San Ciprian — Lugo

PART IV

COASTAL, ESTUARINE

Estarit — Gerona, costa Brava

CHAPTER 187

MIXING OF THERMAL DISCHARGES IN COASTAL WATERS

By N.M. Ismail[1] A.M. ASCE, R.L. Wiegel[2] F.ASCE.
P.J. Ryan[3], M. ASCE and S.W. Tu[4], M.ASCE

ABSTRACT: Mixing of thermal effluents, being discharged from thermal power plants on coastlines and which head into surface waves was investigated by analyzing extensive field and laboratory data on plume and ocean ambient conditions. Emphasis was given on the effect of waves and surf zone currents on the modifications of plume surface area and vertical temperature profile in the near-field area.

The results of this investigation showed that large opposing waves increase the plume surface area, in the vicinity of the outfall, for all cases of tide level and wave direction. Moreover, waves focused cold bottom currents on the discharge outlet and consequently the temperature of the released warm water was decreased at the surface and near the bottom. Wave-induced cross flows decreased the plume cumulative surface area which corresponded to fractional excess temperature ranging between 0.8 and 0.5 normalized values. This decrease was shown to be contingent that there is no interaction between the far-field and near-field plume waters. Gradient of wave momentum flux across surf zone was found to be necessary parameter to characterize the incident wave field.

INTRODUCTION

The growing interest in recent times in the pollution of natural water bodies through the discharge of thermal effluents has advanced considerably the state-of-the-art knowledge on the mixing of surface buoyant jets in the aquatic environment. Thermal

---

1. Engineering Specialist, Enppi, Cairo, Egypt; formerly, Bechtel Inc., San Francisco. CA.
2. Professor of Civil Engineering, University of California, Berkeley, CA.
3. Chief Engineer, Hydraulics/Hydrology Group, Bechtel Civil, Inc., San Francisco, CA.
4. Research Engineer, Department of Engineering Research, Pacific Gas and Electric Company, San Ramon, CA.

pollution studies usually involve a field survey in conjunction with either a physical and/or a mathematical model. When warmed water is discharged into the surf zone in the open sea, field surveys reveal that the thermal plume often shows a complicated horizontal shape. This phenomenon may be caused by the influence of waves in shoaling water and by nearshore currents. Such effects were reported by Grider (2) in 1973 to be important, based on the field survey of surface temperatures in the thermal plume discharged into the nearshore zone from the Encina Power Plant, Carlsbad, California. After examining the order of magnitudes of offshore currents and wind velocities, Grider concluded that heavy surf conditions play a major role in determining the size and the shape of the plume. Although a correlation between significant wave height and size, of the plume was shown to exist, some contradictory data were reported. Grider concluded that additional study of surface effects on horizontal surface plumes and detailed analysis of wave effects are warranted.

In 1974 (Wiegel et al., 1976) a 1:75 undistorted scale model of the Diablo Canyon Power Plant was constructed and used to predict the behavior of a 4000 cfs heated discharge into a shallow, rocky cove west of San Luis Obispo, California. In 1984-6 extensive field data were obtained for a wide range of plant operating and receiving water conditions. The data included horizontal and vertical temperature profiles and surface temperature isotherms for over 50 field tests. Key tests were selected, and the data used to calibrate and verify the physical model. The results demonstrated that a physical model is a reliable tool for prediction of prototype behavior as long as key parameters are simulated correctly in the model. Three parameters which are not normally emphasized in jet mixing models were found to be important, including details of the bottom topography, bottom roughness, and incident wave characteristics. The plant layout is shown in Fig. 1-a and an expanded view of the discharge cove is illustrated in Fig. 1-b. The lattest figure shows the main features of the bottom bathymetry of Diablo discharge cove.

The field and model data showed that deep water-significant wave height and its associated period were sufficient parameters to characterize the incident wave field. An increase of height of waves, coming at 255^{o} with north, from 4.5 to 6 ft destratified the south edge of the plume, and higher waves shifted the plume to the north. Further (Ismail et. al., 1987), it was found that the asymetric distribution of the horizontal temperature profiles of the plume observed for all field tests conducted under large waves (> 6 ft), of 255^{o} angle of approach, was due to a reverse eddy current. This eddy is generated in the discharge cove by wave breaking along the shallow plateau near the cove west entrance. These wave effects were similar at both low and high tides. Further it was observed that when the wave approach was changed in the model from 255^{o} to 278^{o}, there was a corresponding trend

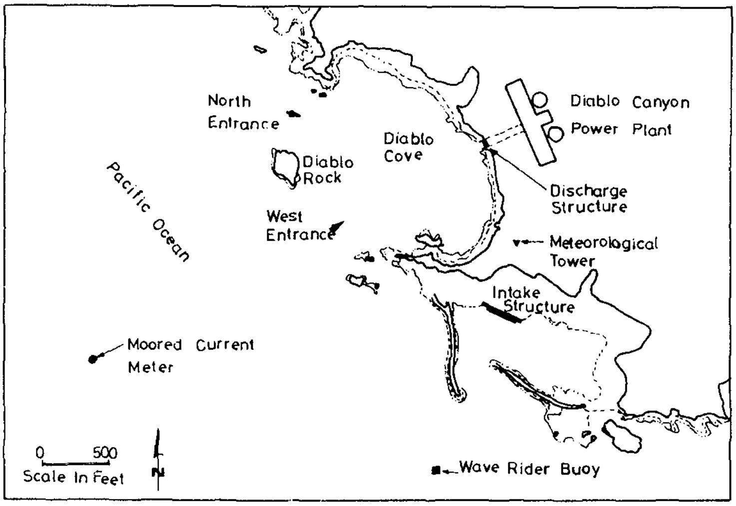


FIG 1-a DIABLO CANYON POWER PLANT AND RECEIVING WATER

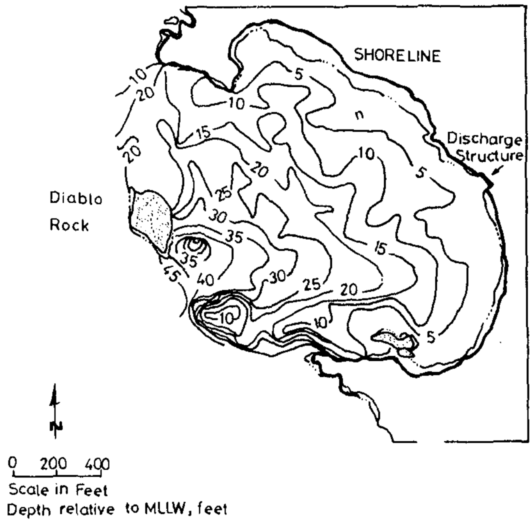


FIG. 1-b BOTTOM BATHYMETRY OF THE DISCHARGE COVE

of recirculation of warm water within Diablo Cove. The extent of this recirculation depended on the incident wave height and tide level. This recirculation had flattened the horizontal temperature profiles in the cove and increased the plume surface area within isotherms close to the discharge point. However, there was no attempt made to crystallize the effects of wave parameters and its induced-nearshore circulation on the plume surface area and the accompanied vertical temperature profiles.

Objective - The main purpose of the present work was to determine effects of wave parameters such as height, direction on the isotherm surface area in the near-field zone of thermal plumes discharged in coastal waters. In addition, the corresponding modifications of the plume vertical temperature profile will be determined. Emphasis was given to the effects induced by the interaction of the incident wave field with the nearshore bathymetry/topography. The results will be derived from examining the field data available on the thermal discharges from three power plants. Two of these plants; namely Fukushima in Japan and Encina in Calif. are located on straight long beaches. The third plant which is Diablo Canyon in Calif., is located on a partially closed embayment. The derived results from the field data will be supplemented with experimental prediction reduced from a systematic set of experiments which was conducted on the physical model of Diablo Canyon. This set of experiments will focus on effects of wave direction and modifications of vertical temperature profiles.

MIXING OF JETS/PLUMES IN WAVE-CURRENT FLOW

Most predictive models of thermal diffusion in the coastal zone consider an offshore current and/or tidal current, but do not consider the influence of surface waves and/or nearshore currents due to breaking waves. Among the few predictive models in the literature is the mathematical model developed by Tanaka and Wada (17) in 1982. Their evaluation of the numerical model was based on a comparison between the model predictions and data collected on a physical model. The authors came to the conclusion that in order to improve the capabilities of their model, it is necessary to acquire more field data on both the nearshore currents and diffusion patterns of large discharges of warm water under strong wave conditions. In addition, virtually all past hydraulic model studies of jet mixing problems have been performed in the absence of surface gravity waves.

The studies of Ismail and Wiegel (Ref. 4-7, 1980-83) which were performed for the case of non-buoyant jets were of considerable assistance in understanding the effect of waves during the analysis of the field and model data for Diablo Canyon thermal discharges. This is particularly valid in the zone close to the discharge area (near-field zone) where advection and free turbulence created by the shearing action, of the discharge causes jet diffusion.

Ismail has found that the interaction of waves with jet driven flows modified the undisturbed coastal circulation of each and the combined bottom mass transport is always focused on the jet outlet (6, 1982). In addition, it was shown experimentally and theoretically that momentum jets expand at a greater rate than in the absence of waves (7, 1983). Also, velocity measurements at the jet-longitudinal-axis have shown that mean velocities of the current near the bottom are decreased with a tendency of the current shear near the water surface to increase as it is illustrated in Fig. 2. The effects of waves on jet spreading and bottom mass transport are shown in the sample photographs of Fig.3

FIELD DATA OF DIABLO CANYON

A total of 56 field tests were performed from late 1984 to mid 1986, including tests for a wide range of power levels (300-2280 Mwe), pump flows [500 - 4000 cfs (14.2 - 114 cms)] and ambient conditions. The ambient conditions included extreme low to extreme high tide, strong and weak currents both upcoast and downcoast, and low to high waves. Thirteen field tests, from the total of 56, were used to verify the model. The vertification tests incorporated one unit, two unit and heat treatment operation, two and four pump flows (including co-flowing warm and cold jets), and a wide range of ambient conditions.

During each field test,temperature profiles were taken at 4 depths in the top 10 ft (3m), along 5 transect lines in Diablo Cove, ranging from approximately 400 ft (122m) from the discharge structure (Line 4) to just outside the west entrance [1400 ft (429m)] from the discharge (Line 14). Surface temperatures were measured outside Diablo Cove to approximately the 1^{o}F (0.5^{o}C) contour, typically a distance of 2-4 miles (3.2-6.5 km). Vertical temperature profiles were taken at 9-10 locations in the cove and 3-6 locations offshore. currents were measured both with drogues and moored current meters. Waves were measured with a wave rider buoy. The duration of each field test was 2-3 hours.

PHYSICAL MODEL OF DIABLO CANYON

The model is an undistorted densimetric Froude model with a scale of 1:75, and covers a prototype area 6400 ft (1960 m) along the coast by 4800 ft (1468 m) normal to the coast. The model basin is 85 ft by 64 ft by 2.5 ft deep (26 m x 19.6 m x 0.76 m). Model bathymetry was based on prototype hydrographic studies plus aerial photography. Coastal currents parallel to the coast were generated using a pump/manifold system. Dynamic tides were simulated using a computer controlled system. Monochromatic waves were generated using a piston-type wave maker. Temperature measurements were taken using a 45 sensor array, spaced at 50 ft (15.2 m) (prototype) centers in the horizontal, and 4 ft (1.2m) in the

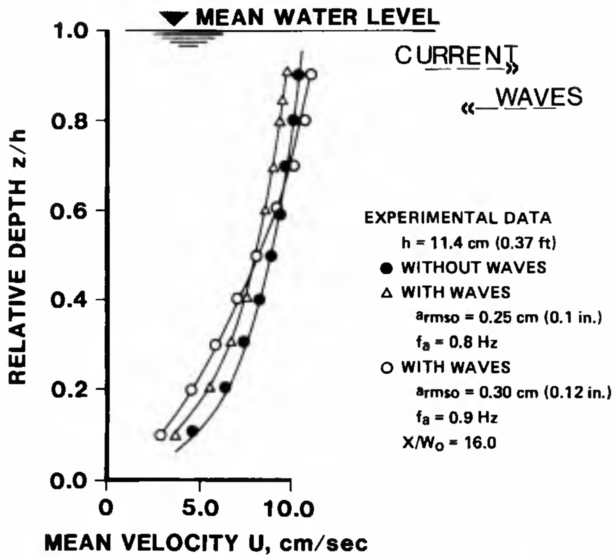


FIG.2 VELOCITY MODIFICAT. OF CURRENTS
Ismail (1980)

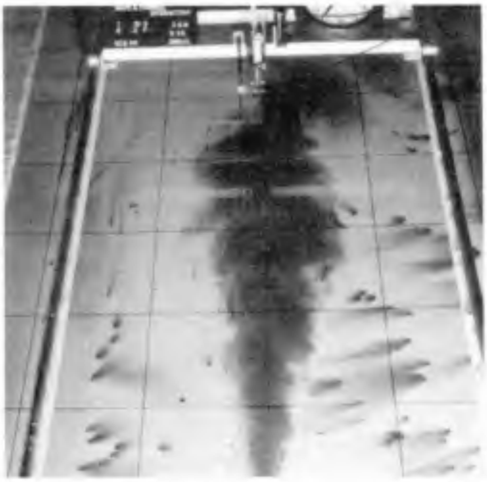
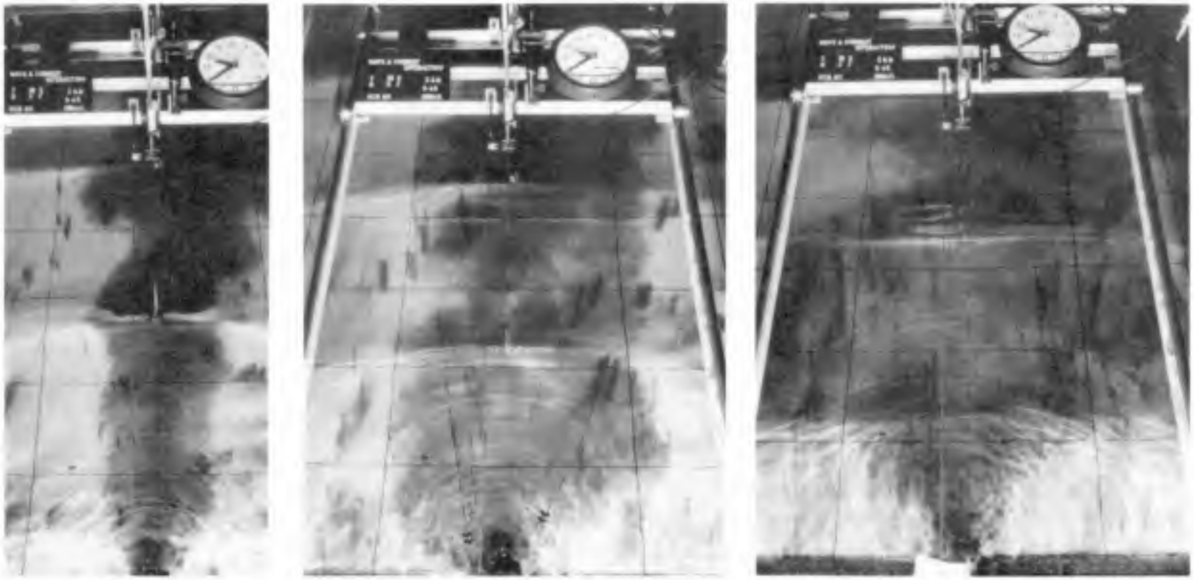


FIG. 3A FLOW VISUALIZ. OF SURFACE JET

After ISMAIL (1981)



t=3 sec t = 15 sec t=45 sec

FIG. 3.b MOMENTUM JET IN PRESENCE OF OPPOSING WAVES
wave period 0.8 sec; wave height $a_0 \approx 0.9$ cm

vertical. The entire array could be moved in 3 directions, allowing the 3 dimensional plume field to be measured.

Experimental procedures- Detailed model operating procedures for the model were developed and strictly adhered to. Water level, currents and waves were established to simulate field conditions. Discharge flow conditions were established and temperature of the discharge was set so that the density difference in the model was the same as during the field test. Temperature probes and wave gages were calibrated prior to each test. The system was allowed to come to quasi-steady prior to taking any temperature measurements.

FIELD AND LABORATORY RESULTS

One the simplest methods of parameterizing plume spreading and decay is in terms of surface areas within isotherms. For Diablo Canyon surface temperature data in the field were used to develop isotherm contours. The far-field isotherm contours refer primarily to the area outside Diablo Cove. The near-field isotherms correspond to the area within Diablo Cove. The cumulative surface area for the complete field versus normalized temperature is shown on Fig. 4 for six field tests which reflect the effects of wave height and tide level. On the same figure the available field data for Encina and Fukushima power plants are plotted. To establish a comparative basis to examine wave effects on the thermal discharges from the three power plants, wave parameters in the surf zone were evaluated from deep water wave conditions. Figure 5 displays the shoreline configuration for the power plant sites. On the same figure, values of wave breaker height and surf zone width and flow pattern of surf zone currents are illustrated.

The results shown in Fig. 4 indicate that higher waves in general increase the plume total surface area in the near-shore zone. However, for Diablo Canyon and at low tide, the increase of surface area is limited close to its discharge structure . Thereafter , the initial region, entrainment is inhibited due to the restricted bottom bathymetry of the shallow plateau in the south cove. And further, the plume is shifted to the north by the induced offshore cool water ingress and circulation in the cove. This decrease of plume surface area in the presence of higher waves and at low tide was confirmed in the laboratory as it is illustrated in Fig. 6.

For extreme high tide, it is noticed on Fig. 4 that , under data for high waves, there is a slight trend of decline of the total surface area in the medium range of excess temperature. Examining this trend in the laboratory indicated that the decrease of the total surface area is mainly contributed by the action of the cool water return current. The extent of this decrease of the surface area depends greatly on the angle of wave incidence as it is demonstrated in Fig. 7. The corresponding modifications of the

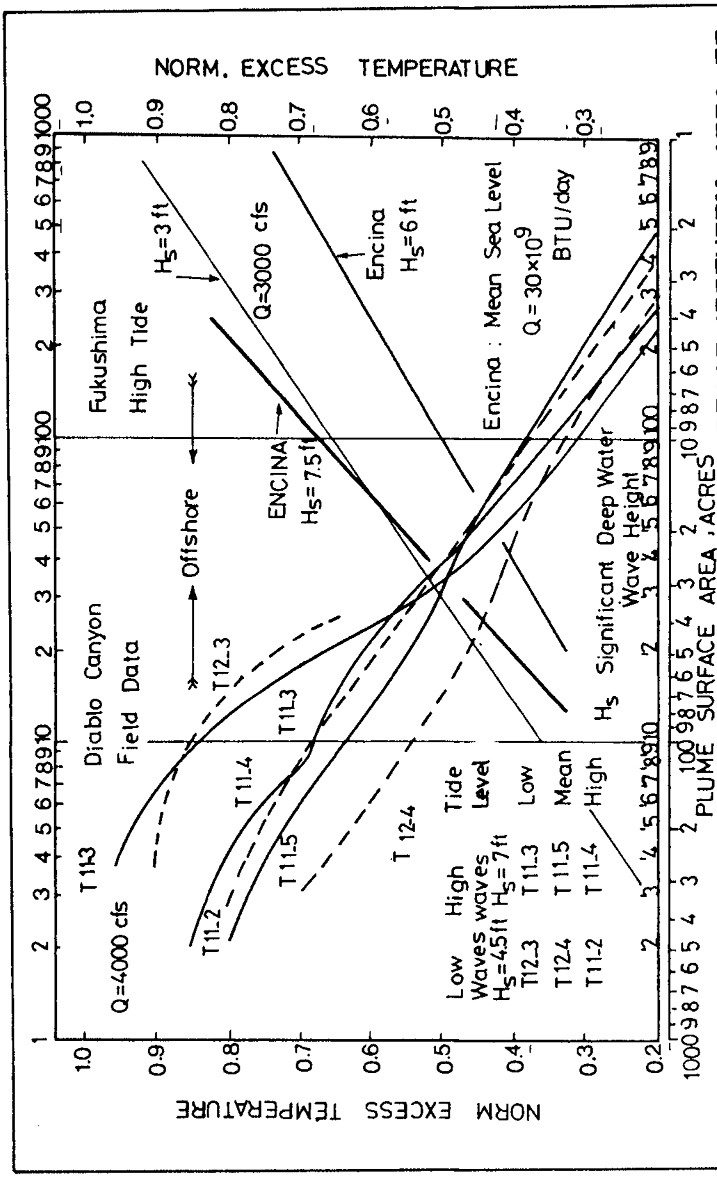


FIG.4 COMPARISON OF DIABLO CANYON SUREACE ISOTHERM AREA TO FIELD DATA FROM OTHER POWER PLANTS ON A STRAIGHT SHORELINE

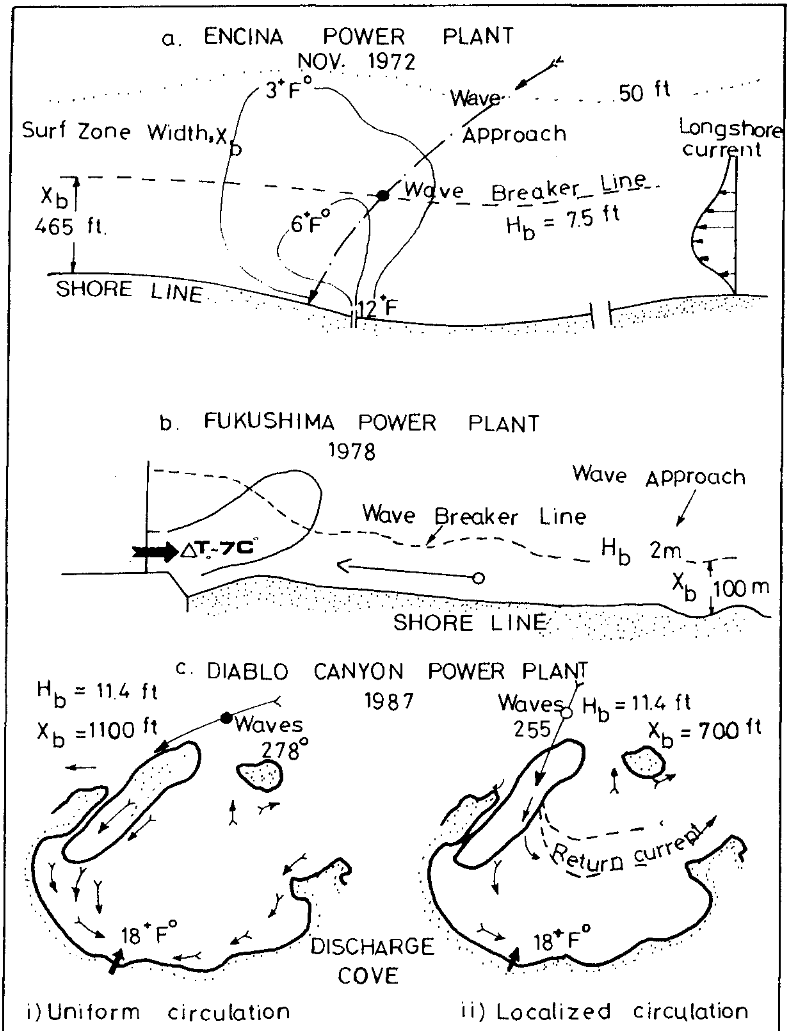


FIG. 5 PATTERNS OF WAVE-INDUCED CIRCULATION VS. SHORELINE CONFIGURATIONS

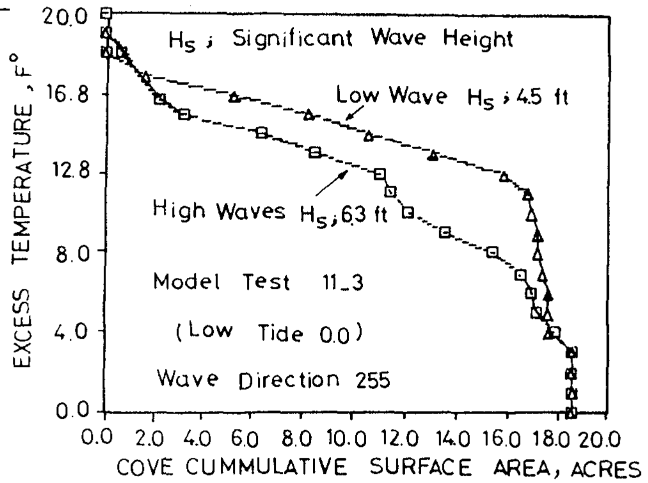


FIG. 6 PLUME SURFACE AREA VS. WAVE HEIGHT

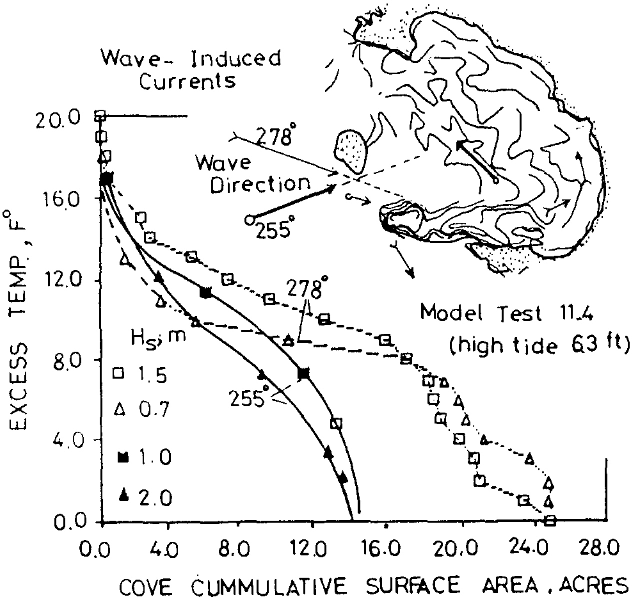


FIG. 7 WAVE PARAMETERS VS. PLUME SURFACE AREA

vertical temperature profile as a result of high waves are shown in Fig. 8 for cases of low and high tides.

The surface isotherm data for Diablo Canyon, obtained within Diablo Cove, and defined in terms of fractional excess temperature, are somewhat of less extent than surface areas for thermal discharges into open water. For thermal discharges on straight long beaches, it is possible to describe the surface area within the isotherms as it increases exponentially with decreasing relative excess as shown on Fig. 4. The slope of such a functional correlation was found to depend greatly on the gradients of wave momentum fluxes across the surf zone. Therefore, deepwater conditions of water waves are not generally sufficient parameters to characterize the incident wave field.Instead, wave characteristics in the surf zone and its associated currents should be evaluated from statistical wave data at deep water locations

CONCLUSIONS

Extensive field data on horizontal and vertical temperature distributions of thermal plumes, discharged horizontally from thermal electric power plants into coastal waters, were analyzed with a view to obtain basis of qualitative prediction of wave and currents effects on near-field mixing. Information on winds, swells/seas, currents, tide, shoreline configuration and sea bottom bathymetry were avaialble for the analyzed data. Two of these plants Fukuskima in Japan and Encina in southern California are located on straight long beaches. The third plant is Diablo Canyon and is located on a partially closed embayment. In addition, a series of sensitivity laboratory tests was conducted on the 1:75 physical model of Diablo Canyon to provide complementary data on the effect of waves and its induced currents on plume surface area and vertical temperature profiles. The results of the study lead to the following conclusions:

(i) Cumulative surface area for the overall isotherm contours, of excess temperature ranges in the near field of thermal plumes, increases in the presence of opposing waves of finite height. This increase might be inhibited by restrictions due to water depth and side boundaries. Further, this trend of surface area increase might not apply uniformly over all ranges of excess temperature in the near field. This is due to the different mechanisms by which surface waves affect plume mixing in the surf zone and the plume densimetric Froude number.

(ii) Within the upper range of normalized excess temperature, $\geq$ 0.8, opposing waves increase the plume surface area due to the excess longitudinal momentum flux of waves. Further it is also seen that the wave-induced cold bottom currents are entrained into the plume upper layer, close to the outfall, and thereby destratifies the vertical temperature profile.

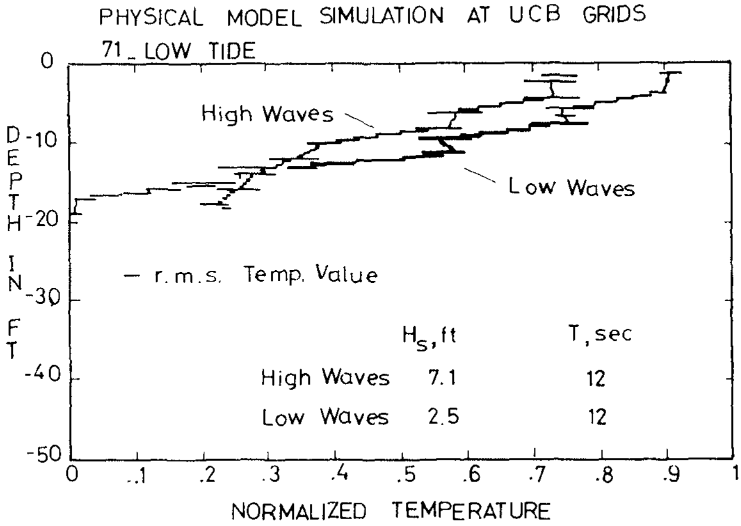


FIG 8-a MODIFICATION OF VERTICAL TEMP. PROFILES

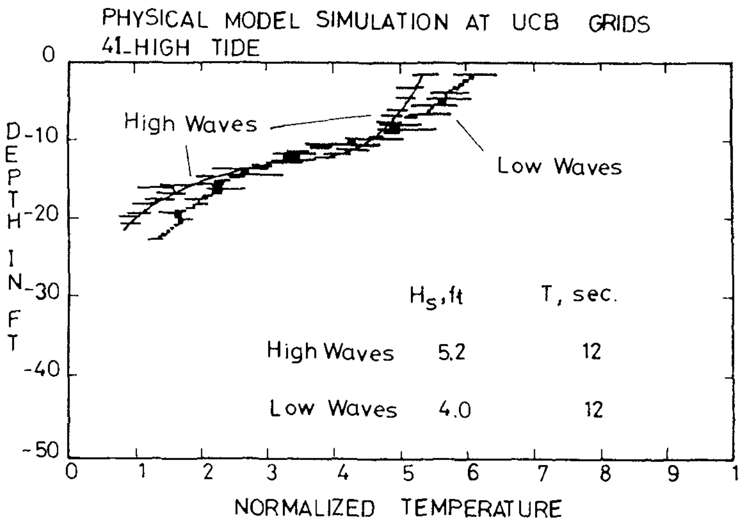


FIG8_b MODIFICATION OF VERTICAL TEMP. PROFILES

Longshore or return rip currents, generated on straight long beaches and within shoreline embayments reduces plume surface area for the medium range of (0.8-0.5) normalized excess temperature in the near field zone.

(iii) Interaction of incident oblique-wave field with a partially enclosed embayment induces a basin secondary circulation with an offshore wave-breaking current. This flow pattern forces a part of far-field plume warm water to return to the discharge area and be rentrained in the plume near-field. Thus waves under certain conditions may interact with the nearshore topography leading to a much higher effluent concentrations and larger surface areas for the high and medium ranges of excess temperature.

(iv) Gradient of wave momentum flux across the surf zone is an important parameter in shaping the slope of functional relationship between plume surface area versus fractional excess temperature in coastal waters.

APPENDIX 1. REFERENCES

1. Adams, E.E., "Discussion of Reynolds Number Effects on Buoyant Surface Jets", ASCE, Journal of Hydraulic Engineering, Vol. III, No. 8, August 1985.
2. Grider, G.W., "Some Effects of Heavy Surf on a Horizontally Discharged Thermal Plume, Proc.Offshore Technology Conference, Paper 1721, Houston, TX, May 1973.
3. Horikawa, K., Lin, M-C and Sasaki, T.O, " Mixing of Heated Water Discharged in the Surf Zone", Proc. 16 th Int. Conf. Coastal Engineering, Ch. 155, Hamburg, Germany, Aug. 27-Sept. 3, 1978.
4. Ismail-Awadalla, N., "Wave-Current lnteraction", Technical Report HEL 27-7, Hydraulic Engineering Laboratory, University of California, Berkeley, CA, October 1980.
5. Ismail, N.M., "Effects of Opposing Waves on the Mixing of a Horizontal Surface Momentum Jet", Technical Report HEL 27-9, Hydraulic Engineering Laboratory, University of California, Berkeley, CA, June 1981.
6. Ismail, N., "Effect of Wave-Current Interaction on Littoral Drift", Shore & Beach, Vol. 50, Jan. 1982.
7. Ismail, N.M., and Wiegel, R.L., "Opposing Wave Effect on Momentum Jets Spreading Rate", Journal of Waterways, Port, Coastal and Ocean Engineering, Vol. 109, No. 4, Nov. 1983.
8. Ismail, N.M., Ryan, P.J. and Tu, S.W. "Role of Wave Transformation on Mixing of Buoyant Jets", ASCE Speciality Conf. on Nearshore Hydrodynamics, Delaware, June 29-July 1, 1987.
9. Kuhlman, J.M., "Reynolds Number Effects on Buoyant Surface Jets". Journal of Hydraulic Engineering, ASCE, Vol. 110, No. 6, June 1984.
10. Leighton, J.P., Tu, S.W., Petroccitto, A.A., Eastman, L.K., "Characterization of Receiving Water Temperatures During Power Accension Testing of Unit 1 Diablo Canyon Power Plant", Report

No. 420-85, Pacific Gas and Electric Company, Department of Engineering Research, March 1986.
11. Phillips, O.M., "The Dynamics of the Upper Ocean", Cambridge University Press, Cambridge, England, 1977.
12. Porter, B.A., "Model Verification Study of the Thermal Plume Discharge Geometry and Temperature within Diabio Cove", Report No. UCB/HEL 27-14, U.C. Berkeley College of Engineering, June 1985.
13. Ryan, P.J., Tu, S.W., Leighton, J.P., and Wiegel, R.L., "Hydraulic Model Tests for Unit 1, Diablo Canyon Power Plant, Report No. 420-86. 557, Department of Engineering Research, Pacific Gas and Electric Co., November 1986.
14. Ryan, P.J., Ismail, N.M., Lou, R. Tu, S.W. and Wiegel, R.L., "Hydraulic Model Verification Tests for Units 1 and 2 Diablo Canyon Power Plant", Report No. 420-DC-87. 15, Department of Engineering Research, Pacific Gas and Electric Co., March 1987.
15. Ryan, P.J., Kloepper R., Ismail, N., Tu, S.W., and Wiegel, R.L., "Hydraulic Model Tests for Heat Treatment Conditions at Diablo Canyon Power Plant", Report No. 420-DC-87.16, Department of Engineering Research, Pacific Gas and Electric Co., April 1987.
16. Safaie, B., "Mixing of Buoyant Surface Jet Over a Sloping Bottom", Journal of Waterways, Harbors, and Coastal Engineering Division, Proc. ASCE, Vol. 105, No. WW4, 1979.
17. Tanaka, H. and Wada, A., "Prediction of the Diffusion of Discharged Warm Water Influenced by Nearshore Currents", Coastal Engineering in Japan, Vol. 25, 1982.
18. Tu, S.W., Leighton, J.P., White, C.O. Hsu, C.C. "Surface Buoyant Jet Characteristics of the Thermal Discharge Plume at Diablo Canyon Power Plant", Report No. 420-86, 475, Department of Engineering Research, Pacific Gas and Electric Company, Novemoer 1986.
19. Wiegel, R.L., Harms, V.W., Safaie, B., Cumming, J.D., Della, R.P., C.B., Leidersdorf, and C. Young, "Report on Model Study of Cooling Water System of Pacific and Electric Company Nuclear Power Plant Located at Diablo Canyon, California", Technical Report HEL 27-2, Hydraulic Engineering Laboratory, University of Califirnia, Berkeley, CA, January 1976.