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Abstract

Midtronics in cooperation with both U.S. and U.K. battery users have performed both conductance and discharge capacity tests on literally thousands of batteries and cells in two, six and twelve volt configurations. The results of these extensive studies have been published in several technical papers presented to various technical and industry groups in North America, Europe and Asia. These papers clearly demonstrate the utility of conductance technology for determining battery state-of-health and show analytical procedures for identification of premature capacity failures. This paper will show the results from VRLA (Valve Regulated Lead Acid) 24 volt synthesized equivalent monobloc batteries using an averaging procedure for single cell conductance/capacity data measured from 1000 ampere-hour telecommunications batteries. These synthesized data will be used to demonstrate the correlation, diagnostic sensitivity and utility of the conductance measurements as applied to the 24 volt battery configuration generally used in aircraft applications. This paper will also present test data on a limited number of 24 volt aircraft battery systems, which indicate that conductance measurements are capable of detecting batteries with seriously deteriorated capacity.

Introduction

For many years, a reliable real time indication of battery condition has been sought for aircraft batteries. Methods for determining state-of-charge and state-of-health have been developed, but success has been limited because of the complexity, cost, and reliability. Conductance technology has been demonstrated to be an effective means of testing the state-of-health of VRLA batteries. This technology has also been successfully tested on large industrial 200 Ah pocket plate Ni-Cd (Nickel-Cadmium) batteries. If adequate diagnostic capability can be demonstrated for sintered plate Ni-Cd and VRLA 24 volt aircraft batteries, the potential for conductance technology in aircraft applications is enormous. Applications of conductance technology include hand held portable test equipment used by ground personnel to pre-flight the aircraft and on-board monitoring devices from which the pilot can test the aircraft battery by momentarily activating a switch in the cockpit. Cost reductions in battery maintenance time, savings of good batteries and extension of battery service life could be obtained.

History of Conductance

Over the last several years Midtronics has published the most significant amount of conductance/discharge capacity behavior data in the world [Refs. 1-9]. These publications present data on well over 5000 VRLA cells ranging in size from 25 to 1000 ampere-hours, in 24 to 500 volt series strings used in telecommunications, railroad, electric power utilities and UPS applications. Evidence showing the relationship of discharge capacity and conductance for VRLA telecom cells has also been shown in several other publications in the U.K. [Refs. 10-12]. These data clearly show the effectiveness of conductance tests when applied to real life cell/battery performance conditions. In each case studied, respective capacity and conductance behavior were measured and good linear correlations were established. Moreover, the correlations remain good irrespective of whether the conductance/discharge capacity conditions were permanent or temporary (i.e. poor capacity could be sometimes corrected by some type of restorative conditioning regime). While this relationship has been generally accepted, there are extensive studies being conducted to determine the absolute reliability and predictability of the conductance method.

Why Should Conductance Identify Failed Aircraft Batteries?

In most failure modes of Lead-Acid and Ni-Cd cells, the loss of capacity is accompanied by a decrease in the cell's conductance. In the case of VRLA batteries, post seal, jar-cover leakage, positive grid corrosion and valve malfunction result in cell dry-out, thereby decreasing capacity and conductance. The loss of grid/paste contact, loss of separator compression, electrolyte stratification, grid corrosion and loss of contact in the top leadwork all result in a loss of capacity as well as conductance. Thus, when applied to VRLA aircraft batteries, it is clear that battery conductance monitoring should provide the user an indication of the battery's state-of-health, provided that adequate sensitivity is maintained in a 24 volt string.

In the case of vented Ni-Cd aircraft batteries, the failure modes include carbonate build-up in the electrolyte, loss of electrolyte, passivation of the negative electrode, positive electrode swelling, and active material degradation. For both vented and sealed Ni-Cd batteries degradation of the separator often results in shorts between the positive and negative electrodes, which would affect the cell's conductance. In the case of sealed Ni-Cd aircraft batteries, cell dryout can occur due to leaking seals, repeated cell reversals, or excessive overcharge. These failure modes normally result in a loss of capacity and should result in decreased conductance. Thus, there also appears to be an opportunity to use conductance as a means to determine state-of-health of Ni-Cd aircraft batteries. The extent of the correlation between conductance and battery capacity will need to be verified with empirical data.

Conductance Technology

Conductance is the ability to conduct current; it is the reciprocal of resistance. The AC conductance measurement technique is performed by applying an 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 test uses the ratio of the AC current component that is in-phase with the AC voltage. Several conductance measuring units were utilized for the purpose of this paper. The first type is the Midtron Air, which is a self contained, fully portable tester designed to measure the conductance of lead acid and nickel cadmium 24 Volt batteries. This unit displays the average conductance for the 24 Volt battery in cell Mho units. The second is the Celltron CCT-20 tester which allows conductance testing of single cell or three cell battery combinations from 10 to 8000 ampere-hours.

Synthesized Equivalent Monobloc 24 Volt VRLA Battery Data

Detailed data obtained while performing conductance and capacity discharge testing on 48 volt VRLA telecom cells allows for the synthesis of 24 volt equivalent monobloc batteries which are common in aircraft applications.

The procedure used for the synthesis is as follows: Each 24 cell string capacity/conductance data is divided into two groups, i.e.: cells 1-12 and 13-24. The reciprocal of each cell's conductance is then calculated and added to obtain the total for each 24 volt group. The reciprocal of this total was then obtained which represents the average conductance for the 24 volt group. The discharge times (minutes) to 1.88 volts for each of the cells in that 12 cell group are then added and averaged, to obtain

"Synthesized" Equivalent Monobloc
(24 Volt) Average Conductance / Capacity

String# and Cell Group#	Conductance KMhos	Average Discharge Minutes to 1.88 VPC.
#4, 1-12 Cells	2.475	69.2
13-24 Cells	2.104	45.8
#5, 1-12 Cells	2.222	33.4
13-24 Cells	2.329	52.8
#6, 1-12 Cells	2.028	22.8
13-24 Cells	2.408	38.5
#8, 1-12 Cells	2.470	64.8
13-24 Cells	2.365	63.5
#9, 1-12 Cells	2.639	81.8
13-24 Cells	2.523	76.3
#10,1-12 Cells	2.910	105.3
13-24 Cells	2.810	99.2

Table 1

the average discharge capacity for that group. Table 1 shows the results of the calculations performed on twelve 24 volt equivalent units. Figure 1 shows the same data in a correlation plot which shows surprisingly good correlation R2= 0.881 and adequate sensitivity for defining battery acceptance (fit for service) criteria. Figure 1 also shows the regression line intersection with the 80% capacity (96 minute) value and the vertical line which is was drawn to show the conductance value representa-

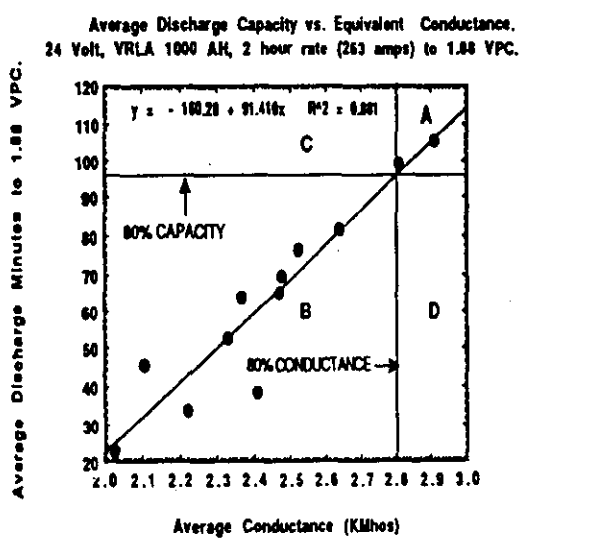

Figure 1

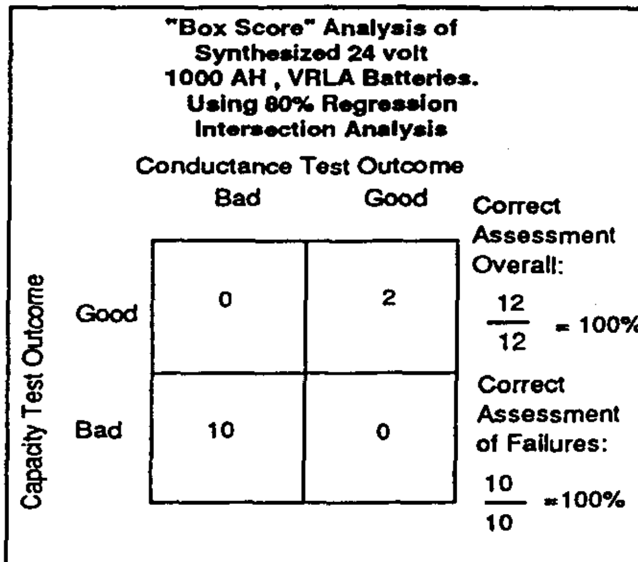

Figure 2

tive of 80% discharge capacity. This analysis describes the four quadrant "Box Score" labeled A, B, C, D. Figure 2 shows the "Box Score" with the accumulated data points for each quadrant and quantifies the results in terms of overall accuracy and in detection of failed battery units.

Sensitivity Analysis Using Synthesized Equivalent Monobloc 24 Volt VRLA Cells

To understand the sensitivity in detection of one,

VRLA Cell Data Table
2 Hour Rate Capacity >
80% (96 Minutes)

Cell	Discharge Minutes To 1.88 Volts	1/KMhos
A	100	0.345
B	96	0.370
C	96	0.394
D	112	0.325
E	130	0.287
F	98	0.340
G	103	0.358
H	98	0.351
I	124	0.314
J	120	0.294
K	105	0.370
L	96	0.345

MEAN CONDUCTANCE = 2.93 KMhos
MEAN CAPACITY = 106.5 Minutes

Table 2

VRLA CELL SUBSTITUTION DATA

Cell	Discharge Minutes To 1.88 Volts	1/KMhos
R	66.0	0.375
S	66.0	0.361
T	56.0	0.418
U	48.0	0.383
V	48.0	0.403
W	48.0	0.408
X	8.0	0.469
Y	1.9	0.469
Z	1.8	0.459

Table 3

two or three failed cells in a 24 volt (12 cell VRLA) battery, synthesized equivalent monobloc data were used while varying the degree of capacity degradation. Table 2 shows the cells selected with capacities greater than 80% (96 minutes). The average discharge capacity and equivalent conductance for these cells is 88.75% capacity and 2.93 KMhos. Shown in Table 3 are the substitution cells which were used to simulate various conditions (i.e. one bad cell, two bad, three bad cells etc.). The results of these substitutions are shown in the Table 4 "Result" column and include the assessment accuracy (i.e.. good called good (G/G), bad called bad (B/B), good called bad (G/B) and bad called good (B/G) by capacity/conductance) for detection of 80% capacity/conductance failure criteria (96 minutes, 2.82 KMhos) established in Figure 1 regression analy-

Senstivity Test Results Table

Criteria	Cells Removed	Cells Substituted	Mean Discharge (Minutes)	Equivalent Conductance KMhos	Result G/G	Result B/B	Result G/B	Result B/G
Replace Best with Lowest.	E	Z	95.8	2.81		x		
Replace 2 Best with 2 Lowest	E,I	Z,X	86.1	2.72		x		
Replace 3 Best with 3 Lowest	E,I,J	Z,Y,X	76.2	2.61		x		
Replace 3 Best with 3 @ 50% Capacity	E,I,J	R,S,T	91.0	2.76		x		
Replace 3 Best with 3 @ 40% Capacity	E,I,J	U,V,W	87.3	2.73		x		
Replace 3 @ 80% with 3 @ 40%	B,C,L	U,V,W	94.5	2.87				x
Replace 3 @ 80% with 3 Lowest	B,C,L	Z,Y,X	83.5	2.74		x		

Table 4

sis. The average capacity and equivalent conductance results shown in Table 4 closely follow Figure 1 regression line.

Nickel Cadmium 200 Ah Pocket Plate Cell Data

Preliminary studies have been conducted on 200 Ah pocket plate Ni-Cd cells. Below is a discussion of results from both field conductance measurements and laboratory discharge testing which shows conductance measurements properly identifying premature capacity failures.

In June of 1992 field conductance measurements were performed on pocket plate Ni-Cd 200 ampere-hour cells. Table 5 shows conductance tests for these cells as measured in the field. These same cells were tagged and taken to Midtronics laboratory for discharge capacity (performance) tests. Prior to performance testing, the cells were charged at a constant current rate of 48 Amps for eight hours, rested for ten hours and then discharged at the manufacturer's suggested one hour constant current rate to 1.0 volts per cell. Table 5 also shows the results of the discharge tests performed on the same cells. Calculation of the individual cell discharge capacities show extremely poor performance. The significance of this is that these cells were at half the expected life and should have been in good condition under the application conditions. Subsequent charge/discharge cycles were performed on the cells and showed no appreciable improvement in discharge capacity performance or conductance.

Since base-line or reference conductance values for new products of this same design were not available from the manufacturer, new cells were obtained for testing in order to establish a basis for conductance and capacity performance for comparison to the results obtained from tests performed on the failed cells. Table 6 reveals the results from the conductance/capacity tests performed on the new cells. As expected these new cells show substan-

200 Ah Flooded Pocket Plate Ni-Cd Cell Measurements

Cell	Voltage Open Circuit	Average Two Cell Conductance KMhos	Discharge Minutes 1 hr Rate to 1.0VPC
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.

Table 5

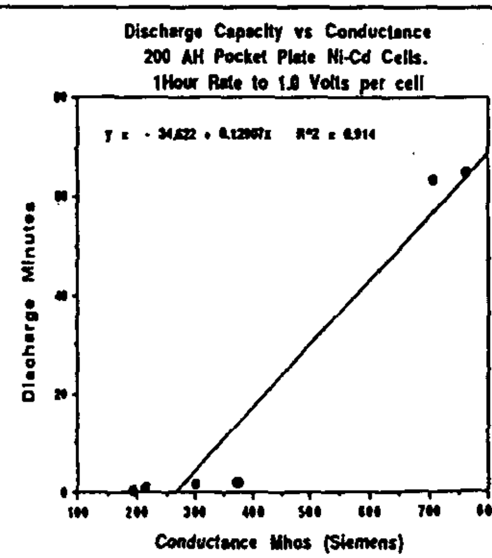

Figure 3

New 200 Ah Flooded Pocket Plate
Cell Ni-Cd Measurements

Cell #	Voltage Open Circuit	Average Two Cell Conductance KMhos	Discharge Minutes 1 hr Rate to 1.0VPC
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.

Table 6

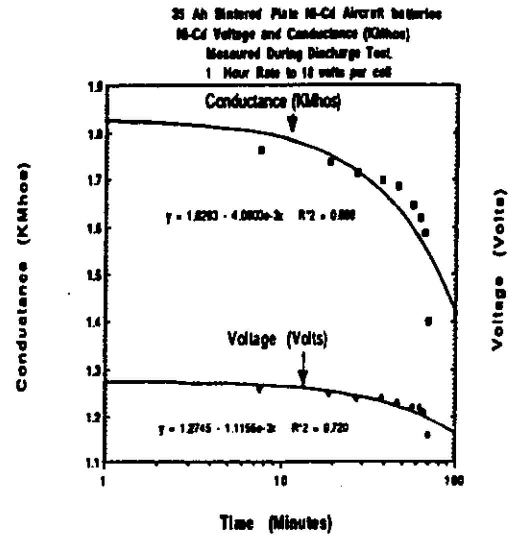

Figure 4

tially higher conductance and discharge capacity. Figure 3 shows a correlation plot of both the new and aged cells conductance/discharge capacities with a R2 correlation coefficient of 0.91. This preliminary information indicates a useful correlation between the conductance and state-of-health for the Ni-Cd technology which may be used to establish criteria for cell/battery acceptance or replacement. Further testing is currently being performed to substantiate these findings.

Conductance vs. State-of-Charge for Sintered Plate Aircraft Ni-Cd Cells

Unlike the lead acid battery where the electrolyte takes an active electrochemical role in the charge and discharge process, the Ni-Cd electrolyte only serves as a conductor of ionic species and does not undergo any significant compositional change during the charge and discharge process.

Figure 4 shows the cell voltage profile during a constant current discharge at the one hour rate for the sintered plate Ni-Cd cell. Also plotted in this figure are the conductance values measured during this same constant current discharge. The conductance decay is approximately 4 times that of the voltage. This indicates the internal cell conductance change is sensitive enough to identify small changes in the conductive states of the active materials as they change state during the discharge process. By contrast, the voltage measurement does not show this same sensitivity to the change in chemical state of the active materials as this cell is discharged. The application of this information may be useful to interpret not only the state-of-health (permanent changes) but also judge non-permanent changes of the cell state-of-charge or depth-of-discharge.

Conductance Measurements on 24 Volt, 37Ah VRLA Aircraft Batteries

Limited data provided from testing several 24 volt 37 ampere-hour aircraft VRLA batteries is shown in Table 7. The static open circuit voltages were obtained, conductance measurements were made and finally discharge capacity and conditioning cycle tests were performed as follows: 35 Amps constant current (one hour discharge rate to 18 volts per battery), charge at 3.5 Amps for 14 hours, discharge at 35 Amps, charge at 50 Amps initial current, 28.5 volt upper limit. Figure 5 shows this data with addition of new battery data (22 samples, Mean 990 Mhos, Std. Dev. 45.9 Mhos) supplied from the manufacturer of this product. It should be noted that for these 22 samples no discharge capacity data were

Bat#	Static OCV.	Initial Capacity AH.	Initial Conductance (Mhos)	After Charge Capacity AH
H3	25.56	13.50	770	28.42
H4	25.29	7.91	329	41.23
H5	25.92	22.34	948	28.27
H6	25.85	22.56	973	31.16

24 VOLT, 37 Ah VRLA AIRCRAFT BATTERIES
Conductance/Capacity Data
1 Hour Rate To 18 Volt End Voltage.

Table 7

available, therefore these 22 samples were all assumed to have 100% discharge capacity. Figure 5 correlation plot reveals good correlation R2=0.898 between measured conductance and discharge capacity for the older batteries. However, the correlation decreases to only R2= 0.606 with the addition of the new cell mean assuming that they all have 100% discharge capacity. After charge/discharge conditioning, these same batteries show improvement in discharge capacity (see table 5). Further testing is underway to explain the reason for the improvement in capacity as well as to determine the new conductance values.

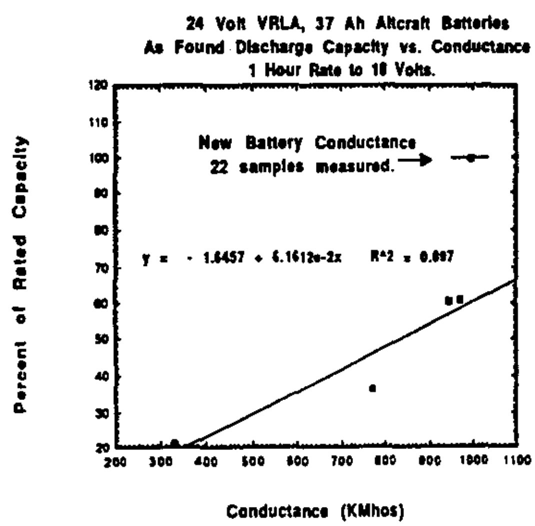

Figure 5

It is important to note, irrespective of the final capacity after the conditioning cycles, the conductance tests generally show the inability of these batteries to provide suitable capacity for service. As expected, the open circuit static voltage as-received did not indicate the anticipated performance level for these batteries. This has been shown many times in previous publications which demonstrates the poor correlation between cell/battery static/float voltage or specific gravity to actual discharge capacity.

Conclusions

1. Based on the synthesized 24 volt equivalent VRLA data, conductance measurements appear to show adequate correlation and sensitivity for establishing battery acceptance criteria.

2. With the limited VRLA and Ni-Cd test data to date, conductance measurements are capable of detecting 24 volt batteries with seriously deteriorated discharge capacity. However, further testing is necessary to verify the reliability in detecting modestly deteriorated discharge capacity for 24 Volt aircraft batteries.

3. Conductance measurements on sintered plate (Ni-Cd) aircraft cells during discharge tests show more sensitivity to state-of-charge than voltage measurements.

4. Conductance measurements may be used to monitor 24 volt aircraft batteries and provide an assessment of the battery's condition, irrespective of permanent loss or temporary loss of battery capacity.

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