

Field experience with large Nickel Metal Hydride (NiMH) batteries in stationary applications

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Abstract - Nickel metal hydride batteries bring some unique values to stationary applications - high energy and power densities, cycle life, quick charge capability and safety, to name a few. Since the late 80's, small cylindrical nickel metal hydride batteries have been widely used in portable applications requiring high rate discharge and rapid recharge, for example, camera flash and power tools. Recently, large prismatic nickel metal hydride batteries have become the technology of choice in hybrid electric vehicles due to their good cycle life, wide temperature range of operation and high rate capability. Additionally, these batteries have been tested and installed in large stationary applications due to their unique values. In one of those applications, a flooded lead acid battery system, used to back up 560kW, was replaced with nickel metal hydride battery system to provide the same 15 minutes of back up time. A case study with this large nickel metal hydride battery installation will be presented in this paper.

I. INTRODUCTION

Both AC and DC power back up systems have been using lead acid batteries for over 150 years. Nowadays, lead acid batteries are manufactured in two different types, flooded (vented) and valve regulated (VRLA).

Most of controlled environment applications today use flooded systems while outdoor uncontrolled systems tend to use VRLA batteries due to their low maintenance need. In some installations, VRLA batteries are also being used in indoor applications due to their high energy density and low maintenance requirements.

Flooded batteries are the oldest among the lead acid technologies and have large amounts of free sulfuric acid in each cell. Cell elements like electrodes and separators are therefore immersed in the acid. This large amount of sulfuric acid in each cell presents safety challenges during manufacturing, transportation, installation and operation. In some countries, including the USA, flooded battery installations require additional safety measures such as spill containment systems as per regulations (in USA, Uniform Fire Code Article 64). Moreover, vented batteries release more hydrogen during normal float operation, as compared to VRLAs, and require the surrounding environment to be well ventilated.

As far as maintenance goes, flooded batteries require periodic service to be performed in order to function properly for which they are designed [1]. Routine maintenance includes the following tasks: checking the electrolyte level in each cell and adding water as necessary; keeping track of charge voltage and specific gravity of the electrolyte; inspecting the jars, covers and terminals for potential electrolyte leaks; periodic cleaning and re-torquing of the terminals; coordinating routine discharge tests and so on. During the operational life of the batteries, the total maintenance costs could add up to more than the battery system cost itself. Also, un-installing old batteries and installing new ones can be laborious and expensive and should only be performed by trained personnel. Due to the complexity of the above tasks and the consequence on the product life and performance, manufacturers often require detailed documentation on battery maintenance for warranty purposes.

Going back to the chemical properties of lead acid batteries both flooded and VRLA suffer from the "coup de fouet" effect. This phenomenon is described as a temporary, severe voltage drop which occurs when a heavy load is suddenly placed on the battery. It is caused by the inability of the chemical reaction in the battery to accommodate the instantaneous demand for current.

The severity of this effect varies on an application basis. Indeed, the amount of voltage drop is proportional to the current drawn from the battery. At higher rates, the voltage drop is more significant and in certain cases could trip the low voltage disconnect of the system. This will make the batteries incapable of supplying the backup power they were designed to provide. Moreover, the age of the batteries will increase the impact on the system. In fact, this phenomenon can also be used to estimate the state of health of lead acid batteries [2, 3]. This is why lead acid battery installations requiring high rate discharges have to be oversized to accommodate this sudden voltage drop.

Although in many developed countries long power outages are not common, short shallow discharges are still an issue. Batteries are often subject to frequent shallow discharges. Numerous such discharges can thus reduce the calendar life of the lead acid batteries significantly. Often,

lead acid battery manufacturers require their customers to install cycle life counters for warranty purposes. In such applications, batteries are often replaced a long time before the warranted period is over. However, in underdeveloped countries, frequent long power outages are still common and the need for a high cycle life battery is crucial.

A lead acid battery is considered to have reached its end of life when the capacity of a fully charged battery reached 80% of its original capacity [4]. This is mainly because, after it reaches 80% of its original capacity, the available energy can suddenly drop and the performance of the battery during future discharges can not be predicted. This is commonly known as “sudden death” syndrome.

However, the real end of life of the lead acid battery occurs due to a gradual chemical reaction. Indeed, the positive grid in the lead acid battery is corroding continuously during float charge. Since the product of this corrosion is lead dioxide, PbO_2 , and its volume is higher than lead, the grid material, the positive grid in the battery will grow in size. Note that the growth rate of lead antimony and lead calcium grids are higher than that of pure lead.

When a rectangular battery grid grows, it tends to deform and gradually loses contact with the active material. As part of this process, the active material will slowly shed off from the grid. After the battery reaches about 80%, the loss of material is significant enough that the capacity drops suddenly and the battery can not successfully support the load. Due to this uncertainty, it is recommended by various standards that the lead acid batteries be replaced when they reach 80% of their original capacity.

Figure 1 shows the severely corroded lead calcium grid with overlaid bare grid to show initial and final dimensions (Courtesy of Bell system technical journal). As you can see, the active material pellets are losing contact with the grid material due to its deformation.

Finally, the need for higher currents and longer duration keeps on growing with the expansion of the UPS market. Some users have chosen to expand their facilities to incorporate more strings. However, in many cases it is expensive to add more battery room and in some cases it is not possible to do so. Hence, the higher energy density batteries are becoming more and more attractive for these applications.

II. NICKEL ELECTRODES

One of the best positive electrodes available in alkaline batteries for high cycle life applications is Nickel. It is used in nickel cadmium (NiCd), nickel zinc, nickel iron, nickel hydrogen and more recently nickel metal hydride (NiMH) cells.

NiCd batteries provide advantages like high cycle life, robustness and long life. The negative electrode in NiCd batteries is cadmium and the positive is Nickel oxyhydroxide. The electrolyte is potassium hydroxide (KOH). The nominal cell voltage is 1.2V. Small cylindrical NiCd batteries were popular in consumer applications. However,

they lost their popularity in that market due to their “memory effect”. This is the phenomenon where the useful capacity of a battery can be significantly diminished if they are continuously subjected to shallow discharges.

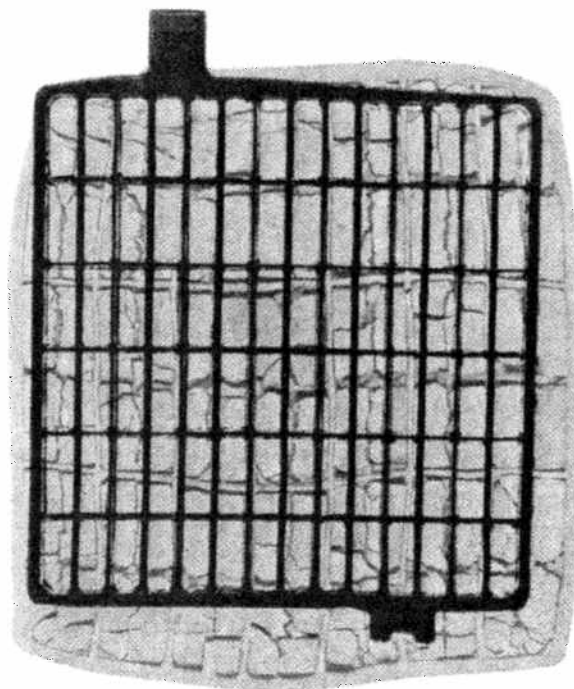


Fig. 1: Picture of PbCa grid after severe corrosion

Moreover, Cadmium is not an environmentally benign material and needs to be disposed of or recycled properly, which in some countries including the USA, can be a difficult and costly undertaking.

Large flooded NiCd batteries are used in utility switch gear applications due to their high rate capability. Recently flooded NiCd have also been tested [5] in outdoor telecom applications, where they are expected to bring values such as long life, low maintenance and smaller foot print. However, maintenance and memory effect are still an issue with NiCd batteries in these applications.

III. NIMH BATTERY TECHNOLOGY

Since the early 70's Nickel hydrogen batteries have been widely used in aerospace applications like Low Earth Orbit (LEO) requiring over 40,000 cycles and Geosynchronous Earth Orbit (GEO) requiring a long life over 15 years. In addition to higher cycle life and long calendar life they also provide high specific energy (Wh/kg). On the down side, nickel hydrogen batteries have low volumetric energy and high self discharge due to high pressure hydrogen vessel.

In Nickel metal hydride (NiMH) batteries, the negative electrode has been replaced with the metal compound to store

the hydrogen. The metal hydride is capable of undergoing reversible hydrogen absorbing-desorbing reaction as the battery is charged and discharged. Both NiMH and Nickel hydrogen batteries use the same electrolyte, potassium hydroxide (KOH).

NiMH batteries have similar electrical characteristics to NiCd batteries; however, their electrode has higher energy density than the cadmium electrode, hence making the NiMH batteries a higher energy density battery. Note, unlike NiCd batteries NiMH do not have the memory effect.

Small cylindrical Nickel metal hydride batteries have been in existence in portable applications since 1987. They have been the life saver for the high power consumer applications like power tools, camera flash and electric cars. Moreover, flooded or VRLA batteries could not provide the cycle life, rate capability and energy density required for the Electric Vehicle (EV) applications. Large NiMH batteries were developed for the EV applications due to their long cycle life and high rate capability. Many car manufacturers tested NiMH batteries extensively for these applications.

In recent years large prismatic and cylindrical NiMH batteries have been designed, widely tested and used in the hybrid electric vehicle market. The cycle life performances, high rate capability, as well as the wide range of operating temperature of NiMH batteries have contributed to making them the technology of choice for this application today.

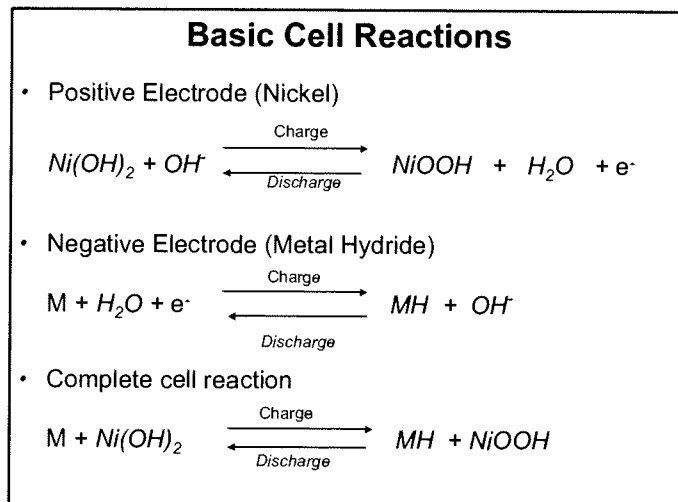
Since 2002, NiMH batteries developed for EV applications have also been tested for telecom stationary applications in the laboratory environment. The results show that NiMH batteries can have 30 years of operation life [6] at room temperature. Small NiMH batteries were also developed and tested for outdoor applications and can last 15 years at 30 C and the operating temperature of -10 C to 60 C [7]. They also bring unique and obvious advantages to the stationary markets like space savings, weight, cycle life and high rate capability.

IV. NIMH BATTERY CHEMISTRY

The following equations provide basic cell reactions of a NiMH battery. In a fully charged state, the active material on the positive electrode is Nickel oxy-hydroxide and that on the negative electrode is metal hydride. During the charge reaction, hydroxide from the electrolyte reacts with the nickel oxy-hydroxide $Ni(OH)_2$ found on the positive electrode to form $NiOOH$ and water, while, on the negative electrode, water reacts with the metal alloys to form metal hydride. The charge reaction is exothermic. The heat produced during the charge process must be released to avoid continuous temperature rise of the cells.

As can be seen in the cell reactions above, normal charge conditions do not result in any gas evolution. However: Oxygen is generated during over-charge conditions. Overcharging happens when a cell is charged even after all the available positive material in the cell is fully

charged. This transition to overcharge is normally noticed by a small decrease in the cell voltage.



Oxygen generated during overcharge is then recombined with the excess negative material to form water. Oxygen transport to the negative is enhanced by the starved nature of the sealed design. The oxygen recombination reaction is also an exothermic reaction. There will be a sudden increase in temperature when the oxygen recombination begins. Usually the two characteristics of the NiMH batteries, decrease in cell voltage and the rate of temperature increase, are used to detect the full charge condition and charge can be terminated.

NiMH batteries are designed so that there is excess negative material incorporated to accommodate some overcharging. This means that, in NiMH batteries, the capacity is limited to the amount of available positive material.

Also during over-discharge hydrogen is generated and it is recombined with the negative electrode to form metal hydride.

During a significant overcharge or over-discharge state, the rate of oxygen or hydrogen generation exceeds the rate of recombination which causes pressure build-up inside the cell. For that reason a high pressure safety valve is designed into the cell. Eventually the valve opens and gas is released in the atmosphere. The components released are oxygen, hydrogen, water and potassium hydroxide vapors. This release only occurs under extreme abusive conditions.

V. CELL CONSTRUCTION

Figure 2 shows the cutaway view of the Cobasys Series 9500, NiMH cell. It is 1.2V nominal 85 Ah cell. Each positive and negative electrode is enclosed in a polypropylene separator. The electrolyte KOH is absorbed in the separator. These cells have thick terminals to handle large currents. Each cell is equipped with a safety vent to handle high pressure during any overcharge conditions.

Also, each cell is enclosed in a steel container to protect from bulging when high pressure is built in the cells during over-charge conditions. These steel cans enhance dissipation of the heat generated in the cell during various charge/discharge conditions. Each cell has a width of 1.32 inches, depth of 4 inches and a height of 6.9 inches.

Figure 3 shows the construction of a 10 cell module, where ten of the above cells are connected in series. This 10 cell module forms a 12V battery.

Each module has a width of 4 inches, depth of 14.4 inches and a height of 6.9 inches. This also has an energy density of 155 Wh/L and a specific energy of 60 Wh/Kg.

Figure 4 shows the % of remaining capacity with cycle life at 25 C and at 80 depth of discharge at C/3 rate. For this study the cells were charged at C/3 rate followed by C/10 rate until it was fully charged.

the above elements reduces the hydrogen absorbing capability of the negative electrode.

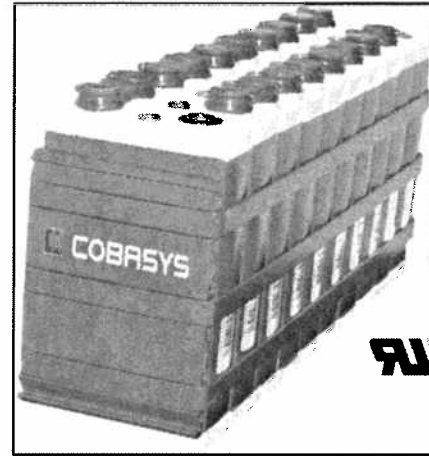


Fig 3: Picture of a 10 cell, 12V series 9500 NiMH battery module

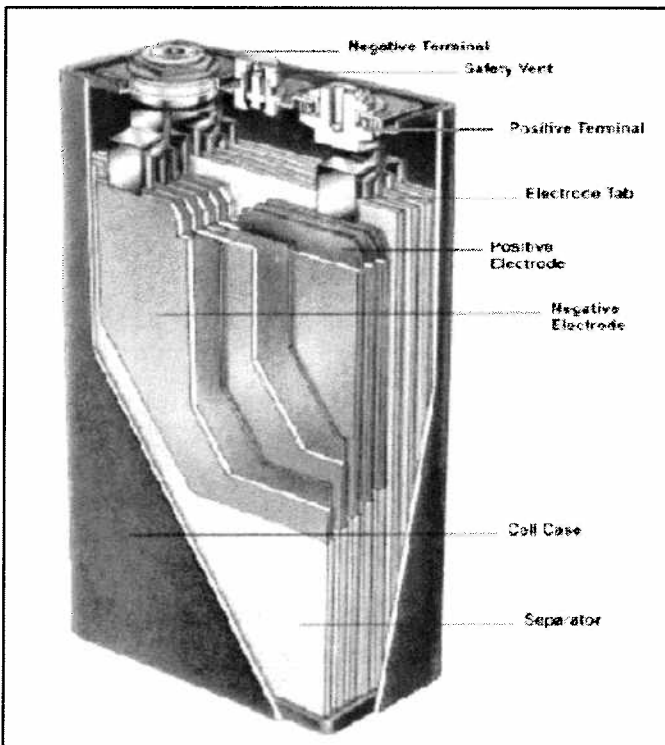


Fig 2: Cutaway view of series 9500, 85 Ah NiMH cell

The fully charged condition was detected and charge was terminated at the voltage rollover condition. The modules were then discharged at C/3 rate.

Even after 1700 cycles the capacities of the modules were about 90% of the rated capacity. Cycle life tests were conducted at lower depth of discharge and found to be extremely high compared to common stationary batteries. The mechanism for capacity decay during cycling was found to be due to the diffusion of elements [8] forming the metal hydride. The charging efficiency of the NiMH battery declines slowly the available capacity is diminishing. Loss of

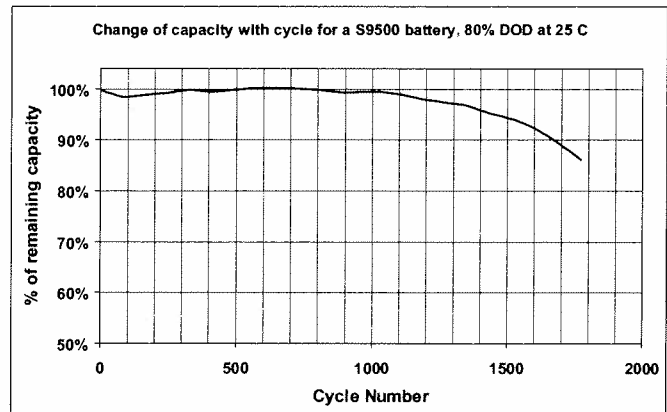


Fig 4 Percentage of capacity versus cycle life of the series 9500 NiMH battery module

As discussed above, overcharging NiMH batteries can reduce the calendar life. Overcharging can also generate heat. The charging efficiency is reduced at higher temperatures. For this reason controlled charging and termination of NiMH batteries is critical for long life and the efficient operation of the batteries.

VI. NIGUARD® BOX CONSTRUCTION

For UPS applications, four ten cell modules are connected in series to form a 48V 85 Ah battery system. These four modules are enclosed in a box with charge controller and integrated monitoring system. Each module's

charge voltage, temperature and charge/discharge currents are monitored. The battery charging parameters are changed as per the state of charge and temperature of the modules. Each "NiGUARD®" box has a high speed Controller Area Network (CAN) bus output for monitoring purpose. The outputs from each box can be connected common bus and the whole system can be monitored from a single location.

Fig 5 shows the top view of the 48V 85Ah NiGUARD® box, without the top cover. The charge control electronics are at the back of the box. Also at the back of the NiGUARD® box are positive and negative terminals and a fan which allows for better heat transfer during charge and discharge.

There is also a green/red LED in the front for visual indication of normal operation or any fault conditions. Each 48V box can provide 10.5 kW of power for 10 minutes.

Each NiGUARD® box has dimensions of 17 inches in width, 20.5 inches in depth and 7.5 inches in height and can be mounted in a 19 inch rack. Different number of boxes can be connected in series and/or parallel to provide the required voltage and power, or capacity.

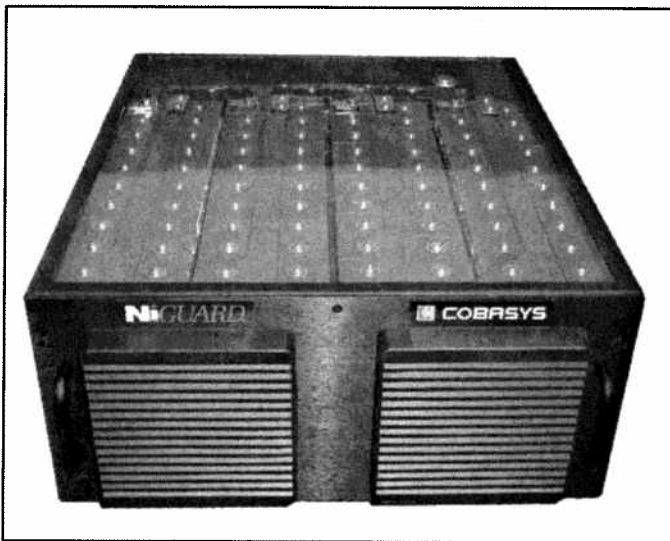


Fig. 5 Top view of the 48V 85Ah NiGUARD® Box

Fig. 6 shows the constant power discharge curves for the NiGUARD® box.

VII. FAILURE MECHANISM

The primary electrochemical failure mechanism of a NiMH battery is negative corrosion. The corrosion of the metal hydride electrode not only decreases the hydrogen absorption capability but also the kinetics of the hydriding/dehydriding step [9,10]. During cyclic operation, elements released by the corroded negative AB₃ alloy and coat the positive electrode. This leads to loss in charging efficiency [11]. Since corrosion also consumes water this ultimately leads to the separator dry out.

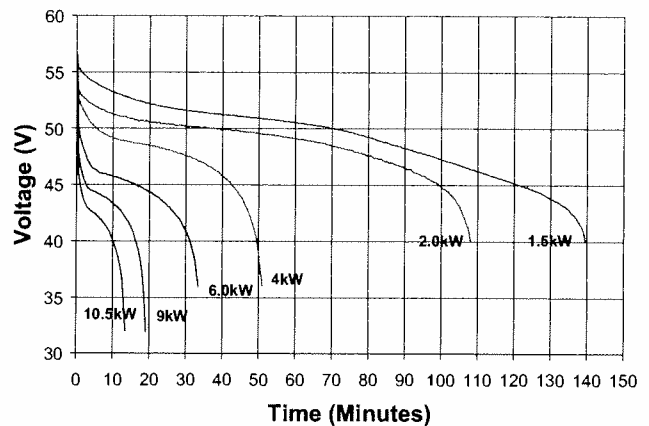


Fig. 6 Constant Power discharge curves of a 48V NiGUARD® box at 25 C.

Corrosion is caused by over-charge and charge at higher temperature or high voltages. The corrosion rate of the negative electrode increases with cycling and depends upon the composition of the negative alloy. To increase the cycle life, the alloy composition has to be optimized [12].

Water loss can occur through the cell casing material and eventually leads to dry out and to reduced battery life. Therefore, choosing the jar material with low water and hydrogen permeation is critical for the life of the NiMH battery. The life of NiMH batteries can be significantly increased by proper charging at higher temperatures and by avoiding overcharge.

VIII. CASE STUDY – UPS APPLICATION

Fig 7 shows two strings of a flooded battery installation, connected with a large UPS system, which was replaced by NiGUARD® systems. There were three strings of flooded batteries in total, along with spill containment in the room. The NiGUARD® system was designed to provide 560 kW for 15 minutes. It was designed in combination with 48V and 24V building blocks to provide the required run time and the operating voltages. The NiGUARD® system was installed during June 2004.

The charge voltage of the NiMH battery is different from that of flooded lead acid batteries. In this installation the charge voltage of the rectifier from the UPS system was adjusted to provide efficient charging of the NiMH batteries.

Forty nine 48V and seven 24V were connected in parallel and series combination to provide 420V nominal system to provide 560 kW power for 15 minutes.

Before the replacement the three strings of flooded batteries along with battery disconnect switches almost filled the entire room space.

Fig 8 and 9 shows the space savings realized by replacing the flooded batteries strings with NiMH battery systems. The total weight of the flooded battery string

including spill containment systems was 40,000 lbs compared to 10,700 lbs for the NiMH battery system. Both options were sized for the same reserve time and at the same power.



Fig. 7 Picture showing the two tier single row flooded battery strings with spill containment.

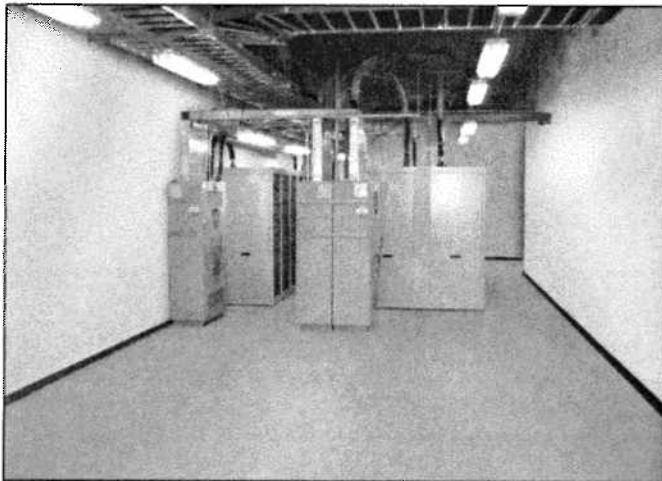


Fig 8 The space remaining after the NiMH battery system was installed.

Replacing the flooded battery system with NiMH provided a 65% space savings.

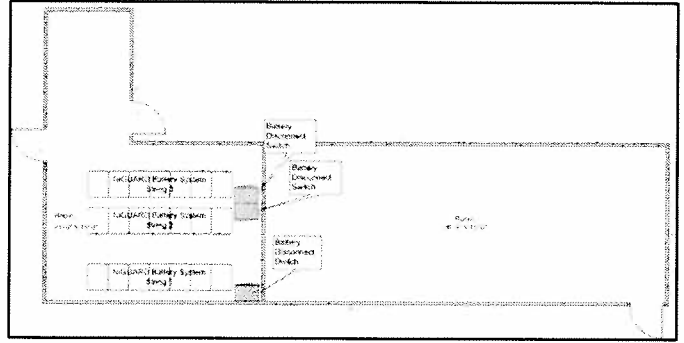


Fig. 9: Diagram showing space savings by the NiMH battery system.

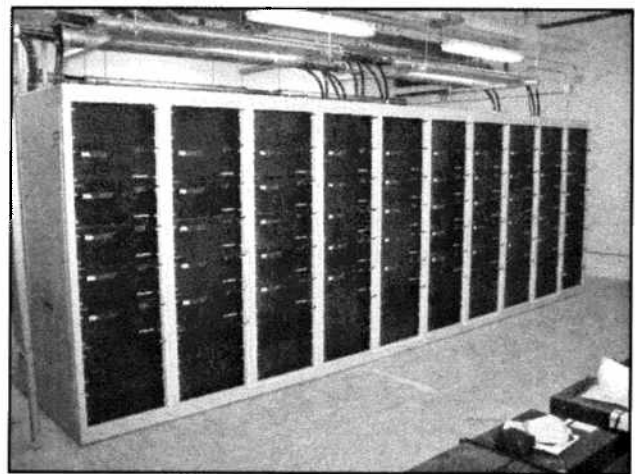


Fig 10: Front view of the NiMH battery system, showing 10 cabinets.

Table 1 shows the actual footprint and weight of the flooded lead acid battery system compared to those of the NiMH battery system. The actual floor space occupied by the NiMH battery systems was only about 35% of the flooded lead acid battery system and the weight of the total system was only 27%.

TABLE 1

Foot Print and Weight Comparison

	Flooded Lead Acid System	Nickel Metal Hydride system	Comments
Reserve time at 560 kW	15 minutes	15 minutes	Same reserve time
String floor space (sq. feet)	51 x 2.5	15.3 x 2.6	Only 35% floor space required
Weight of the system (lbs)	40,000	10,700	Only 27% of the weight

IX. CONCLUSIONS

The sealed nickel metal hydride batteries bring the following advantages to large stationary applications over the conventional lead acid batteries.

- Cycle life of 1600 or more at 80% depth of discharge and at 25 C.
- In UPS applications NiMH battery system could save about 65% of the space taken by the flooded lead acid battery system.
- NiMH batteries weighed only 27% of the flooded battery system with spill containment.
- Since large sealed NiMH batteries do not have free electrolyte, they do not require spill containment and spill response kit in the battery room.
- Because hydrogen release is limited no special ventilation is necessary.

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