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OTEC

The Potential Environmental Consequences of Ocean Thermal Energy Conversion (OTEC) Plants

MASTER

A Workshop

January 22-24, 1980
Brookhaven National Laboratory
Upton, New York

May 1981

U.S. Department of Energy
Office of Energy Research
The Ecological Research Division
Office of Health and Environmental Research

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THE POTENTIAL ENVIRONMENTAL CONSEQUENCES OF OCEAN THERMAL ENERGY CONVERSION (OTEC) PLANTS

Edited by John J. Walsh
Oceanographic Sciences Division
Brookhaven National Laboratory
Upton, New York 11973

A Workshop Held January 22-24, 1980
at Brookhaven National Laboratory

Contents

Page

PREFACE

The workshop on Environmental Consequences of Ocean Thermal Energy Conversion was convened at Brookhaven National Laboratory January 22-24, 1980. The objective of the workshop was to obtain a direct and independent evaluation of the environmental impact of ocean thermal energy conversion technology on tropical marine systems. The group assembled consisted of nationally and internationally recognized marine scientists and oceanographers interested in the properties and behavior of marine ecosystems or components.

The participants were divided into three panels to consider physical, chemical, and biological oceanographic responses with regard to an operating commercial OTEC activity. The panel reports are reproduced in the appendix.

The panels assess OTEC to be a relatively benign environmental perturbant of marine ecosystems, in the near term with only small scale deployment of a commercial technology. However, there are a number of environmental uncertainties and fundamental questions raised by the participants in regard to large scale development of this technology. The general conclusions and recommendations of the panels are listed in the summary section. A five-year environmental research program plan is also presented in that section.

I would like to thank Dr. Lloyd F. Lewis, Division of Ocean Energy Systems, U.S. Department of Energy, for presenting in plenary session alternative time schedules for the development of the technology and for discussing important legislation pending at the time of the workshop. Dr. George W. Saunders played an important role in presenting the environmental basis for the workshop deliberation and in coordinating various activities necessary to the conduct of the workshop and publishing the proceedings. I would also like to thank Dr. John J. Walsh, Brookhaven National Laboratory, for organizing the workshop and for editing the report. Dr. Donald W. Pritchard, Dr. David W. Menzel, and Dr. Richard W. Eppley chaired the respective panels and were instrumental in integrating the panel recommendations. Finally, I would like to thank all of the participants for their enthusiastic input to the workshop and for their help in writing and editing.

The report places the environmental issues of OTEC development into perspective from the point of view of marine sciences. I know that it will prove interesting and useful to persons and institutions interested in the commercial development of the technology.

Helen M. McCammon, Director
Ecological Research Division
Office of Health and Environmental Research
Office of Environment

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SUMMARY

Introduction

The concept of generating electrical power from the temperature difference between surface and deep ocean waters was advanced over a century ago. A pilot plant was constructed in the Caribbean during the 1920's but commercialization did not follow. The U.S. Department of Energy (DOE) earlier planned to construct a single operational 10 MWe Ocean Thermal Energy Conversion (OTEC) plant by 1986. However, Public Law P.L.-96-310, the Ocean Thermal Energy Conversion Research, Development and Demonstration Act, and P.L.-96-320, the Ocean Thermal Energy Conversion Act of 1980, now call for acceleration of the development of OTEC plants, with capacities of 100 MWe in 1986, 500 MWe in 1989, and 10,000 MWe by 1999 and provide for licensing and permitting and loan guarantees after the technology has been demonstrated.

A group of marine scientists convened at Brookhaven National Laboratory during 22-24 January 1980 to consider the possible environmental consequences of OTEC operation on the natural physical, chemical, and biological processes of oceanic systems.

Both the 1979 DOE Environmental Readiness Document and the 1979 DOE Environmental Development Plan for Ocean Thermal Energy Conversion were used as a background material. The participants (see Appendix I) divided into three working panels to consider the physical, chemical, and biological consequences of OTEC. Detailed analyses of the panels are attached as an appendix to this document. A synopsis of conclusions, recommendations, and research plan is presented here. In general the panels agreed with earlier analyses that there is a low probability that Ocean Thermal Energy Conversion Technology will produce significant environmental disturbances in ocean systems, particularly in the near-term development of the technology. The panels also agreed, however, that there are uncertainties concerning the scale of impacts which may result from increasing numbers of OTEC plants. Uncertainties exist either because specific processes which may be impacted are not understood in general or have not been studied in tropical ocean systems in which OTEC would be developed. The panels attempted to determine the most important processes to study and determine at what scale of operational deployment of OTEC plants significant impacts would occur. Research recommendations have thus been made.

Brief Description of OTEC

Ocean Thermal Energy Conversion plants will use warm surface sea water to evaporate a working fluid (ammonia) in heat exchangers, to drive a turbine which will produce electrical power. The working fluid will be condensed with cold sea water pumped from a depth of about 1000 meters. The deep water is nutrient rich while the surface water is nutrient poor. The deep and shallow waters discharged from the two heat exchangers (evaporative and condensing) would be mixed first and then injected into the thermocline, i.e., the upper reaches of the ocean where sharp vertical temperature gradients occur with depth. Depending on the design of the discharge system, very little of the deep nutrient rich water is expected to mix directly with the upper illuminated layer of the ocean.

Discharged water will be denser than the surrounding water and thus would tend to sink (Fig. 1). The sinking outfall plume, initially having high velocity and shearing forces, would entrain surrounding water at the boundaries of the moving plume. The volume of the plume would increase

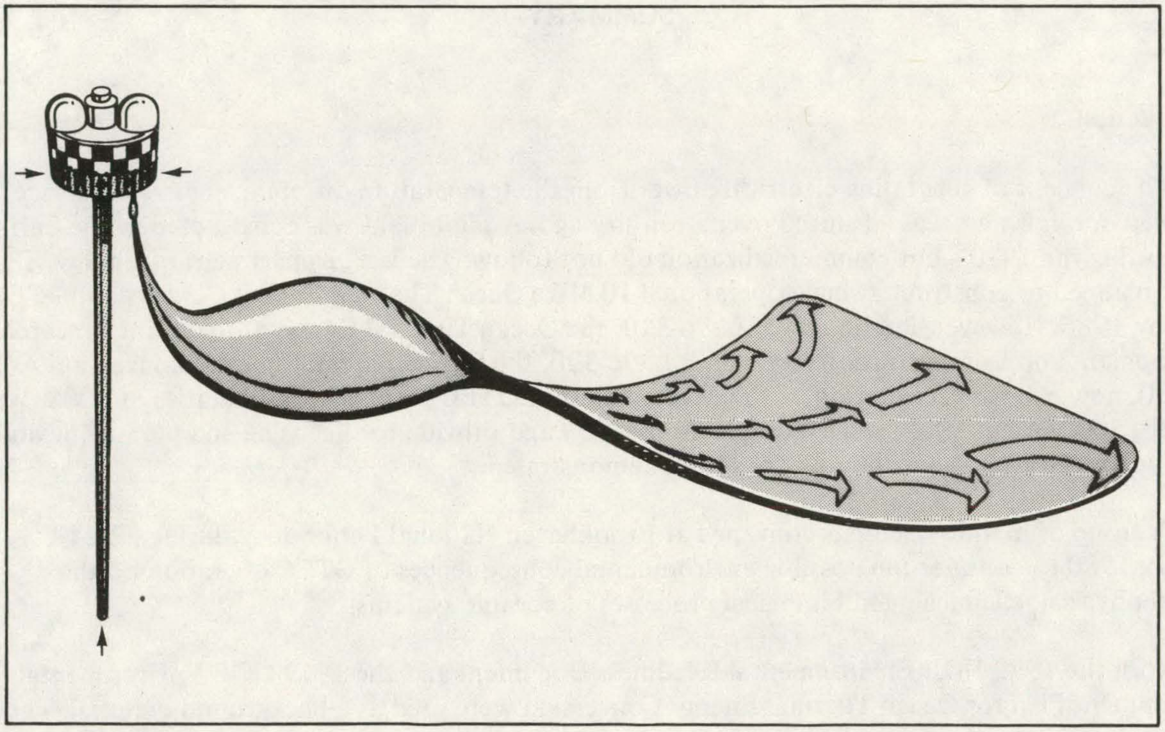


Figure 1. A concept of the mixed water discharge plume from an OTEC plant.

by becoming thicker and more wide. Isotherms in the upper layer of the thermocline would tend to rise. The plume would continue to sink, and as it lost momentum, would entrain less water. It would also spread and become less thick. At some point in the far field, part of the plume would move upward into the mixed layer and part would move downward. This mixing would be very diffuse but would constitute a partial closed circulation cycle in the upper ocean influenced by OTEC plant deployment.

Withdrawal of water from the surface will cause a radial flow of surrounding water towards the warm water intake (Fig. 2). The earth's rotation will cause the flow to deflect and spiral toward the intake in a vortex. This vortex is similar to a large shallow whirlpool. If the circulation of surface water has sufficient directional velocity, the shape of the whirlpool will be elliptical rather than circular. The direction of the major axis and the shape of the ellipse will vary depending on the direction and velocity of general water mass motion. This vortex may cause isotherms in the thermocline to lift toward the surface. The extent of possible uplifting is very uncertain.

The brief description above provides a general model of the circulation of water drawn into and discharged from an OTEC plant. The specific dimensions of the plume and its location, however, are quite uncertain. Field verification will be required to validate models developed to predict the plume field accurately. This general scenario for water motion produced by an OTEC plant is based on the following physical scale of structure of motion.

100 MWe plant
$900 m^3 sec^{-1}$ total volume flow of mixed water
10-40 m depth of intake of warm water at 25°C
1000 m depth of intake of cold water at 5°C

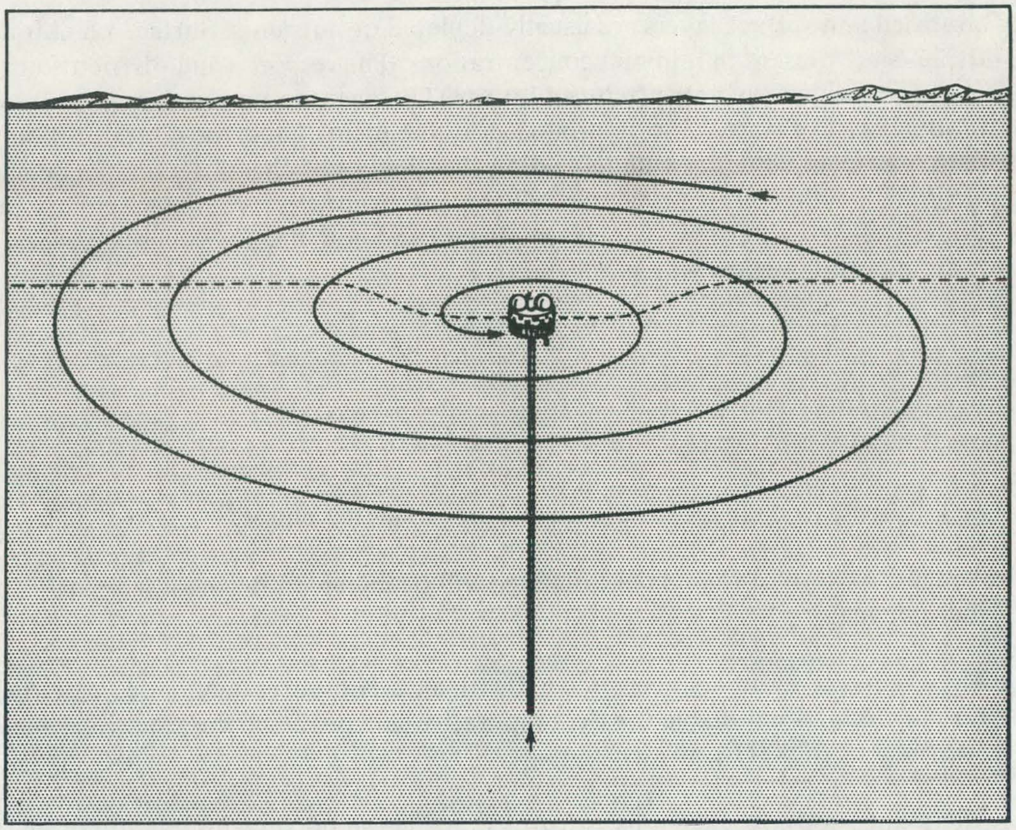


Figure 2. A concept of the surface water flow field toward the intake of an OTEC plant.

50-150 m depth of mixed layer of the surface ocean
10°C ambient temperature at 200-400 meters
15°C mixed discharge
60 m depth of discharge

If 100 MWe modules are aggregated in groups of four to form a larger plant, i.e., 400 MWe, the four surface layer fields produced would interact, as would the four plume fields. The physical fields of motion would be much larger, more complicated, and more difficult to model and empirically evaluate than for a single 100 MWe plant.

The above description also applies to stationary OTEC plants in the open ocean. However, the first OTEC commercial plants are proposed for areas near the shores of Hawaii and Puerto Rico. Water circulation in the vicinity of islands is complex, variable, and not well understood. Near island food webs and biological interactions are also more complex than offshore food webs which do not interact so strongly with the bottom community. Coastal food webs could be greatly modified by the effect of highly complex OTEC operations on island water circulation patterns. Whether complex flow fields and biological interactions can be modelled adequately in the context of OTEC is not known. Island sites should be studied in the case where funds are limited.

The above predictions of water motion around a commercial OTEC plant also describes the general pathway in which soluble chemical substances will move. Tropical ocean waters are permanently stratified and surface layers are usually depleted of nutrients. Surface plankton that depend on these nutrients are present in minimal concentrations. The response and distribution of biological activity resulting from disturbances produced by an OTEC plant in oceanic waters will tend to be confined to boundaries of water motion produced by the plant. Thus, the concentration of organisms and the intensity of their activities will depend on the kinetics of chemical and biochemical reactions within the physical field of influence of the OTEC plant. To predict whether chemical and biological effects will be beneficial or detrimental, it is important to know the physical dimensions of the field of motion of intake and outflow waters.

Panel Conclusions

A. Physical Panel

1. The effluent from an OTEC plant will form a sinking plume.

2. A major portion of the mixed discharge will be injected into the upper part of the stable thermocline.

3. The rise in the thermocline associated with an OTEC vortex could decrease the temperature of the water available for the evaporative side of the process and thus decrease the efficency of the OTEC plant.

4. There does not now exist a basis for forecasting the possible interaction of an OTEC vortex with transient thermal structure in an island coastal boundary layer or in the natural wake of an island.

5. No studies have been conducted of the structure and intensity of an OTEC vortex as a function of plant size and ambient oceanic conditions.

6. The behavior of OTEC plant induced mesoscale circulation patterns in the presence of natural oceanic eddies, or warm/cold core rings, has not been studied.

B. Biological and Chemical Panels

1. The dispersal of chemicals from an OTEC plant depends on vertical mixing rates and current velocities, the values for which are likely to be site specific. However, with a deep discharge, very little nutrient rich water would mix directly into the surface layer, though some nutrient will diffuse into the euphotic zone.

2. Easily measured physical and chemical variables are not sufficiently sensitive to define plume dispersion fields. The use of fluorescent dyes seems to be the only practical way to delineate plume dimensions in the far field (up to dilutions of approximately 1:1000).

3. Dissolved gases will be supersaturated by 3-4% in the discharge plume of a closed system OTEC plant. No deleterious effects on organisms are expected at this degree of supersaturation.

4. An open cycle OTEC plant, which requires degassing of the evaporative/condensing water, would release significant amounts of carbon dioxide to the atmosphere compared to current emissions from the burning of fossil fuel.

5. The effect and chemical form of biocides and their products on oceanic organisms are not well understood.

6. Trace metal concentrations will not be sufficiently enriched by discharging deep waters into surface waters to have significant effects on marine organisms.

7. If heat exchangers contain potentially toxic metals, it will be necessary to know the corrosion rate of the exchanger, particularly in the case of copper nickel alloys. Titanium and aluminum heat exchangers are not expected to affect marine organisms.

8. The surface layers of tropical oceans are relatively stable, with productivity varying from year to year by a factor of two. This compares to a factor of ten in temperate oceans. The concentrations of organisms and nutrients are low because of unchanging physical systems. Exceptions occur only in regions of equatorial divergence or during major storms.

9. By far the most important source of nutrients in tropical waters is from biological regeneration in the surface layer, indicating that grazing and subsequent excretion by zooplankton are tightly coupled to the primary production of the plants. The effect of OTEC plants on algal growth will depend on if and how the present steady state food web is altered.

Recommendations for Research

A. Physical Oceanography Panel

1. Models should be developed and verified to forecast the possible interaction of an OTEC vorticity field with transient thermal structure in an island coastal boundary layer and/or in the wake of an island.

2. Models should be developed and verified to describe the structure and intensity of flow of an OTEC vortex as a function of plant size and ambient oceanic conditions.

3. Models should be developed and verified to describe the behavior of OTEC induced mesoscale circulation patterns in the presence of natural oceanic eddies and/or warm/cold core rings.

4. Detailed site specific field measurements are required of the mesoscale flow environment of a prototype 100 MWe OTEC plant.

5. Evaluate the extent to which discharge water reenters the surface layer. Several processes that influence surface reentry need to be analyzed quantitatively:

   a. instabilities of an isopycnal layer embedded in a vertical density gradient

b. diffusive losses from a thin (≤ 5m) layer of high concentration set in a vertical density gradient

c. erosion of a surface layer density gradient by mechanical mixing

d. deepening of the surface mixed layer by vertical convection

e. upwelling mechanisms that can raise the effluent water mass into the euphotic zone

6. Develop a climatology of coastal currents near proposed OTEC sites by examining variations in hydrographic structure and currents over 100 km of shoreline and at appropriate frequency of temporal sampling.

7. Measure and analyze in detail the complexity of the velocity fields in passages such as the Yucatan Strait and the Straits of Florida. These details must be known to understand forcing factors which drive closed basin circulation.

8. Conduct studies of closed basin circulation. These studies should be coordinated with the NOSS spacecraft launch scheduled for 1985.

9. Determine how ocenaic scales of water motion are locally modified by island masses and negative buoyancy plumes resulting from OTEC operations. As island effects are unique, these studies must be site specific.

B. Chemical Oceanography Panel

1. Develop models of the kinetics of chemical reactions and changes in concentrations of chemicals resulting from mixing surface and deep water based on appropriate physical models of the trajectory, dimensions, and dilution rate of the discharge plume. Site specific analyses will be required.

2. Verify plume dispersal models by means of synoptic measurements using unique sensitive tracers such as fluorescent dyes. Other easily measured physical and chemical variables are not likely to be sufficiently sensitive to fully describe the plume field.

3. Quantitatively evaluate the extent of degassing of evaporative/condensing water of an open cycle OTEC plant and the significance of the accompanying release of carbon dioxide to the atmosphere.

4. Determine the corrosion rate of heat exchangers fabricated of materials (i.e., copper) likely to be toxic to marine organisms.

5. Model the chemical and biological effects of a massive rupture of an OTEC plant, which may release some 100 tons of ammonia. Such a rupture will cause massive precipitation of carbonates and metal hydroxides and may have severe biological effects on a local scale.

6. Initiate research on the effects of chlorination on organisms likely to be found at OTEC sites. Such data are virtually non-existent.

7. Determine the products and kinetics of production of chemicals associated with chlorination, in particular those inorganic bromine compounds and organobromine compounds which appear to mediate the toxicity of chlorination per se.

8. Determine the effect of chlorination on the organic chelating capacity of sea waters which may affect the availability to and toxicity of trace metals on marine organisms.

9. Determine the concentrations of trace elements in surface and deep waters for which sensitive analytical procedures have been developed.

C. Biological Oceanography Panel

1. Develop procedures to measure biological reaction rates and biomass concentrations in presently unproductive tropical marine systems. Analytical tools for obtaining precise and accurate measures of biological structure and activities have not yet been adequately developed for use in tropical marine systems.

2. Develop time series information on the local, site-specific assemblages of marine organisms, and where possible, time series measurements of rate processes and standing stocks at the time scale of the life cycle of the organisms.

3. Develop time series models of (2) above in such a way that they may be coupled or linked to routinely measured parameters. In this way, and from first principles, determine environmental forces driving natural variability.

4. Couple ecological models with physical and chemical models of OTEC-induced circulation.

5. Develop time series information and models for the spatial distribution of nutrients, oxygen, organic compounds, and certain trace metals used in OTEC construction materials.

6. Develop time-series measurements of the flux of sinking particles at the depth of expected OTEC plumes (about 200 m) and the flux reaching the bottom benthic assemblage. Organic matter, minerals, and trace metals associated with particle flux provide information for multi-dimensional models, which can be coupled to the physical models of OTEC water circulation.

7. Continue the above studies after OTEC operations commence until a new quasi steady-state has been reached such that the environmental effects of OTEC operations, if measurable, can be seen against natural background variation.

Research Plan: Five Year Program

A. Physical

Objective I. Determine near and intermediate field flow patterns, and variations in the natural thermal structure induced by an OTEC plant.

Task 1 Develop analytical and numerical models of the OTEC vortex.

	Task 2	Develop analytical and numerical models of the near and far field plume from an OTEC plant.
	Task 3	Collect field data to adjust and verify models developed under Tasks 1 and 2. (These studies would involve measurements in the vicinity of the first several OTEC plants placed in operation.)

Objective II. Determine the interaction of an OTEC vortex with natural transient circulation patterns and thermal structures in an island coastal boundary layer and in the wake of an island.

Task 4	Conduct site specific field studies at proposed island locations for OTEC plants of the transient flow pattern and thermal structure in the island coastal boundary layer and in the wake of the island.
Task 5	Model the interactions of an OTEC vortex with time varying flow patterns and thermal structures in island coastal boundary layers and island wakes.
Task 6	Collect field data to adjust and verify models developed under Task 5.

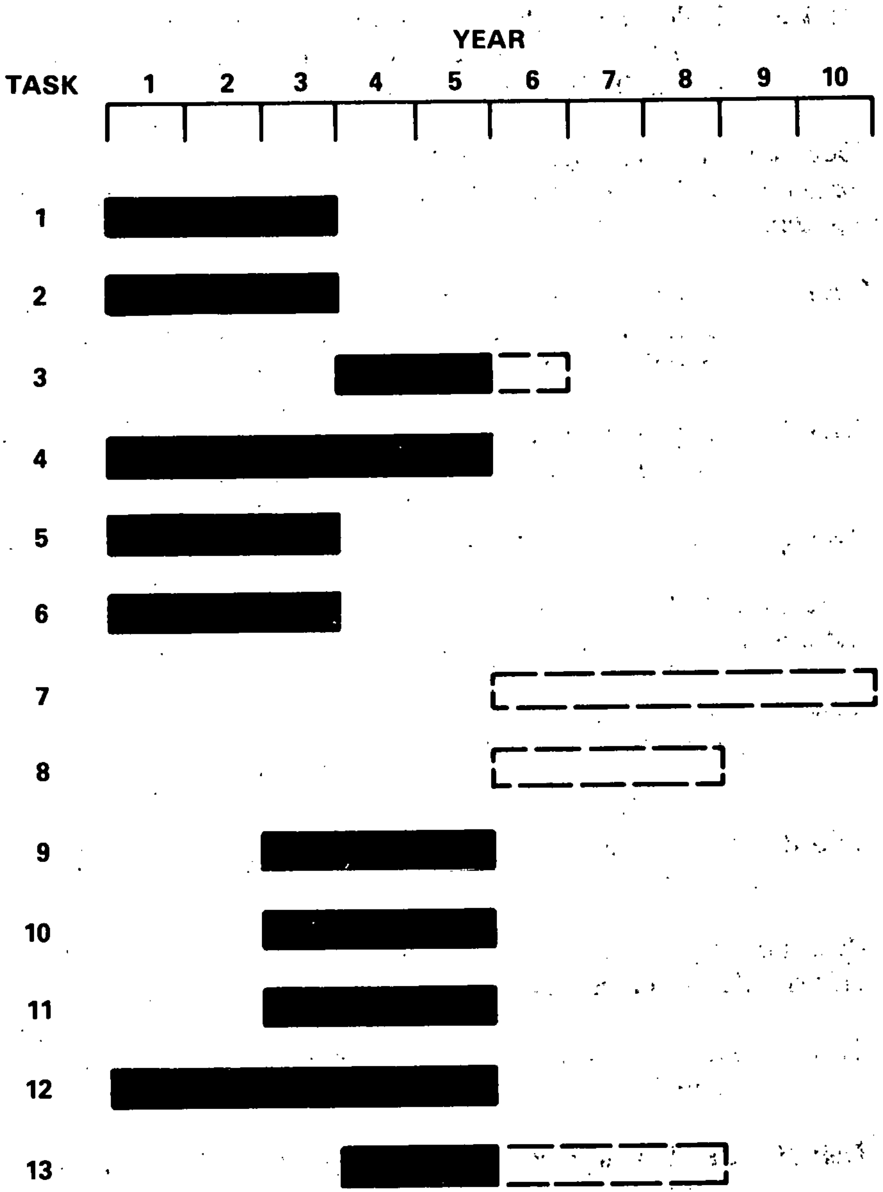
Objective III. Determine the interaction of an OTEC plant's mesoscale circulation pattern with natural oceanic eddies, or warm/cold rings.

Task 7	Conduct field studies, in the vicinity of proposed open ocean OTEC plant sites, of the time varying flow pattern and thermal structure of warm/cold core rings which advect past the site.
Task 8	Develop models of the interaction of an OTEC plant's mesoscale circulation pattern with natural warm/cold rings.

Objective IV. Determine the far field fate of the discharge plume from an OTEC plant-advective and diffusive flux of plume constituents into the surface layer.

Task 9	Develop models of large scale circulation patterns induced by an OTEC plant.
Task 10	Develop improved models of vertical diffusive flux from a thin layer of high concentration set in a stable vertical gradient.
Task 11	Develop improved models of the horizontal diffusive spread by the far field plume from an OTEC plant.
Task 12	Conduct field studies to provide data to aid in developing models described in Tasks 9, 10, and 11, including fluorescent tracer studies of dispersion in the permanent thermocline, and studies relating Lagrangian and Eulerian measurements of diffusion.
Task 13	Conduct field studies to provide data to aid in adjusting models developed in Task 12 and to verify the accuracy of the models under conditions of plant operation.

TIME SCHEDULE
PHYSICAL RESEARCH PLAN



B. Biological/Chemical

Objective I. Determine effects on biological assemblages which result from changes in circulation and nutrient redistribution associated with OTEC operations.

Task 1 Use models of plume dispersal and alterations to normal circulation patterns to determine where biological effects are likely to occur and to define the spatial scales at which biological studies are required.

Task 2 Determine biological reaction rates, biomass concentrations and species assemblages of plankton, nekton, and benthos to establish the natural scale of temporal and spatial variations at OTEC sites over the area of OTEC-induced flow fields. Determine spatial and temporal distributions of chemical species known to affect biological processes (N, O_2, selected metals).

Task 3 Determine the effect of predicted nutrient/metal enrichments on the production of organisms.

Task 4 Develop analytical tools as needed to measure biological reaction rates and biomass concentrations in tropical waters. Determine what indices (e.g., feeding rates and egg production of zooplankton; microbial activity; changes in photosynthetic rates; redistribution of metazoan biomass) can be used to measure changes in community metabolism. Establish natural rates in the field against which to apply these indices.

Task 5 Determine natural rates of sedimentation of minerals and organic matter over the expected scale of OTEC flow fields.

Task 6 Develop models to predict the effects of OTEC induced changes in circulation (temperature) regimes on specific benethic communities if physical models predict that near island populations may be affected by discharge plumes. Specific research plans should be developed if need is indicated. Water temperature, underwater light fields, and food input rates to benthic communities are important features to consider.

Task 7 Develop coupled models of physical flow regimes, chemical distributions, and biological dynamics at OTEC sites.

Task 8 Validate models developed under (7) after an OTEC plant is operational.

Objective II. Determine the effects of elements/compounds which are added to the marine environment by OTEC operations.

Task 9 Identify organisms most likely to be impacted by OTEC discharges particularly those found at or mitigating through the expected depth of discharge plumes.

Task 10 Initiate research on the kinetics of the disappearance of chlorine and production of the byproducts of chlorination with and without enrichment with NH_3.

Task 11 Develop and conduct studies of the effects of seawater chlorination on tropical organisms. If effects at possible dilution concentrations are evidenced, initiate studies of organic and inorganic chemistry, specifically:

a. Develop and conduct proper bioassays of chlorination effects on tropical marine organisms.

b. Examine the extent to which chlorination influences the speciation of potentially toxic trace metals.

c. Identify organic compounds produced by chlorination-determine their effect on organisms.

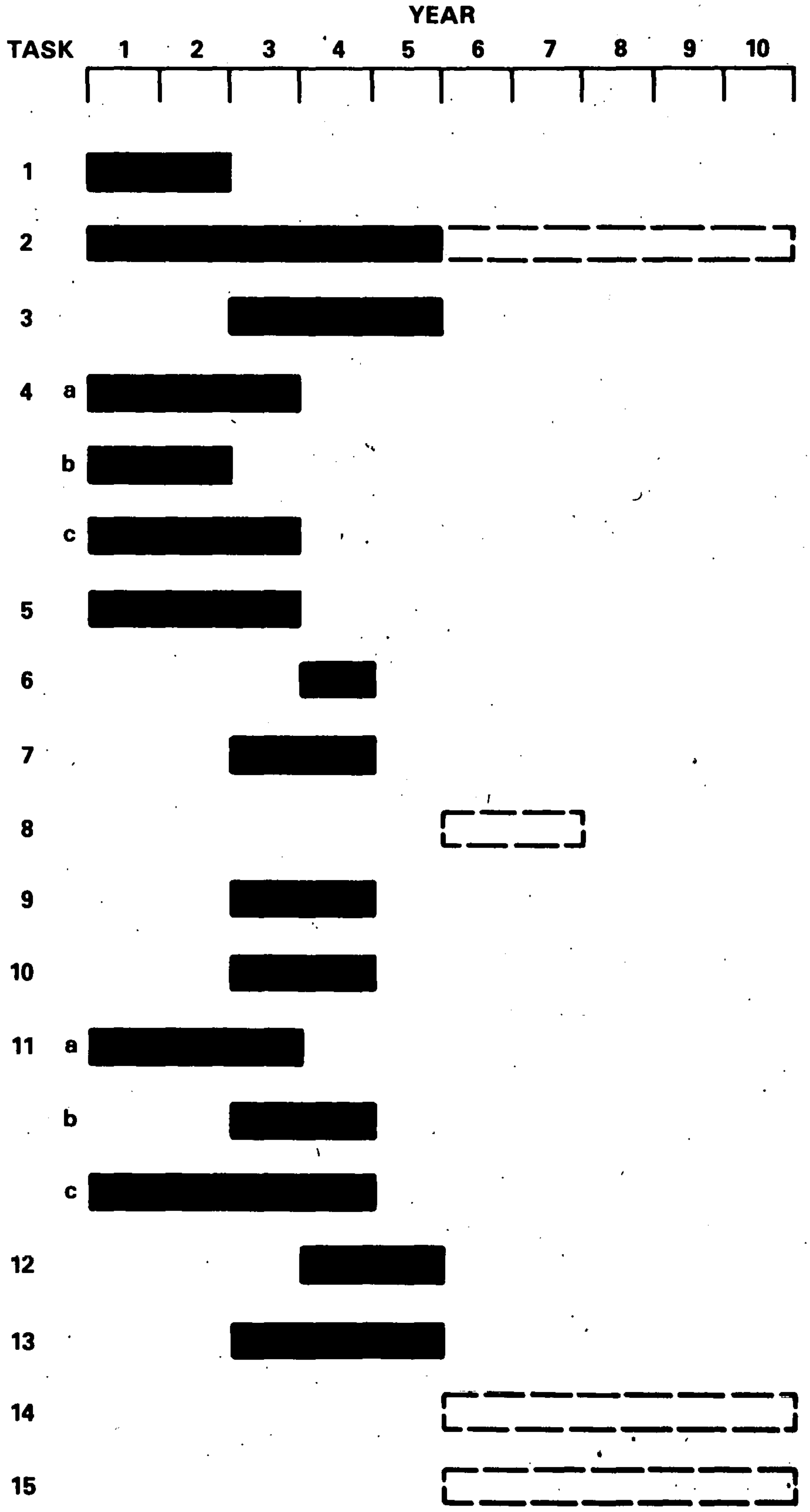
Task 12 Determine the corrosion rates of metallic components of heat exchangers. If significant enrichment of the water appears likely, develop and conduct bioassays of the effects of the element concerned.

Task 13 Incorporate observations from Task 9-12 into physical models of OTEC effluent circulation to predict possible biological effects.

Task 14 Verify the model (13) after an OTEC plant is operational.

Task 15 If an "open" OTEC scheme is considered, model possible effects on global climate, etc., which may result from the release of CO_2 to the atmosphere.

TIME SCHEDULE
BIOLOGICAL AND CHEMICAL RESEARCH PLAN



Appendix 1

Workshop Report

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Introduction

The potential exists for commercial development and deployment of Ocean Thermal Energy Conversion (OTEC) plants to generate electricity in sub-tropical regions of the world ocean (Cohen, 1979). The concept of pumping deep cold water to the warm surface of the sub-tropical ocean, and using the temperature differential to condense and vaporize a working fluid to generate electrical power is not new (d'Arsonval, 1881; Claude, 1930). Over 50 years ago, Georges Claude built a pilot plant in Cuba (Othmer and Roels, 1973), but commercialization did not follow. Continuing societal needs for increasing amounts of energy and for alternatives to fossil fuel now suggests that OTEC might be a possible source of power for populations located in the subtropics, i.e. Hawaii, Puerto Rico, and along the Gulf of Mexico.

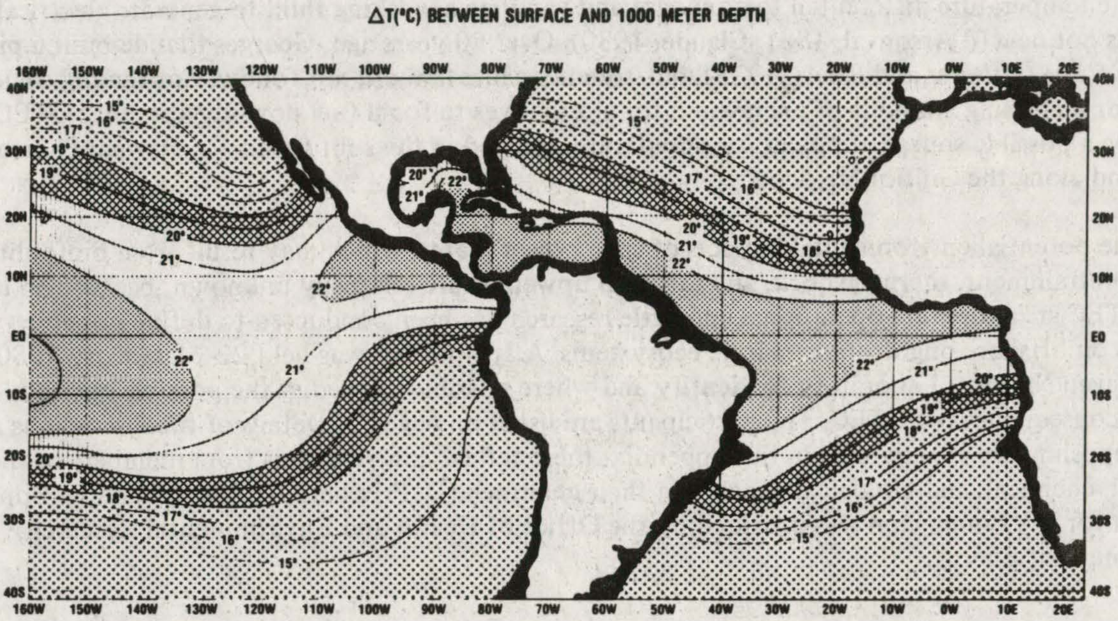
The potential environmental impacts of such power plants, which may result from biofouling agents, entrainment, thermal shock, and artificial upwelling are relatively unknown, because no large-scale OTEC structures are operational and little research has been conducted to define possible impacts on offshore oligotrophic marine ecosystems. A symposium was held 22-24 January 1980 at Brookhaven National Laboratory to identify and where possible to predict the possible environmental consequences of OTEC. The participants are listed on page 55. Details of the discussions at the symposium are summarized in this appendix; these reflect contributions from members of the physical, chemical, and biological panels and their chairmen (D. Pritchard, D. Menzel and R. Eppley). Support for the symposium was provided by the Office of Health and Environmental Research, Department of Energy.

The Ecological Context

Oceanic regions with year-round vertical temperature differences greater than 20°C between surface and deep waters (1000 m) are the potential sites for OTEC plants (Fig. 3). Physical aspects of the ocean circulation that produce this permanent temperature gradient also result in low surface biological production. Slow rates of vertical mixing between surface and deep waters allows the temperature gradient to persist, and limits the transfer of plant nutrients from the nutrient-rich deep to surface waters. Surface waters are thus nutrient-poor (oligotrophic) and the biological harvest they can provide to man on a per unit area basis is very low (Ryther, 1969). Over a depth of 200 m, at least 50 km^2 would need to be strained to catch the 500 tons of fish, e.g. myctophids, necessary to make an ocean-going trawler profitable (Cushing and Walsh, 1976). OTEC plants may measurably alter this natural state of oligotrophic marine ecosystems by artificially enriching surface water.

As expected this symposium raised more questions than were answered. Among these were fundamental questions such as whether the environmental impact of an OTEC plant, or a group of them, will result in a net gain or loss of pelagic organisms and whether existing methodologies are sufficiently advanced to provide answers to the questions asked. The effects of biocides, corrosion, entrainment, leaks of the working fluid (ammonia), thermal effects, climatic changes, and gas exchange were considered by drawing analogies to research results on coastal power plants. Little is known about the effect of induced upwelling on oligotrophic ecosystems (Walsh, 1980); the effects of ocean water mixing from OTEC will depend on the relation between discharge depth and that of the euphotic zone.

A — Western Hemisphere OTEC resource.



B — Eastern Hemisphere OTEC resource.

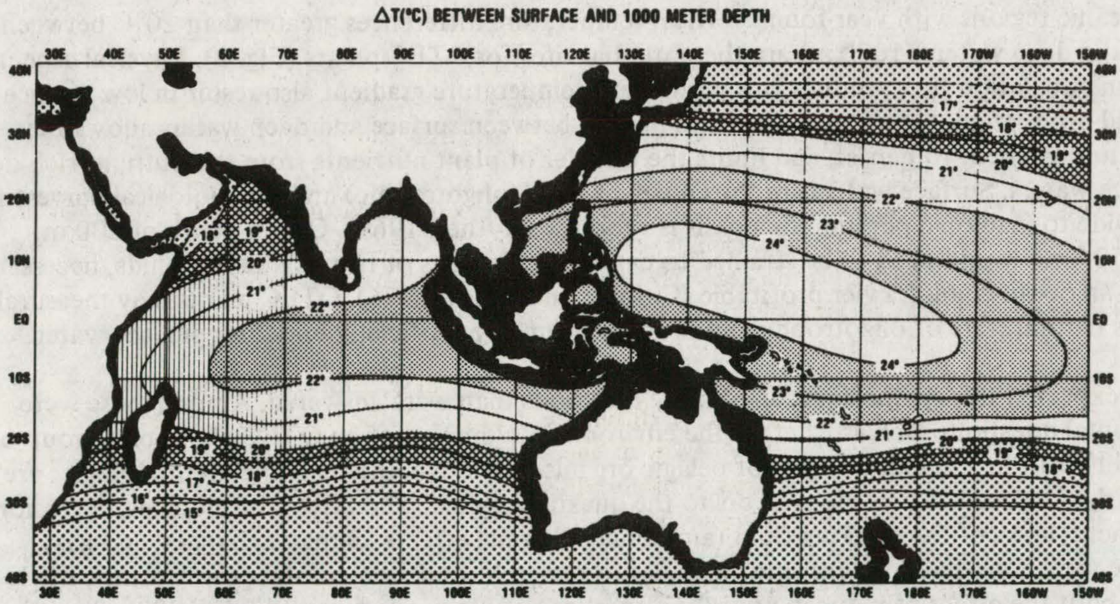


Figure 3. Contours showing the annual average monthly temperature differences (in degrees Celsius) between the ocean surface and depths of 1,000 meters for (A) the Western Hemisphere, and (B) the Eastern Hemisphere.

For example, one commercial Ocean Thermal Energy Conversion (OTEC) plant of 100 MWe capacity might have a sea water flow-through of $\sim 0.7 \times 10^8$ m^3 day^{-1} (Lockheed, 1975). Assuming an equal mixture of cold water from 1000 m and warm water from 0-30 m, nutrient rich water ($\sim$30 mg-at NO_3 m^{-3}) would be artificially upwelled at a rate of $\sim 0.4 \times 10^8$ m^3 day^{-1}. The induced nitrate flux of $\sim 1.1 \times 10^9$ mg-at NO_3 day^{-1}, discharged at the surface over a 11 km^2 area of the upper 200 m, would add $\sim$0.5 μg-at NO_3 ℓ^{-1} day^{-1}. This could be approximately ten fold that now found in the mixed layer of oligotrophic ocean water. Simultaneously, the surface temperature of the water in the 11 km^2 around the OTEC plant would be lowered by $\sim$0.3°C (Bathen, 1974).

In comparison with the natural process of upwelling $\sim$11 km off Peru, the nearshore upwelled input of nitrate into a 20 m surface Ekman layer can be estimated by the equation, $\frac{\partial NO_3}{\partial t} = \frac{w(\partial NO_3)}{\partial z}$ where w is the upwelling velocity (10 m day^{-1}), (∂NO_3) is the nitrate gradient between 15 and 25 m (5 μg-at NO_3 ℓ^{-1}), and ∂z is 10 m (Walsh, 1975). A nitrate input of $\sim$5 μg-at NO_3 ℓ^{-1} day^{-1} is associated with a surface temperature ($\sim$16°C) at the Peru coast which is about 3°C less than offshore waters ($\sim$19°C). Thus, the nutrient increase and reduction in surface temperature from ten to 100 MWe OTEC plants within a 11 km^2 area might be equivalent to that of a similar area off Peru, the world's most productive coastal upwelling region (Walsh, 1974).

The discharge and hence nutrient input of OTEC plants may be confined, however, to depths below the euphotic zone. For OTEC plants to be efficient, the temperature gradient between surface and deep water has to be maximally utilized. This implies that the mixed discharge must not be recirculated into the plant surface intake, as a decrease of 1°C in the thermal gradient would reduce the efficiency of the plant by about 10% (Allender et al., 1978). For this reason, current OTEC design emphasizes plants with combined discharge at a depth of about 60-70 m for OTEC-1 and perhaps deeper for subsequent plants.

The temperature-salinity characteristics of surface and deep seawater of the tropical oceans are such that the discharged OTEC mixed seawater at 60-70 m is likely to sink to a depth between 150 and 200 m. This is shown by sigma-t (density) values estimated from the vertical distribution of temperature and salinity (Defant; 1961) in the Gulf of Mexico and the Caribbean Sea (Table 1). The combined surface-deep water OTEC output and water entrained in a sinking plume would remain either at the top of the pycnocline or around the depth of density equalization, below 150 m for the Gulf of Mexico and below 200 m for the Caribbean Sea. Allender et al. (1978) estimated this depth of a sinking plume to be 216 m south of Puerto Rico.

Because the depth of the mixed layer in a typical tropical ocean is less than 100 m, nutrient enrichment of the euphotic zone by OTEC discharge zone would be limited to vertical diffusion (about 10^{-4} m^2/s) in the immediate vicinity of the plant, i.e. certainly much less than estimated above in the surface discharge scenario. This implies that OTEC plants, rather than being a major source of upwelling, might cause downwelling by drawing significant fractions of the surface layer below the euphotic zone. For example, assuming that a 100 MWe plant circulates a volume of 0.07 km^3/day (half of this volume from the surface and half from 100 m) and that the surface intake is from a layer 30 m thick (0-30 m), the plant would cause a surface layer 30 m deep extending over an area of about 1.3 km^2 each day to sink below the euphotic zone. In the discharge plume below the euphotic zone, phytoplankton and then zooplankton would die and sink. If a park of OTEC plants with mixed discharge were located near spawning grounds of tuna or other tropical fish, it could cause a significant direct loss of larvae of commercial fish.

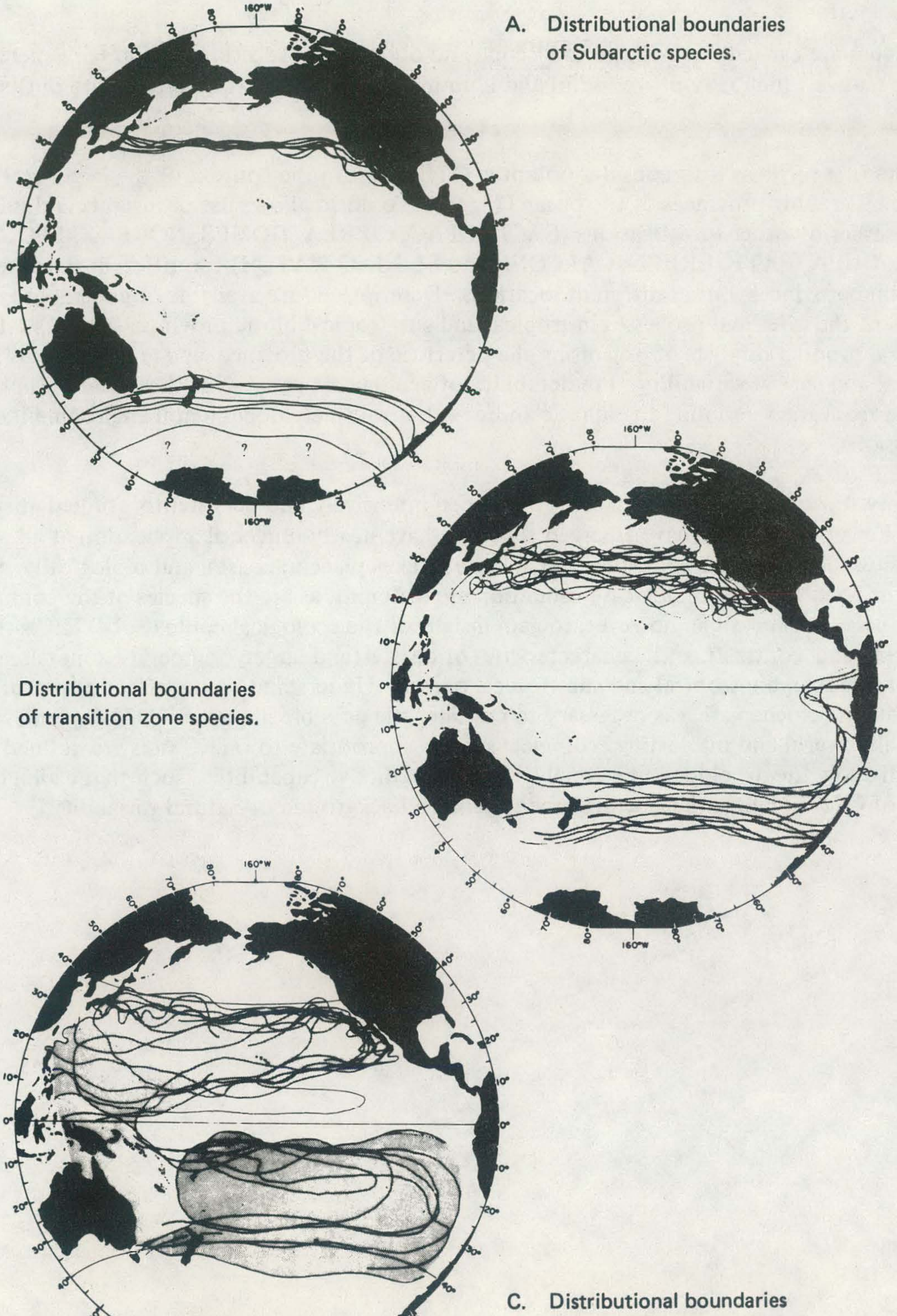
Table 1. Vertical distribution of temperature, salinity, and σt in the Gulf of Mexico (25.8° N, 92.5° W) and in the Caribbean Sea (14° N, 68.6° W). Temperature and salinity data from Defant, 1961).

Depth	T°	Sal.	σt	(Gulf of Mexico)
0	22.94	36.16	24.89	Hypothetical properties of OTEC
50	21.90	36.12	25.10	Mixed water (50% surface and 50% 1000 m)
100	19.30	36.31	25.95	Temp. = 13.69
150	16.00	36.18	26.69	Sal. = 35.55
200	13.40	35.70	26.87	σt = 26.692
400	7.99	34.96	27.26	
600	5.77	34.87	27.50	
800	4.94	34.92	27.64	
1000	4.54	34.93	27.69	
				(Caribbean Sea)
0	26.08	36.38	24.08	Hypothetical properties of OTEC
50	26.01	36.28	24.03	Mixed water (50% surface and 50% 1000 m)
100	24.97	36.68	24.65	Temp. - 15.63
150	21.86	36.80	25.63	Sal. = 35.61
200	18.15	36.35	26.30	σt = 26.322
400	10.90	35.25	27.02	
600	7.71	34.82	27.20	
800	6.10	34.75	27.36	
1000	5.18	34.84	27.55	

Hydrodynamic models of the circulation induced about an OTEC plant (this report) suggest the water will downwell adjacent to the plant, with entrainment of surface waters into the effluent plume. The plume from a large OTEC plant will stabilize at a depth of about 200 m and spread laterally, well below the illuminated surface waters where plankton photosynthesis takes place (the euphotic zone). At some distance from the plant, however, an uplifting of density surfaces and perhaps of the concentration gradient of plant nutrients may occur. It is in this far-field zone that increased nutrient input to the euphotic zone may take place, stimulating the growth of the plankton. Clearly, it is not yet known if OTEC operations will result in a net gain or a loss of surface plankton; obviously plankton populations will be displaced in the vicinity of the plant.

If an OTEC plant is adjacent to a sub-tropical island, the circulation induced by the effluent may interact with the coastal boundary layer and its unique circulation leading to increased complexity in predicting nutirent redistributions. A possible effect is to increase nutrients in the euphotic zone near the island. Another measure of concern in island siting beyond that of open ocean siting is that site-specific scenic and recreational attributes of the island will be changed. Deep-blue waters may become blue-green and the transparency of the water, so attractive for sport diving, may be reduced. Coral reefs and benthic plants may become shaded to the extent that growth in deeper portions of the communities may be slowed. Mild eutrophication at sites near islands may be beneficial, however, as long as water color, transparency, or coral reefs are not highly desirable features of the locale.

There is currently a modest DOE sponsored research program at potential OTEC plant sites. Within a limited scope it is providing site-specific information needed to obtain permits. Several potentially significant ecological impacts are presently being evaluated. It is easy to criticize



A. Distributional boundaries of Subarctic species.

B. Distributional boundaries of transition zone species.

C. Distributional boundaries of Central species in OTEC regions.

Figure 4. Some biological provinces in the Pacific Ocean from: J.A. McGowan. 1974. The nature of oceanic ecosystems. In: (C.B. Miller, Ec.) The Biology of The Oceanic Pacific. Oregon State Univ. Press, Corvallis. p. 9-28.

studies that are carried out with narrow scope and objectives. Additional efforts of general and specific nature which may prove useful and illuminating in future OTEC studies are outlined below.

The first of these is to consider potential OTEC sites in the context of the larger setting in specific biographic provinces of the ocean (Fig. 4). To do so allows use of insights and information gained earlier by other investigations (EASTROPAC, CIPREA, DOMES, NORPAX, EPOCS, INDEX, CUEA, FATE, ERFEN, CALCOFI, and EL NINO WATCH) for different purposes in these same provinces, but at different locations. Descriptions are available of general broad scale features of the rates and processes in tropical and sub-tropical biotic provinces, such as rates of biological production, lists of organisms characteristic of the province, and gross patterns in temporal and spatial variability. Predictability of ecological processes at these scales can be deduced from their coupling to climatic and/or other routinely documental environmental progressions.

Very few oligotrophic ocean areas have been intensively and persistently studied at smaller scales. Fewer generalities have emerged that may have nearly universal application at all potential OTEC sites. Most marine ecological research now takes place in coastal and biologically rich areas where the forces driving biological production are different, as are the species of the common plants and animals. It is possible, however, to gain insight of the ecological context of OTEC sites by comparing and contrasting the characteristics of coastal (and largely temperate zone) areas with those of oligotrophic tropical and sub-tropical oceans. Understanding the effect of perturbations on oligotrophic ocean areas is necessary to consider the possible impacts of OTEC plants. Potentially useful and interesting ecological studies appropriate to OTEC sites are defined. This will allow the development of analytical and predictive capabilities, such that ecological effects of OTEC plants might be discerned against a background of natural variability.

Physical Consequences of OTEC

by

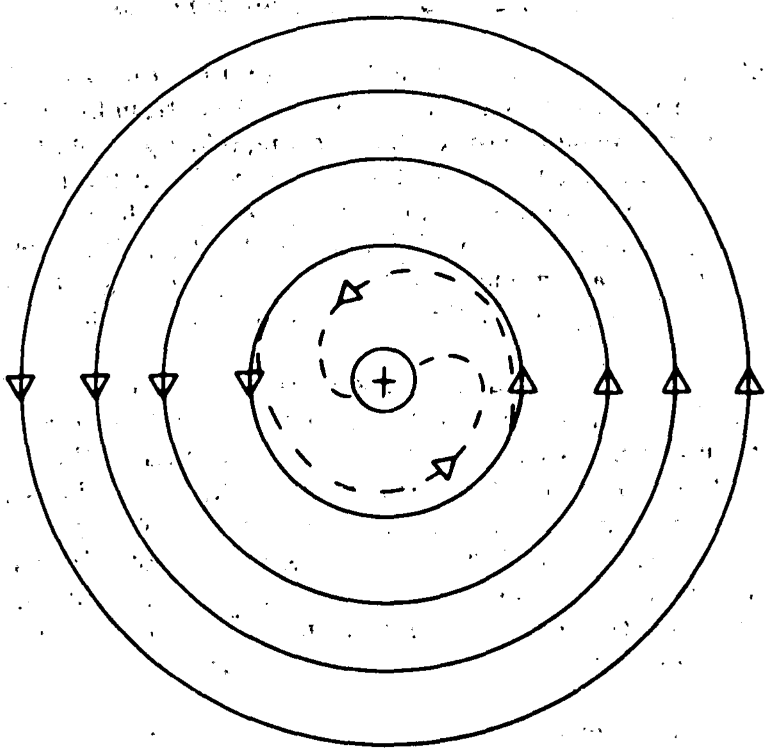
D.W. Pritchard, J. Blanton, G. Csanady, J. Ditmars, T. Hopkins,
G. Maul, G. Mellor, D. Pillsbury, and D.-P. Wang

A medium size, closed cycle OTEC plant of 100 MWe capacity and a temperature differential of 20°C would require an intake of about 450 m^3 sec^{-1} of warm surface water ($\sim 25°C$) and an equal intake of cold "deep" water ($\sim 5°C$). Warm water intake pipe(s) would be centered at depths of 10-40 m while the cold water intake would be located at a depth of about 1,000 m. Within the plant the warm water will be cooled 2°C to 3°C at the evaporator, while at the condenser the cold water will be heated the same amount. Effluents from the evaporator could be discharged separately or combined as a "mixed" discharge. In either case, the effluent discharge ports would be located below the warm water intakes at a distance which would prevent recirculation. Tropical and sub-tropical regions (Fig. 3) where the required temperature difference of 20°C in the upper 1,000 meters occurs are characteriized by an upper mixed layer of 50-150 m thickness. This overlays water of rapidly increasing density with depth (the pycnocline), which coincides with the thermocline where temperatures decrease rapidly. Within this thermocline, temperatures decrease 10° to 15°C over a depth interval of 100-200 m; thus, a temperature of about 10°C is found between 200-400 m. The rate of temperature change with depth decreases markedly below about 300 meters, with temperatures $\leq 5°C$ seldom occurring above depths of 750-1,000 m.

To reduce complexity of the following discussion it is assumed that after passing through the evaporators, slightly cooled surface water will be mixed with the slightly warmed deep water from the condensers. The general nature of our conclusions would not be changed from the case of separate discharges. Mixed discharges, having a temperature of about 15°C, would be released into the lower part of the mixed layer, at depths of perhaps 60-70 m. Where ambient thermal structures, favor OTEC power production, the in situ temperature at 60-70 m would be at least several degrees warmer than the discharge. The effluent from the OTEC plant would therefore form a sinking plume. The sinking plume would entrain surrounding water and would ultimately spread horizontally in the upper layers of the thermocline, at the density of the mixed effluent. The density would be somewhat modified by mixing with the entrained ambient water added to the plume during sinking. Most of the mixed discharge will accumulate in the upper reaches of the stable thermocline.

In this scenario, very little nutrient rich water from the deep intake would directly mix into the upper layer. The spreading plume of the mixed discharge within the upper thermocline would likely change the vertical gradient of subsurface nutrients in a restricted region around the plant site. This could increase the normal rate of vertical diffusion of nutrients across the thermocline into the euphotic zone. Also, as noted later, the withdrawal of surface water from above the thermocline and of deep water from below, coupled with injection of the mixed effluent into the thermocline, will cause the thermocline to thicken, i.e. the thermal gradient within the thermocline to weaken, thus further favoring vertical diffusion of nutrients.

A. Plan View



B. Section View

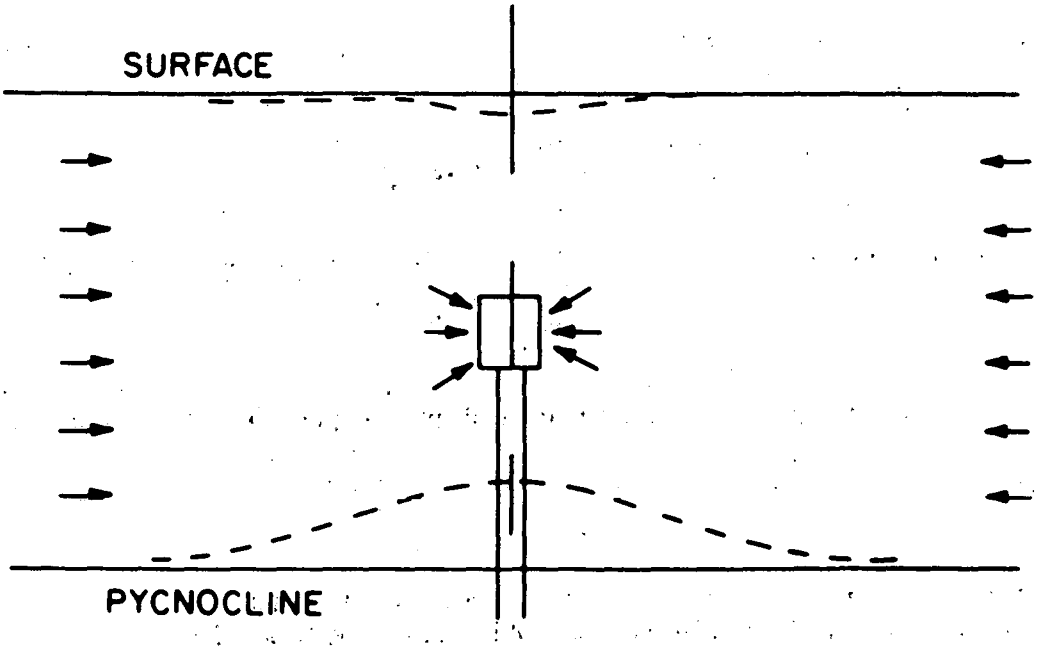


Figure 5. Suction applied to the surface layer at an OTEC plant causes a slight lowering of surface level, much more pronounced rise of the pycnocline, inflow of fluid deflected by the earth's rotation into a cyclonic vortex, with water particles spiralling to the center.

Surface Circulation near an OTEC Plant

The local withdrawal of some 450 m^3 sec^{-1} of water from the surface layer will probably require a radial inflow toward this sink. At a distance of 1 km from the intake, assuming that the flow is drawn from a layer 40 meters thick, the inflowing velocity would be small (less than 0.2 cm sec^{-1}). However, it is possible that a much more intense, vortex type, flow pattern might develop as a result of the local sinking of surface water (Fig. 5). Whether this scenario of near field OTEC circulation effects would actually develop and remain stable depends on the nature of the dissipative processes of friction and mixing and on convective acceleration terms. The argument that such an OTEC vortex flow pattern of surface water would develop follows.

At any latitude other than the equator coriolis effects will cause the inflow to turn and approach the OTEC sink as a spiral. Pressure drop associated with this withdrawal of surface water will cause a slight depression in sea level above the plant, and a rise in the isotherms in the upper part of the thermocline. The horizontal pressure field resulting from this rearrangement of the density field would support a geostrophically balanced, cyclonic flow characteristic of a cold core eddy. Our first order models of an OTEC vortex suggest that a 100 MWe plant drawing warm water from a mixed layer 100 meters deep would produce an eddy with a radius of from 10 to 20 km, having a maximum tangential velocity of about 15 cm sec^{-1} at a distance of about 1.5 km from the sink. The thermocline below the sink would be raised about 15 meters.

Our simple two-layered model of this vortex, with the bottom layer regarded as infinitely deep and therefore motionless, is constructed from a frictionless outer region (radius $r \geq r_o$) and a solid body motion core. Similar models have been used to study the flow in a hurricane. In the dissipative core the tangential velocity is assumed to be (for the coordinate system see Fig. 6):

$$v = \omega r \tag{1}$$

with ω = constant expected to be of order F ($\equiv$ Coriolis parameter). If the density deficit of the surface layer is $\epsilon = \Delta\rho/\rho$ (of order 10^{-3}), this radial pressure gradient is

$$\frac{1}{\rho}\frac{\partial p}{\partial r} = \epsilon g \frac{\partial \zeta}{\partial r} \tag{2}$$

where ζ is the displacement of the pycnocline. The balance of forces in the radial direction is

$$-\epsilon g \frac{\partial \zeta}{\partial r} = fv + \frac{v^2}{r} \tag{3}$$

With Eq. (1) it may now be shown that the displaced pycnocline surface is a paraboloid:

$$\zeta = \zeta_c - \frac{\omega r^2 \ (f+\omega)}{2\epsilon g} \tag{4}$$

This shape of the pycnocline on the frictionless outer region may be calculated using potential vorticity conservation. For the quasi-geostrophic case ($\omega << f$) one finds

$$\zeta = \text{const.}\ I_1\ (\frac{r}{R}) \tag{5}$$

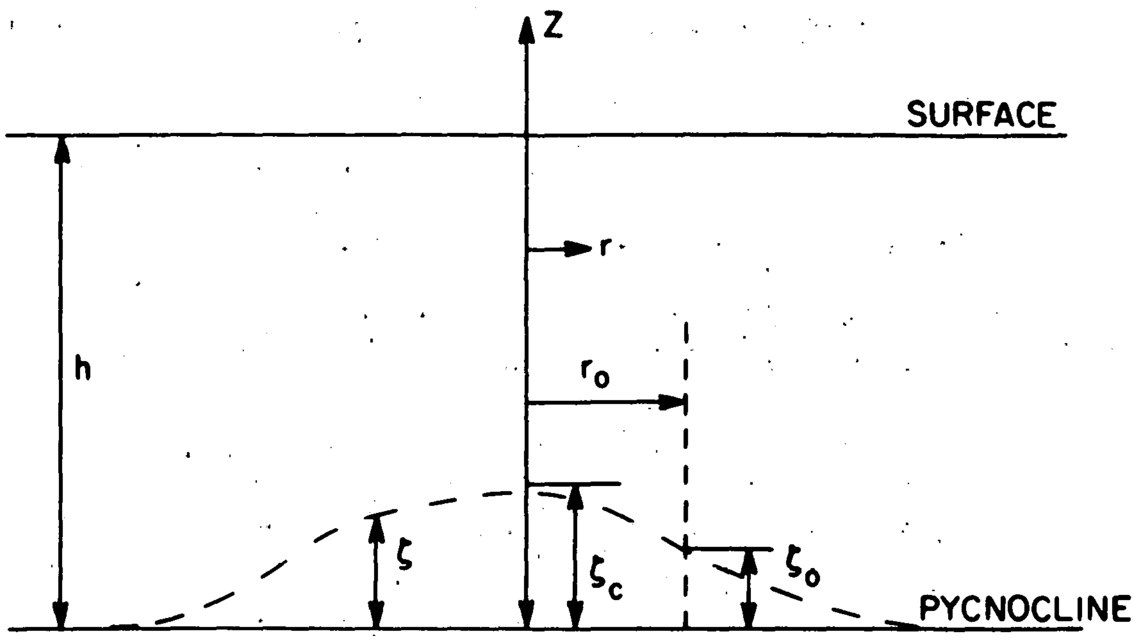


Figure 6. Coordinate system and definition in OTEC vortex model.

where I_1 is a modified Bessel function and R is internal radius of deformation:

$$R = f^{-1} \sqrt{\epsilon g h} \tag{6}$$

To match the solid rotating core to the frictionless exterior at $r = r_o$ may be taken to be from the last result (Eqs. 5 and 6).

$$\left.\frac{\partial \zeta}{\partial r}\right|_{r_o} = -\frac{\zeta_o}{R} \tag{7}$$

where ζ_o is the pycnocline displacement at r_o. From (3) now

$$v = \frac{\epsilon g}{f+\omega} \cdot \frac{\zeta_o}{R} \quad (r = r_o) \tag{8}$$

In the frictionless expression, the inflow takes place within a thin Ekman layer above the pycnocline. The shear stress at the pycnocline may be expressed by a ,

$$\tau = c_d \, v^2 \tag{9}$$

where c_d is an interface drag coefficient with a typical value of $c_d = 0.4 \times 10^{-3}$. The total radial inward transport in the Ekman layer is

$$Q = 2\rho r \frac{\tau}{\rho f} \tag{10}$$

This flow rate is prescribed by the plant design. From the last few equations it is easy to show now that

$$\frac{\zeta_o}{h} = \frac{r_o}{R} \cdot \frac{(f+\omega)\,\omega}{f^2} \qquad (11)$$

where r_o $(fQ/2\pi c_d \omega^2)^{1/3}$.

Putting $Q = 450\ m^3\ .\ sec^{-1}$, $f = 0.5\ 10^{-4}\ sec^{-1}$, $\omega = f$, $c_d = 0.4\ .\ 10^{-7}$, $\epsilon g = 0.01\ m.sec^{-2}$, $h = 100$ m, one finds $R \simeq 20$ km, $r_o = 1.5$ km and

$$\frac{\zeta_o}{h} = 0.15$$

or $\zeta_o = 15$ m, $\zeta_c = 15.5$ m. The velocity at $r_o = 1.5$ km (the maximum tangential velocity) is 15 cm sec^{-1}.

Such a distortion of the thermal field would probably not significantly affect the efficiency of a 100 MWe OTEC plant. However, there are large uncertainties inherent in this first order model, and the rise in the thermocline could be much greater or less than 15 m. If greater, the rise in the thermocline could reduce the temperature of the water available as a heat source to the plant, and the efficiency of the plant could be significantly decreased. A sufficiently severe disorganization of a density field by an operating OTEC plant may thus pose a significant practical problem if it indeed lowers the temperature of surface intake water. Although the above calculations suggest that such will not be the case for a 100 MWe plant operating on a surface mixed layer 100 m deep, the inaccuracy of our predictions (± three fold) is too wide to dismiss the possibility.

A more thorough and detailed investigation of the OTEC vortex interaction with a cold or warm core ring, andwith a boundary current is required. Perhaps the greatest potential for environmental impact by an OTEC plant arises when the plant is located close to an island. The dynamics of coastal circulation around islands needs tobe explored in depth, beginning with simple analytical models, an evaluation of scattered evidence now available, and leading ultimately to experimental work and synthesis of dynamical theory and observation. The interaction of the OTEC vortex with island coastal circulation should be specifically explored, since the first OTEC plants will most probably be located near islands. Thermal structures in coastal boundary layers are subject to large natural transients related to wind induced upwelling and downwelling. We have no basis on which to forecast the possible interaction of an OTEC vortex with the transient structure in an island coastal boundary layer or in the natural wake of an island.

Simple considerations of fluid dynamics suggest that 100 WMe or larger plants would alter the oceanic environment sufficiently to set up their own mesoscale (order 10-30 km) circulation patterns. Far from coasts, "OTEC vortices" would be embedded in larger scale oceanic flow and could interact with other mesoscale flow features, such as cold or warm core eddies. The vortex produced by a plant located close to the coastline of an island would interact with the specific mesoscale flow environment of an island, i.e. with the coastal boundary layer of an island and with any wake produced by the island. We know of no studies of the possible structure and intensity of the expected OTEC vortex as a function of plant size and ambient oceanic conditions. Nor has there been an attempt to elucidate the behavior of plant induced mesoscale circulation in the presence of a naturally occurring oceanic eddy or a coastal boundary current. Mesoscale circulation systems may be particularly effective in advecting nutrients, biocides or other constituents away from or toward an OTEC plant on time scales of a few days. Their explanation and quantitative understanding are required to evaluate the environmental impact of OTEC plants.

Re-entry of the Discharge Plume into the Surface Layer

Discharges from an OTEC plant will create a new water mass with distinct physical-chemical properties. The discharge rate, equilibrium level, and near field dilution of the effluent plume will be functions of the plant design and site specific conditions (e.g. density structure). The characteristics of water mass (temperature, salinity, and chemical constituency) will depend on the cold and warm water characteristics and modifications incurred during the heat exchange cycle. The ultimate disposition of this effluent water mass (Efwm) is of critical importance for several reasons:

1) the possibility of re-entry of heat, nutrients, and contaminants into the surface waters, and

2) the possibility of field of mass modification such that the initial conditions are significantly altered.

These two reasons are not separable, but for the moment we will focus on the first.

In general, the probability of re-entry is reduced at deeper equilibrium levels (EL); or, the time scale of re-entry is extended with deeper equilibrium levels. When the EL is above the permanent pycnocline, nearly complete re-entry on a seasonal time scale is almost assured; and when the EL is below the permanent pycnocline time scales will be determined by basin characteristics. In any case, re-entry will occur. The tasks are then:

1) to define what constitutes a significant re-entry problem. This must be done for each of the Efwm characteristics since they will have different intrinsic time scales. For example, the scales for heat will, generally, be less than for nutrients since the amount of heat in the surface layer is influenced by air-sea interaction, whereas the amount of nutrients is much less, e.g. from rain.

2) to specify tolerable limits for re-entry. To illustrate this, we define three situations--(a) re-entry is not a problem, (b) re-entry occurs but is acceptable, (c) re-entry is intolerable either from an environmental or plant efficiency sense. These limits must be specified for potential OTEC sites and for a plausible range of OTEC plant capacities.

A research program to address the re-entry problem must be broad since it would deal with vertical mixing processes. However, it could be tailored to specific OTEC application. This can be done by dividing the effort into:

a) systems modeling of re-entry effects,
b) modeling and analysis of re-entry processes,
c) site-specific data acquisition.

a) Systems Modeling

The objective would be to evaluate the effects (environmental and operational) at specified re-entry rates. This would allow evaluation of the potential re-entry problem (as specified above) for any given set of conditions. It would necessarily involve the surface layer ecological model (environmental) and a surface layer heat model (operational).

b) Process Modeling

There are several physical processes that may influence the surface re-entry. These may be studied separately, although it is not essential to do so. Eventually these processes would be quantified in a site-specific time-dependent model so that estimates of re-entry rates may be computed. The most important processes to be studied are:

1) general instabilities of an isopycnal layer embedded in a vertical density gradient,

2) diffusive losses from a thin (≤ 5 m) layer of high concentration set in a stable vertical density gradient,

3) erosion of surface layer density gradients by mechanical mixing,

4) deepening of the surface mixed layer by vertical convection; in particular, that caused by the sinking of surface water,

5) vertical advection (upwelling) that can lead to raising the Efwm to within the euphotic zone.

c) Data Acquisition

For the purpose of driving the process models, the following site specific information is required:

1) a seasonal history of density cycling in surface and pycnoclinal layers,

2) distribution of kinetic energy density in the surface layer,

3) velocity structure through the pycnocline,

4) air-sea interaction forcing,

5) large scale ($\simeq 100$ km) velocity field and field of mass to identify regions of surface convergence and divergence,

6) chemical gradients and seasonal cycling through the entire water column over a large region.

Influence of Adjacent Nearshore Circulation on Transport and Dilution of OTEC-Generated Plumes

Plumes located within 10-20 km of a coastline may be carried onshore where coastal circulation will influence the dispersion. Wind induced onshore movement of subsurface water, i.e. upwelling, is likely to trap plumes along the shore, while rapid dilution of the plumes will occur when wind reversals lead to offshore flow near the bottom, i.e., downwelling. Deep stratified oceans are characterized by strong vertical density gradients (pycnocline) until these gradients intersect the bottom near the shore. Turbulent mixing caused by internal waves in the pycnocline will affect mixing, but their associated energy is damped close to shore, thus removing one of the mixing energy sources for dilution of nearshore OTEC plumes. Finally, eddies induced by currents adjacent to continental and inland shelves can also upwell significant amounts of water from 100-200 m depth. The effects of this type of upwelling depend upon the dynamics of the longshore currents and bottom topography, but the nearshore transport of OTEC plumes could be significantly altered by circulation processes controlled by events farther offshore. The following studies should be undertaken:

1) a climatology of coastal currents should be developed in areas adjacent to coastlines where OTEC plants could be sited.

2) variations in hydrographic structure, coupled with current measurements, should be determined over approximately 100 km along the shoreline. These measurements should resolve time scales of tidal forcing and weather-induced events (order of 12 hours to 14 days), thus defining the frequency and persistence of events which cause the pycnocline to upwell and downwell.

3) hydrographic and current measurements must describe the effects of offshore circulation on the distribution of density in coastal regions. These effects may be manifested by intrusion of ocean water onto shelf and shoreline areas.

4) generic studies of Lagrangian and Eulerian measures of diffusion should be conducted for use of current meter data in determining non-advective fluxes.

An experimental program that encompasses the above four objectives should consist of several intensive field studies coupled with numerical modeling to provide a conceptual and theoretical framework for the field studies. While the exact strategy for the field program will depend on the region, the studies should include hydrographic surveys designed to resolve the above spatial and temporal scales. Complementary measurements of currents will require moored arrays with spatial resolutions increased near the shore. The horizontal and vertical resolution of the array will depend largely on dominant topographic features, the known scales of mesoscale eddies and horizontal and vertical variations in density. Simultaneous measurements of the dispersion of free drifting drogues and dye should be conducted within the moored array of current meters at a scale set by prior estimates of the spatial coherence of the velocity field.

Previous satellite measurements, long-term current meter records, and CTD measurements have shown that oceanic circulation is not uniform in space or time. Models when run with enough resolution also show this variability. We expect that islands which occur in variable oceanic flow fields will perturb the flow. These perturbations will produce local currents which in turn will influence the down stream flow field around an OTEC plant. Local currents will not affect the oceanic scales of motion, but the converse will certainly be true. Thus a study of circulation near an island will require a global perspective to understand large scale forcing in conjunction with measurement programs concentrated near island OTEC sites. Such global perspective may be gained in part from historical data on winds, sea level, tides and hydrographically predicted currents. It may also be gained from satellite data on wave fields, sea level, and sea surface temperature and possibly wind fields.

The Role of Numerical Models in OTEC Environmental Impact and Resource Assessment

Numerical models of the ocean organize knowledge of physical processes into integrated syntheses which attempt to simulate both the natural environment and man's perturbations. The first step–simulation of the natural environment–is the more difficult and the degree to which numerical models succeed has not been established. However, numerical simulations of the atmosphere, as applied to the prediction of weather (fast change of synoptic stages) and climatology (slow change of seasonally varying averages of synoptic states), are encouraging, e.g. numerical weather forecasts are now standard NOAA products. There has been continuous improvement in both parameterizing small scale processes, such as turbulence through theoretical and experimental research, and computer technology. Larger and faster computers or conversely, decreasing cost will noticeably improve our predictive power in the next ten years. While these statements apply to both ocean and atmospheric models (fundamentally the physical processes and describing equations are identical), the ocean does introduce unique problems. For instance, the Loop Current in the Gulf of Mexico and, downstream, the Gulf Stream in the Western Atlantic exist because of continental interruption of the oceanic hydrosphere. Their numerical description awaits solution to severe problems of the underlying physics which require future research. Model development thus derives continuous sustenance from observational programs and model performance must be measured against observations since data acquisition and model validation cannot be separated in programmatic planning and execution. Models of particular interest to OTEC studies are:

1) Surface Mixed Layer Models

During the past five years there has been considerable progress in developing analytical models to describe very small turbulent mixing processes that will not be resolved by direct numerical computation. Such turbulence models, when incorporated into numerical models with reasonable vertical resolution (for example 1 m near the surface increasing to 5 m to 50-100 m depth) have been able to simulate the dynamics of oceanic surface mixed layers and their response to surface wind stress and heat flux as conditioned by water column stability characteristics. These models assume no horizontal variations in velocity, temperature and salinity and are computationally simple. More work will be done in this area but the subject is well understood.

2) Simulation of OTEC Vortex Generation

As discussed previously, in the idealized situation of zero mean current, and OTEC power plant, by sucking in surface and deep water and discharging both at intermediate depth will, through Coriolis interaction, cause a rotating eddy system. This process should be amenable to numerical simulation, with addition of longshore currents in future revisions of the vortex model.

3) OTEC Plume Simulations

Models of near field plume dispersions in a stratified fluid are available. However, numerical models based on turbulence physics, which eliminate previous approximations, should be executed both for near (order 1 km) and the intermediate fields (order 10 km). The near field simulation of a realistic OTEC power plant geometry can be first modeled, with immediate utility in the OTEC design process and in assessing environmental impacts.

4) Frontal Simulations

The sharp front which separates the western edge of the Loop Current and the Gulf Stream poses difficulties in constructing large scale models of the Gulf of Mexico. High resolution simulations of fronts per se would resolve important questions (for example, sensitivity of computed results to horizontal viscosity) which might lead to conceptual understanding of Loop dynamics and which, most certainly, will usefully guide large scale modeling effort.

5) Coastal Regions

In coastal regions special circulation problems exist. These include wind induced coastal upwelling/downwelling, conversion of barotropic tidal energy into baroclinic internal wave energy, mixing and processes such as sediment transport. A relatively high resolution numerical model should supply useful information to guide large scale models and the siting of OTEC power plants.

6) Ocean Basins

The fate of OTEC effluents may be examined with a limited area/large scale circulation model; in particular, it is important to compute the entrainment rate into the upper layer. Since vertical mixing may dominate the dispersion of effluents, the synoptic scale weather disturbances must be properly modeled. At the same time, impacts on climate due to many OTEC plants can be examined using a basin-wide circulation model. Computation of temperature anomalies would be satisfactory but extensive diagnostic analyses are required in order to differentiate the plant's influence from natural variability. A complete air-sea coupling study, on the other hand, is probably suitable only in limited areas.

It is important to develop "realistic" numerical models for OTEC environmental impact assessment. On the other hand, previous experience with some sophisticated three-dimensional models indicated that the model results may be very sensitive to the boundary conditions, the parameterization of mixing processes, and the initial conditions. Model sensitivity may result from inconsistent numerical scheme. This problem can usually be worked out through diagnostic analysis of the energy, momentum and mass balances. However, the more severe problem usually comes from neglecting, or inappropriate formulation of, important physical processes. Because it is not *a priori* clear what the governing processes are in a given region, models per se will never solve the sensivitity problem. Instead, major physics can only be unveiled through process-oriented theoretical studies with experimental verification. In fact, validation of a full circulation model probably can only be achieved (with the present technology) by verifying its individual major components.

OTEC Parks Within Enclosed Seas

The possible impact of numerous OTEC plants on the circulation and climate within enclosed seas cannot be answered until their natural circulation is well understood. Numerical modeling of circulation requires verification before OTEC impact simulations would be considered valid. Consequently, well-conceived field collection and data analysis programs are required to define the mean circulation and its variability at the above scales *before* long-term, large-area OTEC parks are considered or legislated. For example, a numerical model is being developed for the Gulf of Mexico which is designed to address questions concerning the impact of OTEC plants. Discussions about model spatial resolution and verification are continuing, but data required to verify models are not now available. More importantly, the mean and variance of circulation in the Gulf of Mexico is poorly known even on 1° x 1° spatial scales. Less is understood about the Caribbean Sea. A measurement program which contributed significantly to understanding of the Gulf or Carribean circulation would be a multi-disciplined program involving feedback from numerical models, hydrographic station data, Eulerian and Lagrangian current measurements, satellite and aircraft observations, and expanded meteorological coverage.

Horizontal spacing of current meter arrays in the Florida and Yucatan Straits must be less than the baroclinic radius of deformation, and compatible with the numerical model's spatial resolution; temperature and conductivity must be recorded to identify the advecting water masses. Satellite tracked surface drifters need to be deployed in areas outside of the immediate influence of the Gulf Stream, and ALS acoustic floats need to be deployed at 1,000 m throughout the basin, and at the equilibrium level of the OTEC discharge. Periodically throughout the experiment, multiship and aircraft hydrographic surveys are required to define density distributions, and direct current measurements will have to be made in model-defined critical localities to separate baroclinic and barotropic induced flows. Continuity of observations between cruises and flights will be maintained by satellite radiometry, moorings, drifters, sea-level gages, etc., depending on the instruments available.

Determining circulation in the Gulf of Mexico or the Caribbean Sea well enough to confidently predict the impact of a park of OTEC plants is a non-trivial task. For example, notably missing from the above has been a discussion of the vertical circulation. Direct measurements have been successfully made in regions of vigorous upwelling, but vertical velocities estimated from continuity considerations for OTEC have not been demonstrated. A major effort such as proposed must incorporate state-of-the-art technology. For this reason, the effort should be coupled to the launch of the first NOSS spacecraft in 1985 which will obtain data on wind stress, surface temperatures, visible radiances, and sea surface topography. Gearing up the field observation program will require several years. This will provide sufficient time to conduct numerical model sensitivity studies, to design proper experiments, and to make the international agreements. A substantial effort is required, but is necessary to quantify the impact of future large-scale OTEC farms on enclosed seas.

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Chemical Consequences of OTEC

by

D.W. Menzel, L. Atkinson, J. Carpenter, P. Kroopnick, J. Lopez,
J. Ryther, T. Whitledge, and P. Williams

Impacts on ocean chemistry which may result from the operation of an OTEC plant can be divided into four general categories:

1. Redistribution of dissolved gases
2. Redistribution and release of trace metals
3. Release of working fluids
4. Release of biocides

For the purposes of discussion and accompanying calculations, we assumed an OTEC plant of "closed" design, a generating capacity of 100 MWe, a combined discharge of surface and deep water in a ratio of 1:1, with intakes located at <50 m and 1000 m. The total volume pumped was assumed to be 0.7×10^8 m^3 day^{-1}.

The ability to predict the trajectory and dilution rate of discharge plumes is critical to understanding chemical kinetics and changes in concentration which result from the OTEC introduction of elements/compounds into the ocean. Dispersal will vary depending on vertical mixing rates and current velocities at a given site. Not knowing these factors, most predictions of probable impacts are clearly subjective. Thus, it will be necessary to test plume dispersal models. This will require synoptic scale observations, which may best be accomplished if unique tracers of the plumes can be identified.

Unfortunately, the two most easily measured parameters, temperature and salinity, will not be sufficiently altered at the discharge to serve as useful tags in the farfield. Other easily measured parameters include nutrients and oxygen. A summary of expected concentrations within, above, and below the discharge plume is given in Table 2. These calculations are for the Caribbean and do not take into account variations in concentration with depth that may be affected by coastal boundary currents.

Table 2. Expected concentrations of nutrients, oxygen, and light scatter within, above, and below a discharge plume (Caribbean Sea).

Nutrients	Plume Concentration	Ambient Concentration	
		Above	Below
Nitrate	~15 μM	0	5 μM
Phosphate	~ 1 μM	0	0.5 μM
Silica	~15 μM	0	5 μM
Particulate Matter	25 μg/1	~30 μg/1	~10 μg/1
Oxygen	3-4 m1/1	~5 m1/1	~6 m1/1
Light Scatter	~3	~5	~2

Of the above parameters, only oxygen and light scatter can be measured *in situ.* It is unlikely that any can be measured with sufficient accuracy to discriminate the position of a plume after it has been diluted more than 1:10 with ambient sea water.

^{222}Radon occurs in relatively high concentrations in deep water and may provide a useful tag for studies of vertical mixing rates. Since the methodologies used to measure radon are difficult and time consuming, its use as a general, routinely measured, tracer in the far field is limited. The most effective general purpose tag would be flourescent dyes which can be injected into an OTEC outlet. This would require $\sim$7.5 m^3 dye day^{-1} to create a concentration of 100 ppb in the discharge of a 100 MWe plant. Since dyes may be detected with towed instrumentation down to levels of 0.1 ppb, it should be possible to track plumes until diluted 1:1000.

Redistribution of Dissolved Gases

With respect to potential changes in the concentration of gases in OTEC discharge plumes and possible effects on marine organisms, Table 3 shows that a 3-4% supersaturation of oxygen and nitrogen can be expected in the discharge water. Fish are known to be affected when supersaturation values reach 10%. Hence, OTEC effluents should cause no problem in this regard.

Table 3. Solubility of oxygen and nitrogen in water.

Temperature	Solubility (ml/l)	
	O_2	N_2
6°C	6.88	12.35
16°C	5.54	10.21
26°C	4.63	8.60
1:1 mixture of 6 and 26°C water	5.76	10.48
Saturation	104%	103%

Because of pressure effects, there should be no release of bubbles due to supersaturation if effluents are discharged at modest subsurface depths. On the other hand, cavitation caused by circulating pumps has been noted at the Hawaiian Mini-OTEC plant. Bubbles, if released, would accelerate vertical mixing of the effluent water. Cavitation is a design problem which presumably will be addressed by engineers.

Carbon dioxide. Total CO_2 concentrations at the surface and 1000 m are typically 2.0 and 2.3 m moles kg^{-1} respectively. Differences relative to total concentration are trivial, and no effect due to redistribution can be foreseen in a closed OTEC plant. Should an "open" OTEC system be designed, requiring that sea water be degassed, approximately one-half of the total CO_2 would be released to the atmosphere; for a 100 MW plant, this would amount to $\sim 0.3 \times 10^{10}$ g day^{-1}. This OTEC release rate clearly could be a problem when added to current emissions from the burning of fossil fuel, since a coal-fired 100 MWe power plant emits $\sim 0.2 \times 10^{10}$ g day^{-1}.

Redistribution and Release of Metals

Analytical problems associated with the trace metal chemistry of sea water are severe, and technology for the measurement of such elements is continually being refined. In general, values reported as recently as five years ago are now considered high. Table 4 gives values which are considered the most reliable at this time. In most cases, trace metal content of surface waters is at the lower limits of analytical detectability. This places considerable uncertainty on deep/surface ratios. Elements selected for this exercise occur in extremely low concentrations in both surface and deep water. Enrichments of many elements in deep, relative to surface waters, are directly related to nutrient concentrations. This suggests that elevated levels of trace metals at depth result from normal decomposition processes and reflect nothing more than a change in phase.

Enrichment of ambient surface waters by plume discharge of trace metals from 1000 m will not remotely approach total concentrations known to affect marine organisms. However, if the natural chelating capacity of sea water is destroyed by strong oxidants such as chlorine, the speciation of metals will be affected. Phytoplankton photosynthesis is known, for example, to be inhibited at free ion Cu concentrations as low as 6 ng ℓ^{-1} (Table 5). Though most Cu is complexed by inorganic carbonates and hydroxyls, the complete destruction of organic compounds in entrained water may release 10% (or 15 ng) of the total in ionic form (Sunda and Guillard, 1976). Chlorine, because of its rapid decomposition, would have no effect on surrounding water in the very near field, and natural complexation with ambient organics should be rapid. A ten-fold dilution of the plume discharge also would reduce the free ion concentrations to levels well below those known to inhibit photosynthesis. This assumes that no Cu is introduced from the OTEC plant.

A second source of OTEC trace metal enrichment is from corrosion of metallic parts in the heat exchangers. Of the present three options (Titanium, Aluminum, CuNi alloy), titanium and aluminum pose no apparent problem. Titanium is essentially inert. Aluminum will scale rapidly, presumably reducing heat exchange efficiencies to the extent that repeated descaling will be required. This will introduce Al, mostly in particulate form, which will settle rapidly. Again, we see no problem. The last option, CU-Ni alloys, may be severely corroded, resulting in the release of large amounts of Cu. Because there are not guidelines available to predict probable OTEC release rates, an arbitrary corrosion rate of 6 kg Cu day^{-1} is used. This rate of corrosion would raise the ambient concentration of Cu in the immediate discharge by 20 ng ℓ^{-1}, or less than half that normally found in surface waters.

The fate of dissolved trace metals, such as titanium, copper, aluminum, chromium, etc., which may be introduced into the OTEC effluent also depends to a large degree on the concentration of suspended particulate matter. Metals may be removed from solution by adsorption to particulates, although very high concentrations of particulates would be necessary to decrease dissolved metal loads significantly. Suspended material will probably not be produced within the OTEC system itself; thus, particulate concentrations will depend on ambient concentrations in the vicinity of the inlet pipes. Surface concentrations of particulates are typically 5 times higher than in deep water. At an OTEC site, however, concentrations of suspended matter may be abnormally high at 1000 m, depending on the magnitude of resuspension of bottom sediments, a process which depends on bottom boundary currents. Because currents may be strong in proximity to continental shelf and slope, it is probable that nepheloid layers (layers containing high loads of particulate matter) will exist in the vicinity of OTEC intake pipes. There is little possibility, however, that enough particulates can be introduced from such layers to significantly affect dissolved metal concentrations or to otherwise impact the environment.

Table 4. The concentration of selected trace elements in surface and deep waters.

Metal	Study Location	Vertical Gradient	Minimum Surface Concentration (η mo1 kg^{-1})	Concentration Below Thermocline (ηmo1 kg^{-1})	Nutrient Correlation	Approximate Deep/ Surface	Reference
Cu	South Pacific	Surface only*	1*	3*	Yes	––	Boyle and Edmond, 1975
	N. E. Atlantic	No	2	2	No data	1	Moore and Burton, 1976
	Sargasso Sea	Maybe	1.9	2.4	No data	~ 1	Bender and Gagner, 1976
	Pacific	Yes	1.6	3.1	Partial	~ 2	Boyle et al., 1977
	N. E. Atlantic	Yes	1.4	2.0	Partial	~ 2	Moore, 1978
	East Pacific	Yes	1.6	3.8	No data	2	Bruland and Franks, 1979
Cd	Sargasso Sea	Yes	0.04	0.22	No data	~ 5	Bender and Gagner, 1976
	Pacific	Yes	0.3	1.0	Yes	~ 3	Boyle et al., 1976
	East Pacific	Yes	0.06	0.60	Yes	~10	Martin et al., 1976
	N. E. Pacific	Yes	0.13	1.0	Yes	~10	Bruland et al., 1978
Ni	Sargasso Sea	Yes	1.7	3.4	No data	~ 2	Bender and Gagner, 1976
	Pacific & Atlantic	Yes	4.0	9.4	Yes	~ 2	Sclater et al., 1976
	East Pacific	Yes	5.2	9.9	No data	~ 2	Bruland and Franks, 1979
Zn	N. E. Pacific	Yes	0.5	6.6	Yes	~10	Bruland et al., 1978
Hg	Gulf Stream	Maybe	0.01	0.02	Yes	~ 2	Mukherji and Kester, 1979
A1	North Atlantic	Yes†	22-37	22-37	No	?	Hydes, 1979
	Mediterranean Sea	Yes	37	148	Yes	~ 4	Caschetto & Wollast, 1979
	Mediterranean Sea	Yes	74	148	Yes	~ 2	Mackenzie et al., 1978

*Surface samples in upwelling area with variable NO_3 concentrations.

†Mid-depth minimum @ 750 m.

Table 5. Copper sensitivities of selected laboratory cultures, and natural phytoplankton assemblages. Copper concentrations (as -log Cu^{2+} ion activity in moles) are those necessary to cause a 50% reduction in growth rate.

Species	Clone	Sens. pCu	Preference
Thalassiosira Pseudonana	3H	8.6	Sunda & Guillard, 1976
	13-1	9.3	Davey *et al.*, 1973
T. aestevalis	–––	9.2-9.7*	Hollibaugh *et al.*, in press
Skeletonema costatum	Skel	8.5	Morel *et al*, 1978
	Skel	9.4	Guillard & Gavis, in prep.
Dunaliella sp.	Dun	8	Hughes & Morel, 1979
Nannochloris atomus	GSB nanno	9.3	Sunda & Guillard, 1976
Gonyaulax tamarensis	429	10.4	Anderson & Morel, 1978
Monallantus salina	GSB sticho	8.5	Guillard & Gavis, in prep.
Monochrysis lutheri	Mono	10.0	Guillard & Gavis, in prpe.
	Mono	8.4	Sunda & Lewis, 1978
Natural phytoplankton	––––	9.2-9.7*	Hollibaugh *et al.*, in press
	––––	9.3-9.8*	

*pCu estimated from total Cu concentrations by these authors.

Release of Working Fluids

A massive rupture of heat exchangers, would release some 1000 tons of the ammonia working fluid to the environment. This would cause the affected sea water to become strongly basic, resulting in a massive precipitation of carbonates and metal hydroxides. This material should sink and the biological effects would be short-term if an accident occurred over deep water OTEC sites. In the worse case, if the catastrophic release occurred within one day and the ammonia were mixed with the total effluent of the OTEC plant (0.7×10^8 m^3 day^{-1}), a concentration of ~215 μg-at NH_4^+ ℓ^{-1} would be found at depths of 40–200 m next to the OTEC plant, i.e. partly within the euphotic zone. In the immediate vicinity of an OTEC plant, primary production may be severly depressed because at concentrations of 300 μg-at NH_4^+ ℓ^{-1}, ammonium is a potent inhibitor, uncoupling light energy during photosynthesis.

Assuming that the OTEC NH_3 gas is converted quickly to NH_4^+ and dispersed in seawater, it appears, however, that there might be little environmental impact of a catastrophic NH_3 release from one 100 MWe OTEC plant. In a contrasting coastal situation, 2000 μg-at NH_4^+ ℓ^{-1} is the usual pipe concentration at the White Point's sewage outfall off Los Angeles, California. Up to 50-150 μg-at NH_4 ℓ^{-1} at 15 m and 4-5 μg-at NH_4^+ ℓ^{-1} at the surface have been found 1 km away from the diffuser (T. Whitledge, personal communication). Simulation models (Walsh, 1972) and field observations suggest that these surface ammonium concentrations are reduced 50% within 1.5 km during 48 hr of accompanying phytoplankton growth. The fate of small chronic leaks of ammonia, however, when combined with OTEC chlorinated water to form toxic bromamines, is an unknown factor of plant operation.

Release of Biocides

OTEC technology is predicated on unusually high performance of heat transfer which will require maintenance of very low levels of biofouling films on the plant structures. The need for high performance may necessitate the use of mechanical and chemical biofouling controls. The biocide most extensively used in land based power stations has been either gaseous or a hypochlorite solution of chlorine. Alternative biocides may be grouped as other oxidative compounds (ozone or bromine chloride) or compounds whose mode of biofouling control is not through oxidative reactions (pesticides). Cost, ease of handling, on-site electrolytic generation from seawater and presumed lack of persistence in the discharge environment may favor the use of chlorine. Persistent pesticides are not attractive because of cost and potential long lasting environmental effects.

The most recent estimate of a "water quality criterion" for chlorine in marine waters is 10 $\mu g/\ell$ (EPA, 1976). Information available to support the choice of this criterion is modest and, in particular, research utilizing the species of organisms likely to be found at OTEC sites is non-existent. However, on the basis of the current criterion, the anticipated rapid dilution of the discharges from small (1-40 MWe) OTEC plants should limit the area that exceeds the current criterion to a few miles downcurrent from the point of discharge. There is no basis for rejecting the use of chlorine in the early feasibility studies, but the possible environmental impacts from major usage of the OTEC technology remain to be assessed.

Effects of chlorinated discharges on marine organisms may arise through the following mechanisms:

1. Direct toxicity of "residual oxidants"
2. Toxicity of halogenated organic products
3. Formation of carcinogenic, teratogenic or mutagenic compounds
4. Avoidance responses by motile marine organisms (fishes) to chlorine products.

Chlorination of sea water leads to rapid reaction with the natural bromide ion content (rate constant = $3 \times 10^3\ M^{-1}\ sec^{-1}\ [HOCl]\ [Br^{-1}]$) Farkas et al. (1949). Sugam and Helz (1980) computed that oxidation to hypobromous ion would be 99% complete in 10 seconds. Thus, reactions of chlorinated sea water involve hypobromous acid, rather than hypochlorous acid and organic halogenated by-products will be largely brominated compounds. Other oxidizing biocides may react similarly with the seawater bromide ion and no real alternative oxidative biocide has been identified. For example, Williams et al. (1978) found that ozone oxidized bromide ion to hypobromous acid in seawater.

Inorganic bromine compounds in chlorinated open ocean water can be expected to be a mixture of hypobromous acid, hypobromite ion (ca. 60/40), and tribromamine resulting from reaction with ammonium ion in the sea water and tissues of organisms (Carpenter and Macalady, 1975). Presumably these are the compounds that are assayed with the commonly used techniques for the "residual oxidants" or "chlorine produced oxidants" (CPO). Organic bromamines should also be formed and react in the assay for CPO, but there has been no effort to identify these compounds.

The values of CPO in chlorinated nearshore sea water and estuarine waters show a rapid decrease during 30 minutes or so after chlorine addition and a much slower decrease for several days. Most authors favor the supposition that rapid decrease results from reactions of the CPO compounds with more labile fractions of organic matter. The products of these reactions have only been partially identified.

Organic matter + CPO = ? ? ? ? products

For nearshore waters, bromoform and chlorodibromomethane have been identified as part of the products (Carpenter and Smith, 1978) in yields of ca. 4 percent of the added halogen. The pattern with time of essential completion for the haloform appearance in 30 minutes indicates that this reaction contributes to the rapid decrease in CPO.

An obvious possible product is carbon dioxide, which for the expected chlorine doses of 100 ppb or less would be an innocous discharge. Similarly, Singelo et al. (1980) could not detect measurable carbon dioxide one hour after chlorination of Chesapeake Bay water with 1000 ppb of chlorine. After storage for a week at pH 2, however, the samples yielded about one third mole of CO_2 per mole of initial chlorine. These authors feel that partial oxidation of organic matter is a major pathway in the disappearance of the CPO in estuarine waters. The products of the presumed oxidation again remain to be identified.

The extent to which halogen addition or substitution occurs in chlorinated sea water has not been established. However, Morris and Baum (1978) showed that several constituents of open ocean water (i.e., chlorophyll) react with chlorine to produce compounds with carbon-halogen bonds, rather than oxidation products, to an extent of 10-30%. The nature of the products has not been elucidated for lack of the required research but, as these authors note, "since, according to data currently available on carcinogenic effects, most simple chlorinated compounds show about the same level of risk, it is prudent to consider that the health risk is represented more completely by the total chlorinated bond level than by the extent of formation of chloroform or other haloform only".

An indirect effect of chlorinating sea water might be to release toxic ionic copper from natural organic copper complexes. As shown by Carpenter and Smith (1978), chlorination of water from Biscayne Bay, Florida can cause complete loss of copper complexing capacity.

It is clear that an understanding of the potential environmental effects of the discharge of large volumes of chlorinated sea water from major OTEC plants will require the following:

1. Determination of the time course of the disappearance of the chlorine-produced oxidants in waters at proposed OTEC sites. These kinetic data would be coupled with expected dilution patterns to predict the field of CPO concentrations.

2. Determination of the extent of formation of new partially oxidized organic compounds and the responses of the biota to such compounds.

3. Determination of the extent of formation of new halogenated organic compounds and the responses of biota to these. Waters at OTEC sites can be expected to be relatively free of anthropogenic, reactive organic compounds such as phenols, polyaromatics etc., so that halogenated organics could be less toxic than those formed in coastal waters.

4. Determination of the chlorination effects on the copper-organic system for waters at the OTEC sites.

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Biological Consequences of OTEC

by

R.W. Eppley, G. Anderson, F. Azam, M. Dagg, P. Falkowski,
J. Hirota, A. Horne, D. Karl, C. Lorenzen, G. Paffenhofer,
M. Perry, J. Walsh, and P. Yoshioka

Plankton Biology at OTEC Sites

While most of the world plant biomass is terrestrial, the small amount of plant biomass in aquatic systems accounts for 30-50% of the global primary productivity. Of aquatic production, it is estimated that 75%, about 24 x 10^9 tons year^{-1} as carbon, occurs in the open oceans (Table 6), while coastal regions, which account for only 7% of the surface area of the oceans, are responsible for about 13% of the marine primary productivity. The remaining marine productivity is distributed among estuaries, algal beds, and coral reef systems. Within the open ocean, oligotrophic waters of subtropical areas account for *ca* 19% of the estimated annual marine primary production, while these regions occupy over 40% of the oceanic surface areas (Eppley and Peterson, 1979). It is possible that artificial upwelling due to OTEC plants could increase the primary production of these regions tenfold as presently occurs in coastal upwelling areas (Walsh, 1976).

Small organisms characterize the plankton of subtropical and tropical ocean environments, suitable as OTEC sites. Of these, the larger zooplankton are usually omnivores or carnivores which feed on the smaller herbivorous zooplankton. Most of the organisms cannot store energy in chemical storage compounds, such as lipids, compared to animals from temperate zones which must survive over winter (Lee and Hirota, 1976). These observations suggest that food supply has to be virtually continuous for the survival of most tropical zooplankton. Vertical losses from this community must be minimal and the size of the fecal pellets produced must also be small. Small pellets sink slowly and disintegrate fast (Honjo and Roman, 1978; Paffenhofer and Knowles, 1979); it is estimated that less than 1% of the organic matter eaten by zooplankton leaves the euphotic zone

Table 6. Summary table of recalculated values for annual plankton productivity of the five oceans, divided into inshore and offshore zones (Platt and Rao, 1975)

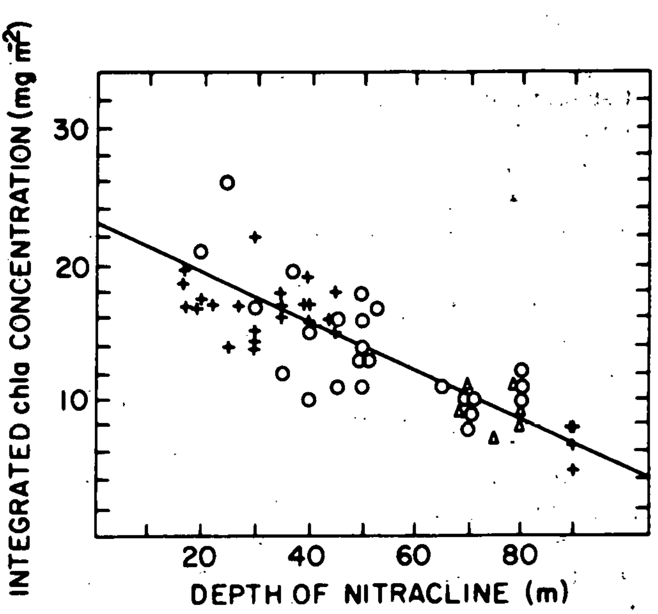
				Primary production				
	Area (10^6 km^2)			(g C m^{-2} d^{-1})		(10^6 t C yr^{-1}) per zone		Total production (10^6 t C yr^{-1} per ocean)
Ocean	Total	Shelf	Offshore	Shelf	Offshore	Shelf	Offshore	
Indian	73.92	2.80	71.02	0.71	0.23	725	5875	6 600
Atlantic	92.57	8.65	83.92	0.41	0.28	1295	8461	9 760
Pacific	177.56	10.67	166.89	0.52	0.15	2037	9360	11 400
Antarctci	23.8-11.8	4.80		0.89				3 300
Arctic	13.10	6.11	6.99					13
Total		33.03				4057	23 696	31 100

(Klinck et al., manuscript submitted). An outcome of the predominance of small organisms with limited swimming abilities (viz. not strong vertical migrators) in the upper 100 m of the tropical ocean is that the rates of life processes and element cycling are very rapid compared to vertical loss rates of particles by sinking. The ecosystem must be very nearly "closed" and approaching a steady state of food production balanced by food consumption, i.e. the biomass of each component of the food web remains approximately constant in time.

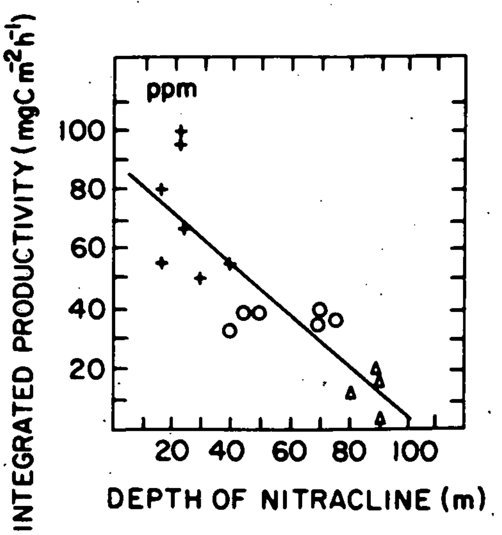
The few studies in tropical waters which have documented temporal variability in standing stock and primary productivity with long-term time series measurements, suggest that variables such as chlorophyll *a*, photosynthesis, and macrozooplankton crop vary by about two-fold about annual averages (Blackburn et al., 1970; Owen and Zeitzschel, 1970; McGowan and Hayward, 1978). In contrast, temperate regions exhibit more than an order of magnitude fluctuations in seasonal abundance of organisms. McGowan (1974) has emphasized the relatively great uniformity of biological parameters in the central North Pacific and the consistent patterns in relative abundancies of macrozooplankton species. Less information is available on the small to mesoscale plankton spatial heterogeneity, but some recent evidence suggests that patchiness and frontal gradients are far less important in possible OTEC regions that other marine environments (Staff and Mullin, 1979).

This difference in spatial pattern may be the result of the relatively great biological age of the surface layers. That is, the residence time of surface waters is long relative to the generation times of organisms inhabiting them and to the biological processes which drain off the nutrients that limit the standing stock of these organisms. This aging process results from physical characteristics of these regions, i.e., essentially permanent stratification and isolation of surface waters depleted of nutrients from the richer deep waters. Exceptions are seen only in areas experiencing high turbulence such as in regions of equatorial divergences, and during the passage of major meteorological disturbances. Dissolved nutrients, such as ammonium, nitrate, nitrite and phosphate are uniformly low, and are then often indistinguishable from the analytical blank, in most subtropical and tropical open ocean surface. A nutricline for NO_3 and PO_4 is usually observed between 100 and 200 m in oceanic waters, and may develop at slightly shallower depths in proximity to land (e.g. 65-95 m off Hawaii). Dissolved nitrogen and phosphorus, whether supplied from depth or by biological regeneration, are immediately stripped out of the water by phytoplankton and perhaps bacteria; hence dissolved nutrients are maintained at low or undetectable levels in the euphotic zone.

Several mechanisms may be responsible for replenishing NO_3 and PO_4 from below the nutricline to support new production within the euphotic waters of the upper 100-150 m. On a local scale, the amount of new nitrogen and phosphorous that is injected into the euphotic zone may be controlled by the depth of the nutricline, the slope of the nutricline, or both. In the Gulf of Guinea (Herbland and Voituriez, 1979), the total primary production of the water column showed an inverse linear correlation with the depth of the nutricline, suggesting a low probability of new nitrogen or phosphorous reaching euphotic waters from a deep nutricline (Fig. 7). Phytoplankton living at or around the 1% light level (the bottom of the euphotic zone) may act as effective filters or traps for nutrients reaching the lower euphotic zone from below the nutricline. In an analogous situation, the steeper the gradient or slope of the nutricline, the higher the probability for nutrient injection into euphotic waters. In addition to local variations in depth or slope of the nutricline and rates of nutrient input into the bottom of the euphotic zone, large scale climatic changes, as reflected in variations of sea surface temperatures, may be linked to rates of input of new nitrogen and phosphorous through changes in nutricline depth or slope. This is the case in the subtropical waters off southern California.



A. Linear regression between the depth of the nitracline and the integrated value of chlorophyll a in the water column.



B. Linear regression between the depth of the nitracline and the depth of integrated value of primary paroduction in the water column.

Figure 7. Correlations of phytoplankton biomass as chlorophyll and primary production with the depth of the nitrate concentration gradient, the nitracline. Measurements from the tropical Atlantic Ocean. From: A. Herbland and B. Voituriez. 1979. Hydrological structure analysis for estimating the primary production in the tropical Atlantic Ocean. J. Mar. Res. 37: 87-101.

By far the most important source of nutrients for photosynthetic growth in tropical and subtropical waters (i.e. ~90%) is from *in situ* biological regeneration in the euphotic zone (~90% vs. 10% "new" nutrients) by excretion of micro-and macrozooplankton and microbial decomposition processes. In the subtropical central North Pacific, for example, zooplankton retained by a 102, μm mesh net can supply on the order of 50% of the phytoplankton daily nitrogen or phosphorous ration required to sustain the low growth rates observed (Eppley et al., 1973; Mullin et al., 1975). The abundance of very small zooplankton, the microzooplankton, in addition to the higher weight-specific regeneration rates of these smaller animals relative to those of larger animals, suggests that microzooplankton contribute a large proportion of the regenerated nutrients (Jackson, 1980).

Nitrogen fixation is an alternative source of new nitrogen in tropical and subtropical euphotic waters. The blue-green alga *Trichodesmium* (Mague, 1977) has been reported to fix nitrogen in subtropical waters, although the reported rates of fixation vary considerably. The importance of N_2 fixation by *Trichodesmium* and endosymbiotic cyanobacteria to the oligotrophic nitrogen budgets may be significant in restricted habitats.

Figure 8 represents a conceptual model for the production, transfer, and fate of organic matter in the euphotic zone at proposed OTEC sites. The rate of primary production in tropical marine ecosystems has been regarded for many years as dependent upon nutrient input rate. The nutrient uptake flux is positively correlated with the *in situ* concentration of nutrients, the metabolic state of the phytoplankton populations and the total biomass of algal cells. The biological oceanographic community is currently in a state of controversy over plankton growth rates and the corresponding rates of uptake and supply. Is growth of phytoplankton nutrient-limited and slow, or is it rapid and not nutrient limited? If the growth is rapid, will an increase of nutrients from an OTEC plant

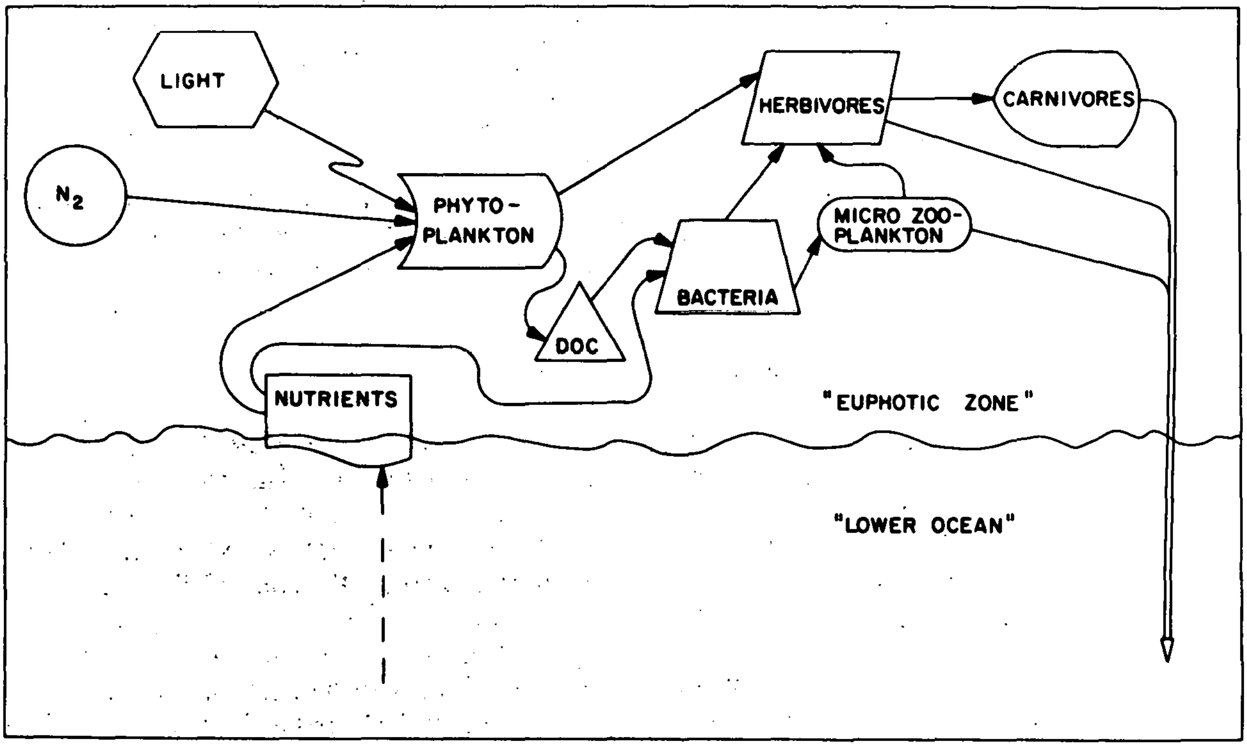


Figure 8. Schematic of ocean food chain within OTEC regions.

cause any increase in phytoplankton biomass and production? In certain natural open ocean ecosystems (e.g. the equatorial divergences in the Atlantic and Pacific), nitrate concentrations are sometimes in excess of needs, yet phytoplankton is unable to increase its population size and consume the excess nutrients either because of high grazing pressure by zooplankton (Walsh, 1976) or for other less obvious reasons. A future resolution of these questions will provide valuable background information for the assessment of the potential results of OTEC nutrient redistributions.

Experiences with Enriching Tropical Waters with Nutrients

Deep water has been artificially upwelled from 870 m off the island of St. Croix in the Caribbean Sea to provide nutrients for continous outdoor cultures of diatoms (Malone et al., 1975). In this case, a mixture of EDTA (chelated) trace metals and vitamin supplements was added to the upwelled water. No zooplankton were initially present in the growth tanks, and a phytoplankton innoculum was introduced at the beginning of each experiment. Under conditions of presumably little trace metal toxicity, small grazing stress, and a coastal phytoplankton species rather than an oceanic community of microalgae, the nitrate content of the artificially upwelled water was depleted after 1-2 days of phytoplankton growth. These experimental results suggest that artificial upwelling of deep water can lead to eutrophication, if, as in the experiments, the surface community is displaced from the equilibrium conditions of the oligotrophic oceanic ecosystem towards the transient conditions of the coastal upwelling ecosystems.

If the OTEC plants, rather than being a source of local upwelling, might act as a source of local downwelling by sinking below the euphotic zone significant fractions of the surface zooplankton community, then the ambient grazing stress of the off-shore oligotrophic ecosystem would be decreased. If all of the OTEC far-field nutrient supply was not being used because of quasi-continuous grazing pressure, then partial removal of the grazers might result in increased nutrient utilization, higher primary productivity, and perhaps higher terminal yield of local fish populations. There has been much discussion of the fragility of tropical terrestrial ecosystems in response to human perturbations (Ferri, 1974). It is possible also that tropical oceanic ecosystems, with their relatively low nutrient input, low frequency of variability, and long residence time of surface waters may not have the necessary resilience (Holling, 1973) to response to such perturbations of the plankton communities, as might result from OTEC operations. These organisms are not usually subject to the same high frequency fluctuations as those of the coastal ecosystem.

Roles and Importance of Microorganisms

During growth in oligotrophic marine ecosystems, phytoplankton may excrete up to 25% of their gross carbon production as small molecular weight organic molecules. This mechanism contributes to the maintenance of the dissolved organic matter (DOM) pool which collectively represents the largest reservoir of organic carbon in the ocean. Other major sources include soluble excretory losses, death and autolysis, and carbon losses during grazing. Pomeroy (1979) has recently emphasized the importance of the DOM to the productivity and functioning of marine ecosystems. The ability of bacteria, and other microheterotrophs to efficiently scavenge dilute concentrations of soluble organic material and convert many of its molecular species into a more concentrated particulate from has only recently been acknowledged as a potential source of carbon to the marine food web. Pomeroy (1979) estimates that this DOM - bacterial link, i.e., the detrital food web, may represent an increase of ~30% to our currently measured levels of primary production. If OTEC plants were to release chlorine produced oxidants to the ambient oligotrophic ecosystem, the role of DOM in the decay or reduction of these oxidants may be important (see report of Chemistry panel).

Problems of Measurement

The interpretation of observed changes in oligotrophic ecosystem rate processes and the relative importance of those processes that might be altered by OTEC plants must be considered in the context of the limitations of our present analytical tools: (1) In oligotrophic waters, detritus comprises about two-thirds of the total particulates. In the central North Pacific, for example, phytoplankton carbon is about 35% of total particulate carbon. The large proportion of detritus makes planktonic biomass and rate measurements difficult to calculate and evaluate; (2) rate measurements, such as phytoplankton ^{14}C and ^{15}N-assimilation techniques suffer from two basic problems - a containerization effect with species mortality (and differential mortality within an experimental bottle) and/or sensitivity problems due to the low number of organisms giving a relatively low signal to noise ratio in the analysis); (3) specific rate processes of phytoplankton, attached bacteria, and microzooplankton are difficult to analyze separately. The organisms and detrital particles are about the same size and it has been impossible so far to separate them adequately; (4) the large species diversity of the plankton and the lack of a few dominant species (numerically or by weight), makes it difficult to generalize from the physiology and behavior observed for the few species so far studied in the laboratory to the entire plankton. This is important in assessing transfer efficiencies between predator and prey as well as in modeling, since to some degree "every species is different". The importance of any one factor such as nutrient limitation or herbivory in controlling nutrient utilization in the sea depends upon the spatial and temporal scales of habitat variability characterizing the ecosystem (Walsh, 1976). Further evaluation of OTEC environmental consequences will have to await information on the rate processes of the plankton communities at the projected sites, with attention to the above caveats. Appropriate time series measurements need to be begun now with respect to the life cycles of the "sensitive" organisms of the oligotrophic ecosystem and the natural inter-annual and seasonal variation in standing stocks and production.

Ecological Modeling

Our physical, chemical, and biological evaluations of possible response to commercial operation of OTEC plants suggest that one 100 MWe plant would have little or unmeasurable effect on the ambient oceanic oligotrophic ecosystem, with increasing probability of impact close to land. In contrast, an OTEC park of 500 or a thousand plants could have a significant impact on the climate, ocean circulation, and the oligotrophic plankton community (Fig. 6). At present, our expectations of the use of ecological modeling to evaluate the future effects of such an OTEC park are restricted to those of heuristic value, i.e., as a research tool rather than as a management tool. Models are extremely important in guiding measurement programs by identifying gaps of knowledge during initial synthesis efforts. Models also serve as a valuable integrating tool for interfacing information exchange between investigators. At the end of a research program after proper validation, OTEC ecological models can be used as management tool at the appropriate time and space scales.

All ecological models are functions of the data sets used in constructing them, however. Non-causal models, such as regression and time series analyses do not necessarily examine mechanisms, but provide correlative information. Causal models involve declarative statements about forcing functions and mechanisms of energy transfer which can be used to erect testable hypothesis for field validation experiments (Walsh, 1972). The necessary mathematical tools already exist for analytical or numerical (i.e. simulation) solutions to equations of causal models; the stumbling block is the absence of qualitative conceptual models and measurements of pertinent rates and concentrations. It is impossible to build a "general" model of the "real world"; the construction of an ecological model for a park of OTEC plants must thus be in response to a series of specific questions. The following questions have therefore been raised concerning the ecological effects of OTEC technology. Research needs can be identified in the course of seeking answers to them. Some answers may be provided by relatively simple modeling studies based upon physical sub-models of OTEC-induced circulation. Others may have to await operational OTEC plants and measurements in the field. Additional studies are needed at prospective sites before operating plants are on line in order to establish scales of natural variability in rates and concentrations.

Specific Questions

1. Will OTEC operations result in a net gain or a net loss of planktonic organisms?

Loss of organisms can be expected in the flow of seawater through the OTEC heat exchangers and in surface waters entrained within the sinking effluent plume, especially during chlorination. If we assume all the plankton involved in these flows is ultimately lost, then the quantities can be calculated from the physical model of the sinking plume, flow rates, and ambient concentrations of plankton. Residual oxidants in the spreading plume at depth will then be of significance only to the plankton indigenous to the depth of the spreading plume and to vertically migrating animals that may swim through it.

Net gains of plankton organisms may result some distance away from the OTEC plant as a result of increased nutrient input to the euphotic zone associated with the shoaling of isopycnal and nutricline depths (Voituriez and Herbland, 1979). The interaction of nutrient input rate and herbivore grazing rate in regulating an oligotrophic ecosystem must be resolved. Studies using models of the OTEC-induced circulation can then provide, with appropriate assumptions, the relative magnitude of losses and gains of planktonic organisms to be expected. Later these expected effects must be measured in the circulation region of an operational plant. Measurements of net gains of plankton associated with shoaling nutricline depths and increased primary production are state-of-the-art in oceanography, however. Assessment of plankton losses in the field is not so readily done. Sediment traps to collect sinking particles under the spreading effluent plume may provide a useful approach to assessing plankton mortality. Evidence from sediment traps at 200 m in the North Pacific Central gyre indicates that most of the material now settling out of the euphotic zone is fecal pellets from crustacean zooplankton. The ability to measure increased activity of bacterioplankton and flows of material and energy through detrital food webs associated with the sinking and spreading plume is becoming more experimentally tractable and may prove useful.

2. What will OTEC operations do to fish and other nekton?

Fish and other nekton in general are attracted to offshore structures (Rounsefell, 1972) can be expected to increase their ambient concentrations about OTEC plants. The annual yield of marine fisheries is presently 60-70 million tons, with most fish caught on continental shelves. If technological capture problems could be solved, very large additional catches of lantern fish (Myctophids) and other small oceanic fish could be taken from oligotrophic areas of the ocean (Gulland, 1976). These fish feed on zooplankton, are sources of food for tuna, and are in an average abundance of one in every thousand m^3 (Cushing and Walsh, 1976), i.e. only *one* potentially harvestable 10-15 cm long fish is presently supported in a thousand cubic meters in the oceanic habitat. Increased concentrations of these fish would lead to an increase of their potential harvest.

No information is available on biocide or entrainment impacts on oceanic fish and nekton species expected at OTEC sites. The daily intake of surface water would be $\sim 0.3 \times 10^8$ m^3 day^{-1} for a 100 MWe OTEC plant and entrainment on the heat exchangers could lead to essentially 100% mortality of large zooplankton and fish eggs and larvae. Small zooplankton may not be mechanically damaged since the heat exchange tubes will be ~5 cm in diameter, but because of thermal shock due to displacement from surface to OTEC equilibrium levels (10°C) and small body size, they may not be able to return to the surface from the 150-200 m depth of the effluent plume. Without a vortex flow pattern, at an OTEC entrainment rate of 2.5 cm sec^{-1} at the plant and <02.5 cm sec^{-1} at a distance of 1 km, adult fish could escape, but the former is half the mean flow of surface water in the Middle Atlantic Bight, e.g., and faster than the speeds of weak-swimming plankton. Although the total amount of oceanic plankton mortality may be lower than at coastal plants, the percentage of community mortality resulting from OTEC entrainment maybe similar or higher than that of coastal regimes.

Acting as a predator on plankton, an OTEC plant might daily deprive 0.25×10^5 adult fish of their prey in the vicinity of an OTEC plant. If each fish weighs 10 g, a loss in carrying capacity equivalent to 0.25 metric tons per day of oceanic fish might occur with the emplacement of each OTEC plant. As with plankton, however, net gains or losses of fish and nekton will result both directly, as a result of mortality due to impingement, entrainment and biocides, and attraction to the structure, as well as indirectly via changes in the amount of biological production of plankton and in its character (i.e. whether via detrital food webs of pathways leading to fish forage).

3. *Will the nature of local food webs leading to commercially harvested species be influenced by OTEC plants?*

This question is difficult to answer for a number of reasons: 1) the degree of increased nutrient input rate to the euphotic zone by the OTEC-induced circulation is not yet clear; 2) present theory and observations on food web changes associated with increased nutrient input rate are not well advanced; 3) in the real ocean, the spatial scale of the area of increased production would likely play a large role in the extent and persistence of any qualitative changes in pelagic food webs. Theory is not well developed here ether.

Comparisons of rich, coastal areas, with relatively high rates of nutrient input and production, to the oligotrophic central ocean reveal that there are few species in common. Equatorial upwelling areas are more appropriate comparisons with potential OTEC sites (Walsh, 1976). But the plankton dynamics of these ecosystems are not well known. Short term laboratory-scale enrichments of oligotrophic oceanic surface water (in bottles) have thus far shown changes in plankton species composition along with increased photosynthetic production (Menzel, Hulburt, and Ryther, 1963). Large experimental vessels, such as huge plastic bags (e.g., as in CEPEX experiments) have not been used in such work as they have at coastal sites (Harrison et al., 1977; Lee et al., 1977; Thomas et al., 1978). Reduction of vertical circulation and turbulence in such devices might impede their use in simulating the real ocean, however.

An OTEC park of ten 100 MWe plants could essentially convert its host area from an oligotrophic to a eutrophic ocean area with production analogous to that in upwelling areas if we purposefully set about to do so. We expect this would result in wholesale changes of the species assemblages in the vicinity of the OTEC plant, since experience in different regions of the oceans suggests that the linear dimensions of the phytoplankton tend to increase with increased nutrient input rate. These larger phytoplankton are associated with larger crustacean zooplankton that provide food forage for harvestable fish. The size of the organisms at each level of the food web (O'Connors et al., 1978) may be as important as total production in determining the ultimate yield of the food web to man. Thus question 3 is non-trivial, especially as it concerns a) beneficial effects of the technology, and b) effects that may increase with the spatial scale of induced circulation and hence may be relatively more important for multiple OTEC plants than for a single plant.

4. How close together can OTEC plants be placed to optimize plankton production?

Although the present physical conceptions of the 60-70 m discharge depth and an OTEC vortex circulation suggest minimal nutrient enrichment of the euphotic zone, some worst case calculations may provide perspective. Here we include two sets of rough calculations. The first is based upon studies of natural coastal upwelling, the second on observations off the southeast coast of the U.S.

The Offshore Upwelling Example

Spacing of the plants will be determined largely by the need to avoid recirculating discharged water. However, it is instructive to consider plant spacing from a production biology viewpoint. Pertinent historical observations are: 1) phytoplankton generation times in nutrient-rich euphotic zones are 2-3 days; 2) maximum natural levels of chlorophyll in coastal diatom blooms are about 15 μg liter^{-1}; 3) maximum daily production is about 5-10 g carbon m^{-2}; day^{-1}; and 4) maximum chlorophyll in the euphotic zone is about 300 mg m^{-2}; and 5) the ratio of phytoplankton chlorophyll produced, to nitrogen consumed is about 1.0 g/mole. Conditions 2 and 4 suggest a 20 m euphotic zone. In practice, the euphotic zone will be deeper unless there is a surface discharge and effort is deliberately made to restrict the nutrient redistribution to such a shallow layer.

Nevertheless, as a worst case we assume a surface discharge which injects a mixture of deep and surface water containing 15 μM nitrate ℓ^{-1} (recall Table 2) and that this discharge remains in the upper 20 m long enough to allow complete utilization of the nitrogen by phytoplankton. At steady state we have a phytoplankton standing stock with a maximum value of about 300 mg chlorophyll m^{-2} or 300 m moles phytoplankton N m^{-2}. This crop doubles itself by growth in two days (a maximum estimate), and thus consumes 150 m moles N m^{-2} day^{-1}. The maximum nutrient input of a 100 MWe plant may be 1.1×10^6 moles NO_3 day^{-1}. The requisite area of phytoplankton production to consume this input (without recycling of NH_4^+) is (1.1×10^6 moles N m^{-2} day^{-1}) $\div$ (0.15 mole N m^{-2} day^{-1}) or 7.3×10^6 m^2 = 7.3 km^2. This is equivalent to the area of a circle ~3 km in diameter. If conditions were such as to maximize phytoplankton production, as in this example, plants would need to be spaced ~3 km apart if the affected area were circular about each plant. Ocean currents would probably result in elliptical or plume-like areas of high production and, obviously, plants should be spaced in a line perpendicular to the current in order both to minimize recirculation of discharged water and to maximize primary production.

The Nearshore Upwelling Example

Certain predictions regarding the permissible clustering of OTEC plants are possible using analogies to the southeast continental shelf circulation regime. The regime consists of: (1) travelling, recurring eddies which upwell water at the shelf break and are analogous to the downstream dispersion of plumes; (2) trapped intrusions from which rates of nutrient utilization, etc., can be derived and (3) areas of continuous upwelling which are most analogous to areas in close proximity to an OTEC plant.

Assumptions regarding upwelling velocities and volumes from a 100 MWe OTEC plant (see the Executive Summary) suggest:

(a) The volume upwelled by a typical travelling eddy on recurring time scales of 5-10 days is equivalent to the output of eight 100 MWe plants over approximately two weeks.

(b) In the Charleston Bump and northeast Florida regions upwelling is continuous. In the former case, depending on assumptions concerning velocity gradients, one "bump" eddy upwells water from 400 m at rates of between 6 x 10^9 and 2 x 10^{10} m^3 day^{-1}, equivalent to respectively 200-600 OTEC plants of 100 MWe capacity.

For the purposes of further discussion we assume that eight 100 MWe plants, or the equivalent, will operate in an area of 100 km^2 (the size of a typical eddy), that deep water from the plant is discharged directly into the euphotic zone and that downstream dispersal rates in the two cases are equivalent. The following tentative predictions relating to effects on primary-secondary production are then possible:

(a) little or no effect on phytoplankton production will be seen within an area of approximately 3 days downstream distance from the OTEC plants. Increases in production would then reach values of up to 1 g $C/m^2/d$ (10 times over tropical values), depending on dilution rates, and plant species dominance would be changed from typical tropical flagellates/coccoliths to diatoms. The nutrients will be exhausted in a distance about 14 days downstream travel time from the plant and no further effect should be evidenced at the surface.

(b) Zooplankton will develop in the plume, obviously at a slower rate than phytoplankton. These would be dominated by small forms with short generation times and production could most likely be limited to the development of single cohorts. Enhanced zooplankton production will certainly compensate for mortality resulting from entrainment but occurrences will be displaced spatially.

(c) The temporal sequence of diatoms to small zooplankton will provide a downstream environment which could enhance the production of filter feeding pelagic fish.

(d) On the negative side Haddad and Carder (1979) show that red tides may be triggered by periodic upwelling of the west Florida Loop Current. If transport were offshore the effect would be slight but if deep upwelled water were trapped along shorelines a significant impact could result, particularly in areas of coral reefs. Also mortality of fish or lobster larvae caused by entrainment of surface water could be serious but this is impossible to predict until site-specific information on abundances, spawning times, etc., is available.

From the above, a cluster of between 10 and 50 100MWe OTEC plants would have no more eutrophication impact on biological events than normal intrusions/eddies which occur on the southeast Atlantic coast of the U.S. These impacts will be entirely acceptable if plume dispersal rates from such OTEC plants are anywhere near those evidenced near intrusions. These rates, of course, will be influenced by site specific events and topography, namely currents, winds, variations in the depth of the mixed layer, σ_t differences between water pumped and depth of discharge, proximity to shore, etc. Yet, we may be able to predict the magnitude and sequence of biological events that will result from discharging cold water into the surface and how many OTEC plants can be clustered in acceptable proximities, when realistic dispersal models and information on fish larvae and plankton abundances becomes available. Excluding the latter unknowns there would have to be huge differences in physical parameters between proposed OTEC sites and the southeast continental shelf of the U.S. to make an OTEC park less than 800 MWe in a 100 km^2 area unacceptable. This prediction has a huge safety factor built in as the upper limit, based on Charleston Bump calculations, and could increase the number of OTEC plants to at least 4000 MWe within the same area, i.e. 4 plants 10 km^{-2}.

5. *If the ecological effects of OTEC are small, how may they be recognized from natural variability?*

Small changes in plankton stocks and metabolic rates induced by human activities are difficult to discern because of natural variability – i.e., the signal is lostin the noise. Several recent studies of this natural variability have revealed that the variations are not entirely stochastic but are linked either to mesoscale processes, as wind-induced upwelling, or to larger-scale climate changes with time scales of months (Walsh, 1978). These larger scale variations can be identified, for example, through sea level and sea surface temperature anomalies. Such studies can be extended to potential OTEC sites. They involve collecting information for many months or years in order to establish a time series of variability, for example in plankton stocks and production and nutricline depth, for comparison with climate records such as sea level or temperature. Success is not *a priori* assured that such correlations will be found. Nevertheless, a search for them should be part of any extensive ecosystem study of OTEC sites. Recent studies off southern California, for example, have been successful (Smith and Eppley, in prep.).

At the other end of the temporal spectrum, beyond gross seasonal and year to year patterns, the present OTEC biological sampling rate of every 2-4 months makes impossible any statements about the variability in organisms that live 2-4 weeks or less. Additional thought must be given to the impact of increased sources of mortality (impingement, thermal shock, biocides, and trace metals) on the herbivores of the oceanic system. If present theory (Walsh, 1976) is correct, these organisms would be the most sensitive "control" of the oceanic systems. The herbivore scale of interaction with the OTEC plants must thus be coupled to the physical forcing in an ecosystem context, i.e. study must be made of the appropriate scales of natural and OTEC-induced variability of the oceanic system.

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WORKSHOP ON THE ENVIRONMENTAL EFFECTS OF FUTURE OTEC PLANTS

January 22-24, 1980

Brookhaven National Laboratory, Upton, New York 11973

Participants

George Anderson	University of Washington
Larry Atkinson	Skidaway Institute of Oceanography
Farooq Azam	Scripps Institution of Oceanography
Jack Blanton	Skidaway Institute of Oceanography
Jim Carpenter	RSMAS, University of Miami
Gabe Csanady	Woods Hole Oceanographic Institution
Michael Dagg	Brookhaven National Laboratory
Jack Ditmars	Argonne National Laboratory
Richard Eppley	Scripps Institution of Oceanography
Paul Falkowski	Brookhaven National Laboratory
Jed Hirota	University of Hawaii
Tom Hopkins	Brookhaven National Laboratory
Alex Horne	Lawrence Berkeley National Laboratory
David Karl	University of Hawaii
Peter Kroopnick	University of Hawaii
Lloyd Lewis	U.S. Department of Energy
Jose Lopez	University of Puerto Rico
Carl Lorenzen	University of Washington
Bernie Manowitz	Brookhaven National Laboratory
George Maul	Atlantic Oceanographic and Meteorological Laboratory
Helen McCammon	U.S. Department of Energy
George Mellor	Princeton University
David Menzel	Skidaway Institute of Oceanography
Gus Paffenhofer	Skidaway Institute of Oceanography
Mary Jane Perry	University of Washington
Dale Pillsbury	Oregon State University
Don Pritchard	State University of New York
Gil Rowe	Brookhaven National Laboratory
John Ryther	Woods Hole Oceanographic Institution
George Saunders	U.S. Department of Energy
Sharon Smith	Brookhaven National Laboratory
John Walsh	Brookhaven National Laboratory
Dong Ping Wang	Argonne National Laboratory
Terry Whitledge	Brookhaven National Laboratory
Peter Williams	Scripps Institution of Oceanography
Paul Yoshioka	University of Puerto Rico

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