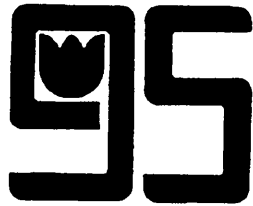


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**VRLA Battery Monitoring
Using Conductance Technology**
**Part IV: On-line State-of-Health Monitoring
and Thermal Runaway Detection / Prevention**

**17th International
Telecommunications
Energy Conference**

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VRLA Battery Monitoring Using Conductance Technology

Part IV of INTELEC Series on battery conductance measurements and their interpretation:

On-line State-of-Heath Monitoring and Thermal Runaway Detection / Prevention

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Abstract:

A new method of monitoring the conductance of batteries while in service will be introduced, showing the effective use of relative conductance measurements to detect capacity loss, reduced state of charge, and the onset of thermal runaway.

1.0 Background:

Since 1992, the authors, in cooperation with the telecommunications industry have tested and published the results of the most significant study of Valve Regulated Lead Acid (VRLA) battery capacity and conductance behavior ever undertaken. These published results ^{1,2,3,4,5,6,7,8,9,10,11,12} demonstrate a remarkable correlation of measured conductance vs. actual timed discharge capacity performance. More importantly, the results demonstrate the utility of using an alternative measurement technique to identify potential VRLA premature capacity failure (i.e. cells and batteries with less than 80% capacity). For the users of VRLA products, these results have exposed an alarming number of cell/battery failures while testing large populations from various manufacturers, in cellular and telecommunications applications of 12 and 24 cell configurations, 25 to 1000 ampere hour sizes, in both uncontrolled and benign (temperature controlled) environments. Fortunately, the results of these studies have brought about heightened user awareness of VRLA battery premature capacity failure and have stimulated the users of VRLA products to call for urgent investigation and corrective actions from the manufacturers. In fact, VRLA product technology is in the developing stage and calls for the user and manufacturer of VRLA technology to closely monitor these products. Clearly, both the user and manufacturer of VRLA batteries have a significant need to better understand the application limitations and seek innovative solutions for improved thermal management, cabinetry design, definition and measurement of battery quality, charging, monitoring and control to allow practical and safe operation of VRLA products in today's telecom operating network. These factors coupled with a competitive business environment, increased requirements for network reliability, objectives for operating cost reduction and dwindling resources for maintenance in the telecom network, attest to the telecom industry's desire for cost effective VRLA battery monitoring and control.

In a recent INTELEC paper¹³, a significant attempt was made to assess the needs of today's remote telecommunications power plant. In that paper the authors provide guidance and general requirements for monitoring telecom remote power plants which include:

1. Flexible modular design.
2. Early warning detection of potential battery failures on line.
3. Thermal runaway protection and compensation.
4. Predictions of battery reserve.
5. Elimination of full discharge capacity testing.
6. Remote access control and safety.

In an attempt to satisfy those requirements, this paper will show data from monitoring operating telecom battery installations in the U.S. This continuing program in cooperation with many U.S. and Canadian Telecommunications companies should, in time, provide significant data showing real operating conditions and battery performance characteristics in remote (uncontrolled envi-

ronmental) telecom plants, particularly in warmer geographical locations in the North America.

One significant area of concern within the telecom industry is thermal runaway. Papers presented at previous INTELEC conferences^{14,15,16,17} have either discussed or demonstrated the susceptibility of VRLA technology to thermal runaway and suggest more consideration be made to thermal management of the battery design and associated cabinetry or enclosure. While many of these papers suggest application of transducers for monitoring of the battery, too little data have been presented to demonstrate the actual results of monitoring. Discussions with many U.S. telecom users of VRLA batteries indicate an alarming number of thermal runaway events have occurred within the telecom industry, in remote applications. Regional Bell Operating Companies, significant users of VRLA batteries, have asked Bell Communications Research (Bellcore), to study the thermal runaway phenomenon. Their studies have resulted in a technical report, GR-1515-Core¹⁸ which describes Generic Requirements for Prevention and Control of Thermal Runaway. The Bellcore studies provide guidance and suggested methods for detection and control of battery thermal runaway using temperature measurements to allow control of the rectifier battery charge voltage.

Ideally one would like to monitor internal cell/battery temperature. However, VRLA products do not allow for nor provide access to the interior area of the cell/battery. In actual practice, it is unlikely that all batteries or cells would be monitored with temperature transducers nor could it be assumed that identification and selection of the particular cell/battery which is most susceptible to thermal runaway be identified and interfaced with the temperature measuring device. It is also reasonable to expect that temperature transducers when installed to the case wall or negative/positive post of a single "Pilot" cell/battery will suffer from thermal lag with respect to the internal element temperature or the ambient reference temperature and require calibration for relative location selection and placement.

Monitoring of battery current suffers several general application obstacles also. Difficulty is often encountered when attempting to physically interface hall effect or clamp-on current measurement devices due to the diverse cabling configurations in telecom applications. Additional difficulty is often encountered with limited clearance within the bussing and connection structures used to interconnect the cells or monoblocs. Shunt devices can suffer from inadequate resolution inherent in the wide range (three to four orders of magnitude) of float, charge and discharge current conditions for which the device must be capable of surviving.

2.0 Transducer Design Characteristics:

Based on the objectives defined in the previously mentioned 1994 INTELEC paper¹³, a monitor system was developed which utilizes conductance measurements to detect loss of charge, the loss of capacity over time, and the conditions which cause thermal problems, and to alarm the user at the time of the loss of conductance, detect and control the onset of the thermal event.

The Midtronics MonitorTM battery monitor measures the battery's relative conductance (as the authors define in a previous paper¹² page 287) in real time, and by using pre-established thresholds, it will alarm the user when the relative conductance drops below an 80% threshold. At this threshold, the device will indicate low warning, indicating either a temporary loss of charge, or a permanent capacity loss. It will provide an additional alarm when a more severe condition is recognized, typically a loss of conductance down to 70% of a standard. These thresholds have been suggested in draft standard 1188: "Recommended Practice for Maintenance, Testing and Replacement of VRLA Batteries for Stationary Applications" currently undergoing final balloting by the In-

stitute of Electrical and Electronics Engineers (IEEE) Standards Coordinating Committee 29 (SCC29). Finally, to identify thermal events, the device measures "high fault" conditions where the relative conductance rises during a thermal event. Typically, this is indicated by a high relative conductance threshold of 120%.

The device was designed to provide alarms when these thresholds are reached, but it is also capable of on-line measurements of actual conductance, relative conductance, voltage, and temperature data for use in these experiments.

The transducer design incorporates a number of new inventions which are covered under a U.S. patent applied for by one of the authors.

3.0 Conductance Measurements:

Previous papers 1,2,3,4,5,6,7,8,9,10,11,12 have shown measured conductance and capacity discharge tests performed on battery plants when removed from service. While this was the selected scientific approach to obtain the data in the previous papers, this process is not the desired practice used in actual field practice. For the purpose of this paper, on-line measurement means that the battery remains on float charge with load equipment in service.

4.0 Measuring Battery Conductance Under Excessive Over-Charge Conditions:

In the majority of U.S. telecom DC power applications, a constant voltage battery charger or rectifier is utilized to maintain both the battery state-of-charge and load equipment. Sometimes chargers, batteries or ventilation systems fail and provide conditions which if left unattended or undetected result in battery thermal runaway. Discussions with experienced users who have witnessed only the aftermath of such events, suggest the following conditions have been observed or reported from the field:

1. Charger failure, for which the battery is subjected to an excessive over-voltage condition resulting in excessive battery charge current.
2. Single or multiple cell internal shorts or path for acid migration (discharge) between two adjacent cells.
3. Failure of power plant ventilation system resulting in excessively high ambient temperatures.
4. Inadequate thermal management of surrounding heat sources, cell/battery design, and cabinetry design.
5. VRLA cell/battery water loss (dry out).
6. Inappropriate float voltage or excessive extended charger equalize settings

Under any one or combination of these possible conditions, the battery could be expected to exceed its "threshold level" where the heat generated internal to the battery is much greater than the ability of the battery to dissipate the heat. Ultimately, these conditions left undetected and uncontrolled will result in thermal runaway.

5.0 Monitron Battery Conductance Monitor Set Points:

The following alarm points were selected as base line criteria to identify potential battery problems. These parameters allow one to define the "safe operating range" for the particular battery installation by observation of relative conductance.

The ranges selected are as listed:

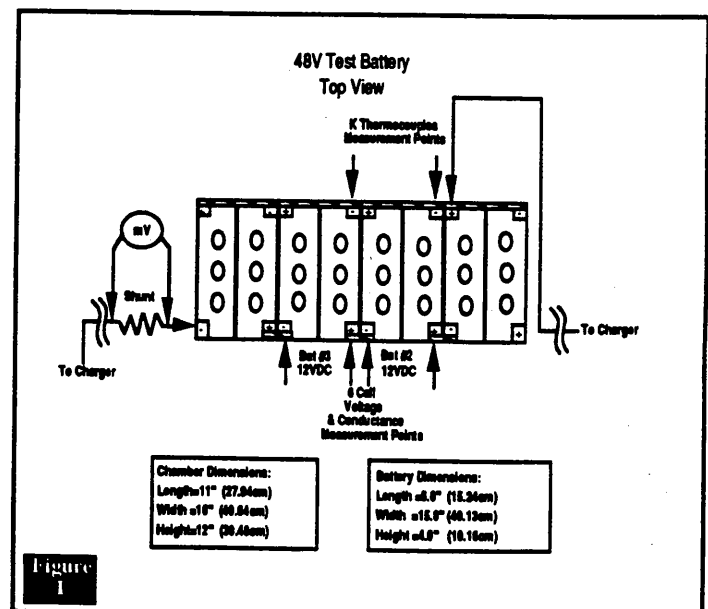
1. A drop to 80% of the conductance on a single 12 volt monobloc from the baseline initiates "Low Warning Condition" a minor alarm dry contact output from the monitor to the maintenance administration location.
2. A drop to 70% of the conductance on a single 12 volt monobloc from its baseline initiates "Low Fault Condition" a major alarm dry contact output from the monitor to the maintenance administration location.
3. An increase to 120% of the conductance of a single 12 volt monobloc from the baseline initiates "Thermal Event Condition" a major alarm dry contact output from the monitor as well as a contact interface to the charger equalize function and lowers the string float voltage to a value recommended in the Bellcore specification¹⁸.

6.0 Thermal Event Test Method Rationale:

Previous papers 2,4,5 have shown that battery conductance increases and decreases in response to battery temperature increase and decrease. This is the premise for investigating the possible use of measured conductance to assess the onset of a thermal event.

In our experiment, excessive over-voltage conditions have been used to compare and contrast the response of several measurement transducers which are considered for detection of VRLA battery thermal runaway. For the purpose of this paper the "thermal event" precedes actual "thermal runaway". Ideally, best case measurement and control should be predictive and provide control of the thermal event rather than to allow thermal runaway which, of course, would be too late. The experimental conditions created were an attempt to simulate and monitor behavior of multiple cell interactions, as configured in series, using constant potential charging methods. These data demonstrate conditions in a laboratory and may or may not be indicative of all possible conditions and behavior.

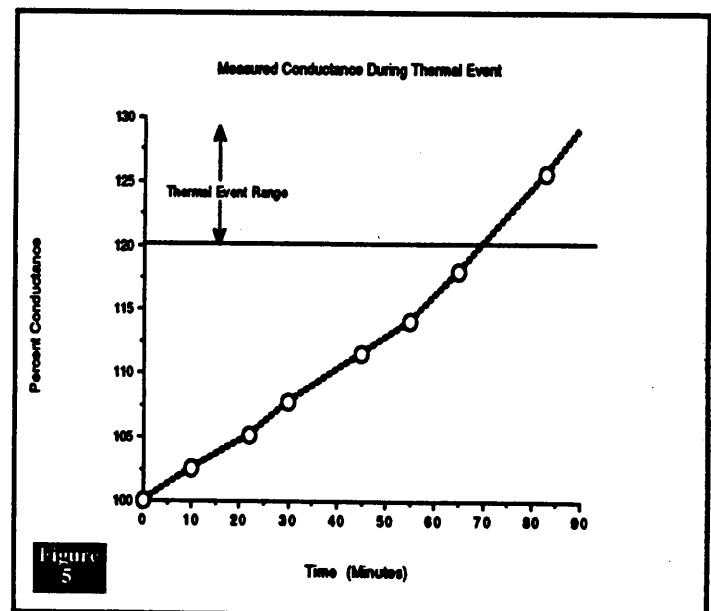
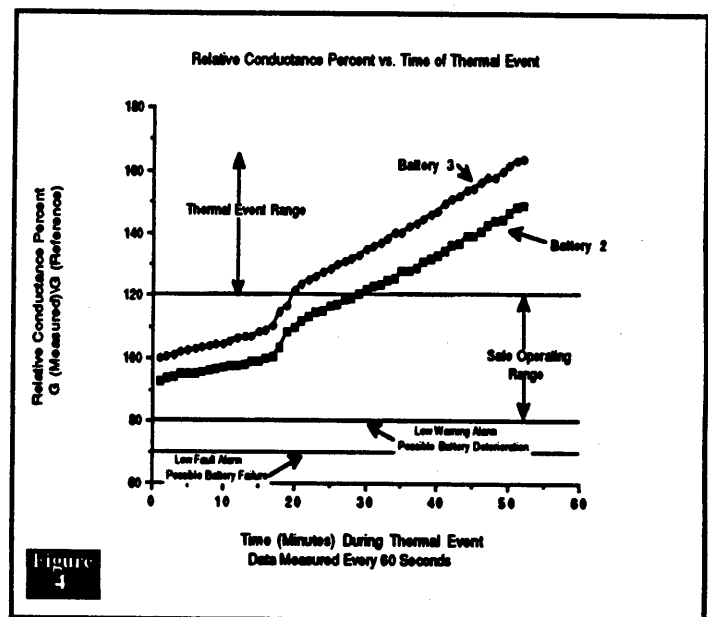
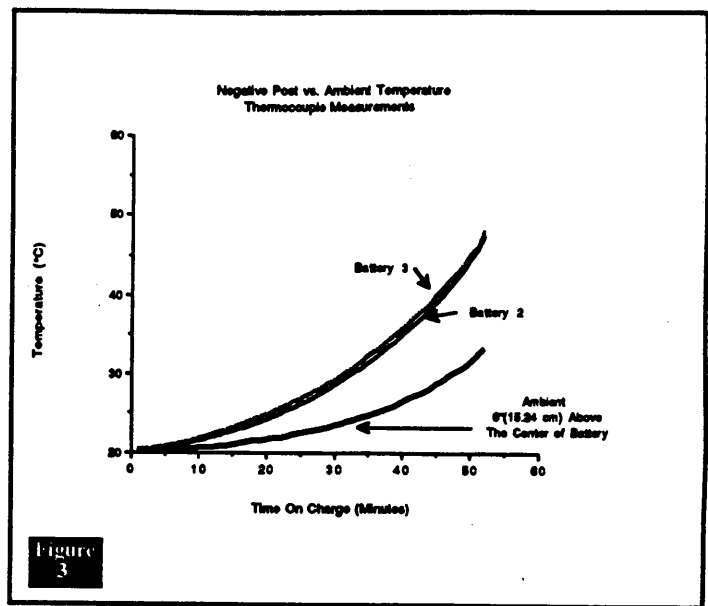
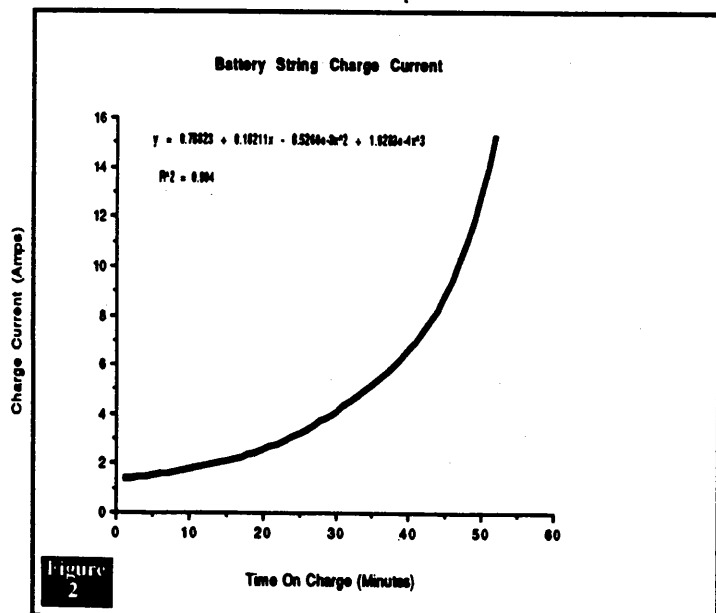
Through the RS232 port, our laboratory data has demonstrated that it is possible to observe the conductance measurements in real time, and our data shows that the rise in conductance is a viable indicator of an increase in internal battery temperature which takes place when a battery is going into a thermal event. Characterization of temperature, current and measured conductance will be shown while a 10 ampere hour 48 volt battery is being subjected to excessive over-voltage conditions. Six cell voltage, current and negative post temperature data were automatically collected using conventional data acquisition techniques i.e. programmable data logger (Fluke Hydra data Logger) and Personal Computer (PC). Data logger channels were configured to measure the individual 12 volt monobloc voltages and negative post temperatures using K type thermocouples. Remote conductance measurements and data acquisition are performed with the Midtronics Monitron battery monitor. Both the Monitron conductance monitor and data logger PC clocks are synchronized for purpose of event data analysis. Preparation of the battery included placing it on charge at 54.4 volts for two weeks. Prior to beginning the experiment, the battery was removed from the charger and left open circuit for 24 hours. For purpose of providing thermal insulation only, the 48 volt battery was placed in an environmental chamber enclosure. All data acquisition wiring and charger cabling were passed through a wire way into the chamber which was subsequently sealed. To excite the thermal event, in a reasonably short time, a constant potential over-voltage of 2.9 volts per cell (VPC) was selected. The over-charge voltage is approximately 0.6 VPC above the manufacturer's maximum recommended voltage at 25°C. Due to the limited charger output voltage capability, only two of the four 12 volt batteries received the overcharge voltage and were fully instrumented. Figure 1 shows the test configuration diagram and identifies the location for all the transducer measurements, battery, charger connection and enclosure dimensions.

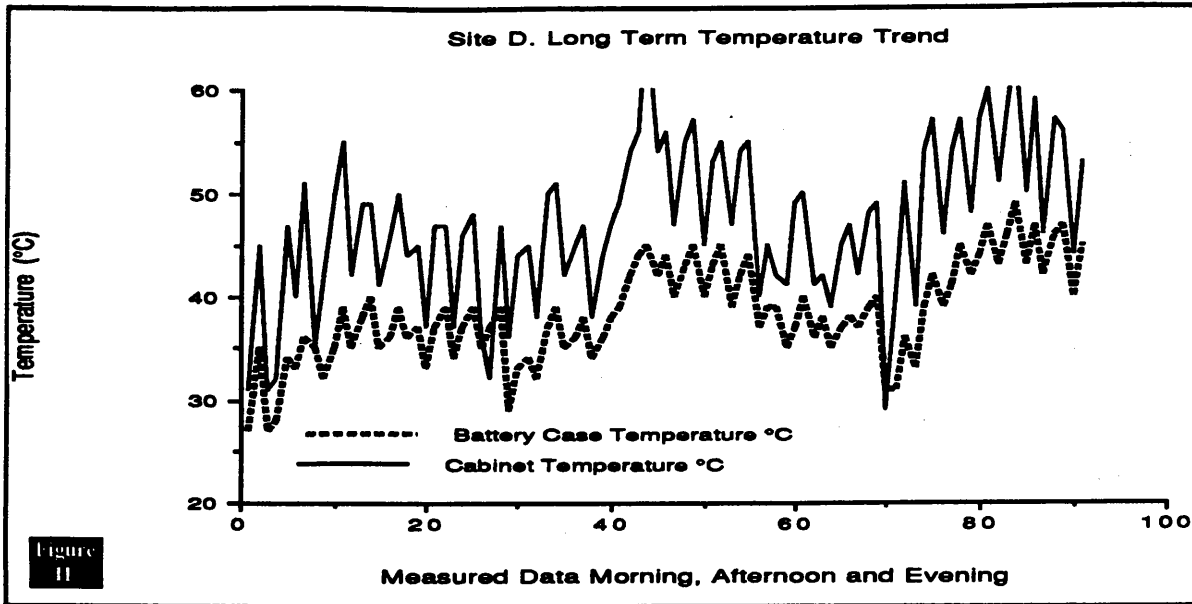


6.0.1 Thermal Event Results:

Figure 2 shows a plot of the charge current into the battery string. As we expected the current profile shows a dramatic increase from 1.35 Amps to 15.4 Amps during the duration of experiment. At 54 minutes the experiment was terminated for safety purposes. Figure 3 shows the thermal lag between the ambient temperature vs. the temperature measured at the negative post and demonstrates the significance of the relative location for placement of these sensors if one were to rely on a relative temperature as a feedback for detection of thermal events. Shown in Figure 4 are the two battery profiles measured during the thermal event. The data from the two monoblocs are now used to show the conductance increase in response to the thermal event. As shown the first battery exceeds the 120% threshold at 20 minutes into the test indicating a thermal event is taking place. Using the control concept proposed by the Bellcore specification¹⁸ the Monitor is capable of sending a control signal to the charger and would cause the rectifier float voltage to drop to a lower prescribed output voltage. The lower output voltage would then reduce the current into the battery and allow for recovery. Although the second battery shows a similar relative conductance profile later into the event, the Monitor would have previously responded to the earlier alarm caused by the first battery. These data demonstrate that such control is viable, using relative conductance.

To try to and understand how the conductance in the first experiment could have increased so dramatically we performed a similar test, on a VRLA 12 volt 40 ampere hour monobloc battery. However, we used a lower charger voltage (2.7 volts per cell) and a thermocouple was actually inserted and sealed into the battery. Figure 5 shows the measured conductance profile during the thermal event. Figure 6 shows the case temperature and the internal battery temperature. Contrasting these results demonstrate the effect of thermal lag between the "ideal" internal battery temperature and an external case temperature sensor and shows the measured conductance increase more closely resembles that of the battery internal temperature. While there is a thermal lag indicated in the difference between the ambient temperature and the case temperature of the battery shown in figure 3, there is also thermal lag between the internal battery temperature and the temperature of the case. Observe the significant incline of the internal battery temperature and the lag period before we observe any appreciable incline of the battery case temperature. What this means is that when a thermal event is taking place, the increased temperature is being generated from within the battery. Since no thermometer or other temperature transducer would be practically inserted into the VRLA battery, it is possible for such a condition to develop to a significant degree before the case temperature of the battery rises enough to be sensed. During this period, significant damage to the battery may take place, and the possibility of a runaway event is significantly increased. While these data represent preliminary results at the time of this publication, further testing is underway to further substantiate these findings and includes using reference electrode measurements under similar induced thermal event conditions.





8.0 Experience Measuring The Deterioration of Battery Conductance and Capacity Over Three Years:

In order to demonstrate the relative conductance as would be measured with a Monitron battery conductance monitor, during battery deterioration over time, a battery plant with known problems, in a cellular telecommunications site was chosen. Every six months since October of 1992, conductance data were measured and recorded for each cell in two 24 volt strings. The equipment used for the first four conductance tests was a Midtronics Celltron CCT20 cell conductance tester, while testing off-line. The latest measurements were performed using the Monitron conductance monitor and confirmed with the Celltron PLUS cell conductance tester which tests the battery while on-line, using a conversion factor which correlates with previous off-line data. The single cell data were gathered together to synthesize the relative conductance of 6 cell monoblocs as would be monitored had the Monitron monitor been available for the whole period. Figure 12 shows a comparison of the four synthesized monoblocs being tested approximately every six months starting in October of 1992, and ending in July of 1995. It can be easily observed that battery G1 started at 100%, and is still operating in the safe operating range at this time. Battery G2 started at 93%, and is today operating at 63% relative conductance, below the low fault alarm threshold of 70%.

Synthesized battery G3 started out below the low warning threshold of 70%, and by July, 1995, it had deteriorated further to 61%, which is below the low

fault threshold. Synthesized battery G4 started out below the low fault threshold, at 67% and by July, 1995, it had deteriorated further to 45% relative conductance.

While the Monitron monitor was not available to make the early measurement these data demonstrate the utility of such a monitor to identify and alarm the user of severe capacity loss. Obviously, it is up to the system owner to decide what action to take when battery failure is indicated.

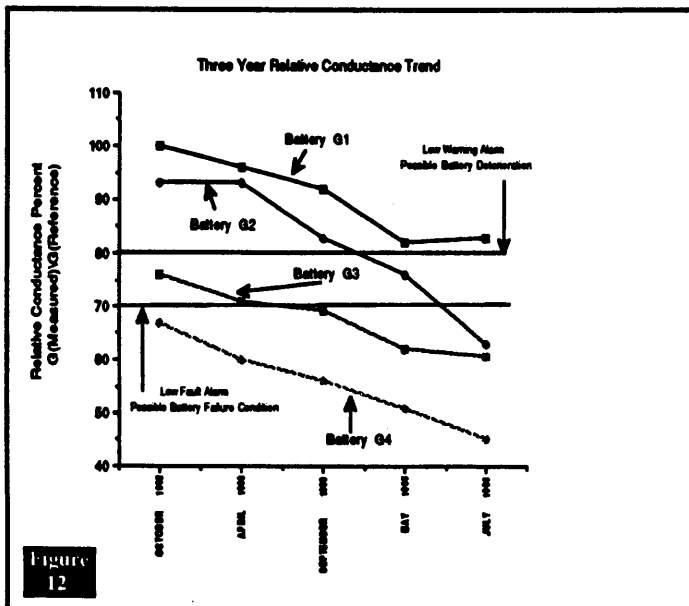
In order to determine the capacity degradation associated with the drop in conductance shown in figure 12, a conductance / capacity correlation plot was prepared from ten 24 volt battery strings of similar size cells, located in 8 cellular offices. The data were grouped into twenty one six cell equivalent monobloc and synthesized equivalent conductance calculated. Using these data and the correlation plot (correlation coefficient $R^2=0.846$), we can estimate that the equivalent capacity of the four 6 cell monoblocs trended above, decreased 25% to 30%, during the three year period.

9.0 Use of Conductance Monitoring During Battery Discharge:

The ability of the conductance measuring device to obtain information on-line without being affected by electrical noise from the rectifier or load, permits conductance measurements during battery discharge and recharge conditions. Comparing the conductance performance, it will be shown that conductance is a much more effective indicator of state-of-charge than voltage is. Such measurements allow us to demonstrate the temporary loss of conductance during such discharge and to demonstrate the viability of alarming the user of such events.

9.0.1 Results While Under Discharge Conditions

In one experiment, an attempt was made to monitor the conductance behavior while performing an 8 hour discharge at a 1.7 amps rate to 10.5 volts on VRLA 15 ampere hour battery. Figure 13 contrasts the conductance and the discharge voltage profile for the duration of the test. One can see the typical discharge voltage profile and the expected break as the battery voltage reaches the 10.5 end voltage. Of particular interest is the measured conductance which shows a very nearly linear profile for the entire duration of the test. This profile continues well past the 10.5 volt cut-off end of discharge voltage. Figure 1 also shows the time at which each alarm threshold is exceeded and in this case would provide the low warning alarm at 2 hours and the low fault alarm at 2 hours well in advance of the end of discharge voltage at this discharge rate which is reached at 7.25 hours. Figure 14 shows a plot of conductance vs ampere hours removed from this battery and shows that an 80% decrease in conductance represents 90% removal of available ampere hours at this particular discharge rate. These data show another possible utility of conductance monitoring under discharge conditions and provide an alternative measurement technique for estimations of power or energy removed during a discharge. The



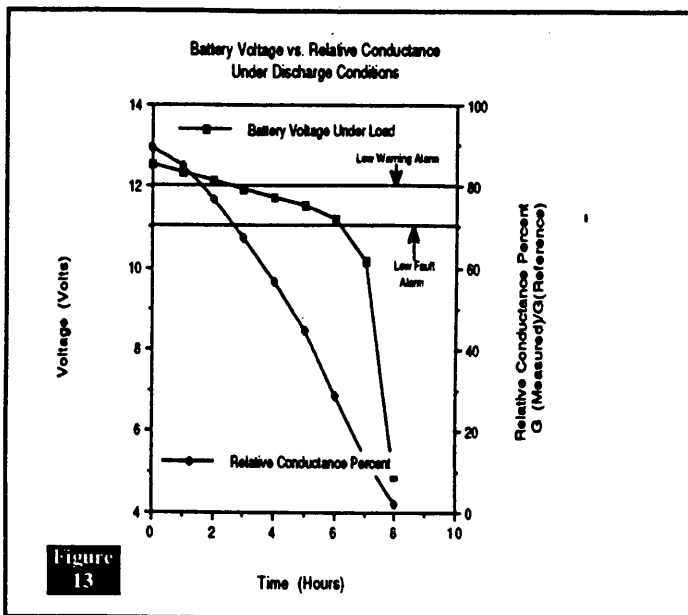


Figure 13

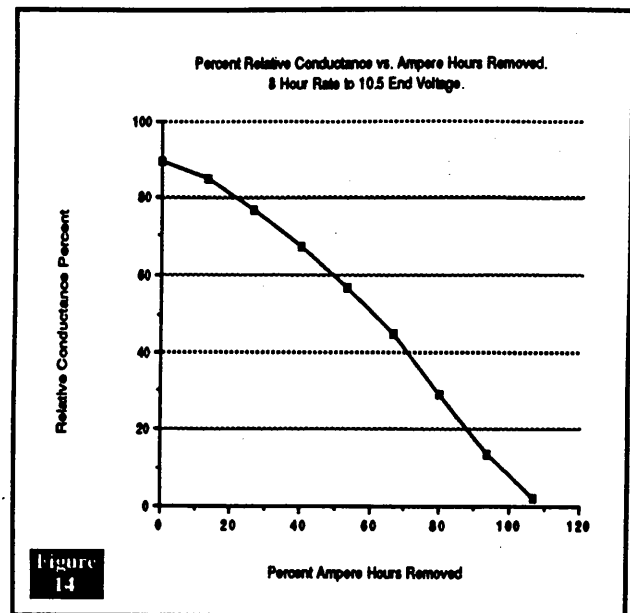


Figure 14

obvious benefit is that continuous relative conductance conditions can be used to trend battery behavior. Trending of conditions are generally difficult to achieve through the use of event-based monitoring systems which generally use historical data to serve as a reference. Event-based monitors must wait for an event to take place to establish what curve it is on and may be too late if an event has not occurred recently.

Conclusions:

1. New technology has been developed which effectively measures the relative conductance of battery systems on-line without regard to electrical noise caused by the rectifier or load.
2. This technology has been effectively designed into a monitoring device which detects capacity loss by observing relative conductance in a similar way to the devices used in earlier studies of battery conductance behavior.
3. Measurements during a thermal event indicate that there is a measurable increase in conductance during the event which can be used to alarm or to control the event before damage is done, and before a thermal runaway takes place.
4. Single day trending of conductance data shows the effect of temperature on battery conductance.
5. Simple graphical presentation of relative battery conductance provides a useful tool in characterizing battery performance during everyday use, including temperature effects, discharge effects, capacity loss, as well as observation of thermal events while they are happening.
6. Trending conductance of 6 cell equivalent monoblocs in cellular use for a three year period indicates a decreasing relative conductance of 16 percent to 30 percent which corresponds to a capacity decrease of 25 percent to 30 percent.

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