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Overseas Trends in the Development of Human Occupied Deep Submersibles and a Proposal for Japan's Way to Take

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1 Introduction

Japan's human occupied deep submergence vehicle, the Shinkai 6500, is the only submersible in the world capable of diving to the maximum depth of 6500m. The Shinkai 6500 was launched in 1990, began research dives in 1991, and recorded her one-thousandth dive in March 2007. This submersible has produced a number of impressive achievements in research on the topography and geology of the ocean floor, life inhabiting the deep seas, among others, not only in the seas neighboring Japan, but in oceans around the world.[1] Moreover, use of this vehicle is not limited to specialized researchers; the Shinkai 6500 has also been made available to budding researchers aiming at future science and technology, and has won an outstanding reputation in this connection as well.[2]

Since the Shinkai 6500 was launched, a variety of improvements have been made in the vehicle, and various individual parts have been replaced with high performance components. As a result, it has continued to operate safely without serious problems, thereby contributing to the establishment of technologies for safety and reliability. Nevertheless, 20 years have already passed since the Shinkai 6500 was built. Aging and obsolescence of the system as a whole are progressing, and other countries are developing and building new human occupied vehicles (HOV) which can equal or exceed the maximum depth of the Shinkai 6500. At the same time, unoccupied submersible research vehicles are also under development or in operation. Thus, the time is fast approaching when Japan must examine the significance and proper form of HOV, including what type of vehicle should be built as a successor to the Shinkai 6500.

In addition to the Shinkai 6500, Japan formerly operated a 2000m class HOV called the Shinkai 2000. When the Shinkai 2000 was taken out of service in 2004, a discussion was held on the question of whether to continue to use HOV in deep-sea research in the future, or to use remote-controlled or autonomous unoccupied vehicles.[3,4] One side in this debate consisted of people who held that HOV are necessary and indispensable because researchers investigating deep-sea life rely on direct observation by the naked eye. The other side advocated using unoccupied vehicles with high performance cameras as a tool for wide-ranging observation. This group argued that, if the region that can be observed clearly is narrow and satisfactory observation is impossible, it would be possible to develop camera technologies that enable 3-dimensional observation and expanded observation in the depth direction. In this discussion, some also expressed the opinion that a true unoccupied vehicle would be a completely autonomous underwater vehicle with artificial intelligence. Thus, the argument extended as far as the definition of "human occupied." Ultimately, however, this discussion failed to clarify the basic issue of whether there is any significance, for the viewpoint of pure science or science and technology, in using HOV to conduct deep-sea research.

When the Shinkai 2000 was retired in 2004, her contribution to science and necessity of HOV was also the subject of a paper.[5] As reasons why HOV are necessary, one of the authors made the following arguments based on his own experience in dives. Firstly, he cited the acuity of the human eye, noting that it is impossible to reproduce the capabilities of the human eye with current technology. Secondly, he mentioned "intellectual curiosity," in other words, the notion that science will not progress without a thirst for knowledge. As 3rd and 4th points, he also mentioned a "feeling of presence" and the importance of the researcher's intuition. While these are undoubtedly essential conditions for scientists, we must also ask how important they actually are for progress in deep-sea pure science and science and technology. Many marine researchers hope to do research aboard HOV, and it is obvious that trouble in the current HOV would impede marine research. However, even if these researchers hope to see new HOV built, they themselves are not responsible for the building. Without a development budget, manufacturers cannot build these vehicles, and as time passes, it becomes difficult to maintain the technologies necessary for building.

Japan's Third Science and Technology Basic Plan mentioned "Development of human occupied submergence vehicle" as one national critical technology,[6] but, at present, this has not been adopted in next-generation deep-sea research technologies by the Ministry of Education, Culture, Sports, Science and Technology (MEXT).[7]

However, the time will soon come when Japan must consider whether HOV are necessary for humankind or not. While it may undoubtedly be true that deep-sea research is necessary for humankind, the question is whether HOV are necessary for Japan, and if so, is it necessary to develop new building technologies. In other words, is the form of HOV used to date adequate, and if not, what form should a new, next-generation HOV take? It is not too early to begin study of these fundamental questions.

Moreover, when the present generation of HOV was developed, built, and put into service, the technology for unoccupied vehicles was still immature. In recent years, the background of this argument has changed significantly as a result of the active use of unoccupied vehicles in deep-sea environments and remarkable progress in technical development. Because occupied and unoccupied vehicles have respective strengths and weaknesses, the division of roles must be clarified from the viewpoint of technical development and operation. A similar debate is also underway in the United States.[8]

This article considers trends in the development of deep-submersible HOVs in the United States and China and proposes the future direction for Japan to take. It would be too easy to say that Japan should develop a new HOV simply because other countries are doing so. Therefore, in this report, the author would like to review the evolution of HOV and examine the proper direction for Japan with regard to a next-generation HOV referring to this history.

2 Challenging the depths: An historical perspective

2-1 Nothing at abyssal depths?

Historically, humankind only recently acquired the ability to observe scientifically the underwater world.[9] Until the invention of the aquarium in England in the mid-19th century, pictures of sea life had, almost without exception, depicted either fish and whales swimming at the water surfaces, or desiccated bivalves, conchs, and other mollusks lying on beaches.[10] We could not begin to imagine the kinds of creatures that actually live in the world's oceans. Few if any believed that living organisms could exist at abyssal depths, and it was inconceivable that ocean floor crust is born in the abyssal fissures.

Until the middle of the 19th century, it had been thought that life could not exist in deep seas due to the extreme high pressure and utter darkness in such regions. However, dredging of the ocean floor using a tool attached to the end of a long chain revealed an astonishing variety of life. At the end of the 19th century, the English warship Challenger made a voyage which applied the scalpel of science to the deep sea for the first time, and discovered deep-sea life and manganese nodules. At the beginning of the 20th century, the great powers of Europe carried out marine research, laying the foundations for marine science which led to the present. From around the Second World War, science and technology, exemplified by underwater acoustic technology and electronics, were applied to marine research, particularly in the United States, and marine science entered a period of rapid progress.

2-2 Origin of "deep-submersible vehicles"

In 1930, the American biologist William Beebe descended to a depth of 428m in a steel sphere 1.4m in diameter (called a bathysphere) suspended from a wire rope. Beebe was the first human to observe fish and other diverse forms of deep-sea life with the naked eye. In 1934, he descended to a depth of 908m. However, the sphere itself weighed 2.5 tons, and even adjusting for buoyancy, it was necessary to suspend a weight of 1t from the wire. Thus, there was a constant danger that the wire might break, and the underwater observer was unable to move freely in the water. The HOV of this period is termed the "0 generation."

The "1st generation HOVs" were developed in response to the challenge of creating a maneuverable vehicle. In 1947, the Swiss physicist Auguste Piccard, who is known as the first person to reach the stratosphere in a balloon, invented the bathyscaphe (literally, "deep boat") based on the same principle as the balloon. To secure buoyancy in a pressure sphere (diameter: 2m) carrying a crew of two persons, the pressure sphere was mounted under a tank containing a large amount of gasoline. This 1st generation submersible maneuvered underwater using thrusters (propellers for movement). Applying this technology, the U.S. Navy built a 10,000m class bathyscaphe called the "Trieste," which set a record for a 10,906m dive in the Challenger Deep in the Mariana Trench. The crew for this memorable dive consisted of Auguste Piccard's son, Jacques Piccard, and Don Walsh of the U.S. Navy. The French Navy also built a similar bathyscaphe called the Archmede, which made dives in 1962 to a maximum depth of 9,545m in the Japan Trench and Kuril Trench. Tadayoshi Sasaki of Hokkaido University, who was a crew member on these dives, observed a continuous shower of organic detritus that had formed near the ocean surface sinking to the sea bottom, and named this phenomenon "marine snow."

Bathyscaphes, which enable relatively free movement underwater, require more than 100m^3 of gasoline, including an allowance for surfacing, and as much as 75t of buoyancy material for the 4t hull. The weight of the submersible in air exceeds 80t, making handling difficult and dangerous and maneuvering underwater relatively unresponsive. However, in spite of its slow movement, the fact that this submersible is capable of 10,000m class deep dives is a strong point of the 1st generation HOVs.

2-3 Period of development in deep-sea research

The 2nd generation of HOV was developed giving priority to underwater maneuvering performance. The basic technologies in this generation centered on the development of buoyancy materials, lightening of the pressure hull housing the crew, improvement of the power supply for underwater navigation, and establishment of safety measure technologies. Descent/ascent of HOV is controlled by adjusting the weight of the vessel in the water. Fundamentally, the vessel is manufactured to be heavier than seawater, and is then made lighter than seawater by attaching a large amount of buoyancy material. The vessels are loaded with weights, or ballast, to enable descent. At the sea bottom, a condition of neutral buoyancy, in which the vessel neither sinks nor rises, is achieved by releasing some of the ballast, and the vertical movement necessary for work is achieved using the force of the thrusters. When work is completed, the remaining ballast is released, allowing the vessel to surface. During this period, the buoyancy material must resist crushing regardless of the circumstances.

The 1st generation Alvin was built in the United States in 1964. At the time of building, its maximum depth was 1800m. For the buoyancy material, syntactic foam was developed as a replacement for gasoline. This is a molded material in which glass micro-spheres with a size of several 10μm are embedded in resin. A small-scale, lightweight submersible with a weight on the order of 15t was developed, making it possible to transport the submersible to the intended destination on a dedicated mother vessel rather than by tugboat, as in the conventional practice. This established today's operating practice in which the submersible was launched/recovered at the site.

This technical development greatly expanded the operating range and improved the operational efficiency of the HOV used in scientific research. To date, 2nd generation HOVs include the original Alvin in the U.S. (maximum depth: 4,500m, operated by the Woods Hole Oceanographic Institution), Japan's Shinkai 2000 (2000m class; taken out of service and retired in 2004) and Shinkai 6500 (maximum depth: 6500m; operated by the Japan Agency for Marine-Earth Science and Technology:JAMSTEC), France's Nautile (6000m class; operated by the French Research Institute for Exploitation of the Sea:IFREMER), and Russia's two Mir submersibles (6000m class).

In this generation of HOV, the focus shifted from competition to achieve the greatest depth to scientific research and investigation of resources. Because a maximum depth of 6000m enables scientific research covering 95% of the world's oceans and manganese nodules, which are considered a promising resource for future development, are found at depths of 4000-6000m, the maximum depths of many submersibles has been set at 6000m (Figure 1).

Table 1 presents an outline of the performance of the world's main deep-submersible HOVs in active use at present. Japan's Shinkai 6500 was built in the 1980s, which was a period when several countries were actively developing 6000m class HOVs.[11] Although HOV of this class had been proposed in the 1970s, the risk of moving directly to the building of a 6000m

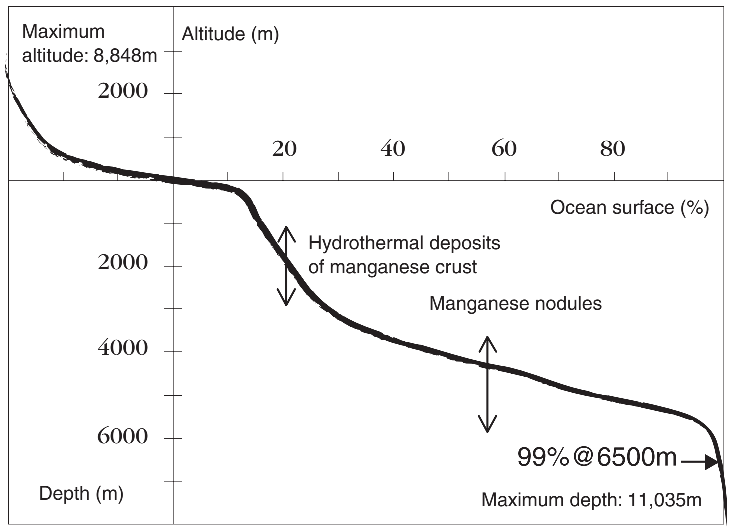


Figure 1 : Distribution of earth's altitude/depth and range of distribution of seafloor mineral resources

Table 1 : World's main human occupied vehicles (HOV)

Vehicle (country)	Alvin (US)	Nautile (France)	Mir 1 & 2 (Russia)	Shinkai 6500 (Japan)
Maximum depth [m]	4,500	6,000	6,000	6,500
Ocean coverage [%]	62%	98%	98%	99%
Dives/year	180	100-115	Irregular (low frequency)	60
Researchers/pilot	2 / 1	1 / 2	Total 3	1 / 2
Bottom time [hr]	4~5	5	10 ~ 15	4
Payload [kg]*	680	200	250	150
Sphere volume [m^3]	4.07	4.84	4.84	4.19
Observation directions	Side/down	Front/center	Front/center	Side/down
Year built	1964	1985	1987	1987

*Payload: Total weight of equipment carried aboard by researchers for scientific research and samples taken during dive.

class vessel using unproven technology was considered unacceptable. First, therefore, Japan developed and built the Shinkai 2000 in order to establish the building technology and navigation technology. Based on the know-how obtained with the Shinkai 2000 and progress in related technologies, beginning with the manufacture of titanium pressure hulls, the Shinkai 6500 HOV, with a maximum depth of 6500m, was developed and built in the 1980s and put into service in 1990. Research dives began in 1991. A variety of the most advanced technologies of the time were incorporated in the Shinkai 6500 to ensure safe navigation, including acrylic resin viewports[12] which enable the pilot and researchers to view the sea outside the pressure hull, an underwater telephone system that allows communication between the deep sea and mother ship on the surface, and an acoustic observation sonar system for locating obstacles underwater, where visibility is limited to only about 10m.

2-4 Achievements of deep-submersible HOVs

Operation of 2nd generation deep-submersible HOVs resulted in numerous achievements in pure science and science and technology.

In the field of resource surveys, hydrothermal deposits had been discovered successively along the mid-oceanic ridge in the Pacific Ocean, but no similar deposits had been found in the Atlantic mid-oceanic ridge. However, in 1986, scientists aboard the Alvin discovered hydrothermal deposits in the TAG ocean area*1 on the Atlantic mid-oceanic ridge. In 1991, Russian and American scientists aboard the Russian HOV Mir discovered the largest scale hydrothermal deposit in the Atlantic, which they named Mir. Following this, a large number of other hydrothermal deposits were also discovered. On the other hand, in research on deep-sea life, in 1992, a Japanese scientist aboard the Shinkai 6500 discovered whale bones with adhering shells and shrimp at 4146m in the Torishima area. In 1994, Russian scientists discovered a large number of hydrothermal organisms in the Atlantic Ocean, and in 1995, Japanese researchers discovered deep-sea chemotrophic life forms in the Okushiri-oki area (off Okushiri Island near Hokkaido, northern Japan). In deep-sea geology, the Shinkai 6500 discovered a fissure on a sloping surface at 6200m in the Japan Trench.

HOVs have also responded to a number of emergencies. For example, in 1966, the 1st generation Alvin successfully recovered a hydrogen bomb which had been lost by the U.S. military at a depth of 914m off the Spanish coast. Following the Challenger space shuttle disaster in 1986, three HOVs and one unoccupied vehicle recovered a 50t fragment of the shuttle, and in 1989, the Mir sampled sea bottom sediments and measured radioactivity after the sinking of the former Soviet Union's nuclear submarine Kursk, and carried out work to seal the ship's bow in order to prevent leaks of radioactivity.

3 Development trends in HOV in the United States

3-1 Future plans for deep submergence science in the U.S.

In 2004, the U.S. Committee on Future Needs in Deep Submergence Science issued a report on "Occupied and Unoccupied Vehicles in Basic Ocean Research."[8] The report summarized how the United States as a nation should direct its future efforts in research on deep submergence science*2, and examined the proper form of deep submersibles, including the necessary human occupied and unoccupied vehicles. Subsequently, in accordance with the recommendations of the Committee, the U.S. began development of a successor submersible to the current Alvin as an HOV, and is also developing an 11,000m class hybrid as an unoccupied vehicle. This hybrid will be a vehicle combining the two modes of remotely operated vehicle (ROV) and autonomous underwater vehicle (AUV).

The above-mentioned Committee was established at the request of the National Science Foundation (NSF), representing scientific research, the National Oceanic and Atmospheric Administration (NOAA), representing marine research projects, and the U.S. Navy. The Committee's study objectives were to evaluate the future image and required equipments for deep submergence science, and to evaluate the feasibility of technologies supporting basic research in deep sea and seafloor areas. The concrete content studied comprised the following items:

(1) valuation of the performance of occupied and unoccupied vehicles currently in use or under study.
(2) Recommendations on integrated use of research equipment for ongoing implementation of world standard deep submergence scientific research.
(3) Study of innovative design concepts and new technologies which should be incorporated in research equipment in order to meet future research needs.

The following four recommendations were presented as a result of study of the development of new vehicles.

(Recommendation 1)

The NSF's Division of Ocean Sciences should build a new unoccupied vehicle for use in scientific research. This will increase the number of deep submergence vehicles contributing to the research activities of a large number of users in diverse research fields and marine geographies.

(Recommendation 2)

The NSF's Division of Ocean Sciences should study the distribution of new unoccupied vehicles so as to minimize the movement time required for periodic inspections and improvements of new and current unoccupied vehicles.

(Recommendation 3)

Unoccupied vehicles are the optimum alternative for investigation of the ocean floor. Considering cost and risk, HOV cannot be used in research at depths greater than 6500m. However, manned research is key to national oceanographic research, and HOV enable direct observation. The current Alvin is inadequate for many of the requirements of scientific research. Accordingly, the NSF's Division of Ocean Sciences should build a new type of HOV with improved functions. (Improvement of functions means improvement of field-of-view performance, expansion of the neutral buoyancy control function and scientific payload, extension of time at working depth, etc.)

(Recommendation 4)

Accordingly, if a new HOV capable of diving to great depths (exceeding 6000m) is to be built, this should be limited to cases in which it can be demonstrated, in the design stage, that there will be no large increase in cost or risk.

3-2 Policy for building of new type HOV

Based on the recommendations in the above-mentioned Committee on Future Needs in Deep Submergence Science, the United States will study concrete policies for the building of a new type of HOV. Before arriving at its recommendations, the fact that a new type of HOV had been studied since 1999, centering on the Woods Hole Oceanographic Institution, was explained in detail. In this process, an 11,000m class all-depth HOV capable of diving to the deepest ocean depths on the planet was also studied. However, it became clear that building of such a vehicle was impossible within a timeframe of several years and with the limited budget available, and because the weight of the submersible would far exceed the capacity of current mother ships (because weight increases by a corresponding amount when the pressure is double that of the 6000m class). Furthermore, the possibility of manufacturing buoyancy materials, batteries, and electronic devices which would retain their integrity at this depth was unclear. Whether human beings could withstand such depths was also unknown. Even assuming that all these conditions could be met, the lack of testing equipment to verify this fact was also a problem. For these reasons, the all-depth HOV was excluded from study. On the other hand, a proposal to improve the current 4500m class Alvin to the 6000m class was also examined, but it was concluded that the improved submersible would not adequately satisfy the needs of deep submergence science. Finally, therefore, this study recommended a new type of HOV that could be built within the budgetary limitations. The following five items were recommended as specific functions which should be incorporated in the new type of HOV.

a) Improvement in the performance of the variable ballast device: In order to conduct research while hovering at intermediate depths, continuous adjustment of the balance of buoyancy and weight must be possible; this is the most important issue for a new type of HOV.

b) Development of a non-mercury attitude control system (trim system): In the current Alvin, attitude is controlled using a mercury-type system; however, for environmental reasons, use of mercury is undesirable.
c) Electronic devices/tools compatible with a 7000m class new type unoccupied vehicle: This is important for commonality between platforms.
d) Use of optical fiber cable: Continuous data transmission from the HOV (status of research, transmission of video images to other researchers, maneuvering data, etc.) should be possible; use of optical fiber cable is also necessary in order to control cameras and other equipment from the ship.
e) System for designating targets for video cameras on ship: This system should enable designation, positioning, and tracking of target objects by tracking eye movements.

Next, the pressure hull carrying the crew was studied. This is an important item for the cost evaluation of the new type of HOV. The current Alvin in the U.S. was built in the 1970s, and the U.S. no longer possesses the equipment and welding techniques necessary to manufacture the titanium spherical pressure hull used in that vehicle. At the present point in time, only Russia and Japan possess the necessary technologies. Improvement of the pressure hull of the current Alvin was also studied. From the viewpoint of cost, this is the most realistic alternative. However, the diving depth would be limited to the current 4500m, and there was also concern that capabilities would be substantially reduced from the present level. Based on this study, building of a new titanium hull was considered a desirable alternative for improving the scientific research capabilities of the vehicle, for example, by increasing the maximum depth, changing the position of the window, etc. However, after further study and evaluation of manufacturing technology and cost, it was concluded that an HOV with a maximum depth of 6000m or more should be built, provided that manufacture appeared possible.

3-3 Specifications and technologies of new Alvin

Various organizations involved in ocean science and other interested parties in the U.S. had studied the necessity of HOV since 1999. Finally, in 2004, the researchers at the Woods Hole Oceanographic Institution proposed a 6500m class submersible as an alternative to the Alvin.[13,14] It can be thought that the plan to replace the Alvin with a new 6500m class submersible was adopted not only due to a desire to upgrade the research capabilities of the current Alvin, but also as a response to the retirement of the 6000m class submersible Sea Cliff (1984), which had been operated by the U.S. Navy.

Table 2 shows a comparison of the specifications of the new Alvin and the current Alvin. Figure 2 shows the assumed appearance of the new submersible. The design issues and results of conceptual design of the new Alvin are discussed in the following sections (1) through (8).

(1) Maximum depth

Maximum depth is the most important design parameter. In the United States, the debate on this issue was similar to that when Japan studied the Shinkai 6500, and the target depth was ultimately set at 6500m, as this makes it possible to reach 99% of the planet's ocean floor. Likewise, where technical limitations are concerned, lightweight buoyancy materials which can be used with confidence to 6500m are available, but at greater depths, the specific gravity of the buoyancy materials increases and the size and weight of the submersible increases significantly. As problems, this reduces maneuverability and makes it impossible to use the current support ships.

(2) Pressure hull

The pressure hull carries a pilot and two researchers, and must provide space for maneuvering of the submersible, observation, operations involved in taking samples, and the like. Therefore, the capacity of the submersible was increased by enlarging the diameter of the current Alvin 6.3%. This improves livability and secures space for internal electronic devices and equipment carried into the vehicle.

Several materials were reportedly studied for the spherical hull. Superhard maraging steel, which was used in Russia's Mir submersibles, is a cast steel with a high content of nickel. Its

Table 2 : Comparison of specifications of the new Alvin and current Alvin

	New Alvin	Current Alvin
Operating depth (ocean coverage)	6500m (99%)	4500m (63%)
Dimensions (L*B*D)	ND (smaller than existing Alvin)	7.3 * 2.6 * 3.7m
Weight	18 ton	17 ton
Sphere material	Ti 6 Al 4 V-EL I	Ti 621/ 0.8 Mo
Sphere inner diameter/volume	2.10m /4.84m^3	1.98m /4.07m^3
No. of viewports	5	3
Crew	Pilot: 1, researchers: 2	Pilot: 1, researchers: 2
Underwater operating time	10.5H	9H (approx.)
Propulsion system (thrusters)	Forward/reverse, vertical: 2; horizontal: 2	Forward/reverse, vertical: 2; horizontal: 1
Speed (forward/reverse)	3 kt	2 kt
Speed (vertical)	44 m/min	30 m/min
Trim angle	±15°	±7.5°
Payload	181 kg	125 kg
Positional control	Automatic position/azimuth control	Manual & azimuth control
Battery capacity	115kWh (approx.)	35 kWh
Descent/ascent method	Seawater ballast	Iron drop weight

strength is comparable to that of titanium, but as a drawback, it is susceptible to corrosion in seawater. The 611 titanium used in the U.S. submersibles Alvin and Sea Cliff are not generally used at present. Finally, the 6-4 titanium used in Japan's Shinkai 6500 and France's Nautile was selected. (Ti6Al4V-ELI: This material is an alloy containing 6% aluminum and 4% vanadium; ELI (extremely low interstitial) relates to the extremely low oxygen content, which secures excellent weldability.)

The number of viewports was also increased from the conventional three to five. The three windows on the forward side are arranged in close proximity so the pilot in the center and researchers on the right and left sides share a common field of view. The two windows on the sides allow the pilot to see to the sides without interfering with the researchers, enabling safe maneuvering without sacrificing observation.

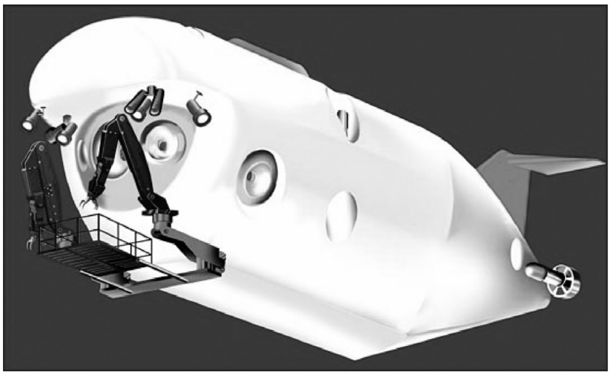


Figure 2 : An artist's conceptual drawing of the New Alvin (US)

From the Woods Hole Oceanographic Institution homepage, May 7, 2007.

(3) Buoyancy material

Buoyancy material is an essential component for securing the buoyancy of the submersible in the deep sea, and is also a controlling factor determining the weight and size of the submersible. The specific gravity of the buoyancy material used in the current Alvin is 0.577, but this was considered too large for the new submersible. The buoyancy material developed for use in unoccupied vehicles has a specific gravity of 0.481 and was the lightest weight material which could be used at a depth of 6500m at the time of the study. Subsequently, development of a buoyancy material with a specific gravity of 0.481 was completed, and further weight reduction is being attempted.

(4) Variable ballast

Ballast refers to water or other substances which are loaded on a ship as weight to improve stability. HOVs also use a variable ballast system in which the weight of the vessel is adjusted by controlling the amount of water in the ballast tanks. Ballast control as three object functions: (a) To secure the weight and buoyancy necessary for descent and ascent, respectively, (b) to compensate for changes in weight when samples are taken during a dive, and (c) to adjust the trim angle in order to increase the rate of ascent or descent. ("Trim" is the bow-to-stern inclination, or attitude, of the submersible.)

Ballast tanks are manufactured in the form of titanium spheres in order to withstand the external pressure at a depth of 6500m while maintaining an internal pressure of 1atm. The submersible begins the dive with its ballast tanks filled with the prescribed amount of seawater. During the dive, seawater is discharged or taken in as required by two pumps. This makes it possible to stop the submersible at arbitrary intermediate depths and conduct observations. A trial calculation has shown that the rate of descent/ascent is 30m/min with a trim angle of 15° and 45m/min at 25°. Assuming a descent rate of 45m/min, it is possible to reach an ocean floor with a depth of 6500m in 2 1/2 hours. It may be noted that the trim angle of the submersible is not adjusted using the ballast alone; it is also possible to move the batteries and weights forward or aft in order to control trim. This weight can also be jettisoned in the event that emergency surfacing is necessary.

(5) Propulsion system

The submersible is equipped with an advanced propulsion system which enables forward/reverse and lateral movement. The propulsion system comprises a total of six reversible electric thrusters. Two thrusters are provided at the stern for forward/reverse movement. For lateral movement and turning, one horizontal thruster is installed at each of the bow and stern, and for vertical motion, one vertical thruster is installed each at the right and left sides. It is possible to maintain the designated position and orientation, depth, and attitude by manipulating these devices. The position maintenance and maneuvering system using these thrusters is the same as that developed for unoccupied vehicles.

(6) Power supply

As the power supply, lithium ion batteries were considered the optimum choice from the viewpoint of energy density and life. Among these, attention was focused on lithium-polymer batteries, as these can be housed in an oil pressure-equalizing vessel. This type of battery has been used in autonomous intelligent underwater vehicles and is considered to have a life of more than 5 years. Fuel cells were excluded from study, as this technology is considered to be in the developmental stage.

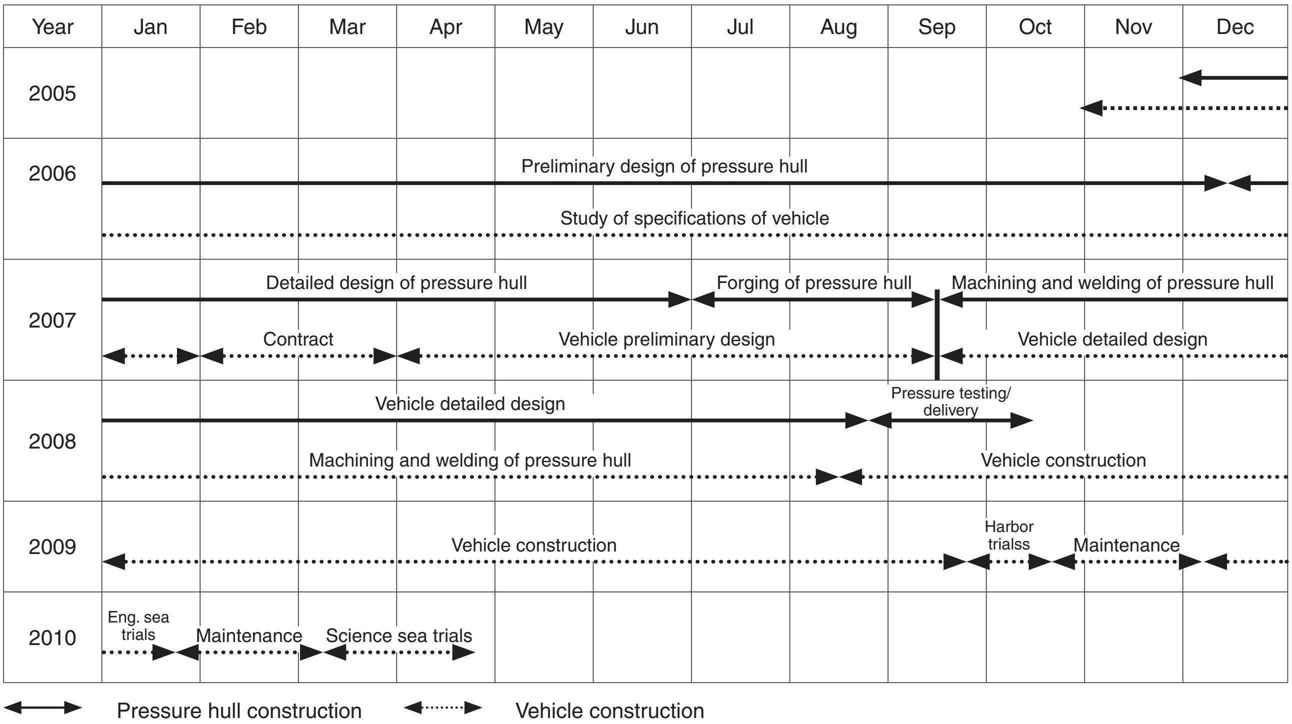
(7) Safety measures

Safety measures comply with U.S. ship classification rules. Provisions include manipulators and weights that can be jettisoned in case of emergency, minimization of the risk of entanglement, improvement of the life support capacity, and others. Because the new submersible employs the variable ballast system in descent/ascent, jettisonable weight for emergency surfacing is provided as a safety measure in case of failure of the ballast system pumps or batteries, and adequate buoyancy is secured. A device for emergency recovery of the submersible is also provided on the supporting mother ship.

(8) Scientific research equipment

Power for the manipulators and various scientific research equipments is provide by a hydraulic system rated at 20.7MPa × 9.5l/min, realizing an improvement of more than 90% in comparison with the performance of the current Alvin. The new submersible has two manipulators, which are mounted on extensible bases. A large sample basket is provided in the center, and rotatable baskets are provided on the vessel's two sides. The TV camera system comprises two high resolution cameras with zoom which can be controlled by the two observers, making it possible to obtain high quality video images. Panoramic TV camera and compact camera mounted on the manipulators are also equipped. Lighting is provided by a combination of high output HMI lights and compact xenon lamps. As an advantage of the xenon lamps, these devices can be turned on and off without warm-up and thus provide a high degree of freedom. For observation under the

Table 3 : Schedule for replacement HOV update in US (as of Sept. 25, 2006)



Prepared by the STFC based on Reference [15].

vessel, the submersible is equipped with sonar for research on seafloor.

The submersible and supporting mother ship communicate by means of an audio modem. The modem has a transmission rate of 7000bps and can transmit a standard quality jpeg image in 8 seconds. When an image is received on the mother ship, the compressed data are decompressed by a dedicated computer and can be used on the ship-board network. The submersible and mother ship are also joined by a small-diameter optical fiber cable, enabling real time communication between them. This allows scientists on the mother ship to participate and cooperate in research. Assuming use of satellite communications, participation from land will also be possible, enabling use of marine research in education, etc. This is also expected to be used to promote public understanding of science and technology.

3-4 Building schedule of new Alvin

Building of the new Alvin began in the fall of 2005 and entered the transition stage from Phase 1 to Phase 2 in the fall of 2007. Work in Phase I included design of the pressure hull and basic design of the boat hull. In Phase 2, the makers responsible for building will be decided and work on the pressure hull will move to fabrication, welding, and pressure testing, while hull-related work will move to detailed design and construction (Table 3).

3-5 Position of HOVs in the U.S.

The United States has established a basic policy of comprehensive operation of HOVs and unoccupied ROV/AUV for research in deep-sea science, and is implementing plans for development and building along these lines. As an HOV, a 6500m class new Alvin will be built, and as an unoccupied vehicle, an 11,000m class hybrid system will be developed. Depending on the purpose of the investigation, the unoccupied hybrid system will have an autonomous-type intelligent underwater robot mode for wide area mapping, etc., and a remote control-type unoccupied research mode for use when detailed, pinpoint research is necessary.

In the development of unoccupied submersibles, the U.S. is undertaking the challenge of new technologies such as use of seamless ceramic hollow balls as buoyancy material. However, the HOV is being built as a synthesis of conventional deep-submergence science and technology. As the reason for this, the U.S. is developing an HOV and unoccupied vehicle in parallel, and in particular, time and budgets leave no room for the development of new technologies for the HOV. There will be no feedback of new technologies obtained in the development of the unoccupied vehicle to the HOV.

Where this point is concerned, although the new HOV now being built in the U.S. will have the capability to investigate ecosystems while hovering at intermediate depths, and will enable comparatively rapid diving and surfacing, the basic concept does not represent an advance beyond the 2nd generation.

4 Trends in the development of HOV in China

4-1 Outline of 7000m HOV

An article distributed by China's Xinhua News Agency on February 2, 2007 announced that China will launch an independently-developed 7000m HOV in 2007 (Figure 3). This project is being carried out as part of the National High-Tech R&D Program (commonly known as the "863 Program") under the country's 10th 5-Year Plan (2006-2010). In September 2006, China announced that the submersible was already in the assembly stage. Experimental operation of the submersible at sea had been scheduled for completion within the period of the 10th 5-Year Plan. However, according to the article of Feb. 2007, "China has developed a submersible capable of covering 99.8% of the world's ocean floor, and is aiming at completion in 2008."

4-2 Performance of 7000m HOV

Although this submersible is being assembled in China, Russia was responsible for production of the pressure hull and life support system. The cost of building is put at 180 million yuan, or approximately US$25 million. The performance of the 7000m HOV is described in the following sections (1) through (5).[16]

Figure 3 : Model of China's 7000m HOV

Source: Beijing Daily, January 31, 2007

(1) 99.8% coverage of world's oceans

Table 4 shows a comparison of the specifications of China's 7000m HOV and the Shinkai 6500. The maximum depth of China's HOV is 7000m, which gives it a diving range covering 99.8% of the world's ocean floor. By comparison, the Shinkai 6500 has a maximum depth of 6500m, giving it a diving range of 98%. The hull dimensions of the Chinese vehicle are somewhat shorter and slightly broader than those of the Shinkai 6500. While its weight is slightly lighter than that of the Shinkai 6500, it is quite heavy in comparison with Russia's Mir (18.6t). Unlike the Mir, there is no equipment for launching or recovery on the broadside of the vehicle, and the size and stern arrangement of these equipments are expected to resemble those of the Shinkai 6500.

Table 4 : Basic specifications of China's 7000m HOV

	China 7000	Shinkai 6500
Operating depth [m]	7000	6500
Researchers/pilot	2/1	1/2
Total length [m]	8.2	9.5
Total height [m]	3.4	3.2
Total width [m]	3.0	2.7
Weight in air [ton]	25.0	25.8
Sphere material	Titanium alloy	Titanium alloy
Sphere inner diameter [m]	2.1	2.0
Viewport diameter [mm]		
Center: 1	200	120
Side: 2	120	120
Life support duration [H]	84	128
Maximum speed [kt]	2.5	2.5
Payload [kg]	220	200
Batteries:		
Type	Silver oxide-zinc	Lithium ion
Capacity [kWh]	110.0	86.4
Underwater working time [H]	6	4

(2) Russian-made pressure hull

The pressure hull, which will hold one pilot and two researchers, is constructed of a 6-4 titanium alloy and has an inner diameter of 2.1m. The plate thickness is 76-78mm, with deviations of ±4mm in the completed radius, and sphericity is 0.4% or less. The pressure hull of the Shinkai 6500 is a titanium alloy 2.0m in inner diameter, the plate thickness is 73.5mm, and error in the diameter is 0.5mm, giving it sphericity of 0.025%. In comparison with the Shinkai 6500, the diameter is 5% larger, but the plate thickness is only about 3% greater and sphericity is also relatively poor. This notwithstanding, the diving depth of the new Chinese submersible is 8% greater.

According to the literature,[3] the pressure hull was manufactured by a Russian maker which also manufactured the Mir 6000m class HOV (nickel steel) and a new 6000m class HOV called the Consul (titanium alloy), which was built around the year 2000. The manufacturing method for the pressure hull involves producing two hemispherical parts by TIG welding*3 6 side plates to a top plate, followed by heat treatment and polishing by machining; the two halves are then joined by TIG welding to form a complete sphere. Pressure tests were also performed in Russia, and included a 1 hour test at a water pressure equivalent to 7700m, or a 10% greater depth than the vessel's 7000m maximum depth, a continuous 8 hour test at water pressure equivalent to 7000m, and a test simulating 0-7000m ascent/descent of the submersible, which was repeated 6 times. No problems were reported in any of these tests.

The viewports in the pressure hull have a circular truncated cone shape. One central viewport with an inner diameter of 20cm and two side ports with inner diameters of 12cm are provided. The central viewport is considerable larger than that of the Shinkai 6500 (12cm), and is the same type as that used in the Russian Mir. The two side windows are arranged closer to the front than in the Shinkai 6500 and Alvin. This design has the advantage of enabling navigation while both the pilot and the scientists simultaneously observe an objective in front of the vehicle. However, safety is reduced, as it is not possible to see dangers on the sides.

(3) Smart propulsion and navigating system

In HOVs, an arrangement of several thrusters is used to move forward and turn the vehicle's head to the sides and vertically. The Chinese 7000m HOV has a teardrop shape tapering toward the stern and four tail fins which form an X shape. Four main thrusters inclined in a narrowing shape are mounted in the spaces between the four fins. Although the four thrusters are not movable, it is possible not only to move forward/backward, but also to turn horizontally and vertically, by composing the propulsive force of these four thrusters. This main thruster system is based on the same design concept as that in the Russian Mir submersibles, and is different from that used in the Shinkai 6500, which is turned by swinging the large main thrusters to the right or left. Side thrusters are also mounted on the front of the vessel's hull. One horizontal thruster is mounted on the top of the bow (same arrangement as in the Nautile and Shinkai 6500), and thrusters for vertical/horizontal turning and aiding propulsion are provided on the two sides of the hull (same as in the Mir and Shinkai 2000). Parallel movement in the horizontal direction is achieved using a combination of the horizontal thruster on the bow and the right and left stern thrusters, while vertical movement uses a combination of the bow side thrusters and the top and bottom stern thrusters.

(4) Other technologies

Silver oxide-zinc batteries are used. The battery capacity is 110kWH (110V, 800AH), which is approximately 30% larger than in the Shinkai 6500. Maximum continuous dive/working time is 6 hours, which greatly exceeds that of the Shinkai 6500. A pair of manipulators for use in taking samples from the ocean floor are mounted on the right and left sides of the vehicle. These devices have joints with 7 degrees of freedom. While it is possible to transmit images to the mother ship, the transmission rate is only 80kbps, compared to 100Mbps in ordinary internet transmissions. Thus, transmission of a color image requires approximately 30sec. A syntactic foam manufactured in the United Kingdom is expected to be used as the buoyancy material. As noted previously, this type of material consists of glass micro-spheres embedded in resin.

4-3 Significance of the Chinese HOV

The core technologies for deep-submersible HOV are a three-point set comprising the pressure hull, buoyancy material, and power supply. However, in addition to these, operation becomes possible only after integrating a diverse range of technologies related to maneuvering, observation, collection of samples, safety, and others. The most important objective in China's development of a HOV is generally considered to be acquisition of military technology. The country also appears to be planning exploration for marine resources and similar activities. Although one feels that China has little interest in contributing to marine science, future operation may have an indirect effect in this connection. As an element in technical development, this project has also given Russia an opportunity to develop a 7000m pressure hull, which significantly exceeds the 6500m class.

Regarding the technical level of the HOV, the target of achieving the world's deepest maximum depth in an 2nd generation HOV is quite obvious. However, when considering the ideal form of a next-generation HOV, there appears to be little that Japan can learn from this Chinese HOV, either in terms of pure science or science and technology.

5 Future direction of deep-submersible HOV development in Japan

5-1 History of development of deep-submersible HOVs

Japan began development of human occupied deep-submersible research submersibles around 1965.[17] In October 1963, the issue was submitted to the Council for Marine Science and Technology, and a 5-Year Plan was drafted envisioning a timeframe extending approximately 10 years into the future. Under this plan, active promotion of marine development was adopted as a national policy and the development of the marine science and technology which is indispensable as the basis for this was made a priority target. At the time, the United States was already conducting wide-ranging research and development as part of plan for development of a 6000m class vehicle. Ultimately, a 6000m submersible was not realized in the United States due to domestic circumstances. In Japan, the target depth for the submersible research vehicle was set at 6000m in response to the issue put before the above-mentioned Council for Marine Science and Technology, based on the fact that a submersible capable of reaching this depth can cover 95% of the world's oceans, and large numbers of manganese nodules, which were considered a promising resource for future development at the time, exist at depths of 4000-6000m. The necessary technical development tasks included the structure, material, and fabrication method for the pressure hull, buoyancy material, power system, position measurement system, various types of research equipment, and others. In addition, it was also considered necessary to construct a water basin for high pressure testing.

The thinking on the necessity of a deep submersible was exemplified by the following comments by the late Kenji Okumura,[18] who was involved in research and development during this period: "In marine development, a system engineering approach which integrates a wide range of science and technology is particularly important. Various types of science and devices must be developed as an optimized system for achieving a single goal. Japan has a high level of marine science, but we have not adequately investigated the science and technology in other countries. Our knowledge is slight, and we must carry out development in the future. A deep submersible will open a window on the deep sea, which is the most delayed area of marine development, and will lay the foundation for marine development in the future."

In 1970, the Japanese Marine Equipment Development Association (now Japanese Marine Equipment Association) established a "6000m Class Deep-submersible Research Vehicle Developmental Research Committee" and began joint research and development with shipbuilders over a 5-year period. This resulted in the elucidation of the mechanism of destruction of the spherical hull, which is the core technology for the development of a 6000m class deep submersible, and the establishment of design guidelines for this key component. These achievements played a major role in the subsequent development of the Shinkai 2000 and Shinkai 6500.

In the development of the Shinkai 6500, the original maximum depth was increased from 6000m to 6500m. The target depth was set at 6500m or greater based on the fact that the epicenter of the Sanriku-oki Earthquake was in an area of the Japan Trench with a depth of 6000-6500m. However, the safety factor of the pressure hull is "1.5 times dive depth + 300m," which indicate the maximum depth of 6700m. Moreover, the standards for various types of equipment also specify a depth of approximately 6700m. Because there were numerous items which failed in pressure tests when the conditions exceeded 6500m, the maximum depth was finally set at 6500m.[19]

5-2 Operation and achievements of HOVs in Japan

One point which requires care when studying the achievements of HOVs is the fact that the achievements attributable to "manned" and those due to "HOV" still constitute a single entity. This is because "submersible research vehicle" was synonymous with "HOV" until recent years. Today, numerous unoccupied vehicles have also made achievements. Nevertheless, in observation of movement of living organisms and discovery of anomalies in the seafloor topography, it must be noted that there are many cases in which results were obtained by tracking research which depends on the scientist's awareness of changing conditions. Furthermore, because the HOVs developed to date have been unable to hover at intermediate depths, few accomplishments have been made in this area. This is a challenge for the future.

The Shinkai 6500 made its maiden dive in June 1990. Table 5 shows main dives and results. The Shinkai 6500 has recorded many important achievements which take advantage of the world's deepest diving capability, including the discovery of a biotic community in the world's deepest cold seep (6374m) at the Japan Trench in the Sanriku-oki area, the discovery of a new type of barophilic bacteria adapted favorably to a high pressure environment at a depth of 6500m, the world's first confirmation of a fissure thought to be caused by plate subduction, and others. In March 2007, it recorded its 1000th dive. Moreover, the activities of the Shinkai 6500 are not limited to the seas surrounding Japan; it has also been used in research on seafloor topography/geology and life inhabiting in the deep ocean in the Pacific, Atlantic, and Indian Oceans. The purposes of this research may be summarized in the following four broad fields.

(1) History of the planet (research on geological processes)

Today's understanding of the planet is that oceanic plates are born at oceanic ridges and undergo subduction at trenches. The continents consist mainly of comparatively light granite and have an average height on the order of 840m. In contrast, oceanic plates are made up of comparatively black, heavy basalt and have a depth of 4000-5000m. Thus, the differences between continents and oceans are not merely topographical; structurally, the two are also completely different. Oceanic plates are underlain by the earth's mantle. In the mantle, hot, lighter-weight substances rise as by convection, while the plates, which have cooled and become heavier, sink to the bottom of the mantle. The oceanic crust and continental crust collide, accumulating energy in the form of strain. Gigantic earthquakes occur when this energy is released suddenly. Geological processes are being elucidated by seafloor observation and research on various phenomena caused by these movements of the earth's interior.

(2) Evolution of life

On land and in the surface layer of the ocean, solar energy and carbon are fundamental to the main life forms of both animals and plants. However, deep sea research has revealed that chemotrophic bacteria which synthesize organic substances using hydrogen sulfide and methane contained in seawater vented from

Table 5 : Main achievements of the Shinkai 6500

August 1989	Recorded dive depth of 6,572m in sea trials.
May 1991	First research dive (Okushiri Ridge, Sea of Japan)
July 1991	Discovered world's deepest cold seep community in Sanriku-oki area, Japan Trench (6,384m).
	Discovered new type of barophilc bacteria on the ocean-side slope in Sanriku-oki area, Japan Trench (6,500m).
	Discovered plate fissure in Sanriku-oki area, Japan Trench (6,270m).
August-November 1991	Joint Japanese-French research at North Fiji Basin, Pacific Ocean. • Seafloor plain of pillow lava (1,970-3,900m)
June 1992	Discovered new type of barophilic bacteria on ocean-side slope (5,118m) in Ryukyu Trench.
	Genome analysis of the new barophilic bacterium was completed in 2003; a large number of papers accompanied this discovery.
October 1992	Discovered community on whale bones off Torishima Island, Izu-Ogasawara (4,037m).
November 1992	Photographed Alviniconcha in hydrothermally active area of Mariana Trough (3,604-3,630m)
June-November 1994	Research dives at Mid-Atlantic Ridge and East Pacific Rise (MODE '94). • Photographed large-scale hydrothermal activity at TAG hydrothermal mound on Mid-Atlantic Ridge; observed large school of Rimicaris shrimp at black smoker (3,632-3,710m). • Photographed Riftia (2,634m). • Photographed scene of egg-laying by Austinograea yunohana crab at Pacific Rise (2,606-2,652m).
October-November 1995	Research dives at Pacific Manus Basin. • Photographed white smokers and gold-colored chimneys (1,708m).
June 1997	Discovered polychaetes in Sanriku-oki area, Japan Trench (6,360m).
July-September	Extended seafloor observation at East Pacific Rise (Ridge Flux Project).
1998	Research dives at Mid-Atlantic Ridge and Southwest Indian Ridge, etc. (MODE '98).
September	First dive in Indian Ocean by human occupied submersible.
October	Confirmed signs of hydrothermal activity at Southwest Indian Ridge (2,692m).
November	Discovered a new type of giant squid at Southwest Indian Ridge (1,055-5,362m).
August -September 1999	Research dives to investigate undersea volcanoes around the Hawaiian Islands. • Photographed pillow lava around Loihi seamount undersea volcano (2,460-4,821m).
December 2001-February 2002	Research dives at Southwest Indian Ridge and Central Indian Ridge.
July 2002	Research dives to investigate undersea volcanoes around the Hawaiian Islands.
October 2002	Research dives off southwest Java Island, Indonesia.
November 2003	Achieved 800th dive.
May 2004	Discovered liquid CO2 pool in sediments at Okinawa Trough (1,370-1,385m).
July-September 2004	Served as core of the Pacific Great Navigation NIRAI KANAI (NIppon Ridge Arc and Intra-plate Key processes Apprehension NAvigational Initiative) research project. • Discovered world's largest seafloor lava plain at East Pacific Rise (3,024m).
July 2005	Achieved 900th dive.
December 2005	Captured live deep-sea life in Sagami Bay (1,215m).
January-February 2006	Research dives at Central Indian Ridge; observed ecology of the scaly-foot gastropod (Crysomallon squamiferum) in deep-sea hydrothermally active environments (2,420-3,394m).
March 2007	Achieved 1000th dive.

Prepared by the STFC based on Reference [20].

the earth's interior, with almost no dependence on solar energy, inhabit the deep sea bottom, and an ecosystem has formed based on these microorganisms. Investigation of these deep sea ecosystems is helping to elucidate the origins of life and the process of evolution.

(3) Exploitation and preservation of deep sea life

Sustainable use of deep sea biological resources as a solution to food shortages that humankind may face in the future and research on the genetic resources available in deep sea life with diverse physiological functions are considered increasingly necessary.

(4) Thermal and material cycles

Because the history of environmental changes affecting the planet, including climate change, changes in ocean weather patterns, and similar phenomena is recorded in the various substances deposited in the ocean floor, research is being carried out to collect and decipher this record. Heat and materials released as a result of sea bottom hydrothermal activity have a significant influence on the global environment, and have been concentrated as mineral resources. Research and results will also be important in the future from the viewpoint of elucidating global environmental changes and exploiting sea bottom mineral resources.

In terms of operational frequency, the U.S. submersible Alvin has made more than 4000 dives since it was first launched in 1964, and thus averages more approximately 100 dives per year. In comparison with this, the Shinkai 6500 makes fewer dives, averaging 60 per year, or a total of 1000 dives in its career to date. This difference is mainly attributable to the cost of operation and differences in thinking on safety risk. When increased priority is given to safety, the cost of dives also increases. The fact that the Shinkai 6500 has accomplished 1000 dives under these conditions without a serious accident is due to constant, unstinting maintenance and management efforts. This kind of technology and know-how are not the result of individual academic results or manuals, but rather, require a deep understanding gained through the accumulated achievements of an organization.

5-3 Conceptual proposal for the 3rd generation of deep-submersible HOV

Japan's Shinkai 6500 has made a large number of research achievements as a 2nd generation deep-submersible HOV. However, 20 years have now passed since its building.

To date, numerous functional improvements have been made in the Shinkai 6500 responding to the research needs of scientists. For example, Ag-Zn batteries were originally used, but because it was necessary to suspend operation for maintenance, these were replaced with maintenance-free, long-life lithium ion batteries, which also reduced operating costs. The TV cameras mounted outside the vehicle as research equipment have been replaced with the CCD type, resulting in improved image quality and reduced weight, while the lighting system used to illuminate research objects has been improved by replacing the original halogen lamps with metal halide, reducing power consumption. A large sample basket has been adopted, increasing sample capacity. A system for transmitting images from the submersible to the mother ship was developed and installed, and it is now possible to give research instructions from the mother ship. However, in spite of these partial improvements, the submersible as a whole is based on a design that is now 20 years old, and the likelihood of accidents due to aging may also increase in the future. Thus, the time has now come when Japan must begin study of a new submersible.

However, it is not possible to move immediately to research and development on a submersible. A period of several years is necessary both in planning, which must be based on the experience obtained in research and development and operation to date, and in the actual building of the vehicle. The United States began building of a replacement for the Alvin 3 years after the start of study. Two years have now passed since building began, and completion is expected to take another 3 years. Reasons for the delay in planning are not limited to technical issues; in many cases, the development budget is also a factor. This is a common problem worldwide.

The author would like to suggest the following keywords for a next-generation deep-submersible HOV. Based on the development of HOVs and unoccupied research vehicles to date, the desires of scientists, and other requirements, the following four keywords may be proposed: "high speed diving/surfacing," "ability to hover at arbitrary intermediate depths," "long dive time," and "system with unoccupied research vehicles."

First, an adequate response to marine/earth science and marine development needs may be possible in the future with a maximum depth of 6000m. With the current technology, it takes approximately 2 hours to reach a depth of 6500m. Thus, the lost time in descent/ascent account for half of the possible dive time. This is a problem not only from the viewpoint of research efficiency, but also the researchers' comfort. A vehicle that can shorten this time by diving and surfacing at high speed is desirable. At present, however, time is required because the vehicle does not use its propulsion system in descent or ascent, but rather, dives by sinking naturally due to its own weight, and surfaces slowly employing buoyancy. To achieve high speed diving and surfacing, it will be necessary to use propulsion, but this will require large capacity batteries or the development of a new power source. This is perhaps the core technology for extending research time. Furthermore, the current deep research vehicles use their own heavy weight to dive, and then carry out research activities in a state of neutral buoyancy at the seafloor. This is adequate for research on seafloor topography/ geology and life. However, most large marine life inhabits the intermediate depths. To carry out research on this life, it must be possible to remain static and conduct tracking research for extended periods of time. In its new HOV, the U.S. has adopted a variable buoyancy system which will enable research and measurements at intermediate depts. In comparison with the conventional method of controlling buoyancy by jettisoning iron shot, this will prevent environmental damage in the research area while also improving ascent/descent and attitude control capabilities.

The current HOVs, which are considered to be 2nd generation vehicles, must carry a human pilot as well as scientists. This is because these vehicles were built in a period when technical progress was still inadequate, and the majority of technologies involving perception, judgment, and control depended on the capabilities of human beings. Today, however, unoccupied research vehicles, including autonomous intelligent underwater vehicles, have been developed and are in operation, and advanced recognition tools and control technologies have evolved. The safety risk of these unoccupied research vehicles is far lower than with HOVs, and engineers have taken on the challenges of applying pressure resistant materials, such as buoyancy materials, and fuel cells, and developing new control systems. Naturally, the results of this development can also be applied to HOVs.

Because independent movement has been fundamental to HOVs to date, all necessary functions must be incorporated in the submersible itself. However, a next-generation submersible may perform underwater research as part of a "fleet," accompanied by a number of unoccupied vehicles with respective characteristic functions. For example, the lighting and refueling functions could be assigned to separate vehicles. As advantages of this system, if objects are illuminated with lights from the HOV itself, the field of view is poor due to reflection from suspended solids in the water, but visibility can be improved if an autonomous underwater vehicle is used to provide auxiliary lighting. A dedicated autonomous vehicle could also be used to replenish the HOV's fuel, eliminating the need to install all power supply batteries on the HOV. More efficient deep sea research will be possible if research activities can be carried out safely and efficiently while communicating with and controlling these devices. To date, the necessity of HOVs has been argued mainly from the viewpoint of the division of roles among human occupied and unoccupied vehicles and autonomous intelligent underwater vehicles. However, for the further development of deep sea research, the aim should be to develop a collaborated/integrated system of occupied and unoccupied vehicles in which their roles are divided based on the functions of each device.

6 Concluding remarks

It is generally recognized that modern science began with Newton's discovery of the law of universal gravitation.[21] However, Newton's predecessors discovered and accumulated the various facts that led to this discovery. The individual facts that the earth revolves around the sun, the moon revolves around the earth, and apples fall to the ground from trees were all known before Newton's discovery. Then, one evening in the fall of 1665, when Newton was walking around in an apple orchard near his house, an apple happened to fall from a tree. When he looked up, wondering from which tree the apple had fallen, he found the moon in the sky beyond the apples. In that instant, both the moon and apple were thought to have joined in Newton's mind. If apple falls straight toward the center of the earth, he wondered, why doesn't the moon also fall? His answer to this question was the integrated theory of universal gravitation.[22]

Science includes the tireless accumulation of large numbers of facts and phenomena, as well as individual hypotheses and theories, but science progresses through innovations, by proposing new theories which explain these facts in an unified manner, and verifying predictions based on these new theories. Continuing to provide advanced science and technology which will make it possible to train the outstanding scientists who can do this and thereby propose new paradigms should be the national responsibility.

Human occupied submersibles have played enormous roles in deep sea sciences. The fact that the deep sea is the largest biosphere on the planet has gradually become clear by the research using HOVs. In the future, this kind of research may result in new discoveries, not only through the use of HOVs alone, but by research with remotely operated vehicles, autonomous underwater vehicles, and other new technologies. Moreover, it will be necessary to develop a variety of science and technologies in parallel and to use these in combination, not only in the search for mineral deposits and bio-resources in the world's oceans and at the ocean floor, but also in order to elucidate the meaning of the deep ocean in earth science.

There are some engineering researchers who assert that it is not necessary for humans to descend into the deep sea because it would be able to develop unoccupied vehicles equipped with high performance TV cameras which are adequate for research. This, they say, is the mission of technical development. However, what is seen through a camera lens and what can be seen directly with the human eyes are not perfectly identical. For the science, it is important to clearly view what the researcher sees while also adequately tracking the object of research. Of course, humans cannot travel to the far reaches of space or observe the microscopic world with the naked eyes. For this, it is necessary to develop telescopes or microscopes. This is how science has progressed. On the other hand, if it is possible to provide the tools with which researchers can directly observe phenomena at great depths in the ocean, providing such tools is essential for scientific progresses. This effort will lead to the further development of science and technology.

There would be three viewpoints when discussing the necessity of human occupied submersibles. This is generally common to all fields of science and technology. The first is the contribution to deep sea science (pure science), the second is the application to the industries, and the third is making the tax payers understand. How to balance these three must be the basis for deep sea science and technology policy. The objective of a nation's key science and technology strategy is to maintain the means of securing the national interest. Therefore, it is necessary to maintain and develop the industrial technologies that support this means, and to be able to make people understand who should enjoy the national benefit. Satisfying the individual scientist's intellectual curiosity may be the scientist's motivation for research, but in order to realize this, it is necessary to return the results of research to the nation's people, explain the scientific problems which must be elucidated, and offer a "frontier" which attracts scientists and other technical people. Moreover, the general population must also monitor this science and technology policy.

Japan's deep-submersible HOV, the Shinkai 6500, is capable of reaching the greatest depths of any submersible in the world at the time, but other countries are assiduously developing deep sea research/work technologies that will exceed the capabilities of the this vehicle. Japan must discuss a next-generation deep-submersible HOV while it still enjoys a position of superiority in deep sea technology. Regardless of the difficult challenges we may now face, if we set large goals, the author believes that this country can assemble and train outstanding human resources and this will drive progress in pure science and science and technology. It is hoped that this paper will provide the opportunity to begin debates on the visions that Japan should develop new HOVs in the future.

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Glossary

*1 TAG (Trans-Atlantic Geotraverse): The world's largest hydrothermal mound, located at a depth of 3600m; "black smokers" (a type of hydrothermal vent) approximately 20m high stand on the 200m conical mound.

*2 Deep submergence science: Defined in this report as science constructed on the basis of knowledge obtained by underwater research on the deep sea and seafloor carried out by occupied and unoccupied vehicles.

*3 TIG welding: Tungsten inert gas welding. Welding process using a tungsten electrode with high heat resistance, in which the weld is shielded with an inert gas such as argon, etc. to prevent oxidation of the material. Applied in manual welding of stainless steel and titanium alloys.

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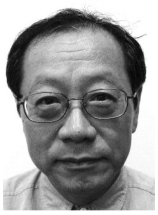

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