Examination of VRLA Battery Cells Sampled From The Metlakatla Battery Energy Storage System

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Abstract:

One of the principal concerns when a Battery Energy Storage System (BESS) is being considered for utility applications is the ability of the battery to provide the anticipated lifetime on which the project was justified. The reason for this is that the battery is a significant cost element in the overall system; and, in the past, the batteries deployed have not been fully able to demonstrate their projected lifetime in these applications. Even though most of the past demonstrations have utilized flooded lead-acid technology which was considered to be matured, unexpected failure modes were often cited for the reduced lifetime of the battery. Valve-Regulated Lead-Acid (VRLA) batteries are becoming more widely utilized and are displacing flooded lead-acid technology in applications ranging from typical standby usage such as emergency lighting, telecommunications backup and Uninterruptible Power Supply (UPS) to more cyclic usage in photovoltaics and other renewable energy systems and even in electric vehicles. Hence, there is a high probability that future BESS projects will utilize VRLA technology. The purpose of this paper is to discuss the surveillance studies conducted by GNB and Sandia National Laboratories on VRLA cells in a BESS installation to assess their progress, after almost three years of operation, in meeting their projected lifetime.

This project was funded in part by the DOE Energy Storage Systems Program.

1. Background

For the past several years, GNB has been intimately involved, in conjunction with Sandia National Laboratories, in developing the concept of battery energy storage as a way to supplement and improve the quality of power received from the utilities. In the past, battery energy storage systems were viewed simply as a way to supplement generation capacity for the utility to meet demands during periods of high electrical usage. In many cases, operation in this limited mode alone could not justify the cost of a BESS. In the more recent vision for battery energy storage, its use has been broadened to correct on-going power quality issues, in addition to providing a reserve of energy for uninterrupted power supply, peak shaving and load leveling. By introducing these additional functions, a BESS can be a viable alternative to other power management solutions. To achieve these objectives however, it would be necessary to construct and operate the battery in an unconventional manner.

First, the BESS would have to be integrated with the utility power feed so that its operation appeared seamless to the power user. This requires that the battery system be at a relatively high voltage. Second, the battery would have to be continuously operated in a partially discharged state, often for months without any equalization recharge, so as to efficiently accept power from the grid as well as to rapidly deliver power to the utility grid to instantaneously correct any power quality issues. These operating conditions in many respects are contrary to what has long been the belief to realize maximum battery lifetime and performance.

In 1996-97, GNB installed and commissioned a large VRLA battery system for a Battery Energy Storage System (BESS) at the island village of Metlakatla, Alaska [1]. The battery's function is to stabilize the island community's power grid providing instantaneous power into the grid when demand from a local sawmill is high, and absorbing excess power from the grid to allow its hydroelectric generating units to operate under steady-state conditions. This nominal 756-volt system is capable of providing 1.4-MWh at about the battery's 90-minute discharge rate. Because the battery is required to randomly accept power as well as to deliver power on demand to the utility grid, it is continuously operated at between 70 and 90% state-of-charge. Equalization charges are conducted during maintenance periods scheduled only twice each year.

Recently, after nearly three years of continuous operation, several cells were sampled at random from the battery and examined. When these samples were taken, the battery's monitoring system indicated that the battery had been maintained at about 75-85% state-of-charge over the entire time period and had received only three equalization charges since its installation. This paper will review electrical testing conducted on the battery samples as well as the results of extensive physical analyses performed on the battery materials and components.

2. How The BESS Solves Metlakatla's Problems

The Metlakatla BESS is located in the community of Metlakatla on the Annette Island Reserve at the southern tip of Alaska. Metlakatla Power and Light (MP&L), a stand-alone island electric utility, operates the BESS to supplement its generating facilities. The primary generation source for the utility is 4.9-MW of rain-fed hydroelectric capability. In addition to its residential customers, MP&L supplies power to a commercial cannery and cold storage facility, and to the Annette Hemlock Mill, a commercial lumber mill operation. The BESS is used to provide instantaneous power to the utility system to satisfy the random instantaneous load demands of a log chipper at the mill without causing brownouts or overvoltage conditions to the remainder of the utility's customers.

In an attempt to solve their power quality problems, MP&L 15 years ago installed a $2 million, 3.3-MW diesel generating system to work in conjunction with their hydroelectric units. With the addition of the diesel generator, MP&L's total generating capacity came to just over 8-MW, twice the average base load on the utility. But to achieve reasonable efficiency for the diesel, a greater portion of the utility's base load had to be shifted from the less expensive hydro generation to the more expensive diesel. Even with the addition of the diesel, electrical frequency often drooped to less than 57-Hz, and system voltage remained very erratic.

Operation and maintenance costs for the diesel added to the problem. Fuel cost was $360,000 to $400,000 per year. Transporting 475,000 gallons per year of diesel fuel by ferry from the mainland, and then through pipe across the island increased both the environmental risk and the financial burden to the community. Each fuel shipment required an average cash outlay of $100,000 – a significant amount for a small local utility. In addition, minor overhauls to the diesel cost $150,000 every three years; and major overhauls every six years cost $250,000.

A feasibility study was conducted by GNB Technologies and General Electric Company with assistance from Sandia National Laboratories that compared battery energy storage to other options using only the existing hydro and diesel units. The study indicated that a 1-MW, 1.4MWh battery energy storage system (BESS) could provide the spinning reserve, frequency control, and power quality improvements that Metlakatla needed. The study concluded that the cost of the BESS could be recovered within three years based on operational cost savings alone.

2.1 The Metlakatla BESS Battery

The battery at the Metlakatla BESS facility *(Figure 1)* consists of 378 GNB ABSOLYTE® IIP 100A75 modules arranged in a single series-connected string providing the system with its nominal 756-volt rating. The 100A75 cell has a nominal C/8 capacity rating of 3,600 Ampere-hours; its rating at the intended 90-minute discharge rate for this application is approximately 2,000-Ah / 3.87-kWh. The entire battery system is rated 1.4-MWH at a 1.0-MW discharge rate. Each 100A75 cell is comprised of three individual 100A25 cells connected in parallel within the cell's modular container, thus providing a statistical population base of 1,134 samples.

The battery connects to a General Electric power conversion system (PCS), based on gate-turn-off (GTO) thyristors, that can support a continuous load of 800-kVA and pulse loads of up to 1200-kVA. The PCS allows bi-directional power flow between the ac system and the battery in less than a quarter-cycle. A 900-kVA filter bank removes harmonics and compensates the voltage of the electrical signal. The BESS connects to the MP&L grid at a 12.47-kV substation. The battery is housed in a 40 x 70-ft steel Butler building that sits on a concrete pad at the substation. An automatic generation control (AGC) system provides computerized control and dispatch of MP&L's hydro and diesel units as well as the BESS for optimum efficiency. The AGC can be remotely accessed to monitor the status of the battery bank.

The battery's 378 cells are arranged in two back-to-back rows, each row comprised of twelve stacks of ABSOLYTE modular trays eight high, separated by an aisle. The battery is positioned to minimize cable runs between rows of battery stacks and to the power conversion equipment. Pilot cell and temperature measurements are made at

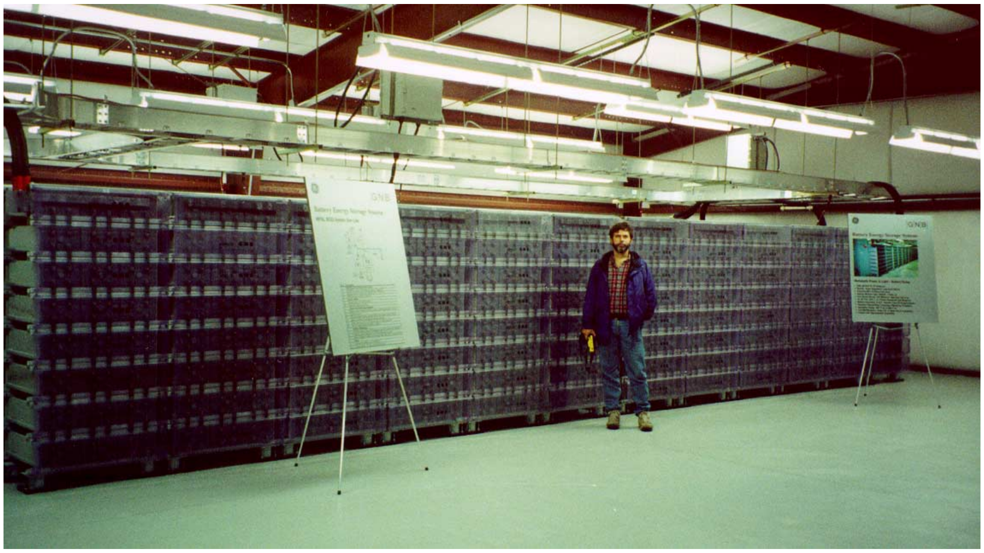

Figure 1

The battery at the Metlakatla BESS consists of 378 GNB ABSOLYTE IIP 100A75 modules connected in series to deliver 1.4-MWH at a 1.0-MW discharge rate at a nominal 756-volts.

locations strategically positioned throughout the battery bank. Air is circulated by a fan to maintain consistent temperatures within the building. A heater is provided to warm the facility during the colder winter months; however, only outside air is circulated to provide forced convection cooling.

Operation of the Metlakatla BESS battery started in February, 1997, and except for a few short periods when the system has been purposely shut down for maintenance to either the battery or the system's electronic inverters, it has operated continuously since its commissioning. Warranty on the battery is based on an 8-year service life.

2.2 Typical Operation of the BESS Battery

The BESS was designed to be connected continuously to the MP&L grid. From a fully charged condition, the battery is first allowed to be discharged to about an 80% state-of-charge (SOC). After reaching that point, the battery is then allowed to accept recharge from the grid when load demand is less than the output of the hydroelectric units. The BESS PCS inverters draw power from the battery to instantaneously satisfy surge events on the grid. The BESS AGC computer monitors the current flowing out of or into the battery and automatically adjusts the output of MP&L's hydroelectric units to essentially maintain the battery at about its 80% SOC point. The control algorithm assumes a 100% charge acceptance efficiency of the battery as it accepts charge at an SOC less than 90%. The charge algorithm that is used to control the recharge of the battery during operation is summarized in *Table 1*. The power limitations of the PCS equipment itself is the only factor that limits battery discharge current.

TABLE 1

BESS Recharge Control Algorithm

Step	Mode	Control Parameter	Limit / Transition
1	Current	35A/100Ah	to 2.25 vpc
2	Current	25A/100Ah	to 2.32 vpc
3	Voltage	2.32 vpc	18A to 2A/100Ah
4	Voltage	2.25 vpc	Continuous
Equalization	Voltage	2.35 vpc	2 Hours Twice Per Year

The PCS provides both active and reactive power to counter load swings created by the log chipper. The BESS sources watts and VArs when the system load jumps higher than the average, and sinks watts and VArs when the load falls below the average. Because the BESS' resultant net output is nearly zero, the batteries require little additional charging. When required, the AGC dispatches the hydro units to provide the minimal overcharge the battery requires. Operation of the battery is shown in *Figure 2*, which shows the printout of the battery system screen for a typical day.

Figure 2

Printout of the Metlakatla BESS battery monitor screen showing system operation on a typical day. The dark line in the center of the screen represents the current flowing into and out of the battery.

3. Sampling Cells from the Metlakatla BESS

In October 1999 (approximately 32 months after system start-up), GNB and Sandia conducted a planned surveillance sampling of cells from the Metlakatla BESS battery. When the cells were sampled, the AGC computer indicated a total output from the battery of 745,735-Ah; total charge input to the battery was reported by the computer to be 751,468-Ah. Four individual 100A25 cells were selected from various locations within the battery to represent positions where variations in temperature had been observed and recorded by the battery monitoring system. The monitor system indicated that the battery was at about 78-81% state-of-charge when the cells were sampled. The samples were purposely taken prior to an equalization charge in order to assess the accuracy of the monitoring system's state-of-charge algorithm.

The open circuit voltage measured on the cells (2.089 – 2.099 volts) correlated well with the monitor's approximation of battery state-of-charge. Previous testing at GNB had shown that new ABSOLYTE cells allowed to self-discharge to an open circuit voltage of 2.09-volts were able to deliver 78.5% of their nominal 1-hour capacity rating. The internal impedance of the cells was measured at an average value of 262-μohms; the nominal impedance for this size cell is 229-μohms.

After the sample cells were removed from the battery string, they were shipped from Metlakatla to GNB's laboratories in Lombard, Illinois – a suburb of Chicago. Spare cells that were being maintained at the Metlakatla BESS facility were used as replacements for the sampled cells. After arriving at the laboratory, the open circuit voltage, impedance and weight of each of the sample cells was recorded. No significant change in open circuit voltage or internal impedance occurred during transit, and cell weights were within the accepted tolerance range for this size cell. One of the cells was retained in the "as received" condition for teardown, visual inspection and chemical analyses. The remaining three cells were reassembled into appropriately sized module trays for further electrical testing and characterization.

4. Electrical Characterization of Sampled Cells

The three cells sampled from the Metlakatla BESS were connected together in series to form a 6-volt battery. The battery was then discharged, without any refreshening or boost charge, at 150-Amps, its nominal C/8 rate. On this first, "as sampled" discharge, the test battery delivered 766-Ah or 63.9% of its rated capacity. All three of the cells performed similarly *(Figure 3)*. The delivered capacity was less than the residual capacity estimated to be available from the cells by the BESS monitoring system. However, since the monitoring system estimates battery state-of-charge simply by summing ampere-hours discharged and charged, some error is to be anticipated especially considering the 6-month interval over which the estimate was made. The monitor resets to 100% state-of-charge following an equalization charge.

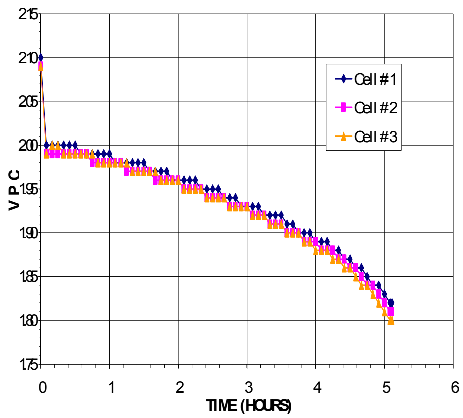

Figure 3
Cells sampled from the Metlakatla BESS delivered 64% of their rated capacity without any boost charge after being operated in a partially discharged state for over 6 months.

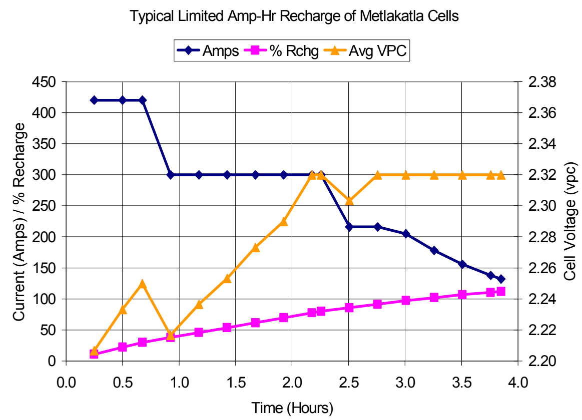

Figure 4
Data recorded during a limited ampere-hour recharge of the Metlakatla sample cells shows their ability to readily accept high levels of charge current even at relatively low charge voltages

4.1 Charge Acceptance Test

The next objective was to determine if operating the battery in a partially discharged state for extended periods had caused any permanent deterioration of the battery. It is widely thought that failing to adequately recharge a lead-acid battery can cause "hard" sulfate to form within the cell's active materials. This would hinder recharge acceptance, especially at low charge voltages, and result in a permanent reduction in the battery's capacity.

On the next several charge / discharge cycles, the amount of recharge was intentionally limited to 112% of the previous capacity discharged. The recharge profile used was the same as programmed for the BESS at Metlakatla *(see Table 1)*. In this way it would be possible to determine the efficiency of charge acceptance of the battery even when the amount of available recharge was limited. The actual C/8 discharge capacity as well as the percentage increase over the previous cycle is summarized in the following table where the recharge ampere-hours have been intentionally limited to 112% of the capacity previously discharged.

TABLE 2
Charge Acceptance Test Results

Discharge #	Discharge Ah	% Rated	Recharge Ah	Capacity Increase
1	766.5	63.9	858.6	-
2	856.9	71.4	959.8	111.8%
3	945.0	78.8	1,058.5	110.3%
4	1,023.0	85.3	N/A	108.3%

The data shows the partially discharged cells accepting almost the full amount of overcharge provided them during each of these limited recharge experiments, with the capacity increase of the cells essentially being equivalent to the amount of overcharge provided. As the cells' capacity increases and approaches a fully charged state, overcharge acceptance efficiency starts to decrease. Interestingly however, these experiments demonstrate an almost 100% ampere-hour charge acceptance efficiency for these samples even after having been operated in a partially discharged state for over 6-months. It is important to appreciate that the recharge voltage during these experiments was limited at 2.32 volts per cell, and that the actual recharge time for each of the recharges was less than 4 hours. Data from a typical recharge where recharge was limited to 112% of the capacity discharge is shown in *Figure 4.*

4.2 Discharge Performance after Equalization Charge

Following the last of the four "limited recharge" cycles, the sample cells were given a standard equalization charge in accordance with the recommendations in the battery operating manual. The test samples were then discharged at the nominal C/8 discharge rate delivering 99.3% of rated capacity to a cutoff of 1.75 volts per cell. The samples were subjected to four additional discharge cycles, and the battery continued to deliver, on average, 101.9% of its rating. In addition to these capacity discharges, the sampled cells were subjected to a series of discharges to verify capacity conformance at various discharge rates. Average compliance to published specifications for this size cell was 105.6% for discharge rates ranging from C/1 to C/24. These discharge data indicate that the cells sampled from the Metlakatla BESS after over 30-months of operation, most of which was continuously cycling between about 70 and 90% state-of-charge, met or exceeded all of the performance specifications for this size cell. Based on these electrical characterizations, it was concluded that there had been no deterioration or damage done to the cell as the result of the unusual manner in which these cells were operated.

4.3 Total Capacity Discharged

Based on cycle life testing conducted at GNB, the data suggests that each unique battery design has a certain lifetime discharge "throughput" that is somewhat independent of discharge rate or depth of discharge [2]. For the ABSOLYTE IIP design this discharge throughput is equal to approximately 1,000 times the nominal C/8 capacity of the cell in ampere-hours; approximately 3.6 million Ah for the 100A75 configuration installed at Metlakatla.

In order to maintain the power quality of MP&L's grid, the BESS battery is required to be alternately discharged and charged to supplement the fixed output of the hydroelectric generating units to meet the variable customer demand on the utility. The BESS monitoring system continuously monitors and integrates current flow into and out of the battery string. The total capacity discharged from the battery since its commissioning was reported by the monitoring system as being 745,735-Ah. Thus it is possible to estimate the amount of "cycling" the cells have experienced and to estimate the discharge "throughput" for the cells at the time they were sampled as being approximately 21% of its lifetime capability. This information will be helpful when the condition of the cell plates is examined.

5. Internal Examination of the BESS Cells

Two of the sampled cells were torn down for physical and chemical analyses – the cell retained in its "as received" condition, and one of the cells that had completed the electrical testing described previously. Both cells were examined at the same time to allow visual comparisons to be made. Sandia personnel assisted during these examinations.

<u>Overall Observations.</u> Both cells appeared "normal" after the covers were removed. The cells were tightly compressed within the cell jar. All plates were completely encapsulated by the glass mat separator. There was no evidence whatsoever of any strap, terminal post or plate lug corrosion. There was no free liquid electrolyte in either of the cell jars once the cell elements were removed.

<u>Negative Plates.</u> Negative plates sampled from three locations within the cell element stack were examined from both cells. All of the negative plates exhibited normal "wetness" as demonstrated by pressing the plates to observe a "halo" of liquid electrolyte around the finger being pressed onto the plate. Negatives from the cycled cell exhibited a shiny metallic streak when tested by striking across the surface of the plate with a hard object. Plates from the "as received" cell also exhibited the metallic sheen, although not quite as shiny as that observed on the cycled cell. Chemical analysis of the "as received" cell negative plates indicated a lead sulfate content of approximately 28% which correlates well with the discharge capacity delivered by the other cells in their initial capacity test. The lead sulfate content in the negative plates from the cycled cell was approximately 10% which is typical for a fully charged VRLA cell.

<u>Positive Plates.</u> Positive plates from neither of the cells showed any visible signs of surface sulfation that might have developed over the time during which these cells were operated at Metlakatla in a partially discharged state. Plates from both of the cells were dark brown to black in color. Although the positive paste on the "as received" cell visually appeared to be slightly drier, the active material on both cells' plates was firm and crispy.

X-ray diffraction analyses of the active materials indicated greater than 89% PbO_2 for the cycled cell and 66% for the "as received" cell. Wet chemical analyses matched with the x-ray data and indicated 12% lead sulfate in the cycled cell and 29% lead sulfate in the "as received" sample. Both the negative and the positive active materials were what should be expected for cells considering their operational history and treatment prior to analysis.

Positive Grids. Samples of the positive grids from the sample cells were taken, cross sectioned and polished to determine the amount of corrosion that had occurred over the lifetime of these cells. An example of the minimal amount of positive grid corrosion that has occurred is shown in *Figure 5.*

Figure 5
Cross section of the positive grid from a Metlakatla BESS cell shows a minimal amount of corrosion after 30 months of operation

Figure 6
Negative plate straps from the Metlakatla BESS cells were examined. These critical connections between individual plates and the current collector exhibited no oxidation corrosion whatsoever.

Measurement of the corrosion layers indicate a corrosion thickness of approximately 0.13 – 0.18mm. Compared to the corrosion rate basis of 0.08mm per year used to determine the design life for the ABSOLYTE IIP product, the actual corrosion rate for these cells was 0.05 to 0.07 mm/yr. These measurements indicate that the rate of positive grid corrosion with the Metlakatla operating and charge regime is less than that experienced under pure "float" conditions. Dimensions of positive grids from both cells were measured to assess the extent of positive plate growth. Growth in the long dimension of the grid was less than 0.4%; growth in the short dimension was less than 0.12%. In either case, the amount of positive grid growth was much less than the 6% allowance provided in the design of the cell.

It is important to note that the accelerated corrosion that was of concern because of the battery's operation in a partially discharged condition (as suggested by the shape of the Lander's curve), is not being observed. If anything, the amount of positive grid corrosion that the samples exhibited was less than what would have been expected even under ideal float charge conditions with temperature and float voltage strictly maintained.

Separator and Electrolyte. The glass mat separator on both cells was adequately wetted. There was no excess free liquid electrolyte observed in either cell. Concentration of the sulfuric acid electrolyte solution from the cycled and charged cell averaged at 1.309 s.g. Variation in concentration between the "top" section of the separator and the "bottom" section was approximately 0.006 specific gravity units. The measured concentration is at the design concentration for this type cell and indicates that there has been no loss of water from the cell that would have caused the electrolyte concentration to be increased. The consistency of the electrolyte concentration across the separator demonstrates the ability of the cell to resist electrolyte stratification, even after being operated for an extended period of time in a partially discharged state. These cells were operated in a horizontal orientation.

The concentration of the sulfuric acid electrolyte solution from the "as received" cell was lower, as would be expected for a partially discharged cell. The average concentration measured was 1.241 s.g. with a variation between the "top" and the "bottom" of the separator of 0.002 specific gravity units. The consistency of the electrolyte's concentration demonstrates the excellent capabilities of the AGM material used in this cell design to support diffusion to prevent electrolyte stratification.

Internal Top Lead. At several recent forums where shortcomings of the VRLA technology have been discussed, concerns have been expressed regarding the stability and corrosion resistance of the internal lead busbars, straps and terminal posts of VRLA designs. These concerns are especially associated with the negative plate hardware internal to the cell. Reaction of these lead parts with oxygen gas, and the minimum amount of negative plate polarization have been identified as contributing to this unusual type of corrosion. Samples of the negative plate busbar strap and the negative terminal post were examined to determine if these internal lead parts were experiencing unusual corrosion under the operating conditions for the Metlakatla BESS. A section of the negative plate strap is shown in *Figure 6.* The negative plate lugs are all firmly embedded within the strap, forming continuously bonded connections. There were no signs of any oxidation corrosion on the negative strap material itself. Similarly, there were no signs of any corrosion of the negative terminal post material or the cover seal bushing.

6. Summary and Conclusions

It has long been held that to achieve optimum life and performance from a lead-acid battery, it is necessary to float the battery under rigid voltage conditions to overcome self-discharge reactions while minimizing overcharge and corrosion of the cell's positive grid. This has resulted in batteries being used, particularly in utility and telecommunications applications primarily in a standby mode. In a BESS however, the battery is rapidly and continuously cycled between discharge and charge. This type of operation has created concern over the lifetime of a battery in this application.

GNB in conjunction with Sandia National Laboratories has been active in the design, installation and monitoring of large battery strings used in conjunction with traditional utility sources. One of these programs has been the BESS at Metlakatla, Alaska. An important part of these efforts is the surveillance of battery cells to assess ageing and performance capabilities over time in these applications. Data is provided to demonstrate the long-term viability of VRLA cells in this type of use, and their ability to perform additional functions such as load leveling, peak shaving and power quality enhancement to justify the cost of the BESS.

Detailed examination of cells sampled from the battery system at the Metlakatla BESS after over 30 months of operation showed no unusual conditions that would signal an early degradation of the cell's components. Positive and negative active materials composition was consistent with the state of charge of the cell when sampled. Active material structure was essentially in "as new" condition. Positive grid corrosion as evidenced by metallurgical examination and dimensional measurements to assess growth appeared to be even less than what one would expect in a perfectly controlled float charge environment. The degree of wetness of the cell's separator materials was appropriate for this design cell and there was absolutely no indications of electrolyte stratification or concentration variations that would suggest excessive self discharge of the cell or loss of water from the cell. Furthermore all hard lead components within the cell (i.e., straps, plate lugs and terminal posts) were in pristine condition showing no evidence whatsoever of any unusual corrosive attack. Overall the condition of the cell could be described as "unremarkable". Admittedly, the data and observations discussed in this paper represent but a single point. However, the data is very encouraging especially for a battery that is at approximately one-third of its design life. It is GNB's and Sandia's plan to continue the surveillance of the Metlakatla battery both by continually monitoring its electrical performance during operation and to further sample cells from the battery throughout its lifetime to provide the rigorous analyses needed to assure reliability of VRLA batteries in BESS applications.

7. Acknowledgement

GNB Technologies acknowledges and appreciates the support and technical assistance provided by Sandia National Laboratories in advancing the use of batteries, and in particular VRLA designs, to support and improve the reliability and quality of utility provided electrical power. Furthermore, GNB acknowledges MP&L for allowing us access to the battery system, to monitor its operation and to collect samples for these aging and surveillance studies and examinations. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Dept. of Energy under Contract DE-AC04-94AL85000.

8. References

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