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JOINT GROUP OF EXPERTS ON THE SCIENTIFIC ASPECTS
OF MARINE POLLUTION
- GESAMP -

REPORTS AND STUDIES

No. 20

MARINE POLLUTION IMPLICATIONS OF OCEAN ENERGY DEVELOPMENT

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NOTES

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"POLLUTION MEANS THE INTRODUCTION BY MAN, DIRECTLY OR INDIRECTLY, OF SUBSTANCES OR ENERGY INTO THE MARINE ENVIRONMENT (INCLUDING ESTUARIES) RESULTING IN SUCH DELETERIOUS EFFECTS AS HARM TO LIVING RESOURCES, HAZARDS TO HUMAN HEALTH, HINDRANCE TO MARINE ACTIVITIES INCLUDING FISHING, IMPAIRMENT OF QUALITY FOR USE OF SEA WATER AND REDUCTION OF AMENITIES."

* * *

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10.	Report of the Eleventh Session	1980	E,F,S
11.	Marine Pollution Implications of Coastal Area Development	1980	E,R
12.	Monitoring Biological Variables related to Marine Pollution	1980	E
13.	Interchange of Pollutants between the Atmosphere and the Oceans	1980	E
14.	Report of the Twelfth Session	1981	E,F,R
15.	Review of the Health of the Oceans	1982	E
16.	Scientific Criteria for the Selection of Waste Disposal Sites at Sea	1982	E
17.	Evaluation of Hazards of Harmful Substances Carried by Ships	1982	E
18.	Report of the Thirteenth Session	1983	E,F,S
19.	An Oceanographic Model for the Dispersion of Wastes Disposed of in the Deep Sea	1983	E
20.	Marine Pollution Implications of Ocean Energy Development	1984	E
21.	Report of the Fourteenth Session (in print)		

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MARINE POLLUTION IMPLICATIONS OF OCEAN ENERGY DEVELOPMENT

CONTENTS

Page

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MARINE POLLUTION IMPLICATIONS OF OCEAN ENERGY EXPLOITATION

1. INTRODUCTION

1. The Working Group met for its second meeting at FAO headquarters, Rome, from 25 to 29 October 1982. The first meeting of the subgroup of the Working Group took place at UNESCO headquarters, Paris, from 29 June to 2 July 1981. A meeting of United States OTEC experts was organized on 11 June 1981 which resulted in the primary working paper of the first meeting.

2. The Working Group wishes to thank the FAO Technical Secretary and the staff of FAO, as well as the staff at UNESCO for providing excellent facilities and assistance in all aspects of its work.

3. The following experts participated:

<u>Washington, D.C., 11 June 1981</u>: Messrs. L. Lewis, E. Myers, P. Wilde, J. Ditmars, D. Evans and L. Neuman (Technical Secretary, United Nations).

<u>Paris, 29 June-2 July 1981</u>: Messrs. R. Gerard, P. Marchand, and B. J. van der Pot.

<u>Rome, 25-29 October 1982</u>: Messrs. E. Myers (Chairman), G. Kullenberg, A. Jernelov, E. Gomez, L. Neuman (Technical Secretary, United Nations) and H. Naeve (Technical Secretary, FAO).

1.1 Terms of reference

4. The terms of reference are set out in the report of the eleventh session of GESAMP, paragraph 12.3, viz:

(a) To review the current literature and results of ongoing research and describe marine pollution implications of the exploitation of the major sources of unconventional ocean energy with special reference to coastal areas and multiple-use concepts, particularly in developing countries;

(b) To discuss long-term environmental impacts to be expected from extensive ocean energy exploitation at the global level.

5. The preliminary report presented to the Group at its twelfth session focused upon OTEC and was used as the basis for the sections of the present report dealing with this technology. The other technologies examined resulted from inter-sessional work according to the criteria described below.

1.2 Technologies considered

6. The oceans possess a number of characteristics that are representative of kinetic or potential forms of renewable energy: temperature gradients, biomass, waves, tides, currents, winds and salinity gradients. The feasibility of technologies that would tap such forms of energy was considered in 1979 and 1980 by the Technical Panel on Ocean Energy of the United Nations Conference on New and Renewable Sources of Energy (United Nations, 1981). As further noted in 1.3.1 (Commercial Applicability) the panel concluded that ocean thermal energy conversion

(OTEC), marine biomass, waves and tides offered the most promise for commercial application by the year 2000.

1.2.1 Ocean Thermal Energy Conversion (OTEC)

7. OTEC utilizes the temperature difference between warm surface waters and cold deep waters to drive a heat engine that produces power. The closed-cycle OTEC process (fig. 1) employs a working fluid (e.g., ammonia, Freon) upon which work is performed by warm, surface water pumped to an evaporator to produce a vapor that turns a gas turbine which, in turn, drives an electrical generator (Abelson, 1978). After exiting the turbine, the gaseous working fluid is condensed through a heat exchanger by the temperature of cold deep waters, that are pumped to near the surface through a long cold water pipe, and the cycle is repeated. The open-cycle process (Lewandowski et al, 1980) is quite similar, with the exception that seawater is the working fluid. Warm seawater, after being deaerated, is flash evaporated to produce a steam vapor that drives the turbine. After being recondensed by cold waters, the condensate can be used for fresh water.

8. The OTEC process is very dependent upon the availability of a suitable thermal resource, defined as the temperature difference (ΔT) between the warm, sea surface water and the underlying cold deep water (Allender et al., 1978). The needed operational temperature differential is about 20°C (36°F) or greater (Gritton et al., 1980; Ditmars and Paddock, 1979); however, due to seasonal variations, this value is not always available in many coastal waters. Figure 2 shows the distribution of the thermal resource between the sea surface and the 1000 m depth on a global basis. Note that the resource is generally confined to a band 20° in latitude, north and south of the equator; also, the broad continental shelves in many oceanic areas prevent the cold, deep water from approaching the coastal areas. Given a suitable thermal resource, an OTEC plant must pump relatively large volumes of both cold and warm water in order to develop net power (see para. 31).

9. Developing countries located within the 40° latitudal band have the best thermal resource for OTEC. These include coastal countries located in the western and central east Atlantic, Indian and Pacific Oceans. Estimates of the thermal resource for countries in these regions have been made and are shown in table 1.

10. Several types of OTEC platforms have been designed to a conceptual level. These include a moored or grazing barge (George et al., 1979, 1981); a spar-shaped vessel (Gibbs and Cox, Inc., 1980); and a fixed-tower (General Electric Co., 1983) or a land-based (or artificial island; Ocean Thermal Corporation, 1983) plant along a coast with a narrow continental shelf. Probably, the unique feature of any of these systems is the attached cold water pipe (CWP) which must be approximately 10 m in diameter for a 40 MWe commercial OTEC plant and extend to a depth of about 1000 m. It has no parallel in offshore construction; therefore, both time and frequency domains of the dynamic response of the CWP to normal and extreme currents and waves must be modelled and tested (Johns Hopkins University, 1980; McGuiness, 1981).

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5.6 Identified research needs

132. The following are identified as priority research needs. Because of the near-term potential of OTEC, they are directed towards that ocean energy alternative.

- Quantification of transfers (e.g. mass, heat, etc.) across the oceanic thermocline, their possible effects on vertical density distribution, heat balance and heat transfer.
- Potential climatic consequence in comparison to natural variability, due to large-scale OTEC developments (possibly this may be accomplished through the use of large- and medium-scale numerical circulation models).
- Quantification of significance of potentiality induced changes of density distributions and circulation features from OTEC development at island sites (again modelling efforts may be used).
- Biological significance of large vertical transfer of nutrients and other constituents in areas where the natural transfer is comparatively much smaller than that due to OTEC developments.
- Effects of primary and secondary entrainment, and the redistribution of biota.

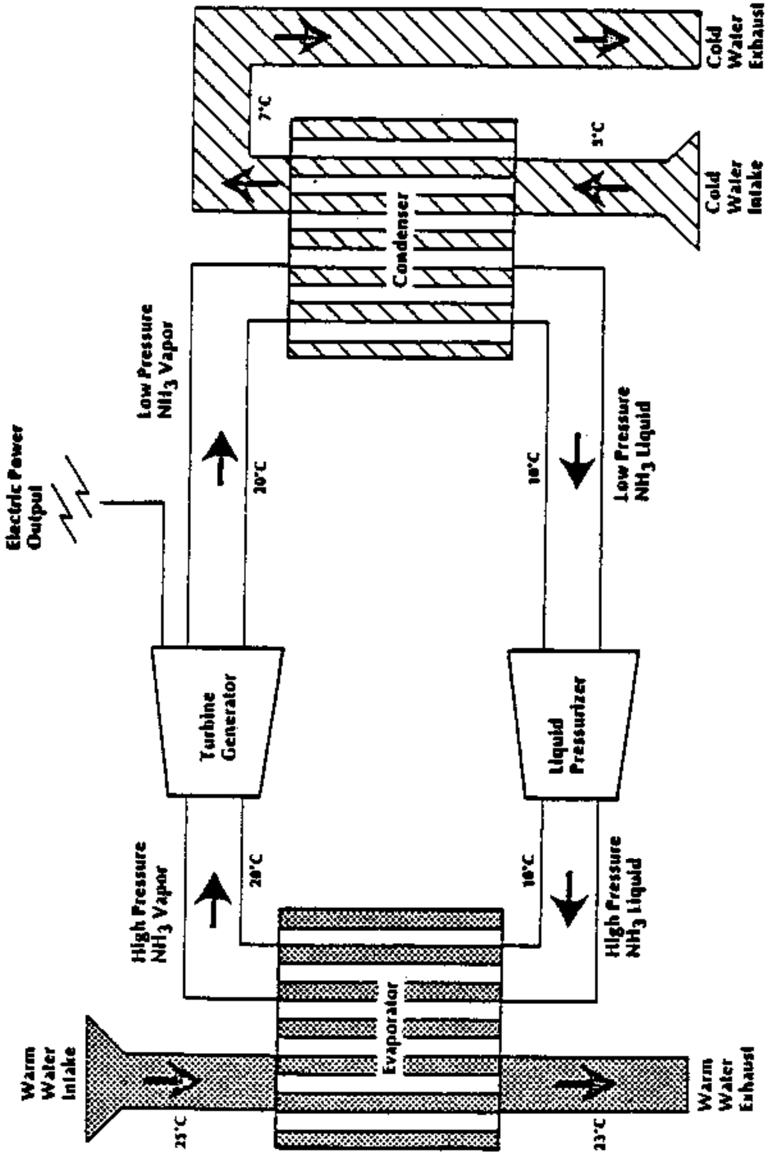


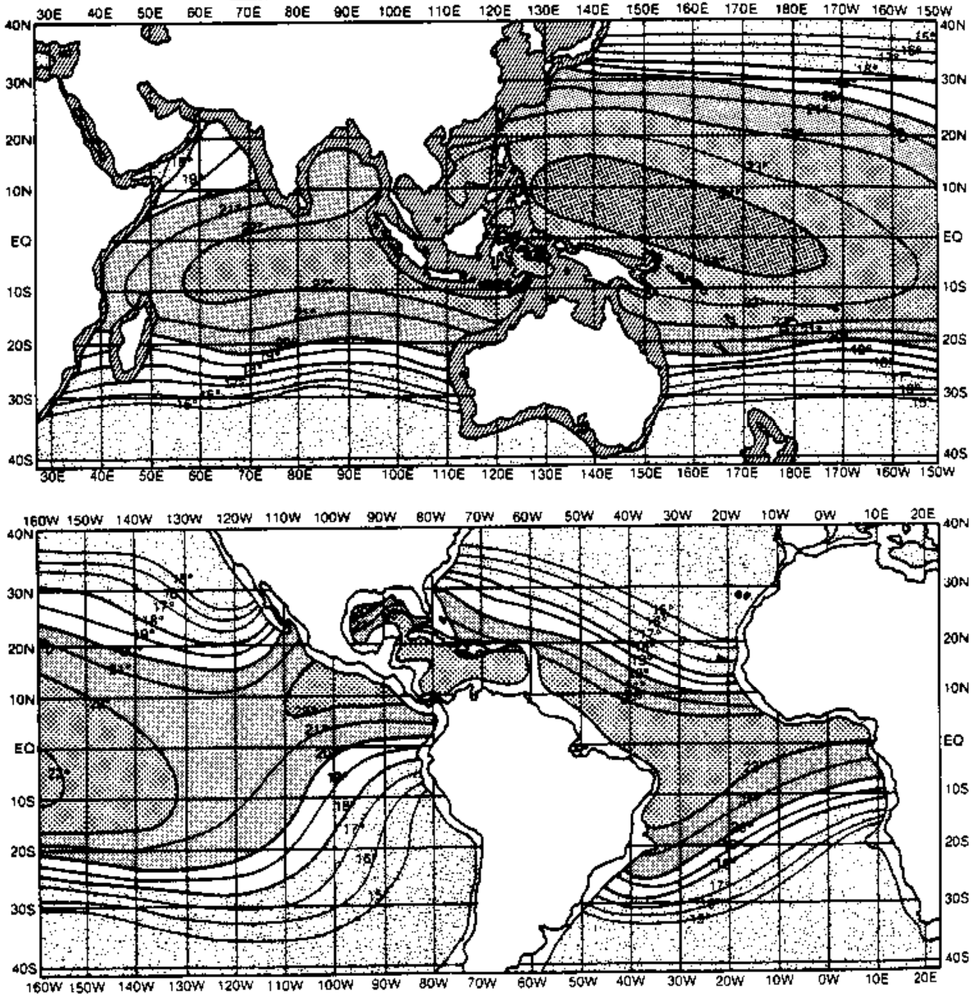
Figure 1. Schematic Diagram of a Closed-Cycle Power System
Source: Adapted from DOE, 1979

Figure 2

Large-Scale Distribution of

OTEC Thermal Resource

ΔT(° C) Between Surface and 1,000 Meter Depth



stratification of marine organisms would minimize the potential impact. Additionally, low intake velocities and the reduction of pipe bends and constrictions would minimize the sheer and acceleration forces to which entrained organisms are exposed. Since fish avoid horizontal flow fields more readily than vertical flow fields, the use of horizontal intake flows (directly or with the use of velocity caps) would tend to reduce fish impingement. Reducing intake flow velocities to a point at which fish, squid and shrimp may escape withdrawal would further reduce impingement rates. Fish return systems might also be examined.

128. The extent and location of secondary (plume) entrainment will depend upon the characteristics and location of the OTEC discharge. It may be desirable, if costs (e.g., piping) permit, to discharge the effluents near or below their level of neutral buoyancy to reduce the plume entrainment of marine organisms in the upper part of the water column, if this proves through detailed assessments or operating experience to cause significant adverse effects. However, such a strategy may result in slower dilution of the effluent plume which may not be desirable because of biocide and other OTEC releases. The orientation and velocity of the discharge can also be varied, within engineering limitations, to achieve certain results. For instance, the plume from a discharge structure oriented downward tends to stabilize deeper in the water column than a horizontal discharge; high discharge velocities promote turbulence and increased dilution.

129. Reduction of the use of biocides to only those levels, and for only those time periods, needed to ensure heat transfer efficiency is obviously desirable. Additionally, the application of biocides at different times to the various heat exchangers, and the subsequent discharge with the total flow, would result in reduced concentrations of biocides within the plume.

130. Plume stabilization below the euphotic zone would decrease the potential for any adverse impacts from biocides, nutrients, and other plant releases (e.g., trace metals). However, such a strategy would also decrease any potential value of introducing the nutrients within the euphotic zone. The benefits and advantages of various discharge plume behaviours should be assessed on a site-specific basis to minimize overall environmental risk.

5.5.2 Other ocean energies

131. The other discussed ocean energy alternatives will have to be examined on a site-specific basis to identify detailed strategies that would minimize potential environmental risk. The siting of these alternatives in areas where they would not conflict with other present uses will again be a major factor in minimizing environmental impacts. Special consideration will have to be given to the discharge of effluents from mariculture and biomass production. Since these effluents will be high in organic and nutrient content, discharge should be made so that significant environmental damage would not result. This will of course depend on the receiving waters and the scale of the operation.

123. Consideration of the expected environmental effects forms the scientific basis for selection of alternative design options or operating procedures. It should include the following aspects (Food and Agricultural Organization of the United Nations, 1982):

(a) Direct effects and their significance;

(b) Indirect effects and their significance;

(c) Possible conflicts between the proposed action and the objectives of other land use plans, policies and controls for the area concerned;

(d) The environmental effects of alternative decisions including the proposed action;

(e) Energy demand and conservation potential of alternatives and any proposed remedial measures;

(f) Natural or other depletable resource requirements and the conservation potential of alternatives;

(g) Urban quality, historic and cultural resources, and the design of the built environment, including the re-use and conservation potential of alternatives and remedial measures; and the

(h) Means to remedy adverse environmental impacts.

124. For coastal applications of systems for ocean energy exploitation, the techniques and methods for information collection will be the same or similar to those in use for assessment of environmental implications of other forms of coastal area development. Information about those techniques can be obtained from GESAMP (1980).

125. Large-scale open-ocean application of OTEC will require sophisticated techniques for information collection and impact assessment. However, such developments are not foreseen in the near future.

5.5 Potential measures to minimize environmental impacts

126. In general, proper siting is the single most effective means to minimize the potential for environmental damage. To the extent practicable, the avoidance of areas of high biological productivity and of other special importance (e.g., critical habitats, spawning grounds, coral reefs), is desirable for most of the ocean energy alternatives discussed. However, once a site has been decided upon, the collected environmental information can be used to decide upon design features which may be more compatible with the environment. Examples are as follows.

5.5.1 OTEC

127. The principal adverse effects that may be associated with the operation of an OTEC plant relate to entrainment and impingement, biocide discharge, and nutrient redistribution. The design and location of OTEC intake structures will influence the number of organisms entrained or impinged, and their mortalities. Where possible, locating the intake at depths that take advantage of any natural vertical

Table 1. Developing countries with adequate ocean thermal resources

Country/area	Latitude	Longitude	Delta T(°C) between 0-1,000 m	Distance from resource to shore (km)
Africa				
Angola	6°S-18°S	11°E-14°E	18-22	65
Benin	6°N	3°E-4°E	22-24	25
Congo	4°S-5°S	11°E-12°E	20-22	50
Gabon	2°N-4°S	9°E-11°E	20-22	15
Ghana	5°N-6°N	3°W-1°E	22-24	25
Guinea	9°N-11°N	14°W-15°W	20-22	80
Guinea-Bissau	11°N-13°N	15°W-17°W	18-19	50
Ivory Coast	5°N	3°W-8°W	22-24	30
Kenya	2°S-5°S	34°E-41°E	20-21	25
Liberia	5°N-17°N	8°W-12°W	22-24	65
Madagascar	10°S-25°S	45°E-50°E	18-21	65
Mozambique	10°S-25°S	35°E-40°E	18-21	25
Nigeria	4°N-6°N	4°E-9°E	22-24	30
Rio Muni	2°N-3°N	10°E	20-22	30
Sao Tome and Principe	0°N-2°N	7°E-9°E	22	1-10
Senegal	13°N-17°N	16°W-17°W	18	50
Sierra Leone	7°N-9°N	12°W-14°W	20-22	100
Somalia	10°N-2°S	41°E-50°E	18-20	25
Togo	6°N	2°E-3°E	22-24	50
United Republic of Cameroon	3°N-4°N	9°E-10°E	22-24	30
United Republic of Tanzania	5°S-10°S	35°E-40°E	20-22	25
Zaire	5°S-6°S	12°E	20-22	50

Table 1 (continued)

Country/area	Latitude	Longitude	Delta T(°C) between 0-1,000 m	Distance from resource to shore (km)
Latin America				
Bahamas	25°N	77°W-79°W	20-22	15
Barbados	13°N	58°W-60°W	22	1-10
Belize	16°N-17°N	87°W-88°W	22	50
Brazil	4°N-32°S	35°W-55°W	20-24	75
Colombia	2°N-12°N	63°W-79°W	20-22	50
Costa Rica	8°N-12°N	83°W-85°W	21-22	50
Cuba	20°N-23°N	75°W-85°W	22-24	1
Dominica	15°N-16°N	61°W-62°W	22	1-10
Dominican Republic	18°N-20°N	68°W-72°W	21-24	1
Ecuador	2°N-4°S	81°W-79°W	18-20	50
El Salvador	13°N-14°N	87°W-90°W	22	65
French Guiana	4°N-5°N	50°W-52°W	22-24	130
Grenada	13°N	61°W-62°W	27	1-10
Guatemala	14°N-17°N	88°W-94°W	22	65
Guyana	5°N-8°N	58°W-60°W	22-24	130
Haiti	18°N-20°N	72°W-75°W	21-24	1
Honduras	14°N-16°N	83°W-88°W	22	65
Jamaica	18°N-19°N	76°W-78°W	22	1-10
Lesser Antilles	12°N-18°N	61°W-65°W	22-24	1
Mexico	17°N-22°N	104°W-108°W	20-22	32
Nicaragua	11°N-14°N	84°W-86°W	22	65
Panama	8°N-9°N	76°W-83°W	21-22	50
Saint Lucia	13°N-14°N	61°W-62°W	22	1-10
Saint Vincent and the Grenadines	13°N-14°N	61°W-62°W	22	1-10
Suriname	4°N-5°N	52°W-58°W	22-24	130
Trinidad and Tobago	11°N	61°W	22-24	10
Venezuela	8°N-12°N	60°W-73°W	22-24	50
United States Virgin Islands	18°N	65°W	21-24	1

It is recommended that a programme of biological research be conducted to investigate what are the possible biological effects of nutrient and other trace constituent redistribution, so that intake and discharge, as well as plant locations can be optimized.

119. In the case of biomass, the environmental concern will be more on the possible eutrophication that may result in the waters near the development. Should pest control measures be resorted to, the possible impact of the substances used needs to be considered.

120. Wave energy development may cause less negative impacts at high latitudes than at low latitudes. The development of passive wave energy over coral reefs can have a significant impact on the productivity of such areas on which a subsistence fishery often depends in developing countries.

121. Tidal energy developments may also have some biological impacts because of the changes in the hydraulic characteristics of an embayment. The changes in water movement can result in temperature effects which could cause changes in the biological communities.

5.4 Information required for environmental impact assessment

122. The basic data that is required for assessment of environmental impact of systems for ocean energy exploitation can be subdivided for convenience into:

(a) Physical oceanography and meteorology;

(b) Biological and chemical conditions;

(c) Sea-bed conditions (bathymetry, sediment transport and bottom deposits);

(d) Living marine resources;

(e) Other existing uses;

(f) Physical characteristics of the coast;

In addition to these data that should be collected in the first phase of a feasibility study, additional information is required for a final evaluation:

(g) Expected discharges of biocides and corrosion products;

(h) Specific sensitivity of local organisms as derived from bioassays;

(i) Special consideration with regard to populations of endangered species; and

(j) Possible antagonisms and synergisms.

For an environmental impact assessment, both the size of the contemplated unit and thus the size of the affected area and the overall sensitivity and importance of that area will determine the degree of sophistication required for information collection and impact statement. The possibility of working at different levels of sophistication in respect of available methods and instrumentation also has to be borne in mind.

5. GUIDELINES AND RECOMMENDATIONS

5.1 General statement

113. The current and future developments in ocean energy exploitation are expected to impact the marine environment in either a positive or a negative way. While positive effects may be welcome, it is nevertheless necessary to monitor them lest they disturb the natural equilibrium in such a way as to result in negative impacts. Some localized habitats may be rather fragile. Certainly on a long-term and large-scale basis, individual or localized perturbations could multiply or proliferate to such an extent that an irreversible, cumulative effect results. There is always a need to give consideration to the protection of the environment when ocean energy developments are proposed.

5.2 Siting options

114. The various types of ocean energy development will be located in various parts of the ocean from the coast to the open sea and their impacts may extend from the deep sea to the surface and into the atmosphere. Of all the developments considered, OTEC has the potential for the most wide-ranging impacts. As presently conceived and planned, OTEC plants will be located within latitudes where a minimum T of 20°C may be realized. The sites can be in the open sea in the case of floating plantships, moored on the continental shelf some distance from the shore, or actually shore-based. Present technology and economics favour the smaller landbased or tethered plants. Because of this, it is anticipated that on an individual basis, their impact will be greater since they will be affecting the shallower, more productive benthic habitats.

115. Biomass development in connection with floating plantships is probably not a near-term possibility. If any biomass development is to take place in the foreseeable future, it will most likely be on land along the coast, whether in juxtaposition to an OTEC plant or unrelated. Artificial islands close to population centres are also envisioned.

116. In the case of wave energy developments, middle or high latitudes are favoured for high energy sites. This would mean that potential sites will be in developed countries. In the case of passive wave energy, the candidate sites are likely to be coral reef areas in developing countries.

117. Tidal energy sites are likewise limited. An average hydraulic head of 5 to 12 m is considered as necessary for development. Sites are necessarily coastal and there may not be more than several dozens of suitable locations throughout the world, generally at mid- or high northern latitudes where the land masses are concentrated and where there is large tidal volume exchange.

5.3 Environmental concerns

118. Large-scale concerns for OTEC development are in a category by themselves and addressed in the previous section. Hence, they will not be dealt with here. The areas of concern with OTEC that need to be considered are the more localized impacts, whether short- or long-term. In the case of both nearshore and offshore plants, special attention should be focused on possible negative impacts on fisheries. The impingement of discharge waters on the benthic habitat needs assessment and monitoring more so than the discharge into the deep water column.

Table 1 (continued)

Country/area	Latitude	Longitude	Delta T(°C) between 0-1,000 m	Distance from resource to shore (km)
Indian and Pacific Oceans				
American Samoa	12°S	165°W	22-23	75
Australia	10°S-40°S	115°E-155°E	18-22	100
Burma	5°N-30°N	95°E-100°E	20-22	75
China	21°N-40°N	108°E-122°E	21-22	50
Comoros	1°N-3°N	43°E-45°E	20-25	1-10
Cook Islands	18°S-22°S	155°E-165°E	21-22	1-10
Fiji	15°S-20°S	175°E-180°E	22-23	1-10
Guam	13°N	145°E	24	1
India	10°N-25°N	70°E-90°E	18-22	65
Indonesia	5°S-10°S	95°E-127°E	22-24	50
Kiribati (Gilbert)	5°S-5°N	172°E-178°E	23-24	1-10
Maldives	2°N-8°N	72°E-74°E	22	1-10
Mauritius	20°S-21°S	57°E-58°E	20-21	1-10
New Caledonia	20°S-22°S	165°E-168°E	20-21	1-10
Papua New Guinea	0°-11°S	131°E-151°E	22-24	30
Pacific Islands (Trust Territory)	15°N-20°S	135°E-150°W	22-24	1
Philippines	18°N-5°N	120°E-127°E	22-24	1
Samoa	10°S-16°S	168°W-175°W	22-23	1-10
Seychelles	1°S-7°S	53°E-57°E	21-22	1
Solomon Islands	4°S-12°S	155°E-165°E	23-24	1-10
Sri Lanka	6°N-10°N	80°E-82°E	20-21	30
Thailand	5°N-10°N	96°E-100°E	20-22	75
Vanuatu	11°S-20°S	160°E-170°E	22-23	1-10
Viet Nam	12°N-23°N	105°E-108°E	22-24	65

1.2.2 Marine biomass

11. The basic concept of the marine biomass system is to utilize macro-algae to capture and store solar energy through photosynthesis (Tompkins, 1982; Ritschard et al., 1981). Photosynthesis is dependent upon the availability of carbon dioxide and nutrients, which are in plentiful supply in deep, cold ocean waters and also in some surface layers of the ocean. To complete the process, the stored energy must be released in a usable form. Current thought focuses on the conversion of the stored photosynthetic energy to methane through an anaerobic digestion process (Tompkins, 1982).

1.2.3 Wave energy

12. The energy contained in the ocean's waves is vast, particularly in those areas beyond 30°N and 30°S characterized by vigorous wave climates (United Nations, 1981). Wave energy converters can be principally classified as follows: (1) devices which employ the vertical rise and fall of waves to activate air or water operated turbines; that is, those devices which utilize the pressure field caused by the vertical wave motion; (2) devices which rely on the rolling, pitching or heaving motion of the waves to utilize, for example, the rocking motion of cams on the sea which activate turbines; and (3) devices which focus the energy in waves by refraction or diffraction (U.S. Department of Energy, 1980). To date, the most technically advanced of these are those that utilize the vertical wave motion to activate air operated turbines by extracting energy from resonance (within an internal chamber) created by the motion of the waves.

13. The principle behind wave focusing techniques is to concentrate wave energy at one location, making it more convenient to convert. One proposed focusing-type method, known as surge funneling, produces energy by channeling shoaling waves into a storage basin and using the hydraulic head developed to run a turbine. A related passive wave energy concept, proposed for application on Mauritius, is to build up the fringing coral reef so as to allow waves to top this wall and create a hydraulic head within the reef (Bott and Lawrence). This head would be utilized to drive a turbine placed at the outlet.

1.2.4 Tidal energy

14. Tidal energy has the unique status of being established on a commercial scale, albeit at only one plant located at La Rance, France (United Nations, 1981). The 240 MWe French plant has been operating for more than 15 years and has proved the reliability of using the hydraulic head created by ocean tides to drive a generator. The Technical Panel on Ocean Energy identified some 40 sites throughout the world that would have the characteristics suitable for developing a capacity of over 200 MWe: favourable geographical location, in order to minimize engineering work; an average tide of 5-12 meters; the possibility of linkage to a power grid, in order to allow the variable output of the plant to be accommodated; and favourable socio-economic and ecological conditions.

1.3 Restrictions of report

15. Several restrictions or boundary conditions were imposed on or adopted by the Working Group. Of critical importance was the sparcity of data and studies on potential ocean energy impacts and the absence or unavailability of investigations on existing installations or pilot plants which operated recently. Although OTEC

the OTEC water. Long-term effects may thus include temperature changes, alterations of species composition, generation of plankton blooms and possibly other blooms which, in turn, may influence the OTEC operation.

4.4 Wave energy

110. Long-term effects of coastally-located wave energy devices will principally involve the possible impacts to the littoral transport of sand. Perturbations could result in a decrease of erosion in some areas and an increase in other areas. This could significantly affect other uses of the coastal zone. Additionally, if a wave energy project is located on a coral reef, impacts to reef productivity would occur.

4.5 Tidal energy

111. The potential for the development of tidal power plants exists in a number of areas of the world. Possible long-term effects of developments will largely depend on the local conditions. The effects will most likely be limited to regional changes and may, in many cases, be local only. Studies of possible consequences of a tidal power plant development in the Bay of Fundy have indicated that the tidal régime may change over the whole Gulf of Maine. In certain areas effects may occur to critically sensitive biological communities. Of course, behind such a tidal barrage, major changes would occur. The example is brought here to demonstrate that also single plant developments may well require due consideration of possible regional effects.

112. Other effects of tidal power plants may be related to alterations of the circulation pattern and alteration of the sediment transport. This may indirectly cause a redistribution and altered transport of associated heavy metals and other contaminants. Clearly, studies will have to be carried out on a case-by-case approach, and will have to be adjusted to the local-regional physical and biological conditions.

103. In areas of limited water exchange, lowering of the surface temperature might occur to such a degree that other uses, such as tourism and navigation, may be disturbed. The temperature lowering may again imply that the temperature difference decreases to such an extent that the operational requirements are not satisfied any longer.

104. Of particular importance for these considerations is the question as to where the discharge waters of intermediate density would move from the plant site. In this context it should be noted that the induced change of the vertical density distribution might lead to circulation changes and a tendency for the mixed discharge water to flow around or along the island.

105. The exchange of warm and cold water across the oceanic thermocline for a 100 MWe OTEC plant would be equal to the average vertical mixing of heat due to natural causes over an area which may be as large as 10^4 km^2. Thus a large number of plants would substantially change the vertical exchange of heat on a large scale across the oceanic thermocline. This may have climatic implications. The possible importance of this effect, as well as possible influences on the SST of the discharge water, might possibly be investigated by means of existing large-scale numerical circulation models.

106. The importance of potential changes of SST due to large-scale OTEC developments is also an open question. It is possible that other effects would be more important at an earlier stage of the development. The thermal stratification may be weakened to some extent, but it would be kept limited by the relatively large advection in the equatorial current systems. This is demonstrated by the thermal stratification present in the equatorial undercurrents. In the natural upwelling systems a thermal stratification is maintained by the advective circulation and the atmospheric heat input. This would probably also be the case in relation to OTEC developments. It does not appear realistic to attempt any calculations as to the long-term effects on the regional or global thermal stratification from any extensive OTEC developments.

4.2.4 Assessment priorities

107. In order to assess long-term effects, the importance of enhancing the exchange of heat, nutrients, etc., across the oceanic thermocline will have to be quantified and compared with naturally occurring exchanges and variations. Changes of SST and vertical temperature distributions could then be assessed in terms of the growing knowledge of the sensitivity of climate to changes of temperature and temperature distributions, especially in the equatorial zones.

4.3 Biomass

108. It appears that biomass developments may, for the time being, be limited to coastal sites. Long-term effects may then be related to changes of the bottom habitat by sinking matter, changes of the oxygen conditions and the light conditions. To a large extent, this will depend upon the local water exchange conditions. Developments in biologically sensitive areas may imply destruction or loss of an existing resource.

109. In relation to OTEC developments, the nutrients brought up from the deep water may possibly be used for biomass production. This will imply that long-term effects must be assessed, considering surface layer discharge and containment of

demonstration plants have operated on several occasions over periods of months, no detailed studies of environmental effects were conducted and any other information on other ocean energy installations is not readily available.

16. Furthermore, although some predictive studies of large plants in the open ocean have been conducted, little or no attention has been paid to the smaller installations (1-15 MWe) currently contemplated or planned for early commercial stages. As a result this report has sought to extrapolate from current information in order to identify environmental concerns and indicate where planning is most important.

17. The following sections indicate concerns which served to focus the report on areas of more immediate interest. Studies which the Working Group recommends to answer primary research needs are presented in the final section.

1.3.1. Commercial applicability

18. In accordance with its terms of reference, the Working Group elected to restrict its attention to the major sources of unconventional ocean energy which could reach widespread commercial application by the year 2000. After considering the conclusions of the Technical Panel on Ocean Energy of the United Nations Conference on New and Renewable Sources of Energy which was held in Nairobi from 10 to 21 August 1981 (United Nations, 1981), the Working Group examined OTEC, biomass, wave and tidal energy. Energy from ocean currents and salinity gradients was excluded from consideration.

19. Although it was recognized that wave energy might not reach extensive commercial application before the year 2000, it was noted that several pilot projects in developing countries were receiving serious attention and possible funding. As a result, it was decided to include a preliminary discussion of wave energy, emphasizing guidelines and basic considerations.

20. Tidal energy is the only proven form of ocean energy currently being exploited on a commercial scale. The major facility is the French tidal plant at La Rance, which produces about 240 MWe (United Nations, 1981). In its discussion of tidal energy, the Technical Panel on Ocean Energy noted that, besides the high cost of investment, the major constraint hampering the development of tidal plants in some locations is potential harm to the environment.

21. Biomass energy technologies have undergone recent advances which may favour their commercialization (Tompkins, 1982). In addition, the large amount of nutrient-rich water which could result from OTEC plant operation could accelerate the development of biomass energy production (United Nations, 1981). For these reasons and the fact that biomass may be a less technologically sophisticated system better adapted to developing countries, it was included in the study.

1.3.2 Normal operating conditions

22. The Working Group has also restricted its attention to normal operating conditions for the energy alternatives considered. Thus, the marine pollution implications of these energy alternatives are limited to those that would develop under normal, everyday operating conditions. This does not imply that accidental catastrophic incidents should be belittled; to the contrary, catastrophic accidents could pose major environmental threats to both marine and human life as briefly

mentioned in the next section. However, to adequately treat such possibilities would require a definition of detail (e.g., working fluid, site location and its relation to areas of biological significance and population centres) that is beyond the scope or purpose of this effort.

1.3.3 Other considerations

23. As noted in the above section, catastrophic events cannot be fully excluded in examining the full environmental implications of ocean energy development. For any potential application of an ocean energy technology, a careful examination should be made of risks and probabilities connected to possible catastrophic events. In this report only some such hazards will be mentioned.

24. In connection with OTEC, catastrophic events could occur leading to a sudden release of operating chemicals (e.g., ammonia, Freon) (National Oceanic and Atmospheric Administration, 1981). For instance, for a closed-cycle 10 MWe system using ammonia as the working fluid, the total inventory of ammonia (including surge and leakage losses) would be in the range of about 230,000-300,000 litres with approximately half in the power system loop and half in storage (Davis, 1983). Because of its thermodynamic and physical properties, the volume of Freon, if used, would be three to four times that of ammonia volume. In the case of an ammonia leakage, the effects could be acute and short-term. The most unfavourable circumstance would be a sudden release from a large installation near a population centre on a calm day, creating a toxic cloud that could pose a serious threat to nearby population centres. In the case of a Freon leakage, a concern would be the long-term effects on the ozone layer and thereby on global increases in transmitted ultra-violet (UV) radiation.

25. In connection with wave energy utilizing wave-focusing techniques, a critical high-wave zone could be created which could affect ship traffic and safety.

97. Deep, cold waters contain increased concentrations of carbon dioxide (CO_2) relative to warm surface waters. The potential excess CO_2 in deep waters pumped to near the surface is about 1.7×10^{-5} kg-CO_2 kg-H_2O^{-1}. Using this difference, a 200 MWe OTEC plant has been estimated to cause a daily flux of CO_2 to the atmosphere of about 1.2×10^6 kg, or about one-half to one-third of that of a fossil-fuelled power plant of the same capacity (Ditmars, 1980). However, for the case of an open-cycle plant, the dissolved CO_2 in the surface waters would be released, increasing the total daily CO_2 release to about 6.5×10^6 kg for a 200 MWe plant, or about 5 times that of a fossil-fuelled power plant (Ditmars, 1980). In view of the present concern over global atmospheric CO_2 increases, large-scale deployments of OTEC (particularly open-cycle plants) would pose additional concern.

98. The nutrient transfer to the euphotic zone might be considerable. Estimates of this have been made and compared to the transfer in the Peru upwelling area, finding that 2-3 OTEC plants of 400 MWe capacity within an area of 11 km^2 would produce a transfer of nutrients comparable to that in the upwelling area of a similar extent (Ref). This is a large amount and potentially important in regions where the national vertical fluxes of nutrients are very weak or about zero.

99. Discharged deep water from OTEC plants may stratify near the deep parts of the euphotic zone. In oligotrophic water this zone (1 per cent light level) is about 80-110 m deep. Depending upon the discharge depth, configuration, and density difference with ambient, discharged OTEC water will sink a distance of 50-150 m which may bring it just below the euphotic zone from a discharge depth around 50 m. The vertical mixing in the areas under consideration is not strong and would only imply a relatively small transfer from the 100 to the 200 m zone into the euphotic zone. This transfer can be estimated to be about 10 per cent of the above direct discharge into the euphotic zone.

100. The sinking of the discharge water will imply a downward transfer of community from the euphotic zone, both due to the surface water intake and to entrailment from the surface layer into the sinking discharge plume. This entrailment will depend upon the ambient conditions and may result in large volume transfers. This could imply considerable withdrawal of biomass if the discharge occurs in areas of high productivity. Also, the discharge volume will contain a certain amount of chemical contaminants. Clearly these may cause a problem in relation to extensive development. Potentially, releases of gases like Freons may also occur, the consequences of which cannot be well estimated on the basis of existing information.

4.2.3 Potential long-term impacts

101. It is pertinent to separate between long-term local effects and long-term regional or global effects.

102. Local extensive development close to oceanic islands may well have long-term impacts on habitats, fisheries and other uses of the area. It has been demonstrated that redistribution of fish occur (Seki, 1983), and that fisheries can locally be disturbed by offshore plant developments. Habitats sensitive to environmental changes may also be disturbed or destroyed. This may integrate to a long-term effect in cases of habitats limited in their extent to regions of potential OTEC developments.

Indian Ocean and Pacific Ocean in regions where OTEC could potentially be developed. Considerable regional studies have been carried out in some such areas or areas immediately adjacent to potential OTEC regions, and insight on OTEC effects may be obtained by using results from such regional studies, e.g. of the Peru and African upwelling areas, the California current system, and the Somali current system. These studies have, among other things, shown that large-scale natural variability on medium- to long-term time scales has a large influence on the biological production of the system. Fluctuations are often related to atmospheric circulation variations over large scales, and feedbacks can occur. Such aspects may have to be taken into account in assessing long-term impacts of OTEC developments.

93. Unfortunately, the relatively oligotrophic areas of potential extensive OTEC developments have usually not been studied either on a regional or on a local basis so as to give information on medium- to long-term variability. Changes in adjacent regions may then have to be used for comparison with potential OTEC-induced changes. For instance, long-term records from the Bermuda Panulirus station (32°N) show near-surface temperature fluctuations of 1.5-2°C over time scales of 5 years and average changes of 0.5-0.8°C over time scales of 15-20 years.

94. Sedimentary records suggest that the surface temperature changes over geological times of 18,000 years in the area in question of the Atlantic have been limited to a few degrees. On the other hand, variability of sea surface temperature (SST) in the equatorial belt has considerable influence on climatic conditions in other regions. Thus, the zone of potential extensive OTEC development can be an area where non-natural changes of SST may have considerable global impacts. It is likely that such SST changes would have to be in the range of about 0.5 to 1°C over an area of several hundred square kilometres to have such noticeable impacts. Natural SST anomalies in the equatorial zone tend to be large in relation to other zones, and they also have a greater potential for influencing the atmospheric temperature. Inter-annual variations of SST in the Pacific equatorial zone can be 5-6°C in the east and 2-3°C in the west.

4.2.2 Potential problems

95. The potential impact of OTEC is related to the redistribution of ocean water and ocean living resources and to the release of chemical contaminants used in the plants. Specifically, the long-term impacts may be related to the long-term change of thermal structure and temperature distribution in the water; a general change of nutrient distributions; destruction of habitats for coastal plants, some of which may have very limited extent globally; and alteration of the fisheries, which may arise from redistribution of fish through attraction, or from changes of biomass and community species composition. Furthermore, the net exchange of CO_2 between ocean and atmosphere may be affected (see para. 97). These non-natural long-term changes must, however, be related to the natural long-term variations which occur in order to assess the potential impact.

96. Cumulative effects of 146 OTEC plants of 400 MWe capacity in the eastern Gulf of Mexico have been estimated and suggest that the water flow would be about 0.5 per cent of the Gulf Stream flow. Of particular importance is, however, that this flow is across isopycnals (vertical) and in that context one may note that the flow represents about 5 per cent of the deep water overflow across the Greenland-Iceland-Faero ridges, which is a major component in the vertical North Atlantic heat flux. The estimates further indicate a decrease of SST in the region of about 0.1 to 0.15°C.

2. OCEAN THERMAL ENERGY CONVERSION (OTEC)

2.1 State of development

26. Ocean thermal energy conversion (OTEC) is a technology which is on the threshold of commercial application. Because the best thermal resource is found in tropical oceans, developing countries are expected to be its principal users (United Nations, 1981).

27. Of all solar-based energy systems, OTEC is particularly attractive because it supplies continuous, baseload power day or night, rain or shine, summer or winter. The source of the power derives from the temperature differences between the warmer ocean surface waters which both collect and store vast quantities of solar energy, and the colder waters at depths of about 1,000 m which are produced over long time periods and continuously replenished.

28. Although considerable interest has been generated in the potential of OTEC, several misconceptions exist regarding its availability, cost and efficacy. OTEC plants do not involve high technology systems as do nuclear plants, giving developing countries an opportunity to participate in the construction phase as well as in operation and maintenance. Furthermore, OTEC technology for land-based or shelf-mounted plants up to 50 MWe is essentially available today.

29. At this writing, OTEC activities are under way in a number of locations and by a number of different entities:

United States: After supporting the conceptual design of two pilot plants in Hawaii, the U. S. Department of Energy (DOE) is supporting the preliminary design of one 40 MWe pilot plant at Kahe Point, Oahu, Hawaii. Also, a private concern has contracted with the Government of the United States Territory of Guam to build a commercial 48 MWe land-based OTEC facility.

France: The French Government National Centre for the Exploitation of the Oceans (CNEXO) is undertaking design studies and site work preparatory to building a land-based 5 MWe prototype open cycle plant in Tahiti in 1986-1988. The plant will have multi-purpose applications for aquaculture, refrigeration, and freshwater production in addition to electricity.

Japan: Private Japanese companies have designed, built and operated a land-based 100 KWe (0.1 MWe) pilot plant for the Government of Nauru in the Pacific Ocean. Current plans call for proceeding to a 2.5 MWe plant at the same site to be operational by 1986. The Japanese Government is also sponsoring OTEC research and development activities.

Sweden: A number of private companies have agreed to form the Swedish OTEC Group for the purpose of building OTEC plants principally in developing countries. Initial activities are taking place in the Caribbean Sea (e.g., a 10 MWe plant is presently being designed for Jamaica).

The Netherlands: The activities of several private Dutch companies have focused upon Curacao in the Netherlands Antilles with the objective of building a 10 MWe land-based plant for electricity.

2.2 Principal impacts

30. The potential environmental impacts of the construction and operation of OTEC plants (table 2) will be dependent upon the type of plant (open, closed or hybrid) and the environmental setting (i.e., a coastally-situated fixed plant or an open-ocean plantship that exploits a thermal resource in some optimum manner) (National Oceanic and Atmospheric Administration, 1981; Sullivan et al., 1981). These potential impacts are classified as such because there is no operating experience with a commercial OTEC plant. However, many of these concerns have not been observed with conventional or nuclear power plant operations; for those that have been observed, it has been only within very localized areas with only limited larger scale effects on marine populations.

31. The large amounts of water needed for OTEC operations is the basis of many of the associated environmental concerns. Due to their low thermodynamic efficiencies, the range of flow rates needed for both the warm and cold water side of an OTEC operation is 3.5-5.0 $m^3\ s^{-1}\ MWe^{-1}$, for a total flow of 7-10 $m^3 s^{-1}\ MWe^{-1}$ (Myers and Ditmars, 1983). For comparison, the flow of cooling water required for a typical commercial nuclear power plant is about 0.05 $m^3 s^{-1}\ MWe^{-1}$. One translation of this is that a 5 MWe plant would need to pump and discharge the same amount of water as a nuclear power plant of about 1,000 MWe capacity.

32. As noted earlier, the OTEC process relies upon the extraction of heat from the surface waters of the ocean and the conversion of part of that heat to electricity or some other form of useful work. Part of the extracted heat is also transferred to the cold water in the condensing phase. The modified cold water and the "used" warm waters are then discharged to ambient waters where they will seek a level of neutral buoyancy (see next para.). In principle this is quite different from the operations of conventional and nuclear, coastally-located, power stations where waste heat is added to the ocean through the discharge of cooling waters. In fact, although water temperature may be modified over the water column with an OTEC operation, they never exceed the range of temperatures naturally occurring in the environment (Myers and Ditmars, 1983).

33. The physical behaviour of the "used" OTEC water upon discharge to the environment will depend on the density differences between the discharged water and the surrounding ambient receiving waters, and upon the hydraulic characteristics of the discharge (Adams et al., 1978; Coxe et al., 1981; Jirka et al., 1977, 1979, 1981; Paddock and Ditmars, 1981, 1983; Piacsek et al., 1976). Two basic designs for the discharge of OTEC effluents have been considered; mixed and separate, both being to locations in the mixed layer or upper thermocline. If the discharge is of greater density (i.e., mixed or separate-cold) than the ambient receiving waters, it will sink (fig. 3), entraining surrounding ambient waters until a level of neutral buoyancy is achieved. However, if the density of the discharge is less than that of the ambient receiving water (e.g., a separate warm water discharge made below the pycnocline), the density would be less than the receiving waters and the discharge would rise, again entraining ambient water along the discharge plume trajectory until a level of neutral buoyancy was achieved (Paddock and Ditmars, 1983).

4. LONG-TERM ENVIRONMENTAL IMPACTS TO BE EXPECTED FROM EXTENSIVE OCEAN ENERGY EXPLOITATION AT A GLOBAL SCALE

4.1 Introduction

89. It is obvious that consideration must be given to long-term impacts of extensive ocean energy exploitation. It may well be that these considerations will suggest serious limitations on extensive, large-scale developments. Considerations of long-term as well as large-scale, environmental impacts from extensive ocean energy exploitation may presumably be based on local case studies and estimates of impacts from single plant developments in various areas combined with knowledge of present conditions in the marine environment in the regions in question. These estimates should be considered along with regional developments and integrated globally. It is clear, however, that any such estimates of impacts will be very uncertain due to our present very limited experience from single plant developments as well as to our limited knowledge of the conditions in the marine environment and their long-term natural variability, although this knowledge is appreciable in some regions. The environmental requirements for presently considered ocean energy exploitation techniques limit the regions which will have to be considered. Drastic environmental changes in these regions may however have an influence on conditions also in other parts of the globe, a possibility which will be necessary to bear in mind.

90. The aim of this discussion is therefore to indicate:

(1) regions where long-term problems may occur;

(2) potential long-term impacts; and

(3) priorities in assessment studies of potential long-term impacts.

Extensive OTEC developments will be considered first.

4.2 OTEC

4.2.1 Regions for potential development

91. Due to the thermal resource requirements of a year-round temperature difference of about 20°C or more, regions of the oceans under consideration are limited to the tropical and subtropical parts, roughly in the belt between 30°N and S. The Gulf of Mexico and some tropical oceanic islands are alternative potential sites. The development may occur in the open ocean or on narrow shelf areas of oceanic islands. It is clear that considerations of local impacts will be different, and such a separate consideration may also be relevant for some of the potential long-term regional and global impacts.

92. Most of the relevant oceanic areas are not very productive due to slow vertical mixing rates because of the stable thermal stratification. The equatorial zone is, however, characterized by a higher production due to the equatorial upwelling. Generally, the coastal zones are more productive than the open ocean ones. Areas of seasonal coastal upwelling occur within the 30°N to 30°S latitudinal belt but in these areas the temperature difference is lower due to upwelling. It is not likely that OTEC developments would occur in these coastal upwelling areas. High production is found in some areas of the Caribbean, West

3.3.3 Siting considerations and planning requirements

88. Given the siting criteria discussed under paragraph 14, only some 40 sites in the world could prove favourable for tidal energy development, with most of these located in industrialized countries (United Nations, 1981). Preliminary studies on micro-tidal plants in areas of average tidal range (5m) having power outputs of a few MWe show that the production costs would be very large. They indicate that such an operation cannot be justified except when electricity from other sources is virtually unavailable or when it is part of a larger programme of coastal protection and multiple use of the facility.

34. If the water column is simply stratified (e.g., homogeneous in density above and below the pycnocline), for both a sinking and a rising effluent the level of neutral buoyancy will occur near the pycnocline. However, normal density distributions are more complex, particularly below the pycnocline so calculations using established techniques (Paddock and Ditmars, 1983) would have to be performed to find both the level of neutral buoyancy and to assess the dilution due to the plume entrainment in this near-field region. Estimates indicate that this initial dilution may be in the range of 5:1 to 10:1 for typical OTEC conditions. For the case of a 10:1 dilution, this means that the plume would consist of one part (by volume) effluent and nine parts entrained water.

35. If the OTEC plant is land-based or located in relatively shallow water, the cold water pipe will probably extend along the bottom offshore far enough to reach cold water and the discharge may occur relatively close to shore (fig. 4). In this situation, the mixed or separate-cold discharged will form a negatively buoyant plume that sinks to the bottom before it mixes sufficiently with ambient ocean water to become neutrally buoyant or, alternatively, the discharge may be at or near the bottom in the vicinity of the plant (Paddock and Ditmars, 1983). In either case, the sea-water effluent will flow along the bottom in a general downslope direction under the influence of gravity and ambient currents. As in the above case, a depth of neutral buoyancy will eventually be reached where the effluent will leave the bottom and intrude into the water column. This general situation will require caution to avoid deleterious effects on exposed substrates and biota.

36. The need for high volumetric rates of water withdrawal and discharge raises a number of environmental concerns. The principal ones relate to the entrainment and redistribution of organisms, the use and discharge of biocide to control biofouling, and the redistribution of nutrients and other trace constituents from the cold, deeper waters. There are other concerns that could be significant under certain conditions (see table 2). One key concern is the potential impact of these various factors on fisheries which may occur through the depletion or redistribution of fish eggs and/or planktonic food sources, effects on recruitment, attraction to structures, increase fishing pressure, etc. Some of these effects may be positive and some negative; an accurate assessment of the true overall impact may have to await a commercial OTEC plant.

2.2.1 Entrainment and impingement

37. The intake of warm and cold water by an OTEC plant will result in the direct entrainment and impingement of marine orgnisms inhabiting that portion of the water column from which the waters are drawn, and those organisms that pass through these zones during vertical migration. Although there is very little vertical migration from 1,000 m, it is extensive from 700 m. This could be an important factor in deciding the depth of the deep intake.

38. Since marine organisms concentrate in the upper part of the water column, the location of the warm water intake will be of particular concern. Organisms drawn into the intake will either be entrained and pumped through the plant or impinged on screens placed to prevent the clogging of heat exchangers. Based on the operation of conventional and nuclear power plants, impinged organisms are usually killed either through impingement itself or through the screen cleaning process. Although some concepts have been tried to divert juvenile and adult fish from the screens before impingement, these have had only limited success.

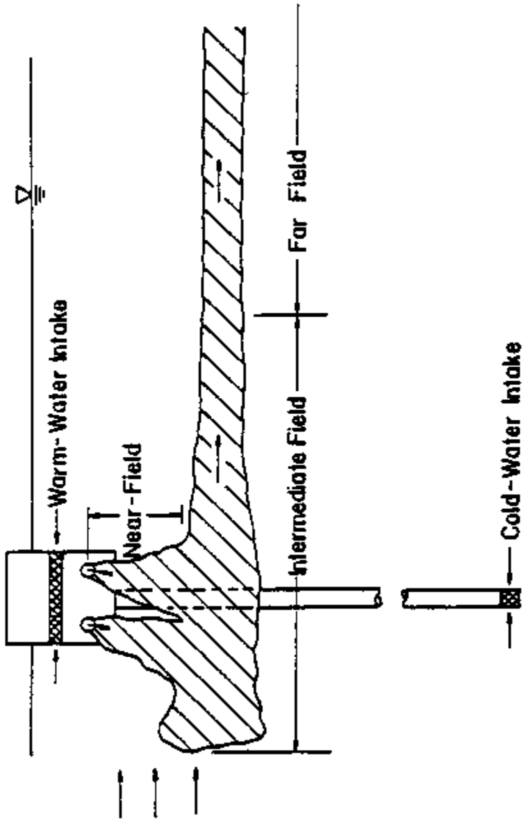


Figure 3. Typical Discharge Flow Field for an OTEC Plan Located in Deep Water (From Paddock and Ditmars, 1983)

eutrophication would be noticed. The worst form, red tides, and other forms of mass occurrence of toxic algae or algae releasing toxic substances could occur. Large macro-algae farms in coastal waters will also result in an increased attenuation of light within the water column, affecting both the intensity and spectral composition of available light. Such changes are likely to influence marine organisms in a number of ways (Ritschard *et al.*, 1981) e.g.: (1) a decrease in the compensation depth, (2) a decrease in primary production, and (3) altered phototactic responses of vertically migrating organisms. Additionally, sinking organic particles from a biomass farm could impose enough of an oxygen demand to the bottom waters to reduce oxygen levels to an unacceptable level. This would result in atypical biotic communities and possibly impact commercial and sport fisheries in the region.

70. The development of large macro-algae farms in coastal waters would displace portions of the natural ecosystems, replacing them with other species. For instance, for the cultivation of *Macrosystis pyrifera* in Southern California waters, some of the species displaced include deep sea fin fish, plankton, certain pelagic birds, and possibly benthic organisms. Species introduced include kelp, nearshore fish species, and species living on a substrate such as sea urchins, abalone, starfish, limpets, etc. (Ritschard *et al.* 1981).

71. Pest control for e.g. organized kelp cultures may require a new set of pesticides, the possible side effects of which can only be speculated about. A principal problem with pesticides, as well as with nutrients, is that of containment.

72. A production of marine macro-algae on land would make containment of both nutrients and pesticides (if required) much easier, thereby reducing environmental impact. A problem that remains unsolved, should marine biomass play any important role as an energy source, is, however, the large areas required for production and thus the competition for land below or above sea level.

3.1.3 Siting considerations and planning requirements

73. Production sites for marine macro-algae should be shallow areas with good exchange of water but protected from devastating storms. Frequently, harvesting is the major problem for production and, although large enough bottom areas with suitable topography are a presently limiting factor, they could be built.

74. Conflicting interests with other uses can be expected as culture areas would be disturbed by industrial and municipal discharges and would interfere with, for instance, boating and water-skiing. The lack of promising economic outlook for biomass production in coastal areas for energy production makes these considerations appear less urgent.

75. The conversion of biomass to an energy product will result in some residual materials which will have to be disposed or utilized. For instance, in the anaerobic conversion of kelp to methane gas, factors to be considered in the installation and operation of the digesters are land utilization, use of carbon dioxide and hydrogen sulfide removed during gas cleaning, and safety aspects related to handling a potentially explosive gas (Ritschard *et al.*, 1981). The fate of the digester effluent will also have to be considered. Four possible options for this material are: post-treatment and disposal, animal feed, fertilizer, and ocean farm disposal (Ritschard *et al.*, 1981).

3. OTHER OCEAN ENERGIES

3.1 Marine biomass

3.1.1 State of development

64. Systems using marine biomass for energy production are not yet developed on a commercial scale. However, the theoretical possibilities are enormous because primary production in the marine environment constitutes a major part of global primary production. With present technology, open ocean harvesting of planktonic algae is not feasible and the resource of interest is restricted to macro-algae, e.g. kelp.

65. The present harvest of macro-algae in coastal waters is large and growing but the uses are for animal feed, fertilizer, emulsifiers, pharmaceuticals, etc. The possibility however exists, that a larger market for macro-algae can be met by scaling up the production methods developed in the Philippines and elsewhere. Presently the production is limited only by the market demand for several species of seaweeds. Available techniques for energy production from marine biomass include anaerobic digestion with formation of methane gas (Tompkins, 1982). With present prices, energy production cannot compete with other uses of marine macro-algae and energy from marine biomass cannot yet compete with energy from other sources.

66. Better economic prospects may be realized through the growing of algae on land, using sprayed sea water with nutrients while regulating temperature and light. Also of interest is the development in better incineration techniques; e.g., a Swedish company has developed a technique for recovering latent heat from steam in fuel gases. The technique has been developed for burning peat but allows economic uses of the energy content in organic matter with a high water content. Such techniques show a promise of rendering marine biomass useable in energy production. Another possibility that might be profitably investigated is the development of continuous mass culture of phytoplankton for biomass.

3.1.2 Environmental impact

67. A controlled production of marine macro-algae with conventional methods, that is in coastal areas, requires that the following three major factors are controlled:

(a) Substrate for culture establishment and harvesting;

(b) Nutrient content for optimal growth rate; and

(c) Pest control directed at grazing animals and attached micro-algae.

68. The artificial preparation of bottom or other substrates will lead to a variety of consequences of a similar principle type as the establishment of agriculture on land has had on the natural flora and fauna.

69. Fertilization of cultures of macro-algae will, with available techniques, lead to a general eutrophication of the area if the nutrients are not totally utilized and containment not developed. This means that planktonic and attached micro-algae could develop to a much higher degree than normal and will compete with the cultured organisms for light. Also in surrounding areas the general effects of

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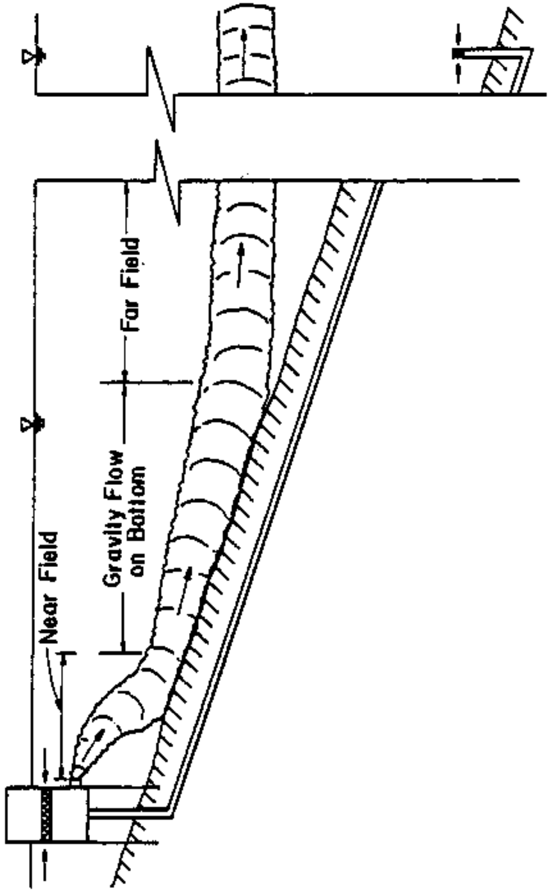

Figure 4. Typical Discharge Flow Field for an OTEC Plant Located in Shallow Water Showing Flow along the Bottom (From Paddock and Ditmars, 1983)

39. The direct entrainment rate will depend primarily on the intake flow rate and the concentration of entrainable organisms in the range of depths over which the intake draws. Thus, impacts will occur to entrainable epipelagic organisms such as phytoplankton, macrozooplankton and microzooplankton. Several factors may influence the degree of impact, including daytime and night-time abundance of these organisms, the possible attractive effects of the OTEC structures particularly to the nekton and, at night, the effect of illumination levels (National Oceanic and Atmospheric Administration, 1981). In the nearshore regions, biological productivity tends to be much higher than in the open ocean, and meroplankton (eggs and larvae of invertebrates and fish) constitute a higher percentage of the zooplankton biomass. Depending on the species and spawning patterns, meroplankton populations will vary from site to site and between season.

40. Indirect, or plume, entrainment will also be important in the assessment of total entrainment effects. Depending on the dilution achieved, plume entrainment may result in many more organisms being exposed to the effluent plume and being transported to the level of neutral buoyancy (Myers and Ditmars, 1983). This "downwelling" (for a sinking discharge) of both water and organisms has not been considered in any detail in OTEC assessments to date.

41. Studies at conventional power plants indicate that the effects of entrainment are quite variable, dependent upon such factors as the plant type, site, species and season (Lawler et al., 1979). There is also a low degree of reliability in the full assessment of entrainment effects due to the high cost and efforts associated with the statistical requirements to impart some degree of confidence to such estimates, and the lack of knowledge concerning the longer-term survivability of organisms that do manage to survive the immediate effect of plant entrainment. This makes estimates of the eventual food chain effects of entrainment even more uncertain.

2.2.2 Biocides

42. The inherent low thermodynamic efficiencies associated with the OTEC process necessitate that the transfer of heat in the evaporation and condensation cycles be very efficient. This will require that the heat exchangers be kept very clean of any build-up of biological growth that would reduce heat transfer. Most likely this will necessitate the intermittent application of biocides, coupled with mechanical cleaning techniques. Furthermore, the biocide of choice presently appears to be chlorine because of its effectiveness and being able to generate it on site, using a small part of the power generated to power an electrolytic chlorine generator.

43. The use of biocides to control fouling leads to residuals with potential for continued biocidal effect (Venkataramiah et al., 1982). Chlorination of sea water results in rapid interaction with chloride and bromide naturally present in sea water, with subsequent formation of HOCl and OCl^-, and some HOBr and OBr^- (Burton and Richardson, 1981; Hartwig and Valentine, 1982; Leao and Selleck, 1982). The reactions depend on the form of chlorine used, and conditions in the treated water. Secondary, slower, reactions may result in a small production of halogenated organic compounds. Chlorine chemistry in sea water is considered more fully in the report of the GESAMP Working Group on Biological Effects of Thermal Discharges.

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details and the handling and treatment of liquid and solid by-product still need to be addressed (Dugger et al., 1982).

2.4.3 Fresh water

60. Throughout the world, population growth and increased industrial and agricultural development is creating great demands upon water resources. The World Health Organization projects that the rate of increase in community water supplies will not keep pace with the demand of the growing populations. Freshwater supplies are limited, both in quantity and distibution, and many potential OTEC sites have freshwater needs. Fresh water can be produced by OTEC installations by two basic methods:

(a) A closed-cycle approach used to produce electricity to operate a multi-stage flash evaporator;

(b) Open-cycle approach in which fresh water is a by-product in the primary production of electricity.

A hybrid system has been suggested which extends the closed-cycle system by using the warm ocean water input to produce steam which is condensed to produce fresh water.

61. A 2 MWe closed-cycle system was suggested by Westinghouse Corporation for the island of St. Croix in the United States Virgin Islands. It would produce 5 million gallons per day of fresh water. Current estimates are that large quantities of fresh water can be produced by such plants with all or part of the electricity generated at the facility. In the United States Virgin Islands, water costs are very high and prospects for importation offer little hope for less costly alternatives. Costs of $US 5 per 1,000 gallons were estimated and are economically attractive in many locations. The possibilities opened up by a generous water supply at reasonable cost would be considered when evaluating OTEC viability.

62. The production of fresh water by desalination using the electricity developed in a closed-cycle OTEC plant will result in residual salts whose disposal might pose some problems. For instance, the production of 5 million gallons of fresh water per day would produce about 700 tons of salt, or the equivalent in brine each day. The disposal of such quantities could present environmental problems, especially for benthic communities if subject to highly saline plumes. However, for an open-cycle plant, approximately one per cent of the sea water is flash evaporated and passed across a gas turbine (Hagen, 1975; Lewandowski et al., 1980), after which it can be used as fresh water. The residual sea water in the open-cycle plant would thus be only about one per cent enriched in salts and, for most situations, should not pose environmental concern.

2.4.4 Other uses

63. Other possible applications include use of OTEC for refrigeration, air conditioning and fish storage. In addition, cold water increases the effectiveness of desalination plants which might have a critical input in plant economies where fresh water is needed. The cold water could also be useful for application to conventional power plants for a "bottoming cycle", using the OTEC concept to increase the efficiency of the plant by extracting more of the available energy from the thermal effluent.

54. A major constraint to all land-based mariculture activities is the requirement for space. The culture of phytoplankton and macroalgae requires sunlight. Hence, there is a limitation in the depth of the culture ponds to be used, requiring more area. Even though bivalves can be reared in a multilayer tray culture system, considerable land space will be required for large production. Crustacean and finfish culture would also require sizeable land area. Hence, large-scale mariculture activities will require considerable land area in addition to the actual site of the OTEC plant. However, development of phytoplankton culturing for biomass production, or the use of technologies such as rope culture of mussels as practised in the Spanish Rias may offer methods whereby mariculture could occur at sea.

2.4.2 Industry

55. OTEC development will have certain industrial applications, including the production of ammonia (NH_3), aluminum refining, and alternative fuel production (Francis and Dugger, 1980; Dugger et al., 1982).

56. World demand for fertilizer has significantly increased in the past decade and a survey of candidate OTEC nations shows a net deficit for nitrogen fertilizer of over 2 million metric tons in 1979. Furthermore, although the primary present use of ammonia is for fertilizer production (75 per cent in the United States), ammonia could also be used as energy source or an efficient carrier of hydrogen for alternative fuel (Francis and Dugger, 1980).

57. Ammonia produced by an OTEC process has been projected to be fully competitive with ammonia produced from natural gas in new plants on shore by about 1990 (Francis and Dugger, 1980; Dugger et al., 1982). Ammonia is presently made from natural gas, a highly valued and limited resource. It could be made by an OTEC plant, combining hydrogen gas (derived from sea water by electrolysis) and nitrogen (separated from air by a partial liquifaction process). It is considered that engineering development and scale-up of the preferred electrolysis systems are needed, if the OTEC energy was available.

58. The Alcoa process for producing aluminum metal by electrolysis of aluminum chloride has been examined as a potential application of OTEC (Jones et al., 1981). It has been concluded that it would be profitable at tropical islands as the availability of hydroelectric power for new aluminum plants is exhausted. The Applied Physics Laboratory of Johns Hopkins University believes this situation has already been reached in the United States (Dugger et al., 1982). Using the Bayer process to obtain aluminum from its naturally-occurring ore, bauxite, would make such application of OTEC particularly attractive for those nations with bauxite ore deposits.

59. OTEC electricity produced on an open ocean plantship can also be used to produce alternative fuels such as methanol, hydrogen and ammonia that can be delivered to United States ports (Dugger et al., 1982). Methanol could be produced by: (1) oxidizing carbon (e.g., coal char delivered to the plantship) to carbon monoxide (CO), and (2) reacting CO with H_2 (from electrolysis of water) to form the methanol (CH_3OH). Hydrogen could be derived from ammonia through processing on shore or directly from the electrolysis of water. Additionally, either ammonia or methanol could be used onshore in molten carbonate fuel cells to produce electricity. All of these applications of OTEC have been considered to be economically feasible and competitive as OTEC is developed; however, additional

44. The toxicity of chlorine compounds to marine organisms varies. At the level of expected dosage at OTEC plants (not more than 0.5 mg l^{-1}), residual concentrations will be low in the large volume of discharge water and the warm temperature of the tropical receiving waters. Cumulative or regional effects of long-term use with possible accumulation of persistent residual compounds remain speculative. If there is concern, compounds accumulated, their concentrations and effects (including behavioural effects) in representative organisms should be measured.

2.2.3 Redistribution of nutrients and other constituents

45. The chemical characteristics of the deeper, cold ocean waters are of particular interest when consideration is given to the OTEC-induced redistribution of water masses. Since most tropical and subtropical surface ocean waters are oligotrophic and have deep photic zones, there is the potential for increased productivity when nutrient-rich deep waters (Quinby-Hunt, 1979) are transported to the upper part of the water column. The potential would, however, depend on the "near-field" fate of the discharged effluent (i.e., level of neutral buoyancy and dilution achieved versus the photic zone depth), the possible adverse effects of biocide addition, and the nutrient needs of the local producers. Furthermore, other natural trace constituents present in deep water may be either toxic (e.g., copper) or enhancing (e.g., manganese, iron), having implications for the biological reaction of the system to the redistribution of constituents (Sunda and Guillard, 1976; Jackson and Morgan, 1978). It may be possible by varying the engineering of the outfalls either to magnify or supress potential increases in productivity. It is not intuitively clear as to whether or not this increase in productivity is likely to be beneficial. In areas where upwelling occurs naturally, the complex structure of the current patterns results in the upwelled water being seeded with both phytoplankton and grazing zooplankton. The ensuing bloom of phytoplankton is often dominated by diatoms; however, in regions such as the California Current, dinoflagellate blooms may occur, some of which are toxic. In the regions which are most suitable for OTEC development, the surface phytoplankton which will be entrained into the outfall will be dominated by nanoplankton and dinoflagellates, hence the bloom of phytoplankton may be dominated by undesirable species. However, without further modelling and experimental investigation, it is not possible to make any recommendations.

46. Note should also be made of the possible lowering of oxygen levels below the pycnocline that will result from a marked increase in surface production. Although this may be insignificant in most regions suitable for OTEC development, there may be situations where it is a serious worry.

2.2.4 Other environmental impacts

47. The above environmental concerns are considered potentially significant by the Working Group because of the lack of both information and predictability. There are, however, other environmental concerns that could pose significant risk to marine organisms under the wrong conditions, such as the: release of corrosion products from heat exchangers and piping; release of working fluids; alteration of sediment transport patterns; and alteration of the heat balance within a region leading to possible ocean temperature perturbations. Site-specific consideration must be given the implications of these concerns.

2.3 Siting considerations and planning requirements

48. The siting of an OTEC plant will be the most important determinant of the potential for environmental impact. For instance, areas of low biological productivity or commercial importance are less likely to experience significant impact from OTEC construction and operation than areas of high productivity and biological importance. The potential impact on areas of special ecological importance such as coral reefs, seagrass beds, reproductive areas, critical habitats and fishery resource areas, will have to be considered. Amenity and conservational considerations must also be examined. Additionally close access to deep, well circulated waters will aid in the advection and dispersion of OTEC effluents, and will minimize engineering and cost factors (e.g., length and cost of cold water and discharge pipes).

49. The planning process for an OTEC operation should ensure that surveys are undertaken to identify possible sites having the needed thermal resource and other physical characteristics to allow construction. In addition, preliminary environmental surveys should be conducted at the potential sites to identify areas of special biological significance, e.g. fishing grounds, migration routes, and critical habitats. The results of these surveys should lead to the choice of one site (or at most a few alternate sites) which could then be subjected to more detailed baseline studies. These studies should be started well in advance of the projected date of construction so that the findings can be taken into account in the detailed design work. Among the factors that should be considered are the following:

(a) The quantities, composition and potential for bioaccumulation or persistence of possible pollutants that may be discharged;

(b) The potential transport and transformation of such pollutants by biological, physical or chemical processes;

(c) The composition and fragility of the biological communities which may be exposed to such pollutants, or entrained either directly or by plume entrainment;

(d) The importance of the receiving or intake water area to the surrounding biological community, including the presence of spawning sites, nursery/forage areas, migratory pathways or areas necessary for other functions or critical stages in the life cycle of the organism;

(e) The potential impacts on human health through direct and indirect pathways;

(f) Existing or potential recreational and fishing activities;

(g) Such other factors relating to the effects of the OTEC structure, its construction and operation, as may be appropriate;

(h) Local occurrence of marine reserves or communities of significance to conservation (e.g., threatened species or those having very restricted geographical distributions).

50. This will necessitate studies that include various aspects of physical, geological, chemical and biological oceanography. These studies should be done in both a cost-effective and timely manner, proceeding from general baseline studies to the more complex and detailed studies. Some of the parameters that should be considered are as follows:

Physical Oceanography: Spatial and temporal distribution of salinity, temperature, density and currents; general surface and subsurface circulation patterns; waves and tides, and sediment transport patterns.

Geological Oceanography: Bottom topography and characteristics.

Chemical Oceanography: Nutrients and microconstituents (e.g. copper, manganese, iron), carbon dioxide, total organic carbon, pH, redox potential, alkalinity and dissolved oxygen.

Biological Oceanography: The spatial and temporal distribution of the dominant phytoplankton and zooplankton species; the distribution and breeding biology of the benthic and nektonic species, particularly those of commercial importance and those of scientific or conservation importance.

In conducting these surveys, it will be important to define the spatial and temporal variability of the important parameters that can be so characterized, particularly in the regions of the proposed intakes and discharges.

2.4 Multiple-use impacts of OTEC

51. While power from an OTEC plant can be used directly for supply to a "grid" which transmits power to users, it can also be applied to special uses such as: mariculture; industrial applications such as ammonia production, bauxite processing, and alternative fuel generation; and freshwater production. Also, while the environmental implications of these uses would have to be examined on a site-specific basis, the beneficial effects of these alternative uses may outweigh adverse effects.

2.4.1 Mariculture

52. One of the promising side benefits of OTEC plants is the potential for the culture of marine organisms using the nutrient-rich cold waters brought to or near the surface. The technical feasibility of artificial upwelling mariculture has been demonstrated in the United States Virgin Islands (Laurence and Roels, 1976; Roels, 1980), and other areas. The Virgin Islands project was a small-scale pilot plant where nutrient-rich deep water was utilized to produce phytoplankton in culture tanks. An annual production of 811 gr-protein m^{-2} was realized in small shallow pools (Roels, 1980). The algal mass produced was used as food for filter-feeding shellfish, principally clams, oysters and scallops. The results of these experiments were promising, although scaled-up production needs to be demonstrated before definite conclusions can be drawn about economic feasibility.

53. Besides phytoplankton and bivalve rearing, diversification to the culture of other marine organisms has been initiated. Work done in California and elsewhere has shown the culture of macro-algae yielding useful phycocolloids is promising. Crustacean and finfish rearing needs to be explored as these are the more desirable table items in mariculture.