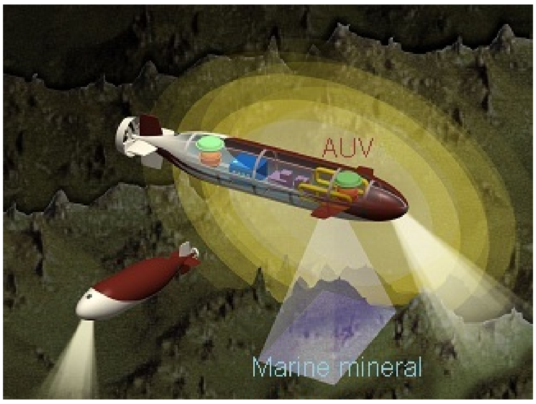
Development of Autonomous Underwater Vehicle (AUV) for Exploring Deep Sea Marine Mineral Resources



Norihide Wakita[*1] Kiyoshi Hirokawa[*2]
Takuji Ichikawa[*3] Yoshiaki Yamauchi[*3]

In recent years there has been a need to develop and deploy an Autonomous Underwater Vehicle (AUV) as a cutting edge underwater sensor platform for marine mineral exploration, the importance of which has been widely recognized and reaffirmed. This paper describes the activities of Mitsubishi Heavy Industries, Ltd. (MHI) in the research and development of the AUV, along with the features of the prototype "URASHIMA" AUV completed in 2000, as well as the survey records compiled by the vehicle's delivery destination, the "Japan Agency for Marine-Earth Science and Technology" (JAMSTEC). This paper also presents new technologies relevant to the AUV and the future direction of MHI's AUV research and development.

1. Introduction

MHI has been constructing many kinds of undersea vehicles including the Manned Deep Submersible, the Remotely Operated Vehicle (ROV), the Saturation Diving System, and so on. The prototype "URASHIMA" AUV was built using the latest technologies, as well as technologies specific for undersea vehicles. This paper outlines the autonomous operation technologies acquired through the construction and maintenance experience of the "URASHIMA" AUV and marine resource exploration technologies in reference to the test records of URASHIMA compiled by JAMSTEC. In addition, this paper presents the new technologies of a hydrogen generator for fuel cells and describes the conceptual design of the multiple AUV system as MHI's future view.

2. Marine resource exploration and AUV

As production numbers of the AUV as sensor platforms for surveying marine data are rising gradually, the conventional oceanographic research tool, the tethered ROV, is being replaced with the AUV.

This may be because the AUV is more suitable as a sensor platform for surveying a wide range of marine data (in the sea, on the seabed and below the seabed) compared to the ROV, as the AUV can move autonomously and freely without a cable connection, while the ROV is connected to the mother ship via an umbilical cable and therefore can survey only within a fixed zone. Marine mineral resources probed by the AUV include hydrothermal deposits, cobalt rich manganese crust and methane hydrate. **Figure 1** illustrates the AUV in operation and deep sea marine resources.

The marine resource exploration depicted in this figure can be classified into three stages: wide-range detection (up to 100 km^2), the medium-range detection (up to 10 km^2) and specific-zone detection (up to 1 km^2).

*1 Project Manager, Engineering, Submarine Department,
*2 Engineering Manager, Electric & Electronic Equipment Designing Section, Submarine Department
*3 Senior Engineer, Submarine Designing Section, Submarine Department

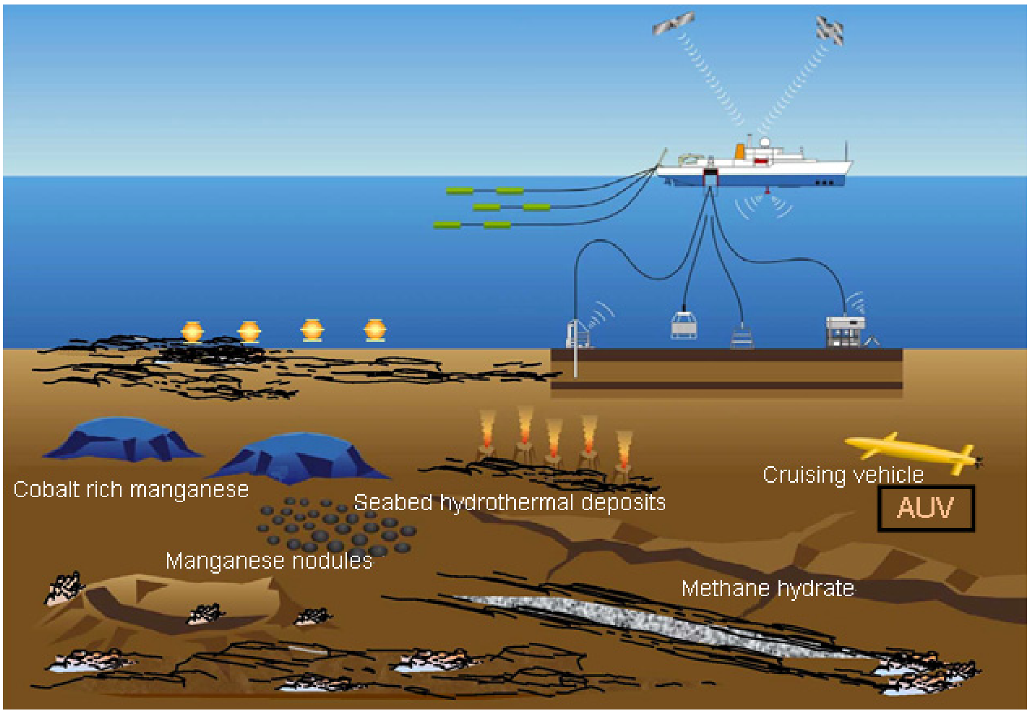


Figure 1 Concept of deep sea marine mineral resources

3. Outline of URASHIMA and its operational results

3.1 Outline of URASHIMA

The "URASHIMA" AUV was built in 1998 through 1999 as a prototype vehicle aiming to research the marine environment and seabed topography of the Arctic Ocean. After the construction of the platform, a closed cycle fuel cell for deep sea vehicles was developed and installed on the platform. On February 2005, URASHIMA, which had been delivered to JAMSTEC, accomplished 317 km of autonomous and continuous cruise at Suruga Bay (the longest such cruise anywhere in the world). **Figure 2** shows the history of the development of URASHIMA.

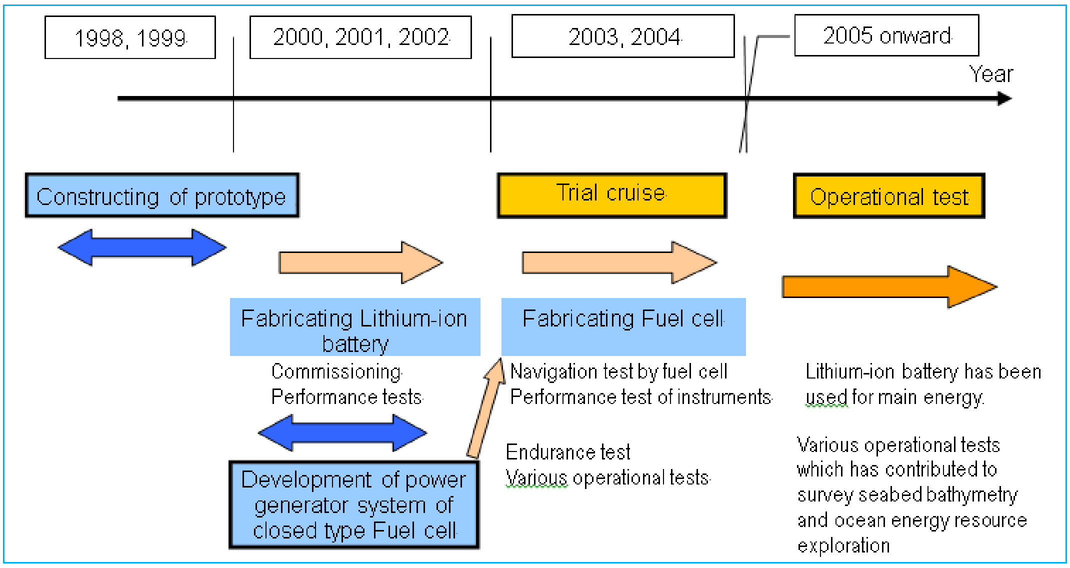


Figure 2 Development history of prototype “URASHIMA” AUV

Figure 3 shows the specifications, an overview and the sensor configuration of the prototype URASHIMA AUV. The principal acoustic sensors for the detection of marine mineral resources equipped by JAMSTEC are listed below with a simple explanation of their functions.

・Side scan sonar

Detects the geometry and texture of the seafloor. This sensor emits fan-shaped pulses down toward the seafloor from both sides of the vehicle and processes the intensity of the acoustic reflections (backscatter) from the seabed to show an image of the seafloor geological features graphically in density gradation.

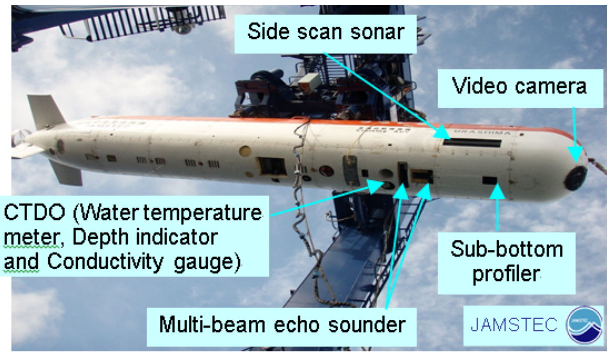
- Multi-beam echo sounder

Measures the depth or altitude and nature of the seabed. This sensor transmits acoustic fan-shaped pulses perpendicular to the moving direction to produce a map of the seafloor. As this sensor transmits sound and receives echoes while the vehicle is cruising near the bottom in deep water, high-resolution images can be produced.

- Sub-bottom profiler

Scans layers of sediment or rock under the seafloor. This sensor repeats the transmission and receipt of acoustic waves while the vehicle is cruising, and data of the uppermost layer under the seabed can be obtained.

Outlook of “URASHIMA”



Bottom view of sensors configuration

(1) Principal particulars:	Dimensions : L 10.7 m×W1.3 m×H1.5 m Weight in air: 10 tons (Fuel cell fabricated) Max submergence depth: 3,500m Cruising range: Rated 300km (Track record) 317km (Feb 26 - 28, 2005)
(2) Power source:	PEFC fuel cell or oil compensated lithium-ion re-chargeable battery
(3) Sensors:	CTDO, side scan sonar, video camera, sub-bottom profiler, multi-beam echo sounder

Figure 3 Overview, specifications, and sensor configuration of prototype “URASHIMA” AUV

3.2 Performance of URASHIMA

(1) Submergence performance

Precise vehicle balance adjustment between weight and buoyancy cannot be attained just by dropping ballast weight. In addition, buoyancy changes caused by water density changes (resulting in increased buoyancy) and shrinkage of the vehicle body caused by increased water pressure and drops in temperature (resulting in decreased buoyancy) should be considered in balance adjustment. MHI has developed an oil bladder type buoyancy adjusting device that can perform such adjustments and attain neutral buoyancy of the vehicle (**Figure 4**).

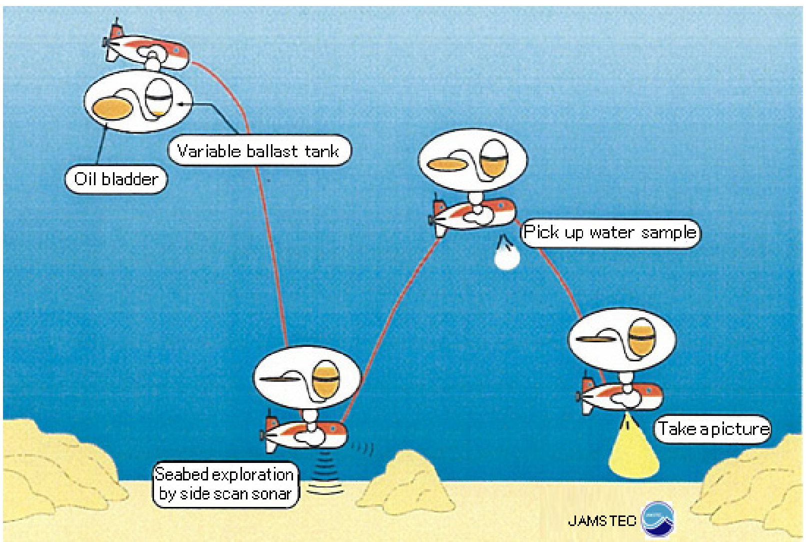


Figure 4 Conceptual figure of buoyancy adjusting device of URASHIMA

(2) Maneuverability

The movement of the vehicle in the horizontal plane is controlled by the vertical rudder. Movement in the vertical plane is controlled by the buoyancy adjusting device described above, the trim adjusting device that adjusts the tilt angle of the platform by moving the weight back and forth and the horizontal rudder.

(3) Navigation control performance

Deviation of a coordinate measured by the inertial navigation system from the programmed swath line is calculated by the control system, and then corrected to 1 m or less by controlling the vertical rudder. The inertial navigation system is based on the ground speed obtained by the Doppler sonar equipped on the vehicle. The position can be updated toward the planned coordinate by the acoustic tracking facility of the mother ship if drift errors due to very small tidal current accumulate (**Figure 5**).

(4) Power source

A closed fuel cell system[1] is installed for the main power source and an oil immersed, pressure compensated lithium-ion rechargeable battery is used as the auxiliary power source.

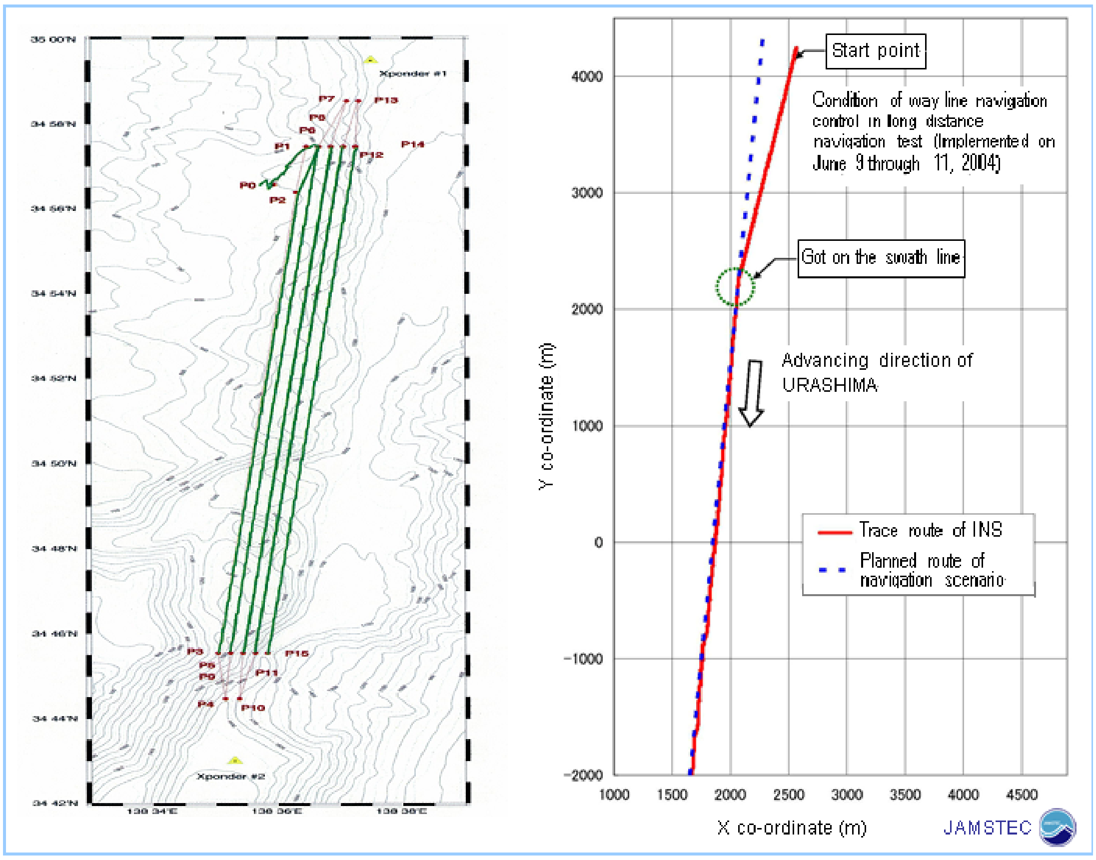


Figure 5 Operational results of navigation control performance

3.3 Operational results of URASHIMA

This section shows bathymetric charts created by processing data from the acoustic sensor as a part of the operational results of URASHIMA. All data were obtained by JAMSTEC[(2)-(7)].

(1) Observation of a mud volcano (probed by the side scan sonar (**Figure 6**))

URASHIMA observed the No. 5 Sea Knoll acting at Kumano trough. The knoll was surveyed using three-dimensional swath autonomous navigation along the preplanned lines, just like mowing. The strongly back-scattered point at the center of the image shown in Figure 6 is thought to be a new crater produced by a recent eruption.

(2) Observation of a hydrothermal plume on the seabed (probed by the Multi-beam Echo Sounder (**Figure 7**))

Figure 7 shows a three-dimensional topographic map of hydrothermal plumes on the seabed observed by the multi-beam echo sounder. This figure makes a number of plumes clearly identifiable and reveals their distribution for the first time.

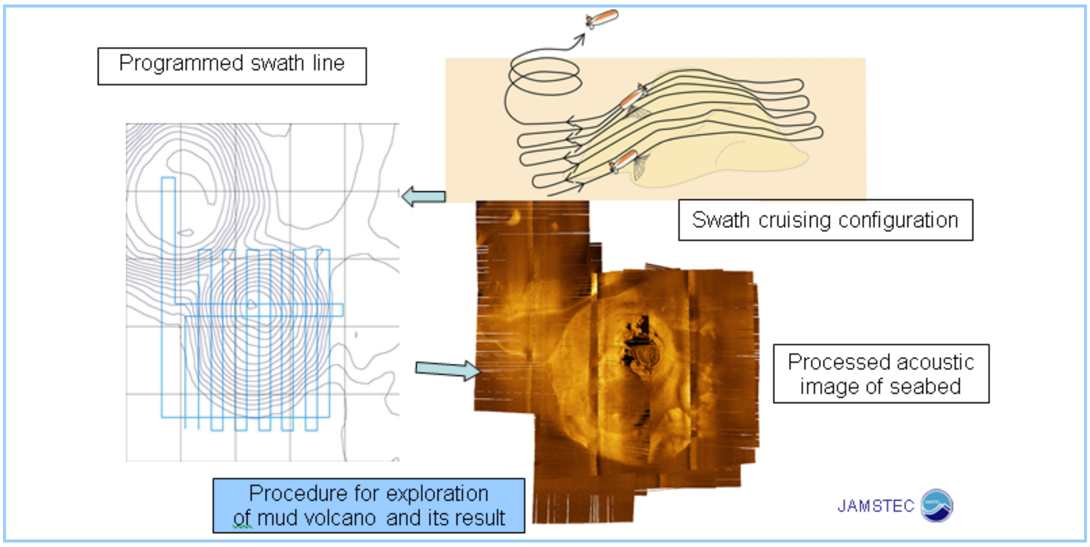


Figure 6 Acoustic survey data by URASHIMA (1/2)

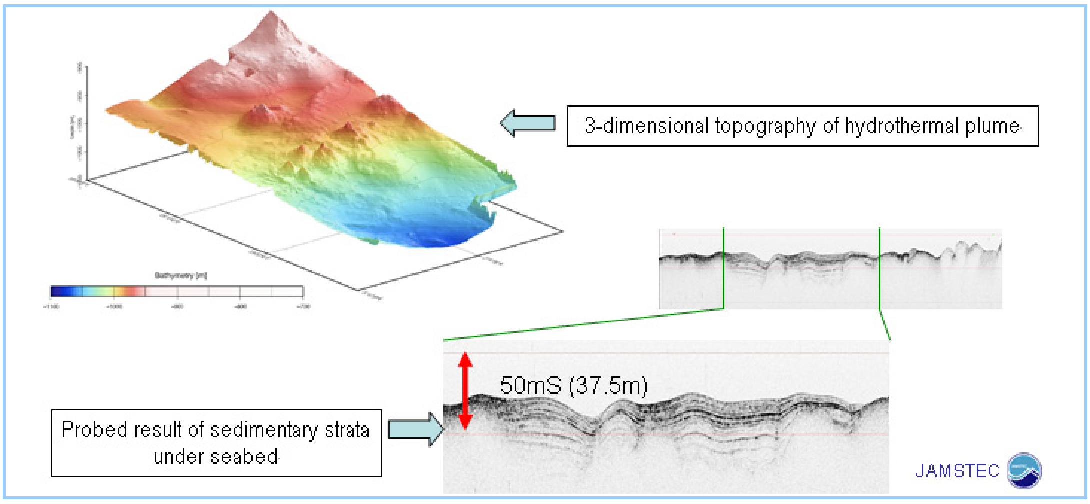


Figure 7 Acoustic survey data by URASHIMA (2/2)

(3) Exploration of sedimentary strata under the seabed (probed by the sub-bottom profiler (Figure 7))

Other data given in Figure 7 clearly show the geographical structure 40 m through 50 m below the sea floor including the disorder of strata, which implies the existence of faults. These results are fruits of operational engineering development of the client for years in the past, and prove the good capability of URASHIMA to serve in marine resource detection, meeting the client's expectations.

4. Development of next-generation AUV

The development of the next-generation AUV is expected to advance in the following two directions.

(1) Long-term cruise AUV

This type of AUV meets with the purpose of building the URASHIMA prototype vehicle, and aims to extend the cruising range drastically to 1,000 km through 3,000 km to enable the collection of marine data under the sea in the Arctic Ocean and the evaluation of the environment there.

To attain this, the following development tasks should be addressed: A) further downsizing and efficiency improvement of a fuel cell as the power source, B) exponentially downsizing and weight saving of hydrogen and oxygen sources used for the fuel and the oxidant, and C) enhancement of the long distance acoustic communication technology in a horizontal direction. All of these tasks are now under development. MHI's progress in the recent development of hydrogen storage and generation system using aluminum hydride is presented later.

(2) Multiple AUV system

It is expected that AUV systems with very high efficiency detection capabilities will be deployed into a wide range of marine mineral resources survey work in the near future. To meet this expectation, it would be favorable to develop a multi-AUV system that simultaneously operates two or more AUVs of a size smaller than URASHIMA. The theme for the development of this system is to establish the concept of an AUV fleet so as to study problems/difficulty with complex cruising and find an integrated fleet control system. The vehicles used in the system can be designed by applying the technology of URASHIMA. The activities of MHI on the next-generation AUV system are described below.

4.1 Development of hydrogen storage and generation system using aluminum hydride (patent pending)

(1) Outline and principle of the system

This epoch-making system can generate a large quantity of hydrogen using aluminum hydride particulate including AlH3, which is unstable at room temperature and can be reacted by just adding water at normal temperature under atmospheric pressure. This system is considered as one of the methods with the highest weight-storage efficiency among various kinds of hydrogen generating methods. This hydrogen generator system for underwater vehicles has been developed based on the current ready-for-practical-use small system for land vehicles (**Figure 8**)[(8), (9)].

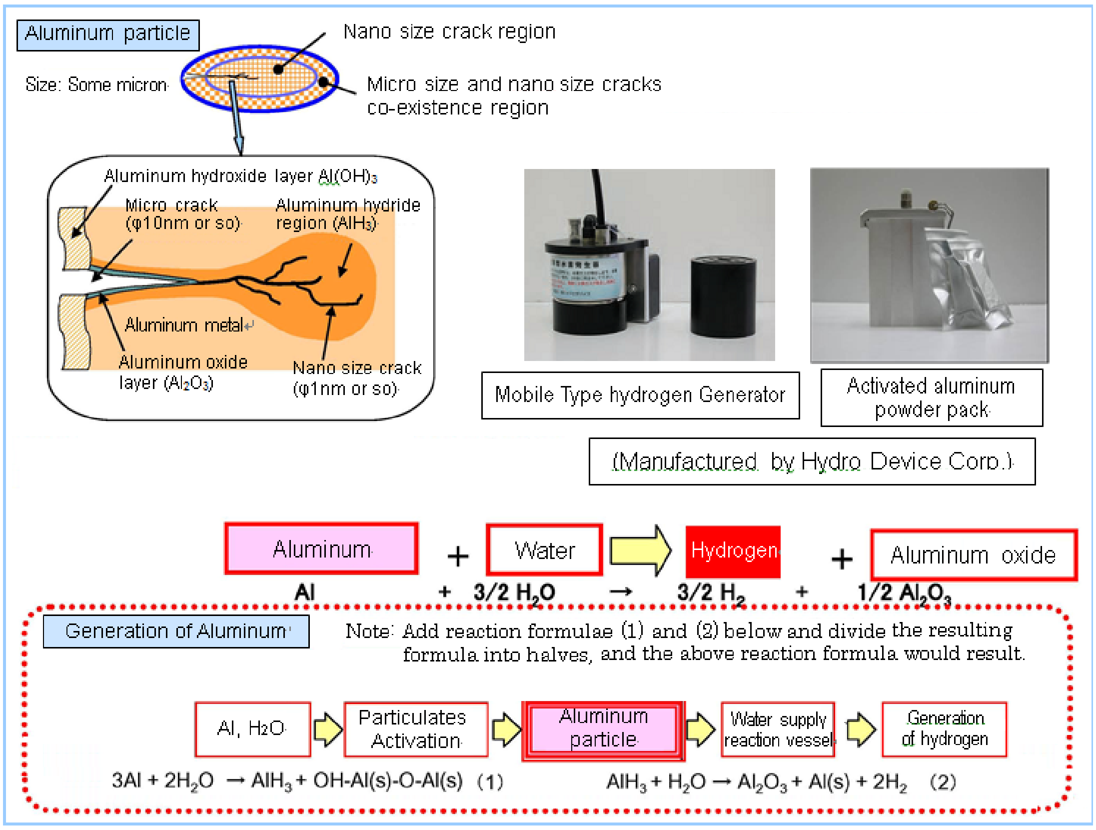


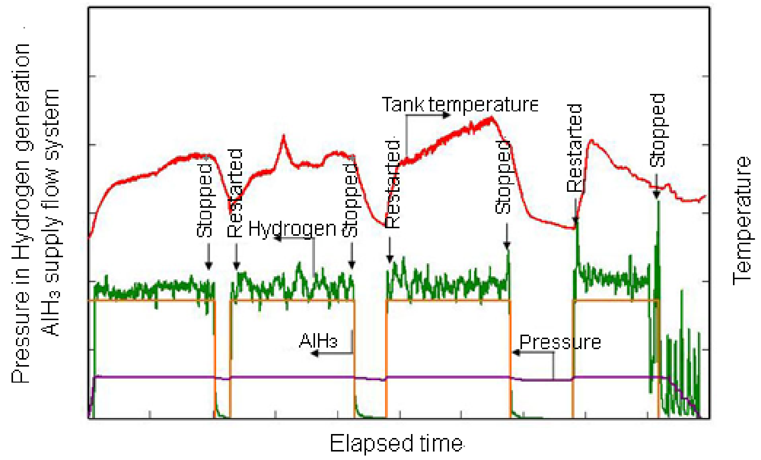
Figure 8 Principle of hydrogen generation by aluminum hydride method

What was important at the beginning of the system study was to decide how to store the raw material of activated aluminum particle powder. It was easy to store aluminum powder simply in a pressure container, but that was unpractical because the weight of the container would be quite heavy for the system of a long-term cruising AUV. To reduce the weight, a pressure-compensated system was developed using aluminum particulate slurry. For slurrying aluminum particulate, it was necessary to find a way to control the state of the raw material so that it maintained an inactive state during storage and could be activated in time of use. As a result of development working on this challenging task, the combination of inactive slurry solvent and activator solution was ultimately obtained.

(2) Verification result obtained with prototype system plant

A test plant was fabricated to verify hydrogen generation performance.

Aluminum particulate was slurried by inactive solvent in the storage tank to suppress the reaction. Then this slurry was transferred to the reactor vessel where activator solution was added to produce hydrogen. The vessel could pressurize the slurry, simulating a deep sea environment. As a result of the verification, hydrogen was produced successfully even under an environment of deep water pressure, and the reaction control performance of the system was favorable as shown in **Figure 9**.



Verification test result of hydrogen generation

Prototype system

Figure 9 Prototype system and verification test result

(3) Trial design of hydrogen generation system for Long-Term Cruising AUV

Hydrogen storage and generation systems for Long-Term Cruising AUV (cruising depth of over 6,000 m and cruising range of over 3,000 km) were trial-designed using this plant, and a comparison between an aluminum hydride system (pressure compensated type) and a hydrogen storage alloy system (pressure proof type) was performed. The volume of the aluminum hydride system was 11 m^3 and the hydrogen storage alloy system was 49 m^3, which meant that the former attained a significant size reduction to one quarter or less. MHI trial-designed a vehicle using the aluminum hydride type hydrogen storage and generation system. The size of the designed vehicle was 9.5 m (L) x 3.4 m (W) x 2.0 m (H) and the weight was 50 t. A reduction of both the size and weight was still necessary, but it was realistic compared to a hydrogen storage alloy system that had an unrealistic size. Aiming to make the system practicable, MHI will make efforts to evaluate the system in field trials in the sea.

4.2 Concept of multiple AUV system

Figure 10 shows the concept of the multiple AUV system.

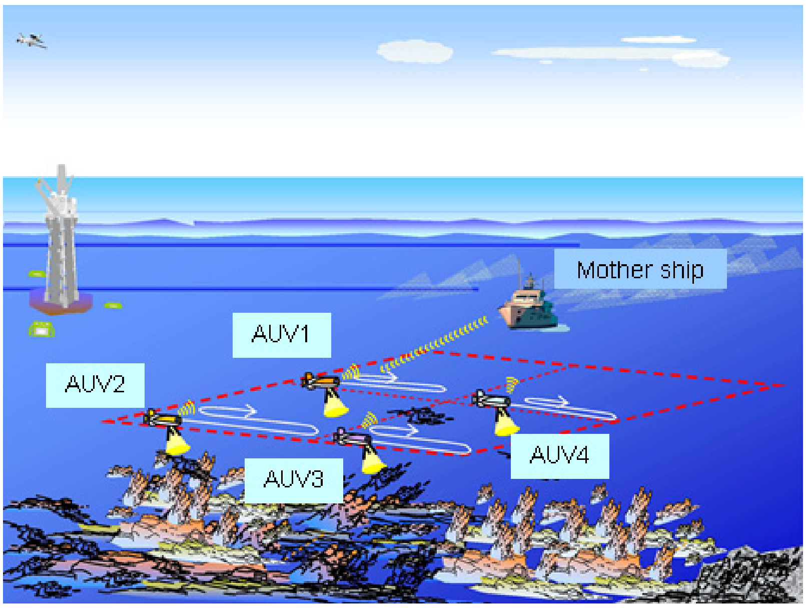


Figure 10 Concept of multiple AUV system

This concept is based on the idea where multiple AUV are autonomously performing survey missions under the supervision of the mother ship. Although there are remaining tasks such as ensuring safety and redundancy, emergency response and co-operative logics, MHI will study and propose a realistic system in the near future.

5. Conclusion

MHI's development process of the Autonomous Underwater Vehicle (AUV) for exploring deep sea marine mineral resources has been presented in this paper. Apart from the aforementioned method of detecting of marine resources using acoustic sensors equipped on URASHIMA, "electromagnetic survey," "gravimetrical prospecting," "magnetic prospecting," and the like are required for resource detection activities. Furthermore, the development of fundamental tools aiming to provide higher accuracy sensors is in progress. The AUV, which is a sensor platform, should be able to deal with these tools with flexibility. That is an important perspective which should be maintained in the future. In addition to the above, there is a plan to establish a maintenance and inspection system for buried network cables, which have been deployed aiming to reduce damage in the time of a subduction zone earthquake. MHI has also been trying to develop an AUV suitable for this need. As all these projects could contribute to the social benefit and safety, MHI will work hard to realize such a next generation AUV. In conclusion, the authors cordially appreciate the kindness of JAMSTEC staff members allowing for the use of various precious technical documents and data.

References

1. Maeda, T. et al., Development of Fuel Cell AUV "URASHIMA", Mitsubishi Heavy Industries Technical Review Vol.41 No.6 (2004) pp. 344-347
2. Aoki, T. et al., Advanced Technologies for Cruising AUV "URASHIMA", (Plenary session), Proceedings of The Seventeenth ISOPE, pp750-757
3. Tsukioka, S. et al., The PEM Fuel Cell System for Autonomous Underwater Vehicles, Marine Technology Society Journal, Fall, 2005, pp. 56-64
4. Tsukioka, S., J. Marine Acoust. Soc. Jpn. Vol. 34. No. 2 (April 2007)
5. ASHI, J. et al., Fine Structures and growth processes of mud volcanoes : AUV "Urashima" survey in the Kumano Trough, Proceedings of the 114 th Geological Society of Japan.(September 2007)
6. Tsukioka, S., The minute mapping of the seafloor by Autonomous Underwater Vehicle, Advanced Marine and Technology (May 2009)
7. Yamamoto, F. et al., Proceedings of Japan Society for Marine Surveys and Technology (2009)
8. Watanabe, M. Chemical Reactions in Cracks of Aluminum Crystal: Generation of Hydrogen from Water, Journal of Physics and Chemistry of Solids, Vol. 71 (2010), in press
9. Watanabe, M. et al., Monthly Journal "Gekkan Display", April 2010, pp. 24-29