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Li-Poly Pressure-Tolerant Batteries Dive Deep

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In the past 15 years, robotic systems have become more prevalent, more reliable and are increasingly used in harsh, more remote environments. The requirements placed on the battery and power systems for robotic applications have increased accordingly. More power and endurance are required, and the batteries must be robust to a wider range of environmental conditions. This is especially true of batteries for autonomous underwater vehicles (AUVs).

Underwater Vehicles and Battery Challenges

An AUV is a small, unmanned submersible vehicle that, deployed from a boat or point on shore, autonomously executes a pre-programmed mission. Most vehicles dive only to a few hundred meters, but deep-rated vehicles can descend several thousand meters below the ocean surface. Batteries intended for the deep-rated vehicles must withstand 10,000 psi with no damage or significant degradation of performance.

An AUV must propel itself both up and down through the water, and energy is at a premium. Therefore, these vehicles are designed to be nearly neutrally buoyant. This requirement affects all parts of the AUV, including the battery system. To make neutral buoyancy easily achievable, many AUVs flood with water while operating.

There are two battery options for flooded underwater systems. More commonly, off-the-shelf batteries or battery packs are housed in a pressure chamber containing air at atmospheric pressure. The trapped air adds a considerable amount of buoyancy to a vehicle, which may be useful, or may require weight to be added to the vehicle.

Alternatively, the battery can remain outside any chamber, but must be pressure-tolerant and completely waterproof. Then the battery can be placed anywhere in the vehicle. Lithium-polymer batteries are fairly dense, so it is a system advantage to place them low in the vehicle, and keep pressure chambers and foam floatation high. This keeps the vehicle's center of buoyancy farther above the vehicle center of gravity, improving the roll dynamic stability of the entire system.

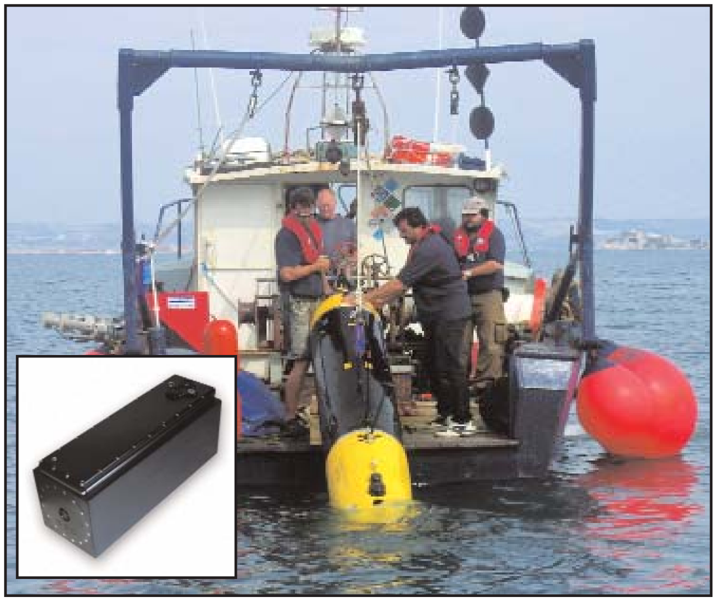

Figure 1. Operators bring on deck the Bluefin-21 AUV at the end of its mission. The vehicle carries out missions to ocean depths of 4,500 meters, and uses li-poly pressure-tolerant battery technology. (Bottom left) the 1.5 kW-hr battery pack which powers many AUV systems.

Li-Poly Pressure-Tolerant Batteries Lead to System Advantages

A useful figure of merit in underwater battery systems is the effective specific energy density, in watt-hours per neutrally buoyant kilogram. This figure accounts for the weight (in air) of the foam required to make the battery neutrally buoyant. This is significant because deep-rated foam is fairly heavy: for 10,000 psi the foam is 0.641 kg/L, or 44 lb/ft3. For vehicles operating at shallower depths, foam of 32 lb/ft3, 14 lb/ft3, or even 9 lb/ft3 may be used.

For example, batteries designed by Bluefin Robotics are made using waterproof building blocks containing many battery cells. One block is 180 W-hr, weighs 1.2kg, and occupies 0.5L volume. Foam added to the vehicle for neutral buoyancy occupies 1.5L and weighs 1kg. Thus, the effective specific energy density is (with more familiar W-hr/kg, for comparison):

180 / 1.2 = 150 W-hr / kg, or 180 / 2.2 = 82 W-hr / neutrally

buoyant kg.

Compare this to 61 W-hr / neutrally buoyant kg for silver-zinc batteries, or 21 W-hr / neutrally buoyant kg for nickel-cadmium batteries, and compare to 42 W-hr / neutrally buoyant kg for silver-zinc in a pressure chamber (using the pressure chamber for floatation) and 17 W-hr / neutrally buoyant kg for Ni-Cd batteries in a pressure chamber.

Figure 2 Free from cumbersome pressure chambers, the Bluefin 1.5kW-hr battery pack is easily swapped out of vehicles.

Placing the batteries outside the pressure chamber has a benefit to system design beyond higher effective specific energy density. The batteries are fairly dense, and can be placed low in the vehicle, while pressure chambers and foam floatation are kept high.

From an operational perspective, pressure-tolerant batteries bring another important advantage to underwater systems. If the battery is to be removed from a vehicle to be recharged or for shipment, should the user have to open a pressure chamber? Re-closing and re-sealing a pressure chamber is a delicate, time-consuming task which, if done improperly, puts the whole system at risk of sinking. Pressure-tolerant batteries eliminate the battery pressure chamber and associated risk, and thus increase system reliability. Further, easy removal of the batteries allows the system user to replace a discharged battery with a charged battery, and immediately continue using the system.

When Bluefin Robotics began commercially manufacturing AUVs in 1997, the high-energy-density chemistry choice for underwater batteries was silver-zinc, with a typical energy density of 110 to 140 W-hr/kg. From the beginning, the intent was to use the Ag-Zn batteries, and shift to a lithium-based cell as the battery technology matured. As the young company advanced the technology of its AUVs, engineers soon desired the better performance of lithium-polymer batteries, which was creeping toward 200 W-hr/kg.

Lithium-based battery chemistries were promising candidates for a pressure-tolerant system for another reason: the solid electrolyte. Most commercially-available lithium-polymer cells are made without air in the packaging, so the cell manufacture needed to be changed only slightly to produce a pressure-tolerant cell. Thus, the effort could be focused on developing a pressure-tolerant pack.

In systems using battery chemistries with a liquid electrolyte, a cell could be made pressure-tolerant by the addition of oil, to fill any air space. The oil floated on top of the electrolyte when the cell was upright, but this type of battery could only be used in a nearly-upright position. This would severely limit the attitude of the vehicle if applied to an AUV. The move to a solid electrolyte cell also eliminated the danger of leaking conductive, corrosive electrolyte, which was a danger with silver-zinc or lead-acid cells.

Lithium-polymer batteries out-perform silver-zinc in cycle life, as well. Silver-zinc systems were known to withstand anywhere from 15 to 50 full cycles, while lithium polymer batteries perform for up to 300 cycles, and this figure can be expected to improve as lithium-polymer battery technology advances.

Years of Battery Development

Bluefin Robotics began experimenting with lithium battery cells in 1999, and produced the first fully-submersible pressure-tolerant lithium-polymer battery in 2001. That battery was evaluated with electrical tests at ambient pressure and full-ocean pressure, with mechanical tests, and by use in early Bluefin AUVs.

The batteries underwent a major redesign in 2003. The mechanical enclosure and protection electronics were both improved based on lessons from the early batteries, and a new cell vendor was selected. Engineers tested cells from more than 30 cell vendors, checking for performance and for consistency across a vendor's cells. Tests included current pulse tests (with pulses of 10C), tests of DC resistance, nail penetration fault test, and localized application of 12 tons of pressure to the cell packaging.

Even robust cells were found not to be reliable enough in high-pressure situations. Bluefin engineers found that the failures all stemmed from the same cause and worked with the cell vendor to produce a cell design that performs reliably. This cell is still used in batteries that power vehicles such as the Bluefin-21.

Safety

As everyone is periodically reminded by the national news, lithium batteries are not without danger. As battery technology develops, safer cells are likely to become more readily available. Meanwhile, designers must carefully design for battery safety.

Balancing electronics integrated into the batteries are crucial to keeping the voltages of all cells in a battery equal, and protection circuits must be included in a battery to stop a battery from being charged if the voltage is pushed too high, or stop a discharge if the voltage falls too low. Bluefin batteries contain electronics to monitor current, voltage, temperature, and state of charge during both charge and discharge, and to stop charge or discharge under dangerous conditions. These electronics, like the batteries, operate under pressures up to 10,000 psi. To this end, individual components are pressure-tested. Some components, such as electrolytic capacitors, contain air in the component packaging and simply cannot be used.

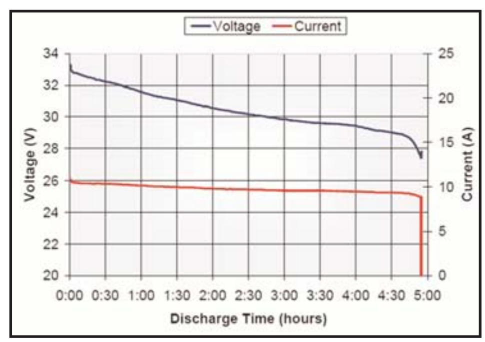

Figure 3 Voltage and Current during a battery discharge at 10,000 psi

Rigorous safety evaluations have been performed on Bluefin's batteries, both informally and formally. During testing in accordance with NAVSEA Instruction 9310.1b, batteries have undergone crushing, nail penetration, short-circuit, overcharge, over-discharge and high-temperature abuse. This provides an abundance of safety information. Bluefin has completed these tests and received the associated safety approval.

To increase reliability, Bluefin tests every cell received from the battery cell vendor. More than 20,000 cells have been pressure-tested thus far. Any cells that fail are removed from production, and failure analysis is performed. Once the cells are built into a battery, the battery is tested extensively as well. Battery tests include pressure cycling and a full charge-discharge cycle before and after the pressure cycle. Testing this rigorous makes the manufacturing process expensive, but is necessary to produce high-quality, reliable batteries.

Applications

Lithium-polymer pressure-tolerant batteries are now used for all Bluefin-designed AUVs. The pressure-tolerant batteries power AUVs that search for mines in shallow-water bays, inspect ship hulls for mines or other undesired hull features, and perform deep-ocean surveys in preparation for development of oil fields.

Bluefin recently made the standard 1.5 kW-hr battery available to other manufacturers of underwater systems. Within only a few months' time, these batteries have been delivered to various customers. Additionally, several other marine technology companies have inquired about custom research projects. Possible applications include any number of undersea robotic systems: manned, remotely-operated and autonomous; for scientific research or industrial research; military ocean systems; power for marine energy capture systems; and energy storage for marine fuel cell systems.

Conclusion

Bluefin Subsea Batteries improve underwater vehicle performance in four distinct ways. Easy battery replacement reduces vehicle service time and reduces the cost of battery removal for vehicle shipping. Pressure-tolerant lithium-polymer batteries increase energy density and effective energy density available to the system. And, for AUVs, Bluefin's batteries give the designer another tool to improve the dynamic stability of the vehicle.

Producing these batteries was not without challenges. A design was required to protect the battery pack and pack electronics from seawater. The design also needed to electrically protect a system of many battery cells. Finally, the design needed to ensure reliable performance under thousands of pounds of ocean pressure.

A lithium-polymer battery that is fully-submersible and pressure-tolerant has been sought by designers of AUVs and other underwater vehicles for years. It is only through thorough research, a good relationship with the cell vendor and continuous internal use that Bluefin is able to make this system available.

Bluefin Robotics Corp., a spin-off from Massachusetts Institute of Technology's AUV Lab, has been designing and manufacturing pressure-tolerant battery systems using lithium-polymer batteries for more than five years. Bluefin is now a wholly-owned subsidiary of Battelle Memorial Institute, and provides customers with batteries in AUVs or as standalone units.

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