Development of temperature criteria for marine discharge from a large industrial seawater supplies project in Western Australia

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Abstract

A multi-user industrial water supply system is under construction on the Burrup Peninsula in Western Australia, 1400 km north of Perth, to support a number of gas-processing plants that convert natural gas into ammonia, dimethyl-ether, methanol or liquid fuels. At full design capacity, the project will abstract 280 000 m^3/day of seawater from King Bay. Seawater will be conveyed by pipeline to each processing plant and used for cooling (using evaporative systems) and process feed water (after desalination). The total return flow (comprising cooling tower blow-down and desalination concentrate) will amount to 210 000 m^3/day. A pipeline collects the return flow from each industry and discharges into a submerged marine outfall in King Bay. As part of the project environmental approvals process, the Department of the Environment (DoE) prescribed discharge criteria for the temperature of the return flow entering King Bay. DoE requires the return flow, at the end of the outlet pipe, to be less than 2°C above the temperature of the intake (calculated over a 24-hour period and expressed as an 80 percentile). For the remainder (20% of the time), the return flow must not exceed 5°C above intake temperature. As more information from the project proponents became available, it was realised that industrial evaporative cooling systems could not comply with the temperature criteria proposed by DoE under certain climatic conditions. Key findings of this study show:

- the DoE temperature limits proposed in the Ministerial Condition are too stringent,
- practical design of evaporative cooling systems on the Burrup will yield a discharge of 6°C above intake temperature,
- discharge at 6°C will not influence the biota in proximity to the diffuser or the corals located 700 m from the diffuser,
- marine organisms in King Bay are exposed and tolerant to large natural variations in seawater temperature,
- relaxation of the return flow temperature from 2 to 6°C (above intake) will not influence the biota of King Bay, and
- environmental management systems are being developed to monitor and manage the temperature of the return flow.

Introduction

Natural gas reserves located off the north-west shelf of Western Australia are connected by deep-sea pipeline to processing facilities on the Burrup Peninsula, situated 1400 km north of Perth. New processing plants are under construction on the Burrup Peninsula to convert natural gas to ammonia, di-methyl ether, methanol and liquid fuels.

This region of Western Australia has a low rainfall (<300 mm/year) and insufficient water resources to meet the new industrial water demand. To minimise the use of scheme water, a major seawater project, the Burrup Peninsula Industrial Water Supplies Project (BPIWSP), is under development by the Water Corporation on behalf of the State Government of Western Australia. The project comprises an ocean intake and pumping facility connected to a 1 400 mm diameter seawater delivery pipeline. The pipeline provides seawater to six development sites within an industrial precinct. Each developer discharges return flow into a common pipeline (1 100 mm diameter) that transports it to an ocean outlet diffuser, located 1 300 m offshore in King Bay (Fig. 1). When the project is operating at full capacity, 280 000 m^3/d (3.2 m^3/s) of seawater is abstracted from King Bay, and 210 000 m^3/d (2.4 m^3/s) discharged back through the ocean outlet. The new industries will use seawater for cooling and desalination. Return flow comprises cooling tower blow-down, desalination concentrate and a small volume of treated wastewater. The system is being built to full capacity although there is only one developer at this stage.

The local environmental regulator, the Department of the Environment (DoE), approved the project in terms of the Environmental Protection Act (1986) of Western Australia (EPA, 2001; 2002). The environmental approvals include a set of Ministerial Conditions. One of the seventeen conditions specifies the temperature of the return flow discharged into King Bay. DoE requires all return flow to be less than 2°C above the temperature of the intake seawater (referred to as ΔT of 2°) at the end of pipe. This criterion is a 24-h average, expressed as an 80 percentile. For the remainder (20% of the time), the return flow must not exceed 5°C above intake sea-water temperature.

A review of evaporative cooling system design carried out by the Water Corporation shows humidity (expressed as air wet bulb temperature) governs the thermal efficiency of these cooling systems. From the onset of the project, the project team and developers were aware that compliance with the DoE temperature criteria was not possible during periods of high humidity. Through the agency of the Burrup User Group (BUG) comprising the developers, DoE, Office of Major Projects and the Water Corporation, it was agreed to undertake a study looking at the environmental, engineering and economic constraints to determine sustainable and achievable temperature criteria. This paper describes a process used to develop temperature discharge criteria, and assesses their influence on the biota of King Bay.

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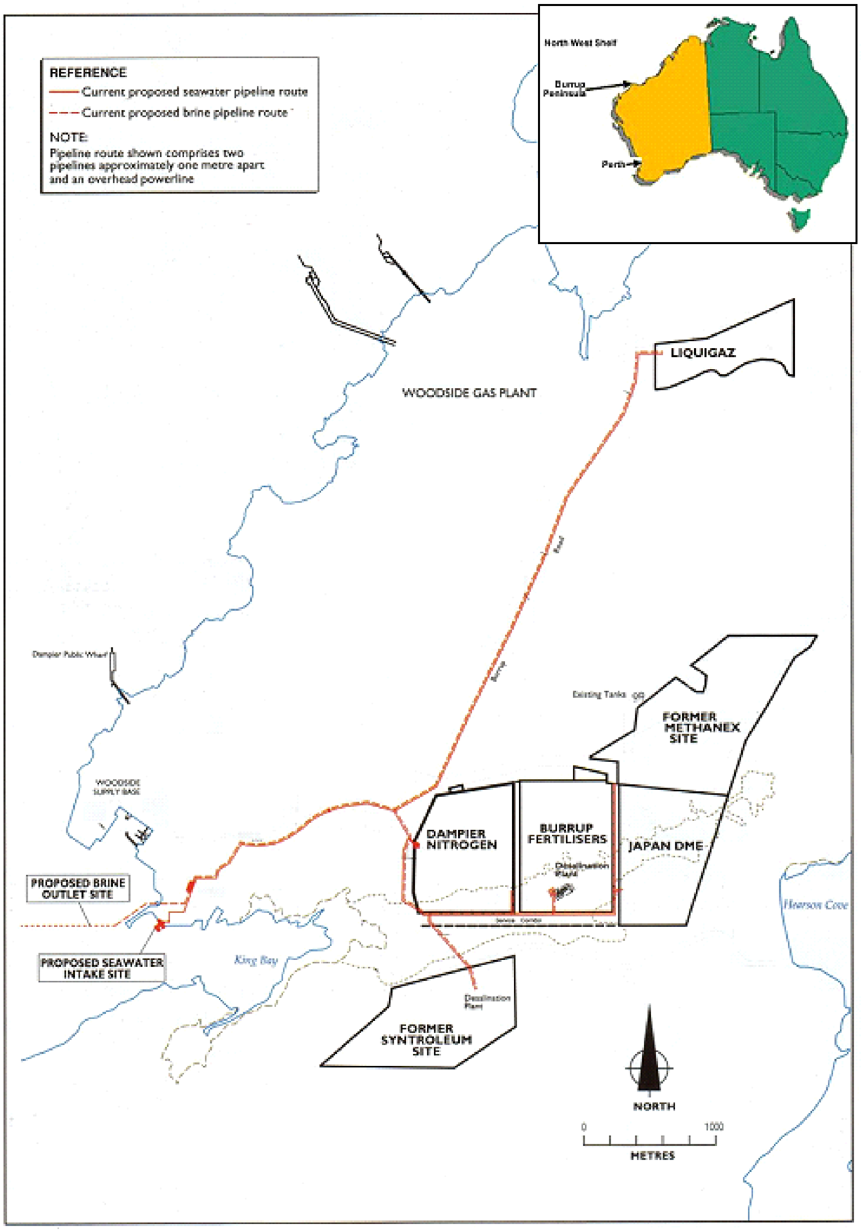


Figure 1
Location of the Burrup Peninsula, King Bay, industrial sites and pipelines

Steps in this process included:

- Identification and quantification of sources of heat within the supply system
- Assessment of the performance of evaporative cooling systems
- Defining revised discharge temperature criteria for the return flow
- Reviewing the dilution capabilities of the ocean diffuser
- Determining reference conditions in King Bay regarding the seawater temperature and thermal tolerance of the biota (infauna and corals)
- Assessing the influence of the revised discharge temperature on the biota within the near field area immediately around the ocean diffuser
- Assessing the influence of the revised discharge temperature on the far field area of King Bay, with reference to temperature change at the nearest corals, and
- Review of discharge criteria.

Results

Return flow heat budget

The two main sources of heat within the seawater supplies pipelines are solar warming of the pipeline and blow-down from the cooling towers. A heat exchange model, developed for this project, provides an estimate of the solar heating of the water within the pipeline. The model takes into account the hourly and seasonal changes in solar radiation, adsorption of heat by the concrete lined steel pipe, and advection of heat by flow within the pipeline. Results from the modelling show solar heating will increase the temperature of the water within the pipeline by only 1°C over the 4 km length of pipeline. However, solar heating will have a greater influence when there is reduced flow in the pipelines. This scenario will prevail for many years until all projects are in operation. Under such conditions, the temperature of the water can increase by as much as 2°C. Modelling of the heat budget shows the main source of heat is the discharge of blow-down from the industrial cooling towers.

Evaporative cooling systems

Industrial developers reduce the temperature of the return flow using evaporative cooling towers. An evaporative cooling tower is a heat exchanger where heat transfers from the water to the air. In a "spray filled tower", the jetting of water creates a rain-like pattern, through which an upward draft of air is created using fans to cool the spray. The governing equation used to estimate the temperature of the return flow leaving the tower (T) is shown below (Eq. 1). The temperature of the return flow is a function of the dewpoint temperature of the air (A_w) that varies with the local climate, and the approach temperature (T_a) set by the design of the tower (CHEMICAL RESOURCES, 2003; Marley, 2004). The approach temperature is the difference between the temperature of the return flow (T) and ambient wet bulb temperature (T_a) given by:

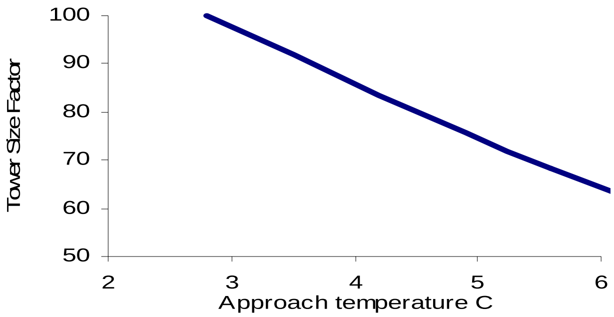
$$T = A_w + T_a \qquad [1]$$

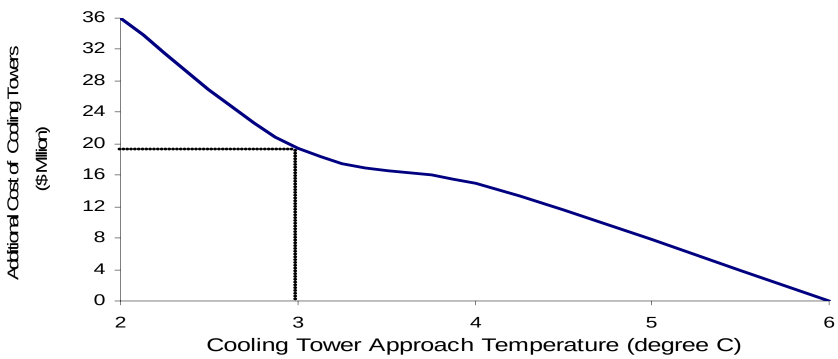
Figure 2 shows the size of the cooling tower is related inversely to the approach temperature (T_a). The lowest practical approach temperature on the Burrup is just below 3°C (Marley, 2004). Physical limits prevent evaporative cooling towers operating with an approach temperature of less than 3°C.

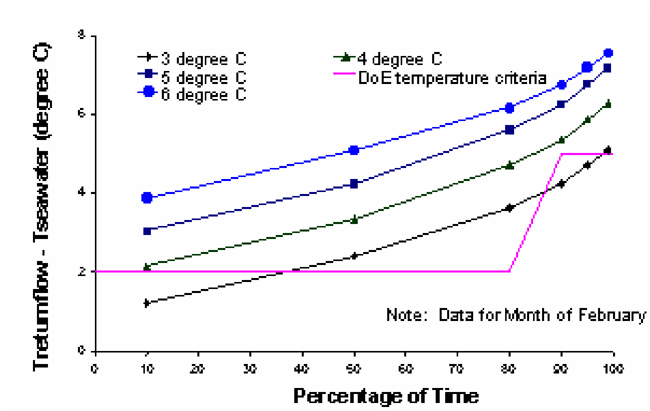
Cooling tower cost

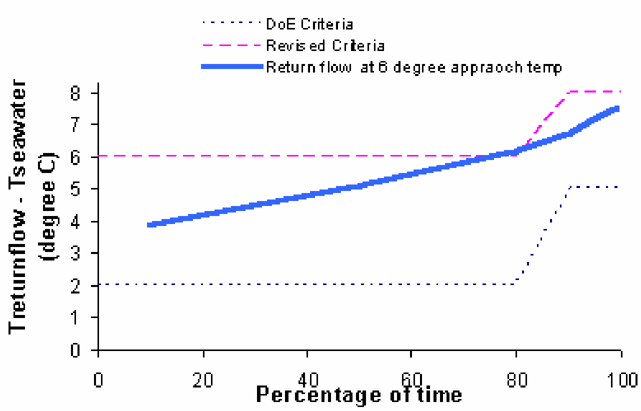
Figure 3 shows the extra capital cost required to build cooling towers for the six developers, based on their typical heat loads, with an approach temperature of less than 6°C. Figure 3 shows that if each developer was required to build a tower with an approach temperature of 6°C, total capital investment will be the base cost of the tower. Reduction of the approach temperature has a dramatic impact on the cost of the cooling towers. For example, if each developer built a tower with an approach temperature of 3°C, the cost of the cooling towers will increase by approximately Aus$20 million above the base cost. In addition to the increasing capital expenditure with reducing approach temperatures, the operating costs, associated with the cost of electricity used by cooling fans, also increases.

Figure 4 shows the output from the heat budget model with the temperature performance of cooling towers using approach temperatures of 3, 4, 5 and 6°C, and the DoE temperature criteria for the return flow (ΔT of 2° for 80% of the time). The model uses seawater temperature data for the Burrup Peninsula at King Bay and worst-case meteorological data from February 1998. Figure 4 shows a cooling tower designed to 3°C approach temperature, at the upper limit of physical design, will only comply with the DoE temperature criteria less than 50% of the time. At higher approach temperatures, there is complete non-compliance with the DoE criteria.









Revised temperature criteria

Based on contemporary cooling tower design, an approach temperature of 3°C for the Burrup Peninsula represents the practical upper limit of design. Figure 4 shows that an approach temperature of 3°C complies with the DoE temperature criteria for less than 50% of the time. Cooling towers designed for an approach temperature of 6°C represent current world's best practice (Marley, 2004). Figure 5 shows that such towers exceed the DoE criteria. As a result, the Water Corporation has proposed a relaxation to DoE's temperature criteria to 6°C for 80% of the time (with a maximum of 8°C). Therefore, it is necessary to assess the influence of the revised discharge temperature on the biota of King Bay.

Ocean outlet diffuser design

DoE specified that the outlet diffuser must provide dilution of at least 17:1 within an initial mixing zone with area of 0.01 km^2. This requirement was based on a maximum increase in salinity of less

Left, from top to bottom:

Figure 2
Relationship between approach temperature and relative size of cooling tower for approach temperatures from 2 to 6°C

Figure 3
Cost of cooling tower as a function of approach temperature. The additional cost represents the extra cost above the capital cost for a cooling tower designed to an approach temperature of 6°C. Costs given in Australian Dollars.

Figure 4
Plot showing the return flow temperature above intake as a function of cooling tower approach temperatures of 3, 4, 5 and 6°C. Where, Treturnflow is the temperature of the return flow, Tseawater is the temperature of the intake seawater, and Treturnflow-Tseawater is Δ. The DoE criterion is also shown.

Figure 5
Existing DoE criteria (Δ of 2° with 5° max) and proposed relaxation with the temperature curve for cooling towers designed with approach temperature of 6°C. Note: curve based on climate data for February 1998.

than 5% at the edge of the mixing zone (after initial dilution). Plume modelling carried out provided a design that met the requirements of DoE (Wallis, 2003). The final design of the diffuser includes 28 ports, 10 m spacing and 150 mm outlets to yield an initial dilution of 17:1 within a mixing zone area of 0.01 km^2. Table 1 shows the key design characteristics for the outlet diffuser.

Figure 6 shows the output from the plume dispersion model predicts the position of the plume (in cross-section between the sea surface and the seabed as a function of distance downstream of the diffuser). The movement of the plume is complex in that the return flow directs upward at 30 degree above the horizontal. The plume mixes with the adjacent seawater, interacts with the surface and then eventually turns downward, as the plume is denser than the ambient seawater. On the seabed, the plume flattens into a wide shallow layer and then mixes upward into the overlying water. The zone of initial mixing, termed the near field, is 12 m wide on either side of the diffuser pipeline, and 14 m wide when accounting for seawater currents.

TABLE 1
Key design characteristics for the ocean outlet diffuser (Wallis, 2003)

Characteristic	Value	Units
Design discharge	210 000	m^3/d
Water depth at MSL	6.7 to 7.6	m
Water depth at MLWS tide level	4.8 to 5.7	m
Median current speed	0.07	m/s
Salinity of return flow	66	ppt
Median salinity of ambient seawater	36	ppt
Velocity of discharge through ports	4.5	m/s
Orientation of ports from horizontal	30°	
Number of ports	28	
Port spacing	10	m
Minimum dilution achieved	17:1	
Mixing zone area	7280	m^2

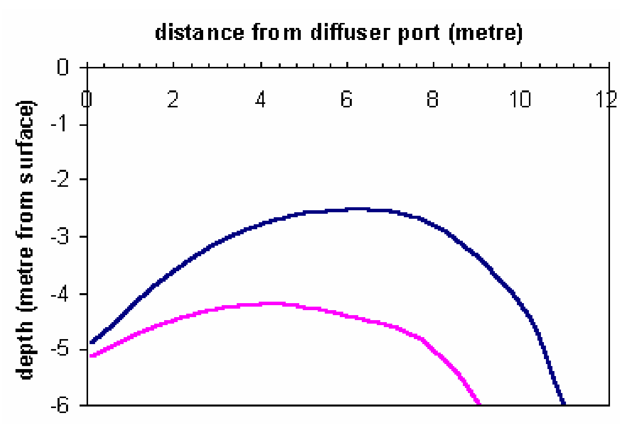


Figure 6
Position of a plume in cross-section between the sea surface and the seabed as a function of distance downstream of the outlet diffuser port.

Reference conditions in King Bay

ANZECC (2000) guidelines do not specify criteria for the discharge of heated seawater into tropical coastal waters. However, they provide guidance to develop trigger values for physical and chemical stressors in marine waters.

"For physical and chemical stressors and toxicants in water and sediments, the preferred approach to develop trigger values follows the order: use of biological effects data, then the use of local reference data, and finally (least preferred) use of table of default values in the guidelines" (ANZECC, 2000).

The monthly mean temperature of the seawater in the outer areas of King Bay varies from 19°C in the winter to 33°C in the summer (see Fig. 7). In the near shore (shallow) areas, solar heating increases this range by a further 2°C on each tidal cycle caused by movement of seawater across the sun-baked mud flats.

The sediments of King Bay (and around the ocean outlet) comprise fine silty sands with some shell and coral fragments. Benthic infauna include annelids, nematodes and sipunculid worms, and molluscs. Surface fauna include crustaceans, echinoderms, bryozoans and hydroids. Unfortunately, there is little available thermal bio-effect data for these species. To assess their tolerance to increases in temperature, it is necessary to review the distribution of species within King Bay. In the shallows, although the temperature increases by more than 2 degree above that in King Bay, there is no influence on the distribution of the infauna and fauna. Corals are the only organisms reportedly influenced by seawater temperatures exceeding 30°C (EPA, 2002). However, the corals also inhabit areas of King Bay that exceed 30°C for 4 months in the summer. Thus, all the biota have adapted to tolerate temperature exceedances of up to 2°C above ambient.

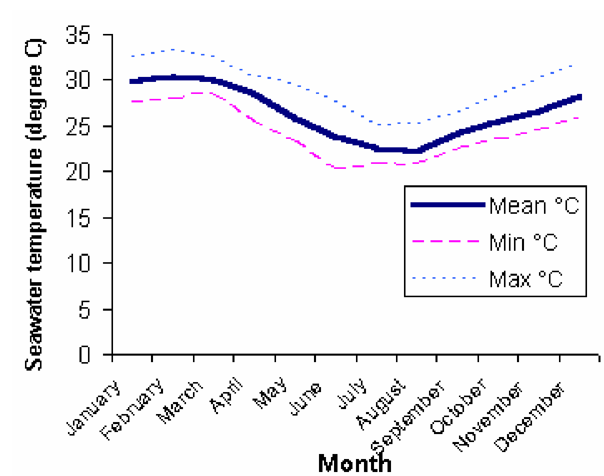


Figure 7
Minimum, mean and maximum seawater temperature measured at the outer (seaward) side of King Bay, in Mermaid Sound. In the near-shore areas, tidal movement over the mud flats increases the temperature range by at least 2°C.

Temperature of the diffuser mixing zone (near field)

The temperature of the return flow and the dilution provided by the diffuser governs the temperature rise at the edge of the mixing zone (termed the near field). Table 2 shows the temperature of the seawater at the edge of the mixing zone as a function of return-flow temperature, and diffuser dilution.

Based on the criteria specified by DoE, the return flow at ΔT of 2°C discharged through the diffuser with dilution of 17:1 will increase the temperature of the seawater at the edge of the mixing zone by 0.1°C. However, discharge of the return flow at ΔT of 6°C through the diffuser will increase the temperature of the seawater at the edge of the mixing zone by 0.3°C. Thus, relaxing the return flow temperature from ΔT of 2°C to 6°C will increase the temperature at the edge of the mixing zone by only 0.2°C. Reference data for King Bay show the fauna and infauna tolerate temperature excursions of up to 2°C above ambient and thus will be unaffected by the discharge of return flow at ΔT of 6°C.

TABLE 2
Temperature of the seawater at the edge of the zone of initial mixing

Temperature of discharge, above ambient (°C)	Minimum dilution within the initial zone of mixing	Temperature zone, increase at edge of mixing above ambient (°C)
2	17:1	0.11
4	17:1	0.23
6	17:1	0.35
8	17:1	0.47

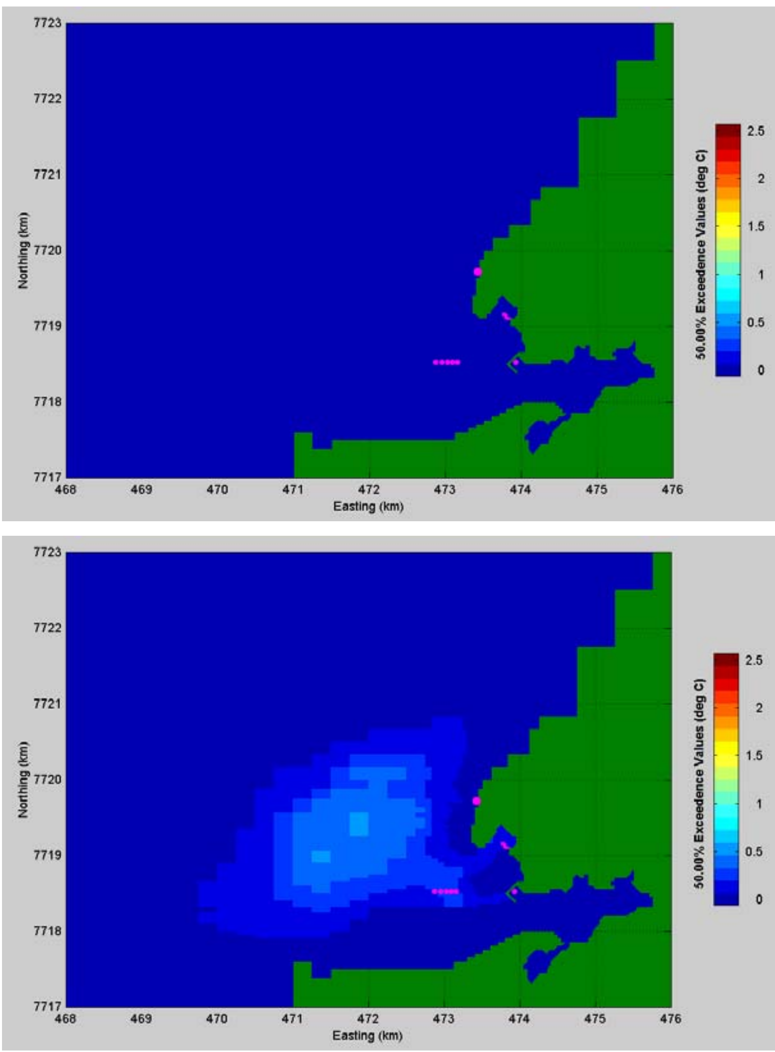


Figure 8
Plan view of King Bay showing the simulated median "Temperatures for the surface layer (upper plot) and seabed (lower plot) for a return flow discharged at Δ of 6°C.

Temperature change in King Bay (Far Field)

The Environmental Fluid Dynamics Code (EFDC) model (Burling, 2003) was set up to estimate the influence of the revised return flow temperature (ΔT 6°C) on the seawater temperature of King Bay. DoE expressed concern that changes in seawater temperature caused by the discharge could affect corals, situated 700 m south of the outlet. The model represents King Bay using a 50 m by 50 m horizontal grid divided vertically into five equal layers. Input to the model includes local climate data, bathymetry, boundary current velocities and return flow temperature data. From Equation 1, the temperature of the return flow is simulated using ambient wet-bulb temperature data and an approach temperature of 6°C.

The model simulation period is 32 days from 1 February to 4 March 1998. In addition, the simulation period includes an extra ten days of additional "warm-up" to initialise and stabilise the background seawater temperature. The period selected provided a worst-case temperature condition in King Bay (Burling, 2003).

The model represented the outlet diffuser using five adjacent model cells to simulate discharge from the 260 m long diffuser (see Fig. 8). The EFDC model is used to assess two temperature scenarios. The first scenario models the revised return flow discharged at ΔT of 6°C. The second scenario models the return flow conforming to the DoE criteria (termed the base case). Figure 8 shows the variation in seawater temperature across King Bay for the surface and bottom layers. Figure 9 shows the time series plots for the revised return flow and base case for the edge of the mixing zone. Figure 10 shows the time series plots for the point 700 m south of the diffuser, at the nearest corals.

Figures 8, 9 and 10 show the density of the plume causes it to sink so that the effect near the seabed is marginally greater than the effects at the surface. In Fig. 10, at both the surface and seabed, the temperature increase above background is <0.2°C for more than 90% of the time. Far field modelling shows the return flow discharged at 6°C above intake will have no measurable influence on the corals with a residual increase in maximum temperature of <0.1°C. Long term monitoring of seawater temperature shows this increase is less than the diurnal variation measured during a tidal cycle and thus will present no influence on the corals.

Conclusions

Key findings of this study include:

- Review of evaporative cooling system performance shows the construction of large towers are unable to comply with the stringent temperature discharge criteria (ΔT 2°C) specified by the Department of the Environment. A more practical, and cost effective approach, is to stipulate the approach temperature for cooling tower design on the Burrup. Tower design should conform to an approach temperature of 6°C. This will result in a return flow discharge ΔT of 6°C, under worst-case conditions.
- Numerical modelling of the near- and far-field areas within King Bay shows the discharge at the revised temperature (DT 6°C) will not

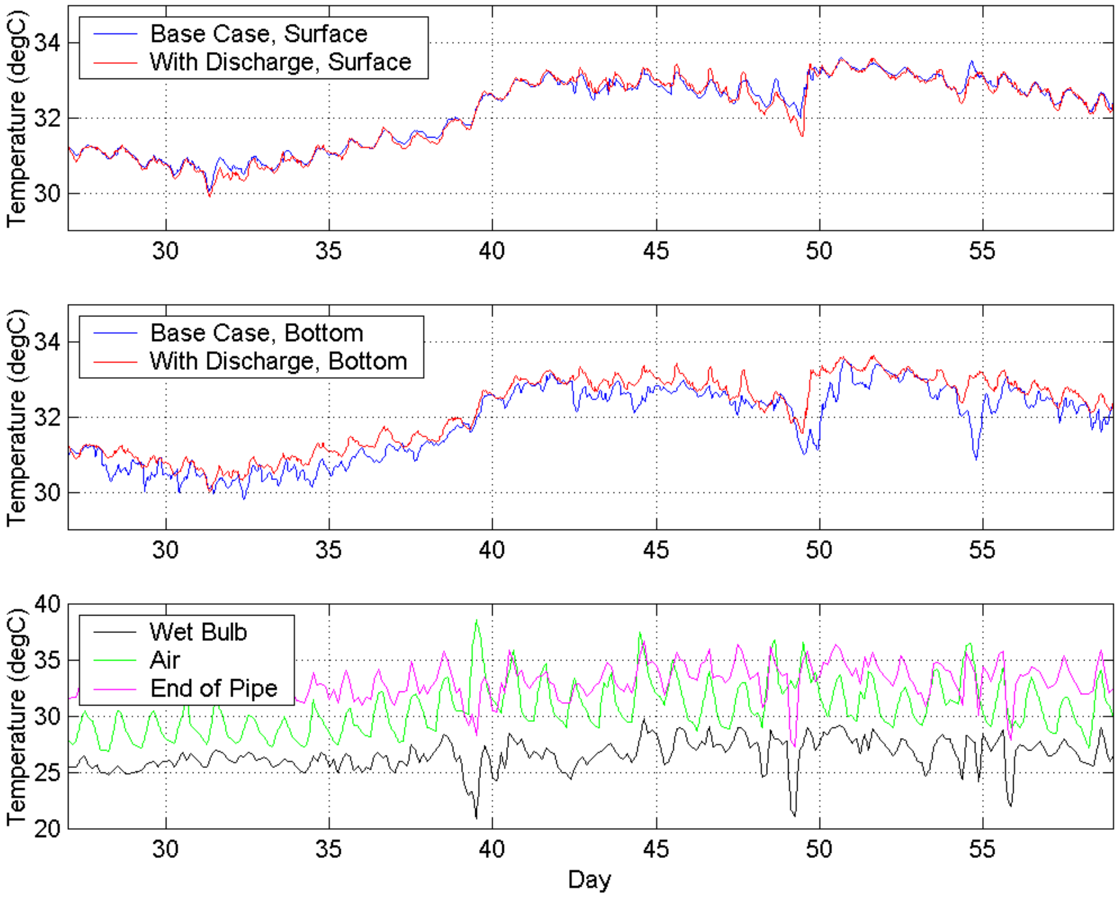


Figure 9

Time series of the temperature data at the edge of the diffuser mixing zone. The upper plot shows the simulated surface data. The middle plot shows the simulated bottom data, and the lower plot shows the measured wet bulb, air and discharge temperature .

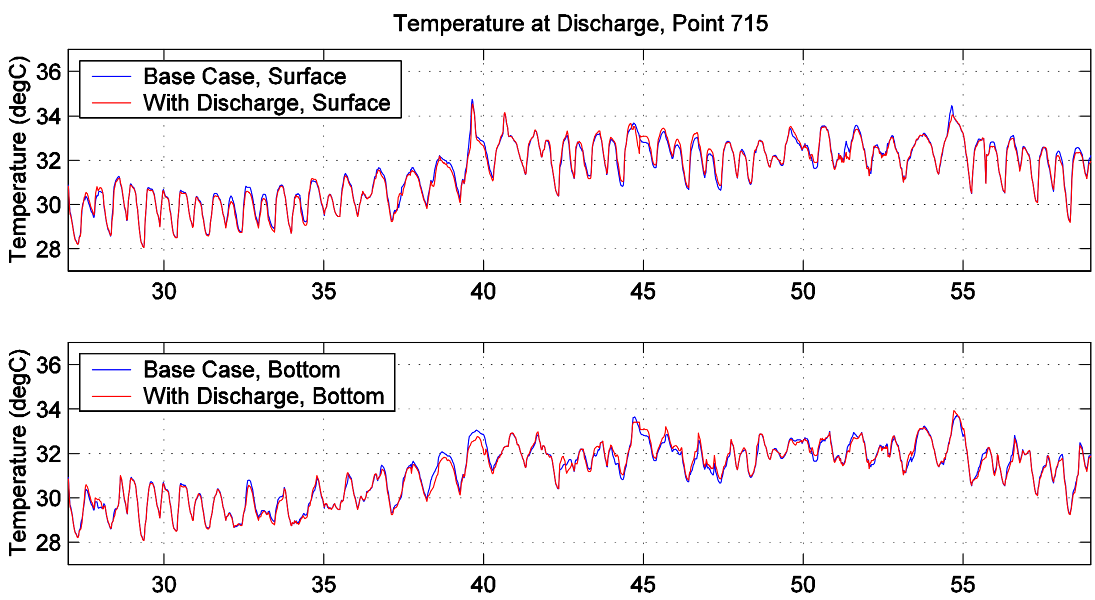


Figure 10

Time series plots of simulated seawater temperature at the southern side of King Bay (700 m from the diffuser) at the nearest coral. The upper plot shows the surface layer with the base case and modelled condition. The lower plot shows the bottom layer with the base case and modelled condition.

influence the biota in King Bay. The local fauna tolerate large seasonal and diurnal changes in seawater temperature. The nearest corals are located 700 m from the diffuser and will be unaffected by the discharge. Thus, the scientific analysis supports an argument for relaxation of the DT 2°C criteria imposed by the DoE for discharge of return flow to King Bay.

This paper describes a comprehensive process to develop and test thermal discharge criteria for marine discharge from large industrial projects. The process draws information from ecological, water quality, meteorological, oceanographic, and engineering sources thus provides a unique understanding of the thermal regime and discharge conditions in King Bay.

The Water Corporation is committed to stringent protection of the environment, and in this regard is developing an environmental management system (EMS) for the Burrup project. The EMS includes intensive real time monitoring of the intake, return flow and the near shore marine areas. Within the EMS, control systems will minimise fluctuations in the temperature of the return flow. DoE has acknowledged that some relaxation to its Ministerial Condition may be required and is currently reviewing this work in relation to the potential for relaxing the temperature discharge criteria.

The BPIWS project is currently under construction and will be operational in time to supply water to the first developer in March 2005.

Acknowledgements

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