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OTEC PHYSICAL AND CLIMATIC ENVIRONMENTAL IMPACTS

by

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OTEC PHYSICAL AND CLIMATIC ENVIRONMENTAL IMPACTS

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Abstract

Assessment of Ocean Thermal Energy Conversion (OTEC) environmental impacts and resource utilization requires an understanding of the physical processes underlying the interactions between an OTEC plant or plants and the ocean. This paper presents an overview of the U.S. Department of Energy program for the development and application of analyses and models for the prediction of the physical aspects of OTEC impacts. Predictive tools are necessary to address problems at different site areas, scales of OTEC deployment, and time horizons.

The effects of intake/discharge designs and of ambient ocean conditions on recirculation and near-field effluent plume behavior have been investigated by means of physical models. Further study of the intake flow fields may be necessary to make estimates of intake impingement and entrainment effects. Mathematical analysis of intermediate-field mixing of plant effluents has shown that effluent plumes may have vertical dimensions on the order of meters and lateral dimensions on the order of kilometers. Models of oceanic regional and island coastal circulation are required to investigate far-field effects on the scale of tens of kilometers. Basin-wide resource renewal and physical environmental effects are being studied by means of a numerical model of the Gulf of Mexico with detailed vertical resolution. Concerns regarding climatic impacts presently are focused on atmospheric CO_2 loading and modification of air-sea heat exchange processes due to OTEC operation.

Introduction

The assessment of the physical aspects of OTEC environmental impacts and resource utilization is an integral part of the overall OTEC Environmental and Resource Assessment program. That broader program includes the biological and chemical aspects of OTEC impingement on the ocean environment and is managed for DOE by the Lawrence Berkeley Laboratory.[1] The purpose of the Argonne program is to provide the development and application of analyses and models necessary for the assessment of potential OTEC environmental and resource utilization problems. Physical transport and mixing processes are at the base of ecological impact assessment, and predictive means for simulating these processes are required. Predictive tools are necessary to address environmental and resource questions for a variety of potential site areas, scales of OTEC deployment, and time horizons. That is, not only must questions regarding initial demonstration plants be addressed, but also questions regarding future large-scale deployments must be addressed in terms of environmental impacts and thermal resource utilization and availability.

The purpose of this paper is to present an overview of the physical impacts program. The overview describes the status of the program outlined at the previous OTEC conference[2] and emphasizes progress achieved and projects initiated within the past year. The approach is to identify the specific problems being addressed, to summarize what we know about their solutions or what tools are available to address them, and to indicate those problem areas where we know little and need tools developed. The details of model development, applications, and results will not be discussed in this overview paper, and the reader is directed to the papers by individual investigators, cited below, where such information can be found.

The discussion here is focused on three general problem areas: thermal resource utilization, physical environmental impacts, and climatic impacts. The problems of thermal resource utilization and physical environmental impacts are treated in terms of single- and multiple-plant deployments and various spatial scales. Several physical processes affect both resource utilization and environmental impacts. Distinct separation of the tools to deal with such processes, in terms of different problems, is not possible, and, in some cases, the same tool will be applicable to more than one problem.

Thermal Resource Utilization (Single Plant)

The OTEC power cycle is driven by a relatively small temperature difference (thermal resource) compared to most other power generating schemes using a thermodynamic cycle with typical temperature differences expected to be in the 18-24 C° range. Due to the fact that about 25% of the normal gross electric power generated must be used to operate the plant and the fact that only about half of the total temperature difference exists across the power cycle, any fractional loss in thermal resource is magnified by a factor of about 2.7 in terms of fractional loss in generating capacity. For example, a 1 C° loss in thermal resource will reduce the net output of an OTEC plant by about 12%.

The temperature difference available to an OTEC plant depends both on the ambient ocean conditions at the site and on the design of the plant itself. The problem is to predict the effects of plant-ocean interactions on available thermal resource as a function of plant design and ocean conditions. Because the temperature of the deep, cold water resource is expected to remain relatively constant, the available temperature difference depends primarily on the warm sea water intake temperature. Warm water (evaporator) intakes will be located in the upper mixed layer, near the surface, where ambient water temperatures are usually greatest. Ambient water temperatures in this region may exhibit variability with hourly, daily, and seasonal time scales in response to perturbations to the heat balance by the passage of weather fronts and ocean circulation features. The water temperature available at the evaporator is a function not only of ambient ocean temperature variability, but of the interactions between the flow fields generated by the intake and the plant discharges with the surface water. The extent of these interactions and the resulting warm water intake temperature will depend on the ambient temperature, density, and current structures in the vicinity of the plant and on the location and configuration of the intake and discharge ports. The thickness of the mixed layer, the ambient currents in the mixed layer, the depth of the intake, the orientation of the intake, the separation of the intake and the discharges, and the orientation of the discharges are all important in determining the resulting flow field and thus the intake temperature.

The effects of intake design and discharge design on warm water intake temperature may not be independent. However, it is convenient to assume initially that discharge effects can be minimized by prudent design and to consider separately what is known about intakes. A discussion of direct recirculation from discharges to intakes will follow.

Evaporator Intake Temperatures

The variability of evaporator intake water temperatures depends both on temporal changes in the ambient water temperature and the mechanics of the intake flows. In physical model experiments the effects of the unsteadiness of the water temperature field in the vicinity of a plant were neglected, and the temperature of water drawn into the evaporator depended on the intake flow fields. An intake in a homogeneous (with respect to density) mixed layer will draw water from over the entire vertical extent of the mixed layer. Withdrawal of colder water from the thermocline region below the mixed layer is possible under certain conditions, but physical model studies[3] have indicated that such withdrawals would not be likely for typical 200-MW OTEC plant designs until the intake structure was within about 10 m of the bottom of the mixed layer. In cases where the mixed layer is so shallow that the evaporator intake is in the thermocline or where some vertical density stratification exists in the "mixed layer," intake water may be selectively withdrawn from over limited vertical extents. While the thickness of such a withdrawal layer grows with distance away from the plant and is not easily predicted, it is likely to be on the order of tens of meters within a kilometer of the plant.[4] The intake temperature is determined by the distribution of flow in the withdrawal layer and vertical ambient temperature distributions. Given relatively symmetric distributions of both flow and temperature, mean intake temperatures will be about equal to ambient temperatures at the elevation of the evaporator centerline. Limited observations of intake temperatures in physical model experiments with ambient stratification do not contradict that suggestion.[5] The evaporator intake flows, then, act to integrate spatial variations in water temperature.

Temporal changes in intake temperature depend on the degree to which temporal variations in ambient water temperatures are damped out by the integrating effect of the intakes. Clearly, the unsteadiness of near-surface water temperatures will not be felt in intake temperatures, if water temperatures over the bulk of the mixed layer remain constant. On the other hand, if temporal variability exists throughout the mixed layer, intake water temperatures may reflect it. Present observational programs for OTEC[6] at potential site areas include the use of thermistor chains that record water temperatures on an hourly basis at ten-meter intervals in the upper 100 m of the water column. Data from the thermistor chains will provide adequate statistics on relatively short-period ambient water temperature variability. Those data and a more detailed understanding of the mechanics of the intake flow fields for various plant designs are needed to assess the potential for short-period variability of intake water temperatures.

Direct Recirculation of Plant Effluent to the Evaporator

The temperature of the warm water drawn in by an OTEC plant can also be affected by the presence of the discharges from the plant, and some fraction of the discharge effluent may recirculate directly into the warm water intake. The mode of discharge (separate evaporator and condenser discharges or a mixed discharge), the vertical separation of the evaporator intake and discharge ports, the depth of the discharge with respect to the mixed-layer depth, the angle of the discharge with respect to the horizontal and to the ambient current, and the discharge and ambient current velocities will all affect the near-field behavior of the discharge jet and its interaction with the evaporator intake flow field. Prediction of the magnitude of the effects of the discharge on the warm water intake temperature is necessary so that the potential for resource degradation through recirculation can be given proper consideration in the process of selecting a discharge mode and designing the discharge ports. The complexity of the near-plant flow fields has resulted in the use of laboratory physical models to examine these effects.

Initial physical model studies focused on highly schematic versions of OTEC plant intakes and discharges and/or of the ambient ocean. The direct recirculation from a single round, non-buoyant jet directed horizontally into a uniform ambient current to a horizontal, radial intake located above the jet was studied by Hydronautics.[7] Discharges into counterflowing (head-on), crossflowing, and coflowing currents were examined, and separation distances between intakes and discharges were varied from 1-2 discharge port diameters. These studies showed that direct recirculation varied with the magnitude of the ambient current such that it increased with increases in ambient current to some maximum (at ambient currents ≈50-70% discharge velocity) and then decreased for further increases in ambient current. The amount of direct recirculation was a function of the orientation between the discharge velocity and ambient current, and the maximum recirculation values observed, for the range of intake/discharge separations considered, were 30%, 10%, and 3% for counterflowing, crossflowing, and coflowing conditions, respectively. Tests with different intake designs yielded recirculation values of the same magnitude or less. Increases in the vertical separation distance between intake and discharge and making the discharge negatively buoyant acted to decrease recirculation below the values given above.

Additional studies[7] on the inhibition of recirculation due to the negative buoyancy of the effluent relative to mixed-layer water involved an intake port positioned 0.5-2.0 port diameters above the interface with a stagnant, denser layer. The inhibiting effect of the density difference was found to be substantial, and the largest withdrawal from the lower layer was found to have occurred for the case of a round intake port drawing water vertically upward. Even in this case, a separation equivalent to 10-15 m was sufficient to keep recirculation to less than 10% for an intake equivalent to a typical 200-MW OTEC plant. The use of a horizontal radial intake was found to reduce recirculation to less than 5% even with vertical separations of only 10 m, and intakes drawing flow from the surface vertically downward were found to reduce recirculation even further.

To put these recirculation values into perspective, if the discharge is 3 C° cooler than the intake temperature (typical of the evaporator discharge) and the total thermal resource is 22°C, a 25-30% recirculation corresponds to a 12-16% loss in net power. This corresponds to experimental results for essentially a worst case situation with a neutrally buoyant discharge located only 1-2 port diameters below the intake and directed into a strong oncoming current. A more typical situation is the one in which only part of the discharge will be directed into the current while part of the effluent will be directed perpendicular to the current and part of the effluent in the same direction as the current. The maximum total recirculation would then be 10-15% even for an intake/discharge separation of 1-2 port diameters and a neutrally buoyant effluent. The corresponding net power loss is only 4-8%.

Additional schematic physical model experiments were carried out at MIT by Jirka et al.[8,9] to study a mixed discharge from an OTEC plant discharged at the mixed-layer depth. Actually only the upper layer of a two-layer ocean was simulated in the model, and it was modeled in an inverted configuration with a 1:200 geometric scale reduction. The model showed no measurable recirculation for a range of discharge conditions for radial slot and symmetric 4-port discharge configurations with an intake drawing flow from the surface vertically downward. Intake/discharge separations ranged from 8 to 48 discharge port/slot heights, and ambient currents were zero or small. Jirka et al. also adapted existing analytical model techniques to the configurations studied in the physical model experiments (mixed discharge at the mixed-layer depth with no ambient current). Based on the predictions of the analytical model and insights gained from the physical model results, an approximate criterion was developed to predict possible onset of recirculation. The criterion is expressed in terms of flow rate, discharge velocity, plant radius, density difference of the mixed discharge with respect to the mixed-layer density, and the mixed-layer depth. They concluded that for a reasonable plant design and mixed-layer depth on the order of 50 m, OTEC plants with capacities up to 200 MW (net) could operate using mixed discharges with little or no recirculation.

The results of these recirculation studies suggested that, under the conditions studied, recirculation could be minimized by appropriate vertical separation of the intake and discharge. More detailed examinations of recirculation for large OTEC plants in flowing ocean environments with realistic vertical temperature stratification were undertaken this past year at MIT.[10] Completed experiments involved both evaporator-only and mixed discharges into stagnant, temperature-stratified receiving waters. Discharge flow rates corresponding to a net capacity of 400 MW were used in most cases, and radial slot and symmetric 4-port discharges were studied. Realistic stratifications were used with mixed-layer depths in the range of 30-70 m, and intake/discharge separations varied from 30-91 m. Recirculation was found to be small in most cases corresponding to changes in intake temperatures of 0.0-0.2 C°. Only in two experiments was significant recirculation observed. These two experiments corresponded to an evaporator-only discharge directed 21° upward above the horizontal and to an evaporator-only discharge from a 600-MW plant. Experiments with a realistic ocean current present, as well as temperature stratification, have been initiated only recently and are expected to provide the first data on a symmetric 4-port discharge in currents of moderate magnitude. Additional laboratory studies at MIT concern the near-plant interaction of separate, but closely-spaced, evaporator and condenser discharges. Interactions may result in the formation of effective mixed discharges without the necessity of mixing the heat exchanger effluents inside the plant and with the apparent advantage of reduced probability of recirculation for mixed discharges.

There are areas related to direct recirculation at individual plants that need further investigation. The effect of large ambient currents upon recirculation is not well understood. There is some evidence from the Hydronautics studies[7] that discharge into an oncoming current of speeds comparable to the discharge velocity may result in substantial recirculation (on the order of 25-30%) for certain intake and discharge configurations. The experiments underway at MIT that involve towing an OTEC model in a stratified tank to simulate large ambient currents will help quantify the extent of the recirculation under realistic stratification conditions. The possibility of using directional discharges or vertically downward discharges to avoid the potential for recirculation, if it exists, should also be investigated. Plants in the 50- to 100-MW size range require additional study. While many of the trends indicated in the investigations of larger plants are likely to hold for this range in plant size, hydraulic scaling does not allow consistent scale-down of existing results for parameters describing both the plant and the ambient environment. Also, little is known specifically about the potential for recirculation for the conditions under which a plant ship would operate. Recirculation may not be a problem for a plant ship underway because its discharge plume would be left behind by the motion of the ship and the intake could be placed forward of the direct influence of the discharge. However, for the small headways expected to be maintained by OTEC plant ships, recirculation might still occur under certain conditions. The potential for recirculation under plant ship conditions should be investigated.

It is not adequate to design intake and discharge systems on the basis of recirculation avoidance alone. The impact on the ocean environment must be considered as well.

Thermal Resource Utilization (Many Plants)

It has been proposed that eventually many OTEC plants may be deployed relatively near one another to form a power park. This type of deployment might minimize undersea power transmission and shore-based power conditioning costs by allowing a single cable and shore facility to service many plants. However, the concentrated deployment of OTEC plants in a power park raises additional questions concerning thermal resource utilization. The spacing between the plants must be selected such that the effluent from one plant does not degrade the thermal resource for other nearby plants. Also, with large quantities of warm and cold water being removed from near the surface and from a depth of 500-1000 m and injected at some intermediate depth, the question of resource renewal arises.

Spacing of Plants to Avoid Resource Degradation

The effluent from one OTEC plant may reduce the thermal resource available to other plants within a power park either by directly entering the warm water intake of a plant downcurrent or by effectively "thinning" the mixed layer downcurrent and therefore increasing the likelihood that cooler water near the bottom of the mixed layer will be drawn up into the intake of neighboring plants.

Jirka[11] has presented a preliminary analysis that can be used for estimating the minimum plant spacing that will preclude the effluent from one plant from degrading the effective thermal resources available to neighboring plants. In his analysis, Jirka assumes that a mixed-discharge mode is used and that the ambient ocean can be approximated by a two-layer system. After initial dilution due to jet entrainment, the mixed-discharge effluent is assumed to form a layer of intermediate density between the upper and lower layers of the ambient ocean. The effluent then drifts with the ambient current and spreads laterally due to buoyancy. The intermediate layer reduces the effective thickness of the mixed layer at neighboring plant sites and increases the potential for recirculation. Using the aforementioned recirculation criterion developed at MIT, the maximum allowable decrease in mixed-layer thickness before the onset of recirculation can be estimated and used to estimate minimum plant spacing that will result in this maximum amount of mixed-layer thinning. This analysis has been applied by Jirka to two power park configurations. For a row of plants oriented orthogonal to the dominant current direction and an ambient mixed-layer depth of 70 m, a minimum lateral spacing of 480 m is predicted for 100-MW plants and 36,000 m for 400-MW plants. In the case of a rectangular grid of plants, the minimum spacing depends on the ambient mixed-layer depth, the magnitude of the ambient current, and the number of rows in the grid. For the case of a mixed-layer depth of 70 m, an ambient current of 0.1 m/s, and five rows, a minimum spacing of 5,570 m is predicted for 100-MW plants, and 160,000 m for 400-MW plants.

The above analysis of plant spacing requirements is a rather tentative one because the model for plant interactions is extremely simple and the model for buoyancy spreading in the intermediate field region downcurrent from the plant is quite approximate. Jirka[12] has been developing a two-dimensional analysis of the buoyancy spreading regime of intermediate-scale plume motions. That analysis deals more directly with the problem of a source of buoyancy in a current than earlier analyses, and initial approximate results suggest that lateral spacing requirements may exceed those indicated above. That is, minimum lateral spacing for 100-MW plants may be on the order of 2 km rather than 0.5 km. It is necessary to caution here that plant spacing requirements may not be driven solely by thermal resource considerations, and assessments of downcurrent environmental impacts may provide other constraints on plant spacing.

Resource Renewal for Large Deployments

The preservation of the thermal resource for utilization by large numbers of OTEC plants, while not an issue for early OTEC plant deployments, requires consideration now in terms of assessment of the power potential of various site areas. The term resource renewal is meant to denote the general availability, on an ocean-regional or basin scale, of the warm surface and cold deep water. In large measure the question of resource renewal is related to the oceanic circulation or water mass transports responsible for replacement of water in various regions, although surface water temperatures may be governed in part by local air-sea exchange processes that might be modified by OTEC plant operations. Our understanding of transport patterns is founded almost entirely on observational data, and in many potential OTEC site areas observational data on transport are sparse -- a prime motivation for the collection of such data under OTEC aegis. Of course, long time-series and synoptic data sets are required to provide data for the evaluation of net transport quantities. Moreover, the effects of OTEC plants on natural resource renewal processes are likely to be subtle and may be evident only after long times. Consequently, numerical modeling of circulation including simulated OTEC effects may provide some insight into the resource renewal question. To date the question of resource renewal at island sites has not been addressed but will receive some attention in relation to modeling efforts of large-scale environmental perturbations at such sites. The past activities related to resource renewal have focused on the Gulf of Mexico.

The Gulf of Mexico basin, with open boundaries at the Yucatan Straits and the Straits of Florida, is large with respect to even large-scale OTEC deployment. However, the warm water requirement for production of 100 GW (1000 100-MW plants) in the Gulf is on the order of 3-6% of the geostrophic transport (relative to 500 m) estimated[13] to enter the Gulf through the Yucatan Straits. Cold water neither enters nor leaves the Gulf through the Straits of Florida, and net transports of cold water from the Gulf through the Yucatan Straits have been estimated on occasion from observations. Estimates[13] of outward cold water flows have been as large as three times the cold water requirements for 100 GW of OTEC production. The long-term transports of cold water to and from the Gulf are not known, and cold water renewal for OTEC operations is also a consideration for the Gulf.

A simple one-dimensional model of the Gulf of Mexico (assuming lateral homogeneity) by Martin and Roberts[14] indicated that 1000 100-MW OTEC plants distributed uniformly throughout the Gulf might result in perturbations to natural ocean temperatures in the water column of as much as 1 C°. The model results are very approximate because of the spatial averaging of the effects of the Loop Current and are sensitive to assumptions regarding exchanges through the straits. While the behavior of the Loop Current and exchanges through the straits are not well-understood, it is apparent that they may influence significantly the thermal resource renewal in the Gulf.

Prediction of the circulation in the Gulf, particularly with regard to intrusions of the Loop Current into the regions of interest for OTEC deployment, is a formidable numerical modeling task. However, questions related to basin-wide environmental impacts also require simulation of the transport field, and these numerical modeling activities may provide insight into the resource renewal question as well. Previous modeling efforts by Thompson and Hurlburt[15,16] were directed toward two-layer baroclinic models of the Gulf driven both by wind and flows through the Yucatan Straits. Circulation patterns similar to Loop Current structures were noted in preliminary integrations. During the past year, a numerical model with the capability for greater spatial resolution in the vertical has been readied for application to the Gulf of Mexico by Dynalysis of Princeton, Inc., as reported by Mellor and Blumberg.[17] This model uses layers of variable thickness in the vertical (a sigma coordinate system) and will be run with 10 (and eventually 20) layers. While the primary motivation for application of this model to the Gulf is assessment of environmental impacts (as discussed below), sensitivity studies regarding exchanges through the Yucatan Straits and simulated OTEC power park perturbations are relevant to resource renewal concerns.

Environmental Impact (Single Plant)

The environmental concerns attributable to the operation of an individual OTEC plant have been grouped in four general categories[18]: redistribution of oceanic properties, chemical pollution, structural effects, and socio-legal/economic matters. Specific problem areas include impingement and entrainment associated with seawater intakes, particularly the evaporator intake, perturbations to the ambient temperature, salinity and nutrient distributions by the discharge plume that entrain ambient water as it sinks or rises to some equilibrium elevation, and discharge plumes as conveyers of biocides, corrosion products, and working fluid (due to leaks) into the water column downcurrent of the plant. Many of the physical processes related to these problem areas are the same as the processes governing resource utilization.

Intake Flows and Entrainment/Impingement

The physical problem associated with intakes and entrainment and impingement effects is the estimation of the mass flux of biota into the sea-water intakes. If the distributions of biota of concern were uniform throughout the water column, the mass flux would be simply the product of the concentration and the intake flow rate. However, because vertical distributions of biota exist, particularly relative to the evaporator intakes, the distribution in the water column of flow to the intake may be important for estimates of impingement/entrainment impacts. Determination of the zone of influence of the intake flows involves the same processes described above in the discussion of evaporator intake water temperature. Additional work on intake flow hydrodynamics is required along with the results of biological sampling to improve estimates of mass fluxes to intakes.

Near-Plant Impacts of Discharges

In order to design a discharge system for an OTEC plant that will be environmentally acceptable, one must first be able to predict the fate of the effluent and then assess its impact on the environment. The immediate fate of the effluent depends on both the plant discharge configuration and the ambient ocean conditions. Initially the effluent will behave as a buoyant jet, entraining ambient seawater as it sinks (or rises) and eventually becoming neutrally buoyant, on the average, with respect to the surrounding ocean water. In this near-field region of the plume the physical impact of the effluent plume can be characterized by the equilibrium depth, the dilution, the plume width and thickness, and the disturbances to the ambient temperature and salinity profiles. Determination of these plume characteristics has been an objective of near-field physical model studies. Most of the experiments carried out to investigate direct recirculation provide the additional opportunity for measurements of gross plume characteristics. Analytical and numerical model approaches are difficult in cases where intake flows and ambient currents make external flow fields complex, but they may provide some guidance for the simpler conditions.

Physical model studies at MIT reported by Adams et al.[5,10] included both evaporator-only and mixed discharges into stagnant, stratified receiving waters. Radial discharge ports and flow rates corresponding to a net generating capacity of 400 MW were used in most cases. Realistic stratifications were used with mixed-layer depths in the 30-70 m range. In the case of the evaporator-only discharges, the near-field plume equilibrium depth was 10-15 m below the mixed layer for discharge depths varying from 10 m above the bottom of the mixed layer to 40 m below. The thickness of the plume at equilibrium ranged from 15-50 m, with plume thickness increasing with increasing distance between the discharge port and plume equilibrium elevations. The centerline dilution 900 m from the point of discharge (well after equilibrium depth had been reached) was measured using dye to be 5-10. In the mixed-discharge tests, the equilibrium depth was found to be 25-75 m deeper than for the corresponding evaporator-only discharge tests, and the plume thickness 60% larger. Dilutions were typically in the same range as observed in the evaporator-only discharge tests, that is, 5-10. A few tests were conducted with 4-port discharge configurations. The limited results suggest that the resulting plume behaves similarly to the plumes from the axisymmetric radial discharge.

Integral-type jet analyses were also applied to estimate discharge plume behavior for various discharge modes, discharge depths, and discharge orientations. Calculations were made using an analysis[19] of a submerged round buoyant jet into a stagnant stratified receiving water body for an ambient density profile based on the average temperature profile for the month of September at Keahole Point, Hawaii. Discharge flow rates corresponding to a 50-MW OTEC unit and discharge velocities of 2 m/s were used. The plume equilibrium depths predicted for the horizontal discharge cases are in general agreement with the recent MIT physical model results for both the evaporator-only and mixed discharge modes. The equilibrium depths in the mixed-discharge cases are about 40 m deeper than for the evaporator-only discharge cases. Vertically downward discharges resulted in equilibrium depths that are 60 m deeper for the evaporator-only cases and 80 m deeper for the mixed discharge cases than found for horizontal discharges. The dilution at the jet centerline when the jet has leveled out at the equilibrium depth are predicted to be in the range of 3-5 (average dilution of 6-10), with horizontal discharges producing slightly larger dilutions than vertical discharges. The diameter of the jet at this point (defined here arbitrarily as the diameter of the contour corresponding to a dilution of 20) is about 90 m for the horizontal evaporator-only discharge cases and 130 m for the horizontal mixed discharge cases. The jet diameter is predicted to be 1.7-1.9 times larger in the case of vertically downward discharges.

The following general conclusions can be drawn from the above physical model and analytical model studies. Mixed discharges and vertically downward discharges produce significantly deeper (50-75 m) equilibrium depths and only slightly smaller dilutions than separate discharges (assuming no interfering interaction) and horizontal discharges. Whether such differences are important in terms of potential biostimulation or biocide distributions is not known presently. The results of biological sampling at OTEC sites and laboratory studies on biostimulation and toxicity will be used with the plume predictions to assess potential ecological impacts.

The near-field behavior of the discharge plume will also be affected by ambient ocean currents. Currents may increase dilutions by increasing the supply of ambient ocean water, but they may also cause the plumes from individual ports to interact with one another and effectively block the inflow of dilution water. Also, ambient currents may act to inhibit the degree of vertical penetration of the plume to depths less than those found for stagnant environments. Physical model experiments presently underway at MIT will study the effect of currents on the external flow field in a stratified environment. If near stagnant conditions exist for long periods of time, however, there may be a buildup of the effluent in the vicinity of the plant. This may also occur in the presence of small currents which reverse periodically and return the effluent to the immediate plant site. Data on ambient ocean conditions and the time scale of changes in ambient ocean conditions at proposed OTEC deployment sites are needed to predict the physical near-plant behavior of the effluent and thus assess the possible environmental impacts.

Downcurrent Effects of Discharges

When the discharge effluent from the plant has reached its equilibrium depth, it has lost its jet-like characteristics and has a velocity only slightly different than the ambient current. Its intrusion into the stratified ocean results in a collapse of the plume in the vertical direction and spreading laterally due to gravity forces. The interaction of the spreading layer and the ambient current in the intermediate field produces a plume that extends upcurrent of the plant and grows in width downcurrent of the plant due to gravity spreading until gravity forces become small and turbulent diffusion takes over as the dominant mixing process.

Jirka[12] has been studying the spreading of plumes from OTEC plants in the intermediate-field region. As indicated above in the discussion of plant spacing for resource utilization purposes, one-dimensional analysis provide estimates of plume spreading downcurrent of the plant. For example, for a 100-MW plant in an ambient current of 0.125 m/s, the plume between the layers of a two-layer ocean is predicted to be about 15 km wide and 4 m thick near the plant and about 30 km wide and 2 m thick 10 km downcurrent. Even in the case of an ambient current as large as 0.5 m/s, the plume is predicted to be 6 km wide 10 km downstream. Recent analysis by Jirka[12] of the two-dimensional (lateral and longitudinal) aspects of intermediate-field spreading allows approximate solutions for the cases of two-layer and linearly-stratified environments. Initial results indicate that the lateral spreading is particularly sensitive to the magnitude of the ambient current and that downcurrent plume widths may exceed predictions from the one-dimensional analysis. Laboratory experiments by Jirka, at Cornell, are being performed to evaluate the approximate solutions in the vicinity of the plant.

Transient plume motions in the intermediate field are being investigated by Jirka in addition to the steady cases discussed above. Little additional dilution of the plant effluent can be expected in the intermediate field, although the plume will be collapsed to a thin, wide layer. Passive turbulent diffusion of that layer at distances downstream of the intermediate field will result in additional reduction in constituent concentrations. Such mixing processes are rather slow and may not result in large dilutions, however, vertical thinning due to gravity spreading may result in breakup of the discrete layer into patches that in turn might experience enhanced mixing with ambient waters.

Environmental Impacts (Many Plants)

Prediction of the large-scale effects of many interacting plants requires an understanding of the interactions among individual plants and of the transport characteristics of the region in which the plants are located. The interactions among plant effluent plumes depend largely on the intermediate-field spreading and plant spacing. Criteria for spacing from an environmental impact viewpoint require some assessments of downcurrent biostimulation potentials and/or biocide levels and are yet to be established. However, the predictive tools for the physical transport are being developed presently and the biological sampling activities are underway. The problem of regional transport pathways and regional accumulation of certain effluent constituents is more difficult to address. Field observations of currents, both historical and those undertaken for the OTEC program, will provide some insight into the transport processes. However, consideration of long-term net transports, of particular interest for the assessment of regional effects at OTEC sites, may require a combination of observational data and numerical modeling. Island site areas, while unbounded in some sense, may be of concern because of the proximity to island coastal waters. Thus, circulation around and in the coastal waters of islands will receive attention in the near future.

The Gulf of Mexico, because of its basin-like features, raises obvious questions about residence times and transport pathways for effluents in the instance of large-scale OTEC operation. Preliminary transport calculations for marked tracers in the two-layer Gulf of Mexico model by Thompson and Hurlburt[15] indicated the differences in transport features for sites in the northern Gulf off New Orleans, in the rather quiet central Gulf, and in the active transport area in the eastern Gulf off Tampa. The focus of the application of the more detailed circulation model of the Gulf of Mexico under development by Dynalysis of Princeton, Inc.,[17] is the examination of the transport and mixing of effluents from OTEC power parks at several locations in the Gulf. The enhanced vertical resolution in the 20-layer Dynalysis model will permit investigation of the large-scale implications of plant designs that result in different near-plant effluent behavior (e.g. evaporator-only vs. mixed discharges). The effects of park location and size on effluent transport pathways and residence times will be investigated as well.

Climatic Effects

Impacts on the climate due to the operation of a small number of OTEC plants are not likely to be measurable. However, the possibility of large-scale deployments of OTEC plants in the future requires that the climatic consequences of such deployments be considered. The possible impacts of immediate concern are atmospheric loading of CO_2 and weather/climate modification due to modification of air-sea heat exchange processes.

CO_2 Loading to the Atmosphere

Deep ocean water is enriched with inorganic carbon with respect to the surface waters, and, because of the buffering capacity of the surface water, CO_2 may evolve from deep water brought to the surface for OTEC condensers. The potential excess CO_2 in cold water brought to the surface over surface water values is on the order of 1.7×10^{-5} kg CO_2/kg H_2O. In terms of a 200-MW OTEC plant, the excess flux of CO_2 available to the atmosphere would be about 1.2×10^6 kg/day.[20] For comparison, the amount of CO_2 released to the atmosphere by a fossil-fuel-fired power plant of the same electrical capacity is two to three times as much.[21] This analysis should yield an upper bound on potential CO_2 additions to the atmosphere, although the results of site-specific measurements may indicate slightly different values of that upper bound. However, condenser effluents from closed-cycle OTEC plants could well be discharged below the mixed layer (as indicated in earlier sections), and the total evolution of excess carbon to CO_2 may not be realized. The fate of the deep-water carbon depends on both the complex carbonate chemistry of seawater and the physical mixing of the effluent in the ocean. Estimates of physical mixing are available from physical model studies and mathematical analysis, but present limited understanding of oceanic carbonate systems precludes defensible estimates of the fate of carbon in the water column.

Air-Sea Heat Exchange Processes

OTEC plants remove heat from the surface layers of the ocean and, consequently, may produce sea surface temperature depressions. The zeroth-order estimate of sea surface temperature depressions for 1000 100-MW OTEC plants operating in the Gulf of Mexico is less than 1 C°.[14] This is a small number, certainly in the noise of ambient ocean temperature fluctuations, but there are suggestions that even small temperature changes may be responsible for climatic changes. Moreover, models for the prediction of climatic changes are not adequately developed to be sensitive to such small temperature changes.

The zeroth-order estimates of sea-surface temperature depressions were found in a laterally-averaged model of the Gulf of Mexico. Actual three-dimensional distributions of water temperature perturbations may be different. That is, local depressions in the vicinity of OTEC power parks may have larger magnitudes and smaller surface areas associated with them than indicated by laterally-averaged models. Application of the multilayer circulation model of the Gulf of Mexico by Dynalysis to the case of large-scale OTEC deployment will provide some estimates of sea-surface temperature depressions. These estimates will, of course, be limited in that the Gulf of Mexico model will not be a coupled ocean-atmosphere model and will not predict atmospheric impacts due to change in the ocean. The results of this study will certainly not overcome the difficulties of modeling climatic changes, but they will provide bounds on the ocean areas affected. The means of assessing the climatic impact from such ocean temperature perturbations remains to be found.

Summary

Physical model studies are being employed to provide answers to questions regarding resource utilization and environmental impacts in the near-plant region. Studies of intake flow fields are required for better definition of the magnitude of evaporator intake water temperature variability and of impingement/entrainment impacts. Mathematical modeling of density spreading in the intermediate field of effluent plumes is producing guidelines for downcurrent impact assessment and plant-spacing requirements. Oceanic regional and island coastal circulation models are necessary for the assessment of far-field effluent plume impacts and resource renewal. A basin-wide numerical model is being applied to the Gulf of Mexico to investigate the transport pathways and residence times for effluents and resource renewal characteristics associated with large-scale deployments of OTEC plants. Determinations of climatic impacts are presently limited to estimates of upper bounds for CO_2 loading to the atmosphere and of sea surface temperature depressions that drive air-sea heat exchange processes.

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