FIELD STUDIES OF BUOYANT JET IN COASTAL WATERS

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ABSTRACT

Studies were made on a surface buoyant jet from a coastal power plant. The cooling water discharges into shallow waters of irregular bottom topography forming a partially enclosed embayment that connects to the open ocean. Near field mixing was found to be influenced by bottom bathymetry, lateral confinement and a large obstruction. Surface centerline temperature decay, bottom separation and the heat and mass distribution within the embayment were analyzed.

INTRODUCTION

Much of the work on surface buoyant jets has been limited to the case where bottom and side boundary effects are absent. This is not the condition for Diablo Canyon Power Plant on the California Coast of the USA. The cooling water system discharges into shallow waters of irregular bottom topography forming a partially enclosed embayment that connects to the open ocean (see figure 1). Prototype studies were conducted during power ascension testing of both units.

A discharge structure drops the condenser water down to ocean level through two chutes, one for each power plant unit. Cut-outs in the center divider wall allow for cross-over mixing when the unit flow rates are different. There are two cooling water pumps available for each unit; each pump has a maximum capacity of 28 m^3/s. Data were collected during periods when the discharge waters represented: coflowing buoyant and non-buoyant jets (4 cooling water pumps and 1 power plant unit in operation-4P/1U); two coflowing buoyant jets of different densities less than ambient but similar discharge volume (4 pumps and 2 units in operation- 4P/2U); and two coflowing buoyant jets of similar density but different discharge volume (2 pumps and 1 unit in operation- 2P/1U). The tide level controls the initial jet depth. At full load and discharge flow, the temperature rise of the cooling water is 10.8^{o}C.

DATA COLLECTION

A field data collection program was implemented to describe the 3-dimensional receiving water temperature and velocity field. Near-field temperatures in the upper water column were measured along transects with a vertical temperature array. Thermistors were placed down to 10 feet below the surface; data were recorded at 10 second intervals automatically in a self-contained data recording unit. Vertical temperature profiles and far-field surface temperatures were measured with profiling and towed bathythermographs, respectively. A thermistor array with data recorder was configured to be used as a free-floating drogue to determine temperature decay along or near the plume centerline. Plastic drogues were also tracked to determine plume veloci-

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ties and ambient currents. Moored current meters were deployed in some tests at the cove entrances at two depths. Boats were equipped either with a range-azimuth microwave navigation system or with retroprisms for a shore-based laser electronic distance measuring system for boat position. Data were taken on intake and discharge temperatures, tide, wind and wave conditions.

The test methods and data analysis results during power ascension testing of Unit 1 are presented in Leighton et al. (1986), and for Unit 2 in Tu et al. (1986). Emphasis will be given here to test data collected during power ascension testing of Unit 1 (see Table 1). A total of more than 50 field tests were made. A test series usually consisted of multiple data collection periods with a common power plant discharge condition, but with differences in tide, wind, wave and offshore current direction and magnitude.

RESULTS

Centerline surface temperature decay

The excess surface temperature was plotted against the ratio of distance traveled to equivalent discharge diameter, $D = (h_0 b_0)^{.5}$, where b_0 = plume half-width, and h_0 = initial plume depth. The power law index, n, was determined for the relation: $\Delta T(x)/\Delta T_0 \sim (x/D)^{-n}$, where ΔT_0 = discharge temperature rise.

With data for the 2P/1U case, for x/D < 30, with one exception, n = 0, and for x/D between 30 and 70, 0.5 < n < 1.0. When the data for 7 tests (2P/1U) are plotted simultaneously, using the equivalent diameter as the length scale, there is significant scatter (see figure 2). When scaling is made with the initial densimetric Froude number (F_0) and aspect ratio (AR), there is significantly reduced scatter (see figure 3). The abscissa is divided by the formula for the transition distance for deep water jets developed by Stolzenbach and Harleman (1971): $12(h_0b_0)^{.5}F_0AR^{.05}$. The ordinate is scaled by the initial densimetric Froude number.

Bottom separation

Bottom detachment was estimated from vertical temperature profiles near the plume centerline, where the bottom excess temperature nearest to the outfall equals zero. The near-field penetration depth varied from 4.5 to 11 meters (see table 2).

The maximum plume depth was not correlated with tide, and poorly correlated with initial densimetric Froude number. The ratio of maximum penetration depth (h_{max}) to initial plume depth (h_0) does show a correlation with initial densimetric Froude number (F_0), based on the initial depth. The results of analyzing 14 tests (2P/1U and 4P/2U) with $5.4 < F_0 < 38$ (Tu et al., 1986), gave a best-fit equation of:
$h_{max} = .46\,F_0^{.87}\,h_0$ with a correlation of .91. The empirical equation of Safaie (1978):
$h_{max} = .91\,F_0^{.50}\,h_0$ worked well in the range $5.4 < F_0 < 12$, but was a poor predictor at extreme low tides, or high Froude number.

At lift-off (or bottom drop-off), the estimated local densimetric Froude number was of value 1.5, based on the results of 4 tests.

Heat and Mass Flux Balance

Since the discharge cove is semi-enclosed, it was possible to obtain velocity and temperature data sufficient to describe the cross-sectional variation in momentum and buoyancy. Vertical temperature profiles and thermistor transect data were used for temperature; drogues with center of mass at 1.2, 2.5 and 5 meters were tracked for velocity. Results are presented in Table 3.

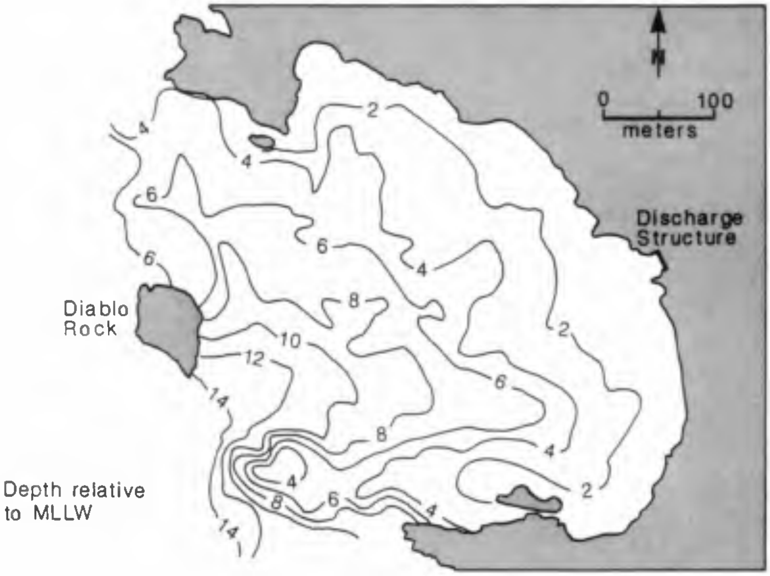

Figure 1. Bathymetry in Diablo Cove

Table 1. Conditions of Selected Tests

Test	Discharge Conditions[1] Unit 1 m^3/s	Unit 1 ^oC	Unit 2 m^3/s	Unit 2 ^oC	Tide m	Wind[2] m/s	Wave m	Offshore Current[2] m/s
2-HT1	44.1	8.8	40.8	0.3	.6	5.4-	.9	.23-
3-2	34.0	8.6	22.6	8.6	.1	4.5x	.8	.10-
3-3	34.0	9.0	22.6	8.9	.3	5.2+	1.0	.06x
4-1	34.0	9.5	22.6	9.4	.8	5.9-	1.6	.13-
4-3	34.0	9.4	22.6	9.3	.1	2.5-	1.8	.08x
5-1	56.6	10.3	56.6	0.7	.7	3.4x	1.6	.23x
5-2	56.6	10.4	56.6	0.8	.5	6.2+	2.0	.18+
5-4	56.6	11.1	56.6	0.4	.8	2.7+	1.6	.06-
6-2	34.0	10.6	22.6	10.4	.9	1.6+	.7	.15+
6-3	34.0	11.0	22.6	10.7	-.1	2.2-	.8	.28+
6-4	34.0	11.1	22.6	10.9	.9	5.6+	.8	.13+

(1) The cut-outs in the center divider wall allow the cross-over of water whenever unit flows are different. The values given refer to conditions at the end of the discharge structure, after the exchange has occurred (Ryan and Tu, 1985)
(2) The direction in which the wind (or current) is headed. A "+" indicates a downcoast movement, a "-" is for an upcoast movement, and an "x" denotes roughly shore normal movement.

Among the conclusions one can draw from this analysis: The plume is a surface condition outside the discharge cove, with an average of 85% of the excess temperature flux within the top 3 meters of the water column. At low tide, the buoyant jet is deflected more to the north, a result of the presence of parallel rock ridges within 75 meters of the discharge structure, with an orientation towards the north. We have found that this effect is reduced at higher tide level (where the ridges serve as bottom roughness instead of as deflectors) and higher initial momentum (as indicated in test 5-1, with 4 pumps). Consistent over-estimation of the heat flux out of the cove suggests some return flow of buoyant water, most likely on the east side of the north entrance, where data is sparse or non-existent.

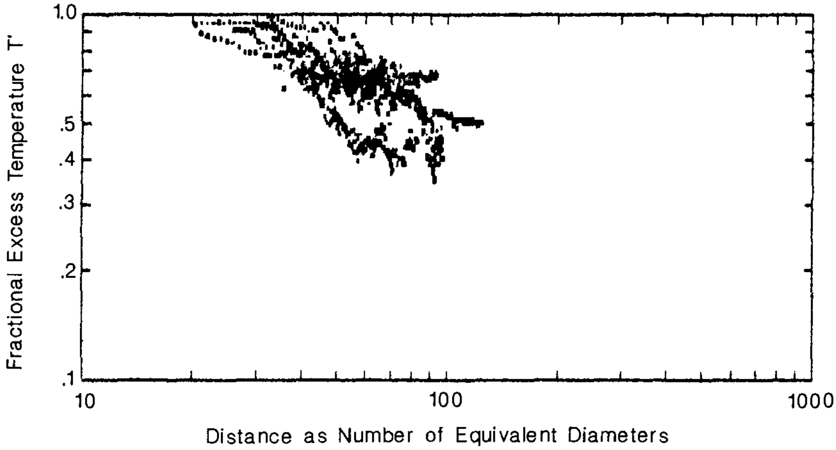

Figure 2. Surface Centerline Temperature Decay

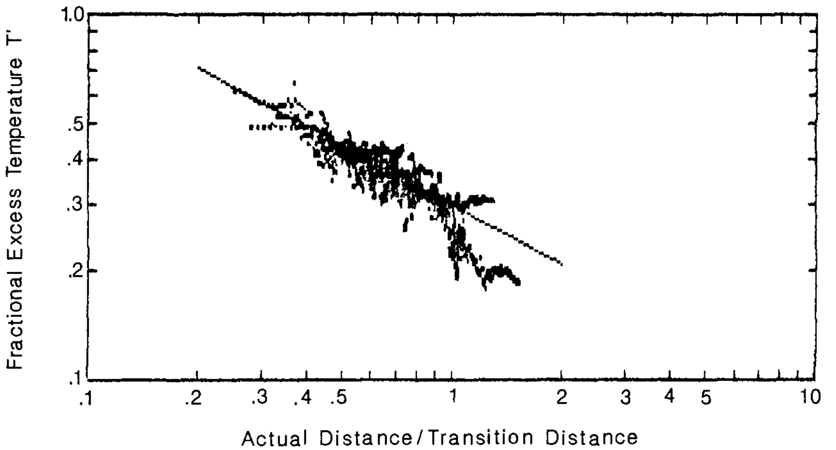

Figure 3. Scaled Temperature Decay

Table 2. Near-field Penetration Depth

Test	Discharge densimetric Froude number	Plume/Jet Depth Initial m	Maximum m	Local Froude No. At Lift-off
2-HT1	8.3	2.0	9.8	–
3-2	11.5	1.5	4.6	–
3-3	9.2	1.7	4.6	–
4-1	6.6	2.2	6.1	1.4
4-3	11.8	1.5	9.1	>.8
5-2	16.2	1.9	10.7	1.3
6-2	5.7	2.3	4.9	1.5
6-3	16.5	1.1	6.7	–
6-4	5.4	2.3	7.6	1.6

Table 3. Heat and Mass Balance

	Percent of Discharge Excess Temperature Flux			
Test	West	North	Difference	In top 3 meters
2-HT1	82	12	6	ID
3-2	50	57	7	100
3-3	78	24	2	>80
4-1	96	68	64	80
4-3	98	36	34	87
5-1	112	0	12	72
6-2	97	28	25	84
6-3	53	53	6	95
6-4	106	-12	6	77

The effects of a large obstruction

Under most receiving water and discharge conditions, the buoyant jet trajectory is oriented towards Diablo Rock. This large obstruction to the flow has been observed to cause a bifurcation of the plume, upwelling in the wake of the island (see figure 4), and plume deepening on the inward side of the island. On the seaward side of the island, lateral temperature gradients as large as a 7^oC drop in 90 meters have been observed. The temperature of the water in the wake of the island is near or equal to the offshore ambient conditions. Imberger and McComb (1984) reported upwelling in the wake of Rattray Island in Australia.

Mixing between coflowing jets

Test 5-1 is a case involving coflowing buoyant and non-buoyant jets. We obtained data perpendicular to the jet, which showed the change with distance of the temperature gradient across the interface. Figure 5 shows that mixing between the coflowing jets is limited. The velocity shear between jets is less than between jet and stagnant ambient waters, which may explain why mixing is relatively limited.

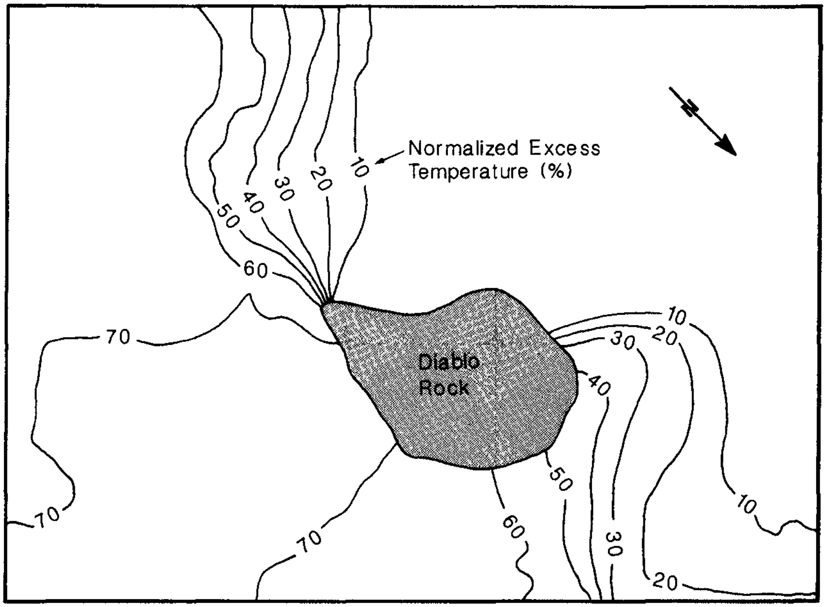

Figure 4. Surface Temperature Pattern around Diablo Rock

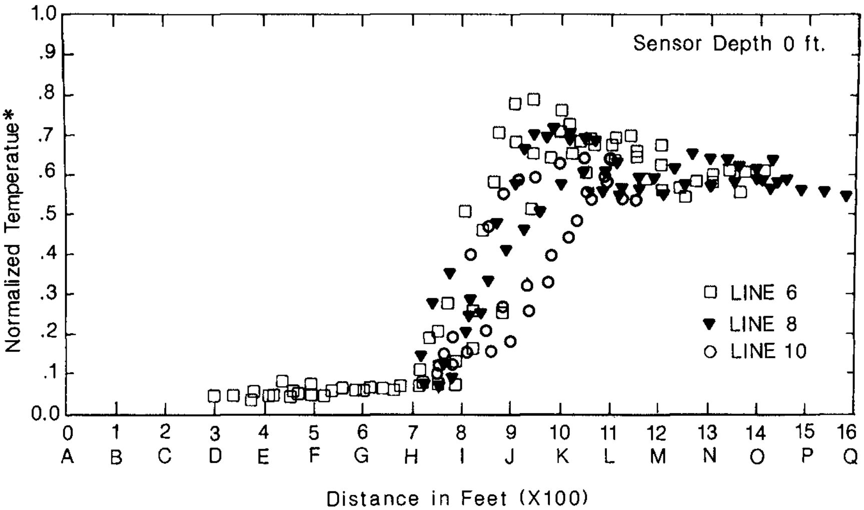

Figure 5. Temperature Transect Data for Test 5-1

Mixing at upcurrent edge between plume and receiving waters

A temperature gradient, as large as 4°C in 25 meters, was measured at the upcurrent limit of horizontal spreading of the plume in the far-field. The presence of a warm water front, marked by a slick along which foam collected, has also been observed by Mimura and Horikawa (1982).

Offshore Plume Conditions

The offshore environment was found to have variable current conditions, in terms of both direction and magnitude. We see a variety of offshore plume centerline trajectories in figure 6. The ocean currents were found to be more a function of wind magnitude and directional persistence than the seasonal characteristics of the California Current. The winds at Diablo Canyon typically show a diurnal pattern and the plume can reverse direction within a day.

CONCLUSIONS

Data collection in the field has been made for a buoyant surface jet where near-field mixing is influenced by shallow waters, lateral confinement and a large obstruction. Maximum plume depth and centerline surface temperature decay can be described using standard scaling factors.

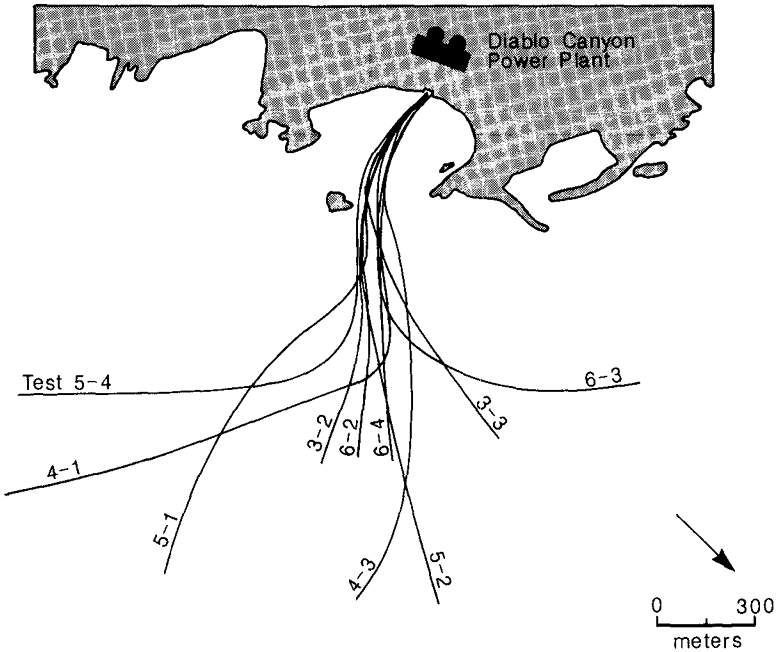

Figure 6. Offshore Plume Centerline Trajectories

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