DOI 10.15302/J-SSCAE-2019.06.017

Development and Application of Manned Deep-Diving Technology

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Abstract: Manned submersible is an important technical means and equipment for deep sea diving, exploration, development, and protection, and represents the development frontier in submersible technology. In this paper, the development status of foreign equipment and technology related to deep-sea manned submersibles is briefly described, followed by a review of their development and application in China. The three primary milestones in China's journey toward the development of state-of-the-art deep-sea manned submersibles are discussed. The development of the manned submersibles, Jiaolong and Deep Sea Warrior, considerably enriched China's experience in the manufacture of deep-sea manned submersibles. With respect to deep-sea diving in the range 4500–7000 m, China has established itself at the international forefront in general, and owns multiple independent intellectual property rights. Its intention to explore the ocean to its full depth and expanse through genealogical development of manned deep-diving technology has become evident over the recent years. Over the next 15 years, China should focus on consolidating and improving its submersibles in terms of their operational ability, field of application, level of intelligence, weight, capacity to carry heavy loads, and cluster coordination. An industrial chain needs to be carefully constructed, to cement China's position as a powerful country in terms of manned deep-diving technology.
Keywords: submersible; manned; deep sea; key technology; genealogy development

1 Introduction

The 21st century is the century of the ocean. The development and utilization of marine resources have become the foci of global competition. Countries all over the world have accelerated the process of marine oil and gas development, gradually transitioning from shallow sea to deep sea. Abundant deposits of flammable ice have been found on the ocean floor, and great technological breakthroughs have been achieved over the recent years in their development and utilization. Moreover, deep sea polymetallic nodules, underwater cobalt-rich crusts, and deep sea resources like hydrothermal sulfide and other minerals have revealed a novel approach to securing reserves of strategic resources.

Driven by the aforementioned strategic demand, marine power have acquired comprehensive pedigree, ranging from the development of advanced surface support mother ships to that of manned/unmanned deep-sea submersibles capable of diving 1000–11000 m below the sea level, besides other exploratory and operational technology and equipment. In particular, development of manned marine exploration has been deemed to be essential as manual experience, emotion, analysis, judgment, and operation on site is essential to gain an understanding of complex oceanic environments, especially the unknown deep sea.

Received date: June 22, 2019**; Revised date:** November 13, 2019
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Funding program: CAE Advisory Project "Research on Maritime Power Strategy by 2035" (2018-ZD-08)
Chinese version: Strategic Study of CAE 2019, 21 (6): 087–094
Cited item: Hu Zhen et al. Development and Application of Manned Deep Diving Technology. *Strategic Study of CAE*, https://doi.org/10.15302/J-SSCAE-2019.06.017

In their capacity as deep-sea vehicles, manned submersibles are capable of rapidly and accurately transporting scientific, engineering, and technical personnel, as well as various electronic devices and mechanical equipment, to target sea-bed environments; conducting efficient exploration, measurements, and scientific investigation; and making crucial on-site decisions as quickly as possible. They have become important tools in carrying out deep-sea research, development, and protection. Over the past 50 years, the safe operation of manned submersibles and the gradual improvement of critical technologies in the field have supported and promoted significant progress in deep-sea exploration [1].

The developmental process and current status of manned deep submergence equipment and technology in China and abroad have been systematically analyzed in this study, with a special focus on the applications and technical achievements of manned submersibles in China. Further, by considering the development and application of Jiaolong and Deep Sea Warrior as examples, the technological system underlying China's manned deep-sea exploration efforts has been summarized, and future courses of development in the field have been suggested.

2 Current status of foreign development

2.1 Manned submersible industry

Driven by strong market demands and advanced technological progress, the global manned submersible industry has gathered significant developmental momentum (Table 1). In 2018, research data obtained by the Marine Technology Society (MTS) Manned Underwater Vehicles (MUV) Committee revealed that there were 160 active manned submersibles in the world, comprising a total of 1624 manned seats [2]. Thirty-eight submersibles are used for submarine rescue, and the remaining 122 are used for other functions like scientific research, commercial operations, tourism, etc.

Table 1. Manned submersibles in service (working depth > 1000 m).

Name	Operator	Depth / m	Capacity	Year built
Deepsea Challenger	WHOI	11 000	1	2011
Jiaolong	COMRA	7000	3	2009
Shinkai 6500	JAMSTEC	6500	3	1989
Mir1	RAS	6000	3	1987
Mir2	RAS	6000	3	1987
Rus	Russian Navy	6000	3	2001
Consul	Russian Navy	6000	3	2011
Nautile	IFREMER	6000	3	1985
New Alvin	WHOI	4500	3	2013
Deep Sea Warrior	CAS	4500	3	2017
PISCES IV	HURL	2000	3	1971
PISCES V	HURL	2000	3	1973
Triton 3000	Alucia M/V	1000	3	2011
Deep Rover	CANDIVE Ltd	1000	1	1984
Deep Rover DR2	Alucia M/V	1000	2	1994
LULA 1000	FRN	1000	3	2011

The manned submersible industry includes manufacturers, operators, research ships, industry associations, etc. Since 2000, several new commercial companies have been established whose primary business comprises the design, manufacture, and operation of manned submersibles. Till date, manned submersibles have maintained a good safety record, which can be attributed to the efforts of classification societies in ensuring safe design and construction certifications. For example, the proportion of manned submersibles certified by third-party classification societies is as high as 92 %.

2.2 Deep-sea manned submersibles

2.2.1 Development history

In January 1960, two Swiss explorers, Picard and his son, took the "Trieste" manned submersible to the ocean floor of the Mariana Trench (10913 m deep) in the Pacific Ocean, which initiated the march to the deep sea. Even though, with Trieste's accomplishment, human beings were able to reach the deepest point in the ocean, there was still a long journey ahead to understand and utilize the deep sea and its bountiful resources.

Strategic Study of CAE 2019 Vol. 21 No. 6
DOI 10.15302/J-SSCAE-2019.06.017

Since the 1980s, France, the former Soviet Union/Russia, Japan, and the United States have pioneered continuous developments in computers, appropriate materials, underwater sound, imaging, and other technical fields. This has propelled major maritime countries to develop deep-sea manned submersibles capable of reaching depths of 6000 m (Fig. 1) [3–6]. The range of applications of these vehicles demonstrates the advantages of direct observation and exploration by professionals in the deep sea and on the ocean floor. These vehicles have made it possible to reach continental slopes and seamounts at depths of 2000–4000 m and craters, ridges, and oceanic floors at depths of 6000 m. A large number of important geological, sedimentary, biological, geochemical, and geophysical discoveries have also been facilitated by such explorations.

Since 2000, there has been further active research on deep-sea manned submersibles, especially ones capable of reaching depths of 11 000 m. This has, in turn, triggered a new round of industrial and technological development [7]. In March 2012, the Deepsea Challenger, a manned submersible developed by David Cameron's team in the United States (U.S.), set the record for the greatest depth achieved by a single dive (10 898 m). Although the Deepsea Challenger is not an operational manned submersible, some of its technical features closely agree with the development trends of modern manned submersibles, including a large inner diameter (1.1 m), the use of high-strength steel as construction material, high submarine floating speed (150 m/min), new layout for illumination (LED light source, maximum range of 2.4 m), etc.

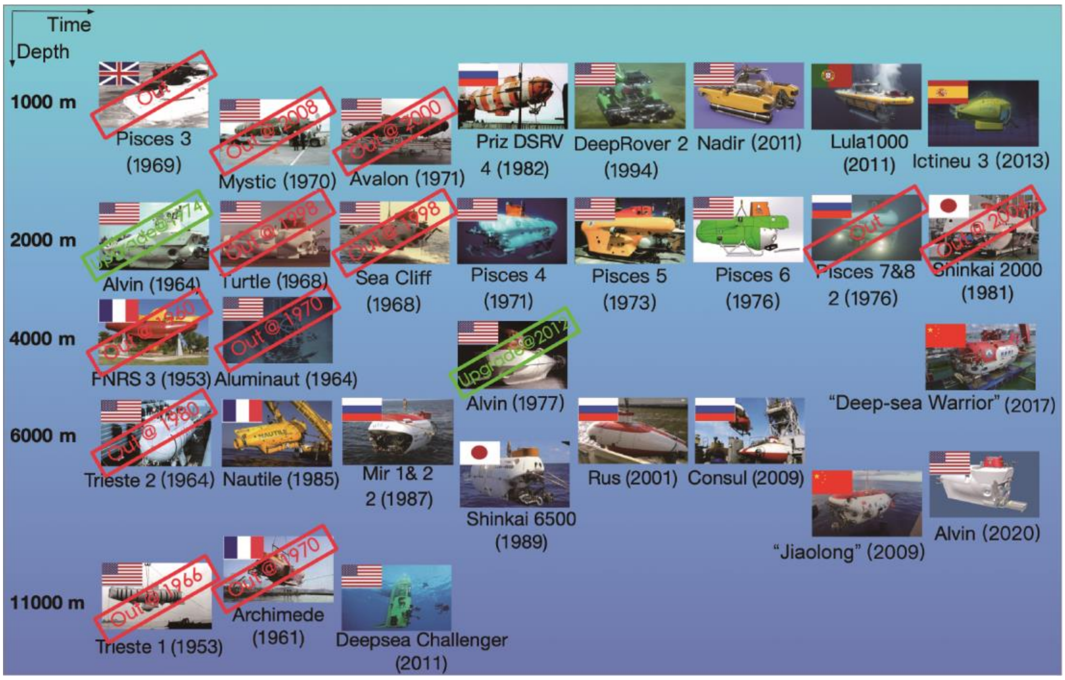

Fig. 1. Development history of major deep-sea manned submersibles.

2.2.2 Development status

(1) Upgrading

The U.S. manned submersible, Alvin, has been overhauled several times since it was initially developed in 1964; its most comprehensive upgraded version was launched in 2013 (Fig. 2). This included a larger inner diameter for the new manned sphere, an improved submergence depth of 6500 m, advanced digital commands and control systems, overhauled propulsion, high-definition photo/video imaging capabilities, digital scientific instrument interactions, a new scientific workspace, manipulator configurations, and other subsystems.

(2) New developments

In view of the demands of exploration of mineral resources at depths of 1000–5500 m in the Indian Ocean, India's National Institute of Ocean Technology (NIOT) has developed a deep-sea manned submersible with a working submergence depth of 6000 m and a rising and falling speed greater than 30 m/min. It can reach the working depth in 3 h. The submersible has been designed with a traditional structure, with a total weight of less than 20 t. Its manned sphere cabin is constructed using a titanium alloy and has a diameter of Φ = 2.1 m. The submersible is equipped to carry three people, and has standard and emergency life support durations of 12 h and 72 h, respectively.

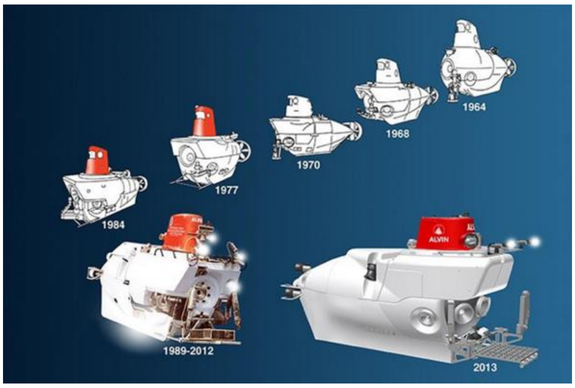

Fig. 2. Upgrades of Alvin.

(3) Commercial tourism

The development of tourism and exploration via manned submersibles by foreign commercial companies has followed a unique path. Although these submersibles have standard submergence indices, they have pioneered breakthroughs in construction material, overall structure, power, maneuverability, deployment and recovery, life support, and emergency self-rescue, providing an advanced model for the development of deep-sea manned submersibles.

In 1995, a commercial submersible was developed by the U.S. company, SEAmagine, which was capable of carrying 2–6 people to submergence depths of 150–1500 m. Since 2005, U-boat Worx has developed a series of products: a 2-person model with a submergence depth of 3000 m, a 3-person model with a submergence depth of 2500 m, and a 5–11 person model with a submergence depth of 200–1700 m. Since 2008, the U.S. company, Triton, has developed a variety of submersibles capable of venturing into any marine environment with a capacity of 1–7 passengers. In addition, Canada, Russia, and other countries have their own small manned submersibles for observations, which have been used to serve market demands.

(4) Development of new technology

In 2018, the U.S. company, OceanGate, completed the construction of the manned submersible, Titan, capable of carrying 5 people to a depth of 4000 m. Titan has been used for commercial exploration and research adventures in deep sea. It is primarily composed of two parts—the body of the submersible that can carry 5 people and an integrated distribution and recovery platform (Fig. 3a).

The highlights of Titan's design include a composite pressure shell, a large acrylic observation window, and an integrated cloth recycling platform. The integrated distribution and recovery platform is meant to be used for the distribution and recovery of manned submersibles. It can also be used as a floating platform for operation and maintenance procedures, enabling simple and low-cost deployment in remote areas. An innovative real-time hull health monitoring (RTM) system has been used. Nine acoustic sensors and 18 strain gauges deployed on the pressure boundary are used to analyze the forces exerted on the hull by variations in pressure during submergence of the vehicle and to accurately evaluate structural integrity.

In addition, Triton Submarines and the EYOS exploration company, both of the U.S., have carried out exploration activities at depths of 10 000 m; they have constructed Triton LF with a vertical flat structure and a large height-to-width ratio (Fig. 3b).

3 Domestic developments

3.1 Overall situation

During the eighth and ninth five year plans, China began to research, develop, and apply the technology of manned submersibles, focusing on rescue and life-saving submersibles, including single normal-pressure diving equipment with submergence depths of 200 m, deep submersibles with submergence depths of 600 m, life-saving bells with submergence depths of 200 m, etc.

Since 2000, the field has experienced rapid development in China. In 2012, the manned submersible Jiaolong was developed, with a maximum submergence depth of 7062 m in the Mariana Trench. In 2015, a humanoid single-person atmospheric diving submersible (ADS) with working a depth of 500 m, and two "Huandao Jiaolong" full-penetration passenger-carrying submersibles with working depths of 40 m and crew capacities of 12 were

DOI 10.15302/J-SSCAE-2019.06.017

developed. Commercial passenger-carrying operations were approved by the state as pilot projects. In 2016, the development of a manned submersible with a submergence depth of 11 000 m was initiated; it is expected to undergo sea tests in 2020. In 2017, the Deep Sea Warrior was developed, with a submergence depth of 4500 m and a localization rate of 95 %. In 2018, the world's first deep-water manned submersible, with a working depth of 300 m, meant for dam detection passed its mid-term inspection. General assembly, joint commissioning, and demonstration of applications are about to be initiated for the submersible. Further, multiple types of mobile life-saving bells have been developed, which provide domestic equipment for the national navy's submarine rescue service.

(a) Titan (4000 m) manned submersible.

(b) Triton LF manned submersible.

Fig. 3. Representative new technological developments of manned submersibles.

3.2 Iconic achievements

After nearly 20 years of development, a complete technical chain and application system was established in the manned submersible industry in China, leading to the eventual achievement of the following three milestones.

3.2.1 Deepest diving record set by the manned submersible, Jiaolong, by reaching a depth of 7062 m

In 2002, the National 863 Program initiated the development of the manned submersible, Jiaolong, with a submergence depth of 7000 m (Fig. 4 and Table 2). Based on joint research by nearly 100 premier scientific research institutions in China during the stages of design, processing, manufacture, general assembly, joint commissioning, pool functional testing, etc., the technical conditions for Jiaolong's sea trial were satisfied at the beginning of 2008. During the periods August–October, 2009; May–July, 2010; July–August, 2011; and June–July 2012, marine test missions to depths of 1000 m, 3000 m, 5000 m, and 7000 m were completed, respectively, and a maximum submergence depth of 7062 m was reached. In 2013, the submersible was introduced into service. Since then, it has completed more than 100 dives in South China Sea, the East Pacific manganese nodule area, the West Pacific cobalt rich crust area, Mariana Trench, southwest Indian Ocean, northwest Indian Ocean, and other seas. A large number of biological, mineral, sedimentary, rock and other samples have been obtained by it; high-resolution sea-bed images have been taken, providing an important foundation for the assessment of deep-sea resources and environments [8]. In 2019, the first test dives were conducted after the completion of a set of technical upgrades.

3.2.2 High frequency application of the manned submersible, Deep Sea Warrior, at a depth of 4500 m

In 2017, the development and sea trial of the manned submersible, Deep Sea Warrior, was completed, and it was successfully delivered to users. Deep Sea Warrior exhibited a localization of 95 % (Fig. 5 and Table 3) and a maximum operating depth of 4500 m. The submersible adopted primarily domestic technology, including its manned cabin, buoyancy material, positioning sonar, thruster, hydraulic source, manipulator, oil-filled lithium battery pack, ultra-high-pressure sea water pump, underwater illumination, and acoustic equipment. with a focus on improving practicability, economy, and maintainability.

Fig. 4. Overhaul and technical upgrade of Jiaolong.

Table 2. Basic parameters of the manned submersible, Jiaolong.

Name	Parameter
Capacity	3 persons (1 driver + 2 passengers)
Size	8.3 m × 3.8 m × 3.0 m
Weight	22 000 kg
Depth	7000 m
Speed	2.5 kn
Payload	220 kg
Propeller	7 electric thrusters
Hull	78 mm titanium alloy
Life support	Standard 12 h (3 people) Urgent 72 h (3 people)
Up/down speed	40 m/min

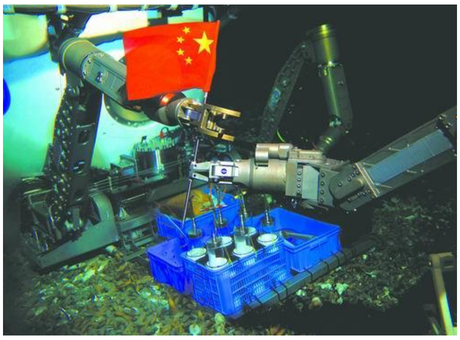

Fig. 5. Deep Sea Warrior and ROV operating together.

Table 3. Basic parameters of the manned submersible, Deep Sea Warrior.

Name	**Parameter**
Capacity	3 persons (1 driver + 2 passengers)
Size	8.0 m × 3.0 m × 3.5 m
Weight	20 000 kg
Depth	4500 m
Speed	2.5 kn
Payload	220 kg
Propeller	6 electric thrusters
Hull	53 mm titanium alloy
Life support	Standard 10 h (3 people) Urgent 72 h (3 people)
Up/down speed	50 m/min

DOI 10.15302/J-SSCAE-2019.06.017

In 2018, practical application of Deep Sea Warrior was initiated. Since then, it has completed more than 100 dives in South China Sea and southwest Indian Ocean. It has undertaken missions pertaining to scientific investigation, marine archeology, underwater salvage, hydrothermal investigation, and other deep-sea operations, and achieved successful results in the context of scientific research. Deep Sea Warrior is capable of nocturnal diving as well as two dives per day for several successive days, with a minimum diving interval of 5 h. Further, it is capable of operating in conjunction with a 6000 m remotely operated vehicle (ROV), exhibiting good performance and reliability in practical scenarios [9].

3.2.3 Target working depth of 11 000 m set for deep-sea manned submersibles

In 2016, with the support of the national research and development plan, the “full-ocean-depth manned submersible project group” was established with the China Ship Scientific Research Center of China Shipbuilding Industry Corporation serving as the overall integration unit. This marked the entry of China’s deep-sea manned submersible project into the implementation stage. A target was set to reach a depth of 10 000 m in 2020. In 2017, the schematic design for the deep-sea manned submersible proposed to meet the target passed the review process. Currently, it is at the stage of key technological research, large-scale ground testing, and sample trial production. Its construction has been primarily based on domestic technology, including the manned cabin, buoyancy material, positioning sonar, thruster, hydraulic source, manipulator, and battery. In December 2018, the spherical shell of the manned cabin, made of titanium alloy, was constructed using the vacuum electron beam welding method, which was of international standard and greatly improved welding accuracy. The manned cabin is a core component of the submersible; it is independently developed and manufactured in China.

4 Key technologies and development trends

4.1 Analysis of the current situation of China’s submarine technology

Manned submersibles are critical components of deep-sea technology and equipment. Due to the long-term technological development and efficient conduction of critical tasks, especially the successful development and application of Jiaolong and Deep Sea Warrior, China’s manned deep-diving industry has established itself at the global forefront.

During the development of the two aforementioned manned submersibles, various breakthroughs were achieved in key technologies [10,11], including the overall optimization of the design and integration of manned submersibles, prediction and optimization of the hydrodynamic performance of complex linear underwater vehicles, overall layout of functional modularization or structural fragmentation of the vessels, unpowered submergence and ascent of the vehicles, design and manufacture of titanium-alloy spherical shells, use of high-energy-density deep-sea power, achievement of stable hovering and positioning of the operation target, human-centered information and automation systems, design of high-speed underwater acoustic communication and high-resolution sounding side-scan sonar, emergency safety and life support of deep-sea manned submersibles, light and miniaturized underwater motor, deep-sea high-pressure seawater pump and valve, design and manufacture of complex line type seawater high-pressure composite light shell, etc.

To achieve the aforementioned developments, select domestically manufactured technical units were organized to address fundamental problems. This led to critical breakthroughs in the field of manned deep-sea diving and promotion of technological developments in the field. For example, based on the innovations motivated by the development of Jiaolong, the following technologies were greatly improved in China: (1) manufacture of thick plates of high-strength titanium alloy, welding process of titanium alloys, manufacture and processing of buoyant materials based on glass beads and high-strength composite materials, etc.; (2) manufacture of deep-sea oil-filled silver zinc batteries, watertight cables, and connectors, development of high-performance deep-sea motors, etc.; (3) development of thrusters, hydraulic presses, water presses, communication systems, submersible control systems, etc. for deep-sea vehicles.

4.2 Core technologies

(1) Design optimization, safety assessment, and application of deep-diving technologies: These include optimization of the type line, general layout, and functional characteristics of manned submersibles, safe and reliable design of various deep-diving equipment and appropriate assessment technologies for their evaluation during their service periods, evaluation technologies for human factors engineering design, applications of manned submersible, and relevant design of specialized systems.

(2) Design, construction, and evaluation of manned cabins: These include the use of metallic and non-metallic materials, the shapes of manned cabins (spherical, cylindrical, etc.), the modes of construction for such cabins, their inspection following the completion of the construction, and their evaluation to ensure safety.

(3) Design of high-energy-density power sources: This includes design of oil-filled lithium batteries, construction and management of power sources, design of underwater fuel cells, assessment of underwater energy security, supplementing underwater energy sources, and development of new energy sources for deep-sea applications.

(4) Design of underwater acoustic technology: This includes integrated design of various acoustic equipment on submersibles, design of high-speed underwater acoustic communication systems, and manufacture of associated equipment.

(5) Development of navigation and positioning technology: This includes development of highly precise and highly reliable underwater acoustic positioning systems, enabling continuous high-precision navigation in complex underwater environments, and the development of underwater target search and operation point return technologies.

(6) Development of buoyancy materials: This includes the design, preparation, and construction of low density buoyancy materials capable of reaching great depths, and testing and safety evaluations of buoyancy materials.

(7) Development of security systems for manned submersibles: This includes design of technical security systems for manned submersibles, development of state detection and safety evaluation for submersibles, and reliable design and evaluation of various throwing mechanisms.

(8) Developing control systems for manned submersibles. This includes development of navigation control systems for manned submersibles in complex submarine environments, integration of visual displays with control systems, and simulation of operational scenarios for manned submersibles.

4.3 Advanced technological trends

In recent years, the injection of private capital has revitalized the research and development of manned submersibles in major maritime countries. Deep-sea manned submersibles and special manned submersibles remain the primary developmental directions in the industry. It can be predicted that the next 15 years will be a concentrated period of upgradation of equipment and technology associated with manned submersibles.

(1) Design and construction of non-metallic manned cabins has become a focus. As evidenced by Titan (Fig. 6), breakthroughs for manned cabins have focused on the use of new composite structures for the cylindrical pressure shell and the front and rear end covers made of titanium alloy, which positively impacts the vessel’s load-bearing capacity and weight reduction features.

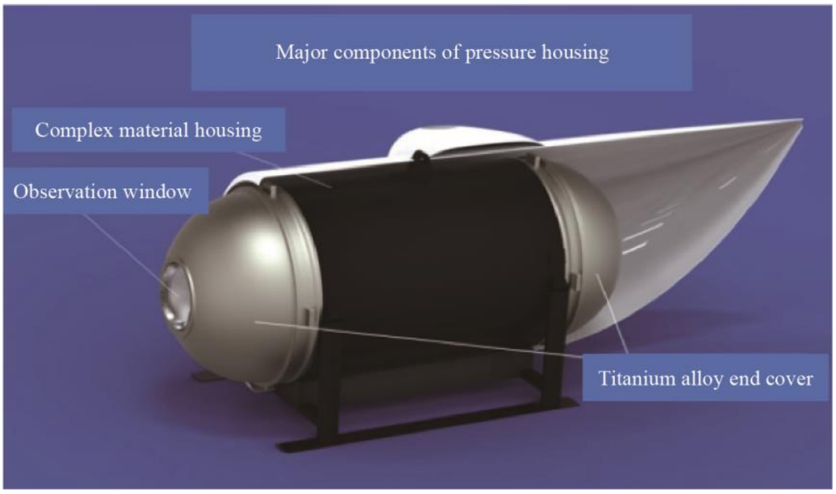

Fig. 6. Complex material pressure shell.

(2) Fully transparent materials have been widely used to construct windows with extended fields-of-views in manned submersibles meant for sightseeing operations (Fig. 7). The Aurora series, developed by SEAmagine, employs such windows and exhibits working depths of 1000 m.

DOI 10.15302/J-SSCAE-2019.06.017

Fig. 7. Fully transparent window with extended fields-of-view.

(3) High-speed and unpowered floatation of submarines has been primarily innovated based on hydrodynamic designs of vessels. The winged submersible developed by DeepFlight adopts the concept of “active buoyancy” (Fig. 8), which leverages the hydrodynamic force exerted on the wings to alter the underwater motion of the submersible. The Triton LF submersible adopts a vertical flat design with a large height-to-width ratio (Fig. 3), enabling it to reach the deepest parts of oceans in approximately 2.5 h.

Fig. 8. Novel shape in the design of submersibles.

(4) New high-density voltage-tolerant batteries have been developed by Spain and the U.S., which are capable of providing maintenance-free plug-and-play features in the deep sea with up to 4000 cycles.

(5) Multi-crew and multi-cabin layouts are being developed by Japan’s deep-sea manned submersible research program, capable of providing a comfortable riding experience and two-day mission time for six crew members, with designated resting and toilet spaces.

5 Conclusion

After nearly 20 years of development, China’s manned deep-sea diving project has established itself at the international forefront, with operational depths ranging between 4500 m and 7000 m. It has successfully created a technological system to support its deep-sea diving industry and obtained multiple independent intellectual property rights.

In the future, it is evident that China’s manned deep submergence technology will develop toward the pedigree of the whole sea. Relying on a new generation of manned submersible equipment, China plans to consolidate and improve its operational capacities in seas, rivers, reservoirs, oil and gas mines, and hydrothermal cold springs over the next 15 years, and effectively expand the scopes of search and salvage operations, archeology, tourism, exploration of polar areas, development of nuclear energy and other applications in the marine environment. At the same time, the country will continue to innovate the intelligent, lightweight, heavy-duty, and cluster coordinated manned submersibles, cultivate and enrich an industrial chain, and support the establishment of a premier maritime power.

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