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OCEAN THERMAL ENERGY CONVERSION CONTRIBUTION TO THE ENERGY NEEDS OF THE UNITED STATES

Ocean Thermal Energy Conversion (OTEC) can provide energy to the United States via direct electric transmission from offshore U.S. island or Gulf of Mexico sites, or via production of an energy-intensive product on an OTEC plantship sited in tropical waters. Ammonia is an outstanding choice for the second option. Projected costs of OTEC ammonia and electricity after 1990 are competitive with projected costs from natural gas and from coal or nuclear plants, respectively.

INTRODUCTION

OTEC is a method of converting into electrical energy the solar energy stored by the sun in the surface layers of the tropical oceans. The electrical energy that can potentially be generated in that way is many times larger than the projected total U.S. energy needs (Table 1).

The technical details of the process have been described previously.[1,2] A working fluid is vaporized at the temperature of the warm ocean-surface water, expanded through a turbine, and recondensed by cold water pumped from a depth of 3000 ft. The key features required are an efficient, durable heat exchanger for the evaporation and condensation of the working fluid and a suitable water pipe to deliver the cooling water to the condensers. Of several possible working fluids, ammonia has the most attractive thermodynamic properties.

Two commercially attractive methods of operation of OTEC plantships are under development.

Table 1

ENERGY POTENTIALLY AVAILABLE FOR OTEC

Ocean area suitable for OTEC plantships (ΔT greater than 40°F)	~20 million mi^2
Estimated minimum operating area per 325 MWe plantship	~650 mi^2
Total OTEC power generation capability on board (20,000,000/650 × 325)	~10,000 GWe ~9 × 10^{13}kWh/yr
Total power generation on U.S. mainland via ammonia and fuel cells	~5000 GWe ~4 × 10^{13} kWh/yr
Energy Demand	
U.S. total consumption (1978)	2.3 × 10^{12} kWh
U.S. peak load (1978)	396 GWe

In the first, OTEC plants will be moored in areas near shore where a suitable temperature difference between surface and lower water layers is available; power will be transmitted by underwater cable to the utility grid on shore. In the second, plantships will be sited in the areas of maximum temperature differences in the tropical oceans and will move about slowly to remain in the warmest surface water, which drifts with the seasons. Oceanographic data show that an annual average temperature difference of 43.0°F could be available for OTEC by using this mode of operation. (The term "grazing" has been used to describe the 0.5 knot speed of the ships.) These grazing plantships are designed to use the electric power generated on board to make a chemical product for shipment to U.S. ports. There this product may be used either to replace a product now requiring petroleum fuel or electric power for its manufacture, or it may be used as a fuel source for electric power generation.

Because of temperature advantages and environmental trade-offs, the cost of energy delivered to mainland U.S. sites is estimated to be nearly the same for the grazing OTEC system as for the moored plants in the Gulf of Mexico. If a temperature difference of 40°F is available between the warm surface water and the cold water at depth, about 25% of the electric energy produced will be needed to drive the water pumps and other auxiliaries, leaving 75% of the gross OTEC power output to be used for other purposes. As is shown in Fig. 1, the OTEC net power output depends strongly on this temperature difference, ΔT. A plant designed to deliver 100 MWe when operating at a site in the Gulf of Mexico where the ΔT is 38°F can deliver 140 MWe with the same water flows when operating in the ocean near the equator where a ΔT of 43°F can be found.

Figure 2 shows the vast region of the oceans that is suitable for OTEC operation, i.e., where an annual average ΔT of 40°F exists. The area enclosed by the 40°F contours is 20 million square miles. Table 1 shows that this area could support 30,000 325-MWe OTEC power plants if all of the suitable ocean area were used. About 3000 such plants would be able to supply the projected total needs of the United States for electric power in the year 2000 via ammonia and fuel cells if one half of the power produced on-board were delivered to U.S. sites via the OTEC ammonia/fuel-cell route.

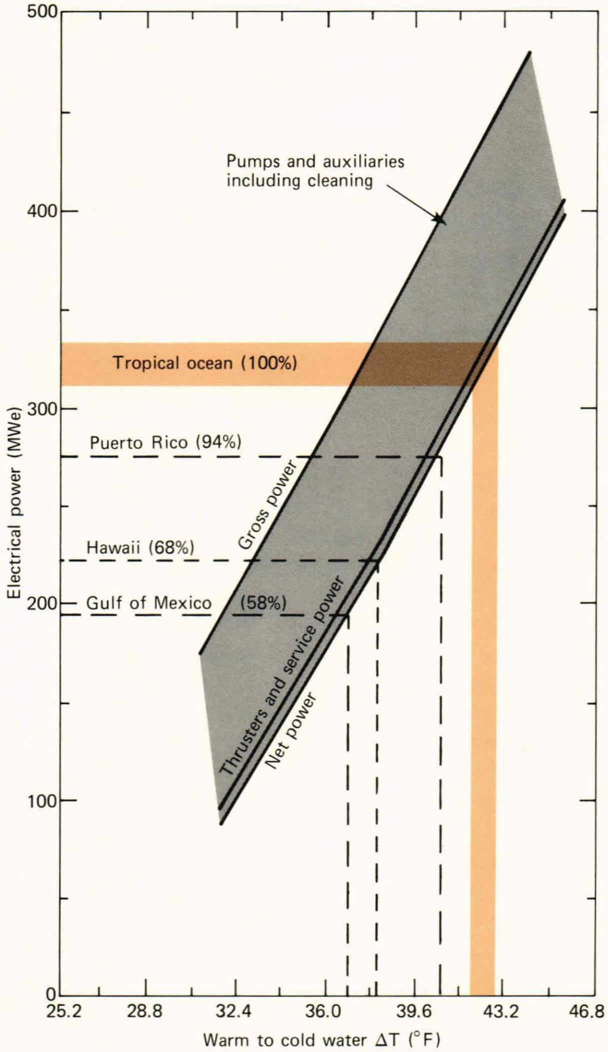


Fig. 1—The estimated power delivery of a 325 MWe plant as a function of the available temperature difference. Numbers in parentheses indicate the power loss that results from lowering surface water temperatures for three off-shore locations.

AMMONIA SYNTHESIS

A survey of chemical compounds suitable for transporting OTEC energy to shore shows that ammonia (NH_3) is nearly ideal for this purpose. By coincidence, ammonia is also the preferred medium for the OTEC plant heat exchanger. It can be manufactured aboard the OTEC ship from nitrogen, which can be extracted from the air, and hydrogen, which is made by electrolysis of seawater.

Ammonia is formed in an equilibrium process with little evolution of heat so that it efficiently transforms electrical energy into storable chemical energy. It is easily liquefied, stored, and shipped. On land it may be stored indefinitely at ambient temperature in pressure containers similar to those used for liquid propane. Ammonia is already a major industrial chemical, since it is the basis for all nitrogen fertilizer made in the United States and for other materials such as Acrilan and nylon. Ammonia production was 18 million tons in 1978; it is expected to increase to 25 to 28 million tons per year by 1995. Ammonia, now made in the United States from natural gas, consumed 630 billion ft^3 of natural gas in 1978. This quantity is approximately equal to the total residential use of natural gas in the New England states plus New York and New Jersey. With a high priority program, substitution of OTEC ammonia for ammonia made from natural gas could conserve natural gas in an amount equivalent to 300,000 bbl per day of oil by 1995 and 500,000 bbl per day by 1999.

Ammonia may be used directly as a synthetic fuel that produces only water and nitrogen as combustion products. In this role, OTEC ammonia would provide an attractive alternative to synthetic fuels derived from coal, which pose problems in mining, transportation, control of emissions, and the long-range effects of carbon dioxide on the global climate. At the estimated delivered cost in

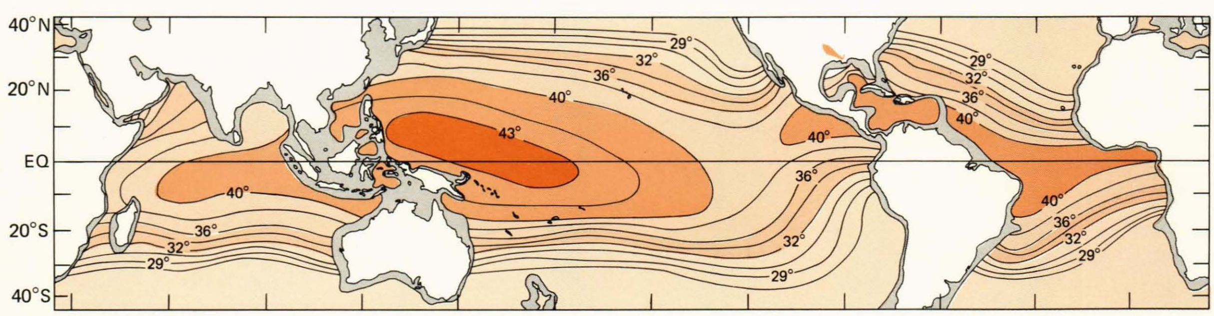


Fig. 2—The available temperature differential between the surface and the 3000 ft water depth in the Atlantic, Pacific, and Indian Oceans (DOE data).

the 1990's, OTEC ammonia would compete in price with gasoline or fuel oil at approximately $2 per gallon (1980 dollars). Although the projected cost is higher than current estimates for synthetic fuel from coal, the favorable environmental aspects warrant serious consideration of ammonia as a synthetic fuel because it is easy to handle and store. Procedures for storage and handling of ammonia already exist because of its use in the fertilizer and refrigeration industries.

The use of ammonia as a fuel for motor vehicles with conventional internal combustion engines has been demonstrated to be feasible by means of modifications to the ignition system and installation of a pressure tank. The modifications are comparable in cost to those required to adapt a vehicle to propane fuel. With the advent of fuel cells adapted for use in automobiles, motor vehicles employing ammonia fuel would have comparable mileage efficiency to that of gasoline-powered cars and could eliminate the pollution caused by undesired combustion products.

Ammonia is formed by combining three parts hydrogen and one part nitrogen under high pressure in the presence of a catalyst. It may be decomposed easily by application of higher temperature and lower pressure in the presence of the same catalyst to provide hydrogen that is chemically pure, except for the 25% (by volume) fraction of inert nitrogen, and is preeminently suitable for generation of electric power through reaction of hydrogen and oxygen in a fuel cell. Fuel cells convert the chemical energy of the hydrogen and oxygen reaction into electrical energy with an efficiency of 50 to 65%, compared to 30 to 35% attainable with gas turbine systems and about 40% maximum for steam turbines.

The most efficient fuel cells currently available are those developed by General Electric, which employ a solid polymer electrolyte (SPE).[3] SPE cells that have practical current densities and use hydrogen and oxygen as reactants now have a maximum demonstrated efficiency (the ratio of electrical energy output to heat of the reaction) of 65%. Some improvement is expected with further research. However, estimates of fuel-cell efficiencies (η) range from 0.5 for state-of-the-art SPE cells to 0.65 expected by 1985-90. The ammonia/fuel-cell cycle is shown in Fig. 3.

There is a loss of energy in using OTEC electric power to form the ammonia that is decomposed later to produce electric power. However, the much larger power output of grazing OTEC plantships operating near the equator and the transport and storage advantages of ammonia compensate for the efficiency loss, when compared with direct transmission of electrical power to shore. Thus the cost of delivered power is estimated to be nearly the same for OTEC plants moored in the Gulf of Mexico and delivering power to shore via underwater cable, as for grazing OTEC ammonia plant-

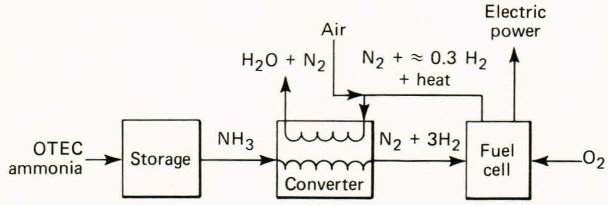


Fig. 3—Schematic diagram of the use of ammonia as the power source in a fuel cell. OTEC-synthesized ammonia is decomposed in a converter. The reaction products (nitrogen and hydrogen) are partially used as the fuel in an oxygen-enriched fuel cell. Ten percent of the hydrogen is burned in air to supply the heat required to decompose ammonia.

ships delivering to shore ammonia to be decomposed and used in fuel cells to produce electric power. The latter mode of operation allows OTEC to draw on the vast tropical ocean area as an energy reservoir and to supply a source of electric power anywhere in the United States. Because fuel cells are quiet and efficient even in small sizes, power generation by fuel cells can be adapted for use by factories or communities where large nuclear or coal plant installations are not feasible.

Figure 4 shows a conceptual design of a 100-MWe OTEC ammonia plantship made up of twenty 5-MWe power modules. It is 450 ft long, 180 ft wide, and 60 ft deep and is made of reinforced concrete.

PROJECTED COSTS

During the past two years, major effort in the Department of Energy (DOE) OTEC program has been devoted to definition of baseline engineering designs of 40-MWe pilot/demonstration plants that will provide a firm basis for industry proposals, with construction to begin in 1984 or early 1985. The purpose of the pilot plants is to provide accurate data on component performance and cost for follow-on construction of moored and grazing commercial plants of 100- to 400-MWe busbar power. Under DOE support, a two-year engineering evaluation effort has been conducted by APL and representatives of the shipbuilding and marine construction industries to define a baseline barge configuration for the 40-MWe pilot plant.[4] Other configurations have been investigated by other organizations but the estimated costs are appreciably higher. The APL design is similar to that shown in Fig. 4, but is scaled down to 40 MWe. The pilot plant configuration is shown in Fig. 5. The barge platform is made of post-tensioned concrete, is 140 ft wide and 444 ft long, and has an operating draft of 65 ft. The launching draft is 33 ft (without the cold-water pipe), which will allow construction in existing U.S. shipyards. The cold-water pipe is 30 ft in diameter and is made of post-tensioned lightweight concrete in 50 ft sections joined by flexible connections. The concrete density is 80 to 85 lb/ft^3. The low submerged weight

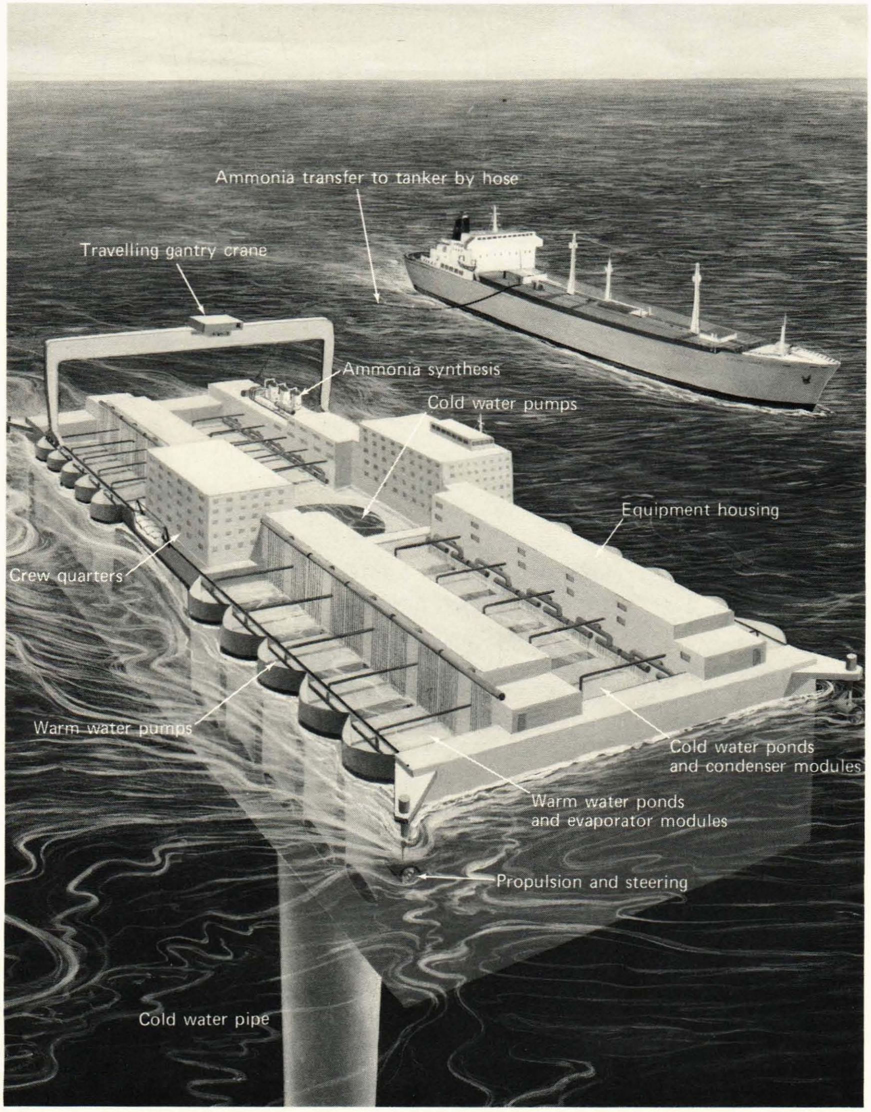


Fig. 4—APL concept of a 100- MWe plantship, for siting in tropical oceans, that consists of twenty 5-MWe power modules. Cold water is supplied from a centrally mounted pipe, extending down 3000 ft into the ocean. Warm surface water flows by gravity through the heat exchanger compartments. Housing is for demisters, electrolysis cells, ammonia pumps and turbines, and generators.

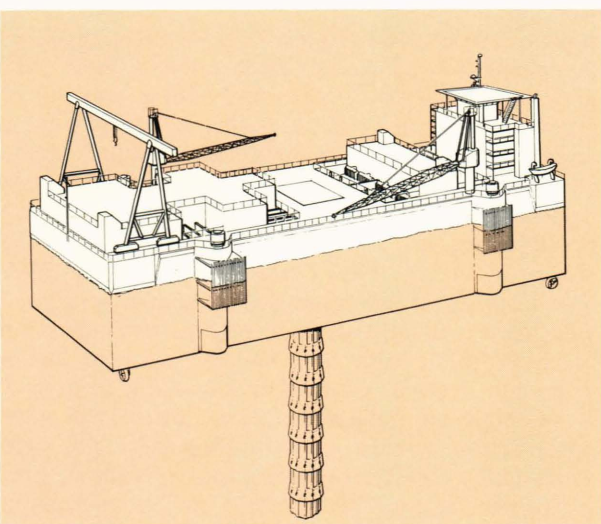
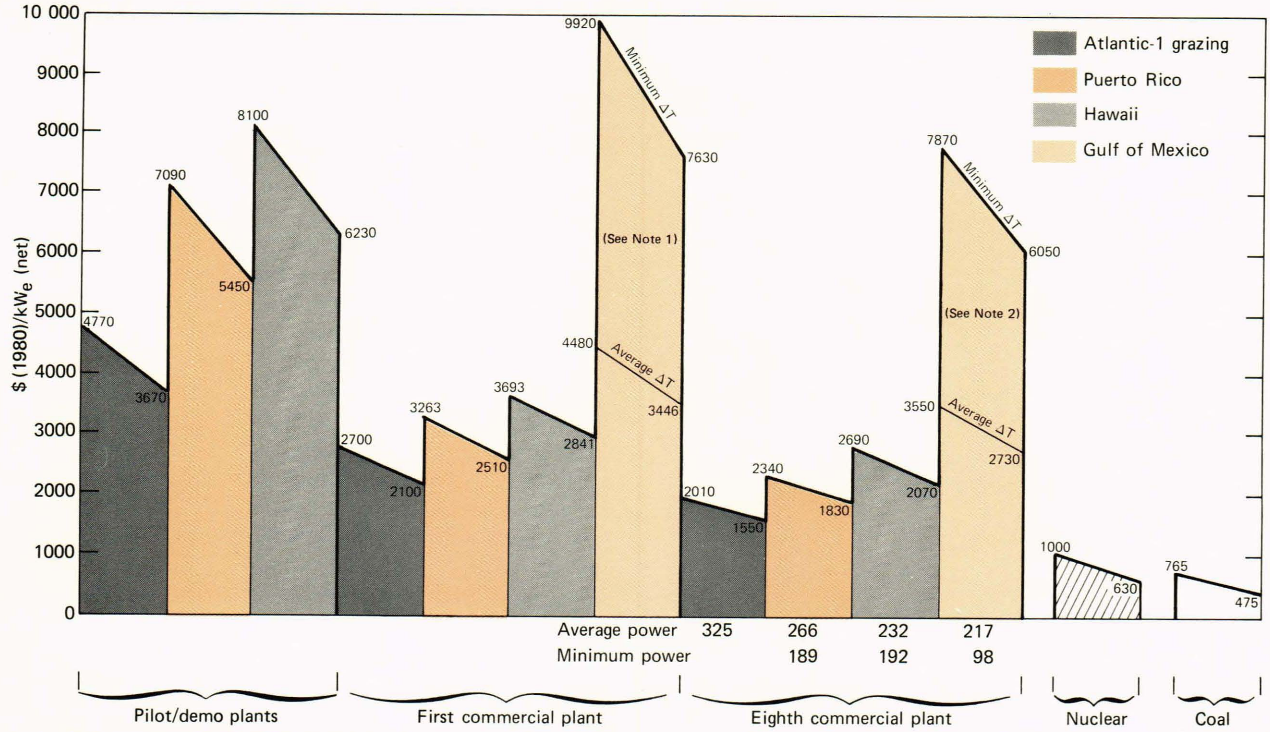


Fig. 5—40 MWe pilot plantship configuration.

(about 20 lb/ft^3) of the pipe and its sectional construction facilitate deployment and ensure that dynamic loads under 100-year storm conditions will be well below safe limits for post-tensioned concrete.[4] A fiberglass-reinforced plastic cold-water pipe is an alternative.[5]

Figure 6 shows the estimated capital costs of the pilot plants and the expected commercial OTEC plantships for moored and grazing options (as projected from work in progress). Costs for the 40-MWe pilot plants are based on preliminary engineering drawings and on industrial estimates of the costs of the platform cold-water pipe and of the folded-tube aluminum heat exchanger. The heat exchanger estimates were made by the Trane Co., which built the full-scale section tested at the Argonne National Laboratory of DOE. Quotations were obtained from vendors for the pumps, propulsion equipment, control systems, ammonia plant, and auxiliary equipment. The cost differences among the pilot plants for different sites reflect the effects of differences in ΔT and in environmental



Note 1 Construction after island installation(s)
2 For 400 MW plant, range is 2810 to 2160 $/KW$_e$ for average power, 5400 to 4150 $/KW$_e$ for minimum ΔT.

Fig. 6—Estimated total capital costs of OTEC power plants in four different locations and at various stages of commercial building cycles compared to nuclear and coal plants. Numbers provide ranges of costs. (Costs are expressed in 1980 dollars at the busbar.)

rigor. Costs of mooring equipment at Puerto Rico and Hawaii are based on preliminary industry estimates. Costs for power conversion and transmission from moored plants at Puerto Rico, Hawaii, and the Gulf of Mexico are based on current DOE-supported work. Estimates are based on data of Winer and Nicol[6] and others.

The data in Figs. 6 and 7 are presented in a format similar to that used by the Nuclear Regulatory Commission (NRC) to show a range of costs reflecting uncertainty in the estimates.[7] The range shown for OTEC options is taken to be from 0 to +30% of the nominal values based on the projected cost. The 30% range provides an allowance for contingencies and profit on capital equipment not covered by quoted costs as well as for uncertainties in the design estimates for moored and grazing barge configurations. This is approximately twice the uncertainty assigned by the NRC to their estimates. It will be recognized that projections of future costs are highly uncertain until full-scale systems have been constructed. Nevertheless, such estimates must be attempted to distinguish the good options from the economically impractical ones. The author assumes sole responsibility for these estimates.

Cost reductions in dollars per kilowatt (Fig. 6) for the first commercial plants relative to the pilot plants result from scale-up of the platform, from colocated aluminum tubing manufacture and establishment of automatic assembly line production procedures for the heat exchanger modules, from more efficient arrangement of the equipment than that used for convenient access in the pilot plant tests, from scale-up of the turbine generators and support equipment, and from design improvements that will be indicated by pilot plant experience. Further cost reductions shown for the eighth plantship are expected to result primarily from volume production and improved manufacturing procedures. Learning curve factors based on shipyard experience indicate that the cost of the second commercial platform will be 80% of that of the first, after which a learning curve slope of 0.93 is used for succeeding platforms.[8] Learning curve slopes of 0.95 and 0.90 are assumed for the heat exchangers and the rotating equipment, respectively, and 0.93 for the ammonia plant.

The capital costs quoted for the grazing plantships are based on the preliminary engineering design of the grazing configuration planned for operation 200 or more miles off Brazil or Central America, where an annual average ΔT of 43.0°F will be available. Higher costs compared to the grazing plantship are estimated for the moored plantship off Puerto Rico because of the need for heavier platform and cold-water pipe construction to meet the more severe environmental stresses, and because the lower ΔT causes diminished power output. Estimated costs for Hawaii are adjusted for

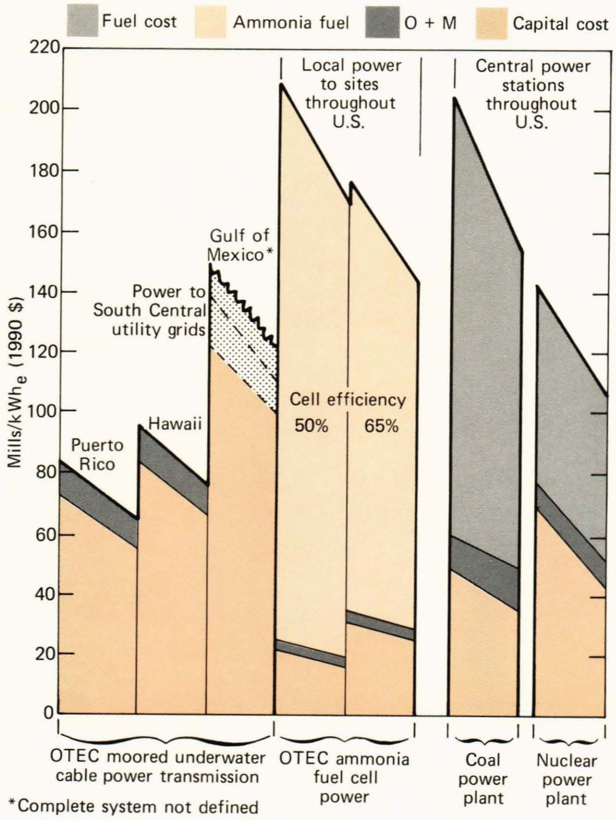


Fig. 7—Estimated busbar price of power (mills/kWh) to U.S. sites for three OTEC plants at near-land locations (Puerto Rico, Hawaii, Gulf of Mexico) with direct power transmission to land, for OTEC-produced ammonia powering land-based fuel cell plants, and for coal or nuclear fuel power stations. (Prices are in 1990 dollars at an 8% inflation rate, and with a 10% discount for coal and nuclear fuel.)

lower ΔT compared with Puerto Rico. Costs for the Gulf of Mexico allow for the lower ΔT and the added cost of the long underwater power transmission system, for which the engineering requirements have not been defined. The upper boundaries for the Gulf of Mexico plants in Fig. 6 are uncertain.

Fuel-cell costs are based on General Electric estimates derived from an ongoing program to scale up their present SPE fuel cell to 5-MWe utility use. Use of pure hydrogen derived from ammonia will simplify fuel-cell construction and make the SPE fuel-cell system significantly lower in cost than phosphoric acid fuel cells. The latter type is designed to be tolerant of impurities in hydrogen derived from coal or petroleum fuels.[9] Because such hydrogen contains sulfur and carbon monoxide contaminants, higher temperature operation and less efficient (and much more costly) fuel-cell systems are required.

The projected costs of delivered electric power are shown in Fig. 7. The data are presented for moored plantships near the shores of Puerto Rico and Hawaii and 150 miles offshore in the Gulf of Mexico, and for grazing plantships producing ammonia that is transported to U.S. sites and used there to provide electric power via fuel cells. For the plants moored where several tropical storms may occur each year, 330 days of operation per year are assumed. Power conversion and transmission efficiency of 97% are estimated for the Puerto Rico and Hawaii installations and 95% for the Gulf of Mexico sites.

For the grazing plantships that operate in the Atlantic near the equator where tropical storms do not occur (the doldrums), 345 operating days per year are projected, leading to an annual ammonia output of 380,000 tons per year for a 325-MWe (net) plantship (1.17 tons/kWe). The fuel-cell costs are shown in Table 2. Costs for production and delivery of OTEC ammonia to U.S. sites are shown in Table 3. This table provides the basis for the fuel cost shown for the fuel-cell installation in Fig. 7. A comparison of projected costs of OTEC ammonia versus ammonia made from fossil fuel stocks indicates that OTEC ammonia after 1985 will be lower in cost.[10]

The costs listed in Fig. 8 are derived by using the detailed procedures developed by NRC and DOE, which are explained in Ref. 7. Further information on recent costs has been provided by Roddis.[11] In accord with that reference and to allow direct comparison of OTEC estimates with those presented in

Table 2

ESTIMATED OTEC AMMONIA
FUEL-CELL SYSTEM COST
$/kWe OUTPUT POWER (1980 dollars)

	Hydrogen-Oxygen Fuel Cell $\eta = 0.50$	$\eta = 0.65$
Ammonia converter	$ 90	$ 70
Fuel cell and power conditioning	200	400
Oxygen separation plant	100	100
Storage	20	20
Total $/kWe	$410	$590
Ammonia cost $/lb	0.100-0.124	
kWh/lb	1.707	1.313
Ammonia cost $/kWh	0.073	0.059

Table 3

ESTIMATED CASH COSTS OF
OTEC AMMONIA DELIVERED (1980 dollars)

Plantship investment, eighth plantship ($/kWe)	$1200
Annual ammonia production (tons/kWe)	1.17
Cost per ton	
Ammonia	$184-$232
Shipping	$16
Delivered	$200-$248

Ref. 11 for coal and nuclear power plants, the following assumptions are made:

- 20% return to the owner/operator on invested capital;
- 9% interest on debt;
- Title XI financing by the Maritime Administration, which provides loan guarantees for 87.5% of the plant investment;
- Thirty-year plant life;
- Thirty-year sum of years' digits sinking fund;
- Federal income tax of 48% with 10% income tax credit in the first year;
- Insurance of 0.5% on plant investment;
- 1% of plant investment per year for interim replacements versus 0.65% used for coal and nuclear estimates (allows for replacement of the aluminum heat exchanger after 15 years);
- No local and federal property taxes; and
- 0.35% annual taxes on other items.

The comparison indicates that both moored and grazing OTEC plants will deliver power in 1990 to U.S. mainland sites at prices competitive with projected coal prices, and power from moored plants in Puerto Rico and Hawaii will be even lower than projected nuclear costs.

COMMERCIALIZATION

Along with technical development of OTEC, studies and investigations have been conducted to determine what institutional, legal, and commercial barriers must be overcome to permit OTEC to become a major new energy industry. The studies have shown that legal and environmental barriers to OTEC operation are minimal. Until recently, however, industry interest has been low. Developments within the past year have modified earlier negative opinions, and support is now emerging both from the electric utilities and from ammonia producers for early demonstration of OTEC capabilities.

Projected costs of delivered power from the first moored pilot/demonstration OTEC plants at sites a few kilometers offshore in Puerto Rico and Hawaii are low enough to make OTEC power a profitable venture if about half of the capital costs of these small sized plants can be supplied from federal funds. The projected cost of power from imported oil, the only present source of power in those islands, makes OTEC power particularly attractive for those sites. To facilitate early commercial plant development, the Commonwealth of Puerto Rico and the Puerto Rico Electric Power Authority (with some local industry support) proposed in 1979 sharing part of the costs of developing a moored 40-MWe pilot plant, if — after the initial shakedown — DOE would assign the power produced by the pilot plant to the Puerto Rico utility. A similar proposal was explored by the State of Hawaii. A group of ammonia producers submitted to DOE a proposal to provide 40 million dollars in cost sharing for the construction of a 40-MWe pilot ammonia plantship if the 125-ton per day ammonia output would be assigned to them for sale. However, none of these unsolicited proposals was accepted by DOE, which favors use of a competitive bidding procedure and a more deliberate schedule for selecting OTEC programs to support.

The proposals to share funding of the pilot plants provide encouraging evidence of industry commitment to rapid commercialization of OTEC after the expected performance of the pilot plant is successfully demonstrated.

CONCLUSION

OTEC plantships that produce ammonia can supply electric power via hydrogen fuel cells to all regions of the United States and can conserve natural gas now used as a feedstock for ammonia-based fertilizers and chemicals. Ammonia also has an attractive potential as a synthetic fuel alternative to synthetic fuels from coal. Moored OTEC plants sited near Puerto Rico or Hawaii, or offshore in the Gulf of Mexico, can supply electric power directly to utility grids onshore via underwater cables. Projected costs of OTEC ammonia and electrical energy after 1990 are comparable with those projected for conventional plants based on fossil fuel or nuclear power. Since OTEC energy will be inexhaustible, economical, and environmentally benign, OTEC deserves high priority among the Nation's energy programs.

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[6] B. M. Winer and J. Nicol, "Electrical Energy Transmission for OTEC Power Plants," in *Proc. 4th OTEC Conf.*, p. III–26 (1977).

[7] Nuclear Regulatory Commission, "*Total Generating Costs – Coal and Nuclear Plants*, NUREG–0248, Table 4-3 (1979).

[8] Each time the number of units doubles, the cost is reduced by this factor. Thus the second unit costs 0.93 times the cost of the first, the fourth costs 0.93 times the second, the eighth costs 0.93 times the fourth, and so on.

[9] A. P. Fickett, "EPRI Fuel Cell Program Overview," *Proc. National Fuel Cell Seminar*, p. 5 (1979).

[10] E. J. Francis, "Investment in Commercial Development of OTEC Plant Ships," Dept. of Commerce (MARAD) (Dec. 1977).

[11] L. Roddis, private communication: "Present capital costs are in the range $1000 to $1200 per kW for both coal and nuclear. Nuclear fuel cost is presently $38 to $40 per lb."