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An Overview of Modeling Efforts and Needs

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OTEC PHYSICAL AND CLIMATIC ENVIRONMENTAL IMPACTS:
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ABSTRACT

The present overview of studies of the effects of ocean thermal energy conversion (OTEC) plant operation on the physical environment of the ocean includes a review of the pertinent results of past and contemporary model efforts in terms of their implications for OTEC development and suggestions for future research consistent with OTEC timetables. Particular consideration is given to the areas of utilization of the thermal resource, effects of a single OTEC plant, and aggregate effects of many OTEC plants. These potential effects include modification of the local temperature, salinity, and nutrient distributions, induced changes in mixed-layer depths and sea-surface temperatures, and dispersal of biocides or working fluids (due to leaks).

Investigation of several early baseline OTEC designs indicates that the fractional net power losses are equal to about 2.4 times the fractional loss in thermal resource. Power cycle optimization appears to require the probability distribution of the thermal resource at a site. Preliminary studies of recirculation show that some design concepts may suffer 5-10% loss in net power output, but that design modifications may eliminate recirculation as a serious problem. Additional physical (hydraulic) model studies are required to put bounds on the recirculation potential of several generic designs in the near future.

Review of model capabilities and limitations suggests that physical model studies also are needed to meet near-term OTEC needs for predictions of the complex near-field (1-3 km) effects of a single OTEC plant. Analytical and numerical models seem best-suited for predictions of the intermediate-field (2-10 km) effects. Evaluation of several generic designs in various possible sites requires the establishment of worst-case scenarios consistent with site data and with the needs of those assessing biological and ecological impacts.

An estimate for the aggregate effect of many OTEC plants on the horizontal thermohaline structure of the ocean is made in terms of the power density that would be required to sustain an induced, mesoscale anomaly against natural dissipation (as measured in a Gulf Stream eddy). Rough calculations for a 160 MWe OTEC plant indicate that plant-plant spacing of 17 km

or more may preclude the formation of mesoscale, OTEC-induced anomalies. It is suggested that a multilevel, baroclinic numerical model of a limited ocean region (perhaps, 100 x 100 km) could be a useful tool to sharpen estimates of plant-plant interactions and spacing.

Careful synthesis of the results of several models, in a spatial hierarchy from near-field to basin-wide scales, is required to provide reliable estimates of physical environmental impacts for OTEC purposes.

1 INTRODUCTION

Our purpose in this paper is to present an overview of studies of the effects of ocean thermal energy conversion (OTEC) plant operation on the physical environment of the ocean. These studies require that predictive modeling techniques be applied to, and in some cases developed for, physical processes of several scales. The necessary predictive capabilities of the modeling approaches are dictated by the potential environmental effects and are qualified by the need to assess those effects within the timetable of OTEC development. Past and contemporary efforts in this area are reviewed in terms of their implications for OTEC plant design and operation in the ocean environment and in terms of the predictive tools available for further assessment. The details of past and current studies are not discussed here, but they may be found in reports of this and previous OTEC conferences. The review of past results, of available predictive tools, and of techniques under development suggests that no single model or predictive technique can address all of the scales of motion and phenomena likely to influence physical environmental modification. Thus, identification of specific research needs and recommendations for the types of models required to address those needs are given. The mix of the predictive techniques, their capabilities and limitations, and the necessary links among them are discussed within the context of OTEC timetables.

Questions regarding the potential effects of OTEC plant operation on the physical environment have been raised many times. From an operational point of view, the degradation of the thermal resource by the plant has been a prime concern. Redistributions of temperature, salinity, nutrients, and other substances throughout the water column are of interest to those assessing ecological effects. Sea surface temperature modifications may influence atmospheric processes significantly. The deployment of many plants raises similar questions about environmental effects, and, in this case, interactions among plants, plant spacing, and siting become important.

In this paper, the effects on the physical environment are addressed in ascending order according to physical scale - from near-plant effects to ocean basin effects. In Section 2, utilization of the available thermal resource is discussed with regard to resource variability, recirculation, and the implications of resource degradation on power generation and construction costs. The physical effects on the ocean environment in the vicinity of a single plant are considered in Section 3. The tools available for the prediction of such effects are assessed, and guidelines for their application to OTEC needs are suggested. The aggregate effects of many OTEC plants on the physical environment are treated in Section 4. The results of existing studies are reviewed, and estimates for the magnitudes of plant perturbations on the ocean are given.

2 THERMAL RESOURCE UTILIZATION

Resource Requirement

Ocean thermal energy conversion power plants will depend upon the temperature difference between the warm seawater intake near the surface and the cold seawater intake 500-1500 m below the surface to drive a heat engine. The temperature difference across the power plant (θ_p) is referred to as the thermal resource. The magnitude of θ_p is expected to be 18-22 C°, depending upon the particular temperature profile where the plant is located and the depth of the cold-water pipe. The thermal resource must be $\gtrsim$ 18 C° due to the low overall thermal efficiencies at which these plants are expected to operate. With a thermal resource of 20 C°, the overall thermal efficiency is expected to be about 2.4%. At this low efficiency, a 100 MWe (net) plant will require evaporator seawater flow rates of 400-700 m^3/s, about ten times the typical cooling-water flow rate required by a 1000 MWe nuclear generating station. A thermal resource of 18 C° would require ~25% larger flow rates. The large flow rates, heat exchangers, and associated pumping power losses required for a plant to operate with a thermal resource significantly less than 18 C° probably would be too large to be economically justified. The upper limit on the thermal resource of ~22 C° reflects the maximum annually averaged thermal differences that can be found in subtropical oceans, although grazing OTEC plants might find a thermal resource of ~24 C° in tropical oceans.

It is clear that the economic viability of the OTEC concept depends on the ability of a plant to use the thermal resource as effectively as possible. The thermal resource probably will not be constant in time. Variations may be due to natural ocean phenomena or due to the operation of the plant itself. Effective use of the resource requires that the power cycle of the plant be designed to make optimum use of the thermal resource as it exists at a particular site. The avoidance of degradation of the thermal resource in the vicinity of a plant requires that the seawater intakes and discharges be properly designed. These two aspects of thermal resource exploitation must be examined.

Power Cycle Optimization

Once a site has been selected for an OTEC plant, it becomes necessary to design the plant to make optimum use of the available thermal resource. If the available thermal resource were constant in time, simply minimizing plant construction costs per net power output of the plant would meet this objective. However, at many possible OTEC sites, the available thermal resource is expected to vary with season and due to oceanographic phenomena such as upwelling/downwelling, internal waves, and the meandering of natural ocean currents. The seasonal variations at deep-water sites in the

Gulf of Mexico and off Miami are expected to be ~4.5 C°. Variations of 2.5-3.0 C° are expected for sites near Hawaii and Puerto Rico [1]. The actual variations at a site will probably be even larger due to the other effects mentioned above. Once a design thermal resource has been selected, any change in the available thermal resource will affect the operation of the plant and its net power output. It may be possible to "tune" the plant by adjusting seawater and working fluid flow rates to maximize the net output of the plant. However, the range and effectiveness of such a tuning procedure is expected to be quite limited. Even for very small losses in thermal resource, it is estimated that less than 20% of the original loss in net power can be regained by tuning [2]. It, therefore, becomes necessary to select carefully the particular thermal resource for which the plant is to be designed.

In order to quantify the effect of changes of thermal resource on net output of an OTEC plant, let us consider the following situation. A plant is operating at the design seawater and working fluid flow rates through the heat exchangers when the loss in thermal resource occurs; the rate at which heat is extracted from the warm seawater in the evaporator will remain approximately constant, but there will be a lowering of the temperature difference across the power cycle. The resulting loss in new power generation can be estimated from the following expression that relates the fractional loss in net power output ($\Delta P_N/P_N$) to the fractional loss in thermal resource ($\Delta\theta_p/\theta_p$),

$$\frac{\Delta P_N}{P_N} \simeq \frac{1}{\varepsilon(1-\alpha)} \frac{\Delta\theta_p}{\theta_p} .$$

In this expression, ε is the fraction of the total thermal resource that exists across the power cycle. Therefore ($1-\varepsilon$) is the fraction of the total thermal resource that is used to drive the heat exchange processes. The value of ε is expected to be ~0.5, although the precise value will depend upon the particular power-plant design and will result from balancing heat exchanger costs against power output. The quantity α is the fraction of the design gross electric generation that is required to run the seawater pumps, working fluids pumps, internal electric transmission lines, transformers and rectifiers, and other equipment. These internal power requirements are referred to as parasitic power losses, and α is estimated to be 0.16-0.40, depending upon the design thermal resource, the design gross electric generation, the length of the cold-water pipe, and possibly other factors.

Table I shows the results of applying this equation to several preliminary OTEC designs assuming a 1 C° loss in thermal resource. For these proposed designs, which are typical of the closed cycle OTEC concept, any fractional loss in the available thermal resource is amplified by a factor of ~2.4 in terms of its effect on the fractional loss in net power output. Note that the fractional loss in net power output for the 1 C° loss is about 10%.

Table I. Effect of a 1 C° Loss in Thermal Resource on Baseline Design OTEC Power Plants

Design	θ_p (C°)	ε	α	$\frac{1}{\varepsilon(1-\alpha)}$	$\Delta\theta_p/\theta_p$ (%)	$\Delta P_N/P_N$ (%)
TRW	21.9	.49	.18	2.49	4.6	11.4
Lockheed	18.5	.65	.36	2.40	5.4	13.0
APL	24	.5[a]	.16	2.38	4.2	9.9

[a]Not reported, estimated to be 0.5.

A loss in thermal resource will lower the net output of the plant, but an increase will probably not raise the net output by a corresponding amount because the plant will not have been designed to utilize the increase. For example, a plant designed for a thermal resource of 20 C° may lose as much as 20-25% of its net power output, if the available thermal resource is lowered to 18 C°; but it might not be able to produce a corresponding increase in net power, if the available thermal resource were increased to 22 C°. It might be desirable to minimize the average cost of electric power produced by an OTEC plant located in an area, where the characteristic variations in available thermal resource are several Celsius degrees, by proper selection of the design thermal resource, rather than by simply choosing the minimum, or the average available thermal resource. Designing for the smallest expected thermal resource will insure a steady power output, but will probably not minimize the average cost of the electric power produced. Designing for the largest expected available thermal resource will reduce construction costs and parasitic power losses because smaller heat exchangers and smaller seawater pumping rates will be required. However, when the available thermal resource falls below the design value, the plant will suffer a significant loss in net power output. The cost savings and the power loss must be balanced against one another to determine the optimum design thermal resource.

The probability distribution function for the available thermal resource at a specific site must be known in order to carry out this optimization. In addition, it has been suggested that the power cycle might be dynamically tuned to adjust for variations in the thermal resource. The time constant of the dynamic tuning process may be on the order of hours and the design of an optimum tuning system would require a knowledge of the magnitude and frequency of expected changes in the thermal resource on this time scale. Determination of the probability distribution function for the thermal resource and determination of the magnitude and frequency of variations in the thermal resource may require in-situ, time-series measurements of ocean temperatures at proposed OTEC sites.

Resource Degradation (Recirculation)

The degradation or loss of thermal resource available to a plant, due to disturbances to the near-field flow and temperature fields induced by the operation of the plant itself, has been termed recirculation. This loss -- generally expected to be a lowering of the average warm-water intake temperature -- may result from direct recirculation of some fraction of the discharge volume flux into the warm-water intake, turbulent mixing in the stratified upper layers of the ocean induced by the discharge jets, or selective withdrawal by the intake over a range of the stratified upper layers. As noted above, any fractional loss in thermal resource is amplified by a factor of ~2.4 in terms of its effect on the fractional loss in net power output.

Plant design -- in particular, size and location of intake and discharge ports -- clearly determines the extent of the recirculation a plant will experience at a particular site under specific environmental conditions. Various intake and discharge concepts have been proposed. These include horizontal and vertical warm-water intakes, axisymmetric and directional intakes, horizontal and inclined discharges, mixed and separate discharges, and axisymmetric and directional discharges. Directional intakes and discharges that are variable have been proposed to take advantage of natural ocean currents to minimize recirculation effects. Inclined and mixed discharges have been proposed to take advantage of negative buoyancy and natural ocean stratification to minimize recirculation effects. In order to choose an intake and/or discharge design that is likely to result in minimal loss of thermal resource, the various concepts should be evaluated under several environmental conditions that are expected to be critical to OTEC operation. These conditions should include ambient currents and mixed layer depths comparable to those normally expected at proposed OTEC sites.

Recirculation is a consequence of the flow field produced near the plant by the interaction of the plant intake and discharge flows with local ambient ocean currents. Any evaluation of the various design concepts in terms of potential for recirculation might best be carried out in conjunction with an evaluation of near-field environmental effects because a trade-off between minimizing recirculation and minimizing near-field environmental effects may be required. A three-dimensional numerical model that simulates the details of the intake and discharge dynamics as well as the temperature, salinity, and current structure of the ambient ocean would be ideal for these evaluations. Such a model would allow complete and consistent comparisons to be made among the various design concepts. However, no three-dimensional calculations have been made for the near-field region of an OTEC plant. Analytical models may be of limited use in estimating near-field environmental effects but are not able to quantify the effects of recirculation. Physical (hydraulic) scale models, although lacking the versatility of a numerical model, can provide quantitative measures of recirculation on a time scale consistent with OTEC program needs and therefore, may be the best approach for investigation of the recirculation question. These different modeling approaches will be discussed in more detail in Section 3 with regard to single plant environmental effects.

Physical model measurements using a two-layer stratification with a uniform fully-mixed upper layer will predict only that part of the loss in thermal resource due to direct recirculation. Only mathematical models, or physical models using realistic, continuous stratification of the upper layers of the ocean can predict the total loss in thermal resource due to the operation of the plant itself.

Several preliminary numerical and physical model studies have been conducted to predict losses in thermal resource due to recirculation. Results from these studies and their consequences in terms of loss of net power output of an OTEC plant are discussed briefly.

Science Applications, Inc. (SAI) [3], has developed a two-dimensional numerical model of the flow field external to an OTEC power plant with no ambient ocean current. The model was applied to the Lockheed baseline design to evaluate the loss in thermal resource due to the near-field flow induced by the operation of the plant. There is some question as to how the problem should be schematized, and whether the model is appropriate, because it is two-dimensional and the Lockheed design is highly three-dimensional. SAI simulated the warm-water intake and the two discharges as two-dimensional slots with a height of 22 m -- the diameter of the design discharge ports -- and with discharge velocities equivalent to slot widths of 15-122 m. They suggested that the results for widths of 30-61 m were appropriate for comparison with actual three-dimensional performance. Some of the results of these calculations and quantities derived from these results are presented in Table II.

The quantity $\Delta\theta_p/\theta_p$ is the total fractional loss in thermal resource, and $\Delta P_N/P_N$ is the associated fractional loss in net power output. If the model and its application to the Lockheed design were appropriate, a loss in net power of ~10% could be expected under the situation of no ambient current. The quantity Q_r/Q_w is the fraction of the warm-water intake flow, that comes from the warm-water discharge by direct recirculation as determined from the streamlines calculated by the numerical model. The loss in thermal resource that would result, if this direct recirculation were the only contributing factor, is denoted by $(\Delta\theta_p)_r/\theta_p$ in the table. Note that, for the range of effective widths considered, direct recirculation only contributes from less than half to as little as 8% of the total predicted loss

Table II. Results of the Application of the Two-Dimensional SAI Model to the Lockheed Baseline Design Plant

Width (m)	$\Delta\theta_p/\theta_p$ (%)	Q_r/Q_w (%)	$(\Delta\theta_p)_r/\theta_p$ (%)	$\Delta P_N/P_N$ (%)
15	8.84	33.3	4.13	21.3
30	4.71	10.8	1.00	11.3
61	2.78	2.5	0.21	6.7
122	0.85	0.8	0.07	2.1

in thermal resource. Apparently, the interaction of the plant-induced, near-field flow with the upper-layer ocean stratification can significantly affect the loss of thermal resource.

Hydronautics, Inc. [4] has conducted a series of laboratory experiments on the hydrodynamics associated with the external flow field on an OTEC power plant. Results of two sets of experiments are considered here. The first set of experiments was concerned with a round non-buoyant jet directed horizontally into a uniform ambient current. Discharges into head-on (counterflowing), crossflowing, and coflowing currents were tested. A radial intake was located above the discharge with the intake flow being horizontal. The experimental configuration is similar to the Lockheed baseline design; the total warm-water intake is represented, but only one of the warm-water discharges is included. Dye was added to the discharge and dye concentration was measured in the intake flow. Recirculation, defined here as the ratio of the dye flux into the intake divided by the dye flux out of the discharge, is comparable to the direct recirculation described above. Measurements were made for various combinations of currents, discharge flow rates, and intake/discharge separations. Intake/discharge separations ranged from 1-2 discharge port diameters. The experimental results indicate that for small ambient currents, recirculation is small. As ambient currents are increased, recirculation increases reaching a maximum when the ambient current is ~50-70% of the discharge velocity. Further increases in ambient current cause recirculation to decrease becoming less than a few percent for ambient currents greater than the discharge velocity. The largest recirculation occurred when the discharge was directly opposed to the ambient current and amounted to ~25-30% for the intake/discharge separations studied. For a cross-flowing ambient current, the maximum recirculation was ~5-10% and for a co-flowing ambient current, it was less than 3%. The Lockheed baseline design has the intake and discharge ports somewhat closer together than those studied in these experiments, but a linear superposition of the Hydronautics' results suggests that the maximum total recirculation will be ~10-15%, corresponding to a loss in net power of ~2-3%. This set of experiments did not include the effects of buoyancy, stratification, flow around the plant structure itself, or possible interactions among the four discharge jets. The negative buoyancy of the discharge jets will tend to reduce direct recirculation, while induced turbulent mixing in and selective withdrawal from a stratified upper layer would increase recirculation effects.

The second set of experiments by Hydronautics, Inc. was concerned with the effects of two-layer density stratification on selective withdrawal by a radial intake. The lower, more dense layer contained dye and withdrawal from this layer by an intake in the upper layer was measured as a function of intake velocity for various separations between the density interface and the intake. These experiments do not simulate directly an OTEC plant because no discharges are present in the experimental configuration. However, the density difference between the surface mixed layer and the colder deep water is simulated by the experiments. The results of the experiments are as expected. As the intake velocity is decreased and/or the density stratification is increased, withdrawal from the lower layer becomes less and less significant. The experimental results indicate that little, if any, water will be drawn into the warm water intake from below the mixed layer depth given the typical intake velocities of proposed OTEC designs and given the mixed layer depths and density differences typical of proposed OTEC sites.

MIT [5] has carried out some schematic physical model experiments at a 200:1 scale to study the external fluid mechanics of an OTEC power plant. These experiments simulate a plant design with a mixed discharge -- the warm and cold water exhausts are mixed and discharged at the interface of a two-layer stratified ambient ocean. Actually, only the upper layer is simulated in the model, and it is modeled in an inverted configuration. The experiments showed no measurable change in the warm-water intake temperature due to the presence of the mixed discharge for reasonable discharge flow rates and discharge temperatures for schematic plants up to 200 MWe (net). In these experiments, the effects of stratification within the upper ocean layer were not included so that losses in thermal resource due to selective withdrawal and induced turbulent mixing were not simulated.

These preliminary model studies of the near-field flow induced by the operation of an OTEC power plant indicate that a design, such as proposed by Lockheed with relatively closely spaced warm-water intake and discharges, may suffer as much as a 5-10% loss in net power output, under certain environmental conditions, due to a local, self-induced loss of available thermal resource. This loss is not particularly large and therefore design modifications may be able to eliminate recirculation as a significant problem. Modifications that deserve study include increased vertical separation of the intake and discharge ports and/or a mixed-discharge design, such as proposed by MIT. MIT has recently initiated a series of laboratory tests to investigate the differences between the mixed and separate discharge options in terms of the induced flow field and recirculation potential under the influence of realistic ocean stratifications and currents. Systematic studies of this type are required to evaluate the various intake/discharge design concepts. Such studies should include the effects of stratification, plant wake, and ocean currents and might best be accomplished through the use of physical scale models in order to put bounds on the recirculation problems in the near future.

3 ENVIRONMENTAL EFFECTS DUE TO A SINGLE OTEC PLANT

Modification of the physical environment by means of the operation of an OTEC plant may not only influence the utilization of the thermal resource, as indicated above, but also may result in deleterious ecological effects. These effects may be the result of OTEC-induced changes in water temperature and salinity distributions, and of the redistribution of nutrients in the water column. Leaks of working fluids or other substances and the application of biocides in the evaporator and condenser discharges also may cause undesirable environmental effects.

Evaluation of the potential modification of the water environment due to a single OTEC plant requires several predictive capabilities. Predictions of the redistribution of temperature and salinity are necessary, with particular attention given to sea surface temperature and mixed-layer depth changes. The locations of and concentrations of substances in the water masses created by the evaporator and condenser discharges must be predicted. These predictions must be made in the context of a variety of proposed plant designs and potential OTEC sites. There are proposals for moored and moving plants, for symmetric and asymmetric intake and discharge ports, and for separate and mixed evaporator and condenser discharges, and each of those configurations may have significantly different effects on the physical environment. The diversity of site characteristics in terms of temperature and salinity stratification and currents complicate the evaluation process further. For example, a mixed discharge configuration at a site with low salinity surface waters may result in a discharge plume with markedly different characteristics than one at a site with similar temperature structure, but with nearly uniform salinity - simply because the discharge buoyancy fluxes are different. Thus, prediction techniques must be capable of addressing the numerous permutations of plant design and site characteristics that are realistically possible.

In this section the approaches available for predictive modeling for single OTEC plant effects are discussed, predictive model applications to OTEC problems are reviewed, and the capabilities and limitations of existing and proposed modeling techniques are assessed. The focus of predictive modeling needs for the immediate future and the requirements for field data are suggested.

Predictive Modeling Approaches

The ideal predictive tool for the purpose of evaluating the effects of a single plant would be a numerical model for a region of ocean at least 15 km in diameter horizontally and 0.5-1.0 km deep. The spatial resolution of the model would be sufficiently fine in the vicinity of the plant to allow prediction of: 1) the three-dimensional buoyant jet behavior at the discharge locations, 2) the plant wake and its effect on the environment, and 3) the temperature and salinity fields. The specification of the boundary conditions would be critical, but their effects might be overcome, except for long integrations in time. However, the ideal numerical model for prediction of modifications to the environment, over the range of scales and for the size of region suggested, does not exist. Despite the significant advances in numerical modeling with first and higher order closure schemes, the problem suggested remains formidable and, we believe, intractable within the time span of OTEC environmental assessment milestones.

The absence of a generally applicable numerical model is hardly a new limitation on such evaluations and requires alternative approaches, many of which have been attempted for OTEC purposes. The general characteristic of such alternative approaches is the partitioning of the environment into zones in which one or two mixing or transport processes are dominant.

A difficulty is, of course, treating those portions of the flow field where several processes are important and interactive. Further, most such approaches are "passive," that is, they take as given the characteristics of the receiving water environment and simply impose the results of some process on that environment. Modifications to the environment must be inferred from such passive model predictions. An "active" approach allows for the modification of the characteristics of receiving water environment, such as temperature, salinity, and currents, as a part of the modeling. Despite the obvious difficulties in patching together predictive solutions in a partitioned environment, we seem to have no alternative. Care must be taken to note those instances in which solutions in one region may influence the boundary conditions of another region. For example, selective withdrawal induced by evaporator intakes may be an isolated process in some instances, while in others, that process may affect or be influenced by the plume generated by the evaporator and/or condenser discharges. In some cases, detailed modeling of a particular portion of the flow field at small scales may be required by the nature of the process, however, the results of that analysis might be incorporated into a larger-scale model in only a schematic way. Thus, the results of detailed modeling of discharge plume interactions with currents near the plant might be represented as only gross wake or averaged plume characteristics in an intermediate-region model with a coarse grid.

An example of the results of partitioned modeling for OTEC environmental effects prediction is provided by Bathen [6] for 100 and 240 MWe plants offshore of Keahole Point, Hawaii. The results of integral analysis of the plume from mixed discharges from the evaporator and the condenser were used as input to a two-dimensional, numerical heat transport model with a grid size of 610 m. The transport velocity field in that model was specified on the basis of independent calculations that relied on field data. Surface heat exchange and diffusion were included in the model. The maximum areas where temperature differentials exceeded background diurnal fluctuations were estimated to be 33.5 and 42 km^2 for the 100 and 240 MWe plants, respectively. Also, a computation of biostimulation was made employing the results of the plume predictions. Many aspects of the calculations are open to question regarding the details of the formulations (e.g., the plume behavior may be oversimplified), but the attempt at a synthesis of parts is worthy of note and provides a framework in which to assess the sensitivity of the integrated results to the components of the model.

Most efforts in the area of physical environmental effects have dealt with the component parts of the flow field with emphasis on the details of the processes. Few attempts have been made to synthesize the results to estimate combined effects on larger regions.

Near-Field Predictive Models

Predictive models have been applied to processes in relatively close proximity to an OTEC plant - the near-field region. For the most part, these applications have been of the partitioned and passive type, and they include the use of both mathematical and physical models. The partitioned processes that were modeled (intake flows, discharges, and combinations of intakes and discharges) are small-scale processes in oceanic terms, but they provide the important boundary conditions for models of larger-scale processes. The models employed often have not included all of the variables, such as stratification, currents, and plant wake, thought to influence the physical environment. Also, the predictions were made typically for limited ranges of the parameters characterizing the plant design and receiving waters.

Evaporator Intake Flows - The near-surface region of flow induced by the evaporator intake has been studied using selective withdrawal analyses for two-layer and linear density stratification [7,8]. The motivation for these studies was the concern for recirculation and degradation of the thermal resource, although some estimates of the vertical extent of such flows were by-products of the work. Unfortunately, the analyses do not include the effects of ambient currents, and realistic source geometries are difficult to include. Some physical modeling of more realistic source geometries, but in stagnant environments, by Hydronautics [4] were oriented toward recirculation and thus reveal little information about the flow field.

Evaporator and Condenser Discharges - The behavior of the discharges from the separate or mixed discharges of the evaporators and condensers is a particularly important component in the assessment of physical effects. The levels to which such plumes sink or rise after mixing are the injection points of relatively large water masses into the environment surrounding the plants. Also, the degree of mixing of the discharges with ambient waters determines the initial characteristics of these water masses, e.g., temperature, salinities, and concentrations of nutrients. Though predictions of discharge behavior are often passive, the plumes are the primary factors influencing the redistribution of temperature and salinity in the vicinity of the plant - the very properties which may in turn govern the discharge plume behavior.

The individual buoyant jets created by evaporator and condenser discharges and mixed discharges have been analyzed by several investigators [8,9,10, 11] by means of well-known integral techniques. These types of analyses apply to that region of the buoyant jet where the turbulence is self-generated, which, for OTEC purposes, typically includes distances less than 1 km from the plant. As long as individual jets do not interact with one another, with the intake flows, or with sharp density discontinuities, the analysis might yield acceptable results for stagnant environments. The zone of flow establishment is important because of the large discharge diameters involved and is not well understood for the low discharge densimetric Froude number cases encountered in most OTEC situations. Also, the presence of the large jet diameters relative to the ambient density gradients raises a question about the validity of the analysis [8]. In the case of the discharge into a current, analyses are available, though less reliable than for the stagnant case. The cases of a jet directed antiparallel to a current (counterflow case) and of a jet in the wake of the plant structure cannot be handled by such integral analyses. Despite the inherent limitations of the integral analysis for the low densimetric Froude number cases common to OTEC and for jet interactions, such analyses may still prove useful for preliminary estimates of the trajectories, dilution, and vertical penetration of separate or mixed discharges for OTEC configurations with relatively simple discharge geometries.

Evaporator/Condenser Discharges in Presence of Evaporator Intake - The prediction of the near field behavior when both evaporator intake flows and evaporator and condenser or mixed discharges are present is difficult to handle in analytical or numerical models. The well known source/sink behavior in irrotational flow may provide some limited insight into recirculation [4], but offers little assistance in the stratified case. A two-dimensional (vertical and horizontal) numerical model for stagnant, stratified flow with first order closure was developed [3] for the region from the free surface to below the condenser discharge for a Lockheed-type design. While demonstrating some of the features of two-dimensional flows, and providing active modification of the density field, the results do not seem applicable to the three-dimensional flow fields expected in most OTEC configurations. Progress in extending such numerical models to three dimensions including ambient currents and the effect of the OTEC structure on the flows seems unlikely in the short term, though clearly advances continue in this area of research.

An alternative to numerical modeling of the complexities of near-field intake/discharge flow fields is physical (hydraulic) scale modeling. Though lacking the flexibility of numerical modeling in terms of simple changes of ambient and discharge conditions, physical modeling does allow three-dimensional effects to be observed. To a limited extent, the effect of the OTEC plant structure can also be observed, and the effects of merging or interacting discharges and intake flows all can be present.

Physical model studies were undertaken at MIT [5] for a schematized representation of an OTEC plant discharging mixed evaporator and condenser flows at the interface of a two-layer ocean. While primarily an investigation of recirculation, the measurements (at a geometric scale of 1:200) of plume temperatures provide information on lateral spreading, vertical penetration, and dilution of the plume under stagnant and small ambient currents (0.1 m/s prototype) for a range of discharge conditions. Both radial and separate jet discharge geometries were considered. These studies indicate that temperature reductions below the temperature of the upper layer are typically decreased to less than 10% of their discharge values within 2 km of the plants, although that result should only be considered in the context of the specific experiments performed and may not be generally applicable for actual site conditions and plant designs. Additional physical modeling studies are underway at MIT to investigate the effects of larger ambient currents and stratification on separate and mixed discharge behavior. Another problem well-suited for physical modeling, that may be studied there [12], is the interaction of closely spaced, separate evaporator and condenser dischargers - they may mix sufficiently well to preclude in-plant mixing.

Physical model studies at Hydronautics [4] also have been primarily focused on recirculation, but a few experiments have included detailed measurements of the temperature fields for a discharge in the presence of an intake. For intake/discharge separations on the order of two discharge diameters, significant interactions and complex three-dimensional flow fields result. Also, a physical model of a discharge into a stagnant, stratified environment, with characteristics in the range of OTEC discharges and sites, indicated downward penetrations of jets to 2-4 discharge diameters - a result similar to that yielded by some integral analyses.

Intermediate-Field Predictive Models

At larger distances away from the plant and beyond the region of buoyant jet behavior of the evaporator/condenser discharges, physical modeling becomes less useful. The plume is transported at essentially the speed of the ambient currents and spreading is likely to be governed by gravity-driven flows, by ambient turbulent diffusion, and by planetary rotation. Predictions in this intermediate-field region would seem more the realm of mathematical modeling, and the framework for such a passive modeling has been suggested [8,12]. Active modeling of the two-dimensional type applied previously [3] to the near-field region may have application here, if lateral spreading effects are sufficiently small. It may be that the discharge plume has sufficient dimension to be considered for inclusion in a multi-level numerical model that attempts to simulate a portion of a baroclinic ocean (discussed below). In fact, only at such scales may active prediction of modifications to temperature and salinity fields be possible, although the perturbations at large distances are likely to be small.

Status of Single-Plant Effects Predictions

It appears that near-field effects of intakes and discharges on the environment will be best understood, in OTEC timeframes, by the use of physical modeling techniques. While overcoming some of the present limitations of mathematical models in the complex near-field region, they, of course, have their own limitations (such as boundary effects which increase the longer the duration of the test). Because physical models can be time-consuming to construct and alter, the numerous permutations of design and site characteristics to be investigated require that some selectivity be employed in choosing test conditions. Recommendations at an earlier OTEC Workshop [13] for the development of a series of "worst cases" in terms of realistic site characteristics against which to screen various design configurations have merit in this regard.

Some of the simpler mathematical models might prove helpful in establishing the important cases for physical modeling. Also, the results of the physical modeling may indicate that such mathematical models or slight adaptions of them provide reasonable zeroth order predictions suitable for initial studies by those investigating ecological impacts. Since the prediction of physical modifications to the environment is an effort in support of the broader ecological concerns, it is worth keeping in perspective that the results of predictive techniques applied in the physical area need to be consistent with the inputs required for ecological prediction.

In the intermediate-field region, numerical modeling appears to be the useful tool. Work has only begun recently in this area, and while modeling of this region may provide some insight into vertical redistributions of temperature and salinity in the vicinity of the plant, it is essentially the link between the near-field models and the oceanic-region models discussed in Section 4. In such a position, modeling must be guided by the recognition of the larger scales of the models into which the results will be incorporated and feedback from the large-scale modelers as to the sensitivity of their model predictions to intermediate-field predictions is necessary.

4 AGGREGATE EFFECTS OF MANY PLANTS

The concept of OTEC power parks raises a number of important environmental issues relating to the ocean and to the atmosphere. Large-scale redistribution of temperature, salinity, and nutrients has been postulated. The potential for widespread modifications of mixed-layer depth and of baroclinic currents also has been suggested. A possible consequence of operating a multitude of OTEC plants is climatic change induced by sea surface temperature (SST) depressions. Several of these questions are related to the spacing of OTEC plants.

Magnitude of Perturbations to Vertical Structure

Preliminary estimates of some of these potential effects are available. SAI [14] assessed the effect of OTEC operation on the vertical thermal structure of the Gulf of Mexico by using a one-dimensional heat conservation equation to predict the horizontal mean temperature. Heat advected into the Gulf by the Yucatan Current was treated as a source, a mean upwelling was calculated to balance the overall heat budget, and mixed-layer diffusivity was simulated by the closure model of Mellor and Yamada [15]. The SAI [14] calculations indicate that 100 OTEC plants (200 MWe each) operating in the Gulf for 30 years would reduce the SST (averaged over the basin) by about 0.05 C° and warm the deep water above the cold water intake (500-1000 m) by about 0.8 C°. For 1000 plants, the SST is lowered by about 0.3 C° in two years and remains approximately constant thereafter. However, the deep water in the region above the cold water intake warms continuously at the rate of about 0.3 C°/year. The warming of the deep water is probably the worst to be expected, because the model does not allow outflow currents to remove heat from the Gulf. The key to resource availability in the Gulf for large-scale OTEC operation may lie in the rate at which the deep water of the Gulf is replaced by water from the Caribbean [14]. The SST depressions stated above are small compared to persistent, natural anomalies that are known to affect ocean dynamics and, at least, regional climate. However, the horizontal scale of the induced depressions will probably not be basin-wide, and thus, the values of regional depressions could be much greater.

Magnitude of Perturbations to the Horizontal Structure

Little or no work has been done that is directly related to the scale of horizontal perturbations caused by many OTEC plants and their aggregate effects. The approximate perturbation scales for a single plant were described above on the basis of near-field dynamics. The manner in which numerous plants interact with each other and with the ocean probably defies simple calculations. However, let us assume that if the modification of the existing thermohaline structure by OTEC is less than or equal to variations in the natural environment, then that impact will be acceptable (or at least not detectable in a statistically significant way). We then seek a simple model to estimate the power density required to induce changes comparable to natural ocean anomalies.

In order to make a rough calculation of the power density, we need to know both the rate at which energy must be added to the ocean to induce a thermohaline anomaly and the rate at which an OTEC plant can add available energy for producing such an anomaly. The first of these rates can be estimated from observations of decay of existing anomalies. The second can be estimated from the energy of the effluent of the OTEC plant.

One such anomalous structure commonly found in the ocean is a detached Gulf Stream ring or cold-core eddy. The decay of such a ring has been reported by Cheney and Richardson [16]. The eddy they studied was monitored on five cruises between March 1971 and April 1972. They found the radius of the eddy decreased from 79 km to 55 km over this time period and the available potential energy decayed at an average rate of about 2 GW. The ratio of available potential to kinetic energy remained essentially constant at about 20. If we take the initial radius as 80 km, then the power density of the dissipation must be greater than or equal to about 0.1 W/m^2. If the dissipation and growth rates are equal (which we shall assume), then it would require an average power density of more than 0.1 W/m^2 to sustain the growth of an induced anomaly against the natural dissipation acting to destroy it.

In order to estimate the effect of an OTEC plant, we will model the discharge of an effluent plume into the environment. The plume is assumed to be discharged vertically downward from a 30-m radius circular port into a non-rotating, stagnant environment. The volume flow rate is chosen to be the same as the total discharge of the 160 MWe Lockheed baseline design and both discharges are assumed to be mixed. Also, it is assumed that the warm and cold water flow rates are equal, giving an exit flow rate of 3200 m^3/s at a temperature of 15.5°C. The ambient regime is chosen to be typical of the area south of Puerto Rico, and is taken from the Crawford Station No. 378 data [17]. The model is based on equations similar to those reported by Turner [18] modified for temperature and salinity effects. The warm water is assumed to be withdrawn from the 10-m depth and the cold water from 1000 m. The model predicts that the plume would reach a maximum depth of 328 m and the point of density equalization between the plume and the ambient environment would be at a depth of 216 m. The transports of kinetic energy (based on the average speed of fall of the plume) and available potential energy (referenced to 216 m) give a maximum transport of energy of about 6.5 MW that could be made available for modification of the environment.

If we assume withdrawal of fluid from the environment also produces 6.5 MW of available power, we obtain about 13 MW/plant as the estimate for the total power available for environmental effects. This gives, for a power density of 0.1 W/m^2, an area of 1.30×10^8 m^2/plant. If the plants are assumed close-packed, then the spacing between plants is about 17 km. An average spacing greater than this, under the given assumptions, should not be able to cause large-scale environmental effects.

Even though a 17-km spacing will probably not cause large-scale effects, it is desirable to estimate the influence of the thermal effluent from one plant on the operation of a neighboring plant. The fate of the mixed discharge from one plant may be described qualitatively as follows: after leaving the discharge port, the plume will sink, entraining ambient fluid, until buoyancy overbalances the inertia of the plume, at which point it will rise slightly and begin to spread; initially, the spreading will be governed mainly by gravitational and inertial forces, but as the plume leaves the vicinity of the plant, rotational effects will balance gravitational spreading to control the ultimate height and width of the plume. Scaling arguments, based on conservation of potential vorticity, indicate that the thickness to width ratio of the plume should be approximately the ratio of the Coriolis parameter to twice the Brunt-Väisälä frequency. If the plume is advected at 0.1 m/s in an ambient ocean typical of south of Puerto Rico, and if its volume flux after sinking is about 8000 m^3/s, then the plume will eventually become 20 m thick and 6 km wide, after rotational effects have become important.

The travel time for the plume to move from one plant to the nearest neighbor would be about 50 hr. For a vertical diffusivity of 10^{-4} m^2/s, the diffusion length scale is only about 4 m. Therefore, unless there is a mechanism to advect the effluent upward by several hundred meters, the mixed plume (assumed to exist here) from one plant will probably not directly impair the operation of a neighboring plant.

The above estimates suggest that redistribution of available potential energy in the ocean by the combined operation of many OTEC plants will not be sufficient to generate mesoscale (of order 50-100 km) anomalies. In other words, naturally occurring anomalies in the thermohaline structure will be greater than the anomalies that OTEC can produce. This fact, in turn, implies that OTEC climatic effects may not be statistically significant. The present calculations also suggest that thermal wake interaction between plants may not be detectable. We stress the fact that our estimates are crude, and are offered as provocative rather than definitive arguments.

Modeling of a Limited Ocean Region

The continued development of relatively sophisticated ocean models that can be focused eventually on OTEC issues offers a potential means for making more definitive arguments about OTEC impact and resource availability. Thompson et al. [19] have reported on the development of a basin-wide model for the Gulf of Mexico with a spatial resolution of about 20 km. Madala and Piacsek [20] have introduced the numerical-geophysical framework for a limited-area ocean model in which horizontal resolution could be as small as 1 km. The assessment of impact presupposes a knowledge of the ambient environment and statements about resource availablity presume, in most cases, that limited measurements are adequate to describe mean quantities and their variances. An important role of the ocean models is to foster a greater understanding of mesoscale ocean features, which, as indicated above, might define the largest acceptable upper bound for artificially-induced perturbations. Added insight about resource availability also is a possible product of the models, since temporal variability at a plant site can magnify its influence through the relationship between net power output and temperature resource.

It may be useful at this point to compare the magnitude of OTEC perturbations in a very crude manner to other known geophysical quantities. For example, the total volume flux of ten OTEC plants (100 MWe each) is roughly equal to the average volume flux of the Mississippi River and is about 1/1700 the flux of the Loop Current in the Gulf of Mexico [21]. It seems clear that a large number of plants would be required to cause the kinds of redistribution of ocean properties associated with major ocean currents. However, the physical and biochemical effects of the Mississippi River can certainly be traced well out on the continental shelf. Thus, it seems reasonable that OTEC power parks could produce observable changes in the spatial distribution of nutrients, temperature, salinity, oxygen, and so on, at least up to length scales of the local Rossby radius of deformation based on OTEC-induced density differences. It is difficult, if not impossible, to state a priori the bounds of such changes in such a nonlinear and poorly understood system.

5 RECOMMENDATIONS

The physical environmental effects of OTEC probably must be studied by using a hierarchy of physical and numerical simulation models, ranging in domain from the near field (1-5 km), to intermediate field (3-10 km), to mesoscale (10-100 km), to basin wide (100-1000 km). The present OTEC timetable dictates different approaches for predictive models of the various spatial domains.

No three-dimensional numerical calculations have been made for the near-field region. The relatively immediate need for information pertaining to vertical redistribution of physical and biochemical parameters near a plant seems to call for physical model studies that can examine some of the three-dimensional effects in the presence of currents and stratification. Integral-type engineering models offer some potential for zeroth order estimates for the behavior of the effluent from OTEC in the near and intermediate field.

A limited-area ocean model compatible with a basin-wide model seems to be the only available tool for quantitative study of plant-plant interaction, induced changes in thermohaline structure, redistribution of nutrients, and dispersion of biocides up to the mesoscale. One of the most important goals of ocean modeling for OTEC should be to estimate how quickly plant effluents will be dispersed. In a sense, this goal consists of simulating the fate of tagged water masses having density anomalies that are small, on an inter-plant scale, with respect to ambient anamolies. Thus, the fate of effluents will be largely a result of advection by simulated ocean currents. The dispersion estimates will be statistical in nature, because they need not, and probably could not, be made in a way that simulates the detailed evolution of OTEC perturbations.

Sufficient techniques and computational resources exist to attempt simulation of a 100 by 100 km region of the ocean with 2 km horizontal resolution and with 10 or more layers in the vertical. Boundary conditions for such a limited-area model would come from a basin-wide model, which for the Gulf of Mexico could have about 20 km resolution. In fact, the need for these boundary conditions may provide the present impetus for basin-wide model development. OTEC perturbations at the plant level would have to be specified at the appropriate locations in the limited-area model. The perturbations would be most likely momentumless source distributions for the various properties of the effluent. Presently, it appears that the distributions would have to be based on the results of physical model studies of the near-field region or the results of intermediate-region analysis.

It must be recognized that the scope of the present problem broaches the frontiers of our knowledge of jet and larger-scale transport dynamics in the ocean. Model solutions need to be carefully tested during development. Detailed data on currents and density fields at potential OTEC sites are needed to aid modeling of the near- and intermediate-field regions. For larger scale modeling, satellite-inferred surface temperatures and current patterns are likely candidates to test the statistical properties of the solutions. Conventional oceanographic data also may return information for at least qualitative comparison, e.g., the recently reported winter intrusions of the Loop Current [22]. The challenge to modelers is to plot a course of scientific development that can produce reliable estimates of future OTEC effects consistent with the limitations of working at such frontiers.

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