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ENERGY FROM THE OCEANS: REQUIREMENTS AND CAPABILITIES

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ABSTRACT

The extraction of renewable energy from the oceans has the long term potential of satisfying much of the world's requirement for energy, while producing minimal adverse environmental impact and virtually none of the security and waste disposal problems associated with nuclear power plants. Eight methods, and a number of variants, of obtaining energy from the oceans are presented: ocean thermal, kelp bioconvension, ocean waves, tides and tidal currents, ocean winds, ocean currents, salinity gradients, and ocean geothermal. Each method is discussed in terms of concepts, geographic areas applicable, and development schedule and costs insofar as information is available. None of these methods releases "excess" heat into the environment, as do fossil-fuel and nuclear-power generating plants. Most of the methods represent relatively new technologies.

The needs for seafloor engineering R & D to support all ocean energy systems center about six principal areas: mooring and anchoring systems; anchor-soil interaction; underwater electrical-transmission cable-soil interaction; in-situ soil properties and soil behavior under applied loads for continental shelf siliceous and calcareous sands, and deep-sea pelagic clays and biogenic oozes; stability-instability relationships of shelf, slope, and deep-sea floor soils; and scour and stability of structures, including large anchors and power cables, with respect to liquefaction, wave loading, and structure-soil interaction in storms.

INTRODUCTION

It is the purpose of this paper to consider briefly the distribution of energy on Planet Earth, particularly with regard to the oceans; to present some ocean-energy relationships, emphasizing those that are renewable; to assess eight concepts that might be used to extract energy from the oceans; and to identify needed seafloor engineering research to support those concepts that appear to have the greatest economic viability. This paper is in its third iteration. The first (Richards, 1975) was a preliminary account that was prepared as a background paper for the Marine Board's Committee on Seafloor Engineering, National Research Council; the second (Richards, 1976) substantially updated the earlier version, but deleted reference to seafloor R & D requirements. This paper includes most of the information in the second iteration, with seafloor R & D reintroduced and updated.

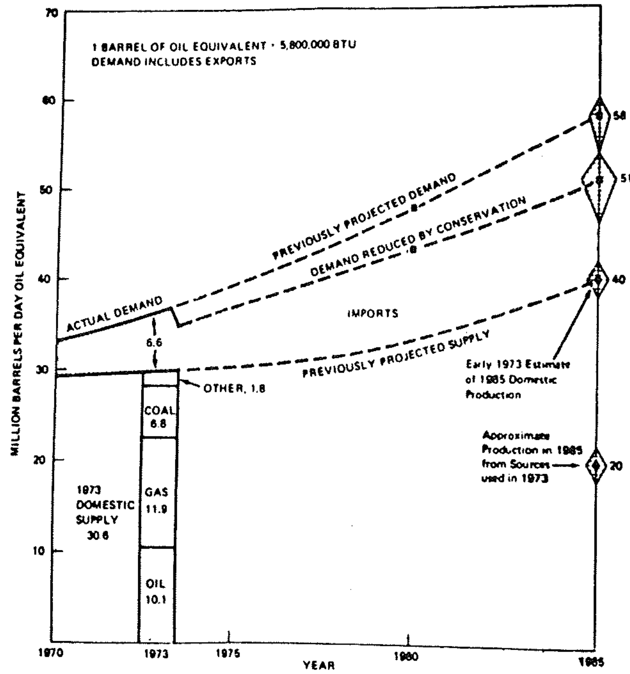

Fig. 1 Energy supply and demand in the U.S. (Task Force on Energy, 1974; reproduced with permission of the National Academy of Sciences).

National Needs

Energy self-sufficiency is essential to an industrial nation. Although it has been claimed that the United States has the resources and technology for self-sufficiency (Ray, 1973), the country obviously will not reach self-sufficiency in the near future. Nor does it appear likely that voluntary conservation of energy resources coupled with increased domestic fuel production and expanded use of nuclear energy will economically yield energy self-sufficiency within a reasonable time period as the nation's growing demands for energy increase (Fig. 1). Consequently, the possibility of economically utilizing the earth's renewable energy resources becomes especially attractive. Among these resources, several related to the oceans appear promising; they will be discussed later.

McWethy (1974) considers that the following sub-goals of the U. S. energy program are assumed to be important: "Energy should be obtained at minimum price; energy systems should have minimum impact on the environment; (and) the energy system should provide masimum security and reliability." Her second and third points warrant discussion. Much has been written about the problems of siting nuclear power reactors on land and at sea. The environmental impact of these reactors is controversial. Perhaps more serious problems in the long term are those of waste disposal from nuclear power plants and the security considerations evolving around plutonium that is a byproduct from spent fuel and a product from reprocessing plants. The breeder reactor is not the panacea in terms of security that it appears to be for the conservation of uranium. Although the gaseous-core reactor conceivably may minimize the waste disposal problem from com-

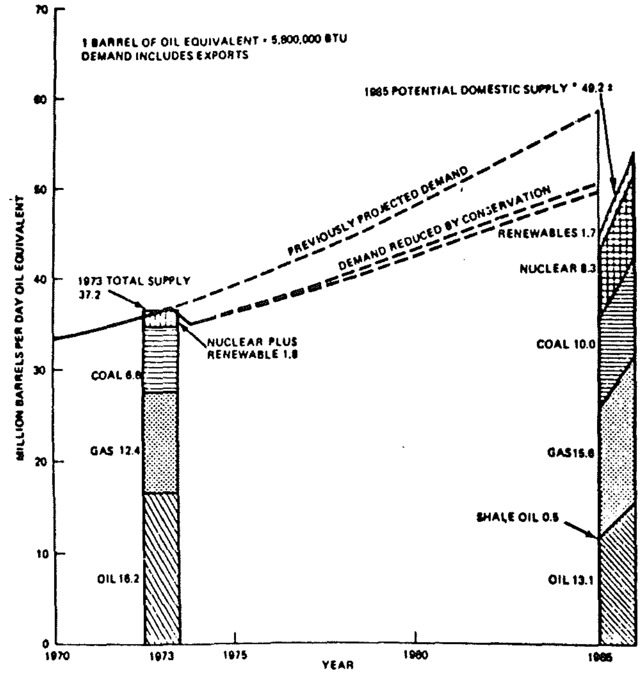

Fig. 2 **Possible energy supply and demand in the U.S. (Task Force on Energy, 1974; reproduced with permission of the National Academy of Sciences).**

mercial nuclear power plants, the security problem still exists (Willrich and Taylor, 1974). It is emphasized that renewable energy resources minimize the impact on the environment and present none of the security and waste disposal problems plaguing nuclear power plants; however, the commercial attainment of the renewable energy from the oceans is apt to occur only relatively late in this century. It will not occur in the next decade (Fig. 2), according to the Task Force on Energy (1974).

Energy in the Oceans

Von Arx (1974) has estimated that about 10^{16} watts of solar energy reach the surface of the earth, and that the world's current power demand is about 10^{13} W. He suggests that 10 percent of 10^{16} W, or 10^{15} W, be considered the "power ceiling" for climatic preservation when diverting power from cycles of energy exchange maintained naturally by the solar-terrestrial heat balance. Von Arx (1974) suggests that any system adding heat to the environment, such as fossil-fuel or neclear plants, should have a 10^{13} W limit so as not to perturb the climatic balance. Almost all the heat content from fossil and nuclear fuels enters the atmosphere by means of two methods: (1) conversion inefficiency in which an appreciable amount of the available energy is initially lost as heat and (2) the remaining amount of energy eventually becomes heat as work is performed. Fowler (1972) discusses the flow of energy wasted and utilized in the United States. If the present rate of world power use continues to increase, the eventual heat generation and resulting global thermal pollution may have major consequences to mankind in the many decades

Table 1

Natural Energy Sources*

Source	Total Power, W	Notes
Solar insolation, earth's surface	10^{16}	
Photosynthesis	13^{13} +	1% utilized by humans
Organic decomposition	10^{13+}	
Available ocean heat	10^{13+}	10^{14} W (J. H. Anderson, 1975, pers. comm.)
Available wind energy	10^{12}	Total world kinetic energy equivalent to 10^{20} W
Total rainfall	10^{12}	
Hydroelectric power	10^{11}	
Geothermal	10^{10}	
Ocean currents	10^{10}	Kinetic energy
Luni-solar tides	10^{10}	10^{12} W (Griffin, 1974) for tides and tidal currents

*Primarily from data in Von Arx (1974).

or centuries ahead, primarily by raising the air and sea temperature sufficiently to promote melting of the polar ice caps and thus eventually raising sea level by about 100 m. A summary of some of these problems has been given by Häfele (1973) and Wilcox (1973, 1975b).

Von Arx (1974) indicates that a world's population of 10^{10} persons requires a subsistence metabolic energy level of about 10^{12} W from the edible carbohydrates, fats, and proteins produced by the solar flux. He estimates that an energy level sufficiently greater than the subsistence level to yield a "good life" would require about 10^{13} or 10^{14} W. Within the range of these numbers it is useful to examine the power potential of a number of natural sources (Table 1).

Wick and Isaacs (1975) have estimated the power flux for several ocean energy sources (Fig. 3). It is noteworthy that the various methods of harnessing the solar energy in the oceans do not produce "excess" heat as do fossil-fuel and nuclear-power generating methods. Most ocean-extracting processes, if large or numerous enough, could have an opposite effect, which would be to influence global temperatures by redistributing heat. This effect might in turn influence the global warming processes summarized by Broecker (1975). As the energy needs of mankind increase on Planet Earth, clearly the consequences of heat generation, extraction, and redistribution should be assessed much more critically than at present.

Eight basic methods, together with a number of variants, of extracting energy from the oceans are considered in this paper: (1) ocean thermal, (2) kelp bioconversion, (3) ocean waves, (4) tides and tidal currents, (5) ocean winds, (6) ocean currents, (7) salinity gradients, and (8) ocean geothermal. McWethy (1974) places greater emphasis on wind energy than I do; however, she does not include wave energy. J. H. Anderson (1975, personal communication) has pointed out that since wind energy produces waves, wind energy obviously has a greater potential; however, I believe it may be technologically easier to extract energy from ocean waves rather than from ocean winds. Tide and tidal

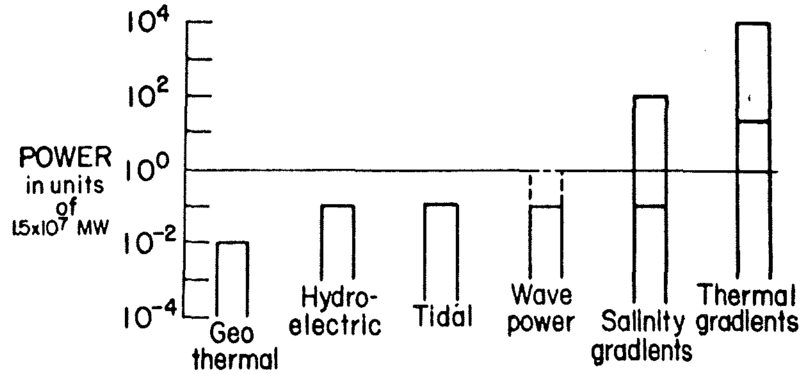

Fig. 3 **Power or energy flux for various ocean energy sources. The baseline is the projected 2000 A.D. global energy consumption. The dotted extension for wave power indicates that wind waves are regenerated as they are cropped. The shading for salinity gradients indicates the concentrated gradients at river mouths. The shading for thermal gradients indicates theoretical power extraction taking into account the Carnot cycle efficiency. (Wick and Isaacs, 1975)**

current methods are technically feasible, but were considered too costly before the recent significant increases in the price of oil. Salinity gradients have a great potential for energy (Fig. 3), but utilizing this potential may take appreciable time, money, and engineering talent. Other methods may be more economical. Offshore Thermal Energy Conversion (OTEC) is considered by many to be the best candidate for intensive development at present. Wave, tide, and possibly kelp bioconversion methods are also particularly interesting.

Current Seafloor Engineering Capabilities and Siting

The eight basic systems to be described have in common an interaction with the seafloor, whether it be by anchors, barrages, islands (McAleer, 1975), gravity-type platforms, piles, or some other means. For all systems, a knowledge of the engineering properties and behavior of the soil is essential. Except for Gulf of Mexico soils, relatively little information is known about the geotechnical properties of soils in the U.S. continental shelf; even less is known about these properties for the soils seaward of the continental margin. Richards et al. (1975b) have summarized the existing information on U.S. continental shelf soils, Monney (1975) assesses marine geotechnical state-of-the art, and Richards et al. (1975a, 1976) discusses siting considerations for offshore facilities. In particular, the Civil Engineering Laboratory papers by Albertsen (1974), Beck et al. (1971), Raecke (1973), and Wilson et al. (1972) are relevant to anchoring floating ocean energy systems. Power transmission to the shore from any energy-generating system at sea is a requirement for most ocean energy systems. According to Morello and McConnell (1975), 300 kV DC submarine power-transmission cables are being manufactured to connect Vancouver Island to the mainland. These authors believe that oil-filled cables, suitable for up to 750 kV AC or DC, can be laid in water depths of up to one kilometer; greater water depths were not discussed.

Bibliography

If one is considering the ocean energy probelm for the first time, he should start with an overview of the entire energy problem, such as given by Ruedisili and Firbough (1975). Two government documents are particularly useful to provide an overview of the U.S. energy situation: the Federal Energy Administration (1974) is the Project Independence volume dealing with solar energy, and the Energy Research and Development Administration (1975) summarizes the ERDA plan and its implementation. Papers by Griffin (1974) and Wechsler et al. (1974) provide a brief overview of methods of ocean energy extraction. The Proceddings of the Third Workshop on Ocean Thermal Energy Conversion (OTEC), edited by Dugger (1975), represents a particularly useful state-of-the art report, which has been briefly summarized in part by Weeden (1975). An interim bibliography of National Science Foundation reports on general energy research and technology prepared by Guthrie (1974) may assist the serious student, but it is already dated. Selected specialized papers, reports, and books are cited under each section describing a specific ocean energy system.

ACKNOWLEDGEMENTS

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OCEAN THERMAL

Concepts

It is a well known fact that the ocean is thermally stratified. Energy from the sun, particularly between the Tropics of Cancer and Capricorn, is collected and stored in the thin surface layers, where the temperatures may be 20-24° C warmer than the underlying water at depths of about 1 km (Fig. 4). The observation by D'Arsonval in the early 1880's that power could be generated using these small temperature differences in the ocean was put to the test almost 50 years later by Claude (1930), who wrote an extraordinarily engrossing account of his several submerged pipeline failures and his ultimate success at the end of 1930 in establishing a working experimental ocean thermal power plant located in Matanzas Bay, Cuba. Massart (1974) discussed Claude's achievement in generating 22 kilowatts of power and noted that the large amount of pumping power and small temperature difference (ΔT) did not yield an effective power output; consequently, the plant was an economic failure. Anderson and Anderson (1965, 1966) proposed to eliminate the deaerating and soft vacuum problems that plagued Claude by using a closed- or Rankine-cycle plant with propane as the power fluid. Subsequently, several groups have considered the Claude cycle (for example, Heronemus and McGowan, 1975, p. 33-34; Brown and Wechsler, 1975 a, 1975b) and many the Rankine cycle. Griffin (1974), Cohen (1975a), and Dugger et al. (1975) have summarized methods proposed by pro-

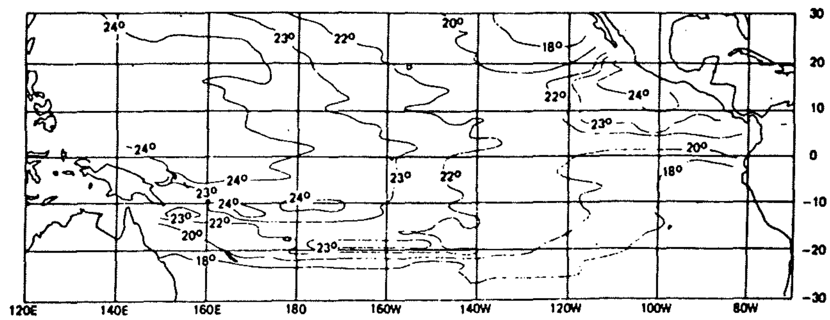

Fig. 4 **Temperature difference (ΔT) in °C between the surface and a depth of 1 km for the Pacific Ocean, summer (Douglass, 1975).**

ponents of the Rankine cycle. Weeden (1975), Lavi and Zener (1975a), and papers in Dugger (1975) update the state-of-the OTEC Rankine-cycle art. Wick and Isaacs (1975) have proposed a modified Claude cycle utilizing the vapor pressure difference derived from salinity rather than from temperature. Beck (1975) suggests using a type of open-cycle system that does not utilize a low pressure steam turbine. It instead operates on the principle of an air-lift pump, in which water vapor replaces the air. Zener and Fetkovich (1975) propose a modification of the Beck concept, replacing the vapor phase with a mixed liquid-vapor phase having a foam structure for greater economy.

Simplified schematic diagrams are shown for the Claude-cycle (Fig. 5a) and Rankine-cycle (Fig. 5b) plants. Major components of a modern Rankine-cycle Ocean Thermal Energy Conversion (OTEC) power plant have been summarized in the proceddings of the first OTEC Workshop (Lavi, 1973):

"1. A boiler or evaporator fueled by warm sea water to change the state of the working medium from liquid to high pressure gas

2. A turbine to convert the thermal energy stored in the working fluid into mechanical energy to drive an electric generator

3. A cold water pipe and pumping system to upwell the cold water from the ocean bottom to feed into

4. A condenser to change the state of the working medium from low pressure gas into liquid

5. Pumps to circulate the working fluid from condenser to evaporator and to pressurize the liquid."

The Claude (1930) OTEC and a design proposed by Snyder (1959) featured the cold-water pipe mounted on the bottom. Recent OTEC designs suspend the long cold-water pipe from a floating OTEC plant. Although the thermodynamic or Carnot efficiency of the OTEC systems is only a few percent (enormous quantities of seawater must be passed through the plant to extract energy from the water), since the water is free of cost the process is considered to be a viable one.

Table 2 presents a net energy comparison between OTEC-produced electricity and electricity from conventional sources. Two useful conversions are that one kilowatt-hour (kWh) of electricity produced is equivalent to a nominal heat rate of 9600 Btu and one Btu equals 1054 joule (Task Force on Energy, 1974).

Anderson (1972) has written on the fascinating prospects of utilizing the OTEC electrical power initially generated to (1) condense fresh water from the plant's evapo-

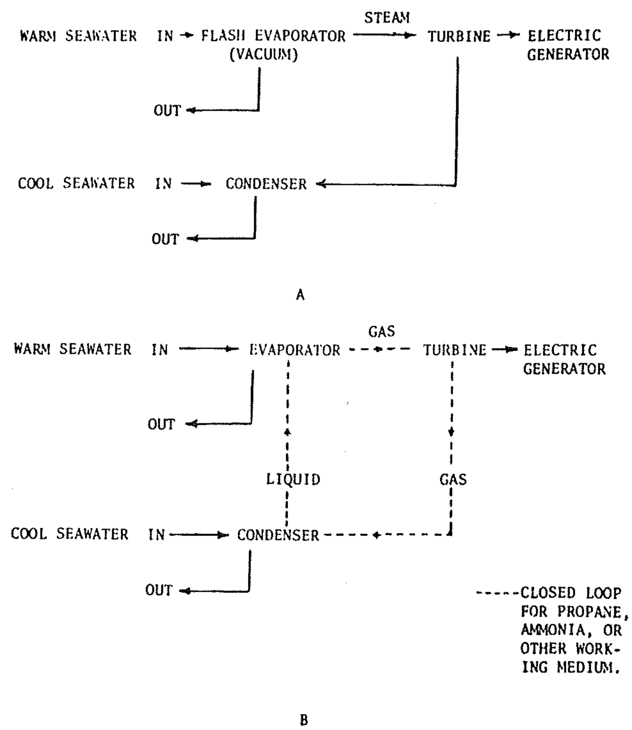

Fig. 5 **Simplified schematic diagrams of basic Ocean Thermal Energy Conversion (OTEC) methods. A. Open- or Claude-cycle OTEC. B. Closed- or Rankine-cycle OTEC.**

Table 2

Net Energy Comparisons*

Energy System	Delivered Energy,[1] Btu	Primary Resource Required,[2] Btu	External Resource Required,[3] Btu	Net Energy,[4] Btu
OTEC-Electric	1000	0	315	+ 785
Nuclear Fission-Electric	1000	7425	451	-6876
Coal-Electric	1000	3498	566	-3064
Oil-Electric	1000	3123	839	-2962

[1] Electricity delivered to the customer.
[2] Energy value of the fuel consumed in generating electricity. The OTEC energy is renewable.
[3] Energy value of the resources necessary to construct and operate the energy system.
[4] Net energy = output-(primary + external resources)

* Adapted from the Lockheed OTEC Second Quarterly Progress Report, 27 February 1975, and Trimble et al. (1975).
A kWh of electricity is equivalent to a nominal energy value of 9600 Btu (Task Force on Energy, 1974).

rators; (2) obtain oxygen from deaerated salt water using a refrigeration process; (3) electrolyze water to yield hydrogen; and (4) promote aquaculture by supplying nutrient-rich water. Concept three also is a main element in the offshore wind system to be discussed later. Weinberg (1973) reports that theoretically water can be electrolyzed using about 15 kWh per 2.2 kg of hydrogen and that over the long term this value may be approached. A discussion of the use of hydrogen, with a detailed cost analysis, has been made by Winsche et al. (1973). Concept four has received much attention; for example, Gerard and Roels (1970), Othmer and Roels (1973), and Roels (1975). Both Anderson (1975) and Dugger et al. (1975a, 1975b) have proposed using OTEC power to manufacture ammonia for fertilizer. Anderson (1975) also has suggested manufacturing a variety of other products from the sea, such as carbon dioxide and methanol.

Geographic Areas Applicable and Siting

Most plans consider that the best locations are approximately between the Tropics of Cancer and Capricorn, or where warm water is carried to higher latitudes by the western boundary currents. If the net efficiency of ocean thermal power plants can be increased, then it may be economical to operate plants using a smaller temperature difference. In this regard, Anderson (1975) reports that a laboratory turbine has operated on a temperature difference of only 1.7° C using R-11 refrigerant as a working fluid. A working model successfully demonstrated the OTEC principle at the Third OTEC Workshop held in Houston in May 1975 (see Dugger, 1975, p. ix). However, a ΔT of greater than 20° C (Fig. 3) is favored in most proposals.

The first OTEC Workshop named four factors for siting a plant (Lavi, 1973):

"1. The suitability of multiple use of plant output, i.e., fresh water, aquaculture

2. Maximum gradients of water temperature and maximum differences in water temperature with high volumes of water supply

3. Proximity of market for plant products

4. Social benefit."

Both island and deep-water sites were identified. The islands of Puerto Rico, St. Croix, and Hawaii were suggested as possible locations for a 1-10 megawatt (MW) prototype plant. The deepwater sites included the Gulf Stream (Florida Current) and along southern California. Another group at the first OTEC recommended 400 MW afloat power plants located in the Gulf Stream.

At the second OTEC Workshop in 1974, a working group (Godshall, 1975) considered the factors to be included in an environmental impact analysis: (1) oceanographic structure changes affecting large-scale circulation; (2) scale of oceanatmosphere interaction; (3) changes in nutrient level and biological impact; (4) leaching of material from the OTEC plant; and (5) the rate of recovery at an OTEC site after either an OTEC accident or long-term operations.

At the third OTEC Workshop in 1975 (Dugger, 1975), Working Group 5 succinctly summarized the assessments needed for geographic siting: (1) oceanic environmental impact on OTEC plant; (2) OTEC plant impact on its oceanic environment and feedback effects; and (3) impact of the plant on the whole biological, chemical, and physical oceanographic environment both locally and on an ocean-wide basis.

One of the two principal industrial OTEC studies, to be discussed later, favors a Hawaiian site (Douglass, 1975), although other sites also were discussed. The favorable characteristics of this site include a summer 20° ΔT difference between surface water and seawater at only 400 m, which occurs only 18 km seaward of Keahole Point on the west side of Hawaii Island (Bathen, 1975). On the other hand, the University of Massachusetts team favors a site east of Miami (Goss et al., 1975).

Development Schedule

Barr (1975) reviewed five types of OTEC configurations: spar, ship, disc or circular barge, semi-submersible with single hull, and semi-submersible with two submerged hulls. A number of variants to these four types have been proposed. The degree of development involving three of the types since the early 1970's has been appreciable, although a ship-hull appears not yet to have been seriously considered. The following OTEC systems proposed by three groups illustrate the methods presently being discussed. The Hydronautics (Brown and Wechsler, 1975a, 1975b) and the Sea Solar Power (Anderson and Anderson, 1966, 1973; Anderson, 1972) systems are not included because of a lack of comparative developmental information. Hagen (1975) reviews 13 papers summarizing earlier work, particularly by the University of Massachusetts and Carnegie-Mellon University.

The current status of the University of Massachusetts (UMASS) group's 400 MW, Mark II semi-submersible OTEC power plant has been given by Heronemus and McGowan (1975), McGowan and Heronemus (1975), and Goss et al. (1975). The cold-water pipe will range in diameter from 24 to 37 m (18-120 ft) and be 323 m (1060 ft) long. Mooring by a very large and heavy concrete anchor subsystem has been proposed. Corrosion and biofouling are identified as the two principal problem areas. Seven other problem areas were cited as requiring solutions. The UMASS team is currently favoring propane as the working medium in a Rankine cycle, a site located about 26 km east of Miami, and a DC power-cable link from the OTEC to the mainland. Morello and McConnell (1975) and Winer (1975) have reported on submarine cable methods of power transmission. The UMASS group has estimated a prototype could be constructed in six years.

The Lockheed 240 MW (160 MW net), spar-type OTEC power plant (Fig. 6) has been described by Trimble and Naef (1975) and Trimble et al. (1975). This OTEC plant is designed to use ammonia as the working fluid in a Rankine cycle. The cold water pipe was designed to range in outside diameter from 32 m at the bottom to 39 m (105-129 ft) at the top and to extend 305 m (1000 ft) below the bottom of the platform, which in turn would extend 156 m (512 ft) below sea level. The proposed Lockheed OTEC system, including anchoring and power transmission to shore, is shown in Figure 7. Major component problems are the heat exchangers and 6 MW ammonia turbines. Lockheed proposed 10 years, beginning in 1976, for development.

The TRW 160 MW (100 MW net) disc-type OTEC power plant (Fig. 8) is reviewed by Douglass et al. (1975) and Douglass (1975). Ammonia was proposed as the working fluid in a Rankine cycle. The coldwater pipe was designed to be 15 m (50 ft) in diameter and 1.2 km (4000 ft) long. The preferred mooring design was a shrouded-pipe water jet, or steerable nozzles, which would permit the plant to move out of the warm-water effluent discharged from the evaporator (Fig. 8). Principal identified problem areas were the heat exchangers, coldwater pipe, positioning, and interaction with the marine environment. A development plan was not proposed.

The stated developmental objectives of the OTEC subprogram of the Energy Research & Development Administration (Solar Energy Program, 1975) are:

"1. to establish design and evaluation criteria for components, subsystems and systems;

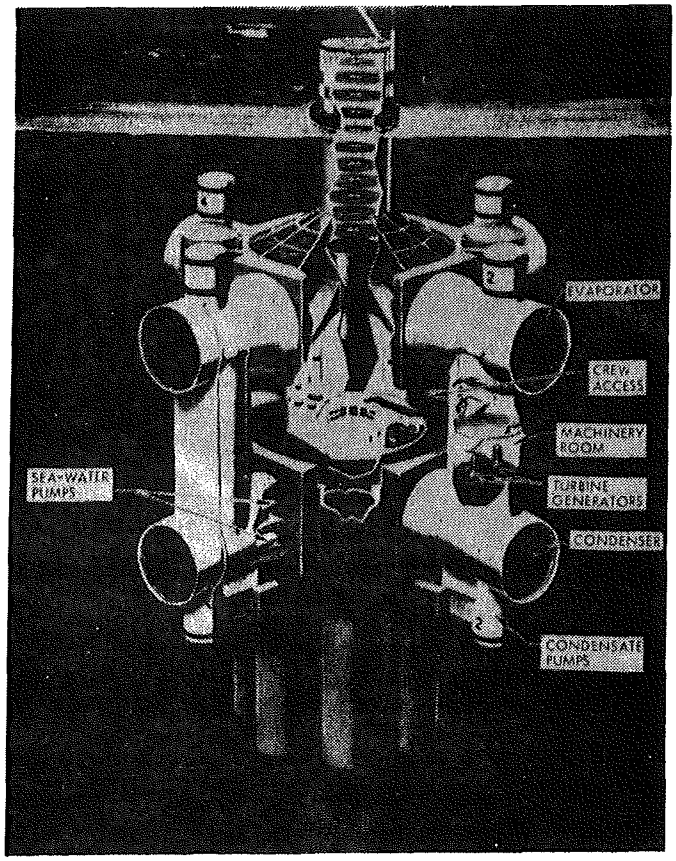

Fig. 6 Major elements of the Lockheed OTEC (Trimble et al., 1975).

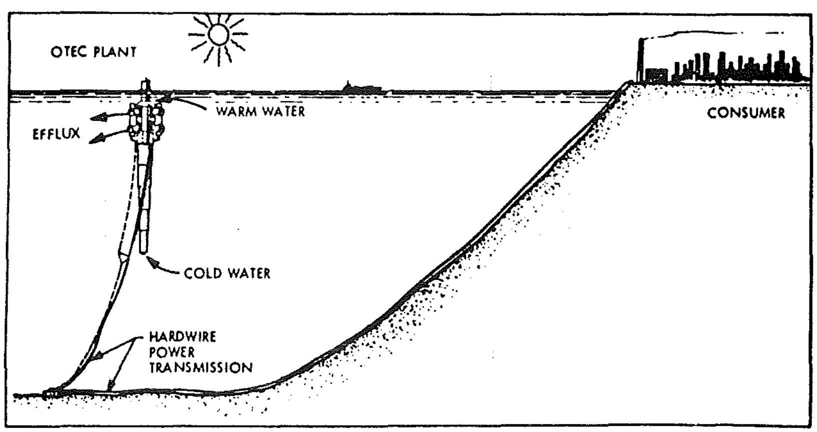

Fig. 7 The deployed Lockheed OTEC system (Trimble et al., 1975).

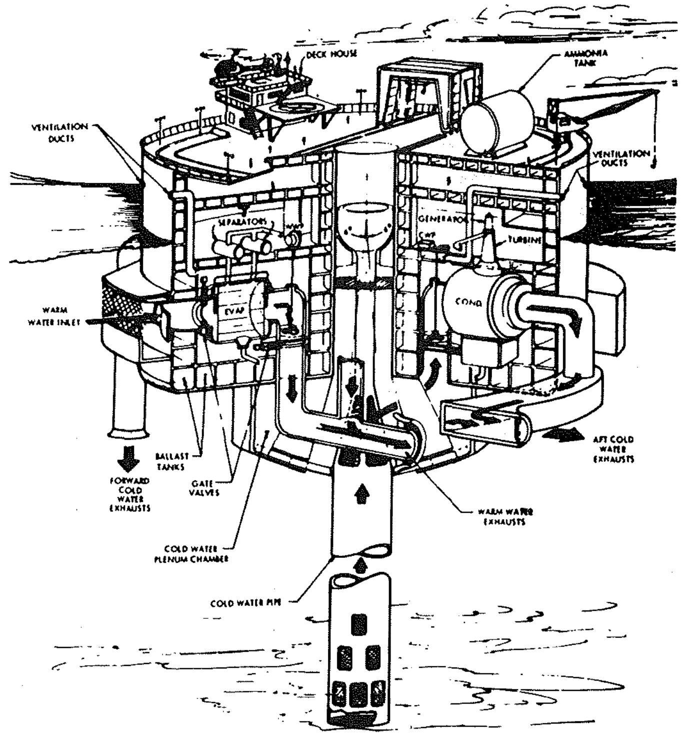

Fig. 8 The proposed TRW Systems Group OTEC (Douglass, 1975).

2. to perform system studies and analyses that will examine the technical and economic feasibility of various ocean thermal concepts (small-scale systems will be designed and constructed to validate the results of these studies and analyses);

3. to resolve and ameliorate possible institutional barriers to technology utilization, including international and domestic legal problems, and to evaluate potential environmental and ecological impacts;

4. to explore energy conversion, storage, and delivery systems for exploitation of the derived energy; and

5. to design, construct and operate a demonstration plant to evaluate a preferred concept by the early 1980s."

Further detail has been given by the Energy Research & Development Administration (1975), which estimates that by the year 2000 from 10 to 25 GW of electricity may be produced by OTEC methods.

Development Costs

Each proponent of an OTEC system has developed a different sets of cost figures. The Working Group on Costs at the third OTEC Workshop recommended the standardization of the total fixed charges, operation and maintenance charges, and transmission charges to determine the wholesale cost and ultimately the sale price of energy (Dugger, 1975).

Table 3

Conventional Power Sources Related to the Lockheed OTEC*

	Fossil Fuel		Nuclear	OTEC Baseline	
	Oil	Coal	Fission	15%	10%
Investment, $/kWe	465	450	500	2660	2660
Use Factor	0.75	0.75	0.6	0.9	0.9
Fixed Charges at 15% (mills/kWh)	11	10	14	35	26
Operating Cost (mills/kWh)	1	1	1	1	1
Fuel Cost (mills/kWh)	20	14	11	0	0
Total Power Cost (mills/kWh)	32	25	26	36	27

*From the Lockheed OTEC Second Quarterly Progress Report, 27 February 1975.

Until this is done, a critical assessment of comparable costs may be premature. Lavi (1975) estimated a range of about $387 to 2594/kW for the capital costs, and generating costs of 20-52 mills/kWh (1 mill = $0.001) at 90 percent capacity for all proposed OTEC plants. Lavi and Zener (1975b) believed that an OTEC plant could compete with fossil-fuel plants burning oil at $12/barrel or coal at $35/ton. The TRW study (Douglass, 1975), including the TRW baseline, UMASS, Carnegie Mellon University, and Sea Solar Power Inc. OTECs, resulted in a range of $1200 to $2400/kW for investment costs at a plant load factor of 90 percent, and a generating cost of 20-40 mills/kW. The Carnegie Mellon and Sea Solar Power costs were least. The comparable Lockheed figures are shown in Table 3. The 1975 costs for U.S. electricity generated by conventional fuels, in mills/kWh for the fuel alone, are: oil, 20-25; coal, 10; and nuclear, 2, according to data from the Pennsylvania Power and Light Company (H. G. Pfeiffer, personal communication, 1975); these numbers do not take into account either total generating or distribution costs. The baseline cost of the Lockheed OTEC was $2660/kW investment at a use factor of 90 percent, and a total power cost of 36 mills/kWh. The comparable TRW baseline costs were $2000/kW investment at a use factor of 90 percent, and a generating cost of about 40 mills/kWh. The Federal Energy Administration (1974) has summarized the quantities of materials that might be used for OTEC construction in five-year periods from 1980 to 2000. The magnitude of the material resources that may be utilized is considerable.

Zener (1973) concluded that the economic feasibility of the OTEC plants is such that he believed that liquid-metal, fast-breeder reactors will be economically obsolete before their development is completed. In this regard, Rose (1974) cited that about 20 percent of the 1.5 billion dollar U.S. energy research and development budget is spent on the liquid-metal, fast-breeder fission reactor. It is noteworthy that the 1975 National Science Foundation (NSF) and Energy Research & Development Administration (ERDA) budget for OTEC 1975 may be only about three million dollars, although $11.2 million was requested from the Congress; however, this sum compares favorably with the $730,688 in 1974, $229,200 in 1973, and $84,100 in 1972 (Cohen, 1975b).

Seafloor Interaction

Douglass et al. (1975) have assessed the advantages and disadvantages of four types of OTEC plant mooring options: wire, chain, synthetic rope, and dynamic positioning with propeller thrusters. Shrouded-pipe water jets were suggested (Douglass, 1975), as a fifth, and favored, method of positioning. Mooring capital costs were estimated at only a few million dollars for the shrouded-pipe water jet, compared to about $30 million for 90-mm (3.5 in.) diameter wire, and about $56 million for 150-mm (6 in.) diameter chain in water depths of about 1 km. Little (1975) and Valent and Taylor (1975) briefly commented on their proposed investigations of deep-water pipe and mooring systems and anchoring systems, respectively; the later types include deadweight, drag embedded, drilled-in pipe, and direct embedment. Ling (1975) also discusses the state-of-the art of anchor technology. Although Hartman and Nash (1975) have assessed the use of light mooring lines in the Gulf Stream, Heronemus and McGowan (1975) note that the mooring and anchoring system proposed for OTEC mooring in the Gulf Stream will be large, heavy, and needs a significant development effort. Earlier, Anderson (1974) considered a variety of anchoring and mooring systems. These included piling and very large concrete anchors, which might cost about $30/kW. An example of a deployed OTEC is shown in Figure 7.

In the candidate areas, detailed seafloor engineering surveys will be required (Treadwell, 1975; Richards et al., 1975a, 1976), followed by sample collection, laboratory testing, and analyses of the samples. On one hand, the foundation investigation is not expected to be greatly different from that customarily made for offshore sites. On the other, relatively little information is known about the engineering behavior of the submarine carbonate sand and rock occurring in the Straits of Florida, cited in the first OTEC Workshop (Lavi, 1973), and of the deep-sea floor soils located between the Tropics of Cancer and Capricorn. In the pelagic nodule area north of the equator in the central northeast Pacific, the soils' and what little is known of their properties, have been summarized by Hirst and Richards (1975). A need for future research and development on anchor-soil interactions and the in-situ soil properties of selected sites was identified by the 3rd OTEC Workshop working group on platform and cold-water pipe (Dugger, 1975).

KELP BIOCONVERSION

Concept

The idea of a "marine farm for the continual conversion of solar energy by the growing and harvesting of marine organisms such as kelp. . ." was briefly outlined in a document written by Howard A. Wilcox in 1972. This idea has been expanded into the Marine Farm Project, which is a cooperative venture of the Naval Undersea Center, Naval Weapons Center, and California Institute of Technology. Wilcox (1975a) describes the concept as follows:

1. ". . . to culture rapidly growing and easily harvested types of seaweeds on lines in the open ocean or coastal nurseries, and then to transport these lines to supporting structures embracing thousands of acres (1 acre = 4000 m^2) and lying 40-80 ft (12-25 m) below the surface of the open ocean.

2. "The water surrounding the crop is to be 'fertilized' and temperature conditioned by bringing up cool, nutrient-rich waters from a depth of a thousand feet (300 m) or so in the ocean. Additional nutrients can be supplied from the farm's processing plants or from shore-based sites if such should prove to be desirable.

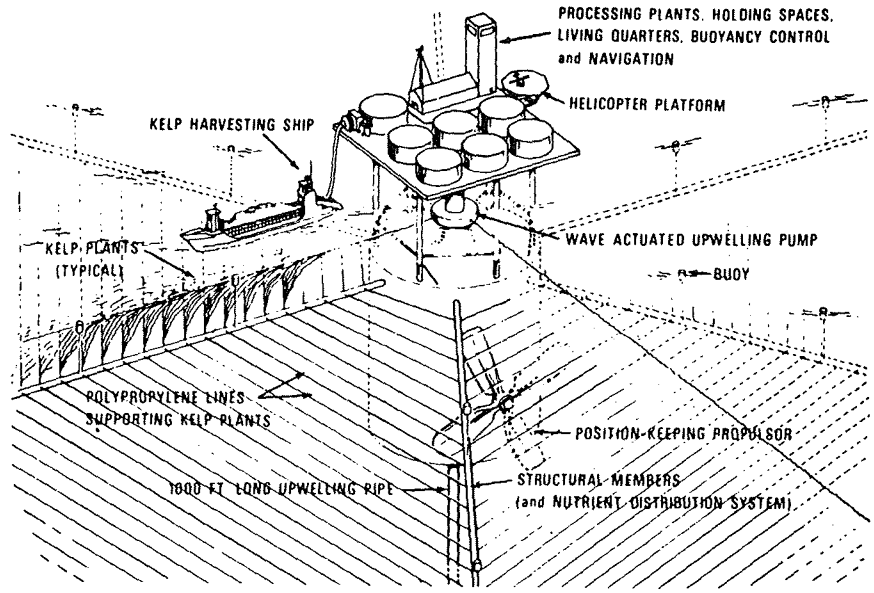

Fig. 9 Conceptual design of Ocean Food and Energy Farm unit (courtesy Naval Undersea Center).

3. "A portion (or all) of these plants and associated animal communities are to be harvested periodically, and the crops of seaweeds and animals are to be taken to at-sea or coastal factories for processing.

4. "The seaweeds are to be converted into foods, fertilizers, methane, and other fuels and industrial materials, at the processing facilities.

5. "Separate livestock and mariculture operations are to be supported with feeds derived from the seaweed."

The Marine Farm (Fig. 9) is based on the simple but elegant principle that solar energy is converted by photosynthesis into seaweed tissue that may be processed to yield fuels, food, and industrial products (Fig. 10). Kelp suitable for commercial harvesting includes *Ecklonia, Laminaria,* and *Macrocystis;* these species prefer water temperatures less than 20°C (Mann, 1973). The giant brown kelp, *Macrocystis pyrifera,* has been selected for farming off the California coast. *Macrocystis* is reported to have the fastest elongation rates of all plants, sometimes exceeding 300 mm/day (Dawson, 1966). In the farm concept, the plants' holdfasts would be attached to mesh or line rafts, constituting an artificial seafloor, positioned 12-25 m below the sea surface. Wilcox (1975a) assumes a spacing of about 3 m between plants to form a square lattice array, or a population density of about 436 plants/acre (4047 m^2) that would annually yield the equivalent of about 10^5 kWh in stored vegetational energy.

A key element of open-ocean seaweed farming away from shore is to artificially upwell nutrients from a depth of about 300 m, or to supply the necessary nutrients from the farm's processing plants or from land, transported to the farm by the supply vessels. Fertilization is required because the surface waters away from land generally are impoverished with respect to nutrients.

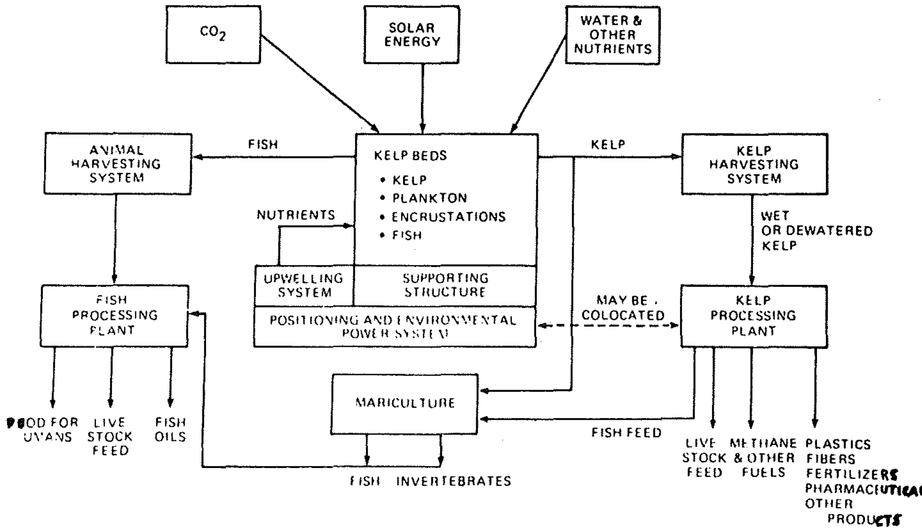

Fig. 10 Concept of Ocean Food and Energy Farm (courtesy Naval Undersea Center).

Wilcox (1975a) believes that the fronds of *Macrocystis* can be harvested about four times per year without damage to the plants. After harvesting, the fronds are ready for processing at sea (Fig. 9) or ashore. The generalized kelp bioconversion process (Figs. 11-12) has been described by Leese (1975). He reports that the carbon-hydrogen ratio of *Macrocystis* is 6.28 compared to 7.08 for fuel oil and the total energy per pound (0.45 kg) of the plant is about one-quarter that of fuel oil.

Geographic Areas Applicable

Appropriate growing conditions for conventional (nearshore) kelp harvesting are found in the Pacific from Alaska to Mexico, northern Peru to Chile, Kamchatka to Japan, and along the east side of New Zealand; in the Atlantic from southern Greenland to Nova Scotia, around Iceland, Beloye More (White Sea), north of Scandinavia to Ireland, off Morocco, and off south Argentina and southwest Africa; and not in the Indian Ocean, according to Mann (1973). Farms overlying upwelling areas probably would have a decided advantage over non-upwelling areas because of the natural fertilization of the surface waters.

In the energy farm concept, Wilcox believes that nearly all areas of the open ocean would be suitable for seaweed farming. In cold water, *Macrocystis* would be eminently suitable, according to Jackson and North (1973), who state that only *Sargassum natans* would be useful for an energy farm in the tropics unless upwelling were artificially induced. In the latter case, they report that temperate-water plants might be suitable.

Development Schedule and Costs

Noth and Wilcox (1975) report on an experimental marine farm that was established in 1974. *M. pyrifera* were fastened to a 0.03 km^2 (7 acre) rope-network raft, which was

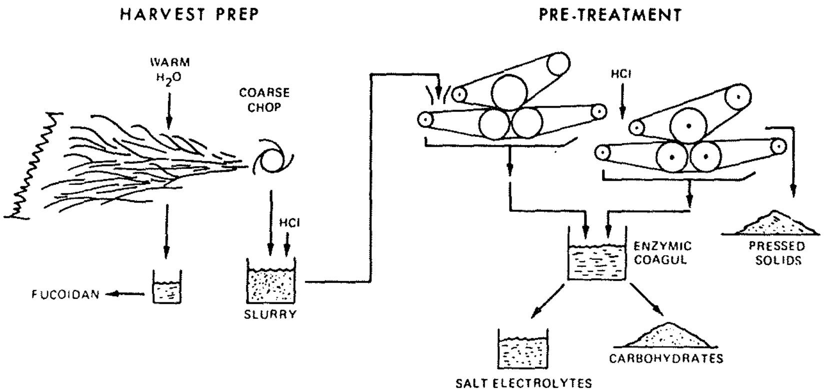

Fig. 11 Kelp bioconversion generalized process (courtesy Naval Undersea Center).

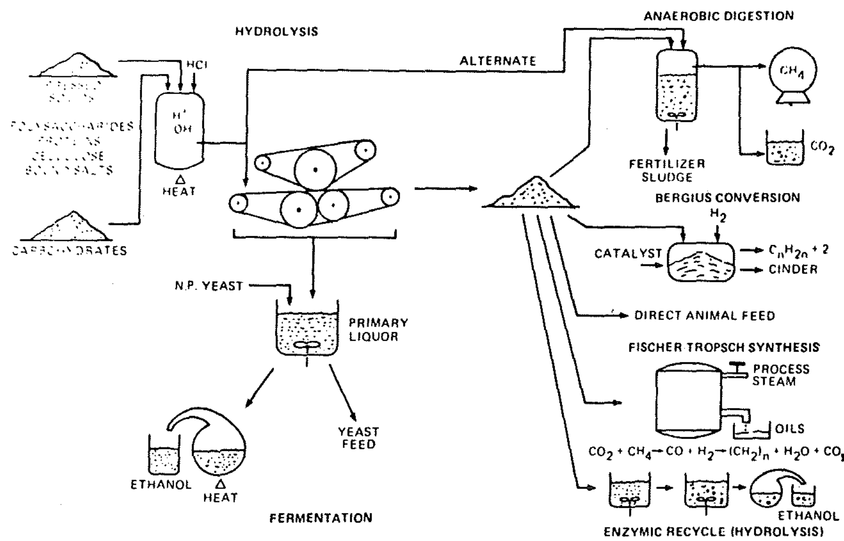

Fig. 12 Kelp bioconversion generalized process (courtesy Naval Undersea Center).

positioned about 12 m below sea level. The raft was anchored in about 100 m of water 1 km off the north-east end of San Clemente Island (Wilcox, 1975a) from July 1974 until the end of January 1975. At the latter date, nearly-total disintegration of the raft structure, possibly from ship transits through the farm site, was reported (North and Wilcox, 1975). The results of this preliminary test were sufficiently encouraging that a three-phased project has been proposed covering a 12-15 year period (Wilcox, 1975a): Phase I is the proof of technical and economic feasibility. It will extend over three or four years and cost slightly more than three million dollars. Two or three small-scale experimental farms are proposed for Phase I. Four major research areas are: (1) Kelp production and harvesting, (2) conversion of crops to methane and other products, (3) production of human and animal foods, and (4) system integration and economic analysis. The first area is understood to be partly funded by the Energy Research & Development Administration, and the other three by the American Gas Association. Phase II si the proof-of-concept, which is estimated to cover four to five years and to cost about 48 million dollars. The principal features will be the establishment of two medium-scale farms of 4 km^2 (1000 acre) in the Atlantic and in the Pacific. Phase III will be to fabricate, install, and operate a full-scale 405 km^2 (100,000 acre) demonstration farm. This phase is estimated to last from five to six years and to cost about two billion (10^9) dollars. For all three phases, the estimated costs are expressed in terms of constant 1974 dollars.

Seafloor Interaction

When this paper was prepared information was unavailable on the anchoring systems that obviously will be required. The present naval capability for deep-sea anchoring, previously cited in the Introduction, appears to be adequate for all phases. It is likely that the proposed farms will be divided into individual rafts of a size that are relatively simple to anchor. Inasmuch as the plants are at or below sealevel, the strain on the anchors should not pose any significant engineering problems.

OCEAN WAVES

Concepts, Development, and Costs

Methods of extracting the solar energy in waves fall into three general categories: (1) utilizing the vertical rise and fall of successive waves to activate either a water- or an air-operated wave-powered turbine; (2) utilizing the to and fro or rolling motion of waves by means of vanes or cams that would turn turbines; and (3) other methods, such as concentrating waves in a converging channel in which the momentum transport of shoaling and breaking waves maintains a head of water that can drive a turbine. Method one wave-activated turbine generators (WATG) have been in use for a decade. Their existing demonstrated capability is to generate only very small quantities of electricity; however, it has been proposed that multi-WATG units may have the potential to develop kilowatts of electricity, which is not of commercial importance except for limited applications. Method two has been proposed and is understood to be in a development stage; it has the potential of generating significant amounts of commercial power, although some formidable engineering problems first need to be solved. The example cited under other methods and illustrated in Isaacs and Seymour (1973), has only been proposed (Charlier, 1968); there are no known plans to utilize it, and it is not further discussed. The first two methods will be summarized in turn.

Masuda (1971) described a pneumatic-type of wave conversion device in which the relative air motion above an internal free surface within a pipe compresses air that drives an air turbine coupled to an electric generator. Masuda's fairway and weather buoys utilize a 70 W wave-activated generator. The use of these buoys at sea by the Japanese Maritime Safety Agency dates back to 1965. Both the 70 and 120 W units are standardized; the 70 W unit with spare parts was priced at 1200 dollars in 1971. Masuda (1974) reported that 300 units were in service. In 1967, a 120 W wave-activated generator was installed in a lighthouse on Ashika Island at the entrance of Tokyo Bay. A 500 W wave-activated generator was demonstrated in 1970, and Masuda (1971) reports plans for a kilowatt unit. Limited U.S. Coast Guard performance tests of a commercial Japanese WATG installed on a buoy were reported by Golburn and Motherway (1975). The average electrical output of the WATG was 5.75 W during tests conducted at various times over nearly a one-year period. The buoy in water was found to have a resonant frequency of 2.6 s, and the water in the WATG center-tube or surge-chamber had a resonant frequency of 4.7 s. Colburn and Motherwell reported a poor correlation between wave heights and power generation. They also noted biofouling inside the surge tube and no salt buildup on the turbine blandes during the limited time the buoy was evaluated. They mentioned that salt fouling of Japanese WATG units deployed over longer time periods has been a problem.

A floating, octohedral-shaped ring buoy has been proposed by Masuda (1974) to utilize waves off Japan having a length of about 120 m. Experiments, prototypes, and model tests leading up to this design date back to 1947, according to Masuda. Buoy dimensions are 120 m outside diameter, 70 m inside diameter, 4 m deep, and the net weight is calculated to be between 1500 and 3000 metric tons; the ring contains about 20,000 tons of water. Masuda reports that the oscillation period of this ring buoy should be about 50 s. The operation principle is that a pump room, having a 4000 m^2 area, will be open at the bottom and, as wave action compresses the air in the room, the air will operate a turbine to drive a generator producing 3 to 6 MW of electricity in high seas. This figure is predicated on 1 m^2 of pumping area serving to generate 1 kW of electricity during 5000 h/year. Masuda (1974) believes that component construction in a shipyard should be simple and that assembly will be undertaken at sea. Total construction costs are estimated to be two million dollars. The cost of electricity generation is estimated to be about 2 cents/kWh, based on an electric output of 15 GWh (15 million kWh) per year for 15 years. Masuda (1974) also reported on a model of a triangular-shaped, three-legged platform-type wave-activated generating system that was being tank-tested. A feasibility study estimated that electricity could be produced by a 100 kW unit for about $0.20/kWh.

McCormick et al. (1975) report on theoretically determining the optimum configuration of the Masuda buoy and have experimentally and theoretically studied a fixed wave-energy converter using the same principle. Their work at the U. S. Naval Academy is in the preliminary stage of designing a semi-submersible using four pneumatic WATG units. Their analysis predicts that a total time-averaged power per wave of 4 to 20 kW can be generated from 1-1.5 m high waves having periods greater than 4 s. These power values result from the fact that the wave-energy converter is a surge chamber and large amounts of wave energy are extracted in the broad-wave frequency band about the 6.1 m diameter chamber resonance frequency (McCormick, 1974, personal communication). McCormick et al. (1975) have also conceived a double-action turbogenerator that is expected to more efficiently convert wave energy into useful electrical energy by continuously rotating over a wave period. Cost analyses for any of McCormick's proposals are unavailable. A variant of the WATG approach is to install the units on a University of Hawaii city-type of platform (Martin, 1974).

A Wave Power Generator has been developed at the Scripps Institution of Oceanography by Isaacs and his colleagues (Wick, 1973; Isaacs and Castel, 1974). Their slack-tethered device consists of a vertical pipe containing a one-way check valve and a buoyant float at the surface (Fig. 13). When the float and pipe descend into a wave through the water flows up the pipe past the check valve. As the float ascends a crest the water is prevented from flowing down by the check valve. Subsequent cycles elevate the water into an accumulator tank or reservoir until pressures are reached suitable for power generation by the flow of water through a turbine. The wave-generator is detuned and will respond to a large frequency range. To date, power output from a 203 mm (8-in.)

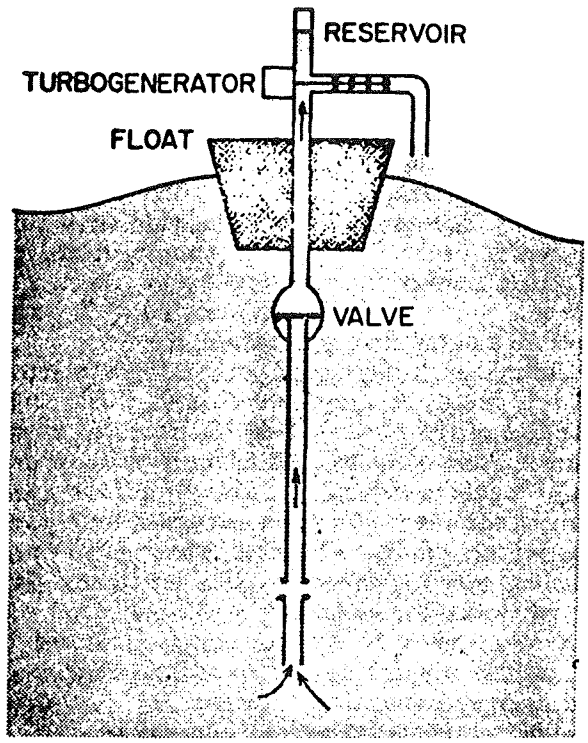

Fig. 13 **Schematic of the Isaacs and associates wave-powered generator (Isaacs and Seymour, 1973).**

diameter pipe 60 m (200 ft) long, operating in waves having 1.8 m significant wave heights and a 8 s period, was only equivalent to 60 W at nonoptimal design conditions. Isaacs and Castel (1974) have calculated that a 90 m long pipe, 0.9 m in diameter, will produce 18-20 kW of continuous power in a trade wind area; more recent calculations yield a figure of 30-40 kW. A cost analysis indicates a capital cost of $2000/kW (Wick, 1975, personal communication). Isaacs (1975, personal communication) states that larger units would be more economical because the power increases with the square of the pipe diameter and the cost increases approximately with the first power of the diameter.

The second method of wave-power generation is based on a specially-contoured rocking vane, or Salter cam, designed to absorb power from waves (Salter, 1974a). The random vane rotations produce unidirectional pulses of water to spline pumps, the output of which drives a single turbine. One system might consist of about 40 vanes connected to a cylindrical member having a diameter of 10-20 m for North Atlantic waves. Swift-Hook et al. (1975) have examined the bandwidth of applicable wave periods. They concluded from model studies that power conversion efficiencies greater than 50 percent can be obtained over the range of ocean wave periods.

According to a brief report *(Industrial Research,* Dec. 1974), Edinburgh University is purported to have received about a $144,000 (£65,000) grant from the U. K. Department of Trade and Industry to continue development of Salter's free-floating concrete and steel breakwater structure. Each structure, about 1 km long and submerged to a depth of

10-20 m, would contain 20-40 vanes or cams rotatted about an axis by the rolling motion of waves to generate electricity. An energy capture ratio of 90 percent was cited. Each structure is estimated to generate 50 MW, and a battery of 10 may cost about 480 million dollars. A promising location for the first installation was stated to be about 10 km west of the Hebrides. Salter (1974) states that the installations could be self-propelled, that electrolytic production of hydrogen was a promising use for the power generated, and that a few hundred kilometers of installation could meet the total 1974 U. K. electrical energy requirements.

An alternate method, using relatively small mass-produced units has been proposed by Woolley and Platts (1975). Their wave-contouring raft design consists of a series of hinged floats having pumps on the hinges. Waves travelling along the chain absorb power from the relative rotation of adjacent floats. The target is to harness the enormous energy in waves off the coast of Britain. These are reported by Woolley and Platts (1975) to have a maximum storm wavelength of 400 m, a 16 s period, and a maximum power content of about 400 kW/m of wave crest; however, Salter (1974b) indicates that power levels of 10 to 100 kW/m are more common in the North Atlantic. Masuda (1974) estimated that an average high (12 m/s) winter wind of the coast of Japan will yield a power level of 60 kW/m of wave crest.

Geographic Areas Applicable

Power generation in the kilowatt range from the Isaacs and associates buoys would depend on a trade wind location, according to their reports, unless a large number of floats are deployed. The Masuda-McCormick buoys are understood to be able to generate power in the kilowatt range in any location having wave heights greater than 0.6–0.9 m. The Salter wave generators are dependent on large waves to generate power in the megawatt range; consequently, locations exposed to storm waves originating over large fetch distances appear to be necessary.

Seafloor Interaction

The mooring methods for the smaller buoys appear conventional and well within the state-of-the art. Knowledge of the deepsea geotechnical properties in tropic areas is very limited (Richards and Parks, 1976). The attainment of this kind of information is recommended before anchors are emplaced for extended periods of time. The problems of anchoring the larger Masuda buoys and the multiple rolling-wave generators, each of the latter a kilometer long and 10-20 m on a side, off coasts known for the severity of winter storm waves will most likely be formidable. In this case, it appears that development will be necessary to design the anchoring systems and that geotechnical borings will be required to determine the soil properties for the engineering design.

TIDES AND TIDAL CURRENTS

Concepts

Six types of tidal power systems have been summarized by Wilson (1973): (1) single-pool ebb-flow generation using simple fixed-blade turbines; (2) single-pool ebb- and flood-flow generation using variable-pitch turbines; (3) single-pool ebb- and flood-flow generation using complex turbines and incorporating pumped storage – the Rance system; (4) double pool, in which the turbines are located between the two pools, one of which is intermittently filled by the flood tide and the other intermittently filled by the ebb tide; (5) double pool with pumping from off-peak system power; and (6) tide-boosted pumped storage. Modifications of some of these basic systems exist. Producing energy from tidal power is entirely feasible, but rather more expensive than conventional methods of energy production. Vernon (1974) states that the total output of tidal power sites capable of being practically developed is on the order of 350 terrawatt (10^{12}) hours; that is, (1.26×10^{18} J) per year.

Tide mills have been in operation for centuries. Heronemus et al. (1974) have reported on modern methods of obtaining power from fast-flowing, riverine tidal currents such as occur in the Piscataqua River between New Hampshire and Maine. They propose using horizontal-axis free-stream turbines of about 9 m in diameter or Savonius-rotor type machines about 6 m in diameter and extending 18 m across the stream; the later method was favored. They believe that considerable electricity could be generated without the equipment cutting off river traffic.

The literature on tidal energy is voluminous: Udal (1963), Charlier (1969a, 1969b, 1970), Gray and Gashus (1972), and Wilson (1973) are useful sources of information.

Geographic Areas Applicable

Wherever the tidal range is large and adequate water storage capacity exists in a natural or artificial body of water located near where there is a demand for electrical energy, there is a possibility for a tidal power plant. Prospective global locations are given by Charlier (1969b). In North America, Charlier cites the northwest side of Baja California, Mexico; off British Columbia; Cook Inlet, Alaska; Frobisher and Ungava Bays, northeast Canada; and the Fundy-Quoddy Bay Area.

Modern tidal power plants are presently in operation in the Rance River, between Dinard and St. Malo on the English Channel (Charlier, 1969a, 1969b), and at Kislaya Guba, U.S.S.R., off the Ura River, which flows into the Barents Sea north of Murmansk (Bernshtein, 1972; Bernstein, 1974). Both these plants are of the pumped storage type. Other locations that have been given a greater or lesser degree of consideration include Cook Inlet (Wilson and Swales, 1972); Passamaquoddy (Udall, 1963; Charlier, 1969a); Bay of Fundy (Lawton, 1972), Bristol Channel, Wales (Heaps, 1972); Golfo San José, at the south side of the Golfo San Matías, Argentina (Fentzloff, 1972); and at Mezen Bay, Tugu Bay, and Penginsk Bay in the Soviet Union (Bernshtein, 1972; Bernstein, 1974).

Development Schedule and Costs

Development of tidal power stations appears to be at a standstill, except in the U.S.S.R. The Rance River plant, annually producing about 555 GWh (10^9 watt hours) gross and 500 GWh net (Wilson, 1973), was expensive, and until the global price of fossil fuels increased markedly in the past few years there was no economic incentive to further develop tidal power. The 400 kW Kisla Guba plant is too small to be an attractive source of energy in the U.S., although the innovative concept of prefabricating the power station caisson in a dry location and then floating the caisson to the site (Bernstein, 1974) is likely to cut construction costs elsewhere. Perhaps the greatest potential centers around the activities in the Provinces of Nova Scotia and New Brunswick for the Bay of Fundy. However, Lawton's (1972) conclusion was that at the best sites of Shepody Bay, Cumberland Basin, and Minas Basin none of the tidal power plans was competitive with alternate sources of power when an interest rate of seven percent was used. The invest-

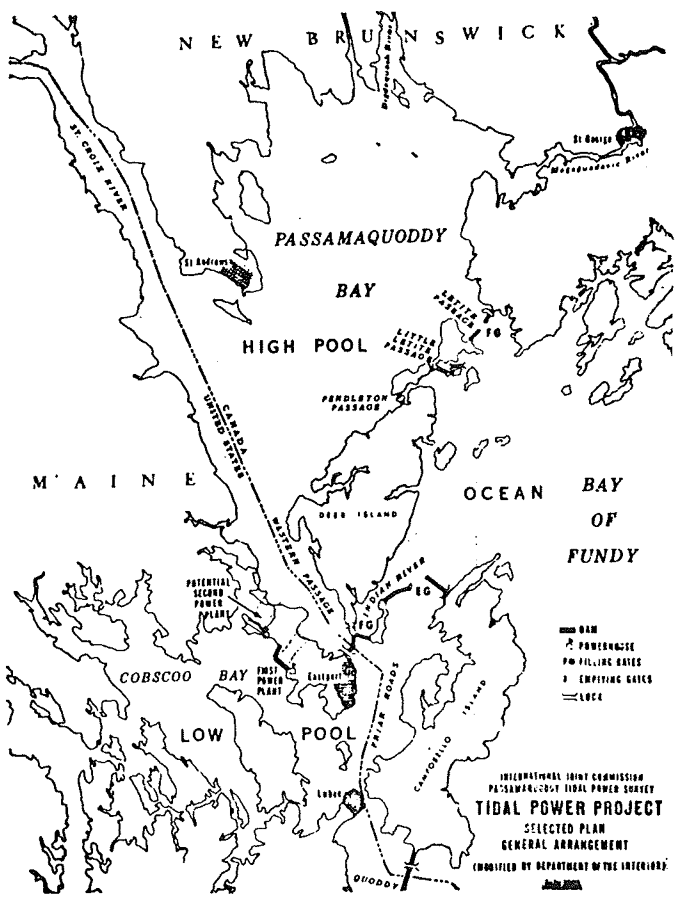

Fig. 14 Location of proposed low and high pools, and dam and power plant sites for the Passamaquoddy Tidal Power Project (Udall, 1973).

ment cost for dependable peak power at the site ranged between 25 and 40 dollars per kilowatt, compared to about 6-9 dollars/kW for oil, gas, or nuclear power. Within the greatly increased fuel costs that currently exist and are projected for the future, the Passamaquoddy location (Fig. 14) might well be reexamined. The project may now be more economically viable than when the 1.25 MW project was recommended in 1963 (Udall, 1963). Nevertheless, Wilson (1973) cautions that the development of large-scale tidal power necessitates (1) the availability of large inter-connected electrical transmission networks to utilize the output; (2) developing engineering methods to build and handle large floating concrete caissons and to sink them onto prepared underwater sites; and (3) developing low-cost electromechanical machinery of high hydraulic efficiency capable of sea-water operation over long time periods with minimum maintenance. Wilson notes that his first criterion is met for some sites and that the second is fulfilled by the concrete caissons built and successfully deployed in the North Sea. His third requirement for cheap, low-head turbogenerators has not yet been achieved. Wilson (1973) believes there is a promising future in using tidal-powered turbocompressors to produce com-

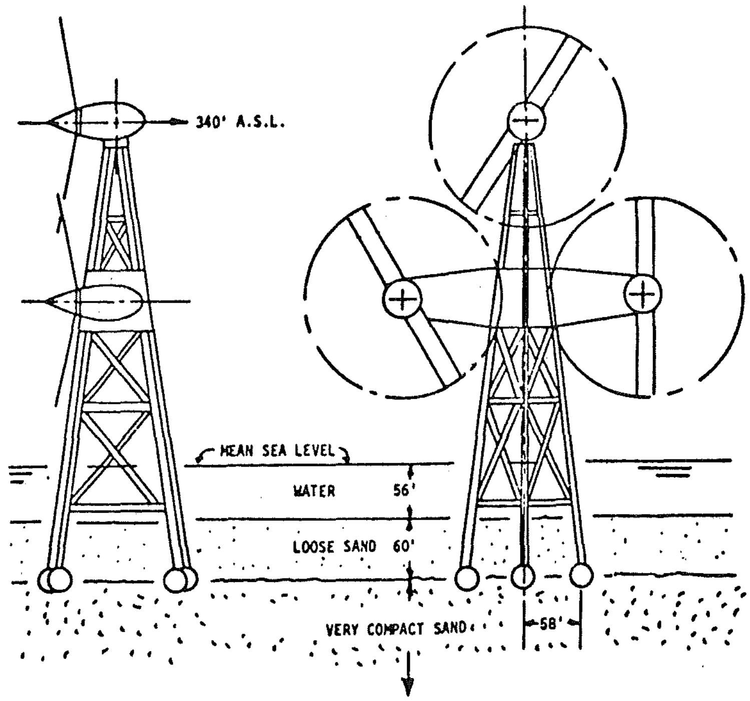

Fig. 15 Wind turbine station (Heronemus, 1972).

pressed air that can be stored in air-tight salt caverns, which have been solution-mined for the purpose. He points out that there are extensive, thick salt deposits in the vicinity of Shepody Bay and Cumberland Basin in the north part of the Bay of Fundy, and that these might make the development of tidal power in this area economical.

Seafloor Interaction

Most of the heavy construction appears to be the building of barrages, which are the artificial dams used to pond a watercourse or estuary. Gwynn et al (1972) have assessed modern methods of barrage construction, including foundation and scour. There do not appear to be any technological difficulties in light of the extensive work undertaken by the Dutch on constructing the barrages used in the Delta Plan.

OCEAN WIND

Concepts, Development, and Costs

Heronemus (1972) has described in some detail an imaginative means of supplying New Enlgand with power. The principal elements of his Offshore Wind Power System (OWPS) are (1) three 2 MW wind-turbine generators attached to one concrete-hulled floating or fixed-pile wind station (Fig. 15) that generates electricity; (2) 165 wind stations and one distillation-electrolyzer station comprise a wind unit that generates hydrogen gas; (3) 83 wind units and associated cables and pipelines to be located along five lines in the Gulf of Maine and Georges Bank area; (4) an offshore collection system consisting of one compressor and receiving station, a number of storage tanks comprising a 435 kPa (3000 psi) pressure-balanced hydrogen-storage system to be located at a water depth of 2.2 km; and (5) a shore-based, dispersed electricity-generating terminal having fuel cells, inverter and transformer equipment, and electrical distribution stations. The wind turbines would be located at elevations of 67 and 103 m above sea level. The peak load of the entire OWPS is estimated at 24 GW. The OWPS cost was estimated in excess of 22 billion (10^9) dollars for a 159 TWh (10^{12} watt hour) per year plant yielding electricity at a cost of 2.8 cents/kWh. It is likely that serious consideration of Heronemus' plan will await the trials of large terrestrial wind-generating units.

Geographic Areas Applicable

Heronemus assessed the annual average wind speeds to be about 11-12 m/s (25-28 mph) for the turbine elevations above sea level he considered. These speeds would correspond to about two thousand hours/year for less than the minimum cut-off speed of 6.7 m/s (15 mph) and 6-7.5 thousand hours/year at speeds greater than 6.6 m/s for the offshore winds. He implied that this was commercially adequate for the Gulf of Maine-Georges Bank area. The candidate wind generators would appear to be suitable for any offshore area having significant wind speeds above the minimum cut-out point for the turbine and at or above the optimum wind speed of about 13 m/s (29 mph). No mention was made by Heronemus about hurricane conditions affecting the OWPS.

Seafloor Interaction

The fixed offshore wind stations would appear to use well-developed seafloor construction technology. The Heronemus single tethered floating wind units might not be as practicable a solution to mooring as a multi-cable anchoring system. Single-point mooring technology and conventional anchoring systems appear to be very well adaptable to the proposed floating wind-unit structures.

The proposed cylindrical, concrete, hydrogen-gas storage hulls were dimensioned by Heronemus to be 244 m (800 ft) long and 30 m (100 ft) in diameter. He proposed to ballast the hulls with sand and gravel and to emplace them in a stable area of the continental slope east of the Veatch submarine canyon in a water depth of 2.2 km. This concept poses some unknown problems regarding the stability of continental slope soils in light of the large slide deposits shown on some subbottom records taken on profiles made normal to the slope near the base of continental slopes. The literature outlining submarine slope stability has been briefly summarized by Richards and Parks (1976). The proposed 1976 U.S. Geological Survey eastern U. S. continental slope drilling program may provide geotechnical information to better assess the seafloor stability of continental slopes.

It is recommended that an assessment of continental slope stability be made using appropriate static and dynamic laboratory tests and in situ tests, together with total and effective stress analyses of the data.

OCEAN CURRENTS

Concepts

Several recent publications have examined the potential of extracting useful amounts of energy from ocean currents (Green, 1970; Stewart, 1974b; and Sheets, 1975). Sheets

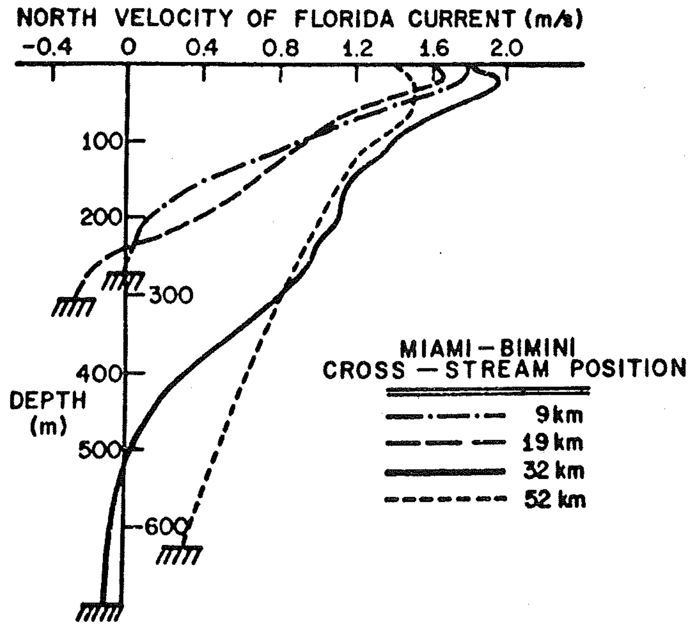

Fig. 16 Florida Current velocity profiles (1972 data from W. Duing cited in von Arx et al., 1973).

(1975) and Heronemus et al. (1974) have reviewed types of water turbines capable of utilizing low velocity currents. The first type is the water wheel or underwater windmill. Heronemus et al. (1974) has proposed that a tethered free-stream, four-stage, six-bladed underwater windmill rated at 20 MW in a 2.2 m/s current could be used. Sheets (1975) compares the theoretical performance of Kaplan, propeller, and vertical axis turbines as power generators in specific velocity gradients. He concludes that the Kaplan and propeller turbines have nearly equal efficiencies, but the propeller-type requires less structure. Sheets (1975) states that the vertical-axis turbine, which is similar in action to a Voith-Schneider propeller, is a good choice to generate power when the flow direction is variable and the energy gradient is large. The Sheets (1975) analysis was based on Florida Current velocities. Von Arx et al. (1974) has pointed out that the idea of tapping the kinetic energy of the Florida Current is an attractive one; this current channels 30 million m^3/s of water east of Miami at a surface speed sometimes greater than 2.5 m/s. Four average velocity profiles are shown in Figure 16, and the maximum theoretical power flux that could be obtained from this current per square meter of turbine area is illustrated in Figure 17.

Other machines that have been proposed to utilize the low hydraulic head available in ocean currents include a tethered, free-stream Savonius-rotor power station rated at 14 MW in a 2.2 m/s current (Heronemus et al, 1974; a tethered, four-disc axial-flow water turbine rated at 24 MW in a 2.2 m/s current (Heronemus et al, 1974); and parachutes attached to a continuous cable as a low water-velocity energy converter (Steelman, 1974). The uncertainties in effectively utilizing the very large-bladed turbines in a low hydraulic head may be expected to delay further consideration of this proposed method of energy generation.

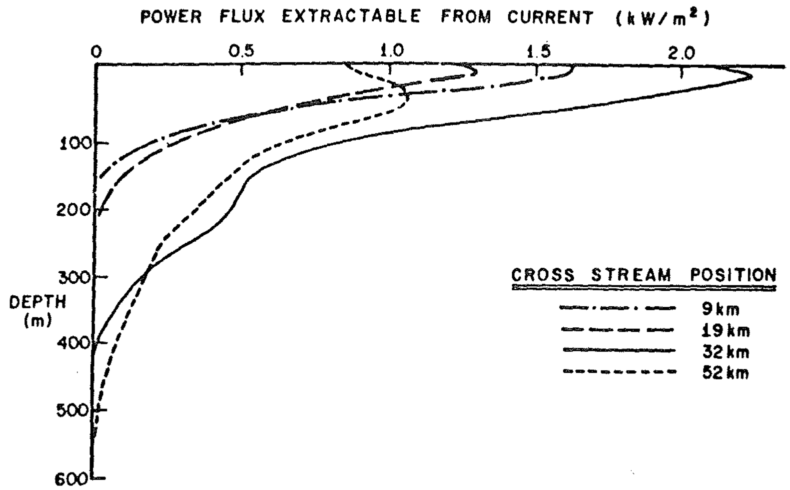

Fig. 17 Power flux from Florida Current (von Arx et al, 1973).

Green (1970) has proposed using Kaplan-type turbines mounted in the core of the equatorial Cromwell undercurrent, which flows at approximately 1.5 m/s west of the Galápagos Islands. Green notes that the Cromwell Current flow rate of about 40 M·m/s, spread over an area 100 m deep and 100 km wide, is three orders of magnitude greater than the flow rate of the Rance River tides. Furthermore, the Cromwell Current is continuous, while the Rance River tide reverses direction on the ebb and flow. Green has calculated that theoretically a turbine having an arbitrary diameter of 60bm located in the axis of maximum Cromwell Current flow would intercept an area that could yield 6.4 MW/turbine, or 0.6 the energy of an equivalent unit at Rance. Green proposed using the turbines to drive pumps to bring up nutrient-rich water as one part of an Oceanic Resource Base. His preferred site for the base was at Lynn Seamount, which is located on the equator at 135° West Longitude.

Von Arx (1974) states that the currents at both Gibralter and Bab el Mandel, at the south end of the Red Sea, have sufficient kinetic energy to produce a gigawatt (10^9 W) of power. Another scheme that was proposed a number of years ago was to dam the Straits of Gibralter, allowing the Mediterranean Sea to partially evaporate to lower the water-level by 100 m, and to utilize this head to produce about 100 MW of power (T. Treadwell, personal communication, 1975). It is not likely to be utilized.

Geographic Areas Applicable

The principal western boundary currents are the fastest oceanic non-tidal currents. Of these, the Florida Current has the greatest speed because it is channeled in the Straits of Florida between Florida and the Bahamas. The location between Miami and Bimini is considered ideal by von Arx et al. (1974). The Cromwell Current's locations on the equator is rather far from the United States to warrant serious consideration at present.

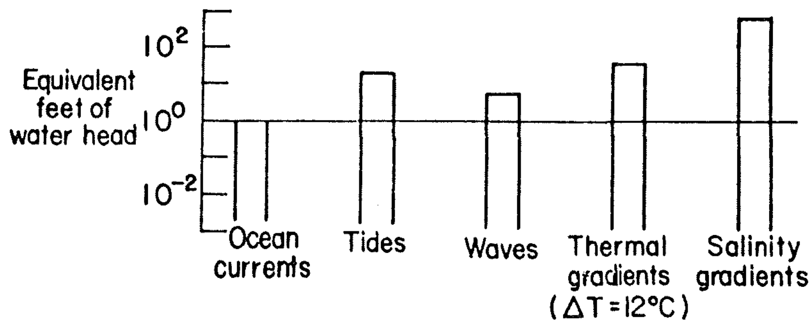

Fig. 18 Energy concentration in the ocean; the current bar is based on velocity head (Wick and Isaacs, 1975).

Development and Costs

Gilman (1974) has proposed a two-phase Florida Current project consisting of a feasibility study and a pilot installation optimistically scheduled for only two years. Stewart (1974a) more realistically reports on a three-phase study and development program. Phase one, covering 12 months, is a study of the (1) local physical oceanography and meteorology; (2) moorings; (3) wind-wave and hurricane loadings; (4) momentum exchange devices; and (5) energy collection and distribution of the total integrated system. Phase two consists of all work up to a 5-20 MW proof-of-concept power plant, the three-year construction of which would be phase three.

Stewart (1974a) reported that the preliminary cost estimates compared favorably with other energy sources in the 1980's. Weigel (1974) and Somers and Shoupp (1974) were more pessimistic about costs.

Seafloor Interaction

A Straits of Florida location poses a number of interesting problems regarding long-term mooring stresses on carbonate soils if an anchoring system is deployed. Drilled-in and cemented anchors may be desirable for anchoring. Pile driving for a fixed platform, if one should be used, would probably follow Persian Gulf technology in carbonate materials, although the water depths in the Straits of Florida are greater.

The attainment of better and more complete knowledge of seafloor carbonate soils, particularly those that are indurated, would be desirable before anchor systems are deployed for extended time periods. An investigation should include laboratory and in situ testing together with applicable methods of analysis.

SALINITY GRADIENT POWER SYSTEMS

Concept

An interesting but as yet uneconomical method of producing power would be to utilize the energy released when fresh water flows into the ocean or into hypersaline sinks. The osmotic or salinity gradient power resulting from the osmotic pressure between fresh and salt water is appreciable (Fig. 18). J. H. Anderson (1975, personal communi-

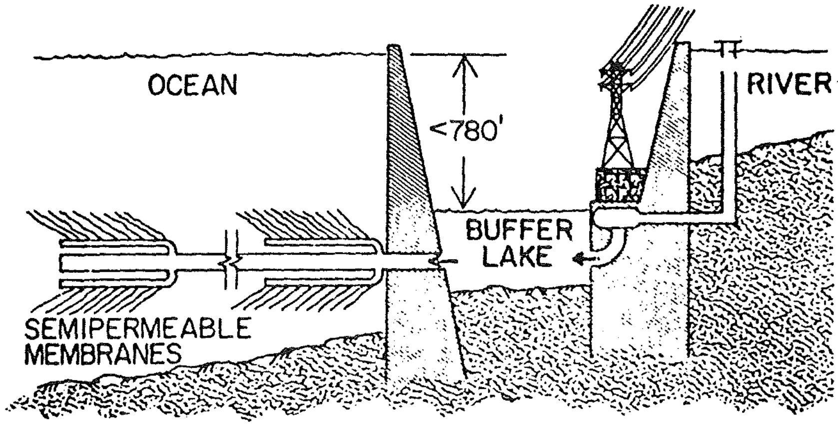

Fig. 19 Salinity gradient power production process shown in Wick and Isaacs (1975); 780 ft equals about 240 m.

cation) states that the thermal gradients head ought to be 688 ft (210 m), which would be nearly as much as the 780 ft (240 m) salinity gradient head. The average height of rivers at their source is about 210 m (700 ft) and, coincidentally, the equivalent pressure head between seawater (3.5 percent salinity) and fresh water is about 240 m (780 ft) or 2.4 MPa (24 atmos), according to Bromley et al. (1974) and Wick and Isaacs (1975).

Five possibilities of harnessing salination power were summarized by Wick and Isaacs (1975): (1) direct utilization of osmotic effects by mechanical means; (2) direct electrochemical conversion using dialytic or reverse-electrodialysis cells; (3) employing substances, such as collegen, that expand in contact with fresh water and contract in contact with salt water or vice versa; (4) utilization of the very small amount of heat generated by the release of free energy when fresh and salt water irreversibly mix; and (5) utilization of a modified Claude cycle by driving a turbine run by a vapor pressure difference of about 18 kPa for a temperature difference of 12° C between surface and deep ocean water. The first two methods are receiving the most attention. The Wick-Isaacs (1975) mechanical method is a two-step process in which the river water falls a distance below sea level less than the 240 m osmotic equilibrium height, utilizing the remaining head to drive the fresh water into the sea through semipermeable membranes (Fig. 19). Levenspiel and de Nevers (1974) and Norman (1974) have presented alternative methods.

Geographic Areas Applicable

Wherever rivers enter the ocean the potential exists for utilizing salination power; however, where the river is channeled less environmental damage, particularly to estuaries, may result according to Norman (1974).

Development Schedule and Costs

There appears to be no plan to progress towards any of these systems until a number of technological problems can be fully assessed and the estimated costs can be reduced. Preliminary cost estimates by Norman (1974) and Wick and Isaacs (1975) are about \$0.20/kWh for membranes. But capital costs per kilowatt may be two orders of magnitude greater than conventional power plants (Wick and Isaacs, 1975). Costs for the dialytic cell and other methods have not yet been made. Wick and Isaacs note that the modified Claude method avoids the use of electrodes, membranes, and reduces the probability of fouling; however, several engineering problems need to be solved before this method can be competitive.

Seafloor Interaction

There appear to be no problems of particular consequence in any of the proposed methods, although large civil engineering structures are probable in several methods. Of the methods that have received the greatest consideration, the construction of very large dams, and either towers or deep basins, for the mechanical method have been proposed. These appear to be within the current state-of-the art capability.

OCEAN GEOTHERMAL

Concepts

Both dry steam and wet steam on land have been used to power turbines for electricity generation, (Robson, 1974). Drilled holes to tap underground steam exist in a number of countries. An alternative method, that of injecting water through one bore hole into hot rock and extracting steam from a second bore hole, has been proposed but has not been attempted commercially. Ellis (1975) discusses geothermal systems and power development, Berman (1975) summarizes geothermal energy, and White and Williams (1975) assess U. S. geothermal resources.

Geographic Areas Applicable

If holes were eventually drilled at sea, more than likely a heat source would be tapped that is located near the boundary of a tectonic plate (Barbier and Fanelli, 1974); in close proximity of active volcanos on islands (Shupe, 1974); or at or near a submarine volcano. For North America, the plate boundary extends from the Gulf of California west of Oregon, Washington, and British Columbia. Klein and Kauahikaua (1975) report that a geoelectric-geothermal survey on Hawaii Island indicated little potential for commercially utilizing rift-intrusive warmed water (located at depth) seaward of the shore. Geothermal prospects on land are appreciably greater.

Development and Costs

The economics of terrestrial geothermal development have been assessed by Armstead et al. (1974). Comparable data for offshore geothermal development are lacking. No plans are known to exist for offshore geothermal drilling.

Seafloor Interaction

The technology of drilling at sea is well developed; there would appear to be few problems of any significance except for corrosion of the drill pipe.

CONCLUSIONS

The need for energy sources to supplement and eventually replace fossil fuels is inescapable. It would appear that the ocean energy sources may be receiving less attention, and less money, than is warranted, based on their potential applicability, provisional economics, and the fact that they are renewable and relatively nonpolluting. Ocean thermal and wave methods appear to have the realizable potential of eventually delivering large quantities of energy. In limited regions, tidal power may now be economically competitive with fossil-fuel and nuclear methods. Wind, current, kelp bioconversion, and salinity methods of energy production are sufficiently intriguing to warrant further research and development. The economic viability of these latter methods may become increasingly attractive as costs of conventional fuels raise in the years ahead.

The economic exploitation of commercial amounts of energy from the oceans constitutes a real challenge to engineers. The possibility of using this energy in the fuel, food, chemical, and other technologies offers the imaginative engineer further substantial challenge. It is hoped that governments and industries will do their part to provide adequate funding to encourage and promote technological development.

The needs for seafloor engineering research and development relevant to ocean energy production center about six principal areas: (1) mooring and anchoring systems for very large and heavy loads; (2) anchor-soil interaction, particularly over extended time periods; (3) underwater electrical transmission cable-soil interaction; (4) in-situ soil properties and soil behavior under applied loads, particularly for (a) continental shelf quartz and feldspar sands, (b) continental shelf calcareous sands and rocks, and (c) deep-sea floor pelagic clays and biogenic oozes between the Tropics of Cancer and Capricorn; (5) stability-instability relationships of continental shelf, slope, and deep-sea floor soils; and (6) scour and stability of structures, including large anchors and power cables, particularly with respect to liquefaction, wave loading, and structure-soil interaction in storms. Relative to some of the basic engineering and/or scientific problems inherent in each basic method of energy extraction from the sea, with the possible exception of tidal energy, problems in the seafloor engineering aspects are considered by me to be of lesser importance.

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Post-publication note

Since this paper was written, an important classic paper by Stahl (1892) on wave power utilization was called to my attention by Stephan Salter. Two major symposia have appeared: Legal, Political and Institutional Aspects of Ocean Thermal Energy Conversion (1976) and Energy from the Ocean Fact or Fantesy (Kohl, 1976). Griffin (1975) has published a condensed version of his 1974 Navy report. The U.S. Congressional Office of Technology Assessment is preparing for public release documents critically assessing several methods of extracting energy from the ocean. ERDA's OTEC programs are summarized in Ocean Thermal Energy Conversion (1976). Richards (in press) has evaluated the applicability for OTEC plants off southeast Iran, and Atwood et al. (1976) have assessed resources and evaluated the environmental impact for OTEC plants at a proposed Puerto Rico site.

With respect to wave-power generators, Isaacs et al. (1976) report results of model tests at sea; Salter (1976) favors replacing the spline pump within the Salter cam, or "nodding duck," with radial piston units that will produce a flow of hydraulic oil to drive a swash-plate motor and a generator; and Salter, in a July 1976 selected bibliography, indicated that a report on "A world wide survey of wave power" is being prepared by J. M. Leishman and G. Scobie of the National Engineering Laboratories, East Kilbridge, U.K. Palmer et al. (1975) have applied multiple-use concepts to the exploitation of ocean geothermal energy and discuss three prime sites in the British West Indies, Japan, and New Zealand.

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