Under High Pressure: Spherical Glass Flotation and Instrument Housings in Deep Ocean Research

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ABSTRACT

All stationary and autonomous instrumentation for observational activities in ocean research have two things in common, they need pressure-resistant housings and buoyancy to bring instruments safely back to the surface. The use of glass spheres is attractive in many ways. Glass qualities such as the immense strength–weight ratio, corrosion resistance, and low cost make glass spheres ideal for both flotation and instrument housings. On the other hand, glass is brittle and hence subject to damage from impact. The production of glass spheres therefore requires high-quality raw material, advanced manufacturing technology and expertise in processing. VITROVEX® spheres made of DURAN® borosilicate glass 3.3 are the only commercially available 17-inch glass spheres with operational ratings to full ocean trench depth. They provide a low-cost option for specialized flotation and instrument housings.
Keywords: Buoyancy, Flotation, Instrument housings, Pressure, Spheres, Trench, VITROVEX®

Introduction

When Jacques Piccard and Don Walsh reached the Marianas Trench in 1960 and reported shrimp and flounder-like fish, it was proven that there is life even in the very deepest parts of the ocean. What started as a simple search for life has become over the years a search for answers to basic questions such as the number of species, their distribution ranges, and the composition of the fauna. The discovery of swarming snailfish at 7,700 m by University of Aberdeen's (UK) Oceanlab so far presents the culmination of these researches. Although the oceans have been investigated for a long time, the deeper depths present a challenge to exploration due to the extreme environmental conditions that exist there. It is totally dark, constantly cold, and the pressure is immense. At a depth of 1,000 m, the weight on every square centimeter is 100 kg but increases to 1,100 kg at 11,000 m.

Still, researchers today have a suite of stationary and autonomous instrumentation available for hadal observation. All these instruments have two fundamental requirements in common: (1) they need to have pressure-resistant housings to accommodate sensitive electronics, and (2) they need either positive buoyancy to bring the instrument or sampler back to the surface for recovery or to establish neutral buoyancy for manned or remotely operated vehicles to dock and lift the package (Figure 1).

FIGURE 1

Benthic lander with VITROVEX® flotation spheres.

Advantages and Disadvantages of Glass Spheres

Because of the compressive force of water pressure, the pressure case design and the material selection for buoyancy elements or pressure housings are vital. Like the crew compartment of the *Trieste* 50 years ago, the ideal shape is a sphere. Because of its geometry with no corners, a sphere distributes the external forces of the water evenly over its structure, making it the strongest possible shape. The material chosen may be steel or other metals, molded plastic, ceramics, or glass.

The use of glass is attractive in many ways. Glass has an immense strength-to-weight ratio and it is inherently cheap. It is corrosion resistant and nonpolluting. Additionally, glass spheres are transparent, nonmagnetic, and electrically

nonconductive. Command and control of instruments, including uploading mission profiles or downloading data, may be done through the glass with hall effect or reed switches, infrared, or blue tooth. Radio and flashing light recovery beacons have been shown to work effectively housed internally. GPS, ARGOS, or Iridium transceivers as well as VHF radio links penetrate the glass without problem. Status lights and LCD displays are visible to deck crews before deployment. The high-quality glass may even have been polished to create a viewport section for high-resolution digital cameras or sensors utilizing light. The use of external pressure-compensated lithium polymer batteries, as described elsewhere in this issue, means the spheres need never be opened at sea, and the use of small vessels of opportunity becomes more attractive. Indeed, a research team from Scripps Institution of Oceanography/UCSD deployed two free vehicles, described below, using 17-inch VITROVEX® spheres to 8,400 m (27,500 feet) from a 53-feet boat in November 2006.

As appealing as it is, glass has, however, some drawbacks in that it is difficult to machine accurately, it is brittle, and hence is subject to damage from impact and spalling. The glass may spall when cycled. The bearing stresses under standard connectors can cause spalling at the corner of the spotface and the diamond drilled hole. A large 4-mm-thick "flat washer" with a larger diameter o-ring can be used to spread out the load over a larger area. The connector o-ring rests on the top of the "flat washer," which has a smooth finished o-ring surface. Some underwater connector manufacturers, including SubConn and Teledyne Impulse, have created connector bodies that are specially adapted to glass housings.

Handling spheres at sea can be nerve wracking when opening and closing the fragile glass in bumpy seas. The hemispheres take some practice to feel comfortable moving and lifting them. A rubber bumper over the exposed glass faces brings some measure of protection, but a system design that precludes the need to open the sphere at sea, as described above, is preferred. The glass sphere housing requires some skill to seal. The sealing surfaces must be very well cleaned and free of any grease, oil, lint, or other foreign material. The low-pressure seal around the equator is made with butyl rubber and wide black tape. A vacuum port is quite useful. A pocket altimeter mounted to the interior is easily viewed providing confidence the sphere is sealed and not slowly leaking. The sphere is protected in a thick wall LDPE hardhat, which also simplifies mounting.

History of VITROVEX® Glass Flotation and Instrument Housings

All pressure housings depend on geometry, outside diameter, wall thickness, and material to reach their desired design depth. VITROVEX® glass spheres of 10- or 13-inch diameter can withstand pressure at 9,000 or 7,000 m, respectively. Larger 17-inch spheres are made to reach 6,700 m, and now to 9,000 m and 11,000 m. The flotation spheres and instrument housings are composed of two mated glass hemispheres that are evacuated and locked into position by a sealant and protective tape. Once the spheres are sealed, the two hemispheres are kept together by the atmospheric pressure on land and the pressure of the water column when deployed. VITROVEX® spheres are made of borosilicate glass 3.3 with standardized physical, chemical, electrical, and optical properties, also well known as DURAN®. This kind of glass was first developed by the German glassmaker Otto Schott in the late 19th century. Borosilicate glass is created by adding boron to the traditional glassmaker's frit of silicate sand, soda, and ground lime. Borosilicate glass has a very high physical strength and very low thermal expansion coefficient, about one third that of ordinary glass. This reduces material stresses caused by pressure and temperature gradients, thus making it more resistant to breaking. Borosilicate glass is commonly used in ovenware, where it is known by its commercial name of "Pyrex®" (Figure 2).

FIGURE 2

Production of VITROVEX® hemispheres requires high-quality raw material, precision molds, advanced manufacturing technology, and processing expertise to meet the challenge of ocean trenches.

As a result, VITROVEX® flotation spheres and instrument housings show very little deviation in shape even under the high pressure found in ocean trenches. Since two hemispheres have to be put together to form one sphere, matching the geometries is critical. In addition to precision molding of the right type of glass, skilled craftsmanship directs the pressing of each hemisphere to exactly the same dimensions, outer

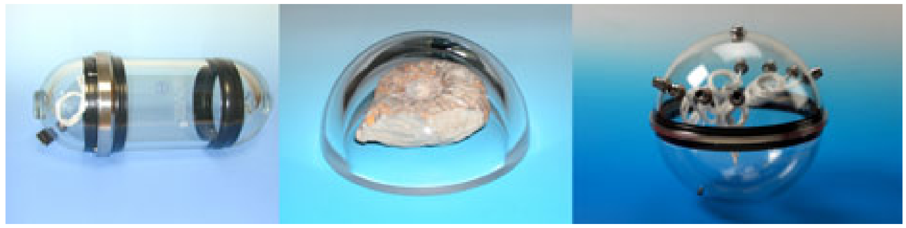
diameter, inner diameter and wall thickness, as all the others of that size. The mating surfaces require a triple grinding process: milling with diamond tools, manual smoothing, and manual polishing to ensure the parting plane sealing faces are honed to a precise flatness and finish. The congruous surfaces are so closely matched that when two hemispheres are set together, with no butyl and tape at the parting line, and a hard vacuum is pulled, it takes a day for the vacuum to bleed down molecule by molecule. Place the butyl rubber and tape on the seam, and it might take forever. As a result of precision forming, VITROVEX® hemispheres of the same outside diameter and wall thickness are completely interchangeable and can be replaced individually. During assembly, they are aligned along the outer circumference only; there is no need to rotate the hemispheres to find matching alignment markers. This is a very valuable feature when it comes to instrument housings.

Spheres can be made with a variety of drill holes to accommodate connectors, feedthroughs, and a vacuum port for connection to electronics and batteries inside, or releases, sensors or other packages on the outside. With the ability to exchange a single hemisphere, one can easily be exchanged by another with a different arrangement of drill holes.

Different sizes of glass spheres and even cylinders provide high-pressure flotation and instrument housings options to meet design requirements up to full ocean depth (Figure 3).

FIGURE 3

Examples of VITROVEX® glass products.



Further Development of VITROVEX® Glass Spheres to Full Ocean Depth

Nautilus Marine Service successfully developed 13- and 17-inch spheres with 7,000 and 6,700 m pressure rating in the early 1990s. So it was in the nature of things to face the challenge of going deeper.

This development was driven by various scientific institutions such as Scripps Institution of Oceanography/UCSD (Kevin Hardy, 2000, in collaboration with Emory Kristof, National Geographic Society), and later, the Oceanlab from the University of Aberdeen.

"Our initial plan," said Hardy, "was to use the 7 km VITROVEX® spheres simply as self-buoyant housings, with exterior lights and a camera. The plan changed instantly when the delivered spheres appeared to be high enough quality to polish a viewport in the glass and place our camera inside. Our final design placed the camera, flash, control electronics, release system, batteries, and recovery beacons inside a single sphere, making deployment and recovery a simple matter from virtually any size vessel. Hardy and Nautilus' Gerald Abich discussed means to modify the VITROVEX® tooling to thicken the walls for 11 km trench depths. Seeing the first of the new thicker wall glass spheres, bathyscaph *Trieste* Pilot, Don Walsh, who personally looked out a porthole at the floor of the Mariana Trench, exclaimed, "Deep and Cheap. I like it!"

The first camera pod, *DOV Mary Carol*, was used successfully in the Aleutian Trench, Puerto Rico Trench, and even modified to function as a towed camera in the Sea of Cortez to confirm the presence of bacterial mats (Figures 4 and 5) (Hardy et al., 2002).

FIGURE 4

Deep Ocean vehicle *DOV Mary Carol*, built from a single VITROVEX® 17-inch sphere, is recovered on the stern of Scripps Institution of Oceanography/UCSD's R/V *Sproul* by Scripps engineer Kevin Hardy in August 2003. (Photo by Emory Kristof.)

To create these thicker wall variants of glass hemispheres with the same desired precision, all production parameters had to be redefined. The major challenge for the project team

FIGURE 5

This image is taken through a viewport polished into the 7-km sphere of *DOV Mary Carol* at a depth of 1.4 km off San Diego, CA, June 2003. Similar quality images have been acquired with thicker 12 km spheres in ocean trenches.

was to adjust the relation of glass temperature, molding, and cooling precisely in order to keep the massive amount of DURAN® glass in the desired geometry. Due to very close cooperation with its long-time partner DURAN Group GmbH, a specialist in borosilicate glass 3.3, Nautilus Marine Service successfully accomplished this project.

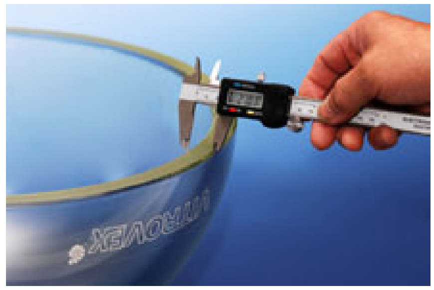
As a consequence, a new type of VITROVEX® self-buoyant sphere with a depth rating of 12,000 m and a wall thickness of 21 mm was made for those who want to explore even the deepest parts of the oceans. A more lighter weight version with pressure rating of 9,000 m also became available.

Use of Deep Water VITROVEX® Spheres in Oceanography

Over the recent years, deep water VITROVEX® spheres have become component parts of many deep ocean explorations. The 12,000-m sphere with a wall thickness of 21 mm (Figure 6) was part of the ascent system for Oceanlab's Hadal-lander. A more

FIGURE 6

VITROVEX® hemisphere for full ocean depth with all wall thickness of 21 mm.



detailed description about this application is given by Alan J. Jamieson in a separate article in this journal.

Elsewhere, a team of deep ocean biologists from Scripps Institution of Oceanography/UCSD directed by Dr. Douglas Bartlett tested a 17-inch VITROVEX® 9,000 m rated sphere with multiple feedthroughs in Deep-Sea Power & Light's 20-inch pressure chamber in June 2009. The sphere was being qualified for operation in the Puerto Rico Trench, where depths can reach 8,400 m. The sphere was successfully taken to 12,750 psi, equivalent to 8,750 m. The sphere is part of a two-sphere free vehicle that gathers 60-L water samples from the benthic boundary layer 2 m above the trench floor layer along the axis of an ocean trench. A sediment sampler deployed from the lander collects surface sediments for other microbial studies. "The test was particularly useful in confirming the integrity of the sphere which experienced some minor spalling during its deployment to 8,400 m last year," said the researchers (DeepSea Power & Light, 2009) (Figure 7).

The French Company SERCEL uses the VITROVEX® 9,000 m spheres for their MicrOBS_Plus (Figure 8) Ocean Bottom Seismometer (OBS). An OBS is designed to record seismic waves in the seafloor generated by

FIGURE 7

Double VITROVEX® spheres provide lift for a free vehicle ocean trench water sampler built by Scripps Institution of Oceanography/UCSD in 2006. (Photo by Kevin Hardy, Scripps Institution of Oceanography/UCSD).

FIGURE 8

MicrOBS_Plus OBS from Sercel.

earthquakes, or artificial sources, by means of hydrophones and geophones. An OBS is deployed from a ship and free falls through the water column,

landing on the seafloor. Upon completion of the mission, an acoustic signal is sent to the instrument to release an anchor weight. The OBS then floats to the surface and recorded data can be uploaded. In such applications, the VITROVEX® sphere provides buoyancy as well as pressure protection at once.

Conclusion

Glass spheres are indispensable in underwater research for both flotation and instrument housings. They may become even more important in the future. Ongoing analysis at DOER Marine in the United States, with the aid of VITROVEX® glass, provide a glimpse into the future where human occupants may utilize a fully spherical, glass-hulled manned submersible with a panoramic view. That is probably something Jacques Piccard and Don Walsh would have liked to have seen 50 years ago.

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PAPER

Flotation in Ocean Trenches Using Hollow Ceramic Spheres

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ABSTRACT

Spherical flotation units of 99.9% Al_2O_3 ceramic have been successfully produced by DeepSea Power & Light for application to ocean trench systems, such as the Woods Hole Oceanographic Institution (WHOI) hybrid remotely operated vehicle (HROV) *Nereus* and other high-performance systems requiring maximum buoyancy with minimum air weight. WHOI successfully operated their HROV in the Mariana Trench Challenger Deep in Summer 2009, scooting across the trench floor for a total of 11 h at 36,000 feet (11,000 m). More than 1,750 3.6-inch (91.45 mm), OD seamless hollow ceramic spheres, each generating 0.6 lb (272 g) of lift, provided *Nereus* its buoyancy. The spheres, with a 0.34 weight/displacement ratio, withstood proof testing to 30,000 psi (207 MPa), 1,000 h of sustained pressurization to 25,000 psi and 10,000 pressure cycles to 20,000 psi (138 MPa). In addition, each of the WHOI spheres withstood 15 h at 18 ksi static pressure hold. When encased in a 0.2-inch thick buoyant elastomeric boot, they withstood impact on a concrete floor from a 6-foot elevation. An extensive quality assurance (QA) procedure is applied to 100% of manufactured spheres, with strict adherence to tight dimensional and thickness specifications as well as pressure test acoustic emission criteria (Figure 1).

DeepSea Power & Light has additionally demonstrated the process for casting larger alumina ceramic spheres with an 8.6-inch (218.4 mm) outside diameter for the whole range of ocean depths from 10,000 feet (3000 m) to 36,000 feet (11,000 m). The larger spheres were successfully used offshore by Scripps Institution of Oceanography/UCSD in summer 2005 in an experimental free vehicle sediment sampler that impacted the seafloor at 2 m/s at a water depth of 2,200 m, dropped a weight, then rebounded to the surface with its cargo of sediment.

Background

To lift a payload while submerged, all underwater vehicles require buoyancy provided either by the pressure hull, flotation units attached to the hull, or both. Flotation for deep submergence vehicles has traditionally been made from syntactic foam, glass, or ceramic spheres or, in the case of the bathyscaph *Trieste*, lighter-than-water aviation gasoline. Syntactic foam, a composite of plastic and glass microspheres, produces buoyancy from the displacement of the myriad glass microspheres embedded in a plastic matrix. The buoyancy of the foam is a function of the wall thickness of the glass spheres and of their packing density in the plastic matrix. By screening the glass spheres for size and wall thickness, manufacturers can tailor the pressure resistance of the syntactic foam. Utilizing this process, industry has developed syntactic foams for the whole range of ocean depths. The factor limiting their buoyancy is ultimately the packing density of microspheres in the plastic matrix since the plastic binder does not provide any buoyancy.

Glass or ceramic macrospheres may be held in place in a framework made of lighter than water plastic. The sizes of spheres and their pressure resistance can be tailored to the requirement of the vehicle. The crucial items in maximizing their pressure resistance are material with high compressive strength, absence of joints, and minimum deviation from perfect sphericity and uniform thickness.

The presence of joints introduces local tensile stresses causing glass or ceramic spheres to fail under long-term, and/or cyclic pressurizations at a lower pressure than it would in the absence of joints (Stachiw et al., 1993). The lack of a fabrication processes that would deliver seamless spheres with uniform sphericity and shell thickness was a major stumbling block to achieving maximum buoyancy of ceramic spheres of utmost reliability.

A solution was found in 1964 at COORS PORCELAIN with the development of a casting procedure to allow production of seamless hollow 10 inch spheres with a nominal depth rating of 20,000 feet (Reardon, 1969). However, because of the large variation in structural performance

FIGURE 1

Engineers at WHOI demonstrate the toughness of DSPL's jacketed hollow ceramic spheres they use to provide lift at extreme pressures for their deep diving HROV, *Nereus*. (Photo by Tom Kleindinst, WHOI).

between individual spheres, they were considered too risky for application on manned submersibles. As a result, their share of the market decreased to the point where the fabrication costs became unprofitable and by the late 1960s COORS PORCELAIN closed their production for good.

It required the appearance of ROV's and AUV's for deep ocean exploration to renew the demand for ceramic floats with buoyancy at depth superior to any syntactic foam available on the market. Woods Hole Oceanographic Institution (WHOI) used its hybrid remotely operated vehicle (HROV) vehicle development as a context to push the design limits of current ocean engineering. Not satisfied with the buoyancy provided by syntactic foam for 36,000 feet (11 km) service, WHOI looked to find a supplier capable of manufacturing ceramic seamless spheres for 36,000 feet (11 km) service. This paper focuses on the design, fabrication, structural performance, and quality control (QC) of 3.6-inch OD spheres supplied to WHOI by DeepSea Power & Light (DSPL).

Introduction

Before the spheres could be incorporated into the 11-km HROV under construction by WHOI, several issues had to be resolved satisfactorily to preclude implosion in service. Implosion even of a single sphere may initiate sympathetic implosions of other spheres on the vehicle and the resulting loss of buoyancy would sink the vehicle. To preclude implosion in service, sufficient care had to be exercised over the design, fabrication procedure, quality inspection, and performance testing. With proper attention to details, the ceramic spheres should be as reliable in service as are the acrylic plastic spheres serving as the pressure hulls on manned submersibles.

Design

The design criterion selected for the 3.6-inch OD spheres was a safety factor of two based on the 16,500-psi (113.8-MPa) pressure specified by WHOI for its 11 km HROV with 36,000 feet (11,000 m) service depth. The same safety margin had to apply both to the magnitude of stresses as well as elastic stability at critical pressure. To achieve the 100% safety margin, the average shell thickness of the spheres was calculated to be 0.060 inches (1.5 mm) using Equation 1 for prediction of material failure (Roark, 1965) and Equation 2 for prediction of buckling (Roark, 1965; Krenzke and Charles, 1963):

$$\text{EQ 1}: \ p_{cr} = \delta(R_{o3} - R_{i3})\ 1.5 \times (R_{o3})$$

$$\text{EQ 2}: \ p_{cr} = K \times E \times (t_2/R_{o2})$$

Where E = 56,000,000 psi, modulus of elasticity, δ = 550,000 psi, compressive strength of 99.9% Al_2O_3, and K = 0.56 has been derived by Dr. Stachiw from destructive testing of over thirty 10-inch OD ceramic seamless spheres fabricated by COORS PORCELAIN for the Naval Ship Research and Development Center in 1969 (Reardon, 1969).

The calculated critical pressures of 34,844 psi by buckling and 35,209 psi by material failure were high enough to allow +0.01-inch variation in local wall thickness without reduction of calculated critical pressures below 33,000 psi mandated by the SF = 2 requirement.

Validation of Design Criteria

It has been experimentally shown that the implosion pressure under long-term and/or cyclic pressurizations is significantly less than under short-term pressurization because ceramic under tensile strain exhibits time dependent failure. Although the loading on the spheres under hydrostatic pressure is compressive, some tensile strains are always present at microscopic discontinuities in the material causing it to fracture under time dependant static or cyclic load application.

The selected SF = 2 based on short-term destructive testing is more than adequate to provide a safety margin for a single service dive to design pressure. Whether it is adequate to provide a safety margin for long-term and/or

cyclic pressurizations to design pressure, typical of ROV and AUVs, was to be experimentally validated.

The validation of the 100% short-term safety margin focused on generating experimental data on the static and cyclic fatigue of DSPL's 3.6-inch OD 99.9% Al_2O_3 spheres.

A minimum operational requirement of the ROV/AUV is assumed to be 10,000 h of static and 1,000 cyclic pressurizations to service depth of 36,000 feet (11 km). The intention of this testing is to validate whether the static and cyclic fatigue life of the 3.6-inch OD spheres with 0.06-inch wall thickness could meet this criteria.

The classic approach to generation of this data set is to subject several spheres to sustained design pressure loading until they implode. The average length of time to implosion would be considered their static fatigue life. By the same token, their cyclic fatigue life can be formulated by pressure cycling several spheres to design pressure loading until they fail. The number of cycles prior to implosion would be considered their cyclic fatigue life.

Because the classical approach requires the utilization of pressure vessels for thousands of hours, it is not utilized frequently. Instead, the spheres are tested at pressures above design pressure, substituting the pressure differential above design pressure for time. When the durations of sustained loading prior to implosion of pressure above the 16,500 psi (113.8 MPa) design pressure are analyzed, one can extrapolate from it the static fatigue life at 16,500 psi (36,000 feet/11 km in service depth). [8] This was the approach taken by DSPL for prediction of static and cyclic fatigue life for the 3.6-inch OD spheres with 0.06-inch wall thickness.

Discussion of Design Validation Results

The test results generated during the experimental design validation phase fall into three categories: critical pressures under short-term pressurization, sustained pressurization, and cyclic pressurization. Each one of these test categories plays a different role in the validation of chosen sphere design, that is, thickness of shell selected for the 16,500 psi (113.8 MPa) design pressure.

It is an accepted practice in the industry to rely solely on short-term non-destructive proof tests to qualify a flotation unit for a given pressure rating. In the opinion of the authors, this is not sufficient, unless a pressure test program utilizing destructive short-term, sustained pressure and cyclic pressurizations has already validated the design of the sphere. Only after such a design validation program has been successfully completed can non-destructive short-term pressurization serve as QC and QA acceptance tests.

The objective of *short-term destructive tests* in the design validation program is twofold; it serves as a check on the calculated magnitude of critical pressure based on Equations 1 and 2 for prediction of implosion either by material failure, or elastic instability, and as a QC tool on the uniformity of structural performance of mass produced spheres. For the spheres designed on the basis of 100% safety margin, the short-term critical pressure was expected to be 35,200 psi if the implosion was caused by material failure at 550,000 psi compressive stress level and 38,400 psi if the implosion was triggered by elastic instability. Unfortunately, pressure vessels were available only with 30,000 psi capability and thus all the short-term pressurizations were conducted only to 30,000 psi level. However, by extrapolating the static critical pressures of spheres with weight <139 g, the critical pressure of 139 g spheres has been predicted to be >35,000 psi. Since testing to 30,000 psi stresses the material only to 85% of the calculated material short-term strength and 78% of buckling pressure, any failure of a sphere at 30,000 psi would be an indication that the structural performance is inadequate caused either by shortcomings in material quality or shell construction. In either case, it would not be a representative example for long-term or cyclic pressure testing. All spheres meeting the technical specification requirements of weight, minimum shell thickness, and sphericity passed short-term (<2 s) pressurization to 30,000 psi. It can therefore be concluded that their structural performance exceeds 85% of design strength.

The objective of *long-term destructive tests* in the design validation program is to establish by experimental means the static fatigue life of the spheres at 16,500 psi design pressure. This was to be established by extrapolation of sustained pressure test results at 30,000 and 25,000 psi. Pressures higher than the design pressure were chosen to accelerate the implosion of spheres under sustained loading. Some tests were also conducted at other pressures in pressure vessels of opportunity.

The number of tests was not sufficiently large to provide an adequate number of data for statistical analysis. It was, however, large enough to establish confidence in the safe performance of spheres at design depth during a mission of the WHOI 11-km HROV under extended duration. The results indicate that at 16,500 psi (11-km depth) design pressure, the static fatigue life is

in excess of 10,000 h, providing adequate time for more than 400 missions of 24-hour duration (Weston et al., 2005).

The objective of *cyclic pressurization destructive tests* is to establish the cyclic fatigue life of the spheres under design pressure. Since the spheres are of seamless construction there was no opportunity to develop cracks at the equatorial joint, typical of spheres assembled from hemispheres. It is known from other studies conducted on ceramic and glass specimens that the intrinsic cyclic fatigue life of those materials under cyclic compressive loading is large enough to be beyond the engineering design scope of flotation units and housings for oceanographic service.

Only if mechanical joints are present in ceramic pressure vessels for an oceanographic applications does the cyclic fatigue life become the controlling factor of their service life.

The cyclic pressure testing conducted on the seamless spheres has, on the other hand, demonstrated that their cyclic fatigue life at compressive membrane stress of 478,000 psi is >5000 cycles and under compressive stress of 337,000 psi is >15,000 cycles. Needless to say, at design stress of 256,000 psi generated by 36,000 feet design depth, the cyclic fatigue life of spheres with 0.06-inch thick wall will exceed the above values by a factor of at least 2.

The service fatigue life requirement for 11 km HROV is less than 1000 dives to 36,000 feet design depth. This generates 256,000 psi membrane stress in the shell of the sphere. The experimentally demonstrated cyclic fatigue life is in excess of 5000 cycles with 478,000 psi membrane stress. This surpasses by a wide margin the specified service fatigue life requirement for the 11 km HROV. Although the typical duration of the pressure test cycle was less than 4 s and the duration of a service dive is on the order of 10 to 20 h, the effect on the cyclic fatigue life is the same. Published data indicate that it is the cumulative time under load rather than the number of cycles that define the cyclic fatigue life of brittle materials (Shand, 1958). Since the demonstrated 6×10^4 s cumulative duration of 15,000 pressure cycles at 337,500 psi membrane stress is less than the demonstrated static fatigue life of 36×10^4 s at the same pressure on ceramic spheres, the effect of cycling can be disregarded so long as the static fatigue life at design depth exceeds the cumulative time under pressure during pressure cycling.

Fabrication

The seamless spheres were fabricated by roto-molding in spherical molds assembled from well-fitted plaster hemispheres to meet the technical specification developed by Dr. Jerry Stachiw for 3.6-inch OD ceramic spheres with 16,500 psi pressure rating.

QA Program

To minimize departure in structural performance from the test data generated during validation of design, a strict QA program was applied to the production of 3.6-inch OD ceramic spheres for service on the WHOI vehicle. Main features of the QA program include

a. checking of weight for conformance to technical specification;
b. checking for minimum thickness for conformance to specification;
c. checking of diameter and diametrical run-out for conformance to technical specifications;
d. visual inspection for surface flaws and other anomalies; and
e. weeding out unacceptable structural deviations by subjecting each sphere to two pressure cycles, first to 30,000 psi, followed by a second one to 20,000 psi while monitoring for acoustic emissions.

The acoustical testing was accomplished by the use of a custom-built pressure chamber acoustically instrumented to detect sounds emanating from within.

Discussion of QA Program Results

A group of spheres was made to the Technical Specifications (Table 1). A sample batch of 20 spheres was then selected and subjected to this QA program. Of the 20 samples, 2 were rejected because of surface flaws, providing an overall 90% pass rate in the visual screening. With the potential for sympathetic implosion, however, any failures are unacceptable and DSPL acoustically tests 100% of its spheres. This proof test subjects each sphere to 30,000 psi while monitoring acoustic emissions. On average, an additional 25% of ceramic spheres do not pass acoustic emission testing.

Findings

DSPL's 3.6-inch alumina ceramic spheres with a 0.06-inch wall meet the design and service requirements of flotation for 36,000 feet (11 km) service; they do not implode under short-term proof pressure to 36,000 psi (207 MPa) and 10,000 dives of 10,000 h cumulative duration to 35,000 feet (11 km) design depth.

TABLE 1

Technical specifications.

a. Slurry composition: 99.9% Al_2O_3
b. Weight: 140 ± 1 g
c. Minimum thickness: 0.06 ± 0.01 inches
d. Outside diameter: 3.60 ± 0.05 inches
e. Diameter variation on each sphere: ±0.03 inch max

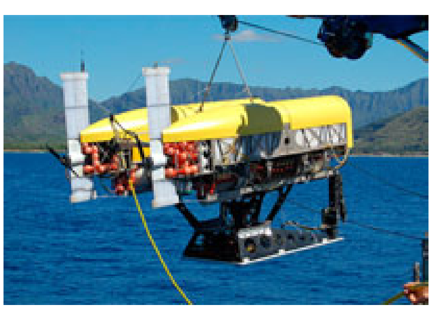
Typical Characteristics of Roto-molded 3.6 in Ceramic Spheres for 11-km Service

	Maximum	Minimum	Average
Weight (g)	140.761	139.128	139.901
Diameter (in)	3.629	3.565	3.597
Thickness (in)	0.065	0.052	0.058

The QA program developed for the production of these spheres assures that the spheres delivered to the customer for mounting on the ocean trench vehicles will perform in the same manner as the spheres tested in the design validation program. This is accomplished by checking each sphere for conformance to the Technical Specification (i.e., weight, diameter, thickness of shell) and structural performance requirements (i.e., proof testing twice to 30,000 psi while monitoring acoustic emissions) (Figure 2).

FIGURE 2

After four years of design and construction, *Nereus* took its first plunge in deeper waters during a test cruise in December 2007 off the Waianae coast of Oahu, Hawaii. Because *Nereus* was a little tail heavy, additional spheres were added in red mesh bags for trim. The one-of-a-kind vehicle can operate either as an autonomous, free-swimming robot for wide-area surveys, or as a tethered vehicle for close-up investigation and sampling of seafloor rocks and organisms. (Photo by Robert Elder, WHOI).



Conclusion

DSPL has succeeded in developing an economical mass production process for roto-molding alumina ceramic spheres whose dimensions and structural performance are repeatable, making them interchangeable in application. At the present time the production process is being applied only to 3.6-inch OD spheres with 0.06-inch wall thickness and their performance experimentally verified for 36,000 feet (11 km) service. Spheres with 3.6-inch OD but lesser wall thickness are also being produced by the same manufacturing process and equipment for structural evaluation.

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PAPER

Modular Design of Li-Ion and Li-Polymer Batteries for Undersea Environments

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ABSTRACT

Li-Ion chemistry is ideal for undersea environments. The cells are sealed and do not outgas, and the polymer versions can withstand pressures greater than 10,000 psi. This combination results in a battery that is easier and safer to use and one that does not require heavy, expensive pressure vessels.

Recent advances in electronic control of the Li-Ion battery and new modular design concepts for construction of complex battery systems have resulted in battery systems that are more robust, more flexible, longer lived, easier to charge and maintain, and safer than their lower density counterparts. These new Li-Ion battery systems can be designed to deliver this energy at high voltages and high currents. Electronic charge control within the battery system allows charging by direct connection to power supplies or constant power sources such as fuel cells and solar panels.

The modular design concept for Li-Ion and Li-Polymer battery systems are presented with an emphasis on construction for undersea applications. Key to the modular battery system design concept is the ability to electronically balance all the cells within the battery system automatically without operator intervention. Two different methods are described, which show how electronic balancing of all the cells within the battery system is accomplished. Examples of production battery systems already in service are shown, and systems under development are provided.
Keywords: Modular Lithium-Ion Undersea Batteries

The battery industry is on the verge of a significant growth cycle in large format lithium-ion (Li-Ion) battery systems due to expected demand for electric land vehicles. Important to this growth is what was once thought of as a detriment of the Li-Ion chemistry—that it requires monitoring and control electronics for safety and for reliability. Engineers are turning this detriment into an advantage by using intelligent electronics to make battery systems that have capabilities that would not be practical, or even possible, without these electronic tools. While the land version of these battery systems is not necessarily suited for undersea environments, the same battery chemistry and electronics can be adapted for hadal zone regions deeper than 6 km. This article will show how a new concept of modularly designed Li-Ion and Li-Polymer batteries can be incorporated into marine vehicles that are not in the high production mainstream and that have the unique performance requirements of operation in a freezing and horrendously high pressure environment. This new battery system development methodology utilizes battery modules to construct complex battery systems.

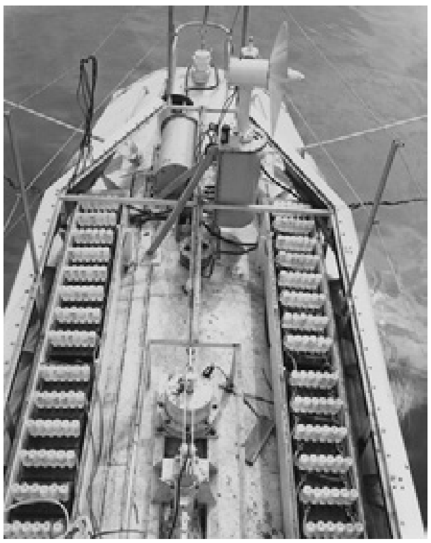
Challenges of High Pressure on Batteries and Electronics

People familiar with undersea batteries using the conventional lead-acid or nickel-cadmium chemistries know that even though the name of the cell or battery may contain the term "sealed," these chemistries are not really sealed. They have to breath, and when they are being fully charged they have the nasty characteristic of giving off highly flammable and explosive gases. Therefore, discharge can be done in a sealed environment but full capacity charging can only safely be done in an unsealed and a vented environment. Where these cells cannot be vented (as in operation in an oil bath), it is possible to undercharge them to prevent outgassing, but this is at the expense of reduced life. The consequence, for safety reasons and when housed in a pressure vessel, is these batteries require the pressure vessel to be unsealed and vented during charge and resealed for use, with the nagging knowledge that multiple unseal and reseal cycles can result in leaks (Figure 1).

Thus, a restriction on undersea missions using conventional rechargeable batteries is that the battery cannot be charged during the subsurface mission. This limits mission time to the energy capacity that can be carried on the exploration vehicle. If the battery could be charged, a low current tether could be used to maintain capacity of the battery system assuming its energy output is a mixture of low power observation current and high power current bursts for vehicle transient and

FIGURE 1

Trieste's pressure compensated batteries are seen in two of the four external battery boxes with the lids removed. Batteries are overfilled with electrolyte in riser pipes, then the boxes are filled with oil. A compensating system provides additional fluid to the interior as pressure increases. Also seen are two of *Trieste's* five pressure compensated propulsion motors, plus the emergency ballast hopper release. (Photo: U.S. Navy, courtesy John Michel).



positioning. Depending on the mission, this could significantly extend mission time while keeping battery payload at a reasonable level. The problem of needing a significantly higher energy density battery and of longer or potentially continuous missions (manned or unmanned) is a severe restriction for conventional rechargeable battery chemistries.

Rechargeable lithium-ion (Li-Ion) cells and batteries, introduced in the 1990s, have matured and promise reduction or even removal of the restrictions of conventional battery chemistries. The rechargeable Li-Ion cell is not only two to four times more energy dense than other rechargeable chemistries, it is also truly sealed and can be charged and discharged without outgassing. The only problem is that the chemistry is very sensitive to any contamination. If the cell's seal is broken, foreign material such as water or oils render the cell inoperative and may actually cause it to outgas just prior to failure. For this reason, cylindrical Li-Ion cells that work fine within a pressure vessel cannot work at hadal zone pressures in oil submersion because there are air pockets within the metal encased cells. High outside pressure can therefore deform cylindrical cell cases and burst cell seals with resulting oil contamination and cell damage. However, as the Li-Ion technology maturity has continued, a new packaged form of the same chemistry cell has been developed, called Lithium-Polymer (Li-Polymer). The Li-Polymer cell contains a Li-Ion chemistry that is housed within a sealed foil pouch. The pouch is vacuum sealed, which removes almost all air pockets. When this cell is correctly constructed, it can be submerged in oil or flexible potting material. Charge and discharge cycling of cells has been tested at and above hadal zone pressures of 10,000 psi. The cell does expand and contract during charge and discharge cycling. Expansion and contraction volume changes are limited to 1% to 3% and, like hadal zone amphipods, internal and external pressure equalization allows this normal "breathing" function without damage to the cell. The difficulty presented by these new Li-Ion chemistries is that they require sophisticated electronics for monitoring, for charge control, for discharge control, and for balancing functions. Can these necessary electronics survive hadal zone pressures?

The majority of electronic components and integrated circuits used today are encapsulated in epoxy. This encapsulation typically allows these dense, complex electronics to be submerged in oil and exposed to crushing hadal zone pressures. However, not all types of electronic components can be used; for instance, any electronic components that contain air pockets such as electrolytic capacitors can be damaged by hadal zone pressures. Interestingly, the integrated circuits that conform to stringent military specs and that have traditionally been used in very high reliability military applications are almost exclusively housed in sealed ceramic chip carriers. These ceramic chip carriers contain air pockets under thin metal lids that will collapse at high pressures and therefore are disallowed for hadal zone environments. In fact, any sealed electronic component is suspect since sealed or potted components can contain trapped air or vacuum spaces. Since electronics components are almost never specified for operation at pressure extremes, it is good practice to test finished circuit assemblies at pressure extremes to verify there are no component problems.

Having designed the electronics circuits and the cell assembly, a means to uniformly distribute external pressure to the assembly must be accomplished. Oil encapsulation is an ideal way to uniformly distribute external pressure and to fill air spaces between components and cells. However, oil can allow movement of the submerged parts that may be damaged by differing orientation or ship-board shock and vibration. Semi-firm potting tends to be more resistant to uncontrolled orientation, shock, and vibration. However, if components are potted, much care is required to select flexible potting and to guarantee that the potting fills all potential air pockets. This results in component orientation during the potting process, and the potting process itself, becoming critical. Finally, with oil or potting encapsulation, there is a necessity to

seal the battery and the electronics away from salt water. This is typically achieved using housings, which contain flexible bladder seals that allow for the finite compressibility of oils and potting materials at the extreme hadal zone pressures.

Li-Ion Safety Issues

A high hurdle to overcome in a lithium chemistry battery system, where the battery energy density is many times higher than with previous chemistries, is safety. Designing a safe Li-Ion battery requires experience and a significant design effort. Safety is associated not only with use of the battery but also in transportation of the battery. When the design effort is completed, its safety must be tested. Two organization types are involved in regulating safety of lithium chemistry batteries: transportation regulation organizations and military organizations.

The transportation regulations are something of a moving target because they are changing almost continuously. However, most countries, including the U.S. Department Of Transportation (DOT), have settled on a common test requirement for lithium chemistry batteries transported via air, land, or sea. This common test requirement is the UN Manual of Tests and Criteria commonly known as T1 through T8 tests. The UN tests for battery assemblies containing multiple battery cells require 16 to 24 completed battery assemblies. The tests typically irreversibly damage or destroy about half of these batteries and stress or use a portion of the cycle life in the other half. If the battery is large and expensive, these tests can result in enormous capital expenditures both for labor and for material. If the quantity of batteries produced is not very high, the cost of these tests can kill lithium battery development projects.

The military regulating organization for undersea battery systems in the United States is the U.S. Navy. The U.S. Navy has developed a safety handbook, NAVSEA S9310-AQ-SAF-010, which defines both assessment methods and destructive tests that must be performed on all lithium chemistry batteries used in, or transported on, U.S. Navy vessels. The assessment requires calculation and screening by safety engineer experts. The tests are designed to cause the destruction of the battery by high heat to determine the extent of potential damage that can result from the battery releasing its energy via either extended or violent battery disassembly. A safety determination is made by both the assessment and the destructive tests as to the potential for endangering personnel and the estimated cost of potential property damage. Fortunately, the destructive test does not require a large quantity of test batteries. Nevertheless, both assessment and destructive testing are a significant expense for a large battery system especially where production quantities are not large.

Battery Size Versus Safety, Reliability, Availability, and Maintenance

How to resolve the safety problem that can result from the high energy potential of a large battery system and the safety testing expense of a large battery system is a significant hurdle. However, this is not the only hurdle. A large battery system that must operate in an extreme undersea environment can be particularly unforgiving should there be a component failure. Personnel danger, property loss, down time, mission failure, and significant maintenance expense are real risks in a large battery system. The system design must provide for reduction of personnel danger, property loss, down time, mission failure, and maintenance expenses.

Personnel danger can be reduced if safety is increased by using smaller batteries. Battery safety test costs are lower if the battery is smaller. Property loss is also reduced if the battery is smaller. Mission failure is reduced if the battery system has built in redundancy. Maintenance expenses and down time are reduced if failed components are smaller, less expensive, and easy to replace.

It is evident that the challenge is how to build a large battery system using small, identical, easily replaceable component parts that work in a coordinated fashion, that can be individually safety tested, and that are constructed in situ in an arrangement that is inherently redundant. This is a tall order. However, there is a design concept for a Li-Ion battery that has potential for meeting all of these requirements—battery modularity.

Battery Modularity Concept

Battery modularity design methodology is the construction of a complex rechargeable battery system using series and parallel combinations of identical, independent battery modules. Each battery module is a separable, self-contained, rechargeable battery of a convenient size for on-site construction of multiple battery system applications and for meeting DOT requirements for transport safety.

A predecessor to modular battery construction concept is shown in Figure 2. Figure 2 is a photograph of a large, 25.9 V, 356Ah Li-Ion battery. This battery, constructed for Applied Research Labs, utilized 36 battery

FIGURE 2

Early version of a modularly constructed battery pack.

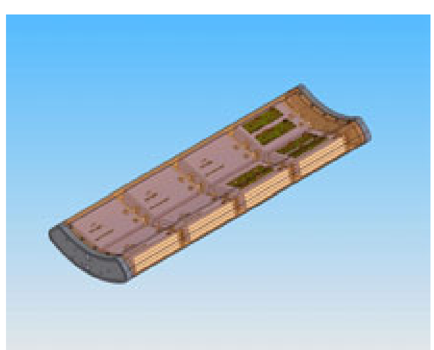
modules. Four modules were built into a cylindrical layer and nine layers were stacked on top of one another. The modules each had simple pack-protect circuits to prevent overcharge, overdischarge, and overcurrent. The modules were not separable, did not contain cell balancing or module balancing, and did not contain built in charge control. The battery had to be charged using a specially designed Li-Ion charger. Since this battery was constructed using cylindrical cells, it had to be installed in a pressure vessel to maintain it at a nominal 1 atmosphere pressure during use at depth. The battery did not have to be unsealed during charging. Charging was done on the surface with the battery sealed within its pressure vessel.

Today's modularity design methodology utilizes much more sophisticated module electronics. It does not require unique chargers for the battery system. Instead, it relies on the battery module having a means of internal charge control that allows it to be charged from multiple energy sources such as power supplies, solar panels, fuel cells, or combinations of these. A battery system constructed from these modules has the capability of using these multiple energy sources to charge the whole battery system while deployed.

Figure 3 is a smaller battery pack constructed using Li-Polymer cells. This battery pack, built for FMC Technologies, Inc., utilizes a four-battery module section housed in a quarter cylinder case. Each one of these quarter sections is potted. The battery system contains eight of these sections. Although the four modules are not separable, the battery sections are separable. Each section is mounted into a small pressure equalization housing containing pressure equalization fluid and a pressure equalization bladder.

FIGURE 3

Illustration of a Li-Polymer battery pack containing four battery modules.



The system has a low current power tether that is capable of slow charging the battery pack to maintain it for continuous mission utilization. This battery system has been tested at 10,000 psi while performing low current charge and high current discharge.

Figure 4 is a schema of a proposed new battery system for the Alvin manned submarine at Wood's Hole Oceanographic Institute. This battery system is a large 47.2- to 56.6-kWh battery system constructed from 64 rechargeable and replaceable battery modules. Eight modules are series connected into an eight-series section of modules that are separated from one another by ideal Or'ing diodes. The Or'ing diodes prevent the failure of a battery section from affecting other battery sections, thus providing redundancy of each section.

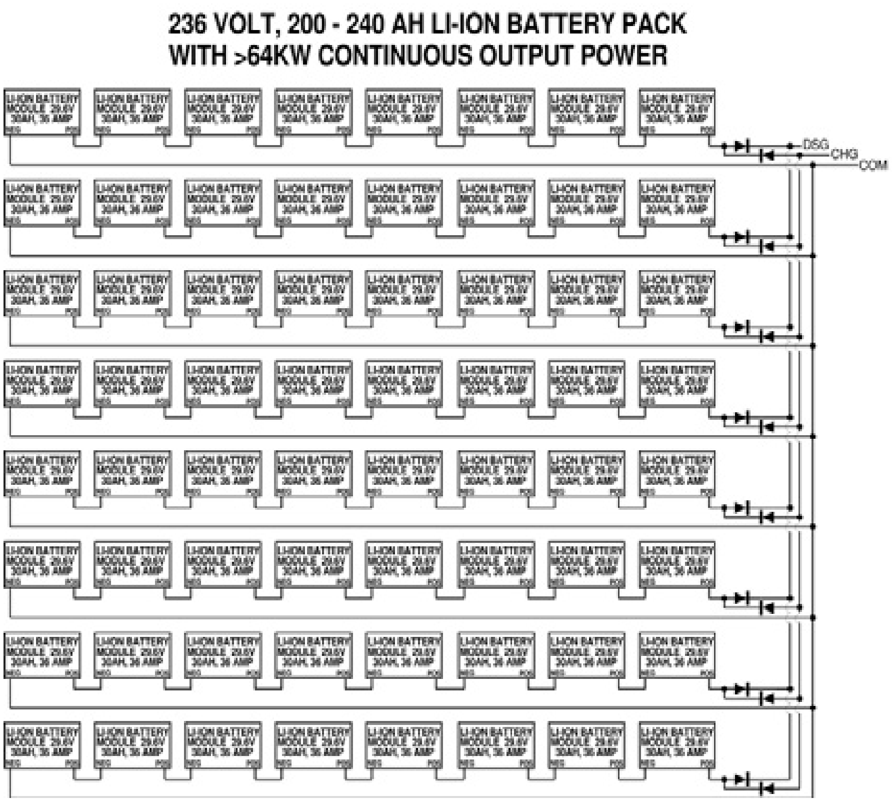
The system shown can be charged at 32 kW and discharged at 64 kW. The Alvin is not tethered; therefore, the battery system is surface charged prior to the subsurface mission. Full recharge time in this instance is as fast as 2–4 h or can be slower depending on the constant voltage, constant current power supply used. Since the Alvin power requirements are 48 kW, this system can run at full power with as many as two 8-series sections (16 modules) disabled. The battery system is sized so that two of the battery systems shown can be attached to the Alvin for a total capacity of well over 100 kWh. Not shown is an RS-485, Modbus computer interface into each module. The computer interface will be utilized by the Alvin to monitor and control each battery module and the whole battery system.

Battery Module Advantage Summary

Advantages of constructing large battery systems using battery modules include:

FIGURE 4

High-energy battery system constructed from battery modules.



1. extreme flexibility of battery system design,
2. fast development,
3. cost reduced DOT testing,
4. increased safety in handling and shipping,
5. lower assembly costs,
6. lower repair and replacement costs,
7. lower inventory costs, and
8. improved time to repair and system availability.

Battery Module Requirements

Construction of dissimilar battery systems using a multiplicity of the same battery module requires considerable foresight into the battery module design. The following is a list of typical requirements:

1. fast and easy maintenance;
2. battery module replacement at any state of charge;
3. internal charge control;
4. configurable for distinctly different applications;
5. high battery module reliability;
6. programmable architecture;
7. support for centralized status monitoring and remote control;
8. support for display of state of health, capacity, charge status, etc.;
9. chemistry agnostic; and
10. the key requirement: a means to balance all cells and all battery modules in the battery system.

Why Balancing Is the Key Requirement

Modern Li-Ion cell chemistries are remarkably robust in their ability to maintain balance. Nevertheless, field return data on high series count batteries support the need for a robust balancing capability for complex battery systems. For high cell count battery systems, battery pack unbalance is the number one reason for pack failure. To understand why, consider the following:

1. The likelihood of imbalance increases with the number of series connected cells.
2. A larger battery pack has a greater likelihood of portions of the pack being at different temperatures.
3. Pack imbalance can be caused by differential leakage currents external to the cell such as:
   a) differential leakage currents within the pack-protect circuit itself,
   b) differences in the insulation resistance between cells, and
   c) humidity and condensation on the pack-protect circuit board and on the cell insulators.
4. Pack imbalance can be caused by intermodule or intramodule capacity differences due to:
   a) different lots of same cell,
   b) differences in module age, and
   c) cell electrolyte leakage, contamination, or other damage.
5. Replacement of battery modules typically requires a system rebalance due to:
   a) the replacement module's capacity being different from other modules or
   b) the replacement module's state of charge being different from other modules.

The resultant requirement is that a robust balancing capability must be designed into the whole battery system. In the instance where the module design concept is utilized, this means intra- and intermodule balancing.

Example Implementation of Intra- and Intermodule Balancing

Electronic cell balancing is not new. Two common intramodule balancing methods are discharge balancing and charge transfer balancing.

Discharge balancing is balancing by discharging higher capacity cells until they match the capacity of the lowest capacity cells.

Charge transfer balancing is balancing cells by transferring charge from the higher capacity cells into the lowest capacity cells until the cell capacities are equalized.

Both methods can theoretically be done at any time and in any battery operating mode. Neither method will reduce the usable capacity of a battery pack from what it was prior to being balanced.

These two intramodule balancing methods are commonly only described for balancing across a complete, inflexible, battery system using centralized control. For highly configurable battery systems constructed from independent, rechargeable battery modules there is an unmet need for an intermodule balancing method. The following two methods, developed by Southwest Electronic Energy Group, meet this need[1].

Zener Diode Intermodule Balancing

A simplified schematic of two, 4-series Li-Ion battery modules that utilize Zener Diode Intermodule Balancing is shown in Figure 5. Assumed, but not shown, are the pack-protect circuits associated with each of the modules. The two modules in the figure are unbalanced and are in the process of being charged. The first module has attained full charge status and its charge Field Effect Transistor (FET) (shown as a simple switch) has opened. The other module is at a lower relative state of charge and has not yet attained full charge status. Charge current is bypassing the fully charged module via the Zener diode and current limiting resistor and is charging the module at the lower state of charge. The charge current will continue until both modules are balanced at which time the 2nd module's pack-protect circuit will open its charge FETs.

Figure 6 illustrates how Zener Diode Intermodule Balancing works. Each module in the example has internal charge control. Module 2 is at a higher state of charge than Module 1. At the beginning of the data set, Module 2 is near its end-of-charge cycle and has begun pulse charging—allowing charge current to flow into both modules in a pulsed fashion. When Module 2 is at full charge, it stops pulsing and opens its charge FET. Module 1

FIGURE 5

Zener diode intermodule balancing circuit.

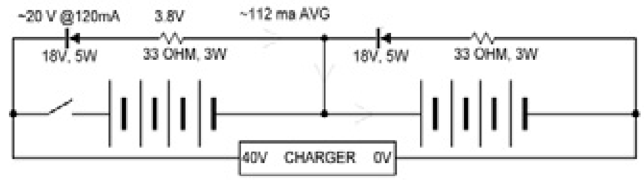
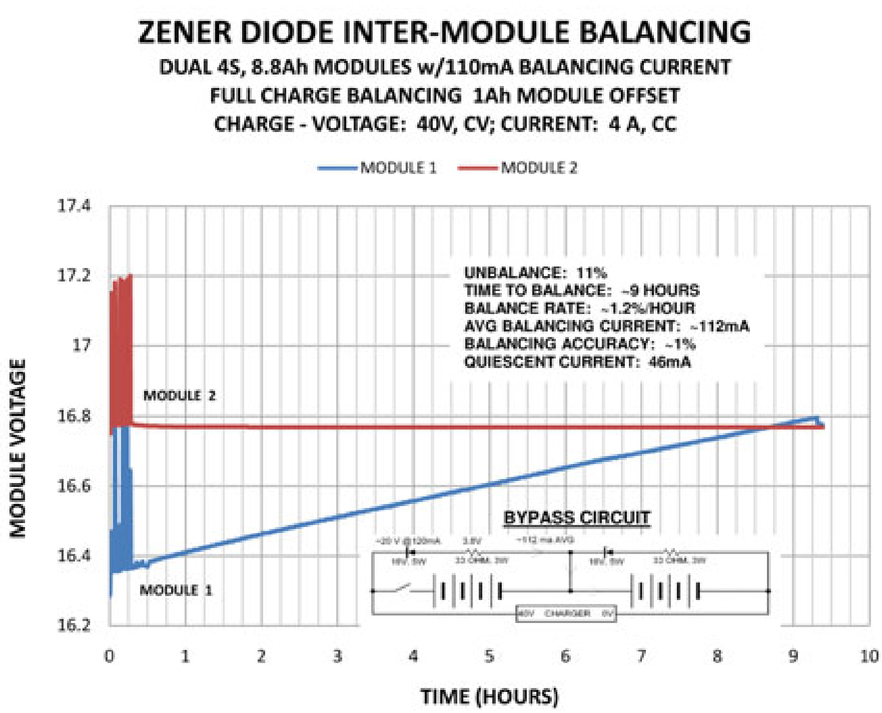


FIGURE 6

Zener diode intermodule balancing example.



[1]The methods in this article are protected by US patents 7,609,031 B2; 7,279,867 B2; and other US and international patents already granted or pending.

completes its charge using the bypass Zener diode current. When Module 1 has reached full charge status, it also opens its charge FET. Both modules are now balanced and charge current stops going through the modules. Some small amount of quiescent current will bypass both modules as long as the charging power source is attached.

Discharge Intra- and Intermodule Balancing

A simplified schematic of a four-series battery module that includes the Li-Ion cells and the protect circuit is shown in Figure 7. The circuit in the figure is capable of intramodule and intermodule discharge balancing. The circuit is constructed using off-the-shelf parts including a microprocessor, an AD converter, an Analog Front End circuit, external balancing switches, and external discharge balancing resistors. An 8-Amp implementation of the pack-protect circuit in Figure 7 will fit onto a 2.5 × 0.75-inch printed circuit assembly.

As in the previous example, consider a battery system made from two, Figure 7 modules connected in series. Each Figure 7 module is able to balance the cells it is connected to using the external FET switches and the 25-Ω, 3/4-W discharge resistors. This is conventional intramodule balancing. What may not be obvious is that each Figure 7 module, under appropriate internal software control, is also capable of intermodule balancing with the other module connected in series with it without any control communication between the modules.

Figure 8 illustrates how discharge intermodule balancing using two, Figure 7 modules connected in series, is accomplished. The two modules are programmed for intramodule charge control to 80% capacity as might be required in a battery back-up application. There are no control signals connecting these modules; the battery modules' external connections are only PACK+ and PACK–. A description of the action taking place in Figure 8 follows.

Prior to being balanced, Module 2 is at a higher state of charge than Module 1—they are unbalanced. A 34-V, current limited power supply is connected across the two modules as a charge source. Module 1 has its charge FETs constantly on but Module 2 is close to being fully charged so it pulses its charge FETs reducing average

FIGURE 7

Discharge intra- and intermodule balancing circuit.

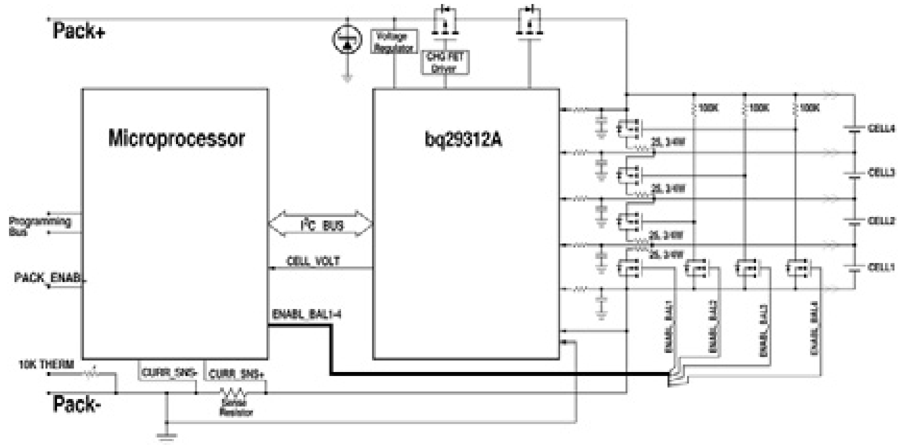
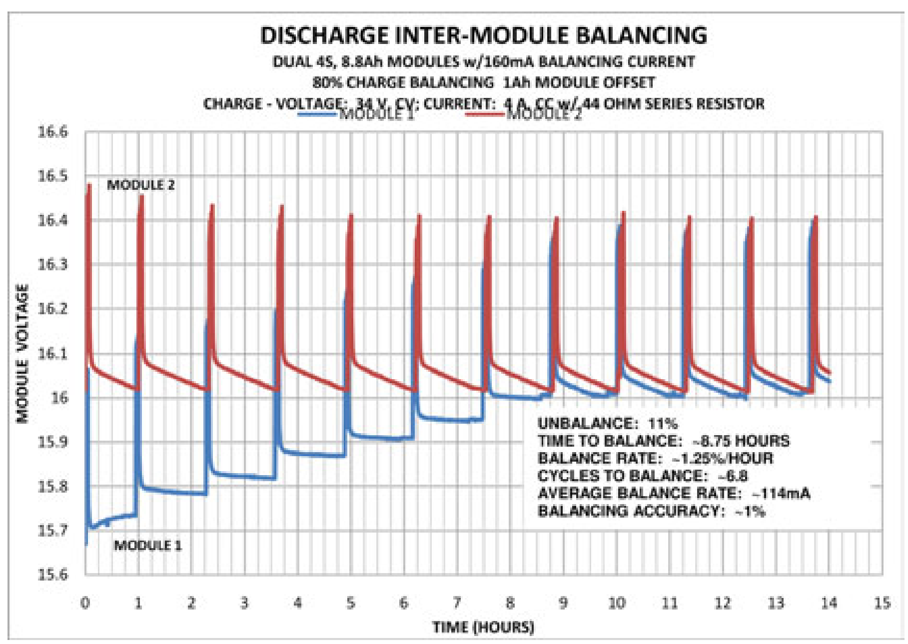


FIGURE 8

Discharge module balancing example.



charge current. The pulsed charge current from Module 2 charges both Module 2 and Module 1 until Module 2 reaches 81.5% capacity, opens its charge FET, and stops pulse charging. Between charge pulses, Module 2 discharges itself down to 80% capacity by enabling all four of its balancing resistors. Module 1 does not discharge itself during this time because it has not reached 81.5% capacity. When Module 2 discharges down to 80% capacity it begins pulse charging once again until it again reaches 81.5% capacity and opens its charge FET. Thus, Module 2 charges and discharges itself between 80% and 81.5% capacity while Module 1 only charges without discharging. This continues until Module 1 attains the same 81.5% capacity at which time the two modules become balanced. Once balance is attained, both modules continue to perform 1.5% capacity charge—discharge mini-cycles. Pulse charge current range is approximately 2.2 to 3 Amps due to 0.44-Ω resistor in series with the 34-V charge source. Charging and discharging mini-cycles of 1.5% at about 80% capacity is not stressful on the cells. Cycle rate is about 0.8 cycles per hour, 19.2 cycles a day, and 7,008 cycles a year. If end of life of a cell is set at 80% of its full charge capacity, an obvious question is how many of these mini-cycles does it take to cause the cells to reach end of life? Some NASA studies indicate this number may be in the 10s to 100s of thousands. Thus, it is expected that continuous mini-cycles such as this do not appreciably affect battery module life. Nevertheless, if mini-cycles are objectionable, it is possible to lengthen them or to cause them to stop altogether once balance is attained.

Conclusions

The lithium-ion polymer version of lithium-ion cells have been successfully tested for both charge and discharge at pressures experienced in hadal zone regions. Since the energy capacity of lithium-ion cells is two to four times that of conventional chemistry cells, operation at depth is significantly extended when using these cells. The Li-Ion chemistry does not outgas during charge or discharge and can therefore be safely housed within sealed containers without the necessity of unsealing and ventilating the container during charging. This feature allows faster, safer, and more reliable redeployment of lithium-ion powered marine systems. It also allows the potential for continuous operation at depth when a charging umbilical is used.

Electronic balancing is a requirement for large lithium-ion battery systems because the chemistry does not provide for overcharge balancing as do previous rechargeable chemistries. Engineers, having to live with this restriction, are discovering that the ability to automatically electronically balance all parts of a complex battery system leads to new paradigms in battery system design, use, and maintenance that are only recently becoming evident. Among these are the following:

1. use of battery modules to enhance safety and reliability and to reduce costs;
2. applying electronic balancing to other non Li-Ion rechargeable chemistries;
3. increased number of series connections in a battery;
4. increased flexibility in modularity and replaceable unit concepts;
5. smarter battery systems;
6. more flexible charge control;
7. multiple charger energy sources;
8. potential for multi-energy source hybridization; and
9. potential for construction of multi-voltage, multicapacity battery systems each having intramodule and intermodule balancing capability and each constructed using the same type of battery modules in each system.

TECHNICAL NOTE

Pressure Testing: Best Practices

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ABSTRACT

Success below the seas comes from careful preparation topside. Pressure testing remains one of the most useful tools designers have available to assure their systems function as intended, whether a company chooses to have in-house pressure test capability or to work with a commercial test facility.

Capt. Don Walsh, pilot of the bathyscaph *Trieste* on its historic two-man dive to the floor of the Challenger Deep in the Mariana Trench, said with a grin, "Successful operations depend upon a Skill-to-Luck ratio. While luck is important, you always want skill to be more than 50%."

Given the limited availability of ship time, the danger to personnel in close quarters onboard ship or in a submersible, the high cost of ship operations and equipment, and the long lead time of grant and project funding, pressure testing makes sense to validate system integrity before deployment. Simply put, equipment should not see pressure for the first time on its first operational deployment. Pressure testing is a vital environmental check of mechanical integrity, analogous to electronics and software burn-in. Ideally, pressure testing will simulate the actual conditions of deployment and operation. A solid test provides the operator and deck crew confidence in the system being deployed.

While pressure testing will appear to add time and cost, in practice it saves both by eliminating failure modes, some potentially catastrophic, while offshore.

This technical note is intended to summarize current best practices in pressure testing for engineers and programs managers new to the field, including tips for coordinating work with pressure test facilities. The lessons are based on the authors' combined experience as users and operators of pressure test facilities.

Advantages

There are distinct advantages to pressure testing. Pressure testing is the best means to validate housing integrity before expensive electronics are placed inside, exposing hidden mechanical flaws in extruded tubing or welded seams or flaws in castings or forgings. Testing and development of pressure compensated systems can be done faster at lower cost in the controlled conditions of the pressure test laboratory, with far more access to the system under study than in the open ocean. Testing of any component exposed to pressure, even soft rubber molded cable terminations and urethane overmolds, is good practice. Black rubber terminations have been known to have interior air voids that show up only under pressure when the void collapses and wires short out. The bulk modulus of plastic may cause a part to shrink to unacceptable dimensions and not function when needed most. Back on the surface, the part operates as expected, and thoughts turn to deep sea mythical creatures to explain the lack of data or recovered sample. In one case, a professor had a double o-ring seal on a sliding piston. The small volume between the o-rings caused the o-rings to seat and seize the piston. The trap did not catch animals as expected. Careful study and testing in a pressure chamber revealed the problem. A pressure relief port between the two seals in the open position ended the problem and it worked fine thereafter.

While pressure testing can appear to be time consuming, and does add cost, in practice it saves time and adds confidence for a successful operation by eliminating failure modes, some potentially catastrophic. You will get the best value by communicating with the test facility as early as possible. They have a lot of experience that they are delighted to share.

Pressure testing is useful at three key junctures of development: (1) component validation, (2) system validation, and (3) proof testing.

Component validation qualifies a part or a subset of parts for integration into a system.

System validation tests the full assembly to the maximum defined static pressure of the "design depth" and should include cyclic testing to be certain the material can survive repeated deployment. A test to "crush depth" confirms failure mode. If it is a new and critical application, or safety margins are being trimmed pretty close, it may be wise to test at least one article of the housing to implosion. This may be a costly test but important information can be gleaned by analyzing the failure mode and comparing calculated versus actual implosion pressure and mode.

Proof testing is an in-process quality control test to "rated depth" after manufacture or overhaul.

Testing protocols may vary for the general end user need: research, government, military, or commercial.

Should a part fail in a chamber, it is easy to pick up the pieces for forensic engineering. Feedthroughs allow data logging and external power supplies. You can get in and out of a chamber faster than you can access the deep sea, and for far less money. Pressure chambers are run by knowledgeable and experienced technicians who can often see the early signs of leak or failure, and end the test before things get out of hand.

Limitations

There are limitations to pressure chambers. While some chambers are large enough to fit the smaller work class submersibles, like *Deep Rover*, there are times the ocean is the only place large enough to pressure test a fully assembled system. Jacques-Yves Cousteau confirmed the integrity of his new two-man diving saucers by lowering them into the Mediterranean Sea, unmanned, on a winch line with a weight below.

Tests of sympathetic implosion require the "infinite volume" of the sea as pressure chambers rapidly loose pressure with the loss of any amount of volume due to the largely incompressible nature of water. The chamber walls may also artificially cause interactions which could dampen or amplify a shock wave.

Computer-Aided Engineering

Computer-aided engineering programs, such as DeepSea Power & Light's freeware "UnderPressure," provide designers a first-order analysis of simple housing integrity against the affects of external pressure. Advanced users will want to study the program for opportunities to modify default material properties to match their actual material. Other simulation programs, such as COMSOL 3.5 (COMSOL, Inc., Burlington, MA) and SolidWorks COSMOS (SolidWorks Corporation, Concord, MA), provide motion, stress, or thermal models but are costly and not routinely available to the average designer.

Common Types of Pressure Vessels

Many pressure test vessels are in operation today, and odds are there is one that has the size, pressure rating, and kind of feedthroughs you need (Figure 1).

FIGURE 1

This new ASME-certified 20-inch chamber at DSPL can operate to 20 ksi and includes multiple feedthrough ports. A 17-inch glass sphere from Vitrovex is shown being lowered into the chamber for testing to a pressure equivalent to 8.4 km, the deepest trench in the Atlantic Ocean.

Test vessel closures often incorporate feedthroughs for power, signal, hydraulic power, or displacement.

Pressure ratings for pressure test vessels widely vary and are often dependent on size. Vessels with ratings of 12,000 psi with a working diameter of 12 feet exist, but more common chambers are 6 to 9 inches inside diameter.

Commercial enterprises may have chambers constructed to meet testing requirements particular for their needs. Construction of test chambers can be costly; in-house testing versus contract testing must be considered when deciding on new construction.

The most common type of high-pressure pumps is a piston pump. These are pneumatically driven, high-pressure liquid pumps, such as made by Haskel Pumps (http://www.haskel.com). A large piston is powered by compressed air, driving a small piston that alternately draws fluid into a chamber through one check valve, then out through another check valve, providing a direct multiplication of force in the ratio of the two piston areas. They are a simple design with few parts, easy to field strip and repair, and reasonably inexpensive. The action is reciprocal, and pressure is added in incremental step increases.

Other pumps include plunger pumps, hand pumps, and gear pumps.

The Test Plan

Careful consideration should be given to the test plan. Whether the test is a simple hydrostatic proof test, or a complicated operational test with data acquisition, adequate prior planning insures success. The goals of the particular test as well as the capabilities of the test facility should be given thought.

Pressure testing should simulate the actual conditions of operation as well as the extreme conditions expected in operation. Both deep and shallow depths should be considered in the test plan, and real-world situations need to be modeled. For example, dwell time at the surface before a dive may produce a low-pressure leak that seals with increased pressure. This weakness may be masked by a rapid transition to high pressure in a chamber.

The function of o-ring seals may be marginal at low pressure, but not at high pressure, under certain conditions. To understand this requires some insight as to how o-rings function. There are two basic kinds of o-ring seals: static and dynamic. A static seal is between two parts that do not move; a dynamic seal has to accommodate some motion of parts, perhaps linear or rotary movement. Static seals, however, share some characteristics with dynamic seals in that the o-ring itself moves, sliding into sealing position in compliance with increasing pressure. Thus, there maybe low-pressure conditions where the movement of the o-ring is compromised, perhaps because of use of a high durometer rubber, improper surface finish, or even too much grease. A low-pressure test, even a soak test in a tub of water, can reveal this problem. A rush to push the test sample to high pressure may cause the engineer to overlook this potential seal failure mode.

An autonomous undersea vehicle or a wire lowered conductivity-temperature-depth instrument package will see cyclic pressure stresses. Plastics may creep or compress under long-term exposure to high pressure.

Testing Best Practices

When working with a testing house, it is important to define the test plan in writing. The act of writing will help clarify your thinking. The plan should be offered to the testing facility with enough time for them to carefully review and comment on the testing. They have lots of experience, which can be quite helpful. Include the proposed test dates to ensure your desired window fits within their availability.

The test plan should consider the following, if relevant:

1. Purpose: Define what constitutes "pass/fail." That may simply be "Is it dry inside?" The question may be defined by whether the test is for component validation, system validation, or proof testing as defined above.
2. Standards and certifications: If the testing is to meet specific standards, such as American Bureau of Shipping, Underwriters Laboratories, or U.S. Government Specification (MilSpec), be sure to inform the test facility of what they may need to provide in terms of gauge calibrations or other data. It will be you that is responsible for defining the test protocols and submitting the results to the certifying agency.
3. Safety factor: Discuss with the pressure facility what are the design limits, including safety factor, and how they were determined.
4. Use blocking. If this is the first time an empty housing is being taken to the design depth, the interior implodable volume should be filled to 90% or better with an incompressible material to limit the amount of energy released by a catastrophic implosion. A 98% fill may be required if the system is being taken intentionally to failure. If practical, a water-filled interior vented through the end cap to atmospheric pressure is a good choice. Another good practice is the use of polypropylene plastic injection molding pellets which float if spilled, making them easy to clean up. These are also good energy absorbers if an implosion occurs.
5. Measurement techniques: The test may look to simply confirm that no seals leak. Other tests may measure volumetric displacement, strain gauge deflection, voltages, system function, video, or count pressure cycles. Define what test equipment will be needed and where it will come from. Consider asking the test facility what equipment they might have or to suggest where they might rent it.
6. Calibrations: Pressure facilities typically have a yearly schedule for recalibrating their gauges, meters, and other measurement devices.
7. Environmental simulation: Define rate of pressurization and depressurization, number of cycles, hold times at pressure and at sea level, water temperature, fresh or saltwater, and maximum test pressure. Not all test facilities can offer this great an array of options, but some do.
8. Electrical interface: Specify the voltage and current requirements for any power-on testing, as may be required. Specify the required connectors and cables your project uses. Ask the test facility if they have an adapter for the thread size of your bulkhead. If one has to be fabricated, it is better to know sooner than later. This may incur additional costs and preparation time. Send the adapter to check fit. It is your responsibility to bring the connectors and dummies you need.
9. Pressure compensation systems: If there is oil, specify how will it be managed during fill, and if any leaks or spills. Provide the Material Safety Data Sheet to the test

facility. If the compensation system is compressed air, specify the venting plan intended during depressurization.

10. Hazards: If the housing fails and water gets inside, specify if there materials, like primary lithium batteries, that will react vigorously with water. If a seal fails, and the interior becomes positively pressurized, specify if there a way to relieve the interior pressure safely, such as a PRV.
11. Specify how many tests are needed for the statistical sample size.
12. Scheduling
    A. Schedule with the facility as early as possible so they know to have the gauges you want, and not be out for recalibration.
    B. Communicate well in advance with the pressure test facility, giving them a detailed plan a minimum of 2 weeks before you show up. They cannot quote costs unless they know what you want to do and what you expect from them.
    C. Ship ahead. UPS is great, but allow a day or two extra so you do not sweat it.
    D. Allow adequate time for setup and breakdown.
13. Come prepared. If you need feedthroughs, or an extra tech, let them know what to plan for. Make certain you have everything you need before you ship your gear. Do a dry-run setup and think it through. Checklists are always helpful. Talk with your colleagues to be sure you have all the right connectors, cables, test equipment, and gizmos you will require.

Use of this checklist will help you be ready when the clock starts running (Figure 2).

FIGURE 2

Southwest Research Institute prepares a submersible for hydrostatic test. Southwest Research Institute operates ocean simulation chambers with diameters up to 90 inches and pressures to 30,000 lb per square inch.

Rules of Thumb

1. Provide a well-written plan, including materials and checklists. If you are not going to be present, review the plan with the pressure test facility before the test day to prevent a needless delay while the operator tries to contact you to determine exactly what was intended. Consider low-pressure and low-temperature cases as well and high pressure.
2. Allow time for setup and breakdown, easily a half day on each end, depending on system and test complexity. If you need more time than this, let the pressure facility know and they will be able to set you up with appropriate work space.
3. Leaks or implosion may happen, that is why we pressure test things. Have a plan to cope with the loss. If expensive components do not need to be inside the housing for the initial test, save yourself the grief. Consider the possibility that the interior of a pressure case that leaked may hold high interior pressure when handling. Perhaps you can release pressure by loosening connectors.
4. Handling:
    A. If there is something that should not be touched, like a sensor, or needs extra attention, like a plastic connector, let the operator know. They really do appreciate you speaking up. It is really desirable for the owner of the equipment to be present to operate their data logging equipment or simply observe the test. Simple pressure testing may be dropped off and picked up later, but the basic protocol of going through the best practices noted above with the operator should never be short cut.
    B. Wet things can be slippery. Use gloves that maximize grip strength. Pay attention when and where you grab something. The use of pressure facilities is at your own risk. Operators do not assume any liability for damage to you or your equipment.
    C. Facility managers do not generally allow clients to load and unload chambers or operate the pressure system controls. However, most openly welcome your participation on site in giving detailed direction to testing your system. You are welcome to discuss training and experience of the pressure system operators.
5. Agree on payment terms before coming to the facility. Review any liability waivers for clarity. Understand that most quotes for pressure testing are estimates based on the test plan provided. Delays are inevitable as procedures get more complex.

Future Funding

Federal agencies that provide block funding for ship days to research orga-

nizations would do well to also consider pressure testing block funding. Researchers will have greater success at sea and stretch research dollars by testing their equipment before they go.

Conclusion

Pressure testing is a critical part of preparation and a key to success at sea. It is a critical environmental test that should always be part of routine design and manufacturing plans. Pressure testing provides the operator, deck crew, and submersible crew confidence in the system being deployed.

Acknowledgments

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PAPER

Microbial Life in the Trenches

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ABSTRACT

Microbiologists have been making use of advances in ocean engineering to explore life in deep-sea trenches for decades, including for many years preceding man's conquest of the Challenger Deep. This has fostered the development of an unusual branch of microbiology, referred to as *high-pressure microbiology*. Evidence for deep-trench microbes that grow best at elevated hydrostatic pressure was first obtained in the early 1950s, and isolates were obtained in pure cultures beginning in the early 1980s. Here I describe some of the history of deep-trench microbiology and the characteristics of microbial life in the trenches.
Keywords: Barophile, Challenger Deep, High pressure, Piezophile, Trench

Introduction

In this article, I focus on the smallest inhabitants of trench ecosystems—the microorganisms, those tiny life forms less than one millionth of an inch in length. It is they that account for most of the evolution that has occurred, it is they that represent the largest numbers of cells and combined biomass on the planet, it is they that provide us with the bulk of our biologically derived pharmaceuticals and biotechnology products, and it is they that drive the biogeochemical cycles that sustain our biosphere on spaceship Earth. During the past half century of science, we have learned more about both hadal environments and microbes than in all the preceding time periods. Here I discuss the intersection of these fields.

The opportunity to engage in the science of deep-sea microbiology has relied on those advances in ocean engineering of which regular *Marine Technology Society Journal* readers will be well aware. Restricting these considerations only to the Challenger Deep still offers many examples of the tools of the trade. Challenger Deep descents have been accomplished sporadically since the middle of the 20th century. Some of these are well known, like the dramatic undertaking of the manned bathyscaph *Trieste*, and some, such as the benthic sampling operations of the former Soviet Union in this and other trench environments, have received much less international fanfare. These deployments have used deep trawls and bottom-grab sediment samplers, free-falling/ascending vehicles, deep conductivity, temperature, depth sensor (CTD) casts, deep current meter moorings, the remotely operated vehicles *Kaiko* and *Kaiko7000*, and most recently the hybrid remotely operated vehicle *Nereus*. Similar operations have taken place in many other trenches, most notably the Aleutian, Kermadec, Tonga, Philippine, Japan, and Kuril-Kamchatka trenches in the Pacific Ocean, the Java Trench in the Indian Ocean, and the Puerto Rico Trench in the Atlantic Ocean. Readers interested in a virtual trip to any of these locations should download Google Earth.

Danish and Soviet Contributions

An examination of the history of deep-trench microbiology provides lessons beyond the science itself to the noble and the brutish that is possible in human society. Voyages of discovery often require sacrifice. This was certainly true for the Danish research expedition that took place during the early 1950s, conducted on board the Royal Danish Navy ship *Galathea*. A focus of this research enterprise was to determine the deepest places where life existed. It is a tribute to the people of Denmark that this great undertaking took place at all. The great deep-sea microbiologist, Claude ZoBell, recorded in his memoirs that "having been impoverished during World War II and its sequelae, the people of Denmark had little to contribute except an active interest in the expedition. School children were organized to contribute or collect funds and to sell bananas, coffee, pineapples, and other coveted commodities at black-market prices with official permission. American cigarettes alone netted more then 8 million kroner (about $75,000) for the Expedition Fund."

Even greater sacrifice was required by certain Soviet scientists of this period (Mishustina, 2003). Anatolii Evseevich Kriss, a contemporary of ZoBell and another creative force in marine microbiology, suffered as a result of political persecution. Kriss took over the leadership of the Depart-

ment of Marine Microbiology at the Institute of Microbiology (USSR Academy of Sciences) in 1950. He made the astounding claim that in the depths of the Black Sea, dark fixation of carbon dioxide exceeded the levels of photosynthesis by plants in surface waters. This claim was decades ahead of the experimental work that would one day be corroborated. It was also apparently too far ahead for Soviet scientific thinking. He was permanently criticized for his statements about chemosynthesis. Things were much worse for G. A. Nadson, Kriss' teacher and founder of the institute who was arrested and later executed. Kriss survived these ordeals and went on to explore the bacteria and fungi of many marine, including deep-trench environments, and wrote a textbook on marine microbiology, which was widely read owing to its English translation.

Claude E. ZoBell

The aforementioned Royal Danish Navy ship *Galathea* "Round the World" made possible a tremendous amount of deep-sea science, and in particular the expedition afforded ZoBell with the opportunity to examine the microbiology of many exotic deep-sea sediment samples (ZoBell, 1952). He made good use of this material, using it to obtain the first evidence of deep-ocean trench high-pressure adapted life.

This discovery highlights the unusual nature of doing microbiology at high pressure. It was accomplished by using as inocula mud that had been collected from trenches exceeding 10,000 meters and incubating at pressures of 100 MPa (1,000 atmospheres or ~15,000 pounds per square inch) and temperatures near freezing. To do this was no small feat. Once the sediments were hauled on board, ZoBell and his student had to quickly transfer some of this material into bottles with culture media, stopper them, and place these inocula into pressurizable steel cylinders. This type of microbiology is a very odd business and is basically unchanged in its operation today, involving just as much ability in plumbing and chemical engineering as sterile technique and microbial physiology. The culture apparatus of a deep-sea microbiologist requires that the "soup" containing the microbes to be grown be placed into some sort of a pressure-transmitting container. It can be a bag that is squeezable, a sealed syringe (the movement of the plunger relays the pressure to the cells), or a glass tube with a movable stopper. These containers are then placed inside a pressure vessel of some design and pumped full of water to the desired pressure. Water (hydrostatic) pressure is generally used and not gas pressure because gases can be toxic to microbes and pose an explosion risk to scientists (Figure 1).

FIGURE 1

The odd business of high-pressure microbiology. Shown is the great deep-sea microbiologist Claude E. ZoBell with his vessels and hand-operated high-pressure pump. Courtesy of Scripps archives.

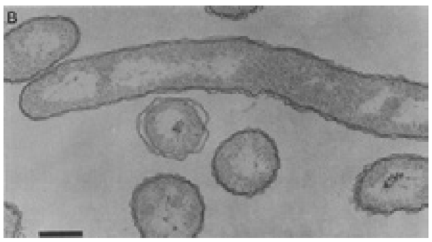
A. Aristides Yayanos

Although ZoBell was successful at finding evidence of piezophilic (formerly barophilic; high-pressure adapted) life, he failed to isolate any piezophilic microbes or indeed to maintain any cultures of consortia of piezophilic bacteria that could be made available for others to examine. This breakthrough was accomplished by another microbial oceanographer also at Scripps Institution of Oceanography, A. Aristides Yayanos (Yayanos et al., 1982). It required about three more decades, during which time the very existence of piezophiles was an issue of active debate. However, in 1979, Art Yayanos, through great care, patience, and dedication, isolated the first piezophilic bacterial strain. Shortly thereafter, in 1981, he obtained a piezophilic microbial species from the Mariana Trench that could not grow at atmospheric pressure and hence was referred to as being obligately piezophilic. Yayanos went on to isolate hundreds of new strains from the Aleutian, Kermadec, Mariana, Philippine, and Tonga trenches as well as other deep-sea locations. These continue to be the gifts that keep on giving as other scientists can now "go deep" so to speak by simply cracking open a pressure vessel containing one of Yayanos' strains (Figure 2).

Part of the reason for Yayanos' success may have been his choice of starting material. Many of his piezophiles can be traced back to the decaying remains of an amphipod. These benthic crustaceans have two advantages for the isolation of piezophilic microbes: (1) they harbor large numbers of bacteria on and in them, and (2) each species is restricted to a narrow physical range, and thus deep-trench amphipods must contain a microbial flora

FIGURE 2

The most important discovery ever made in the Mariana Trench. Shown is an electron micrograph of the high-pressure requiring microorganism strain MT41, isolated by A. Aristides Yayanos and colleagues. The scale bar is equal to 0.5 μm. Courtesy of ASM Press. (Chastain and Yayanos, 1991).



that is adapted to high-pressure deep-trench conditions.

Program DEEPSTAR

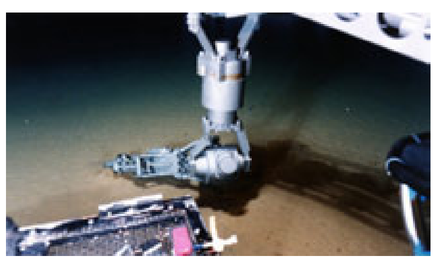
Since the initial isolations of piezophiles, others have gone on to obtain and to characterize additional trench microbes. Particularly spectacular have been the activities of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), beginning in 1990 with the establishment of the DEEPSTAR program. This organization has placed great emphasis on the science of the inner space of the oceans, particularly within the Japan, Ryuku, and Mariana trenches.

Advances in ocean engineering have preceded many of the JAMSTEC accomplishments in deep-sea microbiology. These have included the development of a series of submersibles and remote-operated vehicles. Another engineering marvel is the JAMSTEC DEEPBATH system. Although environmental microbiologists have come up with ingenious approaches for cultivating deep-sea microbes at high pressure, the most sophisticated system ever developed is undoubtedly DEEPBATH. This system is used in conjunctions with specialized pressure-retaining mud samplers that can be used by either manned submersible or remote-operated vehicle. Once obtained, the samples are kept at deep-sea pressures and temperatures until processing time. After delivery of this un-decompressed material to the DEEPBATH system, it is diluted under *in situ* pressure conditions and delivered to an isolation devise for extinction to dilution isolation of single microbial species and laser-based automated monitoring of growth. Then the individual isolates are pumped into a flow-through cultivation vessel where they are grown up in sufficient quantities for biochemical or molecular biological studies. The entire DEEPBATH operation is monitored and controlled by a single console.

JAMSTEC microbiologists have used DEEPBATH to isolate and taxonomically characterize a large variety of deep-trench microbes that grow under diverse physical and chemical conditions (Kato et al., 1998) (Figure 3).

FIGURE 3

The remote-operated vehicle *Kaiko* collecting mud in the Challenger Deep. Courtesy of Dr. Chiaki Kato, JAMSTEC.



Microbial Invaders

One of the curious features of many of the microbes that have been isolated from deep-sea settings including trenches is that they do not display adaptations for growth at either the high pressure or the low temperature from whence they were isolated. This seems counterintuitive, after all how could life exist at depth that cannot grow under the conditions present at depth? The answer to this riddle may rest on the fact that deep-ocean habitats are physically connected to their overlying surface waters, and a variety of physical and biological processes exist, which can deliver microbes from land, air, and shallow sea to deep-oceanic pelagic and benthic environments. Thus, the nonpiezophilic organisms present in trenches may represent those immigrants that have survived the lengthy transit from much shallower locations. Although the conditions at depth are extreme, the prevailing physical conditions may have the effect of putting some cells into a state of suspended animation, and the turnover of such nongrowing microbes may be very low. This may be particularly true for spores, those dormant stages of some bacterial groups. A reflection of this phenomenon is that high numbers of sewage microbes may remain viable for years at deep-ocean dump sites, something policy-makers should be aware of when considering deep-ocean locations for waste disposal.

Deep-Trench Microbes Love the Big Squeeze and Do Not Get the Bends

There are two common misconceptions about deep-sea piezophilic microbes. First they do not generally blow up (get the bends) during decompression. At least this is true for most of the microbes present in culture, including those obtained without decompression. The reason is because they do not typically have gas spaces inside their cells, and so there is no

gas expansion during decompression. The most piezophilic microbe ever obtained, Yayanos' first obligate piezophile isolated from the Mariana Trench, was obtained with decompression during capture and delivery to surface waters. It does lyse after decompression; however, viability only goes down about 2-fold after 10 h and about 20-fold after 30 h at atmospheric pressure. Some cells are not so lucky. The hydrothermal vent microbe *Methanocaldococcus jannaschii*, which lives off of dissolved gases of hydrogen and carbon dioxide, undergoes extensive cell rupture under the specialized conditions of rapid decompression.

The second misconception is that piezophiles must have a super thick and tough cell wall, like the hull of a submarine, to withstand all that pressure. The pressure inside a piezophile is pretty much the same as that outside the cell. Their adaptations are not a reflection of mechanical engineering but rather of biochemical adaptation. The availability of piezophilic microbes in culture collections at places like Scripps and JAMSTEC has made it possible to address the biochemical and molecular bases of life at high pressure (Michiels et al., 2008). Deep-sea organisms have many biochemical adaptations for life in the big squeeze. Most seem to possess high levels of omega-3 polyunsaturated fatty acids in their membranes, the sort of "heart-healthy" molecules that many of us consume daily in the form of fish oil pills. These function to keep membranes of deep-sea life from freezing up. Other adaptations enable them to make DNA and protein and to be motile and undergo cell division at high pressure. It is likely that many proteins from piezophiles have evolved structural changes that maintain their ability to interact with other proteins or with substrates required to carry out enzymatic function. Also, because nutrients tend to be scarce in the deep sea, the microbes there have evolved abilities to take up and metabolize a great range of food sources, many of which cannot be used by surface-dwelling bacteria.

In addition to possessing adaptations to the dark ocean, piezophiles lack adaptations necessary to exist in lighted surface world. They lack enzymes referred to as photolyases that are used to repair DNA damaged by exposure to ultraviolet light. We have found that the addition of a single shallow-water photolyase gene to a deep-sea microbe may render it 10,000× more resistant to ultraviolet rays (Bartlett and Lauro; unpublished results).

Thank You, Piccard and Walsh

Much of our current knowledge of the operation of piezophiles has been made possible by advances over the past decade in genetics and genomics. This has resulted in the identification of genes important for high-pressure sensing, the control of gene expression and growth. It is now possible to go from the isolation of a deep-trench microbe to the elucidation of its blueprint genome sequence in less than 1 year. Biophysicists now ponder the role of specific membrane-spanning regions in a hydrostatic pressure-sensing protein that can relay information needed to turn on or to turn off a gene. It is unlikely that this level of detailed analysis was ever contemplated by Jacques Piccard and Donald Walsh or even Claude ZoBell and Anatolii Evseevich Kriss. However, it all traces back to their legacies.

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TECHNICAL NOTE

Recovery of Live Amphipods at Over 102 MPa from the Challenger Deep

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Introduction

In the early 1970s I began a program to bring live animals from the Marianas Trench into the laboratory. In one sense, this is the inverse of what Piccard and Walsh accomplished in their historic and heroic dive in the Bathyscaph Trieste (Piccard and Dietz, 1961). That is, just as Walsh and Piccard were protected from the known lethal effects of compression to view animal inhabitants in the Challenger Deep, these inhabitants would need to be protected from the presumed lethal effects of decompression to be viewed in our environment.

The essential tasks were first to identify a trench inhabitant and then to devise a method for catching it. Deep-sea photography provided the clue. E. Newton Harvey may have been the first to use an attractant to bring organisms into the field of view of a deep-sea camera (Harvey, 1939). He used a wooden model of a fish painted with spots of luminescent paint and failed to photograph any animals. Since he was the leading pioneer in the study of bioluminescence, it seems natural for him to have employed luminescence as an attractant. The photographic investigation of deep-sea life with the use of attractants of any kind was apparently not resumed in earnest by anyone until the 1960s with the work of Isaacs and his colleagues at Scripps Institution of Oceanography (Bailey et al., 2007). Their work with bait and cameras (so-called baited cameras) yielded pictures showing the presence of large, mobile mega-fauna in the abyssal and hadal ocean (Isaacs, 1969; Isaacs and Schwartzlose, 1975). This research brought about a significant change in our view of deep sea ecology (Dayton and Hessler, 1972; Haedrich and Rowe, 1977).

In 1972, deep-sea photographs showed not only that amphipods were attracted to bait but also that they would swim into containers where bait had been placed (Hessler et al., 1972). This made them prime subjects for live capture for physiological studies. The proliferation of baited camera and baited trap deployments into the deep sea that began in the 1970s led to the conclusion that amphipods, usually less than 10 cm in length, are perhaps ubiquitous in the deep sea, including trenches (Hessler et al., 1978; Yayanos and Nevenzel, 1978). Not only are these amphipods ubiquitous but also thousands of them are often caught in a single small trap. This is not surprising based on the number of them seen in baited camera photographs.

Figure 1 shows a sequence of pictures taken for me by Simon Ferreira of the Isaacs research group on INDOPAC Expedition in 1977 in the Marianas Trench at a depth of 10,599 m (11° 21.3′ N 142° 13.8′ E) close to if not in the Trieste Deep (11° 18.5′ N 142° 15.5′ E). The number of amphipods increases for several hours in the field of view of the camera in successive photographs taken 5 min apart. Figure 2 is a shipboard photograph of an individual amphipod retrieved in a basket trap from the Challenger Deep of the Marianas Trench. Figure 3 is a graph showing the number of

FIGURE 1

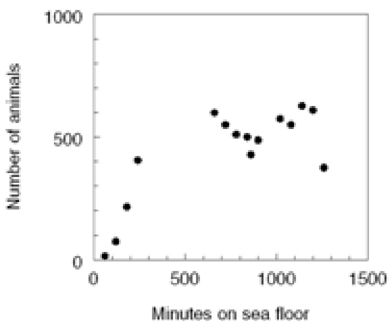
Four of 365 time lapse pictures taken at a depth of 10,599 m close to 11° 21.3′ N 142° 13.8′ E in 1977. If we assume, frame A was taken at 5 min, B was at 45 min, C at 950 min, and D at 1,500 min. Almost all of the animals in the 365 photographs were amphipods.

FIGURE 2

This picture of a specimen (approximately 4.5 cm long) of *Hirondellea gigas* was taken at atmospheric pressure on board ship. So far, traps set in the Marianas Trench have recovered this species exclusively.

FIGURE 3

The graph shows the number of amphipods surrounding bait on the sea floor of the Challenger Deep as a function of time after the arrival of bait. The amphipods were counted in a consistently chosen field of view of the camera in photos such as those in Figure 2.



these amphipods approaching bait over time. Parenthetically, fish were not observed in this sequence of over 365 photographs. Failure to observe fish does not imply their absence as inhabitants or transient visitors in the Challenger Deep because not enough is known regarding issues such as succession of scavengers at bait falls, scavenger food preferences, whether fish from shallower depths are only occasional visitors and other factors (Jamieson et al., 2009).

In summary, photographic observations and trapping results clearly showed that amphipods are excellent target organisms for retrieval in pressurized traps. Furthermore, most amphipods are small enough to be caught in a trap of manageable size, an important consideration for a pressure vessel trap.

Methods

Figure 4 shows a pressure-vessel I designed and had fabricated in 1973 for the purpose of trapping and recovering live amphipods at high pressure from any ocean depth (Yayanos, 1977). The blocks of titanium (the 6Al4V alloy) from which the traps were fabricated were acquired at no cost from U.S. surplus government property. Curiously, I designed the trap based on the size and shape of this block, as apposed to designing the trap and then acquiring the block. One essential feature of the trap is the sliding piston closure (Figure 4) that allows closing the pressure vessel on the bottom of the sea with a sliding motion. Macdonald and Gilchrist (1969) also used a sliding closure, namely, a ball valve, in devices that retrieved water under pressure to depths of 2,000 m and live amphipods from a depth of 2,700 m (Macdonald, 1978). They further showed that a gas-containing accumulator was essential for a pressure-vessel sampler to maintain its contents close to the pressure at which it closed. An accumulator minimizes the pressure drop inside a pressure-vessel trap as the external pressure falls during ascent from the sea floor causing (1) the seals in the trap move and (2) the trap itself to expand because of metal compressibility. An accumulator of appropriate size and filled with nitrogen gas minimizes these two effects. For example, a pressure drop of 20 MPa can be reduced to 2 MPa with an accumulator.

Figure 4 shows a pressure equilibration hole drilled into the pressure-retaining animal trap (PRAT) body. With the trap in an open position, the O-rings on the piston straddle this hole. Without the hole, the thin cylindrical space bounded by the O-rings, the piston wall, and the cylinder wall becomes a sealed space at atmospheric pressure at the beginning of a deployment. As the external pressure increases during descent to the sea floor, the O-rings move toward each other and the piston cannot be moved at depth. I established the need for this equilibration hole by using a pressure testing facility at the Arctic Submarine Lab in San Diego. The pressure equilibration hole keeps the pressure on both sides of the O-rings the same and allows the piston to move freely at any depth.

FIGURE 4

This sketch of a PRAT is modified from one previously published (Yayanos, 1977). When deployed to the sea floor, the top of the piston is below the trap cavity, allowing animals to enter. The piston slides to seal the cavity along with any animals in it. As the trap rises from the sea floor, the O-rings on the piston are pushed equally in opposite directions until a seal is formed. Along with an attached accumulator, the pressure in the trap cavity remains close to value on the sea floor.

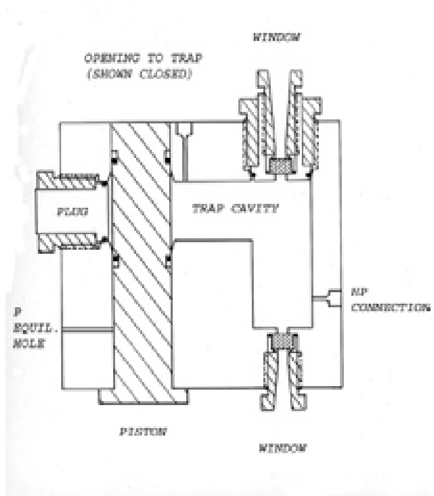
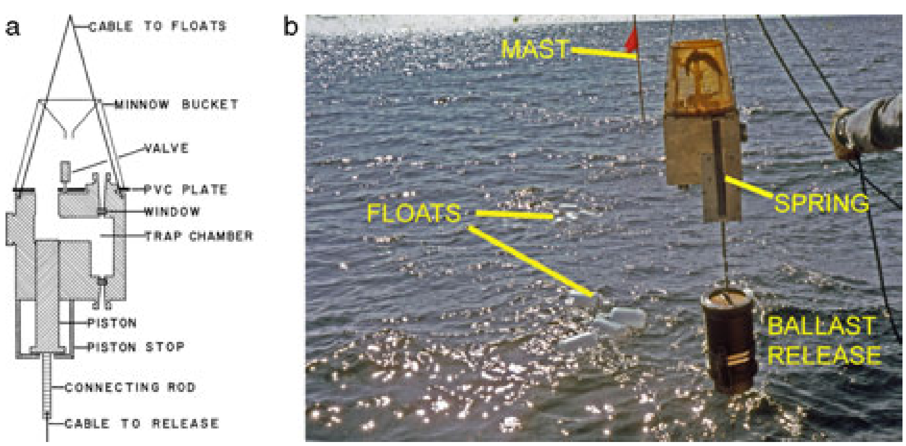


Figure 5 shows the first ocean deployment of a PRAT over the Aleutian Trench in 1974. The overall design of the free vehicle in Figure 5 is based on the designs of others at Scripps Institution of Oceanography (Shutts, 1975). Our free vehicles with their 450 liters of Isopar-M® for buoyancy (Figure 5) are decidedly easier to use on ships with low freeboard.

FIGURE 5

Panel a, on the left, is from a previous publication (Yayanos, 1980) and shows how a PRAT appears during deployment and on the sea floor. The minnow bucket contains bait (panel b on the right) to attract amphipods and some of these usually enter the trap chamber. The mast and floats attach to a cable on the body of a PRAT. The expendable ballast, not shown, attaches to the timed ballast release mechanism via a magnesium back-up release. The tension caused (1) by the weight of the ballast pulling the piston out of the body of the PRAT until it rests on the piston stop and (2) by the buoyant force of the floats keeps the trap entrance open. Two springs (one visible in panel b) move the piston to the closed position when this tension disappears due to release of ballast. The floats are linear polyethylene jugs filled with Isopar-M® (Shutts, 1975; Yayanos, 1976).



Results and Discussion

The first trial over the Aleutian Trench failed because of the lack of a pressure equilibration hole (Figure 4) and the equipment was almost lost because the ballast release timer (Figure 5) did not work. In 1975, we recovered amphipods under pressure, but not alive, from the Philippine Trench. The timed ballast release mechanism shown in Figure 5 again did not function properly causing a reliance on magnesium releases. This in turn resulted in unpredictable surfacing of the free vehicles, in a delay of recovering them, and in the temperature of PRATs equilibrating with that of warm surface waters. In 1977, we began to use highly reliable timed releases (Sessions and Marshall, 1971) and to insulate the PRATs. By 1981, we were using insulation fabricated from 2-inch-thick sheets of Lexan® (Figure 6). In 1977, we successfully recovered live animals at 58 MPa from an abyssal depth of 5,800 m (Yayanos, 1978).

Not until RAMA Expedition Leg 7, to the Philippine Trench and the Marianas Trench, were we successful in retrieving live animals from hadal depths. On November 21, 1980, we recovered a PRAT containing live animals at 102.6 MPa. The PRAT had been deployed at 11° 18.7′ N 142° 11.6′ E over the Marianas Trench to a depth of approximately 10,900 m. Observations of amphipods through the windows in PRATs (see Figure 7), although rudimentary, provide new information of the potential of amphipods to migrate vertically (Yayanos, 1981) and of their status during confinement in a trap. Amphipods have appendages called pleopods that serve essential functions such as locomotion and respiration (Boudrias, 2002). Table 1 shows the pleopod beat

FIGURE 6

PRATs deployed in the Marianas Trench were in rectangular cases to provide insulation of trapped animals from the warm temperatures of the surface waters. The walls and cover (not shown) of each insulation case were made from Lexan®, 2-inches thick. The accumulator attached to the piston side of the PRAT is visible in this photo.

FIGURE 7

Photograph shows a live swimming abyssal amphipod near one of the windows of a PRAT at 58 MPa.

TABLE 1

Pleopod beats per minute at 103 MPa for randomly observed amphipods (5) in PRAT 6. The amphipods were sealed in the PRAT on the sea floor at 06:30 on November 21, 1980.

Date	Time	Beats/min
November 21, 1980	06:30	
	15:36	40.5
	20:45	52.5
	21:50	61.1
	22:40	94.7
	23:00	55.6
	23:05	100.0
November 22, 1980	18:10	121.6
		140.0
		65.9
		73.0
		57.6
		69.2
		133.3
November 23, 1980		70.2
		80.0
	7:00	81.1
	20:50	70.1
		140.0
November 24, 1980		137.6
		76.4
		83.3
November 25, 1980	14:35	87.0
	16:05	77.3
	16:07	77.4
	20:36	69.4
November 26, 1980	9:15	79.1
	16:55	84.5
		120.0
		68.2
		67.9
		67.6
November 27, 1980	15:50	120.0
		51.1
		104.3

frequencies observed in any of five animals randomly selected over several days of confinement in the PRAT at 102.6 MPa and 2.8°C. The temperature at the bottom of the Marianas Trench is 2.46°C (Mantyla and Reid, 1978), very close to that measured in the Philippine Trench (Bruun and Killerich, 1955). We kept the animals alive for 5 days by periodically circulating filtered seawater through the trap with a high pressure seawater circulating system.

Experiments conducted with amphipods from the Marianas and Philippine Trenches show that these animals may be capable of a substantial vertical migration to depths as shallow as 3,800 m. Their tolerance for decompression seems greater than that of amphipods living at 5,800 m. The duration of tolerance to shallower depths, however, remains to be determined. In the few experiments conducted, decompression completely to atmospheric pressure was lethal, with the noted absence of activity following recompression. It remains a possibility that if we had employed a different recompression regime, then the amphipods would have recovered. Recent studies of Tonga Trench amphipods suggest that their ability to live at shallower depths is important in their reproductive biology (Blankenship et al., 2006). The vertical migration of Tonga Trench amphipods is well within the limits surmised from experiments with Marianas Trench and Philippine Trench amphipods.

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PAPER

Living Deep: A Synopsis of Hadal Trench Ecology

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ABSTRACT

The ocean's deepest environments are fraught with extreme conditions, including the highest hydrostatic pressures found on earth. The hadal zone, which encompasses oceanic depths from 6,000 to almost 11,000 m, is located almost exclusively within deep-sea trenches. Fauna inhabiting these hadal trenches represent intriguing yet possibly the least understood communities in our ocean. We present a brief historical account of hadal exploration and a synopsis of the fascinating biogeographical trends that have emerged from 60 years of sporadic hadal sampling. Biodiversity and chemosynthesis, two important concepts in deep-sea ecology, are also discussed in relation to hadal trenches.

Keywords: Amphipod, Biodiversity, Biogeography, Hadal ecology, Trench

Historical Perspective

The great depths of the ocean were known to explorers at the time of the Challenger Expedition (1873–1876); these intrepid scientists took soundings up to 8,200 m. Their incidental collections of fourteen different foraminifera shells from sounding tubes suggested that that protists might live as deep as 7,220 m, although it could be not be determined if the foraminifera were truly living at the depth of capture (Brady, 1884). Conclusive evidence of life at depths below 6 km did not occur until more than a half a century later (Belyaev, 1989). In 1948, a Swedish deep-sea expedition aboard the *Albatross* recovered the first benthic animals (polychaetes and holothurians) from depths between 7,625 and 7,900 m in the Puerto Rico Trench (Wolff, 1960; Belyaev, 1989). This enlightening discovery spawned a decade of vigorous trench exploration, resulting in some of the most comprehensive biological surveys of the world's deep-sea trenches to date. The Danish *Galathea* Deep-Sea Expedition (1951–1952) sampled in five trenches and captured animals at depths slightly greater than 10 km in the Philippine Trench. Beginning in 1949, many trench sampling expeditions were conducted aboard the Soviet vessel *Vityaz*, resulting in the capture of benthic animals from 10.6 km in the Tonga Trench and 10.7 km in the Mariana Trench (Belyaev, 1989). In January 1960, the golden age of trench biology reached a pinnacle when the bathyscaph *Trieste* dived into the Challenger Deep of the Mariana Trench. There, oceanographers Jacques Piccard and Donald Walsh traveled deeper in the ocean than any human before or since and observed an unidentified benthic animal, confirming that all oceanic depths are inhabitable. During this decade of discovery, it became increasingly evident that fauna living deeper than 6–7 km were distinct from the fauna inhabiting the shallower abyssal depths (4–6 km). In 1956, A. Bruun first described depths in excess of 6 km as a unique ecological realm: the hadal zone.

The hadal zone is almost exclusively confined to the ocean's 37 deep-sea trenches, the nine deepest of which are located along the western arc of the Pacific Ocean. The deepest 45% of the ocean's maximal vertical range (which is 11 km) represents the hadal zone, although these extreme depths comprise only 1% of the seafloor surface area. The terms *hadal biology* and *trench biology* are often considered synonyms, but there is a distinction. Trench biology includes all depths within a trench, including depths shallower than 6 km. Conversely, a few oceanic depressions exist outside of trenches that slightly exceed 6 km in depth. For this article, we discuss the biology of hadal depths within deep-sea trenches.

The year 2010 marks the golden anniversary of the *Trieste* exploration of the ocean's deepest depths. The past 50 years has brought remarkable and profound advances in almost all facets of biological oceanography. Yet, hadal biology is still very much in its infancy. Sending deployments to hadal depths is technically challenging and expensive, making it diffi-

cult to collect the biological samples necessary to generate a thorough species list. Manipulative studies (e.g., recruitment experiments), so critical to understanding ecological function, are yet to be conducted at these depths. Consequently, our current understanding of hadal ecological structure is akin to extrapolating the picture printed on a 500-piece puzzle by viewing only a few of the puzzle pieces. In this sense, trench biology represents major frontier in deep-sea studies.

Here, we describe briefly a few of the major ecological paradigms that have emerged from the intermittent hadal sampling efforts conducted over the past 60 years as well as selected ecological questions that remain unanswered.

Biogeography of Hadal Fauna

The extreme hydrostatic pressures that correlate with hadal depths necessitate that hadal organisms adapt both biochemically and physiologically to this cold and extremely high-pressure environment. These adaptations are formidable. Consequently, there are certain deep-sea fauna that appear to be routinely excluded from invading trench environments. For example, organisms with calcium carbonate tests or siliceous skeletons would have difficulty adapting to hadal environments as these depths exceed both the carbonate and the opal compensation depths. At these great depths, calcareous and siliceous skeletons either thin out or dissolve (Todo et al., 2005). While some taxa seem precluded from these depths, other invertebrate and foraminifera groups appear to tolerate and adapt readily to extreme pressures. Consequently, these fauna are well represented in most trench samples and are thought to dominate the hadal communities of the deepest trenches (Belyaev, 1989). Foraminifera and nematodes dominate numerically in benthic environments (Figure 1A) (Danovaro et al., 2002; Gooday et al., 2008). Among the larger taxa, holothurians, polychaetes, amphipods, isopods, soft-shelled gastropods, and even frenulate siboglinids (pogonophorans) are taxa typical in trench samples and are known to inhabit the deepest depths. Amphipods in particular are pervasive throughout the entire hadal zone (Figure 1B). Baited traps set in hadal depths can return with thousands of individuals of one or more species belonging to the Lysianassoidea superfamily. These consistent findings imply that the hadal scavenging guilds are absolutely dominated by a single superfamily of Crustacea (Figure 2). Other important deep-sea invertebrates such as prawns and echinoderms are known to inhabit depths between 6 and 8 km but appear to be insignificant or absent at greater depths (Belyaev, 1989; Jamieson et al., 2009a).

Recent observations with baited traps on landers have expanded our knowledge of fish depth distributions and behavior in the hadal realm (Jamieson et al., 2009b). Fish were once considered to be of little consequence to hadal communities, with the majority of hadal fish known only from the shallowest hadal depths. Indeed, there are 15 species of fish reported from depths greater than 6000 m, but the majority of these species have broad bathymetric ranges and are considered vagrants in the hadal zone. However, there are four liparid (snailfish) species, one each in the Japan, Kurile-Kamchatka, Kermadec, and Peru trenches, that have been reported from hadal depths exclusively; these species are considered trench endemics (Jamieson et al., 2009b). To date, the deepest record of fish was actually made by observations aboard the Archimede bathyscaph in the early 1960s. Observers noted the presence of living fish on the floor of the Izu-Bonin Trench at approximately 9.2 km and also at 8.3 km in the Puerto Rico

FIGURE 1

Examples of dominant hadal fauna. (A) A multicorer deployment at 9,941 m in the Kermadec Trench in 2001 recovered hundreds of Foraminifera specimens belonging to the genus *Hyperammina*, but no animals. (B) *Uristes chastaini*, a small lysianassoid amphipod caught in a baited trap set at 7.3 km in the Tonga Trench in 2001. Removal of exoskeleton parts revealed two eggs nestled in the brood pouch (arrow). This was the first recording of hadal lysianassoid females responding to bait while brooding. Until this discovery, hadal lysianassoid amphipods were thought to purposefully avoid carrion during gestation.

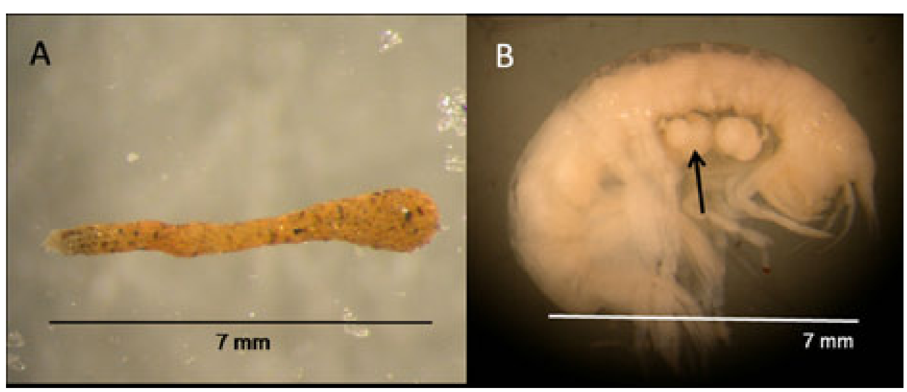


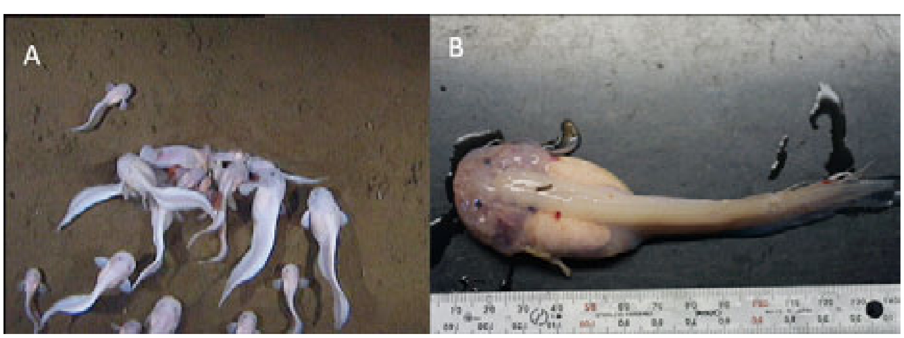
FIGURE 2

John Isaac's *Monster Camera* revealed the vigorous response of lysianassoid amphipods to bait placed at 10.5 km in the Mariana Trench (1974). Note that the bait itself is not visible. Feeding amphipods have completely covered all surfaces of the bait while hundreds more swarm in the immediate area. (Photo used with permission of Scripps Institution of Oceanography Archives, UC San Diego Libraries).

Trench (Belyaev, 1989). Unfortunately, no photographic evidence exists of these observations; the fish species remain unidentified. Recently, the Hadal Environmental Science/Education Program (HADEEP) deployed baited landers to hadal depths, capturing excellent images of fish (*Pseudoliparis amblystomopsis*) responding to bait at 7703 m in the Japan Trench (video is available at http://www.abdn.ac.uk/mediareleases/release.php?id=1531). This is the deepest photographic documentation of living fishes to date (Figure 3). Lander observations have revealed that both fish and large shrimp feed on the abundant scavenging amphipod populations and exhibit swimming and activity rates surprisingly similar to those of their shallow-water liparid counterparts (Jamieson et al., 2009b).

FIGURE 3

Deepest living fish ever photographed. (A) Individuals of the species *Pseudoliparis amblystomopsis* swarm over bait placed at the seafloor in the Japan Trench at 7.7 km. (B) An individual specimen of *P. amblystomopsis* from the same site. (Photos courtesy of Oceanlab University of Aberdeen).



Truly hadal fauna (those that live 7 km and below) do not readily enter adjacent abyssal or bathyal environments (Belyaev, 1989). The primary force of this "abyssal exclusion" appears to be inability of hadal organisms to tolerate lower hydrostatic pressures. Decompression experiments on both deep-sea amphipods and bacteria corroborate this concept (Yayanos, 1981, 1986). Accordingly, the adaptations that permit hadal species to inhabit such depths conversely prohibit ascension into the adjacent abyssal plains. Since deep-sea trenches (and their respective hadal zones) are typically separated from one another by vast stretches of bathyal or abyssal plains, many species appear to be locked into a specific trench or group of neighboring trenches. Confinement of species into a single trench or a group of trenches in close proximity undoubtedly has consequences for gene flow, speciation, and ecological structure of trench communities.

One striking feature is the high degree of endemism that is attributed to hadal fauna as a whole and also within each trench (Wolff, 1960). Belyaev (1989) reports that 56% of the bottom-dwelling hadal species recovered are known to the hadal environment exclusively. Endemism increases with depth. That is, the abyssal zone shares fewer fauna with the 8 to 9 km depth gradient compared with the 6 to 7 km gradient (Belyaev, 1989). In fact, fauna found 10 km deep in the Tonga, Mariana, and Philippine Trenches are not known in the adjoining abyssal

environments. A distinctive trend is that trenches in close proximity (e.g., the Tonga and the Kermadec Trenches) appear to have more species in common compared with trenches that are distantly separated. Disjointed trenches share a very small fraction (less than 5%) of their fauna at the species level (Vinogradova, 1997) and thus exhibit considerable endemism (Belyaev, 1989). We note, however, that accurate estimations rely on sufficient sampling and most agree that no trenches have been "sufficiently" sampled.

The origin of hadal organisms is both a highly interesting and a highly speculative question. We know that the deep sea was approximately 10°C warmer in the Miocene era and experienced a glacier-induced cooling as recently as 16 million years ago (Zachos et al., 2001). This significant cooling probably caused a massive extinction of deep-sea fauna including hadal species during this time (Thomas, 2007). Therefore, current hadal assemblages are probably the outcome of relatively recent invasion and speciation events.

What is the source of a novel hadal species? Three primary repositories — abyssal fauna, other hadal fauna, and polar fauna — are frequently proposed as source fauna, although the relative contribution of each source is unclear. Abyssal fauna with the ability to adapt to greater hydrostatic pressures would certainly be one source of new species, and several abyssal species (e.g., the large amphipod *Eurythenes gryllus*) have populations residing in the upper limits of the hadal zone (Belyaev, 1989; Blankenship et al., 2006). Existing hadal fauna are also likely candidates. If a hadal species somehow emigrated into a different trench, this new population would be exposed to a different array of environmental conditions (i.e., nutrient input, bottom topography, community structure). Adapting to a new environment could eventually lead to speciation. Today, deep water masses that circulate through most of the trenches (especially the Western Pacific trenches) largely originate at high latitudes. Antarctic Bottom Water, for example, most certainly influences trenches in the southern hemisphere; this is evident from temperature profiles. Hyperpiezophilic (ultra pressure-loving) bacteria recently cultured from the Kermadec Trench (located between the 25°S and the 35°S latitudes) show the closest relative to be a psychrophile (cold-loving species) identified from the shallow waters of Antarctica (Lauro et al., 2007). Interestingly, the trench with the lowest degree of hadal endemism is the South Sandwich Trench at an estimated 37% (Belyaev, 1989). This trench is distinguished for its sub-Antarctic positioning and thus proximity to shallow-water Antarctic species.

The relatively large degree of trench endemism (taxa endemic to a single trench) is reduced to an average of 10% when considering genera instead of species (Belyaev, 1989). Thus, individual trenches contain unique faunal assemblages at the species level, but not necessarily at the genus level. This trend hints at relatively recent speciation of hadal fauna. Yet the capacity for gene flow between trenches or between a trench and its adjacent abyssal area is unknown. As an example, the Tonga Trench and the Kermadec Trench (located in the SW Pacific Ocean) are connected by a sill that is 5.2 km at its deepest point. Thus, a hadal organism migrating between these trenches would need to ascend to at least 5.2 km to traverse the sill connecting the Tonga and the Kermadec Trenches. Both trenches contain robust populations of the mobile scavenging amphipod *Hirondellea dubia*; the vertical upper limit for this species is determined to be approximately 7 km based on response to baited traps (Blankenship et al. 2006). To what extent, then, do these two trench populations mingle? If early life stages are capable of surviving such an ascent, then gene flow could be quite high. Extreme pressure tolerances are known in larvae of some invertebrates (Mestre et al., 2009) but not others (Young and Tyler, 1993). For instance, the juvenile stages of at least two trench amphipod species (including *H. dubia*) exist primarily in the shallower depths of the species' vertical distribution (Blankenship et al., 2006). Thus, the younger individuals appear to have greater dispersal potential compared with mature adults. Yet it is also possible that the two trench amphipod populations have been isolated completely into their respective trenches for thousands of years or more. In the latter scenario, gene flow between the two trenches would be zero. That we lack the information to address such questions emphasizes just how little is known about hadal ecology.

Biodiversity: High or Low?

A single hadal sample typically returns with low diversity and often low biomass if collected from an oligotrophic area. Indeed, some deep core samples have returned devoid of a single animal. It is not surprising that the general perception of the hadal environment is one of exceedingly low biodiversity (Grassle, 1989). An appreciation for the exclusionary force of extreme hydrostatic pressures on certain deep-sea taxa only reinforces

this notion. Cumulatively, however, the trenches represent an important realm of speciation and may contribute significantly to deep-sea biodiversity. The isolation of species into individual trenches appears to restrict gene flow, thus facilitating a relatively high rate of speciation as suggested by high rates of endemism. Moreover, the heterogeneity of habitats in trenches is underappreciated. Trench walls are steep and jagged, exposing numerous outcroppings of hard substrate interspersed among localized pockets where sediment accumulates. Trenches are regions of high tectonic activity and therefore possibly places to support chemosynthesis where sulfide or methane escape (e.g., the seep community discovered at 7,300 m in the Japan Trench; Fujikura et al., 1999). The unusual isolation, distribution, and geomorphology of trenches offer exceptional opportunities to test ecological and evolutionary theories about speciation, community assembly, and ecosystem function (Levin and Dayton, 2009).

To date, most sampling efforts have focused on the areas that are logistically accessible: the flat and soft benthos that accumulate in the trench axis and, to a lesser degree, the pelagic fauna in trawls. Technical advancements in sampling or observational apparatus, such as pressure-tolerant cameras (Figure 4), landers, or remotely operated vehicles capable of descending to all hadal depths, may reveal numerous microhabitats along with novel fauna inhabiting these yet-unexplored areas.

The importance of vertical zonation, ambient water temperature, and nutritional input are potential but poorly understood drivers of biodiversity (Jumars and Hessler, 1976; Vinogradova, 1979; Gambi et al., 2003). Deep-sea trenches are extremely steep; a relief of thousands of meters (and corresponding changes in physical parameters such as pressure and temperature) can occur over a few horizontal kilometers. In the Tonga Trench, four species of scavenging lysianassoid amphipods recovered from the hadal zone vertically partition the hadal depths (Blankenship et al., 2006). This vertical partitioning of habitat by amphipod species, similar to the zonation patterns observed on seamounts, may be a mechanism to facilitate coexistence of four similar species, thus increasing the biodiversity in a single trench. Ambient water temperature, which ranges from 0 to 4.5°C, is often ignored in the discussion of trench community structure and speciation. Yet, even temperature changes of a few degrees may factor into an organism's tolerance for a particular environment and therefore govern its distribution (Yayanos, 1986). The influence of temperature on an organism's distribution and therefore speciation and biodiversity should not be discounted without further studies. Likewise, productivity in overlying waters is roughly correlated to benthos biomass, which probably impacts community structure and therefore biodiversity. Trenches under highly productive waters (termed "eutrophic trenches") receive and concentrate large quantities of organic input (Danovaro et al., 2003). This may be both boone and bane to trench bottom fauna. On one hand, the more abundant and diverse food supply may support a greater biomass. For example, beneath the world's most productive waters off Peru and Chile, the Atacama Trench supports higher densities of meiofauna at 7800 m than at 1050–1350 m (Danovaro et al., 2003; Gambi et al., 2003). On the other hand, the steep slopes of these trenches serve to concentrate this matter in what becomes a sediment trap. Tectonic activity creates periodic mudslides off the deep slopes, sending a disproportionately large amount of sediment and organic material into the trench axis. These disturbances are speculated to be a major contributing factor to low species diversity in eutrophic trench bottom fauna (Jumars and Hessler, 1976; Grassle, 1989). However, the

FIGURE 4

(A) A pressure-tolerant camera system capable of withstanding depths up to 10 km is shown in the Deep Tank at Scripps Institution of Oceanography (2001). (B) An enlarged view of a pelagic sea spider (Pycnogonida) captured in the distance by the same camera system deployed in the Aleutian Trench (2005). Although the particular photo was taken at non-hadal depths during ascent, this revolutionary camera is capable of taking hundreds of quality photographs during hadal deployments. (Photos courtesy of Georgia Ratcliffe and Kevin Hardy).

true effect of eutrophic input on trench biodiversity is still undetermined.

Chemosynthesis in Hadal Trenches?

The tectonic events within trenches can trigger turbidity flows and massive slope instability. Therefore, it should not be surprising to find methane emissions and exposed sulfidic sediments along the rims, walls, and ledges of trenches. Where this occurs, methane seeps support dense assemblages of symbiont-bearing clams that rely on reduced compounds from below (rather than organic matter from surface waters) for their nutrition. There are large vesicomyid clams reported from the abyssal zone sections of the Aleutian Trench (Rathburn et al., 2009) and from Sanriku Escarpment of the Japan Trench at 6437 m (Fujikura et al., 1999), but at the deepest known seep in the Japan Trench at a depth of 7326 m, the dominant clams are thyasirids (Fujiwara et al., 2001). As with all seeps, biomass appears to be very high for the depths involved. Common hydrothermal vent taxa such as mussels and tubeworms are not reported from trenches. We do not know yet whether methane seep production reaches the non-seep (ambient) trench animals, but mobile taxa like amphipods could possibly use and transfer this production to the surrounding trench ecosystem.

We speculate that seep communities, which are wide spread along Pacific margins at shallower depths (Levin, 2005), will turn out to be very abundant at hadal depths in tectonically active trenches. Such environments may host new species not yet described from seeps. However, seep environments are extremely patchy and localized at all depths and thus difficult to locate. Their discovery and exploration will require use of ship surveys to detect methane plumes and systematic autonomous underwater vehicle or camera sled transects once evidence of methane is found. If more seeps are found at hadal depths, we may discover novel animal–microbe interactions shaped by high pressure.

These Remote Depths Remain a Mystery

The hadal trenches and the biology and ecology of the creatures that inhabit them remain one of the least understood marine environments. Each expedition greatly adds to our knowledge, sometimes shattering old paradigms but more often leading to more questions than answers (see Figure 1b). For example, the multitude of amphipods that live in the deepest parts of trenches were once thought to be obligate scavengers. Through new molecular techniques, these amphipods are now known to be quite resourceful foragers—feasting on an array of diet items, including their fellow amphipods, phytoplankton, other invertebrates, fish, and even a dairy cow that somehow made its way onto a trench bottom (Blankenship and Levin, 2007). The latter finding demonstrates that trenches, although remote, are not immune to anthropogenic influence. However, because we have no baseline to build from, we cannot ascertain how our presence influences trench communities. Truly, we are still in the "exploratory phase" of research in this fascinating realm.

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PAPER

Deep Sound: A Free-Falling Sensor Platform for Depth-Profiling Ambient Noise in the Deep Ocean

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ABSTRACT

Ambient noise in the deep ocean is traditionally monitored using bottom-mounted or surface-suspended hydrophone arrays. An alternative approach has recently been developed in which an autonomous, untethered instrument platform free falls under gravity from the surface to a preassigned depth, where a drop weight is released, allowing the system to return to the surface under buoyancy. Referred to as *Deep Sound*, the instrument records acoustic, environmental, and system data continuously during the descent and ascent. The central component of Deep Sound is a Vitrovex glass sphere, formed of two hemispheres, which houses data acquisition and storage electronics, along with a microprocessor for system control. A suite of sensors on Deep Sound continuously monitor the ambient noise, temperature, salinity, pressure, and system orientation throughout the round trip from the surface to the bottom. In particular, several hydrophones return ambient noise time series, each with a bandwidth of 30 kHz, from which the noise spectral level, along with the vertical and horizontal coherence, are computed as functions of depth. After system recovery, the raw data are downloaded and the internal lithium ion batteries are recharged via throughputs in the sphere, which eliminates the need to separate the hemispheres between deployments. In May 2009, Deep Sound descended to a depth of 6 km in the Philippine Sea and successfully returned to the surface, bringing with it a unique data set on the broadband ambient noise within and below the deep sound channel. The next deep deployment is planned for November 2009, when Deep Sound will descend almost 11 km, to the bottom of the Challenger Deep at the southern end of the Mariana Trench. If successful, it will return with continuous acoustic and environmental recordings taken from the sea surface to the bottom of the deepest ocean on Earth.

Introduction

Deep Sound, shown in Figure 1, is an autonomous, untethered, free-falling instrument platform designed to descend under gravity from the sea surface to a depth of 9 km. After releasing an expendable, cast-iron drop weight, it then returns to the surface under buoyancy. The descent and the ascent rates are similar at about 0.6 m/s. A Vitrovex glass sphere, with external and internal diameters of 43.2 and 39.6 cm, respectively, and 3.6 cm thick, houses data acquisition, data storage, and power management electronics along with lithium ion batteries.

FIGURE 1

Deep Sound Mk. I, photographed during a tethered engineering test in 100 m water off the coast of La Jolla, Southern California.

Outside the sphere, hydrophones mounted in vertical and horizontal alignments detect the ambient noise field continuously throughout the descent and the ascent. Additional sensors are mounted on Deep Sound for continuous monitoring of temperature, depth, and salinity (hence sound speed) as well as the pitch, roll, and yaw of the platform itself. All the data recorded by the system during the deployment are downloaded after recovery of the system via a USB data link passing through the Vitrovex sphere. Another throughput allows the batteries to be recharged without their removal from the sphere.

A high-density polyethylene (HDPE) casing not only protects the sphere but also provides a mounting structure for the hydrophones, along with the environmental and system sensors. To aid deployment and recovery of Deep Sound, a titanium bail is attached to the HDPE casing, and a high-intensity strobe light, a radio beacon, and an Argos GPS antenna all help to locate the system when it returns to the surface.

During deployment, acoustic data, environmental data, and system data, such as internal temperature, remaining battery life, and system orientation, are centrally processed on an embedded microprocessor, which lies at the heart of the instrument's electronics. This processor also triggers the burn wire switch based on incoming depth data. In the event that the burn wire is not triggered at the preset depth, a number of fail-safe mechanisms are built into the system to ensure that the drop weight is indeed released.

Two versions of Deep Sound, designated Mk. I and Mk. II, have been built and successfully tested in the field. The Mk. II has several improved features over the Mk. I, including four hydrophones instead of two, and a silent solid-state memory rather than the original, mechanically noisy hard disk. To date, the deepest descent has been achieved with the Mk. I version, which reached a maximum depth of 6 km in the Philippine Sea in May 2009 and returned to the surface after a 6-h round trip.

The Deep Sound Channel and Ambient Noise

Deep Sound was developed to profile the ambient noise in the ocean from the surface to the greatest depth, which is approximately 11 km in the Challenger Deep at the southern end of the Mariana Trench. Much of the noise in the ocean is generated by acoustic sources near the sea surface, including surface ships and bubbles created by breaking waves (Wenz, 1962). A sound ray from a surface source penetrates down into the ocean, following a path that is curved due to refraction arising from the depth-varying sound speed.

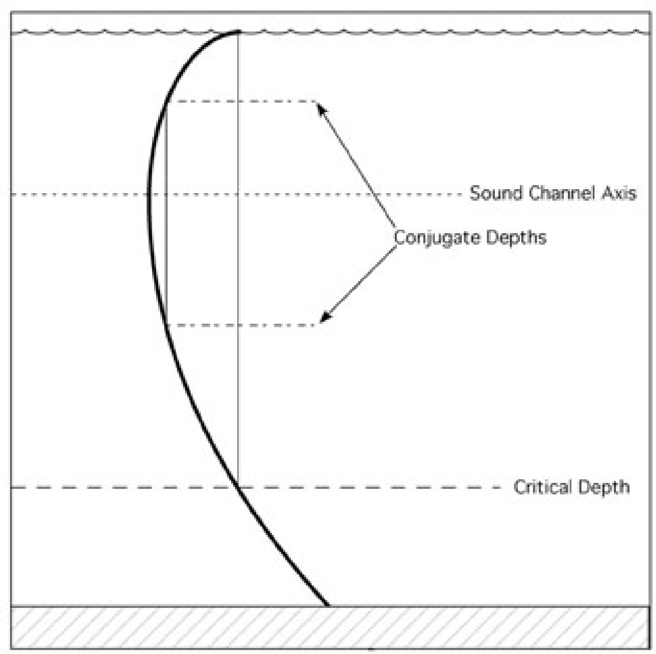
In deep water, the primary factors affecting the speed of sound are temperature and pressure. A schematic of a deep-water sound speed profile is shown in Figure 2. With increasing depth, the temperature decreases giving rise to a corresponding decrease in the speed of sound. Eventually, however, the effect of pressure becomes dominant, causing the sound speed to increase with further increases in depth. The net effect is a sound speed profile that exhibits a pronounced minimum, as illustrated in Figure 2. In temperate waters, the sound speed minimum occurs at depths of approximately 1000 and 700 m, respectively, in the Atlantic and Pacific Oceans.

The sound speed profile acts like a lens, causing sound rays to bend towards regions of lower sound speed. As a result, a deep-water sound speed profile forms a waveguide, known as the deep sound channel, trapping rays around the minimum, or channel axis. It is possible to propagate sound through the deep sound channel over thousands of kilometers (Ewing and Worzel, 1948; Munk et al., 1995) since the attenuation is minimal in the absence of acoustic interactions with the sea surface and sea bed.

Points with the same sound speed on either side of the channel axis are referred to as conjugate depths, and the surface conjugate depth is known as

FIGURE 2

Sketch of a deep-ocean sound speed profile showing the sound channel axis, two conjugate depths, and the critical depth.



the critical depth (Figure 2). According to Weston (1980), at upper and lower conjugate depths, the ambient noise fields have similar properties, and below the critical depth, the noise from surface sources is thought to decay to a negligible level. In equatorial and temperate waters, the critical depth is in the region of 5 km. At such great depth, it is difficult to confirm Weston's predictions due to the difficulty of deploying conventional cabled and moored arrays in such a hostile environment. Consequently, the available data on the depth dependence of deep-water ambient noise are sparse (Gaul et al., 2007; Morris, 1978).

Deep Sound has the capability of descending well below the critical depth, recording the ambient noise field continuously as it progresses. The raw acoustic data collected by the system may be processed to yield the ambient noise spectrum level as a continuous function of depth over a frequency band from 3 Hz to 30 kHz. A depth profile of the vertical coherence of the ambient noise over a similar bandwidth may also be obtained, thus providing a measure of the vertical directionality of the noise as a function of depth and frequency. Such information is needed to test the validity of the various deep-water ambient noise models that now exist, including Weston's.

Design Criteria for Deep Sound

To operate at the greatest depths for periods of several hours, Deep Sound had to meet a number of demanding design criteria. First and foremost, it had to be capable of withstanding enormous pressures, up to the equivalent of 1,100 atmospheres, encountered at the bottom of the Challenger Deep. In both the Mk. I and the Mk. II versions of Deep Sound, a Vitrovex glass sphere was selected as the pressure casing. The sphere also provides the main source of buoyancy. For ease of deployment and recovery, the system had to be small and light enough for two people to manhandle over the side of a boat using a small davit (Figure 1). Since the two versions of Deep Sound that have been built are similar to one another, the Mk. I will be described first, followed by a brief account of the modifications that were introduced into the Mk. II.

Deep Sound Mk. I

The Vitrovex glass sphere, with a maximum depth rating of 9 km, is actually comprised of two hemispheres with flat, polished surfaces of contact. No O-rings are necessary to seal the join, which is kept watertight by hydrostatic pressure. The hemispheres are kept in register with Henkel adhesive and a single wrap of 3M Scotchrap 50, with a vacuum pulled on the sphere through one of its ports. Besides the vacuum port, the sphere has seven ports for electrical bulkhead connectors and a further feedthrough for the internally housed pressure sensor. The bulkheads connect the external sensors to the internal data acquisition hardware as well as providing interfacing for data downloading and battery recharging.

For protection and handling, the sphere is encased in an HDPE hard hat, to which is bolted a titanium bail and an HDPE frame. Two HDPE arms extend away from the frame (Figure 1) and hold the two hydrophones out of the wake of the main body of the instrument. The hydrophones are vertically aligned with a separation of 0.5 m. The overall footprint of the instrument is 0.6 × 0.6 m, with a height of 1 m and a total mass in air of 68 kg. The buoyancy is 215 N, which provides a steady ascent rate of 0.6 m/s, and a 21-kg cast-iron drop weight provides a matching descent rate of 0.6 m/s. At this speed, the round trip from the surface to a depth of 9 km takes 8 h and 20 min.

Data acquisition, data storage, power management, and burn wire control are coordinated by an Arcom Apollo EBX motherboard with a low-powered, fanless Intel Pentium M CPU. The two simultaneously sampled channels of acoustic data are acquired through a National Instruments PCI-4462 analogue-to-digital converter with 100 kHz acoustic bandwidth and 24 bit dynamic range. The pressure and temperature data are recorded, respectively, via serial and USB ports. The Windows XP Embedded operating system and software run from a 2-Gbyte compact flash card, while data storage is provided by a USB-connected 150-Gbyte hard disk.

An OceanServer Technology BA95HC power management unit comprised of four lithium ion batteries powers the motherboard and the individual components of Deep Sound. The appropriate voltages for each component are provided by ATX DC/DC and Vicor Power DC/DC converters, while battery condition is monitored by the main system via a serial port controller. The battery pack is rated at 95 Wh, which allows Deep Sound to operate continuously for 9.5 h. Power is isolated by another DC/DC converter and channeled by the parallel port to the burn wire. A separate circuit with an independent timer, a 9-V battery and an isolated DC/DC converter, provides backup power to the burn wire in the event that the main system software or hardware fail. The expendable

burn wire is fabricated from Seven-Strand Sevalon 250WN nylon-coated stainless steel fishing line.

After the glass sphere has been assembled, an external magnetic switch is used to boot the system. Once running, an external computer can network with Deep Sound through an Ethernet bulkhead connector or by using a wireless ad-hoc connection. Data may be downloaded by networking a hard disk to the system through a USB bulkhead connector. The system may be shut down from a remotely networked computer or the power can be cut with the magnetic switch.

The two acoustic sensors used in Deep Sound Mk. I are Hi-Tech HTI 94 SSQ hydrophones mounted on the HDPE casing with 0.5 m vertical separation. Each of the phones, independently calibrated over a frequency band from 2 Hz to 30 kHz, shows a flat frequency response of approximately −165 dB referenced to 1 μPa. The phones are also calibrated over pressures up to 600 bar, corresponding to a maximum ocean depth of 6,000 m. Hi-Tech Inc. specifies the maximum operating depth of their HTI 94 SSQ phone as 6096 m, but our own independent tests, using the pressure chamber at Deep Sea Power and Light, show that the HTI 94 SSQ functions satisfactorily under much greater pressure, equivalent to a depth of 12 km. Little change in the calibration occurs with increasing pressure.

The operating depth of Deep Sound is determined using a Paroscientific Pressure Sensor 9000-20K, which is mounted inside the glass sphere and measures hydrostatic pressure through a titanium bulkhead. Sea water temperature is measured with a Seabird SBE 38 Digital Oceanographic Thermometer, which is mounted external to the sphere and is rated to a maximum depth of 10.5 km. Every half second, temperature and depth are recorded and, from both measurements, sound speed is estimated.

An Ocean Server compass interfaced to the motherboard via a USB connection is used to measure the pitch, roll, and yaw of the platform. These data are useful in the diagnosis and correction of undesirable system motions during the descent and ascent.

To aid in locating and recovering the instrument after it returns to the surface, three Novatech systems are mounted on the HDPE casing above the glass sphere: an ST-400AR Xenon Flasher, an RF-700AR Radio Beacon, and an AS-900A Argos Beacon. The xenon flasher is a high-intensity strobe light that has proved to be invaluable for visual sighting during a nighttime recovery. The radio beacon broadcasts an intermittent tone, allowing a shipboard radio detection finder to determine the bearing to the instrument. The Argos beacon uses GPS satellite navigation to determine the instrument's position coordinates (latitude and longitude), which are then transmitted to an online server. Each of these systems has a pressure switch to ensure operation only when Deep Sound has returned to the surface. The Novatech systems all have the same type of pressure housing, which is rated to a maximum depth of 7.5 km by the manufacturer. However, in our own independent pressure tests at Deep Sea Power and Light, the RF-700AR Radio Beacon and antenna module were subjected to pressures as high as 1,100 bar (equivalent to a depth of 11 km) without failure.

Deep Sound Mk. II

The design of the Mk. II version of Deep Sound is similar to that of the Mk. I, but with the following improvements.

A Kontron 986LCD-M/mITX motherboard with a low-power, fanless Intel Celeron CPU is used because it has half the power consumption of the original Arcom unit. For data storage, a silent 128-Gbyte solid-state memory chip replaces the mechanically noisy hard disk. In place of individual temperature and pressure sensors, Deep Sound Mk. II has a Falmouth Scientific Standard 2 Micro conductivity, temperature, and depth sensor, with a depth rating to 9 km, which returns salinity in addition to temperature and depth measurements.

Deep Sound Mk. II has four acoustic channels, with the HTI 94 SSQ hydrophones arranged in an "L" shape. Three of the phones are aligned in the vertical and two in the horizontal, with one phone common to both configurations. The spacings between the phones are adjustable, ranging from 0.3 to 1 m. The horizontally aligned phones yield the horizontal coherence of the ambient noise, which is related to the horizontal directionality, while the additional phone in the vertical provides enhanced angular resolution as well as returning information on the spatial homogeneity of the noise.

The Deployment Phase

Deep Sound Mk. I and Mk. II both run National Instruments LabView software to coordinate operations during deployment. After the instrument is powered up using the magnetic switch, a remotely networked computer sets various deployment parameters. Prior to use, the LabView program is assigned depths at which to start and stop recording and a depth at which to drop the ballast weight. Sample rates, dynamic range, and data acquisition parameters

are adjustable through this program. Visual displays of the real-time output of the hydrophones, along with battery life and system temperature, show the operator that the various components of the instrument are functioning correctly.

Two countdown timers are activated on start up: one with a length that is adjustable in the LabView program and the other on an independent circuit, with a length that can only be changed by separating the glass spheres and adjusting a variable resistor. Both timers are fail-safe devices. If either timer reaches zero, the burn wire will be activated and the ballast weight dropped, allowing the system to return to the surface under buoyancy.

Once deployed in the water, the data acquisition system remains idle until reaching the start depth, as determined by the pressure sensor. At this point, continuous data recording during free-fall begins. When the instrument reaches the preassigned drop depth, a voltage is activated on the burn wire, which oxidizes to the point of mechanical failure in less than one minute. The weight then falls away and the instrument begins to ascend while continuing to acquire acoustic, environmental, and system data. Near the surface, when the third preassigned depth is reached, the data acquisition software shuts down and the system returns to idle. Upon arrival at the surface, independent pressure switches activate the xenon strobe, the radio beacon, and the Argos beacon.

The Deep Sound LabView program incorporates the incoming data into real-time decision making, above and beyond the routine deployment procedures. The main purpose of the decision-making function is to avoid the loss of Deep Sound due to errors that may occur in individual system components. Battery life and system temperature (inside the glass sphere) are monitored and if a low-battery threshold is crossed or if the system begins to overheat, data acquisition is terminated and the remaining power applied to the burn wire. In the event of a software or hardware error, such as a data buffer overflow, full data storage, or a non-responding peripheral, operations cease and the burn wire is activated. Descent and ascent rates are continuously monitored, and if significant changes are detected or if the instrument hits the sea bed before reaching the preprogrammed ballast-weight drop depth, the burn wire is activated.

The Lab View program is easily altered, allowing Deep Sound to be deployed in a variety of modes without opening the glass sphere or modifying the control hardware. For example, with the descent-speed monitoring disabled, Deep Sound could sit on the sea bed for a specified time before starting its return to the surface, or to conserve power and extend the deployment time, Deep Sound could be programmed to record data on a duty cycle. Outside the sphere, the acoustic channels are modular, capable of supporting any type of sensor with a bandwidth up to 100 kHz in place of the hydrophones. Indeed, the design philosophy underlying Deep Sound has been the development of a deep-diving platform with software and hardware architectures that provide flexibility in terms of data acquisition, mode of deployment, and sensor pay load.

Deep Sound Mk. I in the Philippine Basin

The first deep deployments of Deep Sound were made in May 2009 during the North Pacific Acoustic Laboratory experiment in the Philippine Basin. Operating from the R/V Kilo Moana, three descents were made to depths of 5,100, 5,500, and 6,000 m. On each occasion, the system descended to maximum depth, released the ballast weight, and successfully returned to the surface. Acoustic and environmental data were recorded continuously during each of the round trips. Figure 3 shows the depth versus time trajectory of the system and the measured sound speed profiles for the third and deepest drop.

During the descent and ascent, Deep Sound measured the ambient noise field on the two vertically separated hydrophones over a frequency band extending to 30 kHz. Although both the sensors were placed outside the wake produced by the main instrument housing, one of the phones was always in the wake of the other, with the result that excess flow noise appeared on the trailing hydrophone. By comparing the spectra from the two acoustic channels, the effect of the flow on the output of the trailing phone becomes apparent, as illustrated in Figure 4. At frequencies below 1 kHz, the trailing phone shows a spectral level some 10 dB above that of the leading phone, although above 10 kHz the excess decreases to about 5 dB. In this particular case, the system was descending and the top phone exhibited the excess noise. A similar excess-noise phenomenon occurs in the ascent but with the lower phone returning the higher spectral level.

Since returning from the Philippine Sea, the Mk. I and Mk. II systems have been modified by fitting open-pore foam flow shields around the hydrophones. These tailor-made flow shields are highly effective at reducing the turbulence-induced noise to negligible

FIGURE 3

(a) The depth versus time profile of Deep Sound Mk. I for its deepest deployment in the Philippine Sea experiment. (b) The measured sound speed profiles from the descent and ascent.

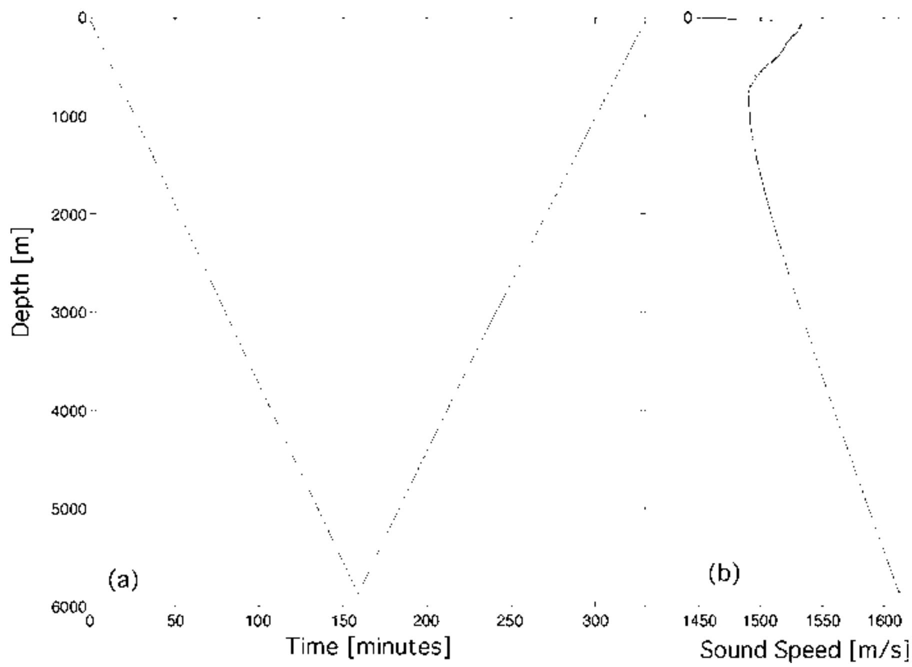
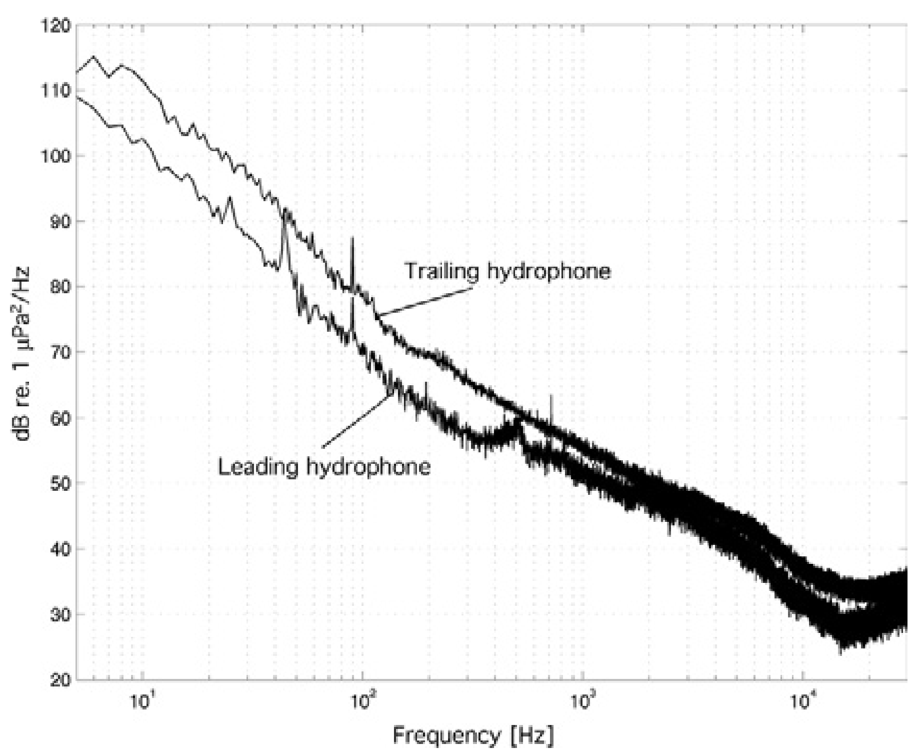


FIGURE 4

Ambient noise spectra from the Philippine Basin deployment, taken while Deep Sound Mk. I descended from a depth of 5667 to 5679 m. The higher level of the spectrum from the trailing hydrophone is due to flow noise from turbulence generated by the leading phone.



levels across the whole frequency band shown in Figure 4. In effect, the flow shields trap still water around the phones, keeping the turbulent flow at a distance from the active faces of the sensors.

Future Deployment and Development of Deep Sound

Since the successful deployment of Deep Sound Mk. I to a depth of 6 km in the Philippine Sea, the Mk. II version, with four acoustic channels, has been tested in the shallow ocean off the coast of La Jolla, southern California. Both systems are now ready for the next deep deployment, which is scheduled for November 2009 in the Challenger Deep at the southern end of the Mariana Trench. The ocean at this location is the deepest in the world at just under 11 km. The Vitrovex glass spheres in both systems are rated by the manufacturers to 9 km. Following a cautionary plan, the Mk. I. and Mk. II systems will first be deployed within specifications to a maximum depth of 9 km. Assuming a successful return to the surface, the batteries of Mk. I will be recharged, taking a little less than 3 h, and the system sent down again, but this time to within 100 m of the bottom. Thus, the maximum deployment depth in this deepest of deep descents will be around 10,800 m, corresponding to a round trip travel time of 10 h. One or more hydrophones near the surface will listen for the sound of an implosion, which, if it were to happen, would be useful for failure diagnosis.

A third version of Deep Sound, the Mk. III, is currently in the planning stage. This new instrument will use a Vitrovex glass sphere of diameter

0.43 m, with a depth rating of 11 km, significantly greater than that of its predecessors. This improved depth capability, along with our independent pressure tests of the HTI 94 SSQ hydrophones and the Novatech instrument housings to an equivalent depth of 12 km, will give Deep Sound Mk. III a full ocean depth capability. Other modifications will include the addition of high-precision, very-low drift tri-axial accelerometers, which will be used for inertial navigation of the system. The intention is to provide a current-profiling capability by monitoring the motion of the platform due to advection by local currents during its descent and ascent through the water column.

Acknowledgments

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PAPER

HADEEP: Free-Falling Landers to the Deepest Places on Earth

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ABSTRACT

The hadal zone, comprising mostly deep trenches that plummet to nearly 11 km deep, represents the largest poorly understood habitat on Earth. This knowledge dearth has been technology induced rather than of scientific interest. The U.K.–Japan collaborative project Hadal Environment and Educational Program (HADEEP) is one venture where scientists and technologists have been working to fill this knowledge gap, particularly from a biological perspective. With limited funds and even more limited time, two 12,000-m autonomous free-fall baited imaging landers, known as hadal landers, were constructed to follow in the footsteps of the 1960 *Trieste I* dive; "to remotely go where two guys had gone before." In the past 2 years, the hadal landers have been deployed in five hadal trenches in the North and South Pacific Ocean across a depth range of 5,500–10,000 m. This new technology has led to many new discoveries including, among others, large aggregations of fish at 7,703 m, which are the deepest video footage of fish ever taken. Here we describe the origins of the HADEEP project, the challenges in developing the technology, and the scientific outcomes of exploring the deepest environment on Earth some 50 years after the pioneering *Trieste I* dive to Challenger Deep.
Keywords: Hadal zone, Trenches, Free-fall baited landers, Deep-sea technology

Introduction

The hadal zone (6,000–11,000 m) is a geographically disjunct deep-sea environment comprised mostly of deep trenches formed by tectonic subduction (Stern, 2002). Hadal trenches account for the deepest 45% of the oceanic depth range and host active and diverse biological communities (Beliaev, 1989). The first major trench sampling campaigns were conducted during the early 1950s on the Danish *Galathea* and Russian *Vitjaz* expeditions. Using trawl and grab methods, the diversity, abundance, and biomass of invertebrates were described and showed a seemingly high degree of endemism. Since then, very few trench sampling campaigns, particularly at an intertrench level, have been undertaken and as a result ecological information is sparse. All reviews of the hadal environment (Wolff, 1960, 1970; Angel, 1982) have primarily been based on the two 1950s data sets; therefore, ecological interpretation of hadal trench ecosystems is not comprehensive and is at best speculative. Considering all trenches to be a single habitat is likely to confuse interpretation of environmental drivers. Intertrench ecosystems are likely to be determined by the interaction of, for example, the geography, hydrology, food supply, topography, seismic activity, substrata, hydrostatic pressure, and temperature.

The biology and the ecology at hadal depths are perhaps no more complicated than at shallower depths. This knowledge gap is a result of insufficient technology and therefore access to this environment. Renewed interest in these deep trenches combined with modern technological advances has created new opportunities to explore and understand the deepest environment on earth.

Among other new international efforts, one such project is currently addressing this knowledge gap and providing a more detailed insight into life in the trenches: the Hadal Environment and Educational Program (HADEEP). HADEEP is funded jointly by the National Environmental Research Council (NERC, U.K.) and the Nippon Foundation (Japan) as a collaborative project between the Oceanlab, the University of Aberdeen (U.K.), and the Ocean Research Institute (ORI), University of Tokyo (Japan).

Conceiving HADEEP

The HADEEP project was conceived during in impromptu trip to a bar in Aberdeen town centre during the Benthic Dynamics conference (March 25–29, 2002). The conference was comprised mostly of participants involved in Sediment Profile Imaging (SPI) cameras. Among those present were Martin Solan, a benthic ecologist, and Alan Jamieson, an engineer from Oceanlab. A few beers later, the

conversation turned to "who has taken the deepest SPI image?" The award went to a brave SPI enthusiast from Virginia who had taken an image at 6,000 m despite his camera only being rated to 5,000 m (Diaz, 2004). Several beers later, the conversation meandered into how that could be beaten, which eventually led to where it could not be beaten. That place of course was *Challenger Deep* in the Marianas Trench (~11,000 m). Although the details are now perhaps a bit fuzzy, the night ended with a confident "let's go to the Marianas Trench."

At that time, the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) were successfully operating a 12,000-m rated remotely operated vehicle (ROV) called *Kaiko* (Takagawa, 1995; Mikagawa and Fukui, 1999). The next day at the conference, members of JAMSTEC who were also attending were approached by two guys from Aberdeen with an enquiry to deploy a mini-SPI camera on *Kaiko*.

Developing the Hadal-Cam

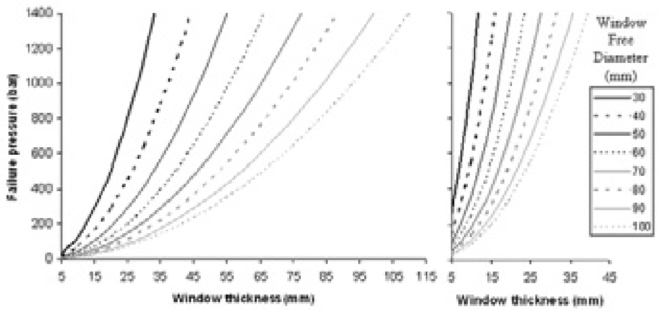
The following year saw efforts in both Japan and the U.K. to secure funding to develop the technology required for hadal rated instrumentation. The original idea was to design a camera system capable of both SPI imaging and seafloor imaging. This also coincided with a part-time PhD study developing autonomous instrumentation platforms for deep-sea biological studies (Jamieson, 2004). As part of that PhD, pressure vessel and optical viewports were theoretically designed and prototypes were tested to withstand pressures of 1,400 bar (11,000 m operational depth with 3,000 m safety factor). A sum of money was eventually secured from internal Aberdeen University funds to develop a 12,000-m rated video camera that became known as the Hadal-Cam. Although the Hadal-Cam was only one piece of a potentially larger project, it provided an asset in which to secure a larger supporting grant to use the *Kaiko* ROV. The money for developing the Hadal-Cam was awarded on May 19, 2003. Elsewhere on May 19, 2003, the *Kaiko* ROV was tragically lost at sea while surfacing in an emergency during a typhoon (Momma et al., 2004), an unprecedented loss to deep-sea exploration. Meanwhile, it was decided to continue developing the Hadal-Cam. Knowing that any video footage would be of public interest it was important to source a camera "better than TV" quality. A Hitachi HV-D30, 3CCD color video camera was chosen (800 TV lines) with a 2.8- to 8-mm wide-angle varifocal lens. The system was designed to operate autonomously, and video capture was controlled by mission control software, specially developed by John Kinmond at NETmc Marine (U.K.).

The software permits user defined power up/down sequences, repetitions, and start delay. A relay board, with built in microprocessor, was used as the interface between the camera, lights, and recorder and enabled the recorder to power off and on to maximize battery life. The recorder was a modified NETmc Marine DVR Inspector, a high-end broadcast quality MPEG2 recorder with an Opti-base encoder card (type MPG9005). This gave a screen resolution of 704 × 576 pixels. Illumination was provided by twin 50-W lamps, and the entire system was powered by a 12-V lead acid battery (SeaBattery; Deep Sea Power & Light, USA). The camera and lights required in-house customizing to withstand the enormous pressures at hadal depths. The pressure-resistant housings designed by Jamieson (2004) were based on the elementary mechanics of *Roark's Formula for Stress and Strain* (Young, 1989) and prior experience of designing for 6,000 m. To lighten the payload weight of the ROV (or other potential vehicles), titanium 6Al-4V provided the best strength-to-weight ratio and corrosive properties. While the main body of the housing was relatively straightforward, the camera window or "viewport" became the most challenging development. It was apparent that the problem of transparent viewports at high pressure was not a new one, even the crew of the *Trieste I* dive noticed a 2-mm creep of their viewports (Lt. Don Walsh, 2004, personal communication). Based on principles described by Gilchrist and MacDonald (1980), a series of acrylic beveled disc test pieces were pressurized to 1,400 bar. On each cycle, the acrylic crept into the air cavity behind it. The distortion increased with time at pressure, eventually resulting in the entire viewport being squeezed into the housing, that is, baroplastic deformation (see Gonzalez-Leon et al., 2003). No noticeable deformation took place until beyond approximately 800 bar (8,000 m). After a series of pressure tests at the Scottish Offshore Material Centre at the University of Aberdeen, acrylic viewports were abandoned on the grounds of baroplasticity. Further research into materials, viewport shape, and seating design were investigated, and decisions were made with the limited budget in mind. To keep costs low, a plane disc window design was favored as they required less machining, less wasted material, and therefore reduced costs. With acrylic eliminated from the study, borosilicate glass and sapphire

discs were tested. Sapphire offered the best solution in terms of size and reliability, whereas borosilicate windows were unpredictable and become disproportionately large. So much so, the equivalent thickness of a plane disc window in sapphire is less than half that of borosilicate (Figure 1) and furthermore did not incur any significant cost increase. The free diameter, that is, the hole that the camera lens protrudes through the housing end cap, was just 30 mm; therefore, a sapphire disc of 60 mm diameter by 15 mm thick, seated on a 5-mm^2 axial quad-ring (40 mm inner diameter) sufficed. This relatively small and cheap solution was then successfully tested to 1,400 bar for up to 24 h.

FIGURE 1

A comparison of window thickness against failure pressure of borosilicate glass (left) and sapphire (right) of varying window free diameters. The equivalent window in sapphire is less than half the thickness of borosilicate.



With the lamp housings, a different solution presented itself. A chance encounter with Gerald Abich at Nautilus Marine Services (Bremen, Germany) led to an idea of using two Vitrovex® glass mini-spheres (100 mm inner diameter). These spheres were design to be small and just coincidentally could hold 1,200-bar pressure. As the optical path of the illumination is not as critical as the camera, the mini-spheres provided another very simple and cost-effective solution. In the end, the 12,000-m rated 50-W lamps cost less than off-the-shelf commercial 50-W lights rated to 6,000 m.

At this point, the Hadal-Cam was not completed as the spiraling costs of titanium had put Ti 6Al-4V beyond the financial limits of the project. So by the end of 2004, all that was achieved was a PhD thesis, two lamps, a sapphire window, the guts of a camera, a bag of deformed acrylic, and a big idea. Following several unsuccessful attempts to secure funding, it seemed that determination and delusions of grandeur alone were not enough.

The HADEEP Project Origins

During 2006, negotiations with our Japanese collaborator, who by then had moved from JAMSTEC to the Ocean Research Institute, University of Tokyo, had opened a dialogue with the Nippon Foundation (Japan). The Nippon Foundation liked the idea and agreed to fund a joint project to investigate life in the hadal trenches. The complication was that although they would support access to research vessels, there was not enough money to actually construct a hadal rated vehicle and there were still no signs of a *Kaiko* ROV replacement. However, things started to fall into place from hereon. Oceanlab, founded by Prof. Monty Priede had been built around a 20-year history in constructing baited landers (autonomous free-fall vehicles) used to image deep-sea fauna. With some consideration of deep-sea ecology and optimal foraging theory, the remoteness from surface derived particulate organic matter should result in animals relying more on carrion falls (dead fish and cetacean carcasses) that should reach the seafloor irrespective of depth. It then seemed logical to extend this deep-sea baited lander expertise to full ocean depths and not go down the mini-SPI route as originally planned. A grant application entitled "HADEEP—Life at extreme depth; benthic fishes and scavenging fauna of the Abyssal to Hadal boundary" was submitted to the NERC (U.K.) and was successful. The application proposed the construction of two hadal rated baited landers and a full-time Postdoctoral Research Fellow. The landers would be a baited video and a baited stills lander. The still imaging technique provides a time course of scavenging fauna to estimate population size whereas the video system would provide behavioral and physiological data of the observed fauna. Around that time, an opportunity of a research cruise was offered by Prof. Hans-Jochen Wagner of the University of Tubingen, Germany, who had secured a 3-week expedition between Samoa and New Zealand on the German research vessel *Sonne*. Although the cruise was primarily mid-water trawling, the cruise path just so happened to transect the Tonga and Kermadec Trenches in the SW Pacific, both of which are deeper than 10,000 m. The cruise left from Samoa

on the 1st of July but the funds from NERC were not received until the 1st of February. The shipping time to Samoa was "at least 2 months" leaving just 3 months to design, construct, test, and mobilize the landers from Scotland to New Zealand.

The Hadal Landers

Autonomous landers are comprised of two parts: The delivery system (buoyancy, ballast, structure, and acoustic releases) and the scientific payload (cameras and environmental sensors). The basic delivery system carries and protects the scientific payload within a frame. Buoyancy is coupled to the topside while ballast is coupled to the underside and temporarily held by the acoustic releases. With the ballast on, the lander free falls to the seabed where the autonomous instrumentation perform preprogrammed tasks. By acoustic command from the ship, the releases jettison the ballast weights and the ascension to the surface begins by virtue of the positive buoyancy where it is retrieved by the surface vessel (for further details on lander design see Tengberg et al., 1995; Bagley et al., 2005).

The Delivery System

The structure of the landers were based on existing Oceanlab video tripod landers (for, e.g., Priede et al., 2006) made from marine grade aluminum 5082 but re designed to 3/4 the size. The buoyancy was tethered in off-line modules on a mooring line above the frame. This method permits the landers to be deployed from relatively small ships and can be modified/replaced depending on how the lander evolves. A 45-kg clump of ballast weights were suspended from each of the three legs approximately 250 mm from the seafloor to give a confident drop when triggered. The biggest challenges in the delivery system were sourcing the 12,000-m rated acoustic releases and buoyancy.

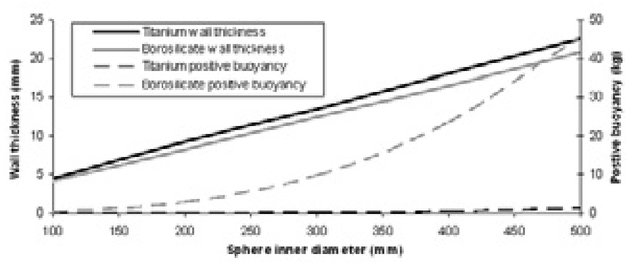
For over 10 years, Oceanlab had been using IXSEA acoustic releases, formally MORS and OCEANO. IXSEA were approached about extending their product depth range to 12,000 m. The acoustic releases are a key component in lander operations and thankfully IXSEA did not quite fall off their chair when asked. On the contrary, a couple of months later, four "ultimate depth" 2500-ti acoustic releases arrived in Aberdeen. Two releases were incorporated into each lander, simultaneously coupled to a ballast release catch to provide back-up in the unlikely event one should fail. The releases comprised the standard electronic sub-assembly of the Oceano 2500 Acoustic Release range, rehoused in a titanium grade 5 body tested to 1,420 bar. In good environmental conditions, the acoustic performance allow ranges >12,000 m. The remote communications were provided by the standard TT801 Deck Unit.

There were a few avenues to explore in sourcing the buoyancy: syntactic foam, ceramic spheres, titanium spheres, and glass spheres. The syntactic foam option was unavailable partly due to time constraint and partly due to costs. The ceramic spheres were investigated but that technology at the time was in its infancy and was felt to be too high risk in this application. Interestingly, titanium spheres will not produce significant positive buoyancy at 12,000 m. For example, assuming a design safety factor of 1,400 bar failure pressure, the positive buoyancy generated by any diameter of sphere will be less than 2.5 kg due to the require wall thickness (essentially weight) required to withstand the ambient pressure (Figure 2). Again, as luck would have it, Nautilus Marine Services in Germany, who had previously supplied the mini-spheres, appeared confident they could increase the wall thickness of their standard 17-inch Vitrovex® sphere for 12,000 m operations. The spheres had an outer diameter of 432 mm and an inner diameter of 393 mm (20 mm wall thickness) producing 19 kg of positive buoyancy each. The catch was that they would not be ready in time for the U.K. to Samoa shipment and therefore had to be shipped directly from Germany to Samoa.

One other component to the delivery system is the location aiding

FIGURE 2

The required wall thickness (mm) and resulting positive buoyancy (kg) of titanium and borosilicate spheres of varying inner diameter (100–500 mm) at 1,400-bar pressure. Titanium spheres cannot produce significant positive buoyancy at these depths.



devices for when the landers surface. These are typically a strobe light, a VHF beacon, and a flag. The flag was as standard (orange); however, a great deal of time was invested in redesigning the VHF radio and Xenon strobe (Novatech RF-700A and ST-400A, respectively; Cobham Ltd, Canada). These required rehousing into a Nautilus 12,000-m glass sphere as they are supplied as 7,300 m rated. Roger Scrivens at RS Aqua (U.K. agents for both Cobham and Nautilus) randomly suggested sending one of these housings to Nautilus to pressure test it as he had a feeling it was good to 1,000 bar. Some further calculations were done and surprisingly the standard off-the-shelf 7,300 m rated Novatech radios and strobes are capable of 10,000 m operations.

The Scientific Payload

The old plans for the Hadal-Cam housings were reviewed and with the costs of titanium now increasing beyond all reason they were reluctantly redesigned in Stainless Steel UNS32550. The electronics were housed in one large cylinder (later described as a "cannon-barrel") and the camera was housed remotely in a smaller version incorporating the sapphire viewport. The size of the electronics housing was such that it weighed over 100 kg in air and would not fit into any pressure test vessel capable of 1,400 bar. It was therefore tested to 700 bar at Oceanlab with the remaining few thousand meters relying heavily on crossed fingers and Roark's formulas. The Hadal-Cam was positioned on the landers lower deck 1 m off the seafloor. The camera and lamps face vertically down and focused on a 10-mm diameter × 1,000-mm bar where the bait is secured. This produced a field-of-view of 68 × 51 cm (0.35 m^{-2}). The bulkhead connectors and cabling were readily available as standard Impulse 20,000 psi rated wet pluggable series (Teledyne Impulse, USA). When ready to explore the deepest places on earth, it was essential that the depth was recorded. Another chance encounter, this time with Calvin Lwin from SeaBird Electronics Ltd (USA) led to the purchase of two SBE-39 temperature and pressure sensors rated to 10,500 m with an accuracy of 0.0002°C and 0.1%, respectively.

The last item of scientific payload to be sourced was the digital stills camera. With the time constraints, it would be difficult to design and build one in-house. Oceanlab typically use Kongsberg Maritime 6,000 m rated digital stills cameras and so they were approached. Like Nautilus, Kongsberg gratefully agreed to supply such a camera but again could not make the shipment to Samoa with the rest of the equipment; therefore, a third shipment was scheduled to rendezvous in Samoa. The camera was an OE14-208 5-megapixel digital stills camera based on Canon G5 technology. It had a remote flash gun and both were housed in grade 5 titanium. The camera and the flash were powered by a 24-V lead acid battery (SeaBattery; DeepSea Power and Light, USA).

In addition to the landers "high-tech scientific payload," three baited funnel traps, made from garden wire and drainage pipe, were lashed to the feet to collected any small scavenging crustaceans for taxonomic and genetic studies.

The landers were finally assembled, albeit still missing several crucial components, a few days before the shipment date, just in time for a quick dunk in a test tank before loading the 20-foot container destined for Apia, Samoa (Figure 3).

FIGURE 3

An almost complete Hadal-Lander A ready for testing (left). The Hadal-Cam camera housing and sapphire window assembly (top right) and a 50-W lamp housed in a 114-mm diameter mini glass sphere.

Into the Hadal Zone

The South Pacific

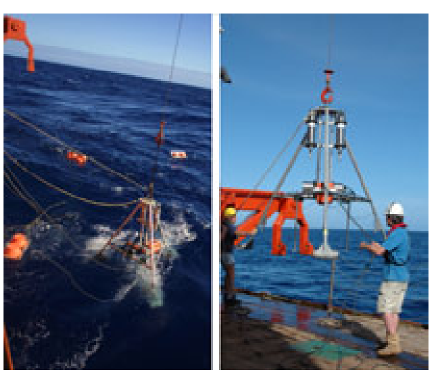
At the end of June, Drs. Jamieson and Solan and the newly appointed Dr. Toyonobu Fujii met the RV *Sonne* in Apia. After a trying time getting the equipment cleared of customs, it became apparent that there may be problems with the other shipments. The camera eventually arrived with 2 days to spare. On the day of departure, the ship was due to sail at 0930 h. The thirty 17-inch glass spheres finally cleared customs at around 0900 h and were hastily thrown on board in disbelief before transiting to the Kermadec Trench. When exactly they arrived in Apia is still unknown.

The very first time the landers were completely assembled and tested minutes before the descent to 6,000 m on the edge of the Kermadec Trench. The landers were christened, rather unimaginatively, Hadal-Lander A (video; i.e. Hadal-Cam) and Hadal-Lander B (stills). The Hadal-Cam was set to record 1 min of footage every 5 min (1 min on, 4 min off), 120 times, and the stills camera was set to 60-s intervals. Thankfully, both landers returned on command the following morning. Over the next 2 days,

the landers were deployed to 7,000 and 8,000 m. Unfortunately, as a result of a fault in the voltage regulation, the Hadal-Lander B stills camera failed to operate. However, Hadal-Lander A was an unprecedented success. The 6,000- and the 7000-m deployments captured both the deepest ever decapods (a family including prawns, crabs, and lobsters), on this occasion the natantian prawn *Benthesicymus crenatus* (Jamieson et al., 2009a), and filmed the endemic snail fish *Notoliparis kermadecensis* alive for the first time (Jamieson et al., 2009b). This snailfish has only ever been trawled once in the early 1950s and the Hadal-Cam managed to capture extensive footage of three individuals swimming and feeding in their natural habitat. The landers were later deployed to 9,000 and 10,000 m in the Tonga Trench. Interestingly, the Tonga Trench is apparently the resting place of the radioisotope thermoelectric generator from the aborted Apollo 13 mission (which supposedly contained ~4 kg of plutonium). The 10,000-m deployment (Figure 4) was a great milestone in the project, proving after all these years the capability for full ocean depth observations. The video footage from 8,000, 9,000, and 10,000 m showed ever increasing numbers of small amphipods (Crustaceans), almost exclusively the endemic species *Hirondellea dubia*. The baited funnel traps managed to capture thousands of amphipod specimens for taxonomy and population genetic studies.

FIGURE 4

The deployment and recovery of Hadal-Lander A to 10,000 m in the Tonga Trench from RV *Sonne* in July 2007.



From an ecological perspective, the cruise was an enormous success and not only gave an insight into what could be achieved and proved that each of the components were capable of 10,000-m operations, which came a great relief to the HADEEP team and the component suppliers alike.

The North Pacific

The RV *Sonne* returned to Auckland, New Zealand, where the landers were shipped to Japan for the next wave of expeditions. Between October 2007 and March 2009, four trench expeditions were undertaken in the NW Pacific: two to the Japan trench (7,100 and 7,700 m) on the RV *Hakuho-Maru*, one to the Izu-Bonin Trench (8,100 and 9,300 m) on the RV *Tansei-Maru*, and one on the RV *Kairei* to the edge of the Marianas Trench (5,500 m), which was later declared a national monument by former U.S. president George W. Bush in 2009. Over the course of the cruises, the landers were upgraded and improved on several levels. Firstly, a 2-L Niskin water bottle (Ocean Test Equipment Inc., USA) was added to each system and were coupled to the ballast release mechanism to collect bottom water for laboratory based oxygen measurements. Also, the environmental suite was upgraded with SBE19plus V2 CTD profilers rated to 10,500 m (SeaBird Electronics, USA). The CTDs provide a temperature, salinity, and pressure resolution of 0.0001°C, 0.4 ppm, and 0.002%, respectively, from the sea surface to the trench floors and were set to sample every 10 s throughout the deployment. The invertebrate traps also received an upgrade. Dr. Fujii, determined to trap "something bigger," constructed a "giant funnel trap" from garden wire and an old sewage pipe, a classic mix of high tech meets low tech, but with amazing results.

The highlights of these cruises were the deepest ever decapods (again; Jamieson et al., 2009a), the deepest ever grenadier or "rat-tail" fish (*Coryphaenoides yaquinae*, family Macrouridae), and the first ever live footage of another snailfish, this time *Pseudoliparis amblystomopsis* (family Liparidae; Jamieson et al., 2009b). Perhaps the most significant single deployment of the project was with Hadal-Lander A at 7,703 m in the Japan Trench in October 2008 when a total of 20 snailfish were seen in view of the camera. This was the deepest footage of fish ever taken and of so many it was truly remarkable. Furthermore, Dr. Fujii's giant trap captured not only three juvenile snailfish, but two five giant amphipods of two species and two gastropods (Figure 5).

FIGURE 5

High tech meets low tech: Hadal-Lander A with the new CTD system pictured on the RV *Tansei-Maru* (left). The large and small funnel traps (top right) which caught the large amphipods (middle right) and the remains of the mackerel bait after 12 h on the trench floor (bottom right).

Due to adverse weather, ship time restriction, and another unrelated electrical fault, Hadal-Lander B was only successfully operated in the 5,500-m Marianas Trench deployments.

At some point in the North Pacific expeditions, the landers developed nicknames: Hadal-Lander A became known as *Alfie* after a long story involving a horse and Hadal-Lander B became known as *Jonah* after its rather incredible run of bad luck.

Technical Evaluation

After 15 deployments in five trenches over 2 years, it is now possible to technically evaluate the performance of the landers (Table 1).

The landers descended to the seafloor at a mean velocity of 45.6 m·min^{-1}, which equates to 3 h 27 min to reach 10,000 m. The average ascent speed was 33.6 m·min^{-1}, resulting in a 10,000-m ascent time of 4 h 40 min. As the landers travelled through various water masses and changes in density and pressure, the descent slowed with depth and after ballast release slowed again during ascent, both by about 6 m·min^{-1} (Figure 6). For practical reasons, a mean terminal velocity, as described by Tengberg et al. (1995), is sufficiently accurate to plan experimental times.

One concern prior to hadal operations was glass sphere fatigue under such immense pressure cycling. To date, only one glass sphere out of 22 regularly used spheres has been retired due to excessive accumulation of glass dust on the inside but no failures at depth have occurred.

The video camera was always set to record 1 min of footage every 5 min (1 min on, 4 min off) 120 times. The 1-min files in MPEG2 were 50.5 megabytes each, resulting in ~6 gigabytes per deployment. The average digital still image size was 1.6 megabyte resulting in ~1.3 gigabyte of images per 12 h on the seafloor.

The acoustic communications with the landers have been good. Two-way communication between the releases and the deck unit via an 8- to a 16-kHz hull mounted transducer on the *Sonne* provided extremely accurate slant ranges (within 100–200 m of the bottom depth). However, when using the over-the-side remote transducer head, the return signal to acknowledge command execution is not detected until the landers are ~6,000–7,000 m deep depending on location. The release function always executed

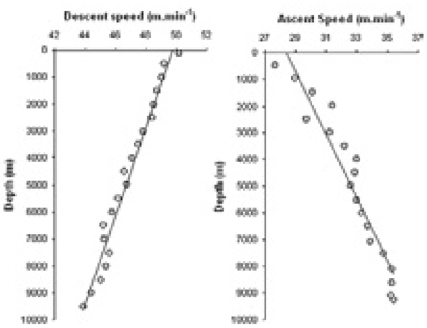
TABLE 1

Specification summary of Hadal-Lander A and Hadal-Lander B.

Lander	**Hadal-lander A**	**Hadal-Lander B**
Type	Baited Video, CTD	Baited Stills, CTD
Nickname	*Alfie*	*Jonah*
Depth rating	12,000 m	12,000 m
Delivery system		
Acoustic releases	Oceano 2500-Ti UD (x2)	Oceano 2500-Ti UD (x2)
Buoyancy	17″ glass spheres (x13)	17″ glass spheres (x9)
Total positive buoyancy	247 kg	171 kg
Ballast weight (wet)	135 kg (45 × 3 kg)	135 kg (45 × 3 kg)
Vehicle weight	180 kg	110 kg
Total weight (descent)	68 kg *−ve*	74 kg *−ve*
Total weight (ascent)	67 kg *+ve*	61 kg *+ve*
Descent velocity	45.6 m·min^{-1}	33.6 m·min^{-1}
Ascent velocity	54.2 m·min^{-1}	34.0 m·min^{-1}
Scientific payload		
Camera	Hadal-Cam	Kongsberg OE14-208
Camera resolution/format	704 × 576 pixels (MPEG2)	5 megapixel (JPEG)
Camera sample interval	1 min every 5 min	1 min
Camera sample number	120	2000
Battery	12v lead acid	24v lead acid
Camera field of view	68 × 51 cm (0.35 m^{-2})	63 × 47 cm (0.29 m^{-2})
CTD	SBE19plus V2	SBE19plus V2
CTD resolution (S,T,P)	0.4 ppm, 1 × 10^{-4}°C, 0.002%	0.4 ppm, 1 × 10^{-4}°C, 0.002%
CTD sample interval	10 s	10 s
Water sampler	2-L Niskin	2-L Niskin
Funnel traps	30 cm Ø × 40 cm (×1)	None
	10 cm Ø × 30 cm (×2)	
Bait	~1 kg mackerel/tuna	~1 kg mackerel/tuna

FIGURE 6

Free-fall hydrodynamics: The decent and ascent speeds of Hadal-Lander A over 10,000 m in the South Pacific. The lander slows down by ~6 $m{\cdot}min^{-1}$ during both descent and ascent.



first time but the long delay in acknowledging this can be uncomforting.

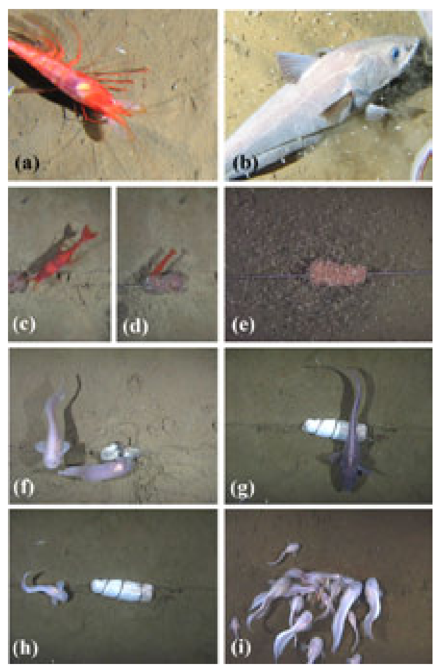
Free-fall vehicles are prone to sticking on the seafloor if deployed on soft sediment. Sinking was observed in the Kermadec Trench at around 7,000 m and in particular the deepest Izu-Bonin Trench deployments (9,300 m). There, the lander sunk approximately 15 cm into the sediment (as indicated by the bait arm in the field of view). However, due to sufficient positive buoyancy (post-ballast release) and perhaps aided by the perforated footpads, the landers are sufficiently capable of rising out of soft sediments.

Conclusion

Over these past 2 years, the hadal landers have provided a great insight into the biological community of the hadal zone (Figure 7). Every expedition has revealed something new and unforeseen, such as extending the known depth range of decapods, a large and important crustacean taxa, by over 2,000 m. Likewise, the abyssal grenadiers or "rat tails" are an extremely common family of deep-sea fish, which are now known to extend at least 1,000 m deeper than previously

FIGURE 7

Images from the hadal landers: (a–b) Still images of a decapod and a rat tail from Hadal-Lander B from 5,500 m in the Marianas Trench. (c–d) The decapods *Benthesicymus crenatus* and *Acanthephyra* sp. from ~7,000 m in the Kermadec Trench. (e) Swarms of the amphipod *Hirondellea dubia* from 10,000 m in the Tonga Trench. (f) The first and only live footage of the snailfish *Notoliparis kermadecensis* from 7,000 m in the Kermadec Trench. (g) The deepest rat tail (*Coryphaenoides yaquinae*; Macrouridae) ever found, 7,100, Japan Trench. (h) The first live footage of the snailfish *Pseudoliparis amblystomopsis* (Liparidae), 7,100 m, Japan Trench. (i) The deepest fish ever filmed alive, 7,703 m, Japan Trench (*P. amblystomopsis*).



thought. The video footage of the two snailfish has perhaps been the biggest surprise. This new physiological and behavioral information suggests that despite being endemic to >6,000 m they are in fact not unlike their shallow water counterparts (Jamieson et al., 2009b). Furthermore, the Hadal-Cam observations of such a large aggregation at 7,700 m have highlighted the need for reappraising hadal fish communities. The historical trawl records indicate that fish living in the trenches are merely eking out an existence in extremely low numbers. This misinterpretation is apparently caused by the difficulty in trawling at such great distances from the surface, the efficiency of which is even hard to evaluate. The passive nature of a baited camera sitting idly on the seafloor appears far better suited in this application than, for example, trawling, or ROVs.

The uses of deep submergence vehicles such as ROVs are paramount in hadal exploration and the mapping of habitat and infaunal/epifaunal communities but have in the past been unsuccessful in quantifying larger mobile animals. The sighting of a fish at Challenger Deep during the *Trieste I* dive was quickly claimed to be erroneous (Wolff, 1961), and the archives of the *Kaiko* ROV do not contain any noteworthy records of significantly mobile fauna. One tantalizing discovery made within HADEEP was that the species composition and behavioral observations of fish beyond 7,000 where uncannily similar to those described by J.M. Pérès in the *Archimede* Bathyscaph in 1964 (Pérès, 1965). Very specific details relating to, for example, swimming behaviour, distribution, and colorings were almost identical in both studies. Why this is surprising is because the HADEEP records were from the Japan Trench and the *Archimede* records where from the Puerto-Rico Trench, some 4,000 nautical miles apart in different oceans. Unfortunately, Pérès did not take any photographic records nor has anyone since, suggesting there is a diverse and active community inhabiting the Puerto-Rico Trench waiting to be found.

Combining all these technologies will pave the way to a better understanding of the trench environment;

for example, acoustic and photo mapping with selective sampling for biology and geology and *in situ* experimentation combined with more passive short-term observations and long-term monitoring of, for example hydrology, seasonality, food supply, etc.

Underwater technology aside, laboratory based technology has moved on a great deal since the last major multi-trench sampling campaigns in the 1950s. Phylogenetics and biochemical analyses of specimens, such as those collected by the funnel traps (Figure 8), can now reveal evolutionary pathways and food web structures both of which are particularly interesting given the geographic isolation of the hadal trenches.

FIGURE 8

Specimens from Hadal-Lander A funnel traps: (top row) scavenging amphipods from the Japan and Izu-Bonin Trenches, 7,000–9,300 m. (Middle row) A cumacean and a large amphipod from the Japan Trench 7,000–7,700 m. (Bottom row) Gastropods and the snailfish *Pseudoliparis amblystomopsis* from 7,700 m in the Japan Trench.

The HADEEP project has not only provided the marine science community with new insights into life in the deepest parts of the oceans but has also managed to grab the imagination of the public. The publicity surrounding the filming of fish deeper than ever before became international news in October 2008. It was covered by most major news networks and newspapers around the world resulting in public lectures and exhibitions in national science museums and ended up in the top five most watched videos on YouTube.com for a spell. The footage even found its way into the in-car TV screens of the Tokyo underground on the JR Chuo-Line and the JR Keihintohoku-Line and was broadcast to five million commuters per day for 2 days. A lot of this publicity included details of the both the *Galathea* and the *Vitjaz* expeditions and the famous *Trieste I* dive to Challenger Deep, which raised both the profile of hadal science and renewed the interest of these achievements, hopefully inspiring a new generation.

The next step technologically is to upgrade the landers further with acoustic current meters to monitor tidal flow in the trenches and possibly *in situ* oxygen measurements. Funding is also being sought to upgrade the Hadal-Cam with smaller electronics and a higher resolution video camera. The next wave of expeditions will see the introduction of 12,000-m rated fish traps and sediment grabs currently in the design and construction phase. Scientifically, the project will continue aiming to achieve as many deployments in as many trenches as possible to build an extensive archive on which to draw inter- and intratrench comparisons to provide a better understanding of trench ecology and just what is going on in the deepest places on Earth.

Although the NERC-funded component of HADEEP recently came to an end, the Nippon Foundation support continues until 2011. Although further funding is being sought to expand the scientific, technological, and expedition elements, the project is still very much in full swing. Between October 2009 and June 2010, both the hadal landers will be deployed in the Kermadec and Tonga Trenches with help from the National Institute of Water and Atmospheric Research (NIWA) in New Zealand. The landers *Alfie* and *Jonah* will then be reunited with the RV *Sonne* for an expedition to the Peru-Chile Trench in the fall of 2010 before, all going well, returning to Tokyo for a planned series of expeditions to the Japan and Izu-Bonin Trenches in 2011.

As for autonomously following in the footsteps of the *Trieste I* to Challenger Deep, it was once said that "Alfie won't sleep until Challenger Deep." This sentiment still stands.

Acknowledgments

We thank Dr. A.K. Matsumoto, Dr. K. Kita-Tsukamoto, Prof. H. Tokuyama, and Prof. M. Nishida at the Ocean Research Institute, University of Tokyo, Japan, and crew and company of the Research Vessels *Sonne*, *Hakuho-Maru*, *Tansei-Maru*, and *Kairei*. The HADEEP project was funded by the Natural Environmental Research Council (U.K.) and the Nippon Foundation (Japan), with additional support from the University of Aberdeen (U.K.)

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PAPER

Charting a Course for the Marianas Trench Marine National Monument

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Monument Overview

The Marianas Trench Marine National Monument consists of approximately 95,216 square miles of submerged lands and waters of the Mariana Archipelago. It will be managed in three units: the islands unit, the waters and submerged lands of the three northernmost Mariana Islands; the volcanic unit, the submerged lands within 1 nautical mile of 21 designated volcanic sites; and the trench unit, the submerged lands extending from the northern limit of the Exclusive Economic Zone of the United States in the Commonwealth of the Northern Mariana Islands (CNMI) to the southern limit of the Exclusive Economic Zone of the United States in the Territory of Guam (Figure 1). No waters are included in the volcanic and trench units, and CNMI maintains all authority for managing the three islands within the islands unit (Farallon de Pajaros or Uracas, Maug, and Asuncion) above the mean low water line.

Objects of Scientific Interest

In January 2009, President George W. Bush created this largest of marine reserves under the authority of the Antiquities Act of 1906, which protects places of historic or scientific significance. Only recently have scientists visited the realm of the monument, observing previously unknown biological, chemical, and geological wonders of nature.

The *Marianas Trench* is the deepest point on Earth, deeper than the height of Mount Everest above sea level. It is five times longer than the Grand Canyon and includes some 50,532,102 acres of virtually unknown characteristics.

The *volcanic unit*—an arc of undersea mud volcanoes and thermal vents—supports unusual life forms in some of the harshest conditions imaginable. Here species survive in the midst of hydrothermal vents that produce highly acidic and boiling water.

The Champagne vent, found at the NW Eifuku volcano, produces almost pure liquid carbon dioxide, one of only two known sites in the world. A pool of liquid sulfur at the Daikoku submarine volcano is unique in all the world. The only other known location of molten sulfur is on Io, a moon of the planet of Jupiter.

In the *islands unit*, unique reef habitats support marine biological communities dependent on basalt rock foundations, unlike those throughout the remainder of the Pacific. These reefs and waters are among the most biologically diverse in the Western Pacific and include the greatest diversity of seamount and hydrothermal vent life yet discovered. They also contain one of the most diverse collections of stony corals in the Western Pacific, including more than 300 species, higher than any other U.S. reef area (Figure 2).

The Monument Planning Process

Presidential Proclamation 8335 established the Marianas Trench Marine National Monument in January 2009 and assigned management responsibility to the Secretary of the Interior, in consultation with the Secretary of Commerce. The Interior Secretary placed the Marianas Trench and volcanic units within the National Wildlife Refuge System and delegated his management responsibility to the U.S. Fish and Wildlife Service. The Secretary of Commerce, through NOAA, has primary management responsibility for fishery-related activities in the waters of the islands unit.

NOAA and the Western Pacific Fishery Management Council are considering how to manage sustenance, recreational, and traditional indigenous fishing as sustainable activities. These activities will be folded into the monument management plan.

The structure of the plan will be similar to a National Wildlife Refuge System Comprehensive Conservation Plan, which provides a 15-year guide, using the best available scientific information, to help managers achieve the purposes stated in the Proclamation and the co-managing agencies' missions. The plan will outline a vision, goals, objectives, and management strategies for the Marianas Trench Marine National Monument. It will

FIGURE 1

Nautical chart showing the extent of the three components of the Marianas Trench Marine National Monument: trench unit, islands unit, and vents unit.

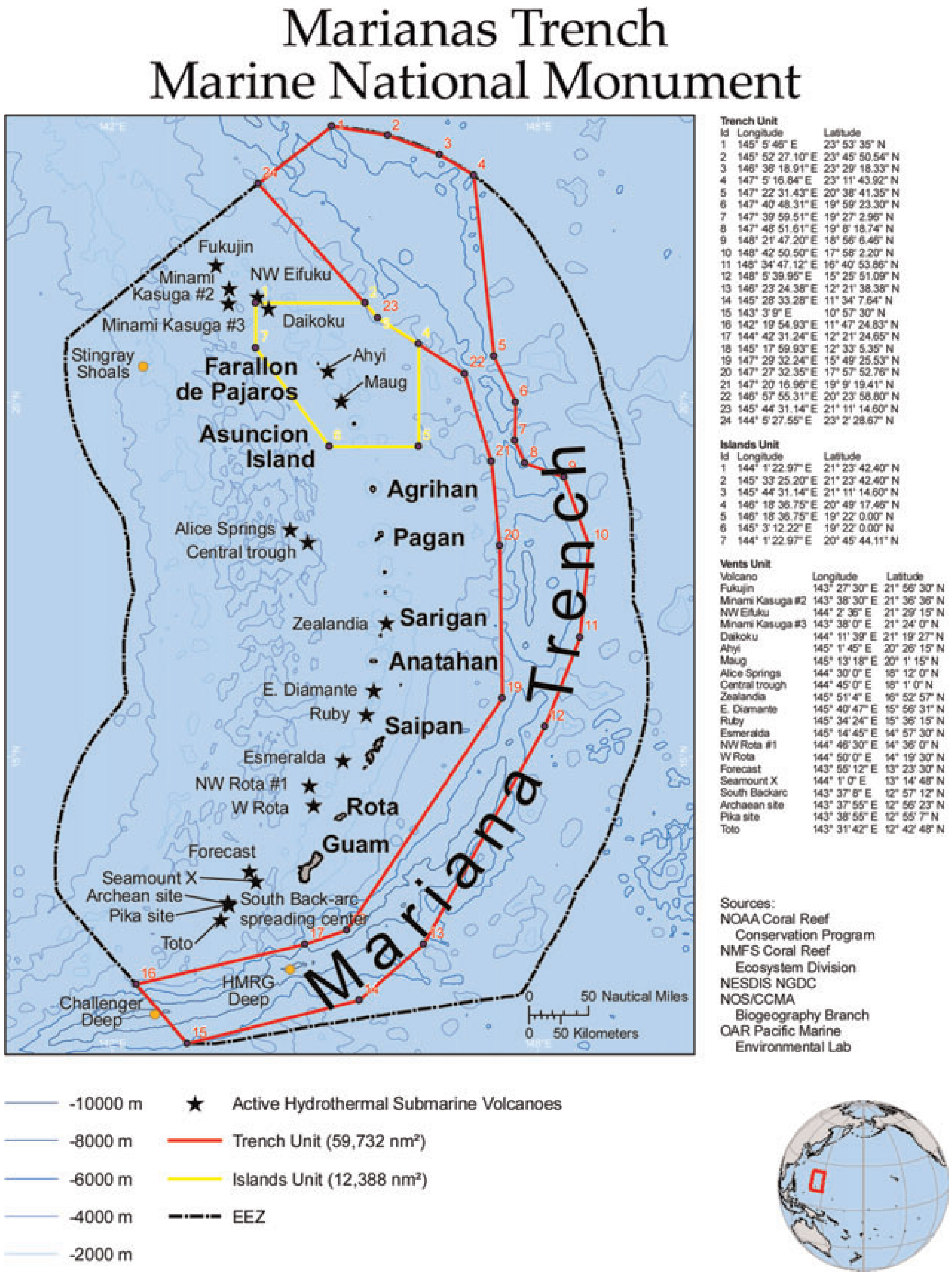
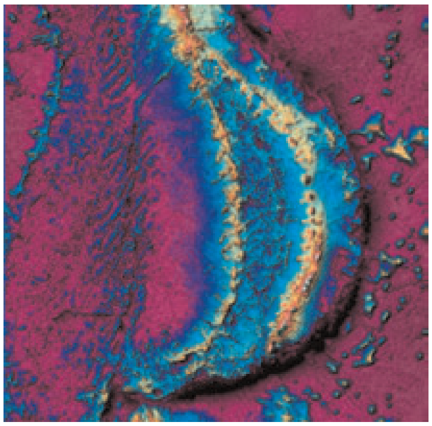


FIGURE 2

Satellite-derived bathymetry of the Mariana Arc region is shown in this computer-enhanced image. EM300 MultiBeam bathymetry collected during the Pacific Ring of Fire 2004 Expedition is overlaid on the satellite data. Image courtesy of Dr. Robert Embley, NOAA PMEL, Chief Scientist.



be accompanied by an environmental assessment describing the alternatives considered and their environmental effects.

The management plan will be flexible and a "living document." It will be reviewed periodically to ensure that its goals, objectives, and implementation strategies and timetables remain appropriate.

You may find further information online at http://www.fws.gov/marianastrenchmarinemonument/, and <http://www.fws.gov/refuges/whm/pdfs/MTMNM_brief.pdf>.

COMMENTARY

The Old Arguments of Manned Versus Unmanned Systems Are About to Become Irrelevant: New Technologies Are Game Changers

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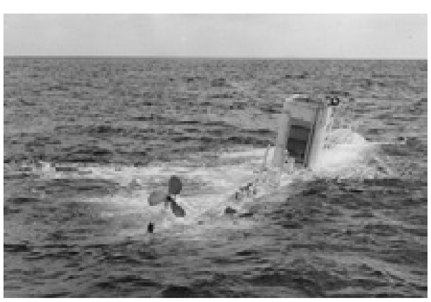
Full ocean depth has always been the Holy Grail; a rite of passage to the future.

In fact, there have been many dives to the deepest ocean since the historic dive by Don Walsh and Jacques Piccard in the bathyscaph *Trieste* (Figure 1), including three dives with the Japanese remotely operated vehicle (ROV) *Kaiko*, numerous unmanned free vehicle landers, and the most recent dives with Woods Hole's fiber optic tethered hybrid (ROV/autonomous underwater vehicles [AUV]) *Nereus*. Nearly half a century after the *Trieste* dive, *Nereus* made a transect, wall to wall, across the trench, from a ship of opportunity, recovering samples along the way. The *Nereus* dive prompted Don Walsh to comment that "*Nereus* just drove a stake through the heart of any idea of building a manned submersible for full ocean depth"—a typically pithy comment from Walsh and, right or wrong, signals a new debate.

FIGURE 1

Bathyscaph *Trieste* commences a deep dive. (Photo: U.S. Navy, courtesy John Michel).



As I see it, if man is to have any meaningful role in the future of deep submergence (beyond record-breaking or individual exploration), to be cost-effective, manned craft will need to be about 1/10th current costs—and visibly safer, so that there is no effective resistance from that quarter. The cost factor alone requires a "disruptive, conceptual leap forward" and one that cannot be achieved by any conceivable development from existing, classical, manned vehicles.

The Silicon Valley definition of disruptive technologies—those non-linear, leap-ahead advances that wipe out the old and rewrite the future—are those inventions that step down market costs to 10% of previous levels. The author witnessed such an event; the extinction of commercial manned submersibles for the offshore oil and gas industry in the early 1980s. At that time, offshore oil work was conducted by either manned submersibles or heavy saturation diving systems (both at similarly high daily costs of approximately $50,000 per day). Large companies, such as Vickers Oceanics, dominated the industry and operated large fleets of submersible mother ships, each supporting a single, large working-class manned submersible.

The introduction of atmospheric diving suits (ADSs) (Figure 2) and ROVs disrupted the settled order. Even though ADSs and ROVs were initially poorly adapted to the work, their operational costs were roughly $1/10^{th}$ that of conventional submersibles, and the systems were available at a moment's notice, "Where, When And As Needed (WWAAN)" from smaller 'ships of opportunity.' It turned out that it was primarily the freedom from being a ship owner that spawned competition and drove down intervention response costs disruptively.

FIGURE 2

Nuytco's experimental exosuit swimming ADS.

At the time, no one knew to call fledging ADS and ROVs "disruptive technologies." Rather, they were called many things, usually derogatory. Then to everyone's astonishment, the icons of the industry, like Vickers Oceanics, vaporized overnight, killed off by the unrelenting daily burden of their marvelous mother ships. The author always thought it ironic that one of the

last niches left for manned submersibles was science, the one user group claiming poverty.

The lesson I learned from the North Sea was that there would be no competitive future for any diving system if, by weight, volume, or other need, it would be so dependent on surface ships as to effectively tie its operation to a dedicated mothership. As I saw it, to eliminate the mothership and to get to WWAAN meant that all up vehicle weight (for launch and recovery) should not exceed 10,000 lb. Thus, I set a 5-ton limit for our submersibles based on the general availability and the launch/recovery capability of ships for hire.

So for manned craft to be competitive for the long-term future and to serve science as well as industry, the requirements I saw would be the ability to accommodate a crew of two, with hover and work capability, all under 10,000 lb (Figure 3). In addition, while we're at it, it seemed a good idea to eliminate the depth question. So the subs should be rated to 37,000 feet, with minimum 1.5 safety factor (structural strength to 56,000 feet). This was a tough challenge that could not be met by further development of existing deep subs. Hence, a fresh start and experimental approach was needed. I "retired" from industry, where sales of manned craft had tailed off anyway, and built a skunk works, Hawkes Ocean Technologies (HOT), and developed a long-term experimental attitude.

We knew the fundamentals of packaging two humans in the ideal sphere drove displacement/weight too high. For example, our lightweight, spherical, acrylic pressure hulled, two-person Deep Rovers weighed over 12,000 lb, and conventional subs that are closer in depth rating to our full ocean depth goals weighed in at about 50,000 lb. This told me that a spherical pressure hull accommodating two in reasonable comfort, no matter how attractive from a structural point of view, was a non-starter.

So to get weight down to less than one-quarter that of conventional submersibles and be comfortable, the kind of anthropomorphic, form-fitting pressure suits of the ADS, rather than traditional spheres, was closer to the answer. Again from early studies, the lowest practical displacement for 2,000- to 3,000-feet ADS "pressure suits" is about 2,000 lb (2,500 lb more realistic). In the 1970s, the best compromise adopted was the "Mantis"-type pressure hull—a cylindrical form (next best to sphere, but a distant second), with crew prone. We came to think of this hull form as a "pressure pod." In the late 1980s, HOT used this configuration for our first prototype, *DeepFlight I*, which we launched in 1995 (Figure 4).

We took a giant leap forward in 2005 when the late adventurer, Steve Fossett, commissioned HOT to build a 37,000-foot vehicle, *DeepFlight Challenger* (Figure 5). We were not able to discuss the project during its development, but I can now tell you that indeed we designed and built a 37,000-foot submersible, and all pressure and active components (thrusters, lithium batteries, control actuators, weight drop, lights, buoyancy, sensors, etc.) were functionally pressure tested to 16,000–20,000 psi in a DoD facility.

There were two problem areas: First, and as Jerry Stachiw predicted, modern development of carbon fiber resins had not solved the "unexplained" loss in compressive strength of massive carbon fiber at extreme compressive load. This surprised both the knowledgeable carbon manufacturer as well as myself. In order to test to failure, we had several 1/3-scale pressure hulls built, each with variations from the intended design in order to cause failure within the available test range. Typically, the model hulls predicted to fail at 13,000 psi would fail at 11,000 psi—a significant loss. After minor improvements over a 12-month development period, the final pressure hull design was modified to use the lower,

FIGURE 3

DeepFlight II concept "work class" vehicle.

FIGURE 4

First prototype winged submersible, *DeepFlight I* with form-fitting pressure hull.

FIGURE 5

DeepFlight Challenger and HOT Team.

allowable maximum stress as indicated by the model testing (Figures 6 and 7).

FIGURE 6

Side view of the *DeepFlight Challenger* pressure hull.

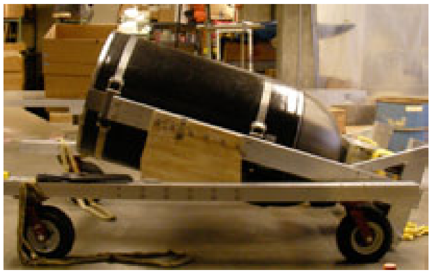


FIGURE 7

Face view of *DeepFlight Challenger* pressure hull.

The second problem area was the failure of the expensive glass dome (Figure 8), which we experienced on the "final" testing of the fully assem-

FIGURE 8

Glass dome as originally built for *DeepFlight Challenger*.

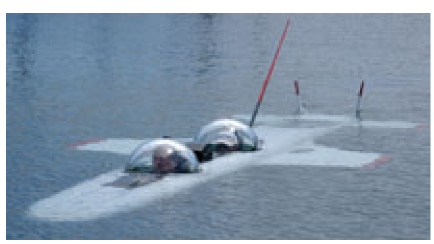
bled pressure hull. This failure was proven to be caused by mis-machined or warped titanium seat rings. The problem was fixed in a few days, but the submersible now needed a new glass dome and needed to be re-tested. Unfortunately, Steve Fossett perished in a plane crash before we were able to replace the glass.

Obviously exotic materials were needed for these new pressure pods and the work of Jerry Stachiw at NOSC led the way. Jerry was an active consultant for the *DeepFlight Challenger* design and build and was greatly missed when he passed away.

Well aware we needed to design to be competitive against future unmanned systems, and with cameras evolving faster than human eyes, this meant that view ports were also non-starters. (I always hated them anyway.) So all pressure pod alternatives we developed included full-view, hemispherical, clear domes (Figures 8 and 9). Adding personnel would obviously involve a second accommodation pod, so the whole concept became very modular, and many advantages accrue from such modularity.

FIGURE 9

Glass domes for *DeepFlight Super Falcon*.



Such low-volume pressure hulls could be built to be extremely comfortable, even soothing, but they are best thought of as "pods" rather than "hotel" accommodations. Therefore, mission times needed to be 4–6 hours maximum. Follow that reasoning, descent and ascent times ideally needed to be kept to 1 hour. Hence, for full ocean depth, vertical descent speed needed to be something like 7 mph. Ignore over-inflated speed numbers for existing subs, add fudge factors, and descent speed is almost an order of magnitude higher than current rates. Follow the numbers for thrust (square of speed) and power (cube of speed) and, gulp, this is not your father's submersible.

Not only does the drag/speed/power numbers put the design in a different class, it can no longer just sink, maintaining fixed "sitting" attitudes in the cabin. At those speeds, the nose of the craft's attitude (nose up/down) has to point where the vehicle needs to go—just as surely as does left/right to keep the streamlined axis in line with the intended direction of travel in three dimensions. This is quite different from conventional submersibles, which access two dimensions, and are basically akin to underwater ballooning.

The craft then transitions from a chambered nautilus, drifting up or down with buoyancy changes, to a dolphin. The best way to describe where we ended up is that we ran headlong into the need to transition to full-on underwater flight. Whether or not "underwater flight" is the right descriptor, it is the right concept since the math (adjusted for fluid mass) is almost the same for similar mastery over three dimensions in air or water.

Once we had the pressure hull geometry, the materials, and the need for underwater flight in the works, then the additional pieces of the puzzle seemed mundane: friendlier life support management systems, comfortable ergonomics, lithium batteries, efficient thrust, electromechanical flight control/actuators, flight software/control, etc., underwater flight instrumentation, ambient pressure composites, safer

buoyancy, etc.—all of which has been tested for the experimental *DeepFlight Challenger* to 16,000–20,000 psi.

Flight proved to have more value than at first understood. Efficient control of large (lift) forces was obvious, but the simplicity and extraordinary safety advantage of fixed buoyancy was not immediately obvious. Ultimately, HOT adopted aerospace thinking and did not question the need for experimental craft. It took five generations (*DeepFlight I*, *Wet Flight*, *DeepFlight Aviator*, *DeepFlight Challenger*, and *DeepFlight Super Falcon*) before arriving at Super Falcon—the first "next generation" production craft. Super Falcon was not imagined at the beginning of the DeepFlight program (1980s) and is the author's favorite to date (Figure 10).

FIGURE 10

The future of manned submersibles could be the elegant *DeepFlight Super Falcon*.

Of the five generations (six subs), three were full-on experimental craft (*DeepFlight I*, *DeepFlight Aviator*, *DeepFlight Challenger*), one was a one-off film project craft (*Wet Flight*), and *DeepFlight Super Falcon* (two built in 2008–2009) were the first full production vehicles. We are now building the next iteration of Super Falcon for private clients and have other production types in the works. Bear in mind, HOT was efficiently using experimental craft, stripped of unnecessary bells and whistles, to pioneer and prove the next step. Such craft are bridges to the future. If successful, they enable the future vehicles to then be relatively easily built, adding back all the bells and whistles needed.

However, relative to the early thinking and "focus on full ocean depth," *DeepFlight Challenger* has provided the boost across the board to the Holy Grail. So even though *DeepFlight Challenger* has yet to make the deep dive, it has already completed full functional testing to 16,000–20,000 psi ambient pressure and is the bridge to our next generation craft. Our new "work-type" 8000-lb craft, with a safety factor of 1.5, has the same relationship to the "final" modular working solution long ago published as *DeepFlight II* that *DeepFlight Aviator* had to our next step, production version, *DeepFlight Super Falcon*.

To HOT, the data and proof are in hand to build the idealized future working submersibles—modular craft, with one or two crew, flyable (longer range and efficient survey, together with full mid-water capability), with in-flight conversion to hover mode, and modular work packages that would obviously include manipulators, etc. The subs have ideal viewing for both pilot and passenger, and all weigh in under 10,000 lb and are WWAAN capable. Depth on *DeepFlight Challenger* was 37,000 feet with a safety factor of 1.5 (current certification standards for titanium), but new materials warrant higher margins. So the early depth limitation HOT sees for its first commercial "work" craft is about 27,000 feet.

Don Walsh and Jacques Piccard opened the pubic's eyes to the possibilities for deep ocean exploration. *DeepFlight Challenger* perhaps was the first manned craft scheduled to make a serious exploration of the Challenger Deep post *Trieste*. The contract between HOT and Steve Fossett was that the craft would be built to win for its owner (Fossett) the deepest solo dive record and, for HOT, it was the proof of concept for full ocean depth working vehicles.

For the author, both *DeepFlight Challenger* and Woods Hole's *Nereus* are the harbingers of the future, with the first prize going to *Nereus* for a stunning success. The next descendants from each will be wonderfully usable and cost-effective solutions. Unlike AUVs and ROVs, which have very sharply defined capabilities, and are very good at some tasks, and poor at others, the descendants of *Nereus* and Challenger are the general solutions needed anytime work intervention and range are necessary. I say this because work intervention eliminates the AUV, and range eliminates the ROV.

So what happens to the old manned versus unmanned argument and who now wins—given two good choices. Before trying to answer that, bear in mind that time changes more than the technology. When all this started, the customers for the sixty or so manned craft this author built were primarily offshore oil and gas, with a small science component. The rate of build was approximately five per year. In the intervening 15 years, the rate of sales fell to near zero, with only a few sales anomalies: Deep Rover 1 for Phil Nuytten and the two classic Deep Rover 2s for French television. The sales rate stood essentially at zero, or one submersible every five years.

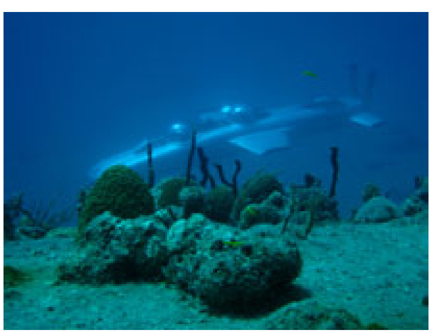
With our breakthrough to ultralight, flyable manned craft, HOT's sales tentatively kicked in again and are now at the rate of 1 or more per year and increasing. So the patient has a pulse, is out of intensive care, and prospects are good. However, sales are not to the old market. This is all new. Our early sales are now (skewed) to

early adopters—those who delight in new technologies and in pushing forward (i.e., venture capitalist Tom Perkins), or those who need the new capabilities (i.e., adventurer, Steve Fossett), and those who see business opportunity (Richard Branson). Look at the names and you see a new day. James Cameron is widely rumored to be headed into the deep and Sylvia Earle is rumored to have deep pocket backing for deep vehicles—all private, new money.

So getting back to the question, manned or unmanned—and this time with different users, different markets—the question is most likely irrelevant. Manned versus unmanned was an agonized debate once upon a time when only science was in the deep, and manned subs were horribly expensive. The next generation users are more likely to have a clear need for manned craft or an obvious preference for remote vehicles. The AUV, ROV, AUV/ROV hybrid, and next generation-manned craft are all in it for the long haul (Figure 11).

FIGURE 11

A *DeepFlight Super Falcon* propels downward into the blue crystal waters of the Caribbean.



PAPER

Project Deepsearch: An Innovative Solution for Accessing the Oceans

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ABSTRACT

The year 2010 marks the 50th anniversary of the first and only manned visit to the deepest part of the sea. Over the past 50 years, even as technology has advanced with breathtaking speed, there have been very few changes or advances in applying new technology to manned (human-occupied) vehicles for deep sea exploration. Today there are only a handful of deep research submersibles and all, with the exception of the Chinese Harmony 7000, are aging assets. None are capable of exploring all areas of the ocean. Project Deepsearch is being undertaken by a small business working under the premise of a collaborative open source effort. Our goals are to bring innovative solutions to bear in five key areas of engineering and technology while engaging industry contributors and the public, enhancing awareness of the importance of the oceans, marine science and education.
Keywords: Glass, Lithium batteries, Ceramic flotation, Pressure testing, Dive profile

"What's your number"? It was the question posed time and time again over the past 17 years, to each other, to staff members, to colleagues, to visitors—what would the cost be for building a manned submersible capable of providing full access (11,000 m) to the oceans? More importantly, what would the cost be for not doing it?

It is said that we know more about the surface of the moon than we do about the deep ocean. People fly everyday 7 miles up in the sky. By 2008, there were 4,102 ascents to the summit of Mt. Everest. Fifty years have now elapsed since the first and only manned dive to the deepest point in the sea. While some were content to rely upon drones and robot technology to explore the deep ocean, we were not.

With every project completed, our team saw first-hand the need for greater knowledge and better tools for ocean exploration. We read and re-read Busby (1969, reprinted 2006) and Stachiw (1990, 2003), weighing their arguments about the advantages and disadvantages of materials and even pros and cons of submersibles in general. Peter Rona's (2000) discussion on the importance of tooling, manipulators, and the ability to collect samples resonated with us as did his argument for the irreplaceable scientific value of human presence in the deep ocean.

During the 5 year Sustainable Seas Expeditions (1997–2002), DOER was engaged by Nuytco Research (www.nuytco.com) and National Geographic Society (www.nationalgeographic.com) to train scientists, teachers, artists, and others to operate small one-person Deep Workers and Deep Rover submersibles working from many vessels of opportunity.

We listened and learned from the scientists, what they liked and disliked. Most loved the simplicity of Deep Worker but wished for deeper capability. The single-person Deep Rover could go a bit deeper, but having been built in 1982, it was an aging asset. Beyond that, when thinking of the handful of deeper water vehicles in particular, the wish was for longer mission duration (less transit/more work) and greater field of view. All agreed with the axiom that "if a picture is worth a thousand words, being there is worth a thousand pictures."

We kept track of some of these assets, Alvin (4,500 m), Nautile (6,000 m), Mir I and II (6,000 m), and Shinkai (6,500 m), and realized that over the years, real innovation had been slow in coming to deep human occupied systems. Even the new Chinese Harmony 7000 is very similar in appearance to what exists, although it is poised to become the deepest diving manned submersible, surpassing Japan's Shinkai by 500 m.

When the replacement Alvin design was released, the moan was audible throughout the building along with a loud "Couldn't the artist even step out on a limb!?" from the engineering offices. The answer, of course, was no. The artist could not and neither could the scientists or engineers involved. Constrained by an existing mother ship, committees, and a myriad of other parameters set forth early on, innovation was not a consideration, budget was.

FIGURE 1

Original artist's conceptual painting, 2003.

The DOER team did not have to worry about budget for Project Deepsearch; there simply was not one, only ideas and concepts percolating and growing. In 2003, an artist showed up at DOER. Filmmaker David Riordan stopped by to say that he was for the first time in his life truly afraid. Afraid of what was happening to the oceans and what the consequences might be for people if something was not done and soon. He wanted to talk to our founder, Sylvia Earle, about a report he had seen: 90% of the big fish in the ocean were gone in the last 50 years. He was eager to find a way to communicate the problem to the general public. He listened to Sylvia describe the need for improved technology and basic understanding and protection of broad ocean systems, "our life support system," she said. Sylvia continued, spelling out the importance of engaging the public, providing knowledge, and having the capacity to care. He vowed to help her however he could. Then he listened to our wild ideas for Project Deepsearch: to develop and build a pair of innovative human-occupied submersibles capable of providing scientific access to all parts of the oceans while engaging the public along the way.

Together, we pursued an integrated strategy for video games, social networking, film, and books, the proceeds of which we envisioned would fund the design and development of Project Deepsearch. Artist Richard Taylor of Star Trek and Entertainment Arts fame worked with our engineers to develop concept art (Figure 1) while David worked with us on story lines, expedition possibilities, and more. By then, we estimated that the number was $10–15 million per submersible using a traditional steel or titanium personnel sphere while pushing for new, larger view ports. We speculated about the possibilities of advanced ceramics, grown sapphire, and glass.

A group of us went to Washington, D.C. to the National Geographic headquarters to pitch the idea. We did not expect them to fund the project entirely but hoped they would collaborate, provide some seed money, or at least lend their name to the effort. While they listened with interest, and praised the vision, they could not find a fit within their existing programs (Walsh, 1990; Craven, 1990).

Moving forward, we pursued Project Deepsearch with limited resources and encouragement from ocean exploration luminaries, including Don Walsh and John Craven. Drawing upon their papers and those of others in the special "Deepest Ocean Presence" issue of the MTS Journal (1990), we identified many needs and many possible solutions. We honed to a science of the use of standardized ISO containers and equipment handling methods. This "mission module" philosophy allows us to be self-contained with workshops, labs, and equipment, reducing mobilization/demobilization time and minimizing impact on the ships themselves. We analyzed battery technology research in conjunction with deep workers and a variety of multi-passenger submersibles that passed through our workshop.

Every ship we mobilized equipment on or off became an opportunity to further the operations plan for Deepsearch. We evaluated ships of all kinds—refit, purpose-built, SWATH, and single hull, moon pool equipped, those with A-frames, side launch, gantry cranes, internal marina bays, heave compensated systems, and more. The fact is that deep-water sites are not always conducive to over-the-side operations. Oceanic swell, wind, and other environmental factors reduce the operational window. Thus, the launch and recover system must be able to safely release, capture, secure, and handle the crafts.

The ideal ship for such operations would be one with Dynamic Positioning level II or better, with a full suite of deep-water assets: autonomous underwater vehicle (AUV) for broad

survey work, multi-beam for basic mapping, deep-water remotely operated vehicle (ROV) for ground truthing and providing real-time video to the surface, and two deep-water submersibles.

More was learned during the development of DOER's Morpheus, an advanced long tunnel inspection system, and Tules, an integrated levee evaluation system. Looking at aging infrastructure and the aftermath of hurricane Katrina, it became abundantly clear to us that lacking sufficient information, especially predictive information, people could not make meaningful or informed decisions. The same thing applied to the oceans.

It was around this time that Sylvia Earle went to Spain to receive an International Geographical Society award. John Hanke, one of the principal developers of Keyhole Markup Language, which became integral to the development to Google Earth, was also an award recipient at the event. Sylvia, in her speech, praised Google Earth but went on to say it really should be called Google Dirt since they left out the oceans. This comment led to meetings with Sylvia, John Hanke, DOER, David Riordan, and a small team from Google, including chief technology advocate Michael Jones and outreach specialists Rebecca Moore, Jenifer Austin, and Steve Miller.

Ideas bounced around and finally what emerged was a plan and template to populate an ocean layer with bathymetric data, stories, videos, and images from 10 "focus areas" to start with. For the next three years, DOER worked with Google and the Navy via a three-way CRADA (cooperative research and development agreement) on bathymetric data sets and more than 40 science advisors and hundreds of contributors to the effort. The Ocean in Google Earth launched with the release of Earth 5.0 in February 2009.

Our work with development of the "ocean layer" required much by way of networking and outreach to potential contributors. We did not limit ourselves to scientists but also contacted artists, film makers, photographers, U.S. and international government agencies, and yacht owners, many of whom had "SeaKeeper" (www.seakeepers.org/technology.php) units aboard their ships collecting underway oceanographic data. Some even had ROV or submersible footage to contribute. Invariably the question arose: why had we humans not done more to explore the deep ocean? Why had we only once made a manned dive to the deepest point in the sea?

A Turning Point

We hosted many visitors and workshops in conjunction with the project and often shared our vision for Project Deepsearch. One day, we had such a meeting with a group of VIPs and when asked, we elaborated on the plan—six to nine months of targeted research into five key areas of innovation to start with, followed by a course of testing, design, and development of prototypes and then the push to build.

Two days later, we received a call confirming a funding commitment to explore the feasibility of developing a full ocean depth (FOD) human occupied submersible (HOV). The stipulations: make our research findings open source, seek out collaborators, innovate, publish, and make a difference. Although the funding came through a foundation (www.deepdeep.org), the sponsor went further and actively engaged with the engineering team, becoming personally involved through meetings and a constant stream of e-mail, demonstrating the shared commitment to further knowledge about the oceans.

After clearing a number of projects out the door, we commenced.

The Five Areas of Innovation

- Platform/Submersible diving mechanism—dynamically controlled vs. buoyancy based
- Personnel sphere—evaluate materials
- View ports—increase size
- Batteries—investigate technologies
- Flotation—ceramic spheres vs. syntactic foam

Platform and General Design Goals

The oceans are a three-dimensional environment. One of the most common complaints from scientists is the amount of time spent in transit to the working depth and the inability of most deep-water submersibles to stop, hover, and dive again for mid-water studies.

Existing deep-water research submersibles generally have a similar dive profile: they take on weight to sink to the desired depth, they shed weight once that depth is achieved, and they shed more weight to return, floating back to the surface. This strategy has not changed much in more than 50 years, and on every dive, with the exception of the Mir, the submersibles leave litter in the form of metal plate, shot, or sandbags.

The Deepsearch strategy is to make the personnel sphere positionable for comfort and then to use a combination of thrust, movable trim

mass, and a variable buoyancy system (VBS) to pitch nose down, moving at up to 6 knots through the water column to the working depth. This is achieved by changing the center of gravity and by using power assist. The vehicle can stop at any point along the way to adjust buoyancy and attitude and can open the clear Perspex to extend lights, cameras, and manipulators for work before continuing the dive.

Minimizing the transit time and maximizing the working time solve another problem posed by scientists. Speaking with key science advisors such as Drs. Edith Widder, Bruce Robison, Larry Madin, and Phil McGillivary, we confirmed that the ability to stop at any place along the descent path and to then continue the dive or to come part way up and then descend again would be an incredible breakthrough, especially if coupled with a large field of view.

In the case of Deepsearch, the variable mass will be the battery pods themselves, which move up and forward for diving, center and down for stability during the science mission and launch and recovery, then up and aft for ascent, leaving nothing behind.

Our basic design goals for each submersible are:

Length: 11.3 m (37 feet)
Beam - Operational: 3.44 m (11.3 feet)
Beam – Shipping: 2.33 m (7.66 feet)
Operating depth: 1,000 m/11,000 m (3,280 feet/36,089 feet)
Normal Dive Duration: 10 h
Speeds:
 Cruising: 3.7 km/h (2 knots)
 Full: 11.1 km/h (6 knots)
Height: 2.31 m (7.58 feet)
Draft: 2.31 m (7.58 feet) surfaced
Gross weight: 20 metric tons (44,093 pounds)
Payload: 680 kg (1,500 pounds) includes occupants
Complement:
 Pilot: 1
 Observers: 2
Pressure hull: 172.7 cm (68 inches), thickness TBD acrylic—1,000 m/172.7 cm (68 inches), 10.16 cm (4 inches) thick glass—11,000 m
Hatch opening: 40.64 cm (16 inches), 39.37 cm (15.5 inches) maximum diameter for science equipment
Total power: 2 ea. × 91 kWh per main propulsion batteries (260VDC × 350 Ah), Mission battery is 91 kWh usable (260VDC × 350 Ah)
Maximum cruising range (FOD): 26 km (16 miles) submerged at 3.7 km/h (62 m/min)
Life support duration: 246 man-hours (10 h × 3 persons + 72 h × 3 persons)

With this design (Figure 2), a sub can reach FOD in approximately 90 min. Lesser depths are obtainable at a scaled fraction of this time. New battery technology allows for the power density to drive the submersible for this period of time. However, close consideration to drag is a prime objective in the design. Six knots was a reasonable speed compromise yielding relatively fast times to depth against a battery package that meets the weight goals of the design.

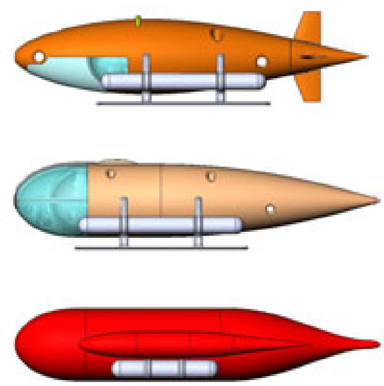
FIGURE 2

Conceptual rendering of Deepsearch submersible, September 2009.

Streamlining for drag pushes back against the need for internal volume to carry flotation and other systems. Several rounds of light computational fluid dynamics (CFD) have been undertaken to refine the basic shape (Figure 3). Rigorous CFD and tow tank testing will need to be run to finalize drag (and related propulsion power requirements) and other dynamic terms at speed to assure stability, that there are no control surface inversions, and that there is resistance to de-stabilizing inputs. One advantage to a dynamically stable platform is that on bottom, Deepsearch will always have a tendency to put its nose into currents.

FIGURE 3

Deepsearch form evolution.



While steel or titanium personnel spheres can withstand FOD pressures, there have been significant advances in materials over the past 50 years. We investigated carbon fiber (Garvey, 1990), ceramics (Yano, 2005), alumina (a metal/ceramic material), and traditional materials. We considered spheres, hemispheres, cylinder shapes, view ports, and viewing domes. We compared weights, compressive strengths, tensile strength, and numerous other factors.

Personnel Sphere and View Ports

Paired with the personnel sphere question was the view port question. Could we create a sphere, half alumina, or half glass? How would we seat the dissimilar materials? Where would the hatch be? How big could it be?

We were offered and took the opportunity to examine the craft being built for the late adventurer Steve Fossett. That vehicle had a full glass "nose cone," which fractured during pressure testing. The presumed failure was in the seating of the glass to the titanium ring. It was a sobering visit.

In our quest for larger view ports, perhaps even grown sapphire, we engaged with a number of glass experts and made an exhaustive review of the works of the late Dr. Jerry Stachiw (2003). While much work on glass had been done by the Navy up through the 1970s, including a very innovative three glass sphere design by Will Forman (1999), it essentially stopped there. The consensus for this was that technology did not exist at the time that would allow the detailed modeling and failure analysis techniques available today.

In due course, the path led to investigation of a full glass personnel sphere (Figure 4), melding two areas of innovation into one big undertaking. Glass has been proven to withstand great ocean depths as evidenced by the widely used "Benthos spheres" (www.benthos.com) and newer Vitrovex spheres (www.nautilus-gmbh.de). The questions addressed failure analysis, ease of manufacture, and practicality of mounting in the framework of the submersible. Today, this research is ongoing and continues to be extremely promising. If achievable, it will afford an unprecedented view with a significant weight savings for the submersible as a whole.

FIGURE 4

Volume and form study of 68-inch ID glass personnel sphere.

With the realization that an all-glass man-sphere was more than a possibility, a push has been made to move the sphere as far forward as practical (Figure 5). Normally, this would have been rather simple, adding flotation high forward and above the sphere to offset the weight of the front tool porch equipment. However, the desire to utilize the view afforded by the glass sphere has lead to the concept of a complete, 180° acrylic fairing, with a retractable lower half allowing tool porch use *in situ*. Additionally, Deepsearch has run out of room in height and width with the desire to keep the frontal cross section sufficient to fit in an ISO container. This requires adding the floatation aft and creating a counter moment by moving the drive motors aft as well. The shape and volume to achieve this are the lowest shape shown in Figure 3. This is not as ideal from a drag or gross vehicle weight stand point but is still capable of obtaining the design goals.

FIGURE 5

Cutaway study of Deepsearch showing internal assemblies.

Massive Glass

Glass as a personnel sphere material is at once intriguing and breathtaking. Despite years of successful deep-sea service (Benthos and Vitrovex instrument housings), there is a natural reservation against using glass because of its brittle nature. Yet when we think of Japanese glass fishing floats washing up intact on a beach after a storm or the venerable "message in a bottle" being found after years at sea, we realize that glass is stronger than it appears. The virtues of unimpeded views are well recognized: Deep Rover, DR1002, Johnson Sea Link, SeaMagine, DeepSee, and others have proven the concept with acrylic spheres.

Melding art and science together, we are investigating

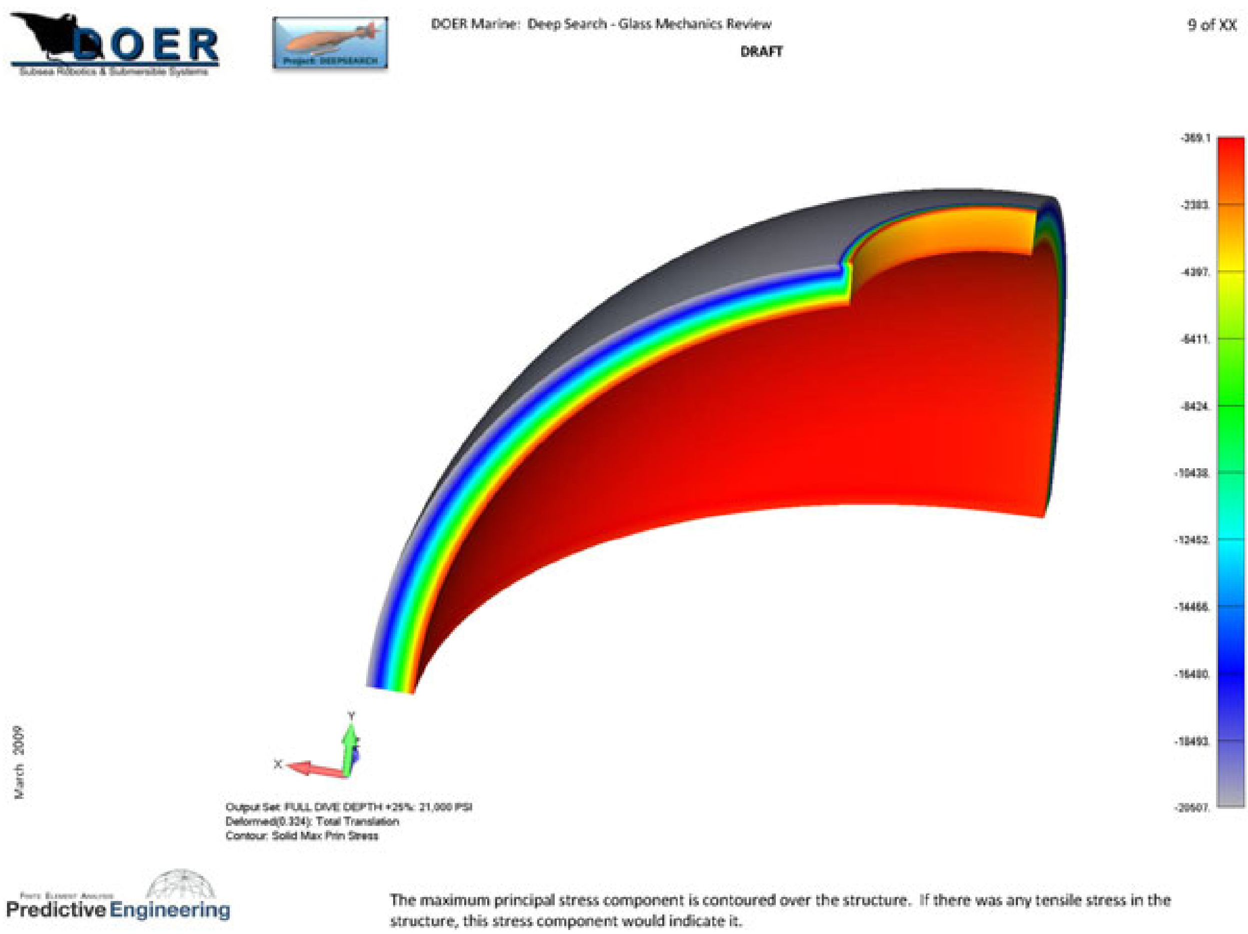
- Ease of manufacture
- Composition and coatings
- Testing protocols
- Hatch and penetrators
- Reliability
- Mounting in frame

Working with world experts such as Dr. Suresh Gulati and top manufacturers Schott (www.us.schott.com) and Corning (www.corning.com), DOER is systematically addressing these questions. Finite element modeling is being used extensively for all processes (Figure 6).

A revolutionary hatch concept has been developed that completely changes the approach to the glass interface. It avoids the high bearing stresses

FIGURE 6

Finite element analysis results showing absence of detrimental tensile forces in the model.



experienced when a hemispherical glass shell is joined to a metallic hull. All past attempts at massive glass for subsea use have had problems in this area.

Test fixtures for seal material testing have been built, and tests are in process. Results from these tests will yield constituative relations for the design of our seal. Trelleborg Sealing Solutions (www.tss.trelleborg.com) is collaborating with DOER to develop a unique seal in parallel to our glass research efforts.

Fracture mechanics techniques are being used to quantify strength characteristics of porthole geometries, to evaluate different glass compositions, and asses the reliability of the structure.

Scale model spheres are being fabricated using Vitrovex flotation spheres. Pressure tests will determine seal interactions at the glass interface. Cycle testing of the scale models will be undertaken in a 24 inch cold isostatic press (CIP) to FOD × 1.25 or existing hydrostatic test chambers to FOD.

Strategies for sphere retention will be tested as well for shock loading protection, practical serviceability, and human factors.

To date, all research, modeling, and testing have yielded positive results; in most cases, better than expected. However, if glass research does not yield a good solution and path for mitigating risks, or simply proves too costly to manufacture, a steel or titanium personnel sphere can certainly be used but at a weight and view penalty.

Testing and Safety

We investigated pressure testing facilities around the world because we did not want to have to extrapolate; we wanted actual test data from 1.25× FOD pressure. We found that

many facilities had decommissioned or de-rated their chambers due to age and safety considerations.

Collaborating closely with Avure (www.avure.com), DOER developed an innovative testing program using three different sizes of cold isostatic presses or CIP chambers. These tools will allow us to conduct a full range of destructive materials testing, scale model testing, and ultimately pressure testing of the personnel spheres to 1.25 × FOD. Undertaking this program will not only provide the data we require for Deepsearch, but it will also become an asset to the entire marine community, replacing aging hydrostatic test chambers with safer, modern alternatives.

Batteries

Batteries were not nearly as daunting a task given the tremendous influx of new research in the area. Selection evaluation criteria include

- Chemistry
- Availability
- Cycle Life
- Safety/Handling
- Energy density
- Packaging
- Cost
- Charging time
- Duration between charging

With the push in recent years toward electric vehicles, AUVs, and higher energy densities, batteries are an area where technology is evolving at an incredible pace. Thus, the majority of research surrounded handling, packing, charging protocols, and testing. However, because of this rapid evolution and the potential inconsistencies in package sizes and manufacturing, our design must be adaptable. Oil-filled housings are attractive if we can be assured of consistent package size and chemistry. The alternative is to develop one-atmosphere, ceramic housings. Both paths are being investigated.

Battery power is split into three systems: main/propulsion, house/hotel power, and emergency power. The main power is for the rapid descent and ascent assist and slower speed maneuvering while at work. House power is used for ancillary devices such as lights, cameras, and sampling systems. Emergency power is for critical functions in the event of main power loss.

Most shallow-water submersibles still use lead acid gel cell batteries. Deep research submersibles have used chemistries, including silver/nickel, nickel/cadmium, and nickel/hydride (Takagawa et al., 1995). A recent trend has been toward Lithium chemistries, including lithium ion and lithium polymer. These have been proven in AUVs for a number of years but require additional safety/handling steps. Germanischer Lloyds (www.gl-group.com) has approved a lithium battery for use in the small two- and three-person u-boatworx submersibles (www.uboatworx.com) and has implemented new rules for vehicles rated for 6,000 m and below.

On a larger scale, the Navy used proprietary lithium battery chemistry in swimmer delivery vehicles until a battery fire shut down their most recent project. While the cause of that accident is not openly known, the common belief is that it was a handling problem and not a manufacturing defect. For Project Deepsearch, we are trending toward lithium ion battery chemistry, which has been tested and approved by the Navy while developing more stringent handling protocols to minimize risk.

Floatation

Syntactic foam is a great material and was a boon to the industry when it was introduced in 1964. However, for FOD applications, it simply becomes too great a weight penalty resulting in an impractically large submersible. Additionally, high percentage water absorption requires a larger variable buoyancy system (VBS) to compensate. Syntactic foam can be used but at a size and weight penalty for the design. For the Deepsearch submersible, ceramic spheres appear to be the optimum solution if the following questions can be answered:

- Can they be economically manufactured in sufficient quantities?
- Will sympathetic failure be an issue?
- Can packaging mitigate sympathetic failure?
- Is fatigue a factor, and if so, can they be acoustically monitored for fatigue before failure?
- Can they be tested thoroughly enough to obtain a manned rating?

We worked to team with an off-the-shelf provider who later declined to bid. We dug deeper and found Custom Technical Ceramics (www.customtechceramics.com), a provider who was willing to collaborate on both new and existing ceramic/metal combinations to truly optimize a design.

The 2009 success of the Woods Hole *Nereus* ROV proved that ceramic spheres could go to FOD (http://www.whoi.edu/page.do?pid=10076&tid=282&cid=57586).

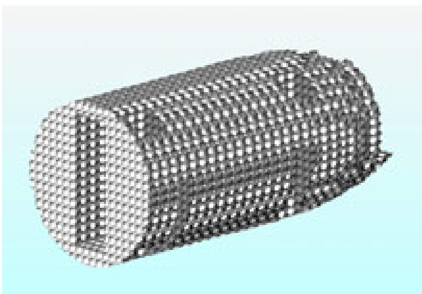
Our task is to optimize the design and to work with an independent classing agency to have the spheres approved for use on a human-occupied submersible. To do this, we have to

break some balls, literally. This can be accomplished in a small 60,000 psi CIP chamber. Destructive tests on the ceramic spheres will provide the K factor necessary for full analysis and a step towards classification.

Foremost is the concern about sympathetic failure. With a tight packed array of thousands of spheres (Figure 7), sphere design must be robust enough to absorb the collapse of a flawed or damaged sphere. A chain reaction could result in the loss of the primary submersible floatation. A first step is to increase the overall strength and toughness of the sphere design. This requires more material, at a loss of buoyancy efficiency, or moving to a more advanced ceramic. Additionally, the matrix the spheres are packed in can be used to absorb the shock wave generated by the collapse of a flawed sphere.

FIGURE 7

Ceramic floatation sphere matrix study.



It was initially hoped this matrix could be conventional FOD syntactic, increasing package efficiency even more. However, difficulties and cost in fabrication of this method make it prohibitive. Casting of the spheres in a syntactic slurry and curing as a monolithic assembly have proven to stress the ceramic spheres in an unacceptable manner, initiating buckling at lower than design pressures. Two dimensional, the three-dimensional assemblies of the packaging with these high strength spheres will be tested for sympathetic failure resistance in a chamber at FOD. The inner sphere can be intentionally flawed to force failure at FOD or other depths.

In researching ceramic materials, we learned that once the spheres are "set" at a high stress level, meaning that they no longer propagate flaws (which translates to noise, the Kaiser Effect) when cycled to a lower stress level in a chamber, that they then will not fail even after thousands of cycles. Is there a fatigue limit? If so, can flaws propagating prior to failure be monitored acoustically as a warning?

Answers to these questions and consistent proof of design, manufacturing reliability, and long-term safety will all have to be satisfactorily addressed if we are to incorporate them into the floatation system of a human-occupied submersible.

Today and Tomorrow

By April of 2009, the research phase was complete, but we wanted to continue with some additional research on glass—the highest risk component in terms of testing and ease of manufacture. Much has been learned and more work is ahead.

We published many of our findings at the project Website, www.deepsearch.org. In the meantime, we developed a plan to build a 1,000 m test platform, which would enable us to test and qualify the design in all other areas and continue pressure cycle testing materials and components for deeper work using an acrylic personnel sphere. In no way would the design be one that we would conceive if our job was to build a 1,000 m submersible. However, it was the optimal depth for a test platform and would allow us to use an acrylic personnel sphere of the same internal diameter as the all glass design, 68 inches.

Today DOER has compiled a 500-plus-page internal design document, and we are adding more information weekly. When complete, it will provide the build plan for the test platform and carry over into the FOD systems as the targeted glass research is completed.

Additional funding for documenting the research is being sponsored by the Marine Science Technology Foundation (www.mstfoundation.org), and others, both private and corporate, are beginning to come forward. It is a big step ahead and a chance for collaborators and sponsors to make a substantive difference in our ability to understand and explore the oceans in ways heretofore unattainable.

Our goal is not to plant a flag 50 years later in the Marianas Trench. Rather, our goal is to honor that achievement of 1960 by building upon what *Trieste* started, and what Alvin and others have achieved, and by providing science with tools with which they can make direct observations at any point in the water column anywhere in the world.

Although a submersible can usually be more economically supported by an ROV or AUV, having a pair of submersibles provides invaluable collateral benefits. This has been proven by the Mir and Johnson Sea Link operations. One sub supports the other and can provide rescue assistance. One can be outfitted with cameras while the other acts as the lighting platform. One can position above and photograph the other at

work capturing, the so called "God's eye view," building a far greater rapport with the public and achieving greater visibility in the media and a deeper appreciation for the oceans and their role in sustaining life on Earth.

To that end, our second goal is to help others better technology through what we learn along the way. We may discover things that fail miserably at 20,000 feet but are a breakthrough for systems operating at 10,000 feet. We would like to see this philosophy carry over into the science itself with findings and images made readily available via platforms such as Google Earth or online databases such as the Census of Marine Life that are openly accessible, allowing information to flow more freely, thus engaging the public and policy makers, expanding our knowledge about the oceans.

We still ask each other the "how much will it cost?" question every day. But in realizing the value of knowledge weighed against the price of ignorance, each day that passes reminds us of how much it will cost if we do not do this.

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Excerpt from *The Sea: A New Frontier*, 1967

Guest Editor's note:

As this journal was coming together, we found a book written when bathyscaphs ruled the deep sea. *The Sea: A New Frontier*, by Donald MacLean, Department of Education, San Diego County, and Sam Hinton, Scripps Institution of Oceanography, was published in 1967. I knew Sam from my days at Scripps and looked for him as we prepared for this issue. We think Don and Sam's words bring back a sense of the people and how they felt at that time.

But rather than considering this excerpt as just a look back, we are placing it in the section of this volume that focuses on education. And if it is about education, it is about the future. "In a perfect world," said Lee Iacocca, "the best of us would be teachers, and the rest of us would have to settle for something less."

Following the book excerpt, you will find a paper by two current teachers who demonstrate that students still learn best when building things hands-on. Like I did. And probably you, too. *Trieste* is the vessel they use to explore science.

To you mariners of the deepest abyss: the legend of *Trieste* lives on with a new generation! This hands-on science project was created for this issue of the *Marine Technology Society Journal* in tribute to you. Already one of the author-teachers has presented the project at a local teacher workshop in San Diego. By the publication of this issue, teachers everywhere will find detailed step-by-step instructions online.

Perhaps some pre-teen students will discover they have a knack for ocean science and engineering. They may pursue their interest, and a career, that could well extend into the latter half of this 21st century.

And the memory of that day 50 years ago, when water ballast tanks were flooded and the dive was begun, will journey with them.

Kevin Hardy

FIGURE 1

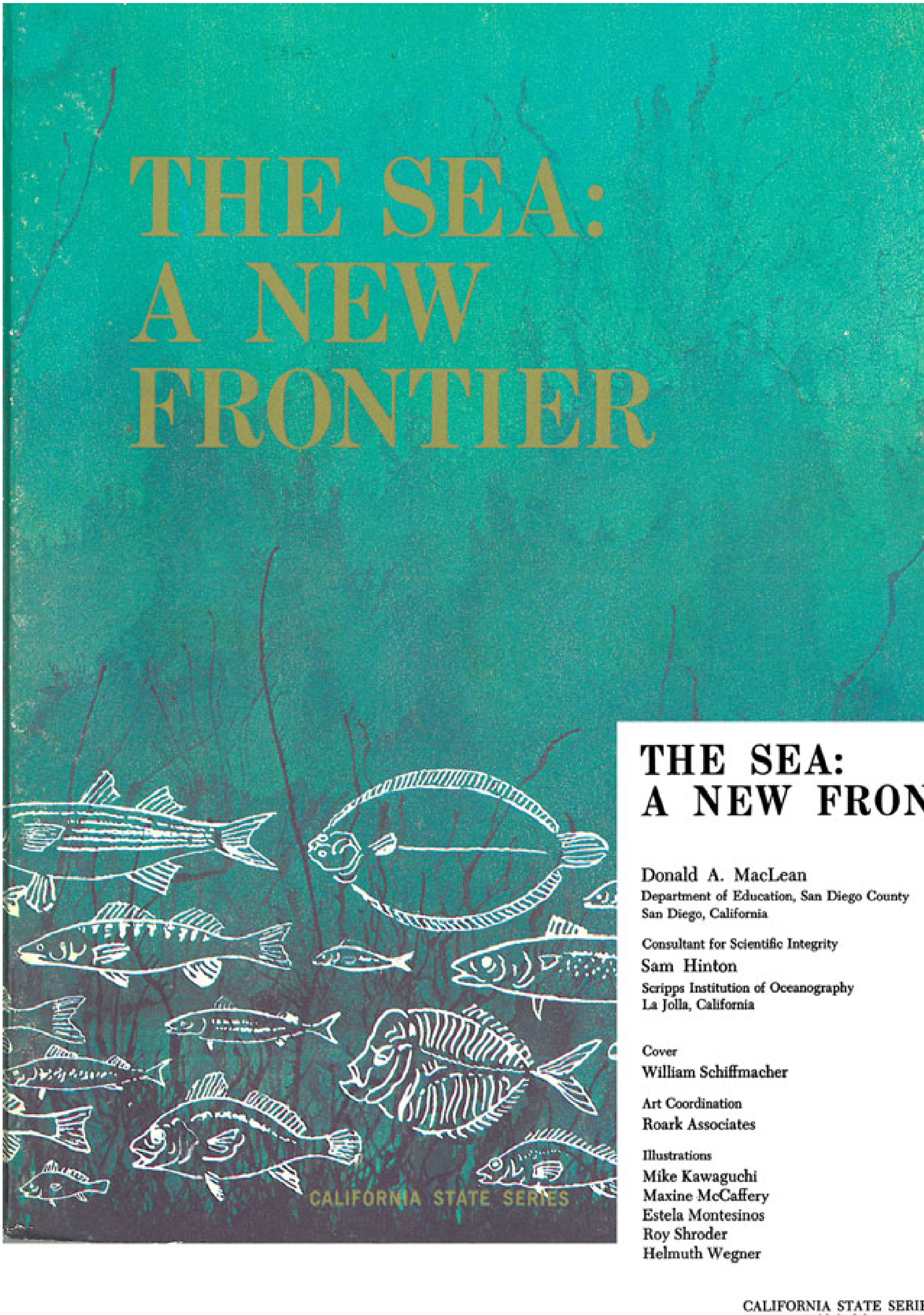
Trieste Program Director and Science Advisor Andy Rechnitzer and his son, David, look at a book for young students about the Deepest Dive.

Foreword by Nancy Taylor

K-12 Science Coordinator, San Diego County Office of Education

The San Diego County Office of Education is proud to assist in providing science education resources like this to inspire tomorrow's innovators. While we learn from the past, we are indeed inspired to use this information to develop new technologies for research and discovery. San Diego's story of innovators and innovation is told in the pages of this journal with a unique approach. Middle school teachers and their students in San Diego and beyond have the opportunity to look back to the innovators whose incremental discoveries coalesced into the bathyscaphe *Trieste*. The following pages tell students the story of *Trieste*, discussing both submersible engineering and the pioneer spirit. This historical perspective adds motivation to a new era of innovation and engineering that is emerging in our nation and especially in our region.

Thank you, *MTS*, for thinking of the students and teachers who will benefit from this work.



THE SEA: A NEW FRONTIER

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Maxine McCaffery
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CALIFORNIA STATE SERIES
Published by
CALIFORNIA STATE DEPARTMENT OF EDUCATION
Sacramento, 1967

Seven Miles Deep

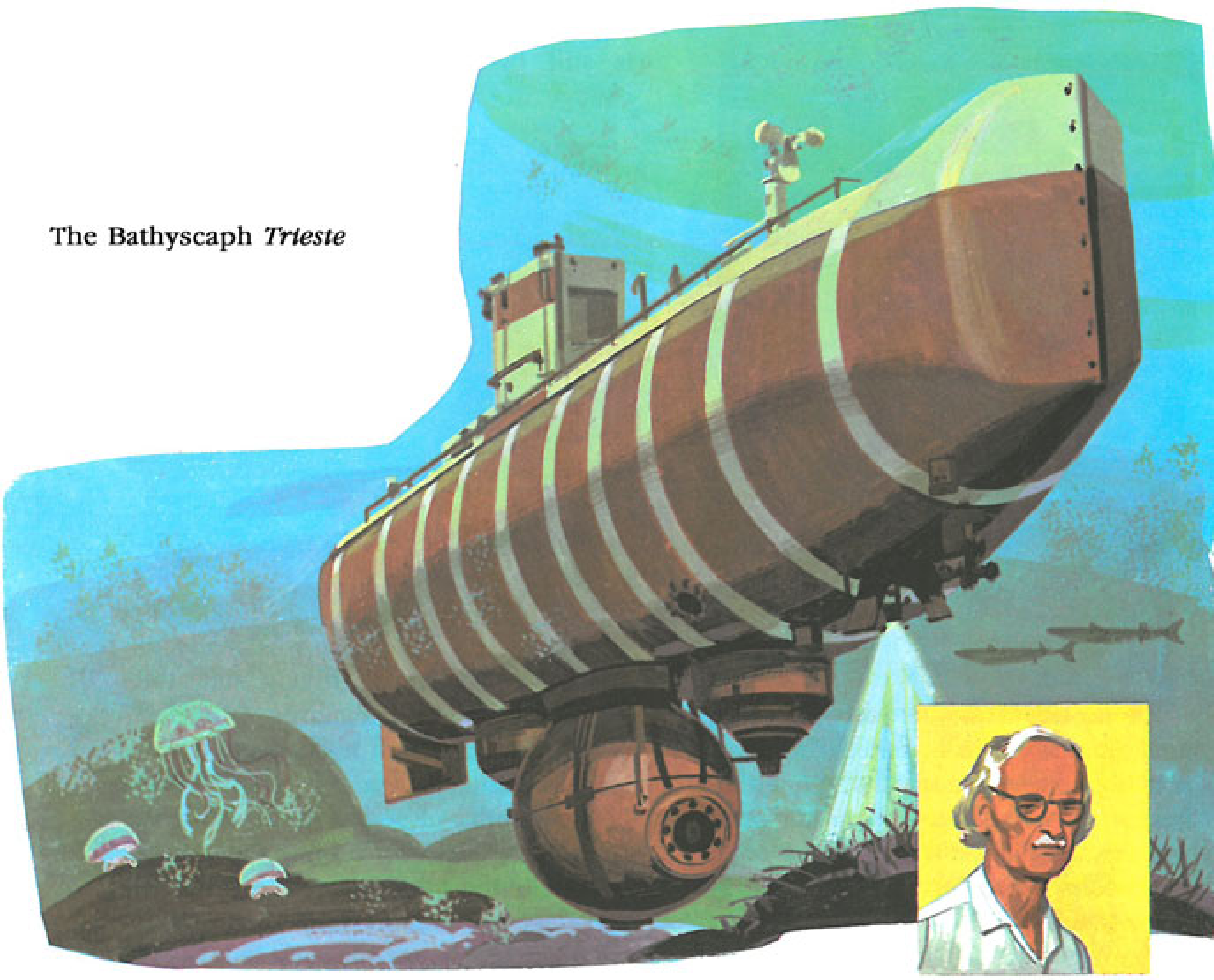
(Reprinted from the book, "The Sea: A New Frontier," written in 1967 by Donald MacLean, Department of Education, San Diego County, San Diego, CA, and Sam Hinton, Head Aquarist, Scripps Institution of Oceanography, La Jolla, CA, and published by the California State Department of Education, Sacramento, CA, 1967).

This chapter is a story of the development of a craft that brought man to the bottom of the Marianas Trench, 35,780 feet below the surface of the Pacific Ocean. It is a story of two men who looked through the window of an observation sphere, switched on powerful searchlights, and saw ghost-like shrimp feeding on an ocean floor over 7 miles deep, an ocean floor where the pressure is over 8 tons per square inch. It is the story of the "bathyscaph," a name made from the Greek words "bathy" meaning "deep" and "skaphē" meaning "light boat." The story of the bathyscaph *Trieste* is a strange and exciting one.

Yet like most stories of scientific achievement, the story of the bathyscaph began years earlier.

The story starts with Auguste Piccard, physicist and balloonist. Piccard first conceived of a bathyscaph when he was a college student in Zurich, Switzerland. Piccard did not go to the ocean to prove it his theory, however. Instead, he developed a hermetically sealed observation sphere, which would keep a man safe in a self-contained, pressurized living space or environment. The pressurized observation sphere was attached to a giant balloon.

The Bathyscaph *Trieste*



Auguste Piccard

Instead of moving downward into the ocean's depths, Piccard's observation sphere carried him 11 miles into the air. The observation balloon was named *FNRS*. The initials "FNRS" refer to *Fonds Nationale de la Recherche Scientifique*, from the Belgian government, which financed the development of Piccard's first balloon research. The flight of the FNRS convinced Piccard that the same type of observation sphere might be used to explore the depths of the ocean.

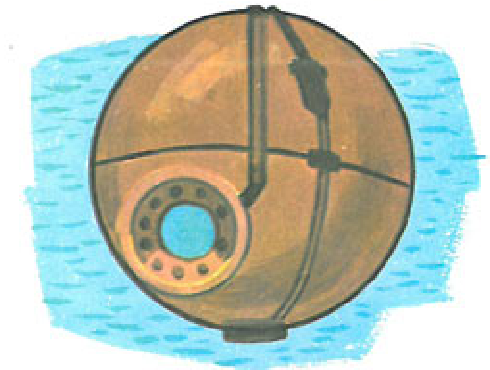
Piccard's Balloon Ascent

While Piccard was making his successful balloon ascension in 1932, two Americans, Dr. William Beebe and Otis Barton, were exploring new ocean depths in a small deep diving sphere called a "bathysphere."

Beebe's Bathysphere

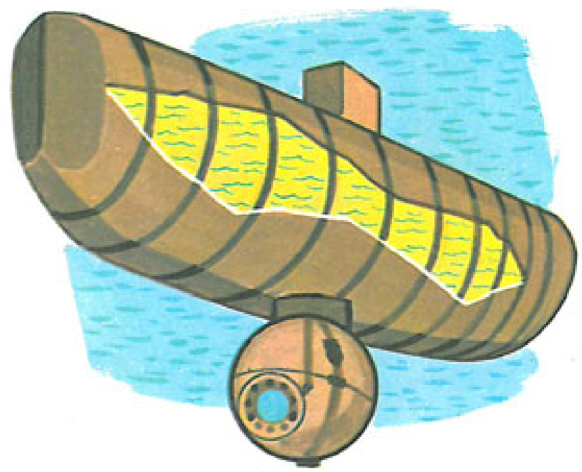
William Beebe was lowered in the bathysphere to a depth of 3,028 feet. He was the first man to see the strange new world of darkness where fish carried their own light. The accounts of his dives are filled with exciting and weird stories of never-before-seen sea creatures. But the bathysphere was dangerous, perhaps even more dangerous than Beebe realized. The cable on which the bathysphere was attached could have been broken easily under the weight of the observation sphere or from the sheer weight of the cable itself. The bathysphere was not able to move along the bottom of the ocean either.

Piccard read accounts of Beebe's undersea explorations and decided that the bathysphere had many serious disadvantages. Piccard reasoned that man needed a craft that was able to move about the bottom of the ocean without attached cables. An observation sphere had to be built that would withstand extreme pressures and at the same time be attached to a craft that could be made to be lighter than water.



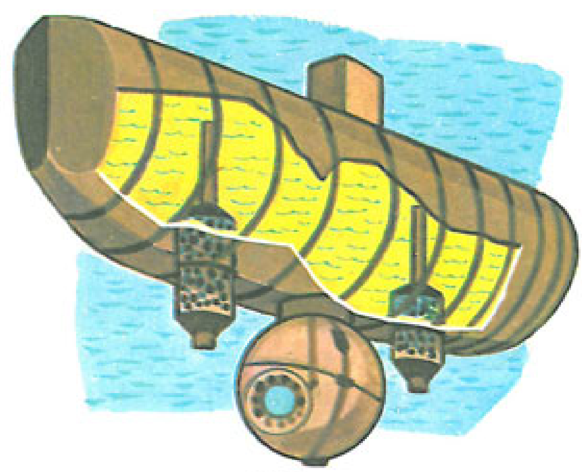
Observation Sphere

Piccard had an idea. The observation sphere could be attached to several large steel floats. The floats would not contain air, however, because they would easily collapse under the extreme pressure. Instead, high octane aviation gasoline would be pumped into the floats. Gasoline, being lighter than water, would prevent the floats from caving in under the extreme pressure.

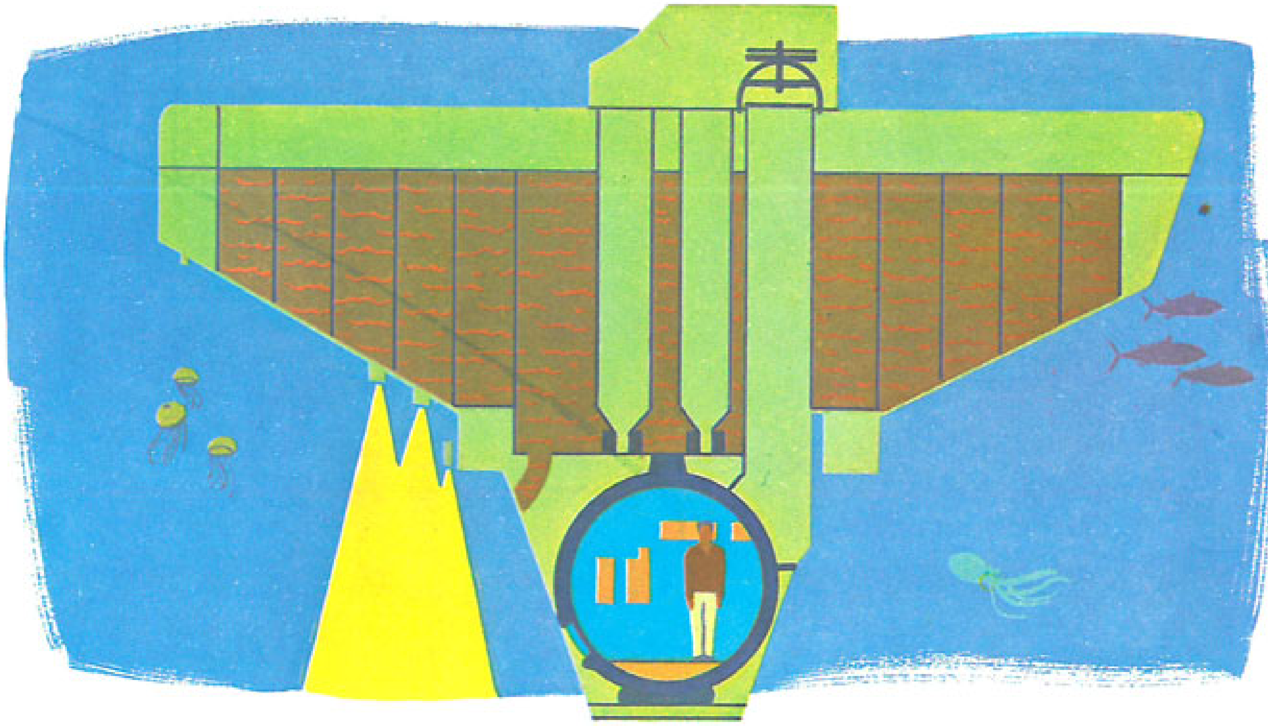


Steel Floats

Weights, called ballast, could be attached to the vessel to allow it to sink to the bottom. To return to the surface, the weights or ballast could be released, and the vessel would float to the surface. As Piccard planned and experimented with his dream of an undersea craft that would go to the oceans' depths, Hitler was seizing power in Germany. Suddenly in 1939, all of Europe was at war, and Piccard's bathyscaph had to wait for peacetime.



Ballast



French bathyscaph, *FNRS-3*

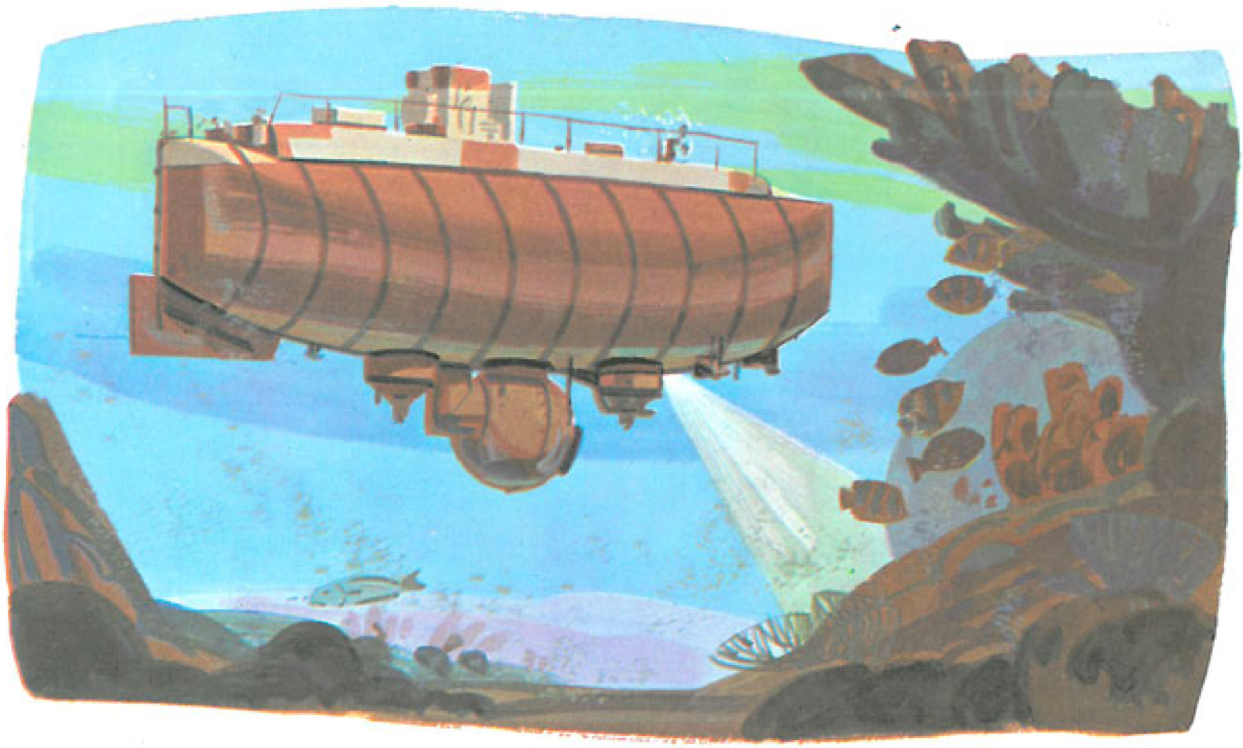
In 1948, Piccard's long-awaited bathyscaph was completed. It was called *FNRS-2*, named for the same group that financed his famed observation balloon and now promised to help build his new bathyscaph. It was a strange looking craft, looking more like a dark steel balloon than a craft that would take man 25 times deeper than a submarine.

The new bathyscaph, *FNRS-2*, contained six large floats that were filled with aviation gasoline. Each float was designed so that sea water could enter its underside as the craft went down into deeper water. This allowed equalization between outer and inner sides of the float tanks, keeping the tanks from being crushed by water pressure. Because water pressure was equal on both sides of the float tanks, the metal could be thin. This allowed the float tanks of the bathyscaph to be lightweight and rather inexpensive to build.

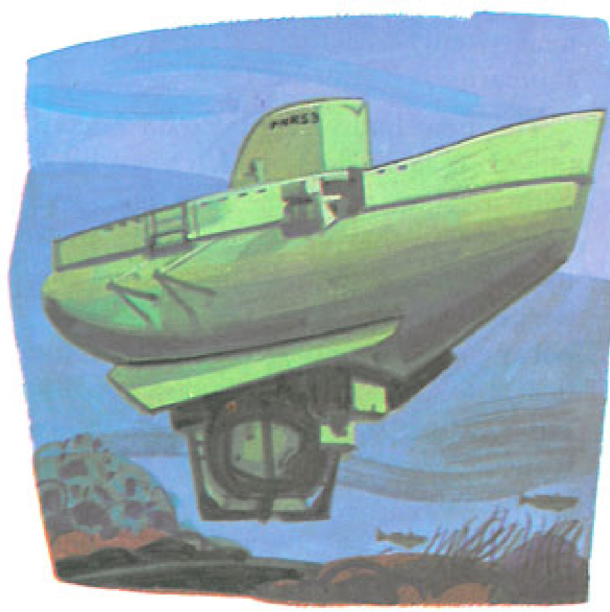
Attached to the six gasoline floats was the observation sphere. Its walls were three and one-half inches thick, and it contained equipment that would keep two men alive during the dives. Two small propellers propelled the craft. To submerge, the bathyscaph was loaded with ballast. The ballast was in the form of an iron shot, which could be released as needed.

In 1948, the unmanned bathyscaph, *FNRS-2*, dove to 4,620 feet. Convinced of its safety, Piccard took the *FNRS-2* on its first and last manned dives to 3,300 feet.

The bathyscaph *FNRS-2* was a success. Piccard proved to the world that the depths of the ocean could be explored in safety. Before Piccard's bathyscaph, man had depended upon the submarine. But the submarine had to be designed to withstand the total pressure of the depth. Now man had proof that only the observation sphere need fight the extreme pressure.



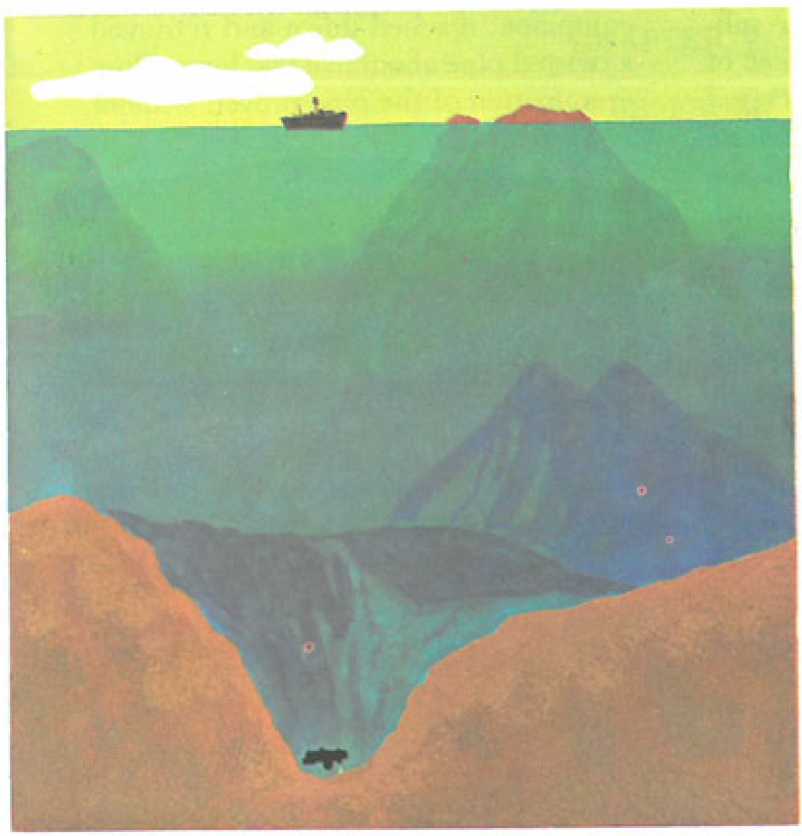
Bathyscaph *Trieste*



French *FNRS-3*

In 1953, the *FNRS-2* was sold to the French Navy, and Piccard began working on a new bathyscaph designed to travel to the deepest part of the ocean. It was named the bathyscaph *Trieste* after the city of Trieste, Italy, which financed its construction. It was a larger, more streamlined bathyscaph, containing five more gasoline floats. In September 1953, Piccard's *Trieste* reached a depth of 10,200 feet.

During the same time, Piccard served as an advisor to the French Navy in its attempt to rebuild his older bathyscaph into the newer *FNRS-3*. In 1954, the French Navy took the *FNRS-3* down to 13,400 feet, breaking the *Trieste* record by over 3,000 feet. This record held until 1960.



The Challenger Deep

Jacques Piccard

Lt. Don Walsh

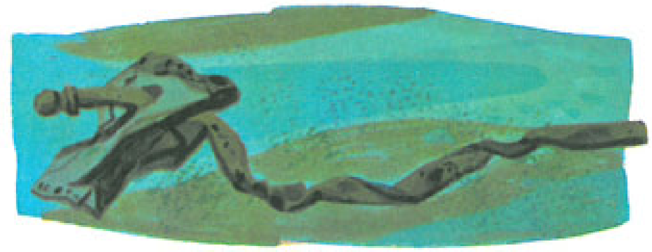
In 1958, the *Trieste* was purchased by the United States Navy. It was outfitted for one place, the deepest place in the ocean known as the Challenger Deep. Early in the 1960, the *Trieste*, manned by Auguste Piccard's son Jacques and by U.S. Navy Lieutenant Don Walsh, was gently set down on the floor of the world's deepest abyss, 35,800 feet below sea level. Through the thick cone-shaped acrylic window of the observation sphere, the two men saw living fish in the searchlights. Life existed in a world of total darkness and a pressure of eight tons per square inch.

Man was fulfilling a dream that he had carried for countless centuries. Man was exploring a new frontier!

The bathyscaph *Trieste* was still a crude, undersea research vessel. It was expensive to operate because it required 9 tons of iron shot to bring it to the required depths. This shot was dropped onto the sea bottom as the bathyscaph rose. The bathyscaph was dangerous because it was filled with high octane aviation gasoline. It was slow moving, and it had a short range. It would be improved because the active minds of scientists, technicians, and engineers are always dreaming of better ways to explore the world in which we live.

On April 10, 1963, the nuclear submarine *Thresher* sank in 8,400 feet of water with her crew of 129 officers and enlisted men. The bathyscaph *Trieste* was the only undersea vehicle in the United States able to reach the depth where the *Thresher* lay. While the slow moving, 59-foot *Trieste* was not intended for search and rescue, it was brought by ship to the scene of the *Thresher* disaster.

On the eighth dive, Commander James Davis, an oceanographer, and Lt. Commander Arthur Gilmore sighted the twisted wreckage of the ill-fated nuclear submarine. The *Trieste*'s mechanical equipment reached down and retrieved a twisted pipe about 5 feet long. Close examination of the pipe proved without a doubt that the *Trieste* had located the *Thresher*. This was to be the last of the *Trieste*'s 70 research dives for the U.S. Navy.



On January 17, 1964, a sturdier and more powerful bathyscaph, *Trieste II*, was launched. The original *Trieste* had a round bottom. *Trieste II* has a flat bottom and will float in shallower water. *Trieste II*'s observation sphere is recessed into its body for better streamlining. *Trieste II* is 67 feet long, weighs 53 tons, and carries 45,000 gallons of aviation gasoline. It travels at 2 knots, twice the speed of the original *Trieste*.

Modeling the *Trieste* to Explore Density and Buoyant Force

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Introduction

Often we see students memorizing definitions for mass, volume, density, and buoyancy. And they are usually able to calculate density and buoyant force, but once they are able to apply these principles to a real-life situation, the concepts take on new meaning. In this activity, students use the context of the historic *Trieste* bathyscaph to measure mass and volume, to calculate density, and to build a working model of a submersible. After building the model, students develop hypotheses and test their model to observe it in action. Students are amazed to see and demonstrate some of the physics behind the *Trieste* submersible and the creative use of different densities to conquer the deep. Amidst their delight and total engagement in working with the models and testing their hypotheses, our middle school students began to make the important connections about density and buoyant forces.

Learning Objectives

Practice measuring mass and volume as well as calculating density.

Explain how the density of an object determines whether it sinks or floats.

Describe the effect of buoyant force.

Demonstrate how the *Trieste* used differing densities to manage buoyant force.

Science Process Skills

Students will measure mass and volume of difference substances, calculate density and buoyant force, build a model, make and test hypotheses, record and analyze data, and draw conclusions.

California Content Standards

Grade 8—(2 a, b, c, d, e) (8 a, b, c, d) (9 a).

Historic Context

In the 1930s, there was a growing scientific and public interest in exploring the deep sea. The challenge of building a personnel sphere to withstand the high pressure was coupled with the challenge of how to float it. Auguste Piccard, the inventor of the *Trieste*, was a physicist and balloonist who looked at these challenges from a different perspective. He used differences in density to provide a creative solution to the challenge of ascending from great ocean depths. Piccard designed and built several bathyscaphs and in 1953, he completed his second bathyscaph, the *Trieste*. His goal was to go deeper than anyone had ever gone before. Using gasoline and iron shot, the crew of the *Trieste* was able to adjust their buoyancy to successfully dive and return to the surface from depths greater than anyone had before.

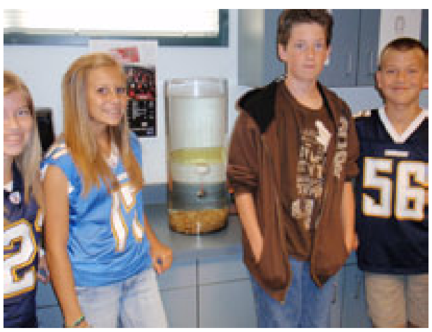
Education Standards

Eighth grade Science Standards include that students know that a force has both direction and magnitude (2a) and that all forces acting on an object have a cumulative effect (2b). They must know that when the forces are balanced on the object, its motion does not change (2c), but when the forces are unbalanced, the object's motion changes. (2e) Students must be able to identify the forces acting on an object (2d). They must know that density is mass per unit volume and that it can be calculated by dividing an object's mass by its volume. They must learn that floating or sinking

can be predicted by comparing densities of fluids and objects within the fluids. Finally, they must know that the buoyant force is equal to the weight of the displaced fluid. (8 a,b,c,d) In addition, they are expected to use and understand the scientific methods of investigation and experimentation (9a,f). It's no wonder that many of them find it somewhat difficult to grasp. It is not until they are able to apply these things to what they enjoy and are familiar with that they really understand the concepts and how they are related. This activity does just that. It brings them to that "Aha!" moment when the light turns on (Figure 1).

FIGURE 1

Eighth grade students find neutral buoyancy for their model of *Trieste*.



Management

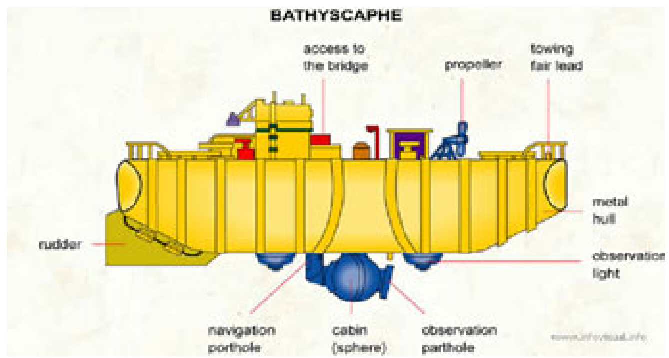
Before introducing this activity, the basic concepts of mass, volume, density, gravity and weight, buoyant force, and the scientific method for investigation and experimentation are introduced.

Students should be familiar with using the measuring equipment and have done several activities calculating the mass, volume, and density of various objects. They should be familiar with the behavior of fluids of different densities and should be familiar with why things float or sink. This can be done through several related activities that use all the learning modalities.

On the day of this activity, I introduce my students to the *Trieste* "bathyscaph." Photos and diagrams help the students to see the connection to the actual model they will be using. I ask the students what the designers needed to know about their bathyscaph before they could be certain it was safe to put into the water. They suggest that they would need to know if it would float in the water, and I ask

FIGURE 2

A schematic drawing of the bathyscaph *Trieste* that carried explorers to the deepest place in the ocean.



them how they could find this information without actually putting it in the water. When they determine that they could calculate its density and compare it to the density of the water, we move to the next question. I ask, if it does float, what needs to be done to it to make it sink. Most will quickly say add weight to it. Then I ask how they will know how much weight needs to be added. When they determine that they need to calculate its buoyant force, and then add more weight than the buoyant force, I ask the final question. What needs to be done to allow the bathyscaph to return to the surface. By now, they can easily see that the weight needs to be removed.

- Bathyscaphs are independent, deep-diving vessels for underwater exploration
- The *Trieste* was the first bathyscaph designed by the Swiss in 1953. It had a high-pressure sphere and a very large tank filled with gasoline. Gasoline is less dense than water and does not compress, or squeeze, which allows it to keep its buoyancy.
- The *Trieste* displaced 50 tons of sea water and carried 9 tons of iron ballast (Figure 2).

Using a model of the *Trieste* filled with oil instead of gasoline, students determine its density, its buoyant force, and the amount of mass needed to make it neutral in tap water. Then they test their hypotheses by placing them in the tank. Finally they add more mass and a release mechanism to determine if it will sink to the bottom of the tank and then return to the surface (Figure 3).

Further Explorations

If time permits, students are encouraged to try other explorations with their models such as:

Will you have the same results if you test your hypotheses in salt water?

Will adding more mass slow the ascent time?

Will adding more mass speed the sinking time?

Can you think of any other release mechanisms for the *Trieste* model.

FIGURE 3

A working model of the bathyscaph, demonstrating application of differences in density.

Will it work in the deepest end of a pool?
Will it work in saltwater, like off a dock in the bay?

Objective

The objective for this activity is to explore how mass and volume affect density and buoyant force.

Materials and Lab Preparation/Assembly

Tools needed:

1. Hot melt glue gun with sticks
2. Push pin
3. Needle nose pliers, 2 pairs
4. Diagonal small cutters
5. Drill
6. Drill bits, 1/16 and 1/8 inches
7. Whisk broom, dust pan, and trash can for clean up
8. Funnel
9. Magic Marker or Sharpie

Materials needed, for each bathyscaph model:

1. Water bottle, 16.9 Fl. Oz, empty, with lid, remove label
2. Washer, garden hose
3. Screw eye, small
4. Golf ball
5. Vegetable oil, to fill water bottle
6. Alka Seltzer® tablets, 2 each
7. Paper clips, medium, 2 each
8. Rubber bands, 2 each, medium
9. Two lids from 35-mm film canisters
10. Paper towels
11. Sharpie indelible pen
12. Test tank. A 10-inch diameter × 24-inch glass cylinder is available from many wholesale flower shops for about $50.
13. Siphon hose to drain test tank
14. buckets to fill/drain test tank
15. Large galvanized steel flat washers from the hardware store, total weight = 3 oz
16. Tap water
17. Twist ties

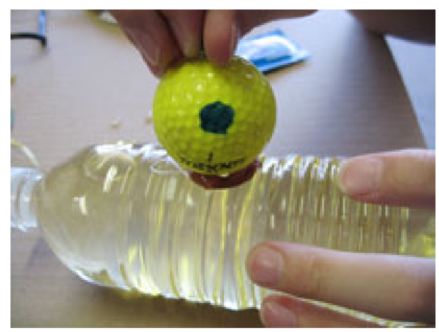
Process (Build the Parts!)

Bathyscaph Body

1. Plan construction in a place where if oil is spilled, the mess is contained and does not become a bigger problem.
2. Plug in hot melt gun and let it come up to temperature.
3. Place empty water bottle on a sheet of paper towel or in a sink. Using the funnel, fill the water bottle with vegetable oil to full. Screw cap loosely onto water bottle. Squeeze bottle slightly to remove any remaining air. Tighten cap. Clean exterior of bottle with dish soap to remove any oil on the outside.
4. Gripping the center of the water bottle with your thumb and center finger like a teeter-totter, locate the center of mass of the filled water bottle. Mark the spot with a Sharpie pen.
5. Using the push pin, make a pilot hole in the golf ball for the screw eye. Install the screw eye into the golf ball. This will serve as the anchor attachment point later.
6. Using preheated glue gun, glue the garden hose washer to the side of the water bottle. Fill the center of the hose washer with hot glue and stick in the golf ball with the screw eye pointing directly away from the water bottle. The bathyscaph vehicle is now complete (Figure 4).

FIGURE 4

Student glues "personnel sphere" to buoyancy tank.



Anchor

7. Weigh 3 oz of washers (or mass determined by experiment as described). Run a twist tie through the center of the washers, plus one medium paper clip. The paper clip will be the hook to attach to the rubber band in the release later (Figure 5).

Release

Each release uses two 35-mm film canister lids and a paperclip bent to

FIGURE 5

Fishing sinkers or flat washers work well for weights.

make a hinge. Drilled holes are done to both lids the same. Segments of the edges are clipped differently depending on which half it is (Figure 6).

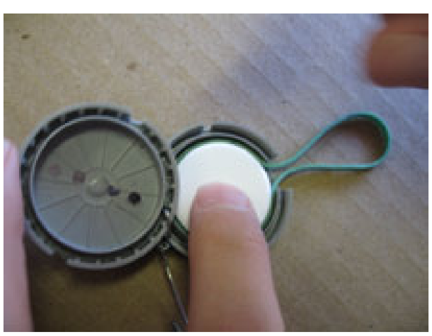
1. Layout 35-mm film canister lids and medium size paper clips for the number of releases to be made.
2. With Sharpie, make alignment mark to establish a "top" position on all lids.

   Important, this initial position will now be referred to as "top. Other positions will be referred to as "bottom", "left," and "right.Note the two concentric "ridges" that make the snap seal when placed on the film canister.

3. Drill a single 1/16-inch diameter hole at the "top" between two ridges near edge as shown.

FIGURE 6

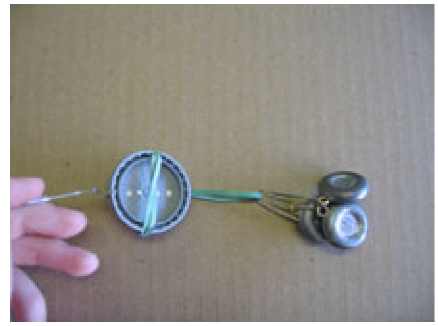
Assembly of the release. When seltzer tablet dissolves, rubber band falls out, releasing weight.



4. Drill three 1/8-inch diameter holes in a vertical line in the center section running from "top" to "bottom" as shown.
5. Modify all lids this way.
6. Separate lids into two equal groups.
7. Modify one group by clipping a single 1/8-inch wide gap through both ridges at the "bottom" position (the side opposite the "top").
8. Modify the second group by clipping a 1/8-inch wide gap through the outer ridge at two locations, at the "left" and the "right" as shown.
9. Another view of modified second group. Note inner all is not clipped.
10. Release will use one lid from each group. Both are placed flat side down, ridges up, with 1/16-inch diameter holes at "top."
11. Using the needle nose pliers, bend the paper clip straight and make hinge by running the wire through the 1/16-inch diameter holes. Bend the wire at the top to make a "hook" like a Christmas tree ornament hander.
12. Slide lids apart and place Alka Seltzer® tablet in center of release.
13. Place rubber band smoothly around Alka Seltzer® tablet, with excess brought through gap at bottom that was cut in Step 7 above.
14. Close release by sliding the top lid over the bottom lid capturing the Alka Seltzer® tablet and rubber band inside.
15. Another view of release when closed.
16. Use second rubber band to hold release closed. Note rubber band is kept from sliding off by dropping into the gaps cut in Step 8 above.
17. Attach weights to rubber band coming out of bottom of release. Release is now ready for attachment to bathyscaph screw eye using hook at top (Figure 7).

FIGURE 7

Anchor weights attached to rubber band of release.



Materials for Each Group of Four Students

Water bottle filled to brim with canola oil, lid tightened, then sealed with hot glue

golf ball with hose washer and screw eye attached

Trieste model (oil filled bottle with golf ball and attachments glued together)

100-ml graduated cylinder	triple beam balance
250-ml graduated cylinder	
15–20 washers of various sizes	two rubber bands
Release apparatus	two to four Alka Seltzer® tablets
Paper clips	

Equipment Positioned at Sinks or on Counter

- three each, 10-inch diameter × 24-inch tall glass tanks (available from Florist shops)
- three displacement cans
- three, 2-L graduated cylinders
- three long sticks with magnet attached to end

Shopping list: 3 gallons of canola oil, 18 empty water bottles, 18 golf balls,

18 hose washers, 18 screw eyes, 1 box small paper clips, hot glue gun with hot glue, 18 film canisters with lids, a 1/8-inch drill, lots of Alka Seltzer® tablets, 3 long sticks, 3 powerful magnets, 3 tall clear glass tanks (we found 10-inch diameter × 24-inch tall clear cylindrical glass vases at a florist shop that worked very well for about $50 each, a real steal!)

Preparation Before Lab

There is a considerable amount of time needed to prepare for this activity; however, once the models are made, they are reusable each year. I had help with the release mechanisms, but the rest of the preparation took about 4 h (well worth the time and effort for years of use).

- 9 release mechanisms need to be drilled and assembled in advance
- 9 *Trieste* models filled, assembled and glued together
- 9 water bottles filled with oil and glued shut
- 9 golf balls with hose washer glued on and screw eye attached
- Glue magnets to three long sticks

Procedures/Student Lab Sheet, Assessment

STUDENT WORKSHEET
Name_________________ Science Period_______________
Exploring Density and Buoyant Force with a Submersible
Objective: Demonstrate by using the lab equipment provided how mass and volume affect density and buoyant force.
Observations (background information on Power Point): We have a model of the *Trieste* bathyscaph. It is not filled with gasoline, but it is filled with oil. We need to know if the *Trieste* Model is less dense than water, and therefore will float. To determine the **density** of the model, **divide its mass by its volume**. After determining the density, we will calculate the buoyant force on the model and determine the amount of mass needed to make it neutral in the water. (same density of water; 1 g/cc)
Finding Mass: Find the **mass** of the *Trieste* model with the **balance** and record this information on your Data Table below.
Finding Volume by displacement: Finding the volume of the *Trieste* model will require 3 steps because the model is too large to fit into our biggest graduated cylinder.
Step 1: Place the filled bottle of oil inside a 2-L graduated cylinder that has 1000 ml of water in it. Gently submerge the bottle using a pencil, so that the pencil does not go below the surface of the water. Read and record this new level of water with the bottle in it. Subtract the original 1000 ml from the new amount. This will give you the volume of the water displaced by the bottle of oil. Record this as the **volume of the oil filled bottle**.
Step 2: Use a filled displacement can at the sink to find the volume of the sphere (golf ball with attachments). Catch the displaced water with an empty graduated cylinder. This will be the volume of the sphere. Record this as **volume of sphere**.
Step 3: Add the volumes from steps 1 and 2. This should equal the total volume of the *Trieste* model. Record this as **volume of *Trieste* Model** on the Data Table.
Calculating Density: Now that we have determined the mass and the volume of the *Trieste* model, **calculate its density by dividing its mass (g) by its volume (cm3).** Record the density of the *Trieste* model on your Data Table. Is the model less dense than water (1.0 g/cm3)? ______ Will the model float in the water?__________
Ask a Question: What is the amount of mass that needs to be added to the *Trieste* model in order to make it neutral (1.0 g/cc)? Then after increasing the mass so that it will sink to the bottom of the tank, what needs to be done to return it to the surface of the tank?__________________________________

Make a Hypothesis: To give a good possible answer to the question, you need to know how much buoyant force that the water has on the *Trieste* Model.
Calculating Buoyant Force: To determine the buoyant force, we will need to know the **weight of the displaced fluid**. In this case the fluid is water, which makes things easier, because the **weight (for which we will substitute mass) of the water equals its volume.** You have already determined the volume of the displaced fluid for the *Trieste* model when you were finding its density. So this volume is also the mass of the displaced water and, therefore, **the buoyant force** pushing up on the object. Record this as buoyant force on your data table.
Now you can make an educated guess, as some hypotheses, are called. You simply need to subtract the mass from the buoyant force. The result will tell you how much mass added to the *Trieste* model will make it *neutral (1 g/cc)* in water. Record this result as your hypothesis.
Test the Hypothesis: Assemble the *Trieste* model with the **added mass from your hypothesis**. Take your prepared model to the tank of water and gently place it into the water. Observe what happens. Could you make your model neutral in the water? __________ Now add another weight to your model with a **release mechanism**.
Did the model sink? __________________
What changed about the model to allow it to sink? ____________________
Did the model rise back to the surface? ___________What changed about the model to allow it to rise?__________
Conclusion: Was your hypothesis correct?___________ How much mass made your model neutral? ___________ sink? ________
Which changed in this experiment, the density of the model or the buoyant force on the model?___________________

Data Table

Mass of *Trieste* Model = ________ g
Volume of oil filled bottle = ________
Volume of sphere = ________
Volume of *Trieste* Model = ________
Density of *Trieste* Model = ________
Mass of displaced water = ________
Buoyant Force of water on model = ________
Your hypothesis of weight to make neutrally buoyant = ________

Assessment

Compare data.
Discuss how it went.

Independent Study

Let's try the deep end of the pool! (Figures 8 and 9).

More Information

Go to <http://www.materover.org> and search for "bathyscaph project." You'll find step-by-step photos showing how to make your own working *Trieste* model including the Alka Seltzer® release!

FIGURE 8

This bathyscaph explores the deep end of the pool.

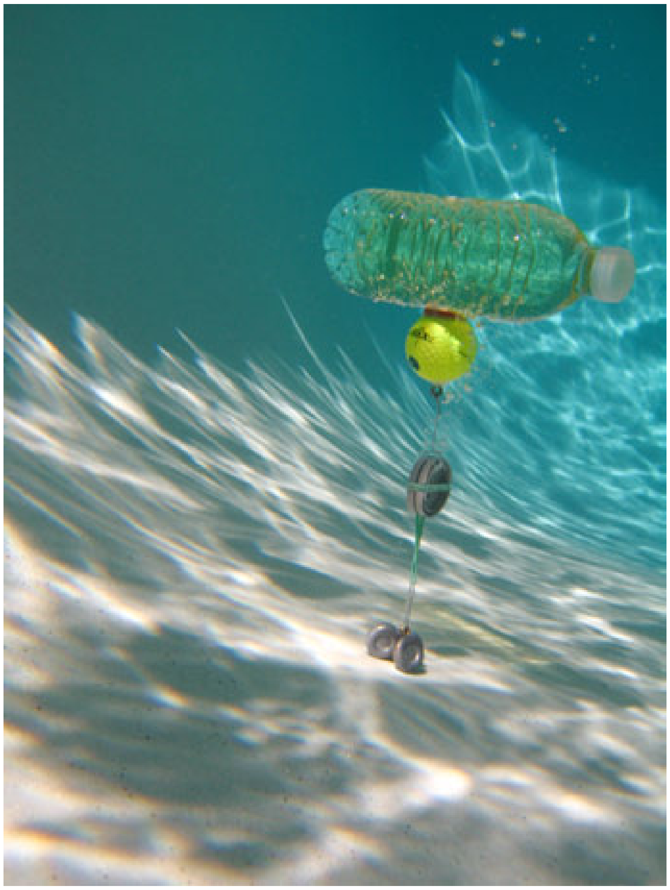


FIGURE 9

Reflected in the surface, the bathyscaph returns from a deep dive.

You can also search the web and learn about the amazing world of ocean engineering and undersea vehicles.

Acknowledgments

The authors thank Kevin Hardy for his help and encouragement with this project, and Michelle's nephew, Justin Linvill, for helping build and test the first working model, including a dive to the deep end of the pool.

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Underwater Intervention 2010

February 9–11, 2010
New Orleans, La.
www.underwaterintervention.com

More than 145 booths are already sold, and there are numerous sponsorship opportunities available. Visit the website to find out how to add your company's name.

ONR/MTS Buoy Workshop

March 9–11, 2010
Monterey, Calif.
www.whoi.edu/buoyworkshop/index.html

The 8th Buoy Workshop will be held at the Monterey Conference Center, but come a day early to enjoy an icebreaker reception at the lodging headquarters, The Hotel Pacific, located across the street from the Conference Center. Over the course of the 2.5 days workshop, presentations will cover many of the aspects of the highly specialized technology and field of oceanographic and other data buoy systems. The buoy group has become quite international, with many applications and projects from the Great Lakes to the coastal and deep oceans around the world.

Offshore Technology Conference

May 3–6, 2010
Houston, Texas
www.otcnet.org/2010

The submission deadline to have your technology recognized in the Spotlight on New Technology Awards is January 15. MTS members have won in the past, so don't miss this opportunity!

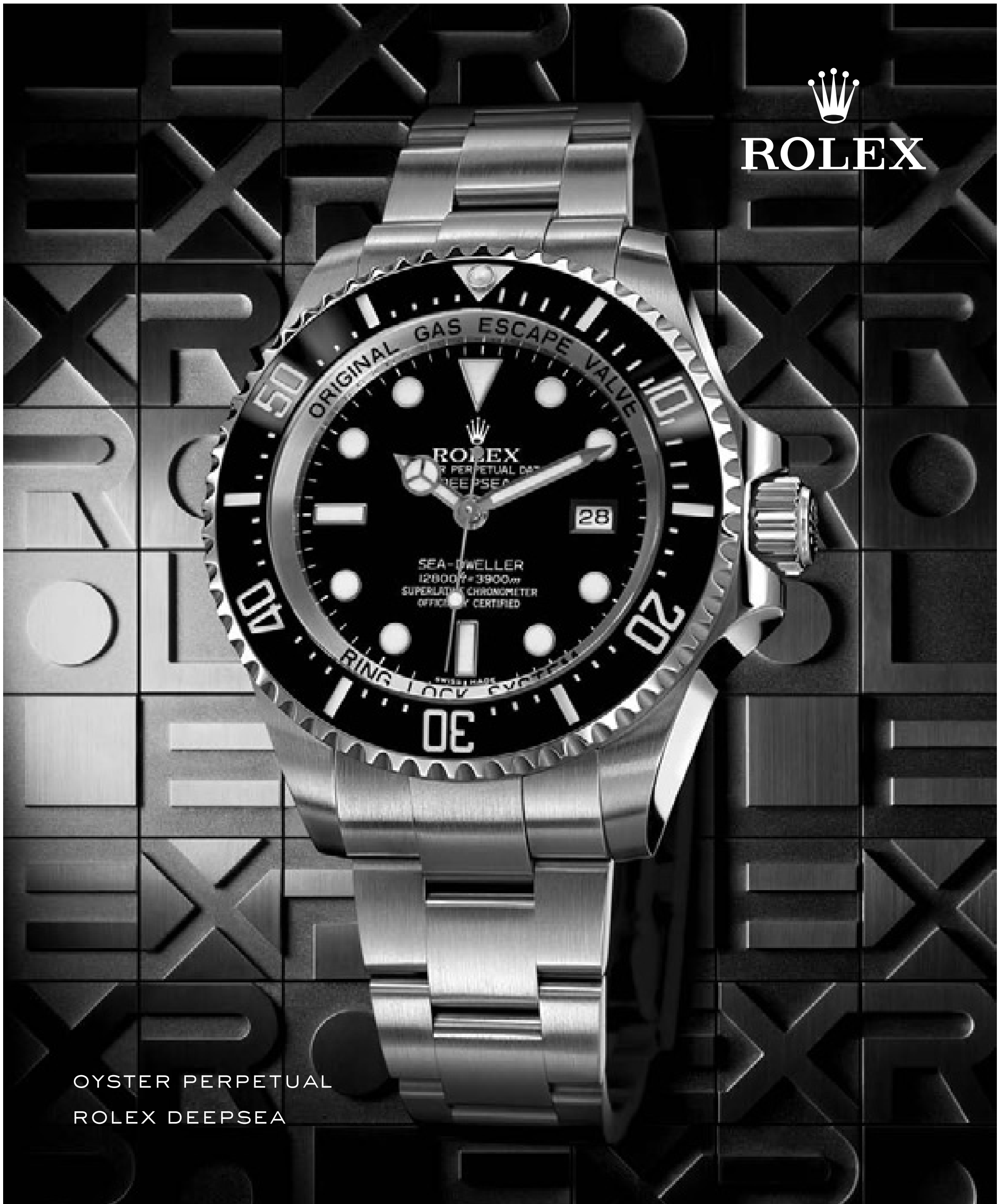
For exhibitors, changes have been made regarding the available indoor exhibition space, which will streamline access to exhibits and enhance the tradeshow experience for both attendees and exhibitors. For attendees, housing information should be available now, and registration information will be available by the end of January 2010.

OCEANS'10 MTS/IEEE Seattle

Innerspace: A Global Responsibility

September 20–23, 2010
Seattle, Washington
www.oceans10mtsieeeseattle.org

Seattle's OCEANS'10 features tutorials on special-interest topics, a comprehensive technical program of lectures and presentations, a student program, and a large exhibit hall with products from over 100 companies. For more information, e-mail info@oceans10mtsieeeseattle.org.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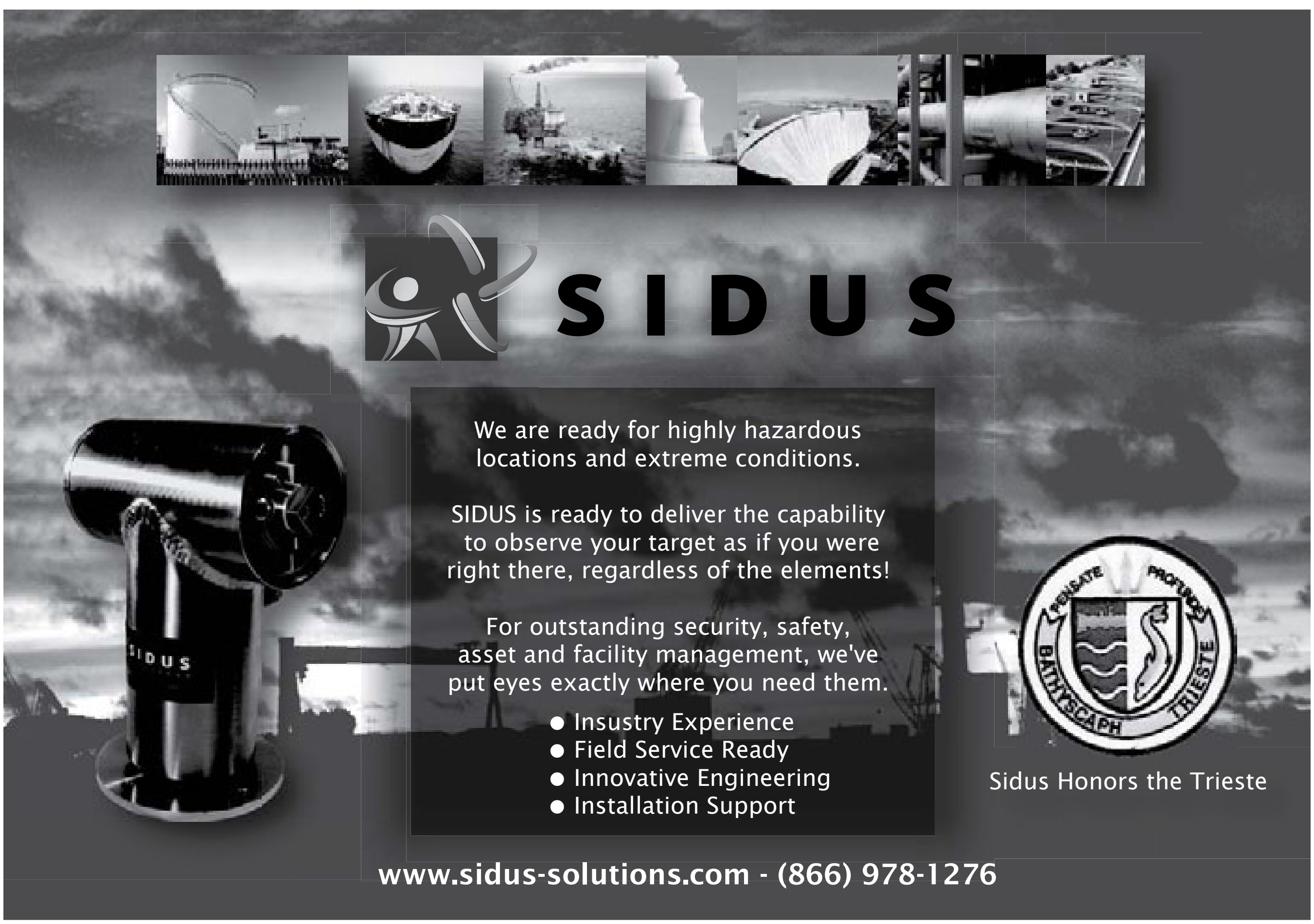
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The Margin of Life

The contrast between ordinary and great living is the difference between what a person is required to do to exist and what he/she feels they can and must do to be their best self. There are parasites in every society. They rely on the efforts and support of others. The margin of life is the difference between what they are and what they might become if they used their potential abilities.

There is a margin in the business world. In every industry and profession there are those who get by with a minimum of effort. They are more interested in money than in service; more concerned about what they can get than what they can give. They are specialists in mediocrity.

Others find work an adventure. They want their product, or their service, to meet the highest standards. They find satisfaction in being part of a team which produces something to enrich life. They strive to make their contribution as nearly perfect as possible. They put something extra into their work.

That attitude constitutes the margin in life.

There is also a margin in personal relationships. Sometimes we make friends reluctantly. We use people for our own ends. We are critical of those who threaten our positions. We make little effort to understand the point of view of those about us. We assume an air of superiority to hide our inner fears.

On the other hand, sometimes we reach out to people.

In commemoration of the great achievements of people on whose shoulders we stand. This is a re-print from an advertisement by LAMB Co. in 1973 and framed in offices for 37 years. Its presence today is a re-affirmation that the spirit lives on through the next generations.

We are not blind to their weakness, but we recognize that there is value in every person. We look for the best. We see every individual as made in the divine image. We search for opportunities to relate to persons.

That attitude constitutes the margin of life.

There is a margin, too, in the realm of character. You have met those who assert that standards of value no longer exist. They believe there is no right and no wrong. Or they declare: “That is right which gives me pleasure, and that is wrong which limits my freedom.”

Concerned people recognize a standard of values. It is steeped in the heritage of the ages. It has been tested in the crucible of human experience. These men and women know that a code of laws must be adapted to each new generation, but they affirm the enduring importance of duty, honesty, and work.

That attitude constitutes the margin of life.

There is another margin in our relationship to society. It is tempting to ignore the call of responsibility – to blame someone else for pollution, or political corruption, or crime.

For a large number of those who are concerned, service is the plus element which helps to make a better world. They expand their horizons by giving their money, time, and efforts to lift the load of poverty, injustice, or hate. It isn’t what they have to do, but what they want to do in order to be their best.

That’s what makes the margin in life.

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