RESOURCE ESTIMATE FOR OCEAN THERMAL ENERGY CONVERSION (OTEC) IN THE GULF OF MEXICO

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Rand
SANTA MONICA, CA. 90406
PREFACE

The Rand Corporation has made a quantitative evaluation of the Ocean Thermal Energy Conversion (OTEC) technology in central station applications. The evaluation required a number of supporting analyses. This note documents an effort to arrive at a first-order estimate of the thermal resource in the Gulf of Mexico that can be profitably extracted by this technology.

The systems approach described here should be a useful contribution to the overall effort to reduce uncertainties in OTEC technology and to achieve a better understanding of resource constraints. The note should be of interest to program and policy offices in the U.S. Department of Energy, as well as to those outside DOE who are concerned with the future of OTEC.

The substantive research was conducted as part of Rand's program of policy studies for DOE under Contract DE-AC01-79PE70078. Part of the preparation of the note was made possible by support provided by The Rand Corporation from its own funds.
SUMMARY

The future of Ocean Thermal Energy Conversion (OTEC) as a useful technology depends to a large extent on the resources that can be profitably extracted. This note addresses the question of resource estimates in the Gulf of Mexico.

For reasons having to do with the economics and performance characteristics of the components of an OTEC system, power plants are usually designed for a nominal water temperature difference (ΔT) of 20°C. Other than the islands of Hawaii and Puerto Rico, it appears that the Gulf of Mexico is perhaps the only area for the United States where a significant amount of ocean thermal energy can be extracted.

One approach to estimating the ocean thermal energy resource is through modeling studies. Unfortunately, sophisticated analytical and numerical breakthroughs and a vast data base are required to do this, and both are beyond the current state of the art.

The problem here, however, is not to generate results precise to many significant figures, but rather to address the great disparities among existing estimates that range from a few to a few thousand GWe. To reduce this uncertainty of three orders of magnitude, we have applied a number of technical and oceanographic considerations that are crucial to the deployment of OTEC plants.

The operation of an OTEC plant requires that the ocean depth be sufficient for the bottom water to be cold enough to yield the necessary ΔT. This is usually on the order of 1000 meters, or 3000 feet. On the other hand, the depth cannot be excessive because a floating central station plant must transmit its generated power to shore and will therefore need to be moored. Advanced mooring technology projects capacities on the order of 6000 feet in depth. The note shows areas in the Gulf of Mexico where the bottom depth is between 4000 and 7000 feet.

The distance from the shore will also have implications for the power cable. To keep the electric losses and cable costs under control, the maximum tolerable distance has been determined to be on the order of 180 miles.
The moored power plant cannot reach the thermal energy available in the open waters outside the Gulf. It must rely on the transport by ocean currents to replenish the warm surface water and cold bottom water in its vicinity. This transport mechanism is the Gulf current system which enters the Gulf through the Straits of Yucatan, bends eastward, and exits through the Straits of Florida. The width of the current is approximately 300 km. The loop current meanders significantly, but by and large keeps to the eastern part of the Gulf of Mexico. Thus, potential areas for OTEC deployment are limited to sites off the west coast of Florida extending northward to New Orleans.

A synthesis of the foregoing considerations results in a likely offshore area to the south and west of the southern part of the Florida peninsula. A final consideration is the spacing among OTEC plants when a large number of them are to be deployed. There is a minimum spacing required, depending on the size of the plant, current velocity, and other local ocean conditions. Spacing below this minimum would cause the discharge from one plant to adversely affect the intake of another. It has been determined that for a plant size of 100 MWe the minimum spacing should be on the order of 10 km.

The total potential surface area off the coast of Florida and New Orleans will permit a deployment of 100 to 300 such plants, yielding a total of 10 to 30 GWe of power. This is not an insignificant resource; the total demand in 1979 of the U.S. south and southeast region was on the order of 112 GWe.
ACKNOWLEDGMENTS

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I. INTRODUCTION

Ocean thermal energy conversion (OTEC) is a solar technology. It uses the temperature difference (ΔT) between the warm surface water and cold water from the ocean depths to operate a thermodynamic cycle to generate electricity. This can be realized, for example, by circulating an appropriate working fluid (such as ammonia) through a conventional type of heat engine cycle. The fluid is vaporized, made to pass through and drive a turbine electric generator, and condensed for reuse in the cycle by the cold deep water drawn into the plant. Thus the warm surface water drawn into the evaporator will be cooled slightly and will be carried away from the plant by the surface current. The cold water will be slightly warmed, and being colder and denser than the surrounding water where it is discharged, should descend again to the depths.

In a previous report* a quantitative evaluation was made of the cost and engineering performances of OTEC systems for power generation in the Gulf of Mexico. In this note, we estimate the generating capacity that can be sustained in the Gulf.

Incident solar energy on the surface of the ocean in the near field of a moored plant is insufficient to maintain a useful ΔT when a significant amount of energy is extracted. The capacity to replenish the warm surface water and cold bottom water and maintain the necessary ΔT determines the extractable resource of a given region. In the Gulf of Mexico, such replenishment is provided by the large transport of warm water from tropical oceans. The characteristics of this transport in terms of both temporal and spatial variations will dictate regions where the thermal energy may be extracted on a continuous basis.

The energy that can be extracted by deploying a number of OTEC plants also depends on the near-field dynamic impact of the plants.

Unlike nuclear-powered generating systems, the near-field dynamic impact influences not only the far-field environment, but also bears a strong impact on its own and neighboring plants' power-generating potential.

One possible approach to evaluating the thermal resource is through modeling studies. However, such an approach would require not only the acquisition and structuring of a vast data base, but also the resolution of a number of extremely difficult analytical and numerical questions. Neither of these requisites is currently available.

Where physical models are concerned [15], they must be large enough to satisfy important laws of similitude to obtain meaningful results of buoyancy and turbulence-induced mechanisms. In situ data have to be collected in undisturbed experiments with sufficient spatial and temporal resolutions, under appropriate conditions.

Numerical models present a number of problems, some of which are related to the appropriate representation of turbulence. For example, the widely used exchange parameter involving the flux-Richardson number has an uncertainty range which may exceed the sensitivity of near-field dynamic responses to the operation of an OTEC plant. Specifically, plant discharge may induce instabilities that could lead to recirculation, reducing its own efficiency and that of neighboring plants [7, 8, 20, 21, 24]. Other difficulties in numerical models include the computation of near-field and far-field dynamics [9] (turbulence closure problem), the specification of initial and open boundary conditions, and long-term integration problems.

In view of the modeling problems mentioned above, the evaluation of OTEC-extractable thermal resources in this paper will be carried out by applying a number of technological and economic considerations. Such an analysis will have neither the rigor nor the precision and/or accuracy of modeling studies. However, it will provide a basis for a first-order approximation and a rationale for the establishment of some bounds.

For example, it is possible to establish approximate upper bounds for the resource potential in the eastern part of the Gulf of Mexico, based on gross thermal balance alone. McCluney and Sivak [1]
considered such an approach by estimating the total potential thermal resources across the mean Florida current in the eastern Gulf. Their estimate was derived on the premise that the Florida current provides the mean flow needed to carry away the thermal plume from the power plants and that all intakes will be on the upper stream and discharges will be on the downstream side of the structure. The authors then considered a tolerable sea surface temperature (SST) depression, e.g., 0.5°C. (The cold water drawn up for reuse is assumed to have been only slightly warmed and, being colder and denser than the surrounding water, to descend again to the depths.) They also assumed that there is no new energy transfer through the air/sea interface resulting from the OTEC-induced SST depression. On that basis, the potential thermal resource in terms of the heat flux passing through a cross section from Miami to Bimini was estimated. By allowing for the partitioning of the available thermal gradient in the heat transfer process and the operation of the heat engine for some conversion efficiency, a total of 75 GWe of electrical power output was estimated.

The assumptions and simplifications necessary for the derivation of the above estimate ignore some of the more important issues that accompany the engineering realization of the OTEC system; neither do they reflect important critical factors in the actual deployment of a large number of OTEC plants. Among the issues and factors which must be considered in order to arrive at a reasonable estimation of OTEC-extractable resources in the Gulf of Mexico are: geopolitical implications (the United States shares the Gulf water with Cuba and Mexico; the latter might access the upstream portion of the loop currents); seasonal variations in the ΔT; constraints imposed by the state of the art of engineering technologies; the effect of current velocity on station-keeping; the economics of plant-to-shore submarine power cables; and the frequency of severe hurricanes. For example, it is likely that depths exceeding 6000 to 7000 feet may result in mooring problems. Another example is that the replenishing currents exhibit a tendency to meander seasonally. The result is a reduction in areas where moored plants can be effectively deployed.
The above considerations lead to a number of constraints: state of the art of the mooring technology, cost of transmission cable, international boundaries, available ΔT, the excursions of loop currents, and the tolerable spacing between plants. The superposition of these constraints will result in bounding an area in the Gulf where moored OTEC plants may be sited. We shall further introduce systems-specific considerations to estimate the necessary spacing requirements between OTEC plants. An estimate of the total number of plants of a given size that can be deployed in the strip can thus be made, and an estimate of the power that can be generated derived therefrom.

This note is organized as follows: First, we present a brief account of the premises on which we base the analysis of the energy balance in the Gulf of Mexico, and the implications of geomorphology and oceanographics. The currents and their variability will be discussed. Next, we examine those technologies that significantly affect the estimation of the extractable resource and engineering considerations and system requirements governing the spacings between plants. Finally, we present a synthesis of the constraints and the results in terms of OTEC-extractable power.
II. THERMAL ENERGY IN THE GULF OF MEXICO

The processes of heating a large body of open water include the following:

1. Absorption of radiation from the sun and the sky.
2. Convection of heat through the ocean bottom from the interior of the earth.
3. Transformation of kinetic energy to heat.
4. Heating due to chemical processes.
5. Convection of sensible heat from the atmosphere.

Cooling of the same body of water may result from:

1. Back radiation from the surface of the water.
2. Convection of sensible heat to the atmosphere.
3. Evaporation.

Of all the processes of heating, only the first one is important.

The incoming radiation depends mainly upon the altitude of the sun, the absorption in the atmosphere, and the cloudiness. Since the water surface reflects only a small fraction of the incoming radiation, the greater part of the radiation energy is absorbed in the water, distributed by a process of mixing over a layer of considerable thickness, and given off into the atmosphere during periods when the air is colder than the sea surface.

The sea surface also receives long-wave heat radiation. A small part of this incoming long-wave radiation is reflected from the sea surface, but the greater portion is absorbed in a small fraction of a centimeter of water.

The diurnal and annual variations of the sea surface temperatures and of the relative humidity of the air over the oceans are small. The effective back radiation at a clear sky is nearly independent of
the time of the day and of the season of the year, in contrast to the incoming short-wave radiation from the sun and the sky, which is subjected to very large diurnal and seasonal variations.

The incoming short-wave radiation from the sun and the sky is greater in all latitudes than is the outgoing effective back radiation. According to Mosby [22], the average surplus of incoming radiation between latitudes 0 and 10°N is about 0.170 gcal/cm²/min, and between 60°N and 70°N, about 0.04 gcal/cm²/min. The surplus radiation translates into only a few tens of watts per square meter, and the role of climate control precludes any significant depression of surface water temperature. In other words, the currents through the Gulf must provide the thermal energy resource to be extracted by any OTEC plant.

The thermal resources in the Gulf of Mexico derive principally from the clockwise current in the eastern Gulf, often referred to as the loop current. Entering through the Yucatan Straits and continuing with increased speed through the Yucatan channel, this loop current bends sharply to the right, then flows with greater velocity out through the Straits of Florida. It has an approximate transport of 30,000,000 m³/sec, moving predominantly in the upper 100 meters. The strong time-varying current has an average width of 300 km, and in the core region (50 to 100 km wide), the velocity can reach up to 3 knots. On the flanks of the main current, numerous eddies are present.

The kinetic energy of the current appears to be derived directly from the difference in sea level between the Gulf of Mexico and the adjacent Atlantic coast. Assuming that this hydrostatic head accounts for all of the energy and assuming frictionless flow, Montgomery [22] finds that the velocity through the Straits of Florida should be 193 cm/sec, which is somewhat higher than the average velocity at the center of the current [22]. The difference in level is probably maintained by the trade winds, further limiting the validity of the McCluney-Sivak study.

The deepest connection between the Mexico basin and the adjacent seas is found in the Yucatan channel, and the deep water of the Mexico basin is therefore renewed from the Yucatan basin by a flow across the sill in the Yucatan channel. The passages to the north of
Cuba are much more shallow, and no renewal of deep water can take place through them.

Deep currents have been observed in the Yucatan Straits [32]. Stratification probably suppresses vertical turbulent mixing and maintains vertical thermo-inhomogeneity. We assume the rate of cold deep water renewal is adequate. More data than are currently available will be required to make this determination in estimating the steady-state thermal resource in the Gulf.

The general spatial distributions of the currents flowing through the eastern Gulf of Mexico indicate a well-mixed surface layer, varying from a small fraction of a meter to over 125 meters, depending upon the location, time of year, and local influences. Over the central Gulf, the mean depth of this layer is on the order of 90 meters during the months of January and February.

The position and strength of the loop current are examples of variability that have time scales with periods from days to years. Figure 1 is a composite of information to exemplify the geographic variability of the loop current on which depends the extractable thermal resource for moored OTEC plants in the Gulf of Mexico. The lines are the locus of the 22°C isotherm at 100 meters depth [27]. These data cover 14 months at 36-day intervals and were observed by NOAA ships in 1972 and 1973 [14]. Statistically, the 22°C isotherm at 100 meters depth is 14 km to the right of the satellite sensible edge of the loop current facing downstream [36]. The northward penetration of the loop current [13] appears to be dominated by an annual cycle with maximum latitudinal extension in summer and a minimum in winter. The change from maximum extent seems to occur rapidly through the formation of an anticyclonic eddy whose typical diameter is on the order of 400 km [25, 26].

Most probable monthly temperature profiles from surface to 1000 meter depths have been developed from nineteen one-degree latitude-longitude squares in the eastern Gulf of Mexico [4]. Much of this part of the Gulf of Mexico is the site of the loop current [35].

The loop current presents difficulties in analysis of the thermal resource. The temperature observations in the eastern Gulf do not
represent a coherent Gaussian distribution for many sites. In many areas, temperature soundings typical of loop current water were found along with another set of soundings representing other Gulf waters. The result was a bi-modal temperature structure. In areas where bi-modal or other non-normal distributions were present, the values of $\Delta T$ have been determined from the most probable sounding in the warmer portion of the distribution. Figure 2 shows some typical contours of mean $\Delta T$ in the eastern Gulf.

Summarizing, in order to sustain continuous extraction of thermal energy in the Gulf of Mexico by means of moored OTEC plants, we must rely on the transport of warm waters in the loop current. The latter's spatial and temporal variations lead to an area limited to the eastern portion of the Gulf for potential OTEC sites.
Fig. 2 — Mean $\Delta T$ (surface to 1000 meters), $^\circ$C
III. TECHNOLOGICAL CONSIDERATIONS

The successful extraction of thermal energy from the ocean requires the effective integration of the OTEC plant with an ocean system and a power transmission system. The ocean system consists of a platform to support the power system and auxiliary equipment and a cold-water pipe to reach down to the depth necessary for the condensing water; the power transmission system for a stationary central station is composed of a "riser cable" connecting the electrical output terminal of the plant on the platform to a fixed junction on the bottom of the ocean and a submarine "bottom" cable on the ocean floor carrying the generated power from the junction to shore. Although each and every component in the OTEC system will interact to some degree with the ocean environment, the following factors are of special importance in the estimate of resources in a given area:

- ΔT: The temperature difference between the warm surface water and the cold bottom water imposes an upper bound on the cycle efficiency achievable (Carnot cycle).

- Depth: The ocean depth must be sufficient for the bottom water to be cold enough to yield the necessary ΔT. On the other hand, the depth cannot be excessive in view of the requirements for station-keeping* and the limitations imposed by the state of the art of mooring technology.

- Siting: As previously noted, the spatial distribution and meanderings of the loop current must be taken into account in siting OTEC plants. If the power generated is to be hard-cabled to the mainland, then the site cannot be too far offshore if electrical losses and cable economics are to remain under control.

- Spacing: To deploy a large number of OTEC plants, spacing requirements between plants are dictated by current velocities

*Dynamic station-keeping employing powered thrusters is not practical in an area of high current velocity because of the large expenditure of energy necessary to power the thrusters.
and local ocean conditions, and must be sufficiently large so that the intake and discharge of one plant will not adversely affect those of another.

The AT in the eastern Gulf and the loop current were discussed in Section II; the technological implications of mooring systems, transmission cable, and spacing requirements for multiple OTEC plant sites will be discussed below.

The fundamental requirement for a mooring system is that it should be able to react against the maximum horizontal force on the moored platform operating in a specified water depth. This maximum horizontal force depends on the total drag force of the plant, and is a function of ocean conditions and design variables. However, to a first approximation, the total drag force may be expressed in terms of plant size and current velocity. Figure 3 shows the estimated total drag force for a current velocity of 2 to 3 knots. It appears that an OTEC plant with net power levels from 100 MWe to 400 MWe will experience a drag force on the order of 10 to 20 MN, when deployed in the loop current.

Catenary solutions for mooring lines* have been obtained for steady-state drag loads [37]. The solution is a function of the type of line used, properties resulting from the platform's excursion conditions—called the "watch circle"—and the depth of water. Figure 4 shows the range of restoring force of typical mooring lines as a function of the depth of water, for a 5 percent excursion condition. The restoring force of a mooring line is seen to decrease rapidly with the depth.

Current practices of the offshore oil industry typically assume that working loads for mooring lines should be one-third of the breaking strength for normal conditions and one-half for storm conditions. Conventional chains used in offshore mooring have a breaking strength

* Catenary solutions do not apply to advanced mooring concepts such as vertically constrained and tension-legged configurations.
on the order of 20 MN, and that of ropes ranges from 3 MN for wire rope to 5 MN for nylon rope. Furthermore, a slack-chain mooring line in 5000 feet (1500 m) of water would experience a line tension equal to one-third its breaking strength, due to self-weight alone. In other words, the chain is at the design limit for line tension with no horizontal load on the platform.

In Figures 3 and 4, we have also included estimates of the current limit of industry capability. A number of conceptual designs such as the hollow cylindrical links [12] have been proposed, with dramatic increases in strength. Even with the projected high capacity, it appears that in water depths of 6000 to 7000 feet, the expected drag load of an OTEC plant will be severely pushing the state of the art of mooring technology.\footnote{The above discussion of mooring technology is based on the assumption that an electrical riser cable can be designed to withstand the same platform excursions. The riser cable technology is another constraining factor, with the additional requirement to maintain electrical integrity.} Since the cold-water pipe will in all likelihood
Fig. 4 — Typical restoring force of mooring line subjected to one-third break strength at 5 percent excursion

Fig. 5 — 4000-foot and 7000-foot contours in U.S. waters
have to reach beyond 1000 meters (3300 feet) for the condensing water, we shall consider a range of depth from 4000 to 7000 feet. Figure 5 shows contours off the coast of the United States bracketing this.

Where deployment of more than one OTEC plant is necessary to extract the energy, the relative location of one plant with respect to its neighbors is an important consideration. The interactions among OTEC plants include resource depletion, chemical and nutrient accumulation, mooring requirements, geophysical effects (basin-wide circulation, meteorology) etc. We will limit our discussion to the aspect of resource depletion.

Ideally, once a general location has been fixed, e.g., the eastern part of the Gulf of Mexico, we should evaluate the spacings in the context of installation costs and operating costs, in an attempt to find the minimum cost sitting pattern. This is impossible at present: not enough oceanographic data are available, the plant designs are far from fixed, and the interaction between plants is little understood.

When a large number of OTEC plants are deployed in a general area, any one of them will have a hydrodynamic influence on its neighbor, and vice versa. The most obvious of such "communications" between plants is in the form of surface waves which have a celerity much larger than the ambient current so that even upstream plants are influenced. However, the surface effects are generally negligible. Of much more interest to thermal resource utilization is the communication in the form of internal waves, primarily the internal density currents. The local wave speed in a density current is dependent on its thickness and thus can be larger or smaller than the ambient current. Upstream and lateral influences are also possible.

The ultimate design of the spacing between multiple OTEC plants must be obtained on the basis of an economic analysis using, among other factors, the expected frequency of ocean conditions (currents, stratification) and an estimate of potential derating under conditions of mutual plant influence. In the absence of such analyses, estimates have been made on the basis of preventing any recirculation for the plant [24]. The analysis was built upon a stability (recirculation) model [38]. Using "typical" ambient and plant design conditions, the
following estimates for the required lateral spacing between plants were obtained based upon an ambient design velocity of 0.1 m/sec and a discharge at the ocean thermocline located at 70 m depth, which appears characteristic of winter conditions in the eastern part of the Gulf of Mexico.

<table>
<thead>
<tr>
<th>Plant Size</th>
<th>Spacing (m)</th>
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</thead>
<tbody>
<tr>
<td>100</td>
<td>5,570</td>
</tr>
<tr>
<td>200</td>
<td>16,270</td>
</tr>
<tr>
<td>300</td>
<td>40,320</td>
</tr>
<tr>
<td>400</td>
<td>160,000</td>
</tr>
</tbody>
</table>
IV. RESOURCE ESTIMATE

We now estimate the OTEC-extractable resources in the Gulf of Mexico by synthesizing the foregoing considerations:

- Depth of 4000 to 7000 feet
- Distance of 180 n mi or less off shore
- Area traversed by the loop current
- International boundary line

When these requirements are superimposed, we obtain a strip off the west coast of Florida extending north towards New Orleans. This result is shown in Figure 6. The total potential surface area has an average width of 25 km over a total distance of 1500 km.

Fig. 6 — Synthesis of constraints on resource availability
Seasonal variations of local currents and fluctuations of warm-water supply resulting from loop-current-induced eddy transport will reduce the amount of extractable energy. These considerations as well as the lack of field data and the tentative nature of existing analyses suggest a further reduction in the effective area for deployment. This will be reflected in applying a spacing requirement of approximately 10 km for OTEC plants rated at 100 MWe. Two 100-MWe plants could be deployed in each row across the strip of water, thus leading to an estimate on the order of 30 GWe. A more conservative estimate would be to assume only a single string of plants spaced 15 km apart, resulting in a total of 10 GWe.
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