Lung Inspired Deep Water Sampling Module

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***Abstract*— A robotic system that can perform in situ microbiological identification and quantification of larvae, bacterial and other microscopic organisms at depths up to 4000m has been developed and deployed by MBARI. The system is composed of an existing low pressure detection instrument and a Deep Water Sampling Module that collects up to 10L of seawater and decompresses it for analysis. The architecture for the Deep Water Sampling Module was inspired by lungs and the mechanics of breathing.**

***Index Terms*—Lung, Hydraulic, …**

I. Introduction

A PRIMARY goal of the Monterey Bay Aquarium Research Institute (MBARI) is to extend the operating depth and duration of ocean scientific instrumentation. The Environmental Sampling Processor (ESP) program utilizes complex, robotic laboratory instruments for *in situ* identification and quantification of larvae, bacteria and other microscopic organisms in near real time [1], [2]. This avoids the time lag and changes of state that occur when samples are sequestered and transported to the laboratory for analysis. Additionally, as a robotic system it can be deployed for months, enabling new research in tracking microbial activity over time without human presence. Although typically deployed in less than 50m seawater, MBARI undertook the task of bringing the ESP scientific capabilities into the deep sea.

To function, the ESP instrument filters a volume of the ambient seawater, collecting the sometimes sparse microbes for autonomous detection. However, this requires processing liters of the ambient seawater through the 500kPa rated fluidic system, resulting in a 50m operating depth limit. The Deep ESP project developed interface systems that would allow an ESP to operate in depths to 4000m, where the ambient pressure is about 41 MPa.

As the ESP instrument has numerous valves, fittings and remotely operated pressure seals, it was much more feasible to develop a pressure modifying interface that could feed reduced pressure seawater to the instrument rather than redesign the instrument to perform the same functions at much higher pressures. A 4000m Deep Water Sampling Module (DWSM) was developed that could collect the seawater sample under high ambient pressure and then create a low pressure environment of that water, so that the ESP instrument could safely filter and identify the microbes present. Out of several concepts, a differential pressure driven system inspired by lungs and the biological process of breathing presented the greatest potential. System design and fabrication found many parallels to lung structures and processes of inhaling and exhaling seawater, even to the point it garnered the nickname, “aqua-lung.”

II. Deep Water Sampling Module Purpose

The Deep Water Sampling Module is the interface between the ocean and the ESP instrument. This complex system has one simple function, to provide low pressure seawater that the core ESP can process while it is still located in the deep ocean.

Starting in 2005, MBARI developed and tested the first deep ESP system to 1000m depth in the Monterey Bay canyon. It worked on a similar concept as the 4000m version, as it used the same ESP instrument for microbiology identification, with an interface system that would sequester and decompress the seawater prior to filtering and analysis. However, the 1000m system was implemented by very different methods and hardware. For background information, a short description of the 1000m Deep ESP equipment follows.

A. Review1000m Deep ESP

The 1000m Deep ESP was developed only to the capability of one day, ROV tethered operations. The Deep ESP system was mounted on a tool sled underneath MBARI’s Ventana ROV, which provided power and communications to the instrument.

The 1000m DWSM used a cylinder and piston system to collect and decompress seawater. One large cylinder was used to inhale and sequester the seawater, and another much smaller one to decompress the sequestered seawater. Two identical oil compensated linear actuators were used to drive the pistons. The method of operation was the sampler cylinder would

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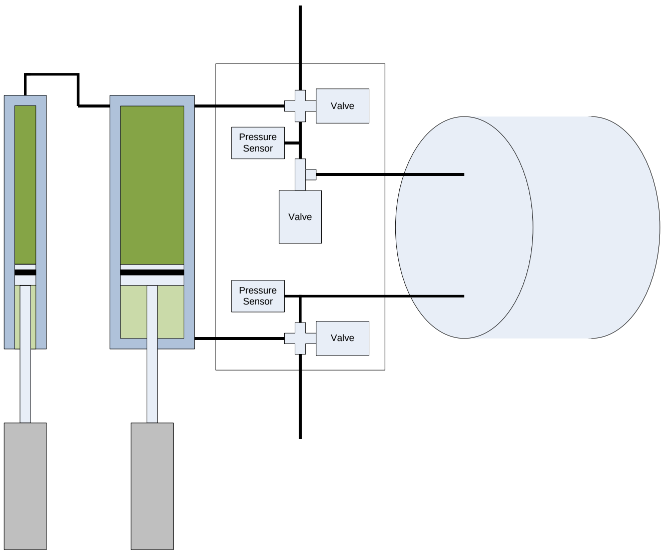
intake a seawater sample, then valve closed from the ocean. The smaller piston would expand that enclosed volume, creating the decompressed condition. The system would then valve to the ESP instrument which would filter the water, passing the filtrate to the back side of the sample cylinder piston.



Although the cylinder and piston method of the 1000m system was a straight forward approach to sequestering and decompressing in-situ, there were drawbacks and lingering problems with this architecture. Much of the decisions in the 4000m DWSM were based upon lessons learned from the 1000m system, and shall be detailed.

B. 1000m Lessons Learned

1) Needed more sample, 10L

In the deep ocean, microbial life can be much less abundant than at the surface. The 1000m Deep ESP used a 1.8L sequestered volume of seawater, which was determined not to be sufficient for the science goals. A 10L sample of raw seawater was estimated to be necessary. However, enlarging the 1000m architecture for a 10L volume would be intractable.

A drawback to the linear actuator and piston assemblies of the 1000m system is that the size of the mechanism is linearly proportional to the volume sampled. The length of the fully assembled linear actuator, anti-rotation rod, and piston cylinder was 1.15m. Increasing the volume of that piston diameter to 10L would have required a much longer mechanism, over 6m. Alternatively, a larger diameter cylinder could be used to increase the sample volume, but at over five times the area. Higher capacity actuators, motor controllers and power supplies would have been needed.

2) Required active dynamic control.

The process of the 1000m system required that both linear actuators be powered and maintain position control at all times, otherwise the decompressed state could not be maintained. Both the sample and decompression piston shafts were exposed to ambient sea pressure via the oil compensator on the linear actuator, and could back drive if power was lost. The sequestered volume would return to ambient pressure very quickly, likely damaging the ESP instrument.

To prevent the need for active dynamic control to maintain a safe operating pressure, during the System engineering stage, we proposed that the 4000m DWSM processes of sequestering, decompressing, sampling, and exhausting, should be a sequence of single actuated steps. Each step transitions from one stable condition to another stable condition, so that a single mode failure at any state would either remain stable at that condition, or predictably drift to the last stable condition.

C. Design for Testing

Any sampling module acts as a controlled interface between the high pressure environment of the deep sea and the low pressure ESP. As such, it is strongly affected by pressure and undesired conditions may only appear while under pressure. Such conditions may prevent the system from functioning, or may cause damaging instabilities.

One development complexity with the 1000m Deep ESP system was that it could not be tested on shore under the pressures it would experience during deployment. The system needed to be fully immersed in the pressure environment for the forces to be exerted during decompression, and it was much too large to fit in any readily available hyperbaric pressure chambers. This made actual deployments in the ocean the only place that engineering testing could be done. It took several months of iterative modifications and dives to resolve a pressure induced control instability with the linear actuators.

To prevent similar development problems in the 4000m Deep ESP, we had another design goal that the system be testable at MBARI, at deployment pressures. This goal put preference on concepts that could be more easily pressure tested.

III. Design Process

The 4000m DWSM project started with determining the system requirements based off the science objectives. It would need to sequester up to 10L of seawater; decompress that from a potential 41 MPa to 300 MPa, provide that water to the core ESP for processing; collect the filtered water back form the core ESP; and prepare for the next sampling event. The functional requirements and design goals are as follows:

a. Operate from 0 to 4000m
b. Sequester single volume for processing
c. Collect a variable sample volume, up to 10L
d. Maintain homogenous sample
e. Prevent sample to sample contamination
f. Deployment duration up to 1 year.
g. Operate in water temperatures, 0-35 C
h. Series of stable sequences
i. Deployment pressure testable while on shore

A. Conceptual Design

A systems engineering approach was used to develop the sequence of operations that the DWSM, regardless of hardware implementation. The 4km DWSM performs a basic process that provides the ESP with a volume of water to sample and process; called the Simple Operating Theory.

1. Intake a volume of seawater, sequestering up to 10L;
2. Decompress, typically to 300 kPaa;
3. If gas is generated from the sampled seawater during the decompression, transfer and vent off so that decompression may be completed.
4. Once stable decompression is reached, open isolation valves to the ESP core
5. Push water thru the filtration stage of the ESP, collecting the filtered water in the resample bag.
6. Once all filtering has completed of that sequestered sample, close isolation valves to the core ESP;
7. Recompress the system to ambient pressure,
8. Exhaust old water, and prepare for next sampling event.

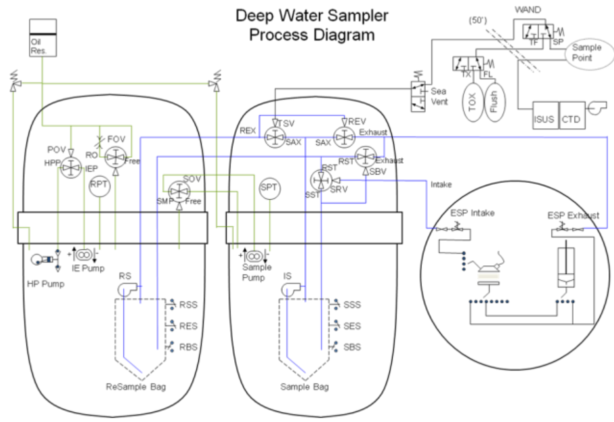
B. Conceptual Design

The conceptual design process was jump started by brainstorming sessions with three key engineers; electrical, mechanical and software. All of which had detailed knowledge of how the core ESP instrument works, the requirements for the 4000m Deep ESP, and how the 1000m system functioned. Over a few days, system diagrams were sketched on dry erase boards, discussed, compared and evaluated against the functional requirements. The system with greatest potential to meet the requirements and goals was modeled after lungs and the biological processes of breathing.

(Lung Diagram)

At the very top level, the 4000m DWSM operates like lungs. To inhale air into the lungs, the human body generates reduced pressure inside the chest in two ways. Most notably, the diaphragm is drawn down by muscles, moving abdominal tissues out of the hard walled chest volume. Also, accessory muscles in the chest lift the ribs upward to expand the volume. When an air passage is open via the mouth or nose, the ambient air pressure drives air in the lungs, filling the volume made available. To exhale, the diaphragm and accessory muscles relax and the weight of the chest places the air inside the lungs at higher pressure than ambient. To exhale more forcefully, abdominal muscles contract to push upward on the diaphragm, increasing the pressure more, and air is forced out.

A major design decision of the 4000m DWSM was to go to a hydraulically pumped system. The raw seawater is drawn into the system, pumped thru the ESP, and exhausted back to the ocean all by pumping hydraulic fluid. This way, all the pumps only move clean oil, effectively eliminating corrosion and contamination concerns. Instead of pistons, the pump design of the 4000m DWSM decouples the sample volume from the size of the mechanisms. The pumps can move greater volumes by just allowing more pumping time. By this manner, the sample volume can be increased by just larger chambers and bags, but requires no changes to the driving mechanisms.



As described, the 4000m DWSM mimics breathing action by pumping oil into or out of the hard pressure shell to generate a pressure differential. Inside the hard pressure housings, the pressure generated by the oil pumps is transferred thru the flexible “lung” membranes to the raw seawater, which then flows accordingly.

The architecture of the 4000m DWSM is two similar assemblies of a dry electronics housing mated to a variable pressure oil chamber. Inside each oil chamber is a flexible bag for containing the seawater. Each dry housing contains control electronics and actuators to valve to direct the water and oil as needed.

Inhale/Exhale

When inhaling seawater, oil is pumped from inside the hard chambers to an ambient pressure storage reservoir. This decreases the pressure inside the chambers and the higher ambient pressure forces seawater to flow into the selected valve port, filling the appropriate seawater bag. In exhaling, oil is pumped into the chambers from the reservoir, increasing the pressure inside the chambers above ambient. The seawater in the appropriate bag is pushed out through the selected valve port.

Decompression

A major benefit of the lung inspired system is that it functions by pressure differentials already. Decompression is the same action as inhaling, pumping oil out of the hard volume. With the intake valve closed, another pump of much higher pressure capacity is used to pump oil from inside the chambers to the ambient storage. As there is no open port for the seawater to make up the pressure differential, the pressure inside the chambers continues to drop until the target pressure is reached.

Sampling

After decompression, a flow path is opened through the ESP instrument’s filtering stage. The sample pump pumps oil from the downstream oil chamber to the sample one, creating the pressure differential between the two seawater bags. This drives the raw seawater through the filter membrane in the ESP instrument, and into the bag of the downstream chamber.

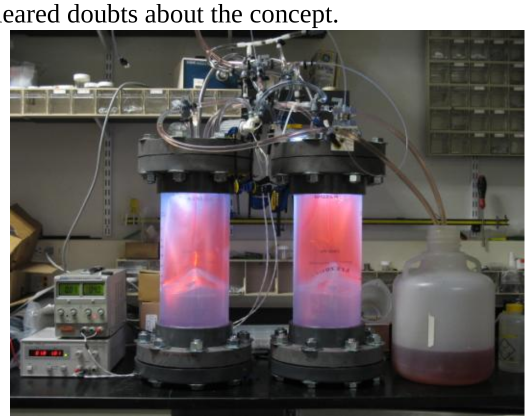
Recompression

After the filtering is completed, the ESP isolation valves are closed and the system can be brought back to ambient pressure safely. Recompression is accomplished by allowing oil from the ambient reservoir to flood back into the decompressed chambers. To prevent a hammer condition, the decompressed volume is initially opened thru a small orifice valve, adding flow resistance. When the pressure differential between the chambers and the sea is small, a full port valve is then opened to the ambient storage so that the pressures may equalize much quicker.

The restricted flood valve also allows for a method of slightly increasing the pressure when decompressed. The decompression pump can only pump one way. If the target pressure were overshot during decompression, say the pressure was brought down to 150 kPaa instead of the desired 300kPaa, the pressure can be brought up slightly, by momentarily opening the restricted flood valve.

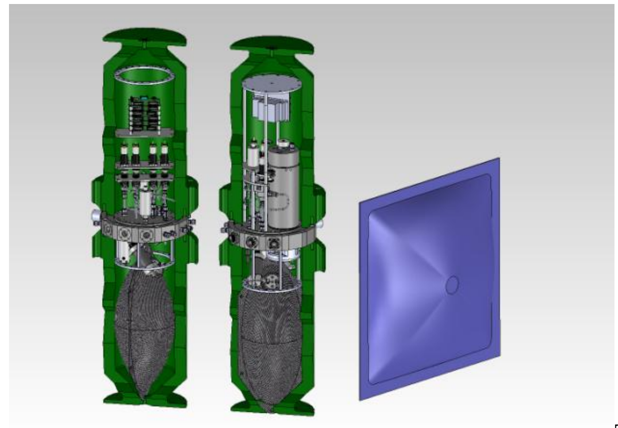
Proof of Concept

The hydraulic lung pumping concept was novel enough that a proof of concept was needed. As the bulkhead plates of the final design are complex machined manifolds, changes to the flow path could not be made without significant cost. Prior to starting detailed design, a 2L sequester proof of concept was fabricated out of PVC piping to demonstrate the system, verify the sequence of operations, lock down the valve scheme, and show that controllable volumes of water could be moved by pumping only the oil. Although this proof of concept was very basic, it did validate the hydraulic lung process quite well, and cleared doubts about the concept.



IV. Detailed Design

The hydraulic fluid used is 20 Cst silicone oil. Silicone oil was chosen as it is nontoxic and inert to the ESP detection chemistry, in the event trace amounts get into the sampled seawater. One drawback of the silicone oil is that it will affect most silicone rubber materials in contact with it, including seals and orings. Nitrile materials were selected whenever possible. Much care was taken in selecting COTS components to ensure that no silicone materials were exposed to the oil.



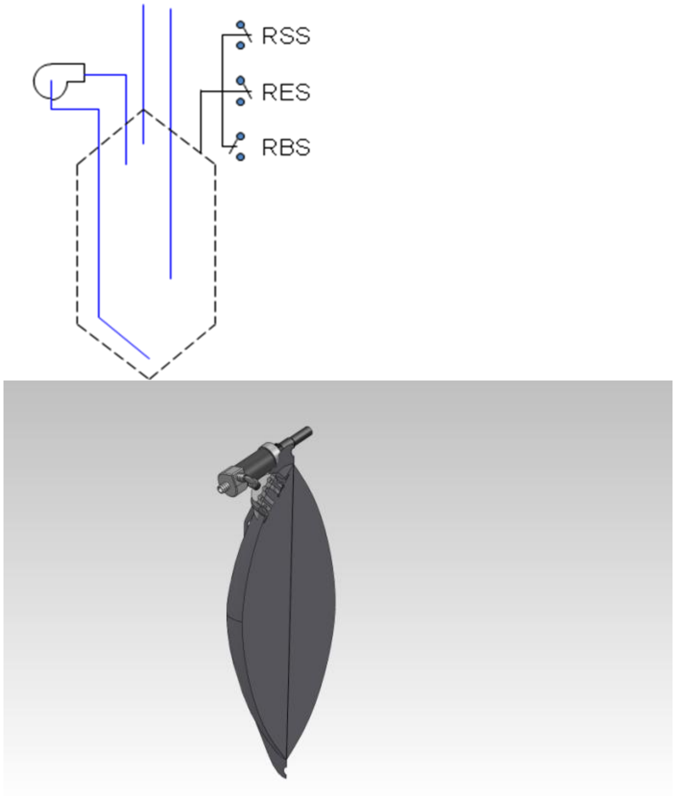
There are several oil pumps and valves, and a reservoir of oil in a storage bag at ambient pressure, outside of the chambers. Three oil pumps are used for the system. The Intake/Exhaust Pump (IEP) is used to generate low pressure differentials to ambient, and is used to fill and empty the seawater bags; a high pressure pump (HPP) is used to pump oil out to ambient storage at high pressure differential, to create the decompressed environment the ESP can sample form. Thirdly, the Sample Pump (SP) is used to move water through the ESP filter stage.

Lungs-Water Bag System

The 4000m DWSM holds the raw and filtered seawater in flexible bag assemblies suspended in the oil chambers. The bag assemblies consist of the bag, a multiport cap, internal tubing, a stirring pump, a pressure switch assembly, and a seawater isolation diaphragm for the pressure switches.

The 10L bag is made of woven nylon with a polyethylene lining, and is commercially manufactured for water storage while camping. The only modification is heat sealing the outer seam of the bag to prevent any shedding of nylon fibers into the process oil. Although there have been no failures of the bags, they are replaced after every major deployment.

The custom designed bag cap replaces the stock cap, and connects the seawater ports of the chamber to filling and sampling tubes that go into the bag. The filling tube opens to the very top of the bag, so that if any gas is present or generated during decompression, it will collect at the top and can be vented out. The ESP sampling tube pulls water from the 2/3 depth point in the bag. This depth point of the bag was chosen to avoid collecting any clumped sediment from the bottom, but to also reduce the likelihood of drawing air into the ESP instrument once filtering has started. Once wetted, air will not pass thru the filter membrane.



(Bag Diagram or Solid Model)

The seawater bags can suffer from the same problems as lungs, microbes and particulate can collect in the lower portions. In the DWSM, settled biological material needs to be prevented from settling for two reasons. For the ESP instrument to accurately measure quantities of microbes per volume of seawater, the sample water must remain homogenous with the particles suspended. In addition, particulate that settles may not be emptied out and could contaminate any future sampling and analysis. To keep the particulates suspended in the 4k DWSM bags, a stirring pump draws water from the bottom of the bag and returns it near the top.

Pressure switches

Just as divers are concerned about barotraumas to lungs or ears, the DWSM bag assembly could be damaged by excessive pressures. The critical “never hold your breath,” rule of diving is mainly to prevent a lung rupture. Air inhaled at depth will expand as the diver ascends to a lower ambient pressure, so it is critical to allow it to escape. Additionally, damage could be caused by a “squeeze” condition, where the pressure outside is much greater than that in the lungs, or more commonly, the ears.

In diving, the solution is to allow flow to equalize pressure, however in the 4k DWSM that is not possible. That would result in the oil and seawater mixing. During normal operation, the driving pumps may produce pressures that can easily damage the bags, however when inhaling or exhaling water, that pressure differential is not across the bag membrane, it is across the tubing and valves that restrict the water flow. It is only when the bag volume has reached the limit conditions that the pressure differential is applied across the bag membrane.

Filling the DWSM bags too much may cause a burst or seeping of seawater into the process oil. In addition, an overly emptied bag can be squeeze damaged in just the same way. The 4000m DWSM detects when a pressure differential exists across the bag membrane. This is needed to detect the squeeze and burst risk conditions, but also the normally encountered condition of a slight pressure on the bag, indicating the “empty” condition.

There are three pressure switches connected to the bag cap. Tthe “empty” pressure switch triggers when the bag volume maintains a 3.7 kPa pressure blow the oil in the chamber. The control system manages this normally encountered condition, shutting off the pump and setting the volume counter to zero, declaring the bag empty. “Squeeze” condition is signaled by a 12.5 kPa pressure below that of the oil, and the “burst” condition is 3.7 kPa above the oil in the chamber. In addition to signaling the controller, the squeeze and burst switches also trip limit switches on the motor controllers, cutting power to any pump that could continue to add pressure in the risk direction.

The switches used have a double contact that is vibration and acceleration resistant. However the contacts are exposed to the working fluids. Although that is not a problem for the oil side of the pressure switches, the seawater side would continuously short out and eventually corrode. To prevent this, the bag cap contains a small flexible diaphragm transfer barrier, filled with silicone oil. In this way, the pressure switch contacts are not exposed to seawater, but still reference the pressure in the bag.

(Bag Cap Solid X-section)

Intake/Exhaust Pump

The Intake/Exhaust pump (IEP) resides in the Resample oil chamber and pumps to and from the ambient oil reservoir. This action generates the differential pressure in the DWSM that inhales and exhausts the seawater from either of the sample bags. Another way of considering this action is displacement. When exhausting, the IEP pumps oil into the chamber volume, displacing the seawater out a pathway that is open to the sea. When inhaling, the IEP pumps oil from inside the chamber to the ambient storage, and the sea pressure forces seawater to enter and take up that space via.

The inhaled volume is controlled by tracking the encoder position of the IEP motor.

(More on the contol of IEP and setting the empty bag, 0 volume state.)

The IEP was originally a gear pump; however this pump had trouble operating at increasing depths. The most likely reason is the formation of low pressure pockets between the meshing gears. At sea level, a small vapor pocket could form in that void. At depth, the high ambient pressure forces the gears together. This increases the drag on the motor, resulting in an increase in current required to maintain pump speed. This theory matches the evidence that the increase in running current is proportional to ambient pressure. This also seems to be the cause of excessive wear seen on the gear teeth of the gear pump IEP.

The initial 1000m tests were done with the gear pumps, and were at the limit of functionality. After several tests and deployments, this pump was replaced with a rotating piston pump, similar in function to the sample pump, but of larger displacement. This pump has been lab tested to 20 MPa, and deployed to 1600m depth, and shows no change in running current with respect to pressure.

A magnetic shaft coupling capable of 100mNm torque was developed so that the motors of the IEP and SP could be located in the dry electronics housings instead of the oil. The 6Al4V titanium pressure shroud is designed so it can be pressurized from either direction to 41 Mpa.

Decompression Pump

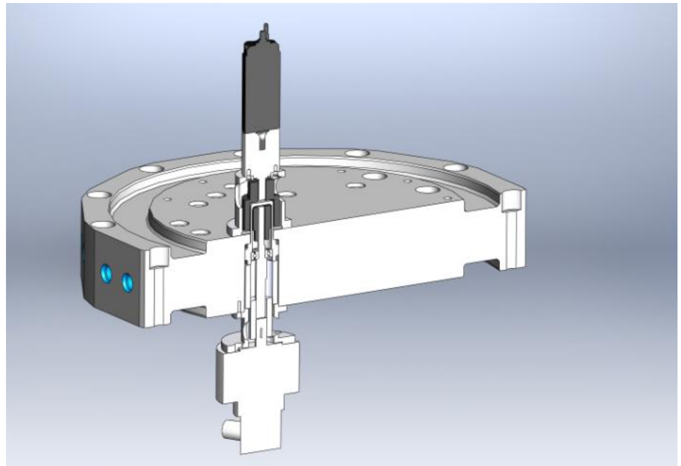
Although water is typically considered to be incompressible, it is slightly compressible. At 4000m depth, seawater is about 2% denser than at the surface. The silicone oil used is also slightly compressible. In addition to pumping the volume needed to expand the seawater and oil, the decompression stage also needs to move the volume that the pressure housings lose when they deform slightly under the pressure. The decompression action is made by valve isolating the 4000m DWSM chambers from the sea, and pumping oil from inside that closed volume to the ambient storage outside.

A high pressure pump is needed to pump the silicone oil to an ambient storage reservoir at 41 MPa. The decompression pump used is a three piston, cam driven, high pressure hydraulic pump. It is coupled to an oil compensated 500W brushless DC motor that in its own pressure housing, an extension from the resample oil chamber. The pump motor is driven from a motor controller in the dry electronics housing. The four conductors for the brushless motor are passed into the oil chamber by a pressure rated connector, but the motor's hall sensor and encoder are located in the dry electronics housing, magnetically coupled to the backside of the rotor shaft. This eliminates the problems associated with the encoder in the oil and under pressure, but allows a much smaller pressure connector to the motor, saving valuable space on the bulkhead plate.

Sample Pump

The sampling action of the 4000m DWSM is used after decompression and the ESP core has placed a new filter membrane into the fluid path. The DWSM is opened to the ESP core, and the sample pump is used to generate the differential pressure across that filter. To maintain stable pressure differential across the filter, the sample pump is servoed to the difference of the two DWSM pressure transducers. Prior to start of filtering, this difference is tared to ESP's internal pressure transducers.

The sample pump is a valveless rotating piston pump, submerged in the Sample side oil chamber. It is also magnetically coupled to a motor and encoder, located in the dry electrical housing on the other side of the bulkhead plate. The pump is bypassed when decompressing and recompressing so that the two chambers equalize.



Compliance

The reciprocating pump action of the IEP causes pressure spikes. Although tolerable, a spring loaded pulse damper was developed to even out the oil/water flow. Typically pulse dampers use an air chamber to buffer the pressure, however, at 4000m depth, air pockets are mostly gone. MBARI developed a bi-directional spring loaded pulse damper is used for both the IEP and the Sample Pump. On the IEP, it functions as a pulse damper, evening out the pressure spikes from the piston pump cycling. For the SP, it also functions as spring driven compliance, resulting in better pressure control, and steady pressure on the filter membrane.

Pressure boundary

A significant design decision was selecting the two story architecture for the DWSM cylinders. It consists of a central bulkhead with identical pressure housings for each side, the top housing being an atmospheric pressure electronics chamber, the bottom is the variable pressure oil chamber.

All equipment in the DWSM is structurally mounted to the bulkhead plates, which also function as the main fluidic manifolds and penetrator bases for cabling and fluid connections. Their design became the focus that all the designs keyed into, but also where they competed for space. To design these plates, many of the other system components had to essentially be designed simultaneously.

Identical anodized 6061-T6 Aluminum bell shaped pressure housings are used for the oil chamber and the dry electronics chambers. They are assembled with the 6Al4V Titanium bulkhead plates sandwiched between them.

As the high torque of the decompression pump is much greater than can be magnetically coupled, the HPP motor is hard coupled to the pump and oil submerged at the same pressure as the oil chamber. It resides in a special 17-4 SS and 6Al4V Titanium two-piece pressure housing that extends from the Resample bulkhead into the dry electronics housing.

Rotary Valves

The oil and seawater paths of the 4000m DWSM chambers need to be isolated from the sea pressure. Several high pressure 3-way valves are used for both the oil and seawater flow loops. Swagelok Trunion valves were chosen due to their high pressure capacity, low actuation torque, and ready availability. The three way valves are attached to a motorized actuator and encoders for the system to automatically set valve positions needed for each cycle of the sampling process. The actuator and encoder are modular components as used in the ESP instrument.

Three of these valves manage oil flow paths, and four valves for the seawater paths. As all these valves are stainless steel, eventually corrosion will require rebuilding the seawater valve system. For ease of maintenance, all the seawater valves are located in the dry pressure housing of the Sample can with a less complicated assembly.

(Rotary valve diagram)

Pressure transducers

The oil pressure of each oil chamber is monitored by pressure transducers reading absolute pressure from 0 to 41.4 MPa. The resample chamber also has a digital pressure transducer, to assist in decompressing the system. The pressure transducers are needed to control the sample pump at pressures very low in their operating range, but temperature changes can drift them outside the allowable envelop. As temperature effects can drift the analog pressure transducers, the digital pressure is used to verify that the analog transducers (and the custom electronics that servo off them) are reading accurately enough to open the bulkhead valves to the core ESP.

A. *Electrical*

As the preliminary design began to develop it was apparent to the design team that many of the same functions in the ESP core were showing up in the DWSM. The ESP core instrument used a distributed Control Architecture where small real time processors monitored and control local functions while a main non-real time processor managed the system as a whole. Because of this the electrical design of the DWSM was based on the reuse of many of the components developed for the core ESP instrument. This meant that there would be a division of functions based upon the capabilities of the ESP core hardware. The core hardware supports the following functions:

- 2 Servo Channels
- I2C interface
- Analog to digital conversion
- 4 Rotary valves
- 8 solenoid drivers

While the core hardware did cover a majority of the DWSM functions there were a few missing pieces. The biggest need was the ability to sense the state of the sample bags. The instrument needs to know the limits of the bags, when they were full and empty and disable the appropriate motor to protect the bags. This ability also allowed the instrument to detect the empty condition thus allowing the pumps to find the 0 volume condition required for sample tracking. To be able to decompress, recompress and pump the sample, the pressures needed to be monitored. To meet these requirements a new board was developed to interface between these sensors and the current hardware. The new board called DPress provided the following functions to the instrument; Pressure sensor signal conditioning and bag limit switch monitoring and the associated motor disable logic.

The signal conditioning required the input of two sensors one input from the local bag and an input from the remote bag. These two inputs were scaled, filtered and multiplex to the appropriate channel of the Dwarf. These sensors are high precision sensors as they need to be able to measure the ambient ocean pressure (4000m, 6000psia) and resolve decompressing pressures around 30 psia. The other function that was required was a differential pressure during sampling. This pressure is used to control the rate at which the sample pump runs and the pressure applied across the Core instruments filter. While the pressure sensors allow the instrument to monitor how the bag is used the pressure limit switches protect the bag from the end points.

V. High Pressure Testing

As was earlier mentioned, a design goal was to be able to operate the system at deployment pressures while still in the lab. The architecture of the lung based 4000m DWSM is such that all the operating pumps and motors are inside the pressure housings. There are only two ports that connect to the outside ambient pressure, one for seawater and one for oil to/from the ambient storage. To test the DWSM at pressure, only three things are needed, a source of high pressure water, a source of high pressure oil, and a mechanical bolting arrangement to hold the pressure housings sealed while pressurized internally. The pressure housings were designed to not only withstand the 41MPa of external pressure when deployed, but also to contain the same pressure internally when tested in the lab. For the bell housings, this required designing a significant flange and bolting assembly, as well as a 41 MPa seal that works equally well with pressure from either direction.

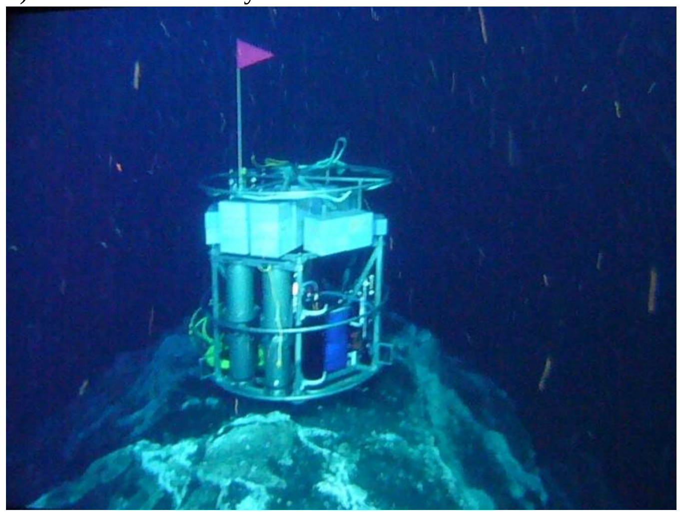
A High Pressure Interface (HPI) system was developed that provided the pressurized water and oil to the DWSM so that it could operate in the lab, executing all the operations under the same loads as when deployed. Like the DWSM, the HPI system is also a lung inspired system. A transfer barrier accumulator provides pressure balanced water and oil to the DWSM. It is filled, emptied and pressurized by pumping just the oil. As it exchanges oil with the DWSM, the same 20 cSt silicone oil is used.

As the deep ocean is cold, to further simulate the conditions while deployed, the fully assembled DWSM, ESP instrument and HPI are placed in a refrigerated shipping container and cold operated at deployment pressure to 2C. In this manner, all the pumps, switches, and valves, operate at the same pressure and temperature as they will during deployment. The operating systems within the DWSM and ESP are under the same conditions and complete the same inhaling, decompression and sampling cycles as at the bottom of the sea. Since the HPI pressure and cold test can be accomplished in just a couple days, it has become standard to do a full system validation at deployment temperature and pressure prior to every mission.

VI. Deployments

The 4km Deep ESP system has been deployed several times at depths up to 1600m.

1) 1000m ROV test dives
2) April 2009
3) May 2009
4) M2 June 2009
5) MARS October 2009
6) MARS December 2009
7) SC Methane Mound August 2010
8) MARS December 2010
9) Axial Seamount July 2011



VII. Future Direction

Incubation Experiments
Longterm cabled observatory
Wand for point source sampling

VIII. Conclusion

The capability of collecting and decompressing deep ocean seawater has been developed for in situ microbial identification. This can enable new scientific research and ocean monitoring with the goal of better understanding the life and chemistry of the deep sea.

Acknowledgment

The preferred spelling of the word "acknowledgment" in American English is without an "e" after the "g."

References

[1] Scholin, C. S. Jensen, B. Roman, E. Massion, R. Marin, C. Preston, D. Greenfield, W. Jones, K. Wheeler, "The Environmental Sample Processor (ESP) – An Autonomous Robotic Device for Detecting Microorganisms Remotely using Molecular Probe Technology." *Proceedings, OCEANS 2006 MTS/IEEE Conference*. Boston, MA. Marine Technology Society, Columbia, MD.
[2] Environmental Sampling Processor website: http://www.mbari.org/esp/