

Pressure-Tolerant Lithium Polymer Batteries

A reliable, swappable high energy density battery for Autonomous Underwater Vehicles and Oceanographic Equipment

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Introduction

Lithium battery technology powers many of the everyday electronic devices owned by millions, including mobile phones, laptops and some hybrid cars. As demonstrated through this consumer market, lithium-ion is a well established, proven chemistry that, when managed properly, provides reliable high-density energy. For over a decade Bluefin Robotics has leveraged COTS (commercial off-the-shelf) lithium-based cells to design, build and deliver hundreds of pressure tolerant lithium batteries. Today, Bluefin's drop-and-play, rechargeable batteries power several underwater applications including Bluefin's line of commercial, scientific and military autonomous underwater vehicles (AUVs) and a number of OEM (original equipment manufacturer) products. The battery technology has successfully operated in shallow and deep water applications as a reliable, rechargeable energy source requiring minimal maintenance throughout its service life.



Figure 1. Bluefin 1.5 kWh Battery Pack

Underwater Battery Challenges

Prior to 2000 Bluefin Robotics used silver-zinc batteries enclosed in pressure vessels to power its AUVs. Though state of the practice at that time, the technology had significant inherent disadvantages. For instance, these batteries required special care and attention, they off gassed, 'burped'

electrolyte over circuit cards, required refrigeration to maximize their cycle life, and required pressure vessels to be opened for each charge. This led to maintenance and logistical complications. In 1998, Bluefin embarked on a path to design and build a pressure tolerant battery system that would reduce the number and magnitude of disadvantages while simultaneously maximizing energy density. Central to advancing Bluefin's battery goal was the lithium polymer (li-poly) battery chemistry that became widely available in the 1990s. This battery technology is essentially a flat-pack sandwich of an anode, a cathode and a gel-like electrolyte, which is able to withstand high hydrostatic pressure. While the path of developing pressure-tolerant li-poly batteries would indeed have challenges, significant advantages were expected in terms of reliability, performance, logistics, and safety if those challenges could be overcome.

In the infancy of the development, the focus of the technology effort was on the single problem of pressure tolerance. However, a plethora of technical challenges arose through each prototype. These have been largely overcome through refinement and testing, enabling the ubiquitous use of these batteries.

High energy density is the driving goal for underwater battery systems. Battery manufacturers specify the energy density of their cells but for fair comparison of disparate systems in the marine environment, ocean engineers often use a slightly different metric – and that is the energy density per neutrally buoyant kilogram. Every watt hour of energy stored on a free-flooded AUV increases mass and that mass requires an appropriate amount of flotation in order to make the vehicle as a whole near neutrally buoyant. Thus with the appropriate metric, one can measure the complete cost of a battery solution when all connectors, cables,

electronics, pressure vessels and foam flotation are considered. Furthermore, flotation also requires volume and every liter of flotation is a liter occupied that cannot be used by a sensor or critical vehicle subsystem. Using this metric, it can be determined that the pressure tolerant battery approach yields the highest energy density solution while preserving the ability to remove and replace the battery without breaking waterproof seals. While the raw li-poly pouch cells have an energy density of 200 watt-hours per kilogram (unpacked in air), the combined mass of flotation, casing, connectors and electronics brings the neutrally buoyant energy density down to between 80 and 120 watt-hours per kilogram depending on depth (this figure is driven by foam density).

For operation in the marine environment, battery components such as lithium cells, electronics, enclosures, and connectors must survive harsh conditions through numerous dives, charge cycles and on-deck conditions. Lithium batteries for consumer products like laptops are manufactured in the millions; however they are not exposed to saltwater, ocean pressure to 10,000 pounds per square inch gauge and temperatures at or below freezing simultaneously. As a result, Bluefin imposes additional screening tests on each incoming cell to ensure the robustness required to survive the added environmental stresses. Testing extends to other steps of the manufacturing process as well. To withstand the repeated pressure cycles, the battery packaging, connectors, materials, cables and electronics all have to be selected, designed and tested to protect against degradation or failure. For instance, during manufacture, battery components and cells must pass capacity and other electrical tests while under pressure to simulate the target operating environment.

Consider the commercial requirements for an underwater battery. For a typical survey AUV every minute that the vehicle spends in non-survey activities increases the cost of the survey - this includes preparation for a dive, time spent on the descent and ascent, recovery and on-deck turnaround for the next mission. Increasing the operational tempo requires a battery solution that is quickly replaceable and reliable.

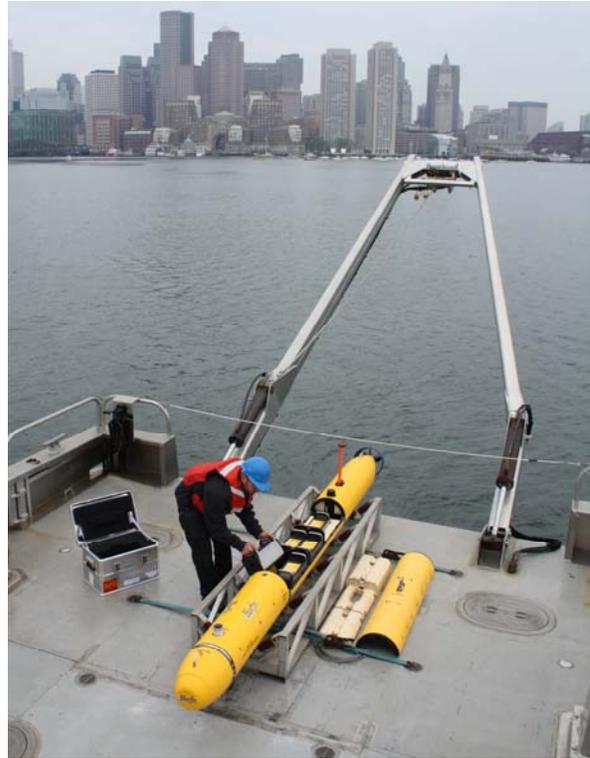


Figure 2. The commercial advantage of Bluefin's swappable batteries is that a freshly charged set can be installed in minutes.

Technical Advantages

The technical challenges faced in designing a pressure tolerant battery are significant, so the only reason to pursue this approach is if the advantages are numerous – and they are.

From a technical perspective, the pressure tolerant battery makes efficient use of displacement to offset the battery mass, and the freedom to arbitrarily design a space envelope allows designers to efficiently package flotation foam into spaces where traditional cylindrical or spherical pressure vessels cannot reside. The outcome of this efficient packaging is the ability to create deep rated AUV's that are small and easy to handle yet retain excellent range performance. The pressure tolerant approach provides the highest energy density while also reducing the cost impact associated with using large pressure vessels.

The commercial advantage of a swappable battery is that a freshly charged set of batteries

can be installed in minutes, so while the vehicle is running the next survey a new set of batteries are charged and previously collected data is evaluated. A fully pressure tolerant battery is the key to quickly and reliably swapping batteries. This is because there are no pressure boundaries to breach, no seals to be serviced or replaced and each battery can be easily removed and hand carried across a moving deck to a charge station. Furthermore, the use of ‘drop and play’ blind mate-able connectors reduces the chance of damage to pigtails and wiring that is seen over the normal course of operations.

In order to achieve the maximum energy density from a battery section using a pressure vessel, the pressure vessel must be quite large to accommodate all of the batteries used on the vehicle; this means that the battery is heavy and difficult to handle. In the case of the pressure tolerant battery, the packaging efficiency is higher and so the weight penalty of splitting the energy section into smaller chunks – individual batteries – is lower. Consequently, as the batteries can now be smaller and lighter, they can be handled, packaged and shipped more easily than a monolithic section. Logistics are simplified across the board.

From a safety perspective, hazards will always exist when storing energy. However, the failure of a pressure tolerant battery is likely to produce a more benign result versus the failure of a battery in a pressure vessel, because the adjacent seawater surrounding the individual batteries provides a very efficient heat sink, thereby reducing the risk of propagation. Furthermore, if a failure in a battery should occur on deck, risk from explosion or bursting of a pressure vessel from internal pressure built up in the vessel is negated.

The Bluefin Approach

Bluefin has employed two different approaches to building pressure tolerant batteries, both of which use a common technology. One approach is a fully encapsulated battery of which the 3.5 kilowatt-hour form-factor received the US Navy 9310 safety testing and approval for the use on the Battlespace Preparation AUV (BPAUV). The other is a ‘hybrid’ battery which will be the focus of this article.

The basic building block of any battery is the cell. Leveraging the commercially available, machine made li-poly cells used in consumer electronics, Bluefin uses a robustly manufactured pouch cell. After being tested, these cells are molded into ‘bricks.’ The number and connection of the bricks dictate both the battery voltage and capacity depending on the electrical series or parallel arrangement. Once assembled, the bricks are tested. A group of bricks are then placed in a housing and restrained, the box is filled with oil and the entire volume is pressure compensated with a simple built-in bladder. Because the exterior of the battery will be directly immersed in the ocean, materials are chosen for corrosion resistance, with a plastic main body and an anodized aluminum plate for a lid. This plate is both a heat sink and mount for the ‘drop-and-play’ blind mate-able connectors and battery electronics control board.

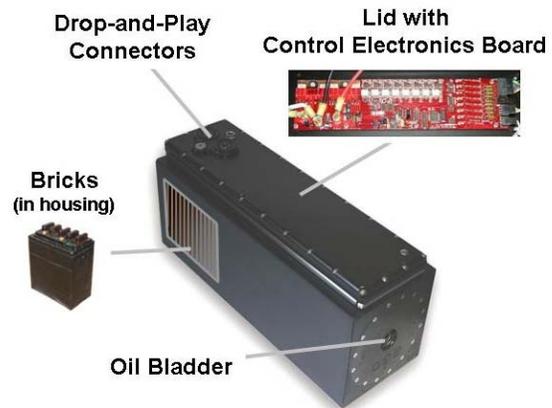


Figure 3. The 1.5 kWh battery is a compact, efficient design for deep-sea use.

Lithium-based rechargeable cells provide excellent energy density, long lifetime and high cycle life when used correctly, but can be permanently damaged when over discharged and present a fire risk when overcharged or overheated. The embedded electronics system in Bluefin batteries controls and monitors the pack cell voltages, temperature and current and prevents the user from unintentionally damaging the pack. “Cell balancing” is the method used to maintain the battery at the highest possible capacity and addresses the tendency of cells connected in series to not perfectly match one

another in voltage over time. All of these parameters and controls are transmitted via a multi-drop serial interface so that multiple batteries can simultaneously be used in parallel.

Beyond AUVs: Other Applications

Many of the design advantages of Bluefin's hybrid battery are applicable to non-AUV platforms. Equipment such as some ROVs and Marine instrumentation, require reliable, easy-to-operate power systems. Current applications use the standard Bluefin 1.5 kilowatt-hour hybrid battery or custom versions with minor internal modifications to change output voltage. For instance, WET Labs, a marine instrumentation manufacturer in Seattle, Washington, incorporates the 1.5 kilowatt-hour pack into their Autonomous Moored Profiler, which can be deployed for over three months at a time.

Using common core elements of the hybrid battery design, Bluefin has also developed a large scale lithium battery platform to address applications requiring proven technology at a scale of hundreds of kilowatt hours of energy and a higher bus voltage. The battery pack's flexible architecture can be scaled up or down to meet requirements of just about any application.

Conclusion

For over a decade, Bluefin Robotics has developed lithium polymer battery technology for underwater operation through innovative and robust integration of COTS products, and has refined the product through extensive testing and field operation. Whether providing power as a simple pluggable energy pack or integrated as building blocks of a larger system, the technology has matured to a point where AUVs are running survey missions

continuously while new, non-AUV applications are emerging. Regardless of what the packs power, they provide a reliable, ease-to-use high-density energy solution for the marine market.

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Bluefin Robotics manufactures and develops Autonomous Underwater Vehicles (AUVs) and subsystems. Founded in 1997, the Company has grown to become a world leader in AUV products designed for military, commercial, oceanographic, and other applications. Bluefin Robotics is a wholly-owned subsidiary of the Battelle Memorial Institute. Contact Bluefin Robotics Corporation at info@bluefinrobotics.com or visit www.bluefinrobotics.com.