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**FIELD & LABORATORY STUDIES TO ASSESS
THE STATE OF HEALTH OF VALVE-REGULATED
LEAD ACID BATTERIES:
PART 1
CONDUCTANCE/CAPACITY
CORRELATION STUDIES**

by:

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PART I-CONDUCTANCE/CAPACITY CORRELATION
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ABSTRACT

In the initial phase of this ongoing program, approximately 500 Valve-Regulated Lead Acid (VRLA) cells (both individual and 6V monoblocs) have been capacity tested and measurements made of conductance as well as conventional diagnostic parameters such as float voltage and specific gravity. Cells studied ranged from four to six years' service, from 200 to 1000 ampere hour in size and included a group of 6V 200 ampere hour monoblocs. Physical arrangements included 18 parallel strings of 48V 1000 Ah cells, in a typical telephone transmission office; two to three parallel strings configurations of 48V 200 Ah cells in cellular telephone sites, as well as three parallel string of 60 - 6V monoblocs in a UPS site. Although individual cell capacities ranged from almost 0% to 100%, within most of the strings evaluated, there was essentially no correlation of capacity with the conventional diagnostic parameters of float voltage or specific gravity. By contrast, correlation of conductance with capacity was universally high, and sufficiently good to allow statistical prediction of capacity to be made from individual cell conductance values. While additional capacity/conductance evaluations are still needed for other VRLA cells designs (especially Gel), other applications and other plant configurations, it can be stated that at this time, the use of conductance testing as a substitute for capacity testing of VRLA cells looks extremely promising, and has many advantages when compared to traditional diagnostic methods.

Additional data document the variety of discharge curve shapes shown by good, fair and poorly performing cells, and invite speculation as to their cause(s). Post mortem diagnostics are scheduled, and will be reported at a later date.

Finally, limited temperature test data, measured during discharge, show a significantly greater increase than would be expected in a vented (flooded) cell, of similar size and at similar rates. Additional data are needed to quantify this effect and determine necessary temperature correction factors for capacity discharge tests of VRLA cells.

BACKGROUND

Over the course of the last ten years, Valve-Regulated Lead Acid (VRLA) batteries have demonstrated an extremely rapid introduction, eager user acceptance, and widespread applications in many areas of battery usage. In telecommunications, they have been increasingly applied as reserve batteries in both controlled central office switching and transmission

environments, as well as in the more extreme environments of fiber optic vault and remote, exposed, subscriber loop cabinets. In addition, VRLA batteries have become a major factor in the application of cabinet-type high voltage (120 to 380V) UPS systems, designed to protect computer systems during loss of commercial A.C. power.

Unlike the more conventional flooded or vented lead acid batteries, measurement of cell specific gravity is not possible, while measurement of individual cell float voltages has not been shown to be indicative of the "state of health" of the cell, as measured by a capacity test. As a result, users have been forced to rely on actual cell or battery performance under load. This is expensive, cumbersome, requires special equipment, trained personnel, and most importantly, generally requires the battery string to be taken off line for an extended period of time, while the test is being performed, reducing the available battery reserve.

Since the expected failure modes of VRLA cells: dry-out; grid corrosion and loss of contact to the active material; jar bulging with subsequent loss of plate/ separator/ electrolyte contact; internal corrosion and loss of contact between post/ strap/ plate lugs; all result in an increase in cell impedance, or a loss of cell conductance, these techniques have been actively pursued as substitutes for capacity testing ^{1, 2, 3}.

The possibility of developing an alternative to timed-discharge testing of standby cells and batteries was suggested by the work of DeBardelaben ¹. Using laboratory test equipment, DeBardelaben measured the complex impedance of lead-antimony telephone cells rated at 7,000 ampere-hours. His analysis disclosed a strong inverse correlation between cell capacity and either the magnitude of cell impedance or its resistive real part. Further laboratory studies by Vaccaro and Casson ² showed that increased impedance and resistance were also good indicators of "dryout" of VRLA stationary batteries. However their studies showed a high degree of correlation between impedance and capacity, but only at very high (5-10 minute) discharge rates. A survey, by one of the authors ³, in the spring of 1991, showed only a very limited data base for correlation, with some data presented which showed no apparent correlation. Nevertheless, for the user, the need is real and urgent, to have available a technique other than capacity testing, for field testing and evaluation of VRLA cells.

This paper presents data obtained in an ongoing study, of the relationship between cell *conductance* and reserve capacity and does not include any measurements of cell *impedance*. Field tests have been performed on several hundred VRLA cells, in working telephone transmission and cellular offices and in UPS and other applications, measuring conductance, ampere-hour capacity, cell float voltages and other parameters which might be indicative of performance under load.

CONDUCTANCE TECHNOLOGY

Conductance is defined as the real part of the complex admittance. The authors have determined by empirical data and computer modeling that low frequency conductance, measured in the international unit: Siemens (or the American unit: Mhos), provides useful information about battery condi-

tion since it reflects the changing characteristics of a battery as it displays defects or shows signs of wear.

The electronic battery conductance testers used in the tests, were developed by Midtronics, Inc. for the purpose of instantaneously assessing the state of health and the stored energy capacity of 6 and 12 Volt monobloc batteries and individual 2-volt cells. Their operation is based upon an adaptation of the conductance testing technology first reported in a paper by one of the authors⁴, and which has been successfully applied for over ten years, and widely accepted by major automotive manufacturers, battery manufacturers, and battery distributors in North American and Europe for testing the available cranking power of automotive engine-starting batteries.

The original problem of testing automotive batteries for use in engine starting applications had presented an entirely different problem. Unlike the reserve battery's mission of supplying energy over an extended period, the primary mission of a starting battery is to supply a large burst of power for a duration of time. Accordingly, automotive batteries are conventionally tested by means of a short-duration (e.g. 15 second) load test. However, the load test, like the timed-discharge test, also requires heavy, cumbersome, equipment and suffers from other serious disadvantages.

In response to these problems, Midtronics first developed conductance test equipment to provide a practical alternative to the common load test. Measurements of conductance have been found to correlate strongly with a battery's power rating expressed in Cold Cranking Amperes and provide a direct measure of the battery's high-current cranking capability.

Because of variations in battery designs, manufacturing processes, extended discharge times, a variety of usages and differing failure modes, the conductance method developed for assessing cranking power could not be directly applied to the assessment of available ampere-hour capacity, as would be desired for batteries in reserve applications. Because of the time required and the complications associated with timed-discharge testing however, it would be obviously desirable to provide a simple, instantaneous, test - such as a conductance test — that could be used to assess stored energy capacity without requiring that the battery be discharged in the process.

Proprietary testing by one of the authors, measuring conductance at various frequencies as well as computer modeling, have shown that very low frequencies are most effective in distinguishing good batteries from worn or defective batteries based on conductance testing. Our research has indicated that while testing of cranking batteries is most effectively performed with a time-varying signal of approximately 100 Hz, that best results are obtained on standby batteries at even lower frequencies. Tests of batteries documented in this paper were taken at a frequency below 25 Hz for monoblocs, and near 10 Hz for individual cells. The appropriateness of these frequencies has been shown in the original work of Yahchouchi⁵ reported by M. Alzieu of Electricite de France⁶.

Two types of conductance testers were used in these tests. The first type of tester, ("Celltron") is a fully-digital, self-con-

tained, electronic device designed to measure voltage and conductance of single, two-volt, lead-acid cells; or of three-cell (6-volt) batteries. The cell/battery undergoing test provides the very small (approximately 1.5 Amp) current for measurement. In addition, the unit utilizes a separate, 15 volt, nickel cadmium battery pack. The "Celltron" is electrically connected to the terminals of a cell/battery and measures its conductance with a small, time-varying signal of approximately 10 Hz. This signal is evaluated with separate voltage and current connections to each terminal of the battery unit being tested. An internal conductance standard permits initial calibration and subsequent calibration checked by the user, to assure accuracy of the cell/battery measurements.

The second type of tester ("Midtron") is a self-contained, electronic device designed to measure battery voltage and conductance of either three-cell (6 volt) or six-cell (12 volt) lead-acid batteries. The Midtron is totally powered by the battery undergoing test and require no additional batteries or connections to external power. This tester is electrically connected to the terminals of the battery undergoing test and senses its conductance with a small, time-varying signal at frequency of approximately 25 Hz.

The majority of the individual cell tests performed and reported on were taken with the Midtronics *Celltron* conductance tester. Those tests made on multiple cell monoblocs were taken with Midtronics *Midtron* conductance testers.

EXPERIMENTAL

Telecommunication Transmission Office Correlation Study Strings 2 through 8.

In January of 1992, the first series of correlation tests were performed in a telephone transmission office. The plant containing the valve regulated cells consisted of chargers, batteries and distribution equipment. The charge portion of the plant consists of fourteen 400 amp ferro-resonant chargers with 480 volt 3 phase input power. The charging bus connects to the battery bus near the discharge end. There is a 10,000 amp charge shunt in the positive conductor of the bus between the last charger and the first battery.

The cells were arranged in strings of 24 cells to form batteries. There were 18 strings in the plant though only 15 strings were tested. The plant was designed to float the batteries at 54.0 volts.

The first group of tests was performed on eight banks of 24 cell 1000 Ah (@ 8 hour rate) VRLA batteries. The approximate age of the battery was five to six years old. The ambient temperature during the testing was approximately 60°F (15.5°C).

All eight parallel batteries (strings 1 through 8) were taken off line and left open circuit for approximately 72 hours prior to performing both the conductance and discharge testing.

The first part of the test included individual cell conductance measurements that were made utilizing the Midtronics *Celltron* cell conductance tester. Conductance data were obtained for 24 cells of each string prior to instrumentation for discharge testing. Each conductance and open circuit voltage measure-

ment was made by simultaneously placing the *Celltron* probes onto both the positive and negative cell posts. Next, intercell connection conductance measurements were obtained for each connection. This was accomplished by leaving one of the probe connections on the positive post, and placing the other probe connection onto the adjoining cell post.

An Alber battery test system was used to perform discharge testing. The Alber system provided controlled load current, single cell monitoring and data storage. Data acquisition for each 24 cell string included: individual cell voltages, total string voltage, load current and elapsed time. A 263 amp constant load current to an end voltage of 1.80 volts per cell was utilized for testing of strings 1 through 8. Individual cell discharge voltage data was acquired at five minute intervals and stored via hard disk. Due to the method used for instrumenting each cell for data acquisition, voltage drops from the intercell connections were included in the individual cell data and suitable corrections were made in processing the final data.

String #1 Conductance vs Time during Discharge.

The same testing technique performed on strings 2 through 8 was utilized on string #1, however, this discharge test was interrupted at 15 minute intervals, conductance measurements were made, and the discharge test was continued. The mean time for conductance measurements made on the 24 cells of string #1 was 0.25 minutes per cell or six minutes total.

Correlation Study Strings 9 through 15.

In April of 1992 a second set of correlation tests were performed in the telephone transmission office on seven additional 24 cell battery strings. The same cell type was studied (VRLA 1000 AH @ 8 hour rate). Float voltages were measured prior to taking the batteries off line. These batteries were left open circuit for approximately 36 hours prior to testing, and open circuit voltages measured. The ambient temperature was at 70°F (21°C). Both conductance and discharge testing were performed as described in the correlation study of strings 2 through 8. However, the cells in strings 9 through 15 were all discharged to 1.75 volts per cell.

Note that voltage individual cell connectors were used for the second set of tests that were performed on strings 9 through 15, and therefore voltage drop corrections for intercell connections were not necessary for processing the final data.

Temperature Measurements.

Temperature measurements were obtained for two discharge tests. Six cells of different conductances were monitored. A Fluke (Model 77) meter with a Fluke (80T-150U) thermocouple interface module was used for this test. Data was obtained by measuring both the top of the negative post and on the jar wall between adjacent cells. Temperature measurements were made at 30 minute intervals.

Cellular Telephone Sites.

Typical battery configurations located in the cellular telephone sites consisted of two to three parallel branches of 24 cell 48 volt batteries. The batteries were located in a controlled environment with both heating and cooling capabilities and typical temperatures of 75°F (24°C). Field testing performed at cellular telephone sites consisted of conductance testing in

conjunction with timed discharge tests. Fluke 87 DVM multimeters were utilized for measurements of float voltage information, Midtronics *Celltron* cell conductance testers were utilized for all conductance measurements and Alber discharge test equipment was utilized for all discharge tests performed at a particular site. The testing sequence performed on the cells at the cellular site consisted of: float voltage measurements, disconnecting one of the parallel branches and performing conductance measurements, cleaning and retorquing of intercell connections, instrumentation of discharge equipment and individual cell voltage monitoring. Both two hour and three hour discharge rates were typically utilized with end of discharge voltages of 1.80 and 1.75 volts per cell.

UPS Application.

Field testing was performed in a UPS application containing 180 6 volt VRLA 200 ampere hour monobloc batteries. The batteries were configured in three parallel 60 - 6 volt monobloc battery strings that were in service for approximately six years. Initial float voltage data were obtained with a Fluke 87 DVM. One of the parallel branches was taken off-line and a sample of 20 batteries was tested to characterize the battery system. The discharge test was performed due to the poor physical condition of the battery, based on a detailed visual inspection. Conductance measurements utilizing the Midtronics *Celltron* conductance tester were made immediately preceding the discharge test. An Alber load bank, controller and battery voltage monitoring system was utilized for discharge control, and data acquisition throughout the entire discharge test..

Railroad Signal Cell Testing

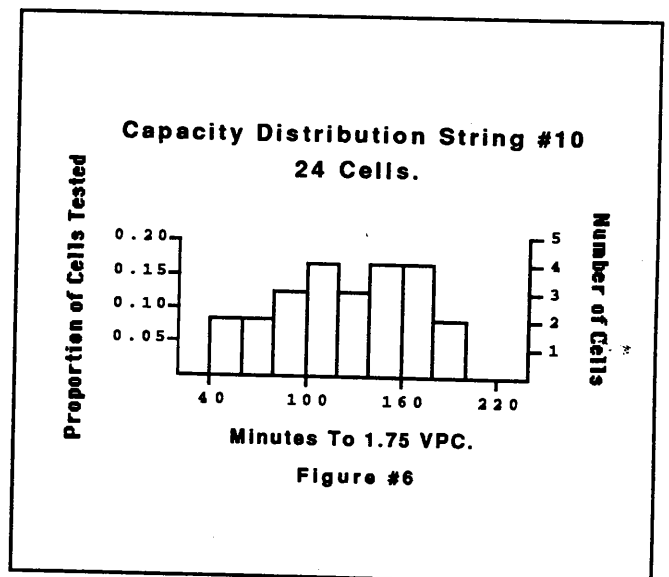
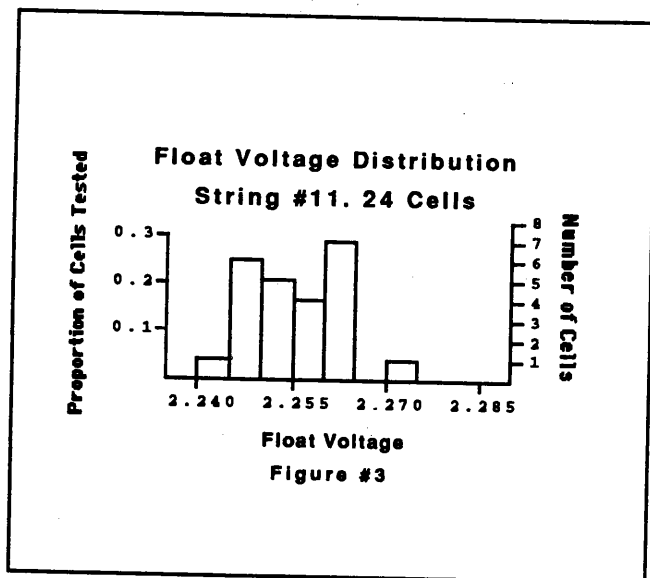
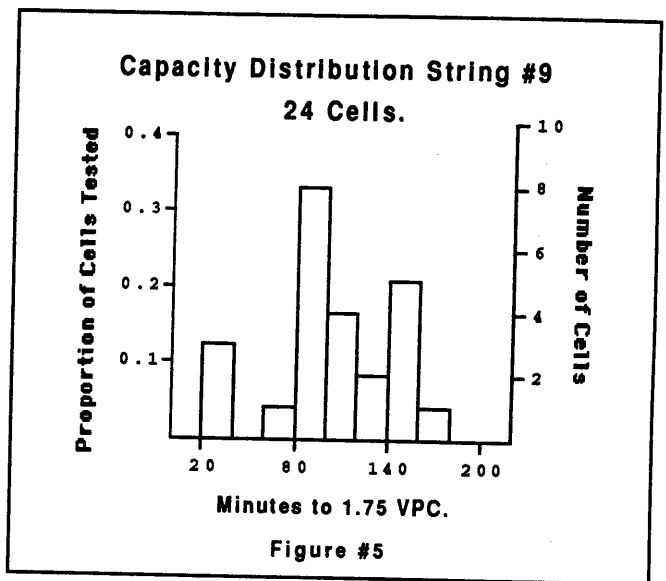
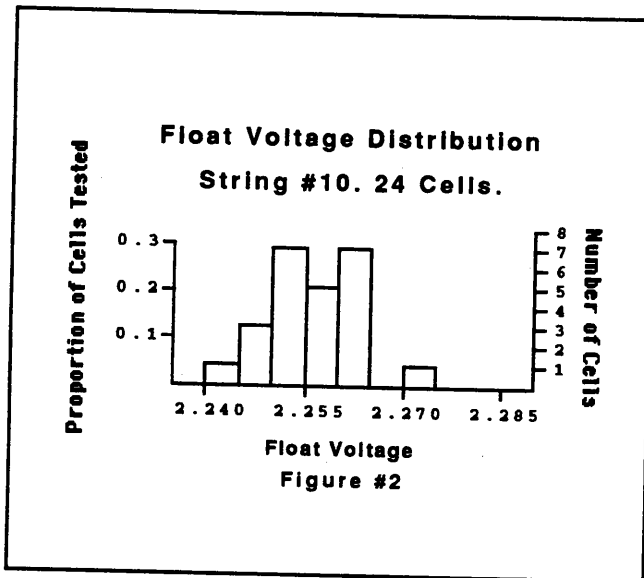
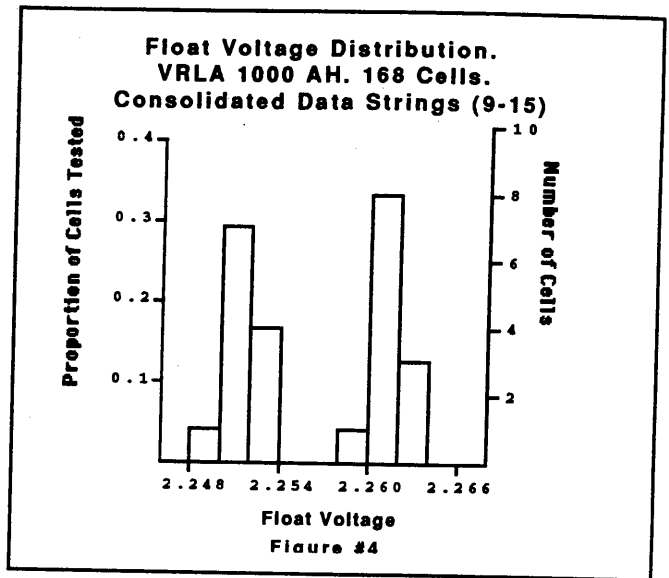
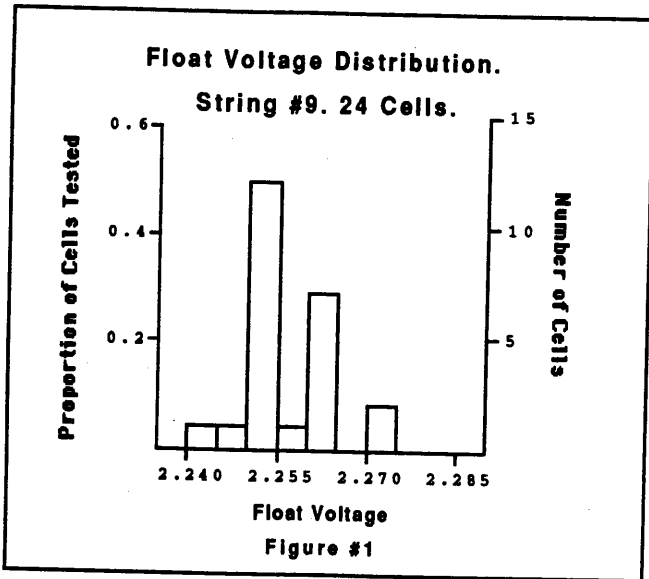
Conductance tests using the Midtronics *Celltron* cell conductance tester on were performed on several VRLA 225 ampere hour cells located in railroad signal sites. Typical ages for these cells were three to four years. Cells that were identified as having high and low conductance values were tagged and sent to Midtronics for discharge testing. Also two new cells of similar construction were also supplied to Midtronics for establishment of a baseline conductance value. Upon receipt, the cells were charged using a Firing Circuits (Digitron) programmable charge/discharge circuit, with individual cell voltage monitoring performed with Fluke Hydra 20 channel data logger. The cells were boosted according to the manufacturer's recommended constant voltage practice, rested for 24 hours, conductance measurements taken, and discharged at a constant current of 42 amps to 1.75 volts per cell. Two charge/discharge cycles have been performed to date

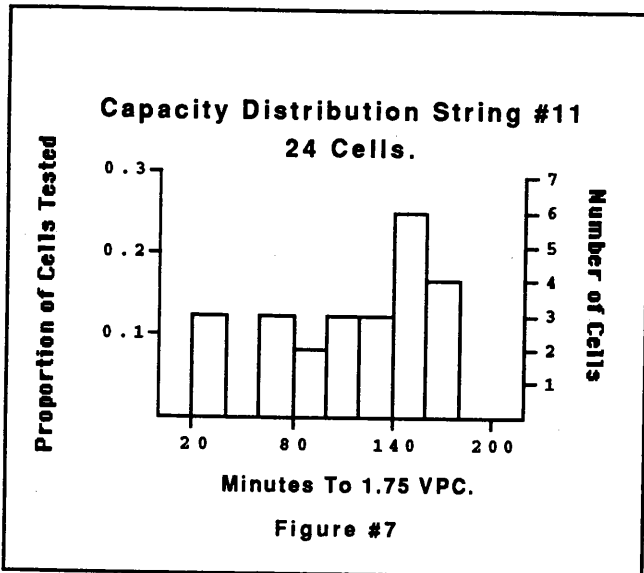
RESULTS AND DISCUSSION

Conventional Parameters as Capacity Indicators

Figures 1, 2 and 3 show the distribution of float voltages for three representative 24 cell strings in the telephone transmission plant. Figure 4 shows the same parameters for the 168 cells of strings 9 through 15 considered as a group. While they may not be "ideal" normal distributions, they clearly show that float voltages are all within nominal specification values recommended by the manufacturer.

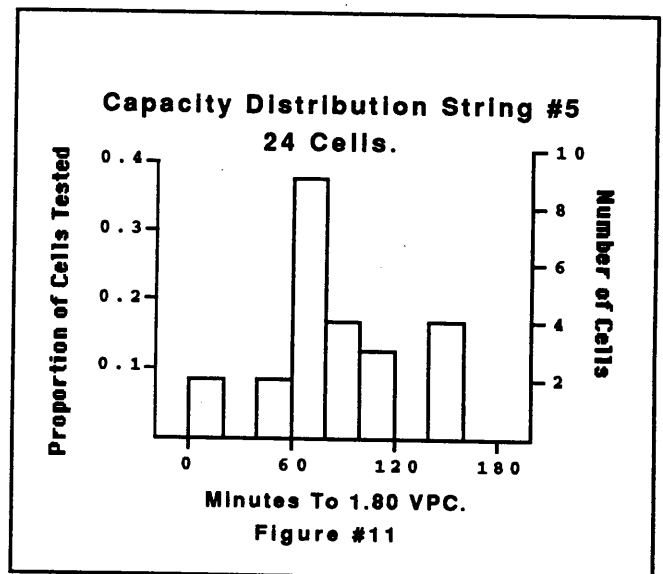
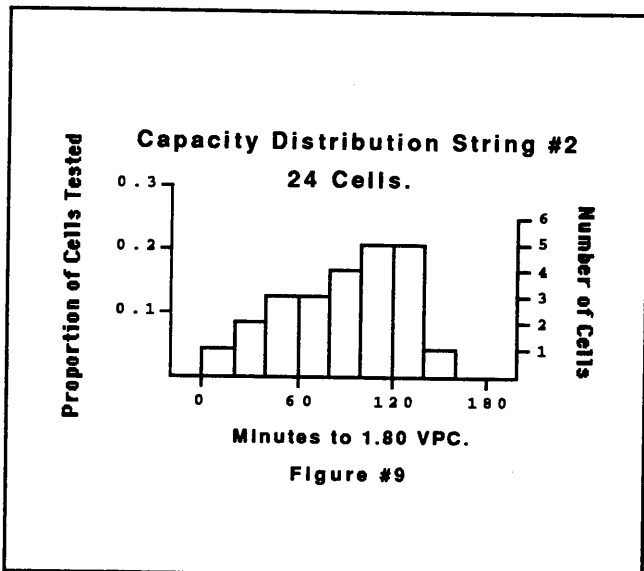
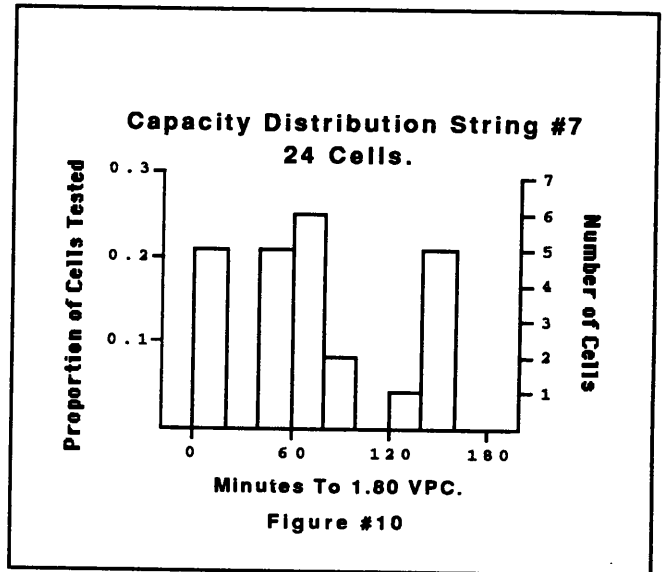
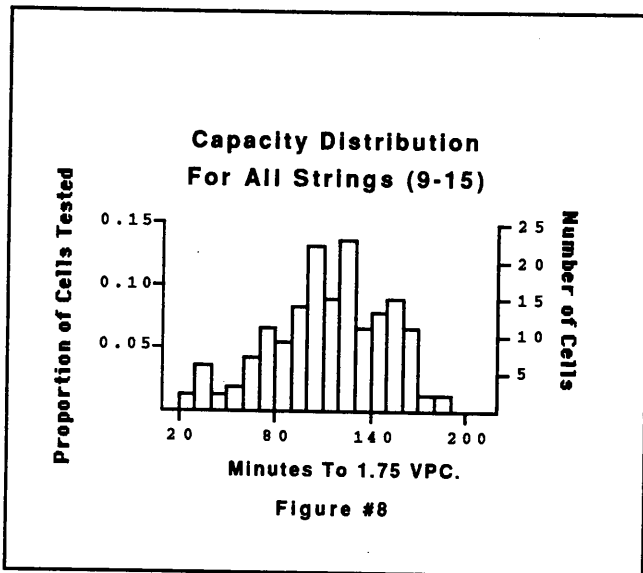
Figures 5, 6 and 7 show the distribution of capacities to 1.75 volts per cell in the same three representative strings from

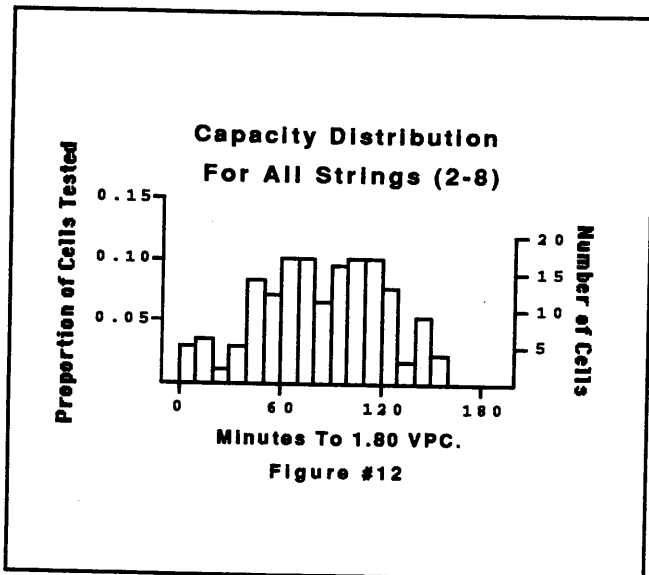




groups 9 through 15. Figure 8 shows the capacity distribution of all 168 cells of strings 9 through 15, all to 1.75 volts per cell. Figures 9, 10, 11 and 12 show similar capacity distributions, both for individual strings and for all 168 cells of strings 2 through 8 for capacity measured to 1.80 volts per cell. The contrast with the voltage distributions is astonishing. In every string and in the groups as a whole, capacities range from a few minutes to 180 minutes (approximately 100% capacity) despite the fact that individual cell float voltage values were completely within normal limits. Similar data for float voltage distribution and capacity distribution for 48 200 ampere hour valve regulated lead-acid cells discharged at the two hour rate to 1.75 volts per cell are shown in Figures 13 and 14. Again, voltage distribution is within nominal, normal tolerances while capacities range from 80 to 115 minutes (66% to 96%).

Even more significant is the attempt to correlate float voltage or specific gravity with cell capacity. While cell specific gravity is not directly measurable in a VRLA cell, it can be determined

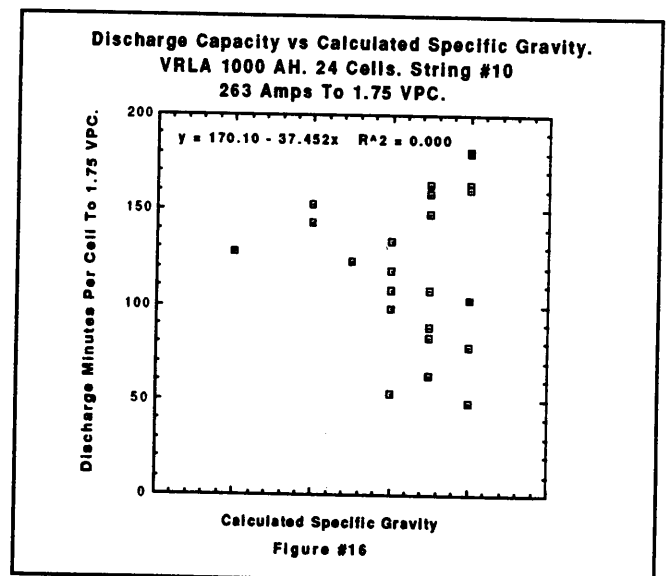
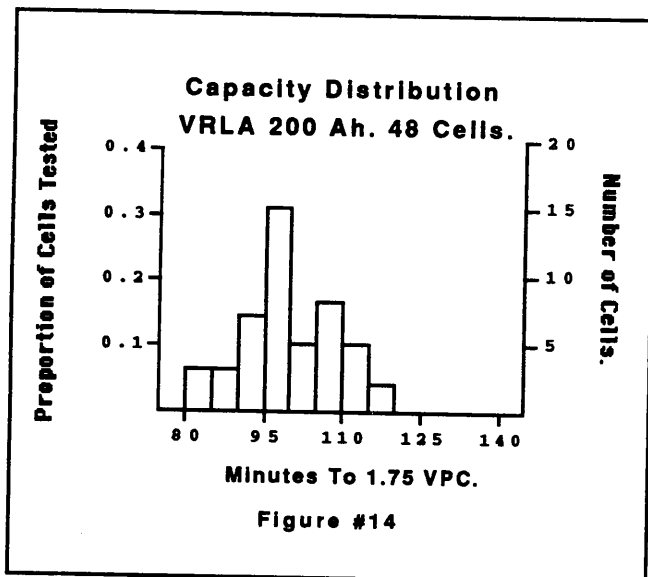
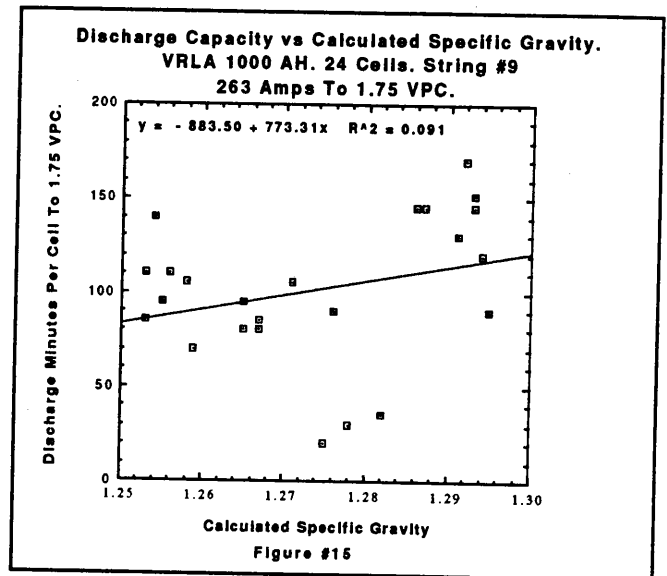
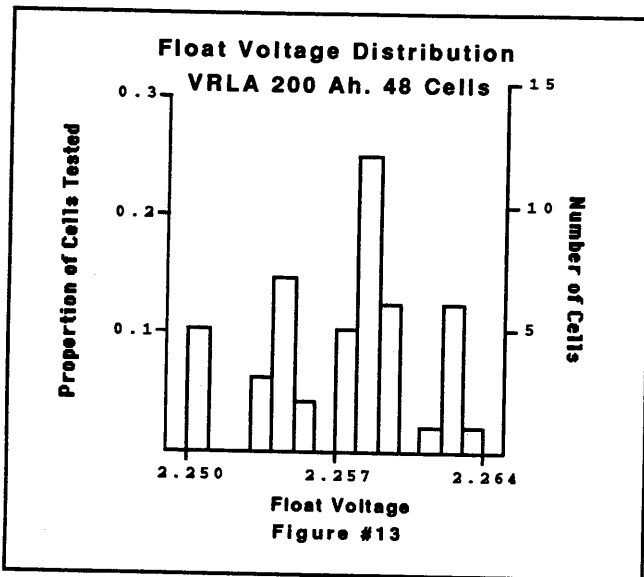


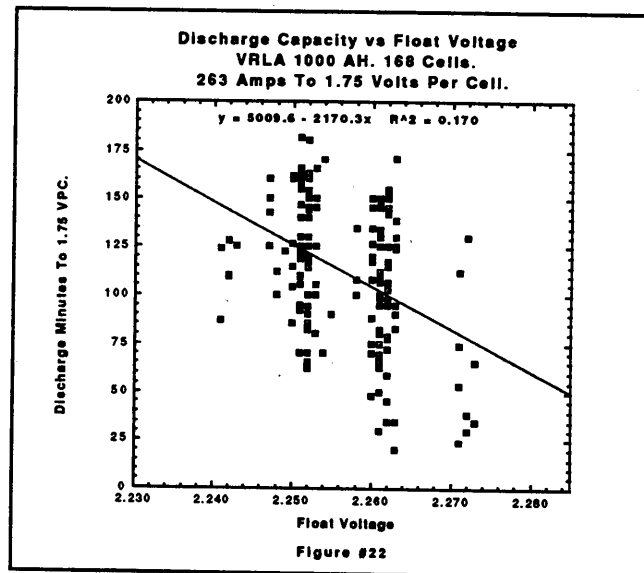
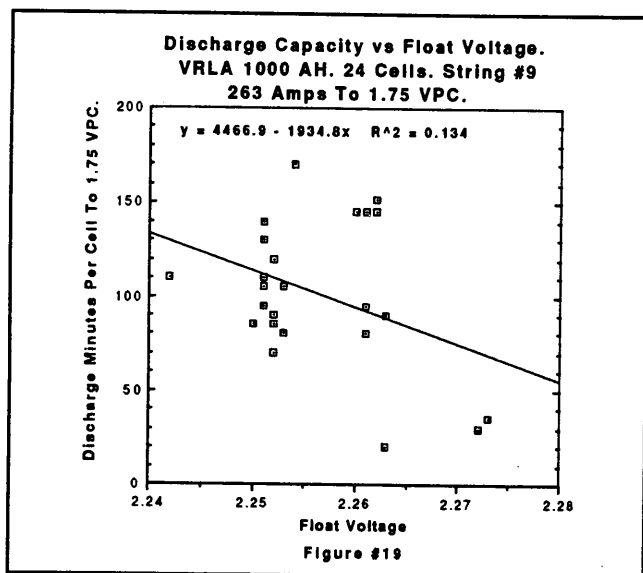
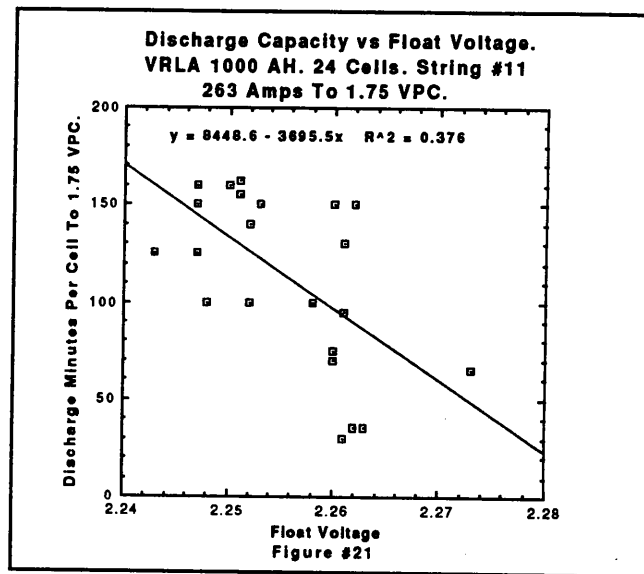
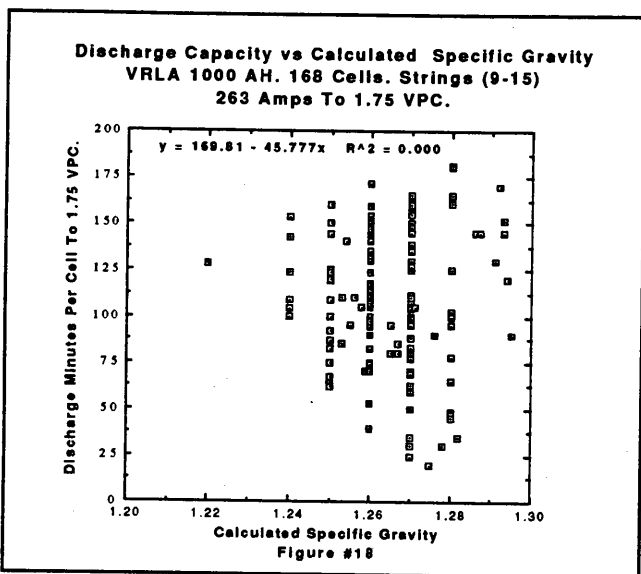
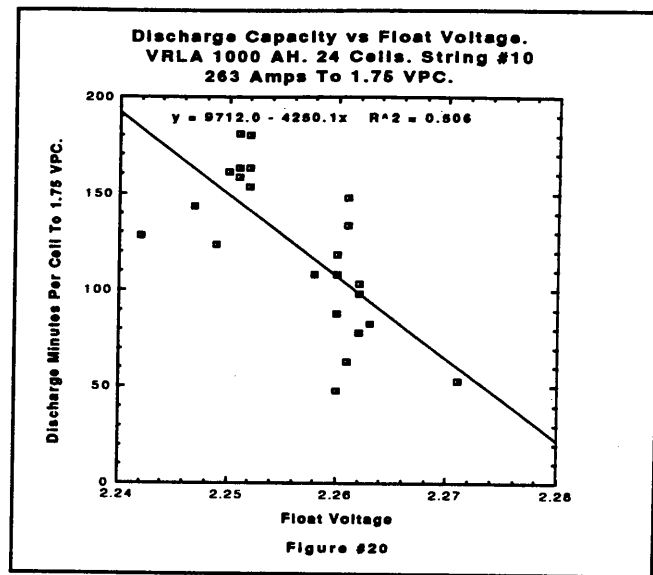
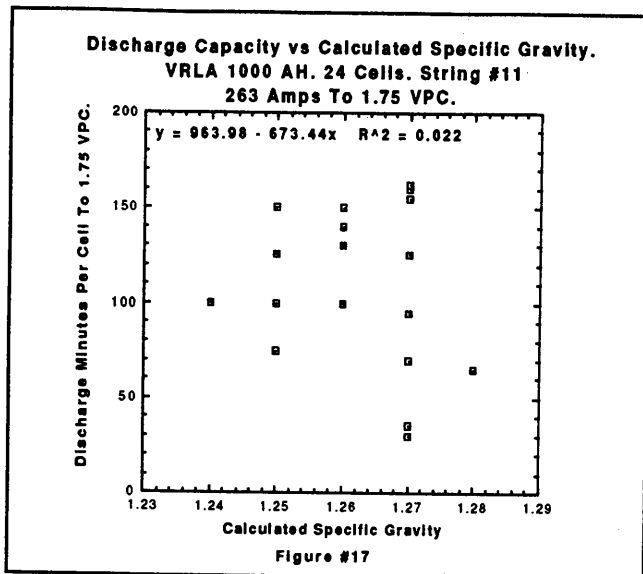


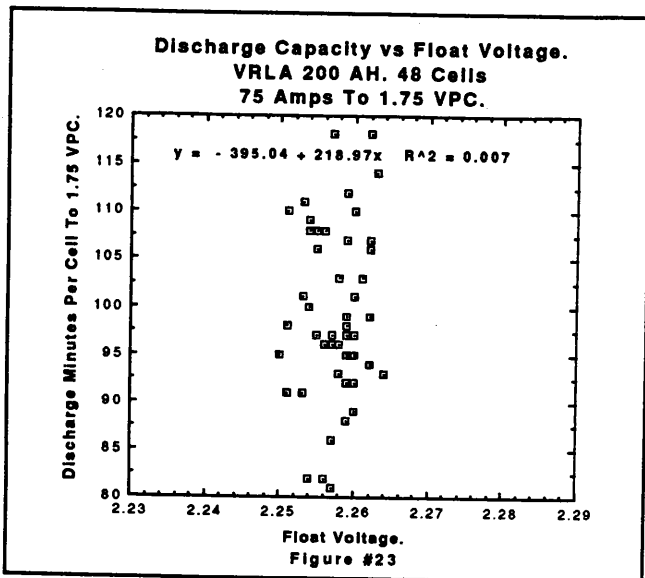
indirectly by measurement of cell open circuit voltage and calculated via the following formula:

$$\text{Specific gravity} = \text{Cell open circuit voltage} - 0.85.$$

Figures 15, 16 and 17 show calculated specific gravity vs. capacity for strings 9, 10 and 11 while Figure 18 shows specific gravity vs. capacity for all 168 cells in strings 9 through 15. There is obviously no correlation. (Note that R is the linear correlation coefficient. In our data analysis, we have utilized R², the squared multiple correlation coefficient.) Figures 19, 20 and 21 show cell float voltage vs. capacity for the same three strings while Figure 22 shows float voltage vs. capacity for all 168 cells of strings 9 through 15. Figure 23 shows float voltage vs. capacity for the 48 200 ampere hour cells. Although some of the correlation plots show a small but finite value of correlation, and the computer can draw a regression line, in no case would this "correlation" be statistically significant and be of practical use in predicting capacity behavior from float voltage.

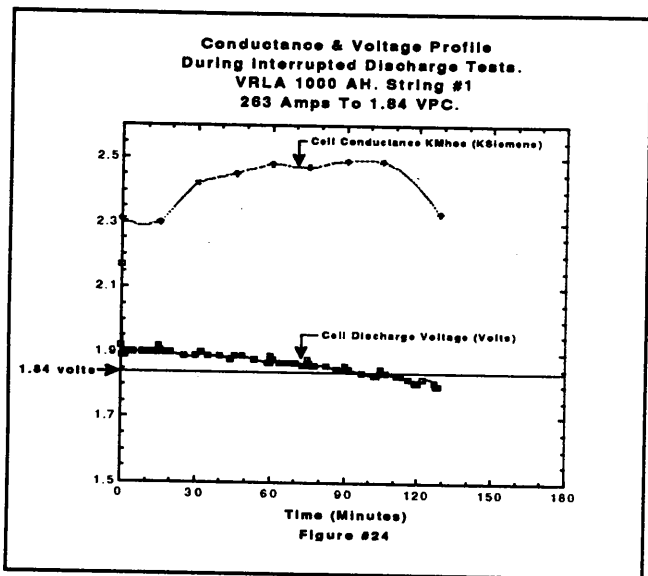






Characteristics of Conductance Measurements:
 Table 1 shows the results of conductance repeatability measurements on all 24 1000 ampere hour cells of string 9 of the telephone transmission plant. In all but three cases, conductance values are repeatable to $\pm .01$ Kilomhos KiloSiemens ($\pm .5\%$). In the three cases, repeatability is within $\pm .02$ Kilomhos KiloSiemens.

Figures 24, 25 and 26 show results of conductance measurements taken on individual high, medium, and low conductance cells during the discharge of string 1 at the telephone transmission office. This data was obtained by momentarily interrupting the discharge, taking conductance readings, and then continuing the discharge. On initial examination, the data of Figure 24 and 25 do not appear to show the expected conductance performance on discharge, i.e. : conductance

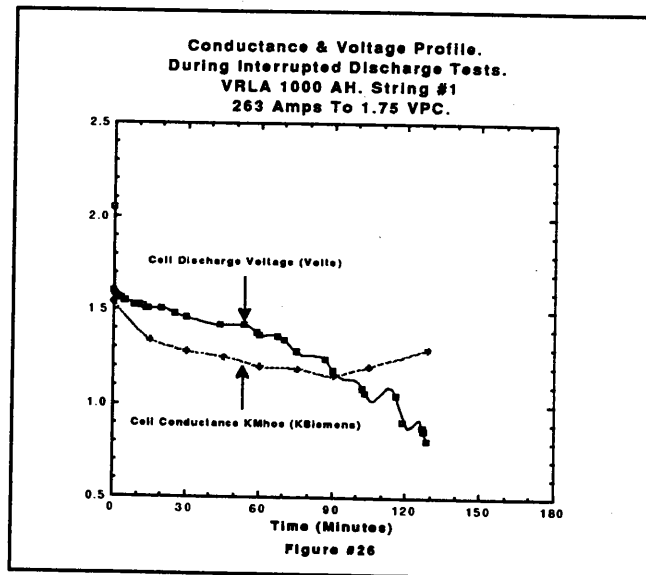
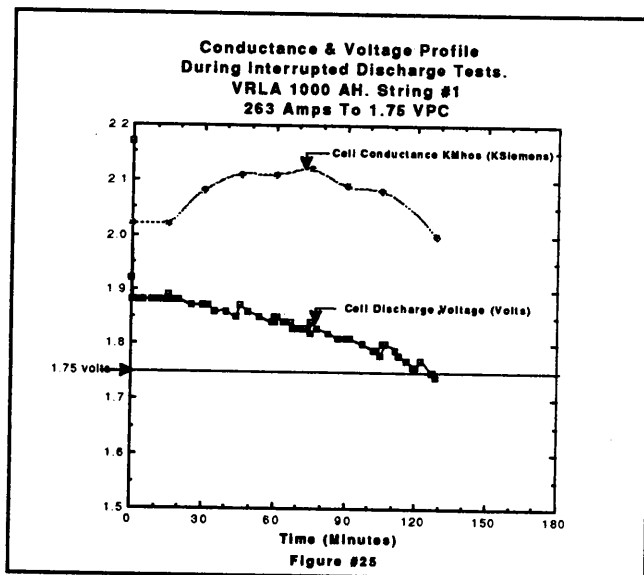


Conductance Repeatability Test.

Conductance Measurements KMhos (KSiemens)

| Cell# | G(1) | G(2) | G(3) |
|-------|-------|-------|-------|
| 1 | 2.650 | 2.680 | 2.680 |
| 2 | 1.940 | 1.960 | 1.960 |
| 3 | 1.830 | 1.850 | 1.860 |
| 4 | 2.430 | 2.460 | 2.470 |
| 5 | 2.300 | 2.310 | 2.310 |
| 6 | 1.850 | 1.870 | 1.850 |
| 7 | 1.980 | 1.990 | 2.000 |
| 8 | 2.100 | 2.130 | 2.120 |
| 9 | 1.940 | 1.960 | 1.960 |
| 10 | 1.580 | 1.590 | 1.590 |
| 11 | 2.300 | 2.310 | 2.310 |
| 12 | 1.550 | 1.560 | 1.550 |
| 13 | 3.010 | 3.010 | 3.050 |
| 14 | 2.080 | 2.070 | 2.080 |
| 15 | 2.740 | 2.750 | 2.760 |
| 16 | 2.350 | 2.360 | 2.350 |
| 17 | 2.660 | 2.680 | 2.680 |
| 18 | 2.440 | 2.450 | 2.450 |
| 19 | 2.440 | 2.450 | 2.450 |
| 20 | 1.980 | 1.980 | 1.980 |
| 21 | 2.350 | 2.360 | 2.360 |
| 22 | 1.450 | 1.460 | 1.450 |
| 23 | 2.350 | 2.340 | 2.350 |
| 24 | 1.970 | 1.960 | 1.950 |

Table #1

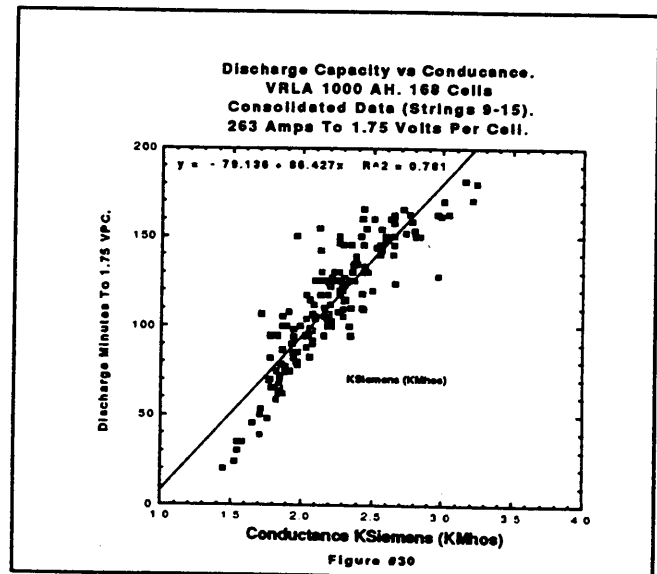
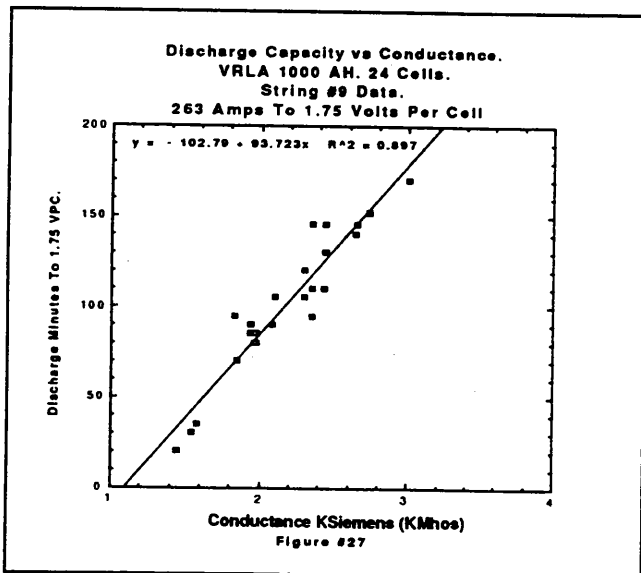
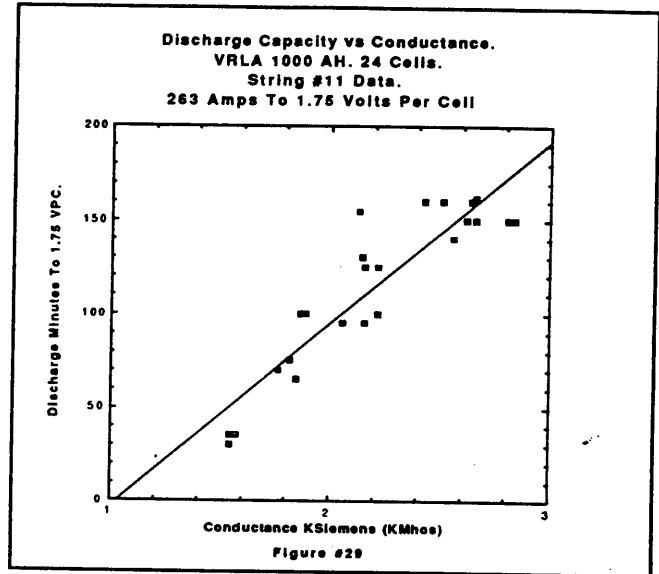
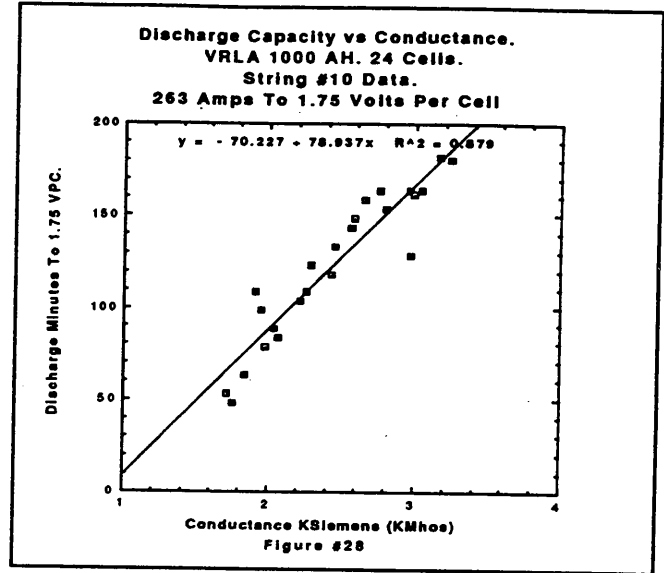


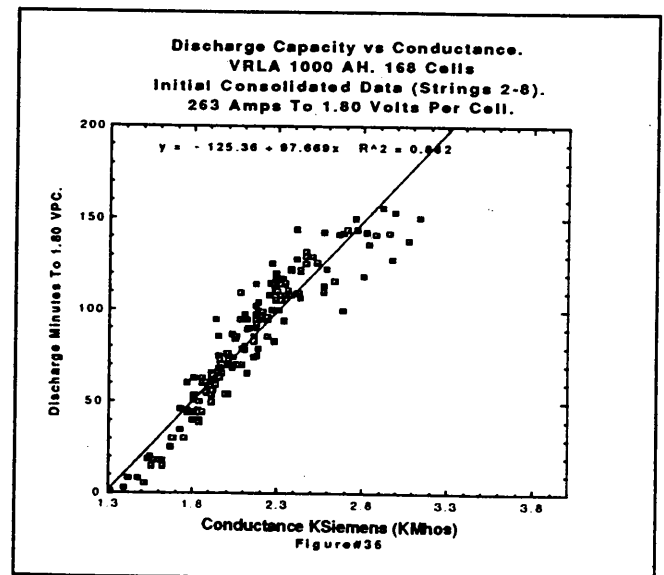
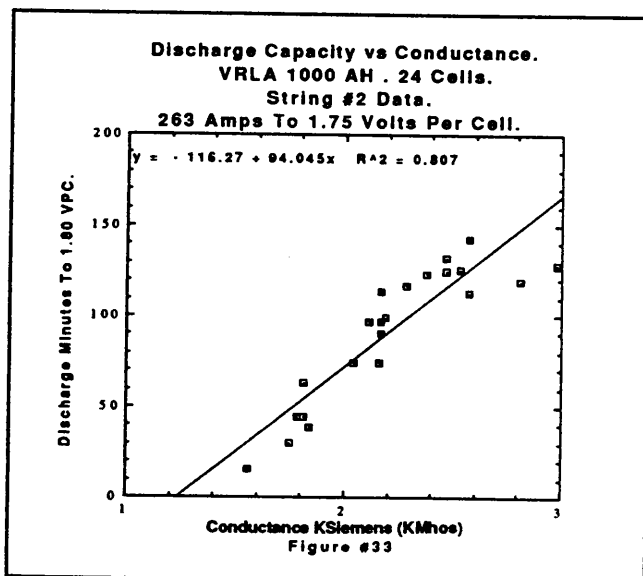
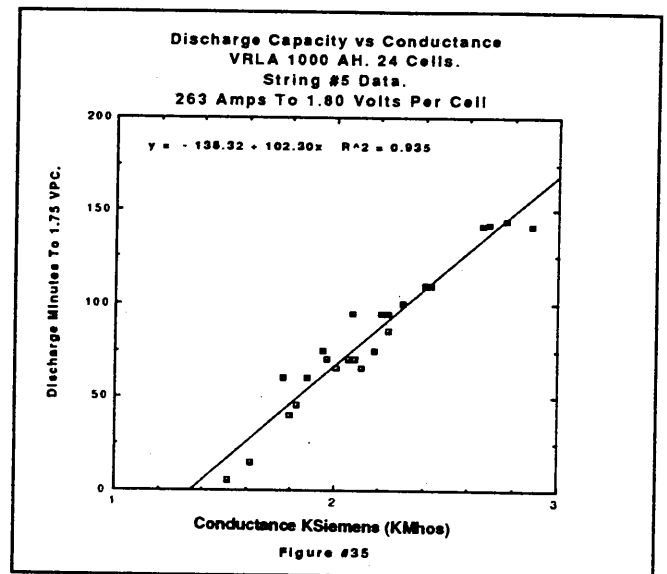
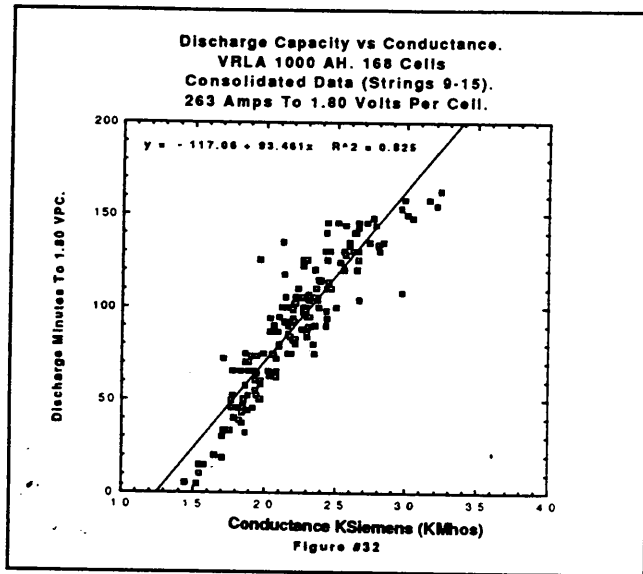
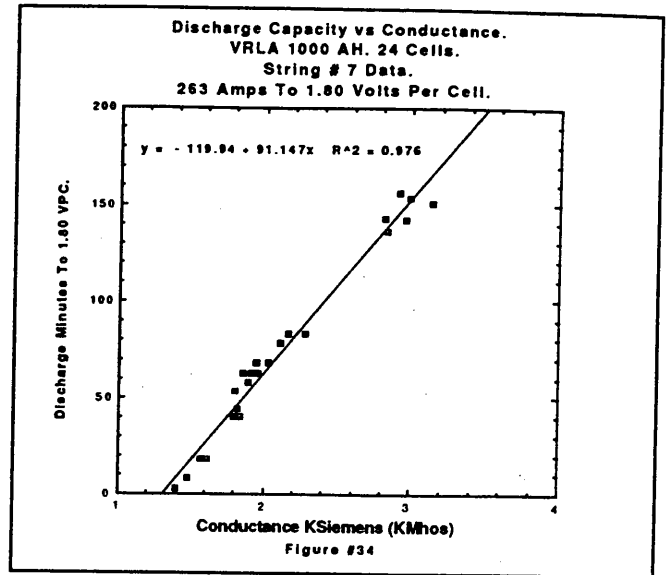
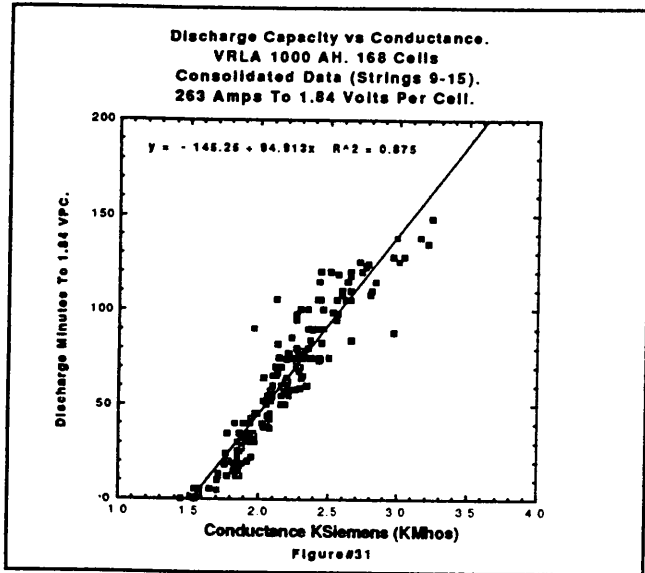
slowly decreasing during the initial phases of discharge and then decreasing more rapidly as the discharge continues to completion.

Instead, for Figures 24 & 25, conductance increases by 5 to 10% for the first 30 to 40 minutes of discharge, then levels off, until cell voltage approaches 1.84, after which conductance drops rapidly. This appears understandable, if one considers the increasing electrolyte conductivity and electrolyte volume which occurs as the specific gravity decreases from 1.300 at full charge to approximately 1.260-1.270 after the first 30 to 40 minutes of discharge. Conductivity then becomes approximately constant until cell voltage drops below 1.84, and then conductivity decreases rapidly. Figure 26, which represents a low conductance and very low capacity cell, shows both voltage and conductance dropping steadily from the start of discharge.

Conductance Measurements as an Indicator of Cell Capacity: Single Cell Measurements

In marked contrast to the lack of correlation with capacity shown by float voltage or specific gravity (Figures 15 to 23), the correlation of capacity and conductance is extremely good. Figures 27, 28 and 29 show capacity vs. conductance for the same strings shown in Figures 1, 2 and 3 with correlation coefficients (R^2) in excess of 0.82. Figure 30 shows correlation of 0.78 between capacity to 1.75 volts per cell and conductance for all 168 cells in strings 9 through 15. Figure 31 and 32 show correlation of conductance with capacity measured to 1.84 and to 1.80 volts per cell respectively for the same group of 168 cells. Again, correlation coefficients range from .83 to .88 for the entire seven strings taken as a group. A similar group of 168 cells in strings 2 through 8 in the same telephone transmission office were also tested at the same current (263 Amps) and capacities measured to 1.80 volts per cell. Figures 33, 34 and 35 show the correlation of capacity vs. conductance for strings 2, 7 and 5, representing the poorest (.80), best (.98), and "typical" (.94) correlations respectively of the seven individual strings. Figure 36 shows the combined correlation of strings 2 through 8 with a correlation coefficient of .88 this entire 168 cell group.



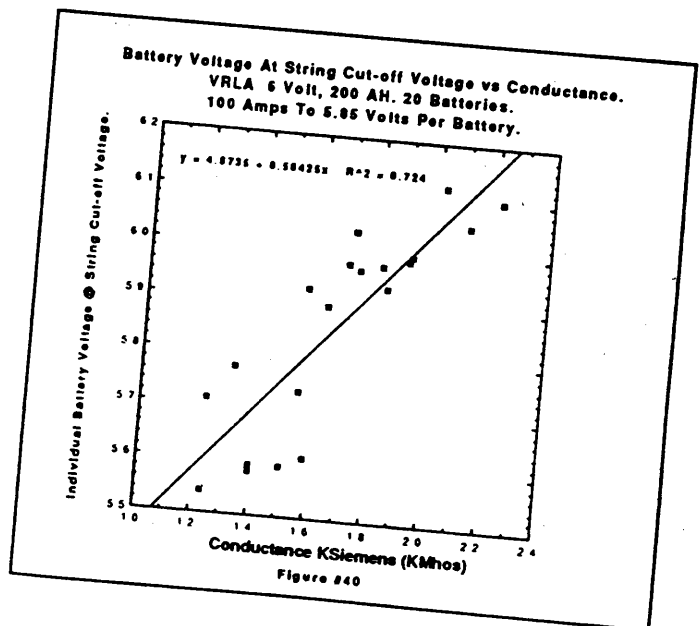
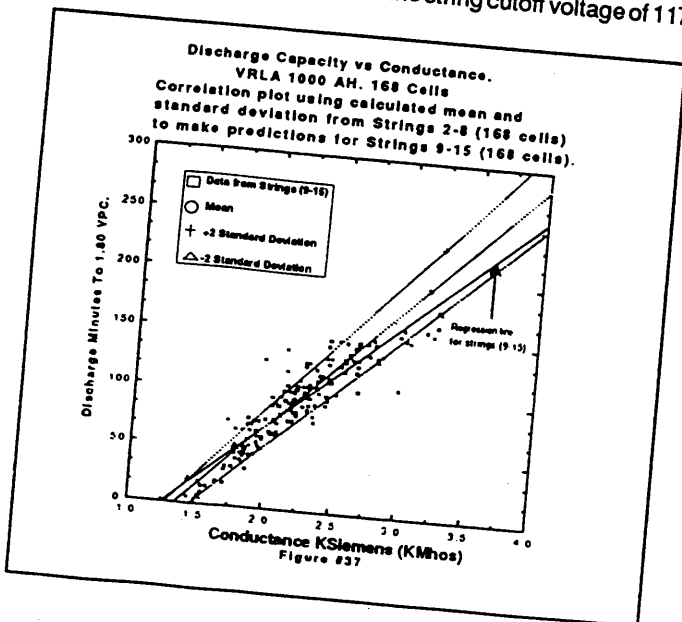
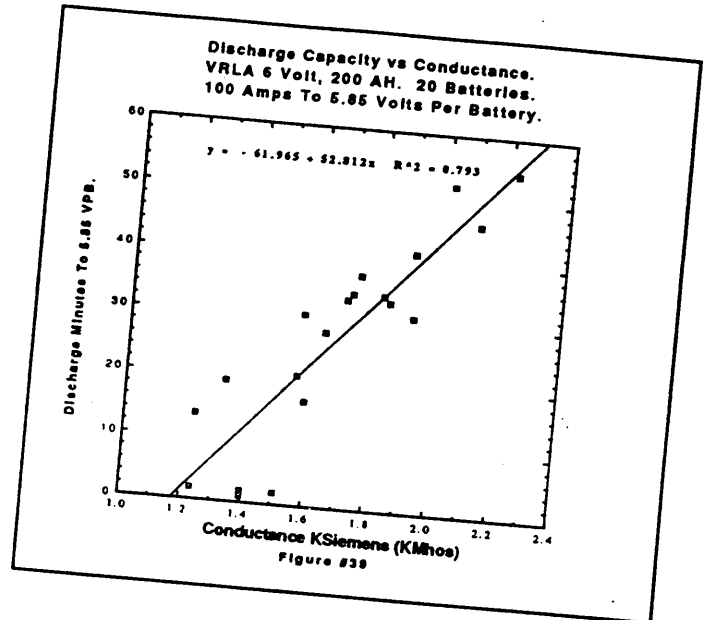
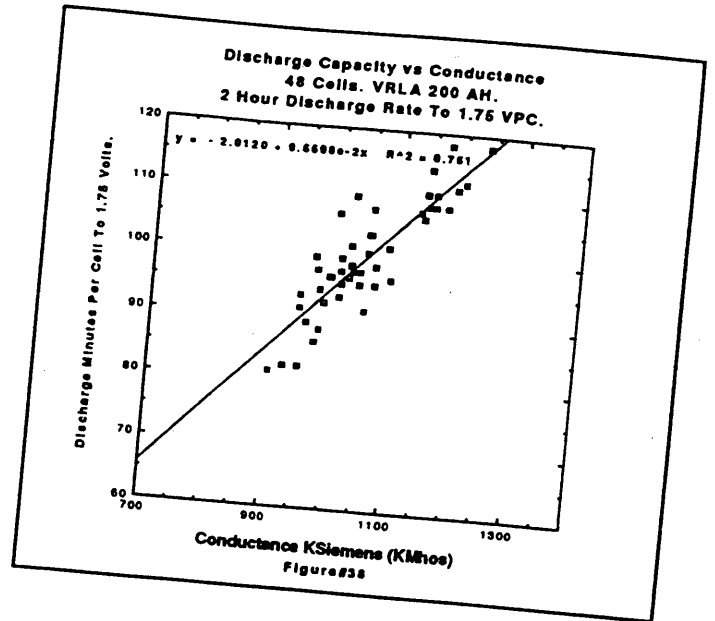


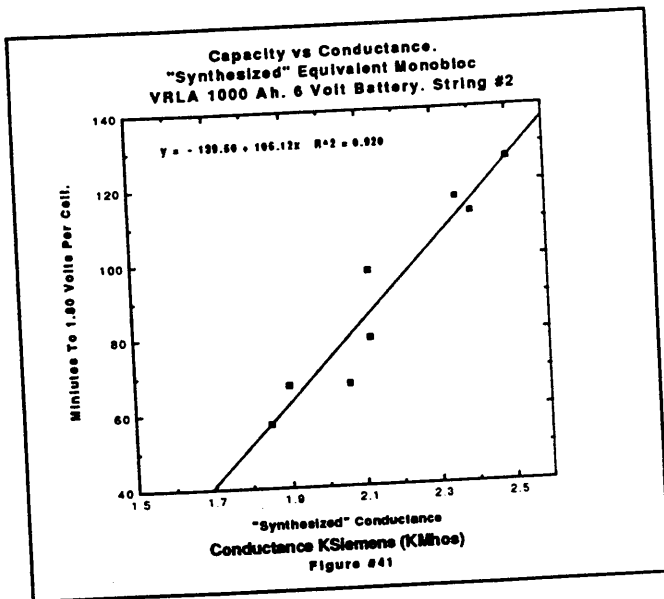
ata from strings 2-8 were used to calculate mean and standard deviation values of capacity for each 0.1 Kmhos conductance interval with results calculated as regression lines for the mean and ± 2 standard deviation values. These statistical calculations were then overlaid (Figure 37) onto the data for strings 9 through 15. This "exercise" provides an indication of the ability to predict the capacity of cells in strings 9 through 15 from their conductance based on the conductance/capacity values of strings 2 through 8. For strings 9 through 15, approximately 90% of the 168 cell population falls within the ± 2 sigma prediction from strings 2 through 8.

Figure 38 shows the capacity/conductance correlation of 0.75 obtained for the 48 200 ampere hour cells for which Figure 23 had previously shown no correlation of float voltage vs. capacity.

Measurements on Multicell Monoblocs

One of the benefits of valve regulated cells is their six or twelve individual units which minimize the number of individual units which must be interconnected. This is especially useful in high-voltage (120 to 360 Volt) UPS applications. The obvious drawback of such a monobloc is the inability to measure individual cell parameters, coupled with the probability that an individual cell failure will require replacement of the entire monobloc, even though the other cells are still functioning properly. In a UPS system, twenty 6 volt 200 ampere hour monoblocs were selected from the top tier of one string from a UPS plant containing three parallel strings of 60 monoblocs each (180 units in all: 60 x 6 = 360 volts per string). These were tested at the published one hour rate (100 amps) to 1.95 volts per cell (5.85 volts per monobloc). Correlation of discharge time to 5.85 volts per monobloc vs. conductance of the monobloc is shown in Figure 39. Again, we see a high degree of correlation of capacity with conductance over a wide range of capacities from three minutes to 55 minutes to the 5.85 volt per unit end of discharge voltage. The 20 cells were discharged in a series connected string to an average of 5.85 x 20 = 117 volts end of discharge voltage. Individual monobloc voltages at the string cutoff voltage of 117





volts are plotted vs. conductance in Figure 40. Again, a significant correlation is indicated.

While the above tests represents the only group of monoblocs tested for both capacity and conductance to date, the detailed data obtained at the telephone transmission site allows us to "synthesize" monobloc results as if eight 3-cell monoblocs per string were being tested rather than the 24 individual cells. By considering cells 1-2-3, 4-5-6, 7-8-9, etc. as "equivalent monoblocs", we can calculate an equivalent conductance and an average capacity for each "equivalent monobloc" and test both the correlation of conductance vs. capacity for individual monoblocs, as well as for the entire string of "equivalent monoblocs". Table 2 shows the results of such a calculation for string 13, compared with actual conductance measurements made with the *Celltron* tester across each three cell group, (as if they were monoblocs). The calculated and measured results are identical, within the precision of the technique. "Synthesized" equivalent monobloc calculations were then performed on strings 2 and 13. Results for strings 2 and 13 are shown in Tables 3 and 4. String data (Figures 41 and 42) show a correlation coefficient of .91 to .95 for the calculated "equivalent monoblocs". Likewise, individual monoblocs with significantly weaker cells show good correlation between degraded average capacity for the specific monobloc and its equivalent conductance for that monobloc.

Relationship between Shape of Discharge Curves and Measured Conductance Values:

Since the conductance and discharge data taken at several sites include a significant number of good, mediocre, poor, and disastrously failing cells, analyses of the shapes of the discharge curves offers the possibility to gain some insight into the failure modes at work. Figures 43 and 44 show two very different sets of discharge characteristics for poor and failing cells. Figure 43 shows discharge curves for three cells with differing conductance values. First, capacity and shape of discharge curve correlate directly with conductance values. However, note that while the two lower conductance cells both fail rapidly at 1.75 volts per cell, their capacity is not lost but is available almost completely at a 1.0 volt per cell cutoff. By

Comparison Of Measured vs 3 Cell ("Equivalent Monobloc") Conductance. String#13.

| Cell Numbers | Calculated Equivalent Monobloc Conductance KMhos (KSiemens) | Measured Monobloc Conductance KMhos (KSiemens) |
|--------------|---|--|
| 1-3 | 2.210 | 2.190 |
| 4-6 | 2.600 | 2.590 |
| 7-9 | 1.970 | 1.950 |
| 10-12 | 1.770 | 1.770 |
| 13-15 | 2.080 | 2.080 |
| 16-18 | 2.230 | 2.230 |
| 19-21 | 2.170 | 2.160 |
| 22-24 | 2.210 | 2.220 |

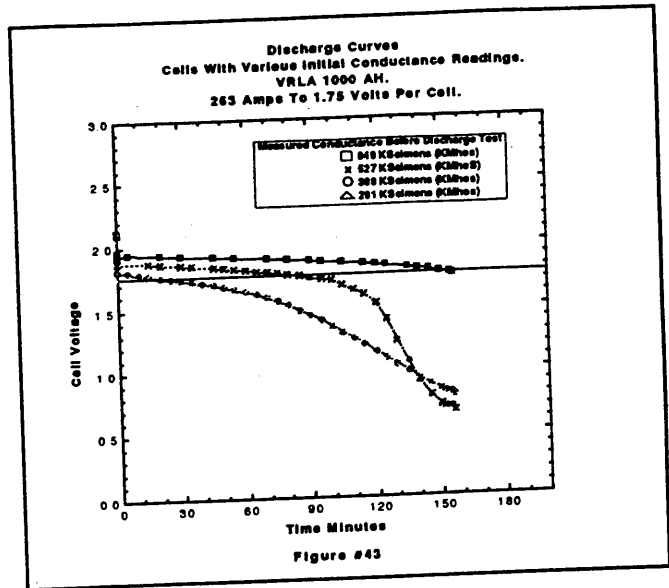
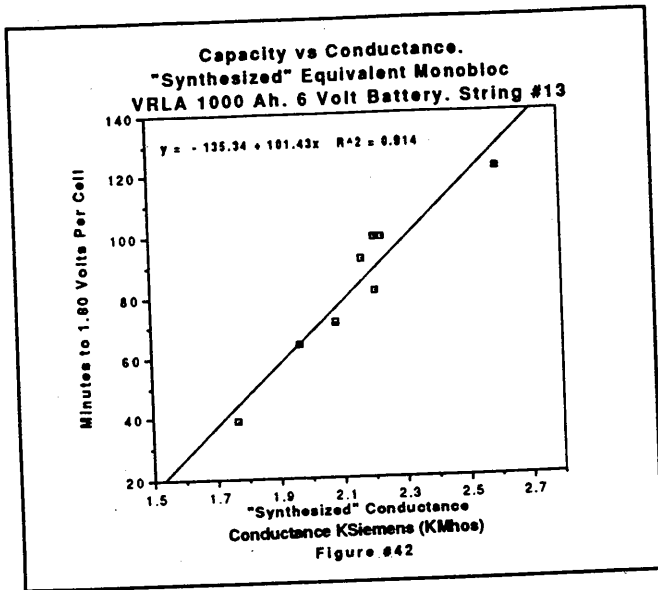
Table #2

contrast, the 5-cells shown in Figure 44 show no such characteristic. There is no indication that the weakest cell has retained its full capacity to a lower cutoff voltage (although 90 minutes to 1.5 volts is clearly superior to 0 minutes to 1.84 volts per cell). Likewise, the other cells do not appear to behave like the cells in Figure 43. Note, however, that the performance to 1.84 volts per cell is directly in accord with the measured conductance values. Finally, four discharge curves are shown in Figure 45 for 225 ampere hour VRLA cells taken from a railroad signaling application. These show a classic pattern of discharge curves taken at increasing current densities. Professor Spinelli's paper⁷ presented at the 1992 ILZRO conference uses computer modelling and documents the effects of

"Synthesized" Equivalent Monobloc (6 volt) Capacity and Conductance. String #2

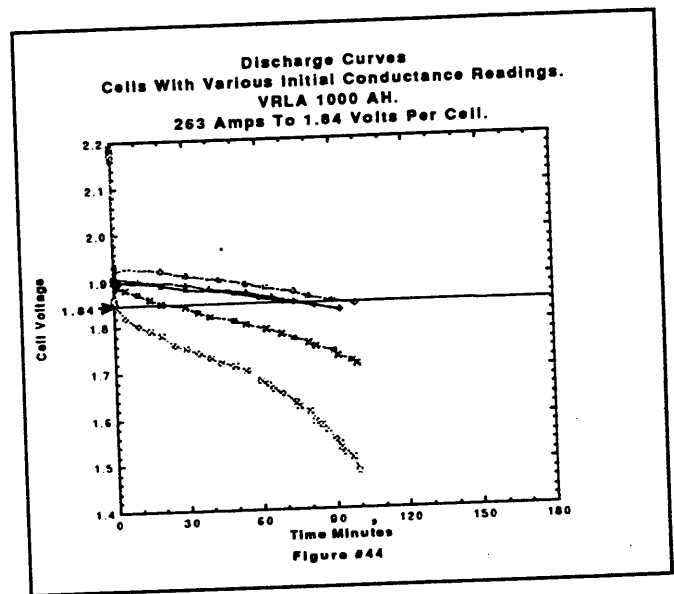
| Cell | Time to 1.80 vpc. Minutes | Average Time to 1.80 vpc. Minutes | Measured Cell Conductance KMhos (KSiemens) | Calculated Equivalent 6 V Monobloc Conductance KMhos (KSiemens) |
|------|---------------------------|-----------------------------------|--|---|
| 1 | 119 | 112 | 2.810 | 2.400 |
| 2 | 117 | | 2.290 | |
| 3 | 100 | | 2.190 | |
| 4 | 44 | 67 | 1.810 | 2.060 |
| 5 | 128 | | 2.980 | |
| 6 | 30 | | 1.750 | |
| 7 | 97 | 97 | 2.170 | 2.120 |
| 8 | 63 | | 1.810 | |
| 9 | 132 | | 2.470 | |
| 10 | 113 | 126 | 2.570 | 2.500 |
| 11 | 123 | | 2.380 | |
| 12 | 143 | | 2.570 | |
| 13 | 97 | 116 | 2.110 | 2.360 |
| 14 | 126 | | 2.530 | |
| 15 | 125 | | 2.470 | |
| 16 | 44 | 67 | 1.800 | 1.900 |
| 17 | 114 | | 2.170 | |
| 18 | 44 | | 1.780 | |
| 19 | 39 | 57 | 1.840 | 1.850 |
| 20 | 117 | | 2.290 | |
| 21 | 15 | | 1.560 | |
| 22 | 74 | 79 | 2.160 | 2.120 |
| 23 | 74 | | 2.040 | |
| 24 | 90 | | 2.170 | |

Table #3



2 times, 4 times, and 20 times increase in discharge current density on the shape of the discharge curves. His calculated curves are shown in Figure 46. The similarity between the two figures (45 and 46) is striking. The obvious conclusion is that the four railroad signaling cells are behaving as though each was being discharged at successively higher loads. Since a constant discharge current was applied to all four cells, it would appear that the current density was increasing by multiple factors (similar to those of Prof. Spinelli's model) from the best to the worst, as a result of the loss of effective active material by any one of several possible mechanisms.

Post mortem teardown diagnostics are scheduled for all of



"Synthesized" Equivalent Monobloc
(6 volt) Capacity and Conductance.
String #13.

| Cell | Time to 1.80 vpc. Minutes | Average Time to 1.80 vpc Minutes | Measured Cell Conductance KMhos (KSiemens) | Calculated Equivalent 6 V Monobloc Conductance KMhos (KSiemens) |
|------|---------------------------|----------------------------------|--|---|
| 1 | 89 | | 2.280 | |
| 2 | 94 | 99 | 2.040 | 2.210 |
| 3 | 104 | | 2.310 | |
| 4 | 114 | | 2.380 | |
| 5 | 104 | 121 | 2.670 | 2.600 |
| 6 | 144 | | 2.780 | |
| 7 | 49 | | 1.860 | |
| 8 | 89 | 64 | 2.200 | 1.970 |
| 9 | 44 | | 1.890 | |
| 10 | 94 | | 2.200 | |
| 11 | 19 | 39 | 1.710 | 1.770 |
| 12 | 5 | | 1.530 | |
| 13 | 39 | 71 | 1.820 | 2.080 |
| 14 | 89 | | 2.310 | |
| 15 | 84 | | 2.180 | |
| 16 | 144 | | 2.570 | |
| 17 | 74 | 99 | 2.070 | 2.230 |
| 18 | 79 | | 2.100 | |
| 19 | 49 | | 1.770 | |
| 20 | 124 | 92 | 2.530 | 2.170 |
| 21 | 104 | | 2.370 | |
| 22 | 94 | | 2.440 | |
| 23 | 84 | 81 | 2.300 | 2.210 |
| 24 | 64 | | 1.950 | |

Table #4

