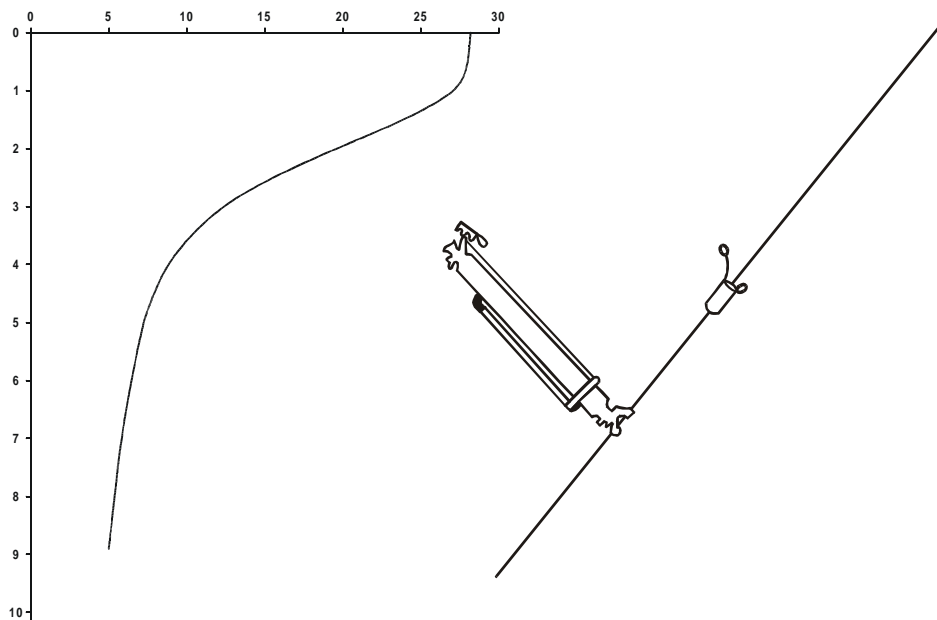


OCEANOGRAPHIC CONDITIONS IN THE VICINITY OF CABRAS ISLAND AND GLASS BREAKWATER FOR THE POTENTIAL DEVELOPMENT OF OCEAN THERMAL ENERGY CONVERSION ON GUAM

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Submitted to

Guam Energy Office

University of Guam, Marine Laboratory

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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° to 35°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 physio-chemical 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 ($\sum\text{CO}_2$), calculated on the basis of pH, total alkalinity, temperature, and salinity (Strickland and Parsons, 1972), represents not only gaseous CO_2 but also all other dissolved inorganic carbon forms, i.e., $\sum\text{CO}_2 = [\text{CO}_2] + [\text{H}_2\text{CO}_3] + [\text{HCO}_3^-] + [\text{CO}_3^{=}]$ (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 function of the density of the water mass in question and the rate of change of density with respect to depth (Williams, 1962).

*Pressure was calculated by assuming one decibar of pressure per meter

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 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

**Taken from Emery, 1962.

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 (ΔT) 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 ΔT . 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 ΔT 's were calculated and are presented in Table 4. Argonne National Laboratory's "Request for Proposal" calls for an operational minimum ΔT of 35°F. Table 4 indicates that for Guam this ΔT can be maintained at a depth of only 1500 ft (457 m) on a monthly basis, with an annual mean ΔT of over 37°F. In fact, an annual mean ΔT 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) ΔT 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 ΔT 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 ΔT 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 ΔT 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 $\mu\text{g-at}/\ell$ for nitrate and 2.7 $\mu\text{g-at}/\ell$ for orthophosphate. These are similar to the values of 36.5 $\mu\text{g-at}/\ell$, and 2.9 $\mu\text{g-at}/\ell$ 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 (ΣCO_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^- , $\text{CO}_3^{=}$ and $\text{B}(\text{OH})_4^-$ 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 $\text{CO}_3^{=}$ 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 CO₂ concentration relatively low in the well-mixed surface layers above the thermocline where light availability allows the O₂-producing process of photosynthesis to dominate. Below the thermocline, O₂ production declines rapidly as light diminishes and the release of CO₂ rises sharply with increased depth. Oxygen concentration generally reaches a minimum at about (1310-1640 ft) 400-500 m while Σ CO₂ reaches its maximum at (1640-3280 ft) 500-1000 m. An increase in O₂ 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 Σ CO₂ 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 CaCO₃ 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 10°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 (σ_t) values over a range of temperatures and salinities can be calculated from specific tables and plotted as of 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 σ_t . The T-S diagram for these depths would, therefore, be parallel to the σ_t curves. By the same reasoning, a sharp downward angle in the T-S diagram would indicate a significant change in the σ_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° and 15°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 (ΔT) 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 ΔT and suitable depth profiles. The suggested minimum ΔT of 35°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°F (22.7°C) ΔT occurs on Guam. Annual mean ΔT 's of 41.1°F (22.8°C) and 42.2°F (23.4°C) are expected at depths of 2500 ft (762 m) and 2800–3000 ft (854–915 m), respectively, with a maximum monthly ΔT of 45.2°F (25.1°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.

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

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.

ACKNOWLEDGEMENTS

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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

ΔT = 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 auxiliary 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

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

Appendix A (cont'd)

where: T_u = true temperature of unprotected reversing thermometer

T_u' = reading on unprotected reversing thermometer

ΔT_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

Calculation of depth (z):

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

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

ρ_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 ₄ -P)	Ascorbic acid reduction ¹
3	Nitrite-nitrogen (NO ₂ -N)	Sulfanilimide diazotization ¹
4	Nitrate-nitrogen (NO ₃ -N)	Cadmium reduction ¹
5	Dissolved oxygen (D.O.)	Iodometric-azide modification of Winkler titration ²
6	Salinity	Inductive salinometer, conduc- tivity meter, or refractive index ²
7	pH	Glass electrode ²
8	Total alkalinity	Potentiometric titration ²

¹As described in Strickland and Parsons (1972).

²As 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		X Temp.	
	1	2	3	4	5	6	7	8	9	10	11	12	10A	13	9A	(°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 ΔT^* 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)												
	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 ₃ -N* (µg-at/ℓ)	PO ₄ -P* (µg-at/ℓ)	D.O.** (mg/ℓ)	Total CO ₂ ** (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 ³)*	Stability
0	28.19	34.4252	1.021826	422 x 10 ⁻⁸
50	28.01	34.5220	1.022037	169 x 10 ⁻⁷
100	27.08	34.5665	1.022883	273 x 10 ⁻⁷
150	23.87	35.1335	1.024247	332 x 10 ⁻⁷
195	20.04	35.0880	1.025741	168 x 10 ⁻⁷
290	12.90	34.5050	1.027337	116 x 10 ⁻⁷
397	8.89	34.4950	1.028579	617 x 10 ⁻⁸
457	7.78	34.4826	1.028949	662 x 10 ⁻⁸
496	7.26	34.4700	1.029214	616 x 10 ⁻⁸
600	6.44	34.5000	1.029855	512 x 10 ⁻⁸
709	5.76	34.5400	1.030413	642 x 10 ⁻⁸
762	5.52	34.5400	1.030753	125 x 10 ⁻⁸
830	5.24	34.5450	1.030838	106 x 10 ⁻⁷
890	4.98	34.5490	1.031473	

* Illustrated in Fig. 8.

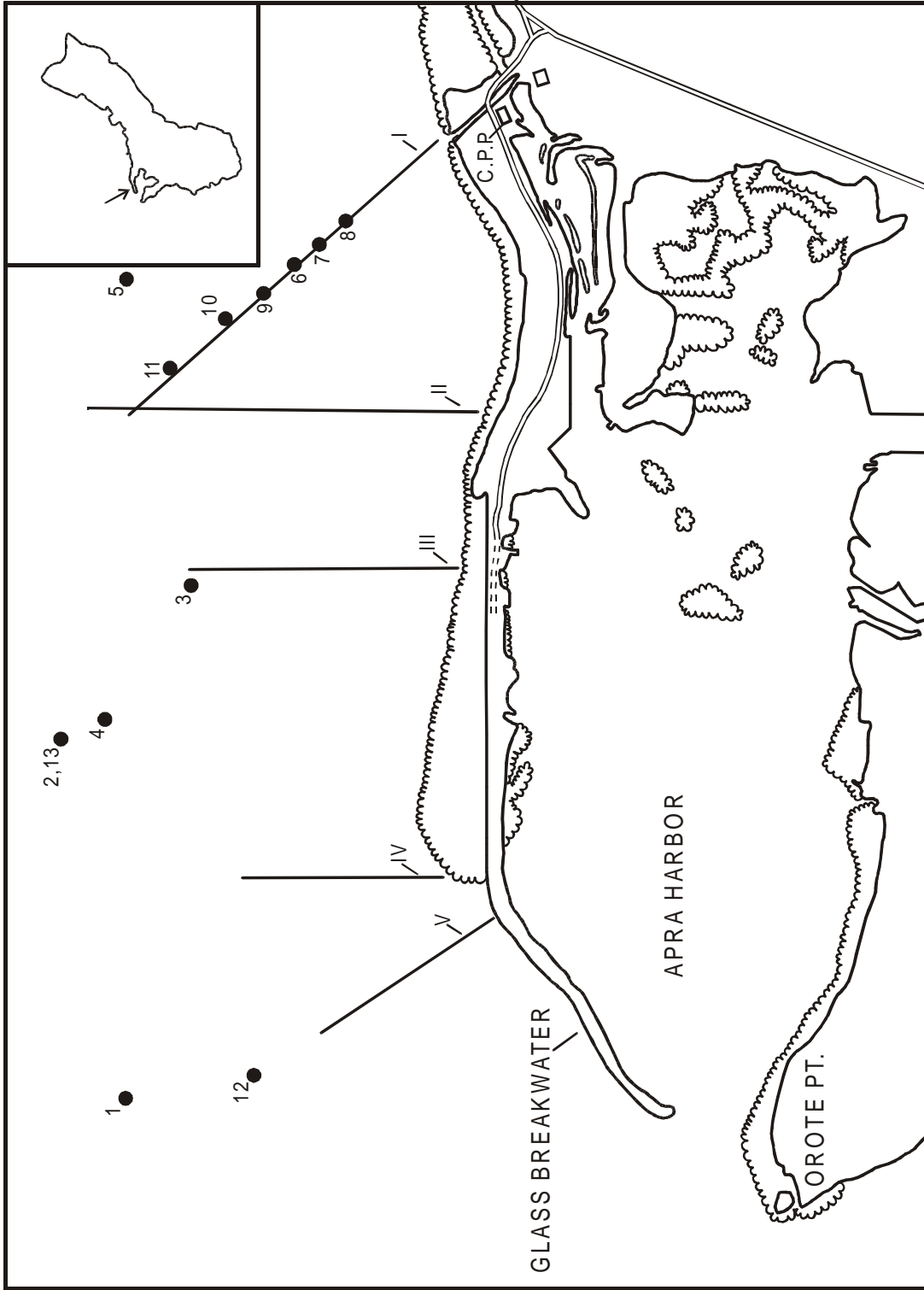


Fig. 1. Map of OTEC project site with locations of stations and bottom profiles.

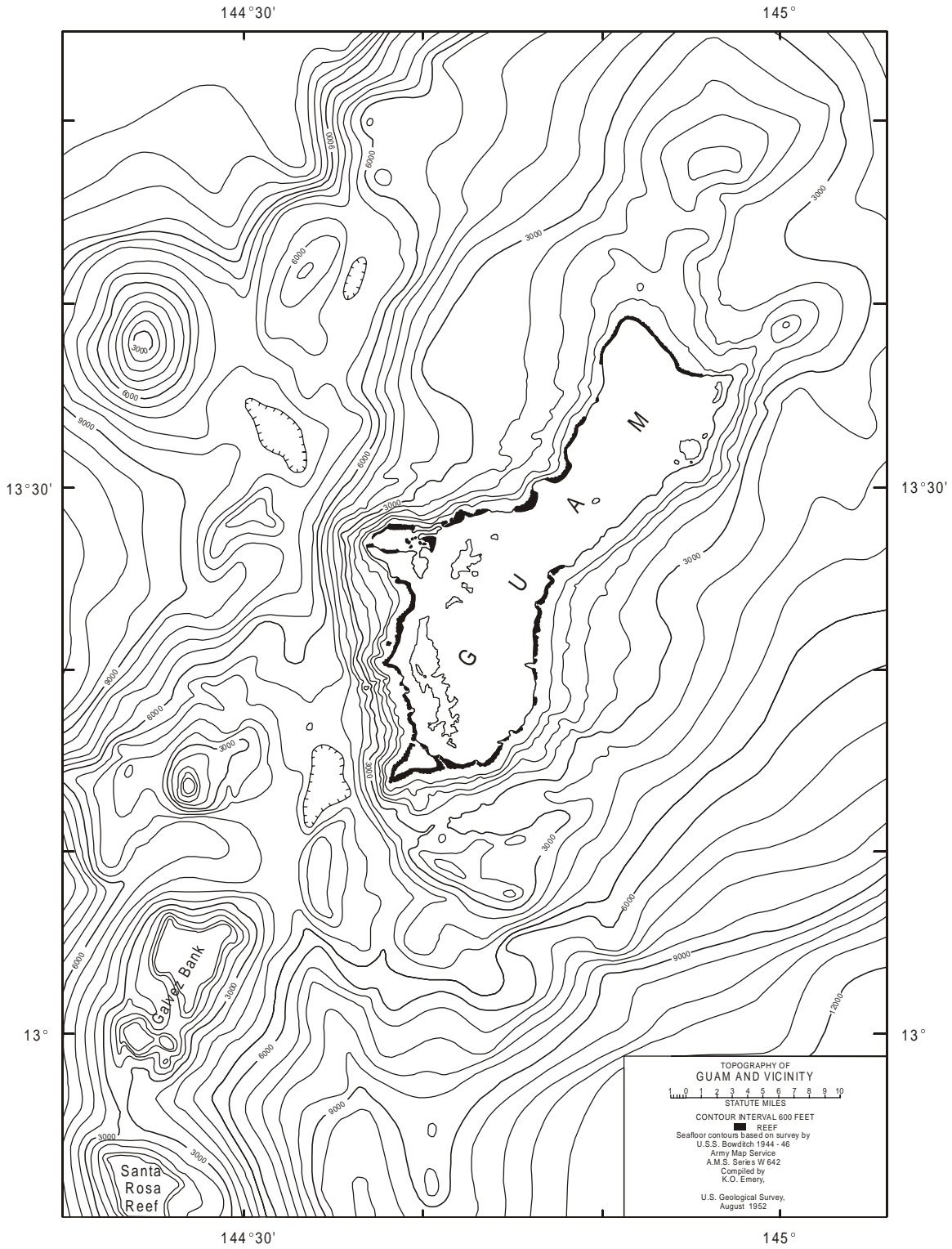


Fig. 2. Bathymetric chart of Guam and vicinity. Contour interval is 600 feet (100 fathoms) on both land and sea floor. Reef areas shown by solid black pattern. (From Emery, 1962)

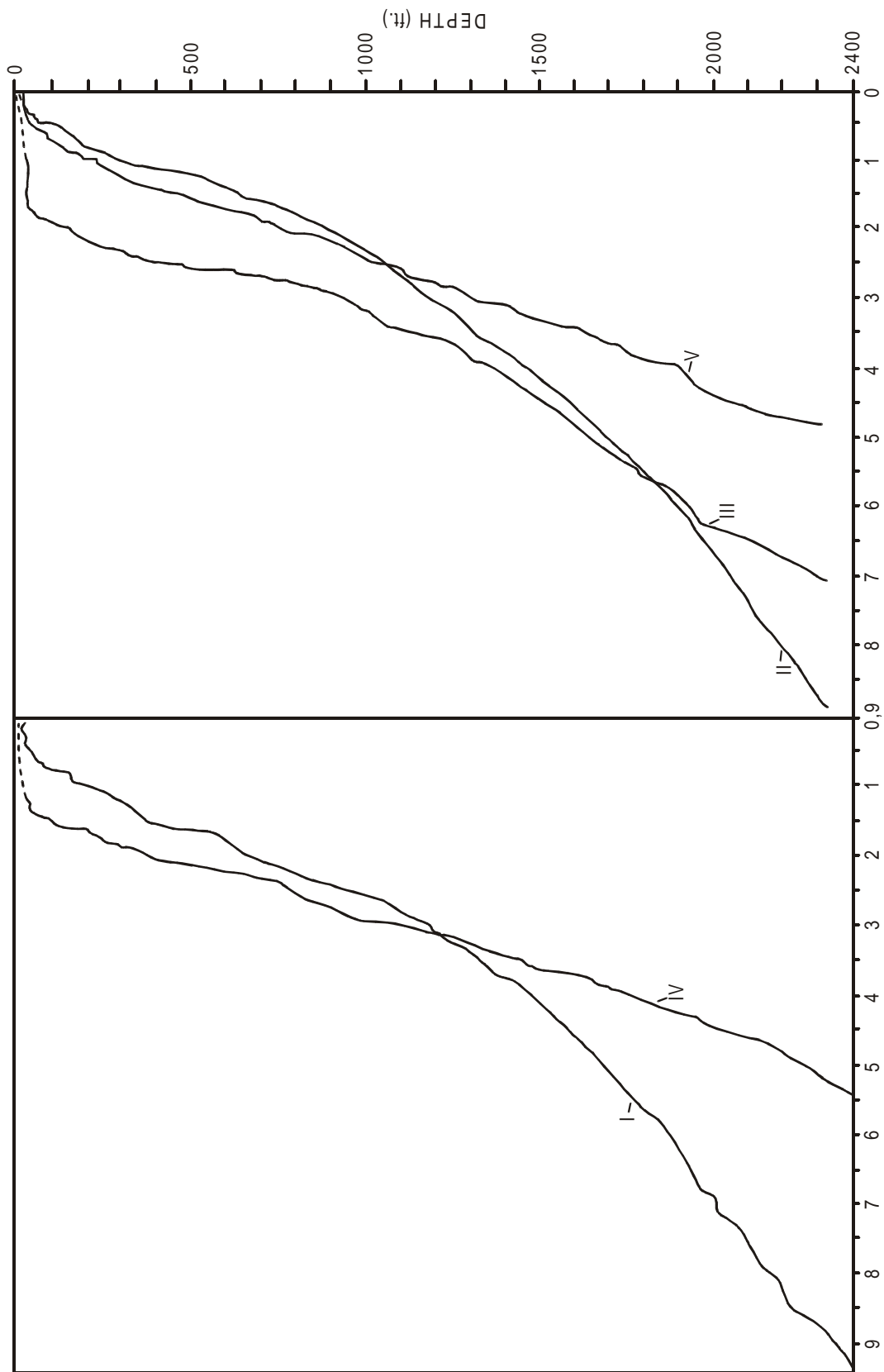


Fig. 3. Fathometer profiles of the bottom at five sites in the vicinity of Cabras Island, Luminao Reef and Glass Breakwater, Guam

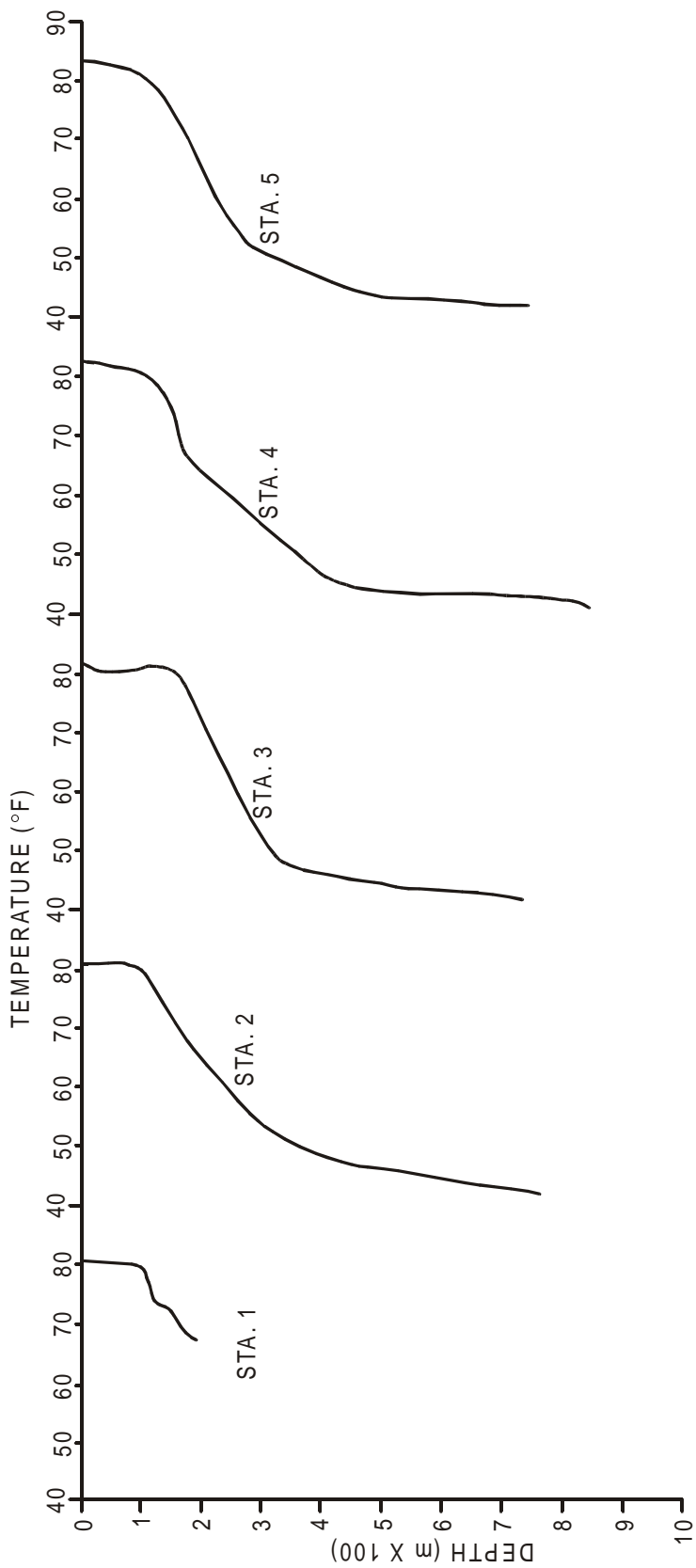


Fig. 4. Temperature profiles for Stations 1 - 5 (Feb., 1978 - April, 1978) at the OTEC project site on Guam.

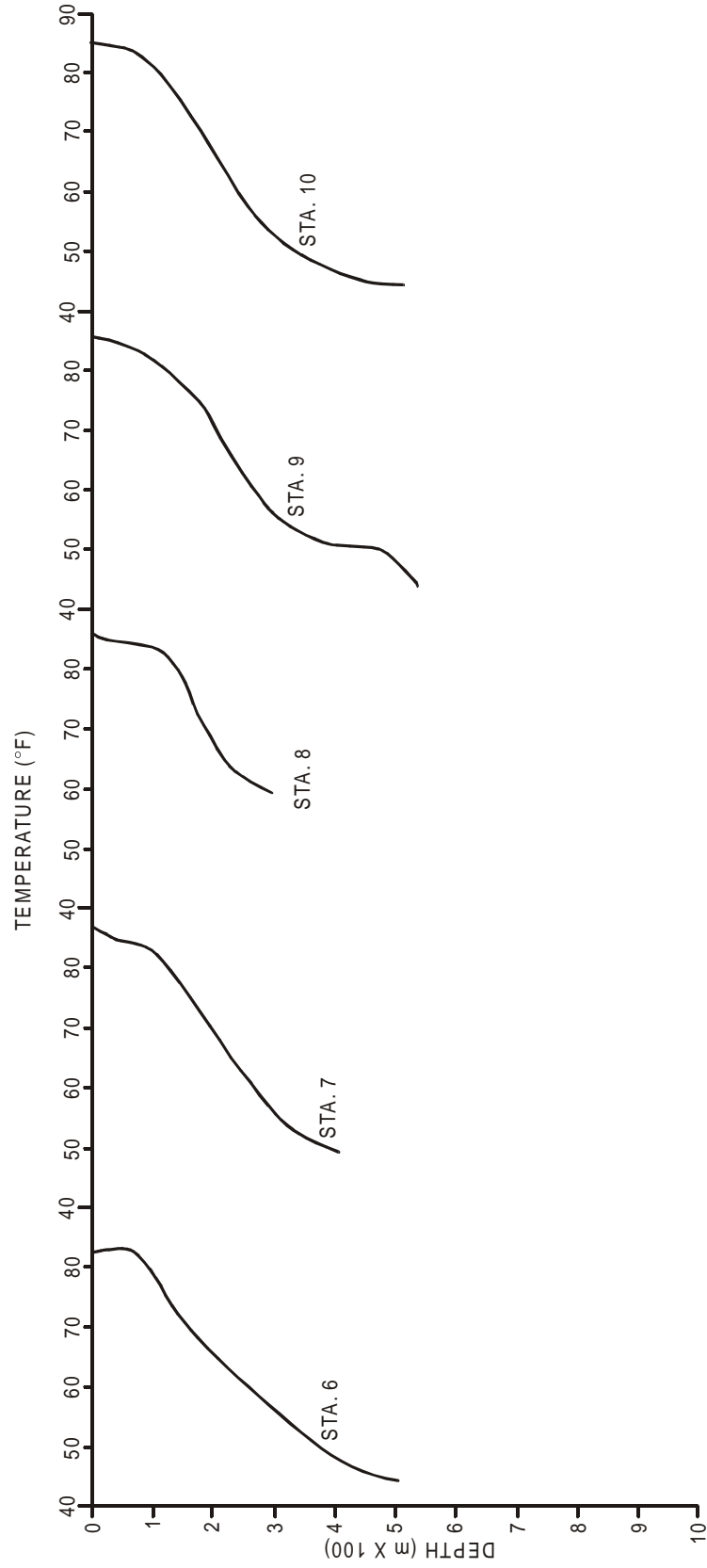


Fig. 3. Temperature profiles for Station 6-10 (May, 1978 - Aug., 1978) at the OTEC project site on Guam.

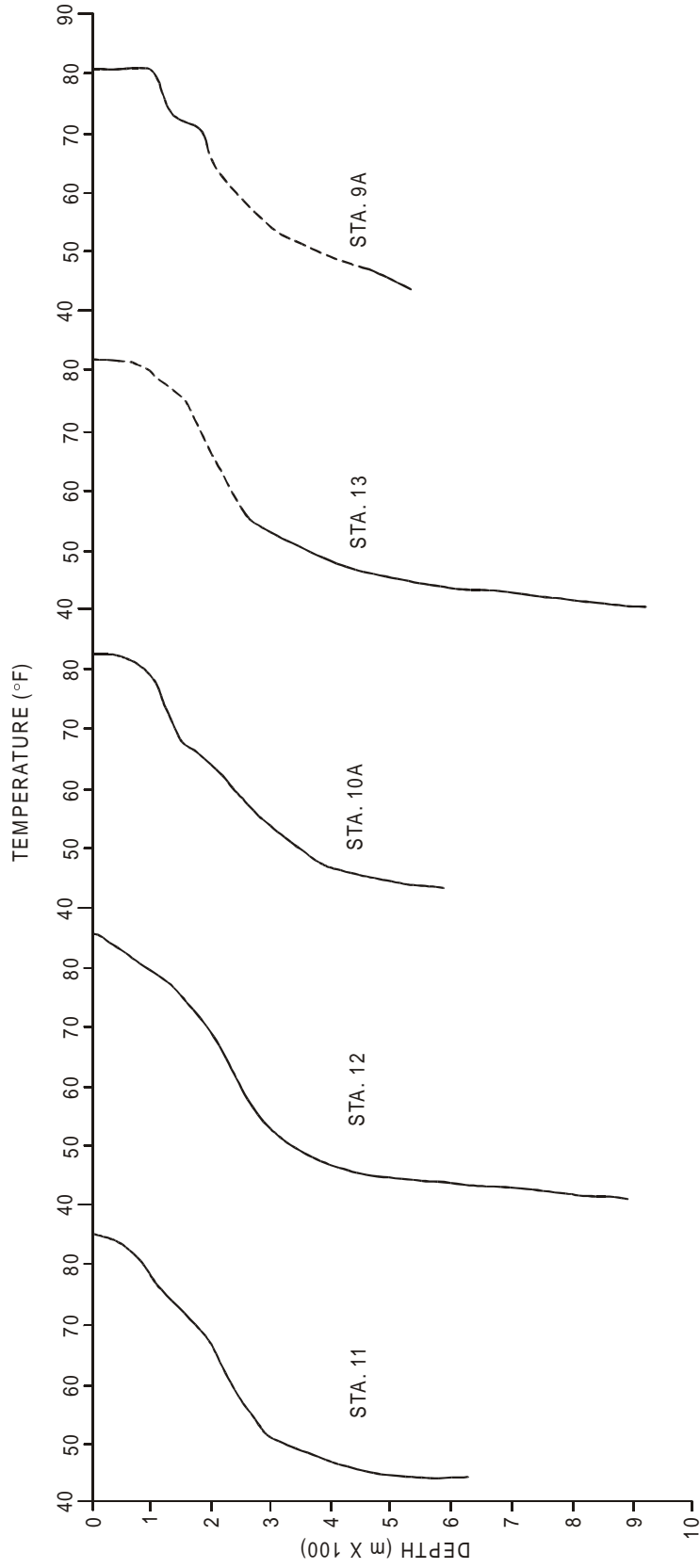


Fig. 6. Temperature profiles for Stations 11-9A (Sept., 1978 - Feb., 1979) at the OTEC project site on Guam.

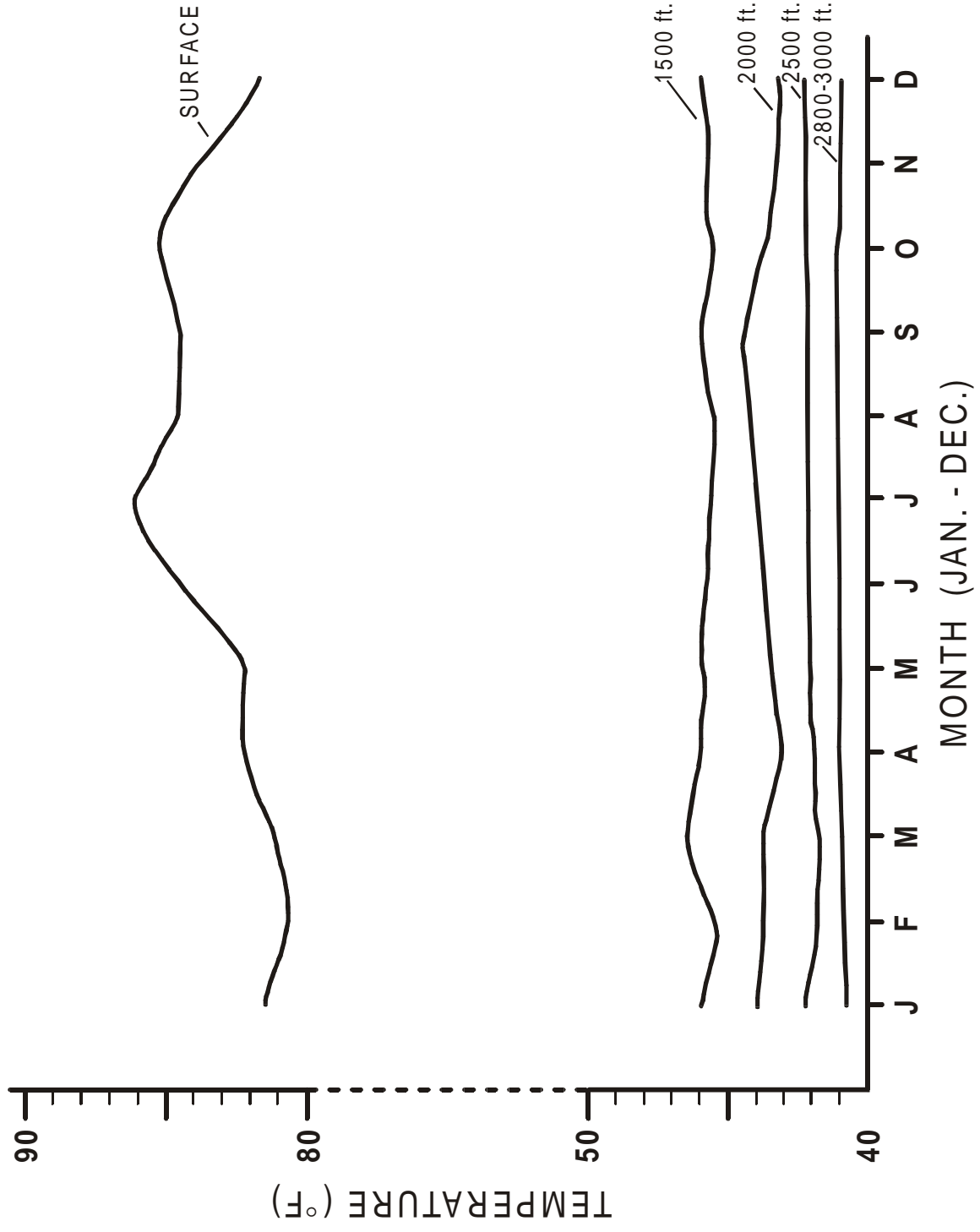


Fig. 7. Monthly mean temperatures for surface, 1500, 2000, 2500, and 2800-3000 ft in the vicinity of Cabras Island, Luminao Reef, and Glass Breakwater, Guam.

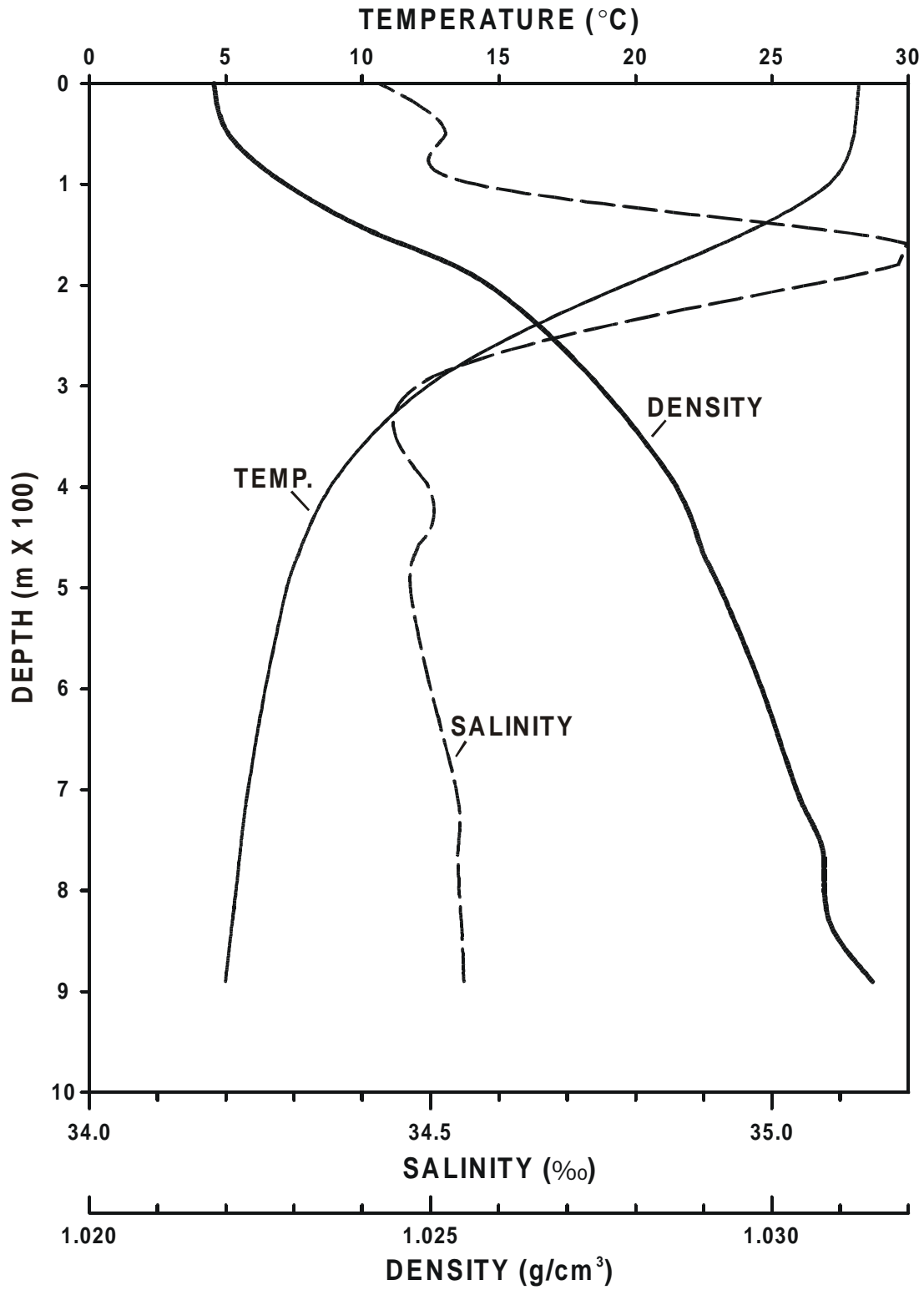


Fig. 8. Mean temperature, salinity and density profiles in the vicinity of Cabras Island, Luminao Reef and Glass Breakwater, Guam (Feb., 1978 - Feb., 1979).

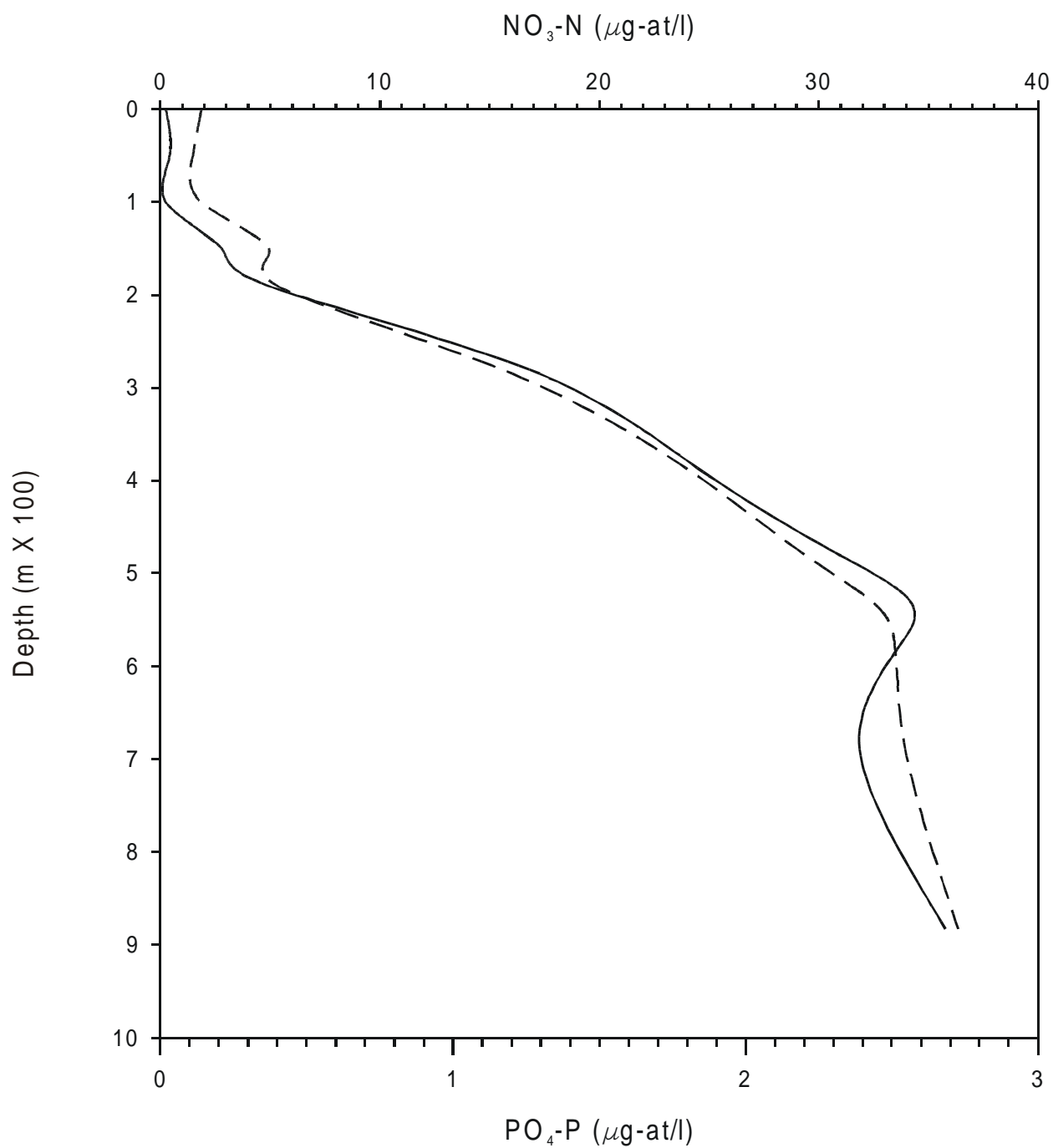


Fig. 9. Mean nitrate-nitrogen (NO₃-N) and reactive phosphorous (PO₄-P) profiles from surface to 883 m (2900 ft) in the vicinity of Cabras Island, Luminao Reef and Glass Breakwater, Guam (Feb., 1978 - Feb., 1979).

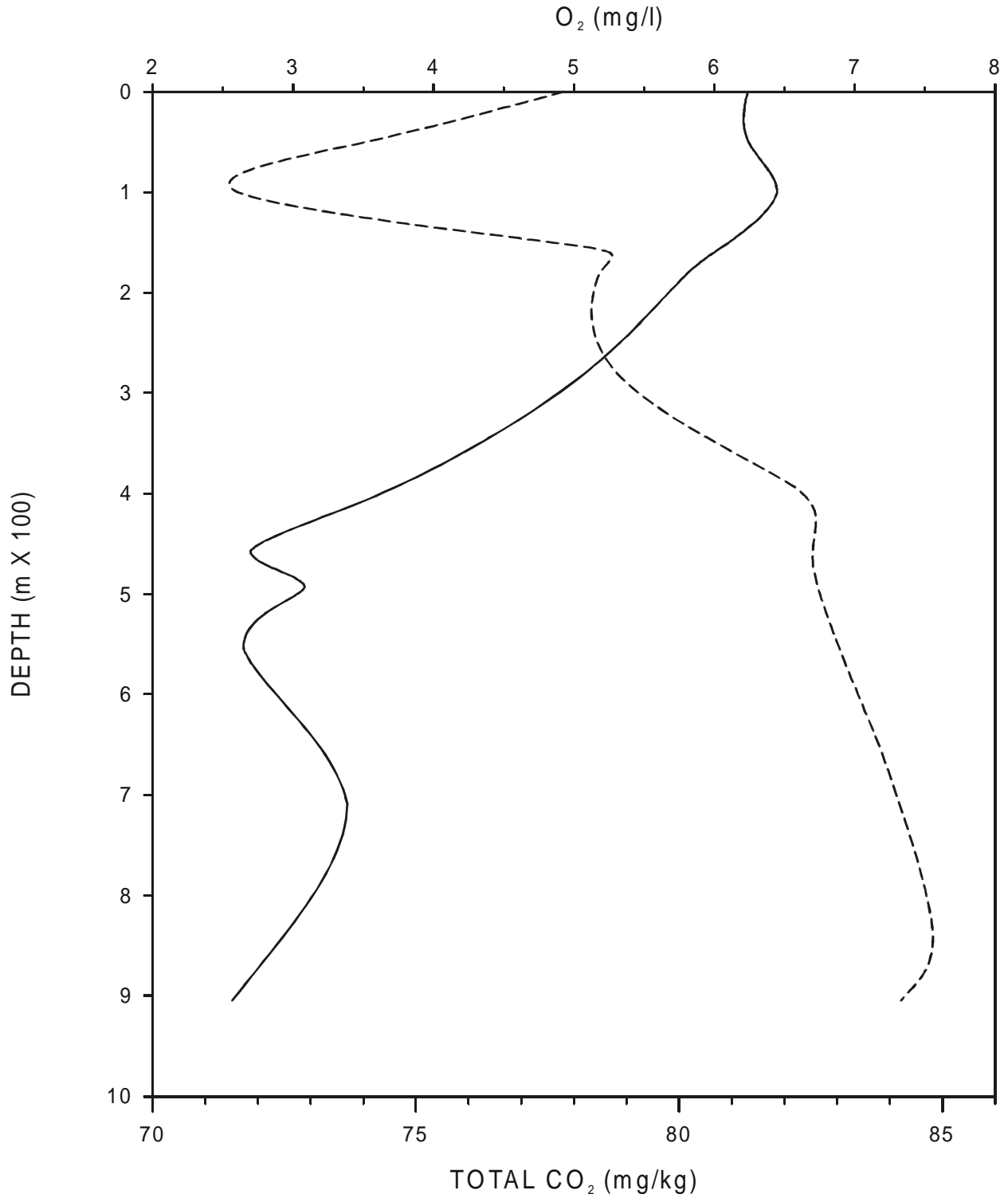


Fig. 10. Mean dissolved oxygen (O₂) and total carbon dioxide (ΣCO₂) profiles from surface to 905 m (2970 ft) in the vicinity of Cabras Island, Luminao Reef and Glass Breakwater, Guam (Feb., 1978 - Feb., 1979).

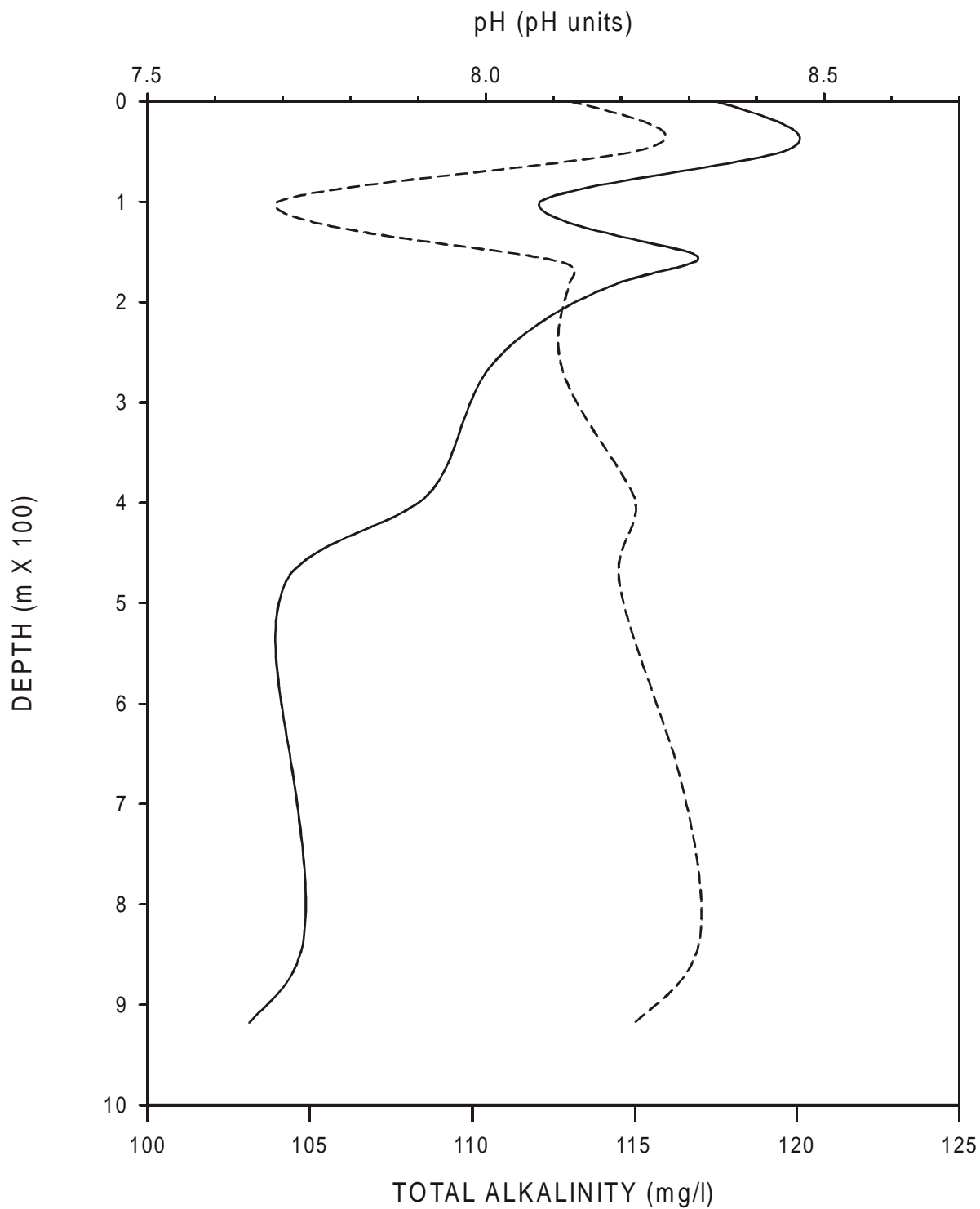


Fig. 11. Mean pH and total alkalinity (T.A.) profiles for the vicinity of Cabras Island, Luminao Reef and Glass Breakwater, Guam (Feb., 1978 - Feb., 1979).

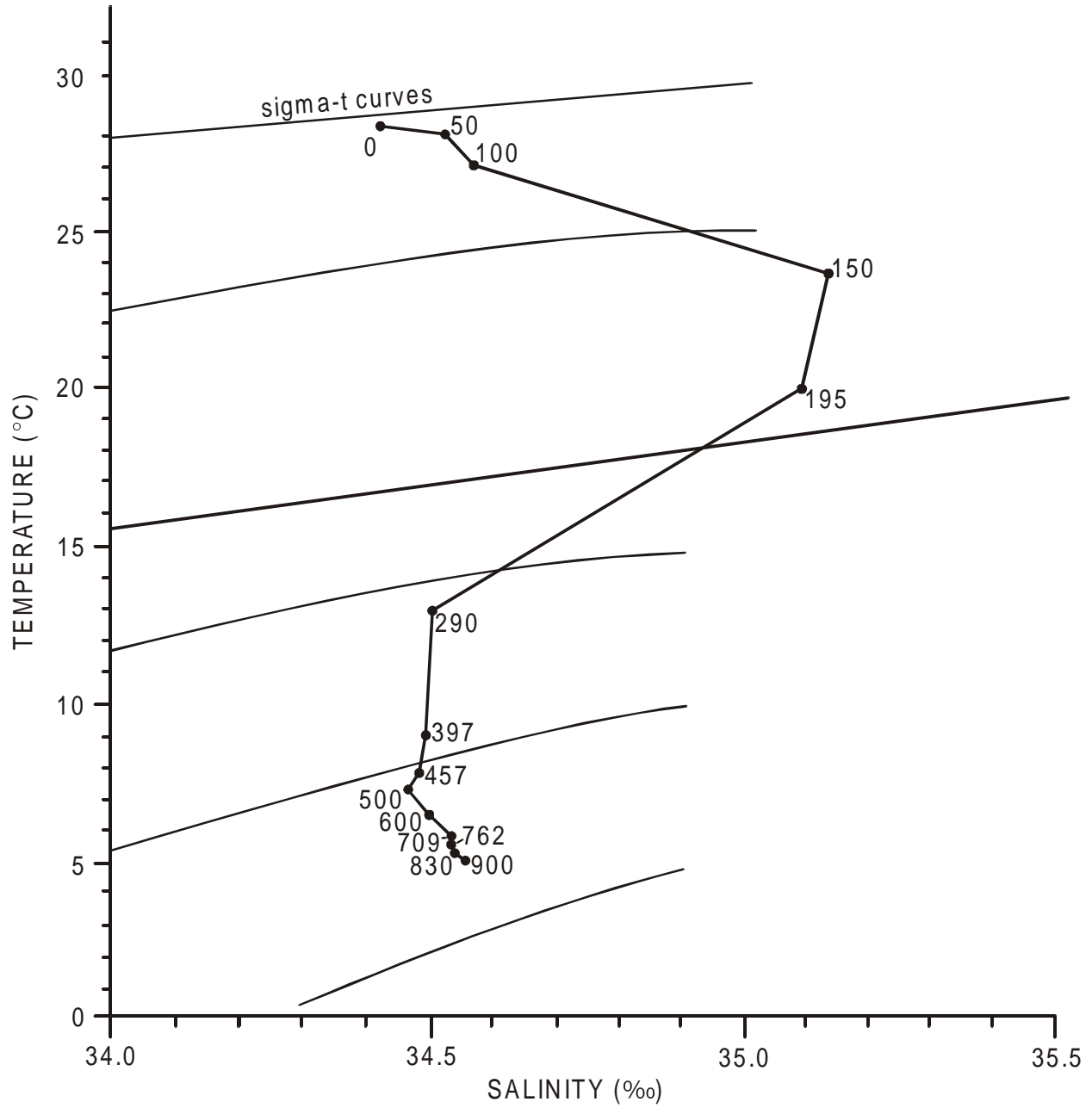


Fig. 12. T-S diagram for the vicinity of the proposed OTEC site on Guam (Based on mean temperature and salinity data taken from Feb., 1978 - Feb., 1979).