Fuel Cell System of AUV "Urashima"

†Ikuo Yamamoto ,Taro Aoki, Satoshi Tsukioka, Hiroshi Yoshida,
Tadahiro Hyakudome, Takao Sawa, Syojiro Ishibashi, Tetsuya Inada,
Japan Agency for Marine-Earth Science and Technology
2-15 Natsushima-cho, Yokosuka, 237-0061, Japan
† iyamamoto@jamstec.go.jp
†Kazuhisa Yokoyama*, Toshio Maeda*, Shinji Ishiguro*,Hiroshi Hirayama*, Kiyoshi Hirokawa*,
Akira Hashimoto**, Nagao Hisatome**, Toshihiro Tani**
MITSUBISHI HEAVY INDUSTRIES, LTD
*: 1-1-1 Wadasaki-cho, Hyogo-ku, Kobe, 652-8585, Japan
**: 1-1 Akunoura-cho, Nagasaki 850-8610, Japan
† kazuhisa_yokoyama@mhi.co.jp

Abstract **- JAMSTEC (Japan Agency for Marine-Earth Science and Technology) and MHI (Mitsubishi Heavy Industries, Ltd.) have been developing the AUV (Autonomous Underwater Vehicle) "Urashima" since 1998.**

Long-distance cruising AUVs generally need an AIP (Air Independent Propulsion) power source characterized by high- energy density and high- energy efficiency.

Fuel cells are the preferred AIP power source for small underwater vehicles and PEFC (Polymer Electrolyte Fuel Cell) have been adopted for "Urashima".

It is understood that one of the main themes with fuel cell is storing the hydrogen, the metal hydride storage has been adopted for "Urashima" as a safer method of storing the hydrogen.

In summer of 2002 the AUV "Urashima" successfully completed an autonomous 132.5 km long-distance cruise using large capacity lithium-ion rechargeable battery.

In the meantime, a Closed Cycle PEFC (Polymer Electrolyte Fuel Cell) system with a metal hydride hydrogen storage system was developed as an alternative AIP power source in order to extend "Urashima" 's cruising range.

The lithium-ion rechargeable battery was replaced by the Closed Cycle PEFC system and this system became the main power source of "Urashima" in winter of 2002.

"Urashima", with its new power source (the Closed Cycle PEFC system) achieved the world's first and deepest fuel cell power source dive in summer of 2003 and completed an autonomous cruise of 220 km in spring of 2004.

In sea trials, the fuel cell system with metal hydride hydrogen storage system worked adequately and underwater fuel cell operation was verified. There were no problem in supplying power to the vehicle and supplying hydrogen to fuel cell system.

"Urashima" will carry out the AUV world record 300km cruising at upcoming trial opportunity.

I.Introduction

The AUV (Autonomous Underwater Vehicle) cruises according with a planned operational schedule. It is capable of cruising independently because there is no power and/or signal cable connected to a mother ship. The AUV is able to collect oceanic data over a long period of time and at low cost. Many groups throughout the world are developing AUVs.

JAMSTEC (Japan Agency for Marine-Earth Science and Technology) and MHI (Mitsubishi Heavy Industries, Ltd.) have developed the AUV "Urashima" since 1998 primarily to be used as a test vehicle for long distance cruising under the ice covered Arctic Ocean.

A fuel cell has been selected as "Urashima" 's power source and its development has started. "Urashima" 's key technology consists of an autonomous cruise control system and a fuel cell system. They have been developed separately.

Between 2000 and the autumn of 2003 a large capacity lithium-ion rechargeable battery (capactiy 300Ah) was installed as the initial power source. The battery was oil-filled pressure compensated battery like "Shinkai6500" battery system. Sea trials were carried out to establish the sea-worthiness of the AUV.

In summer of 2002 the AUV "Urashima" successfully completed an autonomous 132.5 km long-distance cruise using lithium-ion rechargeable battery.

In the meantime, fuel cell system performance tests were carried out on the ground and the fuel cell for "Urashima" was developed.

Cruising range was extended when the lithium-ion rechargeable battery was replaced by the Closed Cycle PEFC system and this system became the main power source of "Urashima" in winter of 2002. Since 2003 "Urashima" , fitted with the fuel cell, conducted sea trials in order to evaluate its performance and reliability.

This report will detail the world's first AUV fuel cell system and provide updated test results.

II. "Urashima" with Fuel Cell System

Table 1 shows the "Urashima" principal particulars and **Fig. 1** shows the general arrangement of "Urashima" with the Fuel Cell System.

The "Urashima" has a cylindrical shape. It is 10.7 m in length, 1.3 m in width and 1.5 m in depth. It weighs 10 tons in the air and includes different types of observation equipment. It has a maximum operating depth of 3,500 m and a cruising range of 300 km. The "Urashima" is made of titanium frames, titanium alloy pressure vessels, syntactic foam buoyancy materials that maintain a balance between vehicle trim in the water and FRP (Fiberglass Reinforced Plastics) faring covers. Each pressure vessel has an autonomous control system, a variable buoyancy control system, a fuel cell system and a metal hydride hydrogen storage system.

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Table 1. "Urashima" principal particulars

Items	Particulars
Dimensions	L 10.7 m X W 1.3 m X D1.5 m
Weight in the air	10 tons (neutral bouyancy in water)
Maximum operation depth	3,500 m
Cruising range	300 km
Speed (Cruising)	3 knots
Ship condition control systems	Trim controller, Variable buoyancy control system, ballast releaser, Emergency ballast releaser
Power sources	Fuel cell system Fuel cell: PEFC 4kW Metal hydride hydrogen storage system Oxygen tank: 14.7 MPa Pressure Lithium-ion rechargeable battery (capacity 30Ah) for hybrid use
Maneuvering systems	Main thruster: 1.8 kW X 1 Vertical thruster: 0.6 kW X 2 Horizontal thruster: 0.6 kW X 1 Vertical rudder, horizontal plane
Observation equipment	TV camera, Light, Side scan sonar, Digital camera, CTDO Sensor
Navigation instruments	Inertial navigation system, Doppler velocity log, Acoustic homing sonar, Obstacle avoidance sonar, Altitude sonar, GPS
Communication systems	Optical fiber communication system,Acoustic communication system,Radio-LAN system, Long distance radio control system

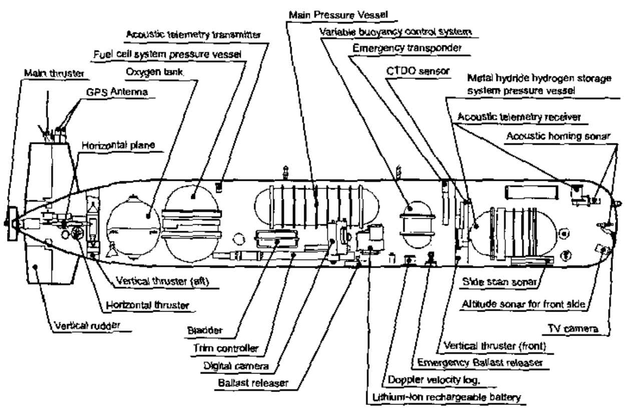

Fig. 1. "Urashima" – General Arrangement

III. "Urashima" Power Source Selection

Lead acid and silver zinc battery has traditionally been used as a power source for underwater vehicles. An increased electric capacity is needed for more extended cruising and this can lead to an increase in battery volume and weight, resulting in a greatly enlarged vehicle.

Since a long distance cruising AUV requires a power source that can operate for a long period of time, it needs a AIP (Air Independent Propulsion) power source characterized by high-energy density and high-energy efficiency. Thus, a power source with high-energy density and high-energy efficiency is essential ingredient for reducing the size of the vehicle.

Although prototype fuel cells, Stirling engines, CCDE (Closed Cycle Diesel Engines) and closed steam turbines have been developed and manufactured in recent years as underwater power sources, a fuel cell was selected as "Urashima" 's most suitable power source due to the following reasons.

IV. "Urashima" Fuel Cell System

A. Fuel cell

Fuel cells have recently received attention as an effective means of generating power and solving energy and environmental problems. Fuel cells will take over internal combustion engines in the near future, eliminating roadside exhaust gasses. In the future, more efficient fuel cell unit generators will supply electric power and hot water for residential utilities. In the near future, easily rechargeable fuel cells will take over battery in cellular phones and personal computers. This will eliminate the need for charging and recharging batteries.

Fuel cell technology is relatively old, having been invented in 1839 by a British physicist Sir William Grobe, the father of the fuel cell.

The fuel cell process reverses the process of water electrolysis. In a fuel cell, hydrogen and oxygen react electrochemically to produce electric power. Conventional internal and external combustion engines first change thermal energy to mechanical energy, and then into electric energy. Fuel cells, on the other hand, change chemical energy directly into electric energy, and therefore have a higher energy efficiency.

Fuel cells are especially effective in reducing CO_2 emissions. If hydrogen is used as fuel and oxygen is used as an oxidizer, the reactive product emitted from the fuel cell will only be water.

Since hydrogen can be produced in various ways, fuel cells are a highly effective power-generation method that can solve energy problems.Fuel cells are the most suitable AUV power source due to the following:

1. High power generating efficiency and less fuel and oxidizer consumption compared with other power sources. This can minimize volume and weight of vehicle.
2. Silence is a necessity for AUVs since they carry acoustic equipments such as acoustic communication system, obstacle avoidance sonar, side scan sonar and so on. Fuel cell stacks have no reciprocities and/or rotational moving parts and are thus superior in terms of silence.
3. Fuel cells emit only water as a result of the hydrogen/oxygen reaction. This allows for easy storage and discharge.

Table 2 Types of Fuel Cell

Type	Phosphoric acid Fuel cell (PAFC)	Molten carbonate fuel cell (MCFC)	Solid oxide fuel cell (SOFC)	Polymer electrolyte fuel cell (PEFC)
Electrolyte	Phosphoric acid	Carbonate	Solid oxide	Proten exchange memblem
Operating Temperature	150 - 200°C	600 - 650°C	800 -1000°C	up tp 80°C
Fuel	Natural gas, LPG, etc.	Natural gas, Coal gasification gas, etc.	Natural gas, Coal gasification gas, etc.	Hydrogen, Natural gas, Methanol, etc.
Exhaust heat utilization	Hot water, Steam	Gas turbine, Steam turbine	Gas turbine, Steam turbine	Hot water
Features	Low temperature operation	Extensive use of fuel/ internally reformable	Extensive use of fuel/ internally reformable	High power density, Low temperature operation

B. PEFC (Polymer Electrolyte Fuel Cell)

Depending on the type of electrolyte, fuel cells are classified into phosphoric acid, molten carbonite, solid oxide or polymer electrolyte fuel cells.

In the types shown in **table 2**, PEFC fuel cells are smaller and have a lower operating temperature compared to other types of fuel cells. They are better suited for distributed power supply, household power supply and an automobile source of power. The development of PEFC has advanced progressively in recent years.

The PEFC has been adopted as the "Urashima" 's power source for the same reasons.

Since the operating temperature is near to the room temperature, it allows for easy starting and stopping operation. It is also possible to use thermal insulation and build a smaller and lighter system configuration.

C. "Urashima" Fuel Cell System

Table 3 shows the specifications of the "Urashima" fuel cell system. **Fig. 2** shows the "Urashima" fuel cell system. The "Urashima" fuel cell system has two stacks connected in series and has an output of 4kW at 120V.

Fig. 3 shows the diagrams of the "Urashima" fuel cell system.

The "Urashima" fuel cell system is a completely closed cycle fuel cell, unlike the fuel cells used on land. The fuel cell system is installed in a pressure vessel .Hydrogen is supplied from a metal hydride hydrogen storage system installed in the other pressure vessel. Oxygen is supplied from a high-pressure oxygen tank.

Unreacted gas that has passed through the fuel cell stacks is re-circulated and the generated water is stored in the reaction water tank installed under level of the fuel cell pressure vessel.

Temperature and humidity controls are very important in PEFCs. Operating temperatures are controlled by changing the circulating water flow rate to the cooler. Operating humidity are controled by the humidifier. Temperature and humidity controls are maintained by thermal insulation and heating of gas lines.

A 30Ah lithium-ion rechargeable battery is also installed with a fuel cell system in order to "assist" to the fuel cell system if and when necessary. When required electricity demand exceeds the fuel cell's maximum capacity due to a temporary overload, the lithium-ion rechargeable battery can supply sufficient current.

Table 3. "Urashima" Fuel Cell System Specifications

Items	Specifications
System	Closed cycle system
Fuel cell type	PEFC(Polymer electrolyte fuel cell)
Output	DC4kW
Voltage	120V
Number of stacks	2
Fuel	Pure hydrogen (Metal hydride storage)
Oxidizer	Pure oxgen (High-pressure tank storage)

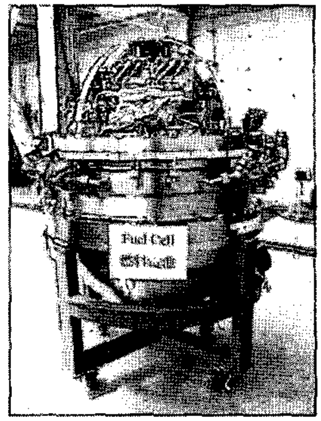

Fig. 2. "Urashima" Fuel Cell System in Pressure Vessel

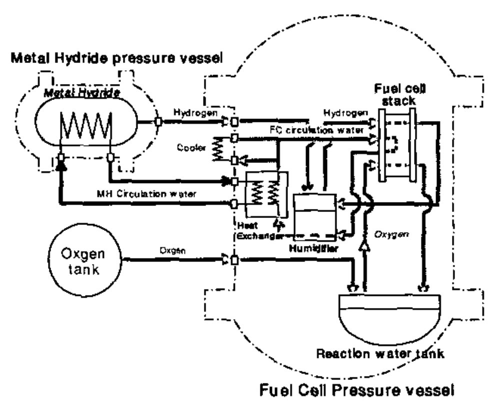

Fig. 3. "Urashima" Fuel Cell Diagrams

D. Hydrogen Storage

One of the main themes with fuel cells is hydrogen storage. **Table 4** shows various proposed hydrogen storage methods.

Taking into account feasibility and adoptability of hydrogen storage in "Urashima", newly deveoped 30MPa high pressure hydrogen tank was intially planned to be used.

But after researching other methods, metal hydride hydrogen storage has been adopted as safer method.

Table 4. Hydrogen storage method comparisons

Hydrogen storage method	Features
High-pressure gas	- gaseous state storage - gas can be compressed to reduce the storage space - vessel weight increses with increase of gas pressure - practical use on land - safety in time of leakage should be considered
Liquid hydrogen	- stored in a liquid state - due to storage method at extremely low tempreature of -250°C or lower (a insulating structure is essentially needed) - liquid hydrogen boils off and arising pressure must be ventilated, so that storage hydrogen volume during long period storage is be reduced. - practical use on land - safety during leakage must be considered
Metal hydride	- presents high volumetric storage density and compact storage are available - hydrogen storage rate changes according to alloy type - hydrogen desorption is a heat absorbing reaction and heat should therefore be applied - presents low gravimetric storage density and heavy weight - decreases hydride temperture and equilibrium hydrogen pressure while desorption,so the reaction restricts large volume of hydrogen leakage when the leakage happens.
Fuel reforming	- reforming of methanol, gasoline, kerosene and light oil is proposed - operating temperature is 300°C or more. - stored in liquid and thus easy to handle - produces byproducts including CO, CO_2
Chemical hydride	- at the laboratory research stage, not yet practically - more research and development is necessary before practical applications can be realized - regeneration requires a huge amount of energy
Carbon nano-tube/fullerene	- at the laboratory research stage, not yet practically - more research and development is necessary before practical applications can be realized - at present,production cost is extremely high

E. "Urashima" Metal Hydride Hydrogen Storage System

Metal hydride desorbs hydrogen with heat absorbing reaction. This reaction decreases hydride temperture and equilibrium hydrogen pressure while desorption. As the result, the reaction restricts large volume of hydrogen leakage when the leakage happens. As a safer method of hydrogen storage,metal hydride storage was adopted for "Urashima"

After several types of metal hydrides had been examined on preliminary stage, AB5 type rare-earth-based alloy was finally chosen for the "Urashima" metal hydride storage system on board.

It shows a good absorption efficiency and is easy to use because its absorption temperature is 10 - 20°C (room temperature) and the desorption temperature is 40 - 60°C (fuel cell operating temperature) **(Fig. 4)**

Hydrogen desorption is accelerated by using fuel cell waste heat .

The metal hydride hydrogen storage system consists of a metal hydride storage container, circulating water pump, sensors and controller in the pressure vessel.

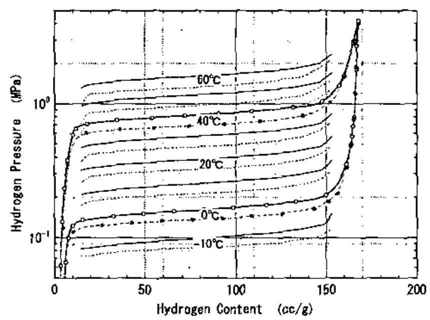

Fig. 4 PCT (Pressure-Content-Temperature) Diagram of AB5 Type Metal Hydride

V. Recent Test Results

A. Ground Tests

"Urashima" fuel cell system was tested on the ground facility at JAMSTEC from 2000 to 2002. Start and stop processes, power generating performance, load variation, inclining, swing **(Fig. 5)** , and continuous power generation tests have been conducted(**Fig. 6**). Solutions to technical themes and the establishment of adequate safety procedures have been achieved. **Fig. 7** shows current-voltage curves of the fuel cell system.

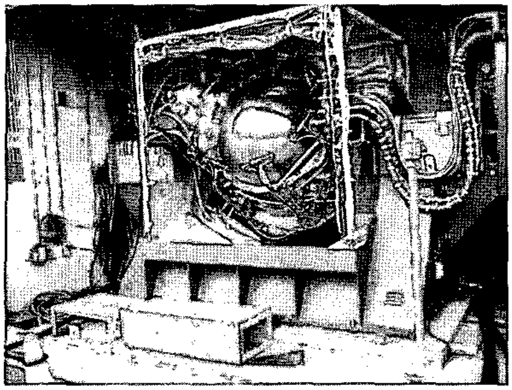

Fig. 5 Fuel Cell System Land Test

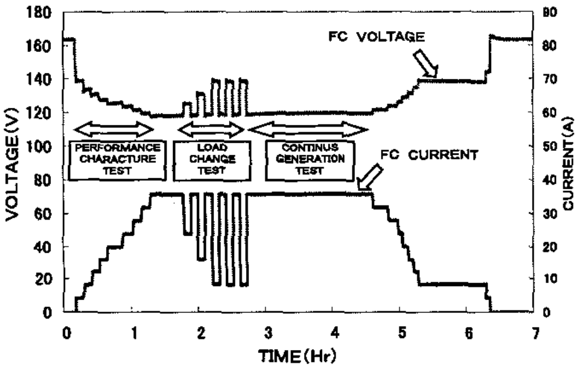

Fig. 6 Experimental Results of Fuel Cell Systems during Ground Testing

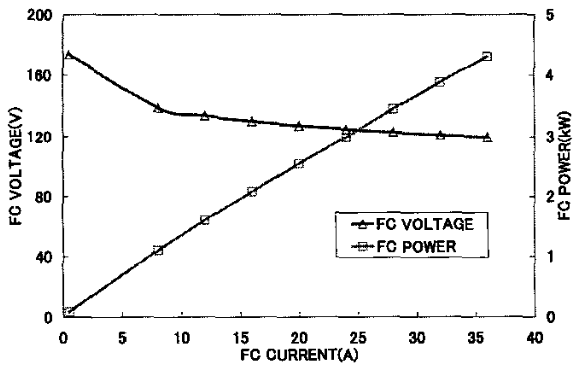

Fig. 7 Fuel Cell Current-Voltage Curves

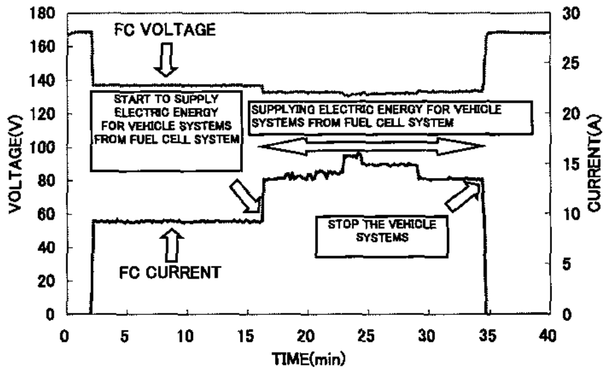

Fig. 8 Experimental Results of Fuel Cell System During Ground Testing After Installation in Vehicle

B. Ground Testing After Installation in Vehicle

After the fuel cell system was installed in the vehicle in 2002, metal hydride and oxygen tank connection, vehicle communication connection and electric power supply to vehicle systems tests were conducted. Fuel cell system compatibility with the vehicle was verified. (**Fig. 8**)

C. Compatibility Test With Mother Ship

"Urashima" was loaded onto the mother ship "Yokosuka" at JAMSTEC pier in the spring of 2003. Fire-fighting training, vehicle launching/recovery training and fuel cell power generating tests were conducted on the mother ship. Compatibility with the mother ship was verified.

D. Tests at the Pier

Vehicle operation verification was conducted under power generating conditions of the fuel cell system at the pier of JAMSTEC in July 2003. Underwater operations were verified.

*E. Sea Trial (First dive) **(Fig. 9)***

Sea trial was attempted in Suruga Bay in August 12th ,2003 and achieved our first fuel cell powered dive. The fuel cell system supplied all the electric energy required by vehicle systems. The fuel cell system adequately controlled system temperature and humidity in the sea. "Urashima" dived to a depth of 300 m and cruised for 2.5 km long at a speed of 2.5 knots. Vehicle received the commands perfectly from mother ship via acoustic communication, and picture in the sea were captured to mother ship clearly via acoustic communication. The fuel cell did not create any problems concerning acoustic noise. Acoustic noise level did not increase when the power source was transferred to the fuel cells from the lithium-ion rechargeable battery.

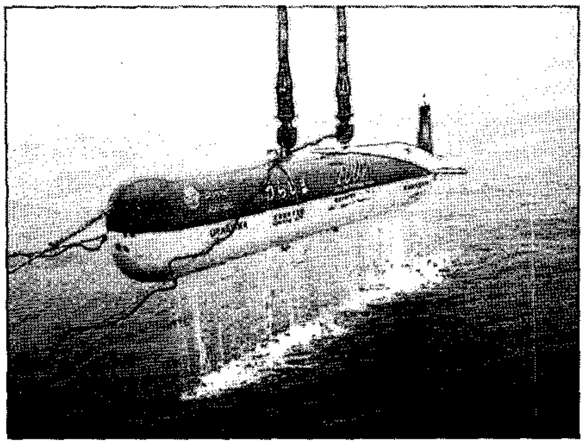

Fig. 9. AUV "Urashima"(FCUV) at the sea trial

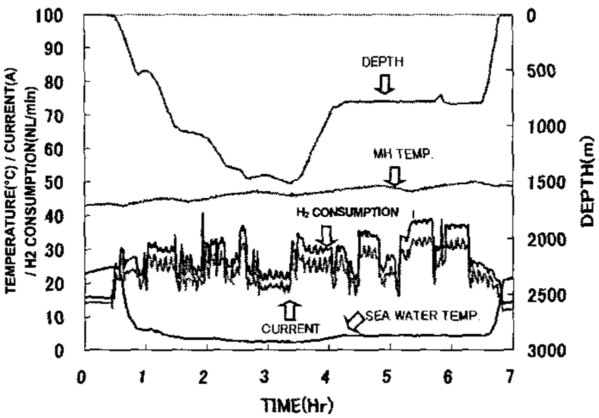

Fig. 10 Experimental Sea Trial Results (first deep dive)

F. Sea Trial (first deep dive)

First deep-sea dive in Suruga Bay was performed in the September 28th ,2003. "Urashima" dived to a depth of 1,500 m. This proved that there were no problem in supplying power to the vehicle instruments, in supplying hydrogen to fuel cell system and in controlling temperature and humidity in 2°C seawater. The heat supply for the metal hydride hydrogen storage system is adequate. **(Fig. 10)**

G. Sea Trial (Long distance cruise)

A long distance cruise was attempted in Suruga Bay in the June 9th to 11th ,2004. The "Urashima" cruise was a round trip of about 25 km between two transponders in the bay.

The "Urashima" dived to a depth of 800 m and cruised for 220 km at a speed of 2.8 knot. The cruise was suspended by the approach of a typhoon.

The fuel cell system and the metal hydride hydrogen storage system worked adequately without any problems. **(Fig. 11)**

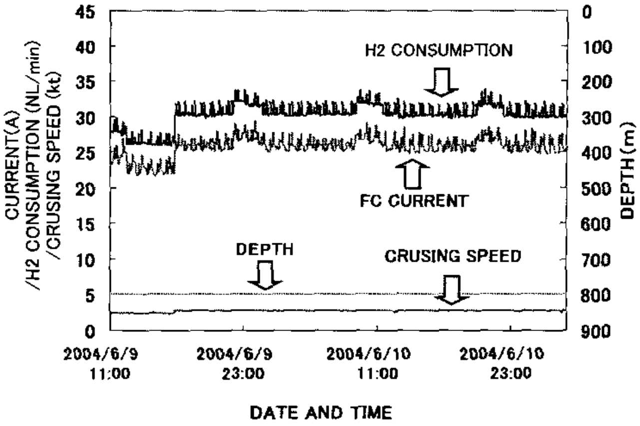

Fig. 11 Sea Trials Experimental Results
(220 km long distance cruising)

VI. Conclusions

The fuel cell has been developed successfully for practical use in automobiles, buses, etc. and as a power source that can solve energy and global environmental problems. "Urashima" fuel cells also demonstrated its value for underwater application.

We carried out a sea trial in Suruga Bay in June 2004 that was suspended by the approach of a typhoon but we achieved an autonomous 220 km long distance cruise. In the sea trial, the fuel cell system with metal hydride hydrogen storage system worked adequatedy, and underwater fuel cell operations were verified.

The "Urashima" will carry out the AUV world record 300km cruising at upcoming trial opportunity.

VII. References

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