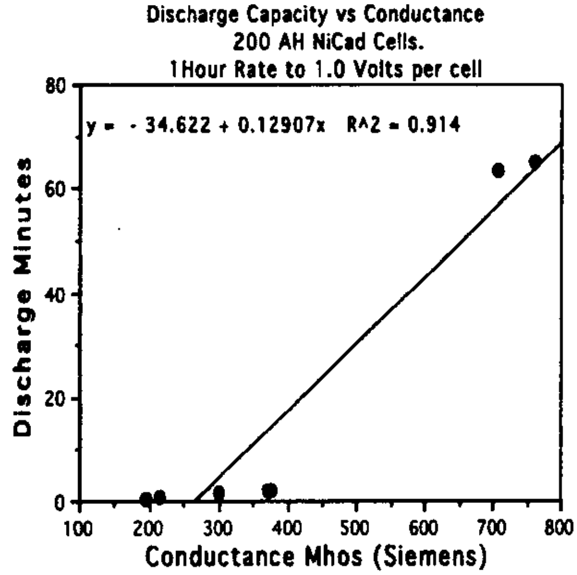


Figure 18

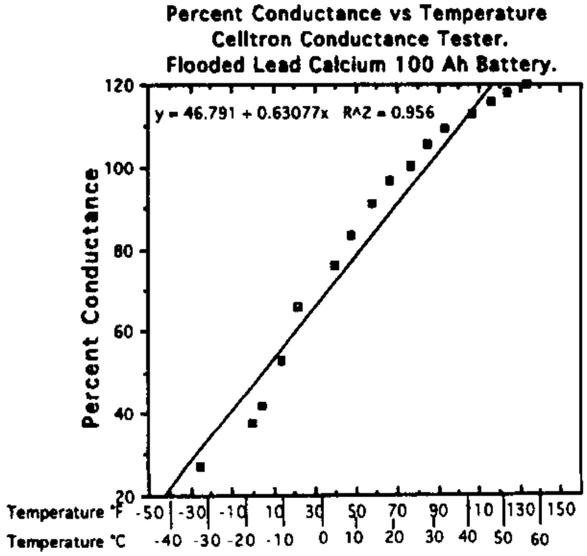


Figure 19

one hour constant current rate to 1.0 volts per cell. **Figure 16** also shows the results of the discharge tests performed on the same cells. As you can see in every case, each cell performed very poorly at only a fraction of its capacity rating. The significance of this, is that these cells were only 13 years old and would have been expected to be in good condition. Subsequent charge/discharge cycles were performed on these cells with no appreciable improvement in performance. Since we did not have an idea of what good cells look like in terms of conductance, we requested the railroad to send four new cells for testing. **Figure 17** reveals the results from the tests performed on the new cells and shows a substantial increase in both conductance and discharge capacity. **Figure 18** shows the correlation plot of discharge capacity and conductance with an R^2 correlation coefficient of 0.91. This preliminary information indicates that there is a useful correlation between the conductance and remaining discharge capacity of NiCad cells. Further testing is currently being performed to substantiate these preliminary findings.

Temperature Data Analysis:

Because of the operating environments and temperature deviations seen in Railroad signal sites, testing was performed to understand the effect temperature has on measured conductance.

Figure 19 shows temperature data which represents a strong linear relationship with R^2 correlation coefficient greater than 0.95 for conductance and temperature. The data listed is representative for a temperature range of -40°F to 120°F.

Figure 20 data shows the differences in the temperature/conductance slopes of AGM, GEL and flooded cell designs. A noticeable slope difference is observed for the AGM design and flooded designs. The data also show that the conductance/temperature slope characteristics for the GEL design closely resemble that of the flooded battery design.

Use Of Conductance To Evaluate Intercell Connections:

The conductance testing technique used in this study shows how the use of the conductance measurement can provide a very meaningful measure of the relative quality of intercell connections. The test is performed by comparing the conductance of the cell-plus-intercell to the cell it is associated with, since the cell-plus-intercell number is always lower than the cell's measured conductance. A properly maintained intercell connection will show a minimal loss of conductance.

Figure 21 shows the method used to make measurements of inter-cell connections. First the conductance of a cell/battery is measured. The conductance value can either be programmed into the instrument as a reference or the actual value can be used.

Next, a measurement of that cell plus the intercell is made. If the cell conductance is used as a reference, the output then shows the interconnection loss as a percentage.

Figure 22 shows a series of cells, their conductance readings, and the reading of the cell plus the intercell connection on the positive side of the cell. It can be quickly noted that every third intercell connection causes a relative drop in conductance readings as would be expected since a cable connection is used between each three cell module, while the connections between adjacent cells is made via lead plated copper strap. While this is to be expected, it can also be noted that certain intercell connections have the effect of causing relatively lower cell-plus-intercell conductance readings, not obviously caused by end of module cable connections. **Figure 23** shows cell conductance and the related cell plus inter-cell conductance. The difference between these graphs show the loss caused by an inter-cell connectors.

While we did not evaluate the exact causes of these conditions, it is reasonable to assume that potential loose connections, corrosion, improper crimping of cable lugs or other inter-cell defects could be observed in this way. Moreover, rather than using a separate instrument to measure the resistance in micro-ohms and then mathematically interpreting the data, conductance testing provides the user with the ability to easily use the tested cell as a reference to measure the quality of the relevant inter-cell connection.

Conclusions:

Valve-Regulated Lead Acid (VRLA) Cells:

With the ever increasing usage of VRLA cells in Railroad Service the results of this study and those reported elsewhere, indicate quite clearly that an effort is necessary to monitor their state of health and that conductance measurements provide the user a technique to do so. Based on these results we can conclude:

Battery Design Type: VRLA-AGM (Absorbed Glass Mat Design)
Temperature Bandwidth: -40°F to 120°F (-40°C to 48.8°C) used for slope characterization.

Battery type/MFG:	Correction %/°F	Correction %/°C
Battery Mfg A 6 volt 200AH	0.50%/°F	0.90%/°C
Battery Mfg B 12volt 225 AH	0.40%/°F	0.72%/°C
Battery Mfg B 12volt 300 AH	0.47%/°F	0.85%/°C
Battery Mfg B 12volt 95 Ah	0.51%/°F	0.92%/°C
Battery Mfg B 12volt 95Ah	0.50%/°F	0.90%/°C
Battery Mfg B 12volt 95Ah	0.51%/°F	0.92%/°C

Battery Design Type: VRLA (Gelled Electrolyte):
Temperature Bandwidth: -40°F to 120°F (-40°C to 48.8°C)
used for slope characterization.

Battery type/MFG:	Correction %/°F	Correction %/°C
Battery Mfg B 12volt 100 Ah	0.73%/°F	1.31%/°C
Battery Mfg B 6volt 200Ah	0.67%/°F	1.21%/°C
Battery Mfg B 12volt 31Ah	0.75%/°F	1.35%/°C
Battery Mfg B 12volt 31Ah	0.74%/°F	1.33%/°C

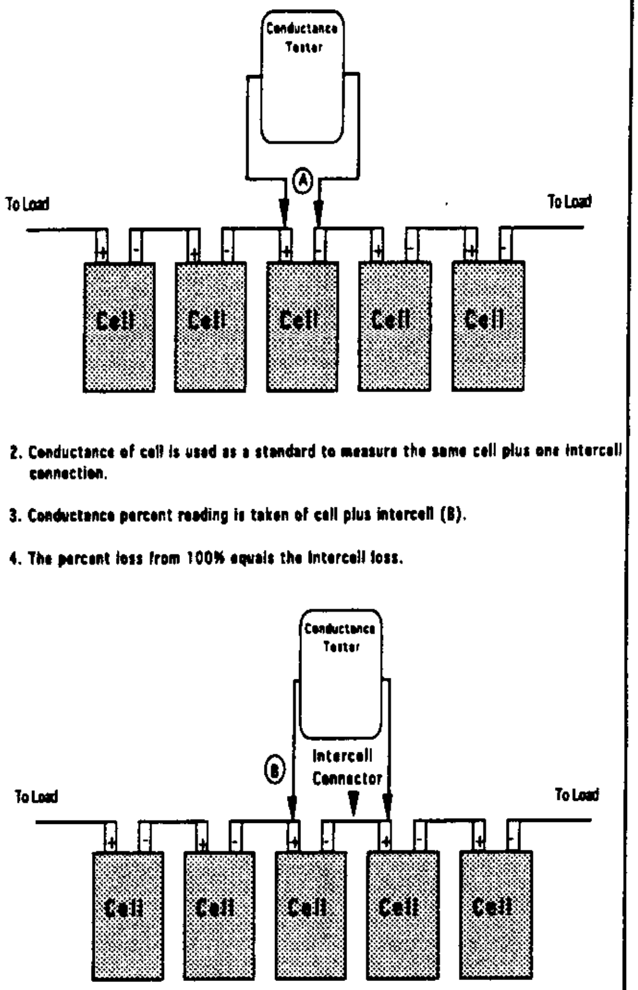
Battery Design Type: Flooded Lead Calcium 1.215 Sg.
Temperature Bandwidth: -40°F to 120°F (-40°C to 48.8°C)
used for slope characterization.

Battery type/MFG:	Correction %/°F	Correction %/°C
Battery Mfg C 6volt 100Ah	0.712%/°F	1.28%/°C

Figure 20

Proper Method For Checking Intercell Connection
Integrity Using Conductance Test Equipment

1. Conductance test is made of cell alone (A).



2. Conductance of cell is used as a standard to measure the same cell plus one intercell connection.

3. Conductance percent reading is taken of cell plus intercell (B).

4. The percent loss from 100% equals the intercell loss.

Figure 21

Cell#	Cell (Mhos) Conductance	Cell Plus Strap (Mhos) Conductance	Conductance % Loss * 10
1	2810	2480	882.562
2	2290	2090	912.664
3	2190	1360	621.005 **
4	1810	1690	933.702
5	2980	2630	882.550
6	1750	1130	645.714 **
7	2170	1980	912.442
8	1810	1680	928.177
9	2470	1430	578.974 **
10	2570	2310	898.833
11	2380	2150	903.361
12	2570	1660	645.914 **
13	2110	1930	914.692
14	2530	2270	897.233
15	2470	1210	489.879 **
16	1800	1700	944.444
17	2170	1980	912.442
18	1780	1050	589.888 **
19	1840	1690	918.478
20	2290	2080	908.297
21	1560	800	512.821 **
22	2160	1970	912.037
23	2040	1860	911.765

Figure 22

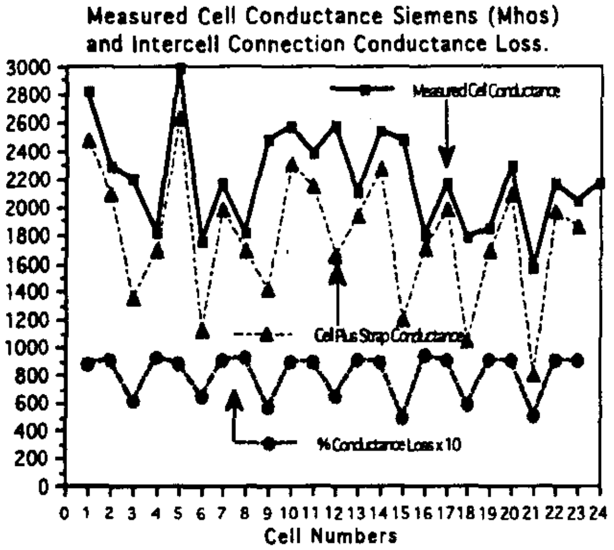


Figure 23

1. All VRLA cells/batteries should be maintained.

2. The traditional measurement of individual cell float voltage cannot give significant warning of potential cell failure.

3. In all cases tested, conductance measurements correlate extremely well with cell capacity and can provide early detection of premature capacity failures, without regard to application, design, size or specific manufacturer of the particular VRLA cells involved.

4. Tear down analysis shows conductance detecting poor cell performance for both mechanical and electrochemical failure mechanisms.

Vented Lead Acid Cells:

Tests, reported in this study, show similar relationships with conventional flooded (vented) lead acid cells. Although the range of capacity degradation is generally much less than with VRLA cells, in the vented cells tested to date:

1. Capacity degradation is rarely, if ever, indicated by the conventionally measured parameters of cell voltage or specific gravity.

2. Conductance measurements correlate well with both serious capacity failures, as well as with capacities which have degraded just below the normally recommended 80 percent failure criterion and can provide warning of potential cell deterioration to the user.

3. Studies of vented cell capacity/conductance correlations are continuing and will add significantly to the limited data base established to date.

Nickel Cadmium Cells:

1. Preliminary findings suggest that there is also a correlation of cell discharge capacity vs. conductance for the NiCad chemistry.

2. Further testing will be necessary to further demonstrate the correlation and to better understand the failure modes for this chemistry.

Measurement Techniques:

This paper also demonstrates the utility of the conductance test measurement for establishing, evaluating and maintaining the integrity of cell/battery intercell connections.

Finally, this paper presents test data showing the relationship of conductance and temperature for cell conductances measured over a temperature range of -40°F to 120°F and discusses a method for application of a temperature correction factor to AGM, GEL and conventional (flooded) lead acid cells.

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