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OCEAN THERMAL AND CURRENT VELOCITY DATA REQUIREMENTS FOR DESIGN OF AN OTEC DEMONSTRATION PLANT

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EXECUTIVE SUMMARY

This report represents a preliminary step in providing ocean thermal and current velocity data to participants in the Ocean Thermal Energy Conversion (OTEC) Program of the Department of Energy. The requirements for oceanographic data needed in the design of an OTEC demonstration plant and a methodology for obtaining these data are presented. In addition, some requirements for environmental impact data are given. The design requirements were obtained from our own assessment, paper's presented at OTEC symposiums, discussions with design engineers, and journal articles.

The design effort for the demonstration plant is in early stages, therefore, the ocean data requirements presented apply to a generic plant design, i.e., one that includes a surface vessel, shape unknown; water intakes and discharges, depths unknown; etc. As the plant design becomes more defined, a more specific data collection effort is envisioned. Thus, this report is seen as the initial iteration in an iterative process between oceanographers and engineers to specify and obtain the required oceanographic data.

It is assumed that the reader of this document is familiar with OTEC concepts. Therefore, a detailed discussion of proposed OTEC designs is not given. In addition, some knowledge of oceanographic terminology is assumed.

Table of Contents

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1. INTRODUCTION

This report represents a first step in determining the ocean thermal and current velocity data needed for the design of an Ocean Thermal Energy Conversion (OTEC) demonstration plant. In particular, the requirements for oceanographic data in design, and the oceanographic data sufficient to address these requirements are specified.

The successful design and operation of an OTEC plant depends critically on an accurate characterization of the ocean environment. The environment will have an economic impact on all phases of plant development from the planning and design of a plant through its daily operation. Both extreme and average environmental conditions are important. The plant is designed to withstand environmental extremes, and thus these extremes affect the initial cost of the plant. The daily operating costs of a plant are in part a function of the average environmental conditions.

This report is to be considered a preliminary step in specifying design requirements for data. As plant design becomes more refined, the data needs will have to be updated. A portion of an OTEC program milestone chart (ERDA, 1977) is presented in Figure 1. The demonstration plant program is at an early stage in its development. At present, three groups are selecting two optimum plant configurations from a group of six. The ocean data to be used in this selection are presented in the OTEC Demonstration Plant Environmental Package, dated 14 July, 1977. The thermal resource and current velocity data are limited to lo square, vertical temperature differences by month, and a normalized vertical profile of horizontal current velocity, for five potential OTEC sites. The velocity information in particular is incomplete because of the lack of data.

The need for more refined data is recognized by the Department of Energy (DOE) and OTEC investigators (ERDA, 1977a), and this need is the rationale for this report. In particular, the lead time required to obtain "average" oceanographic data necessitates an extended duration collection effort. The effort should begin immediately to provide data in time for input to future design efforts (Figure 1).

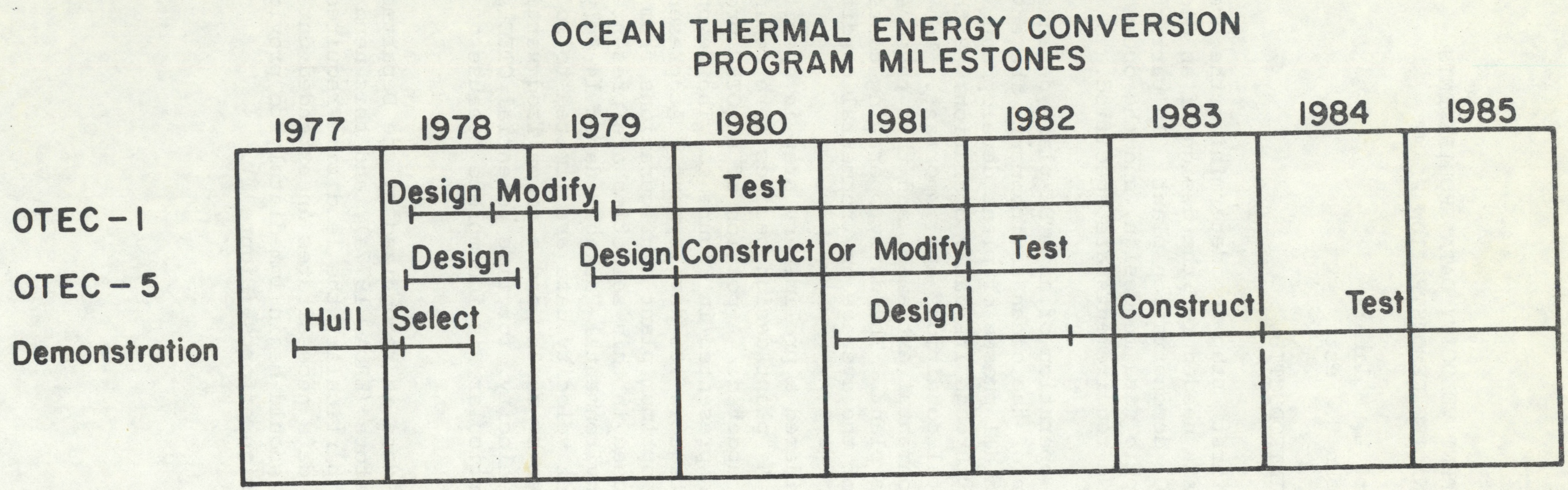

Figure 1. Project milestone chart for several OTEC components (ERDA, 1977).

Information on some conceptual demonstration plant design configurations is presented first, so as to provide the background for the remainder of the report. The requirements for oceanographic data in the design process, and the types of data which can satisfy these requirements will be discussed. Possible efficient methods for obtaining these data are identified, along with a plan to assure timely acquisition of the information. Finally, a brief discussion of the cost effectiveness of an oceanographic measurement program for OTEC is given.

2. BACKGROUND

The OTEC power plant can be considered simply as a heat engine driven by the temperature differential between the warm surface waters and the colder subsurface waters. The immediate output of the plant is the production of electrical energy, the use of which is frequently discussed in terms of two concepts. One concept calls for the electrical output of a moored plant to be hardwired to a land-based power grid (Trimble *et al*. (1975), Douglas (1975), and Goss *et al*.(1975), for example). The other calls for using the electrical output of a grazing plant to power, at sea, an energy intensive manufacturing process, such as ammonia production (Dugger *et al*., 1975). However, in both cases, many of the design features of the plants are similar.

Tables 1 and 2 summarize some of the preliminary proposals relating to OTEC platform and power plant design. The purpose of these tables is to express the range of design variables that must be addressed by an oceanographic observation program.

The design concepts, although diverse, have important similarities. All include a large near-surface vessel to house the power plant, which will be attached to a long cold water pipe. The warm water intakes are within 150 feet (50m) of the surface, and the cold water intakes range from 1100 feet to 4000 feet (370m to 1300m). All power plants require large amounts of warm and cold water to operate. The vertical temperature gradients driving the plants also are similar.

If it is assumed that the final demonstration plant design will be some variation of previous concepts rather than a totally different design, then the common properties of these proposals allow for a generic-type data specification. This specification will be valid for the most important design similarities, and is discussed next.

Table 1: Preliminary Plant Design Specifications

Proponent	Hull Geometry, Dimensions, Material	Cold Water Pipe Design, Material	Mooring or Positioning	Manning	Life Expectancy	Depth Warm/ Cold Water Intake	Depth Warm/ Cold Water Discharge
Carnegie Mellon University	Cylindrical Spar, 2000' longx50' wide, re-inforced concrete	Lower part of spar	Guy wires	Un-manned	40 years	?/2000'	?/?
University of Mas-sachusetts	Submerged twin-hull catamaran, hulls-870'x100' reinforced concrete	Cylinder, 66' diameter, concrete	Single point mooring	Manned	40 years	45'/1120'	?/465'
Sea-Solar Power Incor-porated	Rectangular surface vessel, 380'x650', steel and aluminum	Stockade cylinder, 38' diameter, steel	Dynamic positioning	Manned	25 years	surface/ 2000'	290'/150'
Applied Physics Laboratory Johns Hopkins University	Surface vessel, 275' x225'x175' deep, aluminum	Cylinder, 45' diameter	Grazing	Manned	?	Surface/ 2000'	Surface/ 175'
TRW	Cylindrical surface vessel, 340' diameter, 170' deep, concrete	Cylinder, 50' diameter, re-inforced plastic	Positioning by water exaust	Manned	25 years	100'/200'	400'/1500'
Lockheed	Submerged spar, 432 diameter 410' deep, concrete	Telescoping cylinder, 129' maximum diameter, concrete	Single point mooring	Manned	25 years	100'/200'	400'/1500'

Table 2: Preliminary Power Plant Specifications

Proponent	Net/Gross Power (MWe)	Heat Exchanger Type/Material	Enhancement	Heat Transfer Coefficient (BTU/hr-^{o}F-ft^2)	Condensor or Evaporator area (10^6 ft^2)	Working Fluid	Vertical ΔT Required ^{o}F/^{o}C	Warm/Cold Water Supply 10^6gpm	Warm/Cold Water ΔT ^{o}F	Remarks
CMU	100-140	shell&tube aluminum	tubes fluted on NH_3-side	1000	2-6	ammonia	40/22	8.5/ 8.1	3.6/ 3.6	Designed for optimum heat exchange
U Mass	400/500	plate&fin 90-10 copper nickel	fins on NH_3 side	200-400	10-40	propane	32/18	7.6/ 8.1	1.9/ 5.0	Designed to minimize biofouling corrosion
SSPI	100/125	plate&fin aluminum	thin walls	200	3-10	R-12/31	36/20	10.0/ 4.9	3.0/ 6.0	Designed to minimize cost
APL-JHU	?	aluminum				ammonia	36/20		3.6/ 3.6	
TRW	100/122-138	shell&tube, titanium		400	4	ammonia	38/21	~10.0/ ~ 7.8	4.1/ 4.1	Designed to use state-of art technology
Lockheed	160/240	shell&tube		500	3	ammonia	33/18	6.3 8.1	2.2/ 1.7	Designed to use state-of art technology
DSS Engineers Inc		plate&fin, plastic		271		ammonia				

3. REQUIREMENTS FOR OCEAN DATA IN DESIGN

Oceanographic data are required in the design process so as to minimize:

(1) the detrimental effect of the plant on the environment;
(2) the detrimental effect of the environment on the plant;
(3) the cost of plant construction, and
(4) the cost of daily plant operation.

The final design of an OTEC plant will require accurate site specific data. However, even at this early stage in plant development the less stringent design requirements for ocean data should address these four items.

Ocean temperature and velocity fields will have an impact on many aspects of the OTEC design process. Examples of these impacts are presented in Tables 3 and 4. However, before a sufficient data-set can be developed to address these impacts, the mechanisms by which the data are actually input in the design process are required. The American Petroleum Institute, API (1977), for example, gives a recommended practice for the design of fixed offshore platforms, in which various data dependent expressions are presented to evaluate the effect of the environment on the platform. A similar format will be followed herein for the OTEC ocean thermal and velocity data; however, in contrast to the API report, the relations presented here are merely examples of where ocean data are needed in the design effort.

3.1 Design Requirements for Thermal Data

3.1.1 Power Plant Output

Vertical temperature differential. The efficiency of an OTEC plant is a function of the vertical temperature gradient. The following expression for the Carnot cycle efficiency, η, which occurs at maximum power output, is given by Lavi and Zener (1977) as:

$$\eta = \frac{\Delta T}{2T} \tag{1}$$

where ΔT is the vertical temperature difference (in degrees Kelvin), and T is the warm water intake temperature (in degrees Kelvin). For instance, a $20^{\circ}C$ temperature gradient and $27^{\circ}C$ warm water intake temperature would result in a plant efficiency of 3.3%.

Table 3. Impacts of Ocean Thermal Field on Design Process

1. <u>Power Plant Output</u>
   a. Efficiency
   b. Net output
2. <u>Heat Exchangers</u>
   a. Size
   b. Configuration
   c. Heat transfer enhancement
   d. Instabilities in heat exchange
3. <u>Pumping Requirements</u>
   a. Warm water flow rate
   b. Cold water flow rate
   c. Working fluid flow rate
4. <u>Cold Water Pipe</u>
   a. Length
   b. Diameter
5. <u>Recirculation</u>
   a. Location of warm water intake
   b. Type of discharge (mixed or separate)
   c. Location of discharge
6. <u>Environmental Impact</u>
   a. Effects of discharge on thermal structure
   b. Effects of discharge on biological activity

Table 4. Impacts of Current Velocity on Design Process

1. Surface Vessel

   a. Drag computations

   b. Plant motions

   c. Streamlining requirements

2. Cold Water Pipe

   a. Drag computations

   b. Pipe buckling

   c. Bending moments

   d. Vibrations

3. Positioning Method

   a. Dynamic positioning propulsion requirements

   b. Static mooring requirements

      i. Strength of mooring

      ii. Scouring around anchor during extremely environmental events

4. Recirculation

   a. Potential for circulation

   b. Type and position of discharge - mixed or separate

5. Environmental Impact

   a. Advection of harmful plant discharges

Temporal variability in the thermal field. The net power output of an OTEC plant is a function of the design temperature differential, ΔT^*, and the actual temperature gradient, ΔT, at a site. Lavi and Zener (1977) present the relationship for net power output, P_{net}, as follows:

$$P_{net} = P_{gross} \left(\frac{\Delta T}{\Delta T^*} \right)^2 - P_{loss} \qquad (2)$$

where P_{gross} is the total power output, and P_{loss} is the parasitic power loss. Thus large negative temperature difference excursions would reduce the net plant output, and conversely, positive excursions would increase the output. If large negative excursions are expected, it might be necessary to reduce the design gradient to insure continuous net output.

3.1.2 Heat Exchangers

Vertical temperature differential. The size of the heat exchanger is dependent upon the thermal structure as evidenced by the expression for the number of tubes, N, required for a given power output, P_{net}, in megawatts, (Michel, 1977)

$$N = \frac{20\, P_{net}}{\eta} \times \frac{1}{\upsilon\, \delta t\, di^2} \qquad (3)$$

where υ is the seawater tube velocity (ft/sec), δt is the sea water temperature drop between the warm water intake and discharge (^{o}F), and di is the inside tube diameter (ft). Since the efficiency, η, is a function of the vertical temperature differential, equation 1, N is inversely proportional to ΔT. Therefore, the greater the vertical gradient the fewer tubes needed for the same power output. In addition, the need for heat transfer enhancement surfaces, and the configuration of the heat exchanger are a function of the desired plant output, and thus, dependent ultimately on the available temperature gradient.

Temporal variability in the thermal field. Certain instabilities in the heat transfer as a function of changes in water temperature have been identified. At present, these instabilities are assumed to have a minor effect on the overall system; nevertheless, further tests are necessary (Olsen and Pandolfini, 1975).

Absolute temperature of sea water inflow. Trimble et al. (1975) have shown that heat transfer across the heat exchangers is enhanced at higher temperatures, if other variables are kept constant. They give the following simplified relation for the water side heat transfer coefficient, hw, in BTU/hr-ft^2 °f,

$$hw = 29.3T^{0.392} \, \upsilon^{0.8} \, di^{-0.2} ,$$

where T is the sea water temperature ($^{\circ}$F), υ is the sea water velocity (ft/sec), and di is the inside tube diameter (ft).

3.1.3 Pumping Requirements

Vertical temperature differential. The amount of warm and cold water flow required to maintain a particular plant's output is directly related to the vertical temperature differential. An illustration of the sensitivity of pumping requirements to vertical gradients is presented in Figure 2 (taken from TRW, 1975). The volume flow rate of the working fluid will also vary with the vertical temperature differential, as illustrated for ammonia in Figure 3 (also taken from TRW, 1975). In both cases, the higher the temperature differential, the lower the pumping and flow rate requirements.

3.1.4 Cold Water Pipe

Vertical temperature differential. The length of the cold water pipe is determined by the temperature differential required to drive the OTEC plant efficiently. The length will depend upon the site specific vertical temperature structure and the desired plant output such that the maximum temperature differential will be achieved with the minimum pipe length.

3.1.5 Recirculation

Mixed layer depth. Early plant design efforts made use of a thermal structure which included a fixed mixed layer depth (TRW (1975), Lockheed (1975), and others). The warm water intakes were located within the mixed layer, and separate warm and cold water discharges were placed below this layer in some of these designs (Lockheed (1975), for example). Physical model simulation studies by Jirka et al. (1977) indicate that recirculation of discharged waters with intake waters depends critically on the location of the discharges with respect to the mixed layer boundary. They find recirculation will most likely occur if the discharge is above the lower boundary of the mixed layer. In reality the thickness of the mixed layer varies with time, and the design effort must consider this variability in order to maximize the thermal resource and minimize the potential for recirculation.

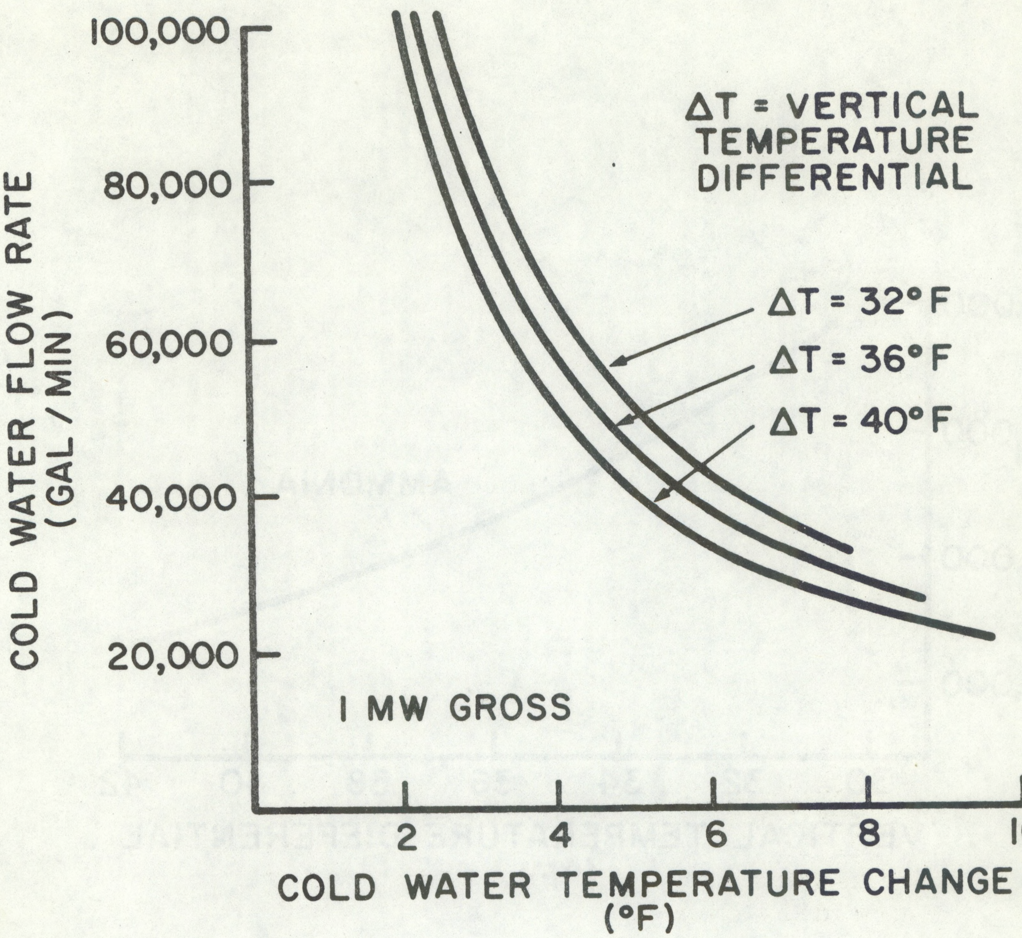

Figure 2. Cold water required for a 1 MW gross plant as a function of cold water temperature change and vertical temperature differential (TRW, 1975).

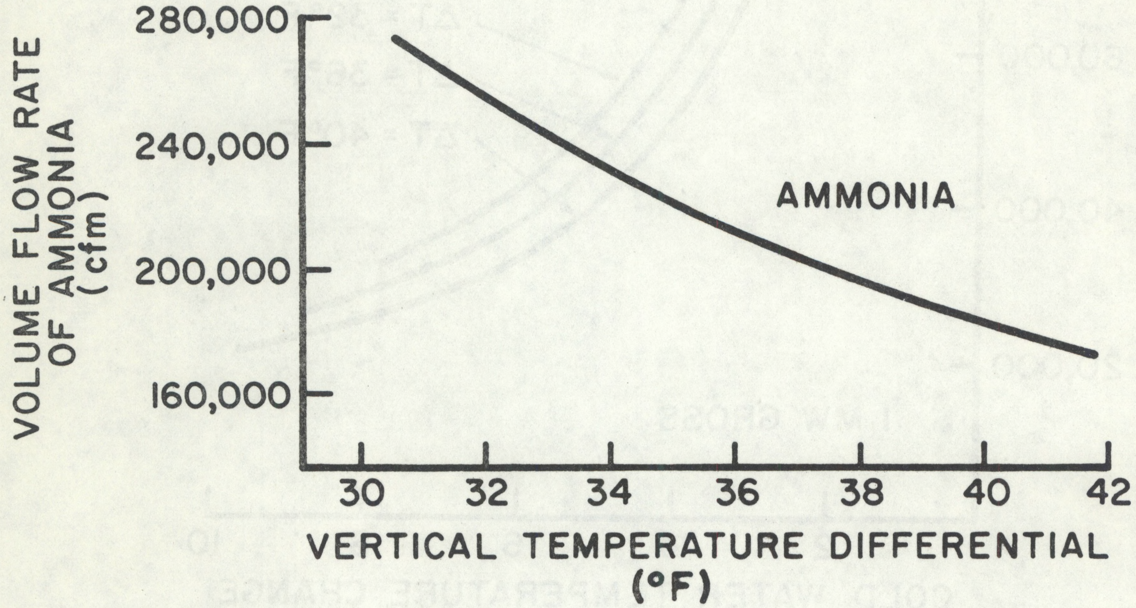

Figure 3. Ammonia flow rate as a function of vertical temperature differential (TRW, 1975).

Depth and intensity of the thermocline. The separate cold and warm discharges of the Lockheed (1975) design are placed within the thermocline to reduce the effects of recirculation. Jirka et al. (1977) conclude that recirculation can be eliminated by using a mixed discharge at the ocean thermocline. However, as in the case of the mixed layer, neither the depth nor the intensity of the thermocline is fixed in the ocean; therefore, thermocline variability could cause recirculation, and must be considered in design.

3.1.6 Environmental Impacts

Site specific thermal data on small time and space scales are required to evaluate the effect of the discharge from a single plant on the environment (ERDA, 1977a). For instance, turbulence data would assist in the parameterization of variables used in numerical models of plant discharge. Data on larger scales are necessary to evaluate the impact of several plants on the environment and to determine possible climatic effects of OTEC operations.

3.2 Design Requiements for Current Data

3.2.1. Surface Vessel

Velocity profiles. Vertical profiles of the horizontal velocity are necessary to compute the current loading on the plant. Current loading can be separated into two components: drag F_D, and lift F_L (API, 1977). The drag component is due to the frictional stress on the object, and the lift component is due to the unsteady forces linked to vortex shedding. Both forces are proportional to the current speed squared. Because of this dependence, the total plant loading is sensitive to the velocity profile used. Streamlining to reduce coupling between the object and medium may be required if the lift and drag forces are too large.

Near surface current data also are necessary to determine the potential for motion of a particular plant design. Plant motion is a factor in evaluating worker safety and comfort.

3.2.2 Cold Water Pipe Design

Velocity profiles. Ocean current velocity data are also required to compute the drag and lift forces, as described above, on the CWP. In addition, current velocity data are used to determine the minimum wall thickness of a CWP so as to avoid pipe collapse due to nonuniform external pressures generated by ocean currents. Wu (1976) finds for a single wall pipe that the wall thickness, t, has the following functional dependence on current speed,

$$t \geq \frac{168 \, \rho \, (1-\gamma^2)^{1/3} \, u^{2/3}}{E} \, R \, , \qquad (5)$$

where, γ is Poisson's ratio, R is the pipe radius, and E is Young's Modulus. For example, for an aluminum pipe with a radius of 30 ft, the minimum wall thickness required to prevent collapse ranges from .17 ft. for a 1 ft/sec (30 cm/sec) current to .26 ft for a 2 ft/sec (60 cm/sec) current. Both currents are ~~within the realm of reality~~. realistic The minimum wall thickness required for a CWP to be free from local buckling caused by current bending is given by (Wu, 1976) as,

$$t \geq 0.896 \times 10^{-5} \, C^{\frac{1}{2}} \, Lu, \qquad (6)$$

where C is a drag coefficient, and L is the length of CWP. A concrete CWP 3000 ft long would need a minimum t of .02 ft to withstand a 1 ft/sec current, and require a minimum t of .04 ft for a 2 ft/sec current.

Current accelerations. Acceleration data are required to determine the possibility of CWP fatigue failure. Fatigue failure can occur if significant internal wave energy exists at the shorter periods (order of tens of minutes).

3.2.3 Positioning Requirements

Velocity profiles. Current data are required to compute the total drag on the plant, CWP, and mooring line system, and thus determine mooring line and anchor requirements. If a drifting plant is used, current data are needed to compute propulsion requirements, since the propulsion power is proportional to the plant velocity cubed (Olsen and Pandolfini, 1975).

Bottom currents. Data on bottom currents, particularly during extreme environmental conditions, are necessary to determine the potential for scour around an anchor, if the plant is moored.

3.2.4. Recirculation

Velocity profiles. Sundaram et al., (1977) find that the percent recirculation is a function of several non-dimensional parameters, one of which is $Q/d^2 u$, where Q is the discharge flow rate, d is the separation between intake and discharge, and u is the current speed. Jirka et al., (1977) find that recirculation potential is inversely proportional to current speed. Therefore, site specific current profiles are needed to evaluate recirculation potentials.

Distribution of horizontal currents. The identification of eddy structures at an OTEC site is important, because of their possible role in increasing recirculation. Eddies (circular current structures) with spatial scales ranging from 10's to 100's of kilometers have been observed in the ocean, and the smaller ones in particular, could quickly advect parcels of discharged water back to the plant. Small ambient currents (non-eddying) can be useful in advecting away plant discharges.

3.2.5 Environmental Impact

Small scale current variability. Local turbulence data are required to evaluate the effect of the momentum discharge of a planton the local ambient current field (ERDA, 1977a).

Regional current fields. The advective field in the vicinity of an OTEC site determines the trajectories of harmful material which may be discharged from the plant.

4. OCEAN DATA TO MEET DESIGN REQUIREMENTS

Table 5 lists the thermal data requirements, and Table 6 the current velocity data requirements necessary to address the design issues discussed previously. Temperature data at NODC standard depths would permit computation of vertical temperature differentials.

Horizontal temperature and current distributions are listed as requirements for several reasons. They are necessary to determine the validity of extrapolating data from a point to the surrounding region, since even a moored plant will experience some excursion around the mooring. The structure of current features in the region partially determines the potential for recirculation. For instance, small scale eddies could be conducive to recirculation, whereas small net drifts away from the plant are desireable. Finally, horizontal temperature and current distributions are required to perform environmental impact studies.

Operational conditions are those which occur regularly, following a seasonal cycle. This cycle could be induced by the seasonal march of atmospheric variables. The seasonal cycle can vary from year-to-year due to yearly differences in seasonal heating or cooling, for instance.

Extreme conditions occur at irregular time intervals and impose severe stresses on the plant. In addition to

Table 5: Thermal Data For Design

Thermal Variable	Vertical Spatial Resolution	Horizontal Spatial Resolution	Temporal Resolution	Additional Requirements
1. Temperature Profiles				
a. Operational conditions	NODC standard depths	Site specific	Average daily cycle by month	Variability about daily cycle, long term trends
b. Extreme conditions	NODC standard depths	Site specific	Daily cycle by event	Frequency of occurrence, persistence of event, predictability
2. Mixed layer depth				
a. Operational conditions	±5m	Site specific	Average daily cycle by month	Variability about daily cycle
b. Extreme conditions	±5m	Site specific	Daily cycle by event	Frequency of occurrence, persistence of event, predictability
3. Thermocline depth (seasonal and permanent				
a. Operational conditions	±5m	Site specific	Average daily cycle by month	Variability about daily cycle
b. Extreme conditions	±5m	Site specific	Daily cycle by event	Frequency of occurrence, persistence of event, predictability,
4. Horizontal temperature distribution				
a. Operational conditions	0-500 m@100m intervals	20 km	Monthly	Define structure of frontal systems
b. Extreme conditions	Event dependent	5 km	Event time-scale	Define structure of frontal systems induced by an event

Table 6. Current Data for Design

Current Variable	Vertical Spatial Resolution	Horizontal Spatial Resolution	Temporal Resolution	Additional Requirements
1. Velocity profiles				
a. Operational	0, 30m, 100m, 200m, 300m, 600m, 1000m	Site specific	Tidal (i.e. diurnal)	Additional vertical resolution at sub-surface maxima, countercurrents, etc. Variability about tidal cycle.
b. Extreme	0, 30m, 100m, 200m, 300m	Site specific	Event time-scale	Frequency of occurrence, persistence of event, predictability
2. Distribution of horizontal currents				
a. Operational	Sea surface, discharge depths	25 km	Monthly	Variability about monthly mean
b. Extreme	Event dependent	10 km	Event time-scale	Frequency of occurrence, persistence of event, predictability

determining their frequency of occurrence and persistence at a site, it is important to be able to determine precisely when an event will occur. Only then can appropriate action be taken on the plant or ashore to reduce the impact of the event.

An extensive historical data-set is required to compute the variables given in Tables 5 and 6. Daily mean temperature profiles can be computed by month from data available at the site. If no significant horizontal temperature gradients are observed in the vicinity of the site, data collected within a 5 km square around the plant location can be used to characterize the site. A smaller averaging square might be appropriate for sites closer to the shore, where large thermal gradients are likely to occur. If the daily variablity is small, i.e., no significant diurnal signal, only mean monthly temperature profiles are required. A similar approach can be adopted in preparing the operational mixed layer and thermocline depth data.

In the semi-tropical and tropical environments proposed for OTEC sites, meteorological forcing by features such as hurricanes are likely to cause extreme conditions. For instance, upwelling induced by hurricanes can reduce the vertical temperature differential and the thickness of the mixed layer. Farther to the north, in the Gulf of Mexico, unusually cold weather can cause abnormal cooling of the upper layers. Placement of the warm water intakes and discharges could depend on these extreme conditions. In addition, statistics on the frequency of occurrence and duration of the event are required to plan for plant shutdowns (if necessary). The signature of these events can be determined from either site specific data, or from data collected in regions with similar oceanographic conditions.

The operational current velocity data are available from long-term site specific current meter arrays. As in the case of the thermal data, extreme conditions can be extrapolated to the site from data collected in regions with similar oceanographic conditions. The operational horizontal current distribution can be estimated from geostrophic computations. These data can be used both in environmental impact efforts, and in determining power requirements for drifting plants. The extremes in horizontal velocity shears, which are probably related to events such as hurricanes, can only be computed from closely spaced current measurements. These measurements can be Eulerian, such as by current meter, or Lagrangian, such as by drifting buoy.

The designer of the OTEC plant must consider the survival environmental state caused by a nonlinear combination of extreme wind, and wave, as well as current velocity events at a particular site. One method of specifying an extreme condition is to determine the magnitude of the individual extreme conditions, independent of their direction, and add them linearly. A second approach is to determine statistically the joint probability distribution of these events considering magnitude and direction. The second approach is likely to provide a more realistic estimate of the survival state and to reduce the initial cost of the plant. Thus, an effort to determine the probability distributions should be undertaken.

None of the sites proposed to date has sufficient data to meet the requirements stated above (Atwood, 1976, Bathen, 1975, and Molinari and Festa, 1977). Therefore, a data collection effort is required to insure a data set for input to the design program.

All available data and literature should be reviewed so as to design an efficient measurement program. The data and literature should be examined for those conditions which could have significant impact on the OTEC operation at a particular site. For instance, hurricanes have been observed at the Puerto Rico and Gulf of Mexico sites, Atwood (1976), Molinari and Festa (1977), while Loop Current eddies have been observed at the Gulf of Mexico site, Molinari and Festa (1977). A methodology for using limited historical data and literature is attached as Appendix A for the Gulf of Mexico site.

However, if no or minimal data exist, a reconnaisance survey is necessary to establish the background for a more detailed survey. Table 7 lists the requirements for such an effort. Many of these requirements are transferrable to the detailed survey.

A number of current meters exist which can meet the specifications of Table 7. Therefore, particular current meter types are not specified. It is important that the mooring be properly designed. The procedure for designing a mooring discussed by Walden and Silva (1976) is one means of insuring that a mooring could survive environmental conditions.

Present state-of-the-art current meter design and mooring technology prohibit inexpensive acquisition of *in situ* current data at depths less than 100 m. Therefore, this information must be approximated with current profile data from a ship servicing the deeper current meter moorings.

As stated previously, these data needs will be updated as the plant design becomes more refined. For instance, once the shape and draft of the platform are known, it will be possible to rearrange the vertical placement of current

Table 7. Site Specific Reconnaisance Survey for Design

Ocean Variable	Instrument	Vertical Resolution	Horizontal Resolution	Temporal Resolution	Accuracy	Duration	Remarks
1. Temperature (vertical structure)	Thermister (thermister string)	0-300 m, every 50 m 300-1500 m every 200 m	on-site	hourly	$\pm 0.5^{0}$C	1 year	
2. Current (vertical structure)	Current meters on same mooring as above	1 mooring, meter placement 0-300 m, every 100 m, 300-1000 m, every 350 m	on-site	hourly	Direction: $\pm 15^{0}$ Magnitude: 10% of speed (minimum ±5 cm/sec)	1 year	Present state-of-the art mooring technology makes surface measurements unreliable. If resources are limited, a minimum of 4 meters would be sufficient.
3. Temperature (horizontal structure)	STD or XBT	Continuous to 1500 m	25 km station spacing in a box around the site	every two months	0.02^{0}C	1 year	Accomplished during servicing of meters. In addition a 3 day serial station on-site taking temperature and current profiles.
4. Current (horizontal structure)	Profiler	Continuous to 500 m	same as 3 above	same as 3 above	Direction: $\pm 10^{0}$ Magnitude: $\pm 5^{0}$ cm/sec	1 year	Same as 3.

meters to sample more efficiently. When the depth and type of discharges are determined, more detailed thermal and current data can be obtained to evaluate recirculation potential. The schedule given in Table 8 is suggested to achieve optimum timely input of oceanographic data to design process. Three options are given depending on the availability of historical data. The first option, as stated previously, is not valid at any of the proposed sites. It is presented to give an estimate of the time required to summarize two or three years worth of data, which should be available at OTEC sites in the future. In addition, considerable interaction between design engineer and oceanographer must take place to insure that the needs and timetables of the designers can be met.

5. COST EFFECTIVENESS OF AN OCEANOGRAPHIC MEASUREMENT PROGRAM

Oceanographic data requirements for design, as described previously, have a direct impact on the cost of building and operating an OTEC plant. Accurate oceanographic site specific data are an important requirement for the efficient design and economic success of a plant. Unfortunately, the data-sets needed for a cost effective design at potential OTEC sites do not exist, and a decision must be made as to how much effort and funds should be expended to obtain such data.

The construction cost of heat exchangers, cold water pipes, surface plant pumps, etc. are all critically dependent upon the ocean thermal and current velocity data. Consider as an example the impact of the thermal structure on design costs. Plant cost is inversely proportional to the overall vertical temperature differential, ΔT, used in design. An approximate relationship between ΔT, and direct cost, C, is given (Lavi and Zener, 1977; TRW, 1975; and others) as

$$C \propto (1/\Delta T)^{p} ,$$

where p varies, for small temperature ranges, between 1.5 and 2.5. Figure 4 (taken from TRW, 1975) illustrates the impact of available temperature differential on direct cost of a 100 MWe plant. The construction cost differential between a plant operating at a $40^{o}F$ ΔT, and one at $38^{o}F$ ΔT, is approximately 20 million dollars. Thus, if a measurement program could refine estimates of the vertical temperature differential from $38^{o}F$ to $40^{o}F$ the savings would be considerable. Conversely, if a measurement program found an average differential of $38^{o}F$, instead of $40^{o}F$, the design temperature differential (equation 2) could be reduced.

Table 8. Timetable for Acquisition of Thermal and Current Veolcity Data

Availability of Historical Data	1978: J M M J O N — 1979: J M M J S N
1. Sufficient historical data to meet all requirements in tables 5 and 6	1) Analyze data; 1) Prepare report
2. Sufficient historical data to meet some requirements	1) Review historical data & literature 2) Analyze data 3) Determine data gaps 1) Collect necessary data 2) Data reports at tick marks
3. No historical data available (current and/or thermal)*	1) Data collection 2) Data reports at tick marks

* If, for example, no current meter data exist at a site but some thermal data do, the data collection effort for obtaining current data should begin while the thermal data are under review.

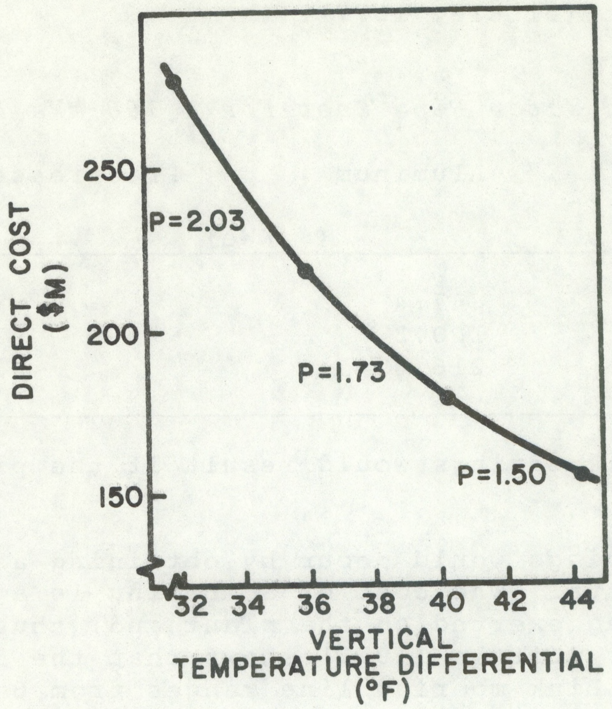

Figure 4. Plant cost as a function of available vertical temperature differential (TRW, 1975).

Similarly, accurate thermal structures would enable designers to minimize the cost of the cold water pipe by shortening its length to obtain the optimal ΔT. Table 9 indicates how the cost of the CWP increases with pipe length for a 100 MWe plant (Little, 1977).

Table 9: Cold Water Pipe Cost For a 100 MWe Plant

Length (m)	Steel	Aluminum	Prestressed Concrete
	($/KWe)		
300	23.6	47.4	15.8
600	49.9	100.3	30.1
1200	107.7	216.4	57.1

Thus, a considerable savings would result if the pipe were shorter.

Additional savings would occur by obtaining accurate current velocity data. The cost of a mooring is a direct function of the drag exerted on the plant and, thus, the velocity structure. Little (1977) shows that the cost of a Hollow Cylindrical Link mooring line ranges from 6 to 240 million dollars depending on required line strength. Thus, if a measurement program found maximum velocities less than estimated speeds, the savings could be quite large.

A realistic estimate of the worth of a measurement program would require a detailed analysis such as outlined above. The few examples given suggest such an effort is desired, and therefore, is recommended.

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Appendix A

Preliminary Thermal and Current
Characterization of the Gulf of
Mexico OTEC Site using
Historical Data
(Duration: 4 months)

STATEMENT OF PROBLEM

A preliminary evaluation of the ocean thermal and current resources at OTEC Site 2, the North Central Gulf of Mexico, would aid design engineers and those concerned with OTEC impact statements in performing their assigned tasks. In particular, the extreme events such as hurricanes, winter storms ,and Gulf eddies which can place large stresses on the plant and cold water pipe and affect the thermal resource should be characterized both in terms of their properties and the frequency of their occurence at the site.

STATEMENT OF OBJECTIVES AND METHODS

The objective of this study is to characterize the current and thermal resource at site 2 with particular attention given to the extreme events which pass through this site. This will be achieved by examining the historical data in the Gulf of Mexico and reviewing pertinent literature.

Data analysis and literature review will be geared to determination of:

1) Thermal Resource

   a) Mean monthly thermal resource - in contrast to previous studies which have determined mean monthly temperature profiles, we will consider the data on a synoptic timescale to insure that the averages are not biased by one or two intensive studies in the area. Our past studies in the region suggest that we will obtain more reliable resource maps by this approach.

b) Characterization of the effect of extreme events such as hurricanes, winter storms and Gulf eddies on the thermal resource. Historical data and reports will enable us to characterize these events and the frequency of their occurrence.

2) Current Resource

a) Mean monthly geostrophic currents - a previous study is now being completed which will provide this information on a 1^o square grid.

b) Significance of tidal and wind induced currents at the site.

c) Characterization of currents associated with hurricanes, winter storms and eddy events.

PROJECTED TIME TABLE

We project that the entire program will take approximately four months commencing in August

August, September, October, November

1) Thermal Resource

a) Mean monthly thermal resource

b) Extreme events

2) Current Resource

a) Mean monthly geostrophic currents

b) Tidal and wind induced currents

c) Extreme events

3) Reporting