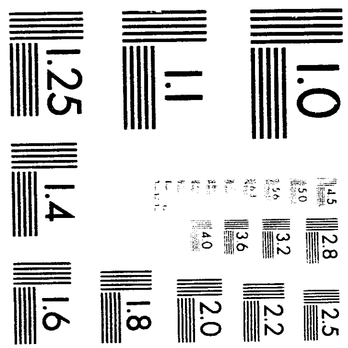
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THE DEVELOPMENT OF ADVANCED LEAD-ACID BATTERIES FOR UTILITY APPLICATIONS

by

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ABSTRACT

Technical advances in lead-acid battery design have created new opportunities for battery systems in telecommunications, computer backup power and vehicle propulsion power. Now the lead-acid battery has the opportunity to become a major element in the mix of technologies used by electric utilities for several power quality and energy and resource management functions within the network. Since their introduction into industrial applications, Valve Regulated Lead-Acid (VRLA) batteries have received widespread acceptance and use in critical telecommunications and computer installations, and have developed over 10 years of reliable operational history. As further enhancements in performance, reliability and manufacturing processes are made, these VRLA batteries are expanding the role of battery-based energy storage systems within utility companies portfolios. This paper discusses the rationale and process of designing, optimizing and testing VRLA batteries for specific utility application requirements. The development efforts described in this paper were supported by the U.S. Department of Energy and Sandia National Laboratories under Contract # DE-AC04-76DP00789.

INTRODUCTION

The lead-acid battery has been in existence for over 100 years and has found use in a wide variety of energy and power storage applications including vehicle engine starting, telecommunications standby power, forklift truck propulsion power, computer backup power systems and naval submarine propulsion power. This widespread use of the lead-acid battery couple is the result of its good electrical performance capabilities under a wide variety of operational scenarios, the ready availability and relatively low cost of its materials and components, and the generally "user friendly" characteristics of this battery system from its manufacture, through its operating lifetime and to its disposal and reclamation for reuse in other lead-acid batteries.

A new era in lead-acid battery history started 10 years ago with the advent of Absorbed Electrolyte Valve Regulated Lead Acid (VRLA) batteries in capacities ranging from 100 Ah to 1000 Ah and more. The telecommunications industry was the first to recognize the advantages offered by VRLA batteries, and today VRLA batteries can be found in ground-based, mobile and cellular telephone switching installations worldwide. The reduced maintenance requirements, lighter weight, reduced footprint and volume, fewer environmental considerations, and lower operating costs make these batteries popular.

GNB was among the first to introduce VRLA batteries. In 1982 GNB launched its ABSOLYTE® product[1] after completing more than 35 man-years of development effort in the laboratory and three years of successful field testing. During the R&D phase, GNB focused on selecting the appropriate materials for the positive and negative grids and plates, the optimum electrolyte immobilization technique, and the separator material that best assured uniform and consistent distribution of electrolyte in this "acid starved" system. Experiments were conducted to better determine how the "oxygen recombination cycle" operated and the design parameters that increased its overall efficiency. Bench tests were conducted, using both accelerated and real-time conditions, to identify the life-limiting mechanisms under float charge, deep discharge cycle and open circuit storage conditions.

GNB conducted field tests at several company locations and selected customer sites to provide battery power for telecommunications standby installations, remote photovoltaic sites, automated guided vehicle (AGV) installations and traditional traction applications, including pallet jacks and fork-lift trucks. In these field tests, batteries were exposed to indoor and outdoor locations, warm and cold environments, and standby float and deep-cycle applications.

During both the R&D phase and early into the commercialization of the ABSOLYTE technology, GNB was fortunate to have the interest, expertise and support of a national laboratory, two branches of the U.S. military and an industrial research organization in identifying specific applications for which VRLA batteries are ideally suited. The specific testing, qualification programs and field installation requirements of these applications complemented GNB's extensive product plan.

Sandia National Laboratories

Sandia National Laboratories in Albuquerque, N.M. recognized the potential of VRLA technology in remote, stand-alone photovoltaic installations where batteries are charged by the sun during the day and provide energy to the site during the night and on cloudy days. In addition to establishing the performance of ABSOLYTE batteries under standardized cycle-life testing conditions where the battery was repetitively discharged to 80% depth of discharge and fully recharged following each discharge cycle, Sandia identified and subjected the ABSOLYTE battery to a "partial state of charge" cycle test where the battery was repetitively cycled between 80% and 20% state of charge. In its final report[2], Sandia concluded that the ABSOLYTE VRLA technology tested under a standardized cycle life regime provided an average of over 800 cycles to 80% depth of discharge. In addition, this battery design provided the equivalent cycle life of a conventional flooded electrolyte battery under the partial state of charge cycle life test.

Although Sandia's initial interest was in taking electricity to the remote Indian villages of the southwestern United States, the lab's recommendation of the ABSOLYTE VRLA battery was quickly accepted by a diverse community of battery users, including railroads, geological exploration companies and the emerging non-traditional telecommunications industry installing photovoltaic systems for signalling, seismic instrumentation and microwave repeater stations. GNB's engineering studies went beyond the Sandia testing in support of the photovoltaics application by demonstrating that the ABSOLYTE battery could be recovered without degradation of performance after being discharged "flat" to zero volts and after being frozen in a discharged condition[3].

U.S. Air Force

In the early 1980s, GNB was contracted to develop a VRLA battery based on its ABSOLYTE technology for the U.S. Air Force's Peacekeeper missile system. To upgrade the standby capabilities of the system, the battery's capacity was tripled and its installation was configured so that routine maintenance, like electrolyte watering, was made impossible. GNB's engineering efforts produced the battery that is deployed in all Peacekeeper missile silos, providing the emergency standby power needed to support the control and launch capabilities of this strategic national defense system.

During its development the battery was subjected to a rigorous qualification program that demonstrated its ability to provide the electrical energy required and to survive abusive and extreme conditions. The battery was designed to withstand the shock, vibration and electromagnetic effects of a nuclear bomb blast without loss of performance, and to recover from overdischarge conditions that would irreversibly damage flooded electrolyte lead-acid batteries in similar missile system facilities.

Tests simulating the anticipated duty cycle in this installation were conducted on a 96-volt, 1500 Ah ABSOLYTE battery configured in three parallel strings, each containing 48 2-volt cells[4]. In addition to conventional discharge cycling to 50% and 80% depth of discharge at temperatures of 15° to 29°C, the battery was subjected to a severe overdischarge during which it was taken down to zero volts as measured across the terminals of the entire battery configuration, and held under those conditions with a resistive load across its terminals for 86 hours. About half of the cells in the battery were driven into reversal and exhibited negative voltage values. With a charger delivering the equivalent of 2.37 volts per cell at a maximum current of 75 amps, the battery was fully recharged within 75 hours following the "flat" resistive discharge which removed 220% of the battery's rated capacity. The ABSOLYTE VRLA battery not only survived these abusive conditions, but completed 13 of these "flat" discharges without a single cell failure.

The knowledge GNB gained from the design of the Peacekeeper battery was applied to the commercial ABSOLYTE product in the form of improved battery tray and stack designs, like those which would be used in a high voltage utility load leveling application.

U.S. Navy Research Submarine

In 1985, GNB was contracted by the U.S. Navy to develop a high power VRLA battery to provide the main propulsion power for a remote controlled research submarine under construction[5]. As in the Peacekeeper program, tight quarters and limited human access demanded that the battery perform its function with a minimum of maintenance. In addition, VRLA technology would significantly limit the hazards associated with battery gas emissions in the confined areas of a submarine.

The battery would consist of hundreds of series connected cells to form a high voltage system, and would be discharged at currents up to 2600 amps to power a DC drive motor. GNB designed a 125-pound (57 kg), 0.75 cubic foot (0.02 cubic meter) cell capable of providing 7.5 kW for 4.0 minutes to a cutoff voltage of 1.50 volts per cell. The vessel, which has been in daily use at the Navy's research facilities since

1986 is still powered by this GNB battery design.

Again, GNB applied the knowledge it gained from this development experience to the commercial ABSOLYTE product design. The copper inserted terminal post design used on all ABSOLYTE cells is the direct outgrowth of this effort with the Navy. In addition, GNB is applying the immeasurable amount of knowledge it gained about the installation and operation of high voltage battery systems to its use of ABSOLYTE batteries for computer system UPS backup and frequency regulation in utility load leveling applications.

Utility Applications

As the demands for electric power increase in our society, battery systems are being examined for Battery Energy Storage Systems (BESS) to provide utility load leveling and power management capabilities. The battery could provide additional electrical energy to meet demand during daily and seasonal peak load periods. Batteries could also be used by the utilities to resolve issues such as capacity constraints, air quality management, power quality deterioration, localized power brown-outs and expensive fuel-powered peaking capacity. Several BESS-type load leveling projects around the world have demonstrated the feasibility and benefits to the utilities of installing and operating battery-based energy storage systems.

In recent years, GNB has been working with the Electric Power Research Institute (EPRI), Argonne and Sandia National Laboratories[6,7], and several utility companies to develop battery energy storage systems using GNB's ABSOLYTE VRLA technology. Testing of production batteries at Argonne demonstrated a life capability of more than 1200 cycles in utility load leveling usage.

The advantages of VRLA in the extremely large battery installations for a utility load leveling and/or frequency regulation application are tremendous. The sheer numbers of cells needed to provide the power and energy (of the order of megawatts and tens of megawatt-hours) for these applications demand battery systems with high density packing capabilities to minimize floor and building space and minimal maintenance requirements. In addition, to be an economically viable alternative to other power generating equipment, battery systems must have initial costs and lifetimes that justify their installation in a utility grid structure. The investments being made in VRLA technology indicate that these batteries have made the technological progress over the last 10 years to assure their role in the future.

Questions remain however regarding the maintenance, reliability and lifetimes of these battery-based energy storage systems, and hence retard the widespread acceptance of BESS-type systems. The objective of this project undertaken by Sandia National Laboratories and GNB and reported herein is to address the major technical issues relating to the battery as it would be used in a battery energy storage system by an electric utility, and to design, implement and validate the advances in VRLA battery technology needed to accelerate the commercialization of BESS.

TECHNICAL OBSTACLES TO BESS

Technical obstacles to the widespread commercialization of BESS installations in electric utilities encompass both batteries as well as the power conversion systems. Although discussion of power conversion equipment is beyond the scope of this paper, it must be recognized that both sets of issues must be resolved to accelerate the acceptance and commercialization of battery energy storage systems.

From the earlier utility BESS demonstration projects, it was learned that battery maintenance could be a major issue in large scale installations. The outcome of these projects was that in addition to other technological advances, future developments in BESS should focus on batteries which are inherently designed to offer low or maintenance-free characteristics. The development and introduction of the VRLA technology offers utilities contemplating the installation of BESS the promise of large ampere-hour capacity, long lifetime and minimal maintenance.

Uncertainty of the lifetime of the VRLA battery and insufficient operating data which demonstrate its reliability are often cited as barriers by utilities to the accelerated deployment of BESS with VRLA batteries. Unlike flooded lead acid batteries used for cycle service which are produced by many manufacturers and have a long history to support their claims for life, VRLA batteries designed for cycle service are made by only a few companies and product history is limited. Although accelerated test data are available, real time operation of VRLA batteries to verify operational reliability of pressure venting mechanisms, terminal and jar-to-cover seals, and charging profiles to maintain battery capacity and provide thermal management is incomplete.

There is a reluctance by the utilities to translate the experiences with flooded electrolyte lead-acid batteries to the VRLA designs, and to extrapolate accelerated test data to real time which must be overcome. It is hoped however that the wealth of data available from a variety of other sources successfully utilizing VRLA batteries, will outweigh the risk of limited VRLA demonstrations in utility applications. It is the objective of this paper to summarize these data and to highlight the steps being taken in the design and manufacture of VRLA batteries by GNB to assure their integrity and reliability for utility battery energy storage system installations.

VRLA BATTERY LIFE

Positive Grid Corrosion

The life regulating component of a lead acid battery is the positive grid. Therefore the type and rate of corrosion of the positive grid material are essential elements in projecting the lifetime of a battery design. GNB's ABSOLYTE VRLA batteries use a patented proprietary positive MFX low-antimony grid alloy. Bare metal corrosion tests of this alloy indicate a corrosion rate of 0.05mm per year at 25°C and a potential equivalent to a cell float charge voltage of 2.25 volts. Based on this corrosion rate and a grid having a corrosion cross sectional inscribed radius of 1.52 mm, the grid should survive approximately 30 years before being completely corroded **(Figure 1).**

The type of corrosion is also significant, and GNB's projection of a 20-year grid life is valid because the corrosion is a uniform surface erosion process. Penetrating or intergranular corrosion, as exhibited by lead-calcium alloys, could cause erratic and premature battery failure not predicted from grid corrosion measurements alone. Estimates of battery lifetime in utility applications for GNB's ABSOLYTE design can be made from analyses of its positive grid.

Samples of the positive grids analyzed from cells retrieved from the field and cells subjected to temperature and voltage accelerated float life tests **(Figure 2)** indicate the design projections of a 20-year lifetime limited by corrosion to be a conservative estimate. The real time data coincide with the curve developed using accelerated life test results, and supports the use of accelerated methods to project VRLA battery life.

A second failure mechanism associated with positive grid corrosion is "grid growth". As the positive grid corrodes, the lead metal in the grid is converted to lead dioxide; the density of the oxidized form is about 17% less than the metal. Because of this difference in density the grid expands or "grows" as corrosion occurs. The way the grid alloy corrodes affects the rate of growth -- intergranular corrosion results in greater growth than a uniform surface corrosion. The battery designer can use positive grid alloys which exhibit low corrosion growth characteristics or accommodate for the expected growth in the design of the cell.

To provide the life and reliability needed in utility load management applications, GNB's approach is to use its patented low-antimony MFX alloy, which ages by a low-rate, uniform surface corrosion process resulting in a total grid growth of 2.5 to 3% over the battery's lifetime. This compares with 6 to 7% growth expected with calcium-based positive grids. As a further precaution, GNB also designed its ABSOLYTE IIP batteries with extra positive grid growth space to minimize the potential for internal short circuiting by grid growth.

Water Loss Mechanisms

By design, a VRLA cell has just enough electrolyte to satisfy the electrochemical reactions and deliver the desired capacity. In addition, the electrolyte concentration - the amount of sulfuric acid and water in the cell pack - is precisely adjusted to balance ionic conductivity and separator saturation to achieve a high level of oxygen gas recombination efficiency. Therefore, water loss by any of several mechanisms must be prevented or considered in the original electrochemical design of the VRLA cell.

The primary causes of water loss from a "sealed" VRLA cell are (i) venting through the pressure relief valve, (ii) water vapor transmission through the cell container itself, and (iii) consumption by the positive grid corrosion reactions. Designers of VRLA cells can control the amount of water lost through proper material selection and other design criteria.

GNB, for instance, installs a pre-tested pressure relief valve that operates above the equilibrium pressure during float and cycle operation to limit the amount of water lost to venting during normal recharge. The utilities are concerned that this pressure relief valve will not operate consistently or that its venting characteristics will change as the battery ages or is operated at varying temperatures. GNB is working with Sandia National Laboratories to demonstrate and improve the reliability of this pressure relief vent system. Baseline testing of a standard GNB ABSOLYTE pressure relief valve **(Figure 3)** shows the valve consistently opens in the range 6 to 7 psig and reseals in the range 5 to 6 psig. Sandia's materials scientists are exploring special rubbers and treated rubber vent cylinders which are even more resistant to chemical attack and aging than the EPDM rubber compound presently being used.

To prevent water vapor transmission, GNB's cell cases and covers are molded of polypropylene, a plastic compatible with the corrosive materials in the lead-acid battery, and a material with one of the lowest water vapor transmission rates available. Compared with other widely used lead battery case materials, polypropylene has a water vapor transmission rate one fourth that of the next lowest material. Calculations have shown that it would take almost 30 years (at 25°C and 36% R.H.) for enough water vapor to be lost through the polypropylene jar of an ABSOLYTE cell before it would begin to affect the cell's capacity. The comparisons of various battery case materials in **Table 1** show that polypropylene's oxygen diffusion rate is similarly low.

The more detrimental causes of water loss are those that cannot be anticipated in establishing the electrochemical specifications and construction details for a VRLA battery. The ways a VRLA cell can prematurely dry out and cause the battery to fail are:

- manufacturing deficiencies which allow water vapor, oxygen and hydrogen to escape and allow air to enter the cell, and

- uncontrolled, excessive and abusive overcharge which can lead to pressure build up, venting and loss of water.

Many of the early reports of VRLA battery failures were linked to these types of occurrences. GNB has developed sophisticated manufacturing processes and on-line tests specifically addressing the requirements for VRLA designs which drastically reduce the likelihood of leaks in its ABSOLYTE VRLA cells.

MANUFACTURING IMPROVEMENTS

Since its introduction 10 years ago, the ABSOLYTE technology's electrochemistry has performed as expected, and upgrades and enhancements of production methods use... manufacture, assemble and test these batteries have improved their reliability. The thrust in manufacturing improvements has been to make each of the processes more consistent by bringing them into tighter control.

For example, in plate manufacturing, all of the processes including grid casting, paste mixing, plate pasting and plate curing were redefined with tighter manufacturing limits. Processes were placed under computer control to assure consistent mold and lead pot temperature control, weights of materials added to formulate the active material paste mixes, and temperature and humidity profiles during the curing process to achieve the proper crystal structure formation and size. More importantly however, several unique manufacturing processes had to be developed to assure VRLA cell reliability -- these include heat sealing, terminal post welding, electrolyte filling and leak detection.

Jar To Cover Heat Seal

Lead-acid cells are universally housed in plastic containers consisting of a jar and cover. In a vast number of battery designs, the jar and cover are joined using a heat seal. In the sealing process, a bead of molten plastic is extruded along the seam between the jar and the cover. When the seal cools, the bead is usually trimmed off for esthetics, before the cell is fitted into the battery tray.

Trimming this bead shortens the sealing path length and removes the "skin" which forms when the melted plastic solidifies. These reduce the inherent resistance to gas and electrolyte leakage at the joint.

To provide increased protection against gas and electrolyte leakage at the jar-to-cover seal, GNB perfected a process and the machinery to provide an additional heat sealing band using the plastic bead at the jar to cover joint **(Figure 4)**. Instead of trimming away the bead, the excess plastic is smoothed over the joint to form a redundant seal. In addition to increasing the heat seal strength and the seal path length, the smoothed bead forms a "skin" which covers any potential porosity in the fused weld region between the cover and the jar.

Terminal Post Fusion

The terminal connections of a cell are typically made by passing a lead terminal post, which is integrally connected to the respective electrodes of the cell, through a lead bushing molded into the battery cover. The bushing and the post are then welded together. The welding is most often done manually with an oxygen/gas torch. Because this technique is very operator sensitive, it is inevitable that wide variations in weld appearance and depth of weld occur. In addition, the torch applies more heat over a wider area than is needed to fuse the two parts together. The plastic adjacent to the lead bushing in the cover is vulnerable to damage from excessive heat. This has been identified as a major cause of leakage in VRLA cells.

To counter this, GNB has developed an automated, computer-controlled terminal post fusion system **(Figure 5)** which eliminates all of the problems caused by manual terminal post welds. The process uses a highly focused tungsten inert gas (TIG) welder which provides precisely directed, high intensity, localized heating to weld the terminal post and the bushing. The resulting weld has a greater and more even depth of fusion. Because it is made without excessive heat, it drastically reduces the potential for heat damage to the surrounding plastic and minimizes the potential for electrolyte leakage. Finally, since the welding is done under a blanket of inert gas, the weld is free of oxidation. This gives it a better appearance.

Electrolyte Filling

The quantity of electrolyte filling the pore volume of the separator and the electrode active materials in a VRLA design is critical in achieving an appropriate degree of oxygen gas recombination. If there is too much electrolyte, the cell becomes saturated, fails to recombine oxygen efficiently and emits gasses through its pressure relief vent. Too much electrolyte can also lead to electrolyte leakage. If there is too little electrolyte, the cell suffers from increased resistance and reduced capacity.

To insure that each ABSOLYTE cell is filled with the specified volume of electrolyte, GNB developed and installed a computer controlled filling station which adds a measured amount of electrolyte to each cell using weight as the measurement criterion. The method eliminates variations caused by temperature fluctuations and any visual methods used in a manual filling operation. Using the "fill-by-weight" approach, electrolyte filling accuracy has increased from ± 4% with a process standard deviation of 2.5% to an accuracy of ± 1% and a process standard deviation of 0.5%.

Leak Detection

The reasons for a leak-free container for a VRLA cell are obvious. To insure that a cell is leaktight, manufacturers of VRLA cells, including GNB, have instituted manufacturing processes that test the integrity of the cells' seals. Throughout the history of its ABSOLYTE product line, GNB has tested every cell and continually improved the sensitivity of its leak testing methods. The initial tests relied upon pressure decay after pressurizing a cell with compressed air. An improvement to that technique included pressurizing the cell and submerging it in a tank of water. However, even cells that passed these tests were sometimes subject to minute electrolyte and gas leaks that appeared after the cells were installed into service. After analyses of these cells and a rigorous calculation involving molecular diameters, hole sizes and surface wetting, we concluded that pressurized air testing could not identify the small leaks in the cell seals which, over time, would allow electrolyte to creep through.

As a result, GNB developed an automated helium leak detection system to assure the integrity of the seals on its ABSOLYTE cells. The system is similar to the one used by the aerospace industry to identify and locate leaks in space vehicles. This test places cells pressurized with helium gas in a vacuum chamber. Using a mass spectrometer, it analyzes the atmosphere in the chamber for the presence of helium. The amount of helium detected after a set period of time determines the level of leak tightness and the size of any micro leaks. This process readily identifies micro holes that are 4 times smaller than will allow electrolyte to creep through.

THERMAL MANAGEMENT AND CHARGING REGIMES

Elevated temperatures have deleterious effects on the life of any lead-acid battery. In VRLA batteries, in addition to accelerating the grid corrosion reactions, elevated temperatures can also induce failures by accelerating the loss of water by gassing and by diffusion through the container material itself. In addition to the heat generation mechanisms associated with the operation of any battery including (i) the resistive heating effects caused during discharge, ii) the heat released due to the chemical and electrochemical reactions on charge coupled with the resistive heating effects during charge, (iii) miscellaneous heating effects from polarization and the grid corrosion reaction, VRLA batteries have one additional significant heat generating source -- the oxygen recombination reaction which is at the heart of a VRLA cell.

Heat dissipation in a lead-acid cell occurs by conduction through the cell materials, by convection from the surface of the battery and its components, and to lesser degrees by radiation and evaporative cooling resulting from gasses being released from the battery. VRLA batteries however have a lower heat capacity than flooded systems, have no internal convection and have an additional mechanism for heat generation. Thermal management at both the cell and battery levels in large VRLA batteries for utility applications, therefore, is a necessary as well as challenging requirement. Further, because charging is intimately associated with the heating effects experienced in the VRLA battery, thermal management and charging profiles must be evaluated together.

Utility energy storage applications require that the battery be recharged during off-peak hours, and usually limit available recharge time to less than eight (8) hours. Additional charging restraints are required to limit temperature rise in the cells, to control grid corrosion and water loss, to extend battery life, and in the extreme case to prevent thermal runaway.

GNB's modular design for its ABSOLYTE VRLA battery **(Figure 6)** not only provides a self-contained, space-saving, easy to install system for large utility battery installations, but also assists the battery with thermal management. The steel battery trays are excellent heat sinks and radiators to remove heat from the cells, and the stacking approach provides inherent air circulation channels to dissipate heat and maintain the cells under uniform temperature conditions. The result is the ABSOLYTE design is resistant to thermal runaway even under extreme abusive overcharge conditions. This is demonstrated in **Figure 7** which shows that even when overcharged at voltages as high as 2.65 volts per cell (excessive considering that the recommended float charge voltage for ABSOLYTE is 2.23-2.27 volts per cell), charging currents remain stable even after extended periods of time. The stable overcharge current indicates the batteries have reached a thermal equilibrium with the environment and are able to adequately dissipate the heat being generated inside the cell.

GNB has been successful in developing recharge profiles for its ABSOLYTE batteries which allow full recharge from a deep (80% DOD) discharge in less than 8 hours without generating excessive gas or heat. One of these recharge profiles is shown in **Figure 8**. The critical parameters in establishing these recharge profiles include in-rush charge current, voltage at which charge current taper begins, finishing current and the method of defining charge termination.

SUMMARY AND CONCLUSIONS

Valve Regulated Lead Acid (VRLA) batteries, in the ten years or so since they were first introduced for industrial applications, have made significant inroads in providing safe, reliable, space efficient and cost effective energy storage systems. As with any new technology, improvements and enhancements have been necessary to assure that these batteries perform to their specifications and expectations. A significant amount of research and development, combined with an investment in highly specialized plant and equipment, is assuring the users of this technology the best battery products possible.

VRLA has been a revolutionary breakthrough in lead-acid battery technology. Over the last ten years this technology has rapidly matured and is ready to be used in the utility industry for load management, energy storage and power delivery.

ACKNOWLEDGEMENTS

GNB gratefully acknowledges the support of the U.S. Department of Energy and Sandia National Laboratories (Contract DE-AC04-76DP00789) in our efforts to improve VRLA battery reliability for utility applications through manufacturing and process control and design enhancements.

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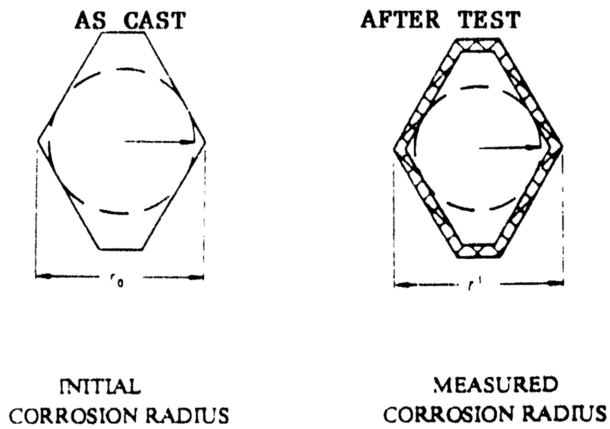
TABLE 1

RELATIVE PERMEABILITY RATES FOR VARIOUS PLASTICS

MATERIAL	WATER VAPOR	OXYGEN
Polypropylene	1.00	1.00
FR-halogenated	1.03	
FR-non halogenated	4.84	
ABS	16.6	0.35
FR	14.6	
Polyvinyl Chloride	4.22	
plasticized		4.41
non plasticized		0.09
Polyphenylene Oxide		
FR #1	9.20	
FR #2	6.70	
Polycarbonate		1.76

Notes:
(1) Values are relative to polypropylene
(2) FR = Flame Retardant
(3) Lower relative values are preferred



$$\text{RATE} = \frac{r_0 - r^1}{\text{time}} = \frac{\text{mm}}{\text{yr}}$$

Figure 1: Grid corrosion measurements can be used to project battery lifetime.

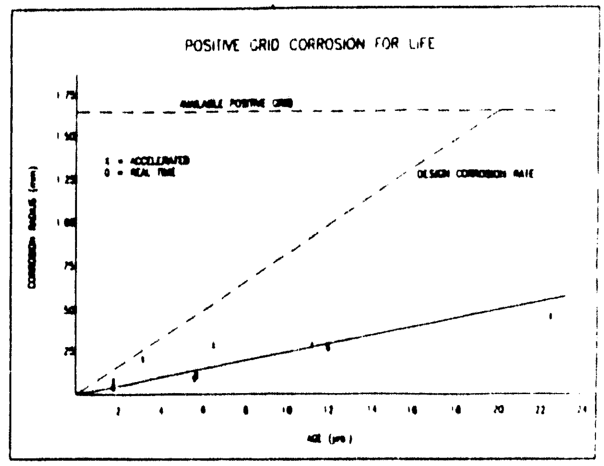


Figure 2: Grid samples from field batteries and accelerated life test confirm a 20-year lifetime.

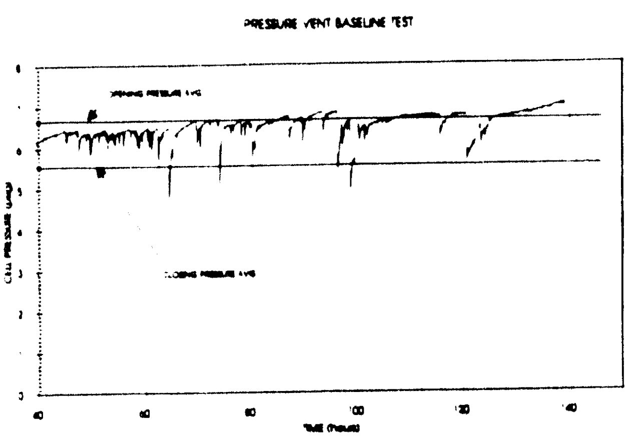


Figure 3: Operation of the pressure relief vent of an ABSOLYTE® cell is within a narrow vent/reseal range.

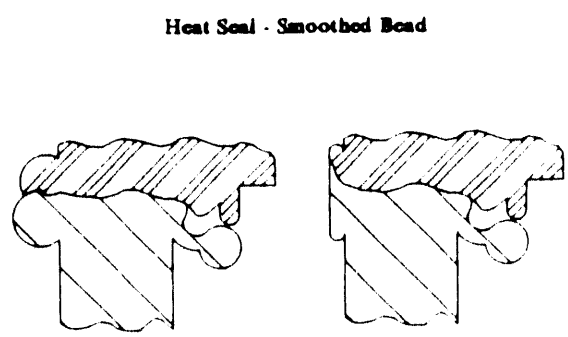


Figure 4: A unique heat seal "bead smoothing" process provides extra protection from leakage.

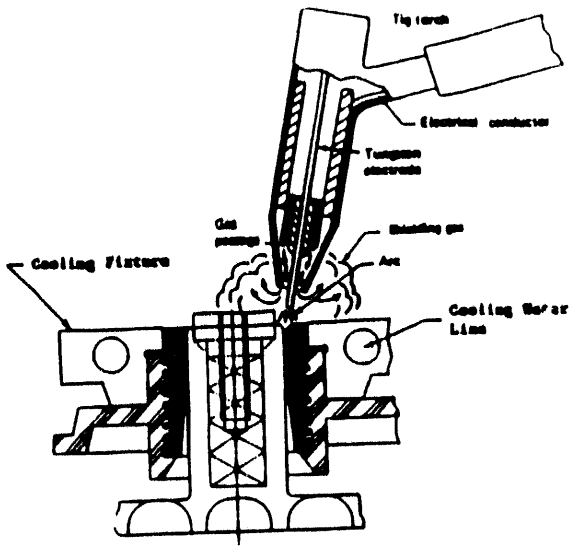


Figure 5: The TIG welder improves weld depth and appearance without heat damage to the plastic.

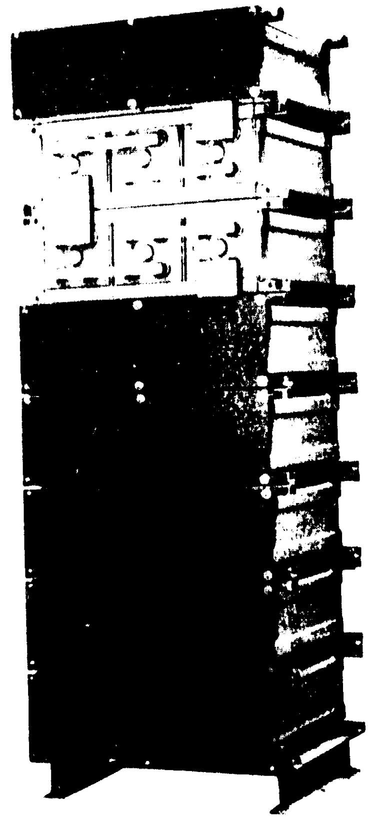


Figure 6: GNB's ABSOLYTE VRLA batteries have a unique space saving racking system.

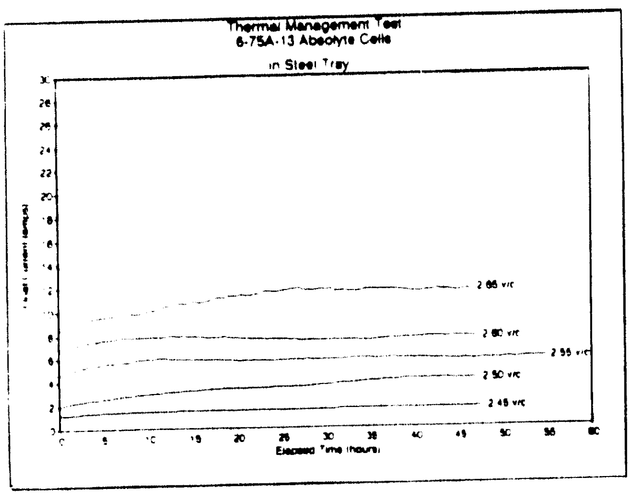


Figure 7: ABSOLYTE's design and packaging maintains thermal equilibrium under abusive overcharge.

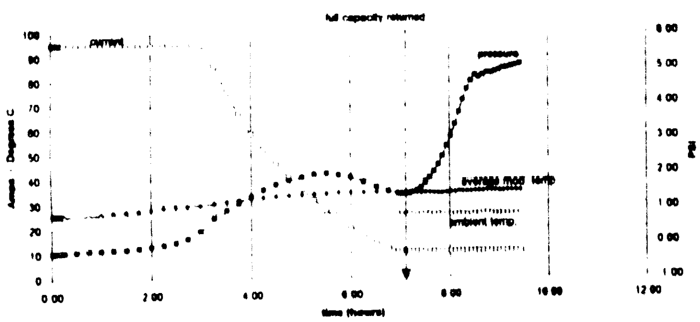


Figure 8: GNB has developed a recharge profile for VRLA batteries in utility applications.

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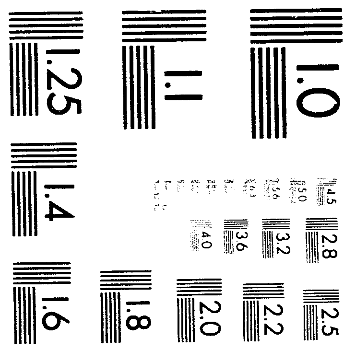
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THE DEVELOPMENT OF ADVANCED LEAD-ACID BATTERIES FOR UTILITY APPLICATIONS

by

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ABSTRACT

Technical advances in lead-acid battery design have created new opportunities for battery systems in telecommunications, computer backup power and vehicle propulsion power. Now the lead-acid battery has the opportunity to become a major element in the mix of technologies used by electric utilities for several power quality and energy and resource management functions within the network. Since their introduction into industrial applications, Valve Regulated Lead-Acid (VRLA) batteries have received widespread acceptance and use in critical telecommunications and computer installations, and have developed over 10 years of reliable operational history. As further enhancements in performance, reliability and manufacturing processes are made, these VRLA batteries are expanding the role of battery-based energy storage systems within utility companies portfolios. This paper discusses the rationale and process of designing, optimizing and testing VRLA batteries for specific utility application requirements. The development efforts described in this paper were supported by the U.S. Department of Energy and Sandia National Laboratories under Contract # DE-AC04-76DP00789.

INTRODUCTION

The lead-acid battery has been in existence for over 100 years and has found use in a wide variety of energy and power storage applications including vehicle engine starting, telecommunications standby power, forklift truck propulsion power, computer backup power systems and naval submarine propulsion power. This widespread use of the lead-acid battery couple is the result of its good electrical performance capabilities under a wide variety of operational scenarios, the ready availability and relatively low cost of its materials and components, and the generally "user friendly" characteristics of this battery system from its manufacture, through its operating lifetime and to its disposal and reclamation for reuse in other lead-acid batteries.

A new era in lead-acid battery history started 10 years ago with the advent of Absorbed Electrolyte Valve Regulated Lead Acid (VRLA) batteries in capacities ranging from 100 Ah to 1000 Ah and more. The telecommunications industry was the first to recognize the advantages offered by VRLA batteries, and today VRLA batteries can be found in ground-based, mobile and cellular telephone switching installations worldwide. The reduced maintenance requirements, lighter weight, reduced footprint and volume, fewer environmental considerations, and lower operating costs make these batteries popular.

GNB was among the first to introduce VRLA batteries. In 1982 GNB launched its ABSOLYTE® product[1] after completing more than 35 man-years of development effort in the laboratory and three years of successful field testing. During the R&D phase, GNB focused on selecting the appropriate materials for the positive and negative grids and plates, the optimum electrolyte immobilization technique, and the separator material that best assured uniform and consistent distribution of electrolyte in this "acid starved" system. Experiments were conducted to better determine how the "oxygen recombination cycle" operated and the design parameters that increased its overall efficiency. Bench tests were conducted, using both accelerated and real-time conditions, to identify the life-limiting mechanisms under float charge, deep discharge cycle and open circuit storage conditions.

GNB conducted field tests at several company locations and selected customer sites to provide battery power for telecommunications standby installations, remote photovoltaic sites, automated guided vehicle (AGV) installations and traditional traction applications, including pallet jacks and fork-lift trucks. In these field tests, batteries were exposed to indoor and outdoor locations, warm and cold environments, and standby float and deep-cycle applications.

During both the R&D phase and early into the commercialization of the ABSOLYTE technology, GNB was fortunate to have the interest, expertise and support of a national laboratory, two branches of the U.S. military and an industrial research organization in identifying specific applications for which VRLA batteries are ideally suited. The specific testing, qualification programs and field installation requirements of these applications complemented GNB's extensive product plan.

Sandia National Laboratories

Sandia National Laboratories in Albuquerque, N.M. recognized the potential of VRLA technology in remote, stand-alone photovoltaic installations where batteries are charged by the sun during the day and provide energy to the site during the night and on cloudy days. In addition to establishing the performance of ABSOLYTE batteries under standardized cycle-life testing conditions where the battery was repetitively discharged to 80% depth of discharge and fully recharged following each discharge cycle, Sandia identified and subjected the ABSOLYTE battery to a "partial state of charge" cycle test where the battery was repetitively cycled between 80% and 20% state of charge. In its final report[2], Sandia concluded that the ABSOLYTE VRLA technology tested under a standardized cycle life regime provided an average of over 800 cycles to 80% depth of discharge. In addition, this battery design provided the equivalent cycle life of a conventional flooded electrolyte battery under the partial state of charge cycle life test.

Although Sandia's initial interest was in taking electricity to the remote Indian villages of the southwestern United States, the lab's recommendation of the ABSOLYTE VRLA battery was quickly accepted by a diverse community of battery users, including railroads, geological exploration companies and the emerging non-traditional telecommunications industry installing photovoltaic systems for signalling, seismic instrumentation and microwave repeater stations. GNB's engineering studies went beyond the Sandia testing in support of the photovoltaics application by demonstrating that the ABSOLYTE battery could be recovered without degradation of performance after being discharged "flat" to zero volts and after being frozen in a discharged condition[3].

U.S. Air Force

In the early 1980s, GNB was contracted to develop a VRLA battery based on its ABSOLYTE technology for the U.S. Air Force's Peacekeeper missile system. To upgrade the standby capabilities of the system, the battery's capacity was tripled and its installation was configured so that routine maintenance, like electrolyte watering, was made impossible. GNB's engineering efforts produced the battery that is deployed in all Peacekeeper missile silos, providing the emergency standby power needed to support the control and launch capabilities of this strategic national defense system.

During its development the battery was subjected to a rigorous qualification program that demonstrated its ability to provide the electrical energy required and to survive abusive and extreme conditions. The battery was designed to withstand the shock, vibration and electromagnetic effects of a nuclear bomb blast without loss of performance, and to recover from overdischarge conditions that would irreversibly damage flooded electrolyte lead-acid batteries in similar missile system facilities.

Tests simulating the anticipated duty cycle in this installation were conducted on a 96-volt, 1500 Ah ABSOLYTE battery configured in three parallel strings, each containing 48 2-volt cells[4]. In addition to conventional discharge cycling to 50% and 80% depth of discharge at temperatures of 15° to 29°C, the battery was subjected to a severe overdischarge during which it was taken down to zero volts as measured across the terminals of the entire battery configuration, and held under those conditions with a resistive load across its terminals for 86 hours. About half of the cells in the battery were driven into reversal and exhibited negative voltage values. With a charger delivering the equivalent of 2.37 volts per cell at a maximum current of 75 amps, the battery was fully recharged within 75 hours following the "flat" resistive discharge which removed 220% of the battery's rated capacity. The ABSOLYTE VRLA battery not only survived these abusive conditions, but completed 13 of these "flat" discharges without a single cell failure.

The knowledge GNB gained from the design of the Peacekeeper battery was applied to the commercial ABSOLYTE product in the form of improved battery tray and stack designs, like those which would be used in a high voltage utility load leveling application.

U.S. Navy Research Submarine

In 1985, GNB was contracted by the U.S. Navy to develop a high power VRLA battery to provide the main propulsion power for a remote controlled research submarine under construction[5]. As in the Peacekeeper program, tight quarters and limited human access demanded that the battery perform its function with a minimum of maintenance. In addition, VRLA technology would significantly limit the hazards associated with battery gas emissions in the confined areas of a submarine.

The battery would consist of hundreds of series connected cells to form a high voltage system, and would be discharged at currents up to 2600 amps to power a DC drive motor. GNB designed a 125-pound (57 kg), 0.75 cubic foot (0.02 cubic meter) cell capable of providing 7.5 kW for 4.0 minutes to a cutoff voltage of 1.50 volts per cell. The vessel, which has been in daily use at the Navy's research facilities since

1986 is still powered by this GNB battery design.

Again, GNB applied the knowledge it gained from this development experience to the commercial ABSOLYTE product design. The copper inserted terminal post design used on all ABSOLYTE cells is the direct outgrowth of this effort with the Navy. In addition, GNB is applying the immeasurable amount of knowledge it gained about the installation and operation of high voltage battery systems to its use of ABSOLYTE batteries for computer system UPS backup and frequency regulation in utility load leveling applications.

Utility Applications

As the demands for electric power increase in our society, battery systems are being examined for Battery Energy Storage Systems (BESS) to provide utility load leveling and power management capabilities. The battery could provide additional electrical energy to meet demand during daily and seasonal peak load periods. Batteries could also be used by the utilities to resolve issues such as capacity constraints, air quality management, power quality deterioration, localized power brown-outs and expensive fuel-powered peaking capacity. Several BESS-type load leveling projects around the world have demonstrated the feasibility and benefits to the utilities of installing and operating battery-based energy storage systems.

In recent years, GNB has been working with the Electric Power Research Institute (EPRI), Argonne and Sandia National Laboratories[6,7], and several utility companies to develop battery energy storage systems using GNB's ABSOLYTE VRLA technology. Testing of production batteries at Argonne demonstrated a life capability of more than 1200 cycles in utility load leveling usage.

The advantages of VRLA in the extremely large battery installations for a utility load leveling and/or frequency regulation application are tremendous. The sheer numbers of cells needed to provide the power and energy (of the order of megawatts and tens of megawatt-hours) for these applications demand battery systems with high density packing capabilities to minimize floor and building space and minimal maintenance requirements. In addition, to be an economically viable alternative to other power generating equipment, battery systems must have initial costs and lifetimes that justify their installation in a utility grid structure. The investments being made in VRLA technology indicate that these batteries have made the technological progress over the last 10 years to assure their role in the future.

Questions remain however regarding the maintenance, reliability and lifetimes of these battery-based energy storage systems, and hence retard the widespread acceptance of BESS-type systems. The objective of this project undertaken by Sandia National Laboratories and GNB and reported herein is to address the major technical issues relating to the battery as it would be used in a battery energy storage system by an electric utility, and to design, implement and validate the advances in VRLA battery technology needed to accelerate the commercialization of BESS.

TECHNICAL OBSTACLES TO BESS

Technical obstacles to the widespread commercialization of BESS installations in electric utilities encompass both batteries as well as the power conversion systems. Although discussion of power conversion equipment is beyond the scope of this paper, it must be recognized that both sets of issues must be resolved to accelerate the acceptance and commercialization of battery energy storage systems.

From the earlier utility BESS demonstration projects, it was learned that battery maintenance could be a major issue in large scale installations. The outcome of these projects was that in addition to other technological advances, future developments in BESS should focus on batteries which are inherently designed to offer low or maintenance-free characteristics. The development and introduction of the VRLA technology offers utilities contemplating the installation of BESS the promise of large ampere-hour capacity, long lifetime and minimal maintenance.

Uncertainty of the lifetime of the VRLA battery and insufficient operating data which demonstrate its reliability are often cited as barriers by utilities to the accelerated deployment of BESS with VRLA batteries. Unlike flooded lead acid batteries used for cycle service which are produced by many manufacturers and have a long history to support their claims for life, VRLA batteries designed for cycle service are made by only a few companies and product history is limited. Although accelerated test data are available, real time operation of VRLA batteries to verify operational reliability of pressure venting mechanisms, terminal and jar-to-cover seals, and charging profiles to maintain battery capacity and provide thermal management is incomplete.

There is a reluctance by the utilities to translate the experiences with flooded electrolyte lead-acid batteries to the VRLA designs, and to extrapolate accelerated test data to real time which must be overcome. It is hoped however that the wealth of data available from a variety of other sources successfully utilizing VRLA batteries, will outweigh the risk of limited VRLA demonstrations in utility applications. It is the objective of this paper to summarize these data and to highlight the steps being taken in the design and manufacture of VRLA batteries by GNB to assure their integrity and reliability for utility battery energy storage system installations.

VRLA BATTERY LIFE

Positive Grid Corrosion

The life regulating component of a lead acid battery is the positive grid. Therefore the type and rate of corrosion of the positive grid material are essential elements in projecting the lifetime of a battery design. GNB's ABSOLYTE VRLA batteries use a patented proprietary positive MFX low-antimony grid alloy. Bare metal corrosion tests of this alloy indicate a corrosion rate of 0.05mm per year at 25°C and a potential equivalent to a cell float charge voltage of 2.25 volts. Based on this corrosion rate and a grid having a corrosion cross sectional inscribed radius of 1.52 mm, the grid should survive approximately 30 years before being completely corroded **(Figure 1).**

The type of corrosion is also significant, and GNB's projection of a 20-year grid life is valid because the corrosion is a uniform surface erosion process. Penetrating or intergranular corrosion, as exhibited by lead-calcium alloys, could cause erratic and premature battery failure not predicted from grid corrosion measurements alone. Estimates of battery lifetime in utility applications for GNB's ABSOLYTE design can be made from analyses of its positive grid.

Samples of the positive grids analyzed from cells retrieved from the field and cells subjected to temperature and voltage accelerated float life tests **(Figure 2)** indicate the design projections of a 20-year lifetime limited by corrosion to be a conservative estimate. The real time data coincide with the curve developed using accelerated life test results, and supports the use of accelerated methods to project VRLA battery life.

A second failure mechanism associated with positive grid corrosion is "grid growth". As the positive grid corrodes, the lead metal in the grid is converted to lead dioxide; the density of the oxidized form is about 17% less than the metal. Because of this difference in density the grid expands or "grows" as corrosion occurs. The way the grid alloy corrodes affects the rate of growth -- intergranular corrosion results in greater growth than a uniform surface corrosion. The battery designer can use positive grid alloys which exhibit low corrosion growth characteristics or accommodate for the expected growth in the design of the cell.

To provide the life and reliability needed in utility load management applications, GNB's approach is to use its patented low-antimony MFX alloy, which ages by a low-rate, uniform surface corrosion process resulting in a total grid growth of 2.5 to 3% over the battery's lifetime. This compares with 6 to 7% growth expected with calcium-based positive grids. As a further precaution, GNB also designed its ABSOLYTE IIP batteries with extra positive grid growth space to minimize the potential for internal short circuiting by grid growth.

Water Loss Mechanisms

By design, a VRLA cell has just enough electrolyte to satisfy the electrochemical reactions and deliver the desired capacity. In addition, the electrolyte concentration - the amount of sulfuric acid and water in the cell pack - is precisely adjusted to balance ionic conductivity and separator saturation to achieve a high level of oxygen gas recombination efficiency. Therefore, water loss by any of several mechanisms must be prevented or considered in the original electrochemical design of the VRLA cell.

The primary causes of water loss from a "sealed" VRLA cell are (i) venting through the pressure relief valve, (ii) water vapor transmission through the cell container itself, and (iii) consumption by the positive grid corrosion reactions. Designers of VRLA cells can control the amount of water lost through proper material selection and other design criteria.

GNB, for instance, installs a pre-tested pressure relief valve that operates above the equilibrium pressure during float and cycle operation to limit the amount of water lost to venting during normal recharge. The utilities are concerned that this pressure relief valve will not operate consistently or that its venting characteristics will change as the battery ages or is operated at varying temperatures. GNB is working with Sandia National Laboratories to demonstrate and improve the reliability of this pressure relief vent system. Baseline testing of a standard GNB ABSOLYTE pressure relief valve **(Figure 3)** shows the valve consistently opens in the range 6 to 7 psig and reseals in the range 5 to 6 psig. Sandia's materials scientists are exploring special rubbers and treated rubber vent cylinders which are even more resistant to chemical attack and aging than the EPDM rubber compound presently being used.

To prevent water vapor transmission, GNB's cell cases and covers are molded of polypropylene, a plastic compatible with the corrosive materials in the lead-acid battery, and a material with one of the lowest water vapor transmission rates available. Compared with other widely used lead battery case materials, polypropylene has a water vapor transmission rate one fourth that of the next lowest material. Calculations have shown that it would take almost 30 years (at 25°C and 36% R.H.) for enough water vapor to be lost through the polypropylene jar of an ABSOLYTE cell before it would begin to affect the cell's capacity. The comparisons of various battery case materials in **Table 1** show that polypropylene's oxygen diffusion rate is similarly low.

The more detrimental causes of water loss are those that cannot be anticipated in establishing the electrochemical specifications and construction details for a VRLA battery. The ways a VRLA cell can prematurely dry out and cause the battery to fail are:

- manufacturing deficiencies which allow water vapor, oxygen and hydrogen to escape and allow air to enter the cell, and

- uncontrolled, excessive and abusive overcharge which can lead to pressure build up, venting and loss of water.

Many of the early reports of VRLA battery failures were linked to these types of occurrences. GNB has developed sophisticated manufacturing processes and on-line tests specifically addressing the requirements for VRLA designs which drastically reduce the likelihood of leaks in its ABSOLYTE VRLA cells.

MANUFACTURING IMPROVEMENTS

Since its introduction 10 years ago, the ABSOLYTE technology's electrochemistry has performed as expected, and upgrades and enhancements of production methods usec manufacture, assemble and test these batteries have improved their reliability. The thrust in manufacturing improvements has been to make each of the processes more consistent by bringing them into tighter control.

For example, in plate manufacturing, all of the processes including grid casting, paste mixing, plate pasting and plate curing were redefined with tighter manufacturing limits. Processes were placed under computer control to assure consistent mold and lead pot temperature control, weights of materials added to formulate the active material paste mixes, and temperature and humidity profiles during the curing process to achieve the proper crystal structure formation and size. More importantly however, several unique manufacturing processes had to be developed to assure VRLA cell reliability -- these include heat sealing, terminal post welding, electrolyte filling and leak detection.

Jar To Cover Heat Seal

Lead-acid cells are universally housed in plastic containers consisting of a jar and cover. In a vast number of battery designs, the jar and cover are joined using a heat seal. In the sealing process, a bead of molten plastic is extruded along the seam between the jar and the cover. When the seal cools, the bead is usually trimmed off for esthetics, before the cell is fitted into the battery tray.

Trimming this bead shortens the sealing path length and removes the "skin" which forms when the melted plastic solidifies. These reduce the inherent resistance to gas and electrolyte leakage at the joint.

To provide increased protection against gas and electrolyte leakage at the jar-to-cover seal, GNB perfected a process and the machinery to provide an additional heat sealing band using the plastic bead at the jar to cover joint **(Figure 4)**. Instead of trimming away the bead, the excess plastic is smoothed over the joint to form a redundant seal. In addition to increasing the heat seal strength and the seal path length, the smoothed bead forms a "skin" which covers any potential porosity in the fused weld region between the cover and the jar.

Terminal Post Fusion

The terminal connections of a cell are typically made by passing a lead terminal post, which is integrally connected to the respective electrodes of the cell, through a lead bushing molded into the battery cover. The bushing and the post are then welded together. The welding is most often done manually with an oxygen/gas torch. Because this technique is very operator sensitive, it is inevitable that wide variations in weld appearance and depth of weld occur. In addition, the torch applies more heat over a wider area than is needed to fuse the two parts together. The plastic adjacent to the lead bushing in the cover is vulnerable to damage from excessive heat. This has been identified as a major cause of leakage in VRLA cells.

To counter this, GNB has developed an automated, computer-controlled terminal post fusion system **(Figure 5)** which eliminates all of the problems caused by manual terminal post welds. The process uses a highly focused tungsten inert gas (TIG) welder which provides precisely directed, high intensity, localized heating to weld the terminal post and the bushing. The resulting weld has a greater and more even depth of fusion. Because it is made without excessive heat, it drastically reduces the potential for heat damage to the surrounding plastic and minimizes the potential for electrolyte leakage. Finally, since the welding is done under a blanket of inert gas, the weld is free of oxidation. This gives it a better appearance.

Electrolyte Filling

The quantity of electrolyte filling the pore volume of the separator and the electrode active materials in a VRLA design is critical in achieving an appropriate degree of oxygen gas recombination. If there is too much electrolyte, the cell becomes saturated, fails to recombine oxygen efficiently and emits gasses through its pressure relief vent. Too much electrolyte can also lead to electrolyte leakage. If there is too little electrolyte, the cell suffers from increased resistance and reduced capacity.

To insure that each ABSOLYTE cell is filled with the specified volume of electrolyte, GNB developed and installed a computer controlled filling station which adds a measured amount of electrolyte to each cell using weight as the measurement criterion. The method eliminates variations caused by temperature fluctuations and any visual methods used in a manual filling operation. Using the "fill-by-weight" approach, electrolyte filling accuracy has increased from ± 4% with a process standard deviation of 2.5% to an accuracy of ± 1% and a process standard deviation of 0.5%.

Leak Detection

The reasons for a leak-free container for a VRLA cell are obvious. To insure that a cell is leaktight, manufacturers of VRLA cells, including GNB, have instituted manufacturing processes that test the integrity of the cells' seals. Throughout the history of its ABSOLYTE product line, GNB has tested every cell and continually improved the sensitivity of its leak testing methods. The initial tests relied upon pressure decay after pressurizing a cell with compressed air. An improvement to that technique included pressurizing the cell and submerging it in a tank of water. However, even cells that passed these tests were sometimes subject to minute electrolyte and gas leaks that appeared after the cells were installed into service. After analyses of these cells and a rigorous calculation involving molecular diameters, hole sizes and surface wetting, we concluded that pressurized air testing could not identify the small leaks in the cell seals which, over time, would allow electrolyte to creep through.

As a result, GNB developed an automated helium leak detection system to assure the integrity of the seals on its ABSOLYTE cells. The system is similar to the one used by the aerospace industry to identify and locate leaks in space vehicles. This test places cells pressurized with helium gas in a vacuum chamber. Using a mass spectrometer, it analyzes the atmosphere in the chamber for the presence of helium. The amount of helium detected after a set period of time determines the level of leak tightness and the size of any micro leaks. This process readily identifies micro holes that are 4 times smaller than will allow electrolyte to creep through.

THERMAL MANAGEMENT AND CHARGING REGIMES

Elevated temperatures have deleterious effects on the life of any lead-acid battery. In VRLA batteries, in addition to accelerating the grid corrosion reactions, elevated temperatures can also induce failures by accelerating the loss of water by gassing and by diffusion through the container material itself. In addition to the heat generation mechanisms associated with the operation of any battery including (i) the resistive heating effects caused during discharge, ii) the heat released due to the chemical and electrochemical reactions on charge coupled with the resistive heating effects during charge, (iii) miscellaneous heating effects from polarization and the grid corrosion reaction, VRLA batteries have one additional significant heat generating source -- the oxygen recombination reaction which is at the heart of a VRLA cell.

Heat dissipation in a lead-acid cell occurs by conduction through the cell materials, by convection from the surface of the battery and its components, and to lesser degrees by radiation and evaporative cooling resulting from gasses being released from the battery. VRLA batteries however have a lower heat capacity than flooded systems, have no internal convection and have an additional mechanism for heat generation. Thermal management at both the cell and battery levels in large VRLA batteries for utility applications, therefore, is a necessary as well as challenging requirement. Further, because charging is intimately associated with the heating effects experienced in the VRLA battery, thermal management and charging profiles must be evaluated together.

Utility energy storage applications require that the battery be recharged during off-peak hours, and usually limit available recharge time to less than eight (8) hours. Additional charging restraints are required to limit temperature rise in the cells, to control grid corrosion and water loss, to extend battery life, and in the extreme case to prevent thermal runaway.

GNB's modular design for its ABSOLYTE VRLA battery **(Figure 6)** not only provides a self-contained, space-saving, easy to install system for large utility battery installations, but also assists the battery with thermal management. The steel battery trays are excellent heat sinks and radiators to remove heat from the cells, and the stacking approach provides inherent air circulation channels to dissipate heat and maintain the cells under uniform temperature conditions. The result is the ABSOLYTE design is resistant to thermal runaway even under extreme abusive overcharge conditions. This is demonstrated in **Figure 7** which shows that even when overcharged at voltages as high as 2.65 volts per cell (excessive considering that the recommended float charge voltage for ABSOLYTE is 2.23-2.27 volts per cell), charging currents remain stable even after extended periods of time. The stable overcharge current indicates the batteries have reached a thermal equilibrium with the environment and are able to adequately dissipate the heat being generated inside the cell.

GNB has been successful in developing recharge profiles for its ABSOLYTE batteries which allow full recharge from a deep (80% DOD) discharge in less than 8 hours without generating excessive gas or heat. One of these recharge profiles is shown in **Figure 8**. The critical parameters in establishing these recharge profiles include in-rush charge current, voltage at which charge current taper begins, finishing current and the method of defining charge termination.

SUMMARY AND CONCLUSIONS

Valve Regulated Lead Acid (VRLA) batteries, in the ten years or so since they were first introduced for industrial applications, have made significant inroads in providing safe, reliable, space efficient and cost effective energy storage systems. As with any new technology, improvements and enhancements have been necessary to assure that these batteries perform to their specifications and expectations. A significant amount of research and development, combined with an investment in highly specialized plant and equipment, is assuring the users of this technology the best battery products possible.

VRLA has been a revolutionary breakthrough in lead-acid battery technology. Over the last ten years this technology has rapidly matured and is ready to be used in the utility industry for load management, energy storage and power delivery.

ACKNOWLEDGEMENTS

GNB gratefully acknowledges the support of the U.S. Department of Energy and Sandia National Laboratories (Contract DE-AC04-76DP00789) in our efforts to improve VRLA battery reliability for utility applications through manufacturing and process control and design enhancements.

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TABLE 1

RELATIVE PERMEABILITY RATES FOR VARIOUS PLASTICS

MATERIAL	WATER VAPOR	OXYGEN
Polypropylene	1.00	1.00
FR-halogenated	1.03	
FR-non halogenated	4.84	
ABS	16.6	0.35
FR	14.6	
Polyvinyl Chloride	4.22	
plasticized		4.41
non plasticized		0.09
Polyphenylene Oxide		
FR #1	9.20	
FR #2	6.70	
Polycarbonate		1.76

Notes: (1) Values are relative to polypropylene
(2) FR = Flame Retardant
(3) Lower relative values are preferred

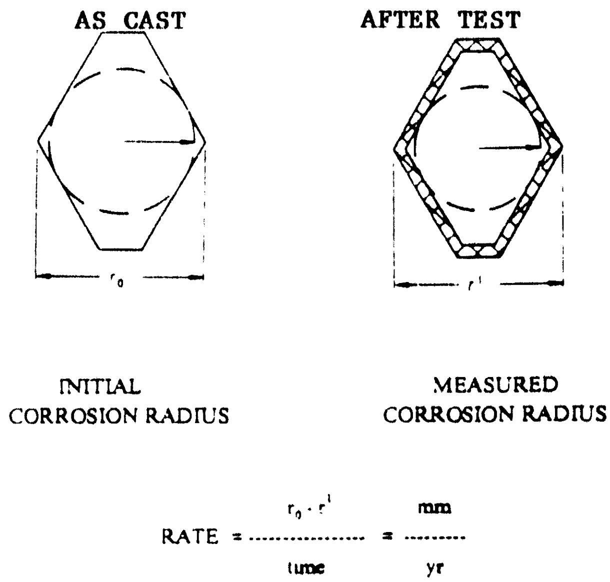

Figure 1: Grid corrosion measurements can be used to project battery lifetime.

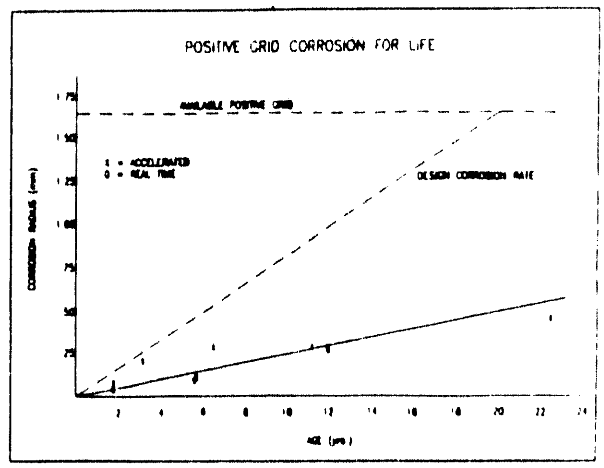

Figure 2: Grid samples from field batteries and accelerated life test confirm a 20-year lifetime.

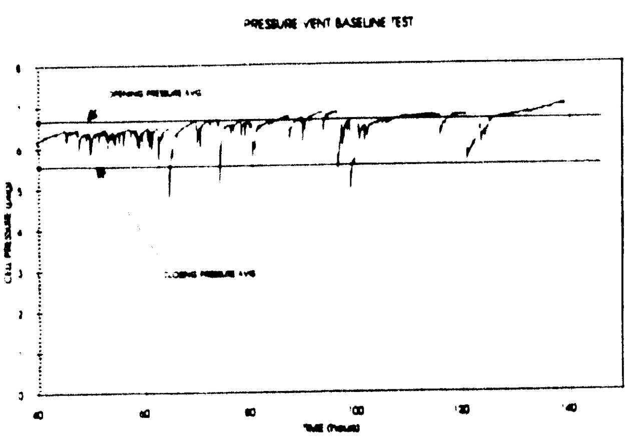

Figure 3: Operation of the pressure relief vent of an ABSOLYTE® cell is within a narrow vent/reseal range.

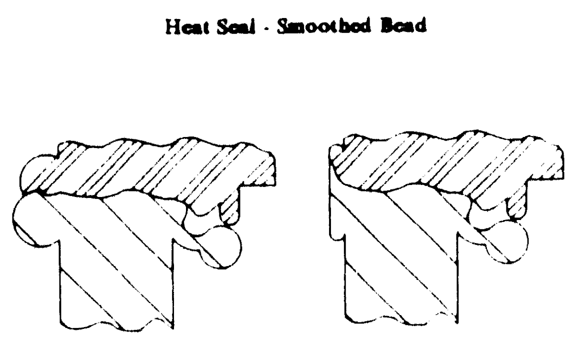

Figure 4: A unique heat seal "bead smoothing" process provides extra protection from leakage.

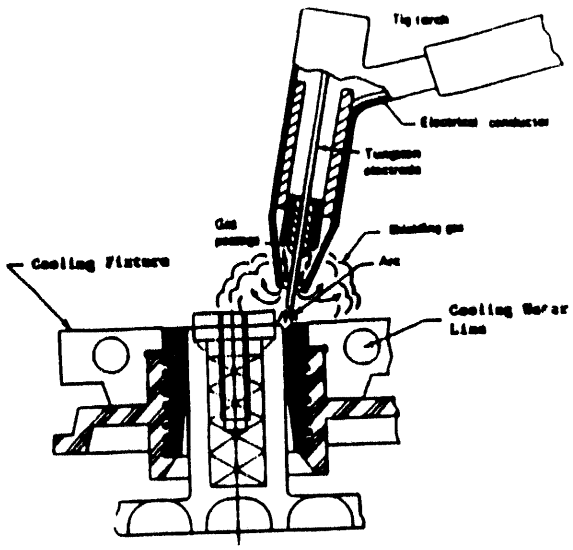

Figure 5: The TIG welder improves weld depth and appearance without heat damage to the plastic.

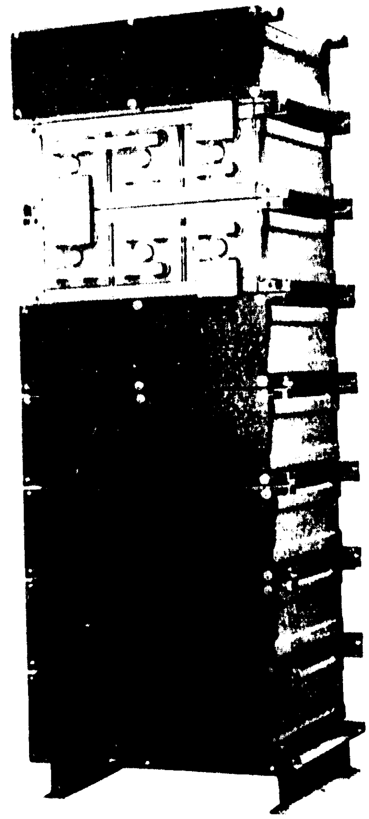

Figure 6: GNB's ABSOLYTE VRLA batteries have a unique space saving racking system.

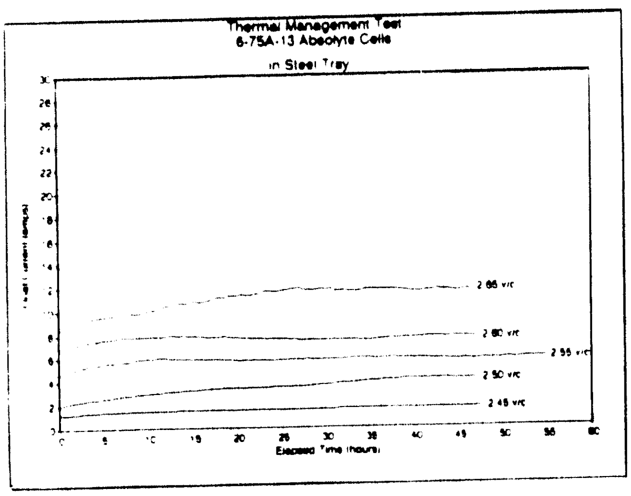

Figure 7: ABSOLYTE's design and packaging maintains thermal equilibrium under abusive overcharge.

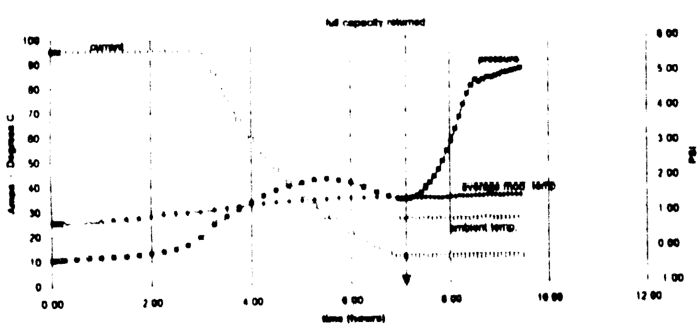

Figure 8: GNB has developed a recharge profile for VRLA batteries in utility applications.

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