Energy from the ocean

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Energy from the ocean

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Renewable ocean energy sources can eventually supply a large fraction of man's energy needs, starting in the 1990s. Their use will require technologies for converting to useful form such naturally occurring ocean phenomena as tides, currents, waves, salinity gradients and thermal gradients.

In view of the technology's substantial resource potential, its comparatively advanced stage of development among the ocean energy options, and other relatively attractive features, this paper focuses on ocean thermal energy conversion (OTEC). However, much of the paper's content has relevance to the use of the other ocean energy sources.

Techniques of ocean thermal energy conversion are summarized, along with the development status of the required power system and ocean system components. The worldwide ocean thermal resource is assessed as a function of geography and time. Environmental impacts and siting considerations are treated. Diverse commercial market applications of OTEC are summarized, based upon the two key options for OTEC of providing electricity by submarine cable and of manufacturing energy-intensive products for shipment to dispersed markets. By-products of OTEC such as fresh water and nutrients for mariculture are discussed.

The constructability and deployment of OTEC systems are considered in the context of their overlap with the related technology for building and deploying offshore petroleum facilities. Much offshore petroleum industry technology and many of its construction facilities are shown to be relevant to OTEC requirements.

OTEC cost projections are related to the competitive costs of other sources of continuous electrical energy. The prospects for the emergence of a commercial OTEC industry in the 1990s are analysed, including a description of OTEC development activity in various nations.

Scenarios for the industrial development of commercial OTEC plants and plantships are presented for electricity applications and for energy-intensive products such as ammonia, hydrogen and aluminium. Economic, financial and international impacts of OTEC are explored. Market penetration forecasts for the 1990s are obtained, with a consideration of the problems and potential of the large early market in developing nations for OTEC-derived electricity. It is shown how OTEC-derived electricity and products, by increasing energy supply in an energy-interdependent world, could help reduce foreseeable polarizations between nations over limited global energy resources.

Introduction

Renewable ocean energy sources can eventually supply a large fraction of man's energy needs. Their use will require technologies for converting to useful form such naturally occurring ocean phenomena as tides, currents, waves, salinity gradients and thermal gradients.

A commercial tidal power plant has been operating for over a decade at La Rance, France. For tides the required technology is proven and available for harnessing tidal resources at suitable locations around the world (Wayne 1981). Technology for harnessing the other forms of ocean energy is still under development.

Research and development efforts in ocean energy experienced a resurgence starting in the early and mid-1970s, as a result of the increasing costs of depletable fuels. During that period, a major wave-energy technology development programme was instituted by the United Kingdom (Baird 1981; McCormick 1981). Starting in 1973, the United States began investing substantial resources to develop ocean thermal energy conversion (OTEC) technology (Cohen 1980). The U.S. ocean energy programme included a modest research and development effort on technology to extract energy from waves, currents and salinity gradients. The status of technology in those areas is described, respectively, by McCormick (1981), Stewart & Wick (1981) and Lissaman (1979), and Wick (1981). Also during the 1970s, Japan started sponsoring work in OTEC and wave-energy conversion, and France revived its historic pursuit of OTEC stemming from earlier French pioneers (d'Arsonval 1881; Claude 1930) in that technology.

In so far as they employ ocean platforms, the various ocean energy technologies have many technical requirements in common: the need for station-keeping, submarine cables, ocean engineering, and processes for manufacturing energy-intensive products on board. The technologies also share the need to become cost-competitive with other energy options serving similar market sectors.

The relative abundances of the ocean energy resources have been estimated by Isaacs & Seymour (1973). They found that the conspicuous ocean energy resources (i.e. waves, tides and currents) can make a significant but less substantial contribution to the world energy supply than can the inconspicuous ones (i.e. thermal and salinity gradients).

In view of its substantial resource potential, its comparatively advanced stage of development among the ocean energy options, and other relatively attractive features of OTEC technology, this paper will hereafter be devoted to OTEC. However, much of the content of this paper is relevant, in many respects, to the other ocean energy options. Also, it should be noted that OTEC applications have much in common with the increasing commercial use of conventional technologies aboard industrial plant vessels.

The attractive features of OTEC technology alluded to augur well for the timeliness and attractiveness of a commercial OTEC industry. For example, in the United States, after a £100M development programme, OTEC technology is perceived as mature in many respects and as being relatively attractive to society from an environmental standpoint. Another factor is that comparative cost projections indicate that OTEC-derived electricity will be competitive at the outset with oil-derived electricity.

The idea of using ocean thermal gradients for generating electricity was first published by d'Arsonval (1881). As is largely true for most solar energy technologies except hydropower, the era of inexpensive fossil fuels has delayed the commercial introduction of OTEC technology. Now that the economic and environmental costs of other technologies that provide continuous or 'baseload' electricity are rising, the advent of commercially competitive OTEC power plants seems imminent. This is particularly true for suitable locations in the tropics and subtropics where oil-fired power plants are the only present option. However, OTEC power plants will probably also become competitive with power plants fuelled by coal, natural gas and uranium. Not only are the costs of depletable fuels rising, but so are the capital costs of the power plants that use them. Thus it now seems timely for the world to begin its inevitable transition from depletable energy sources to renewable energy sources such as ocean energy.

Techniques of ocean thermal energy conversion

Ocean thermal energy conversion takes advantage of the naturally occurring temperature difference (or 'thermal gradient') between warm water at the surface of the ocean and cold water – near freezing point – that is encountered at depths of about 1000 m. The warm surface water acts as a heat source, and the cold water acts as a heat sink. This combination of warm and cold water is capable of operating a thermal power cycle or 'heat engine' to generate

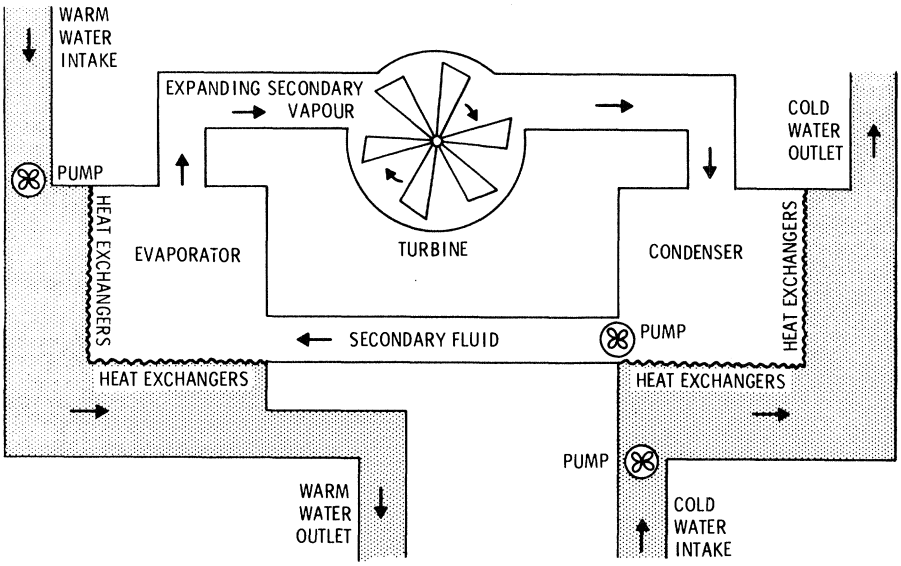

Figure 1. Schematic of an OTEC closed-cycle system.

electricity. Such a thermal power cycle resembles that of a conventional power plant in many respects, except that no fuel is required to warm the water. In OTEC, radiant solar energy is converted to heat and stored by the world's oceans acting as a gigantic solar collector and thermal storage device. Furthermore, despite the intermittence of the solar radiation, the ocean surface temperature tends to remain constant throughout the daily cycle. Thus, unlike most solar energy technologies for generating electricity, OTEC is a source of continuous, baseload power.

The cooling of conventional power plants requires heat sinks, and typically the atmosphere and bodies of water such as ponds, lakes, rivers and the ocean are used for that purpose. Cooling capacity requirements and limitations have greatly influenced and constrained the siting of such power plants. With OTEC, an enormous heat sink is available. On the other hand, the ocean heat sink appropriate to OTEC typically requires access to cold water from depths of 1000 m.

The basic mechanism for operating an OTEC heat engine to generate electricity, as for conventional power plants, is for an expanding vapour to cause the rotation of a turbine attached to an electric generator. In OTEC, the vapour results from the flash-evaporation of warm seawater under a partial vacuum, or another working fluid such as ammonia is caused to evaporate by heating it with warm seawater. When a working fluid other than seawater is utilized, the spent vapour is reliquefied in a condenser after passage through the turbine, and the process is repeated, as shown diagrammatically in figure 1. Because of its cyclic nature, similar to running a household refrigerator backwards, this process is known as the 'closed cycle'. If warm seawater is used as the working fluid, the condensate is not returned to the evaporator. Accordingly, that process is described as the 'open cycle'. The power cycle originally proposed by d'Arsonval (1881) was a closed cycle, whereas the first OTEC experiments in the late 1920s (Claude 1930) employed an open cycle, frequently referred to as the Claude cycle, as shown in figure 2.

Because of the need in the open cycle to harness the energy in low-pressure steam, extremely large turbines (comparable with wind turbines) must be used. Furthermore, degasifiers are needed to remove gases dissolved in seawater. However, open cycles are less vulnerable to

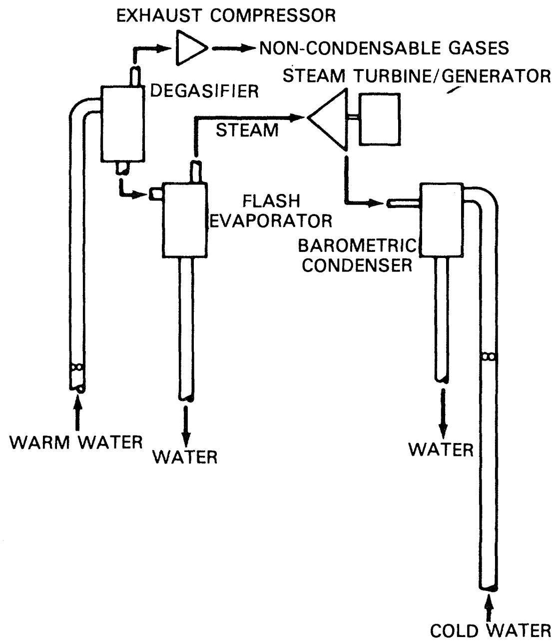

FIGURE 2. Schematic of the OTEC open-cycle system known as the Claude cycle, which uses flash evaporation of seawater under a partial vacuum.

biofouling than are closed cycles, since they do not use heat-transfer surfaces, at least not in the evaporator. Present-day power technologists prefer the closed cycle to the Claude cycle, largely because they regard the requisite hardware as being in a more advanced stage of development.

The cost of a Claude cycle system was once regarded as being prohibitively greater than that for a closed-cycle system, largely because of the potential cost of the turbine. However, a study by the Westinghouse Electric Corporation (1979) indicates that Claude cycle turbines can now be designed at reasonable cost by incorporating turbine-blade technology resulting from experience in the aerospace industry with helicopters and wind machines. This leads the study to the conclusion that projected costs of either power system are probably comparable. Another economic consideration is that condensation of the evaporated seawater in the Claude cycle results in desalinated water. That possibility tends to make the Claude cycle attractive where fresh water is an economic product or by-product (Coffay 1980).

There are several other approaches to the open cycle that may be developed in the future. An idea proposed by Beck (1975) and patented by him in 1976 was to use the heat in seawater to create a column of water by producing cavitation bubbles, as in an airlift pump. The water column can be used to drive a turbine, as in a hydroelectric dam. An advantage of this approach is that the hydraulic turbine employed is more compact and less costly than the gas turbine required in the Claude system.

Zener & Fetkovich (1975) suggested another variation, i.e. that the mixture being lifted should have foam structure. Ridgway (Charwat *et al.* 1979) first proposed that warm seawater be introduced as a mist that is then lifted against gravity by the flow of steam from a low-pressure region to a lower-pressure region. Figure 3 shows how these lift-cycle approaches might work. They are similar to the naturally occurring hydrological cycle that leads to the

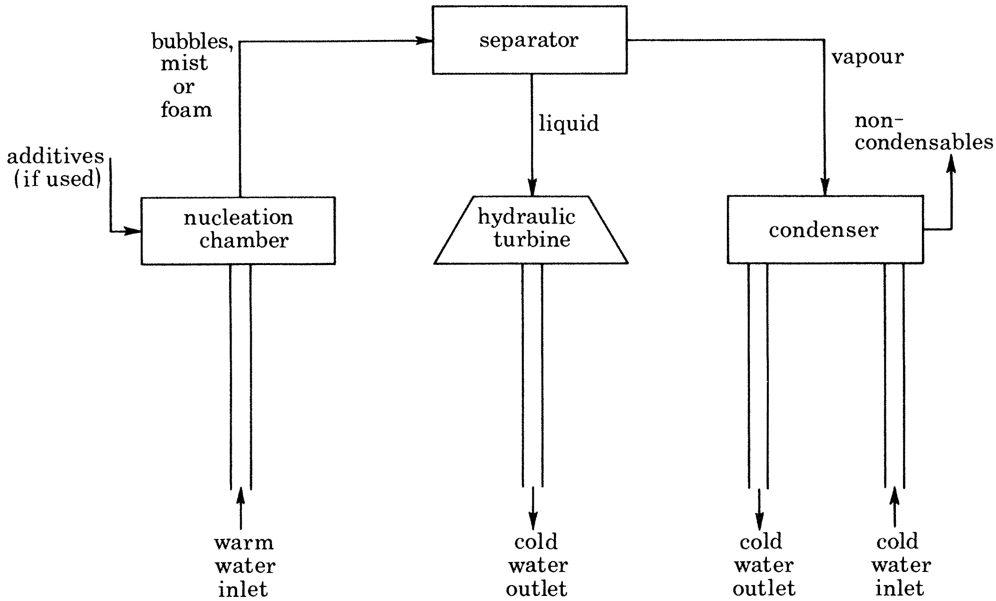

FIGURE 3. Schematic of the OTEC steam lift cycle concept, in which the ocean thermal gradient is converted into a hydraulic head through the formation of bubbles, mist or foam. The potential energy of the elevated liquid water is then used to propel a hydraulic turbine.

conversion of solar energy into hydropower. In OTEC lift cycles, an artificial hydrological cycle is created within a large, ocean-going vessel. The bubble, foam and mist approaches thus convert a temperature head into a hydraulic head. They are advanced concepts that offer certain attractive features, but they also pose a number of problems such as the potential instability of the bubbles, foam and mist.

Another approach to converting ocean temperature differences to electricity is to employ the thermoelectric effect (Jayadev *et al.* 1979). This technique does not dispense with the need for heat exchangers, and it remains to be demonstrated whether its economics are promising.

The temperature difference, ΔT, required to operate an OTEC power cycle economically is estimated to be about 17 °C or greater. This means that for cold water at about 4 °C, the requisite warm water temperature is about 21 °C or greater. Although the ocean cold water supply is stable throughout the year, ocean surface water temperatures vary seasonally, hence the required annual average surface temperature, $\overline{\Delta T}$, is at least 18 °C. Large expanses of the world's oceans satisfy this requirement, and some regions provide a $\overline{\Delta T}$ of 24 °C or greater. The capital cost of an OTEC plant is a sensitive function of its operating $\overline{\Delta T}$ (Lavi 1975), being proportional to approximately $T^{-2.5}$.

Even at the highest ΔT's encountered, however, the theoretical thermodynamic efficiency of an OTEC heat engine, known as its Carnot efficiency, is only about 6 or 7%. The practical or net efficiency that can actually be obtained from an OTEC plant is about 2.5%. This is because of temperature gradients across the heat exchangers and in view of the need for 'housekeeping' or 'parasitic' power to accelerate and circulate water against its own density differences and against frictional losses in the heat exchangers. In other words, 40 units of thermal energy are required for an OTEC plant to produce one unit of electrical energy, i.e. 40 MW_t per 1 MW_e. This in turn means that much larger quantities of warm and cold water must be circulated through OTEC plants compared with conventional power plants, which have net efficiencies ranging from 30 to 40%. OTEC plants require the circulation past large areas of heat exchangers of about 25×10^6 l s^{-1} of both warm and cold water for each 100 MW_e of net power that they produce.

The low net efficiency of fuel-free OTEC plants leads (more precisely, misleads) some technical people – who are accustomed to the higher net efficiencies of fuelled power plants – to become OTEC detractors. Of course, such a low net efficiency would be intolerable if fuel were consumed, but may well be acceptable if the cost of OTEC-derived energy turns out to be competitive with that of alternative energy sources. Cost projections (see below) for mature OTEC power plants indicate that this is likely to be so in the short term for specific market sectors.

Thus, although the net conversion efficiency of OTEC plants needs to be sustainable, and as high as possible consonant with optimum system design, the key question as to the economic viability of a capital-intensive, renewable energy source such as OTEC is the cost of its producing energy over its life cycle. The life-cycle energy cost of a power plant is a function of its capital cost, its cost of operation and maintenance, and the cost of fuelling it. With OTEC and other renewable energy sources the fuel cost is zero, while for conventional power plants the cost of depletable fuels will continue to rise in real terms.

Ocean thermal applications and markets

In that the world's ocean energy resources tend to be located more or less remotely from populated regions, the use of ocean energy by society presents certain logistical problems. There are two solutions to these problems. One option is to transport electricity to shore by submarine electrical cable or other umbilical. The other option is to generate electricity and use it to manufacture energy-intensive products aboard floating 'plant-ships'. The cable option requires precise platform station-keeping, whereas the product option does not.

For OTEC, the electricity-to-shore option (by submarine cable) appears to offer an early commercial market opportunity, especially on tropical and subtropical islands (Cohen & Dunning 1979), where electricity-generation options are limited to imported oil, and where the ocean thermal resource is located relatively close to shore. A conceptual design of a 100 MW_e OTEC power plant employing a surface configuration is shown in figure 4. A conceptual design for a 265 MW_e OTEC plant employing a spar-buoy configuration is shown in figure 5.

The other key OTEC market option will be the manufacture on OTEC plant-ships of products such as ammonia, hydrogen, methanol, aluminium, chlorine, magnesium and other sea chemicals. Floating OTEC plant-ships would achieve some economies not experienced by OTEC plants attached to submarine electrical cables; namely, no cable costs and lower station-keeping costs. Also, they can operate in more remote, warmer waters, thereby allowing significant reductions in the sizes of heat exchangers and ocean platforms required. On the other hand, plant-ships require additional investment to provide them with facilities for manufacturing and handling energy-intensive products. Furthermore, while natural gas is still being flared at many locations, these products can be manufactured more cheaply there. Thus the plant-ship option is unlikely to become competitive as early as the cabled electricity option.

Plant-ship products could be used as fertilizers, fuels and feedstocks; they could also serve as

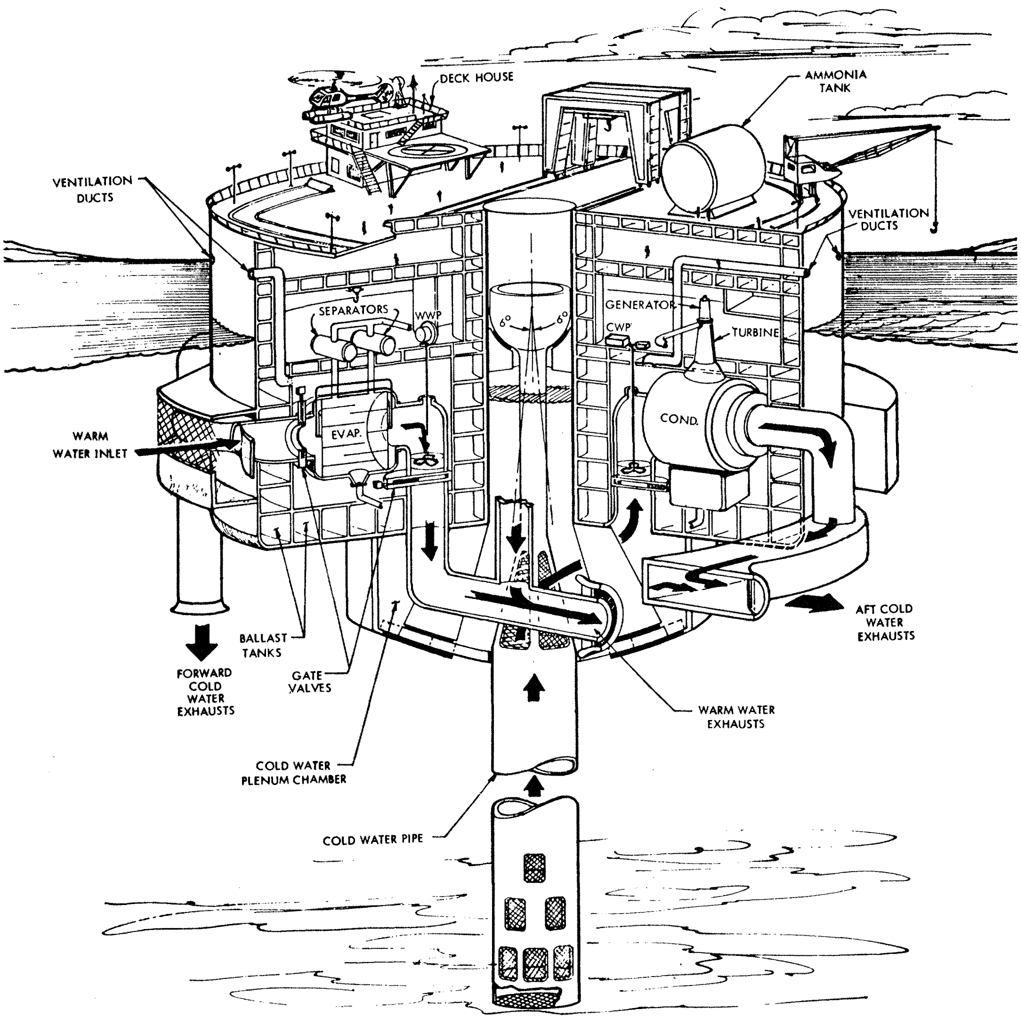

FIGURE 4. The TRW Systems Group, Inc. (1975) concept of a 100 MW_e baseline OTEC power plant. One of the four 25 MW_e power modules is shown in the cutaway portion. The platform has a diameter of 100 m.

a means other than submarine cables for conveying electricity to shore. For example, hydrogen or ammonia (acting as a hydrogen carrier) could be reconverted to electricity in fuel cells ashore. This avenue of transmission can be regarded as an 'electrical bridge', and would provide OTEC with a means for serving dispersed electrical markets, including the provision of peaking power to electrical utilities. Ammonia synthesized aboard floating OTEC plants from nitrogen removed from the air and hydrogen electrolysed from water could well become a viable product for the large and growing fertilizer market, currently being supplied by ammonia derived from natural gas. Similarly, methanol could be synthesized from carbon and

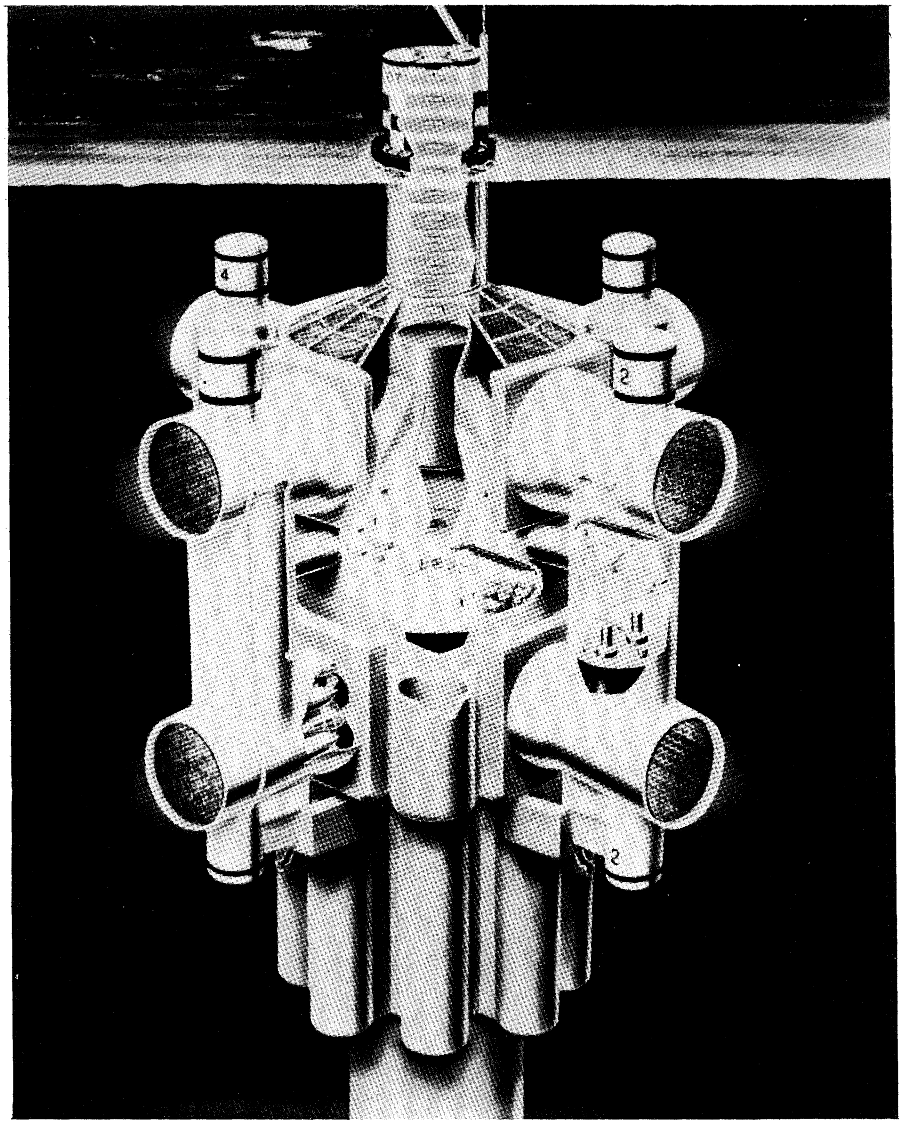

FIGURE 5. The Lockheed Missiles and Space Company, Inc. (1977) concept of a 265 MW_e baseline OTEC power plant, showing details of one of the four external 65 MW_e power modules. The cold water pipe is 38 m in diameter and composed of reinforced concrete sections.

OTEC-derived hydrogen. Methanol can be used for transportation fuel and to supply electricity. A conceptual design for a 100 MW_e plant-ship capable of manufacturing 280 t of ammonia per day is shown in figure 6.

An additional electrical-bridge possibility is to degrade OTEC electricity into heat stored in molten salts, then to convey the salts to shore for reconversion to electricity. This 'thermal bridge' was found (Biederman *et al.* 1979) to be costlier than the lithium bridge, hydrogen bridge and ammonia bridge. However, a thermal application might be economic if the heat were used for industrial processing on or near the OTEC platform.

Two attractive OTEC by-products may be marketable: (1) fresh water and (2) shellfish, kelp or other food or energy crops resulting from mariculture. The maricultural application would use the nutrients upwelled in the cold water circulated through OTEC condensers. The economics

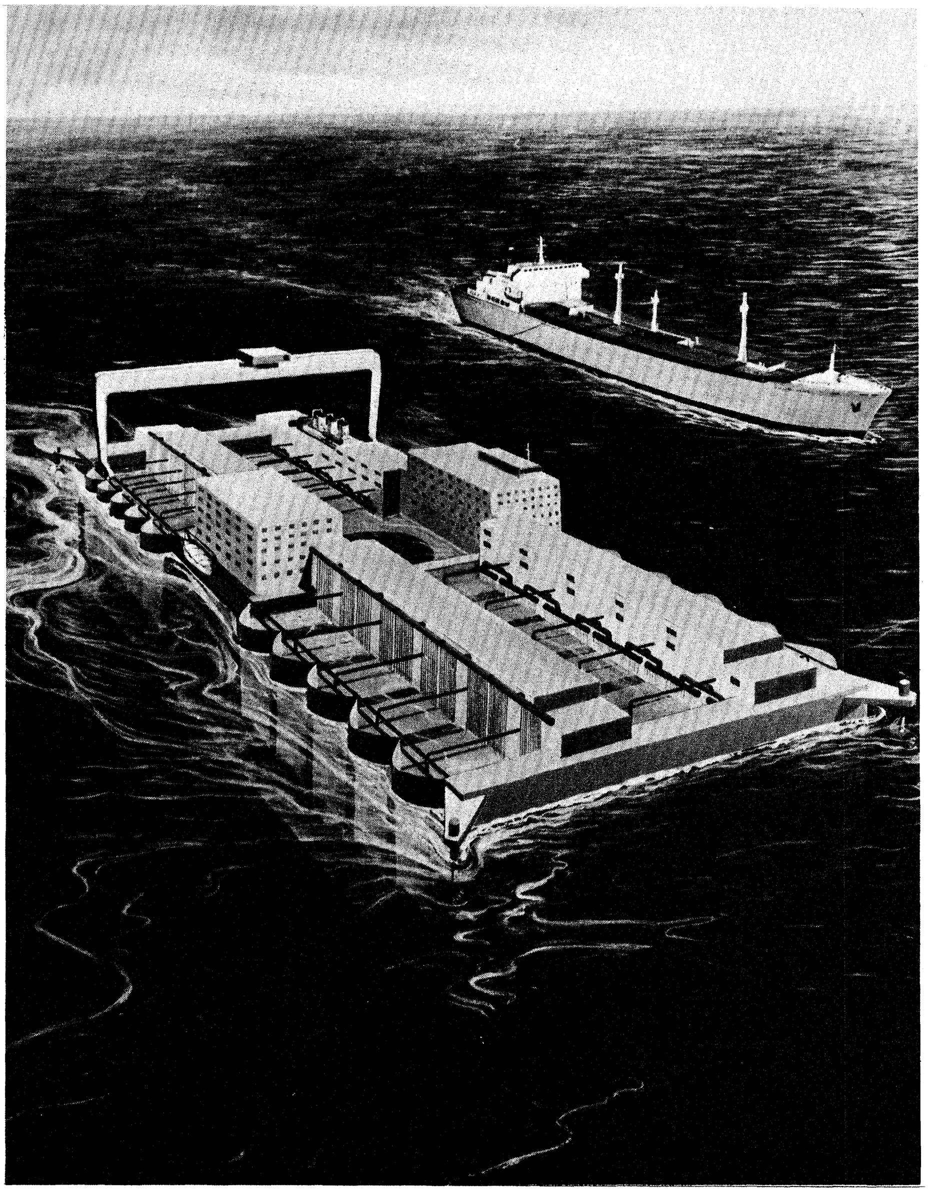

FIGURE 6. The Applied Physics Laboratory of The Johns Hopkins University conceptual design of a 100 MW_e plant-ship concept for producing ammonia by using OTEC power. The platform consists of twenty 5 MW_e power modules and the ammonia fabrication equipment.

of OTEC energy production may well be improved in cases where such by-product manufacture is viable.

Fresh water is in short supply in many islands and in certain developing countries. OTEC power plants, especially those with an open cycle power system, could readily produce fresh water as a by-product. The fresh water might improve the economics of plant operation if logistical costs of conveying it to market did not exceed its value. Although it is probable that the marginal cost-effectiveness of manufacturing fresh water as an OTEC by-product will be favourable for onshore or near-shore OTEC power plants, it is questionable whether this will be so elsewhere. Another option for the production of fresh water is the use of icebergs. An OTEC engine has even been suggested (Fuhs *et al.* 1978) for propelling icebergs from arctic to temperate latitudes. In this cycle, the cold water would be obtained from the iceberg rather than by a cold water pipe. A similar cycle has been proposed (Heizer 1978) for producing energy and fresh water from the iceberg once it reaches its destination.

The technology for open-ocean mariculture of protein crops, such as shellfish, will probably differ from the technology of open-ocean mariculture of energy crops, such as kelp (Laurence & Roels 1976). Although the use of OTEC electricity and upwelled nutrients for associated mariculture activities would be a potential market for available OTEC power and cold water, there may be certain incompatibilities between the technologies. In particular, the retention of significant volumes of cold-water effluents in the vicinity of the OTEC warm water intake might result in recirculation problems and might cause biofouling problems. On the other hand, plants such as kelp (unlike OTEC plants) typically thrive in a cold-water environment, so that any protracted loss of the artificially introduced cold-water environment through OTEC plant shutdown might result in crop damage if kelp culture were combined with OTEC power production.

The resource value of upwelled nutrients is great if they are converted into protein. Such protein could become important to a hungry and malnourished world. However, it would require surprisingly few OTEC plants to pump amounts of cold water containing sufficient nutrients for producing enough shellfish protein to saturate world markets, assuming a viable mariculture technology. Accordingly, even in the most optimistic case, the marginal economics of protein production using OTEC power plants as sources of pumping power would appear attractive for only a modest number of OTEC plants. Such plants would most likely be located on land or on shelf-mounted towers, with ponds being used for the aquaculture. However, in private conversations at this meeting, G. Persoone & P. Sorgeloos questioned whether the concentration of upwelled nutrients would be adequate for commercial mariculture without the addition of supplemental nutrients.

Another OTEC application has been proposed (Penman 1978) for generating electricity at arctic locations. This would use the temperature gradient that exists between cold arctic air and near-freezing ocean surface waters. During much of the year, air temperatures below -30 °C are experienced, which suggests that an air-cooled condenser could be operated in conjunction with an evaporator heated by surface water, probably for land-based electrical production.

Besides the use of cold ocean water for cooling coastal buildings by circulating it ashore, there are several promising hybrid cold-water applications for generating electricity. One important possibility is to employ submarine geothermal energy as a heat source to run a 'geothermal OTEC' power plant. Another option is to use the rejected heat from coastal power plants to generate additional electricity by operating an OTEC 'bottoming cycle'.

From the standpoint of net energy, the time required to pay back (i.e. reproduce) the energy invested in the materials and construction of an OTEC plant seems favourable. If aluminium were used for OTEC heat exchangers, it is easy to calculate that – at about 15 kW h per kilogram of aluminium – it would require about a month of energy output from the plant to replace the electrical energy invested in the heat exchangers, assuming that the plant contains 20 t of aluminium per net megawatt. Even if the heat exchangers were made of titanium, and with the energy inputs for the remainder of the plant included, the energy payback time (or 'breeding time') for an OTEC plant is about a year.

From a global standpoint, OTEC is one of the few energy sources that could eventually supply a substantial portion of world energy needs. In particular, there are short-term markets (Dunbar 1981) for tens of thousands of megawatts of electricity by submarine cable to many nations in tropical and subtropical regions. In addition, in the mid-term, the OTEC plant-ship or 'product' option can supply vast amounts of energy-intensive products to worldwide markets at any latitude. Much of the present combustion of oil to produce electricity could be replaced by OTEC power production. Each megawatt of currently oil-derived electricity that can be so replaced is equivalent to about 40 barrels (ca. 6.4 m^3) of oil per day that can be used for other needs.

The key question is how soon each OTEC product can become available at costs comparable with those of other sources of that product. OTEC-derived electricity supplied to shore at island locations appears to be a highly attractive early market, even at the relatively high capital costs associated with the first commercial OTEC power plants. On the other hand, markets for OTEC-derived ammonia, hydrogen and methanol will probably not materialize so soon. Many island locations will be likely markets for small OTEC power plants (10–100 MW_e) rather than for the more optimal sizes (100–500 MW_e). However, in view of the numerous potential markets for small OTEC power plants in developing countries (Dunbar 1981), industrial production of OTEC plants may well result in economically viable plants in the small size range.

The ocean thermal resource

The worldwide distribution of the ocean thermal resource has been mapped (Ocean Data Systems 1978), as shown in figure 7. Globally, the Sun never sets on the ocean thermal resource, and locally the resource provides a continuous or 'baseload' source of electricity throughout the diurnal cycle. The most attractive ocean thermal resources are located where annual average temperature differences exceed about 20 °C. Hence, the contours of greatest interest in this figure are 20–24 °C. The global region of interest thus includes the tropical and subtropical zones, comprising a band extending between latitudes of about 25° S to 32° N. More detailed descriptions of the ocean thermal resource have now been developed (Ocean Data Systems 1979) for other ocean regions.

Data for ocean thermal resource assessment were obtained from archival sources and through ocean measurements made with both ship surveys and moored ocean buoys. Remote sensing of sea surface temperatures from satellites will become useful for monitoring relative temperature variations for commercial operations of cruising OTEC plant-ships.

Thus a large portion of the world's oceans is suitable for OTEC exploitation, including many places accessible to land with submarine cables and extensive areas where OTEC plant-ships could manufacture energy-intensive products at sea. Favourable regions happen to coincide geographically with the locations of numerous developing nations (Dunbar 1981). Depending upon the ultimate degree of commercial utilization, these thermal resources could provide a substantial addition to world energy production. However, there is a thermal constraint on the number of plants that can be operated per unit of ocean space. Too large a concentration of OTEC plants in a given geographical region could, because of discharge recirculation, degrade the available thermal resource.

Although the ocean thermal resource is quite stable from day to day, it has a seasonal variation that increases with distance from the equator. Examples of this variation are shown in figure 8. This seasonal variation may be advantageous in some cases where it is required to

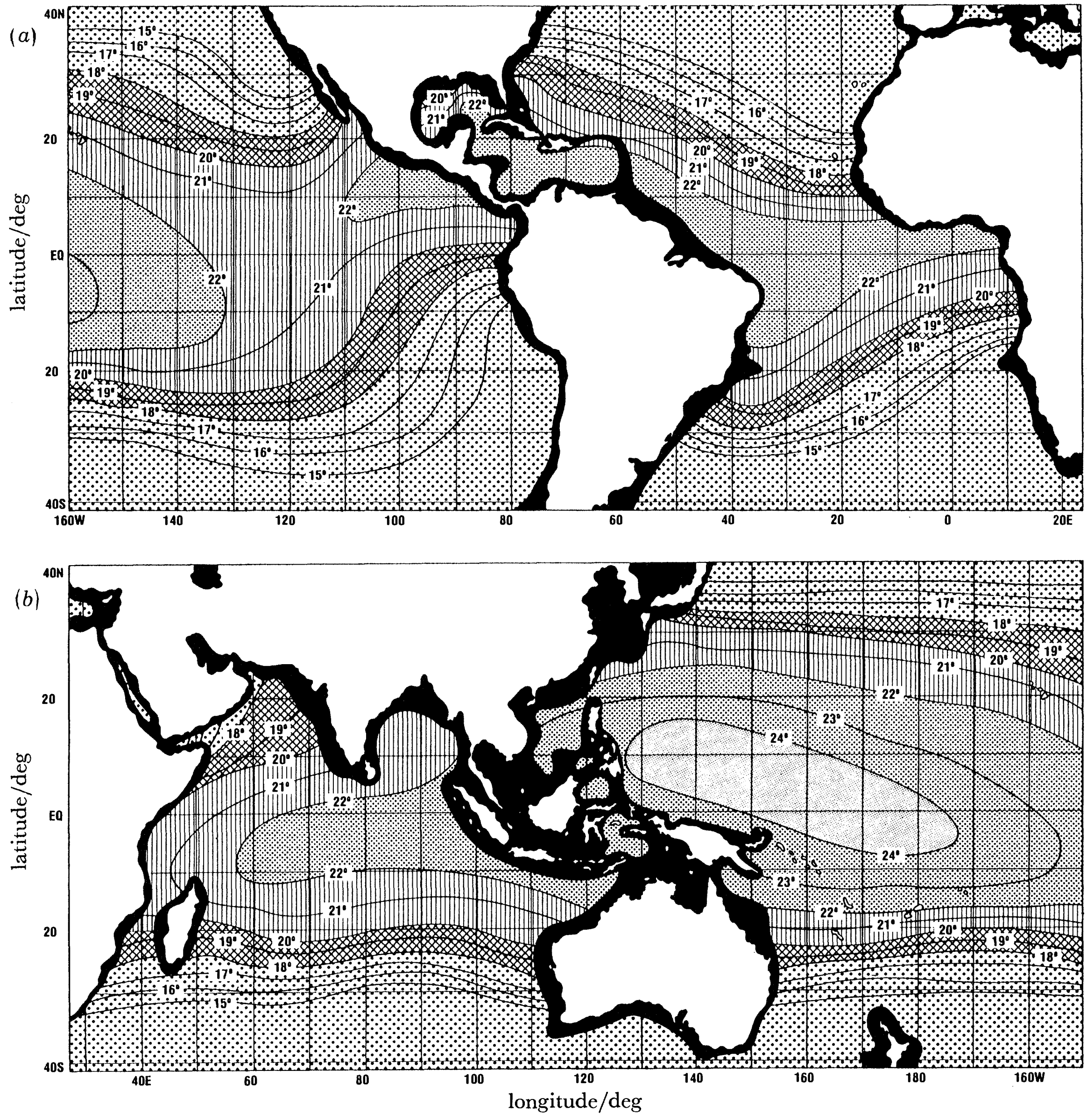

FIGURE 7. Worldwide distribution of the ocean thermal resource. Contours are for the annual averages of monthly temperature differences (in degrees Celsius) between the ocean surface and depths of 1000 m. (*a*) The Western Hemisphere; (*b*) the Eastern Hemisphere. The black areas in coastal regions indicate water depths less than 1000 m.

serve a high summer electrical load. In this case a combination of seasonally varying OTEC power with fixed baseload power sources could better match the seasonal load variations.

Suitable OTEC sites tend to be remote from human habitation. But there are many locations, such as tropical and semitropical islands, where an OTEC power plant could be operated on shore or on a shelf-mounted tower by utilizing aqueducts to convey the warm and cold water to and from the plant. Globally, the potential amount of power available in this way is much smaller than the substantial amounts obtainable by the use of floating OTEC power plants. On the other hand, the operation of floating plants presents problems, including the provision of crews at

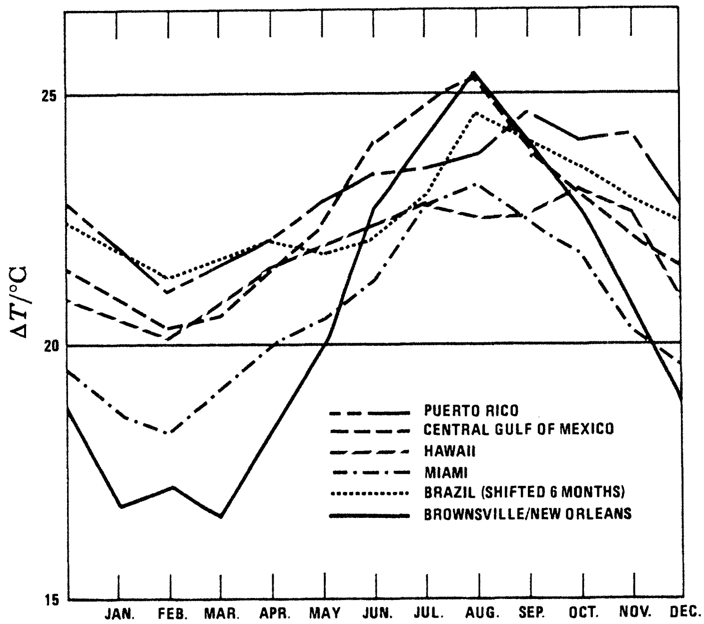

FIGURE 8. Seasonal variation of annual average of monthly temperature differences between surface waters and 1000 m depth for potential OTEC sites (except for the off-Brazil and off-Miami sites, where depths of 800 m were used). Data for the site off Brazil were shifted by 6 months on the graph to compensate for the seasonal reversal between the Northern and Southern Hemisphere locations being studied.

remote locations and the need to transport electricity or energy-intensive products, or both, to shore. For electricity-to-shore applications, where mooring of a plant will probably be required, sites would be limited to ocean regions with depths between about 1000 and 2000 m. This is because about 1000 m depth is required to obtain the cold water, while mooring technology is currently limited to depths to about 2000 m. Economic factors will determine what geographical deployments, plant sizes and market applications are viable, and whether offshore or onshore sites, or both, will be used. In any event, onshore and near-shore sites are likely to be used in the course of developing OTEC technology, both because of their convenience and because they can provide local markets for OTEC electricity and by-products. Such sites typically lack fresh water and fish protein, both of which might be provided as adjuncts to OTEC operation.

ENVIRONMENTAL AND SITING CONSIDERATIONS

OTEC environmental studies have been conducted extensively, both analytically and in the laboratory, to assess, understand and learn how to mitigate possible environmental consequences of OTEC operation. Impacts of the environment (such as sea conditions) on the design, siting and operation of OTEC facilities have also been considered.

Variables of the ocean environment that are likely to affect the design and operation of OTEC plants have been catalogued for relevant ocean areas on a worldwide basis (Bretschneider 1977). This analysis considered sea state and design waves, including the effects of winds, waves and surface currents. The ocean thermal resource can be temporarily disrupted by natural phenomena such as coastal upwellings and hurricanes (Thompson *et al.* 1977). For example, the formation of a hurricane extracts enough ocean thermal energy to reduce the thermal gradient by 1 °C or more, for several days. OTEC power plants must be designed to survive hurricanes and heavy seas. However, oil-drilling platforms comparable with OTEC platforms are operating satisfactorily in the rugged North Sea enrivonment, although ocean engineering of OTEC platforms does present some new challenges in the areas of mooring and of cold-water pipe design and deployment.

Siting of OTEC power plants must take into account a number of factors: the availability of an adequate ocean thermal resource; station-keeping; possible impacts on the environment; possible impacts of the environment – especially the forces of winds, waves and currents – on plant design and operation; ocean logistics; and, where submarine cables are employed, sea floor conditions between plant and shore. Key siting parameters that need to be measured include the distribution of temperature and of ocean currents, salinity, dissolved oxygen, pH, nutrients, light transmittance, and the nature of the sea floor.

Numerous studies have been conducted to determine how the operation of an OTEC plant might modify thermal, biological and chemical properties of its environment. If such perturbations are significant, they could affect the optimal performance of the plant. For example, recirculation of the warm-water or cold-water effluents into the warm-water intake could lower the warm-water intake temperature, thereby reducing the plant's power output and possibly affecting local meteorology (Ditmars & Paddock 1980). With widespread proliferation of OTEC plants, huge flows of warm and cold water would be involved, ultimately raising the possibility of global modifications of the weather.

Recirculation of its own thermal effluents could have an adverse influence on the performance of a given OTEC plant, since its power output is roughly proportional to the square of the available temperature difference (Lavi 1978). Thus there is happily a strong economic incentive and feedback for operating OTEC plants so as to cause minimal perturbation of their own thermal environments. On the other hand, there may be no economic incentive to deter the operator from affecting the thermal environment of a neighbouring plant. However, appropriate discharge of the thermal effluents – for example, by mixing the warm and cold water effluents and discharging them below the thermocline – can minimize this problem. This statement derives from studies based on experimental and analytical fluid-dynamical modelling, which showed that surface temperature decreases can be limited to a small fraction of a degree Celsius.

Another environmental concern is the potential release of large quantities of carbon dioxide into the Earth's atmosphere. Deep ocean water contains greater concentrations of carbon dioxide than does surface water. When the cold water reaches OTEC condensers, its hydrostatic pressure is decreased and its temperature slightly increased. In the course of this process, some carbon dioxide could be released into the atmosphere, particularly with open-cycle systems. Additional environmental concerns include impingement and entrainment of biota; possible discharges of biocides, corrosion products and working fluids; artificial reef, nesting and migration impacts; and worker safety. Research for addressing and resolving these concerns has been planned and conducted (U.S. Department of Energy 1979).

Status of ocean thermal power systems

OTEC hardware development has concentrated on components for closed-cycle systems, although both analytical and laboratory studies have been conducted for open-cycle systems. The account in this section summarizes the studies of OTEC heat exchangers, a key ingredient in OTEC closed-cycle systems.

Closed-cycle OTEC systems rely on transferring heat between seawater and a working fluid such as ammonia. Although other working fluids (such as propane or halocarbons like freon) have been proposed, ammonia is regarded by most investigators as the best economic choice. In closed cycle systems, heat exchangers known as evaporators and condensers are a key ingredient, because large exchange surfaces are needed to transfer vast amounts of heat at the low temperature differences being exploited. The cost-effectiveness of the heat exchangers is a key factor in OTEC economics. The use of fluted metallic surfaces and of special surface coatings to augment the heat transfer per unit area has been studied to economize on the size of the heat exchangers required. However, the increased cost of such surfaces must be justified. It seems likely that heat-transfer enhancement will be used only on the working fluid side of the heat exchangers.

In the ocean environment, it is probable that a layer of slime known as biofouling will eventually accumulate on the seawater side of the heat exchangers. This slime is initially composed of microorganisms, at which stage the biofouling is called microfouling. Subsequently, if the slime is not removed, larger organisms (macrofouling) will become attached. A film of corrosion and possibly of mineral deposits can also accumulate on the seawater side of the heat transfer surfaces. This fouling and scaling will tend to reduce heat transfer, and it must be prevented or removed.

Though biofouling can be inhibited by the use of biocides such as chlorine (through continuous or intermittent dosing), mechanical cleaning is regarded as an important adjunct or substitute. Two mechanical devices currently used commercially to clean heat exchanger tubes are the M.A.N. brush and the Amertap sponge rubber ball. Other techniques include abrasive slurries and water jets.

Biofouling on heat exchangers in open ocean waters will not develop as rapidly as at most coastal locations, where nutrients are more abundant. Studies of the formation of biofouling on the seawater side of aluminium and titanium tubes located in water characteristic of the open ocean have been conducted off Hawaii, the Virgin Islands and Puerto Rico. Such studies off Puerto Rico (Sasscer *et al.* 1981) demonstrated that the fouling layer needs to be – and can be – removed every few weeks to maintain adequate heat transfer, as shown in figure 9.

Although corrosion of OTEC heat exchangers would probably not be a problem if they were made of a titanium or stainless steel alloy, use of those alloys is a costlier solution than other options. Copper–nickel alloys are cheaper and resist biofouling formation, but may not be compatible with ammonia, the most economic working fluid. The key heat exchanger requirement is the ability to withstand erosion, pitting and corrosion in conjunction with mechanical cleaning methods in the presence of seawater and the working fluid. Thus, closed-cycle power systems and their associated heat exchangers present several technical and cost challenges. The exchangers must transfer heat cost-effectively, yet there must be a viable way to avoid their degradation by corrosion and the formation of biofouling layers, both of which inhibit heat transfer. If aluminium alloys can be qualified, they may be best.

Biofouling studies so far have simulated conditions in OTEC evaporators only. They have included tests of corrosion, countermeasures, and cleaning techniques. Results of many of these studies were summarized in papers presented at a workshop (Draley 1979).

The U.S. heat exchanger testing programme has moved from analytical and laboratory studies into testing of hardware of significant sizes, in both land and sea environments. Candidate heat exchanger designs for closed-cycle ammonia systems were produced and tested in

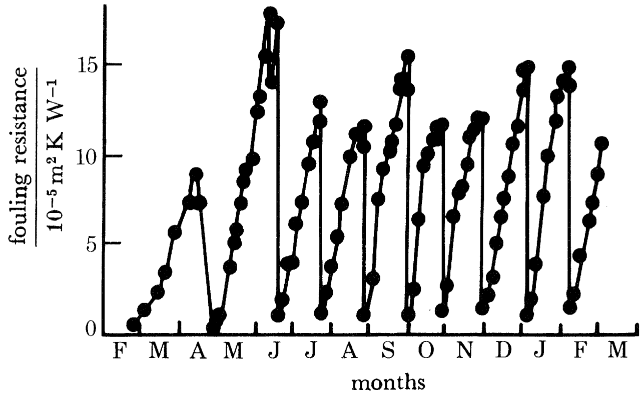

FIGURE 9. The fouling resistance as a function of time, measured off Punta Tuna, Puerto Rico, in aluminium tubes under ocean conditions associated with warm water flows through the evaporator. Periodic decreases in the fouling resistance were achieved by manually passing an M.A.N. brush through the tube 40 times.

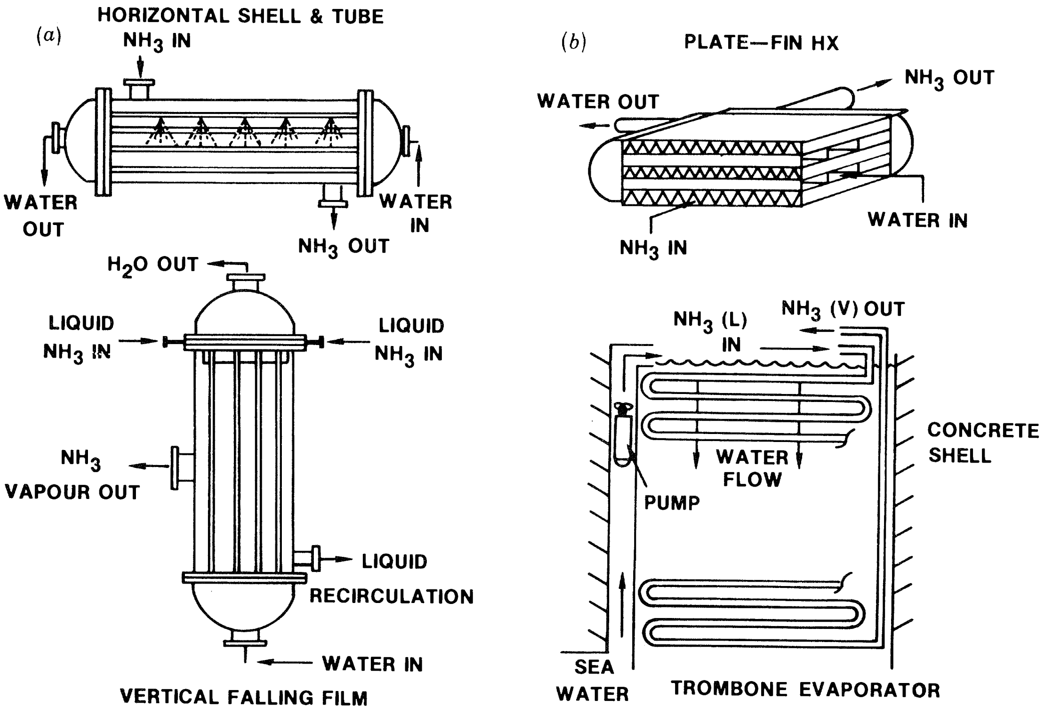

FIGURE 10. Four examples of shell-and-tube (*a*) and plate (*b*) candidate heat exchanger designs that have been tested in the U.S. OTEC power system development programme.

laboratory and core test units (1 MW_t) in a testing facility located at Argonne National Laboratory. Test results there exceeded programme goals, yielding heat transfer coefficients for enhanced surfaces more than twice those for standard industrial heat exchangers.

Heat exchanger configurations fall into two main geometric categories: shell-and-tube and plate. Several examples in each category are depicted in figure 10. Biofouling of tubular shapes can be cleaned by passage of brushes and spongy spheres through them. Plate configurations can be cleaned by using chemical and mechanical techniques.

In the past several years, tests of heat exchangers of significant sizes have been conducted with both warm and cold ocean water. These tests were done in OTEC power systems operated off Hawaii at 50 kW_e (2 MW_t), on the island-nation of Nauru at 100 kW_e (4 MW_t), and off Hawaii at 1 MW_e (40 MW_t). Results of these experiments are summarized in the following paragraphs.

A closed-cycle floating OTEC plant known as Mini-OTEC was operated (Owens & Trimble 1980) from August to December 1979 several kilometres off the Kona Coast of Hawaii. It was sponsored (at a cost of about £1.5M) by a consortium of industry (Lockheed, Dillingham, Alfa-Laval, Worthington Pump and Roto Flow) and the State of Hawaii. The barge-mounted plant, which was not an optimized system, successfully generated the predicted 10–15 kW_e net power of its 50 kW_e gross power. It employed titanium plate heat exchangers manufactured by Alfa-Laval. Its 0.6 m diameter cold-water pipe extended to a depth of 650 m. Although Claude (1930) had operated a land-based open cycle plant on the coast of Cuba, and had generated 22 kW_e of power with it, Mini-OTEC was the first closed-cycle plant, first sea-based plant, and the first OTEC plant to generate net power. Mini-OTEC's output power was dissipated on board.

Mini-OTEC achieved its technical goal of demonstrating the feasibility of OTEC power production. During its 4 months of operation, continuous chlorination of 0.1 mg l^{-1} was employed, and biofouling was not a problem on either the evaporator plates or the condenser plates. Heat exchanger performance equalled predicted values.

The Japanese government Ministry of International Trade and Industry (M.I.T.I.) is sponsoring a 100 kW_e OTEC system that was installed in 1981 on the island of Nauru, an independent nation in mid-Pacific. The system – estimated to cost about £2M – was designed, and is being operated, by the Tokyo Electric Power Company. The plant began operation on 14 October 1981, and testing is scheduled to continue for about a year. It is situated on land, and utilizes three aqueducts, including a 0.9 m diameter cold water pipe extending about 900 m along the sea floor to a depth of about 520 m. Its shell-and-tube heat exchangers are made of 400 copper-coated stainless steel tubes, 2.54 cm in diameter, in the evaporator, with similar tubes of single-fluted-exterior titanium in the condenser. The working fluid is R-22. Only fragmentary test results have been made public; they indicate that 34 kW_e is being generated and fed into the Nauru electrical grid. The power unit was provided by Toshiba Corporation, and most of the construction work was done by the Shimizu Construction Co. Ltd. Although the plant is not usually operated continuously, experiments so far have included a period of 240 h of continuous operation.

An engineering test facility known as OTEC-1 was deployed about 30 km off the Kona Coast of Hawaii in the autumn of 1980. This project, sponsored by the U.S. Department of Energy, was designed to provide performance testing of candidate heat exchangers rated at 1 MW_e (40 MW_t) under ocean conditions. The experiment was not designed for power production, so a throttling valve was installed to simulate a turbine. To serve as an ocean platform for this experiment, a former T-2 tanker was refitted by Global Marine Development, Inc., and equipped by TRW, Inc. with shell-and-tube heat exchangers. The OTEC-1 vessel, renamed the Ocean Energy Converter, is shown in harbour in figure 11*a*, and a schematic drawing of some of its components in figure 11*b*. The 1 MW_e condenser that was tested is shown being installed on OTEC-1 in figure 12. Its design is similar to that of the shell-and-tube configuration depicted in figure 10. The shell – made of carbon steel – is about 15 m in length and 3 m in outer diameter, and it contains 5526 titanium tubes 12.6 m long with outer diameter of 2.54 cm and wall thickness about 0.7 mm. Both the condenser and the evaporator were designed for seawater flow on the tube side and ammonia flow on the shell side. The evaporator was of

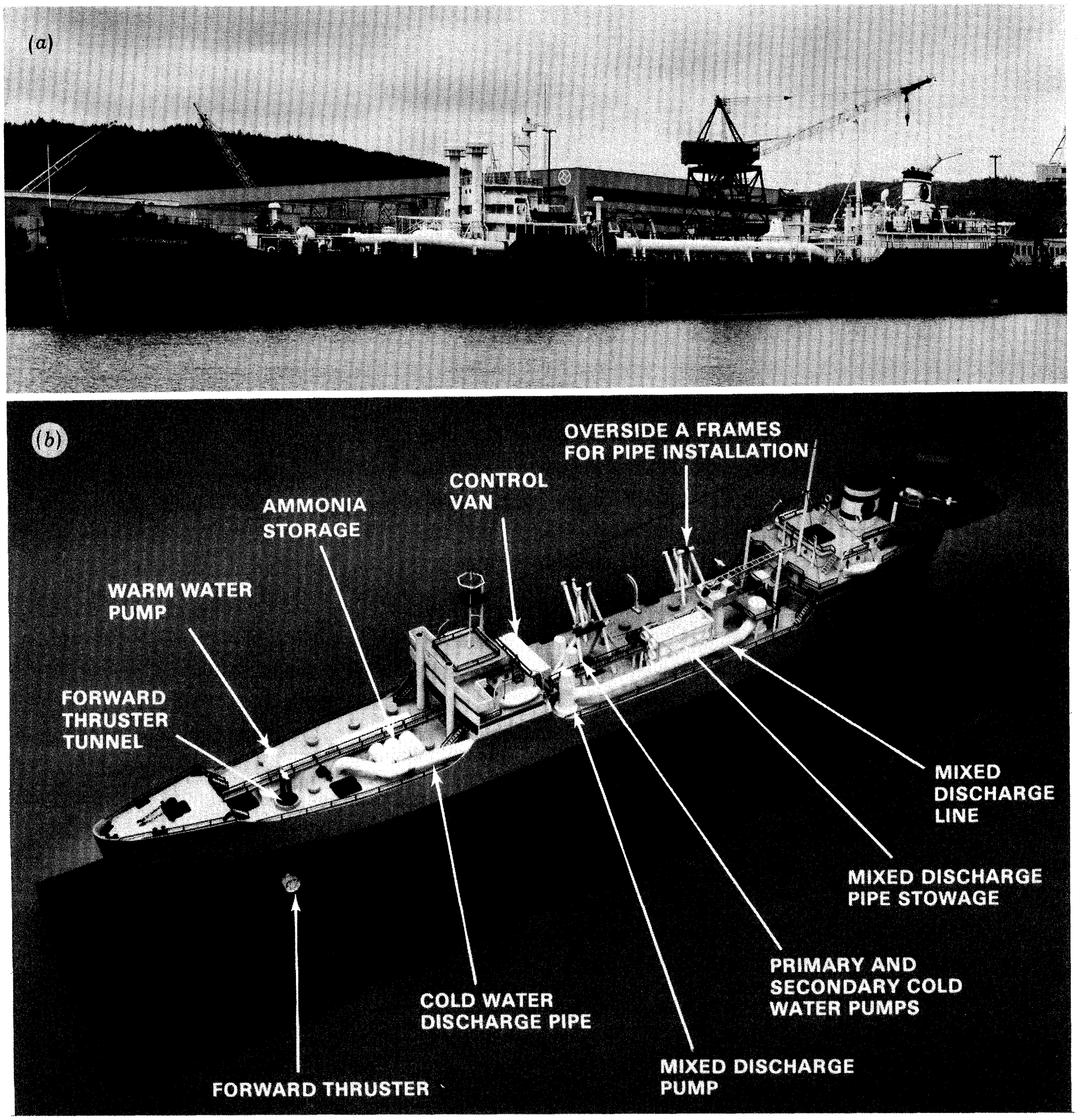

FIGURE 11. (*a*) A photograph of the OTEC-1 engineering test facility, the Ocean Energy Converter, at dockside in Portland, Oregon, before departure for Hawaii. (*b*) Some of its major power system components.

similar design, but it included a bundle of tubes coated on the ammonia side with a Union Carbide High Flux surface for the enhancement of heat transfer.

The mission of OTEC-1 was to obtain performance data on OTEC power system components of significant size in an ocean environment. The key goals of OTEC-1 were to obtain data on heat transfer, biofouling, corrosion, and fouling countermeasures. Deployment of OTEC-1 was accomplished between July and December 1980. Its cold-water pipe, having an effective diameter of about 2 m, was extended to a depth of about 700 m. OTEC-1 began pumping cold seawater on 13 December 1980, and started pumping warm seawater on 22 December 1980. Evaporation of ammonia began on 31 December 1980. Because of ensuing budgetary constraints, testing operations had to be curtailed prematurely and the OTEC-1 project ended on 15 April 1981. By that date, the OTEC-1 mission had been successful in obtaining good heat transfer data, but the limited period of power system testing (about 3 months) was inadequate to obtain conclusive data on biofouling, corrosion, and fouling countermeasures. Results of OTEC-1 power system testing (Lorenz *et al.* 1981) are summarized in this section; OTEC-1 results relevant to ocean systems are discussed in the next section.

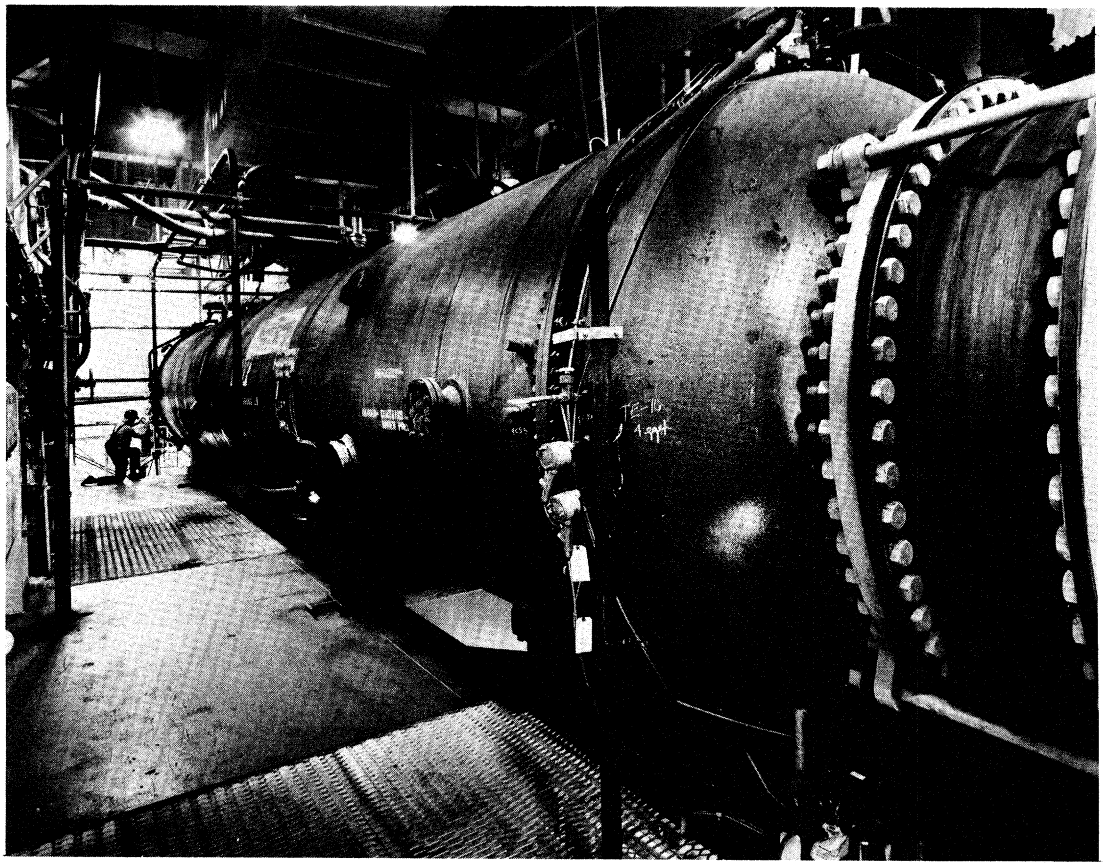

FIGURE 12. The shell-and-tube condenser being installed in OTEC-1 for ocean testing. The shell has dimensions of 3 m outer diameter and length of 15 m, and contains 5526 tubes of outer diameter 2.54 cm and length 12.5 m.

Although the OTEC-1 evaporator was designed to operate in either a sprayed or flooded mode, the available period of operation limited testing to only the sprayed mode. Also, although the upper tube-bundle consisted of plain tubes, and the lower tube-bundle of enhanced tubes, tests of the enhanced tubes proved inconclusive because of difficulties with activating the enhanced surfaces in the presence of a pre-existing deposit of corrosion.

Performance testing of the evaporator (Lorenz *et al.* 1981) was conducted in a total of 95 tests during 370 h of ammonia system operation over the 3 months from January to March 1981. The first 29 tests were trials for eliminating faults from the system and the experimental procedures. Measured values of heat transfer rate proved to be very close to the 2800 W m^{-2} K^{-1} predicted, and measured waterside pressure drops were about 10% higher than the predicted value of 17 kPa. There was no apparent influence of ship motion on evaporator performance; i.e. data taken during high sea states were similar to those during calm weather. However, maintaining steady operation of the ammonia system was difficult during high sea states. Thermal performance of the condenser was comparable with that of the evaporator, and also in accordance with predicted values.

Biofouling was controlled (Gavin & Kuzay 1981) primarily by chlorination, through injection into the evaporator and condenser of chlorine at 0.4 mg l^{-1} during 1 h for each 24 h period when the seawater systems were in operation. In addition to chlorination, Amertap sponge rubber balls were circulated through the evaporator and condenser tubes during one 35 day period. On the average, a ball traversed each tube once every 15 min. This period was followed by a 30 day period of using chlorination alone. These measures were sufficient to prevent any detectable increase in fouling factor. The limited time for testing OTEC-1 precluded obtaining conclusive data on biofouling, corrosion and on fouling countermeasures.

Status of OTEC ocean systems and submarine electrical cables

Most of the ocean thermal resource is only accessible to floating OTEC plants and plant-ships. Consequently, realization of the substantial resource potential for OTEC technology will depend largely upon the viability of floating systems consisting of a power system contained by an ocean platform. As the technology evolves, however, it is likely that some OTEC plants will be installed on land and on shelf-based towers accessible to the ocean thermal resource by aqueducts. In the OTEC development phase, there are those who contend that land-based and shelf-based OTEC prototype plants are a desirable first step, before the construction of floating OTEC plants. This conservatism was reflected by the assortment of proposed pilot plant concepts summarized in a later section. On the other hand, although land-based and shelf-based plants avoid some of the problems that have to be solved for floating plants, the design and deployment of aqueducts from fixed land and shelf installations present significant engineering and cost problems.

This section emphasizes the status of ocean systems and submarine cable technology relating to floating OTEC plants and plant-ships, which are likely to provide the big technological payoff from OTEC, starting in the 1990s. But first, the next few paragraphs summarize the results of several studies of land-based and shelf-based OTEC concepts that were conducted in recent years (Brewer *et al.* 1979; Moak *et al.* 1981; Giannotti & Associates, Inc. 1982).

The studies cited have clarified certain aspects of land-based and shelf-based OTEC systems; in particular, the design and deployment of shelf-mounted pipes were studied, and hydrodynamic loads on various platform and tower configurations were analysed. Shelf-mounted platforms must be capable of installation on sloping sea floors for specific site conditions, and must be readily accessible for operation and maintenance. For shelf-based installations, the platform was found to be the driving economic consideration, whereas the pipe installation and platform foundation present the greatest engineering challenges. OTEC shelf-mounted platforms have many features in common with oil drilling and oil production platforms. They also have some distinctive features, such as using voluminous subsea equipment rather than high-density subsea equipment.

Design and deployment of OTEC aqueducts from land-based and shelf-based installations offer some new technological challenges and difficulties that require a certain amount of improvements in the existing state of the art. About eight concepts for engineering such aqueducts have been examined. Key issues to be resolved include the accurate placement of pipe sections on rugged slopes of up to 35° inclination, piles and structures at depths up to 1000 m, the extension of the capabilities of submersibles, and sea-floor preparation.

In summary, land-based and shelf-based OTEC systems do offer some advantages over floating OTEC systems, but they present certain technological problems that could be costly to solve. One potential problem of such systems that should not be overlooked is the need – which may be complicated by their proximity to shore – to ensure a steady supply of warm and cold water resources and the avoidance of recirculation of thermal effluents. With shelf-based towers, their potential for relocatability would be a desirable factor in their design.

Returning to floating OTEC systems, it is important to note that a key adjunct of OTEC plants, as opposed to OTEC plant-ships, is a submarine umbilical to convey their products to shore in forms such as electricity, compressed air, liquid ammonia or gaseous hydrogen. If an umbilical is used, strict station-keeping of the platform – especially by mooring – will be necessary; this will be discussed below. On the other hand, if OTEC products are transported to market from an OTEC plant-ship or other vessel, the requirement for station-keeping is less stringent.

A key feature of OTEC plants and plant-ships is their cold-water aqueduct, or cold-water pipe, required to circulate cold water to the condensers. There is, by the way, an alternative to a cold-water pipe that is applicable to OTEC plants but not plant-ships. It was suggested by Karig (1972) that, instead of moving large volumes of water, much smaller volumes of vaporized working fluid could be piped to and from the condenser mounted on the sea floor. This concept was considered by a Lockheed team (1977), but found to be less attractive than using a cold-water pipe.

Cold water pipes up to about 40 m in diameter have been considered for plants of 400 MW_e size, but it will probably be possible to get by with much smaller diameters if water flow velocities are increased. For a 40 MW_e plant, a pipe about 10 m in diameter is required. Methods for deploying the cold-water pipe and connecting it to the OTEC platform need to be developed, and the materials and design of the cold water pipe require advances in the state of the art. Two approaches to deployment have been suggested. One is the 'float and flip' technique, where the pipe is towed to the OTEC station and flipped into position. The other, reminiscent of drilling procedures, is to deploy the pipe vertically, section by section. However, vertical deployment may require a weather-window that is unacceptably long.

Once deployed, the pipe will be subject to significant stresses from ocean currents, and the pipe could break unless it is made of a flexible material or constructed with jointed sections. Candidate pipe materials include rubber-like substances known as elastomers, steel, lightweight concrete, and glass-reinforced plastic.

Intakes for OTEC warm and cold water need to be screened to prevent the entry of fish and other organisms that would otherwise damage themselves or the plant, or both, if allowed to enter. These screens would be similar to those now used for cooling-water intakes at coastal power stations.

Large volumes of seawater – about 4 $m^3\ s^{-1}\ MW_e^{-1}$ – need to be drawn up by the cold-water pipe, and a similar amount by the warm-water intake; this requires heavy-duty seawater pumps. The cost of these pumps will probably constitute about 10 % of the total cost of the plant (Little 1978). However, designs for these circulating pumps will represent no great departure from existing pump technology.

The electrical connection between an OTEC plant and shore poses certain problems, and has been studied by the Pirelli Cable Systems Co. and the Simplex Wire and Cable Co., for bottom cables and riser cables, respectively, as reported by Garrity & Morello (1980) and Pieroni *et al.* (1980). One riser cable problem is to connect it to a moving platform in a way that can withstand flexing for long periods. Also, OTEC bottom cables may need to be deployed at depths up to 2000 m, whereas existing power cables have gone only to depths of about 600 m. Some of the other cable problems that must be surmounted are armouring to resist twisting, minimizing the number of splices, and cable recovery and repair. Anti-twist armouring can probably be achieved by using a double layer of steel wires. A quick-disconnect capability may also be desirable, but would increase system complexity. Some OTEC cable problems have already been resolved, for cables up to about 50 MW_e ratings, thanks to the experience (Derrington 1979) of the offshore oil industry in transmitting power from shore to ocean platforms.

For OTEC plants located within 30 km of shore, such as for typical island applications, a.c. current can be transmitted. However, since most sites are farther from shore, the power there must be used *in situ* to manufacture energy-intensive products, or converted to d.c. electricity for transmission to shore. Cost projections for submarine cables suggest that d.c. transmission will probably be limited to distances of about 400 km from shore. A substantial increase in world submarine cable production will be required if more than a few OTEC plants are built annually for electricity-to-shore application.

With a.c. transmission, electrical losses will amount to about 0.05% of the input power per kilometre, or 1.5% over 30 km, which is the longest run now being considered. With high-voltage d.c. cables, conversion and inversion losses will be about 2%, and transmission losses will consume about 0.01% of the input power per kilometre.

Each OTEC power plant will require a source of electrical energy to supply a start-up system that will enable at least one power module to be brought into operation after the plant has been shut down. This system could be energized from an auxiliary diesel–electric generator located on the OTEC platform or on an auxiliary one. If the OTEC plant is connected to a submarine electrical cable, that cable can be used to transmit start-up power to the plant.

Various platform designs for 400 MW_e commercial OTEC plants have been considered. A conceptual analysis of six hull options was conducted in three independent studies (Gibbs & Cox, Inc. 1978; Lockheed Co. 1977; Rosenblatt & Son, Inc. 1978) by industrial organizations for the electricity-to-shore application. Figure 13 illustrates the resulting concepts. A similar study was conducted for a 325 MW_e OTEC platform to be used for the production of ammonia at sea, much like the 100 MW_e platform shown in figure 6. Resemblances are evident between the semisubmersible design in figure 13 and the designs of similar platforms used in the offshore petroleum industry.

Station-keeping requirements can be achieved through dynamic positioning or by mooring, or both. Dynamic positioning uses discharge thrust, powered thrusters or a combination of both (Davidson & Little 1977). However, seawater discharges alone would provide insufficient thrust to maintain station during some sea conditions, in which case additional pumping power would need to be supplied. This extra pumping power could constitute a prohibitive cost for plant sizes in the tens of megawatts (but not hundreds of megawatts) if sea conditions at the plant site were severe. Mooring costs per unit of power output also exhibit an economy of scale (Davidson & Little 1977), decreasing approximately tenfold as plant size increases 50-fold from 20 to 1000 MW_e.

The combination of cold-water pipe, submarine cable and mooring subsystems can be regarded as a single system whereby the cold-water pipe acts as a mooring segment and is also integrated with the electrical riser cable. One mooring option is to use a tension-leg moor connected to the cold-water pipe. A turret moor is another option being considered.

The experience of OTEC-1 during its brief period on station will be applicable to the ocean systems technology requirements for commercial OTEC plants and plant-ships. Its bundled polyethylene cold-water pipe (composed of three individual pipes), with an effective diameter

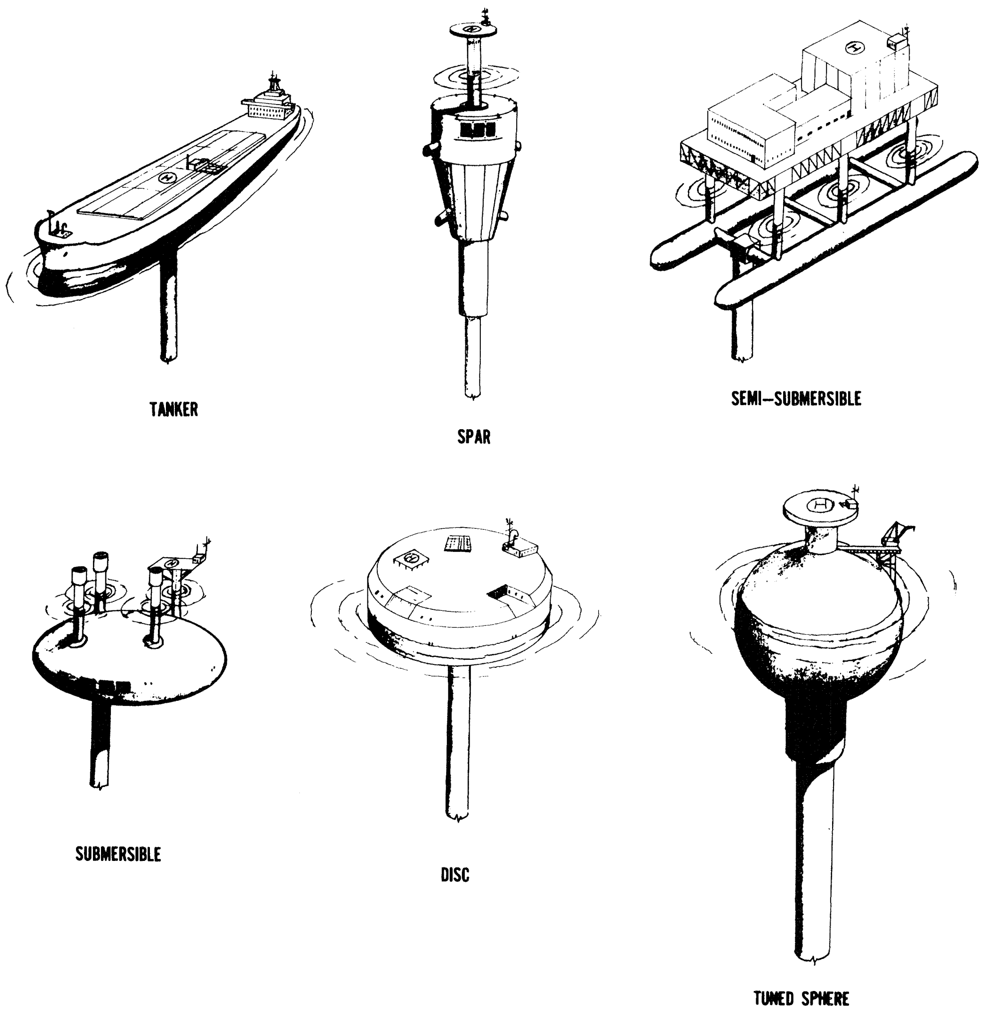

FIGURE 13. Six industrial concepts of candidate OTEC platforms to house 400 MW_e (net) power plants.

of 2 m, was deployed by the 'float-and-flip' technique to a depth of about 700 m. OTEC-1 operation continued even during several Kona storms, with winds gusting to over 84 km h^{-1} and with subsurface currents of over 5.6 km h^{-1}.

OTEC-1's cold-water pipe withstood significant drag forces during a storm on 4 March 1981, when the pipe actually came into contact with the gimbal stops (Harms 1981; Munier & Drahos 1981). Important conclusions about drag forces on the cold-water pipe and implications for future pipe and mooring designs were drawn by these authors. During one storm episode, OTEC-1 was slipped from its mooring and allowed to drift temporarily, rather than choosing the alternative of decoupling from the cold-water pipe. Design of OTEC plants will perhaps require some procedure, such as pipe decoupling, for survival during high sea states.

Constructability and deployment of OTEC systems

Two key features of OTEC plants are their modularity and standardizability, especially the floating plants and plant-ships. Along with these attributes, their ocean environment provides them ready, but not easy, access to the vast oceanic heat sink. In fact, in quest of a heat sink, conventional power plants are increasingly being installed at coastal locations where they can use ocean water for cooling.

The modularity and standardizability of OTEC plants make them especially amenable to serial construction and integration in shipyards. And, since the plants are deployed at ocean locations after construction, they are readily transported from their shipyards of origin, although in some cases transit costs can be large (van der Pot 1980). Estimated shipyard construction time of OTEC plants, on contrast to the time to construct conventional power plants, is about 3 years.

Much of the technology that has been developed for the offshore petroleum industry will be transferable (Derrington 1979; Clare 1981; Wortman 1981) to the construction and deployment of OTEC systems. The potential use of concrete construction for OTEC plants is especially relevant to the capabilities of the offshore petroleum industry (Derrington 1979; Clare 1981; van der Pot 1981). The relative cost of concrete and steel construction could be a crucial factor in the economic viability of floating OTEC plants.

It was indeed a fortunate circumstance for the credibility of OTEC technology that the start of an era of depleting world oil supplies led to the creation of an offshore petroleum industry with its related technology. Without that development and ensuing experience, OTEC technology would have been perceived as quite futuristic.

Techniques for OTEC construction and for deployment of cold-water pipes are discussed by van der Pot (1980). That study concludes that 400 MW_e may be a limiting size for construction in U.S. facilities, and that cold-water pipes made of steel and concrete are difficult to deploy.

OTEC cost projections and competitive costs

A key factor in projecting the economic viability of commercial OTEC power plants is the cost of the energy produced compared with the rising cost of energy from depletable energy sources. This can be estimated from the capital cost of the power plant, based upon a complex set of assumptions (Curto 1978). Since OTEC technology, like other solar energy technologies, requires no fuel for plant operation, the major component of the cost of OTEC-derived energy is for the amortization of the substantial capital investment required. The other cost component is operation and maintenance, which will require significant annual outlays.

Some of the key factors are the plant's capacity factor (percentage of rated capacity achieved), taxes, interest during plant construction, cost of capital and insurance, the rate of inflation, and the cost of power plant operation and maintenance. It is likely (TRW Systems Group 1975) that baseload OTEC plants will attain a high availability factor (percentage of time in operation) and will be capable of being constructed in about 3 years. The operation and maintenance cost component of plant operation is estimated at about 1–2 % of the capital investment per year. However, for small (10–100 MW_e) plants, this component will be considerably greater per kilowatt hour generated than in the case of larger (100–500 MW_e) plants. Thus, minimum energy costs will probably be obtained somewhere in the range 100–500 MW_e. The limiting size of OTEC plants will probably be determined by the ability to construct and deploy them cost-effectively. Optimum module size is yet undetermined, but will probably be in the range 5–50 MW_e.

The range of projected OTEC costs for baseload power is comparable with projected costs for other baseload power sources (such as coal and nuclear) in the 1990–2000 U.S. Gulf Coast market for electricity. However, in island markets (such as Hawaii and Puerto Rico), where most of the electricity is derived from oil, OTEC power plants could achieve by 1990 costs that are less than the projected costs of oil-derived electricity, as shown in figure 14.

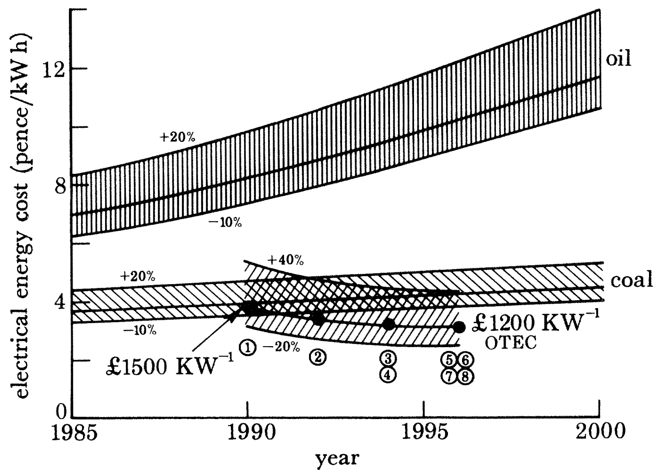

FIGURE 14. Projected levelized life cycle energy costs (in 1980 pounds sterling) of electricity generation in Puerto Rico for commercial oil-fired (fuel-saving mode), coal-fired and OTEC plants. Ranges of projections are shown about a most probable value, extending 40 % above it and 20 % below it for OTEC, and 20 % above and 10 % below for oil and coal. The cost of fuel oil is estimated to increase at an annual rate 3.5 % greater than the rate of inflation. The cost of coal is estimated to increase 2 % faster than the inflation rate. The cost of the first OTEC plant (encircled 1 in year 1990) is estimated at £1800 kW^{-1}, and of the fifth to the eighth production units, £1400 kW^{-1}.

Cost estimates are based upon extrapolating to production units the projected economies expected to be achieved through 'learning curve' or 'experience curve' cost reductions. They are typically the result of estimating the costs for mature plants, i.e. production units achieved after building eight or more plants. Critical integration (Curto 1979; Gritton *et al.* 1980) of the results of key OTEC system studies yields a composite of costs for providing OTEC electricity to shore. The costs projected for each OTEC subsystem and component can be represented as a range of values extending from optimistic to pessimistic, and the cost projections for an integrated OTEC system can be obtained roughly by aggregating the extremes of these constituent costs. The range of system costs typically extends 40 % above and 20 % below the most probable value. The system costs include about £200 kW^{-1} for electrical transmission to points in the southern United States from the Gulf of Mexico. For island locations such as Hawaii and Puerto Rico, cable transmission costs will be about £50 kW^{-1}.

It is likely that all technical problems associated with OTEC are amenable to technological solution. The key question is the total cost of a system that provides those solutions: will it be an acceptable cost from the standpoint of providing OTEC energy at costs competitive with other energy sources?

Legal, institutional and financial factors

OTEC technology is confronted with a more complex institutional problem than most other solar energy technologies, in that most of its products will be manufactured at sea rather than on land. It must be resolved who will be the owner–operators of OTEC plants and plant-ships, how OTEC capital formation will occur, and how to establish a stable and predictable legal régime for operations at sea. It will be essential to resolve these problems in a fashion conducive to the attractiveness of OTEC as a commercial investment. However, the fact that the offshore oil industry and the offshore nuclear industry have made considerable progress in solving comparable problems is somewhat encouraging.

Investment in and operation of OTEC power plants in territorial seas, economic zones of coastal states, and in international waters will require bilateral and multilateral agreements among nations. Some of the relevant legal, institutional and financial aspects have been examined by the American Society of International Law (1977, 1979). One of the key considerations is whether OTEC platforms can be regarded as 'vessels' from a legal standpoint. This classification could differ if the platform is moored or if it operates as an unmoored plant-ship, manufacturing energy-intensive products. On the other hand, in neither case would the platform be a vessel in the sense of plying between ports. The safety, lack of negative environmental impact, insurance coverage and physical protection of OTEC platforms will need to be ensured.

Prospects for OTEC technology thus depend both on economic factors and on institutional factors. Both sets of factors will need to be satisfactorily resolved before OTEC can become commercial. If and when this is achievable, the ocean thermal resource could provide the world with a new source of renewable energy that has a substantial potential to help meet growing worldwide demand for additional energy supplies. OTEC-derived electricity and products, by increasing the world energy supply, could help reduce foreseeable polarizations between nations over limited energy resources.

Prospects for a commercial OTEC industry

The 1990s seem ripe for a commercial OTEC industry to blossom. Such an industry could be phased in as the production of offshore oil facilities begins its inevitable decline. This evolution will be one manifestation of the global transition from depletable fuels to renewable energy sources.

A basic requirement for achieving such an industry is the construction and successful operation of prototype OTEC plants at sizes of commercial interest, starting in the range 1–50 MW_e. Besides providing technical performance data, prototypes will allow a more accurate projection of costs for larger commercial plants. Such prototypes will cost at least £5000 kW^{-1} at the low end of that range, and £3000–4000 kW^{-1} for the larger sizes. Mature commercial versions will cost only about half as much per kilowatt. OTEC technology is now widely regarded as maturing, yet there are still some perceived and actual technological risks that need to be resolved through the realization of prototypes.

The costs and the technical and economic risks of developing OTEC prototypes will somehow need to be absorbed by society. In view of the significant capital costs required, some degree of involvement on the parts of governments and public-interest organizations may well be needed to catalyse this activity. Such involvement could take the forms of subsidizing costs and providing a combination of financial incentives. Possible incentives include loan guarantees, tax credits, accelerated depreciation, and low-interest loans.

Various governments and international organizations have already begun applying subsidy and incentive instruments in moving toward OTEC prototypes. For example, in 1980 the United States enacted two OTEC-specific laws. One law (Public Law 96-310) established targets for federally sponsored development of OTEC demonstration plants, namely 100 MW_e by 1986, and 500 MW_e by 1989. That law also specified a national commercial goal of 10000 MW_e by 1999, implying the creation of an industry that would in the 1990s necessarily achieve annual revenues amounting to several thousand million pounds sterling.

A companion law (Public Law 96-320) defined OTEC plants and plant-ships as 'vessels', thereby qualifying them for federal mortgage loan guarantees previously available to more conventional merchant vessels. In addition, that law (as subsequently amended) provides a streamlined, one-stop licensing procedure and £825M in loan guarantee authority for construction of up to five OTEC demonstration plants. Additional financial incentives are potentially available to prototype OTEC ventures under other legislation. These incentives include energy tax credits, investment tax credits, R & D credits, and accelerated depreciation. If an incentive package containing most of these provisions, especially the loan guarantees, were actually made available, financial ventures for building prototype OTEC plants could well become attractive to investors (Lotker *et al.* 1981). The viability of these ventures would also depend upon the financial attractiveness of contracts obtainable for marketing the products and by-products of such prototypes. (It is probable that OTEC plants will be owned by 'third parties' rather than by utilities, and that they will sell their energy at the busbar to electrical utilities.) In selling electrical energy to a public utility, for example, a contract specifying a price comparable to the cost of fuel-oil saved would be an important provision. Indeed, 'avoided cost' contracts for renewable energy sources such as OTEC are contemplated by other U.S. legislation (Public Law 95-617), known as the Public Utilities Regulatory Policies Act.

To what extent the U.S. Government is now prepared to implement this panoply of favourable legislation is uncertain. A federal procurement of OTEC pilot plants was initiated in September 1980, and two awards to industry were announced by the U.S. Department of Energy on 18 February 1982 for the first phase of work, conceptual design studies. The terms of the contracts that ensue are expected to involve industry's sharing one-third of the costs. This would mean a government contribution of £450000 toward the conceptual design work, with about 50% extra provided by the contractors. Both of these awards pertain to 40 MW_e concepts for Oahu, Hawaii. One award is to the General Electric Corporation to design a closed cycle OTEC plant mounted on a guyed, shelf-based tower. The other award is to Ocean Thermal Corporation, assisted by TRW Systems, Inc., for the prototype OTEC plant to operate in connection with an existing 600 MW_e oil-fired power plant operated by Hawaiian Electric Company. This concept envisages a closed-cycle OTEC plant situated on an artificial island. The OTEC plant will use rejected heat from the fossil plant to raise the temperature of the warm ocean water by about 5 °C.

In the course of announcing the two awards mentioned above, it was also stated that there were bids from six other consortia, including two proposals for 40 MW_e plants at Punta Tuna, Puerto Rico, one shelf-based and one floating, and one proposal for a floating 40 MW_e plant off Key West, Florida. The other three concepts proposed related to a 40 MW_e plant-ship for producing ammonia off Hawaii, a 10 MW_e land-based plant for the Commonwealth of the Northern Mariana Islands, and a 12.5 MW_e shelf-based plant for the Virgin Islands. About 2.5 MW_e of the Virgin Islands concept's power output was to be used for the production of 200×10^6 l of fresh water per day.

It is unclear whether there will be federal cost-sharing of OTEC pilot plant design and construction beyond preliminary design (the 'second phase' of work). Reagan Administration policy is that it is up to industry to take the initiative in the commercialization of OTEC, without further subsidization on the part of the government.

Interest in developing OTEC prototype plants is widespread. It is likely that once a significant-sized prototype plant anywhere in the world operates satisfactorily and projects commercial viability at a scaled-up size, an OTEC industry will rapidly expand. Currently, some of the feasibility and design studies for OTEC plants that are reported to be in progress are as follows. The Japanese government is said to be contemplating one or more prototype plants from 1 to 10 MW_e in size. The Nauru location, where their 100 kW_e plant is currently being tested, is one candidate site for such a prototype. The Dutch government has sponsored a feasibility study for a 10 MW_e floating plant for operation off Curaçao. The Swedish government, with Finnish and Norwegian participation, is sponsoring a feasibility study for a 1 MW_e prototype land-based plant in Jamaica. The Territory of Guam is studying a plan for a 48 MW_e land-based plant. The French government is sponsoring design studies for a 4 MW_e plant in Tahiti. The European Economic Community is sponsoring a feasibility study by a French organization for a land-based plant in the Ivory Coast. A consortium headed by Bethlehem Steel and partly sponsored by the State of Maryland is examining the feasibility of a 60 MW_e floating plant that would be located off Puerto Rico.

Although possible OTEC prototype plants include land-based, shelf-based and floating facilities, there are some dilemmas as to which of these options to select, at what size, to manufacture what product, and whether to include a by-product. It seems likely (Dunbar 1981) that the most valuable OTEC product in the short term will be electricity in competition with oil-derived power. It seems unlikely that OTEC energy-intensive products will be competitive while natural gas is being flared at some locations, since such products could be manufactured more cheaply at those locations. However, the consideration that OTEC plant-ships can serve as a reliable domestic supply of energy-intensive products for a given country could outweigh that of cost differentials.

In locations where fresh water is at a premium, an OTEC prototype plant that would be marginally economic or sub-economic if it produced solely electricity, could well become economic by adding fresh water as a by-product (Coffay 1980), or manufacturing water as its principal product. Similarly, shellfish production using nutrients upwelled in the course of OTEC electrical production could also make a prototype plant viable. Under such circumstances as these, OTEC prototypes could become commercially viable without the need for external financial incentives, although there would still remain the element of risk.

The choice of plant size poses another dilemma. Although larger plant sizes lead to lower costs than smaller plants, per unit of energy produced, they do require a larger investment, hence put more capital at risk. Also, projecting the competitive economics for an investment of large amounts of capital in OTEC plants requires being prophetic: i.e. making a long-term projection of inflation and of the cost of competing energy sources such as oil. The paradox with investments in capital-intensive options like OTEC is that only at the *end* of a plant's 20 or 30 years of economic life will one know how much capital it was worth to invest in it! Alternatively, by *not* investing in capital-intensive renewable energy options early enough, society now runs the risk of rapidly incurring drastically increased real costs of its energy supplies.

Scenarios for industrial development and market penetration in the 1990s

The 1990s appear ripe for what can become massive commercial extraction of renewable energy from the world's oceans. Assuming that one or more floating prototypes of OTEC plants are successfully operated by the mid-1980s, the production of larger commercial units of about 100 MW_e size can get under way by the early 1990s. Scenarios can be projected (Curto & Cohen 1980) for subsequent industrial development of commercial OTEC plants, based on a 3 year construction period and a growing number of graving docks being put into service. By the mid-1990s, plants of 250 MW_e or greater can be put into construction. If much of this production is for plants that will supply electricity, as is likely (Dunbar 1981), then there will also be a need for a significantly increased world production of submarine electrical cable.

By the 1990s, it is probable that increasing global demands for fertilizer and aluminium, coupled with diminishing supplies of oil and natural gas, will begin to make OTEC-derived energy-intensive products a competitive option. Accordingly, although the first wave of commercial OTEC facilities will mainly provide cabled electricity, it is probable that OTEC plant-ships will be added to the production mix by the mid-1990s.

Thus in the early 1990s the market penetration by OTEC will begin what can become an exponential growth, first to serve an electrical market, then with an admixture of plant-ships providing ammonia, aluminium, hydrogen and other products. Ultimately, assuming no environmental or other constraints are imposed on the proliferation of OTEC plant-ships, the expected 'hydrogen economy' and the increasing world demand for fertilizer can be fuelled by an increasing dependence on plant-ship-derived hydrogen and ammonia. The rapidity of the exponential growth will be constrained at first by available production capacity, then by limitations on investment capital. The relative attractiveness of OTEC as an investment opportunity, in an era when the demand for capital will exceed its supply, will probably be a strong factor in determining market penetration.

International aspects: problems and potentials

Clearly, the developing nations, where much of the early OTEC market exists (Dunbar 1981), are in short supply of capital to invest in a capital-intensive option like OTEC. In view of their likely attitude towards sources of a key commodity such as electricity, they will probably want to retain at least 51 % ownership of OTEC plants supplying them with electricity. However, their substitution of OTEC-derived electricity for oil-derived electricity will help relieve the developing nations of much of their outflow of foreign exchange. Hence, in so far as funds continue to be available to them for the importation of oil, their provision of capital for investment in OTEC would be an attractive alternative.

The industrial nations will probably be the source of OTEC technology and of capital for OTEC investments at the outset, although shipyards in developing countries could be employed for plant production. By providing a significant new source of energy on the interdependent world energy market, OTEC could be a factor in moderating the demand for limited world oil supplies, thus helping to stabilize world energy costs. Over the next 20 years, assuming the industry takes off in the 1990s, OTEC could supply a total market amounting to some 50 GW_e. If all of this capacity were for generating electricity that otherwise would have been produced by burning oil, then a saving of about 2 million barrels (*ca.* 320×10^3 m^3) of oil per day would be effected.

The consequences of attaining an annual world production rate of, say, 10 GW_e by the late 1990s would be beneficial in many other respects. This production rate would be equivalent to the construction of 100 OTEC plants and plant-ships of average size 100 MW_e. The electrical generation component of each of these 100 MW_e facilities would cost about £150M. Thus, an OTEC industry with annual revenues of £15G will have been created, with the associated benefits already noted.

Until 1 October 1981, the author was with the Division of Ocean Energy Technology, Office of Solar Electric Technologies, U.S. Department of Energy, Washington, D.C., U.S.A., under whose auspices much of the work reported upon was conducted.

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Discussion

D. E. LENNARD (*Ocean Thermal Energy Conversion Systems Ltd, Orpington, U.K.*). Dr Cohen has referred to the two types of OTEC plant – open and closed circuit – and has said that the closed is some 3 to 4 years ahead of the open system in terms of development. Apart from our colleagues from France, working with Philippe Marchard of C.N.E.X.O., who are devoting approximately equal efforts to open and closed cycle work, the national OTEC programmes seem to be placing greater emphasis on closed rather than open cycle technology.

Is this due principally to the '3 to 4 year lag' to which Dr Cohen has referred or is it, in his view, because the closed cycle systems have broader application than the open cycle?

R. COHEN. Developmental emphasis on the closed cycle is essentially because of that cycle's greater commercial readiness for supplying first-generation OTEC hardware. The applicability of the two cycles is comparable; indeed, the open cycle is more amenable to fresh water production. Also, Westinghouse studies of both open and closed OTEC cycles led that firm to conclude that commercial systems using either approach would have comparable costs. This was partly because of Westinghouse's economic approach to the large open-cycle turbine, employing turbine-blade technology that was based upon experience with helicopter blades and wind turbines.

J. H. TURNER (*University of Cambridge, U.K.*). In view of recent reports from California, I believe it is important to bring to Dr Cohen's notice the remarkable adaption of hydrogeneration to sea power generation. According to the report it is now possible to install a rotary turbine in a large pipe, through which water can fall, and it can be arranged that the water re-enters the sea through the bottom of the pipe. Thus the seawater after giving up its potential energy to the turbine returns to the sea. I believe this technique to be a far-reaching discovery and may be the beginning of unlimited power, for these arrangements can be installed inland using artificial lakes for this purpose, thus providing power at any point almost independent of terrain and without excessive transport systems. I propose that a greater amount of effort be used in investigating this method of power production in the hope that it will produce a method that is clean, simple, amply available and cheap.

R. COHEN. This subject is discussed in the published version of my paper. Mr Turner is calling attention to the so-called lift-cycles, that convert temperature gradients into potential energy by lifting seawater in the form of bubbles, mist or foam. The resulting column of seawater is then converted into electricity by passage through a hydraulic turbine connected to a generator. These techniques are attractive, and their development has been proceeding, although only at a modest rate. However, as I pointed out in my paper, these are advanced concepts posing technical problems that must be surmounted before they can be developed for practical applications. Therefore, their commercial use is likely to become feasible only after that of closed cycle and Claude cycle hardware.

P. WADHAMS (*Scott Polar Research Institute, University of Cambridge, U.K.*). A technique that has been proposed recently is ICETEC – the ice equivalent of OTEC – which makes use of the melt water from icebergs for energy production and irrigation (Heizer 1978; Roberts 1978; DeMarle

1980). The idea is to tow Antarctic tabular icebergs to suitable coastal desert locations in the Southern Hemisphere where there is deep water close inshore, i.e. Western Australia, South Africa, Namibia, Chile or Peru. The iceberg runs aground and is anchored at about the 200 m isobath, which may lie 10–30 km offshore, and is then broken up into smaller fragments by blasting or cutting. The fragments are towed ashore and stored in a small lagoon to melt. The melt water is used for the cold side of an OTEC power station, the warm side being the local ocean surface water. The warmed cold water effluent is partly fed back to the lagoon to enhance the melt rate of the berg and partly diverted for irrigation or drinking purposes. This system has the advantage over other shore-based OTEC stations of not requiring a deep feeder pipe, and also the effluent cold water is put to productive use. There are a host of technical problems involved in the successful towing of icebergs, including the possibility that the iceberg will break up by wave-induced flexural failure while under tow (Goodman *et al.* 1980).

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R. COHEN. This subject is also discussed in my paper. Please keep in mind that about 250 000 $\mathrm{l\,min^{-1}}$ of cold water will be required for each megawatt of OTEC power generation.