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Simulation of Flow and Thermal Characteristics for Cooling Water System of a Steam Power Plant

Osama A. El Masry
Professor of Mechanical Engineering
Collage of Engineering, King Saud University
P.O. Box 800, Riyadh 11422, **KSA**
oelmasry@ksu.edu.sa

ABSTRACT

A 2500 MW steam power plant is planned to be built on the Red Sea coast at Ash Shuqayq, Saudi Arabia. The plant is a Designated Development as specified by the Meteorological and Environmental Protection Administration (MEPA) of Saudi Arabia. A complete study of the power plant impact on the environment and the preparation of an Environmental Impact Statement (EIS) are mandatory under the (MEPA) regulations [1]. The abstraction of seawater for condenser cooling purposes constitutes a major environmental impact of the project. Thermal pollution resulting from the large volume of condenser water is discharged into the sea and affects the marine life and the environment. Thermal modeling studies were performed to identify the extent of the seawater temperature rise area and the edge of the "Mixing Zone" in accordance with the Meteorological and Environmental Protection Administration (MEPA) requirements. A two-dimensional vertically integrated hydrodynamic model of the site was used with simulated typical discharges at 7° C above ambient. The model included the effects of bed friction, turbulent diffusion and convective acceleration. The model was constructed on a l00 x100 m grid size extending 10 km along the shoreline and 4 km offshore. Three significant current regimes were modeled. Injecting heated water into the cells immediately offshore from the outfall site simulated the power station outfalls. The modeling study provided considerable insight into the behavior of the cooling water system and helped to select the most efficient cooling water intake arrangement in order to minimize the impact of the sea water thermal pollution.

1. INTRODUCTION

The increasing demand for electricity in different parts of the world necessities building large thermal power plants. Although thermal power plants are not the sole or largest contributors to environmental pollution, they are, however, a growing concern, as their numbers and sizes will continue to increase in the decades ahead [2-4].

The Electricity Corporation of Saudi Arabia is planning to build an oil-fired Steam Power Plant at Ash Shuqayq, on the Eastern Coast of the Red Seam[5]. The power generating complex will initially consists of 1000 MW power plant, with provision to extend to an ultimate 2500 MW generating capacity. The main environmental impact of the new power Plant related to the seawater results from the effect of large volumes of wastewater discharged from the plant on the water quality and marine life.

Of major concern to the plant designer, the water thermal pollution associated with the plant cooling water system. The Red Sea has higher temperatures and salinity than those occurring in either the Mediterranean or Indian Ocean. Of greatest significance are the seasonal pattern of winds and currents plus the diurnal sea and land breezes, both of which will have considerable influence over the intake and discharge of plant water [6].

Seawater will be abstracted at an intake structure to provide cooling water for the power plant condensers, water for the desalination units and seawater associated with the flue gas scrubbing process. Drum screens with 5 mm mesh will be provided on the intake structure to remove girt and wood and to prevent small fish in the area from passing through. Intake velocities will be kept to a minimum to allow fish and marine organisms to swim back to the sea.

The principle waste water streams are: cooling water from the condensers, boiler blowdown, effluent from the sewage treatment plant, effluent from the desalination plant and effluent from the flue gas scrubbing process. Table (1) summarizes the quantities of wastewater discharges into the sea for Ash Shuqayq power plant.

Table (1) Discharge Water Quantities for the Plant

Source of Discharge	**Quantity of Discharge (m^3 /d)**	
	For 1.0 GW	**For 2.5 GW**
Cooling water	$3.41x10^6$	8.54×10^6
Boiler blowdown	$2.3x10^3$	5.8×10^3
Desalination plant	3.2×10^4	6.4×10^4
FGD plant	1.2×10^4	3.0×10^4
Total Discharge, m^3/d	**3.46×10^6**	**8.64×10^6**
Total Flow Rate, m^3/d	**40**	**100**

The Meteorological and Environmental Protection Administration (MEPA)'s guidelines for receiving water quality [1], (applied at the edge of the mixing zone and beyond for the discharge from any facility to the coastal water) are given in Table (2). The " mixing zone" is defined as the area of water directly adjacent to the area of discharge of contaminants where receiving water quality standards may be exceeded and such area is determined to minimize adverse effects to designated beneficial uses.

Also shown in Table (2), the MEPA's performance standards applied to wastewater at the end of the outfall and before discharge to coastal water [1] .Wastewater of different character shall be segregated to the maximum extent possible. Uncontaminated surface runoff and once-through cooling waters may be discharged to receiving waters without treatment.

In the present paper, model studies are carried out to identify the edge of the Mixing Zone and to establish criterion for the intake/outfall designs of the cooling water system at Ash Shuqayq Power Plant. The main objective of the work is to evaluate the intakeloutfall & recirculation cases suggested by the plant Engineering Consultant of the project [5] .

Table (2) Receiving Water Quality at the Edge of the Mixing Zone and Standards for Wastewater as given by MEPA [3]

Pollutant	Guidelines at edge of the mixing zone	Allowable effluent level for wastewater
Total suspended solids (TSSpp)	5%	15 mg/l (max.)
Temperature	1°C (Maximum change from typical local baseline conditions) at the edge of the mixing zone	MEP A determines the thermal properties of discharged water on a case by case basis

2. METHODS

The Model

The detailed recording current meter (RCM) output from the SOGREAH 1986-88 investigations for the neighboring Assir plant[7] was analyzed to compensate for the frequent periods of malfunction. The shoreline topography, bathymetry and tidal flows of the sea currents were derived from the best available information, most notably from the SOGREAH Assir studies. The Northwest boundary was located at the reef, 2 km west of the Assir plant, in order that the model could take into account the flows around this major feature. This Northwest boundary was defined by its water level so that the current velocities were not pre-determined around the point. The Southeast boundary imposed the required current velocity pattern as indicated on the model printouts and plots.

A 2-D vertically integrated hydrodynamic model of the site was set up with a simulated outfall discharge of $67m^3/s$ @ 7°C above ambient for a 1.0 GW station and $167m^3/s$ @ 7°C for a 2.5 GW station. The model was constructed on a l00m grid extending 10 km along the shoreline and 4 km offshore, a total of approximately 4000 cells orientated on approximately the Northwest -Southeast axis. Two initial intake cases were simulated, a 1200m long pier type and an 800m long sea bed type. The model grid used and the positions of the intake/outfall are shown in Fig. (1). Additional results were obtained for different pier intake lengths. A heat loss from the warmed water surface of 40 $W/^oC..m^2.day$, the input to the intake and recirculation temperature rises was included in the model.

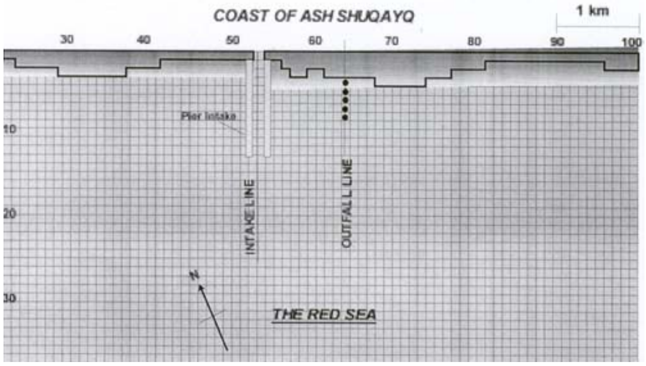

Fig. (1) Model grid used and intake/outfall positions

Current Simulation

The preliminary analysis of the data and the outfall/intake designs of Ash Shuqayq plant suggested that the physical cases, shown in Table (3), were significant:

The cases listed in the table were checked against the MOUK (7) site data to establish typical current flows for various times of the year. Analysis of the MOUK records showed the significant current flow cases to be:

-Strong Northwestwards flow (typically 0. 1 m/s) during the winter months.

-Intermittent Southeastwards flow (typically <0.05m/s) during the summer months.

-Variable direction flows during the "Spring/Autumn" periods.

However, current directions frequently reverse during the winter and particularly the summer months when wind induced or tidal currents dominate the main seasonal currents.

Table (3) Significant Outfall/Intake Cases to be Studied

	INTAKE	MIXING	CURRENTS
CASE A	PIER INTAKE	SURFACE FIELD*	Zero current
			Current from outfall to intake
			Current from intake to outfall
CASE B	PIER INTAKE	MIXED FIELD* *	Zero current
			Current from outfall to intake
			Current from intake to outfall
	SEA BED INTAKE	MIXED FIELD	Zero current
			Current from outfall to intake

* Warm water plume does not mix

**Warm water mixes with ambient

The most commonly occurring condition is probably the variable flow direction (Spring/ Autumn) case. Table (4) gives the percentage occurrence of different current regimes over the year

TABLE (4) Percentage Occurrence Of Different Current Regimes as Hours/Year

Current	NW@ 0.1 m/s	SE@ 0.1 m/s	SE@ 0.3 m/s	S/A
Duration	3216.24 hrs	968.88 hrs	1499.2 hrs	075.36 hrs
Percentage	36.7%	11.1%	17.1%	35.1%

From the above, four significant current regimes were selected for modeling:

1- Constant flow towards the Northwest (NW), for 134 days/year, at 0.1 mls.

2- Constant flow towards the Southeast (SE), for 40 days/year, at 0.1 mls.

3- Constant flow towards the Southeast (SE), for 62 days/year, at 0.03 mls.

4- A simulation of Spring and Autumn (S/ A) conditions with flows alternating from the Southeast (SE) to the Northwest (NW) on a diurnal basis for 128 days/year.

The above velocities were applied at a depth of 10m; the velocities were reduced for the shallower depths at the boundaries to allow for the increased effective bed resistance. The seaward boundary of the model was assumed to be located on a streamline and therefore no flow was permitted across this boundary.

Assumptions and Limitations of the Model

The model used for this study is an adaptation of the US Environmental Protection Agency's. DYNHYD model amended to allow for full 2-D flows [8]. This model now provides 2 dimensional depth integrated solutions to the conservation of mass, momentum and heat transport equations in the horizontal plane. The model includes the effects of bed friction, turbulent diffusion, convective acceleration and, where the information exists, of the earth's rotation and of wind friction. The heat transport equations include for transport by longitudinal dispersion and turbulent diffusion.

The numerical technique involves the solution of the Navier-Stokes equations of the conservation of mass and momentum, resolved into two dimensions, by a finite difference method applied to a rectangular grid of square cells. Each cell has a characteristic depth which, combined with the known boundary data, allows for the solution of the equations by a Gaussian elimination and back substitution method to give water levels, temperatures and velocities at each cell. Net heat flows in and out of the study grid are checked by balancing against the retained heat.[9&10].

Outfall Simulation

The power station outfalls were simulated by injecting heated water into the cells immediately offshore from the outfall site in the following manner:

-For the 1.0 GW model with a total outfall of 67 m^3/s at $+7^{o}C$ above ambient; heat was injected into the 3 cells offshore from the outfall site at rates of 23, 22 and 22 m^3/s per cell respectively.

-For the 2.5 GW model with a total outfall of 167 m^3/s at $+7^{o}C$ above ambient; heat was injected into the 5 cells offshore from the outfall site at a rate of 33.4 m^3 /s per cell.

These patterns for heat input from the outfall were derived from the near field plume studies of the outfalls. The locations of the respective input cells are shown as black dots on Fig. (1) and the temperature plots. It should be noted that the injection of even 33.4 m^3/s into a l00m square grid of 2.5m depth has a significant effect on the local flows; this is observable on the velocity plots.

Intakes Simulation

Two major variants of the intake structures were considered:

1- a surface intake extending 1200m offshore and drawing a full depth of water in between two solid piers. Flows and velocities in this intake channel come from the full depth at the end and are adjusted to match the outfall. The resolution of a model based on a l00m grid makes the total modeled width of the structure at 300m. This does not have a particular effect on the general flows around the end of the structure though small-scale flows will be substantially altered. This will be significant when estimating recirculation where the temperature of the flow drawn in by the intake is critical. To counter this problem, intake temperatures have been taken at the cell adjacent to the pier head on the south east side on the principle that any heated water that travels to this cell will be drawn into a real intake.

2- a sea bed intake located on the same line as the surface intake but 800 m offshore. Since there is no structure to deflect the flows, the temperature for recirculation is the temperature of that grid square. Since the intake water will only be drawn from the lower levels, it is assumed that there will be no recirculation for the stratified (surface) flow model.

Recirculation Simulation

As discussed above, the model simulates recirculation from the intake by always raising the outfall temperature to 7°C above the temperature at the intake. Thus, when the heated plume reaches the intake site, the outfall temperature will rise to 7°C above the temperature of the water taken. Heat is lost from the model by two mechanisms: heat is convected out of the study area by flows at the boundaries. Heat lost through convection does not return. heat is lost by radiation at a constant rate of 40 W /m^2 per °C per day. The remaining heat is retained in the system. Mass balance checks on the heat flows indicate that the three constant current velocity models have reached equilibrium by the end of the model run time, i e, the flow of heat into the study area equals the flow of heat out. Equilibrium is approached, but is not fully achieved, in the spring and autumn case and some further growth in the plume in the long term might be expected. This point was however not pursued since in reality it is unlikely that these flow conditions will continue undisturbed for much longer than the study period.

3. RESULTS

The models were run for a simulation period of 168 hrs (7 days) on a l00 seconds time-step. The results for the constant velocity flow models were derived from output at 168 hours. Three output plots were generated for the spring and autumn flow conditions; at 156, 162 and 168 hours. The calculated recirculation temperature represents the average temperature over the final 24 hrs of the model run. The current flow cases and current velocities considered in this study as modeling cases were identified in Table (5).

TABLE (5) MODELING CASES MATRIX KEY

Velocity	Direction	PIER INTAKE		SEA BED INTAKE	
		Mixed Flow	Surfae Flow	Mixed Flow	Surfae Flow
0.1 m/s	NW	PM1	PS1	SBM1	SBS1
0.1 m/s	SE	PM2	PS2	SBM2	SBS2
0.3 m/s	SE	PM3	PS3	SBM3	SBS3
S/A*		PM4	PS4	SBM4	SBS4

*S/A is the Spring/Autumn case occurring mainly during April and October, no dominant case with variable flow velocities and directions.

Results are given for cell velocities and temperatures as plots over a reduced grid area. Examples of the model outputs for the 1.0GW plant are shown graphically in Figs(2&3). Legand in fig. (2) applied to all temperature figures.

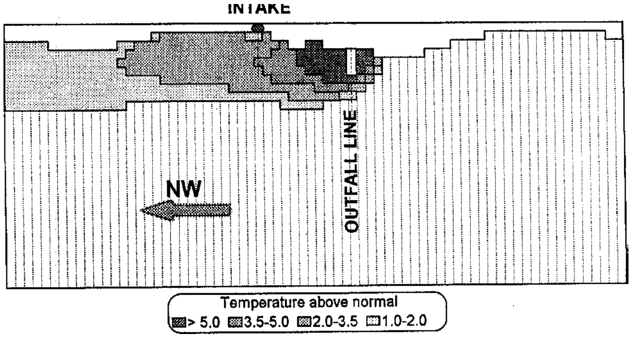

Fig. (2) Sea water temperature difference distribution for 1.0GW plant &Q=67m^3/s; Mixwed Flow, Current:NW.

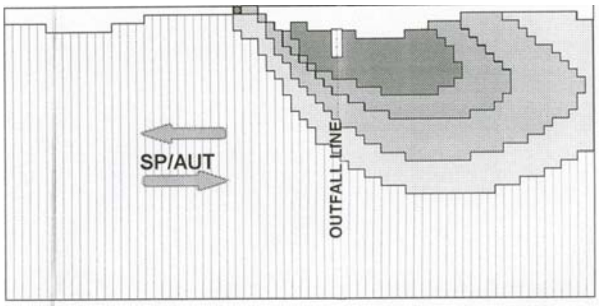

Fig. (3) Sea water temperature difference distribution for 1.0GW plant &Q=67m^3/s; Mixwed Flow, Current: Sp/Aut.

Outputs for the 2.5GW plant are shown likewise in Figs. (4-6).

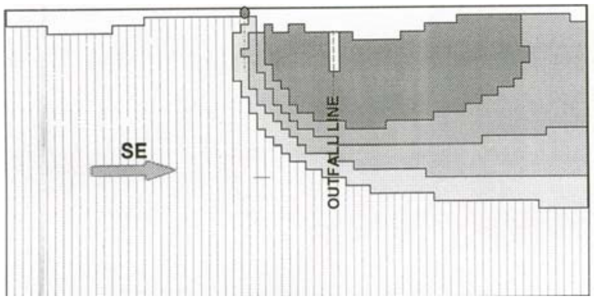

Fig. (4) Sea water temperature difference distribution for 2.5GW plant &Q=167m^3/s; Surface Flow, Current: SE.

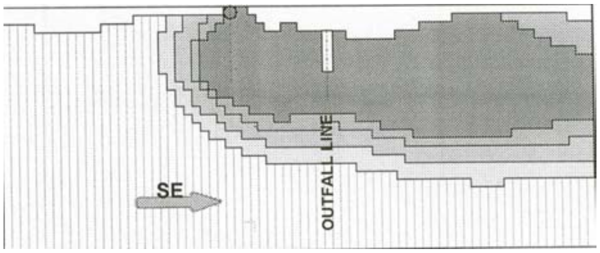

Fig. (5) Sea water temperature difference distribution for 2.5GW plant &Q=167m^3/s; Mixwed Flow, Current: SE.

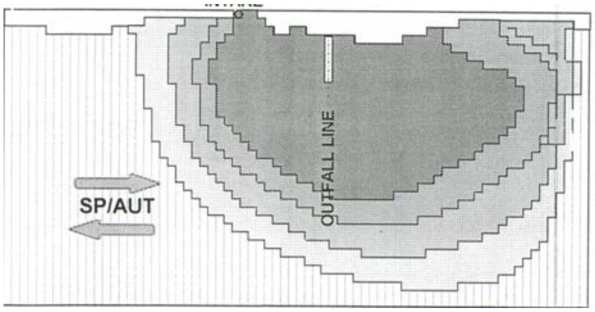

Fig. (6) Sea water temperature difference distribution for 2.5GW plant &Q=167m^3/s; Mixwed Flow, Current: Sp/Aut.

From model runs, the initial temperatures above ambient at those cells from which the intake water will be drawn are obtained. These circulation temperatures (^{0}C) are averaged over two cells where appropriate. The model output results are also developed into net present value (NPV) cost of recirculation assuming $400/ °C and shown in Fig. (7).

4. DISSCUSSION

Cooling Water System

The model studies provide considerable insight into the behavior of the cooling water system, but should not be considered a design study. An important issue in the design process is to select the type of CW system required. The two proposed systems are:

(a)To design for a 1.0 GW plant but with the option of extension at a later date for 2.5 GW.or

(b)To design for both 1.0 GW and 2.5 GW operation.

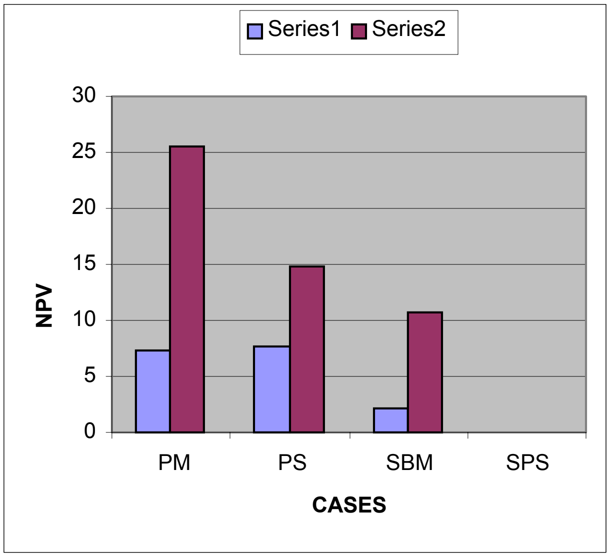

Fig. (7) Cost of circulation,NPV(US$M) for both Power Plants: Series1 is for 1.0MW and Series2 is for 2.5MW.

It is most probable that the NPV cost of recirculation is somewhere between the mixed flow and surface flow cases. Thus for the 1.0 GW station, the NPV cost of recirculation for a 1200m pier intake calculated from the model is of the order of US $7.5 million (average of the NPV of the two cases) and of the order of US $20 million for the 2.5 GW station.

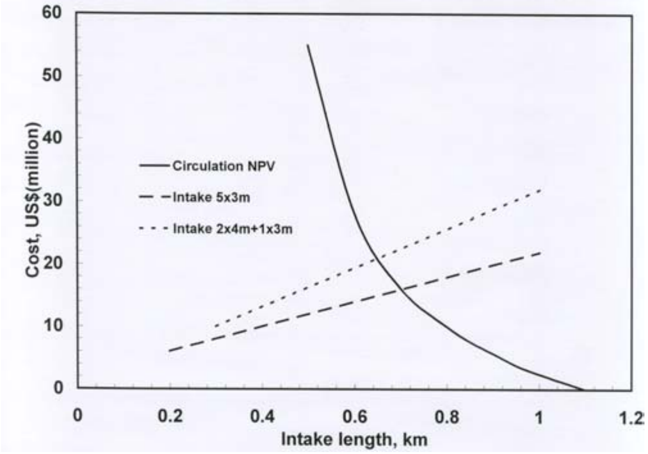

Fig. (8) NPV of Circulation and cost of sea bed intake as a function of intake length(km).

These results may be considered as points on a graph of intake length against NPV, as suggested in Fig. (8). The figure includes NPV cost of circulation results for variable pier lengths (300-1200) for 1.0 and 2.5 GW cases. Construction and operation cost of the pier was estimated according to available data. The figure tends to suggest that 1200m is a reasonable first assumption for a 1.0 GW station, but caculation suggested that 1800m is probably the better first assumption for a 2.5 GW station. The minimum seabed intake length is dictated by the minimum water depth in which it is practical to function, probably of the order of 6m (allowing, say, 3m water depth over the intakes). Existing bathymetric data suggests that for the intakes to be in 6m of water, the seabed intake would have to be 800m long. For the seabed intake, the probable NPV of recirculation for an 800m intake was of the order of US $1.0 million for a 1.0 GW station and US $5.0 million for a 2.5 GW station ,see Fig. (8). No data were obtained for variable seabed intake length and no optimisation graphs were tried.

Circulation

It has been suggested that the environmental standard for thermal discharge should be "water temperature not to exceed + 1°C above ambient beyond a 1.5-2.0 km radius from the outfall". According to the model, this standard will be exceeded in every case except for the 1.0 GW seabed intake with spring and autumn case, Fig. (3). In fact, for the 2.5 GW case with pier type surface intake, the temperature will be greater than 1°C above ambient at 5km down stream from the outfall, Fig.(5), however, as the heated water is likely to be contained within the upper few meters of the water column, the vulnerable benthos is unlikely to be affected beyond the shoreline in the immediate viscinity of the plant. To achieve a blanket standard of <+ 1 °C within 1.5 km would require a fivefold increase in initial dilution. This would be difficult to achieve and would increase the depth of mixed heated water, probably increasing the risk to benthos. It is advantageous to float the warmed water out on the sea surface as this will take advantage of stratification and maximize the heat loss to the atmosphere. Conversely, attempts to mix the warmed water in the stratified water column will cause heat to be trapped, conserved and its impact to be spread. The imposition of a simplistic environmental standard will not be appropriate in this case. The model studies have shown the effects of recirculation, particularly for the pier intake cases, to be greater than those assumed in a previous intuitive study [5]. This is probably due to the model results predict a more significant eddy and hot water pool generation in the lee of the intake during southeasterly flows than had previously been estimated.

To select the most efficient CW intake arrangement, it will be necessary to commission additional investigation which will enable the intake length/NPV optimization graphs similar to Fig. (8) to be established for both the pier and sea bed intakes.

From the model studies it is apparent that the range of uncertainty in terms of intake length is at least +33% This justifies additional investigations to reduce the uncertainty as part of the design. It is provisionally recommended that the following investigations be carried out for the project.

(i) Hydrographic survey (including confirmation of datum) to at least 5krn offshore.

(ii) Marine geophysical survey along the proposed intake line to at least 2km offshore.

(iii) Field investigation of the current structure and stratification of the water column, particularly during the spring/autumn and summer flow regimes.

(v) Thermal imaging studies of the existing Assir plant CW discharge. This may be carried out by commissioning satellite thermal imaging or by aerial survey techniques.

5. CONCLUSIONS

It should be noted that these model studies are preliminary in nature and have not been subject to calibration and verification by specific field studies. However, from the above results and discussion, one can draw the following conclusions:

l- Recirculaticn will reduce the efficiency of the station. The model studies have shown the effects of recirculation, particularly for the pier intake cases, to be greater than those assumed in a previous intuitive study.

2- Existing bathymetric data and the model results suggest that the seabed intake, if selected, would have to be at least 800 m long. The circulation results also recommended an increase of the length to 900 m would be safer for the 2.5GW plant.

3- The modeling results for the pier intake case tend to suggest that l200m is a reasonable first assumptipn for a 1.0 GW station, but that 1800m is probably the better first assumption for a 2.5 GW station. However, additional increase of the length by at least 20% will be advantageous.

4- For outfall design, it was found that it is advisable to float the warmed water out on the sea surface as this will take advantage of stratification and maximize the heat loss to the atmosphere.

5- To select the most efficient CW intake arrangement, it will be necessary to commission additional investigation which will enable the intake length/NPV optimization graphs be drawn.

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