Ocean Thermal Energy Conversion (OTEC)
- Its Position in the Renewable Energy Scene

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Synopsis

This Keynote describes the principle of Ocean Thermal Energy Conversion (OTEC) and gives a brief history of its conception and development to the present day.
Noting that it can have a number of by-products - or Deep Ocean Water Applications (DOWA) - which broaden its usefulness and can improve its economics, together with the fact that it is a base load renewable - unlike many others, the case is made out for demonstrating that, despite its high capital cost when compared with traditional systems such as fossil fuels, the business case for OTEC systems is robust by the normal criteria used for comparative assessments.
OTEC is also environmentally benign when compared with fossil fuels, the proposed Carbon Tax therefore providing a further advantage to OTEC. The market for all energies is set to grow substantially through the years to 2020, with "new" energies set to grow from a zero %age to 6% by that date. A modest share of that 6% would provide a very large target for OTEC manufacturers. Early plants are likely to be located in island states.
This Keynote paper addresses all these points, and thereby aims to demonstrate that OTEC and DOWA have a realistic, economically and environmentally attractive, contribution to make to world energy availability which justifies the establishment of an appropriate R,D&D programme. Finally, it is argued there is also a social and human basis for development of OTEC and DOWA.

The basis and beginnings of OTEC

OTEC is solar energy. The surfaces of the oceans capture huge amounts of this energy – some thousands of times more than the energy consumed by the world – most of this being stored in the form of thermal energy in the surface layers of the oceans. However, those surface layers do not mix freely or easily with the deeper waters, which are much colder. OTEC is therefore based on the extraction of energy from that temperature difference existing between the warm surface waters of the oceans in tropical and sub-tropical areas from approximately latitudes 25° North to 25° South, and the deep waters in those same areas which flow from the polar regions – predominantly the Antarctic. Surface temperatures can reach as high as 29°C in the Pacific whereas the temperature at a depth of 1000m will typically be 4°C, although this temperature can sometimes be found at depths as little as 700m. Figure 1 - the whole basis of OTEC - shows the temperature difference and distribution of this thermal resource world-wide.
The principal of OTEC was first noted as a potential energy source over 120 years ago. In fact it was in 1881 that the Frenchman Arsène d'Arsonval suggested using any working fluid having an appropriate vapour pressure at a temperature close to that of warm sea water, but it is developments in offshore oil and gas activities in the last thirty or so years which have enabled a concept to be turned into a practical engineering reality. Specifically, it has been as exploitation of those fossil fuel resources has moved into ever deeper waters and harsher climates - typical OTEC design cases.

The OTEC power circuit is that of an absolutely standard heat engine cycle, but with the temperature difference much less than that in the case of an internal combustion, or even a steam, engine. By general agreement, the typical design case for an OTEC plant assumes a temperature difference of 20C degrees. After cooling in a surface condenser the liquid working fluid is circulated by pumping to the evaporator where the fluid changes to a gaseous phase – with a considerable increase in volume and pressure, passes through a turbine connected to an electrical generator, and is then recycled on through the condenser. This concept, Closed Cycle OTEC, is shown in Figure 2. Working fluids including ammonia, propane, butane, and freon are suitable. Closed Cycle OTEC requires the design and construction of large surface heat exchangers which are now within the limits of presently available technology to enable the construction of modular Closed Cycle OTEC plants with capacity of the order of a hundred MW.

Nearly fifty years later a second option was proposed by another Frenchman, George Claude, where the working fluid is the vapour formed by the warm sea water itself when boiled in an evaporator maintained at an appropriate low pressure. Water vapour is condensed either through a direct-contact condenser by mixing with cold sea water, or indirectly through a surface condenser. In that latter case desalinated water is an immediate by-product of the thermal process. In neither case is the condensed vapour reintroduced to the working fluid circuit and Claude's concept, Open Cycle OTEC, is shown in Figure 3. The main technical difficulty for Open Cycle OTEC plants comes from the low vapour pressure of the working fluid which means very large turbines and reliable sealing along lengthy joins in the turbine casing to maintain the low pressure. The construction of Open Cycle OTEC plants with capacity of tens of MW are reckoned to be the largest possible at present.

Apart from the closed- or open-cycle options, OTEC plants may be land-based, floating (and moored) or "grazing". Clearly a land-based plant has some advantages in terms of cost and maintenance, but the disadvantage of (particularly) a longer cold water pipe to reach the cold resource - giving rise to greater frictional and thermal losses in the pipe. There is also a limited diffusion zone for the mixed discharge of the warm and cold waters, and also a restriction on access to the warm water resource. A floating plant has the additional costs of the floating structure, including mooring, and also of the power cables and riser from the plant to shore - so the advantage of a shorter cold water pipe and full 360^{o} access to warm water has to be balanced against those increased costs. One way of reducing the costs of a floating plant would be to eliminate the moorings and power riser and cable to shore, allow it to "graze" - drift with the currents - and take power off by producing (for example) hydrogen to be transported in liquified product carriers shuttling between the OTEC plant and the market place to provide power anywhere in the world. For safety reasons alone, some propulsion system will be required - which will also serve to locate the plant in the optimum thermal locations, and "grazing" systems are certain to be later, rather than earlier, developments.

The options are therefore numerous. In the medium term, floating OTEC plants, each of a hundred or so MW capacity, could supply a significant share of the need for electricity in industrialized countries with direct access to the resource. To give an idea of scale, the tropical/sub-tropical ocean regions most suitable to extract OTEC power have an approximate area of 60 million km^2, and an approximate estimate of the potential scale of the world OTEC resource is 12,000 GWe or 18 Gtoe i.e. twice the 1990 world demand for primary energy.

The body which acts as a centre for parties interested in OTEC and DOWA developments is the International OTEC/DOWA Association (IOA) created in 1990 which seeks also to promote international co-operation for OTEC, particularly RD&D, and whose publications are a useful source of detail on the subject.

OTEC development and sphere of applications

Working examples of both closed and open cycles have been built in recent times. The design of OTEC plants for the Ivory Coast and Guadeloupe was undertaken in France at the end of the 1950s, and at that time France could be judged as the pioneering nation for development of this technology. During the period from 1975 onward - following the 1973 " oil crisis" - very much work was undertaken in the USA and Japan. Also, in Europe, the Netherlands, Sweden and the UK undertook R&D for OTEC – including joint programmes by Eurocean in Monaco. More recently Taiwan and India have made progress, and both Palau and the Commonwealth of the Northern Marianas have current OTEC plans.

In Hawai'i, in 1978, a floating Closed Cycle OTEC plant, "mini-OTEC", was installed on a barge and successfully produced electricity. During the same period, Japanese and other US experiments strengthened the feasibility of OTEC by using different arrangements, components and materials. In the 1980s these included an onshore plant in Nauru, and the US OTEC-1 vessel offshore Kea-Hole Point, Hawai'i. France studied the design of a 5 MW OTEC pilot plant to supply electricity to Tahiti in French Polynesia, and GEC-Marconi proposed a small plant for Jamaica. The Netherlands/Eurocean designed a small plant for Bali, Indonesia, and the UK proposed a 10MW floating plant for St. Lucia in the Carribean. Whilst the thermal resource *is* restricted geographically, OTEC offers the potential of a large resource accessible, directly or indirectly, to *any* nation and the capacity therefore to contribute significantly to sustainable development. As already noted, this wide availability can be achieved by using the OTEC energy to produce, for example, liquid hydrogen from seawater, which can then be transported to any part of the world by tanker and/or pipeline. Moreover, and unlike most other renewable energies, such as wind, wave and tidal, OTEC is a base load renewable, available 24 hours a day and 365 days a year due to the thermal mass of ocean waters whose temperature varies little whether the sun shines or not, day or night, and where from summer to winter the variation in energy available will be no more than 10%. Despite the encouraging progress in the1950s to early 1980s, the drastic drop in the price of crude oil in 1985-86 led, in time, to a worldwide reduction of interest for all renewable energies and then to severe cutbacks in funding for renewables R&D. However, research efforts did continue in Hawai'i at the US Natural Energy Laboratory of Hawai'i Authority (NELHA) and the Pacific International Center for High Technology Research, and in Japan where several research facilities were funded by JAMSTEC. The effort was still directed mainly towards OTEC for production of electricity, although there can be a range of additional products, referred to below. The main results were operation of a 200 kW gross power Open-Cycle OTEC at the NELHA in 1992, and design of a 1MW elec. floating OTEC plant, planned to be installed by a joint Japanese-Indian venture offshore the Tamil Nadu coast. Also, the growing interest of Taiwan in OTEC, as a contributor to their energy demand, led to the outline design of modular OTEC plants of several hundreds of MW being envisaged. It was proposed that they should be mounted on floating platforms either anchored offshore and connected to shore by an electric cable, or "grazing" - the energy to be used to produce transportable liquid fuels such as hydrogen from seawater. A full listing of all countries with interests in OTEC may be found in the World Energy Council's triennial Survey of Energy Resources.

These continuing research activities look now to be timely - with the record high cost of hydrocarbons at present (January 2005), and the current increasing emphasis on

environmental aspects of power production which is of considerable benefit to OTEC, with its environmentally benign nature.
To summarise, it is now the case that the greater part of an OTEC plant can be described as routine engineering - even the mooring of a floating plant in depths of 2000 metres or more has precedents from offshore oil and gas activities. Only the cold water pipe has to be classed as "significant further development needed", particularly for the floating variant.

Other products from OTEC, and economic and funding realities
What may be considered bonuses for OTEC are the varied by-products which can result – under the heading Deep Ocean Water Applications (DOWA), which substantially enhance the economics as well. The Deep Ocean Water (DOW) used as the cold resource for OTEC plants is not only cold, but also nutrient rich and free of pathogens. The availability of DOW to academic and private enterprises at the NELHA and in Japanese facilities permitted exploration of the full potential of these benefits. These applications include aquaculture, agriculture, pharmaceuticals, and the production of fresh water. Fresh (potable) water can be a direct product of the open cycle system as previously explained. In the case of the closed cycle, some or all of the power output could be used to drive a distillation plant. For aquaculture, it can be simply making use of the nutrient rich cold water, which produces growth rates considerably in excess of normal - be it for fish or crustacea. The same source can also be used to grow seaweeds and the like at enhanced rates, from which pharmaceutical products can be derived. Agriculture can benefit by piping the exhausted cold water, buried in the soil, and cooling the roots of products such as lettuce and tomatoes, which would otherwise not be capable of growing in tropical/sub-tropical areas. Clearly most of those applications are more readily applied to a land-based plant. One final "product" which could be derived from floating- or land-based plants is air conditioning - simply by using part of the generated power for that purpose. Clearly the mix of products will depend on consumer demand, but the combination of power and potable water is a mix for which there is - and will continue to be - enormous demand, within the developing world in particular. For the wider potential application, the list of usable DOW outputs at NELHA is indicative of the interest of private and public sectors in DOWA - given satisfactory economics.
In the reasonably short term, the OTEC multi-product concept is expected to help the development of smaller OTEC plants of a few tens of MW, to supply electricity, fresh water, and other products to relatively small coastal communities located in the tropical and some sub-tropical regions.
Calculations show that small multi-product OTEC can be commercially attractive when the prices of oil fuel and fresh water reach respectively $US30 a barrel and 0.85$ m^{-3}, so the current oil price of about $US50 a barrel is very good news for OTEC. But there is discerned to be a more general remaining *obstacle* to OTEC development - its capital cost, even though the solar "free fuel" situation has to be set against that. As for many other renewables, the cost of OTEC energy is nevertheless claimed by some to be too high generally to compete with traditional supply, but clearly this situation is changing as the environmental (and perhaps) the social costs of traditional energy are also considered - both of these now showing trends in that direction.
There is one other obstacle to OTEC development presently – true of nearly all new technologies as they are introduced – and that is the lack of experience with the operation of an OTEC pilot plant of sufficient size and duration to build up the confidence of investors in OTEC technology, and better to assess the scale of its environmental benefits and the practical limit of the resource. Particularly relevant to floating plants is the legal régîme of a plant operating on the high seas. The developing declaration of Exclusive Economic Zones

(EEZs) has substantially changed for the better the legal title to operations outside national coastal areas, which is a key factor in obtaining finances for a plant. Outside EEZs, where activities are influenced by the International Seabed Authority, law is still at the developing stage, but it seems at present that only "grazing" plants would be operating in that zone and, as already noted, such plants are expected to be later in coming on stream than land- based or moored floating plants.

OTEC can therefore be described, currently, as a significant renewable energy resource with growing potential for realization. In the shorter term the ocean thermal energy resource can serve the interest of relatively small, isolated coastal communities whose EEZs embrace a major share of the world OTEC capacity. Further R,D&D - particularly the "&D" - is required to convince the financial sector of viability. That work is most likely, and appropriately, to be carried out where full support is available - such as Hawai'i - and the first production OTEC plants will need also to be installed where good infrastructure for support exists. But in the medium term, OTEC development could serve the interest of all nations, including industrialized ones located in the "North", far from the tropical and sub-tropical zones.

Factors in the overall economics

Because of the diffuse nature of most renewable energies, the size of the specific renewable energy generation systems is large when compared with fossil fuel generators, and their capital costs are proportionately large as a result. On the basis of capital cost *alone* therefore, renewables - including OTEC - show up badly against oil fired power generation. Oil fired plants would typically cost a few hundred $s per installed kilowatt, whilst OTEC would cost a few thousand $s per kilowatt. And yet the case for cost 'comparability' is crucial to the acceptability of OTEC. An immediate balancing feature is that fuel oil has a substantial price, whereas OTEC fuel is free. Also, and as already mentioned, almost uniquely OTEC is a base load system which therefore has advantages over other renewables - they require buffer storage to achieve base load characteristics, with commensurate added costs. Maintenance costs for well developed oil fired plants are low, whereas the maintenance of low efficiency OTEC plants will (initially at least) be relatively high; and with the high capital cost of OTEC this means high total interest charges to be serviced in relation to the lower interest charges for the oil fired plant. All these points must be incorporated in the financial calculation if an accurate and realistic cost comparison is to be made.

Figures from a specific design for a 10MW floating closed circuit OTEC plant

So where do all these conflicting factors leave OTEC? There are all the previously described options of closed- or open-cycle, land based or floating - or, later, "grazing" plants, all of which will have their own cost advantages and disadvantages. For the purpose of trying to be explicit, one variant is chosen - and Figure 4 shows the components and layout of a typical closed circuit 10 MW demonstrator plant designed in the UK. As a demonstrator, it has three 5MW power pods, the 3rd pod for development, or use if either of the two main power production pods has to be shut down at any time. The floating plant consists of a single cylindrical hull in concrete, heat exchangers in plate form constructed from titanium/aluminium sandwich, a cold water pipe of 1000 metre length in fibre reinforced plastic, moorings in wire, chain, Kevlar or newer materials (this is one aspect that is subject to continuing progressive development) and transmission to shore over a distance of 10 km. All this resulted in a capital cost figure of $94M - or $ 9400/kW. The percentage costs of major components are: heat exchangers 23%; cold water pipe 6%; moorings 5%; electrical transmission from plant to shore 8%; pumps, turbines, generators and controls 13%; hull, including warm and cold water circuits 20%; site specific data 2%; installation and maintenance 5%; start up and testing 8%. There is a contingency of 10%

The calculations for this 10MW floating Closed Circuit OTEC plant, designed for a Caribbean or South Pacific island where the temperature difference varies from 23C degrees to 21C degrees between summer and winter, show a generating cost of 18 cents/kWh (using the 21C degree temperature difference) or - if potable water is a by-product (highly desirable for both these locations) - then the generating cost falls to11 cents/kWh with the potable water costed at 80 cents/m^3. Since island costs for potable water can be in the range 40-160 cents/m^3, the figure used here is seen to be at the conservative end of the spectrum. For the two islands considered here the uplift (where landed fuel costs are compared with those in a developed country) is only 75% - much less than in many island states - so instead of $20/barrel, oil would be $35/barrel. At that price electrical generation from an oil fuelled plant would be costed at 9 cents/kWh. The OTEC demonstrator plant is therefore seen to be approaching cost competition with such a plant on these islands even if oil is at those low prices compared with current values. General engineering experience suggests that production plant capital costs will be reduced, particularly for a new concept plant such as this, and generating costs would be expected to fall by as much as 35%. If this is achieved, and *without* allowing for the current high price of hydrocarbons, OTEC becomes competitive with oil fired plants for many island locations.

In these examples no financial benefit has been given to OTEC for the environmental benefits which it claims, some of which it has in common with a number other renewables. A recommendation of the 1992 Rio summit was the introduction of a Carbon Tax for fossil fuels, but to date this has not been applied. If that is brought into use – as may well be the case by 2010 – then all renewables, including OTEC, will benefit further in terms of competitiveness with hydrocarbons.

Quite apart from costing figures, as just quoted, it is essential that an operator – or utility - also sees this new technology as attractive. For the figures given here a notional return of 20.4 %, corresponding to a real return of 14.7%, is calculated, both of which are reasonably attractive in terms of commercially accepted practice. So, for both the consumer and the plant operator, OTEC is beginning to look attractive - *extremely* attractive if oil stays at its present very enhanced cost levels.

But, always, new technology has considerable difficulty in attracting finance for first examples, and OTEC is unlikely to be an exception to this. It therefore seems essential that the first two or three plants of realistic size – of about 10MW if of the floating variety - will need to be funded by governments or international funding agencies such as the World Bank, Asian Development Bank, or the European Bank for Reconstruction and Development and, probably, a guarantee mechanism for generated power may be necessary as well. Put simply, funding for the later stages of R,D&D *and* the construction of a demonstrator plant would seem to be essential to enable OTEC to make a practical breakthrough. Virtually all current new energy developments need some initial support - and in this context are merely following in the steps of nuclear power - although the level of initial support is unlikely to be any where near the support for that technology. After construction and operation of the first two or three OTEC plants, and *if* the figures quoted here are achieved, then the venture capital sector may be expected to step in and support further OTEC installations.

Likely Market

Is there a market for OTEC - with or without DOWA? There seems general agreement that the greatest requirements for the world, as developed and developing nations progress through the 21st century, are water and energy - and the opportunity for linking OTEC and potable water has already been noted.

What then is the scale of the energy need? It is anticipated that the percentage of "new" energies will grow from a near-zero figure at the end of the 20th century to 6 % by the year 2020. Using World Energy Council figures, this translates into "new" energies of some 12,000 MW a year averaged over the period from 2000 to 2020. Capital costs for OTEC equipment is of the order of $8000 to $10,000/kW because of its low efficiency, some ten times the capital cost for conventional power systems. If the OTEC capital cost figure is used the funding of "new" energies therefore equates to a total sum each year of ~ $100 -120 billion. By any standards this is very substantial business and therefore for the construction, operational and financing sectors, an activity of very considerable interest. The business will, though, only develop if it is economically attractive to the utilities that will invest in and operate it, and as shown earlier this requirement is now met by OTEC.

Where is the market? Island nations with deep waters around them provide a particular opportunity for OTEC because of the closeness of the resource. Looking then at supply and demand, and a number of other features - including for example likelihood of hurricanes or typhoons, plus (particularly in the early years) adequate technical support, one survey has shown the following countries to be particularly appropriate for production plants: Papua New Guinea; Fiji; St. Lucia; Jamaica; Guam; Bahamas; Cayman Islands; Trinidad & Tobago; Pacific Islands (Trust Territories) and Seychelles. In all cases a relatively small - 5 to 10 MW - size would be required, the build up both there and then in other locations progressing to larger sizes. At 12,000 MW a year - of which OTEC would be only a modest part - the problem is nevertheless likely to be to match development and production to meet demand.

The Opportunity for OTEC

What, then, is the case for OTEC and DOWA?

The technical feasibility of OTEC can reasonably be described as "current state-of-the-art". All that will be new is the design, construction and maintenance of the cold water pipe, and the bringing together of the particular combination of the state-of-the-art components to achieve an operating OTEC plant. In engineering terms this is no more of a task than many other technological challenges which are successfully addressed in the 20th and 21st centuries.

The business case for an operating OTEC plant is also now established - both in terms of the generating cost, and the operating return for a utility. The commercial viability of an OTEC plant is therefore also now demonstrable.

As a renewable energy system, an OTEC plant will show substantial environmental benefits compared with fossil fuel generating plants, therefore contributing to meeting the Kyoto (and subsequent) protocol targets, which in turn will in part address the problem of global warming, now accepted as a reality (according to the Chief Scientist of the World Bank) by more than 95% of the informed scientific community. Also, if and when the proposed Carbon Tax is introduced, OTEC (and other renewables) will have their comparative economics further improved in relation to fossil fuels.

Additionally, as a base load system, OTEC has no need for back up or storage systems, which are required for wave/tidal/wind renewable systems if they are to be capable of matching supply to demand.

All the above are for simple OTEC plants. If the DOWA are, separately or collectively, included both the economics and the flexibility of application are substantially further improved. The particular Application(s) can be tailored specifically to the needs of particular communities.

Finally, and after all these listed benefits have been considered, there is a very real social and human benefit to be counted. The tropical and subtropical areas where OTEC and OTEC/DOWA systems can operate include very many of the nations where their people live at a subsistence level, with minimal natural resources on land and with GDPs which are some of the lowest in the world. For these people two of the most basic requirements are potable water and energy - both readily provided by OTEC and DOWA. Next comes food - and this too can be an output from DOWA. Note that there is no need to argue that these human and social benefits must be equated to some financial cross benefit necessary to make OTEC a commercial and business success - that has already been achieved as described above.

The case for OTEC and DOWA therefore seems clear cut. All that is missing is the funding for the R,D&D to bring these engineering systems into production. As these words are being written the whole world is reeling from the still-unfolding disaster resulting from the relative movement of two tectonic plates off Indonesia - with the loss of life and property spread over a large part of South East Asia. The costs of helping to restore some semblance of civilization to those areas will be measured in billions - whether of $s, Euros or £s is almost irrelevant. In 2005 the G8 Group of countries seem very likely to address the very real and ongoing problems of these and other nations with limited natural resources on their land. The natural resources of the seas in the EEZs of many of those countries could be harnessed via OTEC and DOWA systems - adding substantially to their GDPs, and providing the resources of water, energy and food. All this for a fraction of the billions being (very properly) spent in the aftermath of the 26 December 2004 tsunamis. There would seem to be an almost unanswerable case for the G8 nations - whether directly or through agencies such as the World Bank, IMF and similar organizations - to provide the relatively modest sums of money for OTEC and OTEC/DOWA developments to the point of establishing commercially viable production operating systems.

It should be stressed that to treat OTEC and DOWA in this way is just one example - albeit a very good one - among a number of opportunities for *initiatives* rather than responses. In short, the G8 Group has a real opportunity to be active rather than reactive.

In Conclusion

There is now a good technical, environmental, social and **commercial** opportunity for OTEC and DOWA, within both the renewable and the overall energy scenes, and one which fully justifies a funded R,D & D programme to achieve its market share.

Further Reading

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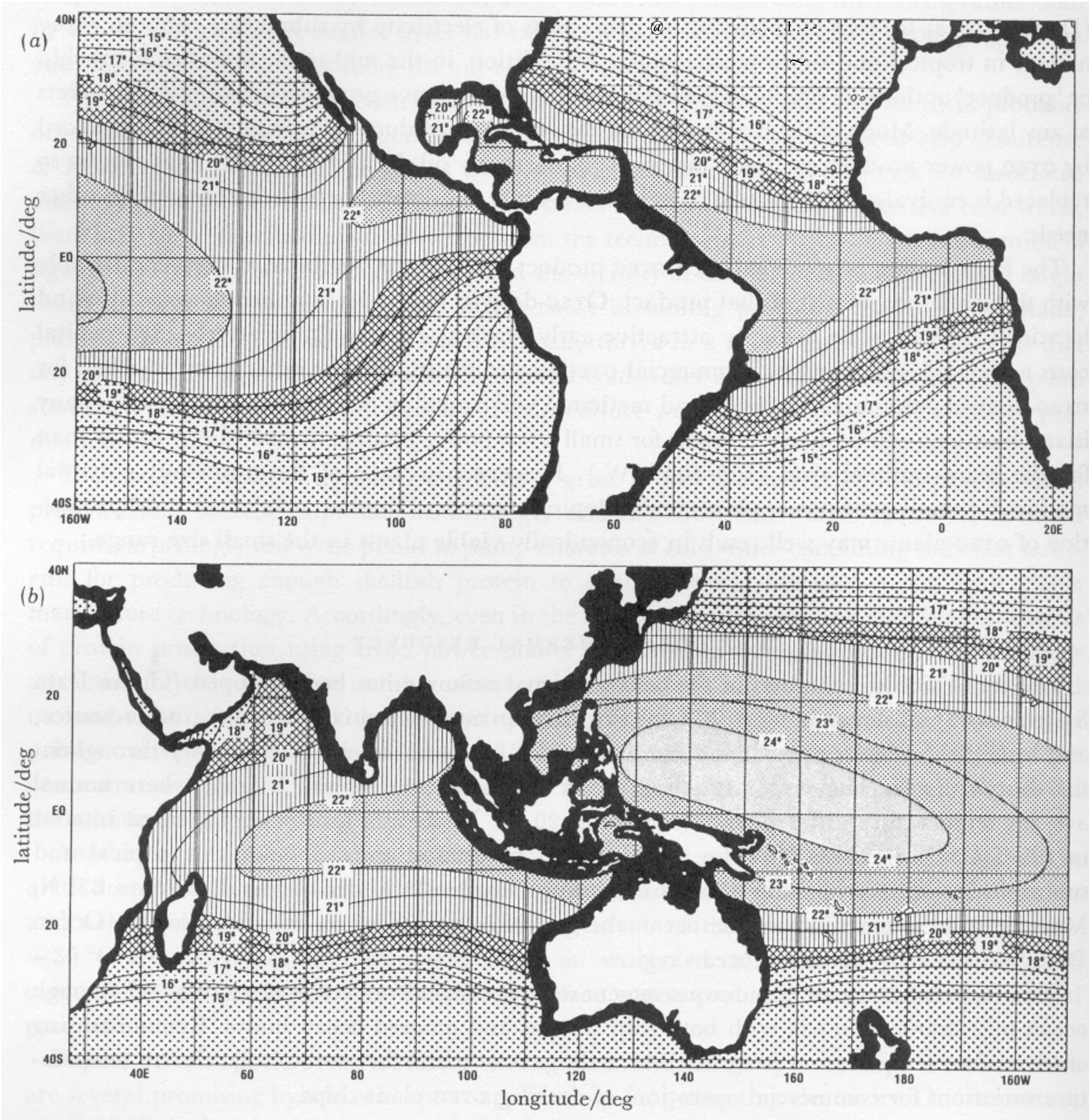
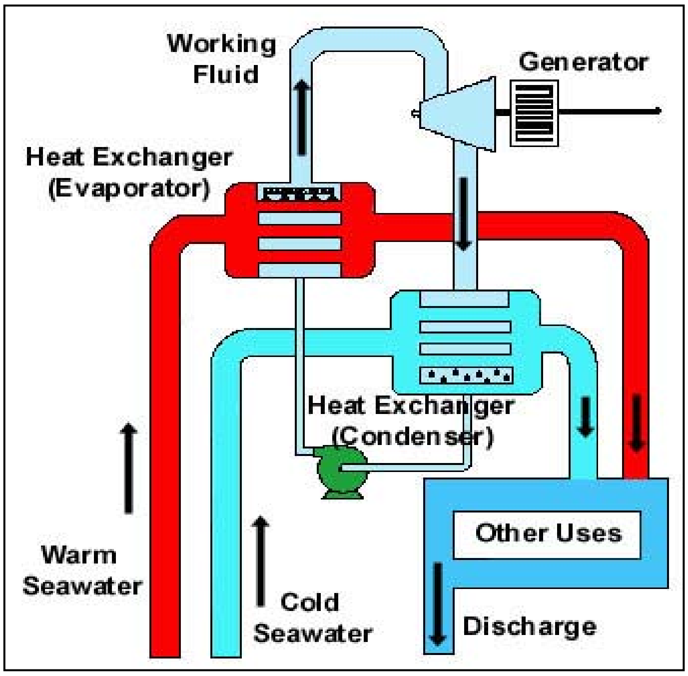


Figure 1 THE OCEAN THERMAL RESOURCE
Average temperature differences in C degrees between the surface and a depth of 1000m.
Credit: US Dep't of Energy/Ocean Data Systems Inc.

Figure 2: Closed Cycle
OTEC: power circuit
Natural Energy Laboratory of Hawaii Authority



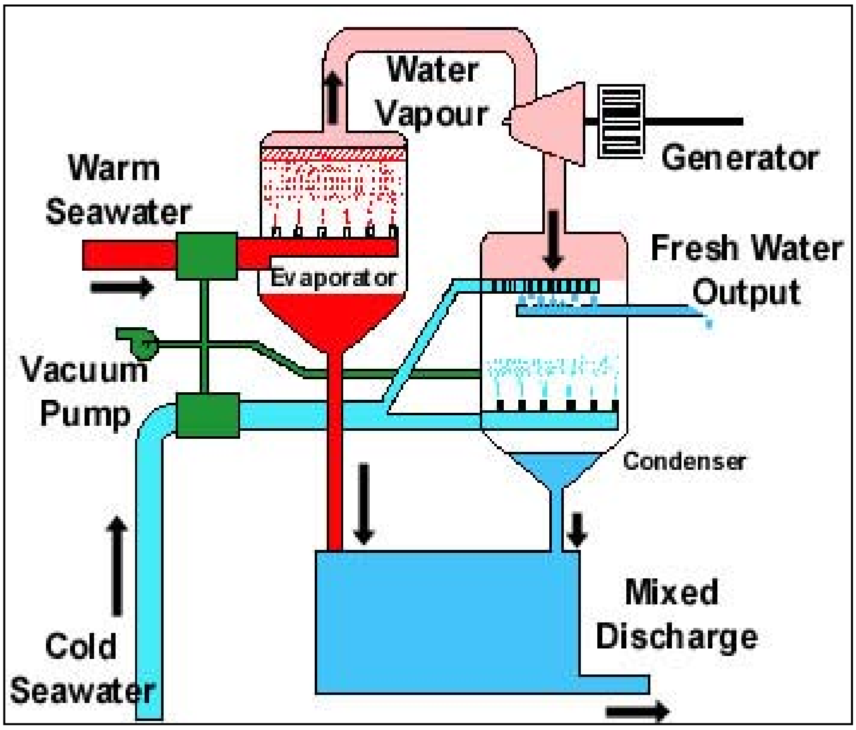


Figure 3: Open Cycle
OTEC: Power circuit
Natural Energy Laboratory of Hawaii Authority

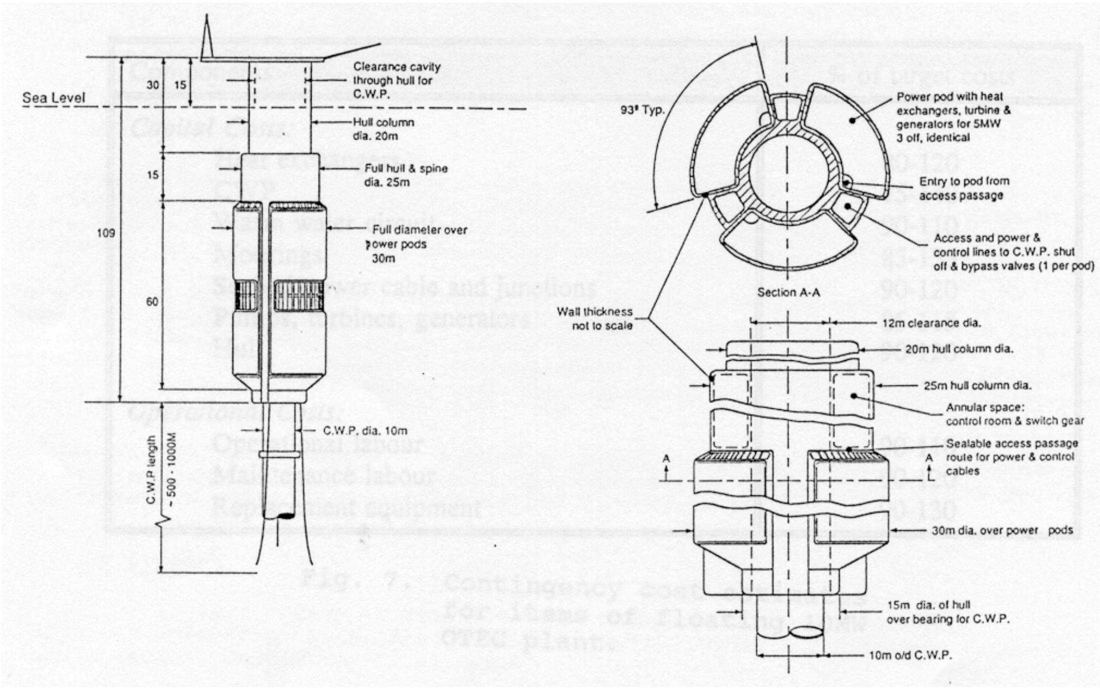


Figure 4: General Arrangement of 10 MW Closed Cycle floating OTEC plant

ALL DIMENSIONS IN METRES

Credit: Ocean Thermal Energy Conversion Systems Ltd.