Development of a Long-Range Underwater Vehicle

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LONG-TERM GOALS

Our overall goal is to develop ways to increase the capabilities of Unmanned Underwater Gliders (UUGs). Specifically, by examining the basic design choices made in arriving at today's legacy gliders, we seek to develop a design with better performance and simpler maintenance and operation. The design metrics are vehicle range, which balances duration and speed, and sensor payload.

OBJECTIVES

Our initial primary goal was to examine energy sources for improving small-glider performance. The energy source is a critical design choice for any autonomous vehicle. Today's gliders usually use self-contained lithium primary batteries. Based on reaction energy and reactant mass, oxidation of lithium is a particularly high energy density option. Each gram of lithium supplies 3.8 A-hr of current at a voltage that, depending on the lithium oxidation reaction, ranges from 2.6 to 3.5 V. The no-load potentials, E, of the lithium-oxygen and lithium-water couples most likely to occur in seawater are

Oxygen reduction in seawater	$4Li + O_2 + 2H_2O = 4\ LiOH$	$E \sim 3.45$ V
Hydrogen evolution in seawater	$2Li + 2H_2O = 2\ LiOH + H_2$	$E \sim 2.60$ V

PolyPlus Battery Company has developed a lithium-seawater battery (http://polyplus.com/liwater.html) potentially suitable for underwater vehicles that has very high energy density. In laboratory tests PolyPlus achieves energy densities near 4.7 MJ/kg, four times that available from the primary lithium batteries used in gliders today. The seawater cells are also substantially safer. The fact that these batteries operate in the ambient seawater also reduces the payload that must carried within the hull.

Batteries are a significant part of a glider payload so a new glider design is needed to use seawater batteries. Consequently, our second objective was to re-examine the design choices that led to the three ONR-developed legacy gliders with the objective of an improved glider for seawater batteries and for entirely internal power sources. Our tasks were

1. Test PolyPlus lithium-seawater cells to define their capabilities for use in marine vehicles.
2. Design a prototype long-range underwater vehicle to exploit the new power source.
3. Build and report the field performance of the prototype vehicle with lithium-seawater batteries.

APPROACH

We initially collaborated with CEO Steve Visco and Director of Research and Development Eugene Nimon of PolyPlus. They are essential technical resources for planning and interpreting tests of the lithium-seawater batteries. PolyPlus was to provide batteries for testing. Davis and Sherman (who developed the Spray glider) were to design and build test facilities, carry out field tests, and head up new-vehicle design studies.

The approach for battery testing was to characterize battery performance in laboratory tests and then at sea in multi-month missions where they were “passive passengers” on Spray gliders. Laboratory tests provide a well controlled environment for pressure cycling and measuring cell performance under different electrical and hydrodynamic conditions. Field missions expose the cells to realistic conditions and including pressure cycling, typical ocean oxygen concentrations and biological fouling.

The major design goal was to compare primary- and seawater-batteries for slow, long-duration vehicles like gliders by developing rough designs for both. For the PolyPlus seawater batteries the new challenges were to (a) achieve good mass transfer for cell performance without adding excessive vehicle drag, (b) effectively extract power from PolyPlus batteries (whose efficiency declines rapidly under intermittent loads and cannot be connected in series to increase operating voltage), and (c) take advantage of vehicle weight savings made possible by batteries that operate in ambient seawater.

As explained below, initial tests of PolyPlus batteries were successful and characterized performance and some limitations of the PolyPlus batteries, partially fulfilling objective 1 (battery testing) above. Meanwhile, other batteries developed by PolyPlus became very successful and demanded the time of Visco, Nimon and the company’s manufacturing facilities. Delivery of cells for continued testing and design studies dwindled then ceased. This year we were forced to abandon work with PolyPlus batteries and adjust our objectives. Project scope and budget were reduced by focusing on our second objective to address the design of a longer-range glider that was still easy to use in the field and could be used from ships and remote land sites.

Our new objective involves quantifying the various design trade-offs for gliders using conventional self-contained batteries. Our focus is long duration, slow-speed, low cost sampling missions similar to what gliders do today. Factors being considered are the impacts on range of (a) operating depth and speed, (b) an ability to occasionally use higher “burst” speeds, (c) the size of the glider, and (d) hydrodynamic factors like hull shape as well as wing area, aspect ratio and angle of incidence. At the same time, we seek to reduce costs by simplifying maintenance and operations at sea while limiting vehicle size and weight to keep down shipping costs and the difficulty of at-sea handling.

WORK COMPLETED

Specific issues in the battery testing phase were (a) confirming that the “solid electrolyte” lithium anodes are not harmed by pressure cycling, (b) documenting how mass transfer between the cell electrodes and seawater affects cell voltage vs. current, (c) finding how to keep cell voltage from being degraded by precipitates forming on the cathode, and (d) understanding how biofouling around the cells affects mass transfer and how to minimize it.

The seawater batteries were extensively pressure tested in the laboratory. Microscopic examination of the electrodes and electrical-performance tests were used to detect any damage to the cell’s fragile solid electrolyte windows. A laboratory rotating arm was used to measure the voltage of individual cells at different through-water speeds under various electrical loads and electrode current densities.

Cell performance under ocean conditions was measured by mounting a pair of cells as a passive test package in the stern of a Spray glider. This enabled inexpensive multi-month exposure of the cells under realistic operational conditions. During a cruise, test batteries were connected to different electrical loads as their host Spray glider cycled vertically recording cell voltage, water temperature, salinity and oxygen concentration. Biofouling was characterized by post-cruise physical examination.

Two Spray missions with PolyPlus cells were carried out off the California coast. The first exposed aspects of cell behavior not accounted for in the test design. A second test of two cells lasted 69 days covering 729 dives, most to 400 m. Ocean temperature, salinity and oxygen profiles were measured with an SBE41CP CTD and an SBE43F oxygen sensor. This test provided high-quality performance data under a range of operating and environmental conditions including significant biofouling.

As interest turned from energy sources to other elements of glider design, we began addressing the fluid dynamical issues of lift and drag that affect size, shape and vehicle configuration. Methods of compututational fluid dynamic simulation were tested against pertinent laboratory measurements reported in the literature. Realizing that empirical verification of CFD predictions would be essential, preparations were made for dynamical tests of glider models. A local wave tank was outfitted with a smoothly- moving, variable-speed “tow cart” that is now being fitted with sensitive electronic force and torque balance to measure lift, drag and turning torque on one-quarter to half-scale models.

Reducing maintenance and field operation costs, and their burdens on a limited specialized labor pool, is a primary design goal. Discussions held among the Scripps glider group (scientists, technicinans and engineers) and operators at other institutions were used to develop a consensus on the characteristics that would make glider construction and operations more efficient.

RESULTS

Extensive pressure cycling in the laboratory and field to 400 decibars showed no performance degradation or visible damage of the PolyPlus seawater cells. The fragile cell windows of the anode were not fractured by pressure cycling, even as the enclosed lithium was depleted, potentially creating stress concentrations in the windows. This electrode, when mounted in a cell, is robust in normal handling and field use. The cell cathodes, thin layers of a porous mat, are less hardy, and are easily distorted in handling or field use. A more robust cathode will be needed for long-term field use.

As reference for field studies, battery output was measured from cells moving at speeds of 5 to 12 cm/s through quiescent seawater saturated with oxygen at our lab. At electrode current densities less than 0.3 ma/cm^2, cell voltage varied only O(3%) over this speed range. Evidently, with well-oxygenated water, normal glider speeds, and current densities < 0.3 ma/cm^2 the direct mass-transfer limitations are minimal. The cathode reaction produces hydroxide ions and the high pH seawater precipitates salts like $CaCO_3$ into the cathode mat, reducing cell output. In laboratory tests, no precipitates were seen below 0.3 ma/cm^2, but the tests were only hours long. Unexpectedly, cells exhibited an O(30 sec) time constant responding to load changes. This is an order of magnitude greater than the cell's L/U time, and presumably reflects slow flushing of the porous cathode mat.

For field trials, two seawater cells were mounted below Spray's tail section. At the field site, O_2 was saturated near the surface, 50% saturated at 50 m, and 10% at 400 m. Performance below 50 m, where O_2 was depleted, differed from laboratory behavior in two respects: cell output was reduced more than the thermodynamic effect of the ambient O_2 concentration on open-circuit cell voltage; and cell response to changing loads slowed, sometimes reaching O(5) minutes. Both effects were strongest with heavy loads, low $[O_2]$, and on ascent when flushing of the cells below the hull was reduced. Clearly, mass-transfer effects not significant in lab tests became dominant as $[O_2]$ dropped.

Field performance is summarized in Figure 1 where cell voltage is plotted against the log of ambient dissolved $[O_2]$; colors indicate loads of 1, 3, 6 and 40 kΩ. Three performance regimes are apparent: at high $[O_2]$, voltage declines gradually with $[O_2]$ but significantly with load; as $[O_2]$ decreases further there is a transition to a steeper V vs O_2; at high current density and low $[O_2]$ the V vs. O_2 slope is very steep. A cluster of low-oxygen points with 1 kΩ load shows a steady cell voltage of 2.3 V; the cathode reaction had switched from oxygen consumption to hydrogen evolution.

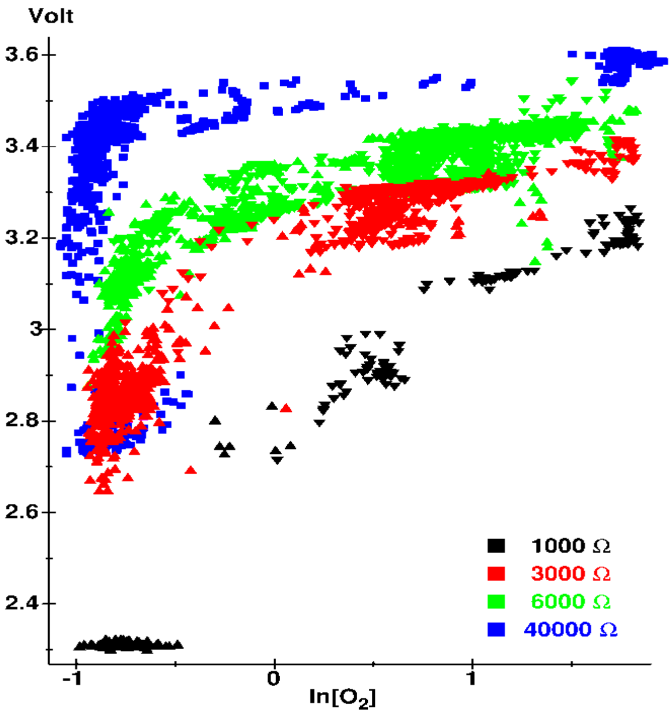

Figure 1. Cell voltage vs ln $[O_2]$ (in ml/l) under various electrical loads in a field trial.

Post cruise inspection showed substantial biofouling around the electrodes and less on them. Immature barnacles, some whose “foot” approached cell dimensions, were common. Inorganic deposits were found in the porous cathode mat and between the electrodes, occasionally connecting the anode and a cathode. Friability and makeup showed these are precipitates caused by high-pH at the cathode. Even at current densities of 0.3 ma cm^{-2}, cell flushing did not prevent precipitation. Although fouling and precipitates were evident, degradation of cell performance was limited.

Lab and field results indicate that the lithium-seawater battery is suitable for long duration vehicles like gliders. With electrode current densities below 0.3 ma cm^{-2} and $[O_2]$ typical of the upper ocean, voltages remain moderately high. Durations of O(100) days are feasible at this current density but battery volume is significant. Maintaining the power density depends on good mass transfer bringing O_2 to the cathode and removing high-pH products. Inevitable bio-fouling impedes this mass transfer.

As $[O_2]$ declines with depth, cell voltage and total energy drop until the cathode reaction shifts to H_2 evolution. Fig. 1 shows this reaction shift; apparently good current density can be maintained in this regime, improving power density but total energy is 1/3 by 2.3V operation. Shallow operation with O_2 consumption maximizes cell energy; deep operation evolving H_2 support high power without oxygen. Ideally these reactions could be used alternately but it is suspected hat cathodes capable of doing this for long times are unavailable. Tests of available cells using both reactions alternately were discontinued by the unavailability of cells to test.

The critical vehicle-design issue is to achieve good cell flushing, to provide O_2 and reduce high-pH precipitation, with low battery drag. Streamlining with good flushing is an oxymoron; the drag coefficient will be high. For example, O(150) cells of dimension 5 x 5 x 1 cm^3 can double the energy for legacy gliders but it will be difficult to make a O(4000) cm^3 battery well flushed without doubling the glider’s drag, and thus eliminating the advantage of doubling battery energy.

Fig. 2 shows the two general strategies for mounting cells: (a) edge-on flow (left) with face-to-face packing or (b) edge-to-edge mounting to form flat surfaces parallel to the flow (right). In the latter, flushing comes through the porous cathode so that cell performance at low current density and high $[O_2]$ was reduced O(15%). Exploring cell flushing would require additional cells.

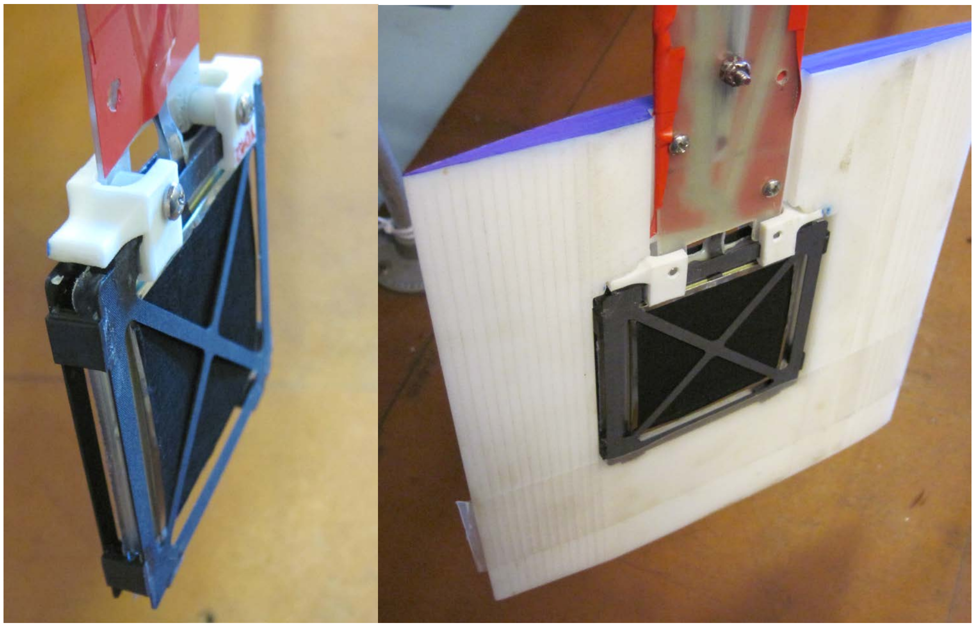

Figure 2. A bare PolyPlus cell (left) and a cell imbedded in a wing section (right) used to compare mass transfer through the cell edges and through the permeable cathodes exposed in both tests.

For vehicle design, our first issues are (a) how to expand glider size, specifically the relative drag costs of increasing diameter and length, and (b) the drag costs of flying with an angle of attack on the hull as needed for wings with no angle of incidence. The former depends on "skin drag" and will be addressed by laboratory tests, but CFD results suggest that the drag penalty for cross-flow may not be serious. For 5^o angle of attack, the drag on legacy glider hulls is O(10%) greater than for flow parallel to the hull axis.

From our efforts to develop a consensus on characteristics needed to make operation efficient, the following picture emerges. Total mass should be kept under 100 kg to avoid the necessity for special purpose handling gear in the laboratory or during launch and recovery so that small boat operations would remain feasible and costs held down. Fouling must be minimized to extend duration and make longer ranges feasible at low speed where flight is efficient. An ability to operate to 1 km depth facilitates this and, when confronted by adverse currents, allows gliders to dive deeper to reduce the average velocity of these currents. Avoiding transient/localized adverse currents is essential to maximizing range and would be facilitated by an ability to operate at a high "burst" speed for short periods. The ability to swap sensors in the field is highly desirable, particularly for operation in remote sites.

IMPACT/APPLICATIONS

The capabilities of sensor systems on autonomous ocean-observing vehicles and the sustained speed and range of those vehicles are all directly proportional to the energy density of the vehicle's power source. Because lithium-seawater batteries potentially significantly increase this energy density, studies of the performance they can achieve in the ocean, and of ways to maximize it, are pertinent to the evolution of long-term scientific and Navy ocean observing systems.