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FEASIBILITY OF USING COMMERCIAL-OFF-THE-SHELF RUGGEDIZED LAPTOP COMPUTERS AND INDEPENDENT POWER SOURCES IN A DISABLED SUBMARINE

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14. ABSTRACT

This project evaluated two commercial-off the-shelf (COTS) laptop computer systems and two power supplies for ruggedness and performance under conditions expected aboard a disabled submarine (DISSUB) for potential use with the Submarine Escape and Rescue Expert (SEAREX) computer program. Computers and power supplies were tested in hyperbaric chambers at Naval Submarine Medical Research Laboratory (NSMRL) under hyperbaric (5 bar), high humidity (>80%) and low temperature (<45F) conditions simulating a DISSUB. One of the two laptop computer systems tested met all requirements. The other failed due to the failure of its keyboard. The lead-acid battery design tested supplied sufficient power to energize a computer for nearly five days and the alkaline battery pack lasted for nearly seven days. This testing demonstrated that COTS hardware capable of supporting SEAREX in a DISSUB is nearly available.

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Summary Page

Problem

The Submarine Escape and Rescue Expert System (SEAREX) is a computer program that provides advice to the senior survivor and/or topside rescue personnel on how to optimize the survival of the crew aboard a sunken/disabled submarine (DISSUB). To function at all inside the DISSUB, the program requires a computer and power source capable of performing for up to seven days in the hostile environment expected in a DISSUB (high pressure, high humidity and low temperature). To be cost effective, the system should use, where possible, commercial-off-the-shelf (COTS) components that are capable of surviving the catastrophic event that disabled the submarine. This project determined whether appropriate COTS computers and power sources were available and subjected several candidate products to simulated DISSUB conditions to assess performance.

Methods

After establishing a set of environmental and operational parameters that reflect a credible DISSUB scenario, the commercial market was searched for candidate computers and power sources. Two ruggedized computers and two battery designs were identified that appeared to meet the required specifications. Hyperbaric chambers were used to simulate DISSUB conditions in which the performance and endurance of the candidate equipment were tested.

Findings

Of the two computers tested during November 1999, one met the required performance standard after modification. The membrane keyboard of the other computer, as configured, was unusable in this simulated DISSUB scenario, although the electronics appeared to function normally. Of the two battery power supplies tested, one was able to power a ruggedized laptop for nearly five days and the other nearly seven. A promising third battery power supply design, based on zinc-air technology and under development for the U.S. Army, was considered, but was rejected due to cost.

Conclusion

A test of a small selection of COTS computers and batteries revealed that at least one ruggedized COTS computer and power supply are capable of supporting SEAREX under likely DISSUB conditions for nearly a week.

ADMINISTRATIVE INFORMATION

This investigation was conducted under Naval Sea Systems Command work unit #WR63713 N0463A99WR00015-5908, entitled "Hardware Acquisition". The views expressed in this report are those of the authors and do not reflect the official policy or position of the Department of the Navy, Department of Defense, or the U.S. Government. This report was approved for publication on 26 June 2001, and designated as Naval Submarine Medical Research Laboratory Report #1220.

Abstract

This project evaluated two commercial-off–the-shelf (COTS) laptop computer systems and two power supplies for ruggedness and performance under conditions expected aboard a disabled submarine (DISSUB) for potential use with the Submarine Escape and Rescue Expert (SEAREX) computer program. Computers and power supplies were tested in hyperbaric chambers at Naval Submarine Medical Research Laboratory (NSMRL) under hyperbaric (5 bar), high humidity (>80%) and low temperature (<45°F) conditions simulating a DISSUB. One of the two laptop computer systems tested met all requirements. The other failed due to the failure of its keyboard. The lead-acid battery design tested supplied sufficient power to energize a computer for nearly five days and the alkaline battery pack lasted for nearly seven days. This testing demonstrated that COTS hardware capable of supporting SEAREX in a DISSUB is nearly available.

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I Introduction

Survival in a disabled submarine (DISSUB) that is unable to surface under its own power is a problem that could be faced by U.S. Navy submariners. Although rescue is the preferred means of recovering survivors[1], hazards such as uncontrollable flooding, radiation, fires, and toxic gas contamination of the atmosphere may make immediate escape necessary. However, escape is also potentially hazardous. The hazards include decompression sickness, pulmonary barotrauma, hypothermia, and drowning[2]. The risk of decompression sickness increases with the depth of the boat and the pressure within the DISSUB; flooding can pressurize the interior of the boat to levels that make escape extremely dangerous[1]. The senior survivor needs to balance the risk of remaining in the boat against that of escaping to the surface and, while waiting for rescue, to optimize the use of the available men and materiel. While it is his responsibility to optimize the survival of his crew, at present, his sources of information are scattered throughout various publications[1].

An obvious solution would be to consolidate this information and advice on DISSUB survival into a single rugged workbook. The British Royal Navy has developed such a tool called the 'Guard Book'[3]. It is a collection of flow-charts, pencil-and-paper worksheets, and instructions that guides the senior survivor on what he and his crew must do to maximize survival. In October 1996, the Naval Submarine Medical Research Laboratory (NSMRL) was tasked by the Chief of Naval Operations, CNO N873, to develop a guide for the senior survivor of a US Navy DISSUB similar to the British 'Guard Book'.

Depending on the location of the DISSUB, it may take up to a week for rescue resources to arrive at the scene. The problem of maximizing survival time while waiting for rescue has been well recognized. A 'Guard Book' can greatly improve the survival time in the DISSUB through the efficient use of stores. However, pencil-and-paper technology limits the complexity of the calculations that can be performed and does not relieve the senior survivor of remembering to undertake tasks with which he is likely to be unfamiliar. Providing more sophisticated and readily understood advice requires computer technology.

SEAREX provides systematic instructions, offers an alarm clock function for important time-critical actions, and consolidates the necessary documentation in hypertext-linked (HTML) files. It undertakes many calculations that are considerably more sophisticated than can be easily achieved on paper. It provides the senior survivor and his topside support forces with a single, reliable source of information to assess and manage the situation.

No decision aid will relieve the senior survivor of his responsibility for managing his men and materiel, nor is this considered appropriate. It is possible to relieve him of the need to remember to undertake tasks that are not normally required of him and to provide risk assessments in circumstances that are beyond his experience. This is the ultimate purpose of SEAREX.

It is envisaged that the SEAREX computer and its power supply would be stowed in a protective container near the escape trunk. It should require minimal maintenance and yet be ready for operation at short notice. To be cost-effective, the system should consist of commercial-off-the-shelf (COTS) components that are capable of surviving the catastrophic event that disabled the submarine.

DISSUB conditions mandate a system that is —

1. Robust
2. Water-resistant, and tolerant of humidity up to 90% RH
3. Pressure tolerant, from 0.9 to 5 ATA
4. Cold tolerant, down to 32°F
5. Capable of seven days continuous operation
6. Compact
7. Cost effective, employing COTS technology where possible

This project was undertaken to determine whether any appropriate COTS computers and power sources were available on the open market to meet these specifications and, if they were, to subject a few candidate products to simulated DISSUB conditions to assess the extent to which they meet the manufacturers' claims.

II Materials and Methods

SEAREX software was designed to run under either the Microsoft® Windows® 95 or Windows® NT 4.0 operating systems (OS). The minimum requirements, based on the needs of the OS, and for adequate performance from SEAREX, are: a 60 MHz Intel® Pentium® central processing unit (CPU), 8 megabytes(MB) of random access memory (RAM), and 200 MB of data storage. SEAREX occupies about 10 MB of this data storage; the balanced is required for the OS to operate properly. Data storage is provided by Flash-RAM technology instead of a hard drive, because of its lower power requirements and greater robustness.

From March through May of 1999, a list of potential computer candidates was compiled through the Internet, various trade magazines and word-of-mouth. The first criterion for inclusion was that the claimed range of environmental parameters of operation included the conditions expected in a DISSUB. The second criterion was having among the highest resistance to water and shock. Furthermore, the vendor had to state that these claims were tested in accordance with military standard MIL-STD-810E (Appendix A). The third criterion was that the computer was equipped with an appropriate color display. The SEAREX software requires a display capable of showing 256 colors at a resolution of at least 800 x 600 pixels. For current laptop designs (in 1999), this implies a back-lit, color, liquid crystal display (LCD) screen which may require a heater to function properly in very cold environments.

From our survey, a review of manufacturers' reported specifications indicated that suitable hardware would require an estimated 10 to 15 watts of electrical power at 12 volts DC. Based on that estimate of power usage and suitability for use in a DISSUB scenario, the Naval Surface Warfare Center, Carderock Division, in West Bethesda, Maryland (NSWC) was contracted to conduct a market survey of COTS power sources. Their report is in Appendix B.

Although NSWC's first recommendation was to use a zinc-air battery that is being developed for the U.S. Army by Electric Fuel Corporation (EFC), a prototype zinc-air battery pack capable of powering a laptop for just 24 hours would have cost about $3000. We did not test this potential power source due to its low probability of being adopted by the fleet due to cost. Nonetheless, the technology has great potential for this application and should be revisited when in full production. For this study, we opted for their second and third recommendations: alkaline and lead-acid battery designs.

A. Materials

Two ruggedized laptop computers were provided under loan arrangement with each supplier for the purpose of testing. These were as follows:

1) **Paravant RLT-515** (Figure 1)
    a) OS: Microsoft® Windows® 95
    b) CPU: 133 MHz Advanced Micro Devices AuthenticAMD
    c) RAM: 8 MB
    d) FlashRAM: SanDisk ATA 220 MB
    e) Cost: Approximately $12,000
2) **Itronix X-C 6250** (Figure 2)
    a) OS: Microsoft® Windows® 95
    b) CPU: 200 MHz Intel® Pentium®
    c) RAM: 48 MB
    d) FlashRAM: SanDisk ATA 220 MB
    e) Cost: Approximately $5,500

The power sources tested were:

1) **Sonnenschein Prevailer® Dryfit® PV-30H Marine Battery** (Figure 3)
    a) Technology: Gelled Lead Acid
    b) Nominal Voltage: 12 V
    c) Amp Hours: rated at 200 AH
    d) Dimensions: 13 x 9 x 7 inches (33 x 23 x 18 cm)
    e) Volume: 0.47 cu ft (13309 cc)
    f) Weight: 80 lbs. (30 kg)
    g) Cost: $150

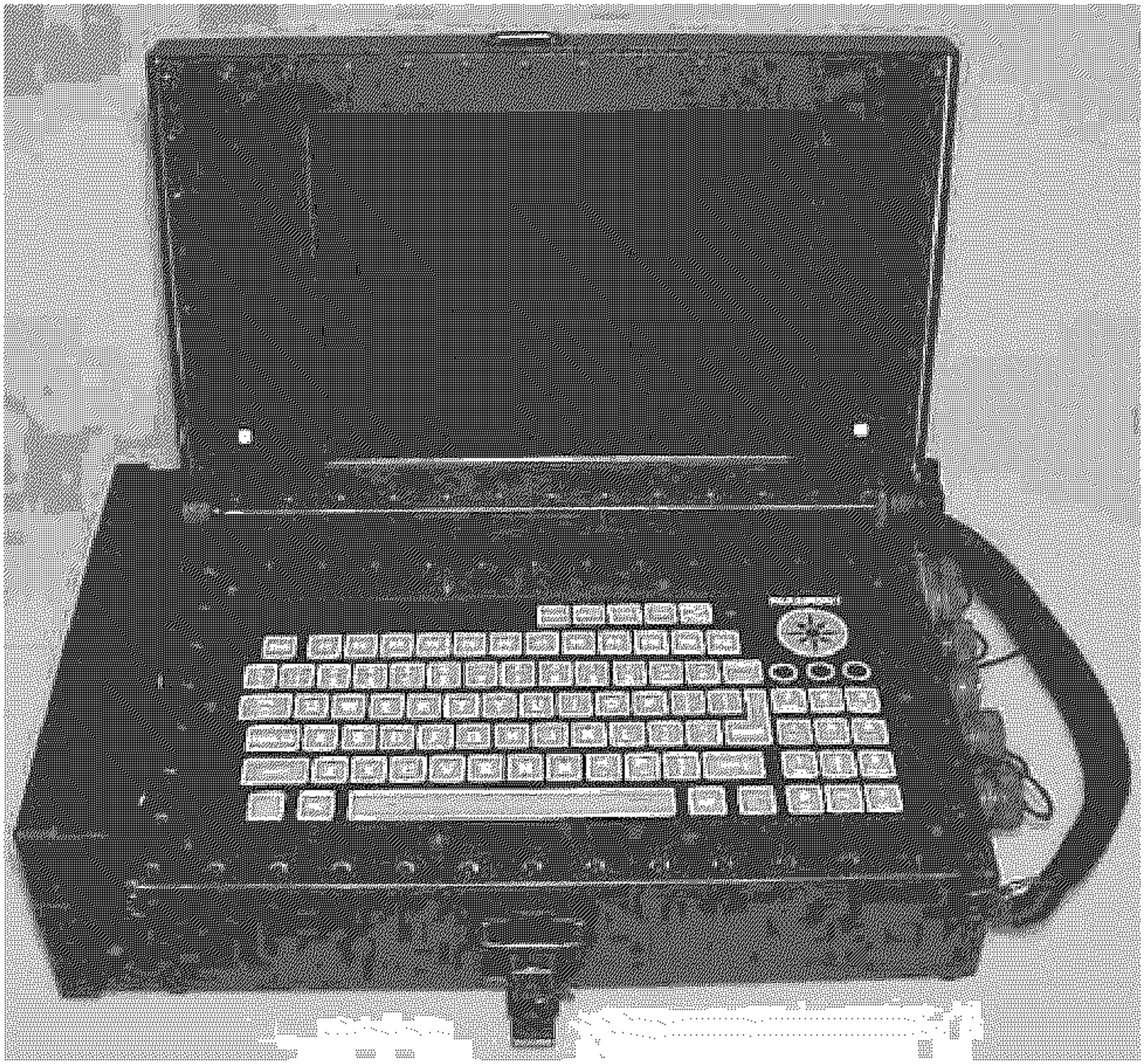

Figure 1. Paravant RLT-515

Figure 2. Itronix X-C 6250

Figure 3. Sonnenschein Prevailer® Dryfit® PV-30H Marine Battery

Figure 4. Mathew Associates Custom Militarized Battery Pack

2) **Mathew Associates Custom Militarized Battery Pack** (Figure 4)

   a) Technology: Alkaline
      (168 standard D-cell alkaline batteries)

   b) Nominal Voltage: 18 V

   c) Amp Hours: estimated at 200 AH

   d) Dimensions: a cylinder 7½ diameter x 18 inches high (19 x 46 cm)

   e) Volume: 0.46 cu ft (13026 cc)

   f) Weight: 60 lbs. (22.4 kg)

   g) Cost: $525

The Sonnenschein Marine Battery is a standard mass-produced gelled lead-acid battery. It was tested unmodified.

The Mathew Associates Custom Militarized Battery Pack is constructed from standard mass-produced D-size alkaline batteries. The batteries are arranged within a disc-shaped plastic housing called a "puck." Each puck holds up to 24 D-size battery cells that can be connected in a number of different ways. Each is filled with epoxy-based filler that seals in the batteries and protects their electrical connections.

The pack used consisted of seven pucks connected in parallel. Each puck contained two strings of 12 cells connected in series. This gave a nominal output of 18 VDC.

B. Methods

The computers and the power sources were tested independently to avoid difficulty in determining the cause of system failures. For all tests, the power management features of each laptop were fully disabled so that the display and CPU were always active and highest levels of power consumption could be measured. While a computer pressed into actual SEAREX service may have some or all of its power management features enabled during normal operation, having them all disabled allowed for assessment of worst-case power consumption.

The computers were tested simultaneously in a specially constructed Insulated Chamber Environmental (ICE) system (locally constructed, Figure 5), which was installed in the NSMRL #2 man-rated hyperbaric chamber (Hyperbaric Medical Research Chamber, 165 ft (6 ATA) capable, Figure 6). The ICE system provided the chilled (below 45°) high humidity environment required for this experiment.

A simple program called SHOWTIME (Appendix C) was run continuously to provide visual confirmation to the chamber operator that the computer's processor and display were functioning normally.

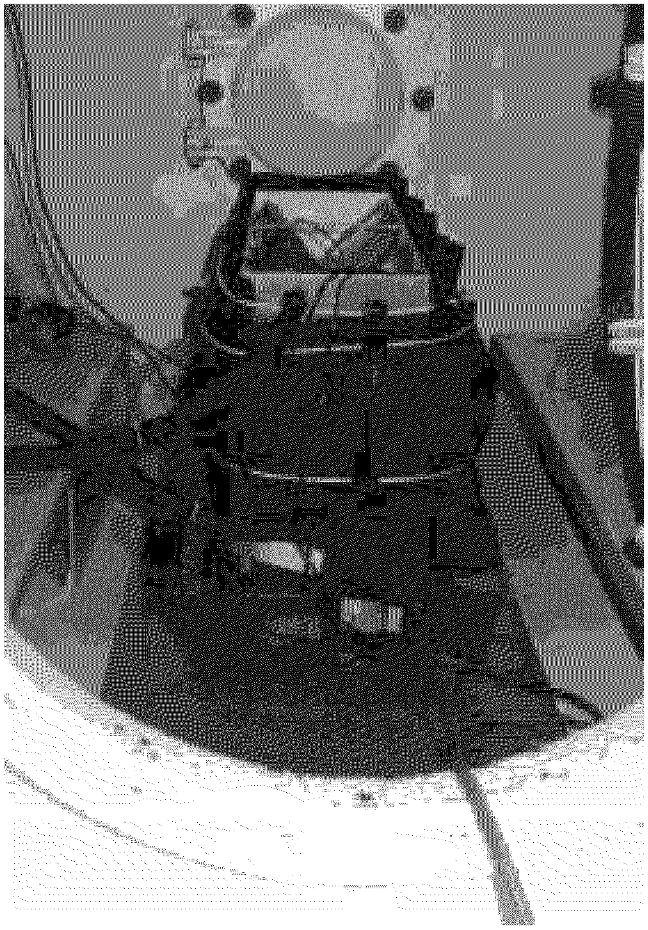

Figure 5. View of the Insulated Chamber Environment (ICE) System from the Hyperbaric Chamber Inner Lock.

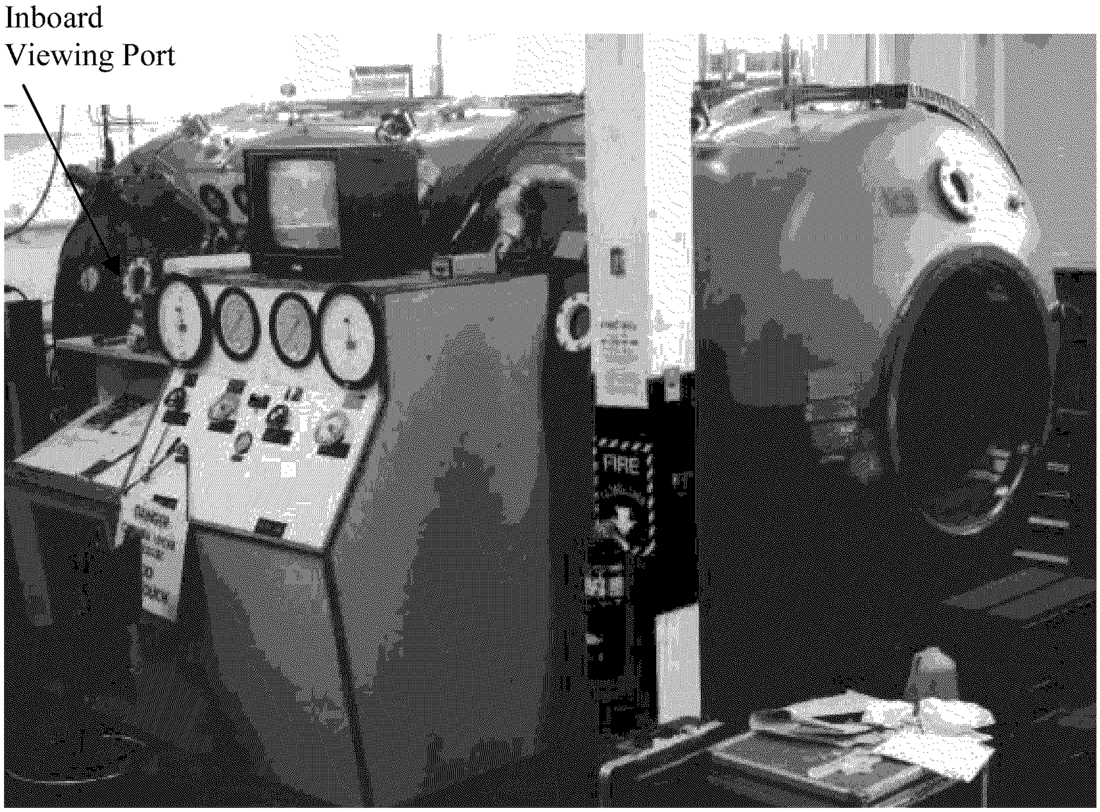

Figure 6. Hyperbaric Medical Research Chamber, F-017 N.B. #324 (Chamber #2)

With the test computers in place and the SHOWTIME test program running, the inner hyperbaric chamber door was closed and the ICE system was placed in operation. The environmental monitoring system was started and initial conditions (temperature <45°F and relative humidity 80-100%) were achieved. A seal on the inner lock door was then established and pressurization of the hyperbaric chamber to 5 ATA was begun at a rate of 10 fsw per hour. During the approximately 15-minute pressurization, the chamber environmental conditions (temperature and relative humidity) were maintained as stable as possible and the computers were monitored regularly for normal operation.

The relative humidity (RH) was measured using two certified hygrometer and temperature indicator gages (Abbeon Calibration Inc. Model HTAB-176): one installed inside the ICE system, the other inside the chamber, but outside the ICE system. Their measurements were manually recorded. The temperature within the ICE system was measured with a thermistor (Yellow Springs Instrument Co. Model 43TF, 32-120°F capable) connected to an electronic analog thermometer, and also with a platinum resistance temperature probe connected to a digital thermometer (EG&G Model 911 DEW-ALL).

1. Computer Testing

To ensure that each laptop was capable of withstanding the high-pressure requirements of the study (5 ATA), candidate computers were briefly pre-tested in a small hyperbaric chamber (Hyperbaric research chamber, Model 18365 HP, Series 76.1011, Bethlehem Steel, Rated @ 450 PSI) to assess their ability to tolerate a raised atmospheric pressure.

For this pre-test, and the subsequent main test, the internal rechargeable battery was removed from each computer for safety reasons. It is unknown if the batteries and hyperbaric conditions could precipitate any kind of dangerous situation, such as explosion or fire. Each computer was then powered by its AC adapter. Since hyperoxic conditions increase the likelihood of combustion in a pressurized chamber, the AC power adapters were placed outside the hyperbaric chamber to minimize the potential for fire. As a further safeguard for the main test only, each computer was also connected via 3-amp fuses and Ground Fault Interrupt protection (GFI) (Appendix D).

The computers were placed on a shelf in the ICE system, positioned so that they were visible from the viewing port and on the video monitoring system. They were also arranged to allow easy access by divers who performed two manned tests. They entered the chamber twice to conduct keyboard tests and other tests of computer function (Figure 7):

- Approximately 24 hours after initial test conditions were established;
- At the end of the seven-day test period, immediately prior to test termination.

On each occasion they halted SHOWTIME and then activated the SEAREX program and tested the keyboard functions as shown in Appendix E. The testing was designed to take about eight minutes per computer.

Figure 7. View Taken From Hyperbaric Chamber Viewing Port of ICE With Diver Under Pressure Conducting Computer Testing on the Paravant Computer.

After the seven-day test ended the chamber was depressurized at 10 fsw per hour, both computers were removed from the chamber and their power consumption was measured. For this test, power was supplied by a regulated DC power supply (Hewlett-Packard Model 6226B DC), set to 12 VDC as measured with a digital voltage meter (Tektronix Model DM 501 Digital Multi-meter) and SHOWTIME was initiated. The current was measured with a digital current meter (Tektronix Model DM 502A Auto-ranging Multi-meter).

2. Power Source Testing

The two power sources were placed in a hyperbaric chamber (Hyperbaric research chamber, Model 18365 HP, Series 76.1011, Bethlehem Steel, Rated @ 450 PSI, Figure 8) equipped with internal piping to carry an ethylene glycol-based coolant. Each power source was connected to a computer located outside the chamber via a pass-through connector. The alkaline battery was connected to the Paravant computer, and the gelled lead acid battery was connected to the Itronix computer for reasons discussed below.

Chamber environmental conditions were read and maintained using the built-in digital thermometer and pressure gage. A chiller unit was connected to the chamber piping and set to maintain chamber temperature between 34°F and 45°F. Because the chamber seal ring was unable to maintain a perfect seal when the chamber was chilled below 45°F, the pressure was checked and adjusted (as necessary) every six hours so that it was maintained between 135 fsw and 155 fsw (5.1 - 5.7 ATA). Manual readings for internal chamber temperature and pressure, and power source voltages were also recorded at these intervals.

External to the chamber, pass-through connectors were attached to a set of screw terminals. Connections were made between the batteries, the analog-to-digital converter and the test computers (which were stowed below the chamber) via these screw terminals (Figure 9). A circuit diagram of the connections made is shown in Figure 10.

Manual voltage readings were periodically taken and recorded approximately every six hours by test personnel by touching the leads of a digital voltage meter (Fluke 8020 multimeter) to the appropriate screw terminals. In addition to manual readings, a two-channel analog-to-digital converter (A/D) (DATAQ DI-150RS Data Acquisition system connected to a Gateway® 2000 Solo® 2300 laptop computer) was connected to the Paravant and Itronix circuits to provide automated logging of the voltage drop. Because the battery voltages were well above the 10 VDC limit of the data acquisition system, resistors were required in the interface. Each resistor was rated to be 470 kΩ. Their actual resistances were measured with the Fluke multimeter: R1 = 449 kΩ, R2 = 510 kΩ. Each channel was calibrated while interfaced with its respective resistor, and with the DATAQ DI-150RS connected to the Gateway® Solo® laptop. These calibrations were conducted using a digital voltage meter (Tektronix DM 501 Digital Multimeter) and a regulated DC voltage source (Hewlett-Packard Model 6226B DC Power Supply).

The Paravant computer has a built-in DC-to-DC converter circuit that allows it to utilize a wide range of voltages (from 10 to 40 VDC). The alkaline battery delivered a starting voltage of around 19 VDC when fully charged. During discharge, this value steadily decreased to around 10 VDC, below which it would no longer be a viable source of power for a computer. The wide

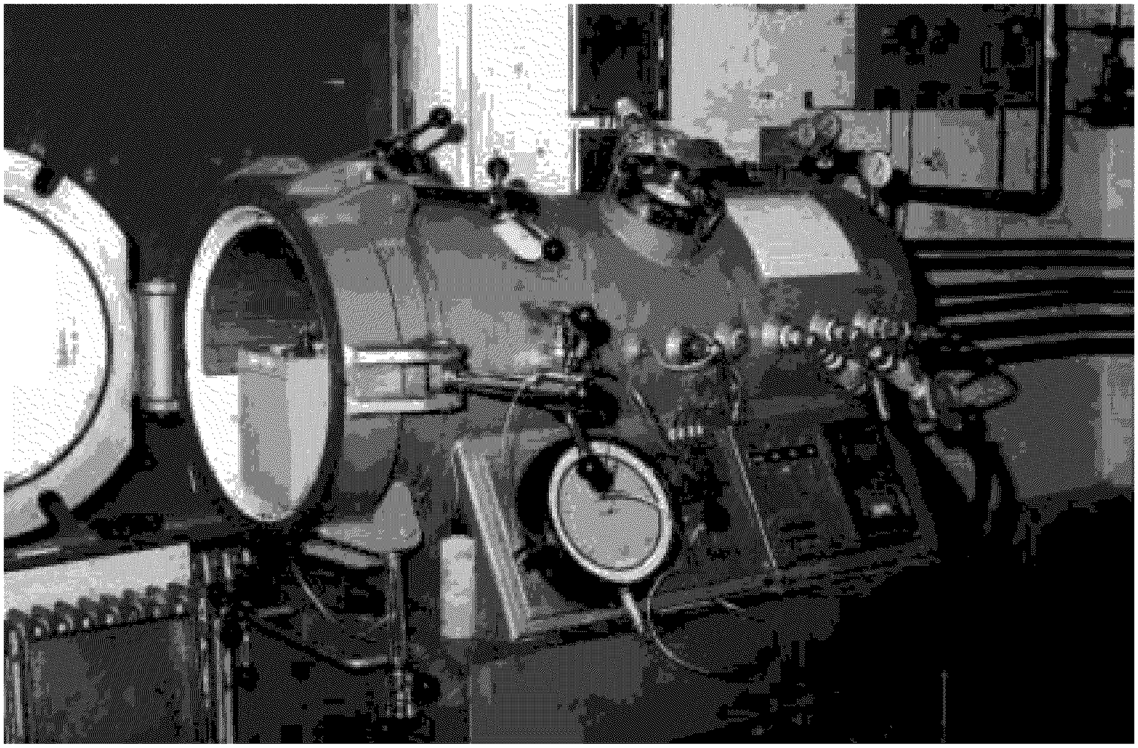

Figure 8. Hyperbaric Chamber Open to Load Batteries Prior to Testing

Figure 9. Hyperbaric Medical Research Chamber F-017 N.B. #324 Under Pressure During Battery Test

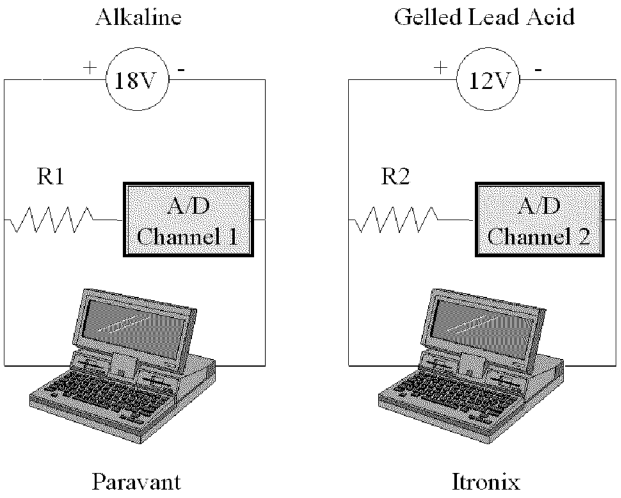

Figure 10. Power Source Test Circuit.

range of voltage delivered by the alkaline battery required the use of a DC-to-DC converter; therefore pairing the Paravant computer with the alkaline battery was the obvious choice.

The Itronix computer required a power supply in a narrower range (11 - 13 VDC). The vendor did supply an adapter that would allow it to operate on 12 - 16 VDC, but this also consumed power and would have added an additional load to the battery. By pairing the Itronix computer with the relatively stable power output of the lead acid battery (rated at 12 VDC, 13.5 VDC fully charged; 11.5 VDC fully discharged), the requirement for an adapter was avoided.

III Results

A. Computer Test Results

1. Pre-Test

Both computers operated normally throughout the pre-test.

2. Main Test

Problems were observed with both computers while establishing a seal on the inner lock door of the hyperbaric chamber. Sealing the inner lock required a quick initial rise of pressure to about 20 fsw in less than half a minute. This rate of pressurization significantly exceeds that expected in a DISSUB if the crew were to remain aboard and survive. A chronology of events in the test follows.

2a. Paravant

The computer failed due to the initial pressurization. At about 20 fsw, the computer appeared to be in a "move a window" mode, i.e., a window outline appeared and the mouse cursor began to translate across the screen. The experiment was suspended to permit an investigation. After de-pressurization, the membrane keyboard appeared slightly ballooned. Some keys were usable; of these, a few worked normally, including the cursor and mouse keys, and the others required great effort in pressing to engage. However, most keys weren't usable at all. The machine was set up again, with its keyboard still somewhat ballooned, and the mouse cursor was carefully placed away from any areas of the screen likely to repeat this problem. The chamber then was re-pressurized. However, the LCD display soon showed a distorted picture with triangular blotches of white on each side of the screen. At about 40 fsw, the LCD screen developed a black blotch in its center. The chamber was again de-pressurized at 10 fsw per hour. The display was inspected and found to be severely damaged with spider-web shaped cracks visible at its center.

The laptop was returned to Paravant. They repaired the unit and performed an ad-hoc design change by drilling vent holes into the frame of the screen to improve its ability to equalize pressure. The holes were covered with semi-permeable material to maintain the unit's water-resistance.

The experiment was restarted soon after the repaired and modified unit was returned to the lab. On Day 1 of the re-test, the computer functioned normally.

On Day 2 a diver was locked into the chamber to conduct the first operability test. The membrane keyboard appeared ballooned and did not function properly. The problem appeared to be due to a false "ALT" key depression caused by the raised atmospheric pressure. After reviewing potential solutions, a second chamber entry was performed on the same day to attempt to free the stuck key. The diver managed to get the "ALT" key unstuck by repeatedly depressing it. When this problem was resolved, the remainder of the operability test was run successfully. The SHOWTIME program ran normally for the next five days.

During the second manned test, on Day 7 of the protocol, the computer exhibited keyboard failure again. It would not respond to any key presses. The mouse keys, however, continued to function. This failure would have meant that data entry would have been a frustrating process when it could be done at all. After the chamber was depressurized, the computer was tested again for operability, but the keyboard problem persisted. It again appeared ballooned and was not fully operable. The investigators eventually managed to remove the air that was trapped in the membrane by massaging it out. After a reboot, the keyboard and computer worked normally again.

2b. Itronix

By design, the Itronix machine resets and reboots when both mouse buttons are depressed for about 10 seconds. During pressurization, at about 20 fsw, the computer was observed to reboot itself. The machine was found to reset and reboot itself at pressurization rates greater than 10 fsw per minute. This is because the pressure gradient causes both mouse button switches to make contact.

The manufacturer requested NSMRL to remove a portion of the gasket that seals the PCMCIA door to the PCMCIA slots in order to allow better pressure equalization. However in so doing, the watertight integrity of the computer was compromised. For this reason, Itronix also requested that NSMRL angle the base of the machine so that the front was higher than the back, thereby allowing any possible condensation to accumulate at the rear of the machine.

The gasket modification resolved the rebooting problem and the computer operated normally during the establishment of a seal on the inner lock door, and the experiment continued.

The machine passed both operability tests, on days 2 and 7. No problems were noted, except that the touch-screen feature of the computer did not work properly under pressure.

The Itronix computer developed a clock function problem, with the computer's time-of-day clock losing five minutes a day. This problem was observed regardless of whether the computer was powered by its internal battery or its AC power adapter. It is not known whether the computer had this problem prior to testing.

3. Power Consumption

The Itronix computer required an average of 12 watts. The Paravant consumed an average of 16 watts.

B. Power Source Test Results

Figure 11 (below) shows the power source voltages over time. The dark curve punctuated with diamonds is the voltage of the alkaline battery pack during its discharge into the Paravant computer. The diamonds represent manual readings; the line is a series of automated readings. Although the Paravant consumed more power, the alkaline battery met its requirements for almost a week, providing 2.5 kilowatt-hours of available power, or 208 amp-hours at 12 volts.

The light curve punctuated with squares is the voltage of the gelled lead acid battery during its discharge to the Itronix computer. The squares represent manual readings and the line is the automated readings. To run the Itronix for a week should take about 2.0 kilowatt-hours, or 168 amp-hours at 12 volts. However, the lead acid battery powered the Itronix for only 4.75 days, providing approximately 1.4 kilowatt-hours, or 114 amp-hours. The gelled lead acid battery is rated for 200 amp-hours when fully charged, so this result was less than expected.

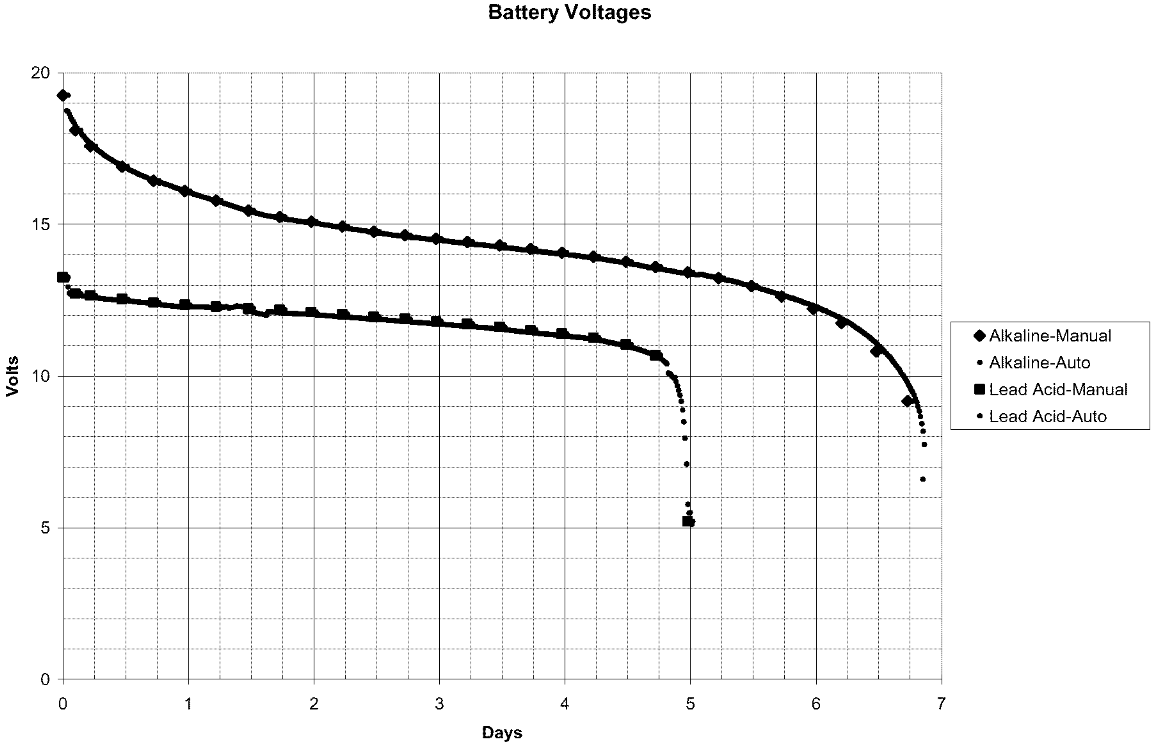

Figure 11. Voltage of Each Power Source During Discharge.

IV Discussion

The goal of this study was to determine the feasibility of using COTS ruggedized laptops capable of running SEAREX software, and power sources in a DISSUB environment, for a period of seven days. Two ruggedized COTS laptop computers were capable of surviving DISSUB conditions; however both required minor modification to function when pressurized using the chamber sealing profile required to seal the inner door of the hyperbaric chamber (there are no dogs on the inner door by design). The Itronix X-C 6250 has undergone a successful at-sea evaluation by the US Coast Guard in small cutters and rescue stations and performs well in that environment. The Paravant RLT-515 is fielded by the U.S. Air Force and used under harsh conditions in its aircraft.

The rather high power consumption of the Paravant computer may have been due to its smaller 8 MB RAM. Windows® 95 would have used the FlashRAM for virtual memory, since it optimally performs with at least 32 MB of memory to run programs. A CMOS SDRAM chip, typically used in laptop design, consumes about 300 mW. The SanDisk FlashRAM card, used in both laptops tested, consumes about 400 mW; hence, it requires about 30% more power to run. An 8 MB RAM machine was requested from Paravant, based on the hypothesis that additional RAM would lead to higher power consumption. The standard configuration of the Paravant laptop is 32 MB or more of RAM. In this study, the Itronix, with 48 MB RAM, required only 12 watts of power.

While one of the batteries tested almost met the 7-day specification with respect to endurance under DISSUB conditions, additional factors such as size, weight, shelf life, and cost would influence a purchase decision. For instance, while the alkaline pack is more expensive than the gelled lead acid battery, and has a similar volume, it is 25% lighter. Importantly, it requires no charging station and would therefore be much simpler to install in a submarine. The shelf life of the alkaline battery pack is between two and four years, but would otherwise be maintenance free. A lead acid battery has a float life (its operational life while continuously connected to a charging station) of up to six years.

A small, light, and low cost power source with long shelf life may soon be available. The United States Army's Communication Electronics Command (CECOM) is funding an effort at Electric Fuel Corporation (EFC) to produce a dual voltage (12 or 24 VDC), 50 W zinc-air battery pack (Figure 12). Designed for use in forward field chargers and communication gear, it is capable of delivering 1.25 A in the required temperature range. Rated at 400 watt-hours (or 33 amp-hours at 12 volts), it would be more than adequate to supply 24 hours of power for the SEAREX system. Seven of these "day packs" would be less than 0.4 cu ft and under 20 lbs. Moreover, according to the NSWC report (Appendix B), their shelf life may be over seven years. However, it is still at the prototype stage. A field-deployable version for the Army is expected to be available by 2004.

Zinc-air batteries require oxygen to generate power. Calculations indicate that the quantity of oxygen used by a zinc-air "day pack" battery is about 45,000 ml per 24 hours of operation, about the same quantity of oxygen consumed in a 2.5 hours of respiration for the average submariner (a person at rest consumes 300 ml of oxygen per minute[4]). In other words, a week's worth of zinc-air battery power (e.g. 7 "day packs") consumes a little less oxygen than one submariner would in a single day.

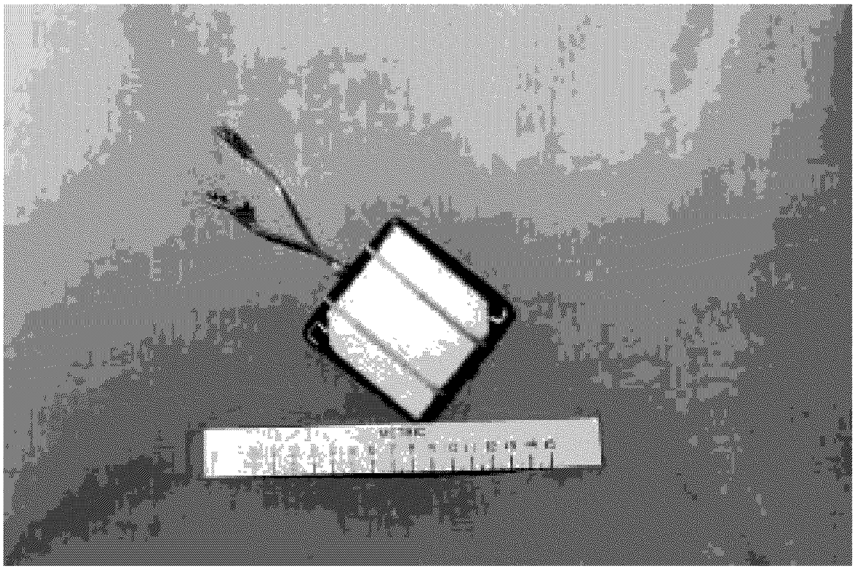

Figure 12. Electric Fuel Corp. Zinc-Air Cell.

Zinc-air batteries generate a small amount of hydrogen during discharge. Dr. Terrill Atwater at NSWC estimated the hydrogen production rate of the EFC zinc-air cell to be less than 0.02 ml per day. Since there are 24 of these cells in a "day pack" the rate of hydrogen production in a SEAREX application would be less than 0.48 ml per day or less than 3.4 ml of hydrogen for a week. Hydrogen presents no fire or explosion risk until reaching 4% by volume.[5]

A potential problem with zinc-air battery systems is that they are directly exposed to the DISSUB atmosphere, which may make them vulnerable to carbonation. This is the absorption of CO_2 from the air, and that degrades the cell's power output. Since the DISSUB atmosphere is likely to contain as much as 6%SE CO_2, and if these cells become commercially viable, testing will be needed to determine if a zinc-air "day pack" would degrade too quickly in the DISSUB atmosphere.

Provided that the battery goes into full production, it would cost between $50 and $100 per "day pack" - perhaps about $500 for power for a week. The typical shelf life of a zinc-air battery is estimated to be 7 to 10 years as long as the airflow into the cathode is restricted. This can be achieved by taping over the air inflow ducts or storing the entire battery in a sealed container.

V Conclusion

The results of these tests show that: COTS ruggedized laptop computers can operate, with minor modification, in a DISSUB environment for at least seven days; and battery power sources can operate, without modification, in a DISSUB environment for over six days. Of the two battery power sources tested, the Mathews Associates alkaline battery pack would appear to be the best choice. However, when zinc-air battery packs for the U.S. Army become available, and presuming a reasonable cost, it is recommended that they be evaluated.

It must be stressed that this study was not intended to be an exhaustive investigation of all available laptops for this application. Rather it was intended to demonstrate whether it would be possible to operate the SEAREX software in a DISSUB using existing COTS products. Successful completion of the test should not be construed as an endorsement of any of the equipment tested.

If a decision is made to deploy the SEAREX program at sea, suggested requirements for the computer are as follows:

- Capable of tolerating:

  Atmospheric pressure 0.9 to 5.0 ATA

  Up to 90% relative humidity

  Temperature 32 to 120°F

  Water spray (not immersion)

  Salt fog 5% for 48 hours

- Color display – 256 colors, 800 x 600 pixels

- Pointing device (e.g., Itronix "eraser head" joystick; Paravant mouse-cursor keys)

- Sound – Sufficient for audio alarms (Note that neither the Itronix or the Paravant computer had audio installed in the configuration provided)

- Power consumption < 15 watts

The candidate power supplies should supply at least 200 amp-hours of power under DISSUB conditions.

Acknowledgments

The authors would like to acknowledge Master Diver Jerry Dearie, who built the ICE system and installed the cooling system within the hyperbaric chamber. Also, the personnel who conducted the computer testing within the hyperbaric chamber: Walter Von Borstel, Lloyd Lenormand, Caron Shake, Dave Brannon, Eric Hanson, and Doug Warnock. We also acknowledge Dr. James Francis for numerous contributions and suggestions, and HMCS(SS) Joe Bertoline for his review and recommendations regarding ruggedized computers.

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Appendix A
Vendors' Environmental Specifications of Each Candidate Laptop

Environmental Characteristic	Itronix X-C 6250	Paravant RLT Model C
Operating Temperature Range	-20°C to 60°C	-20°C to 60°C
Rain	4 in./hr. @ ~ 40 psi for 40 min. per axis for all axes per MIL-STD-810E, Test Method 506.3, Procedure III.	4 in./hr. in 30 m.p.h. wind per MIL-STD-810E, Test Method 506.3, Procedure I.
Shock	54 repeated 1 meter drops on all surfaces, edges and corners per MIL-STD-810E, Test Method 516.4, Procedure IV.	Procedures I and IV in transit case, 40Gs, three-times on each axis and transit drop of 48 in. for a total of 26 drops.
Vibration	0.04g^2/Hz over 20-1000Hz random.	MIL-STD-810E, Test Method 514.4 Category 3. Procedure III categories 6, 8, 10 Procedure I Loose Cargo.
Salt Fog	N/A	MIL-STD-810E, Test Method 509.3, Procedure I 48 hr. (@ 5%).

Appendix B

Submarine Escape And Rescue Expert System Power Supply Selection Report

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Report prepared 15 June 1999.

Table of Contents

Introduction

The Battery Technology Group of the Electrochemistry Branch (Code 683) of the Carderock Division, Naval Surface Warfare Center (NSWCCD) was tasked by the Naval Submarine Medical Research Laboratory (NSMRL) to provide technical design analysis and recommendations for a power source for the Submarine Escape and Rescue Expert (SEAREX) System. This report outlines the benefits and detractions associated with various possible approaches for providing stored power for this application. The major categories of power sources considered include primary, secondary, active and reserve systems. Types of power sources addressed specifically include batteries, fuel cells, and portable, hand-cranked generators. Issues relating to size, weight, safety, storage, shelf life, availability, cost and handling are reviewed for the various power source options.

System Requirements

The SEAREX System consists of a ruggedized laptop computer running a software package designed to provide emergency support to crew who are trapped in a damaged submarine. The expected power requirements are 12 volts DC output at 15 watts (W). The desired mission length is 7 days (168 hours), translating to a capacity requirement of approximately 210 ampere-hours (Ah), or in terms of energy, 2520 watt-hours (Wh). The temperature requirements for the system are 0°C to 49°C under both storage and operational conditions. The expected worst-case scenario for battery performance would involve the combination of prolonged storage at elevated temperature followed by use at 0°C or colder. The power supply must be capable of withstanding shipboard vibration and shock as described in MIL-STD-810E for harsh environments. Other environmental requirements include tolerance to 100% humidity and incidental water contact, e.g., splashing. The power supply must work under atmospheric pressures ranging from 0.9 to 5.0 ATA, and in all atmospheres with partial pressures of oxygen, nitrogen, carbon dioxide and hydrogen that would be capable of sustaining human life.

Active Versus Reserve Systems

An ***active power supply*** is designed to deliver electrical power any time a load is applied; standard alkaline batteries used in flashlights are examples of active batteries. A battery that is stored in an inactive state such that some activation process must occur before it can deliver electrical power is a ***reserve power supply***. This name is derived from the fact that some component of the electrochemical cell is held in reserve prior to activation. Because the active components of the electrochemical couple are stored separately in a reserve system, there is no degradation or self-discharge over time and these batteries can have very long shelf lives. Reserve systems are usually designed to deliver high power for short periods of time. This is often accomplished by selecting cell components such as separator materials or electrolyte compositions that increase the current carrying capability when introduced, but would be detrimental to operation over extended wet-storage periods.

Activation of a reserve power supply may be a manual process or it may be automated. The overall energy density of an automatically activating reserve power source is lower than an active system with equivalent power capabilities because of the additional hardware that is needed for the activation system and the electrolyte reservoir. Manual activation methods include pouring electrolyte into a closed system, submerging an open system in a bath of conductive fluid (similar to a seawater battery), or installing electroactive plates into an otherwise complete system. Because the SEAREX System will be used in a high-stress, emergency situation, the additional step of manually activating the power source is probably undesirable. Also, the unnecessary exposure of personnel to hazards associated with handling caustic or acid electrolytes is not warranted.

Primary Versus Secondary Systems

An alternative way of meeting a long shelf-life requirement in this application is to use a rechargeable power source, also known as a ***secondary power source***. Conversely, a ***primary power source*** is designed to be discharged only once, and should not be recharged and reused. Use of a secondary power source for the SEAREX System would provide the capability of periodically checking the system without degrading the available capacity for emergency use. To accomplish this, the SEAREX power supply could be tied into ship's power, or recharged from an outside source as part of the submarine's standard maintenance schedule. A three to four month stand time between charges is possible for some secondary power sources. However, a secondary battery could lose a significant portion of its energy and service life as a result of four months of storage at high temperature followed by deep discharge in cold conditions.

Modular Approach To Energy Storage

Some commercially available electrochemical systems are only produced in small sizes. Although small building blocks can be connected in various series/parallel configurations to generate a package with the desired total energy content, this approach is not always as straightforward as it might seem. In any battery configuration involving parallel connections of cells, appropriate electrical safety devices must be included to prevent self-discharging or cross-charging of the parallel strings. Adding diodes in this fashion results in a loss of useful voltage. Many rechargeable batteries with parallel cell configurations must include special charge control electronics to maintain balance among the cells during charging. These requirements add cost and complexity to the manufacturing process, and can ultimately impact the reliability of the power supply.

If a single SEAREX System power supply must contain sufficient energy to meet the 15 watt, 7 day (2520 Wh) requirement, several of the small commercial alternatives may be rejected. However, if a modular approach to meeting the total energy requirement is viable, then these alternative systems could be considered. This investigation will include comparison of as many power source alternatives as possible by including the option of meeting total energy requirements with a series of power sources called "day packs." Each "day pack" would have sufficient energy to run the SEAREX System for a minimum of 24 hours (approximately 30 Ah). Thus, seven "day packs" would give the equivalent system life of a single 210 Ah power source. For the purposes of this discussion, a power supply that contains sufficient energy to meet the 7 day mission requirement within a single package shall be referred to as a "week pack."

There are both positive and negative implications associated with the use of a modular "day pack" approach for the SEAREX power supply. On the negative side, the SEAREX laptop will need an internal back-up battery or flash-card to maintain memory when the "day packs" are being replaced. Also, the SEAREX program will need to be automated to alert the user when battery voltage is low and the main power supply requires attention. Thus, the modular approach to power source selection leads to additional logistics requirements. On the positive side, having multiple batteries increases the overall reliability of the system by supplying redundancy; if there is only one battery on board and it does not work, that represents a single point failure for the entire system. Because the "day packs" would be smaller and lighter, this approach provides flexibility in storage, as well as improved handling. The modular approach also lends itself to frequent verification of the SEAREX system between mission deployments, since there could be a designated system verification battery and the remaining batteries could be retained as dedicated stores. This use scenario could result in deteriorated performance with a single, large battery because intermittent use of a primary battery usually degrades its capacity retention over time.

Characteristics Of Major Battery Systems

Table 1 summarizes the basic characteristics of a comprehensive list of battery systems. This table is copied from the second edition of Handbook of Batteries, edited by David Linden. Only those systems that meet the criteria of readily available, environmentally friendly, and ambient temperature will be examined for their practicality with respect to use in the SEAREX System. However, it is obvious from Table 1 that there are many alternatives to consider.

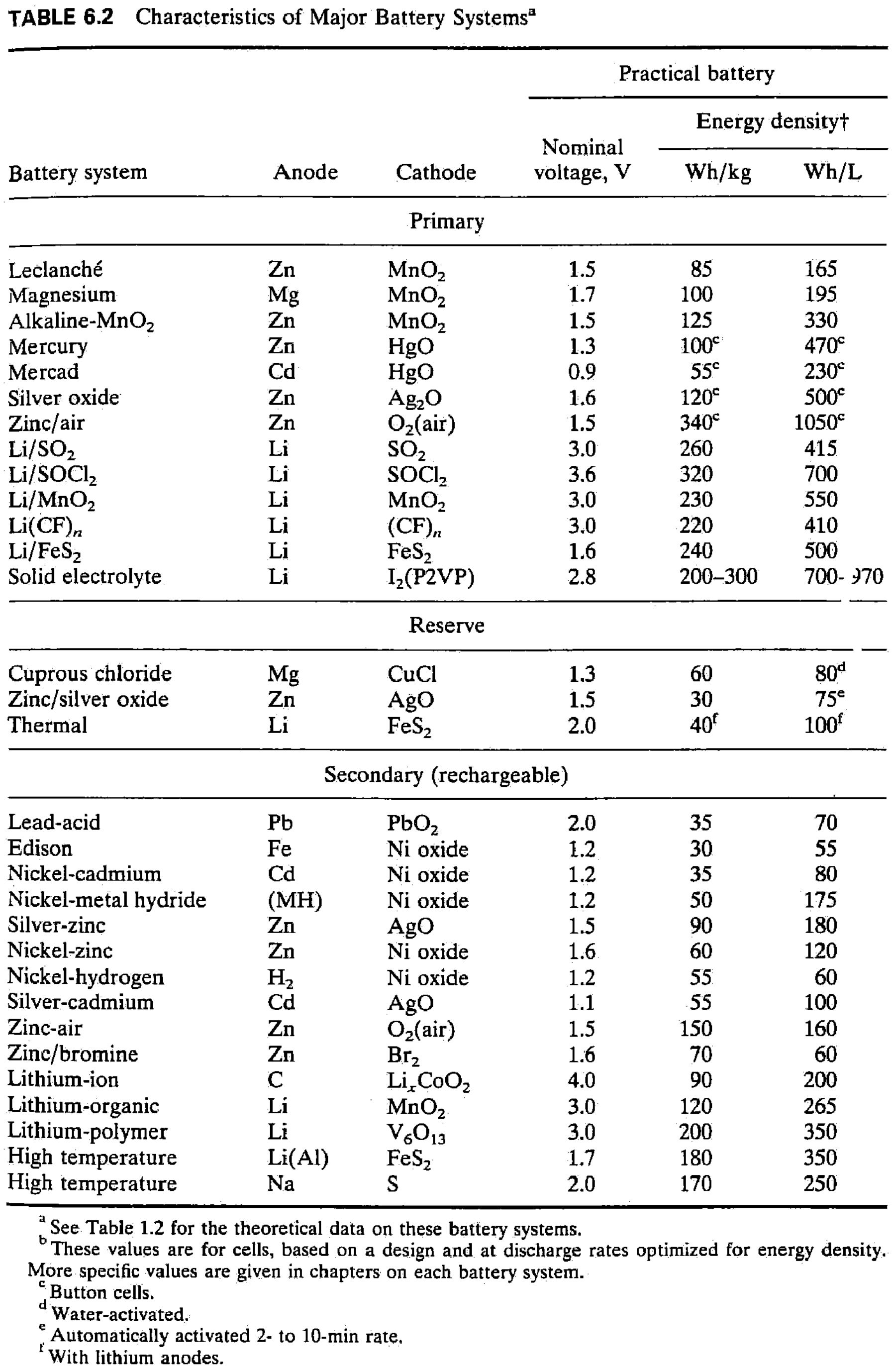

TABLE 6.2 Characteristics of Major Battery Systems[a]

			Practical battery		
				Energy density†	
Battery system	Anode	Cathode	Nominal voltage, V	Wh/kg	Wh/L
		Primary			
Leclanché	Zn	MnO_2	1.5	85	165
Magnesium	Mg	MnO_2	1.7	100	195
Alkaline-MnO_2	Zn	MnO_2	1.5	125	330
Mercury	Zn	HgO	1.3	100[c]	470[c]
Mercad	Cd	HgO	0.9	55[c]	230[c]
Silver oxide	Zn	Ag_2O	1.6	120[c]	500[c]
Zinc/air	Zn	O_2(air)	1.5	340[c]	1050[c]
Li/SO_2	Li	SO_2	3.0	260	415
Li/$SOCl_2$	Li	$SOCl_2$	3.6	320	700
Li/MnO_2	Li	MnO_2	3.0	230	550
Li$(CF)_n$	Li	$(CF)_n$	3.0	220	410
Li/FeS_2	Li	FeS_2	1.6	240	500
Solid electrolyte	Li	I_2(P2VP)	2.8	200–300	700- 970
		Reserve			
Cuprous chloride	Mg	CuCl	1.3	60	80[d]
Zinc/silver oxide	Zn	AgO	1.5	30	75[e]
Thermal	Li	FeS_2	2.0	40[f]	100[f]
		Secondary (rechargeable)			
Lead-acid	Pb	PbO_2	2.0	35	70
Edison	Fe	Ni oxide	1.2	30	55
Nickel-cadmium	Cd	Ni oxide	1.2	35	80
Nickel-metal hydride	(MH)	Ni oxide	1.2	50	175
Silver-zinc	Zn	AgO	1.5	90	180
Nickel-zinc	Zn	Ni oxide	1.6	60	120
Nickel-hydrogen	H_2	Ni oxide	1.2	55	60
Silver-cadmium	Cd	AgO	1.1	55	100
Zinc-air	Zn	O_2(air)	1.5	150	160
Zinc/bromine	Zn	Br_2	1.6	70	60
Lithium-ion	C	Li_xCoO_2	4.0	90	200
Lithium-organic	Li	MnO_2	3.0	120	265
Lithium-polymer	Li	V_6O_{13}	3.0	200	350
High temperature	Li(Al)	FeS_2	1.7	180	350
High temperature	Na	S	2.0	170	250

[a] See Table 1.2 for the theoretical data on these battery systems.

[b] These values are for cells, based on a design and at discharge rates optimized for energy density. More specific values are given in chapters on each battery system.

[c] Button cells.

[d] Water-activated.

[e] Automatically activated 2- to 10-min rate.

[f] With lithium anodes.

Table 1. Characteristics of Major Battery Systems

Primary Battery Alternatives

Alkaline Zinc-Manganese Dioxide

Commercial alkaline cells could be packaged to meet the voltage and capacity requirements of the SEAREX system. The component cells are very inexpensive and readily available. There are a variety of companies who specialize in building large alkaline battery packs. Matthews Associates, Inc. (formerly Battery Assemblers, Inc.) currently produces the Mark 102, Mod 1 alkaline battery for the AN/BST-1() Submarine Emergency Communication Transmitter (SECT) Buoy.

Based on manufacturer's data for the Duracell model MN1300, approximately 165 of these 14 Ah D-size cells could be configured into a 15 volt, 210 Ah battery pack with 11 cells in series and 15 series strings in parallel. The cells alone would weigh 51 pounds and require 568 cubic inches of space. Allowing for another 15 pounds of battery pack housing and potting material, and adjusting the volume to account for packing density, it is likely that this "week pack" would weigh about 66 pounds and require 900 cubic inches of space. A battery assembly of this size would cost approximately $1000 from Matthews Associates, Inc.

An alkaline "day pack" battery would have to be much larger than 1/7th of a "week pack" because two parallel strings of D-cells do not have sufficient current density to support a 1.25 A load. It is estimated that at least four parallel strings of 11 cells in series per string would be needed to meet the 15 W power requirement without severely de-rating the capacity of the cells. This pack would be about one fourth of the size of the "week pack," and might run the SEAREX system for as long as two days.

Some alkaline battery manufacturers produce a 6 V lantern battery that might be used as a larger building block in similar battery packs. Based on manufacturer's data for the Duracell model MN918, a "day pack" of 6 volt lantern batteries (rated at 0.66 A current draw) would require at least four batteries, depending on the current draw and voltage regulation of the SEAREX System. It is estimated that this battery would cost about $150, or just over $1000 for a one-week supply. This lantern battery "day pack" would weigh a minimum of 15 pounds and occupy at least 400 cubic inches of space. It is important to note that a lantern battery is simply a single housing containing an array of cells connected in a series/parallel configuration. It is possible that the internal configuration of this type of battery, which is designed and produced for consumer applications, might not be robust enough to survive military environments. If the cell used in the lantern battery is larger than the standard D-cell, it might provide improvements in weight and volume if it could be packaged professionally in a "day pack" or "week pack" configuration.

Alkaline batteries have a sloping discharge curve, and are subject to capacity degradation under discharge at cold temperatures. The authors estimate that an alkaline battery used in the SEAREX application would lose as much as 25% of its ambient temperature capacity when discharged under a 15 W constant power load at 0°C. Prolonged storage, especially in environments with high humidity, will further deplete the capacity of the battery. For these reasons, it may be necessary to overbuild an alkaline battery with 25% to 50% excess energy to ensure meeting minimum life requirements under all possible discharge scenarios. Thus, the weight, volume and cost estimates in the proceeding discussion should be viewed as minimum values.

Due to current environmental regulations, alkaline batteries are produced with no added mercury, and as a result they may be subject to poor performance in response to severe shock and vibration. Therefore, meeting MIL-STD-810E specifications for harsh environments may be a concern for these systems. In previous use in military applications, alkaline battery packs that were hermetically sealed and encapsulated demonstrated internal self-discharge ranging from moderate capacity loss to uncontrolled shorting as a result of electrolyte seepage along the interconnections between the cell strings. Thus, some performance and environmental testing would be necessary to verify the robustness and determine the final shelf life of any proposed alkaline battery pack.

Zinc-Air

Primary zinc-air batteries are used commercially in small sizes for pagers and cellular telephones. Zinc-air batteries have been used for over 20 years as the preferred power source for hearing aids. Larger systems have been built and tested for specific applications, such as railroad signaling, remote communications and navigational buoys. Some manufacturers have even marketed zinc-air battery designs specifically for laptop computer applications. Currently, the United States Army's Communication Electronics Command (CECOM) is funding an effort at Electric Fuel Corporation to produce a 24 V, 50 W zinc-air battery pack to be used in forward field chargers and communication gear. A 12 V version of this power source is also available, and is reported to be capable of delivering 1.25 A in the required temperature range. The battery is rated at 400 Wh in this current range, and should therefore be considered a potential "day pack" for the SEAREX System. An 800 Wh version could also be made available with a 12 V output. Provided that the 24 V version goes into full production for the Army, either of these 12 V versions could be leveraged off the Army's production line, and would cost between $50 and $100 per "day pack." However, the cost to procure prototype units for preliminary testing is $1500 to $3000 per unit. The typical shelf life of a zinc-air battery is estimated to be 7 to 10 years as long as the airflow into the cathode is restricted. This can be achieved by taping over the air inflow ducts or storing the entire battery in a sealed container.

There are also a limited number of commercially available hybrid batteries that combine zinc-air technology with traditional alkaline battery technology by adding manganese dioxide to the zinc cathode. The addition of the manganese dioxide provides a significant increase in pulse current capability. However, in production these batteries generally have a thicker electrode configuration than some state-of-the-art zinc-air systems, so the "improvement" from the manganese offsets the limitations of the thicker electrodes. Batteries of this configuration are manufactured by Cegasa International of Spain, and are distributed in the United Sates by Celair Corporation. The model 8AS3/120 cell costs $61.60, and provides 12 V (open circuit) for 120 Ah with a maximum current rating of 0.08 A, which is much too low of a current capability to satisfy the SEAREX System requirements. A parallel array of 16 of these batteries would be required to meet the SEAREX current requirements. This configuration would cost approximately $1200, weigh approximately 140 pounds, and would require more than 9000 cubic inches of space. However, this battery would have a capacity of almost 2000 Ah, which translates to over two months of run time at 15 W.

All air cathode batteries require oxygen from the air to generate power, so they would consume a precious commodity in the submarine atmosphere. As such, it might not be prudent to select a power source that uses such a valuable resource. Calculations indicate that the quantity of oxygen used by a 400 Wh zinc-air battery in one day is less than 10% of the amount of oxygen required for an average submariner in one day. It is also important to note that zinc-air batteries generate small amounts of hydrogen during discharge. The production of hydrogen onboard submarines is a concern and presents additional logistical considerations.

Environmental conditions may have an adverse effect on zinc-air systems. Air cathode cells use a semi-permeable membrane that retains a caustic electrolyte (KOH or NaOH) in the cell and permits oxygen to diffuse into the cathode. Operation of these cells is critically dependent on the performance of the membrane. The permeable membrane may be damaged by exposure to salt water from inadvertent submersion or spray. Although an air cathode system should operate independently of atmospheric pressure when a minimum partial pressure of oxygen is present, it is expected that sudden increases or decreases in atmospheric pressure could damage the air-cathode membrane causing rupture or leakage. These concerns highlight the need for test and evaluation of a prototype system under representative environmental conditions.

Lithium Systems

The classification of lithium primary battery describes a broad family of power sources that includes a variety of chemistries and sizes. The single common element is the use of a metallic lithium anode. Primary lithium batteries offer very high energy densities, function in wide temperature ranges, and can be optimized for high current rate, high power, or long duration applications. The principal commercial applications for primary lithium batteries include watches, cameras, computers (memory back-up) and pacemakers. Specialized commercial applications include powering equipment used in oil-well logging and embedded sensors. Larger cells are used almost exclusively by the aerospace and military communities for everything from radios to missiles.

Within the family of lithium primary batteries, there are two major groups: liquid cathode and solid cathode. Liquid cathode systems, including lithium-sulfur dioxide (Li/SO2) and lithium-thionyl chloride (Li/SOCl2), are among the highest energy density batteries known. In the late 1980s and early 1990s, the authors participated in the development of a #6-size Li/SOCl2 cell for use in the Captor Mine Improvements Program. SAFT Research and Development Center located in Cockeysville, MD manufactured the cell. This #6-size cell is slightly larger than a 12 ounce soda can, and has a capacity of approximately 125 Ah at the SEAREX discharge rate. A "week pack" could be configured from a total of eight cells, with two parallel strings of four series-connected cells in each string. This "week pack" could weight as little as 30 pounds, and might be as small as 1.5 times the size of a standard "six pack" of soda cans. However, the battery that was designed to use this cell was never introduced into the fleet, therefore the cell design is not currently in production. In high-volume production, the cell would cost approximately $500. Significant engineering development would be required to design an appropriate housing for this kind of battery, so the authors estimate that the final cost would be $5000 to $6000 per “week pack”.

Liquid cathode lithium batteries pose a significant hazard due to the potential release of acid gases from pressurized sulfur dioxide or thionyl chloride cells. In the enclosed environment of a submarine this hazard is emphasized. Although the #6-size Li/SOCl2 cell was evaluated and approved for submarine carriage (in a specific battery configuration), the system was only approved for short-term missions involving swift deployment. Also, this battery was enclosed in a system housing that was extremely robust. Although a Li/SOCl2 battery design is conceivable for the SEAREX System, the authors feel that the hazards associated with long-term deployment in a submarine environment outweigh the potential advantages for this application.

The solid cathode systems include lithium-manganese dioxide (Li/MnO2), lithium-carbon monofluoride (Li/CFx) and lithium-iron disulfide (Li/FeS2). Solid cathode lithium batteries offer some intrinsic advantages over liquid cathode systems for long-term storage, and they do not pose the hazards associated with potential leaks of acid gases. Of the three solid cathode chemistries, Li/MnO2 offers the best combination of cost, configuration and availability.

Both the Ultralife U336OH D-size Li/MnO2 cell and the Ultralife U3VF-K-T Li/MnO2 Thin Cell could be configured into battery packs to meet the SEAREX requirements. Fifteen D-size cells (arranged as three parallel strings of five cells in series per string) are required for a 30 Ah "day pack." Conversely, 150 of the 1 Ah Thin Cells (with 30 parallel strings of five cells in series per string) would be needed. A “day pack” comprised of 15 D-size cells will weigh about 4 pounds, without including packaging material weights like potting and the battery housing. However, since the Thin Cells are much smaller and lighter than the cylindrical D-size cells, a "day pack" of Thin Cells might weigh as much as 30% less than one comprised of D-size cells. Because of their rectangular shape, the Thin Cells can be packaged much more efficiently than the D-size cells. This packing efficiency of the Thin Cells would afford at least a 3-fold decrease in volume over the D cell configuration. When purchased in volume, the Thin Cells cost approximately 30% more than the D-size cells on a per Ah basis. Also, assembly of the Thin Cell version would be more labor intensive and have a much higher parts count, which would impact the manufacturing cost. An estimated price range (covering either configuration and assuming volume pricing) for a Li/MnO2 "day pack" is $500 to $1000, with the Thin Cell version at the higher end of the range. Therefore, the authors estimate that a full mission complement of primary Li/MnO2 batteries for the SEAREX system would cost a minimum of $3500 (D cell version) to $7000 (Thin Cell version). EAC Corporation of Teterboro, NJ would be an appropriate facility for providing battery assembly capabilities for this type of battery design. The estimated shelf life of a Li/MnO2 primary battery is seven to 10 years, with a capacity loss associated with self-discharge of 5% the first year and 2% per year for every additional year.

The United States Army is currently developing Li/MnO2 pouch cells that would be an excellent building block for the SEAREX power source. These cells would combine the packaging advantages of the Thin Cell with an even larger capacity per unit cell than the

D-size cell described above. Here, similar to the Electric Fuel zinc-air system, cost would depend largely on the ability to leverage against large Army procurements. This approach could represent an excellent opportunity for a long-range product improvement program.

As with any system that stores energy chemically, and especially with large, complex assemblies of cells, these batteries have the potential of venting or rupturing with high pressure and releasing toxic gases and flames. Due to the hazards associated with a potentially violent failure of a large battery pack, the authors do not recommend considering a primary Li/MnO2 battery in a "week pack" design for this application.

Prior to use onboard any United States Navy platform, all lithium batteries must undergo a safety review in accordance with NAVSEAINST 9310.1B of 13 June 1991. In most cases, testing of the battery and the associated system is required. When testing is required, it is conducted in accordance with NAVSEA Technical Manual S9310-AQ-SAF-010, " Batteries, Navy Lithium Safety Program Responsibilities and Procedures, " of 20 July 1988. Also, NAVSEAINST 9310.1B states that "lithium batteries may be used only when it is established that no other safer, environmentally improved battery will provide adequate performance to meet an operational requirement." Thus, using a lithium primary battery as the power source for the SEAREX System should only be considered if minimizing weight and volume is mission critical for fielding the system. Also, consideration must be given to the non-recurring costs associated with evaluating and testing a lithium battery when comparing power source alternatives for the SEAREX application.

Secondary Battery Alternatives

Sealed Lead-Acid (SLA)

Valve-regulated, sealed, lead-acid (VRLA or SLA) batteries, such as those used commercially for marine applications, offer a potential alternative for the SEAREX power supply. These batteries can be procured from a variety of manufacturers in appropriately sized modules to meet the 7-day requirement. Many of these batteries employ a gelled electrolyte that minimizes the concerns related to electrolyte leakage. A 12 volt, 225 Ah battery manufactured by East Penn Manufacturing Company, Inc. weighs 161 pounds and costs $485. Other manufacturers advertise 12 volt, 200 Ah SLA batteries for as low as $350. In order to ensure that the SEAREX system is portable (so it could be moved from a damaged area of the submarine to a more secure area) two or more smaller batteries of this type could be used in sequence or connected in parallel. Three, 12 volt, 80 Ah modules costing approximately $125 each might be used in this manner. Seven to 10 smaller versions (50 Ah each) could be fielded as "day packs" for a total battery cost of about $1000 for a one week supply.

Lead-acid batteries are currently used onboard submarines for reserve power and propulsion. Thus, fielding additional lead-acid batteries for the SEAREX application will not represent the addition of a new hazard, or the introduction of a technology that is foreign to the crew. However, the submarine community requires review and qualification of all new types of lead-acid batteries prior to deployment. Although this qualification process is not usually as demanding as the lithium battery qualification procedure described previously, it should not be overlooked during consideration of the overall life cycle costs of the various power sources.

High-grade SLA batteries produced using glass mat separators have improved vibration characteristics over other SLA batteries. Designing a protective housing for the battery could potentially solve shock and vibration issues, if they arise. SLA batteries produced with flame resistant housings are available and may be desirable for this application. Most SLA batteries designed for portable applications are rated for operation from –15°C to 55°C, and for charging from –15°C to 40°C. However, the service life of a SLA battery stored at the upper end of the temperature range will be reduced to from 7 years to 1 year, and the self-discharge rate will double for every 10°C over ambient temperature. SLA batteries must be stored in the charged condition, and last longest when they are maintained by a float charge; storage in the discharged state will result in battery failure due to sulphation. These batteries do not take a fast charge, and can be degraded by deep discharge. Some manufacturers add special catalysts and additives to improve resistance to damage from deep discharge. SLA batteries generate small amounts of hydrogen gas during charging and therefore have the same concern associated with their use on submarines as mentioned previously for zinc-air systems.

Nickel Cadmium (NiCd)

Nickel cadmium batteries are used commercially in a wide variety of portable applications, such as radios, telephones, video cameras, and power tools. The largest commercial cell that is available for use as a building block for a 210 Ah system is a 20 Ah cell manufactured by Sanyo. Eleven of these cells would be needed in parallel to produce a "week pack" that could meet the 210 Ah capacity goal. Unfortunately, NiCd batteries with multiple parallel connections are subject to inconsistencies in charge rate, and are best recharged on a per-cell level. Special electronics that were developed as an outgrowth of the portable power industry can be used to control charging at the cell level in a large series/parallel array of cells. At a cost of approximately $53 per 20 Ah cell, plus the additional costs associated with electronics and assembly, a NiCd battery for this application would cost 8 to 10 times more than a SLA battery with the same capacity.

The self-discharge rate of a NiCd battery in the SEAREX System could be as much as 4 times higher than a SLA, especially in response to high temperature storage. Fast recharge is preferable for NiCd systems, and a specialized reverse load charge yields the best results by promoting recombination of the gases generated during fast-charging. NiCd batteries function best when they are discharged deeply (to 1 V per cell) and regularly; repeated recharge cycles interspersed with shallow discharge cycles (a likely use scenario for a rechargeable battery in the SEAREX application) lead to poor performance of the battery known as "memory effect." Outgassing of hydrogen can also occur in these cells as a result of overcharging. Given these concerns, consumer-oriented NiCd technology does not seem to be a good fit for the SEAREX application.

A possible source for a specialty NiCd battery designed specifically for the SEAREX system is Acme Advanced Energy Systems. This company produces large NiCd batteries used in starting-lighting-and-ignition (SLI) applications on military aircraft. Although the SLI batteries are not directly applicable to this application, technological advances made by the company (like the use of fibrous nickel plaque materials to replace sintered nickel oxides) could be applied to a battery for SEAREX. Acme is currently working on a development effort in conjunction with the U. S. Army to produce NiCd pouch cells that could be the appropriate size for building a 12 V, 210 Ah battery. If the Army's development effort is successful, this might represent another avenue for a follow-on product improvement program.

Nickel Metal Hydride (NiMH)

Nickel metal hydride batteries are hermetically sealed batteries that provide significantly more capacity per unit than NiCd batteries, and they are not as susceptible to "memory effect." They generally cost about 1.5 times more than NiCd cells of a similar size. However, they are not readily available in sizes much larger than 4 Ah, and, like NiCd batteries, they are also prone to inconsistency in charge rate when too many cells are combined in parallel configurations. Limited numbers of specialized cells are in prototype production for use in electric bicycle and car applications. These cells have capacities as high as 100 Ah. For the SEAREX System, although a NiMH battery produced from commercial cells would be significantly smaller and lighter than a SLA or NiCd battery with equivalent energy content, it would cost much more.

Lithium Ion

Lithium ion batteries are the most recent family of secondary batteries to enter the commercial market, and are used widely in laptop computers and cellular telephones. These batteries offer energy densities roughly two to three times higher than NiCd batteries at comparable discharge rates. Instead of using a metallic lithium anode like those found in lithium primary batteries, lithium ion batteries have a carbonaceous anode material that has been intercalated with lithium ions. Provided that the proper charge and discharge characteristics are maintained, these systems contain no metallic lithium. However, these cells are susceptible to severe performance degradation and premature failure if careful charge and discharge management is not maintained.

In order to protect these batteries from abusive current and voltage conditions, they must include a control circuit and multiple safety shutdown devices. This combination of expensive electronics and state-of-the-art technology means that lithium ion batteries tend to be the most expensive of all of the consumer-oriented portable power supplies. Although large, developmental lithium ion cells and batteries have been produced in limited quantities to support electric vehicle and underwater propulsion efforts, the bulk of the cells produced to date are on the order of 1.5 Ah to 5 Ah in capacity.

Lithium ion batteries are also subject to the same Navy requirements as lithium primary batteries, and therefore require safety review and testing prior to fielding on a Navy platform. This combination of relatively new technology, limited size factor, higher cost, and additional safety requirements make lithium ion batteries an unlikely candidate for a near-term SEAREX System power supply. In the future, continuing trends of technology advancement and cost reduction could lead to the lithium-ion chemistry becoming a viable candidate for technology insertion.

Alternative Power Sources

Fuel Cells

A fuel cell is an electrochemical device in which the chemical energy of a fuel is converted directly into electrical energy. It is like a primary battery that has the fuel and oxidizer stored externally, to be fed in as necessary. Thus, capacity is limited only by the amount of available fuel. Fuel cells have been used in non-U. S. submarines as primary power for air-independent propulsion (AIP), and as a range extender for diesel-electric boats. Fuel cells are classified by their internal design and resulting operational parameters. Proton Exchange Membrane (PEM) and Alkaline are the two most applicable fuel cell technologies for portable power in submarine operating environments, as the Solid Oxide Full Cell (SOFC) and Molten Carbonate Full Cell (MCFC) both operate at very high temperatures (600°C to 1300°C).

Some fuel cells have been developed to run on methanol. Most fuel cells that can use complex fuels (such as diesel and JP6) require extensive pre-treatment of the fuel materials. Most fuel cells function best using hydrogen gas. Various options exist for hydrogen sources for these systems: bottled hydrogen, metal-hydride converters, and ammonia crackers.

Most commercially available fuel cell power supplies provide at least 200 W; this is significantly more power than is needed for the SEAREX System. However, H Power Corporation produces 35 W and 50 W, solid state, PEM fuel cell systems that include a Hydrogen Fuel Supply Module with metal-hydride cartridges. The cost for the 35 W system starts at $3000. Analytic Power also produces a similarly sized and priced power plant, the FC-25. The Analytic Power version is fueled with bottled hydrogen that is supplied in 750 Wh-sized tanks. Operating temperature ranges for these commercially available PEM fuel cells are more limited than for the batteries discussed previously. Operation at the extremes of the specified temperature range for SEAREX may negatively effect the efficiency and power output of these systems.

The safety implications of carrying bottled hydrogen onboard a submarine may limit the practicality of using the Analytic Power fuel cell. As previously mentioned, there is also the disadvantage associated with fielding an air-breathing system. The submarine environment poses a more significant challenge for a PEM fuel cell than a zinc-air battery because the partial pressures of carbon monoxide and carbon dioxide must be maintained at low levels to optimize performance and prevent poisoning the system. Also, because fuel cells rely on balanced airflow through the electrodes, they are likely to experience performance deterioration in response to variations in environmental pressure. Incidental wetting or momentary submersion of the fuel cell membranes could impair operating capability. These myriad performance concerns, coupled with a relatively high cost per unit, render the fuel cell a poor candidate for the SEAREX power source.

Hand-Cranked Generators

A 70 Watt, hand-crank generator (model 700) is available from Matthews Associates, Inc. for $2500. This generator weighs 7.25 pounds and occupies a volume of approximately 175 cubic inches. Both the Army and the Marines have fielded it for emergency portable power and battery recharging. Although the model 700 is capable of providing the necessary power to run the SEAREX System, and would also be appropriate to recharge secondary batteries, the amount of exertion required to operate the generator is a concern. Personnel running the generator will consume more oxygen and create more carbon dioxide, and this would be in opposition to the overall goal of maintaining a life-supporting atmosphere in the submarine for the longest possible duration. It is possible that the most critical time for use of the generator could come when the available air and physical capabilities of the crew are at their lowest. Therefore, the authors would not recommend fielding this item as the only means of power for the SEAREX system. Unfortunately, the relatively expensive price makes fielding it as a back-up system unattractive.

Summary

Tables 2 and 3 summarize the basic characteristics of the most feasible candidates from the technologies presented above. Table 2 summarizes the possible "week pack" variations. Table 3 describes options that involve using the "day pack" approach. The shelf life estimations included in the tables take into account the specific SEAREX environment, and may not reflect the possible shelf life of that chemistry under more general conditions.

	Voltage (V)	Capacity (Ah)	Cost per Ah	Estimated Shelf Life	Recharge Capability	Est. Weight (lbs)	Est. Volume (in^3)
SLA	12	225	$1.50 to $2.25	1-3 years	Yes	160	2285
Alkaline	15	210	$4.75	2-4 years	No	66	900

Table 2. Summary Of Various "Week Pack" Power Source Options

	Voltage (V)	Capacity (Ah)	Cost per Ah	Estimated Shelf Life	Recharge Capability	Est. Weight (lbs)	Est. Volume (in^3)
SLA	12	50	$2.50 to $3.00	1-3 years	Yes	37.6	483
Alkaline	15	56	$5	2-4 years	No	17 to 20	300
Li/MnO2 Primary	15	30	$15 to $20	8-10 years	No	3 to 6	60
Zinc-Air	12	33	$1.50 to $3.00*	7-10 years	No	2.65	60

* based on volume pricing

Table 3. Summary of various "day pack" power source options

Recommendations And Conclusions

If the SEAREX System design can accommodate using a series of smaller power sources that are replaced as necessary, fielding these “day packs” would be preferred over deploying a single, large power source. The rationalization for this recommendation is based on the benefits of redundancy and improved storage and handling, as mentioned previously. Of the four alternatives summarized in Table 3, the authors rank them as follows:

1) Zinc-Air

2) Alkaline

3) SLA

4) Li/MnO2 primary

By far, the zinc-air “day pack” from Electric Fuel provides the highest energy density at the lowest cost. However, the success of this approach is contingent upon many things. First and foremost, the U. S. Army contract for a zinc-air portable power pack (or another similar high-volume commitment) must be in place to generate procurement in the necessary quantity to make this method cost effective. The relatively small quantities that would be procured by the SEAREX Program alone would not result in the volume pricing that makes this alternative so attractive. Because of the performance concerns enumerated previously, environmental testing of a prototype system under representative conditions must be conducted prior to making a final commitment to fielding this technology. This will be an expensive effort, primarily due to the relatively high cost of the zinc-air packs in prototype procurement. However, limited environmental testing of representative commercial batteries (e.g., cellular phone batteries) might provide relevant data at a lower cost, and with minimal risk to the program. Finally, use of a zinc-air system in SEAREX requires gaining acceptance from the submarine community of a system that consumes oxygen and releases hydrogen. Although there are precedents for achieving this acceptance, it should not be assumed.

An alkaline battery pack would be the second choice for the SEAREX applications. This chemistry might be fielded in a “week pack” configuration if logistical concerns negated using the modular approach. In either configuration, it has the advantages of being available from multiple sources, and of being a sealed system that will not impact the submarine environment. However, the expected shelf life is much shorter than zinc-air, and the packs will be larger and heavier.

SLA technology is the only rechargeable solution that appears to be feasible at this time. However, the logistical concerns associated with the maintenance cycle of these batteries require resolution. The shelf life and energy density are both inferior to the zinc-air system. Use of this technology would result in the largest and heaviest batteries of the top four candidates. Although the initial cost is comparable to zinc-air, and less than alkaline, it is expected that the overall life-cycle cost will be higher because of the additional maintenance cycle and associated logistical requirements. Acceptance from the submarine community of a system that generates hydrogen into the atmosphere will also be required for this system.

Judging by performance criteria alone, the Li/MnO2 primary battery has many advantages. It is a sealed system that would be about the same size, and last as long as, the zinc-air battery. However, the cost per unit is seven to 10 times higher, and that estimate does not include the non-recurring costs associated with meeting the safety requirements in accordance with NAVSEAINST 9310.1B. The combination of maximum cost and elevated safety concern results in ranking this approach last among the likely solutions.

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Atwater, T., United States Army Communication Electronics Command (CECOM), personal communication.

Direct Energy Conversion, Third Edition, Angrist, Stanley W., Allyn and Bacon, Inc., 1976.

Handbook of Batteries, Second Edition, ed. Linden, David, McGraw-Hill, Inc., 1995.

Power Sources for a Special-Purpose Buoy, West-Freeman, W. A., Banner, J. A., Davis, P. B. Winchester, C. S., Kilroy, W. P., and Barnes, J. A., NAVSWC TR 91-488, 21 June 1991.

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Vendors

Battery Manufacturers and Assemblers

Acme Advanced Energy Systems, 528 West 21st Street, Tempe, AZ, 85282, (480) 894-6864, http://www.acme-electric.com.

EAC Corporation, 380 North Street, Teterboro, NJ, 07608, (201) 462-2195, http://www.eacnet.com.

East Penn Manufacturing Co., Inc., Lyon Station, PA 19536,
(610) 682-6361.

Electric Fuel Corporation, 1750 Opelika Road, Auburn, AL, 36830,
(334) 502-9001, http://www.electric-fuel.com/cs/defense/index.html.

Matthews Associates, Inc. (formerly Battery Assemblers, Inc.),
645 Hickman Circle, Sanford, FL 32771, (407) 323-3390.

The Power Source, Inc., 2284 Old Middlefield Way, Mt. View, CA 94043,
(800) 847-6947, http://netbox.com/powersource/index.html.

TNR Technical, 17779 Main Street Suite A, Irvine CA 92614,
(800) 490-8418, http://www.batterystore.com/.

Battery Distributors:

Batteries Plus, 844A Rockville Pike, Rockville, MD, 20852,
(301) 738-0606, http://www.batteriesplus.com/stmd.html.

Battery Wholesale Distributors, 2605 Gabriel View Drive, Georgetown, TX 78628, (512) 869-6280, http://www.mywebplace.com/battery-store/.

Celair Corporation, 1455 Oakbrook Drive N. W., Suite 200, Norcross, GA, 30093, (770) 449-8998.

WestCo Battery Systems, Inc., 1645 S. Sinclair Street, Anaheim, CA 92806, (800) 214-8040, http://westcobattery.com/main.htm.

Fuel Cell Manufacturers

Analytic Power, 268 Summer Street, Boston, MA, 02210,
(617) 542-6352, http://www.analyticpower.com/.

H Power Corporation, 60 Montgomery Street, Belleville, NJ, 07109,
(973) 450-4400, http://www.hpower.com/address.html

Appendix C
SHOWTIME PROGRAM

SHOWTIME consists of two MS-DOS batch files, "SHOWTIME.BAT" and "TEST.BAT". "SHOWTIME.BAT" runs "TEST.BAT" twice over (two simultaneous instances of TEST.BAT, each in its own window), and then enters a loop that displays the time of day in regular intervals. It also appends to a log file the current time of day as a means to determine when computer failure occurred. Meanwhile, "TEST.BAT" creates a large file, prints it out to its window, copies it, deletes it, prints out the copy, and then repeats.

SHOWTIME serves several purposes. It provides feedback to indicate the computer is still operating. It keeps the machine fully exercising its FlashRAM, and it also maintains the computer at a high level of power consumption. The wattage reported for the Paravant (16 watts) and Itronix (12 watts) were measured during SHOWTIME operation.

SHOWTIME.BAT

```
echo off

copy \test\crlf \test\run

copy \test\test.bat \test\1\test.bat
copy \test\test.bat \test\2\test.bat

copy \test\test1.pif \test\1\test1.pif
copy \test\test2.pif \test\2\test2.pif

cd \test\1
start test1.pif

cd \test\2
start test2.pif

cd \test

time < \test\crlf > \test\begunat.txt
echo [[ >> runlog.txt
type \test\begunat.txt >> runlog.txt
echo ]] >> runlog.txt

:TimeLoop
time < \test\crlf >> runlog.txt
time < \test\crlf

dir \ /s/b > nul
dir \ /s/b > nul
dir \ /s/b > nul
dir \ /s/b > nul

if exist \test\run goto TimeLoop

exit
```

TEST.BAT

```
dir \ /s/b > q1
copy q1+q1 q0
copy q0+q0 q1
copy q1+q1 q0
copy q0+q0 q1
copy q1+q1 q0


:StartLoop

if not exist \test\run goto ExitTest
type q0
if not exist \test\run goto ExitTest
copy q0 q1
if not exist \test\run goto ExitTest
del q0

if not exist \test\run goto ExitTest
type q1
if not exist \test\run goto ExitTest
copy q1 q0
if not exist \test\run goto ExitTest
del q1

if exist \test\run goto StartLoop

:ExitTest
exit
```