Energy Storage Systems for Large Scale Vehicles

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***Abstract* – The first large scale vehicle, *KOKANEE* (LSV-1), a 3000HP, 155 long ton autonomous submarine model, was assembled at Southwest Research Institute and delivered to the Navy in October 1987. Operated in support of advance submarine propulsor development at the Navy's Acoustic Research Detachment in Bayview, Idaho, *KOKANEE* has several thousand hours underway, using two variants of valve regulated lead acid (VRLA) powering a conventional DC motor. A second large-scale vehicle, *CUTTHROAT* (LSV-2), a 6000HP, 210 long-ton submarine model, is currently undergoing acceptance trials. *CUTTHROAT* employs a permanent magnet motor. The requirements for, and design of, the two energy storage systems, as well as the charge and discharge management process, is described. The maintenance experience for this choice of energy storage method, and the considerations that lead to continued use of VRLA cells is explained.**

I. Introduction

This paper presents the US Navy's experience in utilizing lead acid batteries as an energy storage method for large unmanned autonomous submarine models. Large submarine models have been utilized by the Navy for over 30 years at the Naval Surface Warfare Center Carderock Division (NSWCCD) Acoustic Research Detachment (ARD), in Bayview, Idaho, to conduct a variety of studies leading to improved submarine acoustic and operational performance. The success of early buoyantly propelled model tests provided the necessary impetus for Navy investment in a much more complex test vehicle -- one that was powered, and would serve as a test bed for advanced propulsor concepts. The objective was to provide a platform that would enable the evaluation of propulsor concepts having a radiated acoustic signature almost two orders of magnitude quieter than current fleet submarines. The first vehicle of this type, designated LSV 1 and named *KOKANEE*, is a 150 long-ton 0.25 scale model of the SEAWOLF class attack submarine. The vehicle was assembled at Southwest Research Institute, and was delivered to the ARD in 1987.

The highly successful utilization of this vehicle throughout the 1990's drove an initiative to create a more capable second vehicle, designated LSV 2 and named *CUTTHROAT*. This vehicle, which is in the final stages of acceptance testing, is a 0.29 scale model of the VIRGINIA class attack submarine. This scale factor was chosen to maintain a 10' hull diameter for shared facilities utilization. *CUTTHROAT* will be delivered to the Navy in September 2002.

The names are taken from species of fish indigenous to Lake Pend Oreille, which is the site in Northern Idaho where the vehicles are based and all testing is conducted. Utilization of the lake is shared with the general public, and no restrictions are placed on access to the test ranges. A pictorial of the lake is shown in Fig 1.

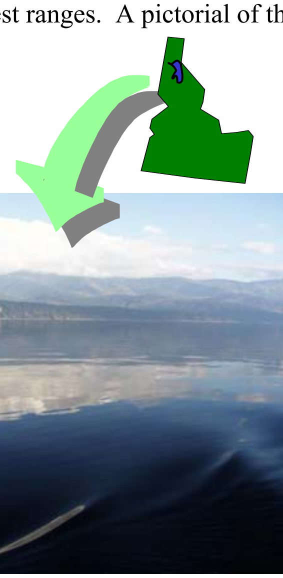

Fig. 1 Lake Pend Oreille

The Lake's characteristics include:

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- Quiet; Sea State Zero or less, 25% of the time, 50% of the time at night.
- Isothermal; 39.5°F below the surface layer.
- Deep; over 26 square miles greater than 1000'.
- Low current; less than 0.1 knot below 100'.
- Acoustic Range; instrumented and calibrated.

II. LSV-1 *KOKANEE* DESCRIPTION

At the time of delivery, KOKANEE was characterized as the world's largest unmanned autonomous underwater vehicle. Although described as a scale model of the SEAWOLF attack submarine, the term applies mainly to the outer shape, and some of the primary hull structure. Internally, the vehicle resembles the parent vessel only in those systems required to control power distribution, ballasting, cooling and ventilation, and steering and diving. There are no nuclear, weapons, life support, or fire suppression systems found aboard the full-scale craft. The vehicle is fully autonomous, and once released for a mission, is capable of managing all aspects of operation, including depth and course control, and fault identification and response

A Ship's Control Computer (SCC) controls the operation of *KOKANEE* while underway autonomously. The topside operator sends commands and receives vehicle status via a link from lake bottom mounted acoustic transducers. That same link provides simultaneous navigation updates to both the LSV-1 SCC and to topside.

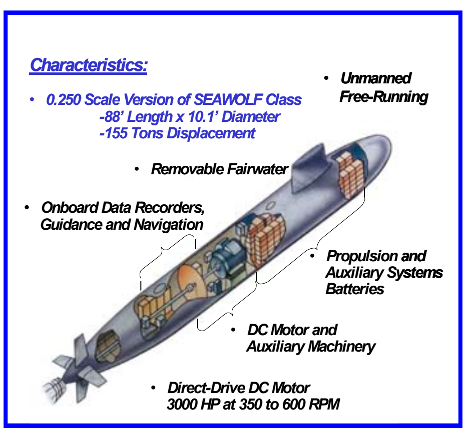

Fig. 2 LSV-1 KOKANEE

A mechanically commutated synchronous conventional DC motor propels LSV-1. A static exciter provides field excitation for the motor.

A. LSV-1 Propulsion Battery

The motor receives armature power directly from the Propulsion Battery, consisting of 480 three-cell LSV-1140 battery modules. Electrically, the battery module is three 2.1 Volts-DC (VDC) battery cells in parallel. Each module is series connected; overall full Propulsion Battery voltage is approximately1000 VDC.

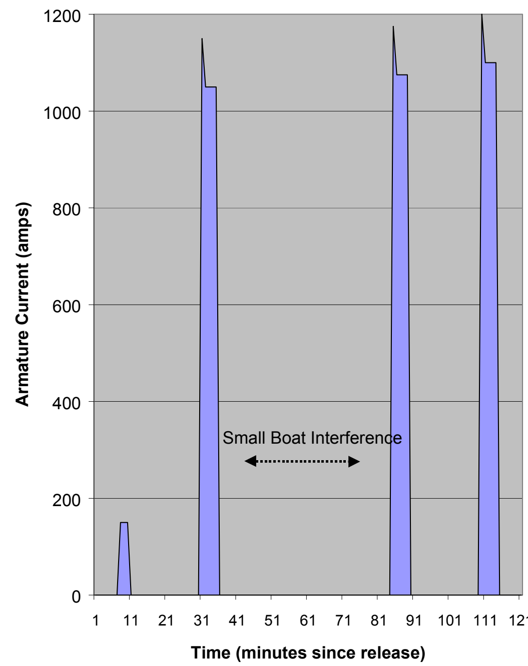

Fig 3 LSV-1 Typical Motor Current Profile

As discussed in a complimentary paper at this forum *"Lead Acid Batteries For Use In Submarine Applications"*, the VLRA battery designed for LSV-1 can discharge continuously at full power for 7 minutes; operating intermittently with low rate rest periods between discharges permits 11 minutes of discharge at full power. Figure 3 shows the discharge profile of the LSV-1 motor during a typical operating day. The operational lifetime of the propulsion battery system is 4 years or 400 cycles.

Typical operations consist of high speed passes through the measurement range, with rest periods of approximately 30 minutes during which propulsion is autonomously shifted to a 15HP, 60 rpm Loiter Motor, coupled to the main shaft by a reduction gear. Loiter operations can continue for hours, providing

flexibility for waiting out acoustically interfering delays such as small boats or rain squalls.
At 3000HP, the LSV-1 motor accommodates a full power propeller design range of 350-600 rpm. The motor operates at all speeds from 50 to full power rpm. To meet acoustic goals at less than full power, the motor requires a reduced battery voltage. The reduced voltage is accomplished by tapping the Propulsion Battery into eight sections of sixty modules each. Consequently, only a portion of the entire battery is used for operations at less than approximately 70% full power. During the 15-year history of LSV operations, most acoustic runs have been performed in the range of 60-80% full power.

In addition to the main motor's requirements for armature and field current, the LSV-1 Propulsion Battery also provides ship's 375-VDC Auxiliary Power for major auxiliary loads, such as hydraulic and cooling pumps. This power is obtained by splitting the Propulsion Battery to provide 500-375 Auxiliary VDC to each of two load centers. The overall Propulsion Battery load requirement, across all eight battery sections, for a typical 3 high-speed run operating day is shown in Figure 4.

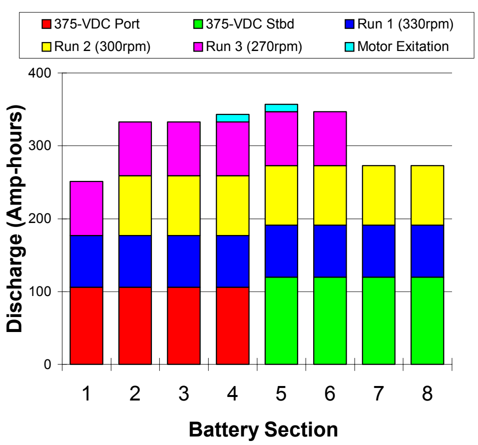

Fig. 4 Propulsion Battery Amp-hrs out

This non-uniform discharge of the Propulsion Battery depicted in Figure 4 presents a similar challenge for battery charging. Eight (one for each section) 150VDC, 0-200 ampere battery chargers deliver constant-current to constant-voltage charging capability. Recharge is typically accomplished in less than eight hours, providing the ability to operate *KOKANEE* on consecutive days if staffed for around the clock operations.

B.LSV-1 Instrumentation Battery

Two parallel strings of the same LSV-1140 three-cell battery modules provide 28-VDC power to Instrumentation loads, such as the SCC, the rest of the Guidance, Navigation, and Control system, and the Onboard Data Acquisition System. This Instrumentation Battery (I-Batt) begins discharge just before undocking, and remains lightly loaded during the 2 hour tow-out to the range, until system start-up prior to diving. The two-string arrangement provides 1500 ampere-hours of capacity at a relatively constant discharge rate, and results in approximately 6 hours of LSV submerged operation plus surface transit to and from base.

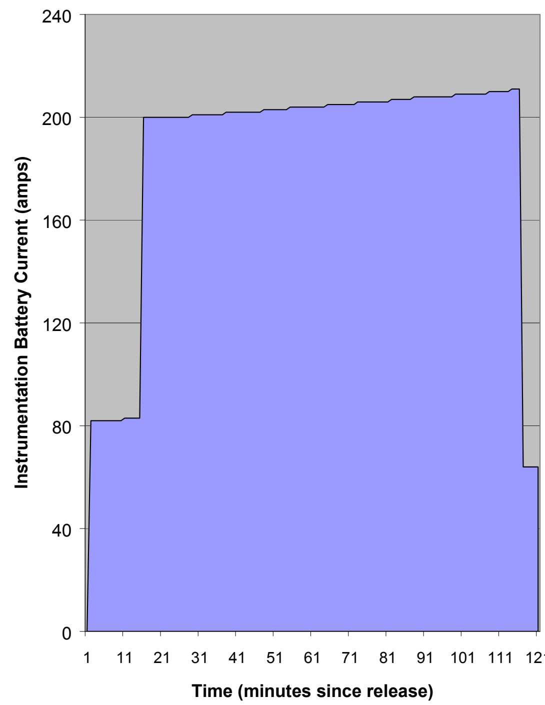

Fig. 5 Typical Instrumentation Battery Discharge

Significantly, the same LSV1140 cell design is performing the disparate discharge routines illustrated in Figures 3 and 5. LSV-2 designers have chosen a different battery suited for each application.

A 24-VDC Emergency Battery, consisting of two 12-VDC high quality automobile batteries, floats on the 28-VDC I-Batt. This is standby power to equipment necessary for an emergency surfacing of the vehicle on loss of normal Instrumentation power.

A separate Instrumentation Battery Charger simultaneously charges both I-Batt strings at up to 400 amperes total charging current. Recharge is typically accomplished in the same time frame as the Propulsion Battery. The 24-VDC Emergency Battery, floating on the I-Batt, receives a charge quarterly or whenever discharged due to fault condition.

C. Battery Maintenance and Fault Sensing

Maintaining the batteries and distribution system in a state of readiness to support trial operations requirements is a continuing process involving the expenditure of 2.5 man-years per year. The effort involves periodic charging, monitoring the performance of the batteries, managing the discharge profile, changing out weak modules, maintaining the integrity of buss work and sensors, and reconstituting modules.

LSV-1 electrical systems are ungrounded. Low resistance to ground is the primary indicator of free electrolyte on a cell, either from vent residue or a leak. The LSV1 crew measures ground resistance daily. An onboard ground detector reads once every 30 minutes operating in autonomous control.

The Battery Monitoring System (BMS) provides individual voltage for each 3-cell module, updated every 4 seconds. Module voltage under discharge closely correlates with remaining capacity. The module voltage vs. time history of all cells is recorded for post-operational review. Between underway days, low voltage modules are proactively removed and replaced with stronger spares. The removed weak modules are broken down into cells and exercised. Often only one of the 3 cells is weak, allowing 2/3 of the removed module to be reconstituted.

Every pair of modules has a temperature sensor mounted in a well on the common busbar plate between the modules. These RTDs provide ambient temperature and indication of a loose busbar connection. All battery module intra-cell and busbar connections are torqued. Micro-ohmmeter readings are taken on battery system connections and compared to specifications.

The Battery Compartment (the forward half of the pressure hull) is continuously monitored for H^2, O^2, CO, CO^2, Fire, and Smoke. Audible and visual alarms alert personnel to hazardous conditions and automatically secure battery chargers if operating.

All current interrupting devices (fuses, switches, etc.) within the Battery Compartment are located inside pressure tight enclosures. At delivery, the enclosures were rendered inert with 0.5 psig N^2. An LSV-2 Design Decision Memorandum in 1998 justified eliminating this feature for LSV-2. Based on that rationale, the N^2 system has been disabled on LSV-1.

D. Autonomous Fault Protection

Because of its autonomous nature, the vehicle must be capable of protecting itself from fault conditions that develop during operations. The SCC monitors a total of 151 faults from all vehicle subsystems, including 18 from the batteries. Associated with each fault, there is one of eleven standard response actions that will execute if the fault is detected. These 11 responses have different levels of priority, consistent with the type of fault detected. At a nominal rate of 10Hz, the SCC monitors the fault conditions defined. It then autonomously executes the response of highest priority among all the fault responses associated with the faults detected. LSV operators are informed of the fault detection and recovery status via the underwater communications system.

Battery faults are monitored on all three LSV-1 Battery Systems. Faults include: cell temperature high, cell voltage low, string voltage low, discharge current high, and resistance to ground low. Fault Response for most battery faults is Surface on the Loiter Motor, with a special action which secures non-essential electrical loads. Low module voltage on the Propulsion Battery terminates the maneuver in progress and allows the operator the ability, in some cases, to select another maneuver that uses different battery sections. Upon mission termination, it is then the operator’s responsibility to establish communications with the vehicle on the surface and conduct a safe shutdown.

Even when all vehicle systems operate flawlessly, if pushed to the limit, a battery low voltage fault will result. The LSV-1 operators and scientific team set the test agenda using previous battery performance history and trends, usually terminating operations before a fault occurs.

III. LSV-1 OPERATIONAL HISTORY

Since beginning service in 1988, LSV-1 has conducted 641 underway days in which at least one successful test run was performed. The lake is icefree in winter, and LSV operations are year-round. Discounting 2001, with *KOKANEE* out of service due to shaft seal and control surface repairs, the historical average is 52 successful underways per year (1/week). Restrictive requirements for ambient lake condition often result in underway cancellation. This year through May, 20 successful underway days have been accomplished, but 21 days were cancelled due to wind greater than a 5-mph requirement. A total of 1821 successful test runs have been executed, an average of 2.8 per underway day.

With endurance limiting test requirements, LSV-1 always departs base with a fully charged battery. Even if the boat does not dive due to weather, the battery is recharged in preparation for the next underway day. Consequently *KOKANEE* is historically achieving 100 cycles per year, coinciding with the battery 4-year operational lifetime.

IV. LSV1 BATTERY COSTS

The Navy has purchased 4 *KOKANEE* battery ship-sets: two sets of LSV153 and two sets of LSV1140. A manufacturing error in the stoichiometry of the first 1140 shipset resulted in a 1997 warranty battery replacement. Approximately 15 months life remain on the current battery, and procurement is beginning on a replacement cell for late 2003.

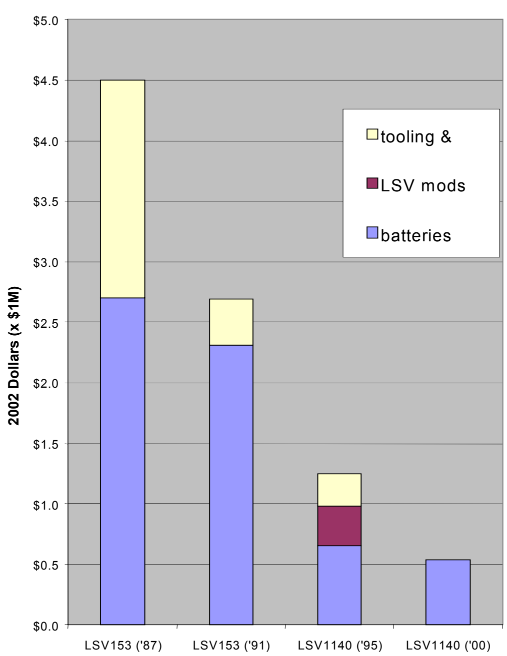

Figure 6 LSV-1 Battery System Costs

Battery procurement and installation costs have continually and significantly decreased over the life of LSV-1, primarily due to the incorporation of Commercial Off The Shelf (COTS) products.

The cost of recycling and disposal of removed battery cells, including transportation, is included in the cost of procurement indicated in Figure 6.

Labor costs for the LSV Crew to remove the old battery, and to receive, inspect, and install a new battery ship-set is not included, because the boat is out of service and the operating crew performs the battery change-out as an "all hands" evolution, without additional labor cost.

V. LSV2 DESCRIPTION

LSV-2 provides tremendous added capability in the area of hydrodynamics and submarine maneuvering studies. A Ship's Control Computer (SCC) controls the operation of other *CUTTHROAT* microprocessors, including the Battery and Environmental Monitoring System (BEMS), via a Fiber Optic Reflective Memory (FORM) net while underway autonomously. LSV-2 uses the same acoustic range and underwater communication system as *KOKANEE*.

CUTTHROAT was designed and built under a Performance Specification, providing the LSV2 shipbuilders with more flexibility than under typical detailed Specifications. The Navy did not specify lead acid batteries for LSV-2, but concurred in the shipbuilder decision.

While LSV-2 incorporates many new and demonstration technologies, a shipbuilder trade study selected VLRA battery technology for propulsion power. This decision was based on cost, readily available design, and LSV-1 success. The LSV-2 propulsion cells, from GNB Industrial Power's "Sprinter" product line, are optimized for short duration, high rate discharge.

The *CUTTHROAT* motor is a 6000HP synchronous permanent magnet (PM) design prototyping a future full-scale electric drive propulsion system. This motor receives a variable frequency, variable voltage six phase input from the motor drive. The delivered motor drive system is capable of providing 3000HP at 2440 VAC rms from two drive cabinets. These cabinets are reconfigurable to a future growth capability of 6000HP to support higher torque propulsors. The PM motor and motor drive system can be considered to have "continuously variable speed control" and is not limited by tapping points as in the LSV-1 motor. The system as configured can be operated at loiter speed, eliminating one requirement for a separate loiter motor.

The AC output to the motor is generated by DC-AC inverters, which take a stable 770-VDC input and provide a "stacked" high voltage AC output by combining each of 3 inverters into one phase of the 6-phase motor input. Each inverter receives its 770-VDC input from a DC-DC converter, which is tied to the LSV2 Propulsion Battery. Eighteen sets of DC-DC Converters and DC-AC Inverters generate the 3000HP variable voltage, variable frequency input to the motor.

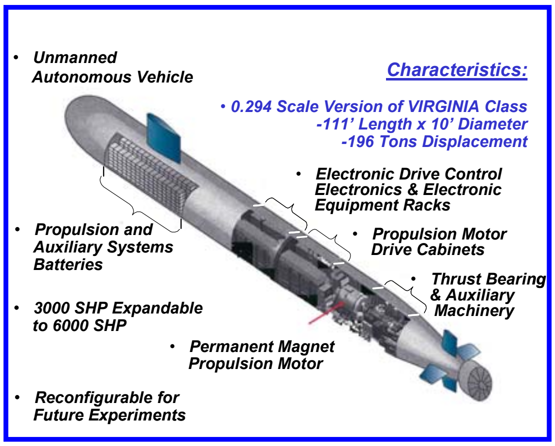

Fig. 7 - Large Scale Vehicle CUTTHROAT (LSV 2)

A. LSV2 Propulsion Battery

Without the need to provide intermediate tapping points, the LSV2 Propulsion Battery is arranged in four parallel strings of 420 VRLA battery cells. The strings have an operational voltage range of 742-900 VDC, compatible with the requirements of the motor drive system. After delivery, charging on the *CUTTHROAT* Propulsion Battery will be accomplished using two 500-VDC chargers per battery string.

The LSV-2 Propulsion Battery is sized to accomplish two flank speed acoustic runs at *CUTTHROAT* maximum speed, three high speed runs at approximately 75% full power, or seven runs at or below 50% power.

B. LSV2 Auxiliary/Instrumentation Battery

One string of 186 GNB Industrial Power's 90A11 battery cells provides nominal 372-VDC Auxiliary Power to *CUTTHROAT*. This COTS battery cell is used in commercial stationary telecommunications applications requiring long-term discharge (6-10 hours), an ideal match to the LSV2 application. The battery is designed to a life of 1000 cycles or 96 months, therefore requiring replacement every other Propulsion Battery changeout.

372-VDC power to large LSV-2 motor loads, such as control surface actuators and cooling water pumps. 372-VDC is also supplied to inverters, which deliver 125-VAC to the boat's Instrumentation loads. *CUTTHROAT's* Auxiliary Battery has been sized to meet a performance requirement for an operating day consisting of seven runs.

During LSV2 design/build, a shipbuilder trade study justified the selection of a 125-VAC instrumentation power system over the 28-VDC LSV-1 legacy primarily on the basis of lower costs for procurement of rack mounted COTS equipment.

Unlike LSV-1, *CUTTHROAT* has no dedicated Emergency Battery in case of a casualty to the Auxiliary Battery. Instead, a portion of one of the Main Propulsion Battery strings is tapped to provide emergency power for surfacing and recovery.

C. Battery Maintenance and Fault Sensing

Every 2-VDC battery cell is monitored by the LSV-2 BEMS, increasing the number of voltage sensors from 509 to 1,866. Based on LSV-1 experience, the total number of temperature sensors throughout both batteries has been reduced from 254 to 45. Sensing requirements overall have therefore grown from 763 to 1911.

LSV-2 fault sensing parallels LSV-1. Most battery related faults surface *CUTTHROAT* on the main motor at low speed.

VI. CONCLUSION

Large Scale Vehicles have successfully used VRLA propulsion and auxiliary batteries since commencing operations in 1988. These batteries have provided highly reliable, safe, and sustained operations that have met the Navy's performance requirements for AUV stored energy. System costs have decreased significantly over time, and the

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relevance of VRLA was demonstrated by its selection in LSV2 in 1998.

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- the battery manufacturer, GNB Industrial Power Systems

on operating and maintaining the Navy's quarter scale AUVs.