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GESAMP: Thermal discharges in the marine environment

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PREFACE

GESAMP, the Joint Group of Experts on the Scientific Aspects of Marine Pollution, was established in 1969 and is today co-sponsored by the International Maritime Organization (IMO), Food and Agriculture Organization of the United Nations (FAO), United Nations Educational, Scientific and Cultural Organization (UNESCO), World Meteorological Organization (WMO), World Health Organization (WHO), International Atomic Energy Agency (IAEA), United Nations and United Nations Environment Programme (UNEP). According to its present terms of reference, the functions of GESAMP are:

- to provide advice relating to the scientific aspects of marine pollution 1/; and
- to prepare periodic reviews of the state of the Marine environment as regards marine pollution and to identify problem areas requiring special attention.

Since its beginning GESAMP involved a large number of experts as members of GESAMP or GESAMP Working Group and produced, at the request of the sponsoring organizations, numerous reports 2/.

This document is the edited and approved report of the GESAMP Working Group on Biological Effects of Thermal Discharges in the Marine Environment, which met from 21 to 25 September 1981 in Dubrovnik, Yugoslavia, from 18 to 22 October 1982 and from 3 to 7 October 1983 in Rome, at FAO Headquarters.

The following members participated in the preparation of the report: François Bordet, Harry H. Carter, Pierre Chardy, Stephen L. Coles, Karl Iver Dahl-Madsen, Edgardo D. Gomez, Gwyneth D. Howells (Chairman, third session), Prabhakar R. Kamath, Branko Kurelec, Milivoj Kuzmic, Edward P. Myers, Heiner C.F. Naeve (Technical Secretary), Velimir Pravdic (Chairman, first and second session), Anne E. Smith, Dale Straughan, Henk E. Sweers.

The Working Group was requested to selectively review available information on the effects of thermal discharges on coastal waters and subsequently evaluate direct and indirect effects of thermal discharges on marine life, particularly fishery resources, and to develop guidelines for the siting of discharges of heated water, with a view to minimizing harmful effects on living marine resources. It was suggested that the Working Group should not only deal with the direct effect of thermal discharges, namely the increase in temperature, but also with possible indirect effects, including alterations in the metabolism and bioaccumulation of toxic substances. Additionally, it was noted that power plants had effects other than those caused by temperature, e.g., those due to chlorination.

The activities of the Working Group were organized by FAO, acting as the "lead agency". The Working Group was jointly sponsored by the Food and Agriculture Organization of the United Nations (FAO), The United Nations Educational, Scientific and Cultural Organization (Unesco) and the United Nations Environment Programme (UNEP).

1/ GESAMP defined marine pollution as "introduction by man, directly or indirectly, of substances or energy into the marine environment (including estuaries) resulting in such deleterious effects as harm to living resources, hazards to human health, hindrance to marine activities including fishing, impairment of quality for use of sea-water, and reduction of amenities."

2/ V. Pravdic: GESAMP, The First Dozen Years. UNEP, 1981.

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THERMAL DISCHARGES IN THE MARINE ENVIRONMENT

1. INTRODUCTION

This study consists of two parts. In the first part (Sections 2-8) problems are identified, ecosystem effects described and potential impacts recognized. In a number of case studies, environmental impacts have been observed. The report also identifies regions of special sensitivity, such as tropical and subtropical zones, as well as those of particular biological importance for the coastal and marine ecosystem.

In the second part (Sections 9 and 10) guidelines for environmentally-sound siting and design practices are developed. Without trying to provide detailed assessment methodologies, or engineering recommendations, these sections list the sequential steps and time scale for studies and evaluations designed to match the engineering and planning steps of site and system selection, construction, commissioning and operation, and indicate how decisions can be made on a systematized, orderly and consistent basis.

2. STATEMENT OF THE PROBLEM

2.1 Cooling Water Systems

Sources of heated effluents discharged to the coastal marine or estuarine receiving waters are almost always directly or indirectly related to power generation. Effluents may be geothermal in origin if such sources are used in power generation and/or ambient heating. Chemical processing plants need process steam, and so do petroleum refineries, steel mills and cokeries. Fossil fuel burning plants may use sea water for flue gas and smoke scrubbing, adding volume, discharged heat and pollutants to the effluent.

A 1 000 MW electricity generating station with once-through cooling typically discharges to the aquatic environment approximately 30-60 m^3/s if the temperature rise across the condensers, ΔT, is limited to 10^oC. The term 'once-through' cooling applies to plants whose condenser cooling water is withdrawn from and returned at an elevated temperature to the water body on which it is sited.

The conversion efficiency of thermal to electrical energy in thermal power plants is fundamentally limited by the basic physical principle of the second law of thermodynamics. Given present limitations to the temperature in turbines, the maximum conversion efficiency is approximately 65% in large conventional power plants. Actual efficiency is lower, approximately 40%, due to technical limitations to designing an ideal machine. To make the system operate, heat must be withdrawn from the system and either discarded or used for example in pre-heating applications or space heating.

When such a heated effluent is discharged, its fate depends upon physical processes which, for the purpose of analysis, may be categorized as either near- or far-field (Fig. 1). The near-field processes are governed primarily by the characteristics of the discharge whereas the far-field processes depend on larger scale ambient conditions. Conditions in the near-field are strongly dependent on the thermal emission rate, i.e. the rate at which excess heat contained in the cooling water is discharged, the temperature of the cooling water and discharge design, i.e. at depth or surface, low or high velocity, jet or diffuser. Conditions in the far-field, on the other hand, depend on the thermal emission rate, but also the receiving water characteristics such as turbulence and stratification, and surface cooling.

It is important to differentiate between these two regions for several reasons, even though the transition is not easy to delineate and is inconstant, and to some degree arbitrary. First, the separation by physical processes simplifies modelling of the thermal plume; secondly, even though the separation is based on physical processes, the biological impact, if present, is more than likely 'long-term' in the far-field, whereas such effects can be either 'long-term' or 'short-term' in the near-field; and finally in an estuarine or coastal situation where the tidal flows reverse, heat discharged at some earlier time (the far-field) may be re-entrained into the near field or even directly recirculated into the plant via the intake. Periodic interactions of this type can and do result in variations of an order of magnitude in the areas enclosed within specific isotherms.

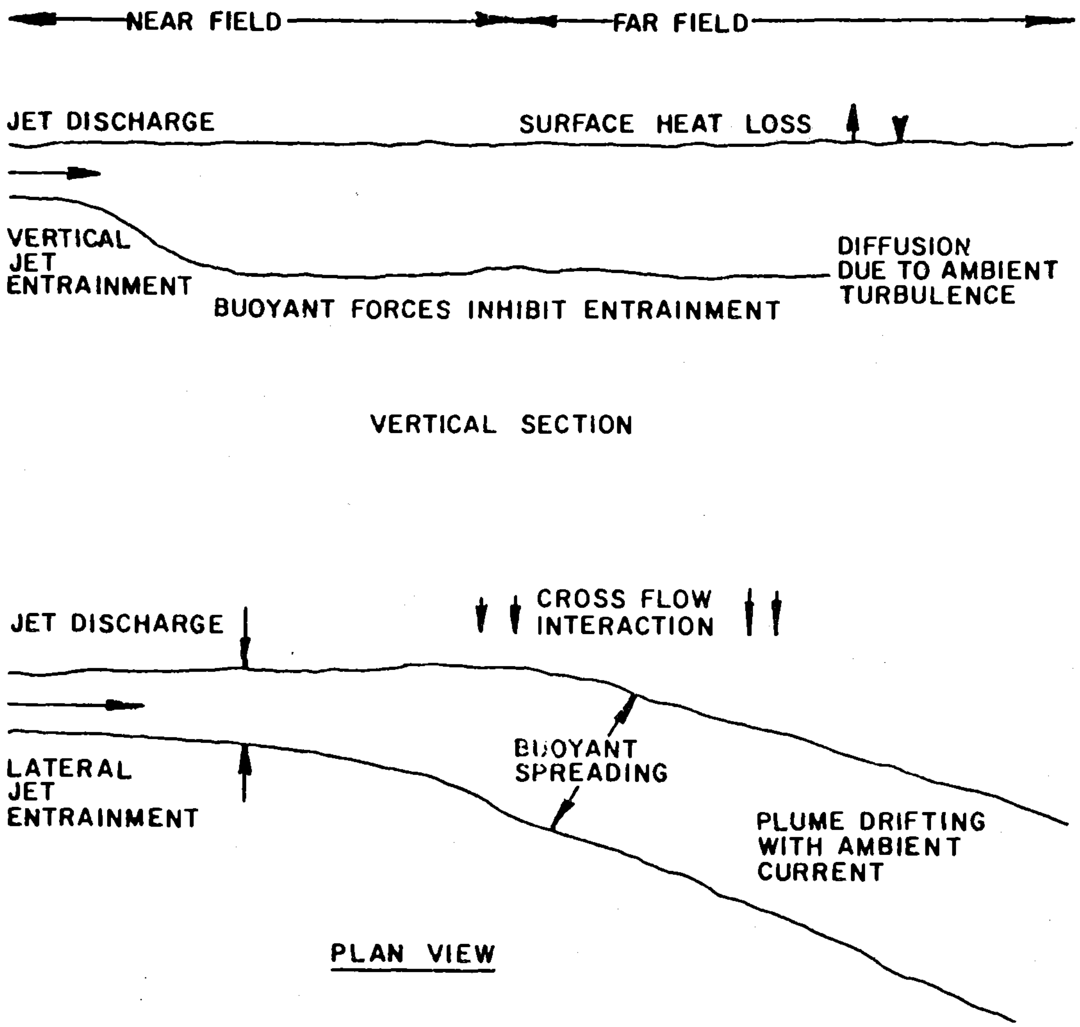

Figure 1. Schematic categorization of plume geometry according to physical processes

2.2 Cooling Water Effects

Many field investigations of the impact of thermal discharges are directed to the observation of overall effect, e.g. 'before and after' studies. However, most field surveys do not distinguish between the changes due to the different components of cooling water abstraction, use and discharge, or of their different constituents, or of the lasting effects of construction and those of operation. It is necessary to distinguish these different components.

The source and the purpose of a cooling water system will dictate its characteristics. Many chemical processing industries, steel mills, cokeries, among others, have need of process water and steam, as well as of power. Many such plants combine power generation and process effluents and discharge them at the same outfall. Power plants and process steam generators using solid and liquid fossil fuel may be required to use sea water for flue gas scrubbing. The resulting effluents may involve acid components, suspended particulates, residual oxidant products due to biocide treatment, metal corrosion products, anticorrosion and wetting chemicals as well as reject heat and radioactive nuclides in the case of nuclear plants. It will be necessary to identify the effects of these chemicals on the marine ecosystem, both as individual agents, as well as their possible interactive (synergistic or compensatory) effects. It will also be important to distinguish effects overall from those caused by pumping and screening of cooling waters, of passage of water through the plant (pump entrainment) and of discharge (e.g. velocity of flow, pressure, turbulence, temperature (see Fig. 2)). Any consequent effect on man, user of the marine ecosystem and its products, should also be considered.

The need to distinguish these components separately arises from their effects on different target organisms and processes, and to identify the causal agents of each effect so that appropriate remedial action can be implemented, if considered necessary.

It will also be necessary to consider operating as well as design conditions at power stations - that is the volume of cooling water abstracted, the operating ΔT across the condensers, the increment of discharge temperature above ambient, the customary pattern of generation, and the practice of antifouling required. Any consequent effects on man, user of the marine ecosystem and its products, should also be considered.

2.3 Sea Water Flue Gas Scrubbing

Sea water washing of flue gases may in future be required at some new sites to reduce atmospheric emissions of acid-forming gases, especially SO_2. The expected consequences would include significant changes in the quality of the discharge waters.

Flue gas washing would divert the heat loss via stack gases to the aquatic discharge, leading to some increase in the temperature and the extent of the heated plume. The acidity in the wash water would require neutralization with lime or similar material and if not completely neutralized the lower pH of the discharge water could have significant effects on marine organisms accustomed to well-buffered conditions around pH ~8. An increase of sulphate in the discharge water could lead to accumulation of sulphide in a poorly oxygenated receiving water but is an unimportant contribution at sites already polluted; at unpolluted sites, reducing conditions would not occur. The scrubbing water will also scavenge fine particulate material normally escaping the precipitators - these fine particulates are high in trace metals which are potentially soluble in the acid wash water.

A recent desk study of flue gas scrubbing at an industrial estuarine site concluded that the effects of enhanced temperature and reduced pH were potentially important. Trace metals were, in general, insignificant in quantity at an already polluted site, and would be well below toxic concentrations at unpolluted sites, with the possible exception of mercury and arsenic, for which good data on concentration in present stack emissions were lacking.

2.4 Antifouling Agents

The use of antifouling agents (usually chlorine or hypochlorite) deserves special attention (see 3.2). The chemical form of chlorine used, the dosing regime (e.g. intermittent or continuous) and the rate of decay of chlorine and its derivatives during passage through the station and in the discharge plume, will be important in measuring and judging the effects of chlorine or of chlorine and temperature.

Chlorine is the most commonly used biocide in intake waters for control of biofouling. Chlorination is either intermittent (generally 12-15 mg/l every 4 or 8 hours at condenser inlet) or continuous (to give 1-5 mg/l at condenser inlet), both with expected discharge concentrations no greater than 0.2 mg/l on average.

Differences between sites in the form of chlorine application (chlorine gas, hypochlorite, ClO_2, electrolytic generated chlorine), in the initial chlorine concentration applied and in the point of application may lead to some variations in the reaction pathways and to the resulting reaction products. The principal reaction is:

$$Cl_2 + H_2O \rightarrow HOCl + H^+ + Cl^- \quad (K = 3 \cdot 94 \cdot 10^{-4} \text{ at } 25^{o}C)$$

This results in a 50:50 mixture of HOCl and OCl^- in sea water. Further reaction with bromides in sea water leads to hypobromous acid and hypobromite ions. Most (90%) of the chlorine dosed decays, principally to chloride, within half hour. These initial fast (~10 minutes) reactions are pH and salinity dependent. Following these are slower reactions (over ~ 10 days) with ammonia, other N compounds and organic matter in the receiving water. Some halogenated organic compounds may also be formed, but at one station employing electrolytic chlorine, less than 0.1 percent was converted to $CHBr_3$ and $CHBr_2Cl$.

Toxicity of the reaction products varies, e.g. HOCl is more toxic than OCl^-, and chloramines are more toxic (to algae) than chlorine alone. Mortality is related to dose, exposure time, temperature, pH, biomass and the sensitivity of the organisms. For the common fouling organism of temperate waters, *Mytilus edulis*, an empirical model of toxic response has been developed:

$$\log D = a - b(T^{o}C) - c \log TRO$$

where D, time to kill in days, is related to a constant a (= 2.99), the water temperature (0.066 • T^{o}C) and the total residual oxidant (0.80 log TRO). Hence at low TRO (<1 mg/l), temperature exerts a greater influence, and at low temperatures (< 20^{o}C) the time for complete mortality is very long. Effective practice at once-through coastal stations in the U.K. is to chlorinate at a rate of 0.2 to 0.5 mg/l at the condenser inlets to control mussel settlement rather than kill during the likely infective period from April to November or when the ambient temperature is >10^{o}C.

Most studies of the decay of chlorine in sea water have been made in the laboratory, since only concentrations of ≥50 µg/l TRO can be measured in the field, while concentrations as low as 5-10 µg/l can be measured in the laboratory. As a result, discharges are largely uncharted and the thermal discharge plume has been used as surrogate. However, recent studies have shown that both decay and dilution reduce the concentrations of TRO so that the chlorine plume is less than the thermal plume, although rates of decay will vary with sea water temperature and quality, and dilution with the configuration of the discharge. Hence, concern for combined effects of chlorine and temperature in the discharge can be limited in practice to the area of the thermal plume.

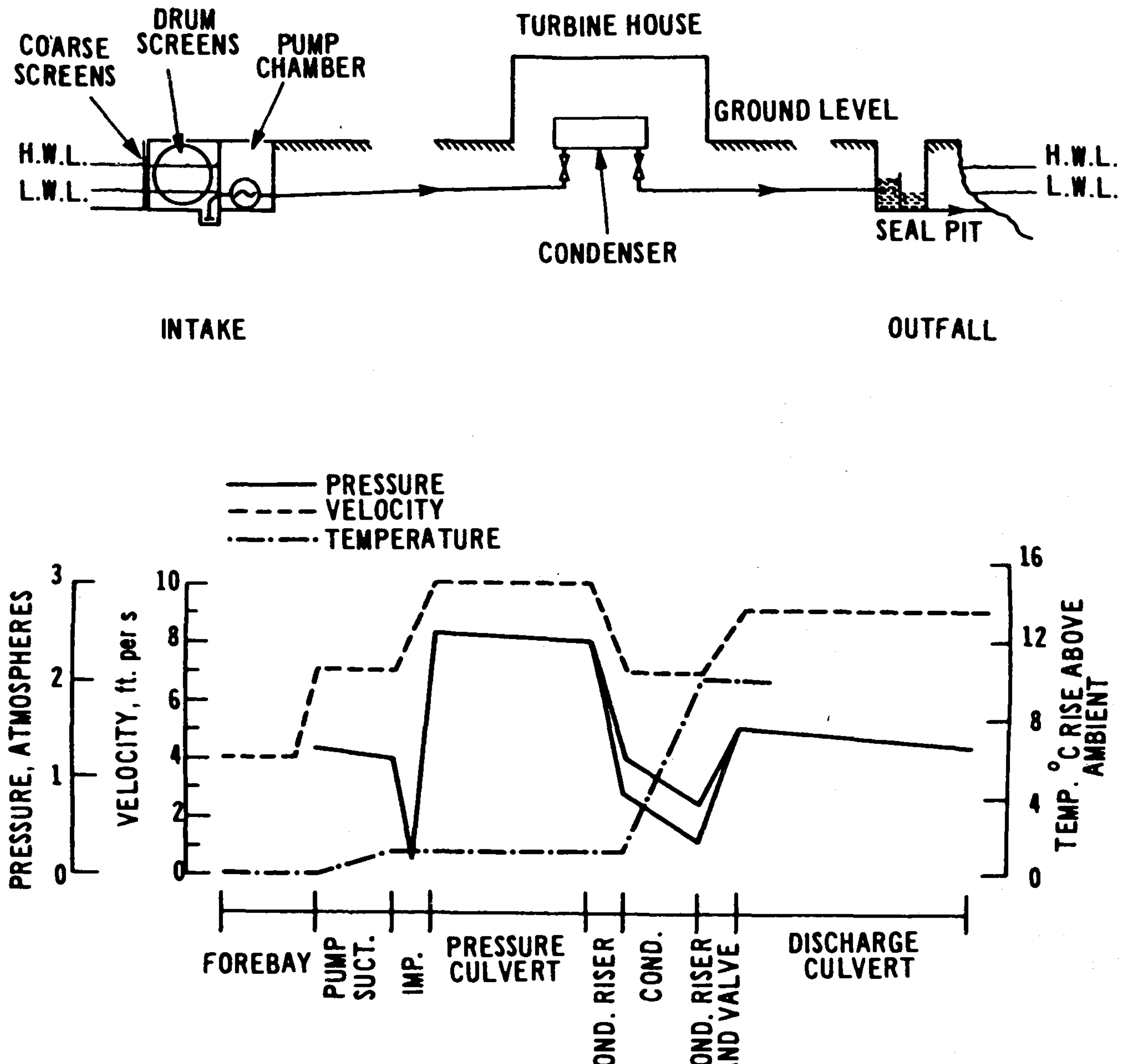

Figure 2. Hydraulic gradient for typical direct cooled c.w. system and associated changes of pressure, velocity and temperature
(from Howells, 1982)

3. OBSERVED EFFECTS

3.1 Pumping and Screening

The occurrence of occasional large catches of fish or macro-invertebrates on intake screens (impingement) is often perceived as a cause for concern, both with respect to the consequences on the fish or invertebrate populations in the vicinity and to the continued operation of screening. The catch may often be comprised of a large number of juvenile fish which are unable to resist the influence of the intake flow. The catch is, however, very variable in quantity, and sometimes in species. It is influenced by seasonal availability of species, seasonal and climatic conditions, tidal state and time of day. At stations where information on catch and its variation with these factors is available, a qualitative prediction of catch can be made. The annual loss of commercial fish due to screen impingement at an open coast plant (450 MW) has been estimated as being only a small fraction of that attributable to a single commercial trawler. At an estuarine plant (2 000 MW) an inshore fish (sand smelt, Atherina presbyter) has not changed in size or structure of the local population as a result of more than 10 years of plant operation. In principle, the removal of a significant fraction of juveniles or adults from a population would be reflected in an anomalous age structure of the 'free' population. However, a large fraction of juveniles may be destined never to reach maturity, and in addition the 'free' population may be augmented by immigrants from adjacent waters. The species or communities most at risk will be those whose habitat is close to the cooling water intake, and which cannot be maintained easily by immigrants. These species or communities are probably of only local significance. Species of wide ranging habit, or those only seasonally abundant, are much less likely to suffer from screen loss. It follows that the severity of damage will be site-specific and largely of local significance.

While screen impingement loss is now documented for a number of inland and coastal stations in temperate waters, adverse effects on commercial catch have not been reported, nor have anomalous age distributions of particular species been observed. In some instances (where legal or public pressures have demanded it) recovery of impinged fish is practiced. It appears feasible to return undamaged fish to the receiving water, but it is unlikely that this results in a change to the local fish population, except in special circumstances.

The intake of fish with cooling water abstraction is governed by physical conditions at the intake - it is possible, by reducing flow and by regulating the direction of flow, to minimize the entry of fish at the intake. Schemes to deflect fish by means of electric screens, bubble screens or lighting have so far been of doubtful or no value.

3.2 Entrainment

'Entrainment' can be defined as the capture and inclusion of organisms in the cooling water stream. There are, however, two modes of entrainment to be distinguished. Pump, plant or intake entrainment is the process by which organisms are pumped through the plant and discharged to the receiving water. Effects, if present, occur in the region defined by a point immediately inside the intake screens and the point of discharge to the receiving water. At this point plume entrainment occurs, a physical process by which organisms in the receiving water are incorporated into the discharge plume without having passed through the plant. Plume entrainment results from mechanical mixing provided by the inertia of the jet discharge (near-field) and by natural turbulent mixing as well as diffusion in the receiving water (far-field). Plume entrainment cannot involve serious damage since the stress is immediately relieved as the waters move onward.

Plant entrained organisms will be bacteria, phytoplankton, zooplankton, fish eggs and larvae small enough to pass through the screen mesh. During plant entrainment these organisms are subjected to changes in pressure, abrasion, velocity shear and turbulent acceleration, as well as to temperature and chemical changes. Such physical stresses exceed the lethal level for striped bass eggs (Morone saxatilis) for example.

Biocide (chlorine) dosing will vary, with 0.2 mg/l at the condenser inlet being a common objective. The chlorine will continue to decay during downstream passage of the discharge - the transit time ranging from less than a minute to hours if the cooling water passes along a lengthy canal prior to discharge. The temperature increment to cooling water across the condenser is commonly 10-12^{o}C (ΔT), with some reduction during subsequent passage, so that at discharge the temperature is lower. The temperature at discharge is usually subject to legal consent and values from 2-10^{o}C above ambient are common.

Different observations are reported as to extent of entrainment mortality. There is uncertainty about the contribution of the different components (mechanical, thermal and chemical) to this mortality. To some extent, differences could be attributed to shortcomings in sampling techniques. In addition, lack of information concerning conditions within the cooling system, and differences between sites may be responsible. Generally, observations include some recognition of delayed mortality (photosynthetic activity of phytoplankton following entrainment, or survival of zooplankton over 48 hours), but even so the overall consequences to the environment may not be clear.

United States experience is that many organisms do not survive pump entrainment, with a median mortality of 30% for all trophic levels and fish larval mortality of up to 100%.

Where careful methods of sampling were employed at United Kingdom stations, bacteria and phytoplankton were relatively unaffected by the physical stresses (including temperature) encountered during the short period of entrainment. In the case of larger and more fragile zooplankton a fraction (5-15%) are damaged. When chlorination is practiced, however, bacteria and phytoplankton will be 90-99% killed by chlorine concentrations of 2 mg/l at the condenser inlet. Zooplankton are variously affected (15-100%) and in some instances a delayed mortality (48 hours) has been observed. (See Table I).

Detailed studies of four zooplankton species entrained at a subtropical site (Gulf Coast, Florida) with an overall temperature increment of 5.9^{o}C across the plant, showed that above a threshold temperature (30-35^{o}C) mortality increased, especially for larger copepods. A greater response to thermal shock was observed in summer. The effect of physical stress on smaller zooplankton was slight, but delayed mortality was not tested.

Rather little is known about the tolerance of marine fish eggs and larvae to chlorine and other entrainment stress but it has usually been assumed that entrainment kill is complete. Herring larvae, however, can tolerate a 30 minute exposure to 0.1 mg/l chlorine.

In some cases estimates of entrainment mortality of different classes of organisms have been made and of the subsequent effect on the population of a species. Some of these estimates have shown significant effects within restricted areas. These estimates have not been validated and are only indicative of trends.

It is clear that many of the organisms entrained in the cooling water stream suffer significant damage with chlorination at customary dosage levels. The effect of chlorine on entrained organisms subjected to mechanical and thermal stress has been reported from a number of operating stations in the U.K. Mortality of 50% of zooplankton was reported at 0.25-0.75 mg/l chlorine residual at an estuarine plant and 85-100% mortality at 0.5-5.00 mg/l. Similar high mortality is reported at other estuarine and coastal sites. sometimes at lower chlorine concentrations (to 2.5 µg/l).

Chlorine also affects entrained phytoplankton, halving primary production of temperate coastal waters at a residual chlorine concentration of 0.5-1 mg/l at ΔT of 10^{o}C. When ΔT was only 4.4 to 5.5^{o}C, the effect of chlorine was reduced to 13%. Use of NaOCl dosed at 10 mg/l, resulting in a residual greater than 1 mg/l, depressed photosynthesis in Pacific coast phytoplankton by 70-80%. At lower levels of residual chlorine (less than 0.1 mg/l) there are some reports of recovery of ^{14}C uptake, but others do record effects at about this level suggesting that sensitivity varies with species or locations.

Macrofouling organisms are generally kept under control with chlorine dosage less than 0.5 mg/l, but dose-response information is imprecise. It is not at all certain, however, whether there is any significant environmental impact. The rapid doubling time (1-2 days) of bacteria and phytoplankton in temperate waters would quickly make good any loss provided the organisms can be recruited from the receiving water. A subtle change in species dominance is possible reflecting different species tolerances, but this has never been reported. In the case of planktonic larvae of local benthic species, or of fish, there is a greater probability that loss of some fraction of the 'young of the year' could have an effect on recruitment to the adult population. Such an effect has not been reported - where the benthic community has changed close to the outfall of a thermal discharge it can be more credibly attributed to the changed nature of the substrate.

3.3 Discharge

In most reported instances, effects have been of a localised nature and when considered within the context of the ecological community cannot be considered to be ecologically significant, even for species of restricted distribution. Some examples of effects reported in different kinds of habitats are given.

3.3.1 Intertidal zone

On **rocky shores**, at tropical sites in Hawaii and at temperate sites in California, impingement of the hot water on the intertidal zone effectively lowered the upper limits of intertidal zonation. In most instances this is measured at distances not exceeding 100 m from the discharge. In addition, it is usually within the natural background variability recorded in the area. For example, a similar type of change was observed due to sand abrasion and to other changes in substrate at 'control' sites.

On **sandy beaches**, there is no indication of biologically important changes due to thermal effluents (see also 6.1). However, there are some indications of changes in the population structure of a sand crab which is the main food source for a surf fish; this study requires confirmation. Another study reports seasonal advancement of sexual maturity.

Little biological information is available for intertidal **mud flats.** However, the thermal influence appears to penetrate for approximately 5 cm below the surface of the sediments. The available information suggests some suppression of the biota in the immediate area of thermal discharge. At a U.K. site where effluent is discharged to a canal influenced by tidal flows, reduced benthos abundance is seen within a zone where the thermal front moves with tide.

3.3.2 Subtidal zone

There are few data available for subtidal **rocky substrates.** However, any change indicated is greatest just below low tide level due to the tendency of the thermal effluent to rise to the surface of the water. There is evidence that plants and algae are more sensitive than the fauna; for example, shallow water sea grass beds are sensitive to temperature change, and kelp beds are sensitive to changes in both temperature and turbidity.

For benthos, usually on **soft bottoms**, the effects depend on the location and design of the discharge. These include scouring of the bottom sediments, increased 'organic rain' due to in-plant mortality, increased coarseness of sediments due to a rain of shell from in-plant fouling and changes in water currents due to plume entrainment. In addition, the biota may be affected by other chemicals in the discharge waters. The general picture emerging is that changes are limited in space and often in time. For example, deposited shell may be reworked and undetectable in a matter of weeks.

3.3.3 Water column

Changes within the water column are due to the combined effects of the discharge (thermal, chlorine and other chemicals) and the plume entrained water. Most planktonic organisms are moved at the mercy of water currents and can therefore be exposed to short-term changes. Due to the difficulty in sampling and in estimating standing stocks for a basic comparison, no reliable field data are available on the extent of any change. However, no evidence is reported that these changes are ecologically significant, in view of the high level of natural mortality and the rapid replacement rate of many phytoplankton species. At some sites where cooling water is taken from nutrient-rich deeper water, nutrients transported in the cooling stream to surface waters can increase primary production significantly. This could be a consequence of ocean thermal energy conversion (OTEC).

Some fish and macroinvertebrates are less at the mercy of the water currents and depending on the characteristics of the species and their swimming ability, actively respond to combined discharge and plume entrainment, for example by choice of preferred temperature regimes.

Both freshwater and marine fish migrate into and out of discharge plumes and it is commonly reported that a greater abundance of fish can be found at the outfall than in adjacent areas but is influenced by seasonal migrations. There is no evidence that any fish species have been lost from local communities in the vicinity of outfalls, but temperature preferences of different species may result in somewhat different communities near to and away from outfalls. This is unlikely to have any wider significance.

Reports of mass mortality of fish attributable to a thermal discharge are rare. At two North Atlantic sites the death of large numbers of menhaden (Brevoortia tyrannus) was observed in the

Table I

Experimental and field studies on heat, chlorine and mechanical effects on some temperate water organisms

(a) Experimental Studies

Taxon	ΔT °C	Effect	Critical temperature	Chlorine	Reference
Bacteria	17	No effect at ≤ 36°			Delattre and Delesmont, 1981
	10	No change in heterotrophic activity		50-99% reduction in activity according to dose	Delattre and Delesmont, 1981
Diatom:					
Gyrosigma spenceri	10	None, initial temperature 12°	39°	Inhibition at 0.5 mg/l	Maggi et al., 1981
	17	None, initial temperature 16°	39°		Maggi et al., 1981
Flagellates:					
Dunaliella tertiolecta	10	None, initial temperature 12°	41°		Videau et al., 1981
	17	None, initial temperature 17°	41°		Videau et al., 1981
Skeletonema costatum	17	Inhibition at 31°	35°		Berland and Aubert, 1981
Molluscs:					
Pecten maximus	10-17	Mortality of larvae increased, growth reduced if initial temperature 15-17°			Dao et al., 1977
Mytilus edulis		Low mortality, larval settlement poor		Settlement inhibited at 0.5 mg/l	Bucaille and Kim, 1981
Crustaceans:					
Maia squinado	10-15	Mortality increases with ΔT	35°		Gras et al., 1977
Acartia clausi		This and other species have 50% mortality varying between 20-34°C	>34°	Increased toxicity with temperature	Benon von Unruh and Gaudy, 1981, 1981a, 1981b
Fish:					
Dicentrarchus labrax	10	100% egg mortality, larvae undamaged	16°	100% mortality of larvae at 0.5 mg/l	Paris et al., 1977
Engraulis encrasicolus	10-17		>30°		
Clupea harengus		Eggs : 100% mortality	39°		Battaglia and Poulet, 1977
		Larvae : 100% mortality		Larvae survive 0.1 mg/l	Dempsey, 1982
Solea solea	10-17	Eggs : 100% mortality	35°		Devauchelle, 1977
Mullus surmuletus	10-17	Eggs and larvae: 100% mortality	30°		Devauchelle, 1977
Scophthalmus maximus	10-17	Eggs : 100% mortality	30°		Devauchelle, 1977

continued

Table I (cont'd)

(b) Field Studies

Taxon	Location	ΔT °C	Mechanical effects	Thermal effects	Chlorine effects	Reference
Phytoplankton	Mediterranean, Martigues-Ponteau	7	Limited effects	Thermal and mechanical effects involve 10 to 60% drop in the number of cells	Serious alterations; 40% average drop in primary production	Bougarde-Le, 1981, 1981a Bougarde-Le and Ramade, 1981
"	North Sea, Dunkerque	7	No significant effects	Inhibition of primary production under 24°; stimulation above	Pronounced inhibition of primary production (between 80 and 98%)	Khalanski, 1981
Zooplankton	Mediterranean, Martigues-Ponteau	7	28% mortality	Limited (0-16%) mortality	Overall effects 63-73% mortality	Gaudy and Benon, 1977 Gaudy, 1981
"	North Sea, Dunkerque	7	Overall transit effects	33-58% mortality on *Temora longicornis* 34-48% mortality on *Acartia clausi*		Khalanski, 1981
Phytobenthos	Mediterranean, Martigues-Ponteau	7	Effects recorded in the discharge path. Considerable alteration in plant cover during summer			Verlaque, 1977 Verlaque et al., 1981
"	Maine, U.S.A.	7	Elimination from rocky shore of *Ascophyllum* and *Fucus* when temperature reached 27-30°			Arndt, 1968
Zoobenthos (hard bottom)	Mediterranean, Martigues-Ponteau	7	Hydrodynamism influences sessile organisms distribution more than temperature. Dominant species may be affected by a large-scale mortality during summer.			Arnaud et al., 1981 Bellan-Santini and Desrosiers, 1977
Zoobenthos (sand bottom	Scotland, Firth of Clyde	8.4	Bivalve larvae unharmed by transit, incl. 0.5mg/l Cl in summer; max. summer peak 24.4°C.			Barnett, 1972
		3-5	At discharge, breeding cycle of gastropod advanced, but no effect on adult population.			Barnett, 1972

discharge canals possibly as a result of a rapid 17°C rise. However, this species normally dies after spawning and natural mass mortalities are common. A similar mortality was reported when discharge temperatures dropped by 7°C. For such a species the loss of post-spawned adults cannot be significant to the population since it is part of their natural cycle.

In European coastal waters no fish kills at the discharge have been reported, even though fish are attracted to the outfalls and temperatures as high as 30°C may be reached.

Although there are a few observations that levels of parasitic infection are greater in fish caught close to outfalls in inland waters, this has not been reported for any marine fish. In one case in a British river a greater infestation with internal worms in fish caught at the outfall was found; this did not affect growth and condition which was better in this group than in those caught upstream. In fish from an Indian lake the ectoparasite burden was much greater in caged fish kept in the outfall, and the fish became emaciated. The incidence of the isopod parasites was greatly increased in the discharge canal but it was not known whether the lake population of fish suffered a greater level of infection as a consequence. Where aquaculture systems are associated with heated discharge water, the potential for epidemic disease in the cultured species must be kept under strict control; if some disease organism becomes endemic it could pose some threat to wild species in the vicinity.

3.4 Field and Laboratory Experiments

In general, early laboratory tests set out to test the tolerance threshold of organisms to identified stress such as an increment of temperature. The most usual response measured has been mortality. Tests on a wide variety of both tropical and temperate organisms indicate a common upper lethal temperature of about 35°C. Acclimation of test organisms at 15, 20 and 25°C, which temperatures are considerably below the upper lethal temperature, allows them to tolerate temperature increments of 8-9°C without damage. Longer-term acclimation to high or fluctuating temperatures may explain why organisms may sometimes be found living above 35°C.

A variety of indirect effects have been observed - these include behavioural responses, changes in feeding and growth, in rate of juvenile development and in metabolic or biochemical functions. While many such effects can be observed in laboratory studies, the ability of many organisms to acclimatize to increased temperature and to avoid adverse conditions, together with the transient nature, both spatial and temporal, of thermal plumes, means that they may be difficult to identify in the field.

Organisms exposed to additional stresses, e.g. mechanical or chemical (to simulate plant entrainment exposure) or longer-term chemical stress (to simulate persistent plume exposure) may respond differently. Experiments to establish the toxicity of chlorine, as reported in the literature, show wide variations attributable to species sensitivity, differences of experimental exposure and poor methodology. Concentrations 0.5 mg/l are usually regarded as lethal to marine and freshwater fish, but lower concentrations (0.01-0.03 mg/l) may be toxic to younger life stages or more sensitive species or to important physiological functions. Some information is included in Table I.

Tests of survival or damage to organisms introduced to a condenser tube simulator with different conditions of velocity, biocide concentration and temperature, have provided comparative information for different species and for the different stress components. In North American temperate estuarine waters, exposure to 29°C, and other characteristic physical and biocide stress, significantly increased mortality. In contrast, plankton organisms in temperate European coastal waters were not much affected when only mechanical stresses were encountered in passage through a station's cooling system.

Fish or macroinvertebrate behaviour in conditions simulating intake or discharge flows can be studied effectively in scaled-down flumes. Field behaviour of suitable organisms (larger fish or crustacea) can also be monitored by telemetry. At high velocities, fish are unable to long withstand the influence of a cooling water intake, and if unable to leave the zone of influence will become fatigued. Juvenile fish may be unable to resist intake velocity greater than 1 m/s, while at lower velocities they may be unaffected. The size of the fish, as well as the swimming capacity of the species and, possibly, environmental factors such as temperature and light level, are important. The horizontal component of intake velocity is more easily countered than the vertical component. Tracking individual fish through intake and plume areas has not so far suggested that these present a significant block to natural migration.

4. MATHEMATICAL MODEL STUDIES

It is convenient to characterize zones between the waste heat source and where biota experience disturbance in the discharge area (see Figs 1 and 3). The terms near-field, far-field and aquatic ecosystem are used commonly to distinguish zones with increasing spatial and temporal scales (Fig. 3). There are also changes in processes with increasing scale: outfall characteristics dominate the near-field, ambient characteristics the far-field. The 'discontinuities' that separate these fields or zones require different approaches and some interface problems are encountered when modelling more than one zone at a time. The two zones where physical processes are important are also referred to as the complete field.

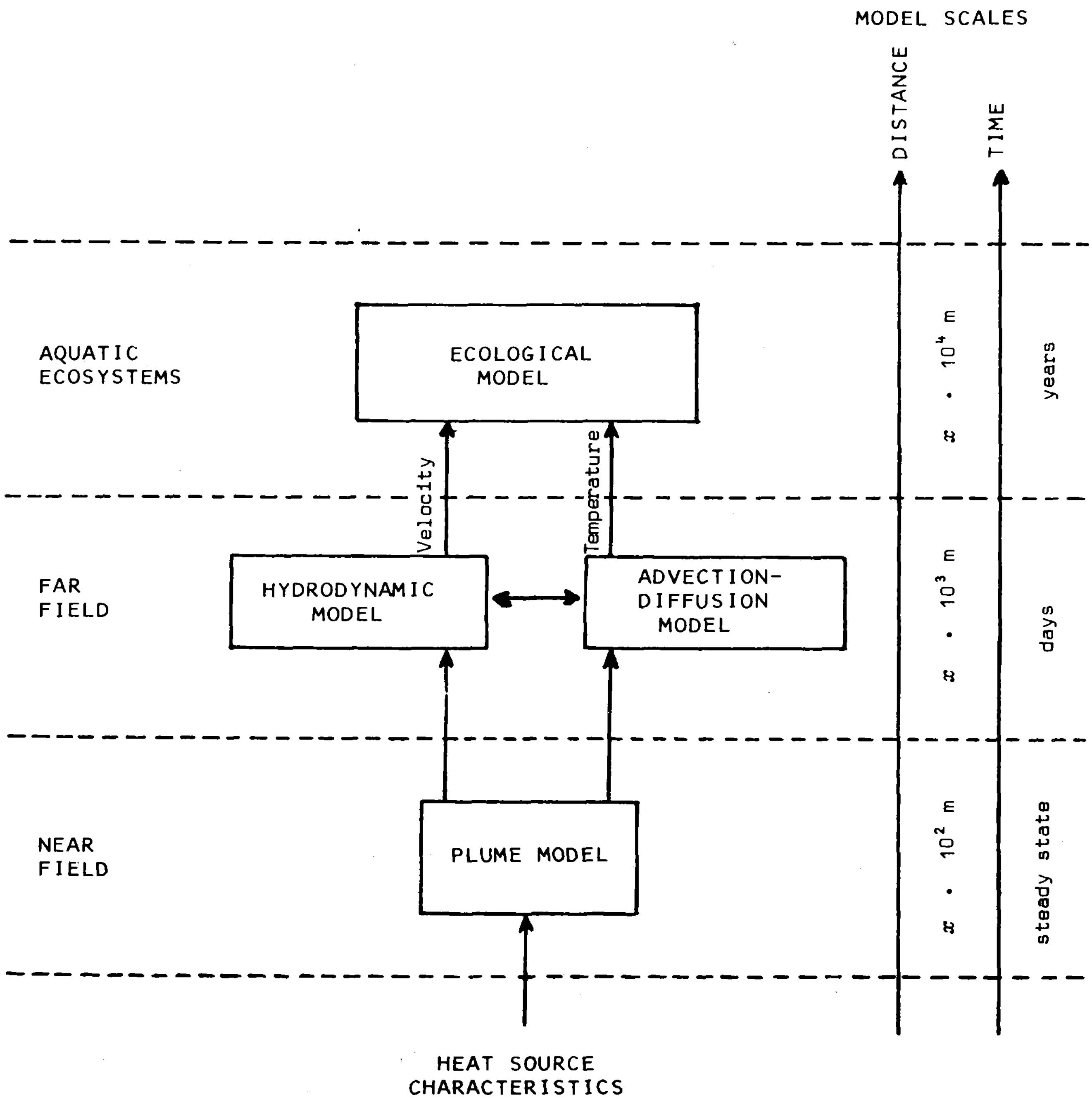

Figure 3. **Characteristic zones and model types relevant for the assessment of heat disposal effects**

Plume models for the near-field are either of phenomenological or integral development. The phenomenological approach is based on empirical correlations of measurable plume characteristics with some plume or ambient variables. The integral approach is based on integrating the governing equations along the jet trajectory, but patching different pieces of theory together with some data fitting is needed to obtain those equations.

In phenomenological models, ambient conditions are commonly characterized by current ratios and bottom slope, whereas integral models require current ratios, as well as plume entrainment and similar coefficients when physical processes are modelled separately.

The nature of both modelling approaches for the near-field restricts these models to steady state situations and spatially highly schematized problems. Some complicated site conditions (boundary geometry, bottom topography, vertical velocity shear, transients, etc.) are generically beyond the capabilities of these two approaches. Both are mathematically straightforward and computationally economical so their ultimate predictive value and usage should depend upon how well any particular problem matches idealizations of these approaches and what degree of accuracy is appropriate.

In far-field, the objective is to account for the time-varying, long-term and large-scale distribution of heat. To accomplish this, one can model the far-field separately and then interface the near-field plume model or attempt to model the complete field with a single modelling procedure.

The complete field zone can be modelled phenomenologically but the numerical approach is often more appropriate. In the latter one attempts to solve the coupled system of equations of motion, heat conservation and state, to predict field temperature and velocity. Fewer assumptions on the nature of plume or ambient have to be made; jet structure can be calculated rather than assumed. But problems remain concerning non homogeneous and anisotropic turbulence, lack of good quality data to set required conditions correctly, and computational difficulties with different solution algorithms. Heavy requirements on computer memory and time limit verification of these models.

These problems indicate that numerical models have limited application to real situations. Rather than solving the complex coupled system of equations for the complete field, decoupled systems for the far-field are often attempted. In a decoupled system, heat is considered a passive substance that does not affect the velocity field so that a closed form or numerical solution to the advection-diffusion equation can be found. The velocity field information can be obtained by running a separate hydrodynamic model of different complexity or by using some analytical expression for its temporal/spatial variability. Here we face another discontinuity on the spatial and temporal scale (Fig. 3). Care must be taken with coupling processes so as not to violate the laws of heat and momentum conservation.

A scheme to overcome the scale barriers and to relate physical conditions to biological responses has recently been developed. The model accomplishes this in several steps. First the fields of excess temperature and velocity appropriate for the plant and the site are modelled over the complete field of elevated temperature and, if necessary, over time. A complete field phenomenological model is set up, consisting of far- and near-field portions combined with vector addition in the case of velocity, and with a simple mixing concept for temperature. Next, time-excess temperature histories or thermal doses of the assumed distribution of organisms are calculated by advecting them through the heated region using the previously calculated velocities and excess temperatures. The thermal dose is the integral of excess temperature over time. Finally, the doses are ordered with respect to maximum excess temperature experienced and compared to thermal dose-excess tempe rature mortality curves for the test organism which are obtained from thermal resistance data or experiments appropriate for a range of mortality levels and acclimation temperatures. Other models describe the total mass fluxes discharged to the receiving area, the relation between these mass fluxes and temperature, and the resulting production of phytoplankton.

A method is still needed to determine whether the mortality levels estimated in this way are manifested in significant reductions in the recruit populations or community changes. Even so, the proposed rationale represents a significant advance in our ability to predict the results of thermal stresses due to power plants.

5. OBSERVATIONS OF NO-EFFECT

When no effects or changes are recorded, this could be due to several valid reasons. Probably the two most important are that, indeed, the biota did not change in response to the thermal effluent or, alternatively, that the biota did change but that natural variability was so high that any response to the thermal effluent was effectively masked. These two 'no responses' are probably related in that both are predicted to occur in areas of high natural variability. For example, in the southern California Bight, monthly mean sea surface temperature can vary by 4°C between years. Further, due to the movement of 'parcels' of water derived from different water masses present in the area, the water temperature measured at any location could change by as much as 7°C in a few hours. In locations such as this the organisms are naturally exposed to a high degree of temperature variation and thus are probably better adapted to withstand periodic thermal discharge fluctuations than organisms from less variable habitats. In addition, behavioural or other response to such variation could also mask a response to thermal effluents, which are similarly variable due to changes in ambient conditions and in-plant operation. Likewise, independent episodic or chance biological changes or interactions may hide a response. It is also possible that the appropriate observations for effect were not identified.

Notwithstanding these difficulties in detection and interpretation, it may be possible to identify limits of temperature or chlorine exposure at which no effects on individuals or communities have been recorded. Extrapolation of these observations to other species or conditions, however, is not justified until a more consistent view emerges, for instance between observations in temperate and tropical areas, or between field and laboratory studies.

The responses of selected organisms of different classes to heat, chlorine and mechanical stresses have been observed in both experimental and site studies. Examples are given in Table I.

Bacteria and phytoplankton appear to be resistant to thermal stress, even at temperatures in excess of 30°C. They are sensitive to chlorine concentrations of 0.2 mg/l.

Macrophytes are reported to be more sensitive to thermal stress and their threshold may be less than 25°C in temperate and up to 34°C in tropical waters. They are sensitive to chlorine at 0.05 mg/l. There are inconsistent reports in the literature.

Zooplankton is not affected in discharges to temperate European waters, where summer peaks rise to 30°C in the discharge. Some zooplankton organisms are sensitive to chlorine below 0.25 mg/l. Lower tolerance thresholds may reflect inadequate methods, since reports are inconsistent.

Benthos in temperate and subtropical waters will tolerate temperatures close to discharge outfalls up to 10°C above ambient, or ~35°C. If sensitive species are lost in peak summer temperatures, recolonization occurs from adjacent areas. Sensitivity to chlorine varies with species with levels greater than 0.02 mg/l - about the lower limit for macrofouling control.

Intertidal communities of both sandy and rocky shores are also resistant to temperature increments, but the upper level of tolerance is at present undefined.

Fish - most temperate species are able to tolerate a wide temperature range but few are resident in waters with temperatures greater than 30°C. The preferred temperature varies with life stage and with season. Little is known of sensitivity to chlorine of marine species, but a sensitive species (herring larvae) is tolerant of short-term exposure to 0.1 mg/l.

6. SPECIAL CONDITIONS AND OBSERVATIONS

6.1 Tropical and Subtropical Ecosystems

6.1.1 Sensitivity of species and habitats

Many organisms adapted to the generally warmer and more stable thermal environments of tropical and subtropical regions may exhibit thermal responses to heat increment that contrast sharply with their temperate counterparts. 'Tropical' has been defined variously in terms of geographic location as regions occurring between latitudes 20°N and S or, more strictly, between 10°N and S. Since a wide range of temperatures may occur around the globe within these

Table II

Temperature effects on some tropical marine organisms

Taxon	Location	Δt °C	Effect	Critical temperature	Reference
Mangroves	South Florida	5°	Net photosynthesis suppressed		Miller et al., 1976
Rhizophora mangle	Guayanilla Bay, Puerto Rico	8-10°	Recruitment failure		Kolehmainen et al., 1975
Mangroves				37-38°	Banus and Kolehmainen, 1976
Thalassia	Florida			33-34°	McRoy and McMillan, 1977
Seagrass	Tampa Bay, Florida	4-5°	Destruction of bed		Blake et al., 1976
Thalassia	Florida	4-5°	Severe damage to denudation of beds		Thorhaug et al., 1978
Algae	Turkey Point, Florida		Death	34°	Thorhaug, 1974
Algae	California	7-10°	Shift in community composition to virtual elimination		Devinny, 1980
Caulerpa racemosa	Guam	2°	Respiration doubled	34°	Hohman and Tsuda, 1973
Algae	La Parguera, Puerto Rico	6°	Death	35°	de Ramirez, 1973
Algae	Tampa Bay, Florida	3°	Reversion to early successional stage with dominance by blue-green		Blake et al., 1976
Acartia tonsa (copepod)	South Biscayne Bay, Florida			34-37°	Reeve and Cosper, 1972
Copepods	Florida		Mass mortality	mid 30°	Alden, 1979
Ophiuroids	Biscayne Bay, Florida		Instantaneous death	37.5-40.5°	Singletary, 1971
Echinometra mathaei	Guam		Development and fertilization inhibited	34-36°	Rupp, 1973

continued

Table II (cont'd)

Taxon	Location	Δt °C	Effect	Critical temperature	Reference
Linckia	Guam		Metabolism disrupted	36°	Strong, 1975
Acanthaster planci			Incipient thermal death	33°	Yamaguchi, 1973
Macrobenthos	Puerto Rico	5-10°	Elimination		Kolehmainen et al., 1975
Mangrove root community	Guayanilla Bay, Puerto Rico		Decrease in species number	34°	Kolehmainen et al., 1974
Corals	West Indies			36°	Kinsman, 1965
Corals	Kahe Point, Hawaii	3-4°	Loss of zooxanthellar pigment and high mortality		Jokiel and Coles, 1974
Ocyurus chrysurus (snapper)			Death	33.5-34°	Wallace, 1977
Marine fish	Gulf of Thailand		Incipient death	34-37.5°	Menasveta, 1981

Table III

Operating characteristics and environmental impacts of tropical or subtropical electrical generating stations

Power station, location	Average ambient temperature range (°C)	Generating capacity (MW)	Effluent ΔT (°C)	Type of outfall	Biocides used	Receiving water environment	Vegetation or basic habitat	Benthic area affected (ha)	Lethal threshold temperature (°C)	Environmental observations	Other pollutants and stresses	References
Florida												
Turkey Point	17-30.5 (min 10)	864	5	Canal (0.6 km)	0.35 ppm chlorine until 1979	Shallow bay, enclosed	Sea grasses	118	33-34	Sea grass mortality at +4-5°C, reduction at +2-3°C; blue green algal mats; avoidance at +2-5°C by motile fauna	Heavy metals, anti-corrosives in cooling water discharge. Scour at canal end.	Thorhaug *et al.*, 1973 Thorhaug *et al.*, 1978 Roessler and Zieman, 1969 Zieman and Wood, 1975
Card Sound (for Turkey Point)	17-30.5 (min 10)	864	3	Canal (9.3 km)	No data	Shallow bay	Sea grasses	No data	No lethal effects	Reduced sea grass growth at +3°C	Heavy metals, sedimentation and freshwater run-off.	Roessler *et al.*, 1975, Thorhaug *et al.*, 1979
Cutler Ridge	11-30.5	Not available	10-11	Canal	No data	Shallow bay	Sea grasses	35	No data	Sea grass mortality	Six-fold increase in turbidity.	Langford, 1982
Key West	14-32	Not available	6-8	Canal	No data	Shallow coastal	Sea grasses	No data	34	Sea grass mortality	Desalination plant nearby, elevated copper in effluent at 35°C. Some increase in salinity.	Chesher, 1975
Tampa Bay	15-30	240	7.2	Canal	No data	Shallow enclosed bay	Sea grasses	81	No data	Blue greens replaced sea grass at +>3°C	Dredging and filling effects on sediments. O_2 supersaturation (200%). Consistent isotherms. No data on effects.	Blake *at al.*, 1976
Puerto Rico												
Guayanilla Bay	25-31	1 100	10	Canal	No data	Shallow bay, exposed	Mangroves on shore	No data	35-36	95% zooplankton mortality; avoidance at +4-5°C by motile fauna; blue green mats	Complex effluents from other industries, hydrocarbons, phenols, heavy metals.	Kolehmainen *et al.*, 1974, 1975
Hawaii												
Honolulu Harbour	21-28	180	5-6	Shoreline	Nc	Estuarine, deep harbour	Vertical harbour walls	None	No lethal effects	Increased zooplankton, fish and coral in discharge area	Moderate sedimentation; freshwater run-off; infrequent oil spills.	McCain and Coles, 1973 McCain *et al.*, 1975

Table III (cont'd)

Power station, location	Average ambient temperature range (°C)	Generating capacity (MW)	Effluent ΔT (°C)	Type of outfall	Biocides used	Receiving water environment	Vegetation or basic habitat	Benthic area affected (ha)	Lethal threshold temperature (°C)	Environmental observations	Other pollutants and stresses	References
Hawaii (cont'd)												
Pearl Harbour	21-29	430	6-7	Shoreline	No	Estuarine, shallow harbour	Sheet piling	None	No lethal effects	Sublethal fouling; community alteration at ca. 32°C	Pollutants from other industries; moderate sedimentation; freshwater run-off	McCain, 1974, 1975
Kahe Point	23-27	500	5-6	Shoreline (pre-1977)	No	Exposed leeward coral reef	Reef coral	1.4	31-32	Coral mortality at +4-5°C, sublethal effects at +2-3°C; sand deposition, algal increases and fish attraction at outfall	Heavy sand load in effluent; rapid effluent dispersion	Jokiel and Coles, 1974 Coles, 1975, 1977 Coles *et al.*, 1982
Kahului	23-27	160	5-6	Supratidal	No	Exposed windward coral reef	Macroalgae	None	No lethal effects	No measurable effects	Intake water from wells at reduced salinity; high COD	Hawaiian Electric Co. Inc. and Bernice P. Bishop Museum, 1975
Guam												
Tanguisson Point	26-29	60	6-8	Shoreline	Yes	Exposed leeward coral reef	Barren reef flat, corals at reef margin	1	32-33	Coral mortality at reef edge. Macroalgae mortality and blue green mat formation on reef flat; fish avoidance during chlorination periods	No data	Jones and Randall, 1973 Neudecker, 1976
India												
Tarapur	24-31	400	1 [1/]	Canal (1 km)	No data	500 m wide shelf	Breen reef flat	None	No lethal effects	Discharge canal silted and minus vegetation; no impact observed offshore	Heavy seasonal rainfall	Kamath, 1981

[1/] Temperature rise of 9-10°C cooled to 1°C in transit through discharge canal boundaries, a more useful definition based on thermal characteristics is appropriate. For the purposes of this report, tropical areas are defined as regions where water temperatures are relatively stable seasonally, seldom decreasing below 25°C and generally not exceeding 32°C. Summer temperatures are typically about 30°C, although in conditions of restricted circulation temperatures may be considerably higher. Subtropical areas are those where lower annual temperatures may fall below 20°C and generally range 20-25°C, while upper values generally do not exceed 30°C, except with restricted circulation.

Temperature regimes in the tropics are such that many organisms live close to their upper thermal limits. Studies of temperature effects on tropical organisms, like temperate species, indicate that temperatures around 35°C are critical or lethal (Table II). Hence, temperature increments caused by thermal discharges need to be regulated to avoid adverse ecological impacts. Because of the prevailing environmental conditions and the sensitivity of many tropical species, ΔTs in the plume at the point of discharge should ideally not exceed 5°C in the tropics.

Shallow-water benthic communities, whether temperate, subtropical or tropical, are the most susceptible to thermal discharges. In the tropics, caution must be exercised to avoid damage to coral reefs, seagrass and seaweed beds and mangrove communities, since these are typically in shallow water and among the most productive marine ecosystems. Shallow estuaries may also be unsuitable for thermal discharges.

6.1.2 Tropical and subtropical site studies

The available information on the effects of power station effluents in tropical and subtropical areas is summarized in Table III. Information from these studies is potentially useful for future station siting and operational practice.

Field studies of seagrass areas and coral reefs have shown damage from impact of the thermal plume at temperatures 4-5°C above the normal ambient summer maxima. Temperature increments of 2-3°C decrease growth in both organisms, manifested by blade decomposition in seagrass and loss of zooxanthellae algae normally retained within the cells of reef corals.

With a raised temperature in the receiving water of 3-5°C, most studies have shown alterations of benthic and fish communities, resulting in reduced species richness. Eurythermal or thermophilic species (bluegreen algae, mangroves and associated fauna, certain molluscs, crabs and fish) are recruited into the discharge area, while stenothermal species (turtle grass, red and brown algae, coelenterates and echinoderms) die or depart. This may result in substantial increases in the number of the tolerant organisms, as competition for available food resources and predation pressure is reduced. Algal blooms occur, and reduced algae species diversity is often seen in temperature-transition areas, with bluegreen mats appearing on benthic areas exposed to the highest temperatures. Where temperature increments have exceeded 5°C, as at the Guayanilla Station, macrobenthic organisms have been totally excluded, and fish diversity decreased by one half.

The Turkey Point case study illustrates the importance of unrestricted access to the open ocean for thermal effluents. Biscayne Bay is only about 1 m deep and semi-enclosed by sand cays, permitting very limited circulation and flushing of thermal discharge. Benthic biota on 118 hectares were killed or damaged during the first two years of operation. Relocation of the effluent canal to Card Sound reduced damage to the sea grasses, probably because the re-designed discharge allowed the effluent to stratify and not impinge on the bottom at an increment greater than 3°C.

Similarly, at a station located on Tampa Bay, Florida, about 81 ha were denuded at temperature increments above 3°C. The restricted circulation in this type of shallow estuary means that intake water will be elevated in temperature during summer, limiting the temperature increment that can safely be allowed. Secondly, lack of access to the open ocean results in impingement of a thermal discharge plume on temperature-sensitive benthic communities over large areas.

Various examples demonstrate that power stations can operate with limited or no damage to the marine environment, provided that temperature increments are limited to 7°C or less in subtropical regions, and to 5°C or less in tropical waters, and that stratification of thermal effluent protects stenothermal organisms. At Honolulu Harbour, Pearl Harbour and Kahului, power stations have had negligible disturbance to the marine environment, indicating the capacity of semi-enclosed harbours and deep estuaries which have good vertical relief for stations up to 500 MW generating capacity. In these areas the discharge may even improve the quality of receiving waters by increasing circulation, Two studies involve power stations located on open coastlines, Tanguisson Point, Guam and Kahe Point, Oahu, Hawaii. Both stations discharged (up to 1973) through shoreline outfalls at about $\Delta T \sim 6.0^{\circ}C$ resulting in coral mortality and damage over 1-2 hectares. Approximately the same areal damage occurred for 26 MW generation capacity at Tanguisson as at Kahe for 500 MW, because wave action at the former site carried the thermal plume along the reef front. These studies indicate that siting on an open coastline with ready access to open ocean water will not necessarily prevent damage, if depths in the path of the plume are insufficient to prevent the plume impacting on the bottom.

Limited information exists for effects of non-thermal components in these discharges. Chlorination may have aggravated toxicity at Turkey Point where fish return to the discharge area at times when chlorination is periodically discontinued. The negligible damage observed at Hawaiian sites may be related to absence of chlorination. Metal discharges at Turkey Point and Guayanilla Bay may have aggravated discharge effects there, and high concentrations of copper were certainly a toxic factor in a desalination plant discharge at Key West, Florida.

Sand entrainment at the Kahe Point station, located adjacent to a sandy beach and offshore sand reservoir, has resulted in offshore transport of beach sand, long-term decreases in the beach system and deposition of transported sand on reef areas adjacent to the outfall. The siting of power station intakes adjacent to sandy beaches is likely to result in operational and environmental complications, suggesting that such areas are best avoided.

6.2 Sites of Marginal Distribution of Species

In areas of zoogeographic overlap of sympatric species (e.g. of two barnacle species), imposition of a thermal change, either by natural causes or thermal discharge, can result in a change in the relative abundance of each species. The warmer water species will dominate in the warmer conditions and vice versa. Other abnormal changes include the advantage of a warmer versus colder water breeding variety of the same species with the changing temperatures. These predictable differences were observed within a distance of 100 m of a thermal discharge.

6.3 Sites Near Spawning Grounds

Because it is not yet certain what damage to fish or benthos communities is due to plant entrainment of larvae or juveniles, it is prudent to avoid the location of intakes or outfalls in spawning areas. The position of spawning areas of commercial species may not always be known, however, nor are they necessarily stable throughout the operational life of a station. It follows that information on possible spawning sites should be obtained prior to final design of cooling systems, and that the position might require review until it can be confirmed that entrainment damage is indeed insignificant to the maintenance of the population.

The possibility of plume damage to a spawning area may also exist. Evidence so far, however, suggests that the smaller increment of temperature in the receiving water (up to $4^{\circ}C$) is unlikely to do more than increase the rate of larval development. Benthic species or bottom spawning fish requiring particular substrate conditions for spawning could be influenced in the area of shell deposition or scour at the discharge site. Additional information for a wider range of both temperate and tropical species seems desirable.

6.4 Sites Near or Under Influence of Other Industries

Most power plants, fossil fuel or nuclear, are usually sited close to demand in order to minimize transmission losses. Large processing industries (refineries, petrochemicals, cokeries, steel mills, etc.) require substantial amounts of cooling water in addition to that used for on-site power steam raising.

There are few general rules applicable and each site will have to be analysed according to its existing pollution load and hydrography.

One of the most probable scenarios would be a power plant sited near a major town, which in many instances may in itself already be giving rise to pollution through disposal of inadequately treated and/or sited sewage effluents. Increased concentrations of organic matter would necessitate application of chlorine or other biocides to cooling waters, resulting in an increased delivery of chlorinated and brominated organics to the eutrophic receiving marine waters. Similar considerations apply to petrochemical processing, port facilities for bulk handling of materials (ore, coal, oil, chemicals). The combined effects of thermal discharge and other discharges may result in a complexity of plumes with a pattern of distribution more extensive and different from that attributable to the thermal discharge alone, as well as the possibility of additive or synergistic effects of different pollutants.

6.5 Special Hydrographic Conditions

Those responsible for siting power stations should be alert to recognize and benefit from oceanographic conditions which mitigate (or, alternatively, aggravate) the thermal characteristics of the discharge. Of most benefit are vertical gradients of temperature. In some cases it is possible to withdraw cooling water from a lower, colder layer in the water column, and discharge to surface waters close to the ambient temperature of the receiving water. Vertical salinity gradients, however, can be both advantageous or disadvantageous. At certain times of the year a vertical gradient of as little as 1 per mille salinity between intake and discharge is sufficient to offset the density decrease in a parcel of water due to a temperature rise of 5-6^{0}C so that a heated plume will sink upon discharge. If the receiving waters are sufficiently deep, the plume will spread out at some intermediate level and dilution will be enhanced due to the absence of a boundary, i.e. the bottom or the water surface. On the other hand, the plume can be deleterious to benthic communities or demersal eggs if the receiving waters are shallow.

Sites with steep bottom slopes are highly advantageous since they will permit shorter intake and discharge pipes and will provide more diluting water per unit distance offshore. Conversely, in the near-field, where waters are shallow or there is substantial stratification, vertical entrainment of dilution water can be suppressed even though, in the latter case, advantage may have been taken of the vertical temperature gradients. Further, in shallow water the plume can impinge on the bottom, resulting in increased stress to benthic communities. When the plume impacts on to the bottom the ambient cross flow, if present, will be blocked and produce dynamic pressures leading to an increased tendency for bending and re-entrainment of plume water in the lee of the jet. Co-flowing plumes or plumes discharged to stagnant receiving waters are generally narrower with consequent higher temperatures. In some instances and on occasions of unusual climatic conditions, design dispersion of the discharge may not be achieved, with resulting retention and heat build-up.

7. SUMMARY OF INFORMATION ON EFFECTS OF THERMAL DISCHARGES

(i) A large body of information is available in the literature concerning the effects of thermal discharges. Many studies refer to the overall consequences of station operation. To understand these effects and their causes it will be necessary to distinguish the separate mechanical processes of cooling water use and cooling water treatment. A major difficulty in interpretation is that the extensive background information needed to provide perspective and to evaluate changes is seldom available, even in regions of long-standing technological activity. Information for tropical and subtropical sites, in particular, is limited.

(ii) At cooling water intakes where large volumes of water are abstracted and passed through grids and screens, a substantial 'catch' of fish and macroinvertebrates may be observed (screen impingement). This catch is variable and its relationship to the population from which it is drawn, and its wider ecological significance, is not clear. Any effects will be of local, rather than of regional or wider, significance, but could be important to a coastal community dependent on exploitation of local marine resources. Some attention to intake design will help to moderate the size of the screen catch. There is a need to get more information about the factors influencing screen catch at different locations and to explore feasible intake design options to minimize catch.

(iii) The analysis of plant entrainment conditions and mortality can be helpful in understanding the separate and combined effects of physical and chemical stresses imposed during passage of smaller organisms through the plant. Mortality is greater during chlorination, so that the possibly significant loss of fish eggs and larvae, and of larvae of important macroinvertebrates, could be minimized by limiting periods of antifouling treatment. The loss of phytoplankton and other zooplankton during entrainment has not been reported to result in significant changes in the receiving waters.

(iv) Discharge conditions are often complex and site-specific, depending on the temperature increment above ambient, the residual concentration of biocide, local topography and water movement and local characteristics of benthic and intertidal substrate. It is convenient to distinguish near-field and far-field areas and conditions. In the near field, the effects on plankton within the plume will not be distinguishable from those already resulting from plant entrainment and those consequent on plume entrainment, although their causes are different. In the far field the same problem occurs, with additional complexity. Some potential effects will be the result of acute exposure, but others, especially on the benthos or intertidal community, may be due to continued exposure. The distinction is not well documented, possibly because of lack of much evidence for either short- or long-term damage, except in the immediate vicinity of the outfall. This can rarely be of much significance (because of its limited area) in the receiving ecosystem but there is evidence in the literature for some more extensive changes to the intertidal habitat and shallow waters. In subtropical and tropical areas some habitats, e.g. mangrove swamps and shallow weed beds are particularly sensitive. The observed greater incidence of parasites in heated waters, and the potential effect on fish stocks merits investigation. The long-term effects of chlorine residuals are not well understood - it is necessary to gain knowledge of the chemical pathways of chlorine decay and to develop instruments and methods for detection of the residuals and of their biological effects.

(v) In general, it can be noted that rejected heat can provide some benefit, especially if it is harnessed to aquaculture systems. But the threshold between potentially valuable and potentially damaging effects of heat is not particularly well defined due to the range of sensitivity of species and the interaction of heat with other water quality conditions. More knowledge of the responses of species of commercial interest and of potential for aquaculture to additional heat is needed to define acceptable (and exploitable) levels of heat discharge. (See also section 9.5.2).

(vi) The methods employed to study cooling water effects have often been poor. They may have been unable to discriminate the component effects - which indeed may not even be recognized. There is a need for development of conceptual models of station impact on ecosystems so that the most important aspects (in relation to ecological or commercial significance) can be identified and measured with economy and appropriate remedial measures identified, if found necessary.

(vii) Too often, ecological observations are made independently of physical and chemical investigations, so that it is difficult or impossible to match observed changes to their causal agents. More systematic physical and chemical data are needed on operating conditions so that flows, temperature and chlorine residuals can be documented for a wide range of conditions, including exceptional tidal or climatic conditions which might be critical for biological components. Such exceptional events, although infrequent, might require long (years) recovery time.

8. METHODS FOR THE DETECTION OF EFFECTS AND PREDICTION OF IMPACT

There is difficulty in selecting appropriate methods for the detection of effects, particularly of biological changes. This arises from the problems of sampling in power station conditions, from the variety of possible target organisms or processes and from the need to select a relevant phenomenon for measurement. Further, it will be necessary to distinguish in the observed response that component attributable to the imposed stress and that attributable to a background variation in abiotic conditions. This response must also be detected against a background of biological variation (signal to noise problem). Most biological observations in the field have to be continued over a relatively long period (i.e. of some years, not months or weeks) and it will not be certain that other conditions remain constant during the period of observation.

8.1 Detection of Effects of Abstracting Cooling Water

The effects of abstracting cooling water are measured at the intake site and at the point where it is screened prior to passage through the plant. Direct field observations can be made at the intake site, and the geographic extent of the influence of the intake can be measured. This area will be strictly limited and small in relation to the overall area of water abstraction so that the significance of such changes need scarcely be considered.

Impingement of larger biota at the cooling water intake screens can be measured by sampling the catch of fish, macroinvertebrates or algae on the screens. Because of unknown and sometimes changing variability between screens, it will be necessary to sample the whole catch. The catch has been shown to vary with time of day, tidal state, season, as well as station load (governing cooling water volume and flow) so that it will be necessary to sample through day and night tidal cycles at different seasons and in different station operating conditions.

The catch may be measured simply as total weight or by total numbers or by species occurrence, but other measurements may be made of the condition of the catch, e.g. individual weight/length, reproductive condition, parasite/disease infestation, according to the objective of the study. The significance of the catch will require information about its age-class distribution and the size and structure of the population from which it comes in the vicinity of the intake, possibly from existing knowledge and trends in commercial catches of fish and macroinvertebrates.

8.2 Detection of Effects of Plant Entrainment

Plant entrainment effects require specialized methods of sampling at appropriate locations in the intake and discharge streams. Considerable physical difficulty may be encountered at both intake and discharge locations. In the discharge it may be impossible to sample upstream of plume entrainment and the high velocity of discharge makes sampling difficult. The possibility of plankton patchiness at the inlet and the time lapse between sampling at intake and outfall should be kept in mind if a direct comparison is made between intake and outfall samples. Success in sampling has been achieved by use of a pump sampler for phyto- and zooplankton but the collection of fish eggs and larvae requires the filtration of large water volumes by the use of specially designed nets which can operate in high velocity flows. Entrained organisms vary in variety and abundance with tide and season so that sampling schedules should include a full range of tidal state and seasons.

The responses measured may be numbers alive, dead and damaged (sometimes calling for some kind of objective measure) or of change in activity (e.g. of microbial function, ^{14}C uptake, respiration) and some account may be taken of delayed effects, especially to zooplankton, by retaining samples for a further period of observation. The effects observed will be those resulting from the combined stresses of physical (flow, pressure, turbulence, velocity, temperature) and chemical (dissolved gases, biocides, adventitious chemicals) conditions. Some laboratory studies may be needed to distinguish these effects, but useful information may be gained from samples taken during different operating conditions, e.g. with/without biocide application, with/without power generation, with variable flow and velocity.

8.3 Detection of Effects of Discharge

These will depend on the specific question posed. While these field studies involve the same scientific principles, the level of effort will differ depending on the aim of the survey. Whether the aim is to resolve a particular research problem or to monitor environmental change, data obtained from laboratory and/or modelling studies (8.4 and 8.5) can assist in either the design of the study and/or interpretation of the results. It should also be noted that in these field studies it will be difficult, and at times impossible, to separate changes due to the different components (e.g. heat and biocides) of the discharge, or due to entrainment or plume effects.

The same kinds of measurements can be made in all the sessile biotic communities (intertidal or subtidal, on rocks or less stable substrates). These include the distribution and abundance of the organisms, biomass, reproduction, larval settlement. The observations need to be related not only to conditions in the discharge, e.g. distribution of temperature, residual chlorine and other chemicals in the plume, deposit of organic material and shell, but also to the natural background of abiotic conditions of significance to the biota, e.g. characteristics of the sediments and of interstitial water. The data then need to be analysed using a multivariate approach because it is seldom, if ever, possible to find a valid 'control' area for simple comparison of conditions. In addition, many areas may be subject to contamination by other industrial effluents. Other field measurements could include growth of marked organisms, abrasion and erosion of mollusc shells, survival of marked organisms.

Sampling of floating and mobile populations (plankton, fish, large invertebrates) is more difficult particularly for plankton, due both to patchiness in natural distribution and to sampling problems. It is therefore difficult to assess the natural level of these populations and any population change due to the discharge, in the field. A better indication of these changes may be gained through laboratory studies in which the organisms are exposed to simulated field conditions (see 8.4).

For fish and large macroinvertebrate populations of commercial importance, estimates are based frequently on either fish catch or field surveys to yield an estimate of the natural population levels. However, data for non-commercial species are generally unavailable. Diver surveys in which the distribution and behaviour of organisms can be precisely related to water temperatures can provide useful data. In addition, laboratory studies should be conducted, exposing fish and large invertebrates to simulated discharge conditions to determine mortality rates and such sublethal changes as behaviour and reproductive modification (see 8.4).

Organisms collected on field surveys should be examined for changes in parasitic infection and incidence of disease.

8.4 Laboratory and Field Experiments

The complexity of conditions during station operation and the diversity of interactive causative agents suggests that experimental investigations will help to understand observed effects and to provide data for incorporation into predictive models. However, even with the best conceived laboratory experiments and field simulations, extrapolation of the findings to actual field conditions is difficult. Extrapolation and use of the findings may be limited by the design of the experiment, for example where cage experiments exclude the use of organisms which employ escape strategies. Designed and used with specific objectives in mind, however, experiments can provide valuable information on the response of organisms to specified conditions. Three types of experiments can be suggested: field manipulations, laboratory simulations and laboratory tests.

Field experiments may involve exposure of caged organisms within the discharge plume and the measurement of, for instance, survival, growth, fecundity, parasite infestation, behavioural or biochemical changes. Alternatively, the removal of organisms from standard areas and measurement of recovery in discharge-exposed and control sites can provide useful information on the responses of selected species or of whole communities.

In laboratory simulations, tests may select a single cooling water function, e.g. intake flow, entrained flow or discharge and single or multiple components, e.g. temperature, velocity, chlorine. Similar observations may be made as in the field but, in addition, free-swimming or planktonic forms can be tested. Conditions of stress may be constant or can be varied to simulate actual fluctuations of cooling water quality. Comparison of the same measurements obtained in the field and in laboratory experiments will give insight into the limitations of both approaches and aid the interpretation of field observations.

Historically, laboratory exposures involve standardized bioassay tests of lethality, employing a derived LT50 (time to kill 50% of test sample) or LC50 (concentration for 50% mortality). Development of thermal criteria for protection of a species will include consideration of response to both short-term and sustained exposure, definition of the range of tolerance, the effect of a previous holding temperature (acclimation) and of specified lethal thresholds (for 50% survival, referred to as 'incipient lethal temperature'). Time-dependent equilibrium loss (ELD50) has been used for mobile organisms using changes in locomotory function as the target response to take account of behavioural changes. The use of ELD50, however, cannot be applied to slow-moving or sessile forms. Exposure periods related to those sustained in the field are most appropriate, as well as simulation of rates of change. Most laboratory studies can be helpful in comparing the responses of different organisms or life stages to standard conditions, and may help to determine mechanisms of impact. The extrapolation of findings to field conditions, however, is limited to those tests which effectively mimic field conditions, taking account of such biological factors as delayed mortality or sublethal responses. The latter, which may include respiration, behaviour, biochemical or physiological functions, can determine survival, as for instance when a stress exposes the target species to a greater level of predation. Laboratory studies have limitations in that animals (especially fish) in the field may be able to escape quickly from adverse conditions.

Thermal resistance functions can provide a basis for assessing and predicting the thermal effects of exposure of organisms to different time-temperature histories. Their validity, application and interpretation are straightforward, at least conceptually. However, appropriate thermal tolerance data are lacking for many of the important entrainable organisms. Criteria for laboratory-derived thermal tolerance data include:

(i) that exposure to an excess temperature be applied instantaneously so that no thermal adaptation can occur;

(ii) that mortalities are reported as functions of both temperature and exposure time;

(iii) that mortalities occur over a range of exposure time from a few minutes to about two hours;

(iv) that experimental organisms are those that cannot avoid the thermal influences of discharge.

In addition, it is important that delayed mortality be measured.

8.5 Biological Modelling

The limitations of observations made in the field or in the laboratory may, in certain cases, be overcome or alleviated by the formulation of suitable models. Moreover, these will be necessary for an objective assessment of the significance of the observed effects on the status of a particular species, community or ecosystem. There is scope for models of species interactions (e.g. prey-predator relationship), or environment-organism interactions (e.g. nutrient transfers, productivity) and of population dynamics. In the last case, given appropriate data, it will be possible to predict trends in population size and their time-course. Models may also be helpful in the selection of the most important forcing terms for significant change so that laboratory experiments or field measurements can be directed purposefully.

In practice, investigations at a site will include some combination of field sampling, laboratory and field experiments, and a large body of data may be collected. These primary data are unsuitable for publication but can often be used to test later hypotheses. For this reason, a systematic recording of data and access to field data is desirable.

9. STRATEGIES AND OPTIONS FOR THERMAL DISCHARGES

In consideration of the biological effects of thermal discharges to the marine environment from power plants, a number of strategies that may either mitigate or reduce biological damage can and should be investigated. Some should be examined early in the decision process. These might be related to overall policy as well as to the need for additional generation capacity versus the benefit of conservation measures, the type of generation (fuel, combined cycle, renewable) and site selection. The examination of these factors will undoubtedly be constrained by certain boundary conditions such as where the power is needed, the existing electrical grid system or other energy transfer systems such as fuel pipelines, the availability of renewable and non-renewable energy sources, economic factors, regulatory criteria and other considerations. These factors, in addition to others of significance, should be carefully analysed by means of a systematic approach such as Cost-Benefit or Decision Analysis. Such analysis should be able to indicate also that a no-option alternative may be preferred. The final choice will imply value judgements which each decision-maker must resolve.

Given that additional power is desired, the next step is to consider the options for obtaining that power. Although the obvious alternatives might be conventional and nuclear power plants, in certain geographical areas some of the renewable sources of energy such as geothermal, wind, tidal, ocean thermal energy conversion (OTEC) may be available for consideration; for the latter two, see GESAMP Report on Marine Pollution Implications of Ocean Energy Exploitation (GESAMP, in press).

The efficient conversion of thermal to electrical energy is limited by basic physical principles. Any system, however, leads to the withdrawal of heat energy and its discharge. Heat is moved out of the system by direct transmission into the atmosphere (flue gases) and by the cooling water discharge. The amount of heat to be discarded and its division over air and water varies with the system chosen (Table IV). The ultimate heat rejection with cooling water can be further reduced by passing through cooling ponds or on towers or by beneficial uses of the heat.

OTEC utilizes the temperature difference between warm, surface waters and cold, deep waters of the ocean to drive a heat engine that produces power. A 'closed cycle' OTEC process employs a working fluid (e.g. ammonia) upon which work is performed (evaporation) by the warm water through a heat exchange process, producing a vapour that turns a gas turbine. The gaseous working fluid is then condensed by cold sea water, completing the cycle, whereupon it is repeated. The 'open-cycle' process is similar but uses sea water as the working fluid; one direct residual of the process is fresh water. The OTEC process is very dependent upon obtaining a temperature difference of about 20°C between the warm and cold sea water. Although there are exceptions, countries located within the latitudinal band of $\pm 20^{\circ}$ from the equator have the needed thermal resource to develop OTEC.

Table IV

Heat rejection by different generation systems

System	Efficiency (%)	Heat rejection (%)	
		Into air	Into water
Nuclear power	30-40	2	58-68
Large conventional units	40	10	50
Gas turbines	36	67	0
Combined gas and steam turbines	45	20	35

Once the basic decisions have been made, the systematic analysis should begin to examine the detailed requirements of the chosen energy option, such as the site and the basic engineering system. Of course these decisions will also have inherent boundary conditions, the most obvious being that the regulatory criteria must be obeyed. As discussed in section 9.3, certain engineering strategies can be chosen to meet both the economic and regulatory criteria presented.

Assuming that the decisions result in the discharge of heat to the environment, certain alternatives might next be viewed for utilizing this as a resource and, in some cases, reducing biological impact. Mariculture is one possibility; waste heat utilization is another. Section 9.5 provides some details on key considerations of such a systems approach.

9.1 Integrating and Evaluating Methodologies

The siting and design of a power plant requires a number of complex decisions in which many goals and policies are balanced against each other. In some cases the relative importance of these goals is undefined, and impacts are discussed in apparently non-comparable terms. Power plant decisions are of major importance from the point of view of the society. For this reason, it is essential that the decisions are taken on a systematized, orderly and consistent basis ('formalized common sense').

Several formal methodologies for securing a comprehensive decision basis exist. A wider use of such methodologies in the power plant siting and design process would be of advantage to society from an environmental point of view, as well as from the aspect of power production. However, it is important to state that the use of a formal methodology does not remove the burden of responsibility from the decision-maker, nor provide ethical neutrality. Furthermore, the logical manipulation of the inputs should not be equated with objectivity.

The choice of the methodology to carry out such an assessment depends on the value system of society, on the time, money and data available, and on the salient characteristics of the decision problem itself. Among those available are Decision Analysis, Cost-Benefit Analysis, Risk Assessment and Cost-Effectiveness Analysis.

Decision Analysis provides a systematic decisional tool. It is responsive to the need to evaluate risks as well as to the expected gains of the different options. Although it requires specification of the relative values that the society places on each effect (value judgements) to be made explicit, these need not be made in monetary terms.

Cost-Benefit Analysis is a subset of Decision Analysis which embodies very distinct value judgements. It follows that this methodology is only appropriate in societies which are prepared to accept these value judgements for themselves. Further, it is weak in its ability to assess options which differ in degree of risk.

Cost-Effectiveness Analysis and Risk Assessment partially avoid the value judgements of Cost-Benefit. They also avoid the necessity to state explicitly society's acceptable trade-offs as required by Decision Analysis. In doing so, they optimize only a part of the total problem and lose the assurance of consistency in policy formulation.

9.1.1 Cost-Benefit Analysis

The most commonly cited form of analysis to cope with this comparison is Cost-Benefit Analysis (CBA).

Detailed descriptions of CBA and its procedures are available in Mishan (1976) and Peskin and Seskin (1975). Briefly, it is an accounting procedure. The analyst compiles a list of each cost-and-benefit component, and develops models to evaluate the magnitude of each in monetary terms. This is done for each option under consideration. The gain in efficiency of each option is represented by total 'net benefits', or the value of benefits less costs. Net Benefits (NB) is called the 'decision criterion' because it indicates the relative increase in economic efficiency that is the deciding factor in CBA. For CBA, the optimal option is the one with the greatest gain in efficiency.

Complications arise mainly when not all of the costs and benefits have obvious or direct economic value. Care must be taken in translating these components into monetary values. Valuation methods that are compatible with classical economic theory are described by Freeman (1975). These methods imply the value judgement that the preferences of individual citizens correctly reflect social goals. More arbitrary ways to set values are possible if individual preferences are considered inappropriate.

CBA thus has the advantages of being well-founded in economic theory and of being a relatively straightforward concept. Its usefulness is limited, however, and when risks and uncertainties prevail, the use of net benefits may not reflect the true concerns of society.

9.1.2 Decision Analysis

Decision Analysis (DA) provides a formal methodology to make decisions which have several sources of uncertainty and provides a tool for assessing the risks as well as net benefits of different options.

DA differs from CBA in its versatility and sensitivity to decision criteria and in its emphasis on risks. The use of expected net benefits assumes that the decision-maker is not concerned with risks. In reality, a society may be risk-averse, especially when the decision involves small but finite risks of exceptionally bad or irreversible outcomes. DA can incorporate risk avoidance either through a formal measure of risk aversion or by using risk criteria rather than the expected value criterion.

Valuation of costs and benefits can be made in the same way as in CBA, but this is not required. Instead, DA notes explicitly that the decision criterion should reflect the preferences of the decision-maker, not solely the goals of economic efficiency. In social decisions, the criterion should be consistent with the social value system. Some examples of possible decision criteria are:

- Maximization of net benefits;
- maximization of NB, subject to zero risk of negative NB;
- minimization of risk that environmental damage is unacceptable;
- minimization of possible damage;
- maximization of unacceptable environmental damage;
- choice of option preferred by majority of citizens.

The essence of DA is summarized in three phases: deterministic, probabilistic and informational. The deterministic phase is analogous to a CBA, with the exception that the decision criterion does not have to be net benefits. A preliminary, deterministic model is developed where all variables are set at some nominal value, often referred to as the 'most likely' value. The purpose of the deterministic decision model is not to indicate the best siting or system option, but to perform sensitivity analysis to determine which variable has now to be used in the probabilistic analysis.

The analysis then moves on to the probabilistic phase, where the sensitive variables are stated in probabilistic terms, and the model is altered to incorporate their Probability Density Functions (PDF). The decision tree is re-evaluated, now reflecting the input PDFs according to the rules of probability. The outcome of this model will now be a PDF on the decision criterion, or statement of risk for each option. To maintain the NB criterion, the option which yields the highest expected NB is chosen. However, one is no longer limited to such a criterion. The probabilistic model provides information on the probability, or risks, of several kinds of outcomes, whether they be degrees of environmental damage in either physical or monetary terms, or the risk that the benefits will not be large enough to outweigh the costs (i.e. the risk of NB <0).

After the probabilistic phase is complete, a preliminary decision can be made. However, a further informational phase should be completed to take full advantage of the additional information that a probabilistic model can provide. The informational phase quantifies how much better a more informed decision would be. This helps determine whether a decision should be made to act now or to wait until more data can be collected to reduce some of the uncertainties. It also helps indicate the appropriate amount that should be spent on further research, and helps set priorities among research projects. This phase is especially useful where sequential decisions are to be made, or where there are opportunities to delay decision-making if more information could be particularly valuable.

This completes the description of the DA methodology where the three phases are actually a cycle. When new information is available, the PDFs can be updated to reflect changed uncertainty and the optimal decision can be re-assessed. Figure 4 illustrates the DA cycle for a power plant siting problem. Numerical demonstrations and more formal mathematical formulations are available. For examples, see Howard (1966, 1975); Raiffa (1970); Howard et al. (1976) and Hietamaki et al. (1982).

A less complex method of adapting CBA to reflect uncertainties is to compute 'best' and 'worst' cases of the problem, where all variables are simultaneously set at the extremes in their ranges of uncertainty. This method should be avoided since, in general, it only confuses the decision. Few decisions will be totally robust to extremes and uncertainty in the assumptions, so CBA will rarely provide the decision-maker with the comfort of certainty on the optimal action. The best and worst cases are exceptionally conservative estimates since they assume that all variables are simultaneously higher or lower than current evidence indicates and so of very low probability.

9.1.3 Cost-Effectiveness Analysis and Risk Assessment

Cost-Effectiveness Analysis (CEA) and Risk Assessment (RA) explicitly optimize on only one portion of the problem. Rather than indicate the best and most efficient policy, they merely indicate the cheapest way of attaining a given goal. For instance, CEA answers questions such as 'What is the physical extent of environmental damage per dollar spent on plant capacity at each site?'

RA compares the probability of specific non-monetary outcomes, such as the probability of a fish kill, with the costs of each option. The decision-maker chooses the option which provides the 'most acceptable' combination of risk and economic damage. The site selection follows as the next step. Both choices retain large intuitive components which may need systematic ordering. Because value judgements are not avoided, the decision-maker will still have to resolve the most difficult issues of social valuation using other methods.

9.2 Regulatory Criteria

Discharges of heat to the marine environment, like that of other contaminants, is subject to regulatory action. The decision on regulation is therefore a constraint on that of siting and system design. Governments may wish to use one of the decision tools indicated in section 9.1 to help define appropriate regulatory criteria. One concern in developing regulatory criteria is that in many cases a thermal discharge is made to a water body already receiving other polluting discharges from urban developments, primary and processing industries, and maritime transport. Indeed, thermal stress may also increase the rates of uptake and reactivity of some contaminants at least in the near field of the thermal plume.

It is proposed that regulatory action for thermal discharge should follow the same principles that are used for other pollutants in areas subject to pollution from various sources and to consider the overall effect of the several discharges to the receiving environment. The capacity of a receiving water to accept the discharge of reject heat without unacceptable disturbance must be determined, although it may not be easy to do so with certainty, even when all the specifics of the environment have been identified. However, even a rough estimate allows a probabilistic approach such as that outlined in Section 9.1.2 to be applied so that the risk of producing unacceptable effects can be assessed. To derive regulatory criteria from this information requires the additional concept

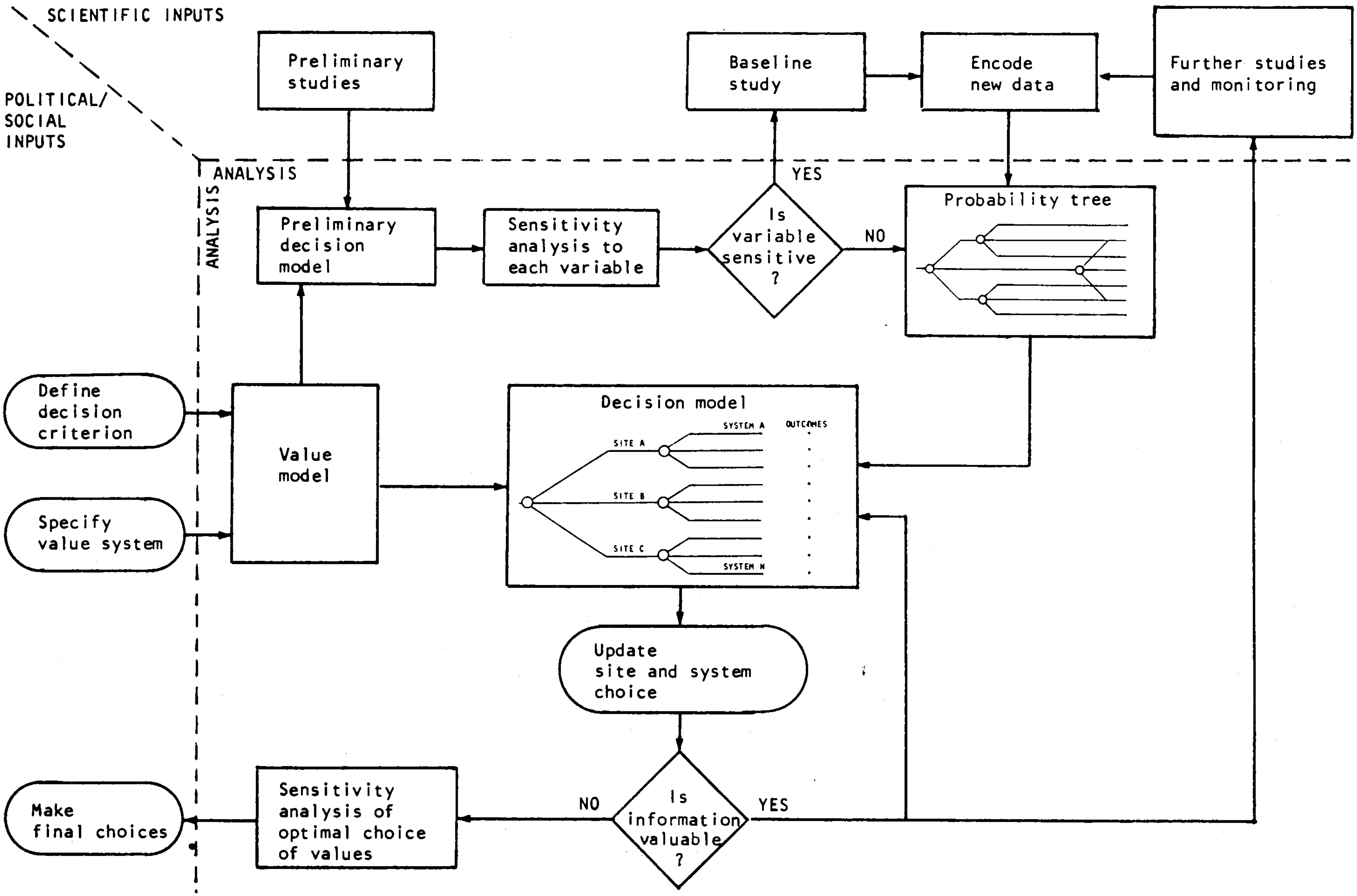

Figure 4. Schematic representation of a Decision Analysis

of environmental quality objectives. The widely used regulatory methodology of uniform effluent standards does not discriminate between capacities to assimilate heat and sensitivity of different receiving water bodies. In adopting this approach, several steps can be identified as follows.

9.2.1 The definition of the impacted area

As discussed in section 4, mathematical modelling can be used successfully to predict the extent of the impacted area which can be defined by criteria such as ΔT of $1^{o}C$ or $3^{o}C$. Similar considerations apply for total residual oxidant. Monitoring can be used to check on the predictions made earlier. The delineation of the extent of the impacted area, important for the consideration of long-term ecosystem effects, will require some more difficult to define parameters but the problem can be resolved by a series of reasonable approximations.

The hydrodynamics of the impacted area will be an essential, possibly the most specific, component in the description of the site.

9.2.2 The establishment of the dose-response relationships

Dose-response relationships should be identified for the major pollutants and targets in the impacted environment. Considerations of rates of uptake, chemical reactivity and biological response are influenced by the elevated temperature resulting from heated discharges. Due to insufficient data, approximations have to be made of the dose-response relationship. The literature of target response to many pollutants indicates some threshold for response or a less sensitive approach at low exposure, so that adopting a 'worst case' would be unduly conservative and a preferable approach would be to develop probabilistic estimates of thereshold and slope of response, following the methods in Section 9.1.2.

Primary standards for a discharge require a scientifically based estimate of the concentration or dose of a contaminant with no unacceptable effect on a target and assume no other sources than the discharge and that the route by which a contaminant reaches this target is known or can be assumed with a high degree of probability. When synergistic or additive effects can be identified, these standards may be different from those established for the same pollutants in the absence of heated effluents. Constraints may need to be imposed to limit the extent or direction of the discharge plume, if some unacceptable risk is identified.

The specific characteristics of various zones (see section 6) indicate that primary standards, and consequently the derived working limits for discharges, will seldom, if ever, be of general validity. Research and monitoring at the site for discharge will thus be an essential element of siting and design decision, and consequently a prerequisite for regulatory action.

9.2.3 The receiving capacity of the environment

On the basis of site-specific information, the capacity of the receiving environment to assimilate heat can be estimated, possibly using the methods described in Section 9.1. The capacity for thermal discharges will strongly influence siting and design decisions, and the maximum allowable power generation. It will also influence decisions on biocide treatment of cooling water, in view of considerations elaborated in Section 2.4. Experience of existing installations at a site may provide good information on the capacity of that site, which can then be judged on the basis of preoperational surveys.

A further step is the regulatory decision on the extent to which the environment can be used for waste heat disposal, taking account of all other inputs to the receiving water.

An environmental impact assessment is desirable for thermal discharges, irrespective of whether other pollutants are present. The assessment, formalized or not, should be an essential part of the decision-making process, since it can ensure that all pertinent information is available and accessible before final decisions are taken and construction is begun.

In some cases, such an allocation involves international agreements on environmental quality objectives and primary standards. While the principles underlying the assessment of receiving capacity or other environmental protection procedures are fundamental and consistent with international conventions and protocols (e.g. the Convention for the Prevention of Marine Pollution from Land-based Sources, Paris, 1974; the Barcelona Convention and its associated protocols; the relevant articles of the Law of the Sea, etc.) any assessment or similar procedures will have to be within the framework of the regulatory and legislative system of each country, so that deviations from the generalized recommendations above might be warranted. However, following the approach outlined above, it will be possible to conform with these international conventions and protocols. These have already been implemented in many regional or semi-enclosed seas, whose coastal areas and marine waters are shared between several nations.

9.3 Engineering Options

Once a site has been chosen, its environmental impact can be moderated by a variety of engineering options. These can be divided into two categories: means of decreasing the impact of a given discharge, and means of reducing the discharge of a given amount of installed power. Plans for additional plants at an existing industrial location must be considered carefully so as not to exceed the acceptable limit of discharges, or to exacerbate the effect of other discharges.

9.3.1 Means of reducing the impact

Means of reducing the impact of a given discharge include:

(a) Utilization of existing thermal gradients by constructing a submerged intake.

(b) Improvement of dispersal via currents and tides by locating the outlet at exposed locations or offshore.

(c) Reduction of recirculation and resulting build-up of temperature by careful planning of the relative positions of inlet and outlet.

(d) Modification of plume characteristics by installing diffusers or by specially designed outlet structures.

(e) Optimization of the relation between temperature increment (ΔT) over the condenser and magnitude (Q) of the cooling water flow. When ΔT is low, the cooling water flow has to be high to discharge a given amount of heat, and mechanical or chemical damage to entrained organisms can become more serious than thermal damage.

(f) Reduction of screen impingement mortality of fish larvae by increasing mesh size of screens where entrainment damage is less than impingement damage (subject to protection of condensers).

(g) Reduction of impingement of fish in areas of significant fish populations by reducing intake velocities, providing visual 'markers' so that fish can orient themselves, and by converting vertical flows to horizontal flows. In some cases, escape of the fish can be encouraged by louvre systems (Hadderingh, 1979).

(h) Reduction of the mortality of impinged fish by installing suitable systems, e.g. travelling bucket screens to remove impinged fish from the screens and to guide them back into their original environment.

(i) Reduction of the impact of anti-fouling agents such as chlorine by alternative methods. These include mechanical cleaning methods, heat treatment (flow reversal), permanent anti-fouling paints. Heat treatment is effective if the temperature in the inlet channel is increased over 30-60 minutes to approximately 40^{o}C. Mussel sieves have then to be installed at the end of the inlet channels or ducts just before the condenser (Jenner, 1983, 1983a).

It is impossible to specify generally-applicable design specifications for the above-mentioned options. These have to be determined on the basis of methods described in section 8. In evaluating the methods (a) through (d), extensive model experiments may be necessary. The cost of some of these options, such as offshore inlet structures, may be very high. It is important to note, however, that the cost of options (e) through (i) is relatively low if they are incorporated in the initial design of the system.

9.3.2 Means of reducing the discharge

If the desired generating capacity of a site has been set, there may still be options to reduce the thermal discharge, for example by developing combined heat and power systems, changing unit

Here, only measures of reducing the thermal discharge of a given unit are presented. Benefits gained have to be weighed against possible adverse effects of increased costs, increased fuel use, visual intrusion, for example.

(j) Cooling ponds or lagoons - this option is feasible only when enough space is available. For a 1 000 MW plant, allowing a mean temperature increase in the lagoon of 10°C, an area of 3 km^2 would be required.

(k) Wet cooling towers - in areas where water is available, but acceptable heat discharges are limited, wet cooling towers can be installed. They can be used for once-through or for closed cycle cooling. The heat discharge will then be reduced to approximately 50% and 2-10% respectively, but some chemical discharges may be unavoidable, e.g. antifouling or antiscaling agents. In the latter case, the efficiency of the power plant is reduced because the temperature of cooling water circulating in a closed cycle is higher than that of water taken in from undisturbed surface waters. In temperate climates, this loss of efficiency is of the order of 2 to 4%.

(l) Dry cooling towers - in areas where water is scarce, dry cooling towers may be installed. Heat discharges into the water are then reduced to zero, but investment and operating costs are high. The loss in efficiency of the power plant can be as high as 10%.

(m) Hybrid cooling towers can offset some of the disadvantages of wet cooling towers, for example vapour plumes, without incurring the cost of a dry cooling tower. In principle, a hybrid cooling tower is a combination of a large wet and a smaller dry cooling unit.

9.3.3 Summary and comparison of engineering options

In Table V below, a summary is given of these engineering options, grouped by their estimated impact on heat and water discharges, as well as by their estimated influence on power plant efficiency and cost.

Table V

Order of magnitude estimates of consequences of engineering options

Measures	Heat discharge	Water discharge	Fuel consumption	Investment
none	100%	100%	100%	100%
a-d	100	100	100	100-110
e-i	100	100	100	100-102
j	determined by local conditions			
k open cycle	50	100	100	102-104
k closed cycle	2-10	2-10	102-104	102-104
l	0	0	108-110	108-110
m	2-10	2-10	104-108	104-106

9.4 Anti-fouling Alternatives

Chlorine has proved to be an economic and effective agent for control of both macrofouling of culverts and condenser slimes. However, the toxicity of chlorine is a distinct disadvantage from an environmental point of view. At both existing and planned power-plant sites the need for chlorination should be evaluated continuously so that the method of chlorination can be changed and fouling organisms in the intake water (e.g. by growth exposure experiments) it is possible to demonstrate whether anti-fouling is needed and, if so, at what time of the year the need is highest.

It may be difficult to assess the potential for fouling at new sites, but some guidelines can be offered through the schedule below.

- Establish likely need, by reference to local conditions - is it observed in the locality?
- Establish likely site of fouling - culverts, condensers, secondary circuits.
- Consider alternatives for control: mechanical cleaning, flow reversal, closed system chlorination, intermittent or continuous dosing.
- Identify fouling organisms within (tidal) range, find seasonal variations in abundance, timing of 'settling' stages.
- Find 'chlorine demand' of cooling water at each season, and derive effective dose.
- Design chlorination regime (concentration · time) and form (chlorine gas, HOCl, ClO_2, chlorine electrolysis) and calculate residual at discharge.
- Validate calculations by measurement at condenser outlet.
- Assess effects of residual in plume areas of ΔT 3^oC and ΔT 1^oC.

This procedure will establish the requirement for chlorination, identify the regime appropriate to the conditions at the site and minimize possible environmental effects in the plume. It is important that fouling should be prevented since it can reduce operational efficiency and so change discharge characteristics, as well as threaten plant operation. Further ad hoc or retrofit measures may be costly and ineffective and may have environmental consequences of their own.

9.5 Ancillary Activities for Waste Heat Utilization

9.5.1 Energy use and recovery

Given the need for energy in our society, the indiscriminate discharge of heat to the environment represents an unused resource. Such heat could be utilized for industrial processes, desalination, space heating, agriculture, mariculture, recreation and 'bottom cycle' OTEC operation. In special circumstances, the productivity of certain warm-water species may be enhanced in a limited, local area of the discharge. All desired options would, of course, have to be evaluated using the methods of section 9.1, taking account of the expected environmental consequences.

One example is mariculture (see section 9.5.2). Another would be a 'bottom cycle' OTEC operation which utilizes ocean waters for the cold condensing part of the OTEC cycle, but the evaporation side is accomplished by utilizing heated water from another source. This could be the waste heat from a conventional or nuclear power plant. Providing the economics are favourable, a bottom-cycle OTEC operation would have two advantages: (i) additional heat is removed from the effluent, thus reducing the potential for thermal effects, and (ii) additional energy is recovered, thus making the overall process more efficient.

Energy recovery is practiced in other fields such as sewage treatment, where methane gas is recovered from the anaerobic digestion process and is used to supply power for certain machinery, to warm the digesters, and in some cases is sold to nearby industries. To the extent that heat recovery can be practiced on thermal effluents, overall systems will be made more efficient and the potential for environmental effects will be reduced.

9.5.2 Mariculture

Reject heat in cooling water from power stations is generally at too low a temperature for most of the applications identified above. However, the temperatures are suitable for the growth enhancement of biological systems in cool and temperate climates, for example in horticulture, and a possibility in non-tropical waters is the use of cooling water for mariculture.

The potential for mariculture at power plants is quite high in principle. The heated water enhances the growth rate of fish and other organisms and increases the production capacity of a fish farm. Year-round mariculture is made possible in coastal areas where ice occurs. Temperature control makes it possible to have an evenly-distributed production over the year, which is advantageous from a marketing point of view. Warm-water species may be grown in summer or even over the year in temperate zones.

The fish holding capacity of a farm is determined in the first instance by the availability of oxygen, at concentrations suitable for optimal growth. While the amount of oxygen in the water from a 1 000 MW power plant is sufficient for the production of approximately 10 000 tons fish/year, there are a number of problems or constraints related to thermal aquaculture. For this reason, it has not been possible to develop more than a small part of this potential.

At present, a number of experimental thermal mariculture facilities are operating but there are only a few commercial facilities. The total European production is of the magnitude of 1 000 tons/year.

The main problem of thermal mariculture is a question of risk and risk management. Currently, production facilities are land-based, with possibilities for pumping, aeration, oxygenation and recirculation. Where variations in the quality of the cooling water are caused, for instance, by variations in ambient water, by power cuts, by accidental spills of chemicals or by intermittent chlorination, it has to be possible to close down or decrease the intake of water to the fish farm so as to reduce risk. It will always be the responsibility of the fish farmer to secure the safety of his fish, and power plants will generally not guarantee that water quality or flow will be maintained. It follows that small single-unit, peak-load stations will be inappropriate.

The constraints of thermal mariculture are several. Land resources are a major limitation to the development of the production potential. An intensive mariculture operation has a land requirement of about 1 000 - 5 000 m^2 per 100 tons of fish produced annually. The land resources for a complete exploitation of the potential may be available only at new power plant sites under planning.

Construction and running costs of intensive mariculture facilities are high, and for this reason production will generally be limited to fish (trout, eel, turbot, sea bass, etc.) or crustaceans (penaeids) of high market value. The costs could be decreased through technological improvements, through inclusion of the mariculture farm in the planning of new power plant sites and by farming herbivorous fish. Construction costs may, in some cases, be decreased by using netcage culture systems in the discharge zone.

Any new mariculture project should not be developed in isolation, but in relation to expected demand, with market and production capacity developing in a coordinated manner.

A fish farm contributes an environmental pollutant load to the discharge area. A complete removal of organic material, nutrients and pathogens may not be possible from an economic point of view. The receiving capacity of the adjacent coastal area may, for this reason, place an upper limit on production. The problems of discharge of organic material and nutrients from fish farms and other sources are well known and can be quantified. At new power plant sites, where land resources are available, it is possible to recycle a major part of the nutrients through lagoons by production of shellfish and seaweed. Furthermore, a cooling effect from these lagoons can be expected. Additional land resources for this purpose may be obtained through land reclamation in shallow coastal zones. The use of solid waste from coal-fired plants may, for this type of land reclamation, be feasible in some cases .

Problems related to human and/or fish pathogenic microorganisms from a thermal mariculture facility are less well understood. The risk of human infection will be low, as primarily the fish farm discharges microorganisms which live in association with fish. Some increased risk of infection of wild fish may exist, but the magnitude of this problem is expected to be low, compared with fisheries and fish production in the coastal zone.

10. ENVIRONMENTAL ASSESSMENT

Any large coastal development requires selection of the most appropriate site, a choice of system with minimal environmental disturbance, and a programme to monitor effects. From initial site selection and planning, through to commercial operation, there is opportunity for information gained to be used to modify decisions on design features or operational regimes so as to achieve minimal effects.

While investigation and assessment continue throughout development and operation, specific information needs vary at each phase, leading to investigations different in nature, detail and time scale. Priorities for research can be determined following the procedures outlined in section 9.1.2.

It is important to achieve consistency and continuity in the investigations, primarily to provide a baseline against which later trends can be observed so that findings can be related to engineering design, both to advise on modification and to identify conditions resulting in minimal environmental disturbance. Consistency of approach at a variety of sites will also aid the general formulation and application of successful siting and design features.

Experience with environmental assessment has been gained over the past decade; some countries (e.g. U.S.A., France) have adopted formalized procedures. Analysis of its value, and appropriate modifications, will no doubt develop with time and further experience.

Since the whole process from site selection through to commercial operation will take some years, and since biological variability in time also requires data to be collected over reasonable time periods, meaningful studies of a monitoring nature must be sustained over several years. The initial programme may be reduced or changed as the study progresses, and as crucial questions are identified. A theoretical 'ideal' for such a study and a time scale are indicated in Table VI.

10.1 Initial Site Assessment

At the initiation of coastal development, the biotic and abiotic characteristics must be defined for preliminary decisions on site, system and design.

Table VI

Phased programme of investigations and assessments

		TENTATIVE TIME SCALE (years)
1.	Preliminary Procedures for Planning and Site Selection	N-12 to N-11
	- Abiotic conditions (terrain, climate, physical and chemical conditions)	
	- Biological assessment	
2.	Baseline Studies at the Selected Site	N-10 to N-8
	- Plume models	
	- Impacted area prediction	
	- Biological assessment	
	- Sampling programme	
	- Fouling assessment	
	- Evaluation	
3.	Preliminary and Baseline Studies	N-7
4.	Further Studies and Monitoring Programmes	
	(a) During constructions (minimal, for continuity)	N-7 to N-2
	(b) Commissioning	N-2 to N 0
	(c) Operating	N 0 to N+4
5.	Evaluation and Assessment	N 0 to N+4

10.1.1 Abiotic conditions

The main criterion is the cooling capacity of the receiving water. In the area of interest, advection and dispersion of heat should be estimated. Atmospheric exchange is not a discriminant parameter in the near-field, and can be neglected.

An estimation of thermal plume can be made at this stage by formulating a mathematical model utilizing site specific meteorological and climatological data, physical characteristics of the sites of intake and discharge, and identifying characteristics of the receiving water. This should identify the extent of the area of impact. Much of this information is available from plant engineering studies. In populated and industrial areas, flux and concentrations of chemical pollution from other discharges must be recorded: heavy metals, PCBs, BOD, agricultural chemicals, possibly bacterial pollution levels. Future developments must also be taken into account. Important geological characteristics of the site include substrate stability and seismicity at the plant site and sediment characteristics and movement in the adjacent coastal area.

10.1.2 Biotic conditions

Initially, a general reconnaissance of the area is a valuable beginning. A survey of current knowledge, to include site-specific features, studies on species of relevant range and habitat, fishery statistics, fish migration routes through the area of impact, will help the initial assessment. Preliminary reconnaissance should include:

(i) The extent of areas of major and important habitats, communities and species;

(ii) limited subtidal samples to determine bottom type (but not planktonic and pelagic communities);

(iii) water depth and circulation data.

Data on fisheries (commercial or recreational) and seasonal fish migration routes are particularly important in considering the potential for screen impingement and plant entrainment of eggs and larvae.

The most sensitive and important habitats are the shallow-water (~30 m or less) nearshore habitats in which the biota form a three-dimensional community structure. These include coral reefs, sea grass beds and mangroves in the tropics, kelp beds, nursery areas, oyster and mussel beds, and wetlands in temperate regions.

Other sensitive areas not generally regarded as ecologically and economically important are intertidal areas comprising rocky outcrops, sandy strands, mud flats and weed beds. However, at some locations these may be important if they support commercial fisheries (e.g. clam beds), provide food in nursery grounds for important species, support mariculture or have some recognized unique feature.

The least sensitive areas are the deeper (>30 m) waters with benthic infaunal and epifaunal communities. These will not be exposed to surface plumes but could be exposed to scouring cold water plumes, or by entrainment of larvae into hot discharge plumes, or possibly, at some sites, by permanent or temporary impact of the thermal plume at the sea bottom.

10.2 Baseline Studies

At this stage, more detailed studies of a more specific nature can be formulated to improve plume modelling and prediction, impacted areas and environmental effects prediction. These studies should also establish a 'baseline' of prior environmental status against which the effects of operation can be monitored. The elements of these studies are discussed further below.

10.2.1 Plume modelling and prediction

Prior to design of baseline and monitoring studies, it is desirable to predict the location and extent of thermal plume. The area of impact will be that subject to a 'significant' temperature increment - experience suggests that this might be near-field areas of predicted ΔT 3°C and ΔT 1°C. In coastal areas the thermal plume is rarely static in either size or location and must be modelled for a variety of conditions. For practical, and conservative, considerations, the predicted area of impact should be the total area subjected to these conditions, i.e. ΔT 1^oC; it should include some measure of error and variability as indicated by the plume model.

This approach may result in engineering or operational modifications when the system is functioning and plume surveys have been made.

10.2.2 Impacted area prediction

Mathematical models for thermal discharge are an important tool for defining the immediately impacted area. The procedure to be followed is:

(i) analysis of the hydrographic, meteorological and hydrodynamic conditions at the site;

(ii) comparison of site conditions with assumptions and approximations made in the models (phenomenological, integral or numerical);

(iii) selection and development of a suitable complex model based on (ii);

(iv) selection of a sampling area to include a range of ambient and discharge conditions.

At this stage, possible inaccuracies in the model and natural ambient variability must be taken into account, site characteristics and model assumptions must be least in conflict, and all dominant site characteristics must be represented.

Despite some conceptual deficiencies, phenomenological and integral models can predict general trends in plume behaviour. Models of both kinds include only important ambient phenomena such as wind forcing, transient effects, or confining geometries. For complex sites, a numerical model may be the only practical method; more satisfactory predictions may be obtained, but a better understanding of existing conditions is required.

10.2.3 Biological assessment

At this stage, this need not require a rigorous sampling programme but experience and a generalized empirical approach will suffice to register major impacts at an early stage and to detect any site-specific problems. The degree of vulnerability to a thermal plume can be assessed by consideration of:

- predicted area of thermal influence, within $\Delta T \leq 3^oC$ and ΔT 1^oC;
- morphometric and surface indices between 0 and -5 m within these areas;
- rocky and soft substrates affected;
- primary production on rocky and soft substrates;
- secondary benthic production on soft substrates;
- fishing in 50 km^2 zone (commercial and recreational); commercial fishing in a larger regional context;
- proliferation of harmful or nuisance species (e.g. red tide);
- turbidity;
- differences in communities included in impacted zones.

At this stage the need for antifouling measures can be identified and the appropriate measures incorporated into the plant design.

This baseline information on plume configuration, impacted area prediction and identification of biological sensitivity should now be used to develop a sampling programme, both to establish baseline conditions and to monitor changes. Figure 4 illustrates how this information can be incorporated in the decision-making process.

10.3 <u>Further Studies and Monitoring Programmes</u>

These should be based on the considerations that

- they should be directed to potential problems;
- the baseline data obtained prior to development (over two years) will later include data from control stations; therefore, the relationships between all sampling stations must be established prior to construction;
- sampling should aim to reduce the natural 'noise'; for example, substrate differences can be overcome by using standardized fouling plates;
- sampling sites should be located on gradients away from the discharge, through a transition area and into non-impacted (control) areas;
- sampling sites should be located along the natural gradients of depth and salinity.

Initially, the area should be oversampled so as to provide continuity if the programme is later modified. Sampling stations may be reduced later without significant loss of information. Sampling should provide appropriate spatial resolution; stations spaced kilometers apart will not define changes over smaller distances. Changes over a large scale may be documented by repeated aerial surveys.

Measurements should include:

- natural variations in species composition, abundance and distribution;
- natural variations in physical, chemical, geological and meteorological phenomena that influence these populations;
- conditions predicted to change with the discharge; these include temperature, turbidity, light penetration, sediment deposition, direction and speed of water flow.

Biological sampling and other measurements should be collected at the same stations and at the same time to the extent practicable. Samples should be replicates at several sites, possibly on a grid within impacted, non-impacted and transition areas to allow statistical treatment. Sampling should be repetitive using a time scale to detect the period of natural variability, e.g. seasonal in temperate areas and in wet and dry periods in the tropics.

The discharge area of primary interest will be within the $\Delta T\ 3^{o}C$ and $\Delta T\ 1^{o}C$ isotherms. The biocide (or total residual oxidant) plume lies within the thermal plume, and measurements within the predicted thermal plume will thus include the impact of the 'chlorine' residual. Since the level of detection of biological change is low in the field, a high degree of accuracy in many field measurements will not improve overall accuracy.

A reference collection of organisms should be established to ensure taxonomic consistency throughout the programme. Methods of sampling should not be altered without intercalibrations.

Data management and analysis will call for a systematic approach. Data should be stored in computer files that allow rapid amendment and addition of new data as well as easy retrieval. A relational data base is recommended because it facilitates expansion, correction and retrieval as well as development of data matrices. Multi-variate analyses can be used to relate the biological data to the natural and discharge-related abiotic data. Standard statistical methods should be used to express probabilities which can then be interpreted in terms of biological significance. Limits of the sampling programme and data analysis should be carefully defined because it is possible that no biological change will be detected.

10.4 Evaluation and Assessment

The preliminary and baseline studies described will provide information which can be used as the basis for deciding whether planned developments, or the proposed designs, should be modified to ensure some further environmental protection. In particular, the recognition that fisheries, sensitive or endangered species, sensitive habitats, recreational or touristic resources, are at risk, or that the assimilative capacity of a water body receiving other wastes may be exceeded, may call for some form of mitigative action. This could lead, for example, to redesign of the intake or outfall, or relocation, alternatives to once-through cooling, or a reduction of the total capacity of a plant.

Continuation of environmental monitoring to validate initial assessments begins as the plant is commissioned and becomes operational. The validation process is an important part of any environmental impact assessment process since it provides the feedback needed for improving the sampling programme as well as to justify and monitor any later plant modifications. In some instances, changed conditions may mean that over time, different issues become paramount, calling for new information or different remedial actions.

If alternatives or remedial measures are proposed, it will be necessary to consider their energy demand and environmental conservation potential, their consequences for natural or other depletable resources, historic and cultural resources.

Whether these guidelines are followed exactly or within some other framework, the environmental impact assessment procedure should lead to a document that becomes an integral part of the decision process. As such, it should contain cost-benefit and risk assessments.

10.5 Validation - Information Access and Use

10.5.1 Model validation

It is important that data gathered in a monitoring programme be fully used. Aside from serving to monitor effects, well collected and organized field data can advance our understanding of complex field conditions and ecosystems. It is common experience that biological models of populations, processes and ecosystems lack sufficient data for their validation, a situation less critical for physical phenomena where quantitative data of definable precision and objectivity can be gathered more easily.

To assess a model's predictive capacity, i.e. to test the validity of approximations and idealizations made, comparison with post operational field data is necessary. To gain confidence in predictions and better insight into the physics of the plume-ambient interaction, synoptic plume surveys obtained for a wide variety of plant and ambient conditions are needed. Surface vessel or aerial surveys and dye studies can all be used. Each method has its own merits, but surface vessel surveys provide the most comprehensive three-dimensional measurements of the plume.

The interface between models of physical processes and biological processes is still relatively undeveloped (see section 4). Integral models would be a welcome advance and would help to ensure compatibility of physical, chemical and biological data.

10.5.2 Information exchange and data access

Much of the information available from studies on thermal discharges is published in the 'grey' literature or is proprietary information and so restricted in circulation and availability. To facilitate information exchange and data access, it is recommended that:

(i) scientific results from environmental impact studies be published promptly in readily accessible open literature;

(ii) 'grey' literature reports be submitted by authors or contractors to abstracting journals so that they are entered into information retrieval systems;

(iii) in case of restricted documents, at least the title of the document and its correct bibliographic citation (including key words) be entered into information retrieval systems, with the restriction noted.

Current abstracting journals and information retrieval systems relevant to the topic of environmental impact of thermal discharges are:

Aquatic Sciences and Fisheries Abstracts	(Dialog File No. 44)
Pollution Abstracts	(Dialog File No. 41)
Environline	(Dialog File No. 40)

Exchange of data or models between research groups with common interests would help to develop models and other methodologies and facilitate comparison between sites and conditions; this can be achieved by the usual scientific method, viz in conferences and seminars.

11. CONCLUSIONS AND RECOMMENDATIONS

- Evidence of environmental impact due to thermal discharges suggests that overall effects may become significant where larger heat discharges are proposed to areas of limited receiving capacity.

- The temperature rise of about 10^{o}C commonly used in power stations in temperate regions is inappropriate for tropical areas, where this temperature increment will approach or exceed the thermal tolerance limits of many organisms.

- Effects due to the discharge alone have to be distinguished from those due to impingement at the cooling water intake, and to entrainment in cooling water passing through a generating plant, so that appropriate remedial action can be taken, if required.

- Where fouling control is needed, damage due to biocide use has to be distinguished from that due to heat and other physical perturbations. A minimum treatment for fouling control should be determined (both concentrations and dose rate); alternatives should be considered.

- When open coastline sites of large receiving capacity are not available, or where economic or other considerations prevail, careful pre-operational assessment of social, economic and scientific impacts will have to be made. The option chosen will require some value judgements.

- Thermal effluents have a potential for mariculture in non-tropical regions to maintain stable, optimum growth conditions throughout the year. Although the heated discharge from some existing plants can be used for mariculture, it is advised that provision be made for this at the planning stage of new plants. Novel uses of rejected heat, e.g. coupling with other industry, should be kept in mind, as well as new initiatives for biological exploitations.

- Sampling programmes to provide information for environmental assessments must be carefully designed to meet identified objectives; they may have to continue over some years. New findings should be fed back so that decisions can be updated or modified.

- Regulatory action for thermal discharges to the marine environment should rely on the concept of receiving capacity and environmental quality objectives. Where transboundary transfer of pollutants may be involved, international or regional agreements will be needed.

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