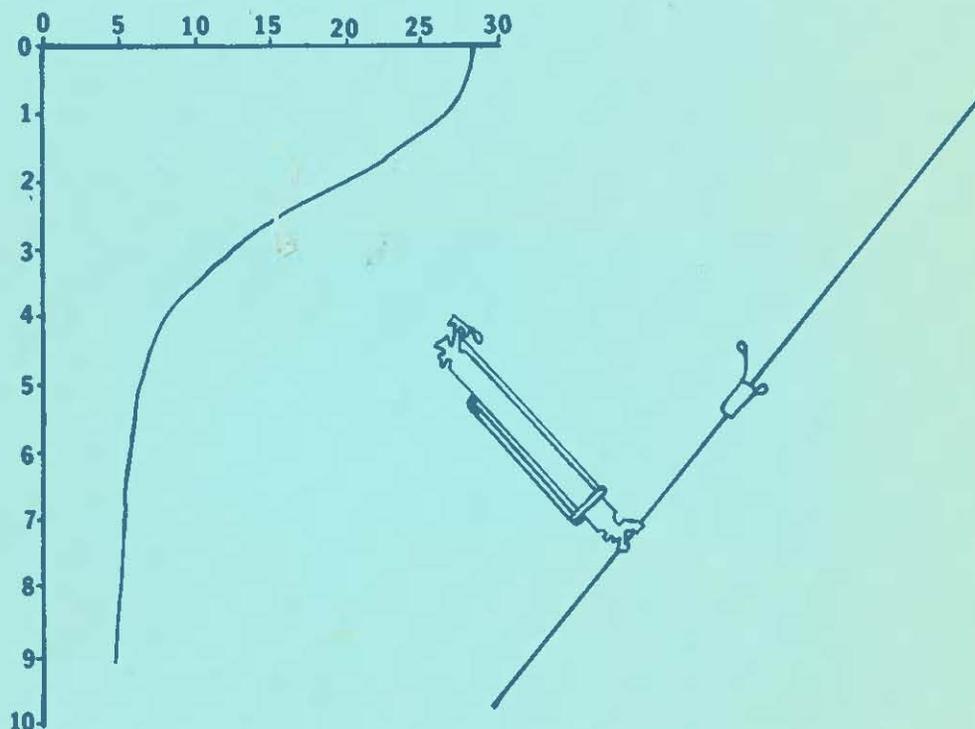


# OCEANOGRAPHIC CONDITIONS IN THE VICINITY OF CABRAS ISLAND AND GLASS BREAKWATER FOR THE POTENTIAL DEVELOPMENT OF OCEAN THERMAL ENERGY CONVERSION ON GUAM

DENNIS R. LASSUY



UNIVERSITY OF GUAM MARINE LABORATORY

Technical Report No. 53

July 1979

This publication was printed under the auspices of NOAA Office of Sea Grant, Department of Commerce, under Grant No. 04-5-158-45 to the University of Guam. The U.S. Government is authorized to produce and distribute reprints for governmental purposes notwithstanding any copyright notation that may appear hereon.

OCEANOGRAPHIC CONDITIONS IN THE VICINITY OF  
CABRAS ISLAND AND GLASS BREAKWATER FOR THE POTENTIAL DEVELOPMENT OF  
OCEAN THERMAL ENERGY CONVERSION ON GUAM

Dennis R. Lassuy

Submitted to

Guam Energy Office

University of Guam, Marine Laboratory

Technical Report No. 53

## TABLE OF CONTENTS

	Page
LIST OF TABLES . . . . .	iv
LIST OF FIGURES . . . . .	v
INTRODUCTION . . . . .	1
METHODS . . . . .	2
RESULTS AND DISCUSSION . . . . .	3
Bottom Profiles . . . . .	3
Temperature . . . . .	3
Nutrients . . . . .	5
Dissolved Gases, pH and Alkalinity . . . . .	6
Salinity, Density and Stability . . . . .	7
Currents . . . . .	8
CONCLUSIONS . . . . .	8
ACKNOWLEDGEMENTS . . . . .	10
REFERENCES . . . . .	11
APPENDIX A . . . . .	13
TABLES . . . . .	15
FIGURES . . . . .	19

## LIST OF TABLES

1. Key to physio-chemical parameters and synopsis of methodology.
2. Station numbers, field dates and measured parameters of each.
3. Surface, 1500, 2000, 2500 and 2800-3000 ft temperatures for each station and their respective mean values (Feb., 1978 - Feb., 1979).
4. Expected monthly  $\Delta T$  at 1500, 2000, 2500 and 2800-3000 ft and their respective means in the vicinity of Glass Breakwater and Cabras Island, Guam.
5. Mean values for all stations for nitrate-nitrogen, reactive phosphorous, dissolved oxygen, total carbon dioxide, pH and total alkalinity (Feb., 1978 - Feb., 1979).
6. Mean temperature and salinity measured at the listed depths with corresponding calculated density and stability (Feb., 1978 - Feb., 1979).

## LIST OF FIGURES

1. Map of OTEC project site with locations of stations and bottom profiles. (C.P.P. = Cabras Power Plant)
2. Bathymetric chart of Guam and vicinity. Contour interval is 600 feet (100 fathoms) on both land and sea floor. Reef areas shown by solid black pattern. (From Emery, 1962)
3. Fathometer profiles of the bottom at five sites in the vicinity of Cabras Island, Luminao Reef and Glass Breakwater, Guam.
4. Temperature profiles for Stations 1-5 (Feb., 1978 - April, 1978) at the OTEC project site on Guam.
5. Temperature profiles for Stations 6-10 (May, 1978 - Aug., 1978) at the OTEC project site on Guam.
6. Temperature profiles for Stations 11-9A (Sept., 1978 - Feb., 1979) at the OTEC project site on Guam.
7. Mean monthly temperatures for surface, 1500, 2000, 2500 and 2800-3000 ft in the vicinity of Cabras Island, Luminao Reef and Glass Breakwater, Guam.
8. Mean temperature, salinity and density profiles in the vicinity of Cabras Island, Luminao Reef and Glass Breakwater, Guam (Feb., 1978 - Feb., 1979).
9. Mean nitrate-nitrogen ( $\text{NO}_3\text{-N}$ ) and reactive phosphorous ( $\text{PO}_4\text{-P}$ ) profiles from surface to 883 m (2900 ft) in the vicinity of Cabras Island, Luminao Reef and Glass Breakwater, Guam (Feb., 1978 - Feb., 1979).
10. Mean dissolved oxygen ( $\text{O}_2$ ) and total carbon dioxide ( $\Sigma\text{CO}_2$ ) profiles from surface to 905 m (2970 ft) in the vicinity of Cabras Island, Luminao Reef and Glass Breakwater, Guam (Feb., 1978 - Feb., 1979).
11. Mean pH and total alkalinity (T.A.) profiles for the vicinity of Cabras Island, Luminao Reef and Glass Breakwater, Guam (Feb., 1978 - Feb., 1979).

12. T-S diagram for the vicinity of the proposed OTEC site on Guam (Based on mean temperature and salinity data taken from Feb., 1978 - Feb., 1979).

## INTRODUCTION

Energy consumption on Guam is presently supported by the burning of fossil fuel, 100% of which is imported. Apparent worldwide shortages of fossil fuels and climbing cost of purchase and transshipment to Guam suggest a need for the development of locally available alternate energy sources. One such alternative is the production of power by a system known as Ocean Thermal Energy Conversion (OTEC).

The OTEC system utilizes the temperature gradient between warm surface waters and cold deep waters as its energy source. Assuming the use of a closed system, it operates by continuously recycling a liquid with high vaporization pressure (e.g., ammonia, propane, freon). The liquid is heated by the warm water, and its vapor then drives a turbine which in turn produces electrical power. In order to complete the system and to obviate the loss of medium, the vapor is then recondensed with the cold water and re-used. The temperature difference between the warm surface water and the cold deep water is directly proportional to the efficiency of the system. The ocean's surface waters have a high heat capacity and thus an OTEC system can operate on a continuous 24-hour basis, regardless of weather conditions or time of day. Ocean Thermal Energy Conversion represents a relatively non-polluting, consistent, and reliable system run by a virtually inexhaustible energy source.

Consistently warm surface temperatures and steep submarine slopes, minimizing the distance from shore to sufficiently cold deep water, make the OTEC system a viable alternative for Guam. In order to proceed with planning for the development of such a system; and in order to secure the help of concerned federal agencies, it was necessary to gather important, relevant baseline data (e.g., temperature, depth, and water quality data). Oceanographic information of this nature was sparse for Guam. This study, then, was initiated at the request of the Guam Energy Office in order to provide relevant data to the possible future development of an OTEC power system especially in the vicinity of the existing power plants on Guam.

The scope of work was agreed upon between the University of Guam Marine Laboratory and the Guam Energy Office in November of 1977 to run until November 1978 and set forth the following objectives.

1. Temperature profiles will be taken through an annual cycle at the Cabras Island-Luminao Barrier Reef vicinity. Profiles will be taken two times a month to establish the 4-6°C water regime throughout the year.
2. Water samples will be taken at various depths to determine phosphates, nitrates, dissolved oxygen, salinity, pH, and alkalinity.

3. Fathometer profiles will be made in the vicinity to determine submarine slopes and bottom topography.
4. Bottom sediments will be collected to determine the nature of the substrate in the vicinity.

Initial delays in the purchase and construction of necessary equipment forced the commencement of sampling to begin in February of 1978. An extension of the contractual time limit was granted in order to obtain a full year's data and sampling was completed in February of 1979. Occasionally, weather conditions or mechanical breakdown prevented strict adherence to the proposed semimonthly schedule of sampling. It was also found that a substantially larger motor was needed to drive the winch for bottom sediment sampling.

#### METHODS

The study area for the OTEC project was the vicinity of Cabras Island, Luminao Reef, and Glass Breakwater from surface to depths of 3,000 feet. All sampling within the area was carried out from the R/V Tanguisson with a motor-driven winch and a 1.2 liter Nansen-type water sampler (G. M. Manufacturing Co.) equipped with Kahlisco deep sea reversing thermometers ( $-2^{\circ}$  to  $35^{\circ}\text{C}$ ). Bottom profiles were made to a depth of 2400 feet (400 fathoms, 732 m) with a Fine Line fathometer (Ross Model 400-A). Sampling stations and the locations of bottom profiles are illustrated in Figure 1. A listing of the physiochemical parameters that were measured directly and a synopsis of the methods used for each are presented in Table 1. Table 2 shows the dates and specific parameters measured at individual stations.

Total carbon dioxide, density, and stability were also calculated. Total carbon dioxide ( $\Sigma\text{CO}_2$ ), calculated on the basis of pH, total alkalinity, temperature, and salinity (Strickland and Parsons, 1972), represents not only gaseous  $\text{CO}_2$  but also all other dissolved inorganic carbon forms, i.e.,  $\Sigma\text{CO}_2 = [\text{CO}_2] + [\text{H}_2\text{CO}_3] + [\text{HCO}_3^-] + [\text{CO}_3^{2-}]$  (Riley and Chester, 1971). In pure water, density is dependent only upon temperature and pressure.\* However, in seawater, salinity also must be considered. Based upon average values of these three directly measured parameters, mean densities from surface to 890 meters were calculated. The term stability is also applied, in an oceanographic sense, to water masses. A particular mass of water can be assigned a numerical value for stability which is either negative, zero, or positive. A water mass is said to have negative stability if it is denser than the water immediately below it, neutral (zero) if it is the same density and positively stable if it is less dense than the water below. Numerical values for stability are calculated as a

---

\* Pressure was calculated by assuming one decibar of pressure per meter of depth (Williams, 1962).

function of the density of the water mass in question and the rate of change of density with respect to depth (Williams, 1962).

Sample calculations of temperature and depth from reversing thermometer readings are shown in Appendix A.

## RESULTS AND DISCUSSION

### Bottom Profiles

The overall bathymetry of Guam as illustrated in Figure 2\* shows a concentration of contour lines at the project site. Perhaps only off the southern tip of Cocos Island, Guam, are the contours more tightly grouped. Fathometer profiles of the bottom at five sites in the vicinity of Cabras Island, Luminao Reef, and Glass Breakwater are illustrated in Figure 3. It is apparent from these profiles that, indeed, some very steep slopes occur in this area, particularly toward the western end of the project site near Glass Breakwater. Profile V in this area reaches a depth of 2400 ft (732 m) at a distance of only 4600 ft (0.87 miles, 1.4 km) from shore. This represents a mean slope of 52.2%. This slope generally decreases and similar depths are found correspondingly further offshore eastward along Luminao Reef toward Cabras Island. Profile I, run directly out from Piti Canal, had a mean slope of 26.1% with a 2400 ft depth occurring some 9200 ft (1.74 miles, 2.8 km) from the mouth of the canal. These slopes are generally much steeper than those found off Ke-ahole Point, Hawaii, which range from 25 to 30% (Anon., 1977).

### Temperature

By using the combination of a protected and an unprotected reversing thermometer, accurate temperature readings were taken and the depths at which the samples were taken were calculated (See Appendix A). This served as a check on the shipboard meter. Individual temperature profiles for each station are shown in Figures 4, 5, and 6.

Inspection of these temperature profiles reveals three quite distinct regions; a warm, well-mixed surface layer of fairly constant temperature, a region known as the thermocline where temperature rapidly declines with increased depth, and a deep cold layer. The depths at which these regions or zones occur may vary on a global scale with latitude or with the season at a given locality. At lower latitudes the depth at which the thermocline begins is much shallower than is usually found at mid-latitudes, primarily because of the relatively

---

\*

Taken from Emery, 1962.

less frequent storm activity in the tropics.

Typically, a lack of storm activity and lower air temperatures in spring result in a shallow, highly angular thermocline. Increased air temperatures and more frequent storms in late summer and fall tend to create a deeper mixed layer thus increasing the depth to the thermocline and smoothing the shape of the temperature profile. The magnitude of these changes is far less for the tropical ocean waters around Guam than, for example, Hawaii but as can be seen in Figures 4-6, are still apparent. Figure 8 combines these individual profiles to represent a mean annual temperature profile for the project area on Guam.

The shape of a temperature profile or, more precisely, the distance in terms of depth between warm surface and deep cold layers and the magnitude of the temperature change ( $\Delta T$ ) are of critical importance to the development of OTEC systems. As stated in the introduction, the greater the temperature difference, the more efficient the power output. Reduced depth to the cold layer obviously results in decreased costs of pumping and also decreases the distance over which heat gain can occur, thus increasing the realized  $\Delta T$ . If a landbased OTEC facility is planned, the distance from shore to the appropriate depth would also influence the pumping costs and the system efficiency.

Observed temperatures for the project site on Guam from February, 1978 through February, 1979 for surface and various depths to 3000 ft (915 m) are summarized in Table 3. The same data are shown graphically in Figure 7. Based on these two sources, expected monthly  $\Delta T$ 's were calculated and are presented in Table 4. Argonne National Laboratory's "Request for Proposal" calls for an operational minimum  $\Delta T$  of 35°F. Table 4 indicates that for Guam this  $\Delta T$  can be maintained at a depth of only 1500 ft (457 m) on a monthly basis, with an annual mean  $\Delta T$  of over 37°F. In fact, an annual mean  $\Delta T$  of 35°F may be maintained as shallow as 1300 ft (396 m). As illustrated in Figure 3, 1500 ft depths occur as close as 3300 ft (0.62 miles, 1 km) from shore at Profile V. Even with the more gradual slopes near Cabras Island (Profile I, Figure 3), this depth occurs only about 4500 ft (0.85 miles, 1.37 km) from shore.

Bathen (1975) reported a surface to 2000 ft (610 m)  $\Delta T$  of 36°F (20.0°C) off Ke-ahole Point, Hawaii, for the month of August. This 2000 ft (610 m) depth occurs approximately one mile (1.61 km) from shore (Anon., 1977) in the vicinity of Ke-ahole Point. A comparable depth on Guam can be reached about 0.80 miles (1.30 km) from shore with an observed mean  $\Delta T$  for the month of August of 22.7°C (41°F) in the vicinity of Glass Breakwater. This distance off Cabras Island, Guam is about 1.36 miles (2.20 km). The maximum single station  $\Delta T$  observed during this study was 44.14°F (24.52°C) at Station 12 in early October of 1978 at a depth of 2937 ft (892 m). A maximum expected monthly  $\Delta T$  of 45.2°F (25.1°C) occurs in July at 2800-3000 ft (m) (Table 4). Although fathometer capacity was limited to 2400 ft (732 m), if you

extrapolate to 3000 ft (915 m) assuming a constant slope, a depth of 3000 ft (915 m) could be reached at a distance of only 1.1 miles (1.75 km) from shore along Profile V.

### Nutrients

Nitrate-nitrogen ( $\text{NO}_3\text{-N}$ ), nitrite-nitrogen ( $\text{NO}_2\text{-N}$ ) and reactive phosphorous, i.e., orthophosphate ( $\text{PO}_4\text{-P}$ ), were measured from surface to (2900 ft) 883 m. Nitrite-nitrogen proved to be negligible at all depths. Spectrophotometric absorption was usually zero or, at maximum, reflected a nitrite concentration of  $0.1 \mu\text{g-at/l}$  or less. Nitrate and orthophosphate, however, were always present in measurable amounts and showed a pronounced and consistent pattern of increase with depth (See Fig. 9). The vertical distribution of these nutrients showed no seasonal variation. All data were therefore combined and are presented as mean values in Table 5.

The observed pattern of parallel nitrate and orthophosphate distribution with low surface concentrations, sharp increase in the vicinity of the thermocline, and relatively constant values below intermediate depths agrees well with the expected pattern as described by Riley and Chester (1971). The actual numerical values for Guam are also in very close agreement with expected values. For example, mean values found at 2900 ft (883 m) during this study were  $35.8 \mu\text{g-at/l}$  for nitrate and  $2.7 \mu\text{g-at/l}$  for orthophosphate. These are similar to the values of  $36.5 \mu\text{g-at/l}$  and  $2.9 \mu\text{g-at/l}$  for  $\text{NO}_3\text{-N}$  and  $\text{PO}_4\text{-P}$ , respectively, which were found by Sverdrup, et al. (1942) at this depth throughout the Pacific.

The growth of phytoplankton, microscopic plant life which form the base of oceanic food chains, is limited in tropical surface waters by the lack of available nutrients. Riley and Chester (1971) state that "the upper layers of the tropical oceans are almost devoid of nutrients." This is evident in the data from Guam (See Table 5). The tropical open ocean has, therefore, often been referred to as a virtual "biological desert." Growth limiting nutrients of major importance are nitrogen, particularly in the form of nitrate, and phosphorous, primarily as orthophosphate.

However, in certain areas of the world ocean, and at times within the tropics, areas of natural upwelling occur in which cold, deep, nutrient-rich water is brought to the surface. This renewed supply of nutrients supports the growth of extremely rich phytoplankton populations and allows the development of very productive fisheries (Raymont, 1976). Experiments in St. Croix where deep, nutrient laden water has been pumped up into small ponds on shore have shown plant growth to be accelerated by as much as 27 times (Pinchot, 1977). Clearly, then, there are potential uses for the nutrient rich water which an OTEC power plant would discharge.

### Dissolved Gases, pH and Alkalinity

Photosynthesis and respiration are the major causes of *in situ* changes in the concentrations of oxygen ( $O_2$ ) and carbon dioxide ( $CO_2$ ). The solubility of oxygen is effected to some extent by temperature, salinity and pressure but, as a gas, it is relatively nonreactive with water. Gaseous  $CO_2$  is operationally indistinguishable from carbonic acid ( $H_2CO_3$ ) (Horne, 1969). Therefore, total carbon dioxide ( $\Sigma CO_2$ ), as explained in the methods, is usually measured. Both  $CO_2$  and  $H_2CO_3$  are much more reactive with water than  $O_2$  and enter into many complex reactions. The dissociation of  $CO_2$  and  $H_2CO_3$  are also influenced by temperature, salinity and pressure. Increased dissociation of carbonic acid with increasing depth and decreasing temperature alter the pH of deeper waters by the release of  $H^+$  ions. Total alkalinity of seawater includes primarily the concentrations of the three anions  $HCO_3^-$ ,  $CO_3^{=}$  and  $B(OH)_4^-$  and is associated with the carbonic acid system and the dissolution of calcium carbonate ( $CaCO_3$ ). The solubility of  $CaCO_3$  increases in a similar manner as the dissociation of  $H_2CO_3$  and thus effects the total alkalinity of cold, deep waters upon the release of  $CO_3^{=}$  ions.

Mean dissolved oxygen measurements and total carbon dioxide determinations for the OTEC project site from surface to (2970 ft) 905 m are listed in Table 5 and illustrated in Fig. 10. Both profiles show good agreement with expected patterns as described by Riley and Chester (1971), Horne (1969) and others. Oxygen concentration is high and  $CO_2$  concentration relatively low in the well-mixed surface layers above the thermocline where light availability allows the  $O_2$ -producing process of photosynthesis to dominate. Below the thermocline,  $O_2$  production declines rapidly as light diminishes and the release of  $CO_2$  rises sharply with increased depth. Oxygen concentration generally reaches a minimum at about (1310-1640 ft) 400-500 m while  $\Sigma CO_2$  reaches its maximum at (1640-3280 ft) 500-1000 m. An increase in  $O_2$  level below this depth is common but depends upon the local dynamics of oceanic water circulation.

Alkalinity and pH were measured from surface to (3010 ft) 918 m for the OTEC study site on Guam. Mean values for both are listed in Table 5 and their vertical distributions are shown graphically in Fig. 11. Comparison of figures 10 and 11 demonstrate, as expected, that pH minimum coincides closely with the  $\Sigma CO_2$  maximum. As a conservative property of seawater, the magnitude of changes in alkalinity are rather small. The observed vertical distribution of total alkalinity for Guam (Fig. 11) might be explained in the following manner. Dissolution of the calcitic or aragonitic skeletons of many tropical reef organisms by turbulent mixing of surface waters tends to increase observed alkalinity values. Below the effects of storms, but still within the range of light penetration, the continued "tying-up" of carbonates as skeletal material reduces total alkalinity. Increasing  $CaCO_3$  solubility and reduced biological activity below the thermocline might then evidence a gradual increase in alkalinity reaching a maximum

at or near the bottom.

Salinity, Density and Stability

Perhaps the most frequently measured chemical parameter of seawater is salinity. Although its definition and the suggested "best" method to measure salinity have long been the subject of controversy (Horne, 1969), the property is certainly a very useful one. It is a single, measurable parameter which can be used in conjunction with temperature and pressure to calculate other properties of seawater, e.g., density. A change of 1‰ in salinity has a much larger effect on density than a 1°C change in temperature (Gregg, 1973). However, the wider range in temperature variation dominates the density profile (See Fig. 8).

The observed mean salinity profile for the Guam OTEC study site (Fig. 8) is very similar in shape to that shown in Williams (1962) from data taken in the vicinity of the Hawaiian Islands and that of Gregg (1973) for the mid-Pacific. Craig et al. (1977) reported average surface salinities of 34.5‰ and a salinity maximum of 34.9-35.1‰ at (492-656 ft) 150-200 m for oceanic waters near Guam. These coincide well with observed values at the OTEC study site (Table 6) of 34.43‰ and 35.13‰ for surface and 150 m, respectively. Williams (1962) showed a salinity minimum at about (1150 ft) 350 m near Hawaii while Gregg (1973) reported minimum salinity at a depth of (1800 ft) 550 m for the mid-Pacific. The minimum mean salinity on Guam occurred at (1625 ft) 496 m.

Sigma-t ( $\sigma_t$ ) values over a range of temperatures and salinities can be calculated from specific tables and plotted as  $\sigma_t$  curves (See Fig. 12). Sigma-t is functionally related to the specific gravity, or density, of the water. By plotting salinity versus temperature and joining progressively deeper points, as in Fig. 12, a T-S diagram is constructed. The position of a given depth's particular salinity and temperature on this curve define its "water type" (Williams, 1962) and acts as a type of "marker" for tracing the movement of oceanic water masses.

The shape of the T-S diagram is also reflective of the stability of the water column. For example, if two successive depths are neutrally stable, (stability equals zero), this indicates that there was no change in density and thus in  $\sigma_t$ . The T-S diagram for these depths would, therefore, be parallel to the  $\sigma_t$  curves. By the same reasoning, a sharp downward angle in the T-S diagram would indicate a significant change in the  $\sigma_t$  values, or densities, of the adjoining water masses and would indicate a positive numerical stability. All calculated stability values in Table 6 are positive. This, in effect, means that the water column in the vicinity of Cabras Island, Luminao Reef and Glass Breakwater is in a state of "stable equilibrium" in terms of density distribution.

### Currents

No actual current measurements were carried out as a part of this study. However, there is a small amount of literature on surface and subsurface currents in the vicinity of Guam and I have abstracted pertinent information from these sources.

Guam's current patterns are heavily influenced by the North Pacific Equatorial Current (NPEC) which moves westward across the Pacific between  $8^{\circ}$  and  $15^{\circ}$ N (Craig et al., 1977). Corey (1975) states that the eastern side and the north and south ends of Guam would not be suitable sites for the development of an OTEC power plant because the NPEC might tend to "push" the cold effluent onto the coral reefs. He therefore concludes that the western side of Guam would be the most suitable site as "prevailing currents would carry cool water surface plumes away from nearshore environments." Current measurements more specifically in the vicinity of Luminao Reef by Huddel et al. (1974) revealed that winter currents at 35 ft (10.7 m) showed a "consistent westerly net movement" travelling at velocities of up to 0.6 knots (0.3 m/sec). Summer currents at 55 ft (16.8 m) were less rapid and showed a net northerly drift. In both cases, the net movement appeared to be away from shore. Craig et al. (1977) reported that current velocities in the NPEC ranged from 0.15 to 0.40 m/sec but that speeds of up to 1.0 m/sec were reached during strong winds. They also found that currents at a depth of 500 m (1640 ft) were somewhat reduced with maximum westward velocities of about 0.1 m/sec.

### CONCLUSIONS

Ocean Thermal Energy Conversion (OTEC) appears to be a viable alternative for Guam. The development of an OTEC power system is dependent upon the consistent presence of a substantial temperature difference ( $\Delta T$ ) between surface and deep ocean waters. Guam seems to be an ideal site for the development of Ocean Thermal Energy Conversion since its off-shore waters are characterized by a large  $\Delta T$  and suitable depth profiles. The suggested minimum  $\Delta T$  of  $35^{\circ}$ F could be maintained in the vicinity of Cabras Island, Luminao Reef and Glass Breakwater in as shallow as 1300 ft (396 m) on an annual basis or 1500 ft (457 m) on a monthly basis. A depth of 1500 ft can be reached as little as 3300 ft (0.62 miles, 1 km) from shore off Glass Breakwater and 4500 ft (0.85 miles, 1.37 km) off Cabras Island. At 2000 ft (610 m), a  $41^{\circ}$ F ( $22.7^{\circ}$ C)  $\Delta T$  occurs on Guam. Annual mean  $\Delta T$ 's of  $41.1^{\circ}$ F ( $22.8^{\circ}$ C) and  $42.2^{\circ}$ F ( $23.4^{\circ}$ C) are expected at depths of 2500 ft (762 m) and 2800-3000 ft (854-915 m), respectively, with a maximum monthly  $\Delta T$  of  $45.2^{\circ}$ F ( $25.1^{\circ}$ C) in July at the latter depth range. These represent perhaps the best temperature and depth criteria observed at any proposed OTEC site to date.

Observed nutrient and other physio-chemical values at the projected OTEC site on Guam seem to fit expected patterns for the tropical Pacific. Work in other areas indicates that cold, deep, nutrient-rich water of similar chemical composition is useful in the development of surface aquacultural activities. The water column off Cabras Island, Luminao Reef and Glass Breakwater is stable over an annual cycle. Oceanographic conditions are expected to remain favorable for the utilization of Ocean Thermal Energy Conversion as an alternate energy source for the island of Guam.

Other distinct advantages in the siting of a future OTEC facility on Guam include:\*

1. The main power generating station is located within 200 yards of the potential OTEC site. The central power distribution station is also located there.
2. A major roadway runs adjacent to the proposed site.
3. The Commercial Port of Guam operates about two miles away from the proposed site allowing for use of excess cold water for prechilling water used in the air conditioning and refrigeration process. Additionally, any equipment shipped to Guam for the OTEC facility can be directly off-loaded to short haul trailers near the site.
4. The U. S. Navy has a complete ship repair facility within the harbor adjacent to the site. The facility has large floating cranes as well as barges and dry docks. Additionally, the Navy has an Engineering Division with a resident officer in charge of construction.
5. Dillingham Corporation has a dock site facility with tugs, barges, dredging equipment, floating cranes and other related equipment.
6. There are numerous other contractors on Island that have done underwater work and they could presumably work on an OTEC installation.

---

\*Compiled by Clark E. Jewell in response to inquiries by the Argonne National Laboratory (June, 1978).

## ACKNOWLEDGEMENTS

Collection of the data presented in this report was largely made possible through the mechanical wizardry of Mr. Frank A. Cushing, UGML Marine Technician. I thank him for his interest and support. I also wish to thank Mr. Richard H. Randall for his assistant in the design and organization of the project. Mr. Clark E. Jewell, formerly of the Guam Energy Office, was also very helpful in the planning and execution of the project. Others that helped with field data gathering were John Eads, Vaughan Tyndzik and Richard "Kuni" Sakamoto. Mr. William Zolan and Mr. Russell Clayshulte were of invaluable assistance in the laboratory analyses of chemical water quality parameters. I am grateful to Mr. Tim Detterman and the Guam Environmental Protection Agency for the loan of the inductive salinometer. Dr. Lucius G. Eldredge reviewed the manuscript and Mrs. Teresita C. Balajadia typed the final report. I extend my sincere thanks to all of these people.

## REFERENCES CITED

- American Public Health Association. 1976. Standard methods for the examination of water and wastewater. Publication Office, APHA, Washington, D. C. (1193 pp)
- Anonymous. 1977. The Natural Energy Laboratory of Hawaii annual report. (24 pp)
- Bathen, K. H. 1975. A further evaluation of the oceanographic conditions found off Keahole Point, Hawaii, and the environmental impact of nearshore ocean thermal energy conversion plants on subtropical Hawaiian waters. Dept. of Planning and Economic Development, State of Hawaii. (77 pp)
- Corey, R. R. 1975. Suitability of Guam from an environmental aspect as a potential site for ocean thermal energy conversion plants. USNA-EPRD-11. (16 pp)
- Craig, H. L., Jr., H. Michel, T. Lee, S. Hess, R. Munier, and M. Perlmutter. 1977. Selected data sets for a potential OTEC site: Guam (manuscript). (n.p.)
- Emery, K. O. 1962. Marine geology of Guam (Geology and hydrology of Guam, Mariana Islands). Geolog. Surv. Prof. Pap. 403-B: 1-76.
- Gregg, M. C. 1973. The microstructure of the ocean. pp. 157-169. In H. W. Menard. 1977. Ocean science. W. H. Freeman and Company, San Francisco.
- Horne, R. A. 1969. Marine chemistry. Wiley-Interscience, New York. (568 pp)
- Huddel, H. D., J. C. Willet, and G. Marchand. 1974. Nearshore currents and coral reef ecology of the west coast of Guam, Mariana Islands. Naval Oceanographic Office Special Publication 259:1-185.
- Pinchot, G. B. 1970. Marine farming. pp. 231-238. In H. W. Menard. 1977. Ocean science. W. H. Freeman and Company, San Francisco.
- Raymont, J. E. G. 1976. Plankton and productivity in the ocean. Pergamon Press, New York. (660 pp)
- Riley, J. P., and R. Chester. 1971. Introduction to marine chemistry. Academic Press, New York. (465 pp)

Strickland, J. D. H., and T. R. Parsons. 1972. A practical handbook of seawater analysis. Fisheries Research Board of Canada, Ottawa. (310 pp)

Williams, J. 1962. Oceanography. Little, Brown and Company, Boston. (242 pp)

## APPENDIX A

## CALCULATION OF TEMPERATURE

Formula for Correction of Protected Thermometer:

$$T = T' + \Delta T$$

where:  $T$  = true ambient temperature  
 $T'$  = reading on protected reversing thermometer  
 $\Delta T$  = change in  $T$  because of pressure

Calculation of  $T$ :

$$\Delta T = \left[ \frac{(V_0 + T')(T' - t)}{K} \right] \left[ 1 + \frac{(T' + V_0) + (T' - t)}{K} \right]$$

where:  $V_0$  = volume of Hg in stem of protected reversing thermometer below zero point (given on thermometer) = 105°  
 $t$  = reading on protected auxillary thermometer  
 $K$  = inverse of the coefficient of relative thermal expansion of Hg in glass ( $K = 1/.000164 = 6097.561$ )

Sample calculation:

$$\Delta T = \left[ \frac{(105 + 26.9)(26.9 - 28.0)}{6097.561} \right] \left[ 1 + \frac{(105 + 26.9) + (26.9 - 28.0)}{6097.561} \right]$$

$$\Delta T = (-0.023795)(1.021451)$$

$$\Delta T = -0.024$$

$$T = 26.90 + (-.024)$$

$$T = 26.876^\circ\text{C}$$

## CALCULATION OF DEPTH

Formula for Correction of Unprotected Thermometer

$$T_u = T_u' + \Delta T_u$$

where:  $T_u$  = true temperature of unprotected reversing thermometer  
 $T_u'$  = reading on unprotected reversing thermometer  
 $\Delta T_u$  = change in  $T_u'$  because of ambient temperature change

Calculation of  $T_u$ :

$$T_u = \frac{(T_u' + V_0)(T - t_u)}{K}$$

where:  $t_u$  = reading on unprotected auxillary thermometer  
 $V_0$  = same as above, but with different thermometer = 132°  
 $K$  = same as above

(continued)

## Appendix A (cont'd)

Calculation of depth (z):

$$z = \frac{T_u - T}{Q\rho_m}$$

where: Q = pressure factor for expansion of glass (given on thermometer) = .0089790

$\rho_m$  = mean density of sea water = 1.037

Sample calculation: for 25 m wire-out correction

$$\Delta T_u = \frac{(27.1 + 132)(26.876 - 27.0)}{6097.561} = -0.003131$$

$$T_u = 27.10 - 0.003131 = 27.097$$

$$z = \frac{27.097 - 26.876}{(.0089790)(1.037)} = 23.29 \text{ m}$$

Table 1. Key to physio-chemical parameters and synopsis of methodology.

<u>Identification No.</u>	<u>Parameter</u>	<u>Method</u>
1	Temperature	Reversing thermometer
2	Reactive phosphorus (PO <sub>4</sub> -P)	Ascorbic acid reduction <sup>1</sup>
3	Nitrite-nitrogen (NO <sub>2</sub> -N)	Sulfanilimide diazotization <sup>1</sup>
4	Nitrate-nitrogen (NO <sub>3</sub> -N)	Cadmium reduction <sup>1</sup>
5	Dissolved oxygen (D.O.)	Iodometric-azide modification of Winkler titration <sup>2</sup>
6	Salinity	Inductive salinometer, conduc- tivity meter, or refractive index <sup>2</sup>
7	pH	Glass electrode <sup>2</sup>
8	Total alkalinity	Potentiometric titration <sup>2</sup>

<sup>1</sup>As described in Strickland and Parsons (1972).

<sup>2</sup>As described in APHA (1976).

Table 2. Station numbers, field dates and measured parameters of each.

<u>Station No.</u>	<u>Date</u>	<u>Parameters Measured*</u>
1	02/03/78	1
2	03/01/78	1
3	03/28/78	1
4	04/12/78	1,2,3,4,6,7,8
5	04/28/78	1,2,3,4,5
6	05/25/78	1,2,3,4,5
7	07/26/78	1,2,3,4,5
8	07/26/78	1,2,3,4,5
9	08/15/78	1,2,3,4,5,6
10	08/23/78	1,2,3,4,5
11	09/20/78	1
12	10/04/78	1,2,3,4
10A	12/21/78	1
13	01/16/79	1,2,3,4,5,6,7,8
9A	02/21/79	1,2,3,4,6

\*Key to parameters is given in Table 1.

Table 3. Surface, 1500 ft., 2000 ft., 2500 ft. and 2800-3000 ft. temperatures for each station and their respective mean values (Feb., 1978-Feb., 1979).\*

Depth (m) (ft.)	Station No.															Temperature	
	1	2	3	4	5	6	7	8	9	10	11	12	10A	13	9A	$\bar{X}$ Temp. (°C)	(°F)
Surface	27.00	27.05	27.55	27.72	28.06	27.86	30.17	30.00	29.18	29.14	29.18	29.57	27.60	27.46	27.06	28.31 ± 1.12	(82.96)
457 (1500)		8.56	7.45	7.33	8.32	7.74			10.15	7.52	7.78	7.60	7.80	7.75	7.30	7.94 ± 0.79	(46.29)
610 (2000)		6.97	6.11	6.11	6.29						6.89	6.49	6.27	6.64		6.47 ± 0.36	(43.65)
762 (2500)		5.54	5.30	5.51	5.46							5.69		5.69		5.53 ± 0.15	(41.95)
854-915 (2800-3000)				5.01								5.05		4.87		4.98 ± 0.09	(40.96)

\* Illustrated in Fig. 7.

Table 4. Expected monthly  $\Delta T^*$  at 1500 ft., 2000 ft., 2500 ft. and 2800-3000 ft. and their respective annual means in the vicinity of Glass Breakwater and Cabras Island, Guam.

Depth (m) (ft.)	Temperature (°C) (°F)												$\bar{X}\Delta T$ (°C) (°F)
	J	F	M	A	M	J	J	A	S	O	N	D	
457 (1500)	19.7(35.5)	19.5(35.2)	19.3(34.8)	20.1(36.1)	20.1(36.2)	21.2(38.1)	22.3(40.1)	21.4(38.6)	21.4(38.5)	22.0(39.5)	20.9(37.6)	19.8(35.6)	20.6(37.1)
610 (2000)	20.8(37.5)	20.2(36.4)	20.8(37.4)	21.7(39.0)	21.4(38.5)	22.5(40.5)	23.6(42.5)	22.7(40.9)	22.3(40.1)	23.1(41.5)	22.2(40.0)	21.3(38.4)	21.9(39.4)
762 (2500)	21.8(39.2)	21.4(38.5)	21.9(39.4)	22.4(40.3)	22.3(40.2)	23.4(42.2)	24.6(44.2)	23.7(42.6)	23.6(42.6)	23.9(43.0)	22.9(41.2)	21.9(39.4)	22.8(41.1)
854-915 (2800-3000)	22.6(40.6)	22.0(39.7)	22.3(40.2)	22.9(41.2)	22.9(41.2)	24.0(43.2)	25.1(45.2)	24.2(43.6)	24.2(43.6)	24.5(44.1)	23.6(42.5)	22.7(40.9)	23.4(42.2)

\* Based on data illustrated in Fig. 7 and presented in Table 3.

Table 5. Mean values for all stations for nitrate-nitrogen, reactive phosphorus, dissolved oxygen, total carbon dioxide, pH and total alkalinity (Feb., 1978-Feb., 1979).

Depth (m)	NO <sub>3</sub> -N* (µg-at/ℓ)	PO <sub>4</sub> -P* (µg-at/ℓ)	D.O.** (mg/ℓ)	Total CO <sub>2</sub> ** (mg/kg)	pH*** (pH units)	Total*** Alkalinity (mg/ℓ)
0	.2363	.1399	6.237	77.810	8.34	113.0
50	.4226	.1107	6.244	74.065	8.44	115.0
100	.2161	.1363	6.447	71.610	8.08	104.0
150	2.7870	.3706	6.103	77.603	8.30	111.0
180				78.496	8.20	113.0
192	5.0963	.4079	5.730			
270					8.00	112.8
285	17.2901	1.2034	5.034	78.908		
395	25.0135	1.8361	3.709	82.236	7.91	115.0
457			2.698			
472				82.544	7.71	114.5
493	31.9781	2.2643	3.084			
555	34.3012	2.4967	2.649			
650				83.794	7.71	116.2
682	31.8423	2.5421				
709			3.385			
837				84.819	7.73	117.0
883	35.7772	2.7276				
905			2.566	84.212		
918					7.65	115.0

\* Illustrated in Fig. 9.

\*\* Illustrated in Fig. 10.

\*\*\* Illustrated in Fig. 11.

Table 6. Mean temperature and salinity measured at the listed depths with corresponding calculated density and stability (Feb., 1978-Feb., 1979).

Depth (m)	Mean Temp. (°C)*	Salinity (‰)*	Density (g/cm <sup>3</sup> )*	Stability
0	28.19	34.4252	1.021826	422 x 10 <sup>-8</sup>
50	28.01	34.5220	1.022037	169 x 10 <sup>-7</sup>
100	27.08	34.5665	1.022883	273 x 10 <sup>-7</sup>
150	23.87	35.1335	1.024247	332 x 10 <sup>-7</sup>
195	20.04	35.0880	1.025741	168 x 10 <sup>-7</sup>
290	12.90	34.5050	1.027337	116 x 10 <sup>-7</sup>
397	8.89	34.4950	1.028579	617 x 10 <sup>-8</sup>
457	7.78	34.4826	1.028949	662 x 10 <sup>-8</sup>
496	7.26	34.4700	1.029214	616 x 10 <sup>-8</sup>
600	6.44	34.5000	1.029855	512 x 10 <sup>-8</sup>
709	5.76	34.5400	1.030413	642 x 10 <sup>-8</sup>
762	5.52	34.5400	1.030753	125 x 10 <sup>-8</sup>
830	5.24	34.5450	1.030838	106 x 10 <sup>-7</sup>
890	4.98	34.5490	1.031473	

\* Illustrated in Fig. 8.



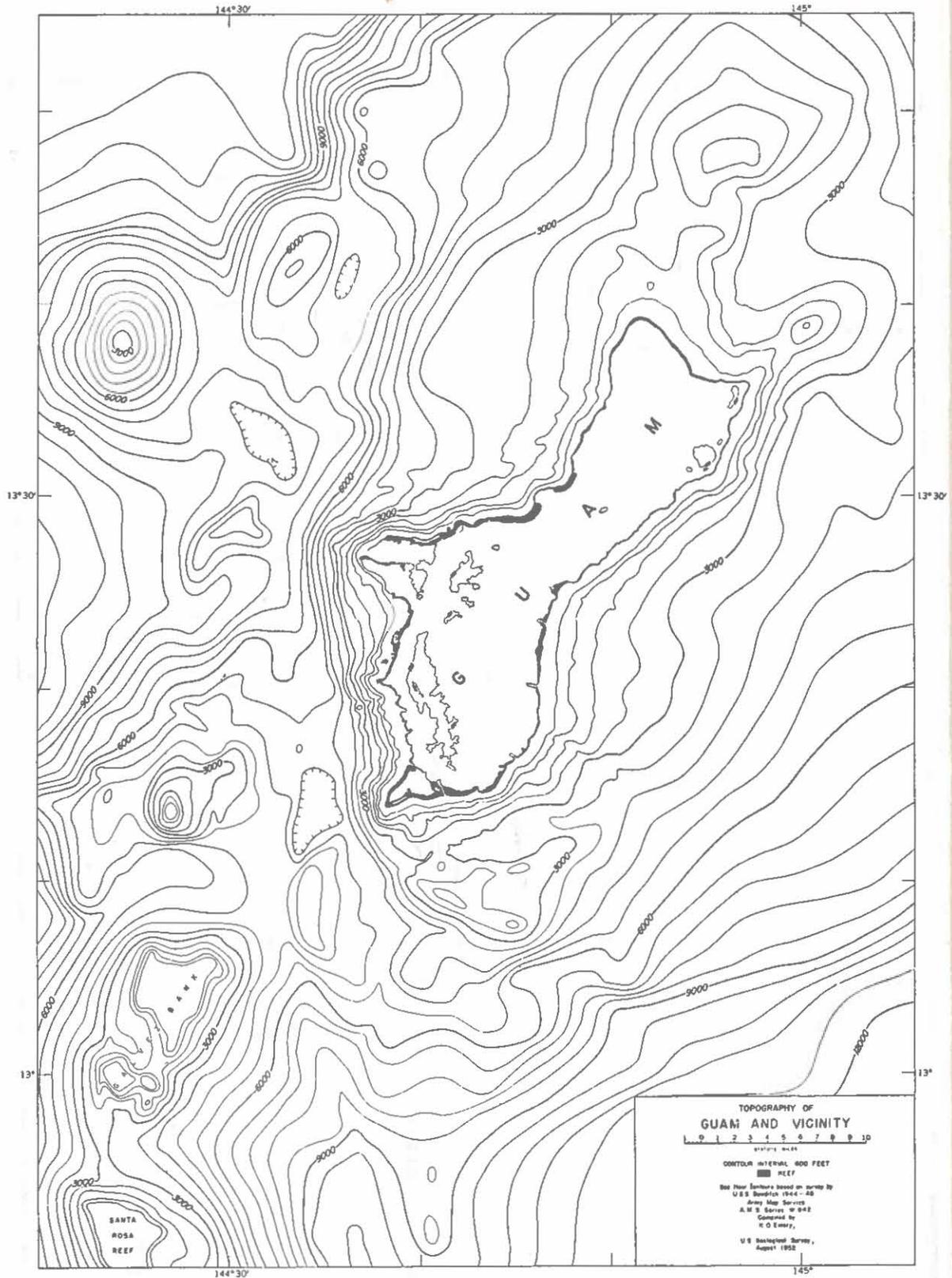


Fig. 2. Bathymetric chart of Guam and vicinity. Contour interval is 600 feet (100 fathoms) on both land and sea floor. Reef areas shown by solid black pattern. (From Emery, 1962)

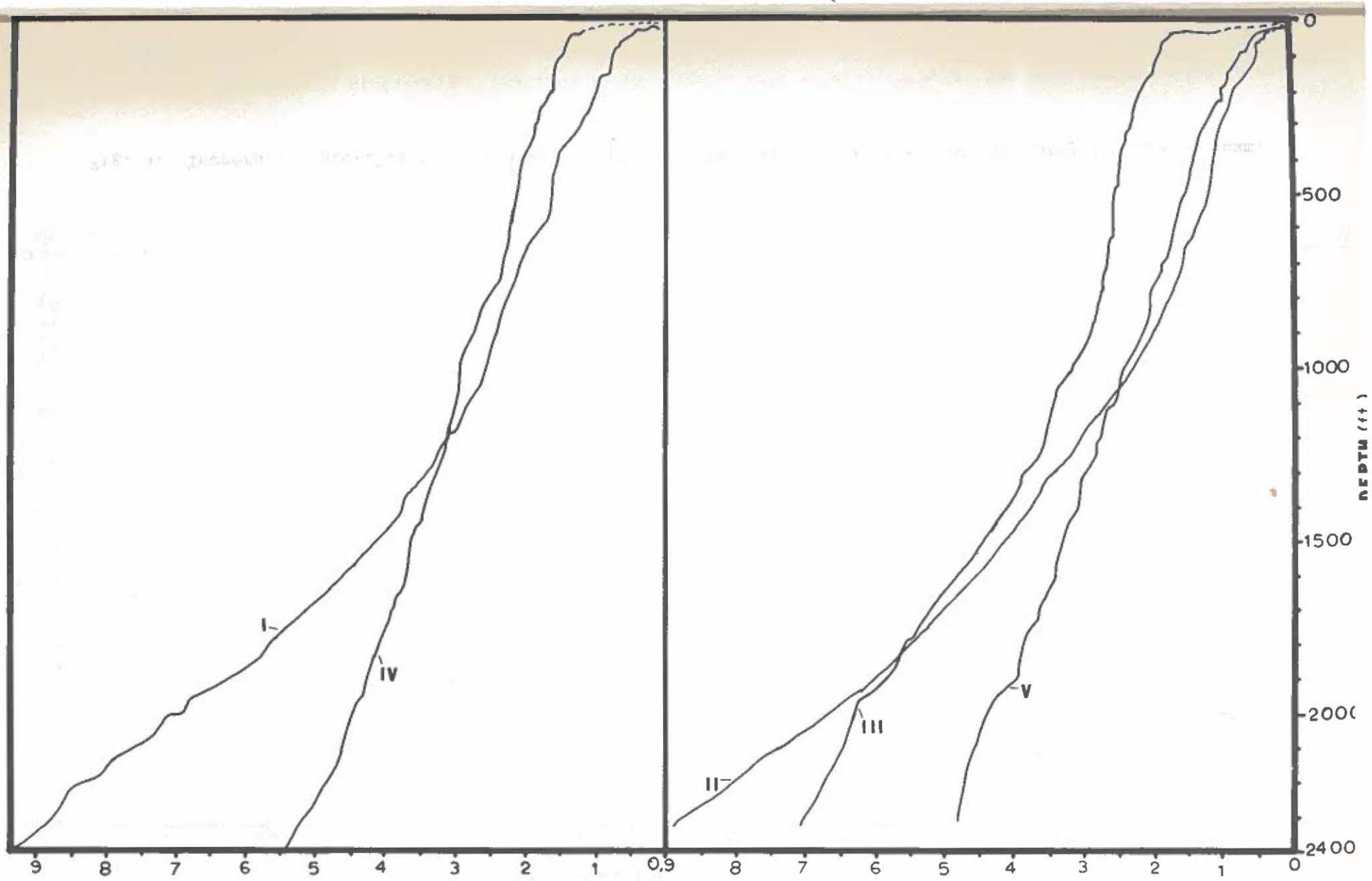


Fig. 3. Fathometer profiles of the bottom at five sites in the vicinity of Cabras Island, Luminao Reef and Glass Breakwater, Guam.

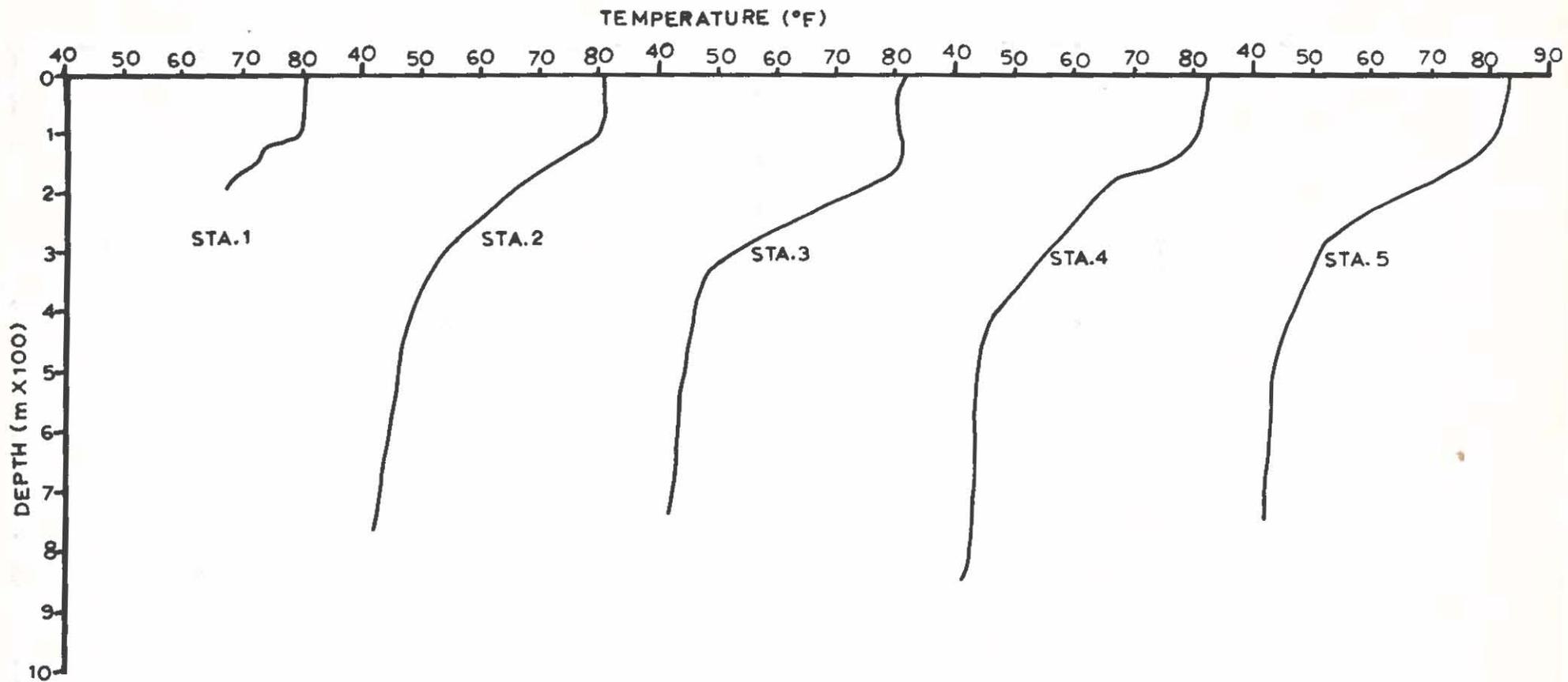


Fig. 4. Temperature profiles for Stations 1-5 (Feb., 1978 - April, 1978) at the OTEC project site on Guam.

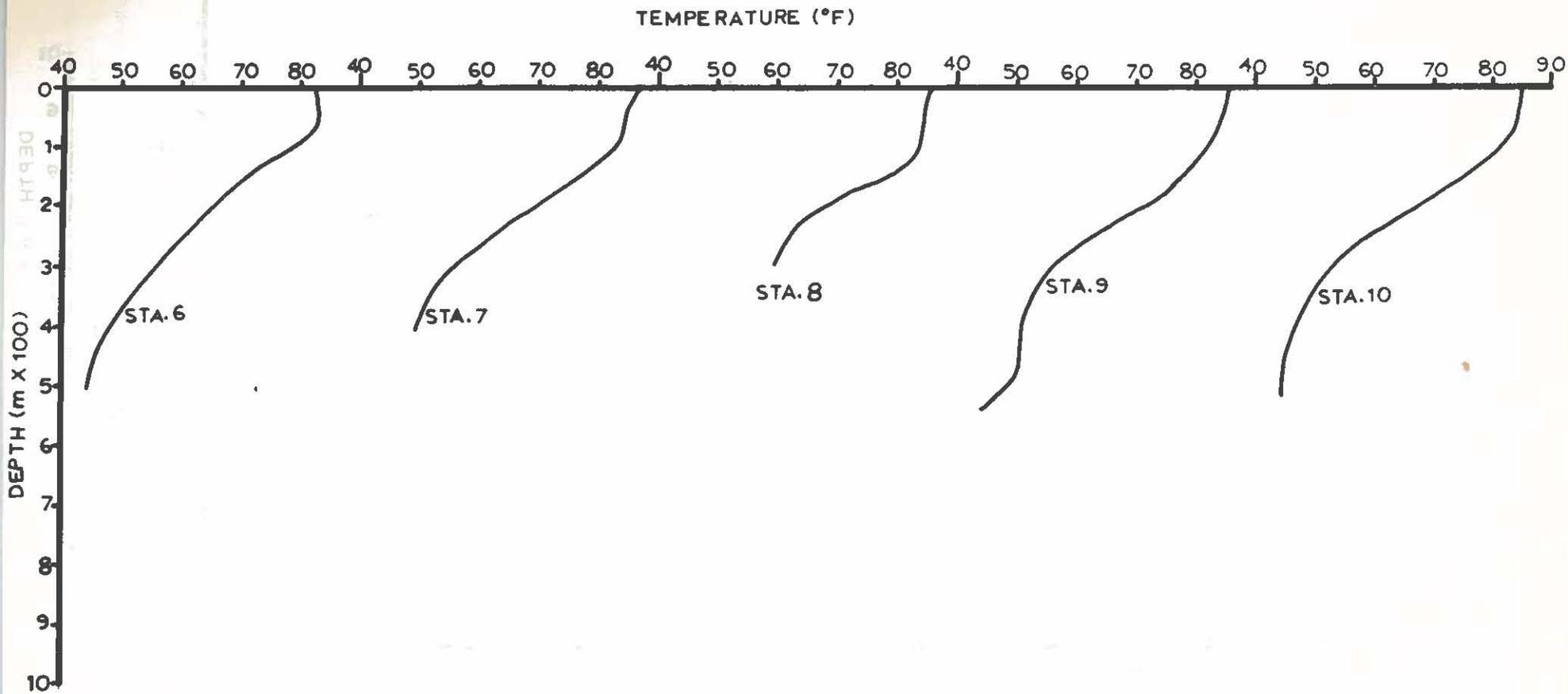


Fig. 5. Temperature profiles for Stations 6-10 (May, 1978 - Aug., 1978) at the OTEC project site on Guam.

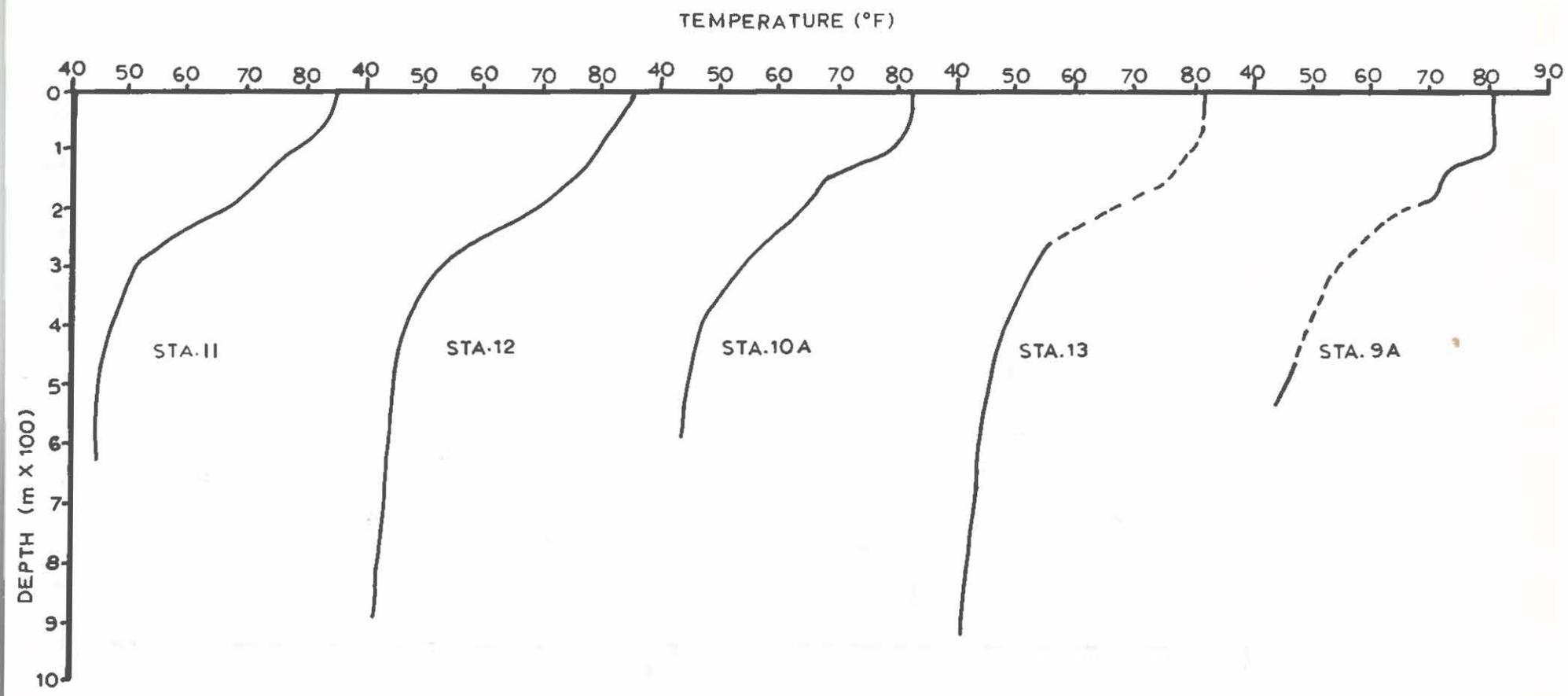


Fig. 6. Temperature profiles for Stations 11-9A (Sept., 1978 - Feb., 1979) at the OTEC project site on Guam.

Fig. 6. Temperature profiles for Stations 11-9A (Sept., 1978 - Feb., 1979) at the OTEC project site on Guam.



Fig. 7. Mean monthly temperatures for surface, 1500, 2000, 2500 and 2800-3000 ft in the vicinity of Cabras Island, Luminao Reef and Glass Breakwater, Guam.

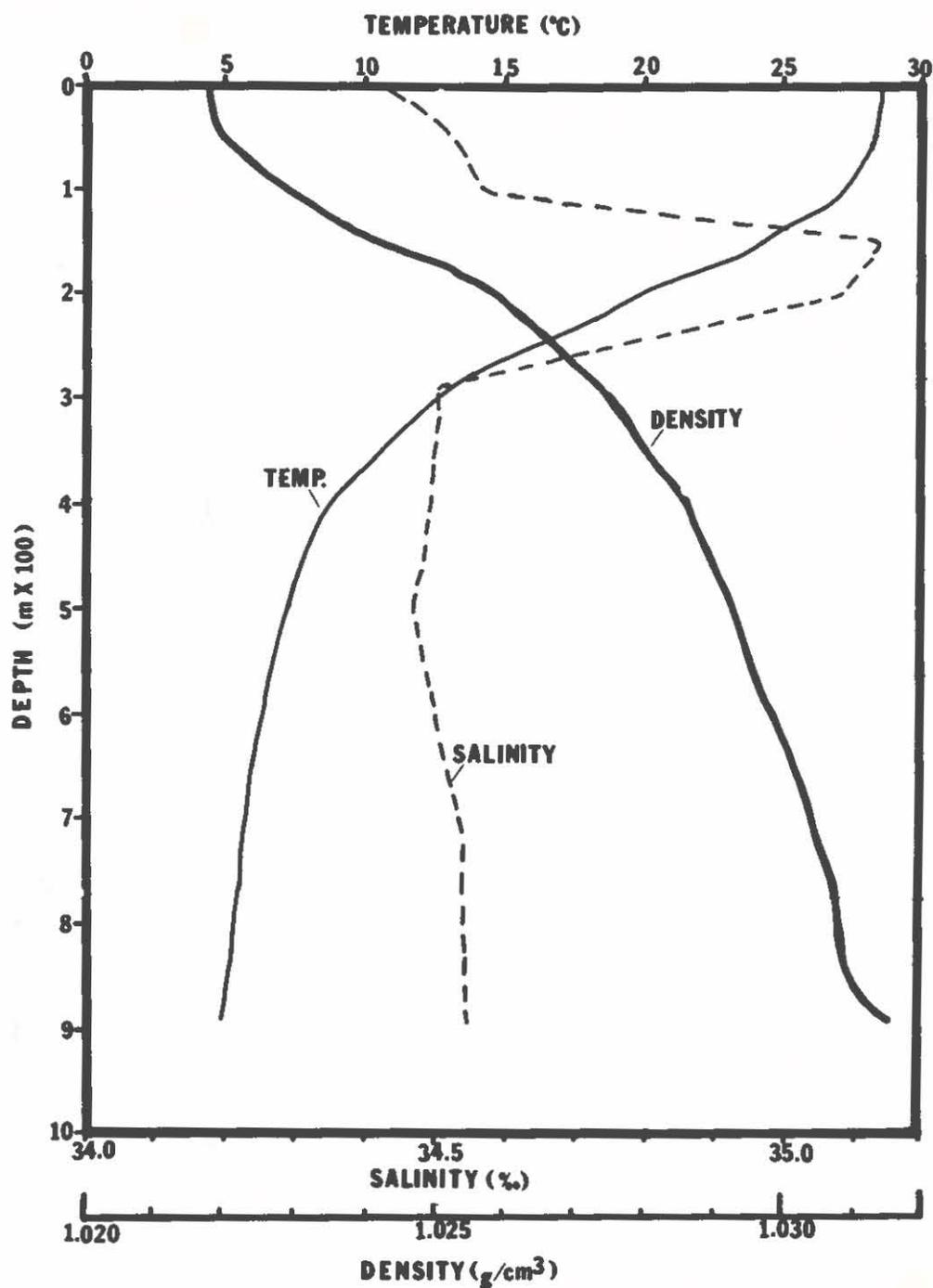
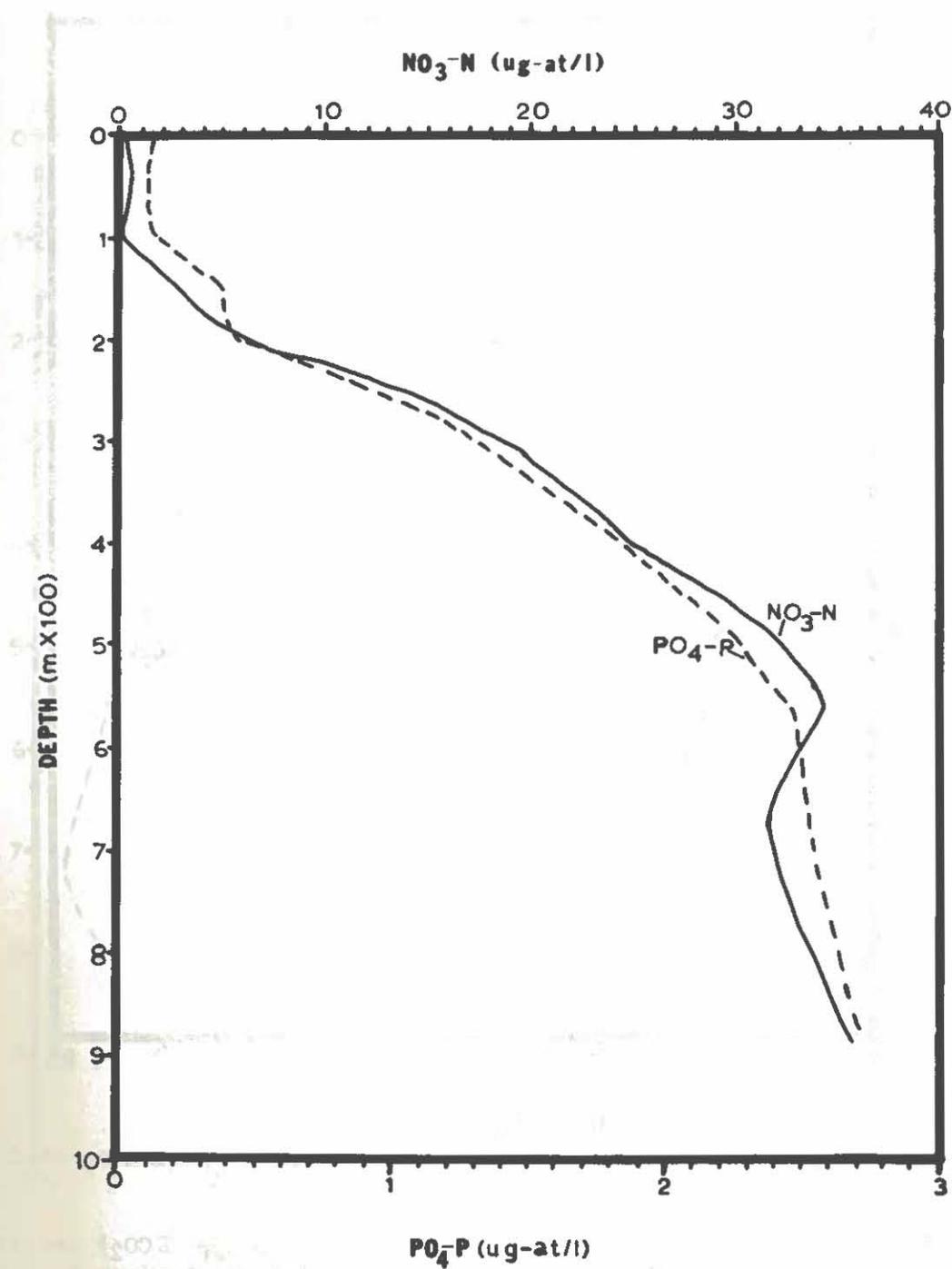


Fig. 8. Mean temperature, salinity and density profiles in the vicinity of Cabras Island, Luminao Reef and Glass Breakwater, Guam (Feb., 1978 - Feb., 1979).



f Cabras

Fig. 9. Mean nitrate-nitrogen (NO<sub>3</sub>-N) and reactive phosphorous (PO<sub>4</sub>-P) profiles from surface to 883 m (2900 ft) in the vicinity of Cabras Island, Luminao Reef and Glass Breakwater, Guam (Feb., 1978 - Feb., 1979).

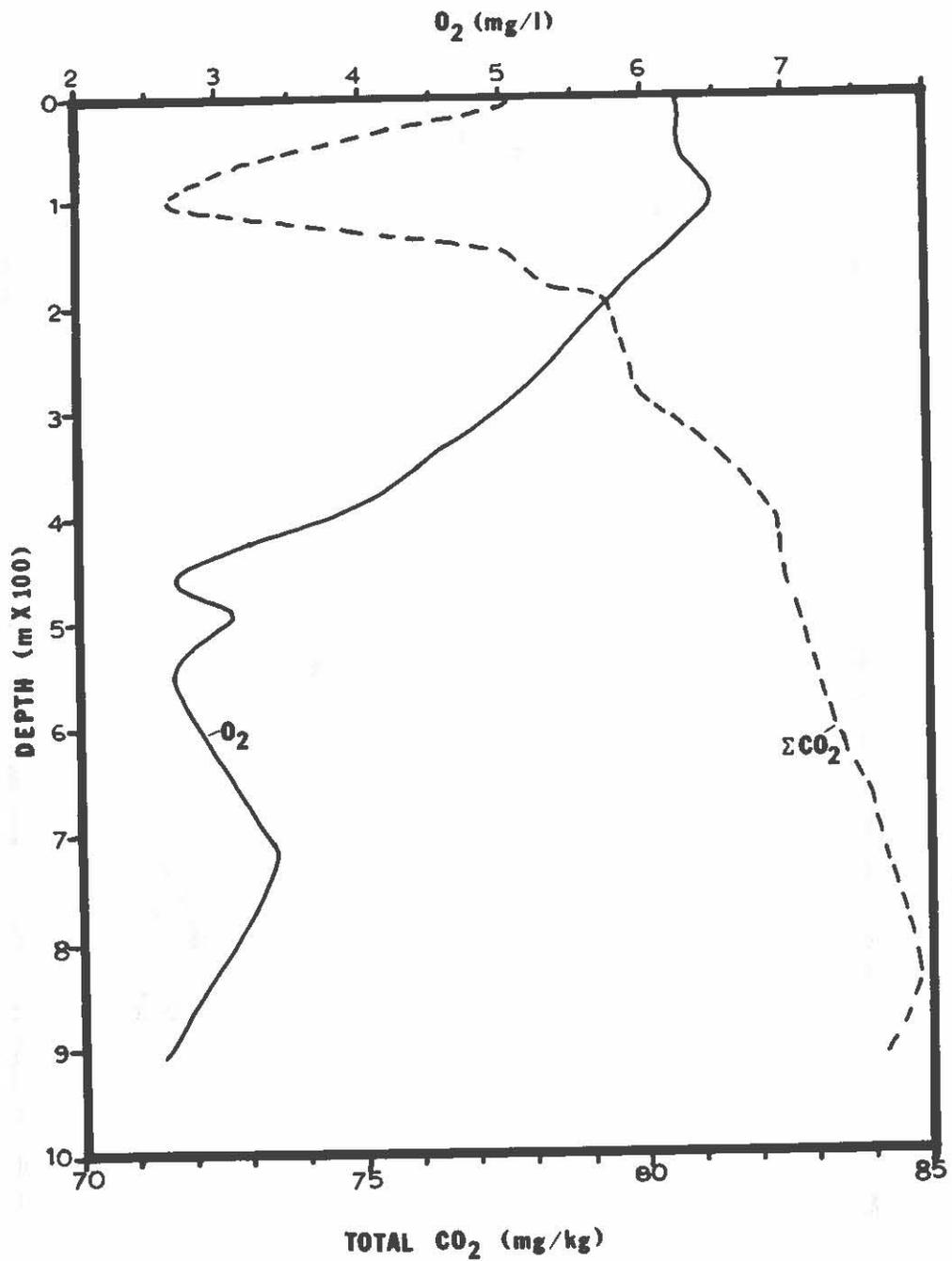
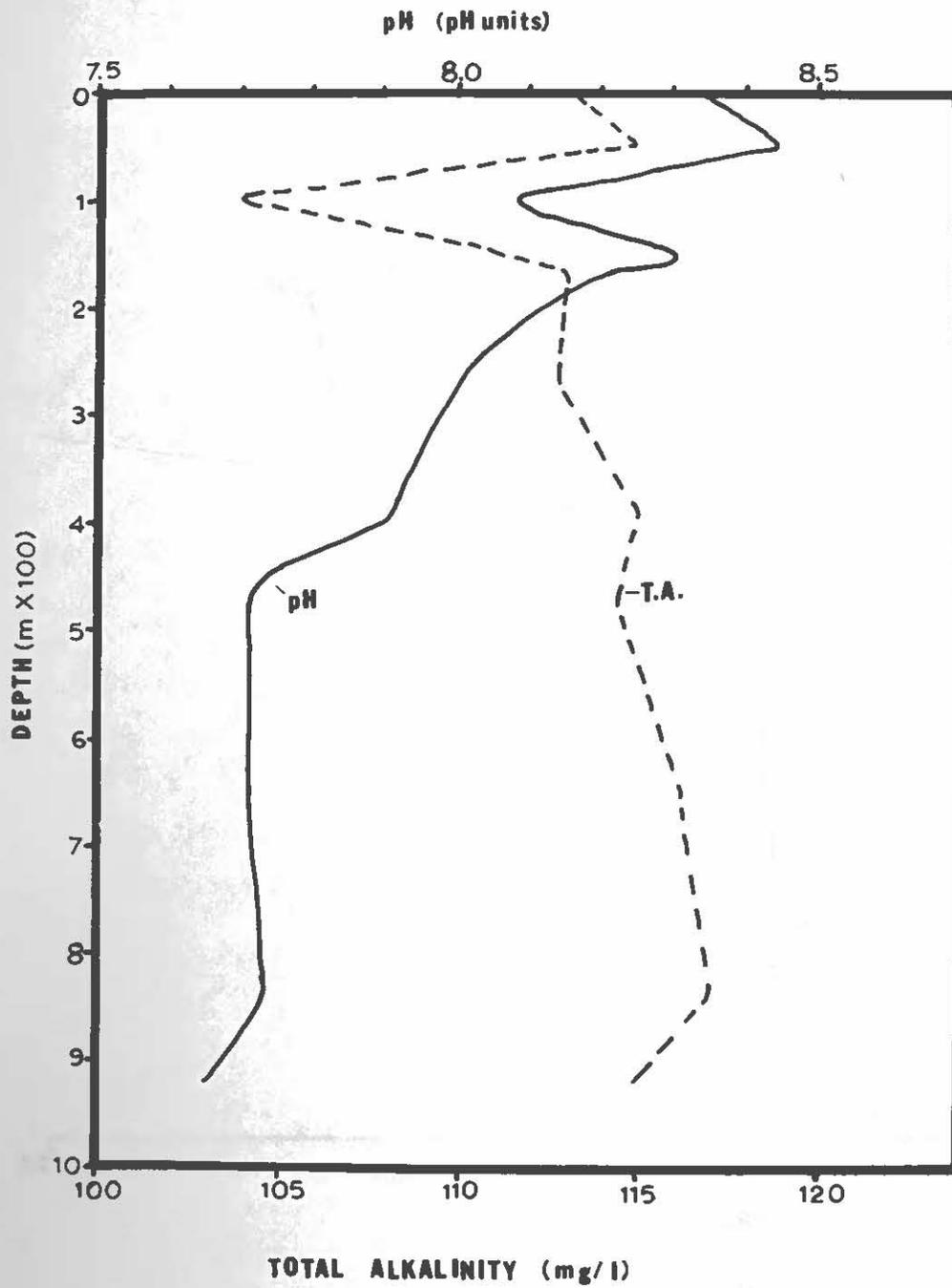


Fig. 10. Mean dissolved oxygen (O<sub>2</sub>) and total carbon dioxide (ΣCO<sub>2</sub>) profiles from surface to 905 m (2970 ft) in the vicinity of Cabras Island, Luminao Reef and Glass Breakwater, Guam (Feb. 1978 - Feb., 1979).



iles from  
and Glass

Fig. 11. Mean pH and total alkalinity (T.A.) profiles for the vicinity of Cabras Island, Luminao Reef and Glass Breakwater, Guam (Feb., 1978 - Feb., 1979).

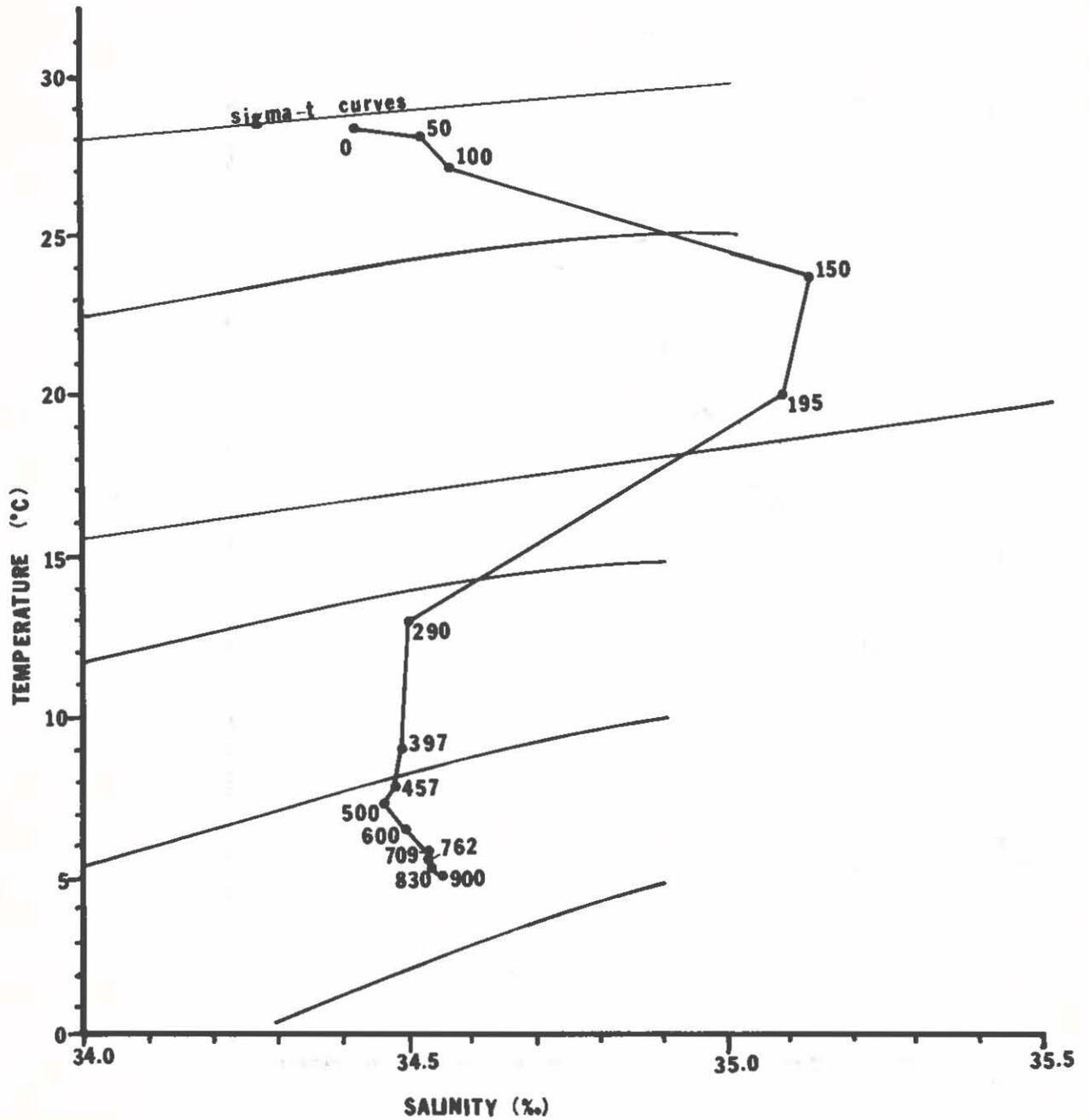


Fig. 12. T-S diagram for the vicinity of the proposed OTEC site on Guam (Based on mean temperature and salinity data taken from Feb., 1978 - Feb., 1979).