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Comparison of Limited Measurements of the OTEC-1 Plume with Analytical-Model Predictions

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Applied Geoscience and Engineering Group

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COMPARISON OF LIMITED MEASUREMENTS OF THE OTEC-1 PLUME WITH ANALYTICAL MODEL PREDICTIONS

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ABSTRACT

Ocean Thermal Energy Conversion (OTEC) requires significant amounts of warm surface waters and cold deep waters for power production. Because these waters are returned to the ocean as effluents, their behavior may affect plant operation and impact the environment. The OTEC-1 facility tested 1-MWe heat exchangers aboard the vessel *Ocean Energy Converter* moored off the island of Hawaii. The warm and cold waters used by the OTEC-1 facility were combined prior to discharge from the vessel to create a mixed discharge condition. A limited field survey of the mixed discharge plume using fluorescent dye as a tracer was conducted on April 11, 1981, as part of the environmental studies at OTEC-1 coordinated by the Marine Sciences Group at Lawrence Berkeley Laboratory. Results of that survey were compared with analytical model predictions of plume behavior. Although the predictions were in general agreement with the results of the plume survey, inherent limitations in the field measurements precluded complete description of the plume or detailed evaluation of the models.

1 INTRODUCTION

An Ocean Thermal Energy Conversion (OTEC) plant extracts energy from the ocean by evaporating a working fluid (e.g., ammonia) using heat from warm surface waters, passing the resulting vapor through a turbine, and condensing the vapor using cold water from depths of 800–1000 m. Thermodynamic limitations result in rather low energy conversion efficiencies because of the small temperature differences involved (about 18–20 C°). As a consequence, large flows of both warm surface waters and cold deep waters are required. The waters are returned to the ocean as effluents, and their behavior may affect plant operation and impact the environment. The OTEC-1 facility[1] tested 1-MWe heat exchangers aboard the vessel *Ocean Energy Converter* (OEC) moored off the island of Hawaii. The warm and cold waters used by the OTEC-1 facility were combined prior to discharge from the hull of the vessel to create a mixed discharge condition.

From a hydrodynamic viewpoint, OTEC-1 does not provide a small-scale version of the interaction of the effluent of a commerical OTEC plant with the ocean. While the OTEC-1 discharge is scaled down, the ocean remains at full scale. Thus, it would be inappropriate to scale up the results of observations of the behavior of the effluent from OTEC-1 to commercial plants. However, analytical models that may be appropriate for OTEC plants of pilot or commercial size can be applied to the unique OTEC-1 situation to test their validity and to verify their predictions of OTEC-1 plume impacts.

The Marine Sciences Group at Lawrence Berkeley Laboratory, in its role as coordinator of environmental studies at OTEC-1, assembled a group of investigators to measure the characteristics of the OTEC-1 effluent plume. On April 11, 1981, this group located and mapped the mixed discharge plume from OTEC-1 within 300 m of the outfall. Rhodamine WT dye was injected into the mixed discharge sump, and a survey boat equipped with a pumping system and fluorometer located the dye and measured its concentration at various downstream locations. Three vertical profiles within 45 m of the outfall and nine horizontal tows at fixed depths at 75-300 m from the outfall were used to locate and measure the dye. Conditions in the ambient ocean were monitored with expendable bathythermograph (XBT) probes dropped from the survey boat and with a current meter onboard the OEC. The measurement procedures employed and the results are reported in Ref. 2.

This report describes the predictions of plume behavior based on simple, available analytical techniques and compares them with the results of the field measurements.

2 AMBIENT OCEAN AND DISCHARGE CONDITIONS

In order to predict the behavior of the plume, it is necessary to characterize the ambient ocean and the discharge during the study period. Ocean currents were monitored with a current meter onboard the OEC. Currents at a depth of 25-30 m were measured and recorded two or three times an hour; the resulting data are plotted in Fig. 1. During the time of the actual plume survey (1249-1632 Hawaiian Standard Time [HST]), the current speed was 0.2-0.4 m/s, with the direction slowly changing from about 30°T (30° east of true north) to about 70°T by the end of the survey. Wind speed and direction were recorded onboard the OEC; the hourly averages are plotted in Fig. 2. The wind was variable but generally from the northeast. During the survey period, the average wind was 2.0 m/s from 40°T.

Five XBT probes were launched near the OTEC-1 site during the day of the plume survey to obtain vertical temperature profile data. Since the effluent was initially 5-10 C° cooler than the ambient ocean, identification of the plume was attempted by taking most of the temperature profiles within

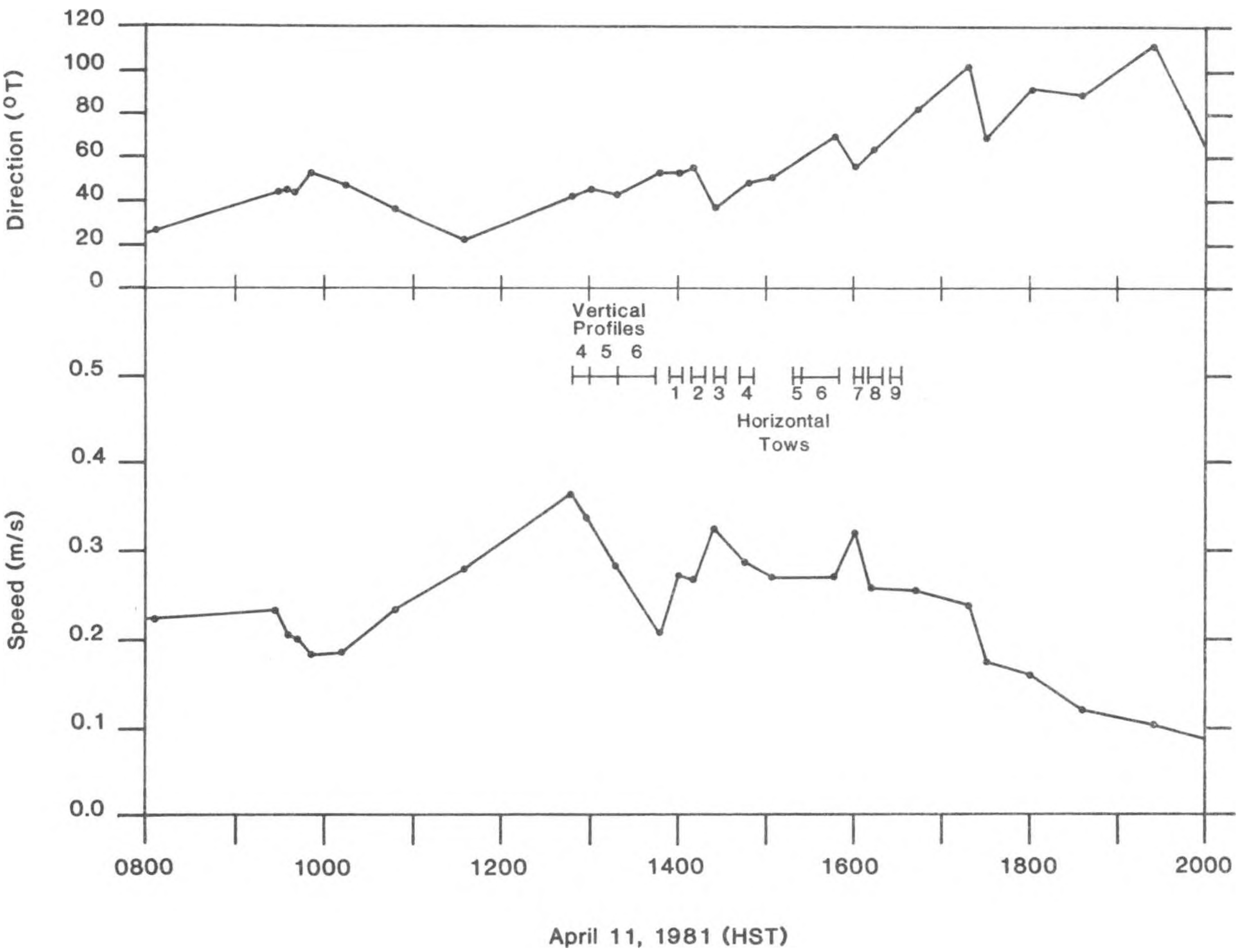

Fig. 1 Ambient Ocean Current Measured from the *Ocean Energy Converter* at a Depth of 25-30 m, April 11, 1981

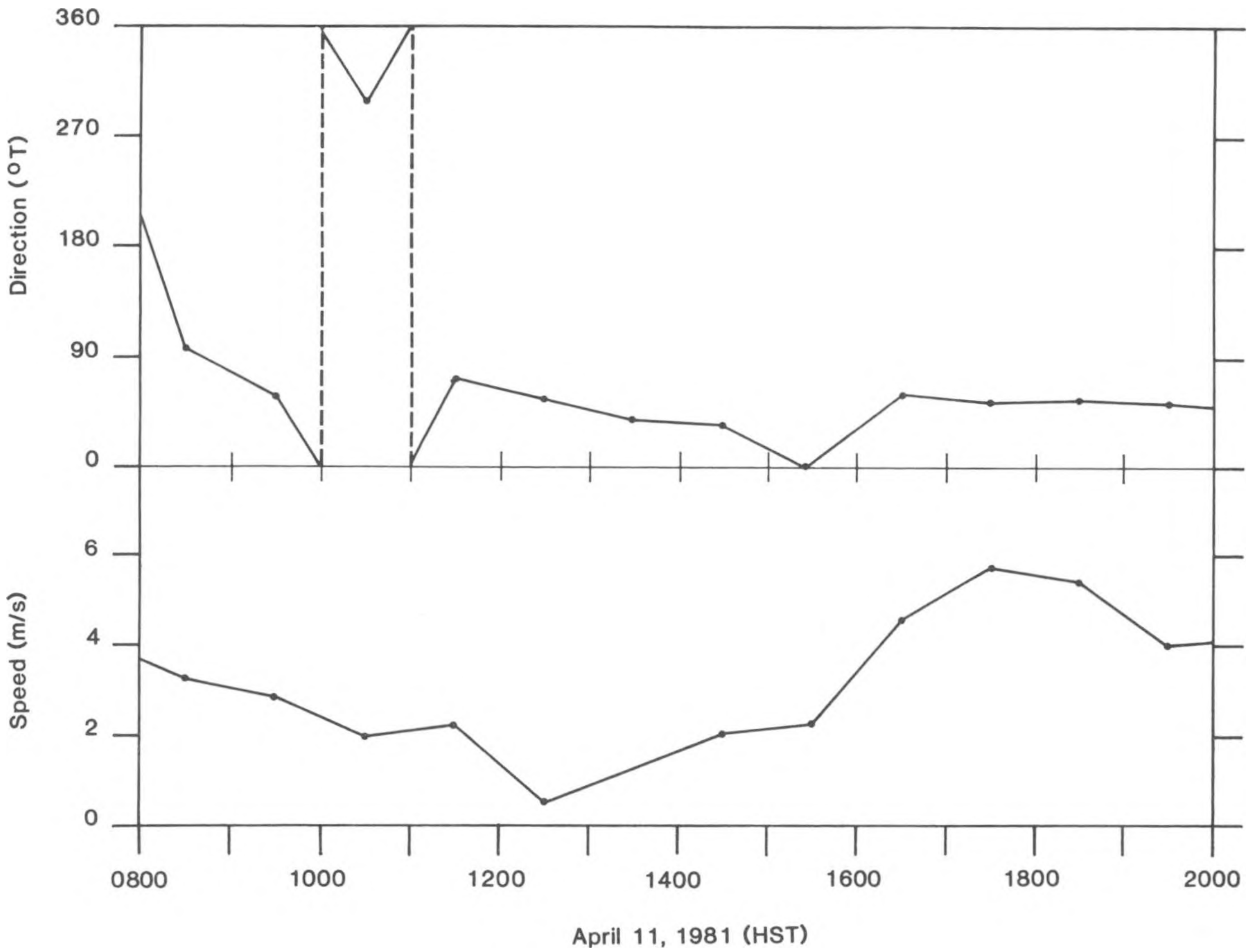

Fig. 2 Hourly Averaged Wind Speed and Direction Measured Onboard the *Ocean Energy Converter*, April 11, 1981

the influence of the plume. However, little if any evidence of the plume was observed because the effluent rapidly mixed with the ambient water and sank to a depth of neutral buoyancy, and the XBT probes had limited resolution.[2] The XBT No. 2 probe was dropped just outside the plume at 0935 HST. The upper part of the resulting temperature profile is shown on the right-hand side of Fig. 3. The temperature was constant at 24.7°C to a depth of about 21 m. Between 21 and 31 m, it dropped to 23.5°C and remained constant to a depth of about 55 m. (The greatest temperature gradient occurred at a depth of about 30 m.) The temperature then decreased gradually to 5.3°C at a depth of 750 m, which was the limit of the XBT probe.

In determining the behavior of the effluent plume, it is the density profile rather than the temperature profile that is important. In seawater, density depends on salinity as well as temperature. A salinity profile was not measured on the day of the plume survey. However, water quality samples were taken on the following day (April 12, 1981) upstream of the discharge at 5-m intervals from a depth of 5 m to a depth of 45 m. Analysis of these samples showed some variation in salinity with depth, with an average value of

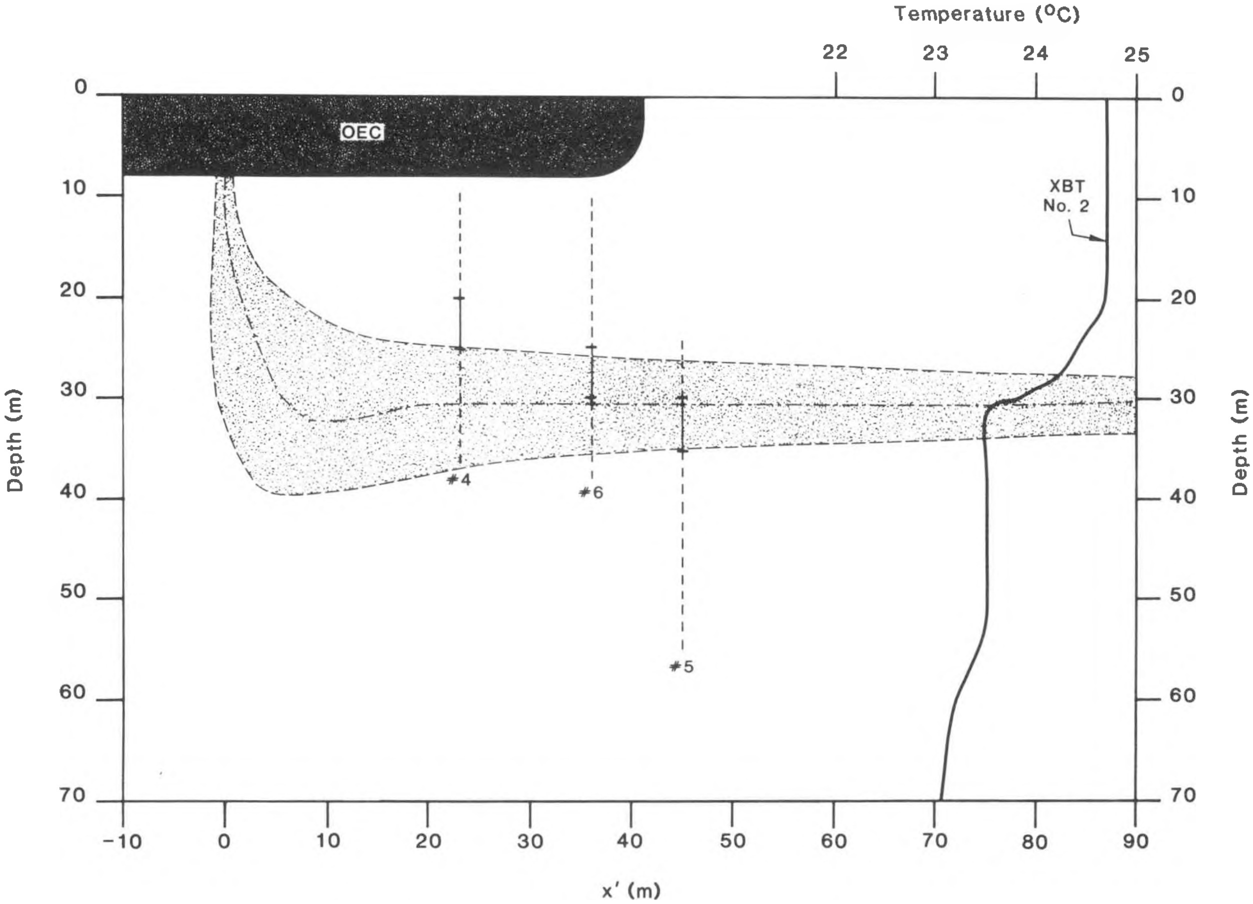

Fig. 3 Comparison of Predicted Plume with Results of Vertical Dye Profiles (locations of observed dye are indicated by solid line segments) and Ambient Temperature Profile Recorded by Expendable Bathythermograph No. 2

34.82°/oo and a root-mean-square deviation from the average of only ± 0.06°/oo.

The warm and cold seawater effluents from the OTEC-1 system were mixed together in port wing tank #5, which was open to the atmosphere. The mixed-discharge pump then transferred the mixed effluent to port wing tank #9, which was sealed. The effluent left the vessel vertically downward at a depth of about 8.0 m below the surface through a 1.8-m diameter hole in the hull at the bottom of the tank. The hole was located about 41 m forward of the stern and 2-3 m inboard of the port side of the vessel. The discharge flow rate was about 9.85 m^3/s -- 5.48 m^3/s from the warm water system and 4.37 m^3/s from the cold water system. The discharge temperature was about 17.9°C as recorded by the OTEC-1 data acquisition system. While the salinity of the effluent was not measured, cold deep water is generally at least 0.6°/oo less saline than the warm surface water, based on other periodic (approximately weekly) measurements of salinity. Because the effluent was a mixture of both warm and cold water, it was probably about 0.3°/oo less saline than the ambient receiving water. Therefore, the density of the effluent is estimated to have been 1.0249 g/cm^3, based on a temperature of 17.9°C and a salinity of $34.52^{o}/oo$. The effluent was negatively buoyant at first, because the density of the ambient receiving water (upper 20 m) is estimated to have been 1.0233 g/cm^3, based on a temperature of 24.7°C and a salinity of $34.82^{o}/oo$.

The initial behavior of a discharge jet depends not only on the flow rate and the initial density difference with respect to the ambient receiving water, but also on the discharge velocity. If the effluent had exited over the entire cross section of the 1.8-m diameter port, the average discharge velocity would have been 3.87 m/s. However, since the discharge port is simply a hole in the bottom of a large sealed tank, the effluent flow undergoes an abrupt change in cross-sectional area, resulting in contraction of the emerging jet.[3] Because the cross-sectional area of wing tank #9 is large compared to the discharge port, the diameter of the contracted jet is expressed by:[3]

$$d_j = \sqrt{\frac{\pi}{\pi + 2}}\, d_p \qquad (1)$$

where:

d_j = diameter of the contracted jet, and

d_p = diameter of the port.

The effective diameter of the discharge jet is therefore 1.41 m rather than 1.8 m, and the resulting average discharge velocity is 6.33 m/s.

3 MODEL PREDICTIONS

Predictions of expected effluent plume behavior, using the ambient and discharge conditions described in Sec. 2, were made using simple analytical techniques. First, an integral jet model for a round buoyant jet into a stagnant, stratified receiving water body was used to estimate jet spreading and entrainment, and to estimate the depth at which the jet would attain neutral buoyancy. The model uses equations of mass flux, momentum flux, and buoyancy flux integrated over the jet cross section by assuming similarity profiles for velocity and for density. Jet mixing is treated through an entrainment relationship, which uses a constant entrainment coefficient. The ambient density profile is approximated by a series of straight-line segments. The model is based on the computer code reported in Ref. 4 and the analyses discussed in Ref. 5.

The model predicts that the jet will reach neutral buoyancy at a depth of 30.4 m. At this point the jet diameter will have grown to 12.4 m, the dilution at the jet centerline will be 4.34, and the average dilution over the jet cross section will be 6.27. The model also predicts that the jet will still have significant downward velocity; the average velocity over the jet cross section will be 0.5 m/s, with a peak velocity at the centerline of 2.0 m/s.

The above analysis neglects the effects of ambient current (about 0.28 m/s) on the behavior of the jet. An ambient current will deflect the jet from its initial downward trajectory and may influence the rate of entrainment of ambient water by the jet. To estimate the effect of the ambient current on the jet, an approximate analysis for buoyant jets in a cross flow was used.[6] In that analysis approximate descriptions of the flow are combined with dimensional analysis to yield correlations for jet trajectory and average dilution in terms of dimensionless constants evaluated by fitting to laboratory data. Although the effect of density stratification in the ambient receiving water is not considered in the analysis, the depth at which the jet reaches neutral buoyancy can be estimated from the average dilution and the ambient density profile. When this analysis was applied to the OTEC-1 case, the jet was predicted to be deflected 6.0 m horizontally by the time it reached neutral buoyancy at a depth of 30.4 m, with an average dilution of 6.28. These results are in very good agreement with the predictions of the integral jet model, which suggests that the only significant effect of the ambient current was the slight deflection of the jet.

Once the diluted effluent plume has reached its depth of neutral buoyancy and lost its initial momentum, it drifts with the ambient ocean current, thereby forming a layer of intermediate density. The layer then spreads laterally as a result of vertical collapse due to gravity forces caused by interaction of the layer with local vertical gradients in the stable ambient density profile. This is referred to as the intermediate-field region of the plume. An analytical model of this intermediate-field region has been developed,[7] which is based on balancing the gravity forces with the pressure drag and viscous forces exerted by the ambient current. In the model the ambient receiving water is characterized by the ambient current and the Brunt-Väisälä frequency. The Brunt-Väisälä frequency is a measure of the vertical density gradient:

$$N = \sqrt{\frac{g}{\rho}\frac{d\rho}{dz}} \qquad (2)$$

where:

N = Brunt-Väisälä frequency,

$d\rho/dz$ = local vertical density gradient,

ρ = density, and

g = acceleration due to gravity.

The effluent is characterized by the total volumetric flow rate, which is given by the product of the discharge flow rate and the average near-field (jet-region) dilution. Additional dilution as a result of mixing in the intermediate field is assumed to be small and is therefore neglected.

The intermediate-field model was applied to the OTEC-1 plume using a near-field dilution of 6.3 as predicted by the near-field analyses discussed earlier in this section. A value of 0.28 m/s was used for the ambient current, which corresponds to the average current speed during the plume mapping survey. Selection of an appropriate Brunt-Väisälä frequency was more difficult, because the observed vertical temperature profile did not exhibit a uniform slope near the depth of neutral buoyancy of the plume (see right-hand side of Fig. 3). A value of 0.013 Hz was chosen based on the average density gradient over a vertical span of ± 10 m on either side of the predicted neutral buoyancy depth of about 30 m.

The model predicts that the plume will be about 30 m wide and 8 m thick at a distance of 50 m downstream (i.e., just beyond the stern of the OEC). At a downstream distance of 500 m, the plume is predicted to be about 90 m wide and only 2.4 m thick. The combined predictions of the jet analysis and the intermediate-field model are shown in vertical cross section at the left-hand side of Fig. 3 and in plan view in Fig. 4. The approximate boundaries of the plume are indicated by dotted lines. In Fig. 3, the x' axis is along the direction of the average current (53°T) and therefore parallel to the centerline of the predicted plume. In Fig. 4, the x and y axes are along the true east and north directions, respectively, with the origin located at the OEC outfall. Because of uncertainties in the Brunt-Väisälä frequency and in the value of a drag coefficient in the intermediate-field model formulation (a nominal value of 1.0 was used), the width and thickness predictions in the intermediate-field region are considered to be estimates with an uncertainty of about ± 30%.

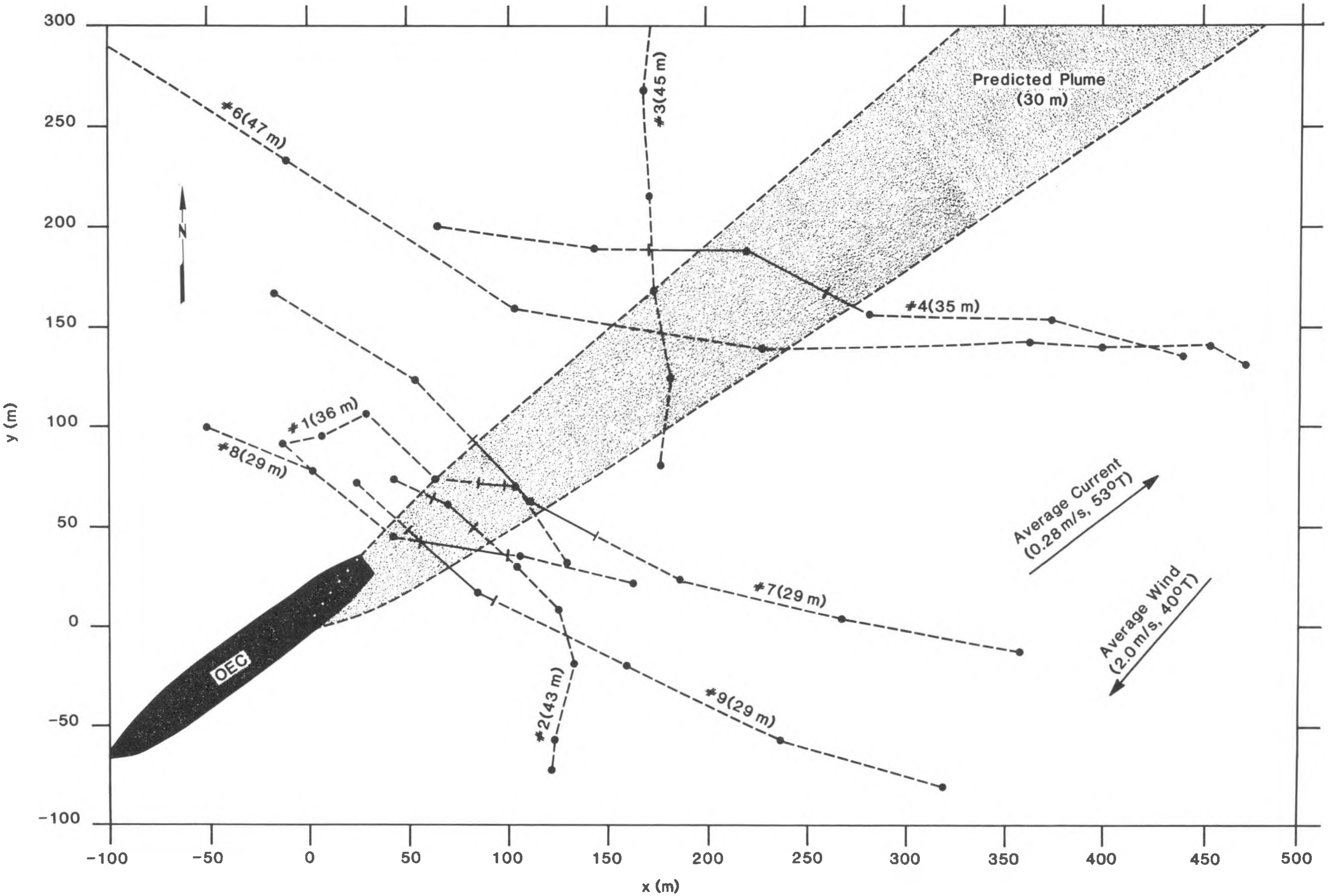

Fig. 4 Plan View of Predicted Plume and Boat Paths for Horizontal Dye Tows (nominal depths of tows are indicated in parentheses and locations of observed dye are indicated by solid line segments)

4 PLUME SURVEY RESULTS

On April 11, 1981, the effluent plume from the OTEC-1 system was located and mapped.[2] Rhodamine WT, a fluorescent dye, was used as a tracer to identify the effluent once it was discharged into the open ocean. A dye solution was injected into the mixed discharge sump (port wing tank #5) at a rate of about 4.2 cm^3/s, which yielded an average initial concentration at the outfall of about 0.43 ppm. A pumping and fluorometer system was used to locate the dye and measure its concentration downstream of the outfall. The sampling and detection system consisted of a Turner Model III fluorometer, a 122-m long hose, and a submersible water pump. The pump was lowered to the desired sampling depth, and seawater was pumped through the hose to the fluorometer onboard the survey boat. About 60 s were required for passage of a water sample through the system.

After initial testing to establish an appropriate dye injection rate and sampling procedure, the survey boat was moored off the port side of the OEC about 23 m downstream of the outfall. This location was estimated in the field to be on the centerline of the plume. The sampling pump was then slowly lowered through the water column to obtain a vertical profile of dye concentration (profile #4). Since the pump could not be lowered at a uniform rate and because of the 60-s transit time through the fluorometer system, a detailed dye profile could not be obtained. However, dye was observed and was estimated to be at a depth of 20-25 m, with a thickness less than but on the order of 5 m and with a maximum concentration of 0.035 ppm. This corresponds to a minimum dilution of about 12. A second vertical profile (#5) was measured about 45 m downstream, just off the stern of the OEC; a third profile (#6) was measured about 36 m downstream, just off the starboard side of the OEC.

The results of the three vertical profiles are summarized in Table 1. Note that it is not possible to be sure that these vertical profiles actually passed through the centerline of the plume; therefore, the minimum dilutions reported may not be the actual minimum dilutions along the centerline of the plume. In other words, measurements away from the centerline of the plume probably would result in lower dye concentrations (i.e., larger dilutions) than measurements on the centerline of the plume. A complete mapping of the

Table 1 Summary of Vertical Dye Profiles

Profile No.	Time (HST)	Downstream Distance (m)	Vertical Location of Dye (m)	Thickness of Dye (m)	Minimum Dilution Observed
4	1249-1259	23	20-25	<5	12
5	1301-1320	45	30-35	<5	10
6	1320-1345	36	25-30	$\simeq 5$	10

Source: Ref. 2.

plume cross section at a given downstream location would be required to determine true minimum and average dilutions at that location. Therefore, the depths and thicknesses reported are only general estimates. The three vertical profiles appear on Fig. 3 as vertical dashed lines, with solid segments indicating the estimated interval where dye was observed. Although it is not possible to make a detailed comparison between the physical measurements and the predicted plume behavior, the data do indicate that the effluent may have stabilized near the depth (about 30 m) where the largest vertical temperature gradient was observed.

Following the vertical profile measurements, the pump was lowered to a fixed depth and towed through the region where the plume was expected to be. Nine such horizontal tows were conducted at various distances from the outfall and at various depths to locate the plume. The reported sampling depths were determined by assuming that the shape of the cable from the survey boat to the pump was a straight line.[2] Thus, only the length of cable in the water and the angle the cable made with the water surface were measured. Because dynamic effects often cause a cable to take on a rather complicated curved shape, the straight-line assumption is not necessarily very good. Consequently, the sampling depths as reported may be in error.

The survey boat paths corresponding to eight of the nine tows are plotted on Fig. 4 as dashed curves. The regions where dye was encountered are indicated by solid lines, and the reported sampling depths are indicated in parentheses. The boat path data have been translated so that they are always relative to the outfall, even though the OTEC-1 vessel drifted 600-700 m about its mooring during the 3 hr of the survey.[2] Since the details of tow #5 are not reported in Ref. 2, that boat path was not plotted. However, no dye was observed during the tow, and the path appeared to be off the right-hand (eastern) edge of Fig. 4, outside the probable boundary of the plume. The minimum dilutions corresponding to the maximum observed dye concentrations are listed in Table 2 for each tow. Again, because the plume was sampled at only one depth on each tow, the minimum dilutions reported may not correspond to the actual minimum dilution at the centerline of the three-dimensional plume.

The general locations of the observed dye agree quite well with the plume predictions. The results of tow #4 are shifted a little to the northwest, and the results of tows #7-9 are shifted a little to the southeast of the predicted plume trajectory. However, Fig. 1 shows that the direction of the ambient ocean current actually changed during the survey period from about 48°T during tow #4 to about 67°T during the last three tows. Low values of minimum dilution were observed during horizontal tows at a depth of 29 m. These values average about 15, which is not in very good agreement with the predicted centerline dilution of 4.3. However, a dilution of 15 should not be treated as a lower limit, because there is no way of verifying that the horizontal tows actually sampled the peak dye concentration within the plume. If the sampling depth were raised or lowered slightly, larger dye concentrations (i.e., lower dilutions) might have been observed. Indeed, the vertical profiles indicate that the minimum dilution is probably 10 rather than 15. Finally, the dilution predicted by the jet analysis may be too low, because the residual velocity of the jet as it reaches the depth of neutral buoyancy may cause additional mixing (see Sec. 3).

Table 2 Summary of Horizontal Dye Tows

Tow No.	Time (HST)	Depth of Tow (m)	Minimum Dilution Observed
1	1355-1404	36	50
2	1409-1418	43	54
3	1424-1432	45	No dye observed
4	1442-1452	35	75
5	1518-1523	39	No dye observed
6	1624-1550	47	No dye observed
7	1559-1606	29	16
8	1610-1620	29	14
9	1624-1632	29	17

Source: Ref. 2.

5 CONCLUSIONS

The analytical models used in this study to predict the behavior of the plume from OTEC-1 involve many simplifications and approximations, e.g., the effluent is assumed to be discharged with a uniform velocity, the ambient ocean current is assumed to be constant in space and time, and the ambient density profile is assumed to have a uniform density gradient in the region of the depth of neutral buoyancy. In addition, the details of the transition between the jet region and the intermediate-field region are neglected. Even if the complete density and current fields in the ocean surrounding OTEC-1 were known, the analytical techniques employed in this study could not make direct use of that information.

The results of the field measurements of the plume are quite limited. Although they give the general location and extent of the plume and provide some indication of the dilution of the effluent, there is no way to confirm that the centerline of the plume has been identified or that the size of the plume has been accurately determined. Because of these uncertainties and limitations, detailed comparisons of the analytical predictions and the results of the plume survey are not possible. However, the predictions do not contradict the survey results and, in many ways, are in good agreement. For example, the vertical location of the plume in the water column appears to have been predicted rather well, and the horizontal trajectory and width predictions generally agree with the observations. Even though predictions of dye concentration or dilution are difficult to compare with the observed values, the few comparisons possible do agree within a factor of four. Still, these comparisons do not permit the conclusion that the predictions have been verified.

The plume survey, the results of which were used for this comparison with model predictions, was not undertaken for the purpose of model verification. However, given the constraints on time and effort for planning and carrying out the survey, it provided much useful data, including biological and chemical data not discussed here. Nonetheless, the lack of sufficient dye concentration data to characterize fully the plume geometry and trajectory for rigorous comparisons of predictions and observations illustrates the type and magnitude of the problems to be anticipated in plume-model verification exercises in the field. In the future, larger plumes at larger OTEC facilities should provide opportunities for more detailed measurements and more extensive comparisons with model predictions.

REFERENCES

1. Svenson, N.A., *An Overview of the OTEC-1 Design,* Proc. 6th OTEC Conf., Washington, D.C. (June 19-22, 1979).

2. Noda, E.K., P.K. Bienfang, W.J. Kimmerer, and T.W. Walsh, *Plume Survey, OTEC-1 Mixed-Water Discharge, April 11-12, 1981,* James K.K. Look Laboratory of Oceanographic Engineering, Univ. of Hawaii (May 1981).

3. Rouse, H., *Fundamental Principles of Flow*, in Engineering Hydraulics, H. Rouse, ed., John Wiley and Sons, Inc., New York (1950).

4. Ditmars, J.D., *Computer Program for Round Buoyant Jets into Stratified Ambient Environments,* W.M. Keck Laboratory of Hydraulics and Water Resources Technical Memorandum 69-1, California Institute of Technology, Pasadena (March 1969).

5. Koh, R.C.Y., and L.-N. Fan, *Mathematical Models for the Prediction of Temperature Distributions Resulting from the Discharge of Heated Water into Large Bodies of Water,* U.S. Environmental Protection Agency Report 16130DW010/70 (Oct. 1970).

6. Wright, S.J., *Mean Behavior of Buoyant Jets in a Crossflow,* Jour. of the Hydraulics Division, Proc. of the American Society of Civil Engineers, 103(HY5):499-513 (May 1977).

7. Jirka, G.H., J.M. Jones, and F.E. Sargent, *Theoretical and Experimental Study of the Intermediate Field Dynamics of Ocean Thermal Energy Conversion Plants (Progress Report 1978-1979), Cornell Univ.,* Ithaca, N.Y. (March 1980).

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