have also been concerted efforts to protect them in some areas, and the growing realization of their value has led to widespread efforts to utilize mangroves in a more sustainable manner, and in some places large areas of mangrove plantations have now been established.

Worldwide, there are currently an estimated 850 protected areas with mangroves spread between 75 countries, which are managed for conservation purposes. These cover over 16 000 km^2 of mangrove, or 9% of the global total. Although this is a far higher proportion than for many other forest types, active protection is absent from many of these areas, and the remaining unprotected sites are probably more threatened than many other forest types because of their vulnerability to human exploitation.

Increasing recognition of the various values of mangrove forests is leading to widescale mangrove plantation in some areas, for coastal defence, as a source of fuel, or for fisheries enhancement. Plantations in Bangladesh, Vietnam, and Pakistan now cover over 1700 km^2, and Cuba is reported to have planted some 257 km^2 of mangroves. Overall, however, when weighed against the statistics of mangrove loss, the area of such plantations remains insignificant.

Active management of these and other existing mangrove areas for economic production is increasing. The Matang Mangrove Reserve in Malaysia is perhaps the best-known example. Studies have shown combined benefits arising from timber and fuelwood products (notably charcoal), but even more importantly from a large nearshore fishery (directly or indirectly providing employment for over 4000 people), from aquaculture on the mud flats below the mangroves, and from tourism. It is rare that such holistic studies have been carried out. Often the human benefits provided by mangrove fall between several sectors of the economy, fisheries, forestry, tourism, and coastal protection, and their combined benefits are not realized. A better perception of these benefits would undoubtedly lead to much wider-scale protection for mangroves globally.

See also

Coastal Topography, Human Impact on. Coastal Zone Management. Crustacean Fisheries. Fisheries Overview. Reef Fisheries. Sea Level Change.

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MANNED SUBMERSIBLES, DEEP WATER

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Introduction

Deep-ocean underwater investigations are much more difficult to carry out than investigations on land or in outer space. This is because electromagnetic waves, such as light and radio waves, do not penetrate deep into sea water, and they cannot be used for remote sensing and data transmission.

Moreover, deep-sea underwater environments are physically and physiologically too severe for humans to endure the high pressures and low temperatures. First of all, pressure increases by 1 atmosphere for every 10 meters depth because the density of water is 1000 times greater than that of air. Furthermore, as we have no gills we can not breathe under water. Water temperature decreases to 1°C or less in the deep sea and there is almost no ambient light at depth because sunlight can not penetrate through more than a few hundred meters of sea water. These are several of the reasons why we need either manned or unmanned submersibles to work in the deep sea.

A typical manned submersible consists of four major components: a pressure hull, propellers (thrusters), buoyant materials, and observational instruments. The pressure hull is a spherical shell made of high-strength steel or titanium. The typical internal diameter of the hull is approximately 2 m, which allows up to three people to stay at one atmosphere for 8–12 h during underwater operations. In case of emergency, a life-support system enables a stay of three to five days. Several thrusters are usually installed on the body of the submersible to give maneuverability. The buoyant material is syntactic foam, which is made of glass micro-balloons and an adhesive matrix. Its specific gravity is approximately 0.5 $\mathrm{gf\,ml^{-1}}$. Observational instruments such as cameras, lights, sonar, CTD (conductivity, temperature, and depth sensors) etc., are also very important for gathering information on the deep-sea environment. It should be mentioned that the power consumption of the lights can reach as much as 15% of the total power consumption of the submersible.

History of Deep Submersibles

The first modern deep diving by humans, to a depth of 923 m, was achieved in 1934 by William Beebe, an American zoologist, and Otis Burton using the bathysphere, which means 'deep sphere'. The bathysphere was a small spherical shell made of cast iron, 135 cm in inside diameter designed for two observers. The bathysphere had an entrance hatch and a small glass view port. As the sphere was lowered by a cable and lacked thrusters, it was impossible to maneuver.

The next advance, using a free-swimming vehicle, occurred after World War II, in 1947. The bathyscaph *FNRS II* was invented by Auguste Piccard, who had been studying cosmic rays using a manned balloon in Switzerland. The principle of the bathyscaph was the same as that of a balloon. Instead of hydrogen or helium gas, gasoline was used as the buoyant material. During descent, air ballast tanks were filled with sea water, and for ascent, iron shot ballast was released. The pressure hull was made of drop-forged iron hemispheres, 2 m in inside diameter and 90 mm in thickness, allowing for two crew members. It was able to maneuver around the seafloor by thrusters driven by electric motors. Later, the second bathyscaph, *Trieste*, was sold to the US Navy, and independently at the same time, the French Navy developed the bathyscaph *FNRS III*, and later *Archimede*. In 1960, the *Trieste* made a dive into the Challenger Deep in the Mariana Trench, to a depth of 10 918 m. This historic dive was conducted by Jacques Piccard, son of Auguste Piccard, and Don Walsh from the US Navy. The bathyscaph was the first generation of deep-diving manned submersibles. It was very big and slow as it needed more than 100 kiloliter capacity gasoline tanks to provide flotation for the 2 m diameter pressure hull.

In 1964, the second generation of deep submersibles began. *Alvin* was funded by the US Navy under the guidance of the Woods Hole Oceanographic Institution (WHOI). At first, its depth capability was only 1800 m. It was small enough to be able to put on board the R/V *Lulu*, which became its support ship. Instead of gasoline flotation, syntactic foam was used. *Alvin* had horizontal and vertical thrusters to maneuver freely in three dimensions. Scientific instruments, including manipulators, cameras, sonar and a navigation system, were installed. Three observation windows were available for the three crew members. In France, the two-person 3000 m-class submersible *Cyana* was built. These two vehicles typified submersibles during the 1960s. At present, the depth capability of the *Alvin* has been increased to 4500 m by replacing the high-strength steel pressure hull with a titanium alloy sphere in 1973. In the 1980s, 6000 m-class submersibles, such as the *Nautile* from France, the *Sea Cliff* of the US Navy, the *Mir I* and *Mir II* from Russia and the *Shinkai 6500* from Japan, were built. They were theoretically able to cover more than 98% of the world's ocean floor.

What will the third generation of deep submersibles be like? Manned submersibles of the third generation, which would be capable of exceeding 10 000 m depth, have not yet been developed at the time of this report. One possibility is a small and highly maneuverable one- or two-person submersible with a transparent acrylic or ceramic pressure hull. Another possibility is a deep submergence laboratory, which would be able to carry several scientists and crew long distances and long durations without the assistance of a mother ship. This would be the realization of the dream like '*Nautilus*' in 20 000 Leagues Under The Sea by French novelist Jules Verne. Strong scientific and/or social goals would be needed for such a submersible design to be pursued. And there is a third possibility that the next generation will be evolutionary upgrades of existing second-generation submersibles.

Principles of Modern Submersibles

Descent and Ascent

There are several methods to submerge vehicles into the deep sea. The simplest way is to suspend a sphere by a cable, known as a bathysphere. Mobility, however, is greatly limited. A second method relies on powerful thrusters to adjust vertical position in relatively shallow water. The submersible *Deep Flight* is a high-speed design which uses thrust power coupled with fins for motion control like the wings of a jet fighter. It descends and ascends obliquely in the water column at speeds up to 10 knots. Most submersibles employ a third method that, while using weak thrusters to control attitude and horizontal movement, relies principally on an adjustable buoyancy system for descent and ascent (**Figure 1**).

When on the surface, the submersible's air ballast tank is filled with air creating positive buoyancy, hence it floats. When the dive begins, air is vented from the ballast tank and filled with sea water, thus creating negative buoyancy and sinking the vehicle. As the submersible dives deeper, buoyancy increases modestly due to the increasing water density created by the increasing pressure. Thus the submersible slows slightly as it dives deeper (**Figure 2**).

When the submersible approaches the seafloor (50–100 m in altitude, i.e., height above the bottom), a portion of its ballast (usually lead or some other heavy material) is jettisoned to achieve neutral buoyancy. Perfect neutral buoyancy occurs when the positively buoyant materials (things which tend to float) on the submersible balance the negatively buoyant materials (things which tend to sink). This allows the vehicle to hover weightless in position and move freely about. As perfect neutral buoyancy is difficult to maintain, most submersibles have auxiliary weight-adjusting (trim and ballast) systems. This consists of a sea-water pumping system to draw in or expel water, thus adjusting the buoyancy of the submersible.

Upon completing its mission, the remaining ballast is jettisoned and the submersible now with positive buoyancy begins ascending. When resurfaced, air from a high-pressure bottle is blown into the air ballast tank to give enough draft to the submersible for the recovery operation.

Water Pressure

Water pressure increases by 0.1 MPa per 10 m depth. Thus every component sensitive to pressure

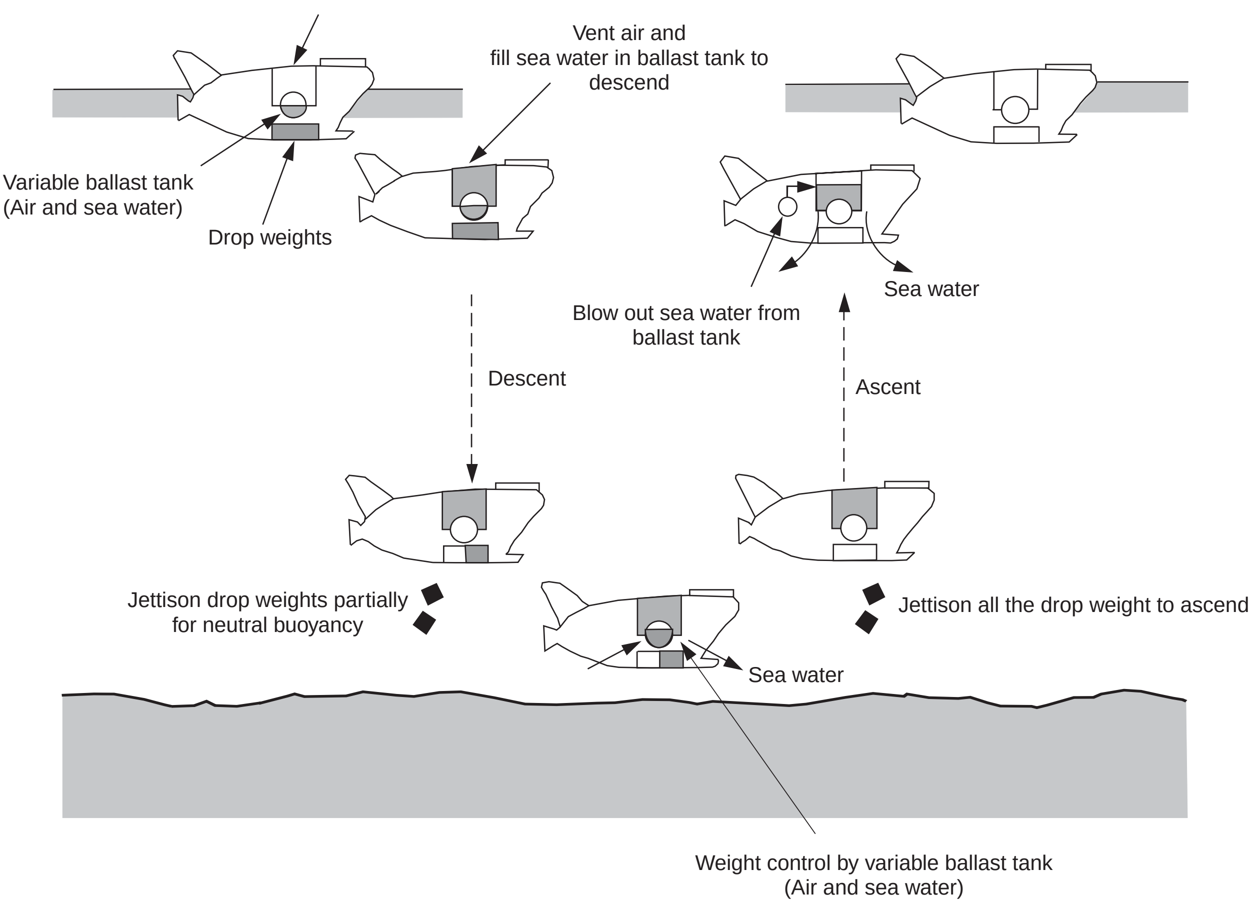

Figure 1 Principle of descent and ascent for a modern deep submersible.

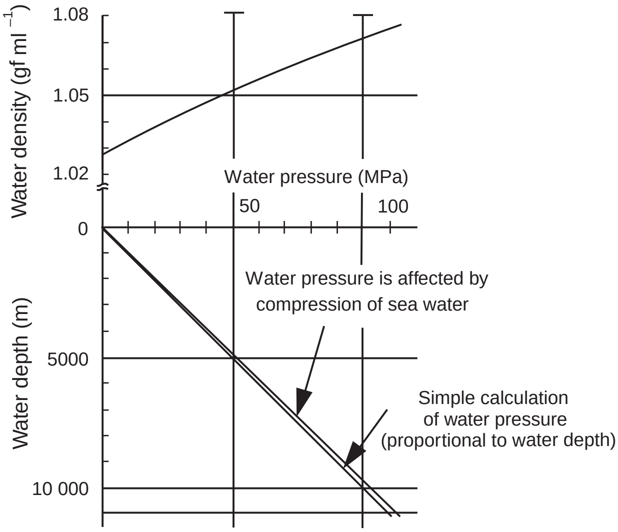

Figure 2 Relations between water depth, pressure and water density at a water temperature of 0°C and salinity of 34.5‰.

must be isolated from intense pressure changes. First and foremost are the passengers which are protected against great ambient pressure by a pressure hull or pressure vessel, maintained at surface pressure. The ambient pressure exerts strong compressional force on the pressure hull which is therefore designed to avoid any tensile stress. The strongest geometric shape against outside pressure relative to volume and hence weight is a sphere, followed by a cylinder (capped at both ends). However, it is not easy to arrange instruments inside a sphere effectively.

In order to increase mobility, it is important to make submersibles small and light. The pressure hull is one of the largest and heaviest components of the submersible. The hull must be as small (and light) as possible, while affording appropriate strength against external pressure. Thus for deep-diving submersibles, a spherical pressure hull is employed whereas shallower vehicles can use a cylindrical shape if so desired.

The material used for the pressure hull is critical. In earlier vehicles, steel was used. Later, titanium alloy was the material of choice. Titanium alloy has very high tensile strength, and is resistant to corrosion and relatively light (specific gravity $\sim 60\%$ that of steel). Recently, the trend in submersible construction is to use nonmetallic materials, such as fiber- or graphite-reinforced plastics (FRP or GRP), or ceramics.

Components not sensitive to pressure or saline conditions need no special consideration. Though those devices which require electrical insulation need to be housed in oil-filled compartments called oil-filled pressure compensation systems (**Figure 3**). These systems do not require heavy pressure hulls and thus reduce the weight of the submersible overall. Electric motors, hydraulic systems, batteries, wiring, and power transistors are all housed in pressure compensation systems. Technology is being developed to apply ambient pressure to electronic devices such as integrated circuits (ICs) and large scale ICs (LSIs).

Buoyancy

With the exception of some shallow-water submersibles, the total weight of the essential systems is larger than the total buoyancy. This means that extra buoyancy is needed to balance the excess weight. Wood or foam-rubber cannot be used for this purpose because they shrink under increasing water pressure. The material providing buoyancy must have a relatively small specific gravity while remaining strong under high-pressure conditions.

Historically, gasoline was used to provide buoyancy in bathyspheres as it did not lose buoyancy under pressure. However, its specific gravity was too large for practical use – huge volumes are needed to offset the weight. With the invention of syntactic foam, a superior material for deep-diving submersibles became available. Syntactic foam consists of tiny microscopic spheres of glass embedded in resin. These microballoons are 40–200 μm in diameter, and are closely packed with resin filling in the surrounding spaces. Proper selection of the

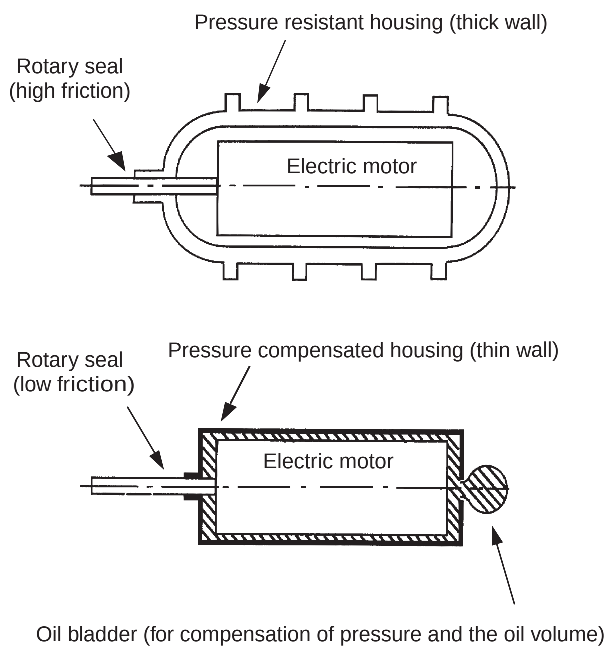

Figure 3 Pressure resistant and pressure compensated housings for electric motors.

balloons and resin allows the proper pressure tolerance and specific gravity to be created. For example, the syntactic foam used by the *Shinkai 6500* is tolerant up to 130 MPa with a specific gravity of 0.54 gf ml^{-1} and the foam used by the ROV *Kaiko* is tolerant up to 160 MPa with a specific gravity of 0.63 gf ml^{-1}.

Life Support

The pressure hull is a very small space where crew members must stay for up to 20 h, depending on their mission. Since the pressure hull is maintained at ambient pressure, no decompression of the occupants is needed. High-pressure oxygen bottles provide oxygen within the pressure hull, while carbon scrubbers absorb carbon-dioxide (**Figure 4**). Extra life-support is required with varying standards depending on the country (from 32 h to 120 h).

Energy

Energy for deep-diving submersibles is supplied by rechargeable (secondary) batteries. There are several types including: lead acid, nickel cadmium, nickel hydrogen, oxidized silver zinc. Batteries which contain a higher density of energy are preferable to reduce the weight and volume of the submersible. However, such batteries are very expensive. These batteries are housed in oil-filled pressure-compensated systems to reduce weight. Recent developments in fuel cell technology offer the promise of higher density energy coupled with higher efficiency. This has great potential for submersible applications.

Instrumentation

There are many scientific and observational instruments employed on research submersibles. Due to the limited payload, these instruments must be as light and small as possible. For example, bulky camera bodies must be streamlined and aligned with lenses in a compact manner, thus reducing the size and weight of their pressure housing (see **Figure 5**). Furthermore, physical conditions such as extremely cold temperatures or the differential absorption of white light must be considered. Thus, for example, engineers must consider both the compactness of video cameras and their color sensitivity.

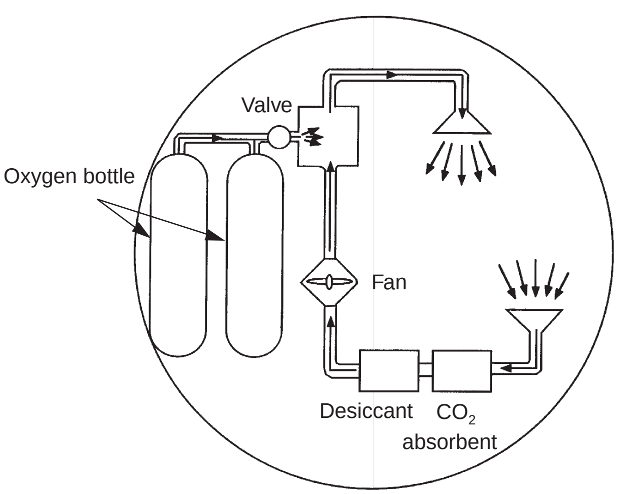

Figure 4 Life support system for a deep submersible.

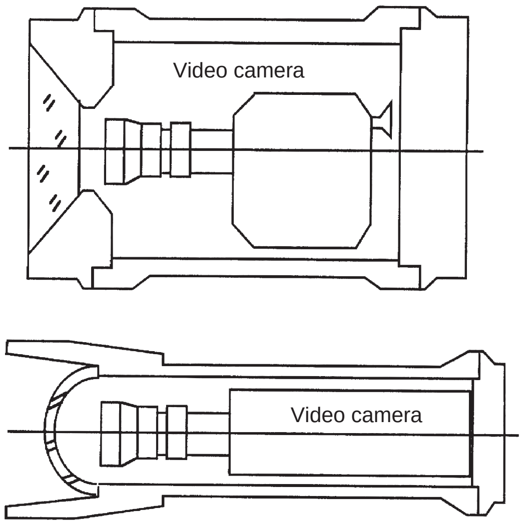

Figure 5 Examples of inside alignments of the pressure case.

Manipulator

Pressure hulls, thrusters, batteries, and buoyancy materials are all essential parts of the modern submersible. One of the most important tools is the manipulator arm. Manipulators extend the arms and hands of the pilot, allowing sample collection and deployment of experimental equipment. Most manipulators are driven by hydraulic pressure. The most advanced manipulators operate in a master-slave system. The operator handles a master arm (controller) which imitates human arm and hand movements, and the motions are translated to the slave-unit (manipulator) which follows precisely the motions of the master arm. There are usually one or two manipulators on a research submersible.

Navigation

Underwater navigation is one of the most crucial elements of deep-sea submersible researches. Usually, long base line (LBL) or super short base line (SSBL) acoustic navigation systems are used depending on the accuracy required. The positioning error of LBL systems is 5–15 m, and it is approximately

2–5% of slant range for SSBL systems. An advantage of SSBL systems is that seafloor transponders are not necessary, whereas at least two seafloor transponders are necessary for LBL systems. In both systems, absolute or geodetic position is determined by surface navigation systems, such as Differential Global Positioning System (DGPS). Although the position of the submersible is usually reported from the mother ship by voice, the *Shinkai 6500* has an automatic LBL navigation system.

Surface Support (the Mother Ship)

The R/V *Lulu*, the original support ship of the submersible *Alvin*, was retired and replaced by the R/V *Atlantis II* in 1983. In 1997 *Atlantis II* was replaced by the newly commissioned Research Vessel *Atlantis*. The support ship not only supports the diving operation, including launch, recovery, communication, and positioning, but also provides a place to conduct on-board research during a cruise. Accordingly, research laboratories, computers, instruments for on-board data analysis, multi-narrow beam echo sounders, etc., are necessary. Also, remotely operated vehicles (ROVs) or autonomous underwater vehicles (AUVs), can be operated during the nighttime, or in case the manned submersible cannot be operated because of bad weather.

Deep Submersibles in the World

Alvin (USA)

Alvin (**Figure 6**) was built in 1964 by Litton Industries with funds of the US Navy and operated by WHOI. Its original depth capability was 1800 m with a steel pressure hull. Later, the pressure hull was replaced by titanium alloy to increase depth capability up to 4500 m. *Alvin*'s size and weight are: length 7.1 m; width 2.6 m; height 3.7 m and weight 17 tf in air. The outside diameter of the pressure hull is 2.08 m with a wall thickness of 49 mm. It is equipped with three view ports, 120 mm in inside diameter, two manipulators with seven degrees of freedom. The original catamaran support ship, R/V *Lulu*, was replaced by the R/V *Atlantis II*. Launch and recovery take place at the stern A-frame. It has been the leading deep submersible in the world.

Nautile (France)

Nautile (**Figure 7**) was built in 1985 by IFREMER (French Institution for Marine Research and Development) in France. Depth capability of 6000 m was aimed to cover 98% of the world's ocean floor. It is 8 m long, 2.7 m wide, 3.81 m in height and weighs 19.3 tf in air. It is equipped with three view ports, a manipulator, a grabber and a small companion ROV *Robin*. The position of the submersible is directly calculated by interrogating the seafloor transponders. Still video images are transmitted to the support ship through the acoustic link.

Sea Cliff (USA)

Sea Cliff was originally built in 1968 as a 3000 m-class submersible by General Dynamics Corp. for the US Navy as a sister submersible for the *Turtle*. In 1985, the *Sea Cliff* was converted into a 6000 m-

Figure 6 US submersible *Alvin*.

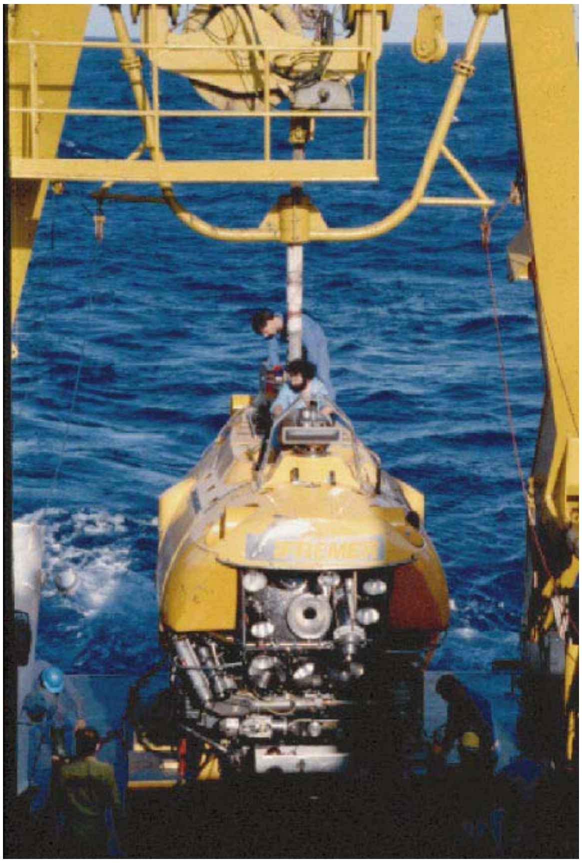

Figure 7 French 6000 m-class submersible *Nautile*.

class deep submersible. It is 7.9 m long, 3.7 m wide, 3.7 m high and weighs 23 tf in air. (*Sea Cliff* and *Turtle* are currently out of commission.)

Mir I and *Mir II* (Russia)

The 6000 m-class submersibles *Mir I* and *Mir II* (**Figure 8**) were built in 1987 by Rauma Repola in Finland for the P.P. Shirshov Institute of Oceanology in Russia. They are 7.8 m long, 3.8 m wide, 3.65 m high and weigh 18.7 tf in air. Inside diameter of the pressure hull, which is made of high-strength steel, is 2.1 m with a wall thickness of 40 mm. Launch and recovery take place by an articulated crane over the side of the support ship, the R/V *Academik Mistilav Keldysh*. If necessary, both *Mir I* and *Mir II* are launched simultaneously to carry out cooperative or independent research. Another characteristic feature of the *Mir* is a powerful secondary battery, 100 kWh of total energy, which allows it to stay more than 20 hours underwater, or to carry out more than 14 h of continuous operation on the bottom.

Shinkai 6500 (Japan)

The *Shinkai 6500* (**Figure 9**) was built in 1989 by Mitsubishi Heavy Industries and operated by the Japan Marine Science & Technology Center (JAMSTEC). It is 9.5 m long, 2.71 m wide, 3.21 m high and weighs 25.8 tf in air. The pressure hull is made of titanium alloy, 73.5 mm in thickness, and has an inside diameter of 2 m. It is equipped with three view ports, two manipulators with seven degrees of freedom. Position of the submersible is calculated and displayed in real time by directly interrogating the seafloor transponders. Still color video images are transmitted automatically at 10 s intervals to the support ship, the R/V *Yokosuka*, through the acoustic link during the diving operation. Launch and recovery take place at the stern A-frame of the R/V *Yokosuka*.

Major Contributions of Deep Submersibles

The dive to the Challenger Deep in the Mariana Trench by the bathyscaph *Trieste* in 1960 was one of the most spectacular achievements of the twentieth century. However, the dive was mainly for

Figure 8 Russian 6000 m-class submersible *Mir I* or *Mir II*.

Figure 9 Japanese 6000 m-class submersible *Shinkai 6500*.

adventure rather than for science. In 1963, the US nuclear submarine *Thresher* sank in 2500 m of water off Cape Cod in New England. After an extensive search for the submarine, the bathyscaph *Trieste* made dives to inspect the wreck in detail and recover small objects. The operation demonstrated the importance of using deep submersibles and advanced deep ocean technology to increase knowledge of the deep ocean. In 1966, hydrogen bombs were lost with a downed US B-52 bomber off Palomares, Spain. The *Alvin* showed the great utility of deep submersibles by locating and assisting in the recovery of lost objects from the sea.

Between 1973 and 1974, project FAMOUS (French–American Mid-Ocean Undersea Study) was conducted in the Mid-Atlantic Ridge off the Azores using the French bathyscaph *Archimede* and the US submersible *Alvin*. The project was the first systematic and successful use of deep submersibles for science. They discovered and sampled fresh pillow lavas and lava flows at 3000 m deep in the rift valley, where the oceanic crusts were being created, providing visual evidence of Plate Tectonics. In 1977, *Alvin* discovered a hydrothermal vent and vent animals in the East Pacific Rise off the Galapagos Islands at a depth of 2450 m. Discovery of these chemosynthetic animals, which were not dependent on photosynthesis, had a profound impact on biology in the twentieth century.

Manned submersibles now compete with unmanned submersibles, such as ROVs and AUVs. Because of the expense of operation and maintenance, national funding is necessary for manned submersibles. However, ROVs and AUVs can be operated by private companies or institutions. In spite of the costs, the ability of the human observer to rapidly process information to make decisions provides an advantage and justifies continued use of manned submersibles.

See also

Autonomous Underwater Vehicles (AUVs). Bottom Landers. Deep Submergence, Science of. Drifters and Floats. Manned Submersibles, Shallow Water. Moorings. Remotely Operated Vehicles (ROVs). Rigs and Offshore Structures.

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