WILLIAM H. AVERY

METHANOL FROM OCEAN THERMAL ENERGY

Ocean thermal energy conversion (OTEC) is a technology for producing electric power from the solar energy that heats the surface waters of the tropical oceans. The power generated may be used on an OTEC plantship to produce methanol fuel or other products for shipment to world ports, or at suitable sites may be transmitted to shore for distribution by the public utilities. The projected cost would make methanol fuel an economical replacement for unleaded gasoline for motor vehicles, thereby opening the way to potential production in sufficient quantities to make an important contribution to U.S. efforts to reduce needs for imported petroleum.

The solar energy that is absorbed in the tropical oceans maintains the temperature of surface waters at 80°F or above, day and night, throughout the year. In the same regions at depths of 3000 feet or lower, the water temperature is always less than 40°F. This fact led F. A. D'Arsonval to suggest in 1881 that the 40°F temperature difference could be used to generate power in the same way as the common steam engine if such fluids as liquid ammonia or propane, which boil at 80°F and produce significant vapor pressure, were substituted for water in the engine cycle. An alternative to the use of a secondary fluid in the OTEC concept was proposed by the French engineer, Georges Claude, and was demonstrated in 1930 at an installation at Matanzas Bay in Cuba. In this variation, steam produced by lowering the pressure of the warm water pumped into the system was used to power the turbine. The Claude experiment proved the validity of the OTEC concept, but the system was not economically attractive at that time.

When world oil prices started to climb steeply in 1973, investigations of the OTEC concept as an energy alternative were begun in the United States and have continued to the present. The key components of the OTEC system based on the ammonia cycle have now been demonstrated at sea at a power level of 1 megawatt (MW). Baseline engineering designs are available for scale-up of this engine cycle on shipboard installations at power levels of 40 to 60 MW (net electrical output). These demonstration plants would provide firm cost and performance data for commercial OTEC installations at power levels of 150 to 300 MW and would provide energy products and electric power at costs estimated to be competitive with conventional nonrenewable sources.

The electrical energy that is generated by an OTEC power plant on a ship could be used in many ways to produce products that could be shipped to shore and then used as a replacement for petroleum fuel or as an alternate source of electricity or heat. Economic studies show that although these ways are technically feasible, most of the OTEC products would not be economically attractive at today's prices for fossil fuel. However, methanol is an exception. An evaluation of the use of OTEC plantships for the synthesis of methanol indicates that they could produce and deliver methanol fuel to U.S. ports at projected costs that would make it competitive with gasoline at present prices, in fuel cost per mile.

OTEC METHANOL

Methanol, or methyl alcohol, is a compound of carbon, hydrogen, and oxygen with the chemical formula CH_3OH. Methanol is synthesized commercially in a process that involves two basic steps: (a) carbon from a source such as natural gas (CH_4) or coal is combined with oxygen to form carbon monoxide and (b) the carbon monoxide is combined with hydrogen to form methanol.

In conventional methanol plants, roughly half the input fuel (natural gas or coal) is burned to provide heat for the endothermic production of hydrogen for step (b). Additional energy must be expended for the production of nitrogen-free oxygen in an air liquefaction plant for step (a). These inefficient processes are bypassed in the OTEC methanol synthesis, which uses the electric power generated from solar energy to produce hydrogen and oxygen simultaneously by electrolysis of water.

The process for making methanol on an OTEC plantship is shown schematically in Fig. 1. Pulverized

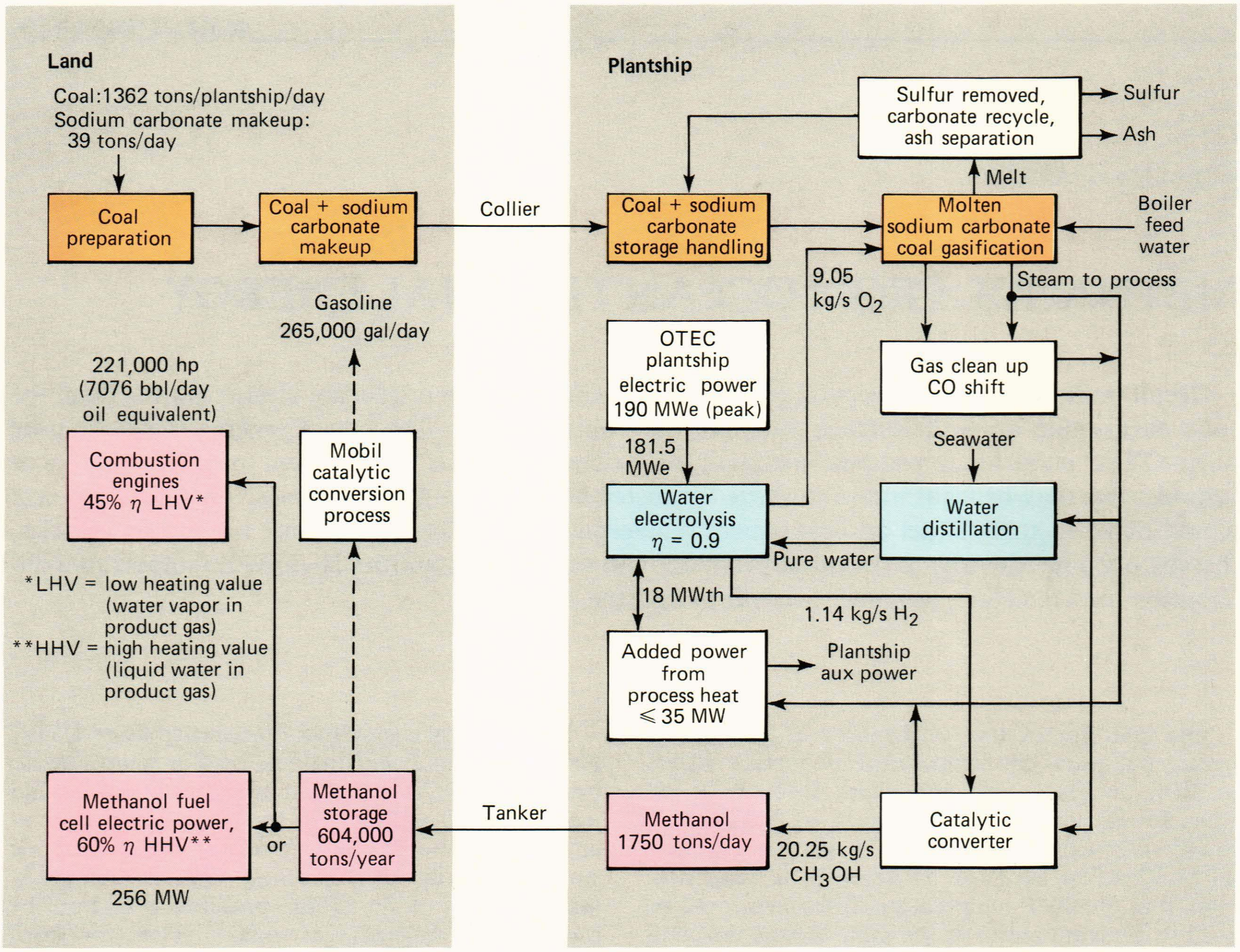

Figure 1 — Flow chart of OTEC methanol plantship process. Collier supplies crushed coal on a monthly schedule to coal gasifiers on board the plantship to produce carbon monoxide. Excess heat of coal oxidation is used to convert water and coal to additional carbon monoxide and to hydrogen. The electricity generated by the OTEC heat engines (augmented by electricity derived from process steam of the coal gasifier) is used to electrolyze water to oxygen and hydrogen, which are used in the coal oxidation and in the carbon monoxide-to-methyl alcohol conversion, respectively. Tankers transport methanol to receiving ports on a monthly schedule.

coal is transported in colliers to the OTEC plantship, where it provides the carbon source for reaction with oxygen produced on board to form carbon monoxide. Since this combustion-like reaction is highly exothermic, steam may be injected simultaneously to produce hydrogen by the endothermic water-gas reaction ($C + H_2O \rightarrow CO + H_2$) along with additional carbon monoxide. The gasification reactions take place in a vessel containing molten sodium carbonate, which not only provides good heat transfer so that chemical equilibrium is attained rapidly, but also reacts with the sulfur and ash in the coal to trap these impurities in the melt. Thus the exit gas is a nearly pure mixture of CO and hydrogen. The hydrogen output from the water electrolysis plant is added, and the resulting mixture after further purification is passed through a catalyst bed to produce methanol as a product. This process has a high energy efficiency. The electrolysis of water converts electrical energy to chemical enthalpy with an efficiency of approximately 90%, and the excess heat generated in the two reaction steps can be used efficiently to produce steam that can power the compressors and other process equipment.

As designed, this process requires 0.78 ton* of coal to produce 1 ton of methanol, compared with land-based methanol-from-coal plants that require 1.5 to 2.1 tons of coal per ton of methanol produced.

An engineering study has been completed to define the layout and component requirements of a 160 MW OTEC plantship that would produce 1750 tons per day of fuel-grade methanol from 1363 tons per day of coal. The coal, with other supplies, would be transported to the OTEC plantship by conventional freighters, stored, and replenished at approximately monthly intervals. Similarly, the methanol product would be stored on board and then delivered by tanker to mainland ports along with elemental sulfur recovered from the coal and waste products. Shipping costs would be a minor fraction of the methanol delivered cost.

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*All product and coal quantities are expressed in metric tons.

The present design of the methanol plantship has resulted from two engineering studies conducted under subcontract. The first, conducted by Brown and Root Development, Inc. (BARDI) used the following basic data: (a) an in-depth engineering design and cost analysis prepared by BARDI for a barge-mounted methanol-from-natural-gas plant intended for the use of offshore natural gas supplies, (b) BARDI construction and operating data for an ammonia-from-coal plant, using the Texaco coal-water slurry gasifier, installed at Muscle Shoals, Ala., for the TVA, and (c) information for the OTEC power plant and the requirements for methanol plant installation on the plantship derived from the APL baseline design of a 40 MW OTEC ammonia plantship, with appropriate scaling to the 160 MW size determined to be optimum from this study.

The resulting artist's concept of the 160 MW plantship based on drawings by BARDI is shown in Fig. 2a. The ship is 900 feet long and 330 feet wide and has a draft of 65 feet. Thus, the size is comparable with that of a supertanker. (A 390,000 ton T-11 tanker constructed recently at Newport News has the following dimensions: length, 1188 feet; beam, 228 feet; draft, 75 feet.)

The BARDI study was deliberately based on use of state-of-the-art components and processes so that the costs could be estimated accurately. It showed that the OTEC methanol concept would lead to a product cost marginally competitive with land-based methan-

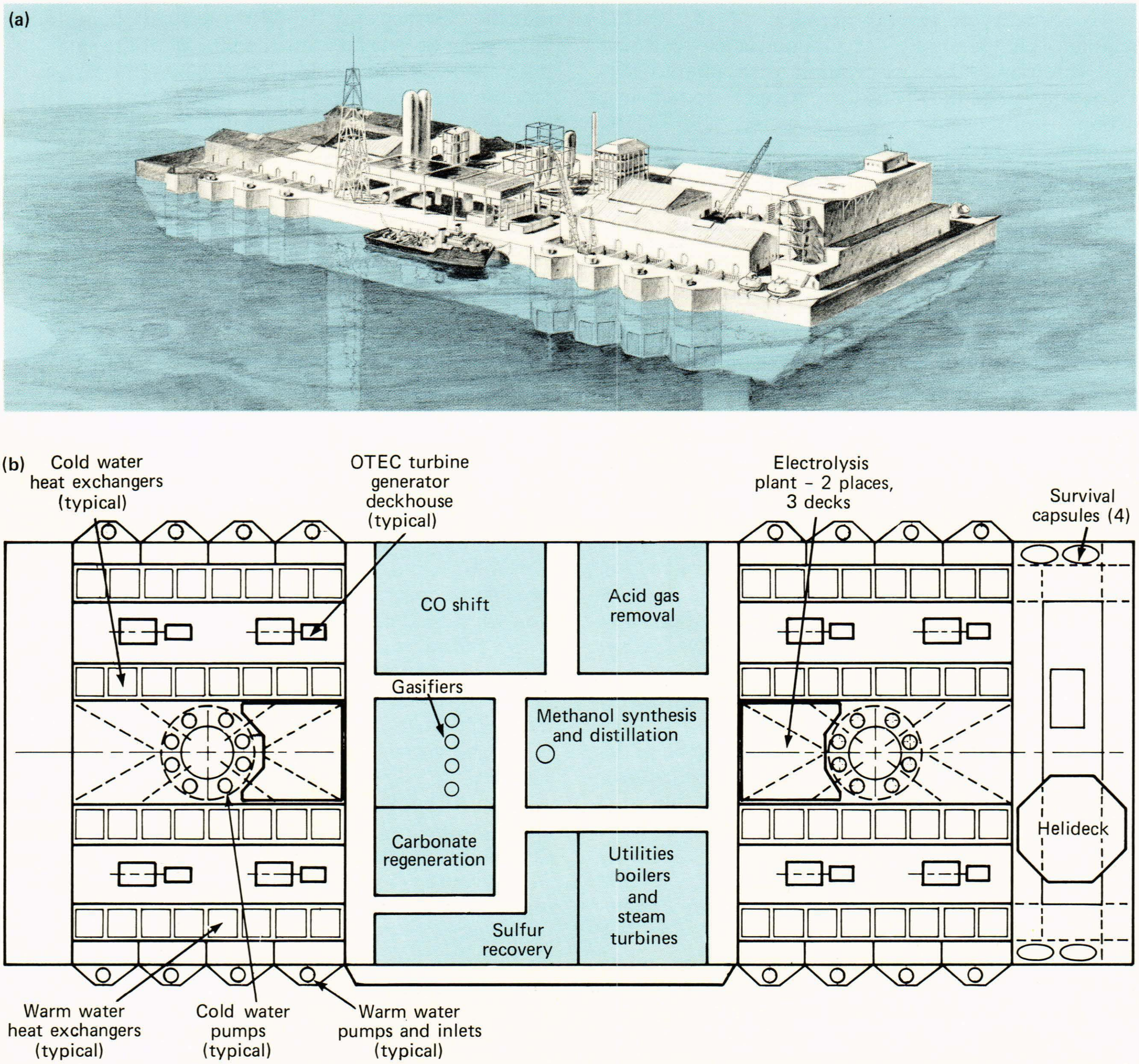

Figure 2 — (a) Artist's concept of the 160 MW plantship, based on drawings by BARDI. (b) Schematic layout of a methanol plantship. OTEC equipment for evaporating and condensing the fluid (ammonia) driving the electric turbine is mounted on the fore and aft ends of the plantship. Coal conversion equipment is mounted on the top deck. Storage for coal and methanol is below deck. Two cold water pipes extending 3000 feet below the surface are mounted on the ship centerline fore and aft.

ol-from-coal plant designs. However, the study also showed that major improvement in output could result from replacement of the coal slurry gasifier, which was used in the BARDI design because full-scale operating data were available, by a new gasifier design using pulverized coal that had been developed and tested on a 25 ton per day scale by Rockwell International Corp.

Whereas the coal slurry gasifier produces a product gas with approximately equal amounts of carbon monoxide and unwanted CO_2, plus gaseous sulfur compounds (along with hydrogen), the Rockwell design produces nearly pure carbon monoxide and hydrogen. The space requirements for the methanol plant are also much reduced by use of the Rockwell gasifier, and the need to handle large quantities of water associated with the slurry feed stock is avoided.

Accordingly, a second iteration of the OTEC methanol design study was subcontracted to Rockwell International in association with Ebasco Services, Inc., to define the process layout requirements, product output, and costs for a 160 MW OTEC methanol plantship based on the Rockwell gasifier. The estimated methanol output from this plantship is 1750 tons per day, with coal input of 1336 tons per day. The space requirements are the same as those estimated by BARDI for a 1000 ton per day methanol output from the coal slurry plant. A plan view of the plantship showing the major plant process sections is shown in Fig. 2b.

The design study included estimates of the cost of installing and operating the methanol plant, shipping coal and other input materials to the plantship, and shipping methanol and other products to shore. From these data the cost of methanol delivered to a U.S. port may be estimated. (In an accurate cost study, appropriate consideration must be given to the complex factors that must be evaluated in judging the requirements for financing the plant construction and operation over the plant lifetime; the requirements depend on the specific organizations involved.) The estimates indicate that the delivered cost of OTEC methanol at U.S. ports after 1990 would be in the range of 48¢ to 62¢ per gallon (in mid-1983 dollars).

Methanol is of particular interest because of its demonstrated effectiveness as a high octane automobile fuel with the potential to replace unleaded gasoline at costs below today's prices. Automobile tests conducted by the Bank of America in California during the past three years with a fleet of over 300 cars show that, in automobile operation on a cents-per-mile basis, 60¢ per gallon for methanol would be equivalent to 80¢ per gallon for unleaded gasoline, indicating an attractive profit potential for OTEC methanol even at today's gasoline prices.

OTEC RESOURCE

Engineering calculations supported by experimental results show that if the temperature difference between warm and cold water is 40°F, the OTEC system develops a net electric output (after allowance for pumping power, ship operation, and personnel needs) equal to 3/4 of the gross power generated. This equates to conversion to net electrical energy of 2.5% of the heat extracted from the surface water that passes through the plant.

The annual average rate of solar heat absorption by the tropical oceans has been measured to be approximately 20 watts per square foot, or 600 MW (thermal) per square mile. Part of the heat (40%) is reradiated as infrared energy to the upper atmosphere and space, and the remainder is dissipated through evaporation, waves and currents. Conversion of a significant fraction of the solar input to electric power would disturb the natural pattern and could raise environmental questions. Therefore, let us assume that grazing OTEC plants will be spaced so that they extract only 0.5 MW (net) per square mile of tropical ocean, i.e., less than 0.1% of the solar input. This heat use would be well below the range of random changes in heat flow produced by clouds and currents and is a conservative estimate for OTEC operation without deleterious environmental effects. With this criterion, we may estimate the world potential for OTEC operation.

Figures 3 and 4 show the temperature difference between the surface and 3280 foot (1000 meters) depth in the world's oceans. The area enclosed by the 40°F contours is approximately 23 million square miles. Therefore, if 0.5 MW of net power were extracted per square mile, the total OTEC power that could be generated would be approximately 10^7 MW. The total electric power generation in the U.S. in 1980 was 2.5% of this amount.

The energy that could be supplied to the U.S. via OTEC-methanol fuel is shown in Fig. 5, in comparison with the consumption of fuel and power from present sources. Figure 5 shows that OTEC methanol could provide a renewable energy source capable of contributing in a major way to the reduction of U.S. demands for nonrenewable fuels. It is worth noting that the potential supply of energy via OTEC methanol in one year would match the total proven reserves in the U.S. of oil and natural gas liquids, plus natural gas, plus uranium.

The potential energy contribution that could be supplied by OTEC-generated ammonia is also shown. Although ammonia is not economically attractive now as a fuel, it could become important in the future because it would provide a storable fuel whose combustion would not generate carbon dioxide, which threatens to produce a greenhouse effect in the atmosphere. Ammonia has been shown to be an efficient fuel for automobiles, yielding approximately the same miles per gallon as methanol.

OTEC PROGRAM STATUS

When studies beginning in 1973 showed that OTEC promised to be technically and economically feasible, R&D programs were funded by the U.S. Department of Energy and its predecessor to investigate

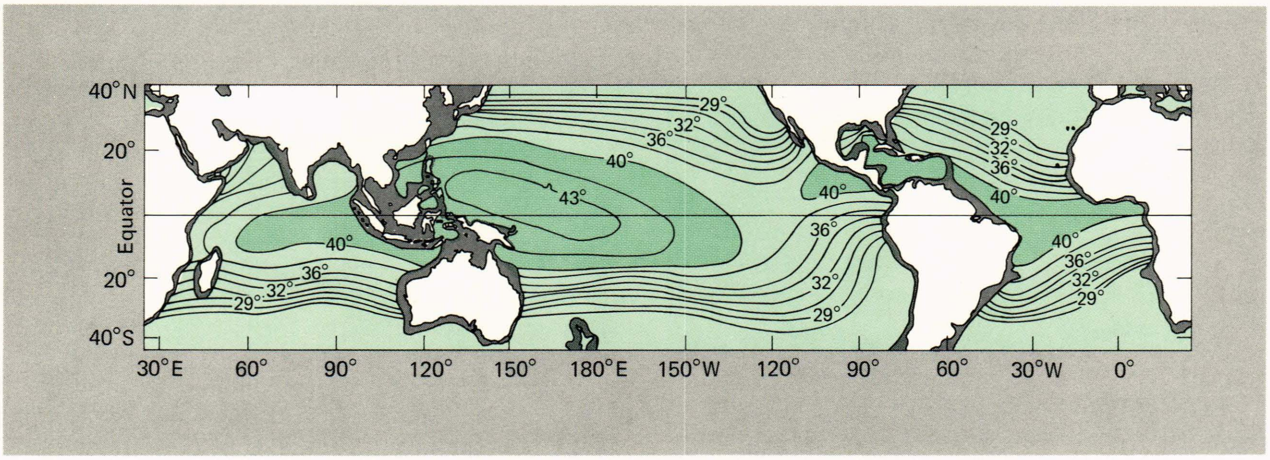

Figure 3 – Temperature contour lines (in degrees Farenheit) between the ocean surface and the 3280 foot depth. The dark green areas encompass the potential areas of operation by OTEC.

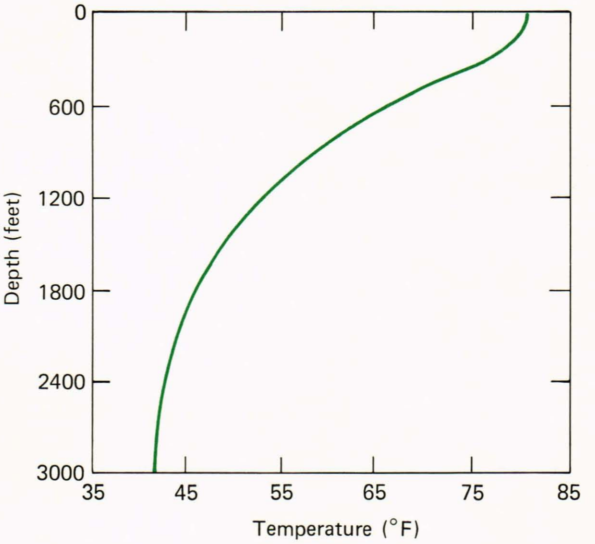

Figure 4 — Typical vertical temperature profile showing the gradient between the ocean surface and the ocean bottom.

the technical questions for which positive answers were essential to the success of OTEC. A facility was established at the Argonne National Laboratory for conducting experimental tests on heat exchanger designs suitable for OTEC to confirm the predicted performance, and a broad program was initiated to devise ways to cope with the expected loss of performance that would occur when marine organisms attached themselves to the heat exchanger surfaces. An engineering investigation was launched to provide basic understanding and experimental verification of construction and deployment techniques that would be suitable for building, installing, and operating cold water pipes tens of feet in diameter and 3300 feet long, suspended from a ship. A design of a complete OTEC shipboard system was required that would survive the worst storms predicted to occur in a 100 year period in the tropical oceans. These problems have all been addressed and solved at a 1 MW scale during the past nine years.

In 1979, a complete OTEC system, called Mini-OTEC, with a cold water pipe 2200 feet long and 28 inches in diameter was mounted on a ship and tested at sea for four months in Hawaii (Fig. 6). The development was a joint effort of Lockheed, Dillingham Corp., the State of Hawaii, and the Alpha Laval Corp. The system delivered 60 kW of gross power and confirmed the expected performance. The experiment was repeated in 1981 under DOE funding at 1 MW size in a ship called OTEC-1, which had an 8 foot diameter cold water pipe 2300 feet long (Fig. 7). Again, although the test was terminated after four months because funds were withdrawn, the performance confirmed the predictions for the test period.

In both experiments, biofouling of the heat exchangers was prevented by chlorine injection at a level far below the limits set by EPA for environmental safety of marine life. Other nonchemical methods of control (brushes, ultrasonics, etc.) have also been tested. Tests of a 1/30 scale model of the OTEC ship with a gimballed cold water pipe connection conducted in a wave tank confirmed the system survivability in a simulated sea environment representing the most severe storm expected to be encountered in the operating area over a period of 100 years.

The next step is to demonstrate operation of complete OTEC systems at a size large enough to provide data that would verify the predicted construction and operational costs, which are comparable on a dollars-per-kilowatt basis with coal and nuclear cost projections when fully commercialized.

Engineering designs are available for 40 MW demonstration plants that could be moored offshore in Puerto Rico, Hawaii, or other islands and that could transmit power directly to a utility network on shore through an underwater cable 2 or 3 miles long; designs are also available for OTEC plantships that could cruise in the tropical oceans to produce 114 tons per day of ammonia for periodic shipment to

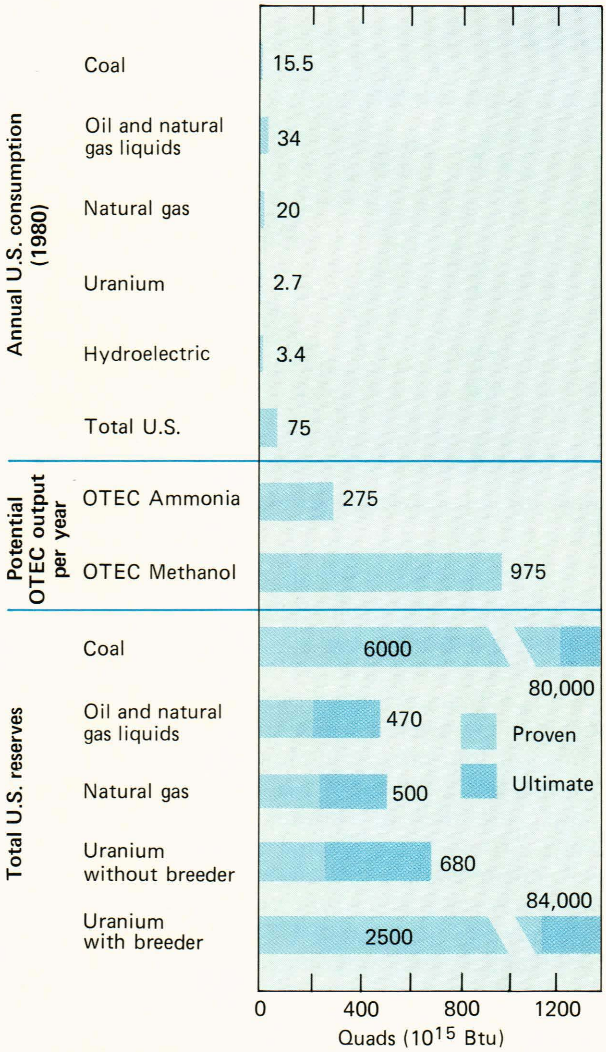

Figure 5 — United States energy consumption (1 quad = 10^{15} Btu) in 1980 by fuel type, potential renewable OTEC-generated reserves, and total reserves of nonrenewable fuels. The assumption made for OTEC output is that the engine cycle efficiency is 2.5% and that 1/30 of the net power potentially available is used. The U.S. reserves of natural gas and oil are insufficient to avoid large-scale importation of oil or shift to a coal- and/or nuclear-based energy supply in the next decade unless heavy reliance is placed on solar-based renewable resources. [Data for conventional sources from National Research Council, 1979.]

shore. A conceptual design is also available for a 60 MW OTEC methanol demonstration plantship that would produce 660 tons per day of methanol.

Two companies were funded by the Department of Energy to produce conceptual designs of bottom-mounted OTEC plants to be sited a few hundred yards offshore for electric power generation in Hawaii. One contract has been awarded for a follow-on preliminary engineering design of this concept. The contractor has stated his intention to continue the development with private funds. Engineering designs are being completed for the 160 MW OTEC methanol plantship discussed above that would produce 1750 tons per day of methanol.

Despite the great promise of this work, support of OTEC development by the U.S. Department of Energy is very small. However, the interest expressed by one company in the U.S. in developing a 40 MW bottom-supported OTEC plant in Hawaii entirely with private funds is encouraging. In contrast, French, Dutch, and Swedish programs are receiving active government and private support. The Japanese government and industry are supporting an active OTEC program that features construction of a 10 MW plant for the island of Nauru. This may allow them to take the leading role in commercialization of this technology, which they believe will lead to a significant export market for OTEC plants in the Pacific as well as to significant contributions to the Japanese economy.

CONCLUSION

OTEC is a technology that could produce inexhaustible supplies of fuels, chemical products, and electric power at costs low enough and in amounts large enough to make a significant impact on world energy needs with minimum environmental effects. The technology has been demonstrated at a 1 MW scale and is now ready for large-scale demonstration as a prelude to commercial production.

OTEC methanol offers promise as an economical replacement for gasoline now, and OTEC ammonia appears attractive as a future replacement of ammonia now made from natural gas. In the future,

Figure 6 — The Mini-OTEC demonstration ship.

Figure 7 — The OTEC-1 1 megawatt demonstration ship.

ammonia could become a practical basic fuel to replace present carbonaceous fuels, which are adding carbon dioxide to the atmosphere and will eventually produce an intolerable greenhouse effect if not curtailed. OTEC electric power transmitted ashore by underwater cable would be economical in Puerto Rico, Hawaii, and other island sites.This would lead to significant benefits to the island economics, which now depend on oil.

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