DISPERSION OF COOLING WATER FROM A COASTAL LNG PLANT.

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ABSTRACT

The object of this case study was to predict the likely degree of pollution resulting from the discharge of heated water from a proposed LNG plant into the sea (Figure 1). The expected thermal loading was 40 m^3/s at a temperature of 10°C above the natural ambient sea water temperature. The investigation was required to provide data for an ecological study to determine the possible impact of the plant on the coastal and marine environment.

Information on tide levels, tidal currents, salinity, sea temperature, wind strength and direction was obtained in a general survey programme which had already been commissioned. These data provided vital information on seasonal variations in marine conditions and further local information was obtained from short intensive hydrographic surveys. The data were analysed to yield a simplified description of the tidal and wind induced currents and suitable values of mixing parameters for use in two numerical models. The first dealt with the "near field" processes of the spread of a buoyant layer of heated water under the convecting influence of the tidal currents. The second model simulated the "far field" processes which give rise to a general increase in the temperature of the sea in the region.

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1. INTRODUCTION

Objectives

1.1 The main object of the study was to obtain approximate indications of the extent of the spread of heated effluent from the proposed LNG plant, together with the probable range of temperature increase at locations which were environmentally sensitive. The methods used relate equally well to other conservative and non-conservative pollutants, and so an ancillary purpose of the work was to assess the spread and concentration of chemical pollutants, for example anti-fouling additives, that might be present at significant concentrations in the plant effluent. However, only the temperature aspects are described here. This information was required for a range of tidal and seasonal weather patterns, to enable other specialists to assess the impact of thermal and other pollution on the marine and coastal ecology. To this end, liaison between the ecologists and hydraulicians was necessary to identify sensitive areas requiring particular scrutiny.

1.2 In the time scale available and within the budget that appeared reasonable for an environmental study, physical modelling was inappropriate. In any case, there are severe limitations in making scale models of the relevant processes. Consequently the chosen method of study was by computer simulation. Within the time and budget constraints many approximations and simplifications were needed but it is believed that the predictions made were of appropriate detail and accuracy for the purposes of an environmental impact appraisal.

1.3 Two numerical models were used, one of which dealt with the "near field" processes of the spread of a buoyant layer of heated water under the convecting influence of the tidal currents. The second model simulated the "far field" processes which give rise to a general increase in the temperature of the sea in the region. In each case, output was presented as the increase above ambient temperature so absolute temperatures were derived by super-position of output data on existing conditions.

The Proposed Scheme

1.4 Woodside Petroleum Development Pty Ltd. are proposing to abstract natural gas from the North Rankin gas field located some 130 km offshore from Dampier in 125 m depth of water. The gas will be brought ashore through a single pipeline to the onshore terminal at Withnell Bay, approximately 12 km north-east of the town of Dampier (Figure 1). Here some of the gas will be piped directly to local markets and to the city of Perth through a proposed 1,500 km long gas pipeline, and some will be liquified to be exported in LNG tankers. It is expected that something like half of the total output from the North Rankin field will be liquified, for export, at Withnell Bay.

1.5 The proposed facilities at Withnell Bay include a gas inlet station, LNG loading jetty, service jetty, LNG storage tanks, offices, and the gas liquifaction plant. It is envisaged that the liquifaction plant will be divided into three equal sized modules (trains), each with a capacity of about 11 mill. m^3 per day. To liquify gas it must be cooled down to -160°C. This is achieved by compressing the gas in large steam driven compressors, typically of 20,000 hp or more each. The enormous amount of heat given off during the liquifaction process is dissipated through heat exchangers into the cooling water system, the heat load being of similar order of magnitude to a nuclear power station.

The Cooling Water System

1.6 Neither fresh water cooling nor air cooling is possible in the hot arid climate of the north-west. The only cooling medium readily available to the site is sea water. Optimisation studies carried out on the LNG complex as a whole indicated an optimum rise in the cooling water temperature of about 10°C, corresponding to a once-through sea water requirement of about 150,000 m^3 per hour, i.e. 40 m^3/s approximately.

1.7 It is proposed that the water will be drawn from near the sea bed several hundred metres off the coast north of the plant site. The heated water will be discharged into a watercourse known as "No Name Creek" south of the plant site. From here the hot water will travel down the watercourse into "No Name Bay" and thence to the open sea. The proposed arrangement for the cooling water system is shown in Figure 2.

2. METHODOLOGY

Physical principles

2.1 The prediction of thermal pollution relies upon a detailed understanding of the mechanism by which the heat from the discharge will spread through the receiving body of water and overlying air. The heat absorbed by the seabed adjacent to hot water outfalls has been shown to be negligible in similar situations elsewhere (1) and so was not considered further.

2.2 As the heated water travels down No Name Creek a distance of 750 m, it will lose a small amount of heat by evaporation and radiation. On entering No Name Bay the heated water will mix with the relatively small body of water in the bay and it may form a surface layer in the deeper part of the bay, depending upon the tidal conditions. The total heat losses in the creek and bay were calculated to give a maximum temperature reduction of less than 1°C. Therefore in the rest of the analysis it was assumed that the nominal 10°C temperature rise through the plant applied at the outfall from No Name Bay into Mermaid Sound.

2.3 At the exit from No Name Bay, the heated water will spread out over the surface of the sea under the influence of buoyancy, momentum and shear stresses between the two layers. In this "near field", the water will be vertically stratified with the hot water forming a plume on the surface of the cooler sea water. This plume will be convected up and down the coast by the currents whilst being gradually dispersed by vertical and horizontal mixing. The temperature concentration will thus reduce and the edge of the plume will become indistinct. The degree of mixing occurring will be a function of the variability of the velocity, which in turn will depend upon tidal and wind conditions as well as local sea bed topography.

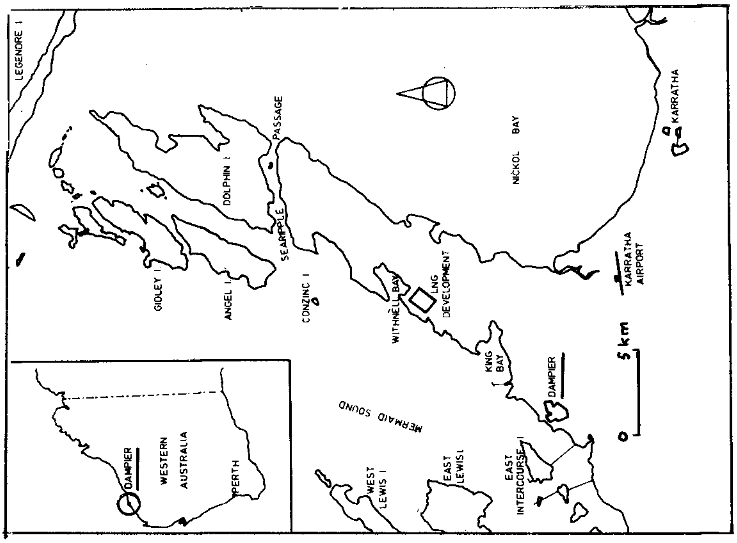


FIGURE 1 GENERAL LOCATION MAP

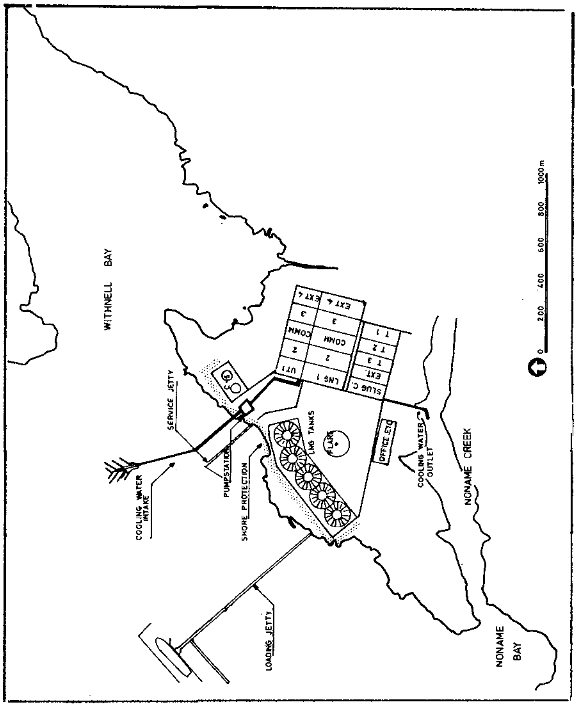


FIGURE 2 COOLING WATER OUTFALL ARRANGEMENT

2.4 The hot water discharge can travel up to one tidal excursion from No Name Bay in the first tidal period after release; however, to travel further, it must rely upon net tidal and wind induced drifts and mixing. These are slower processes than inter-tidal convection. Outside a range of one tidal excursion from No Name Bay, the maximum temperature rise caused by the hot water discharge will be much reduced. The vertical stratification will also diminish progressively until mixing over the water depth is complete.

2.5 The continuous release of heat through No Name Bay will raise the general water temperatures above their natural levels over a large area of Mermaid Sound. The new temperature distribution will depend upon:

- the heat input by the LNG plant.
- the distribution of the cooling water by tidal drift and wind induced currents.
- the mixing of the cooling water with the water in the sound in both horizontal and vertical directions.
- the heat losses through the water surface into the atmosphere.

2.6 The computer programs which model the two main phases of cooling water dispersal are based on different assumptions. The "near field" model indicates the conditions in the intertidal zone close to the outlet at No Name Bay, in the surface layer generated by thermal stratification. The "far field" model looks at a much larger sea area beyond the zone of strong stratification assuming the heat to be distributed through the water depth and to be dissipated by surface cooling and spread by drift currents induced by wind and tides. In practice the "near field" and "far field" processes merge but they are commonly considered separately for simplicity.

Near field model

2.7 The "near field" model considers the initial spread of a buoyant plume entering Mermaid Sound via No Name Bay. It traces the change in shape of the plume and derives the temperature rise at various points within the plume for a variety of wind and tidal conditions.

2.8 The plan shape of the plume was determined by monitoring the movement of discrete labelled patches of hot water in a calculated velocity field over two or more tidal cycles. The velocity of a labelled patch in the surface layer was obtained as the vector addition of the ambient time-varying water velocity and the imposed velocity due to the source (2). The source has significant width compared to the tidal excursion, and was therefore treated as the summation of a large number of closely spaced point sources. The imposed velocity is then given by:-

$$U_x = \frac{Q}{4\pi Da} \log\left\{\frac{y^2 + (x+a)^2}{y^2 + (x-a)^2}\right\}$$

$$U_y = \frac{Q}{2\pi Da}\left\{\tan^{-1}\left(\frac{x+a}{y}\right) - \tan^{-1}\left(\frac{x-a}{y}\right)\right\} \qquad \text{Equ.1.}$$

where a = half width of the line source.
D = assumed depth of surface layer
x,y = co-ordinates of the point relative to the centre of the line source.
Q = volumetric discharge rate
U_x, U_y = velocities in the x and y directions.

2.9 Random eddy motions and the non-uniformity of current patterns are inevitable components of any turbulent flow. Such motions will mix the cooling water discharge with the ambient water, and can be described by using a Fickian analogy in writing a steady-state two-dimensional diffusion convection equation. Taking into account a simple description of surface cooling based on temperature increment above an ambient equilibrium condition, the full cooling expression becomes:-

$$\frac{\partial}{\partial y}\left\{-D_y \frac{\partial T}{\partial y}\right\} + U \cdot \frac{\partial T}{\partial x} + \frac{kT}{h} = 0 \qquad \text{Equ.2}$$

where T = temperature
x,y = the local plan co-ordinates within the plume
U = water velocity in the plume in the x direction
D_y = instantaneous lateral dispersion coefficient
k = surface heat loss coefficient
h = plume depth

In the above, the dispersive flux in the direction of water movement has been ignored because it is generally much less than the convective flux due to the velocity U.

2.10 The solution of equation 2 has been treated by Brooks (3). Although his analysis was restricted to an unidirectional current, it is informative in that it gives an estimate of the likely dilution during either the ebb or flood tide and is therefore appropriate to the early life of the plume. In the equation, the mixing of the plume and the local water is described by a lateral dispersion coefficient which has to be assessed. It is a function of many physical phenomenon, including vertical density gradients, wind effects, tidal currents and local topography, but field and laboratory work has shown that a reasonable first estimate of the dispersive processes is given by:-

$$D_y = 0.01\ L^{4/3} \text{ (in CGS units)} \qquad \text{Equ.3}$$

where L = plume width
D_y = lateral dispersion coefficient.

Substituting into equation 2 and solving gives the centreline temperature of the plume (3) as:-

$$N_d = T/T_o = \exp\left\{\frac{-kt}{h}\right\} \operatorname{erf}\left\{\frac{3/2}{(L/b)^2 - 1}\right\}^{1/2} \qquad \text{Equ.4}$$

where b = initial plume width
L = instantaneous plume width, where

$$L = b\left\{1 + \frac{2}{3}\beta\frac{x}{b}\right\}^{3/2} \qquad \text{Equ.5}$$

$$\beta = \frac{12\,D_o}{Ub} \text{ or } \frac{12D_o\,t}{b\,x} \qquad \text{Equ.6}$$

D_o = initial dispersion coefficient
N_d = dilution at centreline
t = time since particle was released at source
x = distance travelled by particle since leaving the source
T = temperature of cooling water discharge
T_o = initial temperature of cooling water discharge

The initial plume width, b, was assessed from the spread of the plume during its first hour out of No Name Bay and this value was used to derive an initial dispersion coefficient from equation 3. Equation 4 was then used to derive the temperatures at various points in the plume.

The Far Field (background) Model

2.11 Cooling water from the LNG plant will be transported away from No Name Bay by tidal and wind induced currents. Turbulent mixing and dispersion will act to spread the heat horizontally and vertically, so that after the first one or two tidal cycles, the hot water from the LNG plant will have mixed with ambient water over the full depth. Eventually the heat content of the cooling water discharge is lost to the atmosphere by exchange across the water surface at a rate proportioned to the difference between the water temperature and the equilibrium temperature. The actual water temperatures change diurnally and seasonally, and strive to follow the changes in the instantaneous values of the equilibrium temperature, by heat transfer across the water surface. The LNG plant will increase the actual temperature and hence increase surface losses close to the outfall. The far field model calculates the distribution of this increase in the vertically averaged water temperature.

2.12 No Name Bay is situated on a relatively straight coastline. Therefore in order to maintain continuity of mass, the depth average current, in the nearshore zone, must be parallel to the coast. These currents were assumed to be made up of two parts; a steady predominantly wind induced longshore drift, and a periodic current with a tidal average value of zero. During the tide, water moves back and forth along the coast and hence the cooling water passes from No Name Bay into an oscillating tidal plug of water, of length equal to one tidal excursion along the shoreline.

2.13 The time scale associated with significant cooling by surface heat exchange can be shown to be at least an order of magnitude greater than a tidal period. Therefore the temperature distribution which results from this surface exchange can be represented by the tidal averaged equation:-

$$U\,\frac{\partial T'}{\partial x} - D_x \cdot \frac{\partial^2 T'}{\partial x^2} - D_y \cdot \frac{\partial^2 T'}{\partial y^2} + \frac{K}{h}\,T' = 0 \qquad \text{Equ.7}$$

where T' = vertically averaged temperature rise
x,y = horizontal co-ordinates on the moving axis within the tidal plug.
U = longshore drift velocity
D_x, D_y = Tidal average dispersion coefficients in the x and y directions.
h = water depth
K = surface heat loss coefficient.

2.14 The solution to equation 7 for a shore-based outfall into a body of water of constant depth was derived from work by Atkins and Diver (4) to be:-

$$T'(x,y) = \frac{q\,T_o}{\pi h \sqrt{D_x D_y}} \exp\left(\frac{xU}{2D_x}\right) Ko(z) \qquad \text{Equ.8}$$

where $z = \left\{\left(\frac{x^2}{D_x} + \frac{y^2}{D_y}\right)\left(\frac{u^2}{4D_x} + \frac{K}{h}\right)\right\}^{1/2}$

$T'(x,y)$ = the temperature at point, x, y
T_o = the temperature at the outfall, above ambient
q = the outfall discharge
$Ko()$ = is the modified Bessels function of the second kind of order zero.

2.15 Equation 8 represents the solution for one point source at the origin, i.e. staying at the centre of the moving tidal plug. The solution in the present case must represent the movement of the plug past the outfall during each tide. In the tidal average solution this was done by considering the heat distributed over a length of the coastline equal to one tidal excursion centred on No Name Bay. The source was therefore divided into several point sources distributed over the tidal excursion. The solution is linear and therefore the temperature rises due to each of these sources were added directly to give the final solution.

2.16 As a point of interest, equation 8 was compared with a similar solution given by McQueen (5), and was found to agree well at all points except close to the source, where the assumptions on which the two solutions were based differed slightly.

2.17 Equation 8 indicates that the temperature distribution is dependent upon the tidal average dispersion coeficients which are themselves highly variable. The coefficients represent the overall effect of many physical phenomenon including local seabed topography, the variability of wind and tidal currents in time, the variability of velocities over depth and in plan, and the buoyancy of the cooling water itself. According to Talbot (6), a realistic value of the longitudinal dispersion coefficient is given by:-

$$D_x = 3.6\,U_{max}\,H \qquad \text{Equ.9}$$

where U_{max} = the maximum tidal velocity
H = mean tidal depth.

2.18 For effective temperature reduction, the heated water should disperse offshore to mix with the main body of water in Mermaid Sound. It is generally found that such lateral dispersion is less than longitudinal dispersion, 0.1 is a typical ratio for the lateral to longitudinal dispersion coefficients, although this value could increase markedly with onshore/offshore wind activity. In modelling the seasonal changes of water temperature, the 14 day average drift velocity was used with typical dispersion coefficients of $D_x = 5.0\ m^2/s$ and $D_y = 0.26\ m^2/s$. The basic lateral dispersion coefficient was multiplied by a factor of between 1 and 20 depending on the onshore/offshore wind conditions in the preceding 14 days.

2.20 The loss of heat to the atmosphere is a much slower process than the convective and dispersive processes and is therefore not dominant in determining the plan distribution of the excess heat. In general a coefficient of 6 cm/hr was used. This value is typical of that used in recent similar studies (7,8,9). Sensitivity tests with the loss coefficient varying from 3 to 30 cm/hr did change the temperatures noticeably, but did not significantly change the general results. A greater change in the results could be obtained by relatively small changes in dispersion coefficients or drift velocities.

Data Synthesis

2.21 The data required for the models outlined above relate mainly to two basic parameters: the current pattern which determines overall movement, and dispersion coefficients which determine the degree of mixing. However both of these are dependent on many factors and a general understanding of the marine environment is required before suitable input data can be formulated. In particular the influence of winds and tides must be understood to define conditions appropriate to different seasonal or tidal conditions. Furthermore uncommon conditions, and the probability of their occurrence, must be considered.

2.22 As already explained dispersion coefficients were based on values obtained from relevant references adjusted by the application of appropriate empirical rules. Dye tests or similar field work to estimate dispersion coefficients in the Mermaid Sound area were not considered appropriate for this broad-brush study. A large number of tests in a variety of weather and sea conditions would have been necessary and neither funds nor time were available for such detailed work. Having assessed what were considered appropriate values, the sensitivity of the analysis to changes in dispersion coefficient was tested.

2.23 The distribution (spatial and temporal) of currents was required in two forms. For the near field and far field models respectively these were:

As variations over a tidal cycle for surface water in the nearshore zone. These data were required to predict the movement of the surface plume of recently released hot water and therefore could be restricted to a zone close to No Name Bay, about 6 km long and within 2 km of the shore.

As vertically-integrated residual velocities over a tidal cycle, so that the long term exchange of hot water with the aurrounding aea water could be evaluated. The area of intereat is dependent on the smallest temperature rise considered significant, which was considered here to be 20 km by 10 km.

2.24 The following approach was adopted in formulating input data on currents for the models:-

- A general appreciation of tidal currents in Mermaid Sound and identification of principle flow patterns in spring and neap tidea.
- Analyais of the effect of wind on aurface currents and on depth integrated currents and hence the deduction of empirical relationa between wind apeed and current speed. A compariaon waa also made between observed data and available theory. (10,11).
- Analysis of long term wind recorda to deduce typical seasonal wind patterns and the duration of particular events, in particular calm periods which may be critical in the dispersion of cooling water.
- Formulation of alternative current patterns both nearshore e.g. tidal excursion etc. and in the far field zone e.g. residual drift, for use in the heat dispersion models.
- Senaitivity testa to determine where critical valuea of input data occur and where neceaaary to refine these.

2.25 Results of these analyses are presented in the following section.

3. MARINE ENVIRONMENT (Refs 12-20)

Available data

3.1 The main source of data uaed in the study were long-term recordings collected by E.G. & G, the principal survey contractor engaged on the project. An extenaive programme had been organised to provide criteria for design of pipelinea, the harbour, jetties and other coastal facilities: inatrumentation to record data on wind, waves, tides, currents, salinity and temperaturea was installed over a wide area. However, many of the instruments were located offshore and were beyond the zone of interest so far as cooling water dispersion was concerned. It was therefore necessary to supplement the main programme with subsidiary data collection exercises specifically aimed at obtaining data on near shore conditions. Three exercisea were mounted by Binnie International, in the periods 23-24 November 1978, 16-19 December 1978 and 16-22 January 1979.

Winds

3.2 Winda have a significant effect on the marine environment through the generation of wavea, which increase mixing, and through the creation of currents, which change the pattern of advection. Two dominant wind patterns are evident (Figure 3):

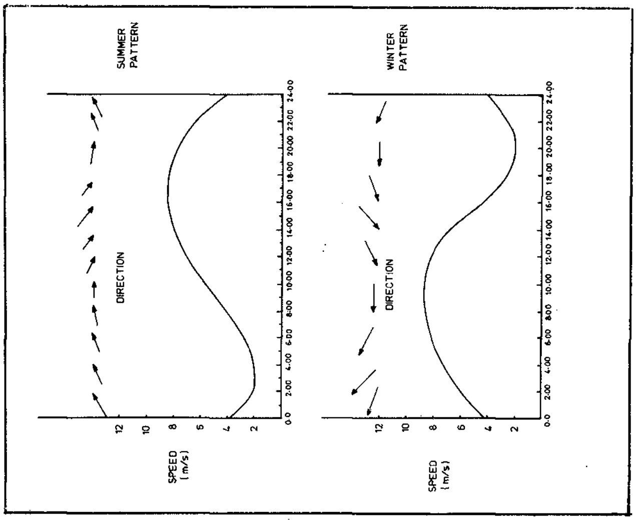


FIGURE 3 TYPICAL SUMMER AND WINTER WIND PATTERNS

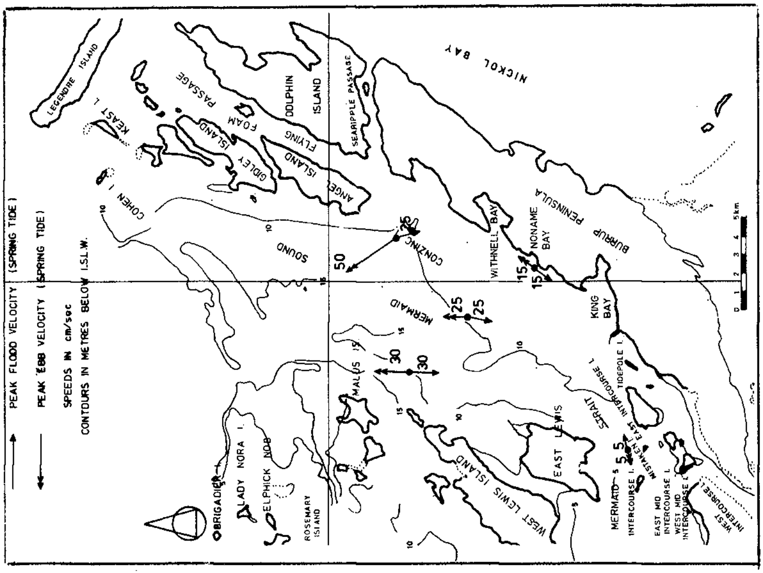


FIGURE 4 MERMAID SOUND

- The summer pattern consists of a prevailing westerly wind, acted upon by the night and early morning south-easterly land breeze and by the afternoon north-westerly sea breeze.

- The winter pattern consists of a prevailing easterly wind, again acted upon by the night and early morning south-easterly land breeze and by the afternoon north-westerly sea breeze.

3.3 Cyclones can occur in the summer months between November and March, accompanied by sea surges and by severe wave action: however so far as the study of cooling water dispersion is concerned these are of little importance since they can only improve the mixing. Of greater concern are the possible calm periods in which there is relatively little mixing by wave action and significantly less convection in the absence of wind induced currents.

Currents

3.4 Tidal streams are summarised in Figure 4 and are given as depth averaged values deduced from the long-term current observations. The pattern is similar to that of a closed bay, with very little tidal flow near East Intercourse Island. The main flood flow is towards the south but is directed southwest along the coastline in the area near Withnell Bay. Ebb currents are generally of comparable magnitude and flow in the opposite direction. An exception to this is in the area southwest of Angel Island where water flowing through Boat Passage creates an ebb dominant flow with nett movement to the North West.

3.5 Tidal velocities along the shoreline between Phillip Point and Withnell Bay are significantly lower than those in the centre of Mermaid Sound and reach a maximum of only 15 cm/s. The tidal excursions corresponding to spring and neap tides in this area are 2.0 km and 0.6 km respectively, and it follows that tidal mixing is significantly less than in many other regions where tidal excursions may be in the range 15 to 25 km.

3.6 Whilst observed data are broadly consistent with the above pattern, the majority of cases are affected by winds. The vertical velocity profiles are complex, particularly where the local topography is irregular and when wind induced currents are generated at an angle to the tidal component. A further complication arises from the duration dependence of the velocity profile. The depth affected by wind stress increases with time. Surface currents were observed to respond within about an hour of changes in wind conditions and the whole depth was affected within 12 hours. However steady state conditions did not appear to be established for considerably longer.

3.7 A simple approach to generating input conditions for the near field model was provided by the obaervation that surface currents were about 1.5% of the wind speed (recorded 10 m above sea level) and were in line with the wind. This result is consistent with previously published data relating to open sea conditions, although in such cases the Coriolis effect is often significant, causing currents to deviate to the left of the wind direction (to the right in the Northern hemisphere). It follows that the typical daily wind patterns (Fig. 3) can be used to derive surface currents, typical values being in the range 3-12 cm/s. Wind induced currents and tidal components were superimposed to formulate conditions under different tide and seasonal wind patterns.

3.8 Current data for the far field model was derived by relating residual movement of water in Mermaid Sound to longer term wind patterns, the tidal residual movement being small in comparison. Residual drift velocities induced by winds are governed partly by the direct action of the wind and partly by larger scale effects which control water movement outside Mermaid Sound. Typical net movements of water in summer and winter are shown in Figure 5. The summer pattern is governed by dominant westerly winds which force water through Mermaid Straight and then North-East into the Sound. In the winter months, South-Easterly winds cause high water levels along tbe North-West boundary of Nickol Bay and result in strong currents flowing Westwards through Boat Passage, which induce South-Westerly currents along the shoreline near Withnell Bay. It is the longshore residual drift which is of importance in the far field model and depends mainly on the longshore component of wind velocity. In addition the offshore component of wind velocity induces south westerly longshore currents. A simple model was proposed in which

$$u = 0.015\,U - 0.010\,V \qquad (V > 0)$$

$$u = 0.015\,U \qquad (V < 0)$$

where u is the longshore drift current (north east)
U is the longshore component of wind velocity (north east)
V is the offshore component of wind velocity (north west).

Values of u ranged from -10 to +10 cm/s.

Temperature

3.9 Water temperatures were available from the long term records obtained from E.G. & G. They are fairly uniform over the area of Mermaid Sound and show an annual variation from 19°C in July or August to 32°C in February or Marcb (Figure 6). Variation over the vertical is generally small tbough anomalies may occur giving temperature differences of about 2°C or more.

3.10 Variation through the tide is only significant in the area southwest of Angel Island, and results from warmer water in Nickol Bay passing through Boat Passage on the ebb tide: here temperature fluctuations of 1-2°C are common over the tidal cycle. Elsewhere the variation is less than 0.5°C over a tide but the effect is detected in variations over the two-week cycle between spring and neap tides. The greater quantity of warm water exchanged during spring tides increases general ambient temperatures by 1-3°C over the whole of Mermaid Sound. This effect is not always apparent when seasonal changes of temperature during the same spring/neap cycle are large.

3.11 Temperature variations in the shallow water of the bays along the coast are sometimes quite pronounced, and diurnal fluctuations of 5°C or more have been reported.

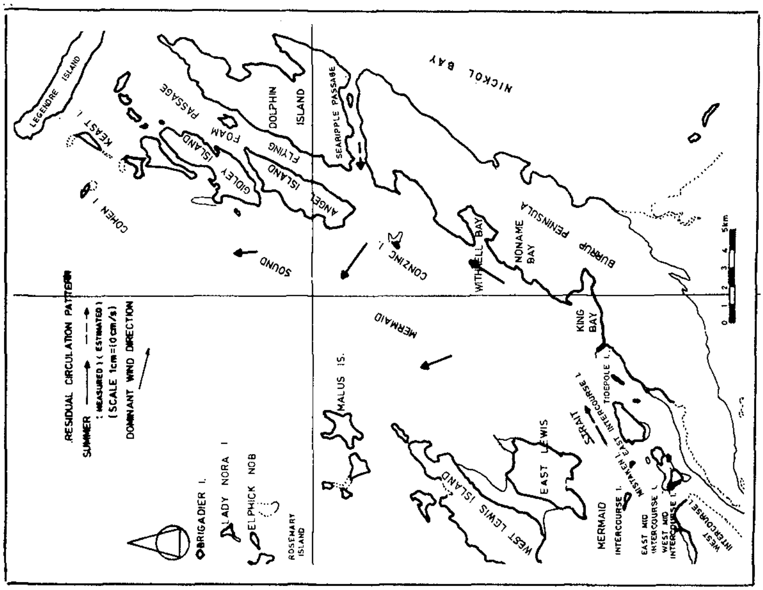


FIGURE 5b RESIDUAL CIRCULATION PATTERN (SUMMER)

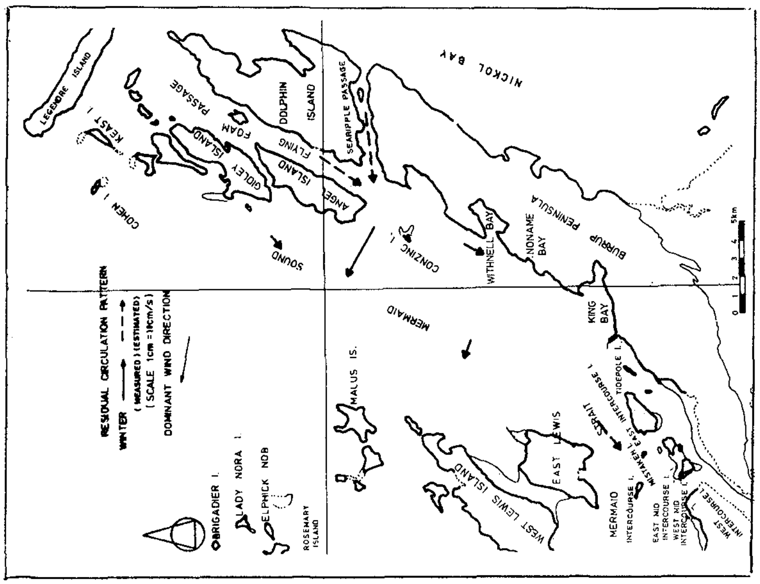
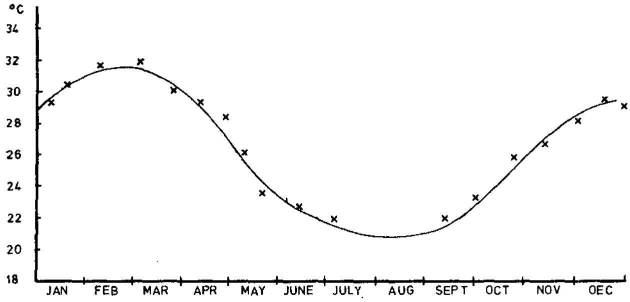


FIGURE 5a RESIDUAL CIRCULATION PATTERN (WINTER)



NOTES :

1 TEMPERATURE DIFFERENCES OVER THE VERTICAL ARE GENERALLY LESS THAN 1°

2 DIURNAL TEMPERATURE VARIATIONS ARE GENERALLY LESS THAN 0·5 EXCEPT IN THE AREA SOUTH WEST OF ANGEL ISLAND WHERE FLUCTUATIONS OF 1-2° ARE TYPICAL .

3 VARIATIONS IN MEAN TEMPERATURE OVER MERMAID SOUND ARE NOT SIGNIFICANT - EXCEPT IN THE SHALLOW WATER OF THE BAYS WHERE TEMPERATURES OF UP TO 45°C HAVE BEEN OBSERVED .

FIGURE 6 ANNUAL VARIATION OF SEAWATER TEMPERATURE IN MERMAID SOUND

4. RESULTS

The buoyant plume

4.1 Output of the near field model is in the form of age-contours and for each of these a temperature dilution factor can be estimated based on the turbulent mixing of the plume with its surroundings, with a minor additional effect due to surface cooling. Typical "plume" shapes are shown on Figure 7. By considering the plume movement over a period of 24 hours, envelopes of areas which reach specified temperature rises at any stage in that time can be plotted. Figure 8 shows conditions for a typical winter day when winds are offshore. In this case, shoreline temperature rises are negligible but in summer conditions when winds are onshore, temperature rises of up to 5°C were shown to occur near the entrance to Withnell Bay.

Background temperatures

4.2 The simulation used the weather pattern of 1978-1979 as 14-day averages to deduce the background temperature field on a tide average basis. The results were related to the environmental issues by extracting the variation of average background temperature at Withnell Bay, 3 km north-east of the cooling water outfall, and at Kings Bay, 4 km south-west of the outfall (Figure 9). Typical isotherm plots are presented in Figure 10.

4.3 The background temperature field has been considered by assuming the water to be fully mixed in the vertical. In practice, there is much overlap between the area swept by the buoyant plume and the background (far field) model. The background temperature results may be considered as applying to the main body of sea water underlying the buoyant surface layer.

4.4 Wherever there is an elevated background temperature beneath the surface plume, the plume temperatures quoted will be increased by a varying proportion of the background rise. There is no available method of combining plume temperature results with background temperature results. The problem is complicated by time and space variation and interaction between the models but for present purposes an adjusted surface temperature may be calculated from:

$$T_{adjusted} = T_{plume} + \left(\frac{1-T\ plume}{10}\right) \times T_{background}$$

This represents a rough upper limit, and is based on application of the estimated plume dilution factor with a warmed dilutant.

CONCLUSIONS

The framework of this study was the need to provide ecologists and environmental scientists with approximate forecasts of the temperature rises to be expected in the area and an indication of the extent of the main thermal impact, so that they could assess the effect on the marine environment should the project proceed.

In the time scale available and within the budget that appeared

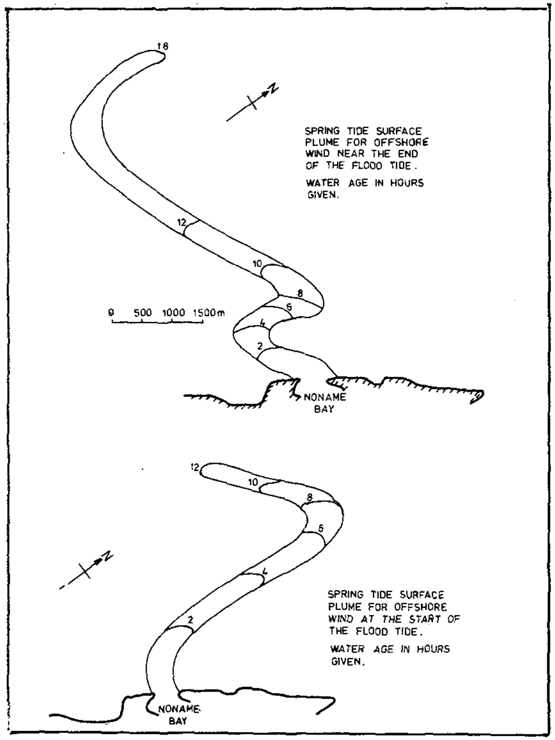


FIGURE 7 TYPICAL PLUME PATTERNS FOR OFFSHORE WIND

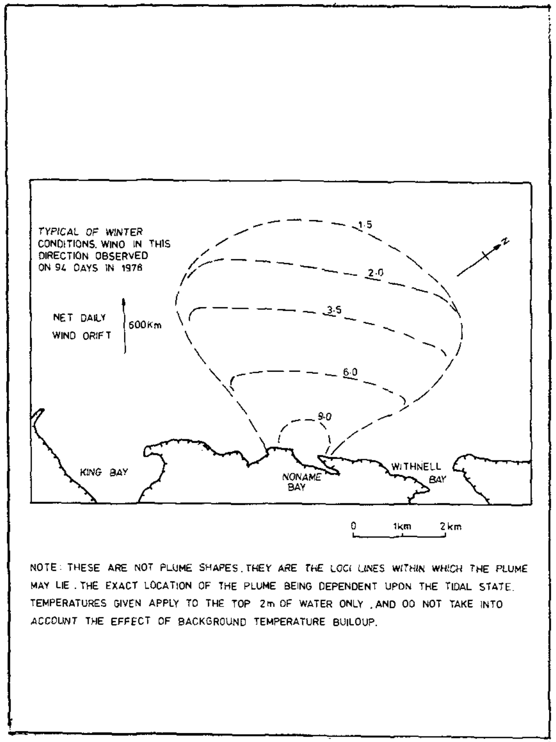


FIGURE 8 ENVELOPE OF MAXIMUM INSTANTANEOUS SURFACE TEMPERATURE RISES

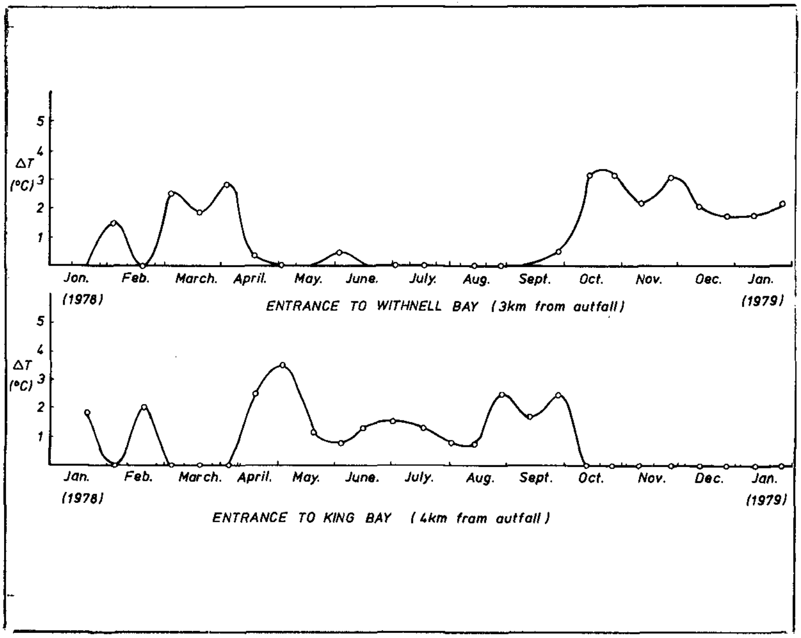


FIGURE 9 ANNUAL VARIATION IN TEMPERATURE RISE AT WITHNELL AND KING BAYS

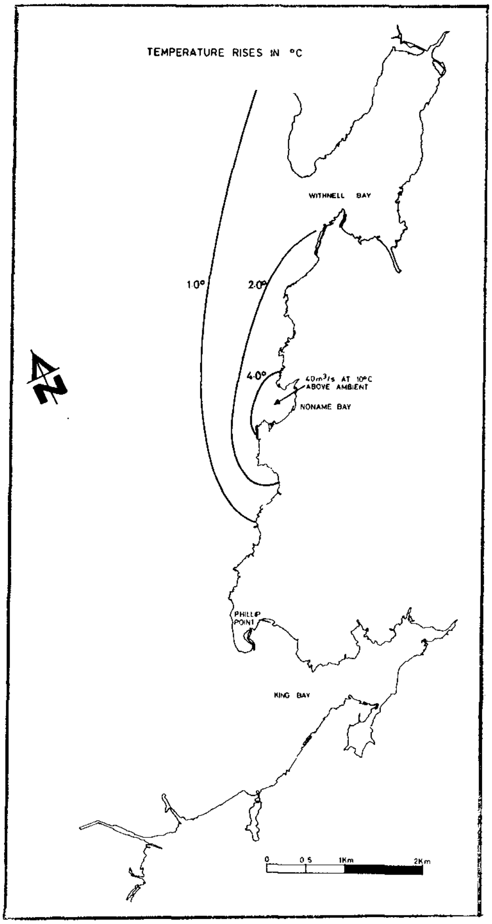


FIGURE 10 TIDAL AVERAGE TEMPERATURE RISE
LATE DECEMBER 1978

reasonable for an environmental study, physical modelling was inappropriate. In any case, there are severe limitations in making scale models of the relevant processes. Consequently the chosen method of study was by computer simulation.

Two numerical models were used, one of which dealt with the "near field" processes of the spread of a buoyant layer of heated water under the convecting influence of the tidal currents. The second model simulated the "far field" processes which gives rise to a general increase in the temperature of the sea in the region.

The simulations of the spread of pollutants, mainly hot water, from the outfall of the cooling water system provided indications of the likely range of temperatures and the extent of the spread of effluent in the environmentally sensitive coastal zone either side of No Name Bay.

The pattern of spread is strongly seasonal, being much influenced by wind induced drift of the tidal waters. The careful analysis of weather patterns and their effect on water movements is an essential part of any investigation of the spread of effluents. The study established the range of likely patterns and indicated the likely persistence at various points along the coast and elsewhere of temperature rises of several degrees Celsius.

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