Proceedings of The Sixth (2005) ISOPE Ocean Mining Symposium
Changsha, Hunan, China, October 9–13, 2005

ISBN 1-880653-65–6

Recent Advances of Ocean Nutrient Enhancer "TAKUMI" Project

Kazuyuki Ouchi
Ouchi Ocean Consultant, Inc.
Karuizawa, Nagano, Japan

Koji Otsuka
Department of Marine System Engineering, Osaka Prefecture University
Sakai, Osaka, Japan

Hisaaki Omura
Fuyo Ocean Development and Engineering Co. Ltd.
Taito, Tokyo, Japan

ABSTRACT

This is a brief review paper to introduce the Marino-Forum 21 project for creating new fishing ground by enhancement of marine primary production using artificial upwelling. The first term was performed from 2000 through 2004 to develop a prototype ocean nutrient enhancer. In the first part of this paper, the building and installation processes and the states of the operation and maintenance are summarized. In the second part of this paper, the research plan of the second term, which started in April 2005 and aims to confirm the effect of enhancement of marine primary production and to establish the technology for practical use of ocean nutrient enhancer, is introduced.

KEY WORDS: Deep ocean water; ocean nutrient enhancer; primary production; floating structure; density current.

INTRODUCTION

Security of food has always been one of the most important subjects for human society. Fish catches, which support human food mainly as animal protein, is also decreasing because of over-fishing and environmental deterioration of habit of fish by various human activities (Takahashi, 2000). Average productivities in the open ocean communities are about 1/10 of the coral communities or even lower. These low productivities in marine environments are mainly resulted from limited nutrient availability in the euphotic zone, where photosynthetic production is carried out by primary producer such as phytoplankton. Primary productivities in the most of ocean are then expected to be enhanced if nutrient availability for primary producer is improved (Takahashi and Ikeya, 2004).

Deep ocean water (DOW) is cold, nutrient-rich and pathogen-free seawater found at depth of several-hundred meters or lower. The DOW has attracted special interest as a renewable resource for energy and marine primary production (Otsuka, 2001). Especially, an artificial upwelling of DOW to the euphotic zone has a great potential for drastically enhancing marine primary production (Liu, 1999). The high potential of artificial upwelling is supported by the results of many researches on natural upwelling, e.g. Ryther's classical report (1969).

The world first in-situ experiment for artificial upwelling in the open ocean was carried out in Toyama Bay (in Japan Sea) in 1989 and 1990 (Yamakoshi et al., 1991). That project was supported by the Science and Technology Agency of Japan (the present name is Ministry of Education, Culture, Sports, Science and Technology). In this project, a barge type platform named "*HOYO*" was developed to pump up both DOW of 26,000 t d^{-1} from 220 m depth and surface seawater of 52,000 t d^{-1}, and discharge the mixed seawater to the water surface. However, the presence of nutrient-rich DOW within the euphotic zone and the fertilization effect were not observed unexpectedly, since the mixed water had a little higher density than that of the surrounding seawater, and might sink down immediately.

The second challenge of the artificial upwelling has been organized by the Marino-Forum 21, a satellite organization under the Fisheries Agency of Japan. The first term of this project was performed from 2000 through 2004. In this project, a density current generator (Ouchi et al., 1998) was applied to develop a prototype ocean nutrient enhancer, since the most important task was to minimize sinking and diffusion of DOW after discharge into the euphotic zone. Following this work, the second term of the project, which aims to confirm the effect of enhancement of marine primary production and to establish the technology for practical use of the ocean nutrient enhancer, has been started since 2005. One of the authors (Ouchi, 2003) introduced the concept and the development procedure of the prototype ocean nutrient enhancer named "*TAKUMI*" in the previous paper. This paper summarizes the results of the first term of this project and introduces the research plan of the second term.

CONCEPT OF OCEAN NUTRIENT ENHANCER

One of the most important technical subjects for artificial upwelling is to minimize sinking and diffusion of DOW after discharge into the euphotic zone. In order to solve this problem, a density current generator, which was proposed by one of the authors (Ouchi et al., 1998), was adopted in the Marino-Forum 21 project. The density current generator is applicable in a stratified water areas, and can intake both high-density deep seawater and low-density surface seawater, and discharge the medium-density mixed water into the stratified water column using a double impeller. The discharged water progresses through the same-density layer as a density current. In Sagami Bay selected as the experimental site, clear temperature stratification is formed in summer season. This means that the density current generator is applicable to the artificial upwelling without sinking in this area.

Figure 1 illustrates a concept of ocean nutrient enhancer, which is an applied density current generator for artificial upwelling. The ocean nutrient enhancer consists of a spar-type floating structure equipped with a double impeller, a riser pipe for pumping up DOW, and a single point mooring system. It can intake both nutrient-rich DOW and warm surface seawater, and discharge the mixed water into the euphotic zone as a density current.

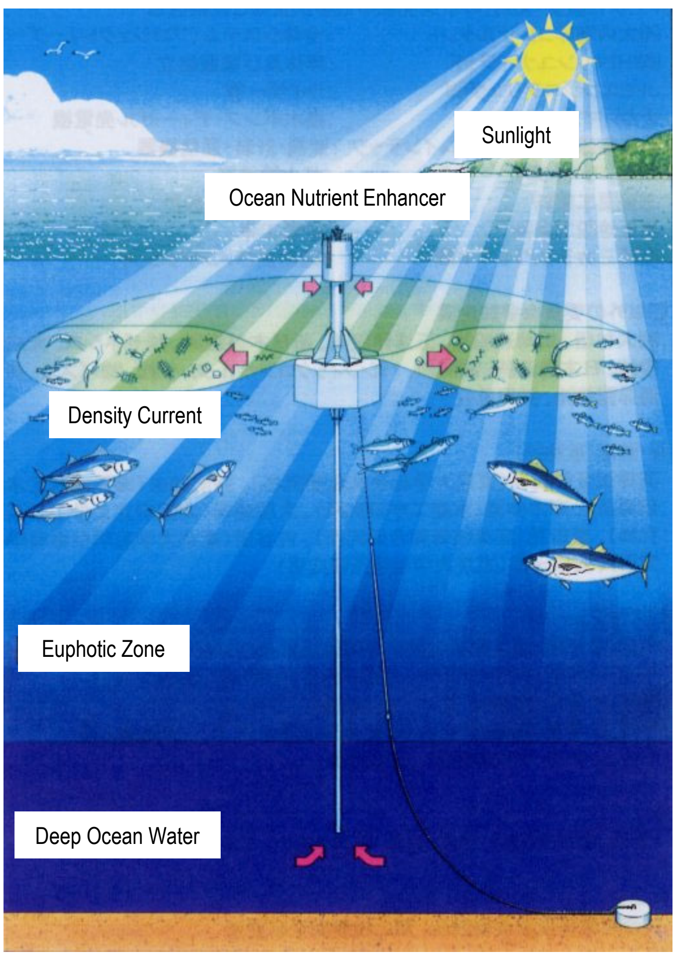

Fig. 1 Conceptual image of Ocean Nutrient Enhancer

DEVELOPMENT OF TAKUMI

Building and Installation

A prototype ocean nutrient enhancer named *TAKUMI*, shown in Fig. 2, was designed and built by a consortium consisting of members from private companies, universities, and national institutes. The height and breadth of the floating structure are 32.0 m and 16.8 m, respectively. The length and diameter of the steel riser pipe are 175.0 m and 1.0 m, respectively. It can intake DOW of 100,000 t d^{-1} from 200 m depth and surface water of 200,000 t d^{-1} from 5 m depth, and horizontally discharge the mixed water of 300,000 t d^{-1} at 20 m depth.

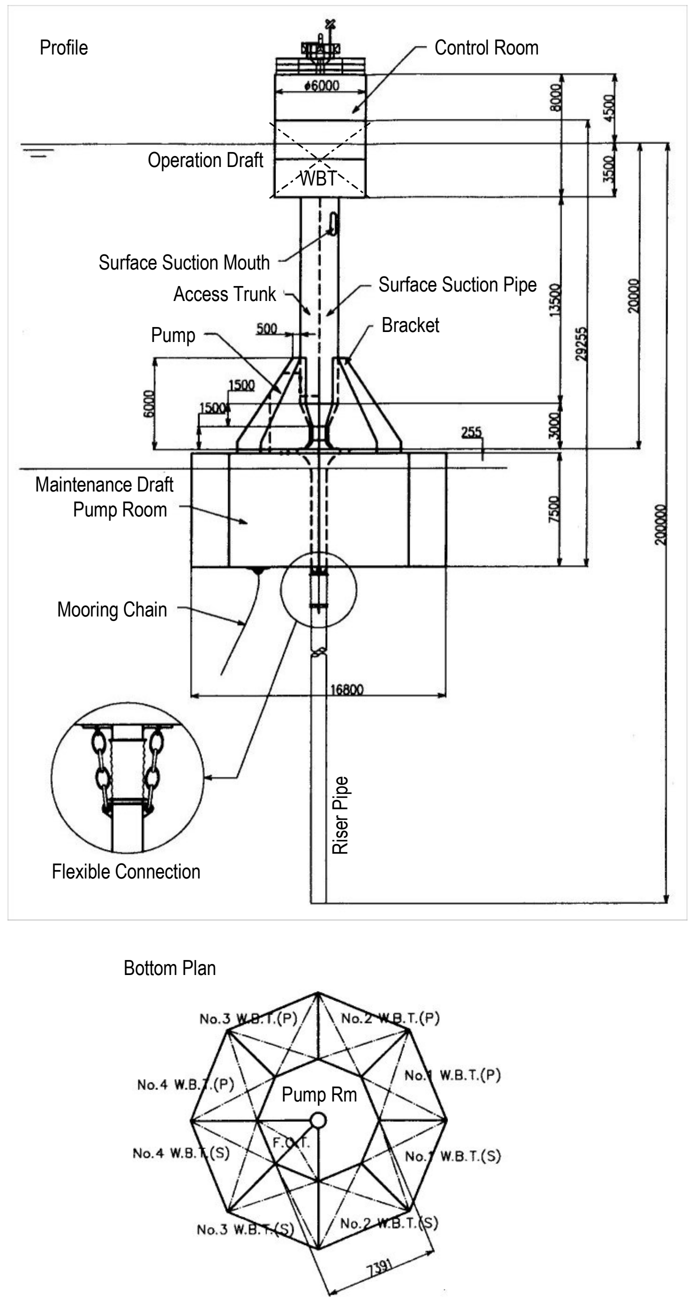

Fig. 2 General arrangement of ocean nutrient enhancer *TAKUMI*

The final fabrication was carried out at Yokohama dock yard of IHI Marine United Corporation as shown in Fig. 3. The riser pipe was connected to the floating structure by a flexible joint, and laid horizontally in final docking. Fig. 4 shows the location of *TAKUMI* installation point. In May 2003, the pre-fabricated *TAKUMI* was towed from Yokohama to the center of Sagami Bay, where the water depth is about 1,000 m, in condition of the horizontally laying riser pipe, and installed using an upending technique, in which the riser pipe freely fell from horizontal position to upright position.

Fig. 3 Photograph of *TAKUMI* in final docking

Fig. 4 Location of *TAKUMI* installation point

Operation and Maintenance

TAKUMI has been operated as shown in Fig. 5 for more than two years without any serious damages, even though some big typhoons attacked. However, the flexible joint connecting between the floating structure and the riser pipe was broken twice. Up to the end of the first term (March 2005), the broken section has been repaired temporally. In May 2005, the flexible joint was fully replaced to a newly developed flexible tube. Usual operation and maintenance plan is shown in Table 1. The fuel oil element and the lubricating oil element are monthly exchanged at the regular inspection. The fuel oil supply and the lubricating oil exchange are quarterly carried out. The engine inspection is semi-annually performed. And the other components, such as motor, Impeller, pump and hull, are annually inspected. Monitoring data except wireless communicating data, such as alarms and water temperature, are picked up at the regular (monthly) inspection.

Fig. 5 Photograph of *TAKUMI* in operation

Table 1. Intervals of operation and maintenance works

	Monthly	Quarterly	Semi-annually	Annually
Regular inspection	○			
FO* element exchange	○			
LO** element exchange	○			
FO* supply		○		
LO** exchange		○		
Engine inspection			○	
Motor inspection				○
Impeller inspection				○
Pump inspection				○
Hull inspection				○
Data pickup	○			

* Fuel oil
**Lubricating oil

OBSERVATION OF DISCHARGED WATER

Observation System

After installing *TAKUMI*, measurements of temperature and salinity were carried out to clarify the behavior of discharged water. Fig. 6 illustrates a configuration of a drifting buoy system for observing the discharged water (Iseki, 2002). This system drifts with the surrounding water masses along the ambient current by a drogue attached to the bottom end. The drift motion can be monitored by GPS system, which can constantly transmit the location of buoy. The main buoy is equipped with a radar-reflector and a light for safety. An autonomous profiling vehicle mounted on a wire guide measures and records temperature, salinity and depth, automatically going up and down according to a pre-inputted program. An electromagnetic current recorder is also set on the top of drogue to measure the relative motion of the buoy system to the ambient current. In the actual observations, this system was put on a point close to *TAKUMI* and downstream side, and set free for drifting with discharged water masses.

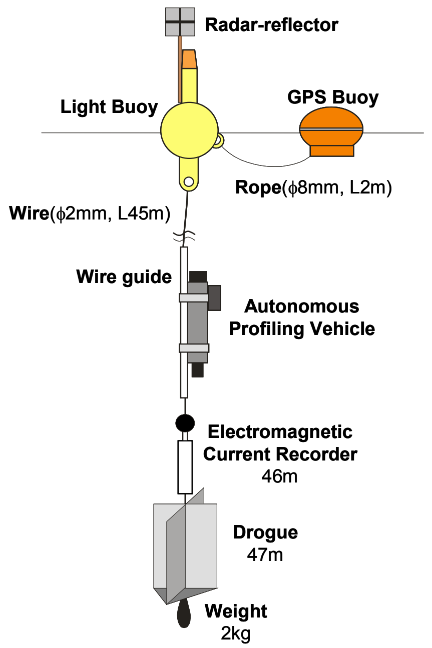

Fig. 6 Configuration of drifting buoy system for observing discharged water

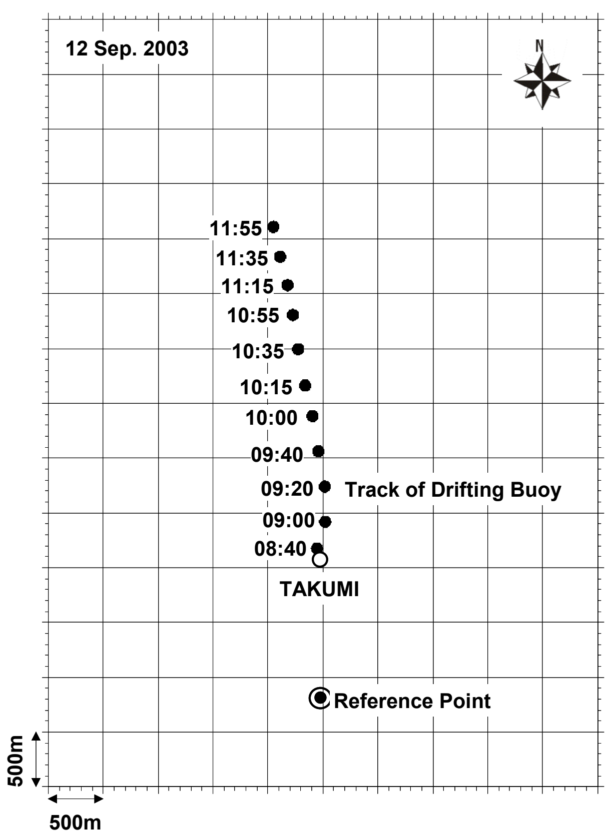

Fig. 7 Locations of observation points and reference point

Observation Data

Locations of observation points and reference point on September 12, 2003, when the conditions of temperature stratification and current were good, are shown in Fig. 7. The drifting buoy system was set free at 8:40 am, and moved to about 3 km downstream along the ambient current of 0.28 m s^{-1} in average. The vertical profiles of temperature and salinity at the reference point were measured by *SEIYO-MARU*, which is a research vessel of Tokyo University of Marine Science and Technology.

The obtained temperature-salinity (T-S) diagram at the reference point is shown in Fig. 8. The potential temperature and salinity in surface layer (5 m depth) are 24.0 ºC and 33.95, respectively. On the contrary, those in deep layer (200 m depth) are 11.1 ºC and 34.55, respectively. From these data, the ideal potential temperature and salinity of mixed seawater discharged from *TAKUMI* can be calculated as 19.7 ºC and 34.13, respectively. The potential density of the mixed water is almost the same as that of the surrounding water at 20 m depth.

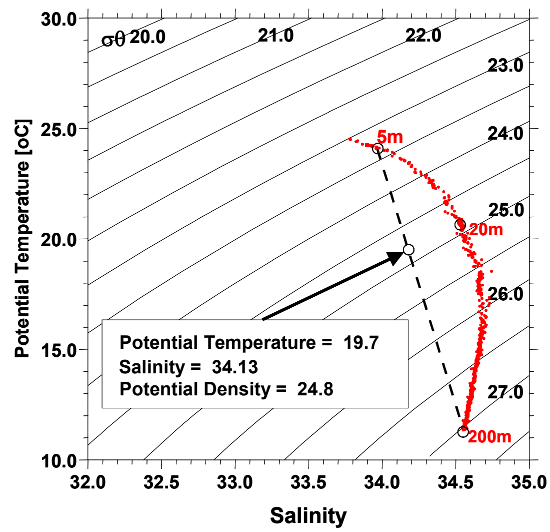

Fig. 8 T-S diagram at reference point

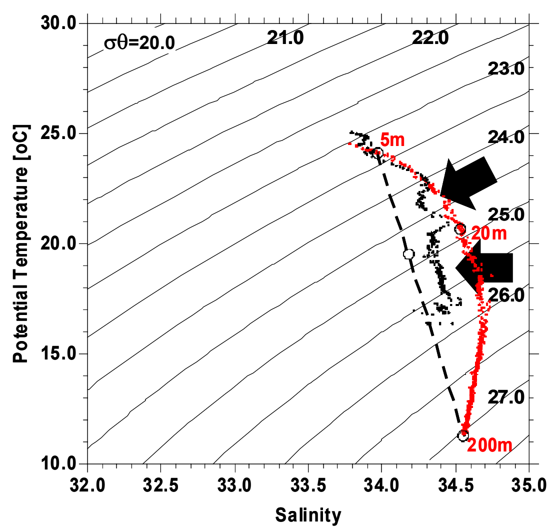

Fig. 9 T-S diagrams at 50 m downstream from *TAKUMI*

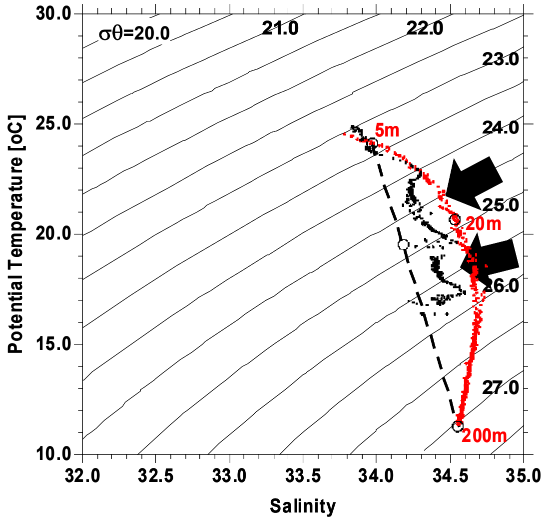

Fig. 10 T-S diagrams at 250 m downstream from *TAKUMI*

Figures 9 and 10 show the T-S diagram at 50 m downstream and 250 m downstream from *TAKUMI*, respectively. In these figures, red points represent the data at the reference point. For both cases, two remarkable peaks closing to the ideal character of discharged water appear in the observation data. This means that the discharged water might separate into two water masses and progress with very small diffusion.

Discussion

The T-S diagram obtained at the observation points, which is shown in Fig. 11, gives some important information as follows. The reference data draw a smooth curve. On the contrary, the observation data has a remarkable peak closing to the ideal character of mixed water. This peak represents the existence of discharged water, which is a mixture of surface and deep ocean waters. The less dilution rate becomes the higher peak value and the thicker peak breadth. This suggests that the vertical distribution and dilution rate of the discharged water can be estimated from the shapes of T-S diagrams.

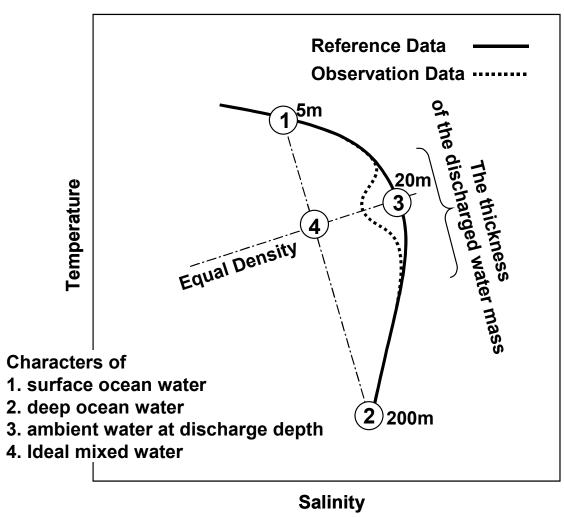

Fig. 11 Explanation of observed T-S diagram

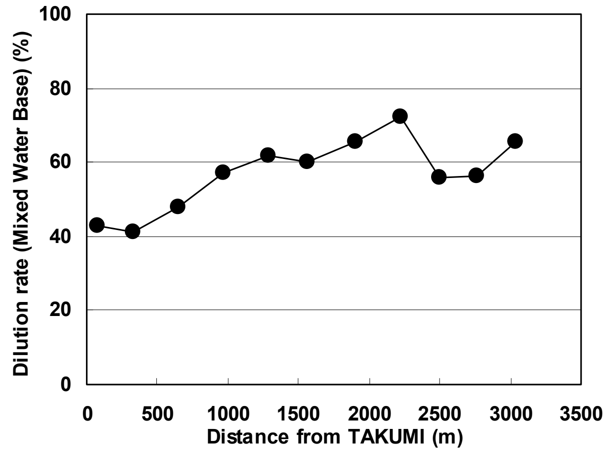

Fig. 12 Time history (corresponds to the distance from *TAKUMI*) of dilution rate of discharged water

Table 2. Research plan of the second term of Marino-Forum 21 project

	2005				2006				2007			
Observation of discharged water		◄	─	─	─	─	─	─	─	─	►	
Observation of phytoplankton		◄	─	─	─	─	─	─	─	─	►	
Observation of zooplankton		◄	─	─	─	─	─	─	─	─	►	
Observation of fish		◄	─	─	─	─	─	─	─	─	─	►
Estimation of fertilization effect				◄	─	─	─	─	─	─	─	►
Estimation of CO_2 emission rate				◄	─	─	─	─	─	─	─	►
Improvement of ONE*	◄	─	─	─	─	►						
Investigation of OTEC** engine						◄	─	─	►			
Feasibility study for practical use									◄	─	─	►
SEA*** for practical use		◄	─	─	─	─	─	─	─	─	─	►

*Ocean Nutrient Enhancer
**Ocean Thermal Energy Conversion
***Strategic Environmental Assessment

Figure 12 illustrates the time history (corresponds to the distance from *TAKUMI*) of dilution rate of discharged water, which is estimated from the peak values of T-S diagrams of all observation data. If the peak value is plotted at the middle of the line from Point 3 to Point 4 shown in Fig. 11, the dilution rate is 50 %. Point 3 and 4 represent the dilution rate of 100 % and 0 %, respectively. The 40 % of the mixed water is diluted just after discharge. However, the dilution rate slowly increases with increasing the distance, and keeps less than 70 % at 3 km downstream from *TAKUMI*. This means that the behavior of nutrient in the discharged water mass is possibly observed, because the limit of dilution rate for the detection of nutrient is about 90 % in this case.

FUTURE PLAN

The Marino-Forum 21 continues to organize the ocean nutrient enhancer *TAKUMI* project. The second term of a three-year project started in April 2005. The purpose of the second term is to confirm the effect of enhancement of marine primary production and to establish the technology for practical use of ocean nutrient enhancer.

Table 2 shows the research plan of the second term of this project. In order to confirm the effect of enhancement of marine primary production, observations of discharged water, phytoplankton, zooplankton and fish will be carried out for three summer seasons. The fertilization effect and CO_2 emission rate will be estimated based on the observation data. On the contrary, in order to establish the technology for practical use of ocean nutrient enhancer, the technology of *TAKUMI* will be improved, and the application of ocean thermal energy conversion (OTEC) will be investigated as a renewable energy for pumping up DOW. Feasibility study and strategic environmental assessment are also listed in the research plan for practical use of ocean nutrient enhancer. These researches will be performed by a consortium, which consists of private companies, universities and national institutes.

ACKNOWLEDGEMENTS

This study is financially and sympathetically supported by Marino-Forum 21 and Fisheries Agency of Japan. The authors are deeply indebted to Prof. Masayuki Mac Takahashi, a chair of Marino-Forum 21 project, for his helpful suggestion.

REFERENCES

Iseki, K (2002). "Fertilization in the Open Ocean and Observation of Behavior of Discharged Deep Ocean Water: Validity of Drifting Buoy and Autonomous Profiling CTD-Chlorophyll Sensor", *Deep Ocean Water Research*, Vol 3, No 2, pp 83-90 (in Japanese).

Liu, CKC (1999). "Artificial Upwelling and Open Ocean Mariculture - Formation of a Nutrient-rich Deep Ocean Water Plume", *Proc, International OTEC/DOWA Conf '99*, pp 288-299.

Ouchi, K, Yamatogi, T, Kobayashi, K and Nakamura, M (1998). "Density Current Generator - A New Concept Machine for Agitating and Upwelling a Stratified Water Area", *Proc Ocean Community Conf '98*, MTS, pp 129-136.

Ouchi, K (2003). "Ocean Nutrient Enhancer "Takumi" for the Experiment of Fishing Ground Creation", *Proc 5th Ocean Mining Symposium*, ISOPE-OMS, pp 37-42.

Otsuka, K (2001), "Recent Researches on Deep Ocean Water Applications in Japan", *Proc 4th Ocean Mining Symposium*, ISOPE-OMS, pp 144-149.

Ryther, J (1969). "Photosynthesis and Fish Production in the Sea", *Science*, Vol 166, pp 72-76.

Takahasi, MM (2000). *Deep Ocean Water as our next natural resource*, Terra Scientific Publishing Co., Tokyo, p 99 (in Japanese).

Takahasi, MM and Ikeya, T (2004). "Ocean Fertilization Using Deep Ocean Water (DOW)", *Deep Ocean Water Research*, Vol 4, No 2, pp 73-87.

Yamakoshi, Y, Aketa, S, Suzuki, S, Maeda, H, Miyajima, S and Shin, H (1991). "Motion Measurements of a Floating-Type Deep Ocean Water Utilization System", *Gyosen*, Vol 292, pp 122-136 (in Japanese).