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JOINT GROUP OF EXPERTS ON THE SCIENTIFIC ASPECTS OF MARINE POLLUTION
- GESAMP -

REPORTS AND STUDIES

No. 24 1984

THERMAL DISCHARGES IN THE MARINE ENVIRONMENT

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS

Reports and Studies No. 24

IMO/FAO/Unesco/WMO/WHO/IAEA/UN/UNEP
Joint Group of Experts on the Scientific Aspects
of Marine Pollution
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FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 1984

Notes

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DEFINITION OF MARINE POLLUTION

Pollution of the marine environment means: "The introduction by man, directly or indirectly, of substances or energy into the marine environment (including estuaries) which results 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".

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PREPARATION OF THIS STUDY

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 Kuzmić, Edward P. Myers, Heiner C.F. Naeve (Technical Secretary), Velimir Pravdić (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 sessions of the Working Group were 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).

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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 $10^{o}C$. 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.

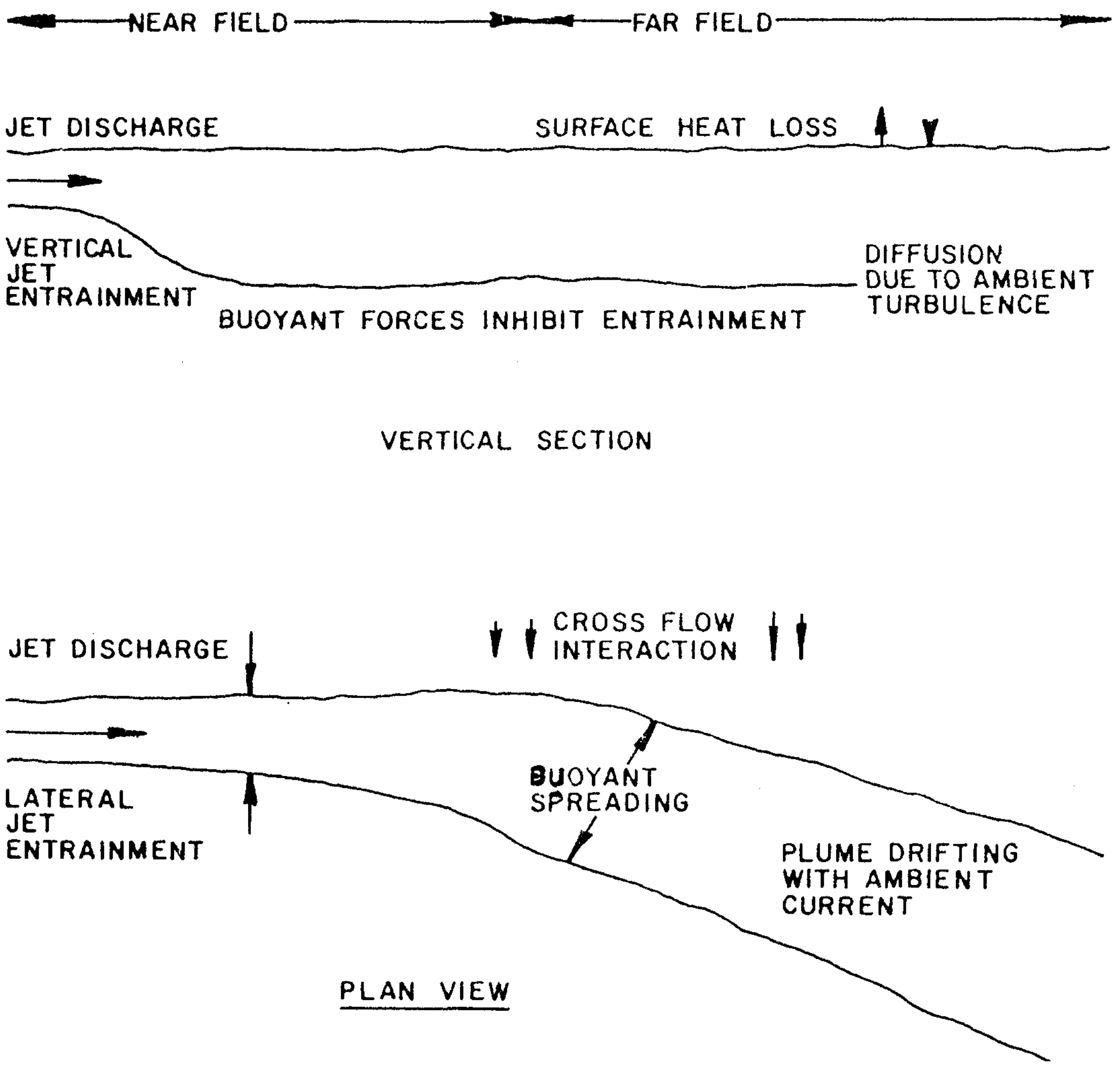

Figure 1. Schematic categorization of plume geometry according to physical processes

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°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°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°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.

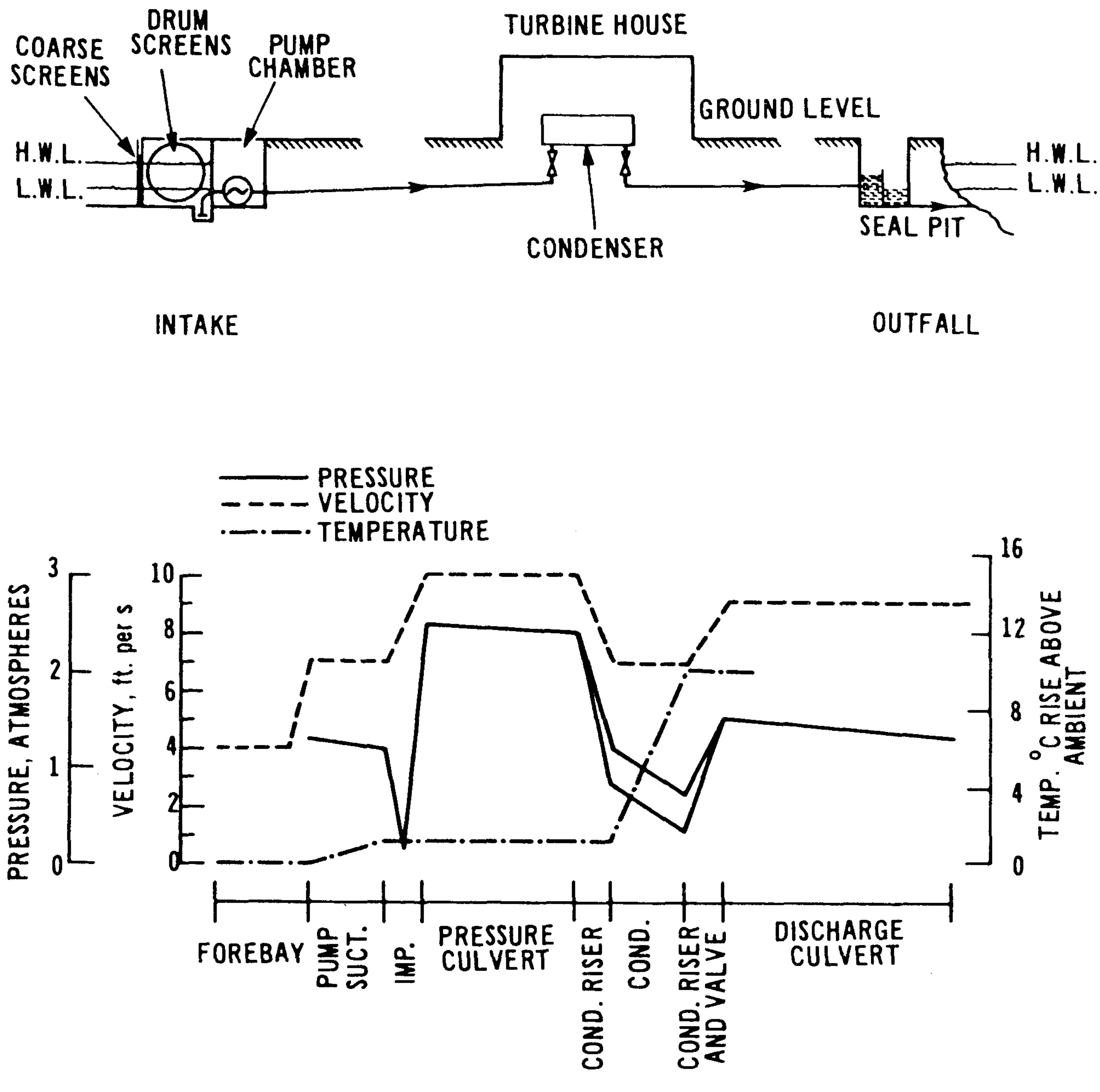

Figure 2. Hydraulic gradient for typical direct cooled c.w. system and associated changes of pressure, velocity and temperature
(from Howells, 1982)

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°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°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^{0}C across the plant, showed that above a threshold temperature (30-35^{0}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^{0}C. When ΔT was only 4.4 to 5.5^{0}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 heterctrophic 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.

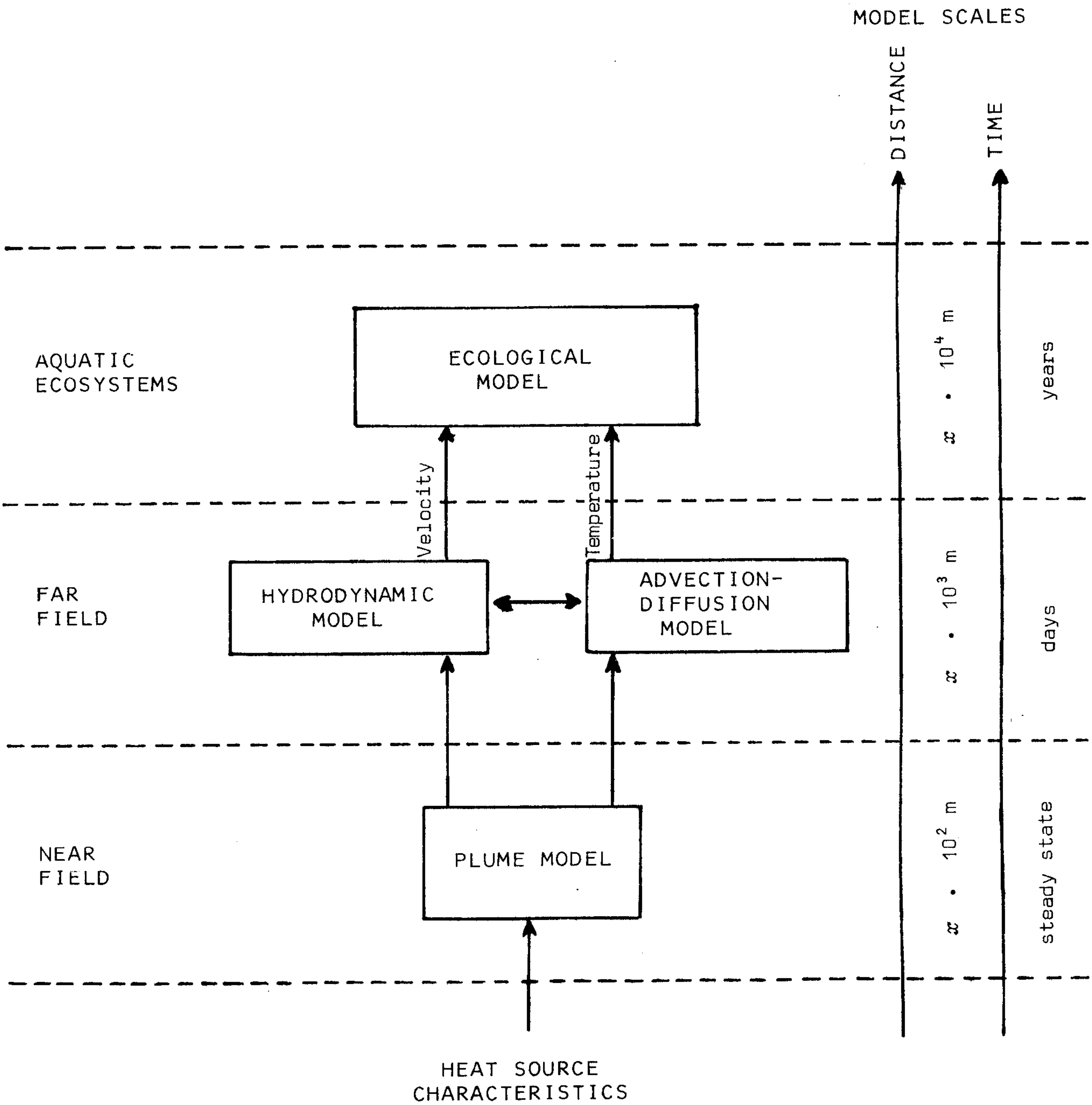

Figure 3. Characteristic zones and model types relevant for the assessment of heat disposal effects