Lead-Acid Batteries For Use In Submarine Applications

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Abstract - **Lead-Acid batteries provide standby and propulsion power in many submarine installations worldwide. As other electrochemical systems develop, they will be compared to the lead-acid battery in terms of energy density, power density, life, safety and cost. Continuing improvements to the "mature" lead-acid technology still make it an attractive alternative when batteries are specified for underwater vessels. This paper examines how the lead-acid battery has been modified to accommodate the specific requirements for several operational underwater vehicles.**

I. INTRODUCTION

In the year 2000, the United States Navy's submarine force celebrated 100 years of service. The U.S. Navy's involvement with submarines can be traced back to 1888 when the Bureau of Construction and Repair sponsored a design competition that won for John Holland a contract to build the experimental *Plunger.* On April 11, 1900 the Holland Submarine Torpedo Boat Company of New Suffolk, New York sold the *Holland VI* to the U.S. Navy for $160,000, and on October 12, 1900, this 54-foot, 64-ton submarine was commissioned into service as the *USS Holland,* the *SS-1.*

This tiny sub, with a crew of only five or six, was equipped with an Otto-type gasoline engine for surface running; a 50-hp electric motor powered by a bank of batteries propelled the boat on dives. Interestingly John Holland then sold his company to his electric battery supplier, and the resulting firm, the Electric Boat Company of Groton, CT, is still today the world's premier builder of submarines. From its beginnings, batteries have been an integral part of the submarine.

Like the submarine, the lead-acid battery industry can also trace its roots to the late 1890's and several of today's familiar lead-acid battery suppliers started in the business to manufacture and sell batteries to the U.S. Navy for this new and emerging market. Today, just as 100 years ago, lead-acid batteries support the world's submarine fleet, providing power for standby and propulsion applications.

II. THE LEAD-ACID BATTERY

The lead-acid battery cell stores electrical energy in the form of chemical energy, releasing this stored energy into an electrical circuit as the battery discharges. Operation of the lead-acid cell can be described by the chemical reaction (1) where the cell's positive active material (lead dioxide - PbO_2) and its negative active material (sponge lead - Pb) both react with the sulfuric acid electrolyte to form lead sulfate ($PbSO_4$) and water.

$$PbO_2 + Pb + 2H_2SO_4 = 2PbSO_4 + 2H_2O \qquad (1)$$

From left to right this equation represents discharge, and from right to left, charge. When the terminals of the charged lead-acid cell are connected through an external circuit, an electrical current will flow caused by a stream of electrons flowing between the cell's positive and negative electrodes. During charge the electrons are provided by an external power source. The nominal voltage of the lead-acid cell is 2.0 volts.

Although packaging and specific details of manufacture differ among the many available types of lead-acid battery – from automobile starting, lighting and ignition (SLI) to main propulsion batteries for submarines – the basic electrochemistry described above applies to all.

A. Lead-Acid Submarine Cells

Although the primary source of power on a nuclear-powered submarine is its reactor, batteries serve to level load the electrical system and to provide emergency electrical energy. Currently there are three types of lead-acid cell used in the U.S. Navy's fleet of nuclear-powered submarines. These cell designs differ in physical size, ampere-hour capacity and construction detail based on the space allocation on the submarine, the submarine's electrical system load requirements and available technology when the cell was designed, qualified and initially deployed.

1) *The PDX-57 Type Cell.* The oldest lead-acid cell design in service, the PDX-57 Type cell was designed in the 1970's specifically for the Ohio-class / Trident submarine.

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The cell has dimensions of approximately 23 x 20 x 46 inches (length x width x height), and each cell has a nominal mass of 2,100 lbs. The rated capacity of the PDX-57 Type cell is slightly more than 10,000 Ampere-hours when discharged at a 3-hour rate. The installed battery is comprised of 128 cells operating at a nominal voltage of 256 volts and providing total stored energy of about 2.6 Mega-Watt-Hrs (MWh). The life of the battery is about 6 years.

2) *The ASB-49 Type Cell.* The ASB-49 Type cell was designed in the mid-1980's as an improved battery for the Los Angeles (688) class submarine. The cell has dimensions of approximately 14 x 14 x 55 inches (length x width x height) and each cell has a nominal mass of 1,300 lbs. The rated capacity of the ASB-49 Type cell is 7,200 Ampere-hours when discharged at a 3-hour rate. The installed battery is comprised of 126 cells operating at a nominal voltage of 252 volts and providing a total stored energy of about 1.8-MWh. Battery lifetime is about 6 years. It is planned to utilize the ASB-49 Type cell on the first of the Virginia class submarines, the next generation of fast attack boats.

3) The LLL-69 Type Cell. The LLL-69 Type cell was designed in the late-1980's specifically for the Seawolf class submarine. The cell has dimensions of approximately 19 x 19 x 41 inches (length x with x height) and each cell has a nominal mass of 1,500 lbs. The rated capacity of the LLL-69 Type cell is 8,100 Ampere-hours when discharged at a 3-hour rate. The installed battery is comprised of 126 cells operating at a nominal voltage of 252 volts and providing a total stored energy of about 2.0-MWh.

The cell types used in the U.S. Navy submarine fleet are shown in Fig. 1.

Fig 1. Three types of lead-acid cell, the PDX-57, the ASB-49 and the LLL-69 are used to assemble the batteries onboard U.S. Navy submarines.

B. Design Enhancements

Over the years the Navy and its battery suppliers have evaluated enhancements to the lead-acid cell design to improve performance and extend battery lifetime. Some of the concepts, such as lower resistance separator materials, thinner plates and separators and more corrosion resistant lead alloys have been developed and introduced into the existing battery designs. Some of the diesel electric submarines of foreign navies use lead-acid cells with a tubular type positive plate to extend deep discharge cycle lifetime. These improvements could be considered to be evolutionary.

More revolutionary concepts in materials and component construction and even in cell design have also been investigated. Negative plate grids have been made from copper instead of lead to reduce the cell's electrical resistance. Welded titanium preforms shaped like the grid have been embedded into cast lead positive grids to increase their strength and extend battery life while still being able to survive severe shock conditions. Battery cells constructed using two separate element groups stacked one atop another in a double-decked configuration in a single cell jar have been built. And although these concepts have achieved their technical objectives and have demonstrated superior performance, often the additional costs of these advanced technologies could not be justified.

C. Commercial Lead-Acid Batteries

The design of lead-acid batteries for commercial applications have evolved more rapidly than for use on submarines. This, in part, is because these batteries do not require as long and as rigorous a qualification period; and, commercial applications change much more quickly requiring battery designs to respond with shorter turnaround times.

The most revolutionary of these changes in commercial battery designs occurred coincident with the widespread introduction and use of computer data centers, electronic control of manufacturing processes and wireless communications. All of these are extremely sensitive to the quality of the power supporting their operation, and even momentary loss of power (even a few Hertz) could result in a systems shutdown. It soon became commonplace to install standby batteries along with these electronic systems to maintain power and ensure their continuous operation.

As for submarines, the battery of choice in these backup power systems was the lead-acid battery. It was not long before the users of these backup battery systems soon discovered the shortcomings and disadvantages of operating large battery banks comprised of lead-acid cells. Installations were complex and took up a lot of space. Special racks, battery rooms, air conditioning and ventilation, and fire suppression equipment was required. The batteries needed frequent cleaning to prevent ground faults especially in high voltage systems. The batteries needed to be watered frequently and required periodic equalization charges to maintain them in a fully charged condition. Soon the managers of these information equipment centers realized, as have submariners for many years, that maintenance of their batteries was a critical and time-consuming occupation.

Unlike sailors however, the operators of these commercial battery installations found this situation unacceptable and applied pressure for batteries that require significantly less maintenance (almost maintenance-free), take up less space, are easier to install, use and replace, and do not require special rooms or other equipment (other than the charger) to achieve reliable operation and reasonable life. The response from the battery industry was a new type of lead-acid battery – the Valve-Regulated Lead-Acid (VRLA) battery.

III. The Valve-Regulated Lead-Acid Battery

It is not the discharge of the lead-acid battery that leads to the problems and issues associated with the lead-acid battery, but rather its recharge. In order to return and to maintain the lead-acid battery in a fully charged condition, energy in the form of a charging current must be provided. The lead-acid battery however is not very efficient, especially as it approaches its fully charged state, in accepting this charging current and applying it to charging the cell's active materials.

Instead several side reactions occur simultaneously that use portions of this charging energy for other, less desirable reactions. These include:

- the generation of heat
- the electrolysis of water into H_2 and O_2 gas
- the corrosion of the positive plate lead grid.

Of these, the one that can be most directly related to the problems and issues typically associated with the operation and maintenance of a lead-acid battery system is the cell's electrolyte and the loss of water from it as a result of electrolysis. Periodic watering, cleaning of cells, ground faults, building ventilation requirements, fire suppression, electrolyte spillage and personnel safety can all be traced back to the cell's electrolyte.

The Valve-Regulated Lead-Acid (VRLA) battery provides a solution. Through a unique design that absorbs all of the free liquid electrolyte, oxygen gas that starts to be evolved during charge from the cell's positive plates at about 80% state-of-charge diffuses to the surface of the negative plate where it is "recombined" by reacting with the sponge lead active material. The sponge lead active material is chemically converted first to lead oxide (PbO) and then to lead sulfate ($PbSO_4$), essentially discharging the negative active material by a chemical reaction while the battery is being charged by the external power supply.

By this "oxygen cycle" the positive active material can become fully recharged to a 100% state-of-charge while the negative active material's state-of-charge is slightly suppressed (at about 95% fully charged) to prevent the generation of hydrogen gas. Since the oxygen gas generated during charge is returned chemically and electrochemically to the electrolyte and hydrogen is not generated, water loss is essentially eliminated and the battery can be operated in a "sealed" condition. Since this balance between charging, oxygen gas recombination and hydrogen evolution can be disrupted by excessive charging voltages, these cells are fitted with a self resealing pressure relief vent; thus the "Valve-Regulated" lead-acid battery.

A. Commercial VRLA Batteries

The first large VRLA cells having capacities greater than 100 Ampere-hours were introduced into the marketplace in the early 1980's, even though small (2 – 10Ah) VRLA cells were available in the mid-1970's. Because all of the cell's required sulfuric acid electrolyte is absorbed and retained in the cell's porous and absorbent separator material by capillary action, battery designers found that by placing the cells horizontally, rather than vertically, large battery cells could be constructed avoiding the adverse effect of stratification of the electrolyte within the separator caused by gravity.

The large, bulky, thick-walled containers used with conventional "flooded electrolyte" lead-acid cells were no longer needed as the jar to hold large quantities of liquid sulfuric acid – all of the acid was now absorbed in the active materials and separator and there was no free liquid to contain. But since thin-walled plastic battery containers, like those used for automotive SLI batteries, could not contain the internal pressure expected during operation of the "oxygen cycle" cells were constructed with a structural support. Designer quickly determined that a low cost steel box or tray could be used as the supporting structure, and at the same time be used as a radiator to eliminate the heat generated by the battery during discharge and charge (Fig. 2).

Fig. 2. Commercial VRLA cells are packaged in modular steel trays.

Soon VRLA battery installations took on a new "look" appearing as stacks of cells positioned one atop another using their modular trays as their racking structure (Fig. 3).

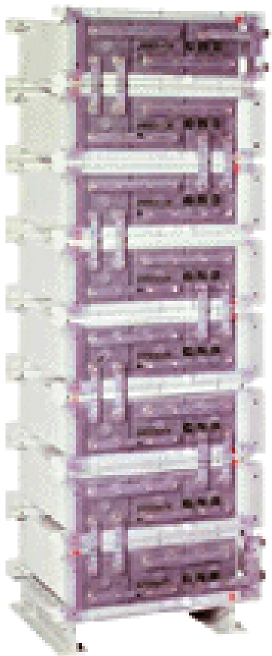

Fig. 3. VRLA battery installations appeared as stacks of cells using their modular steel trays as their racking structure.

This new installation arrangement saved valuable floor space, and made access to the individual battery cells much easier for cleaning, testing, connection torquing and replacement, if necessary. The VRLA battery received UL recognition providing data that indicated virtually no gas emissions if the batteries were operated within recommended charging voltage limits. Soon local fire officials were allowing VRLA batteries to be installed in computer rooms, office areas and other locations without requiring specialized ventilation.

From their commercial beginnings in the mid-1980's, VRLA batteries have grown to represent more than 70% of the market for standby battery power systems used in telecommunications, Uninterruptible Power Supply (UPS), railroad signaling and cable TV installations. Some VRLA batteries are designed even for deep discharge applications such as fork lift trucks, airport ground support vehicles, diesel railroad engine starting, photovoltaics and off-road electric vehicles.

Today, individual VRLA cells are available in a wide range of sizes from as small as 2 Ampere-hours to as large as 3,000 Ampere-hours, and in configurations from single cells to multi-cell monoblocks.

B. VRLA In Military Applications

Commercial VRLA batteries are used extensively throughout the military at installations using electronic equipment that require battery support. VRLA batteries are installed, for instance with the UPS systems at NORAD's facility at Cheyenne Mountain, NASA's down-range telemetry facility at Cape Canaveral and at the CIA's monitoring facilities at Menwith Hill, England. VRLA batteries are used with PV arrays at the San Clemente target range and at Yucca Flats.

VRLA cells packaged in special containers and modules can be found on all Spruance and Aegis class surface vessels; and VRLA batteries are used in certain military aircraft.

A unique VRLA battery was designed, qualified and deployed for redundant backup power in the Peacekeeper missile systems installed and operated during the 1980's and 1990's. As part of the qualification requirements for this application, the VRLA battery had to remain operational after experiencing shock and vibration equivalent to that of a nuclear blast, and to survive being discharged "flat" to zero volts over a dozen times.

C. VRLA Batteries In Underwater Vehicles

Although VRLA batteries are used in the sightseeing submarines operating at the Edmonton Mall and at several Caribbean locations, the most prominent use of VRLA batteries in underwater vehicles is at the Navy's Acoustic Research Facility at Bayview, Idaho. There the unmanned submarines, *Kokanee* and *Cutthroat*, are used for various research studies to identify, measure and mitigate noises emanating from underwater vehicles.

The *Kokanee* was fabricated and assembled at SWRI in San Antonio, TX in 1986. When developmental delays scuttled the nickel-cadmium battery initially planned to be installed on Kokanee, a unique, one-of-a-kind VRLA battery was developed, designed and manufactured in just under a year (Fig. 4).

Fig. 4. The LSV-153 VRLA cell was specifically designed to fit the Kokanee research submarine.

This 22 x 6.5 x 9 inch (length x width x height) module was constructed with 153 automotive sized plates connected in parallel to form a single 2-volt lead-acid battery cell. Its unusual shape was to allow the cell to fit into the battery compartment and racks already designed and constructed onboard the submarine for the nickel-cadmium battery. The cell featured several "firsts" including copper inserted terminal posts (four of each polarity) to carry the very high discharge currents required for vessel operation, a structural rigid foam plastic container to eliminate the steel tray used by VRLA batteries in an effort to reduce overall battery weight; and several unique manufacturing processes including a cast-on-strap process to connect all 153 of the individual plate lugs and cast the terminal posts (with their copper inserts) in a single operation.

Each 2-volt *LSV-153* cell had a nominal capacity of 750 Ampere-hours when discharged at its 5-hour rate. At the maximum discharge rate at which the battery was required to operate, 5kW per cell, the cell was able to discharge continuously for 7 minutes; operating intermittently with low rate rest periods between discharges the battery was able to achieve 11 minutes of discharge at its maximum required discharge rate. The entire battery configured as 480 of the *LSV-153* cells in series was able to provide 2.4 MW of power to the *Kokanee's* propulsion motor. The *LSV-153* battery had an operational lifetime of 4 years or 400 discharge cycles.

The *LSV-153* cell design served on the *Kokanee* until 1994 when it was replaced by a VRLA battery derived from a commercial-off-the-shelf (COTS) battery package manufactured for UPS applications on an automated battery assembly line. This change was made to reduce lead-time (the *LSV-153* manufacturing process was used only once every four years for this one cell type), improve product reliability, and reduce cost. The one large *LSV-153* cell was replaced by three (3) *LSV-1140* cells which were connected externally in parallel to form a single 2-volt element (Fig. 5). The total battery consisted of 1,440 of the *LSV-1140* cells (i.e., three in parallel x 480 in series).

Fig. 5. The LSV-153 was replaced by a VRLA package based on a COTS battery design.

Each 2-volt *LSV-1140* cell has a nominal C/5 rating of 225 Ampere-hours, but is still able to provide high rate performance comparable to the original *LSV-153.* Battery lifetime was still 4 years or 400 cycles.

In 2000, the Navy dedicated its *LSV-2*, the *Cutthroat.* Like its predecessor, the *Cutthroat* uses a VRLA battery. The individual *LSV-2* cells are very nearly the same as the *LSV-1140* cells with minor changes to the package for handling and installation in the submarine's battery racks. The internals of the cell were modified slightly and discharge capacity at the 5-hour rate is back to 250 Ampere-hours. The *Cutthroat's* total battery configuration consists of 1,680 of the *LSV-2* cells connected together as four (4) parallel strings, each string consisting of 420 of the *LSV-2* cells in series. It is planned that in 2003 when the *Kokanee* requires a replacement battery, the improved *LSV-2* cells will be easily retrofitted.

A complimentary paper being presented at this forum *"Energy Storage Systems for High Speed Large Scale Vehicles – Is Anything Better Than Lead-Acid?"* will discuss operational experiences with the *Kokanee* and the *Cutthroat* using the Valve Regulated Lead-Acid batteries.

IV. The Future For Submarine Batteries

As we peer into the future, we seek the "perfect" battery. It will store huge quantities of energy yet will be very light and will take up virtually no space. It will provide maximum power with no loss in total energy delivered even at the highest discharge rates. It will be virtually indestructible, have no components that wearout or degrade with time and use, and will require no maintenance whatsoever. And finally, this "perfect" battery will be constructed using common, readily available, fully recyclable, low cost materials and will be manufactured on a high speed, fully automated and unmanned assembly line.

So now, let's come back down to earth and take a look at the advanced battery systems that are "just around the corner." Because of its widespread use, the VRLA battery could be considered today's "standard." Hence, comparisons of the various battery technologies in the following sections will be relative to the VRLA battery.

A. Energy Density (Watt-hours / Unit of Mass)

The relative energy densities of several battery couples are provided in Fig. 6. It is obviously apparent that all of the advanced electrochemical systems being investigated offer the promise of more energy per unit of weight and / or volume than does the lead-acid battery. The reason for this is simple – lead is heavy, and no one has yet been able to invent "light" lead. Battery systems based on the lighter elements

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offer the greatest potential advantage. However, many of these low mass elements are often the most energetic and harnessing their energy safely may pose some technical challenges.

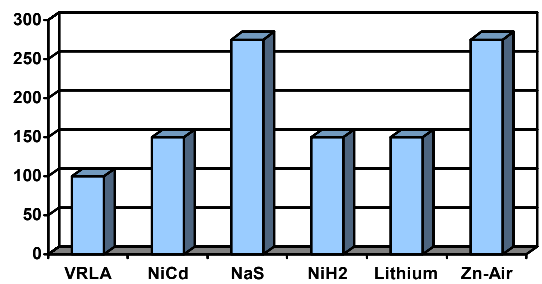

Fig. 6. A comparison of selected advanced battery couples shows that all of the systems being investigated offer the potential for increased energy density (Wh/kg).

B. Power Density (Watts / Unit of Mass)

Although a battery system may be able to store a relatively large amount of energy, it is important when selecting a battery system to understand its capability to deliver that energy, especially in an underwater vehicle, at relatively high rates of discharge. The relative power densities of several battery couples is provided in Fig. 7.

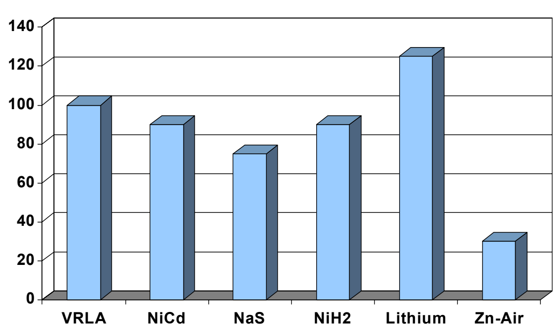

Fig. 7. Despite being heavy and having a lower energy density, the lead-acid battery is able to provide considerable power per unit of mass. Lead-acid batteries can be designed specifically for high discharge current applications.

C. Battery Life

Battery lifetime is an essential parameter when justifying the battery system on the basis of life cycle cost. In many instances, the battery itself may be the least expensive item when a battery replacement is budgeted. Manpower, equipment, other materials and lost productivity may often cost several times more than the cost of the battery. Hence a longer life battery requiring fewer replacements would be more attractive than a lower cost battery requiring more replacements. The relative cycle lifetimes of several battery couples is provided in Fig. 8.

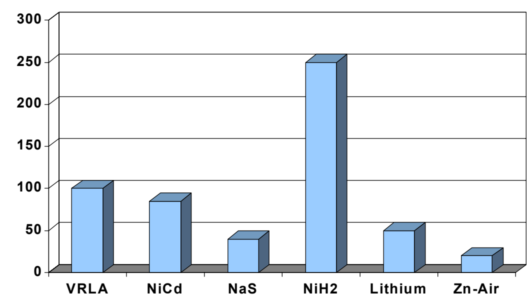

Fig. 8. Lead-acid batteries have proven cycle lifetimes. Some of the other battery systems have yet to demonstrate the projected life in large installations.

Although lifetimes greater than that for the lead-acid battery have been projected for some of the other battery couples, it has yet to be demonstrated for large, high voltage installations.

D. Cost ($ / Unit of Energy)

No matter how good the system, it almost always comes down to the question of *"How much will it cost?"* Because the lead-acid battery uses relatively low cost materials (lead, polypropylene and sulfuric acid) and its manufacturing and recycling infrastructure is established, it has a very low cost basis when compared with other battery systems. Even if manufacturing capabilities are considered to be equivalent, the cost of a lead-acid battery is significantly less expensive than the advanced systems (Fig. 9).

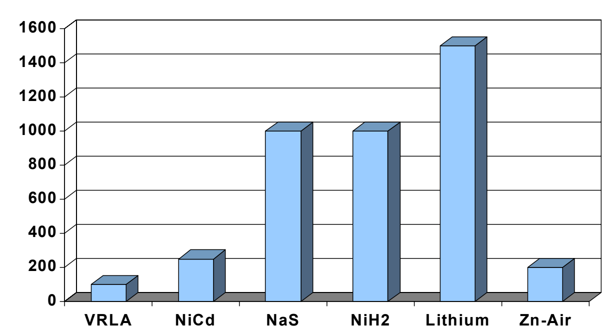

Fig. 9. The relative cost for several battery couples even assuming a fully developed manufacturing infrastructure shows that the lead-acid system is far less expensive.

Although much is reported about the potential for many of the advanced battery systems, it may be many years (possibly decades) before their cells have been scaled up in size to thousands of ampere-hours, that large installations (MWh capacities) have been operated successfully for several years, that their safety even under abusive and combat conditions have been demonstrated, and that their reliability, ease of recharge and maintenance and repeatability of manufacture have been proven.

If this is the case, then what can be done now for the largest group of underwater vehicles – the U.S. Navy's fleet of combatant submarines.

E. VRLA Batteries For Submarines

VRLA batteries have been proven in a wide range of critical commercial applications and have been used in many critical applications within the U.S. Navy, even as the total electrical source for two of the world's largest unmanned submarines, *Kokanee* and *Cutthroat.* Considering that the advanced battery technologies may be many years away from being fully qualified for use on submarines, could the VRLA technology fill the gap until these new batteries are ready?

Recently NAVSEA undertook a study to assess the feasibility of utilizing the VRLA technology both in the existing fleet as well as the next generation of combatant submarines. Following are some of the critical questions asked and answered.

Can VRLA batteries be successfully operated under the conditions anticipated in the submarine's electrical environment?

Yes, commercial VRLA cells were subjected to laboratory testing at NAVSEA – Crane on an accelerated schedule to simulate the ship's loads and electrical environment. The battery has been operated with a simple, straight-forward charge regime and no other maintenance (other than inspection of the cell's connections), continuously for over 2½ years, the equivalent of 10 years on a submarine. Capacity measured at the latest test discharge was 92+% at the battery's C/3 discharge rate.

Can a VRLA battery fit into the battery wells of the existing classes of submarine and provide comparable electrical performance to that of the current flooded batteries?

Yes, NAVSEA working with the two primary design shipyards and a VRLA battery manufacturer determined that even using the preferred horizontal mounting of the VRLA battery, it was possible to fit a VRLA system within the existing battery compartment of the three existing classes of submarine as well as the next generation of fast attack boats. The VRLA batteries would operate at comparable system voltages and provide comparable total MWh capacities. Certain modifications to the compartments would be required but no major structural modifications to the boat would be necessary.

Can the VRLA battery survive the shock and vibration conditions established for a combatant submarine?

Yes, tests were conducted using commercial VRLA cells on the Navy's Medium Weight Shock Machine at prescribed shock conditions to meet qualification for shipboard installation. The cells passed all electrical and mechanical requirements. The results of these preliminary tests indicate the VRLA cell's construction is sufficiently robust so that in its final design configuration, passing shock qualification should be readily achievable.

Having answered these critical feasibility questions with a positive response, NAVSEA has initiated a project to develop the VRLA cell sizes that best fit into each of the submarine classes. VRLA installations at two of the Navy's nuclear training facilities are already scheduled for later this year to develop a database of operations and to begin to familiarize the next generation of submariner with this technology.

It is possible that by the middle of this decade, VRLA batteries will begin to be retrofitted into fleet submarines being one of the most significant changes to the submarine's electrical system since going nuclear.

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