Technological Review of Deep Ocean Manned Submersibles

by

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ABSTRACT

James Cameron's dive to the Challenger Deep in the Deepsea Challenger in March of 2012 marked the first time man had returned to the Mariana Trench since the Bathyscaphe Trieste's 1960 dive. Currently little is known about the geological processes and ecosystems of the deep ocean. The Deepsea Challenger is equipped with a plethora of instrumentation to collect scientific data and samples. The development of the Deepsea Challenger has sparked a renewed interest in manned exploration of the deep ocean.

Due to the immense pressure at full ocean depth, a variety of advanced systems and materials are used on Cameron's dive craft. This paper provides an overview of the many novel features of the Deepsea Challenger as well as related features of past vehicles that have reached the Challenger Deep. Four key areas of innovation are identified: buoyancy materials, pilot sphere construction/instrument housings, lighting, and battery power. An in depth review of technological development in these areas is provided, as well as a glimpse into future manned submersibles and their technologies of choice.

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Biographical Note

Alex is expected to graduate from Massachusetts Institute of Technology in June 2012 with a bachelor of science in mechanical engineering and a minor in energy studies as well as a certificate from the Gordon Engineering Leadership program. In addition to having taken classes in ocean engineering, he has had strong interest in vehicle engineering since childhood as well as an appreciation for the development of advanced materials. Next year, Alex will be working at Accenture in Washington D.C. as a systems integration consultant analyst.

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1. Introduction

James Cameron's dive to the Mariana Trench in March of 2012 set the world record for the deepest solo dive. It was the first time man had returned to the deepest part of the ocean floor since the 1960 dive of the Bathyscaphe Trieste. The Trieste made the dive in 1960 as part of a US Navy program, with little emphasis on scientific observation [15]. The pilots of the Trieste, however were able to observe small marine mammals, revealing an underwater ecosystem that was previously unknown to science. Currently not much is known about the deep ocean, other than the fact that processes in the deep ocean could potentially have significant impacts on shallower marine ecosystems. The deep ocean is one of the final frontiers for human exploration on the planet and knowledge of the geological processes and marine ecosystems that exist in the hadal zone (>10,000m depth) is currently at a minimum. Before Cameron's dive, only two vehicles had been to the deep ocean floor to collect scientific data, the remotely operated Kaiko in 1996 and the autonomous Neurus in 2009.

The Mariana Trench, off the coast of Guam is the deepest point of the ocean floor (referred to as full ocean depth). It reaches a maximum known depth of 35,800 ft (11km) in a valley referred to as the Challenger Deep. At this depth, the hydrostatic pressure reaches 16,500 psi (113.76MPa) making any journey to the Challenger Deep a risky one. The Trieste incorporated a number of revolutionary engineering feats to withstand the pressure at full ocean depth, but was unable to collect any data. Engineering vehicles that can dive 7 miles, withstand the immense pressure of the ocean floor, and then resurface is no easy task. The typical strategy is to create a positively buoyant vehicle that uses ballast weights to sink and then releases the weights to ascend. Pressure housings are kept to a minimum and are often restricted to the cockpit (pilot sphere) as well as external housings for sensitive instruments. Other systems are built robustly to withstand pressure, or employ some type of fluid compensation system to maintain integrity.

With the advent of remote and autonomous vehicles, there was little motivation to send a human back down to the trench. Manned submersibles are not only significantly more costly to build and develop, but also pose a threat to the safety of the pilot(s). However, James Cameron, amongst others saw the value in having a human return to the depth to manage data collection as well as experience the ocean floor firsthand. The development of Cameron's Deepsea Challenger marked the beginning of a resurgence in the development of manned submersibles to explore the deep ocean for both scientific and recreational purposes. Virgin Atlantic has brought back the once defunct Deepflight Challenger, which is currently nearing the end of its development phase and will descend to full ocean depth primarily for recreational exploration. DOER Marine is developing the Deepsearch submarine, which seeks to be the ultimate in scientific data collection.

This paper will briefly cover the many features of the Deepsea Challenger that allow it to successfully operate at depth as well as the original technology in the 1960 Trieste and related features of the two unmanned submersibles that also made the journey. Much like the Deepsea Challenger today, the Trieste was an incredible engineering feat of its time. Many of the design concepts of the Trieste are still used by deep-sea craft today. Some systems, such as the Trieste's life support system worked so well that although they have been improved over time, their fundamentals are still used today. However, there is always room for improvement. The Trieste put into motion a process of innovation that has allowed deep ocean exploration to take off once certain materials and technologies had been developed. Areas that have seen significant innovations are buoyancy materials, external instrument housings, pilot spheres, lighting, and battery power. This paper will cover the development in these areas in detail. A brief overview of the two future submersibles mentioned, Deepsearch and the Deepflight Challenger, will then cover which technologies they plan on utilizing and how their designs will mark an improvement in deep ocean exploration.

2. Overview of DeepSea Challenger Features

On March 26th 2012, James Cameron dove 7 miles to the Mariana trench, the deepest point of the ocean floor, in the Deepsea Challenger. After making its initial dive, the Deepsea Challenger is now in its initial stages of scientific observation. Film director James Cameron and a team of engineers headed by Ron Allum developed the submarine with a series of objectives, including: the ability to take a human to the deepest ocean depths with significant bottom time to perform work and research, the ability to dive repeatedly at any site to collect multiple sets of data, demonstrate the effectiveness of a human piloted vehicle for scientific observation in the hadal zone, successfully use piloted, automated, and remote platforms to gather data simultaneously, return the maximum science value from each expedition, bring back compelling imagery and 3D footage of previously unseen geological processes and species in the hadal zone [5].

To accomplish these objectives, the Deepsea Challenger incorporates a number of modern features and novel technologies shown in Figure 2-1. The Deepsea Challenger dives to depth using the same basic methodology of past submersibles: the buoyant vehicle sinks using added ballast, which is released at the ocean floor allowing the vehicle to ascend. The Challenger uses 1100 pounds of steel weights as ballast to sink to the ocean floor. The weights are attached with an electromagnet system so all the pilot has to do is flip a switch and the weights will drop, allowing the sub to ascend. Unlike previous submersibles, the Deepsea Challenger is aligned along a vertical axis and is designed to spin during descent like a bullet being fired from a gun. Spinning keeps the submarine in the most favorable hydrodynamic position, allowing it to dive vertically without veering off course. The sub's 24 foot tall main structure beam is composed of revolutionary syntactic foam, providing both pressure resistance as well as positive buoyancy. Although the submarine weighs 11.8 tons total, the majority of its volume is made up of the lighter-than-water syntactic foam, giving it positive buoyancy. More information on the development of syntactic foam can be found on page 27. The submarine uses both vertical and horizontal thrust propellers (a total of 12) to navigate the ocean floor during its bottom time. In order to aid scientific observation, a unique "cruise control" system allows the submarine to hover in a fixed position, or glide through the water at a constant speed [5].

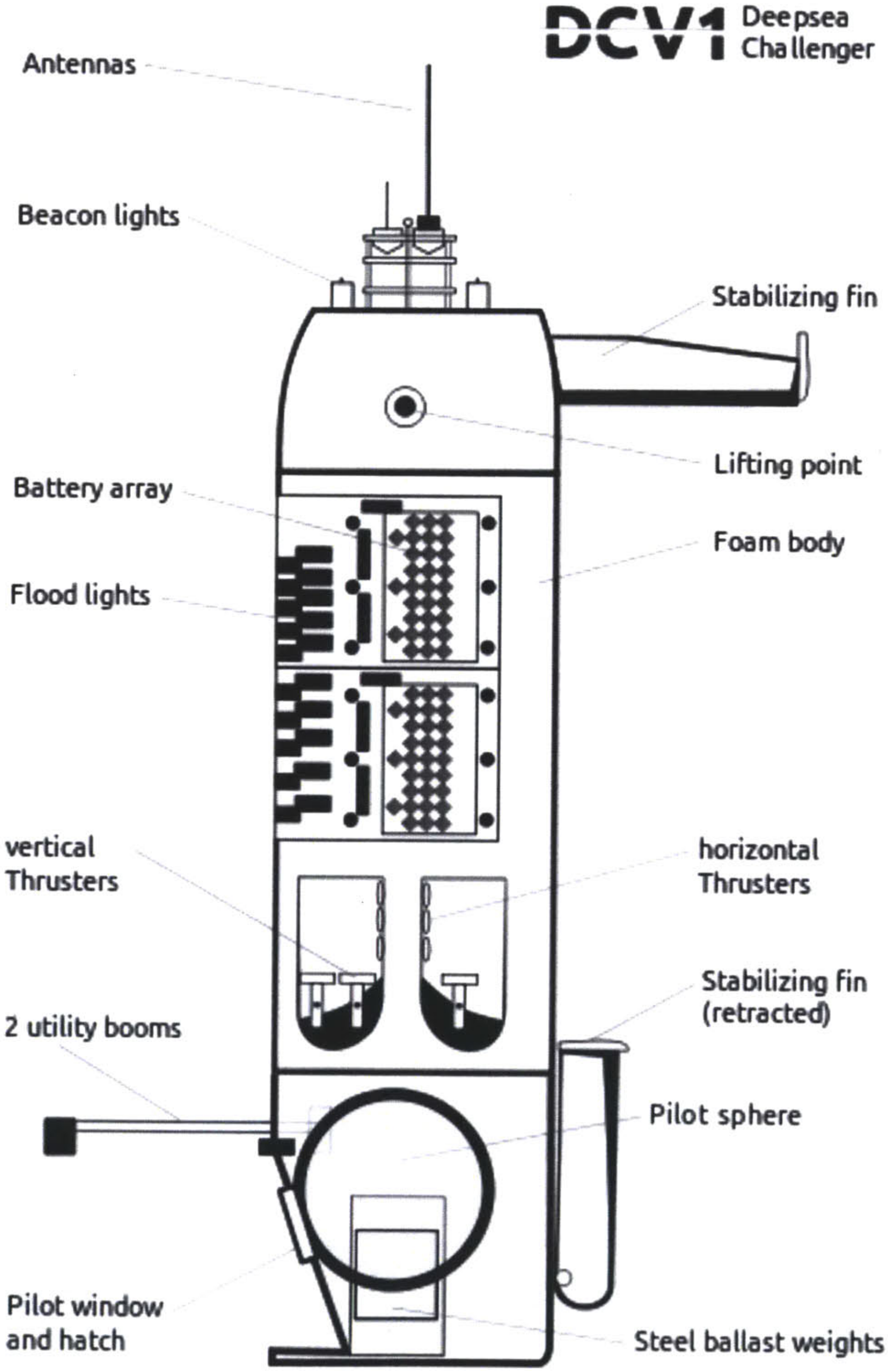


Figure 2-1: Components of the Deepsea Challenger [5]

Cameron is shielded from the massive ocean pressures by a thick steel sphere attached to the main beam with polyester straps. More information on the development of the pilot sphere can be found on page 41. From there, he controls the submarine's instrumentation. For scientific observation, the Submarine contains four external HD cameras as well as a 3D camera mounted inside the pilot sphere at the viewport. Two of the external cameras are mounted side by side on one of the 6.6 foot utility booms and together can create 3D images. The other two are mounted side by side on the manipulator arm and function independently as 2D cameras, one with a wide angle lens, the other with a macro lens to capture footage of small animals [5]. Lighting is provided by an LED array mounted in the structural beam as well as a spotlight on the other utility boom. More information on the development of LED lights can be found on page 48. Cameron controls both booms with a hydraulic operation system. The manipulator arm is hydraulically controlled by a joystick and has the ability to collect rocks as well as deep-sea creatures and place them in a "bio-box". The box is made from thick plastic with a sealed lid and is designed to keep samples cool. The manipulator arm also has the ability to take core samples by pushing a plastic tube into soft spots in the ocean floor. In addition to cameras and the manipulator arm, the Challenger has the ability to communicate with, track, and control two landers that accompany it on dives. The landers use much of the same technology employed in the submarine. They are designed to enhance scientific observation and contain not only 3D cameras with ample lighting, but also Niskin bottles to collect water samples and baited traps to catch small fish and crustaceans [5]. All of the submarine's instruments, thrusters, lights, and cameras draw power from a large modular battery array of thousands of pressure compensated Lithium Polymer cells. More information on the development of batteries can be found on page 51.

The Deepsea Challenger contains many safety features to protect its pilot at ocean depths. Although the battery array generates a massive amount of heat, warming the pilot sphere on the surface, the near freezing temperatures at the ocean floor can cause hypothermia. For thermal protection, the pilot wears an electronically heated vacuum-packed suit in addition to carrying extra clothing layers and a sleeping bag. The sub's life support system is composed of two compressed oxygen tanks, which provide enough air to supply its pilot for 56 hours, seven times the amount needed for a typical mission. Carbon dioxide is removed from the air through scrubbers and water vapor condenses on the sphere and trickles to the lowest point where it is pumped into a bag, available to be drank in emergency situations. The pilot sphere is completely fire resistant and contains independent batteries under the seat which can run the life support system if the main battery array fails. If the battery array fails, the electromagnetic weight release is programmed to drop the weights automatically. Many additional steps were taken to ensure that the pilot will never end up stranded on the floor. Cameron can power up a system called a "frangibolt" which uses heat transfer to break the bolts that hold the weight drop mechanism to the sub, dropping the whole assembly. The weights can also be released by an acoustic signal sent from the surface crew. If all else fails, a galvanic wire connects the weights to the sub and will naturally corrode after 11 to 13 hours at sea, releasing the weights [5].

All of the technological and safety features of the Deepsea Challenger make it an extremely well performing dive craft. Its 12 thrusters are able to propel the sub to speeds of up to 2.5 knots vertically and 3 knots horizontally. By comparison, the Trieste was powered by two thrusters and had a top speed of 0.5 knots [2]. Despite its mass, the sub is surprisingly nimble and able to closely follow small marine animals [5]. The subs compact, lightweight, and advanced design allow it to not only ascend and descend faster, but also allow it to bring equipment to the ocean floor for scientific observation. Due to its rapid ascent and descent as well as advanced life support systems, the sub can remain at the ocean floor for extended periods of time. The 1960 Trieste is the only other manned submersible to have reached the Mariana Trench. Figure 2-2 shows a scaled comparison of the Trieste to the Deepsea Challenger. The use of advanced syntactic foam as opposed to a gasoline flotation system allows the Deepsea Challenger to be a fraction of the size of the Trieste. Table 2-1 summarizes the performance of both crafts, showing how far deep ocean technology has come in the last 50 years.

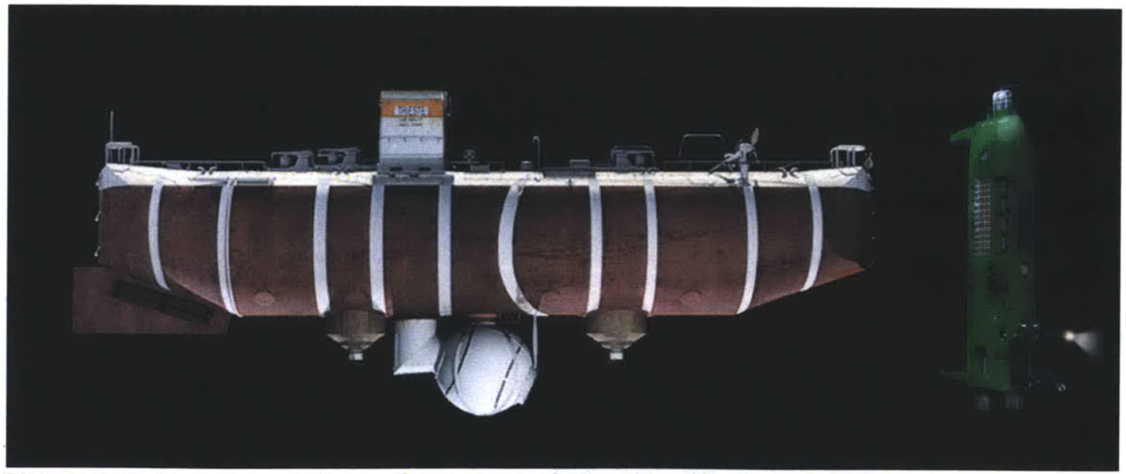


Figure 2-2: Size Comparison of Trieste and DeepSea Challenger [5]

TABLE 2-1: PERFORMANCE OF TRIESTE AND DEEPSEA CHALLENGER [5]

Trieste 1960	Deepsea Challenger 2012
150 tons	11.8 tons
Two pilots	Single pilot
Descent: 4 hours 48 minutes	Descent: 2 hours
Ascent: 3 hours 15 minutes	Ascent 1 hour
Bottom time: 20 minutes	Bottom time: 6 hours
Unable to take pictures	3D cameras, sample collection, landers

3. Overview of Previous Submersibles

3.1 Bathyscaphe Trieste

In January of 1960, The Bathyscaphe Trieste made its historic dive to the deepest point of the ocean floor carrying two pilots. Unlike the Deepsea Challenger, scientific observation was the primary goal of the Trieste. The Trieste was a Swiss-designed, Italian-built submersible originally operated by the French Navy. In 1958, the US Navy purchased it. The goals of the US Navy's Trieste dive program were to: investigate the ocean environment at great depths in situ, evaluate the possibilities of bathyscaph type craft as a research tool, encourage further development of such craft, and most importantly to examine naval uses for bathyscaph crafts either in the form of submarine rescue work or deep diving submarines [15]. The Trieste contained a number of novel systems, shown in Figure 3-1, in order to fulfill these goals and dive to such depths.

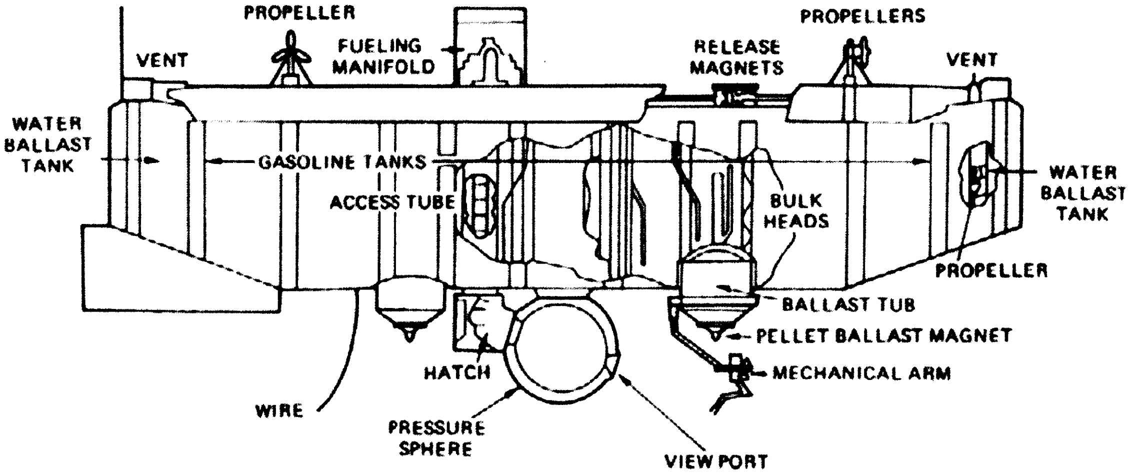


Figure 3-1: Layout of Bathyscaphe Trieste [2]

Many of the basic principles used in the Trieste dive have remained unchanged over time, simply having taken different forms with newer more advanced technology and materials. Spherical pilot spheres have been traditionally used in ocean exploration due to the natural strength a sphere provides over other shapes. However, before the Trieste, deep ocean exploration was commonly done with a robust pilot sphere attached to a cable that was simply lowered. While this method worked well in shallower ocean zones, cable operation in the hadal zone would require cables more than 7 miles long as well as spheres that were pressure tolerant while containing ample life support which is simply not feasible. The Trieste was the first submersible to use ballast to dive and resurface, setting a precedent for deep ocean craft today.

The Trieste essentially functions like an underwater blimp using ballast to control its depth and two battery powered propellers to move laterally. To provide buoyancy, the vehicle's main hull is comprised of a series of tanks filled with gasoline, which has a specific gravity of 0.7. Iron pellets contained in electromagnetic hoppers as well as two water tanks provide ballast. To initiate a dive, the water tanks are filled, causing the vehicle to sink. As the vehicle descends, the gasoline compresses slightly leading to a further loss in buoyancy. Iron pellets are gradually released from the hoppers during descent to counteract this effect [15]. After the vehicle has reached the floor, the iron pellets are released at a quicker rate, allowing the submarine to ascend to the surface. The use of liquid ballast, especially a volatile fluid, is not ideal since it introduces the possibility of leaking. If more than one of the Trieste's gasoline tanks is lost, the vehicle would not be able ascend to the surface [2]. The development of syntactic foams and other solid buoyancy mechanisms used in modern submersibles resolves this issue.

Similar to the Deepsea Challenger, the pilot sphere of the Trieste is the sub's heaviest component, and ultimately determined the size of the vehicle. The pilot sphere of the Trieste measures 2m (78.7 in) inner diameter and had a minimum wall thickness of 9cm (3.54 in) that increased to 15cm (5.91in) to combat stress concentrations near its two viewports. The pilot sphere was responsible for holding both pilots, life support systems, as well as the entire battery power supply. The sphere was forged out of Ni-Cr-Mo steel alloy that provides excellent fatigue resistance and high strength, but at a weight penalty [15]. The viewports were made from acrylic glass (Plexiglas) with a thickness of 15cm. The acrylic windows themselves have a diameter of 40cm, while the viewports themselves have a diameter of 10cm. The concept of extending the window radius past the viewport to create a strong flat seal is one that is applied in the pilot sphere of the Deepsea Challenger. The Deepsea Challenger maintains a pilot sphere design similar to that used in the Trieste at a basic level. It simply takes advantage of more advanced materials, higher-grade lighter steel and borosilicate glass, as well as the ability to be more compact. More information on the Deepsea Challenger's Pilot Sphere can be found on page 41. Although the Trieste's sphere is capable of withstanding pressures up to 22,000 psi, it is far heavier than that of the Deepsea Challenger. The sphere itself weighs 11 tons [15]. Due to the sphere's weight, the Trieste needs 28,000 gallons of gasoline to provide buoyancy, leading to a hull that measures 16m in length and 4m in diameter.

Figure 3-2: Trieste Pilot Sphere [2]

The Trieste's silver-zinc batteries power its propellers, life support system, and lights. The Trieste's life support system is similar to that used in the Deepsea Challenger as well as modern spacecraft. Oxygen is supplied from pressurized cylinders, while carbon dioxide is filtered out by being drawn through three soda-lime canisters [2]. To illuminate the ocean floor, the Trieste uses quartz arc-light bulbs that can withstand full ocean depth pressure without any modification. Although these bulbs are able to withstand ocean pressures as well as LEDs, they are less efficient. The advent of more powerful Li-Ion batteries as well as more efficient lighting allows modern submersibles to use multiple higher-powered thrusters as well as support more instrumentation and systems needed for scientific observation.

3.2 Unmanned Submersibles: Kaiko and Neurus

In February of 1996, ROV Kaiko became the second vehicle to reach the Mariana Trench. The ROV used a unique cable system coupled with a launcher and vehicle to explore the ocean floor. The launcher weighed 5.8 tons and essentially acted as a weight attached to allow the assembly to sink. The launcher was tethered to the surface ship with a thick 12,000m long cable fed through a winch with tensioning system. Once the assembly had fallen to the desired depth, the 3.9 ton vehicle was detached from the launcher and was free to roam about the ocean floor, while remaining connected to the launcher with a thinner, shorter cable. The vehicle had four horizontal and three vertical propellers along with a bright LED light array, multiple cameras, sensors, and two manipulator arms allowing it to move about the ocean floor, gathering samples and data [1]. When the vehicle is ready to surface, it is first reeled into the launcher and then launcher is then reeled up to the surface ship. Of importance is the fact that the vehicle used syntactic foam to maintain neutral buoyancy at the ocean floor and provide structural integrity. Kaiko demonstrated the viability of syntactic foam, the same type of material later used in the Deepsea Challenger. Unfortunately in 2003, rough seas caused the launcher cable to snap and the Kaiko was lost at sea.

The second unmanned vehicle to reach the Mariana trench was Woods Hole Oceanographic Institute's Neurus on May 31, 2009. Unlike the Kaiko, the Neurus is a free diving vehicle, tethered only with a thin, flexible fiber optic cable used to transfer high quality video. The Neurus is a relatively small vehicle, weighing only 3.2 tons [25]. The Neurus uses 2000 Li-Ion batteries packed into an array to power 2 vertical and 3 horizontal thrusters as well as an LED light array, high-resolution camera, various sensors and a multi-function manipulator arm to collect a variety of different samples. The Neurus dives in a similar manner to the Trieste and Deepsea Challenger, using ballast weights to sink to the floor, and then releasing them to ascend. Of particular importance is the buoyancy material used. Unlike Kaiko's syntactic foam, the Neurus uses ceramic macrospheres embedded in a plastic matrix to provide positive buoyancy and structural integrity [23]. Ceramic macrospheres are a promising technology that is likely to be used in future manned submersibles. More information on ceramic macrospheres can be found on page 31.

4. Development of Buoyancy Materials

4.1 Syntactic Foam

The core component of the Deepsea Challenger's main structure is a specially developed syntactic foam called IsoFloat developed by McConaghy Boats in Sydney Australia. Since the main goal of the Deepsea Challenger is a craft designed for scientific observation its structure must be buoyant enough to offset the weight of its equipment. For every 12 kilograms of equipment the craft takes to the bottom, it requires 20 kilograms of foam to float to the top [16]. IsoFloat is the first syntactic foam strong enough to withstand the immense pressures of the deep ocean, while simultaneously being buoyant enough to allow the craft to resurface. Its high strength and buoyancy greatly exceed the petrol buoyancy system previously used in the Trieste. 70% of the submersible's volume is made up of IsoFloat foam [5]. This allows the Deepsea Challenger's body to have a relatively compact design allowing for speedier ocean travel while also providing mounting points for thrusters and other accessories.

Syntactic foam has long been used in both the marine and aerospace industry in applications where high strength and low density are critical. In typical submarine applications, it is often used as a sandwiching layer to fill voids in the hull and provide additional strength. Syntactic foams consist of a metal, ceramic, or polymer matrix filled with hollow particles called microballoons. Microballoons are often composed of cenospheres, glass, carbon, or polymers. The hollow particles provide the high strength, low density, and low coefficient of thermal expansion associated with syntactic foams. Syntactic foam was first patented in 1969 for use in deep-sea applications where a high strength, buoyant material suitable for long term use was needed.

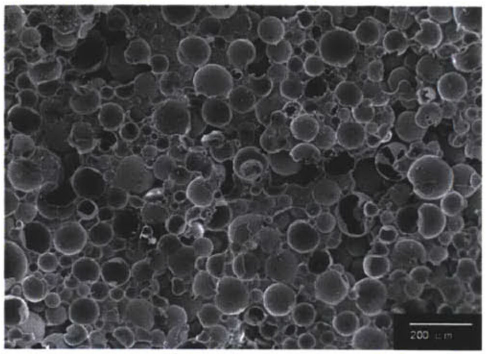


Figure 4-1: Glass-Epoxy Syntactic Foam [28]

The original syntactic was made with high strength glass microballoons 20-90µm and a wall thickness of approximately 1.8µm that were commercially available at the time [17]. The matrix was made up of a roughly 50/50 mix of epoxy resin and hardener combined with an accelerator to allow the mixture to cure. The amount and type of accelerator greatly affects the cure time and temperature. Typically, the accelerator is added in quantities of roughly 1 part to 200 parts of resin/hardener for optimal manufacturing [17]. Varying the amount of matrix (epoxy) and microballoons (glass) determines the properties of the resulting foam. On its own, Resnick's formula for epoxy resin was tested to a compressive strength of 21,600psi. While a higher percentage of glass microballoons decreases weight and increases buoyancy, it also decreases compressive strength. It was found that foams with a concentration of 30-50% of glass microballoons by weight provided superior properties for deep sea submergence [17]. One of the major drawbacks of syntactic foam is its tendency to absorb water at high pressures. Water absorption increases with an increased concentration of matrix material. To combat this, coupling agents are added to the resin system, which decrease the foam's water absorption while simultaneously increasing compressive strength. Since the original epoxy formula proved to be sufficiently strong, the development of higher strength glass microballoons has improved the strength, weight and buoyancy of syntactic foams over time.

Since the original development of syntactic foam, many companies have offered traditional syntactic foams that are rated to withstand pressures at different ocean depths, from shallow depths to the deep ocean floor. While implementation of these foams has been proven to perform successfully in a variety of applications in shallow to deep ocean depths, they have encountered issues in submersibles exploring the Mariana Trench. The Japanese ROV, Kaiko, used traditional syntactic foam with a specific gravity of 0.63 to provide structural support and buoyancy. After its first dive to 10,900m, a survey of Kaiko revealed minute cracks in the syntactic foam that penetrated through the surface to the middle of the foam section. These cracks were not due to a failure of the foam itself, but rather a failure of the adhesive component responsible for binding blocks of syntactic foam together [12]. In addition to assembly issues, traditional syntactic foam tends to be heavy and expensive when compared to alternatives such as ceramic macrospheres. Although, traditional syntactic foam is sufficient in providing buoyancy for ROV/AUVs, manned submersibles, which require a much heavier payload, are more sensitive to weight concerns. For use in manned submersibles operating at the deep ocean floor, traditional syntactic foam that meets the strength requirements is simply too heavy.

The IsoFloat foam used in the Deepsea Challenger represents a breakthrough in the manufacturing of syntactic foams. Uniformity of glass microballoons has been in issue in traditional syntactic foams. Foams with non-uniform glass spheres not only have a lower tolerance to pressure, but also absorb significantly more water at depth, making the vehicle heavier [16]. After a series of US suppliers failed to provide uniform samples, Cameron and Allum decided to manufacture their own syntactic foam. In addition to imposing greater quality control in the production of glass microballoons, Allum developed a manufacturing process to improve the pressure tolerance of syntactic foam. Initial testing of blocks revealed internal cracks that developed during pressure testing [16]. To increase packing and strength, the IsoFloat foam blocks are made in a pressure rather than the traditional method of producing foam in a vacuum [16].

Nevertheless, the submarine still compresses at full ocean depth, becoming 2.5 inches shorter [5]. Strain gauges attached to the foam during pressure testing indicate that the IsoFloat foam will not yield until the ambient pressure well exceeds 22,000 psi. In order to achieve this high compressive strength, the IsoFloat foam still remains relatively heavy compared to other buoyancy technologies and syntactic foams, with a specific gravity of 0.7. The submarine however is still able to ascend rapidly because it is actually far lighter at depth. Due to hydrostatic pressure, water at the ocean floor is denser than water at the surface. However, due to the high strength of the IsoFloat foam, it compresses far less than water at depth, making it far lighter at the bottom of the ocean [16]. The high strength of IsoFloat foam also allows the pieces to be easily machined and formed to create pieces for a hull.

McConaghy Boats, the manufacturer of the syntactic hull, drew upon its decades of composite experience to create a smooth structural beam The main beam of the Deepsea Challenger is composed of 250 pieces of syntactic foam held together with strong bonding adhesives similar to those used in the construction of luxury yachts [16]. The IsoFloat syntactic foam used in the Deepsea Challenger eliminates the need for a heavy metal hull, which allows the submarine to carry more equipment and maintain a compact design improving ascent and descent rates.

4.2 Ceramic Macrospheres

In recent years, ceramic macrospheres have been used in AUVs to provide buoyancy and support as an alternative to syntactic foam. The Woods Hole Oceanographic Institution's Nereus successfully used ceramic sphere flotation units in its 2009 exploration of the Mariana Trench. Engineers at WHOI were unsatisfied with the weight of syntactic foams on the market at the time and elected to use specially designed ceramic flotation spheres made up of 99.9% Al_2O_3 developed by DeepSea Power & Light (DSPL). Ceramic macrospheres were developed in the mid '60s, but are currently not used in manned submersibles due to quality and manufacturing concerns. However, they remain a viable option for AUVs, providing performance advantages over syntactic foams, and there exists a potential for future use in manned submersibles.

While syntactic foams are lightweight and provide excellent strength, the packing density of microspheres limits their buoyancy, since most marketed foams use a plastic matrix material that does not provide additional buoyancy. On the other hand, ceramic macrospheres can be held in place with a framework of low density plastic as shown in Figure 4-2 [19]. Due to their large size and low-density matrix material, ceramic macrospheres have the potential to provide buoyancy and strength with far less of a weight penalty than syntactic foams. Maximizing the pressure resistance of ceramic macrospheres can be achieved by choosing a material with high compressive strength that can be manufactured with the absence of joints, with a uniform thickness and little deviation from a perfect sphere [23].

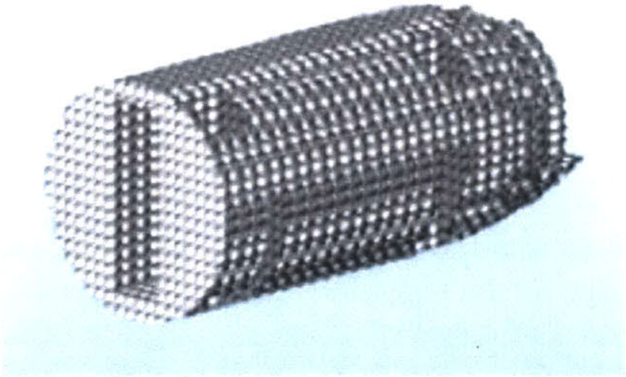


Figure 4-2: Ceramic flotation sphere matrix [19]

Joints or seams in the spheres introduce local tensile stresses that cause glass or ceramic spheres to crack and fail at lower pressures when exposed to long term or cyclic pressurizations [18]. The lack of a fabrication process that could produce seamless spheres was a roadblock in the industry until 1964 when Coors Porcelain developed a casting procedure that produced seamless 10-inch diameter spheres with a depth rating of 20,000 feet. However, variations in the structural performance between individual spheres led to the technology being considered too risky for manned submersibles [14]. Variations in sphere performance can have far reaching consequences since the implosion of one sphere can set off a chain reaction in surrounding spheres, which may sink the vehicle. This is not a problem in syntactic foams, where the spheres are microscopic and fully immersed in a matrix. Due to quality concerns, ceramic spheres were largely unused as a flotation medium until the appearance of ROVs and AUVs.

TABLE 4-1. TECHNICAL SPECIFICATIONS OF DSPL CERAMIC MACROSPHERES [23]

Slurry composition	99.9% Al_2O_3
Weight	140±1 g
Minimum thickness	0.06±0.01 in.
Outside diameter	3.60±0.05 in.
Diameter variation on each sphere	±0.03 in. max

The alumina ceramic spheres used in the Nereus were designed to withstand pressure at the ocean floor with a safety factor of 2 (33,000 psi). Alumina is the most cost effective and widely used engineering ceramic. It is widely available and is the strongest and stiffest out of all oxide ceramics, making it a good choice for the application of ceramic macrospheres. In order to provide a good balance of buoyancy and strength, while maintaining the ability to construct a sound shell 3.6 in. diameter spheres were used with a wall thickness of 0.06 inches to satisfy the safety factor. Calculated critical pressures of 34,844 psi by buckling and 35,209 psi by material failure led to the tolerance specifications shown in Table 4-1 [23]. The seamless spheres were fabricated by roto-molding in spherical molds made up of two well-fitted plaster hemispheres. The process of roto-molding involves filling a heated mold with a charge of material and slowly rotated causing the material to disperse and stick to the mold walls. The mold is continuously rotated on two axis during both the heating and cooling phase to provide a seamless product with near uniform thickness.

TABLE 4-2: TYPICAL CHARACTERISTICS OF ROTO MOLDED 3.6IN SPHERES [23]

	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

Quality of the manufacturing process was measured and documented by DSPL. Table 4-2 shows that the manufacturing process was sufficient in creating parts that fell within design tolerances. A visual inspection of 20 manufactured samples led to 2 being rejected for surface defects. In addition to measurements and visual inspection, DSPL acoustically tests all of their manufactured spheres. In the acoustic testing, spheres are subject to 30,000 psi while sound emissions are monitored. On average, an additional 25% spheres fail the acoustic test, leading to an overall passing rate of 67.5% for all spheres manufactured [21]. In the case of DSPL, a good quality assurance and testing program is able to sufficiently overcome the challenges of manufacturing enough to support use in unmanned submersibles.

While manufacturing of ceramic macrospheres requires improvement, the performance of DSLP's alumina spheres remains outstanding. Before being proven in practice, the ceramic spheres were tested in short term, long term, and cyclic pressure testing. Short term pressure testing was conducted to verify the ceramic spheres held up to the design conditions and safety factor. Due to availability issues, a 30,000 psi pressure vessel was used. All spheres meeting the technical requirements passed the short-term test. In order to determine the static fatigue life of the spheres, a sustained pressure test was conducted at 30,000 and 25,000 psi and the results then extrapolated to the predict fatigue life at 16,500 psi (11km depth). It was found that the static fatigue life was in excess of 10,000 hours, enough for more than 400 24-hour dives. Although the seamless manufacturing of ceramic spheres intrinsically leads to excellent cyclic wear properties, cyclic failure is a concern in applications where mechanical joints are present in the ceramic sphere structure of the submersible. Similar to the long-term tests, the cyclic tests were conducted at higher pressures and then extrapolated. The results of the cyclic test were a fatigue life of well above 30,000 cycles at 11km depth, far exceeding the service requirement of 1,000 dives. [23].

Although some manufacturing issues need to be worked out before ceramic spheres become an option for manned submersibles, their performance potential has not been overlooked. DOER Marine has been designing a manned submersible capable of exploring the deep ocean for sustained periods of time and considers ceramic macrospheres to be the optimal design solution for flotation [19]. Currently, DOER is in the process of rigorously testing ceramic spheres to ensure they can provide reliable performance at depth. While the Nereus has proved the success of ceramic spheres, use in a manned submersible raises additional concerns. DOER is working with Hadron Technologies to develop alumina spheres that can be efficiently manufactured with high quality assurance. [19]. Sympathetic failure (failure of multiple spheres by chain reaction) is the foremost concern as lives are at stake in a manned dive. Acoustic monitoring of the spheres is being looked into as a measure to warn operators of impending failure. In addition to monitoring, the matrix the spheres are packed into can be used to absorb the shock wave generated by a failed sphere. Initially, DOER had designed a structure of alumina ceramic spheres within a matrix of traditional syntactic foam to provide strength and shock absorbance. However, fabrication proved to be an issue as casting the spheres in the syntactic slurry led to high stresses, which initiated buckling and failure at lower pressures [19]. Different arrangements of spheres are currently being tested to minimize the risk of sympathetic failure. The work being done by DOER has initiated the transition ceramic spheres from a technology previously reserved for unmanned vehicles to one that will eventually be reliable and robust enough for manned exploration.

5. Development of Instrument Housings and Pilot Spheres

5.1 Instrument Housings

Glass spheres have been successfully used as instrumentation housing in a variety of deep ocean applications. Unlike the 1960 Trieste, modern deep sea exploration crafts carry tons of instrumentation, sensors, and cameras used for scientific analysis of the deep ocean. In order for these instruments to survive pressure at depth, they must be encased in a pressure resistant housing that is strong enough to protect the instrument while at the same time does not compromise the buoyancy of the submersible. Similarly to pilot viewports, a spherical housing provides the strongest shape as it distributes external force evenly and has no corners.

Instrument housings can be made out of a number of materials ranging from metals, molded plastics, ceramics, or glass. Glass housings provide many distinct advantages that are quickly making them the choice for underwater exploration. Glass as a material is relatively cheap and has a very high strength to weight ratio [13]. Glass is also corrosion resistant, allowing it to withstand salty environments. For instrumentation, glass also has the advantages of being transparent, nonmagnetic, and electrically non-conductive. Not only will glass housings not interfere with sensors themselves, but the command and control of instruments can also be done through a variety of means. Infrared, Bluetooth, GPS, ARGOS, Iridium transceivers and VHF radio signals all penetrate glass without a problem and can be used as effective communication with instruments [13]. Because of its transparency, crews on the surface can see status lights and displays through the glass, and high quality polished glass spheres can be used as viewports for high definition cameras and light sensors.

There are some notable challenges to using glass as a pressure housing, however. Glass is difficult to machine accurately and is subject to damage from impacts due to its brittleness. Under high pressure cycling, flaking and spalling can occur around drilled holes and connecters. In order to combat spalling, manufacturers often use flat washers with larger diameter o-rings for connecters to spread the concentrated load out over a larger area [13]. Figure 5-1 shows an underwater connecter developed by Teledyne Impulse that is capable of withstanding pressures up to 20,000 psi with a flat washer surface and larger diameter o-ring connection.

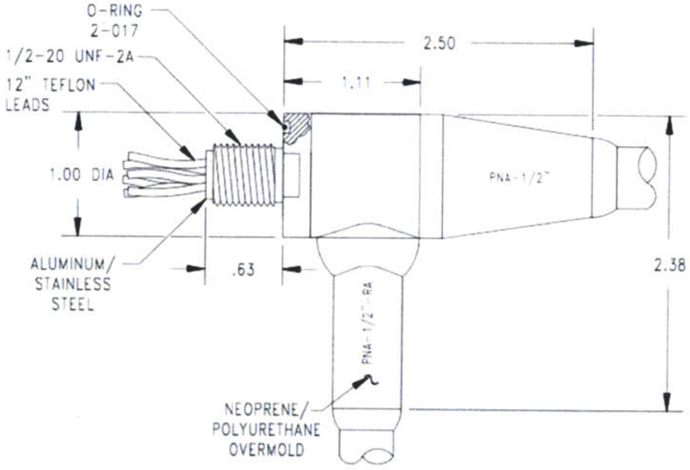


Figure 5-1: Teledyne Impulse Connector For Glass Housings [26]

Nautilus Marine Services has developed a popular line of Vitrovex glass spheres that have been successfully used in a number of deep ocean projects.

Vitrovex spheres are made of borosilicate glass 3.3, a standard glass used in Pyrex jars. Borosilicate glass 3.3 is made up of 81% Silica, 4% Alkali, 13% Boric Oxide, and 2% other materials [27]. In addition to being lighter than traditional glass, borosilicate glass boasts a very high compressive strength as well as a low coefficient of thermal expansion. The thermal expansion coefficient of borosilicate glass 3.3 is about 1/3 that of traditional glass [27]. This reduces material stress caused by temperature gradients in the ocean, making the glass more resistant to breaking. As a result, Vivotrex glass housings show little deformation, even under the high pressure in deep ocean trenches [13].

Vitrovex spheres are manufactured in hemispheres that are then sealed together to form a sphere. The hemispheres are sealed together with butyl rubber and wide black tape, kept together by pressure at ocean depths. In order for the spheres to withstand high pressure, it is critical that the hemispheres fit as closely as possible.

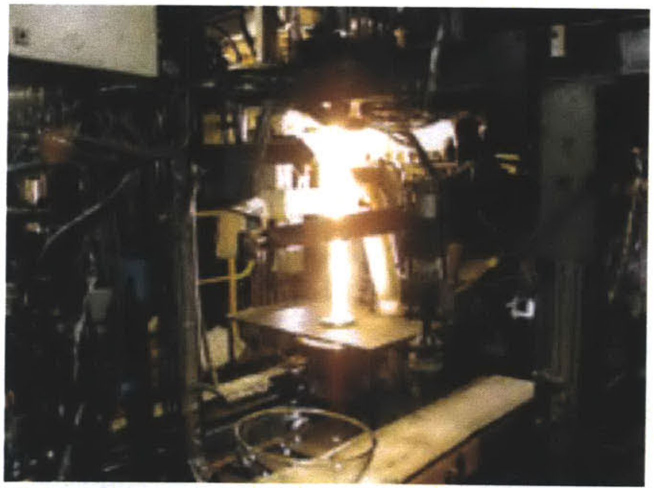


Figure 5-2: Vitrovex Annealing Oven [13]

Precision molding and high quality glass material ensure that when the hemispheres are annealed in a high temperature oven, they match dimensions as closely as possible. After the spheres have cooled, the mating surfaces go through a triple grinding process involving milling with diamond tools, manual smoothing and polishing to ensure the parting plane sealing surfaces are honed to precise flatness and finish [13]. Using precision manufacturing techniques Nautilus Marine Services is available to offer glass instrumentation housings in a variety of configurations that can withstand pressure at full ocean depth.

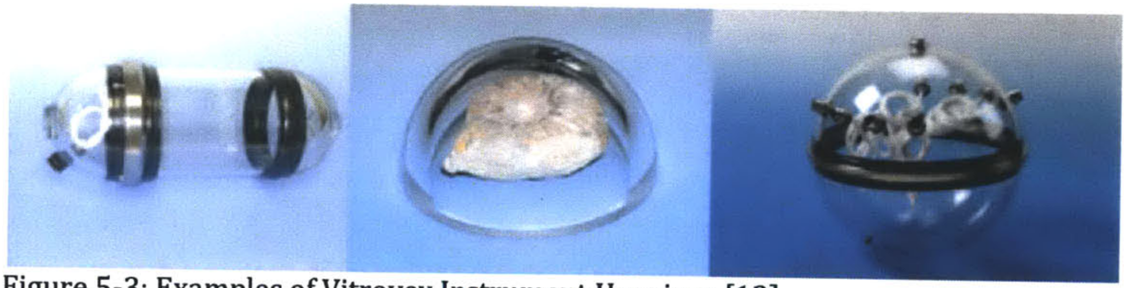


Figure 5-3: Examples of Vitrovex Instrument Housings [13]

Vitrovex spheres tend to perform far better than traditional metal housings. Figure 5-4 shows a comparison of the required wall thickness for borosilicate glass and titanium spheres of different diameters at 1400 bar (about 23,000 psi), as well as the resulting buoyancy [7]. In addition to requiring a slightly lower wall thickness at higher diameters, the borosilicate spheres show a steady increase of positive buoyancy, while the titanium spheres fail to be buoyant. Although borosilicate spheres offer significant advantages over their titanium counterparts, engineers working on the Deepsea Challenger still elected to use titanium instrument housings for the submarine's four external HD cameras [5]. In this application the weight of the instrument housings is significantly offset by the submarine's buoyancy, as the cameras are each about the size of a soda can. The Challenger's cameras are mounted to external metal booms, mounting titanium housings is therefore an easier and more practical option. The two landers that accompany the Challenger on dives make use of borosilicate glass housings for their 3D cameras [5].

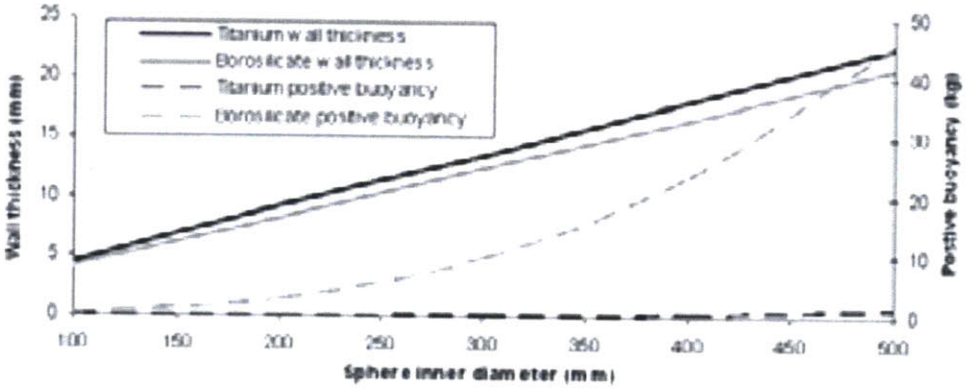
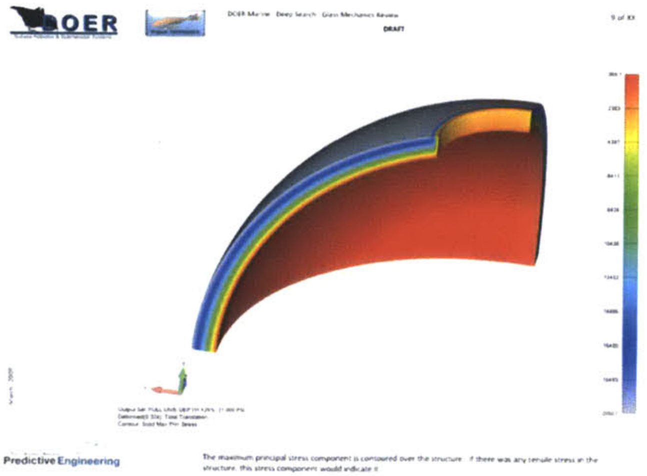


Figure 5-4: Comparison of Glass and Titanium Sphere Thickness at 1400 bar [7]

5.2 Pilot Spheres

DOER's Deepsearch project plans to use a large glass spherical housing for its pilot viewport. Traditional pilot spheres for manned submersibles are often made of a glass hemisphere mounted to titanium or aluminum hull. This approach creates high bearing stresses on the joining surface and has been problematic at deep ocean pressures. Prototypes that employ the idea of glass nose cone have experienced fracturing along the glass-seating surface during pressure testing [19]. Since the successful implementation of glass spheres, such as the Vitrovex spheres, for use in instrument housing, a new approach has been to create an entirely glass pilot sphere as shown in Figure 5-5. DOER's current design is essentially a massive Vitrovex sphere composed of the same borosilicate glass. The elimination of high bearing stresses associated with seating allows a full glass sphere to perform well at full ocean depth. Figure 5-6 shows a finite element model of a cross section of DOER's glass sphere design. The model shows an absence of detrimental forces within the glass sphere at a pressure of 21,000 psi [19].

Figure 5-5: DOER 68 in. Pilot Sphere Model [19]



The maximum principal stress component is contoured over the structure. If there was any tensile stress in the structure, this stress component would indicate it.

Figure 5-6: Finite Element Model of DOER's Glass Sphere [19]

Currently, scale models of DOER's craft have been successfully tested at full ocean depth pressures with Vitrovex instrument spheres [19]. While glass instrument housings are proven to withstand pressures at depths, many issues still need to be sorted out before they can be scaled up to be used as pilot spheres.

Nautilus Marine Service has been successfully manufacturing high quality instrument housings at a diameter of 17 in [13]. Producing the spheres at larger diameters of 68 in. creates many manufacturing concerns since the quality, uniformity, and precision of hemispheres is critical to the sphere's pressure tolerance. In addition to manufacturing concerns, the pilot requires different servicing than instrument housings. Unlike an instrument housing, pilot spheres require a hatch of some sort to make them easily accessible. While hatches are fairly easy to incorporate into metal structures, introducing a hatch into a glass sphere is much more challenging. This has not yet been considered in DOER's design and has the potential to weaken the pressure tolerance of the sphere. A final concern is mounting within the frame of the vehicle. While the utilization of an all glass sphere eliminates bearing stresses between hemispheres, mounting of the entire sphere within a frame can create high stresses against the mounting surfaces. DOER is currently investigating ways to work around these concerns and reports that all research, modeling, and testing of glass spheres has been overwhelmingly positive so far [19]. Once these issues have been resolved, large-scale borosilicate glass spheres will be a formidable option for pilot spheres.

While an ideally manufactured glass pilot sphere would be an ideal compromise of strength and weight, the ability to manufacture such a sphere remains in question. The Deepsea challenger instead uses a steel sphere with a small glass viewport shown in Figure 5-7 [6]. Titanium was the initial choice for the product, due to its higher strength to weight ratio. However manufacturing titanium requires far more expensive tooling, which made it too expensive to be considered for a one-off product such as the pilot sphere [16]. Steel on the other hand, is a much more widely used metal due to its ease of manufacturing; overall cost, and well understood material properties. The steel used for the DeepSea Challenger's pilot sphere is a high-grade steel that is also used to manufacture large gun barrels [16]. Since steel is a relatively heavy metal, the pilot sphere is the heaviest part of the sub. Therefore its size was kept to a minimum. The sphere was designed around the dimensions of James Cameron and measures only 43 inches in diameter, just enough to fit its pilot, life support systems, and controls. It has a wall thickness of 2.5 inches and has been tested to 16,500 psi twice to ensure structural integrity at depth. Strain gauges attached to the sphere led to an estimate that the sphere can withstand 23,100 psi of pressure before buckling [5].

Figure 5-7: Deepsea Challenger Pilot Sphere [6]

The Deepsea Challenger's steel sphere itself maintains its integrity at depth due to its material choice, design, and quality manufacturing. However, part of what enables the pilot sphere to function at depth is its viewport design. This differs from traditional submersible pilot spheres where a glass hemisphere was mounted to the hull structure. In the Deepsea Challenger, the glass viewport can be thought of as a small window on the surface of the steel pilot sphere. Figure 5-8 shows the pilot sphere of the Deepsea Challenger as being manufactured by Design+Industry. The glass window is much larger than the viewport itself and mounted and sealed to the opening in the front of the sphere, which faces ocean water [5]. This creates a strong flat seal and therefore does not exhibit the high bearing stresses associated with mounting the edges of a hemisphere to a hull. The viewport is about the size of a fist when viewed from the inside and made of borosilicate glass [3]. Although its small size allows the sphere to maintain structural integrity, it does not provide sufficient visibility. Instead, Cameron will see through a high definition camera mounted inside the sphere just in front of the viewport. The curvature of the window corrects for the magnification effects of water and allows Cameron to see through a "virtual viewport" on a screen within the pilot sphere.

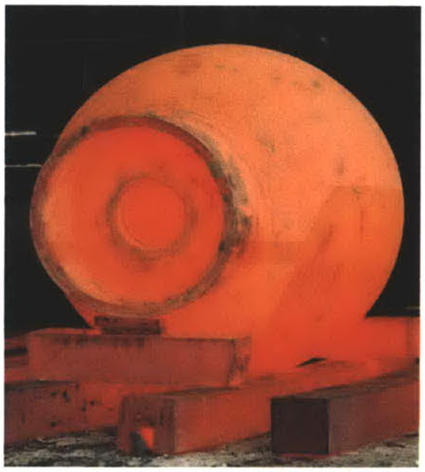


Figure 5-8. Deepsea Challenger Pilot Sphere Manufacturing [6]

5.3 Sapphire Viewports

Sapphire is another material that is commonly in deep-sea applications, particularly as viewports for camera pressure housings. Although the engineers of the Deepsea Challenger elected to house their cameras in glass housings, sapphire does offer a few notable advantages over glass and is widely used when suitable. The Hadeep project was a joint project between the UK and Japan to send landers with cameras down to the ocean floor. The cameras were enclosed in a rugged pressure housing with a sapphire viewport [7]. The viewports were selected to be a plane disc to make manufacturing easier. Hadeep considered acrylic, borosilicate glass, and sapphire viewports as options. Acrylic viewports were tested and began to deform at 800 bar (8000 m depth), therefore they were quickly eliminated as an option [7]. Although borosilicate glass structures have been proven to withstand full ocean depth pressures, sapphire is a stronger material and proved to be the best solution in terms of size and reliability [7]. Figure 5-9 shows a comparison of window thickness and failure pressure of different diameter sapphire and glass viewports. The equivalent window in sapphire is less than half as thick as borosilicate glass [7]. Sapphire is comparably priced to borosilicate glass as well, however it is more difficult to manufacture into larger more complex shapes. Sapphire viewports and housings will continue to be used in applications that require small, simple viewports as they do provide significant strength advantages over borosilicate glass without compromising buoyancy or interfering with instrument signals.

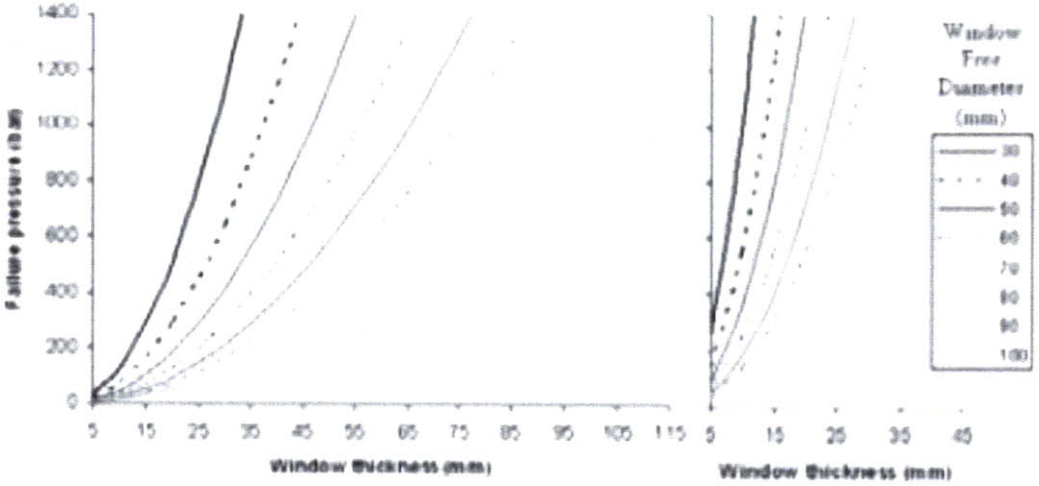


Figure 5-9: Comparison of Sapphire and Borosilicate Viewports [7]

6. Development of LED Lights For Deep Sea Applications

The 1960 dive of the Trieste represented an incredible feat of engineering. However, most modern submersibles attempting to reach full ocean depth are doing so with the added expectation of scientific observation. Sufficient lighting is needed to allow pilots as well as high-resolution cameras to observe the deep ocean floor. Traditional incandescent lamps must be encased in pressure vessels otherwise they will fracture due to the vacuum within the bulbs. The need for a bulky pressure housing limits the number of incandescent lights than can be mounted on a vehicle. LEDs, on the other hand, are solid-state devices, which can be packaged in epoxy or silicon, giving them a high tolerance to pressure. DeepSea Power & Light has tested its LED light engines and drivers to pressures in excess of 20,000 psi [8]. In addition to being inherently pressure resistant, LED technology has thoroughly developed and provides many advantages over incandescent lights for use in deep-sea applications. Due to their compact design, ruggedness and higher brightness, vehicles with LED light arrays can provide far more light at the ocean floor than traditional incandescent bulbs and are the most popular choice for lighting in the deep ocean.

High brightness LEDs are about five times more efficient in producing white light than incandescent lamps. They produce light in the 70-120 lumen/watt range [8]. Efficiency is crucial to submersible performance since in the depths of the ocean, there is virtually no natural light. This means submersibles exploring the deep ocean require vast arrays of LED lights to provide visibility. These lights come at a power penalty, which must be minimized since the submersible's battery system is also needed for a variety of other systems. LEDs also tend to be more shock resistant and reliable due to the fact they are solid state devices. This increased reliability gives them a significantly longer lifespan than incandescent bulbs, up to 50,000 hours or more [8]. LEDs also compare favorably in terms of light produced per weight. A 6,000 lumen LED provides 22.5 lumens per gram, while incandescent lights in a housing rated for an equivalent depth provide 13.2 lumens per gram [4]. While the weight of a single bulb may not be significant, added up across an array of lights, LED bulbs and housings can produce significant weight savings especially in smaller autonomous vehicles. Weight savings translate to less thruster power needed as well as less need for buoyancy compensation.

Although LEDs are more efficient than incandescent light bulbs, they still produce heat, which must be evacuated to the cool ocean to avoid overheating. TO maximize light output and produce the most light with the least heat, LED manufactures often package multiple LED dies onto a single platform, known as a multichip package. In the case of overheating, many underwater LED manufactures choose to dim their lights and continue to operate in a safe range. The other option would be to shut off the LED until it has cooled, but this could leave the camera, instruments, or pilot in a state of temporary blindness. Temperature monitored circuitry and drivers reduce the current to maintain the LEDs within their safe operating range. For manufacturers such as DeepSea Power & Light, this approach has provided years of successful operation in applications at a variety of ocean depths [4].

Although most LEDs tend to perform very well at depth, some do exhibit fluid compensation issues, which still need to be worked out. Browning is a rare, but troubling problem in LED lights and can reduce their output by 50% or more, making them less efficient than halogen or incandescent lights [4]. Browning manifests itself in a thin coating on the inside of the LED envelope and can be caused by either overheating or contamination. While overheating can be protected against with a good design and cooling measures, contamination is a harder issue to detect [4]. Often times, browning occurs due to contamination of the phosphor layer. Deepsea Power & Light had noticed browning in a few of their LEDs and it was initially suspected that the pressure compensating fluid had contaminated the phosphor layer. However, the same problem was noticed in blue LEDs, which contain no phosphor layer [9]. This has led to a growing consensus that the compensating fluid itself is not contaminating, but instead can act as a carrier to move contaminants into the area above the die [9]. Potting LEDs in silicone rubbers instead of using fluid compensation has shown promise in the field of research [9]. Nevertheless, this is a rare problem as most underwater LEDs are designed robustly enough to avoid contamination. LED lights are brighter, lighter, and do not require bulky pressure housings. They are therefore, far more versatile for use in deep sea applications, making them the choice for deep sea submersibles today. The DeepSea Challenger contains a seven-foot LED array mounted to its structural beam that is capable of providing 100ft of visibility at the ocean floor [5].

7. Development of Batteries for Deep Sea Applications

Battery power is essential for modern deep ocean exploration. Modern submersibles all depend on battery power for instrumentation, thruster power, as well as other control and life support systems. Traditional lead acid batteries have long been used to supply power to vehicles at ocean depths. However, lead acid batteries pose significant problems when being operated in closed pressure vessels. The introduction of Lithium-Ion batteries in the 1990s resolved many of these issues while also providing more power than lead acid batteries. Lithium-Polymer batteries represent a breakthrough in the packaging of Li-Ion cells and are currently a popular choice for deep-sea craft. In recent years, lead acid battery technology has evolved to provide lead acid batteries that can function reliably at depth and are better suited in certain applications. However, due to the higher power density of Li-Ion cells, Li-Polymer batteries remain the choice for large submersibles such as the Deepsea Challenger.

Conventional lead acid batteries were initially used to power the Trieste; these were later replaced with silver-zinc batteries. For its 1960 dive, the Trieste's batteries were all mounted within the pilot sphere [2]. The second iteration of the Trieste could afford more power because it contained four external battery boxes and used a pressure compensation system of electrolyte and white mineral oil to maintain integrity at depth [24]. A major issue with traditional lead-acid and silver-zinc batteries is that they have to breathe when they are being fully charged because they can give off flammable and explosive gases. Discharge can be done in a sealed environment, but full charging can only safely be done in a vented environment. When housed in pressure vessels, traditional batteries require the pressure vessel be unsealed and vented during charging and then resealed for use. This is problematic as for many types of pressure vessels, multiple unseal and reseal cycles can result in leaks [24].

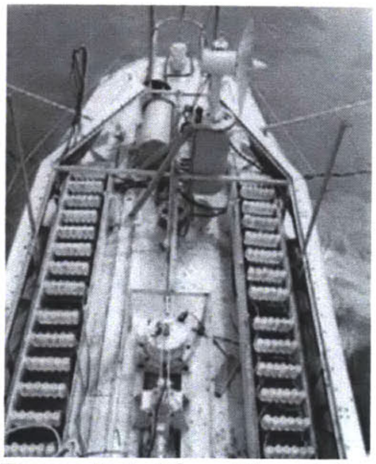


Figure 7-1: Silver Zinc Battery Packs on the 1964 Trieste II [24]

The introduction of rechargeable lithium ion (Li-Ion) batteries in the 1990s marked a turning point in underwater battery technology. In addition to being Li-Ion batteries are not only two to four more times energy dense than lead-acid batteries, but they also have the advantage of being fully sealed. The main disadvantage to Li-Ion batteries is that they are very sensitive to contamination. If the cell's seal is broken, foreign materials can easily cause the cell to fail and potentially trigger a gas release. High outside pressures at ocean depths can be particularly problematic in this regard. Traditionally Li-Ion batteries were packed in metal cylinders that contained small air pockets. High outside pressures can therefore cause the cell walls to deform and burst cell seals resulting in contamination.

A new form of Li-Ion packing technology called lithium polymer cells was developed that can produce batteries able to withstand the pressure of full ocean depth. Li-Polymer cells contain the same chemical as a traditional Li-Ion battery, but packed in a sealed foil pouch. The pouches are vacuum-sealed to remove nearly all air pockets then submerged in oil or a flexible potting material. Charge and discharge cycles of Li-Polymer cells have been successfully tested at pressures at and above 10,000 psi, making them ideal candidates for use on deep ocean craft [24]. The cells do expand and contract during charging and discharging respectively. Typically volume changes are limited to 1-3%. Pressure equalization as well as the flexible nature of cells allows expansion to occur without damage to the cell [24]. The main disadvantage of Li-Polymer batteries is that they require complex electronics for monitoring, charge and discharge control, and balancing functions. Recent technology has been focused on developing electronics that are capable of withstanding pressure at full ocean depth.

The majority of electronic components and integrated circuits today are encapsulated in epoxy. This allows them to be submerged in oil and withstand crushing pressures of the ocean. Circuit components must be carefully selected however. Electronic components are almost never specified for operation at extreme pressures and many ceramic chips carriers contain air pockets under metal lids that will collapse at high pressures. Once cell components have been selected, they must be encapsulated in a medium to uniformly distribute external pressure. Oil is an ideal encapsulation material because it distributes pressure while simultaneously filling air spaces. However, oil can allow the movement of submerged parts, which may be damaged due to changes in orientation, sudden shock, or vibration. Flexible potting materials provide much better shock and vibration resistance, but must be carefully selected and the cells manufactured so that the potting fills all potential air pockets. After the components are encapsulated, they must be sealed from salt water. This is typically done with housings that contain flexible bladder seals allowing the oil or potting material to compress slightly at high pressures.

Although lithium ion batteries provide many advantages over traditional lead acid and nickel cadmium batteries, since the use of lead-acid batteries in the Trieste, there have been multiple technological advances that make them suitable for reliable deep ocean use. Recent developments have eliminated the need for bulky pressure housings for deep-sea applications. Absorbent Glass Mat (AGM) batteries are considered to be the most advanced sealed lead acid batteries on the market [10]. They provide all of the advantages of traditional lead acid gel cells with none of the downsides. To improve shock and pressure resistance, AGMs use electrolyte saturated born silicate glass mats between their plates. The plates are sandwiched together in a rigid frame, providing shock, pressure, and vibration resistance. Like gel cells, they can be operated at all angles.

For some deep water applications, AGM lead acid batteries are better suited than more recent lithium polymer batteries. They are more readily available and less costly to ship due to safety concerns with lithium batteries. AGM batteries can also be designed to give short bursts of higher current due to denser electrolyte concentrations and an increased plate surface area [10]. Lower temperatures in the deep sea have an adverse affect on all batteries. However, the higher pressure of the deep ocean increases the capacity in lead-acid batteries, which tends to balance out the temperature effect [10].

A prior concern of lead acid batteries was their tendency to release explosive gases. AGM batteries inherently produce minimal gas in normal operation, allowing a maintenance free design similar to lithium ion batteries. This is due to the fact that AGM batteries are "recombinant", which means the oxygen and hydrogen generated while charging recombine into water inside the battery because of the use of a low to zero antimony lead alloy grid. DeepSea Power & Light has tested their AGM batteries and has found that the recombinant effect is better than 99%, meaning no water is lost, and almost no gas is generated [10]. Trace amounts of gas generated can be captured within a flexible diaphragm and vented with a pop off valve, although DSPL still recommends recharging on deck [10].

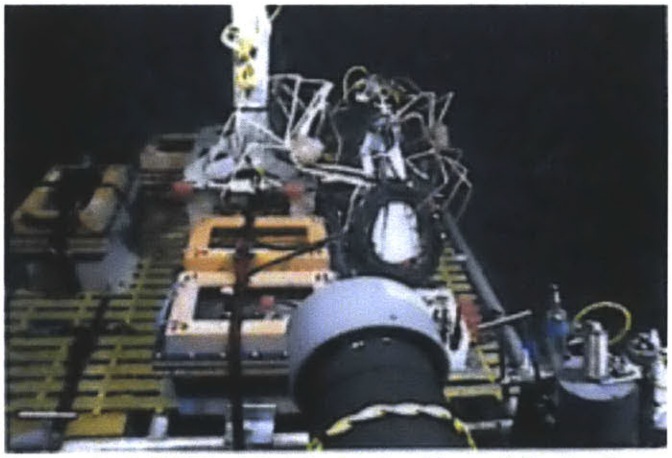


Figure 7-2: DSPL AGM Batteries Tested At the Ocean Floor [10]

The Deepsea Challenger uses a modular array of Li-Polymer batteries for power. Due to its modular design, battery packs can easily be swapped out and the amount of batteries used is tailored to each dive. All of the subs control, power, lighting and instrumentation systems depend on battery power. On any given dive, the Deepsea Challenger carries enough batteries to power two to three modern electric cars [5]. In total, the submarine carries over a thousand Li-Polymer pouches packed into about 70 bread loaf-sized modules. Each battery module is immersed in silicon oil and housed in a plastic case. The silicon oil provides ample pressure resistance for the cells themselves. The silicon oil used in the battery packs, however, does compress and shrink under full ocean pressure. This can lead to batteries shifting as well as deformation of the plastic casings, which are made to be lightweight, not pressure resistant. In order to work around this problem and avoid the use of potting materials that might contain air bubbles, the Deepsea Challenger uses a novel fluid compensation system. In each of the plastic cases, there is a small opening that leads to a flexible bladder inside the pack. As the submarine descends and ambient pressure increases, seawater fills the plastic bladder, which expands as the oil inside the case compresses. This fluid compensation system allows the battery modules and housings to maintain integrity at full ocean depth and is the first of its kind to be developed [5].

8. Future Deep Sea Manned Submersibles

Since the Deepsea Challenger's engineering and dive to the Mariana Trench, there has been resurgence in manned submersible exploration. As the technologies discussed in this paper evolve and become more reliable, more advanced dive craft will be developed. Some such as the Deepflight Challenger will be purely recreational vehicles offering people the experience of seeing the deepest point of the ocean. Others, such as DOER's Deepsearch will be more scientifically based. These submarines are still in their development or refining phases and take advantage of the current state of technology as well as offer improvements on dive methods and maneuverability through significant design changes.

The Deepsea Challenger, shown in Figure 8-1, was designed and developed by Graham Hawkes' company Hawkes Ocean Technologies for businessmen and avid explorer Steve Fossett. The submarine design had been completed and was rated to pressures at full ocean depth was under assembly and about 4 weeks away from dive testing when Fossett died in a plane crash in 2007 [20]. The Deepflight Challenger project was restarted when Chris Welch purchased the unfinished submarine and Virgin Oceanic came on as a sponsor. The Deepflight looks more like an underwater airplane than a submarine. Similarly to the Deepsea Challenger, the Deepflight is remains positively buoyant due to the use of syntactic foam and uses ballast weights to help it descend to the ocean floor [11]. However, in addition to using ballast weights, the submarine's descent is aided by its hydrodynamic wings, which essentially act as upside down airplane wings, providing down force instead of lift. The vehicle weighs only 8,000 pounds and uses two powerful thrusters combined with rudders for propulsion and maneuverability.

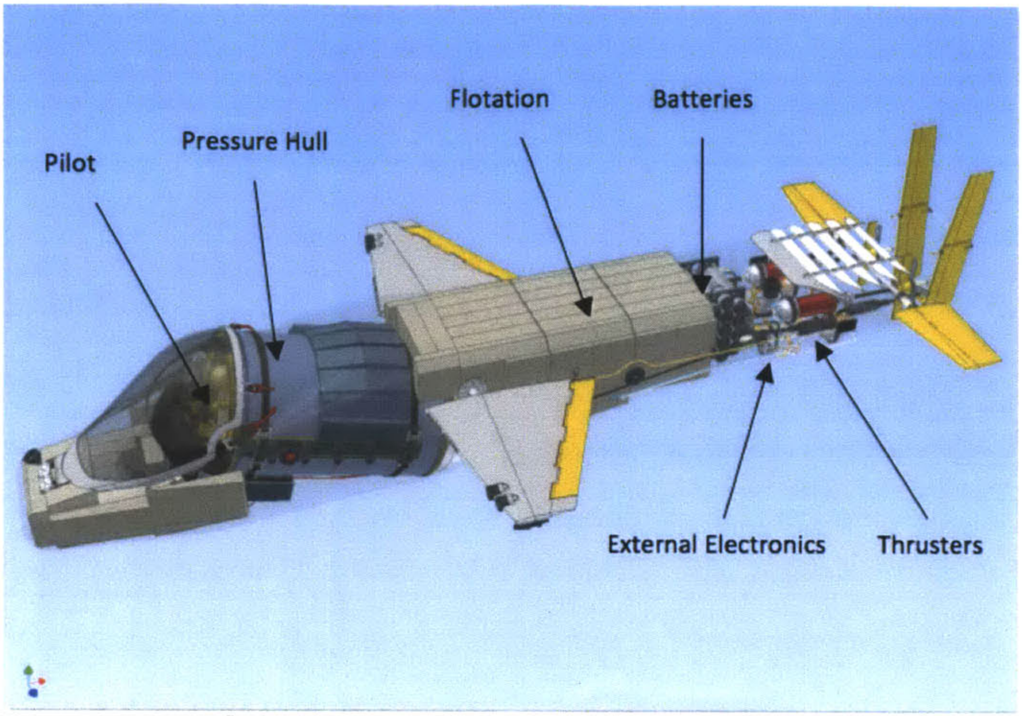


Figure 8-1: Deepflight Challenger [11]

The sub's pressure hull is composed of carbon fiber and epoxy composites and bonded to the pilot viewport by titanium rings. LED lights and a laser navigation system are used to allow the pilot to navigate the deep ocean. Due to its airplane like design, the Deepflight Challenger is the first deep ocean dive craft in development to boast 3-axis maneuverability [11]. Although it is still under development and testing, the sub is estimated to reach a top speed of 6 knots (3 at full ocean depth), have a range of 15 miles, and be able to dive to full depth and return to the surface in 5 hours [11].

DOER's Deepsearch submarine (Figure 8-2) is still in its early development, however, if successful will prove to be a huge advancement in deep-sea exploration.

Deepsearch seeks to carry a crew of three to full ocean depth with the goal of improved scientific observation. Unlike other submersibles, Deepsearch will not use the traditional system of ballast/buoyancy to descend/ascend to depth. The Deepsearch strategy is to use a combination of thrust. Movable trim mass, and a variable buoyancy system to "fly" down to depth [19]. If successful, the Deepsearch will be able to stop at any point in its dive to collect data, making it an ultimate scientific observatory that can function at any depth. As discussed earlier, Deepsearch is investigating the use of a massive glass sphere for its pilot housing as well as ceramic macrospheres to provide hull integrity and offset the weight of other components. The active use of thrust will require significant power. DOER is currently looking into advanced Lithium batteries as well as fuel cells as potential power sources [19]. DOER's design goals are to obtain a descent rate of 6 knots, reaching the ocean floor in 90 minutes, with a maximum cruising range of 16 miles at depth on its 10 hour dives [19].

Figure 8-2: Cut-away of DOER Deepsearch [19]

9. Conclusions

Currently, little is understood about the deep ocean hadal zone. It remains the final frontier for exploration on the planet. The 1960 dive of the Trieste was the first time man had journeyed to the deepest point of the ocean floor. There, the pilots observed small marine mammals, bringing to light an ecosystem that scientific knowledge was previously blind to. It would take 36 years before technology and scientific interest had reached a point where a vehicle would return to the Challenger Deep. With the advent of robotic submarines, there was little motivation to send a manned submersible back to the Mariana Trench until recently. James Cameron's Deepsea Challenger dive in March 2012 marked the first time man had returned to the Challenger Deep, this time for the purpose of scientific observation. Modern technology has made deep diving manned submersibles possible and restored the value in sending people to the ocean depths whether it be to have a person managing data collection at depth, or purely for the experience of exploration.

With pressures at the Challenger Deep reaching 16,500psi, engineering any vehicle to explore the ocean depths poses a difficult engineering challenge. The Trieste pioneered many engineering breakthroughs in deep-sea explorations. Design concepts and systems used in the 1960 submarine are still common practice today. However, there is always room for improvement. The Trieste used an extremely heavy and bulky pilot sphere creating the need for large amounts of buoyancy compensation. This came in the form of large amounts of gasoline which pose leakage and volatility issues. In recent years, syntactic foams have been developed that can reliably withstand pressure at full ocean depth while provided positive buoyancy in lieu of gasoline. A quickly emerging technology in buoyancy structures is the use of ceramic macrospheres, which offer significant performance advantages over syntactic foam if they can be manufactured reliably. The Deepsea Challenger takes advantage of high grade steel in conjunction with a reduced need for volume to drastically reduce the size and weight of its pilot sphere. DOER's Deepsearch seeks to implement an extremely lightweight and strong borosilicate glass pilot sphere. The Triton 36000/3 submarine already claims to have such a sphere ready for production [21].

The Trieste was also unable to take extra equipment to the ocean floor for scientific observation. The development of precisely manufactured borosilicate glass and titanium instrument housings provides a means of allowing instruments to take in data from the surrounding ocean without being exposed to high pressures. Sapphire windows are commonly used in conjunction with metal housings to provide viewports for cameras and other sensors. The use of high resolution underwater cameras requires sufficient lighting. The Trieste used quartz arc-light bulbs, which can withstand high pressures, but are less efficient than modern LED light technology, which is currently used in most submersibles. Increased instrumentation requires more battery power. The silver-zinc batteries used in the original Trieste were stored within the cockpit and provided just enough power for essential systems. The development of fluid pressure compensation systems has allowed designers to mount batteries externally, providing room for massive battery rays. Advances in battery technology have led to Lithium-Polymer cells, which provide far superior energy density as well as pressure tolerance to traditional batteries. These advanced batteries not only have the capacity to power instrumentation, but also to power more, as well as higher powered, thrusters making modern submersibles far more maneuverable.

All of these technological innovations add up to make the Deepsea Challenger a quick, maneuverable submarine that has the capability for immense data collection and scientific observation all while being a fraction of the size of the Trieste. Future manned submersibles are rethinking the ballast/buoyancy strategy of descent and are instead taking advantage of hydrodynamics and high-powered thrusters to further increase maneuverability. Virgin Atlantic's Deepflight Challenger boasts 3-axis maneuverability as well as a high top speed and is very close to its testing phase. DOER's Deepsearch seeks to completely eliminate the need for ballast to descend and will instead "fly" to the ocean floor, maintaining the ability to stop at any point during descent/ascent to collect date. However, it is still in its early stages of development. Future submersibles are taking advantage of current technology while providing design innovations of their own to further advance the field of deep-sea exploration and increase our appreciation for and understanding of the geological processes and ecosystems of the deep ocean.

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