The Blue Revolution: The Key to Hydrogen from OTEC

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While the Green Revolution improved grain cultivation and has been recognized as an important accomplishment of science, the Blue Revolution promises much more. All indications are that the Next Frontier is not space, but the open ocean. At 1000 meter depths in the region bounded by the Tropics of Cancer and Capricorn, is nutrient-rich seawater at 4°C, that can serve as a cold thermal sink for ocean thermal energy conversion (OTEC) systems to produce electricity, and as fertilizer to sustain mariculture activities. If only one part in ten thousand of the daily insolation falling in this band can be converted to useful products, the food and energy needs of society would be satisfied into the foreseeable future. This warm portion of the ocean is characterized as a wet desert, for the net primary productivity is low at around one-tenth that of tropical rain forests. However, as certain aquatic species are known to be from two to five times more efficient than any terrestrial plant, if technology can be developed to utilize this currently unused resource base, at hand will be a vast region providing immense sustainable resource and habitat opportunities. The Blue Revolution promises this broad package of natural products, only one possible option being hydrogen fuel.

hydrogen production, ocean thermal energy conversion, Blue Revolution

□□□INTRODUCTION

While Henry Cavendish discovered hydrogen in 1766, the early history of OTEC begins with D'Arsonval, of France, who first proposed the concept in 1881. One of his students, Georges Claude, conducted field experiments off Cuba in the 1930's. As has been the experience with many ocean engineering demonstrations, a major storm damaged the equipment and Claude never was able to attain net positive electricity.

The modern history has mostly taken place in Hawaii, with a sprinkling of Japanese projects, although India now appears ready to join the net-positive club. Mini-OTEC, a venture headed by Lockheed, reached a net output of 18 kW on a government barge off Keahole Point of the Big Island of Hawaii in 1979. It is interesting to note that in the months following, Senator Spark Matsunaga introduced the very first OTEC and hydrogen bills in the U.S. Senate. OTEC legislation was enacted 1980, and went so far as mentioning a 1999 target of 20,000 MW, but it took another decade for the hydrogen bill to be passed by Congress and signed and named the Matsunaga Act by then-President George H.W. Bush in 1990. Both concepts, though, remain in the formative stage. Unless the India experiment succeeds, OTEC will stay at zero MW installed capacity, and hydrogen continues to be a very expensive proposition.

The Natural Energy Laboratory of Hawaii Authority on the West Coast of the Big Island of Hawaii (see Figure 1) has been home to the major OTEC projects and sprouting marine nutraceuticals, coldwater agriculture crops, seafood, pearls, and a range of other products. Nearing a quarter century of operation, about 30 companies are producing a variety of bioproducts using deep ocean water. Japan now has more than ten such facilities, but mostly for special shrimp, vegetable and imbibable commodities. Korea and other countries of Asia are planning similar activities.

Figure 1. Aerial Photo of the Natural Energy Laboratory of Hawaii Authority

The Blue Revolution came together through a series of workshops and conferences in the United States [1,2,3] as a natural outgrowth of the early OTEC experiments, for it became immediately clear that OTEC electricity would be very expensive for a long time to come, but that the nutrient-rich, coldwater effluent had special attractive qualities to make the package of co-products commercially interesting. A recent thrust appears to be the possibility of the United Nations taking on the mission to coordinate international cooperation in this area [4]

OCEAN THERMAL ENERGY CONVERSION (OTEC)

The driving natural mechanism to power the Blue Revolution is ocean thermal energy conversion, or OTEC, a proven, well-documented technology that extracts clean, renewable solar thermal energy from temperature differences in the ocean [5,6,7]. The U.S. Federal government alone has spent more than $250 million on OTEC R&D. Japan, India, France and Taiwan have also expended many tens of millions.

There are three primary production cycles: open, closed and hybrid. Open cycle generally can be configured to produce the most amount of freshwater, and all show, because of attractive deep ocean water properties, huge potential for supporting a range of co-products, from aquaculture to air conditioning to environmental remediation.

References 5-7 can be consulted to learn more about the thermodynamics, technology and applications areas. Suffice it to say that OTEC works in a manner just the opposite of a conventional refrigerator that consumes electricity to cool things, while discarding heat. For OTEC, the temperature difference of the warm surface and cold deep waters can be applied in a Rankine cycle to produce electricity. As this delta T (about 20 Celsius degrees) is small, the efficiency is low, meaning that the hardware must be massive and expensive. But the fuel, ocean water, is free, and no nuclear and minimal carbon, sulfur and nitrogen gaseous waste compounds are emitted. However, to be perfectly correct, carbon dioxide from the deep ocean water can escape to the atmosphere if marine biomass is not utilized within the total system.

The ocean regions which are best suited for OTEC are located near the equator. All the present total world energy demand, and more, can be supplied through conversion of the ocean water temperature differential that prevails in this zone, either through the generation of electricity or production of energy carriers such as hydrogen, ammonia or methanol.

The primary feature of the ocean in this locality is that the surface temperatures are more than 20 C degrees warmer than the deeper waters at 1000 meters, which the world over is in the range of 4 degrees Celsius. The second advantage of this 1000 meter fluid is that it is rich in nutrients, in the exact proportion as is necessary to promote growth, for these compounds derived from sea life in the photic zone. For example, comparing the water quality of surface with 600 meter waters off Keahole Point in Hawaii [8], there is 78 times more nitrogen and 15 times more phosphorous in the deeper waters.

Widespread implementation of OTEC has not occurred, primarily because of very high capital costs. However, increasing fossil fuel prices and/or possible future restrictions on the use of these conventional energy sources, combined with co-products, including value added environmental benefits, make OTEC a serious contender for future application. Project Blue Revolution was formed to provide a systems approach to integrating all elements of the endeavor.

OTEC TECHNOLOGY DEVELOPMENT

The three critical OTEC components needing breakthroughs are the closed and hybrid cycle heat exchanger, open cycle turbine and coldwater pipe. These are the major pieces of system equipment costing the most dollars.

Titanium was initially used in the heat exchanger because the goal was to prove technical feasibility, that is, show that the temperature differential in the ocean could be used to produce net positive energy. It worked. Now, the key will be cheaper materials. Aluminum appears to be the metal of choice. The economics look promising. A factor of ten improvement in cost appears to be feasible, and much of this has been shown to work in prototype experiments.

The low pressure, open cycle OTEC turbines that have been employed to date in prototype OC-OTEC systems were retro-fit orphans from industry. Open cycle systems are currently limited by a maximum validated (tested) turbine capacity of 250 kW. At 5 megawatt and larger sizes, either an expensive modular approach must be adopted or innovative turbines need to be developed that take advantage of next generation non-metallic materials. There is no market today to promote this development.

A 30 meter diameter coldwater pipe will be required for a 400 MW floating OTEC powerplant. Pipes for OTEC have been manufactured from plastic and/or steel. The utilization of deep ocean pumps pushing the fluid up an inflatable fabric pipe has been discussed to reduce material costs. Mooring and structural strength then will become follow-on problems. Very little R&D has gone into developing innovations.

OTEC FOR ENVIRONMENTAL REMEDIATION

The widespread use of OTEC would displace fossil fuel consumption and reduce atmospheric emissions of greenhouse gases. This would contribute to reducing radiative forcing that can negatively affect global climate. In addition, should a means be developed to promote marine biomass growth using the deep ocean nutrients, it may be possible to modestly increase carbon dioxide uptake from the atmosphere for photosynthesis [9]. It should be noted, however, that deep ocean water contains substantial amounts of carbon that can by itself sustain the photosynthetic processes that will occur when the deep water is exposed to sunlight.

The combination of a floating coal powerplant with an OTEC facility to enable deep ocean sequestration of CO_2 has been proposed [10]. OTEC uses cold deep sea water as a thermal sink, while ocean sequestration treats it as a repository for anthropogenic CO_2. These technologies have the potential for synergy, including the sharing of platforms and equipment, addition of CO_2 to the warm water OTEC intakes to prevent biofouling of pipelines and heat exchangers, exploiting the negatively buoyant CO_2 enriched sea water to drive part of the upward water transport for OTEC, reduction of pumping costs for sequestration, and carbon tax credits.

As an early next step, the International Ocean Alliance Floating Platform Summit [11] suggested a demonstration on a decommissioned oil platform, combining a 10-100 MW fossil fuel powerplant, small OTEC system and various associated co-products for testing offshore Hawaii waters. Hydrogen would be one of those products. In the long term, as OTEC grazing plantships will be located in the warmest portion of the oceans, where hurricanes are formed, it might be possible to reduce the intensity of these ocean storms with an armada of platforms as a result of the associated surface water cooling [12].

OTEC ECONOMICS

The electricity from next generation 1-10 MW OTEC facilities will cost more than $0.25/kWh. There have been island communities long in this price range, with some approaching an unsubsidized $1/kWh. With freshwater, aquaculture, air-conditioning and other co-products, a major resort or military base could justify the installation of an OTEC powerplant.

A 1 MW OTEC plant can produce up to 3500 cubic meters per day of potable water. The value added operational and marketing benefits of natural energy and self-sustainability are exploitable advantages. While the U.S. Department of Defense has carried out several studies to consider this alternative, there are hopes that an international governmental funding organization will have the will to break from tradition to symbolically demonstrate the value of this sustainable option. UNESCO of the UN has been approached to investigate.

With water credit, the Pacific International Center for High Technology Research has reported that a land-based 1 MW plant could be built to produce electricity at $0.25/kWh and 5 MW for about $0.10/kWh [13]. A 50 MW floating closed cycle hybrid OTEC facility, with water sold at $3/1000 gallons ($3/3.8 m^3), could produce electricity for $0.06/kWh (1990 dollars), although cost-effective transport of the water poses a challenge.

The fact of the matter is that energy prices are artificially maintained. Controlling forces, from industry and government, enjoy and want to maintain the current status quo. While World trends point to a greener future over time, the price of the Middle East wars and damage to the environment do not equitably enter into the cost of energy. These externalities can be accommodated through carbon taxes, elimination of certain fossil and nuclear incentives, carbon trading, add-ons to the price of gulf oil, and so on. OTEC/hydrogen and all the sustainable energy options, thus, will continue to have difficulty competing with the conventional alternatives unless a SARS-like or September 11 incident — like a really hot summer, where tens of millions perish — can galvanize decision-makers to level the playing field.

Short of a major crisis, then, OTEC electricity will not be commercially competitive for many years to come. With water, carbon, and/or co-product credits, the equation dramatically shifts in the direction of OTEC for niche island applications today. In the mid term, as oil becomes scarce, OTEC hydrogen and other fuels and chemicals can become attractive options depending on how much conventional energy costs subsequently rise. In the very long term, the concept of artificial upwelling for broad scale marine development with concomitant environmental benefits looms large as an exciting future.

HYDROGEN OVERVIEW

Hydrogen has been touted as the clean fuel of the future, but substantial technical, infrastructure, and economic challenges remain to be overcome before this dream becomes reality. The energy in commercially produced hydrogen currently stands at less than 1% of the world's energy consumption, with the vast majority of the H_2 employed for chemical synthesis. Moreover, most hydrogen continues to be produced from fossil fuels (e.g., steam reforming of natural gas) which attaches a greenhouse gas carbon penalty to H_2.

It is unnecessary to provide an extensive discussion on the state of hydrogen development, as this is a journal on this subject. However, in tune with many of the marine related activities ongoing in Hawaii are several showcase hydrogen projects worthy of mention.

In 2003, the Hawaii Fuel Cell Test Facility began operations in downtown Honolulu. This 4,000 ft^2 (370 m^2) facility currently houses three test stands designed to characterize full-size single-cell PEM fuel cells and a host of supporting equipment including on-site hydrogen generation and storage. Another project underway is the Hawaii Hydrogen Power Park. This facility will deploy and demonstrate an integrated system comprising electrolysis for hydrogen production, hydrogen storage, and a grid-connected fuel cell. The project will be located where a renewable energy source could be used for hydrogen production. Additional efforts at the University of Hawaii include research on ocean resources (CO_2 sequestration and methane hydrates), photoelectrochemical hydrogen production, biological hydrogen production, and hydrogen production by catalytic gasification of biomass in supercritical water.

THE BLUE REVOLUTION

The total marine system effort, beginning with exploratory science, through engineering development and field demonstrations, to develop new products and habitats in an environmentally enhancive manner, is the Blue Revolution. Picture, then, a grazing plantship, powered by OTEC, supporting a marine biomass plantation with next generation ocean ranches. Figures 2 and 3 depict the marine environment and systems configuration to capture this potential. Then consider several hundred, maybe even thousands, of these productive platforms. Current international law dictates that each, under certain circumstances, can legally become a nation. Imagine the United Nations in the 22nd Century.

Such is the promise and political complexity made possible by the Blue Revolution. Much of the thinking and early planning began a little more than a decade ago, when workshops were held, papers were published and plans were sanctioned. This was a period just after the end of the Cold War, when the notion of dual military-civilian applications was in vogue.

In 1992 the National Science Foundation and National Oceanic and Atmospheric Administration commissioned a study called "U.S. Ocean Resources 2000," to serve as a blueprint for action [1]. Another gathering linked to the Pacific Congress on Marine Science and Technology in 1992 projected that a 100,000 ft^2 (930 m^2) ocean resource incubator platform could be built and operated in the year 2000 for $500 million. It was argued that in view of the $2.4 billion cost of each B-2 bomber, this was an opportunity that could not be wasted. No peace dividend appeared after the fall of the Berlin Wall, and the opportunity, indeed, passed by.

What of the future? It can be projected that the Blue Revolution will occur, but maybe more slowly than earlier anticipated. Japan and Korea, the two largest shipbuilders can justify using their shipyards because they have very little natural resources and the open ocean is available at no political or financial cost. Japan, for example, has ten ti-

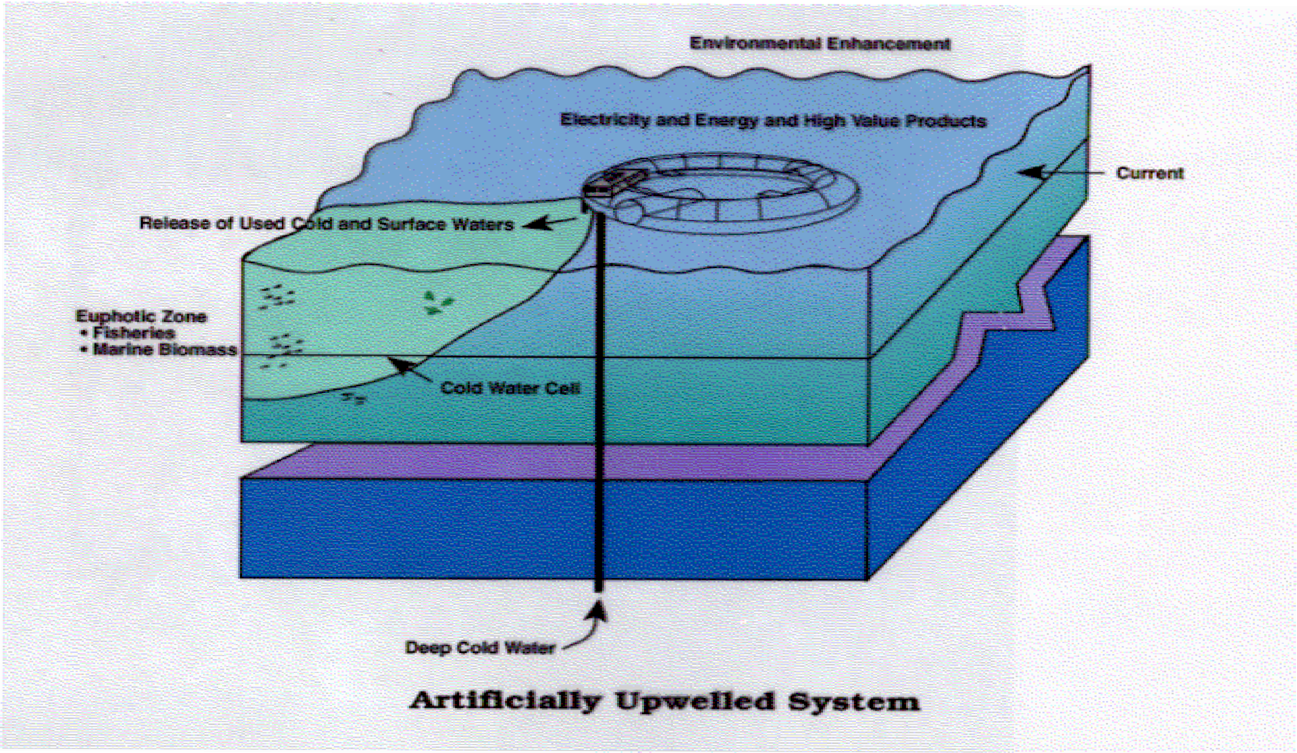

Figure 2. Marine Environment for a Blue Revolution System

PROJECT BLUE REVOLUTION MISSION

OCEAN RANCHING
OCEAN ENERGY
OCEAN MINERALS

SUPPORT ACTIVITIES
- Marine Materials
- Very Large Floating Structures
- Ocean Robotics
- Marine Science

PRODUCTS
- Electricity
- Air Conditioning
- Aquaculture and Agriculture Products
- Marine Biotechnology Pharmaceuticals
- Freshwater
- Strategic Minerals
- Methanol and Hydrogen Fuel

CAPABILITIES
- Commercial Incubator Facilities
- Environmental Observatory
- Science/Technology Laboratories
- Marine Materials Research Laboratory

UNIVERSITY OF HAWAII

Figure 3. Configuration of Systems Within the Blue Revolution Mission

mes more space in their Exclusive Economic Zone than on land, and Okinawa is marginal, but available, as an OTEC development site.

European seafaring nations might again consider colonization, this time the open ocean, where there are no obvious downsides, such as the sociological problems that came with the era beginning with Columbus. One cannot guess what Greenpeace and other environmental advocacy groups might do, but there are no native populations, not even whales, as permanent residents in the middle of the ocean [14].

Yes, if the Blue Revolution shows any kind of movement there is no doubt that society will probably feel compelled to invoke another Law of the Sea marathon, this next one to adjudicate over who can use the open ocean. But one could say that that is the way human systems progress.

THE BLUE REVOLUTION AND HYDROGEN

As it is currently difficult to economically transport electricity thousand of miles across the ocean, hydrogen becomes an obvious medium. Current development trends featuring fuel cells and cleaner air make the combination of OTEC and hydrogen a natural choice, for hydrogen can quite conveniently be produced on floating platforms and shipped using retrofitted tankers in the first stage, but with specially designed container ships in the future.

The Japan World Energy Network (WE-NET) has conducted the International Clean Energy Network Using Hydrogen Conversion Project for nearly a decade now, and has focused on transporting hydrogen by sea, initially from the lowest cost hydrogen soon to be made available from Canadian hydroelectric facilities. Other alternatives are also being studied.

Among the more innovative marine hydrogen related programs being explored are the following:

1. Large OTEC plantships someday will have hydrogen as a product. Studies are available detailing the production of hydrogen via water electrolysis on 50-400 MW OTEC plantships at costs low enough to manufacture on board and delivered to land-based users of ammonia and fertilizers to compete with conventional options [13]. A 64 MW plantship could produce 8270 tons (7500 tonnes) of hydrogen (one million GJ net heating value) per year. When 1000 megawatt OTEC plantships become competitive, this option will become viable to directly convert seawater into hydrogen.

2. Marine biotechnology experiments have begun to combine a genetically engineered marine microorganism, sunlight, and nutrients in the upwelled photic zone for the production of hydrogen. This remains a very long-term endeavor, as there will be many questions related to effects on the environment, capturing of the hydrogen and economics of the process.

3. A floating plantship can process 10 tons of coal per day (1.24 kg/sec) to produce 47,400 tons (43,000 tonnes) of methanol annually, and because of the hydrogen from OTEC electrolysis, provide a 1:1.3 ratio of coal to methanol, whereas, typical plants today have a 1:0.6 ratio. There would also be the carbon sequestration benefit as mentioned earlier. Another variation, a renewable one, would use marine biomass as the feedstock to replace coal, for a large portion of the overall coal cost is due just to delivery [15]. In either case, methanol might well be the ideal input fuel for reformers.

4. Methane hydrates in ocean seafloor sediments represent an enormous energy resource. The amount of CH_4 gas trapped in these ice-like solids is not known presently, but current estimates range between 10^{15} and 10^{16} standard m^3 of gas. Even at the lower end of this range, there is more energy in ocean floor methane hydrates than in all known reserves of conventional fossil fuels. Recovery of the CH_4 for energy is problematic, however, since the hydrates exist at depths in excess of 400 m and are generally found widely dispersed in sediments with complex flow characteristics. Industrial scale production of fuel gas from hydrates will probably not be realized for the better part of a

generation. Exploitation of marine methane hydrates (and ocean floor CH_4 seeps) for specialized subsea power application, on the other hand, may become reality within 5-10 years. The U.S. Navy has shown considerable interest in exploiting the in situ resource. Concepts being pursued include low-power, long-life biological fuel cells for seafloor moored instruments; methane/H_2 fuel cells for autonomous underwater vehicles and other submersibles; and H_2 production (from hydrates) and storage on the seafloor to refuel these submersibles.

IN CONCLUSION

The pathway from the obvious availability of ocean temperature differential resources to commercially viable renewable hydrogen will involve decades of effort. Getting there from here can only be attained through a long-term and purposeful program which can yield early benefits while maintaining the ultimate vision. As Sputnik was the catalyst and Apollo the culmination capturing the spirit of the 20th Century, can a terrestrial equivalent provide the galvanizing force in this new millennium to take our society to the next level of human development through intelligent utilization of our ocean resources in harmony with the natural environment? The Blue Revolution is poised to accomplish this task, and hydrogen could well be the ideal energy form for this and all future millennia.

APPENDIX: ABOUT THE CO-AUTHORS

Patrick Takahashi retired as Professor of Engineering and Director of the Hawaii Natural Energy Institute at the University of Hawaii. In 1979, while working in the U.S. Congress, he assisted in drafting both the original OTEC and hydrogen bills that were eventually enacted into law, which for two decades now, have guided R&D in the United States for the former and a dozen years for the latter. He was instrumental in working with others to bring to the University of Hawaii a number of national centers, including the National Science Foundation Marine Bioproducts Engineering Center, Department of Interior Center for Marine Resources and Environmental Technology and Department of Energy Hydrogen Center of Excellence. He helped create the Pacific International Center for High Technology Research, and formed their OTEC engineering office, while providing funds to initiate the biohydrogen program at the University of Hawaii. He was awarded the Bechtel Energy Award by the American Society of Civil Engineers, and has produced for the United Nations a textbook on OTEC, a chapter in a solar energy publication and various papers on sustainable resources.

Stephen Masutani has been with the University of Hawaii and the Hawaii Natural Energy Institute (HNEI) since 1994. He is currently an Associate Researcher and director of HNEI's Ocean Resources and Applications Laboratory. He also served with the Pacific International Center for High Technology Research from 1989 to 1998 as Senior Mechanical Engineer/CO_2 Project Manager and Program Manager. After receiving his M.S. and Ph.D. degrees from the High Temperature Gasdynamics Laboratory of Stanford University, he was a Visiting Scientist at the Hitachi Research Laboratory of Hitachi, Ltd. in Japan from 1985 to 1989. His current areas of research interest include methane hydrates, CO_2 ocean sequestration, and marine environment technologies.

Kenji Sumida is past president of the East-West Center. He has served in a wide range of capacities, from vice-president at the University of Hawaii to general in the Air Force to co-founder of a computer service company. He was a vice-president for the Pacific International Center for High Technology Research, providing fiscal and administrative supervision over the OTEC project funded by the U.S. Department of Energy and Japan's Ministry of Foreign Affairs. He has been associated with the Blue Revolution movement since the very early days of planning, and for several years, served on the Board of the Pacific Congress on Marine Science and Technology, International.

REFERENCES

1. P. Takahashi, U.S. Ocean Resources 2000: Planning for Development and Management, National Science Foundation and National Oceanic and Atmospheric Administration, June 9-11, 1992
2. D. Inouye, "The American Blue Revolution: a Solution for the 21st Century," Sea Technology, Vol. 33, No. 9, pp 23-26, 1992
3. P. Takahashi, "Project Blue Revolution," Journal of Energy Engineering, Vol.122, No. 3, pp 114-124, December 1996
4. P. Takahashi, J. Vadus and S. Masutani, "Energy from the Sea: The Potential and Realities of OTEC," Bruun Memorial Lecture, XXIInd Assembly of the Intergovernmental Oceanographic Commission of UNESCO, Paris, France, June 30, 2003
5. S. Masutani and P. Takahashi 1999: "Ocean Thermal Energy Conversion," from Encyclopedia of Ocean Sciences, J.G. Webster, ed., John Wiley & Sons, Vol.18, p.93-103, 1999
6. P. Takahashi and A. Trenka, Ocean Thermal Energy Conversion, UNESCO Energy Engineering Series, John Wiley and Sons, 1999
7. W. Avery and C. Wu, Renewable Energy from the Ocean; A guide to OTEC. Oxford University Press, 1994
8. K. McKinley and A. Fast, "Increasing Productivity by the Utilization of Deep Ocean Water," Proceedings of Engineering Research Needs for Off-Shore Mariculture Systems, National Science Foundation, p.421, 1991
9. P. Takahashi, K. McKinley, V. Phillips, L. Magaard, and P. Koske, "Marine Macrobiotechnology Systems," Journal of Marine Biotechnology, Vol. 1, No. 1, p.9-15, 1993
10. L. Golmen and S. Masutani, "Combining Carbon Dioxide Ocean Sequestration and OTEC: A Win-Win Solution?" in Greenhouse Gas Control Technologies, D. Williams,, B. Durie, P. McMullan, C. Paulson, and A. Smith, eds., CSIRO Publishing, Victoria, Australia, p.499-504, 2001
11. S. Masutani and P. Takahashi, Proceedings of the International Ocean Alliance Floating Platform Summit, for the Hawaii State Legislature, Honolulu, Hawaii, December 3-5, 1998
12. S. Dunn, M. Dhanek, M. Teng, and P. Takahashi, "Artificial Upwelling for Environmental Enhancement," Proceedings of Oceanology International IOA '97, Singapore, pp 191-196, May 13, 1997
13. L. Vega, "Economics of Ocean Thermal Energy Conversion," from Ocean Energy Recovery, R. Seymour, editor, American Society of Civil Engineers, pp 152-181, 1992
14. P. Takahashi, "Colonization of the Open Ocean," Proceedings of the Second United Nations International Conference on Oceanography, Lisbon, Portugal, November 14-19, 1994.
15. P. Takahashi, C. Kinoshita and S. Oney, "Facilitating Technology for Fuel Production and Energy-Enhanced Products," from Ocean Energy Recovery, R. Seymour, editor, American Society of Civil Engineers, pp 293-305 1992.