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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.

CONTENTS

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.

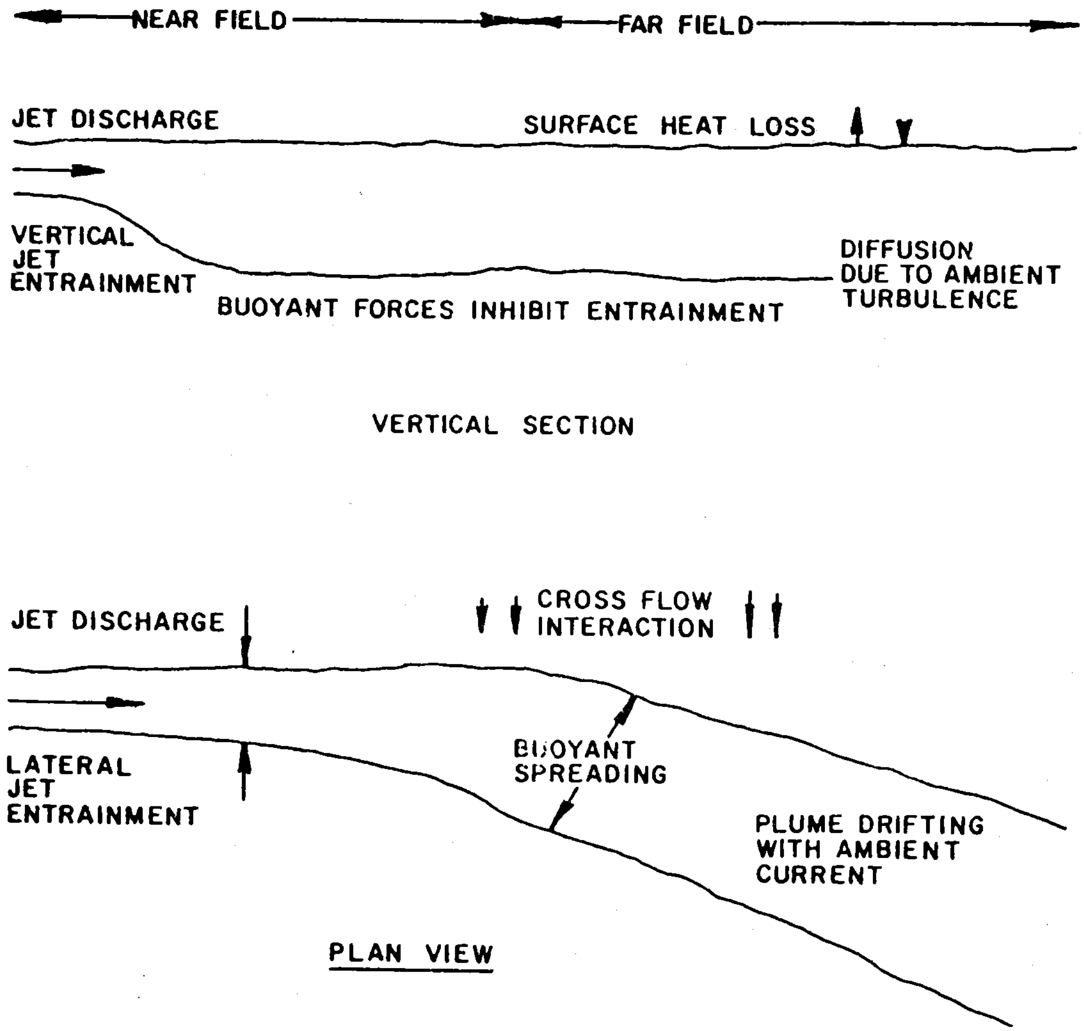

Figure 1. Schematic categorization of plume geometry according to physical processes

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:

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

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:

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

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.