Intergovernmental Oceanographic Commission

Anton Bruun Memorial Lecture

Energy from the Sea: the Potential and Realities of Ocean Thermal Energy Conversion (OTEC)

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The Bruun Memorial Lectures

This series of lectures is dedicated to the memory of the noted Danish oceanographer and first chairman of the Commission, Dr Anton Frederick Bruun. The "Anton Bruun Memorial Lectures" were established in accordance with Resolution 19 of the Sixth Session of the IOC Assembly, in which the Commission proposed that important inter-session developments be summarized by speakers in the fields of solid earth studies, physical and chemical oceanography and meteorology, and marine biology.

Twenty-first Session of the Assembly, 9 - 13 July 2001

Operational Oceanography — a perspective from the private sector by Ralph Rayner. IOC Bruun Memorial Lectures, Paris, UNESCO, 2003. *(Technical Series, 58)*.

Twentieth Session of the Assembly, 29 June - 9 July 1999

Ocean Predictability, by John Woods. In: IOC Bruun Memorial Lectures, Paris, UNESCO, 2000. *(Technical Series, 55)*.

Nineteenth Session of the Assembly, 2 - 18 July 1997

Common Resources, Conflicting Uses: The Economics of Coastal Resources Management, by John A. Dixon. Sixty-five Years of the Continuous Plankton Recorder Survey: 1931-1995, by Philip C. Reid; Sonia D. Batten; Harry G. Hunt.

Eighteenth Session of the Assembly, Paris, 13 - 26 June 1995

Some Results of the Tropical Ocean and Global Atmosphere (TOGA) Experiment Application of El Niño Prediction to Food Production in Peru, by Pablo Lagos; New Applied Knowledge Resulting from the TOGA Programme in all Three Oceans, by James J. O'Brien.

Seventeenth Session of the Assembly, 25 February - 11 March 1993

The Role of Marine Research, Systematic Observations and Related Capacity Building and Technology Development for Ocean and Coastal Zone Sustainable Development: The Global Ocean Observing System, by John Woods; Long-Term Systematic Environmental Monitoring and Sustainable Development: The Role of WMO and of the National Meteorological and Hydrological Services, by G.O.P. Obasi.

ANTON FREDERICK BRUUN

ANTON FREDERICK BRUUN was born on the 14th of December 1901 as the oldest son of a farmer, but a severe attack of polio in his childhood led him to follow an academic, rather than agrarian, career. In 1926 Bruun received a Ph.D. in zoology, having several years earlier already started working for the Danish Fishery Research Institute. This association took him on cruises in the North Atlantic where he learned from such distinguished scientists as Johannes Schmidt, C.G. Johannes Petersen and Thomas Mortensen.

Of even more importance to his later activities was his participation in the *Dana* Expedition's circumnavigation of the world in 1928-1930, during which time he acquired further knowledge of marine animal life of the sea, general oceanography and techniques in oceanic research.

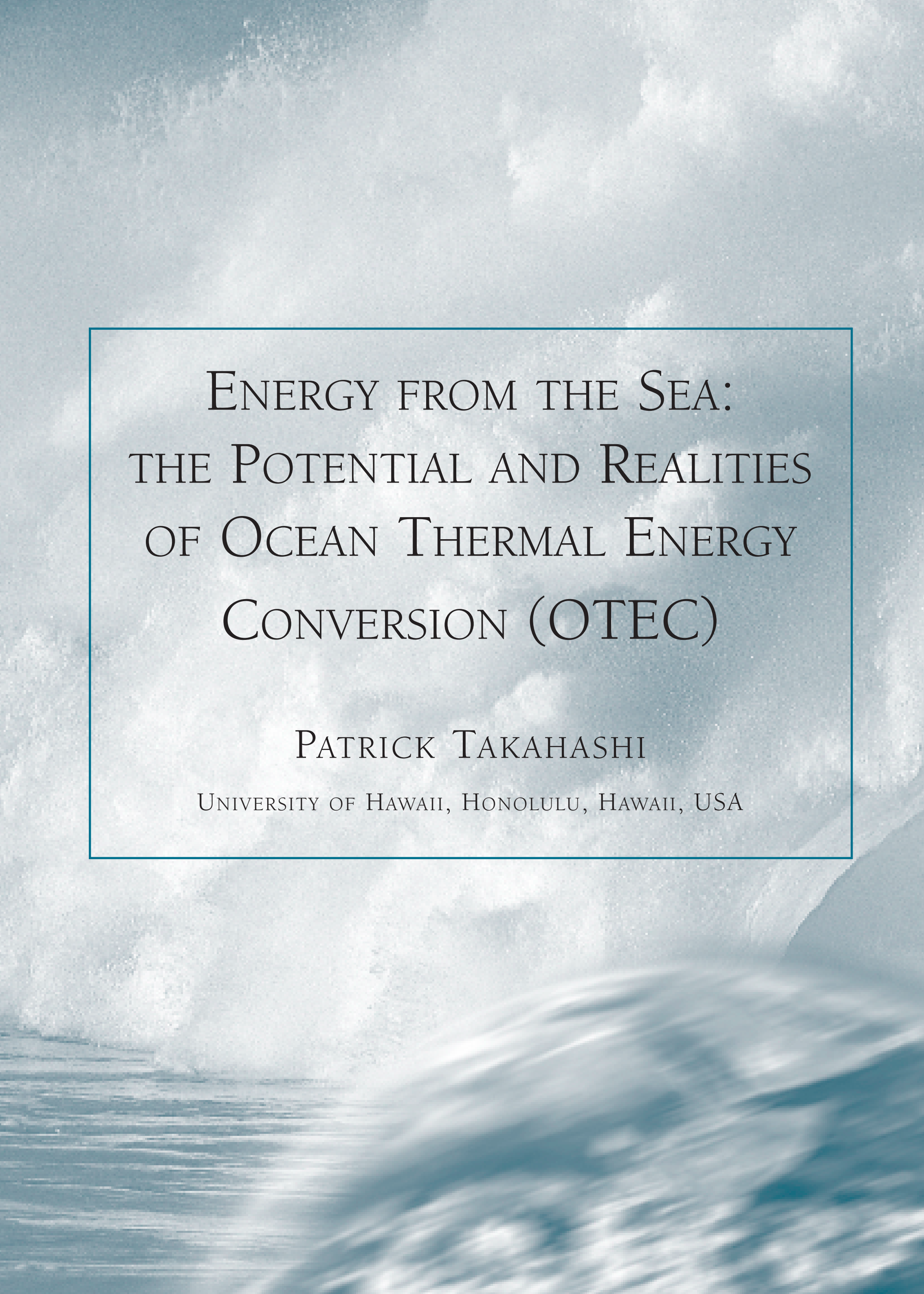
In the following years Bruun devoted most of his time to study the rich *Dana* collections and to the publication of his treatise on the flying fishes of the Atlantic. In 1938 he was named curator at the Zoological Museum of the University of Copenhagen and later also acted as lecturer in oceanology.

From 1945-1946 he was the leader of the *Atlantide* Expedition to the shelf areas of West Africa. This was followed by his eminent leadership of the *Galathea* Expedition in 1950-1952, which concentrated on the benthic fauna below 3,000 m and undertook the first exploration of the deep-sea trenches, revealing a special fauna to which he gave the name "hadal".

The last decade of Bruun's life was devoted to international oceanography. He was actively involved in the establishment of bodies like SCOR, IACOMS, IABO, and the IOC and was elected IOC's first chairman in 1961.

His untimely death a few months later, on 13 December 1961, put an end to many hopes and aspirations.

In 1962, the former US Presidential yacht *Williamsburg* was converted into a research vessel and renamed Anton Bruun in honour of the great scientist. The *Anton Bruun* took part in the International Indian Ocean Expedition (1959–1965) and, in the late 1960's, circumnavigated the globe in one of the last great exploratory expeditions of modern oceanography.



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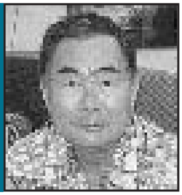


Patrick Takahashi
Director Emeritus, Hawaii Natural Energy Institute

Patrick Takahashi, who presented this Bruun Memorial Lecture 2003, retired as Professor of Engineering and Director of the Hawaii Natural Energy Institute (HNEI) at the University of Hawaii, and served as vice president for development of the Pacific International Center for High Technology Research (PICHTR). 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 bringing 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, and formed the PICHTR OTEC engineering office. He was awarded the Bechtel Energy Award by the American Society of Civil Engineers, and has produced for the United Nations a Guide to OTEC for Developing Countries (1999), a chapter in a solar energy publication and various papers on sustainable resources.

About the Co-Authors

Joseph Vadus was Senior Technology Advisor for the National Ocean Service of the National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce. He headed the Ocean Engineering program in the early days of OTEC and funded many of the research and development activities which established OTEC foundations. He is Vice President of the Institute of Electrical and Electronics Engineers (IEEE/OES) and President of the Global Ocean Inc. From 1980-1995, he served as Scientific Leader for Marine Technology in the U.S.- France Cooperative Program in Oceanography and was awarded the French Order of Merit, "Chevalier de l`Ordre National du Merite." He received the Marine Technology Society

(MTS) Compass Distinguished Individual Achievement Award in 1990; the IEEE Centennial Medal in 1984; and The IEEE Millennium Medal in 2000. He is a Fellow of the IEEE, MTS and U.K.'s Society For Underwater Technology.

Stephen Masutani is an Associate Researcher with the Hawaii Natural Energy Institute (HNEI) at the University of Hawaii. Dr. Masutani was a member of the team at the Pacific International Center for High Technology (PICHTR) who designed and operated the net power producing Open Cycle OTEC system in the early 1990s. He has been project manager of the international field experiment on carbon dioxide ocean sequestration and currently is leading a new program on marine methane hydrates sponsored by the US Office of Naval Research.

Opening remarks

A Google search of the keywords “ocean energy” produced more than a million entries. Merely boiling this information down in a technical presentation describing the various forms of sustainable marine energy options would not be particularly useful, nor productive, for the purpose of the audience and this event.

The Intergovernmental Oceanographic Commission (IOC) has supported a range of Big Ocean projects. This is all well and good, as the IOC is a governmental international organization and we need to first understand the sea around us. But, has the time come to do something more useful for society? While the paper will summarize the essence of ocean energy, the timing might be ideal to more importantly suggest a pathway to interest this IOC assemblage, and potential readers, towards a sea of change, a *Blue Revolution*.

Thus, given the current state of knowledge in this field, a system will be proposed for development to yield next generation forms of sustainable energy, seafoods, green materials and habitats, in a manner which can enhance the environment. This bridge to the future has been referred to as *The Blue Revolution*.

Surprising commercial interest has recently been shown in Deep Ocean Water Applications (DOWA). The attraction of this nutrient-rich, cold, and essentially pathogen-free fluid has, thus far, mostly been nurtured by a romance of the seas, cultural preferences and good marketing, but the sudden availability of more than a dozen deep ocean water facilities is an important early element of *The Blue Revolution*.

As such, and to keep within time and space constraints, in consideration of the vast long-term potential of the package of possible co-products—electricity, hydrogen, bio-alcohol, freshwater, ocean ranches and marine biomass plantations, to mention only a few—from artificially upwelled deep ocean water, this paper will focus on ocean thermal energy conversion, or OTEC, as the driving mechanism to bring reality to *The Blue Revolution*.

Energies from the sea

Marine fossil fuels

Wave energy

Offshore wind

Tidal energy

Current energy

Salinity gradients

Marine biomass plantations

Ocean Thermal Energy Conversion (OTEC)

Marine Fossil Fuel

There is conventional fossil energy, such as oil, coal and natural gas, and an interesting next generation option, marine methane hydrates (MMH) or gas-hydrates. The former is well established, and wells go deeper than one mile. The latter is the subject of the other Bruun Memorial Lecture 2003 given by Dr Harsh Gupta.

MMH are ice-like solids that are found in deep ocean floor sediment and arctic permafrost. The crystalline cages of water molecules can lock up biogenic and thermogenic gases consisting mainly of methane, but also carbon dioxide, hydrogen sulfide and higher molecular weight hydrocarbons. Although very little is known about the true extent of this resource, it is currently accepted that MMH contain at least twice the amount of energy than all the other conventional fossil fuels [1]. Thus, while these deposits are known to be a nuisance when drilling offshore for oil or gas, they are of such magnitude, that national programs have been initiated to develop strategies for commercial recovery of the methane fuel and international conferences have been held to share information on this resource and attendant environmental issues. While Japan is already drilling for MMH at several sites in their Exclusive Economic Zone (EEZ), the expectation is that it will be at least a decade before commercialization is attainable.

MMH, however, come as a double-edged sword, for already, methane is bubbling to the surface, and one molecule of this gas is 20 times more dangerous than carbon dioxide in causing the greenhouse effect. Thus, if global climate warming does occur, further raising the temperature of the ocean, the current metastable state of equilibrium at the lower boundaries could be affected, perhaps even triggering an increasing cascade of methane into the atmosphere. The particularly troublesome factor is that scientists for the most part have not considered seriously this admittedly doomsday scenario, and global climate change models do not generally include marine methane because no one knows how much to crank into the equation.

Recent results, however, suggest that there is historical precedent to be concerned. A study conducted by scientists at NASA's Goddard Institute for Space Studies indicates that destabilization of MMH resulted in a huge release of methane from the ocean into the atmosphere that heated the Earth's atmosphere up to 7 Celsius degrees 55 million years ago during the Paleocene/Eocene Thermal Maximum period.

(Details on the next five sections can be found in Reference [1], Chapter 19, pp 373-402, co-authored by J. Vadus, R. Bregman and P. Takahashi)

Wave Energy

Ocean wave energy conversion systems are producing, maybe, a total of about one megawatt today. Many systems have been tried, and most have failed. Much of the cataclysmic damage can be explained by the fact that water is 850 times denser than air. Wind energy conversion systems can self-destruct for a variety of reasons, so maintaining a configuration with three orders of magnitude more trauma can indeed be a challenge. Understandably, foundation, materials, foul weather and design problems have continued to plague this option.

A report from the United Kingdom estimates that 0.1 % of the energy inherent in offshore waves can supply the world's energy needs five times over, provided it could all be harnessed economically. Another study estimates that the power released by waves breaking along the world's coastlines has the equivalent output of three thousand 1,000 megawatt (MW) powerplants. A good site reportedly can produce 65 MW per mile.

While there is a wide variety of wavepower devices, there are three general types:

- surface-followers using floats and pitching devices,
- oscillating water columns, and
- surge or focusing devices.

Among the notable experiments have been:

- The "Salter Duck," so named because it was developed by Steven Salter of the University of Edinburgh, and is of the pitch type, looking like a series of floating ducks, and capable of capturing up to 80% of the energy from incoming waves.
- Japan has had a wave energy program for many years, with the Kaimei, a 500-ton barge-like platform which produced 125 kW and the "Mighty Whale," a 50 kW system of pneumatically driven turbines, as the two most prominent. Both were based on oscillating water columns.

- Construction is underway at Port Kembla in Australia on a wave energy system based on the oscillating water column principle that utilizes an energy focusing caisson and an innovative air turbine.
- Norway has tried the surge principle using a tapered channel, and operated a 350 kW facility in 1986.
- India proposed a five MW Madras project and Sweden a one MW plant along their Atlantic Coast. The United States, more recently, the State of California, has supported assorted demonstration programs.

Offshore Wind

Offshore windpower shows good promise. One of the world's largest proposed windfarm ultimately hopes to produce 520 MW on a sandbar seven km offshore in the Irish Sea near Dublin, and is expected to provide 10 percent of their electrical needs.

An offshore windfarm of 170 windmills, costing about $700 million, was proposed to be located five miles offshore of Cape Cod. While welcomed by environmental groups, it is opposed by fishermen and some private interests concerned about navigation and aesthetics. There have also been financing delays.

The biggest hurdle to offshore windfarms is cost, exacerbated by the harsh environment. It is tough enough to do it on land.

Tidal Energy

Tidal energy has been used since the 11th Century when small dams were built along ocean estuaries and small streams. The tidal water turned water wheels to mill grains.

Easily the biggest installation is the 240 MW Rance River facility in France, now operating for almost four decades. China built several tidal power stations in the 1950s. In the '70s, a dozen more were installed, with the 3 MW facilities in Jiangxia and Baishakou being the largest. It is reported that eight such facilities are today operating at a total capacity of 11 MW.

Canada and Korea have conducted various feasibility studies. A 1,428 MW powerplant was proposed for the Bay of Fundy and 5,338 MW facility for Minas Basin. Inchon, Korea "only" has a 4.8-meter mean tide range, but a 480 MW design was completed. In Mezenskaya, Russia, with a tide of 20 meters, a 15,000 MW plant was proposed. Ten meter tides sound attractive, but the vast coastal real estate needed, preempting this space for other uses, cost and risk have forestalled development.

Current Engergy

The use of current turbines in the oceans is a comparatively recent idea. The Gulf Stream, for example, carries 30 million cubic meters of water per second, more than 50 times the total flow in all of the world's rivers. It is estimated that 25,000 MW can be generated. Aeroenvironment Company performed the Coriolis Project in these currents, and proposed 242 170-meter diameter turbines to produce 10,000 MW. Power would be delivered at $0.04 per kilowatt hour (kWh) in 1978 dollars. The reduction in current speed would be on the order of 1.2%, much less than its natural fluctuation. Studies have been undertaken in Canada and Australia for applications in those countries, plus the Philippines and Mexico.

The only true experiments were conducted in the Florida Current, where an ocean turbine was suspended at 50-meter depth, developing two kW of power. It is reported that UEK Corporation tested a 20 kW turbine in New York City's tidal East River.

Salinity gradients (SG)

Where rivers enter the sea, it is possible to take advantage of the osmotic pressure difference using a semipermeable membrane. Thermodynamically, the difference in the free energy of the two sides determines the power, which may be generated in a hydraulic system using a membrane, as electrical energy in a reverse electrodialysis cell, in a vapor turbine utilizing the difference in vapor pressure, or taking advantage of extension and contraction of special fibers.

The Amazon River could theoretically produce 470 MW of electricity using this SG and the Jordan River, which flows into the Dead Sea, provides a system capable of supporting a 100 MW powerplant where the calculated cost would have been $0.72/kWh in 1976 dollars.

The potential power from salinity gradients is on the order of one third the world production of energy. However, most of these gradient sites are situated in normal run-off coastlines where conversion would be very difficult and not be cost-effective. The technology to carry out commercial projects await a ten-fold improvement in the costs associated with efficiency of membrane, superstructure and maintenance.

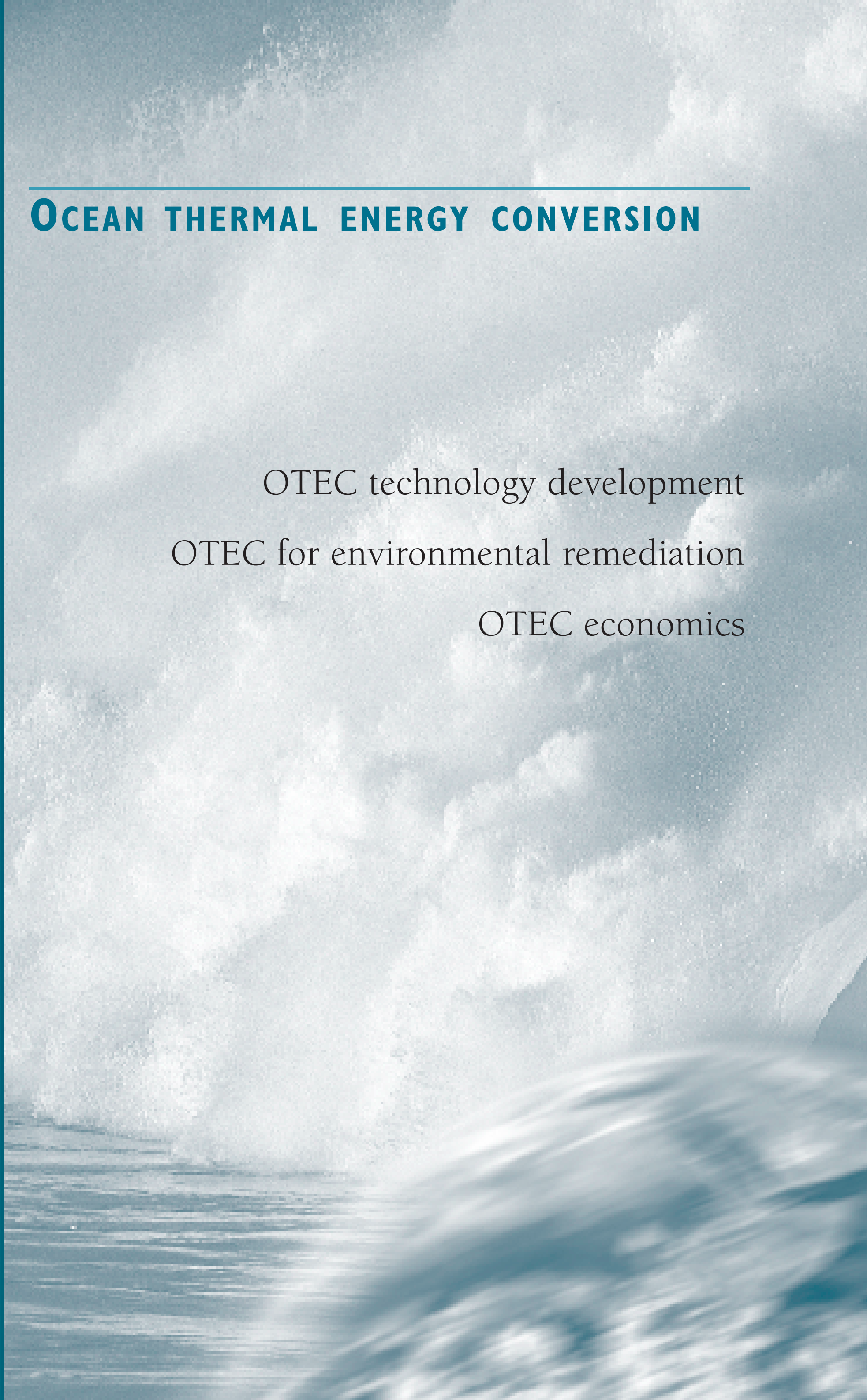
Marine Biomass Plantations

It is reported that marine biomass can grow two to five times more efficiently than any land plant. This is particularly true when comparing marine microalgae with terrestrial plants, such as trees and grasses.

Kelp (*microcystis prifera*), a macroalgae, has been particularly well studied. This plant absorbs nutrients through the entire structure, whereas land species use only the roots, plus, energy needs for maintaining structural integrity are minimal, and thus can be applied to biomass production. The most publicized project is the General Electric-Gas Research Institute effort in 1979 off the coast of Southern California, funded by the National Science Foundation, and, later, what is now the Department of Energy. To put it simply, storms destroyed the project.

Four large advantages of marine biomass are that one, the marine farm can be placed in free ocean space; two, they grow in seawater, making irrigation unnecessary; three, with artificial upwelling, the fertilizer is free; and four, the feedstock and product transport systems do not require man-made roads. The combination of marine biomass plantations and ocean ranches will someday soon become a productive enterprise.

Ocean thermal energy conversion



OTEC technology development

OTEC for environmental remediation

OTEC economics

OTEC is a proven, well-documented technology that extracts clean, renewable solar thermal energy from temperature differences in the ocean [2, 3, 4]. The U.S. Federal Government alone has spent more than $250 million on OTEC R&D. France, India, Japan and Taiwan have also expended many millions.

There are three primary production cycles: open, closed and hybrid. Open cycle produces 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 2 to 4 can be consulted to learn more about the thermodynamics, technology and applications areas. Suffice 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 °C) 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 generated carbon, sulfur and nitrogen gaseous waste compounds are produced. 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 in the band 20 latitude degrees north and 20 latitude degrees south of the equator. Much, much more than the present total world energy demand can be supplied either through the generation of electricity or production of various 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 warmer than the deeper waters at 1,000 m, which the world over is in the range of 4 °C. The second advantage of this 1,000 m 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 zone of the sunlight penetration sufficient for photosynthesis. For example, comparing the water quality of surface with 600 m waters off Keahole Point in Hawaii [5], there is 78 times more nitrogen and 15 times more phosphorous in the deeper waters.

The early history of OTEC is all French. Arsène d'Arsonval (1851–1940) first proposed the concept in 1881, and one of his students, Georges Claude (1870–1960), conducted field experiments off Cuba in the 1930s. As has been the experience with many ocean engineering demonstrations, a major storm damaged the equipment before Claude was able to attain net positive electricity.

The modern history is mostly Hawaiian, with a sprinkling of Japanese, although India now appears to be 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 in 1979. A few years later, a Japanese group succeeded with a 100 kW gross system, also of closed-cycle design, on Nauru, but was, like Claude, wiped out by a hurricane. OTEC-1 tested a one MW size heat exchanger and large coldwater pipe in Hawaiian waters in the ‘80s, and a 260 kW gross open-cycle facility was built by the Pacific International Center for High Technology Research (PICHTR) at the Natural Energy Laboratory of Hawaii Authority (NELHA) in the ‘90s. The latter two projects were funded by the U.S. Department of Energy.

Home to the major OTEC projects and sprouting marine nutraceuticals, coldwater agriculture crops, seafood, pearls, and a range of other products, some examples report on the progress at NELHA:

- *Coldwater Fruit Crop (Strawberry)*: Strawberry plants cannot tolerate dry and hot desert conditions, which prevail at NELHA. However, the cold deep ocean water is passed through pipes, which condense, providing atmospheric irrigation. Apples and grapes fruit and various innovations in agriculture have been demonstrated.
- *Lobsters farming*: Imported lobsters are rejuvenated using deep, cold sea water among which the hybrid blue lobster is a colorful alternative that could have marketing potential.
- *Microalgae raceway:* High value products, such as biopharmaceticals and biopigments offer the greatest hope for commercial success. Astaxanthin, in particular, a natural red pigment of the carotoids group, is showing particular promise. An intriguing future commodity might well be Royal Hawaiian Rainbow Pearls.

Aerial shot of the Natural Energy Laboratory of Hawaii Authority on the West Coast of the Big Island of Hawaii

Nearing a quarter century of operation, nearly 30 companies are growing a variety of bioproducts using the deep ocean water.

Japan now has more than ten such facilities, but mostly for special shrimp, vegetable and water commodities. Korea and other countries of the Orient are planning for similar activities.

It is reported that India is very close to testing a one MW OTEC powerplant.

Widespread implementation of OTEC has not occurred because of very high capital costs. However, increasing fossil fuel prices and/or restrictions on the possible future use of fossil fuels, combined with co-products, including value added environmental benefits, make OTEC a serious contender for future application [6]. Project Blue Revolution describes this scenario in a later section.

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 turbine capacity of 250 kW. At five MW and larger sizes, they need to be completely re-designed to take advantage of next generation non-metallic materials. There is no market today to promote this development.

A 30 m 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 technologies requiring careful development. Very little R&D has gone into these innovations.

OTEC for Environmental Remediation

The widespread use of OTEC would reduce fossil fuel combustion. In addition, should a means be developed to promote marine biomass growth using the deep ocean nutrients, it is possible that carbon dioxide can be absorbed from the atmosphere to further reduce global climate warming [7].

The combination of a floating coal powerplant with an OTEC facility to enable deep ocean sequestration of CO_2 has been proposed [8]. 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 [9] 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 in Hawaiian waters. 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 eliminate or reduce the intensity of these ocean storms. [10]

OTEC Economics

The electricity from next generation one to ten 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 an OTEC powerplant.

A one MW OTEC plant can produce up to 3,500 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.

With water credit, it has been reported by PICHTR that a land-based one MW plant could be built to produce electricity at $0.25/kWh and five MW for about $0.10/kWh. [11] A 50 MW floating closed cycle hybrid OTEC facility, with water sold at $3/1,000 gallons ($0.8/1,000 liters), could produce electricity for $0.06/kWh (1990 dollars).

Can 100 MW and larger OTEC plantships someday produce hydrogen and other clean energy products? [12] 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 be delivered to land-based users of ammonia and fertilizers to compete with conventional options. A 64 MW plantship could produce 8,270 tons (one million GJ net heating value) of hydrogen per year.

A floating plantship can process 107 tons of coal per day (1.24 kg/sec) to produce 47,400 tons 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 just the delivery.

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 Iraq war 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 and most of the sustainable energy options, thus, will continue to have difficulty competing with the conventional alternatives unless a SARS[1] -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 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. The next section on *The Blue Revolution* suggests a critical next step to accelerate the process.

1. Illness known as Severe Acute Respiratory Syndrome that broke out in Asia in winter 2002–2003.

The blue revolution [13]

The next frontier is the open ocean. Largely not owned by any nation, nutrient-rich fluids at 4 °C are available 1,000 meters below the 20 degree-latitude-band surface. Just in this natural solar collector region, if only one part in ten thousand of the insolation can be converted to useful energy, the needs of society would be satisfied.

This warm portion of the ocean is currently characterized as a wet desert, for the net primary productivity is low, at approximately one tenth that of tropical rain forests. Yet, because there is almost ten times more of this ocean space, the annual productivities are similar. However, if artificial upwelling can be utilized to support marine growth only at typical land growth efficiencies, we can have ten times the annual production from this portion of the ocean around the equator. Plus, if scientific projections can be met, that marine productivity can be two to ten times higher than any land crop [14], society would have an even larger and brand new free "land" capable of producing enormous amounts of marine growth, with an intriguing greenhouse carbon sink potential. Let the Great Open Ocean Rush begin!

As only one example, consider seafood. All fisheries are now in some state of decline, some more serious than others, and a few in a very critical condition. The World population will continue to grow for some time, and nutritional patterns show a shift away from red meat to fish. At one time fish was cheaper than meat, chicken and pork. In most markets today, seafood is more expensive. Thus the change has already occurred.

More than 40% of all fish caught comes from 0.1% of the ocean where natural upwelling exists, with the sea already providing more edible protein than land. What if we are able to artificially upwell at profit? Is there a future for the ultimate ocean ranch? [15]

Picture, then, a grazing plantship, powered by OTEC, supporting a marine biomass plantation with next generation ocean ranches. Figures 1 and 2 (*see following pages*) depict the marine environment and systems configuration to capture this potential. Then consider several hundred, no, 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 for *The Blue Revolution* began a little more than a decade ago, when workshops were held, papers were published and plans were sanctioned [16, 17, 18, 19]. 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. Another gathering linked to the Pacific Congress on Marine Science and Technology in 1992 projected that a 100,000 square foot ocean resource incubator platform could be built and operated in the year 2000 for

Figure 1 *Project Blue Revolution Mission*

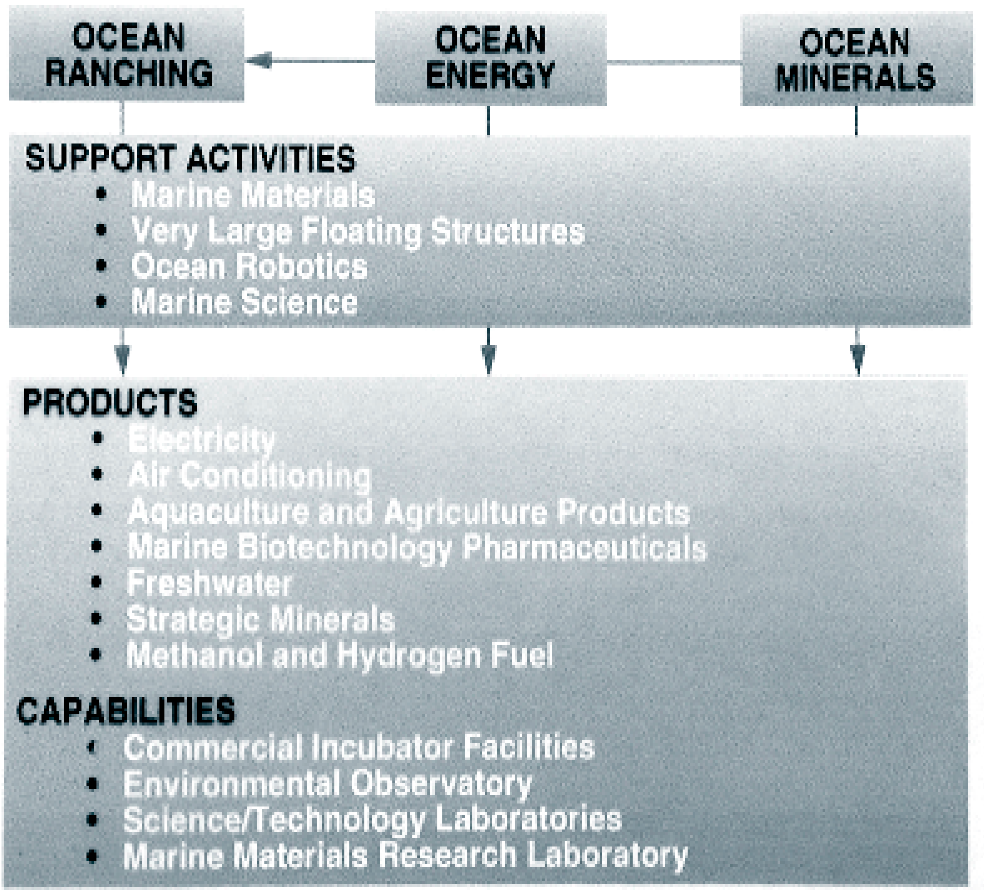
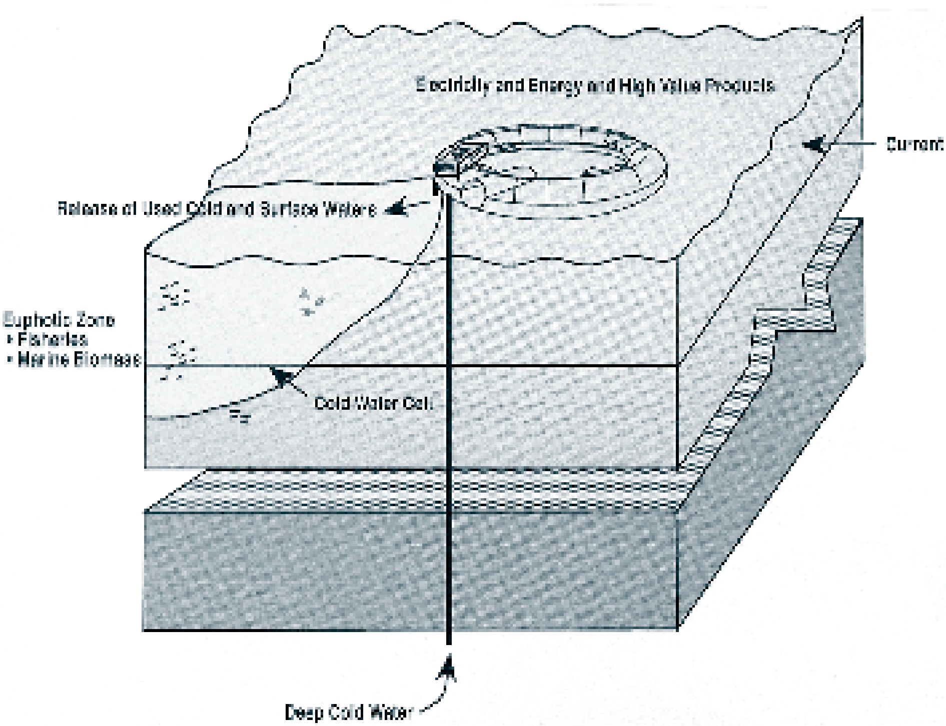


Figure 2 *Artificially Upwelled System*



$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 and financial cost. Japan, for example, has ten times 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 after Columbus. One cannot guess what Greenpeace might do, but there are no native populations, not even whales, as permanent residents in the middle of the ocean. [20]

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.

In Conclusion

The potential for OTEC is enormous, although probably not only specifically as electricity from the sea. It is the package of possible co-products driven by the combination of deep and surface ocean waters that makes this alternative very promising as a major new resource base with very real prospects for improving the environment.

However, the reality is that OTEC energy, because of the small temperature differential, will require massive hardware, with major components not yet ready for prime time, and currently of very high capital costs. The heat exchanger material problem appears to have been solved with roll-bonded aluminum or some other similar manufacturing option. Work on a 100 MW turbine and on the deep ocean water delivery system have not yet really started.

Thus, for the next decade at least, OTEC development will be limited to one to ten MW demonstrations and niche applications, some of the latter ideal to supply renewable electricity, air conditioning, exotic delicacies and freshwater to island resorts, while providing seawater to aquaria, spas and other ecotourism attractions. Carbon credits will help the financial balance. The use of the ocean fluid itself from several hundred meter depths—thus precluding power production—will show growth for special high value and consumer desired commodities, to include biopharmaceuticals, biopigments, pearls, seasonally popular seafoods and vegetables (which then can be supplied the year round) and, even, drinking water and cosmetic applications.

The pathway from one MW to 1,000 MW and more, though, can best be attained through a Blue Revolution. An important next step might be a 10 to 100 MW OTEC facility on a grazing plantship, which could be a refurbished tanker, supplying power and fluids to tenants on the interconnected marine industrial park associated with the platform. The floating craft, which would be dynamically stabilized through controlled effluent flows, would also support a marine biomass plantation and next generation ocean ranches. The entire facility would be located at a site with minimal hurricane activity and near a seamount to take advantage of as much natural upwelling as possible.

As Sputnik and Apollo captured the spirit of those times and influenced the Space Race in the 20th Century, can an equivalent galvanizing force appear early in this new millennium to catalyze marine development for humanity in harmony with the natural environment? Rather than only trying to prevent wars and maintaining the sordid state of life for the needy, can *The Blue Revolution* become an added new role for the United Nations, for sustainable economic development is the best cure for poverty and is a baseline requirement for universal peace?

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